Charnockitic magmatism in southern India

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Large charnockite massifs cover a substantial portion of the southern Indian granulite terrain. The older (late Archaean to early Proterozoic) charnockites occur in the northern part and the younger (late Proterozoic) charnockites occur in the southern part of this high-grade terrain. Among these, the older Biligirirangan hill, Shevroy hill and Nilgiri hill massifs are intermediate charnockites, with Pallavaram massif consisting dominantly of felsic charnockites. The charnockite massifs from northern Kerala and Cardamom hill show spatial association of intermediate and felsic charnockites, with the youngest Nagercoil massif consisting of felsic charnockites. Their igneous parentage is evident from a combination of features including field relations, mineralogy, petrography, thermobarometry, as well as distinct chemical features. The southern Indian charnockite massifs show similarity with high-Ba–Sr granitoids, with the tonalitic intermediate charnockites showing similarity with high-Ba–Sr granitoids with low K_2O/Na_2O ratios, and the felsic charnockites showing similarity with high-Ba–Sr granitoids with high K_2O/Na_2O ratios. A two-stage model is suggested for the formation of these charnockites. During the first stage there was a period of basalt underplating, with the ponding of alkaline mafic magmas. Partial melting of this mafic lower crust formed the charnockitic magmas. Here emplacement of basalt with low water content would lead to dehydration melting of the lower crust forming intermediate charnockites. Conversely, emplacement of hydrous basalt would result in melting at higher f_{H_2O} favoring production of more siliceous felsic charnockites. This model is correlated with two crustal thickening phases in southern India, one related to the accretion of the older crustal blocks on to the Archaean craton to the north and the other probably related to the collision between crustal fragments of East and West Gondwana in a supercontinent framework.

1. Introduction

Charnockites characterized by orthopyroxene-bearing granitic mineral assemblages are a common constituent of granulite-facies metamorphic terrains. However, the relative importance of igneous versus metamorphic processes involved in their origin is debated. They are either granitic rocks metamorphosed to the granulite facies (metamorphic charnockites; e.g., Newton *et al* 1980) or rocks whose pyroxene crystallized directly from magma (igneous charnockites; e.g., Wendlandt 1981). For

example, in Limpopo Belt, South Africa, Bohlen *et al* (1992) proposed *in situ* biotite dehydration to form orthopyroxene in the presence of a fluid phase with locally different activity of CO_2 for the metamorphic charnockite and crystallization from calc-alkaline magmas derived by partial melting of lower crustal rocks for the spatially associated igneous charnockite.

Charnockitic rocks usually show spatial association of rocks (charnockite–charnoenderbite–enderbite) differing in modal abundance of the dominant feldspar species. There is a

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Figure 1. $\text{Fe}^*/(\text{Fe}^* + \text{MgO})$ vs. SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs. SiO_2 plots illustrating the representative trends of I-type granitoids, A-type granitoids, intermediate charnockites, and felsic charnockites.

great deal of scientific literature covering the charnockite (opx-bearing granite)–charnoenderbite (opx-bearing granodiorite)–enderbite (opx-bearing tonalite) (Holland 1900; Tilley 1936; Le Maitre 2002) suite of rocks although no consensus exists about the origin of at least some charnockite occurrences including classic localities. A case of ongoing uncertainty is the origin of *arrested charnockite* in the Chilka Lake area, India. Dobmeier and Raith (2000) postulated that these rocks formed as a result of localized synkinematic fluid migration and were genetically linked to the host leptynite (garnet-biotite gneiss) in which they are enclosed. These authors also proposed that the charnockites are completely unrelated to enderbite layers in the same outcrops. In a comment, Bhattacharya and Sen (2002) claimed that many

rocks interpreted by Dobmeier and Raith (2000) as enderbite are, in reality, charnockites or charnoenderbites. Hence, Bhattacharya and Sen (2002) proposed a common origin for charnockite and enderbite at Chilka Lake. Charnockites, like granitoids, have a common compositional range and can be broadly divided into intermediate charnockites and felsic charnockites, with most reported occurrences showing variation from intermediate to felsic compositions (Rajesh 2004b). Intermediate charnockites are dominantly calc-alkalic (in terms of modified alkali-lime index) and ferroan to magnesian (in terms of Fe-number), while felsic charnockites are dominantly alkali-calcic and ferroan (figure 1). The relatively iron-enriched nature of felsic charnockites imparts to them a predominantly tholeiitic

Figure 2. Shaded relief image of southern India showing the distribution of major charnockite massifs (cf. Rajesh 2004b, c). Not all charnockite massifs are considered in this study. The different crustal blocks are also shown. TB – Trivandrum Block; NB – Northern Block.

affinity, in contrast to the predominantly calc-alkaline affinity of the intermediate charnockites (Rajesh 2004b).

The formation of charnockites may provide important constraints in trying to unravel the mechanisms involved in granulite formation, because their granitic and often undepleted chemistry, which is more akin to the melt fraction rather than the restite, precludes their formation by removal of a hydrous partial melt. As discussed by Kilpatrick and Ellis (1992), the high temperature origin of charnockites compared to I-type granitoids, together with their more enriched incompatible element abundances, clearly excludes the possibility that they represent the remelting of granulitic residues formed after the extraction of I-type granitoids, a model proposed for the origin of A-type granitoids by Collins *et al* (1982). Generation of charnockite magmas by high-temperature, water-deficient melting of mafic to intermediate, high-K sources compositionally similar to alkaline basalts or calc-alkaline basaltic andesites is one of the alternatives (e.g., Rajesh 2004a).

In the granulite-facies terrain of southern India, charnockites include intrusions of gabbroic and tonalitic-enderbitic composition occurring over large areas (massif igneous charnockites), massive

metamorphic charnockites showing relict compositional banding and obliteration of foliation with the adjacent gneiss, to patches and veins of charnockite (incipient charnockites), representing *in situ* stages of granulite formation driven by the influx of CO₂-rich fluids (carbonic metamorphism; Newton *et al* 1980). The aim of this paper is to focus on the characteristics of the magmatic charnockites (charnockite *hereafter*, unless otherwise mentioned) that constitute the major granulite masses in southern India. In the process we compile geochemical data of these massifs to discuss and develop an understanding of how geochemical characteristics relate to their source rocks, petrogenetic processes and tectonic environments.

2. Geologic setting

The southern granulite terrain (south of Dharwar craton) includes several regional *en echelon* Neoproterozoic shear zones which dissect the terrain into different Late Archaean and Proterozoic crustal blocks such as the Madras, Northern, Nilgiri, Madurai and Trivandrum blocks (Harris *et al* 1994) (figure 2). The northern part of the southern granulite terrain consists primarily of charnockite

massifs that form highland areas interspersed with lowlands consisting of felsic rocks generally in amphibolite facies (the Madras, Northern, and Nilgiri blocks). The nature of contacts between highland and lowland rocks is highly controversial, with faults suggested, but not proved, at many of the boundaries of the massifs. With the exception of granitoids, carbonatites, and ultramafic rocks, Pan-African ages are absent from the northern part of this granulite terrain. Granulite-facies metamorphism affected the area at *ca.* 2.5 Ga and 2.8–3.0 Ga. The Nilgiri block was metamorphosed under medium-high pressure (6–10 kbar; Harris *et al* 1982; Janardhan *et al* 1982; Raith *et al* 1990) granulite facies conditions, while Northern and Madras block was metamorphosed under slightly lower pressures (7.5–8 kbar (Janardhan *et al* 1982; Condie and Allen 1984; Rao *et al* 1991) and 6.5–7.5 kbar (Bhattacharya and Sen 1986), respectively) at *ca.* 2.5 Ga (Griffiths *et al* 1987; Jayananda and Peucat 1996). A noteworthy feature of the granulite-facies transition zone, north of the Biligirirangan hills, is the occurrence of discrete veins and nebulous patches of incipient (metamorphic) charnockites (Pichamuthu 1960; Friend 1981; Janardhan *et al* 1982; Stahle *et al* 1987; Naha *et al* 1993). The non-garnetiferous charnockites of the Biligirirangan hill massif probably form the oldest charnockite massif in southern India. The magmatic protoliths of the charnockites from the Biligirirangan hills accreted at 3.47 Ga (see Jayananda and Peucat 1996). Mahabaleswar *et al* (1995) and Mojzsis *et al* (2003) presented zircon ages of 2.96 Ga for magmatic protoliths of charnockites from the northern fringes of Biligirirangan hill massif. Vinogradov *et al* (1964), Crawford (1969), and Griffiths *et al* (1987) reported 2.55–2.6 Ga ages for charnockites from the Madras block. Similar ages (2.5–2.6 Ga) have been reported for charnockites from the Nilgiri and Shevroy hill massifs (Spoonner and Fairbairn 1970; Peucat *et al* 1993; Jayananda and Peucat 1996; Raith *et al* 1999). These charnockite massifs together represent a stage of late Archaean to early Proterozoic juvenile magmatism in the northern part of southern Indian granulite terrain. Nd-model ages from the Biligirirangan hill range from 3.2–3.6 Ga (Jayananda and Peucat 1996), those from the Shevroy hill range from 2.7–2.9 Ga (Peucat *et al* 1989), those from the Madras block range from 2.35–2.8 Ga (Griffiths *et al* 1987), and those from the Nilgiri block range from 2.6–2.9 Ga (Peucat *et al* 1989; Raith *et al* 1999).

The southern part of the granulite terrain contains the same type of highland charnockite massifs (Madurai block) and lowland gneisses as the area north of the zone. In contrast to the northern part of the granulite terrain, the area south

of Palghat-Cauvery shear zone contains ample evidence for Pan-African activity (metamorphism and magmatism). Compared to the older charnockite massifs from Madras-Northern-Nilgiri blocks, the Madurai and Trivandrum blocks expose early- to late-Proterozoic charnockite massifs (Bartlett *et al* 1995; Jayananda *et al* 1995; Miller *et al* 1996; Mohan and Jayananda 1999). Recent studies from Madurai block have suggested a polymetamorphic and multistage P-T (700–1000°C and 5–12 kbar; Harris *et al* 1982; Mohan and Windley 1993; Raith *et al* 1997; Satish Kumar *et al* 2002) evolution for the terrane. Nd-model ages from the Madurai block range from 2.1–3.1 Ga (Harris *et al* 1994; Bartlett *et al* 1998).

The Achankovil Shear Zone marks the southern limit of the Madurai Block and the northern limit of the Trivandrum Block. The Trivandrum Block is subdivided on lithological grounds into three tectonic units; the Kerala Khondalite Belt (KKB), the Nagercoil unit and the Achankovil metasediments. Single zircon evaporation and EPMA monazite ages suggest that all the three units experienced a thermal event possibly under upper-amphibolite facies at ~1800 Ma (Bartlett *et al* 1998; Braun *et al* 1998). This event was overprinted by the granulite facies metamorphism at *ca.* 540–600 Ma at conditions of 750–1050°C and 5–9.5 kbar (Santosh *et al* 1990; Chacko *et al* 1996; Kumar and Harley 2000; Cenko *et al* 2002). The KKB is a predominantly metasedimentary complex characterized by inter-layered pelitic and semi-pelitic metasediments and calc-silicates, deposited under shallow marine conditions (Chacko *et al* 1987). The KKB became well known through its spectacular exposures of incipient (metamorphic) charnockite formation (Hansen *et al* 1987; Jackson *et al* 1988; Santosh *et al* 1990; Raith and Srikantappa 1993; Harley and Santosh 1995; Rajesh 2004a), and was accreted to the late-Archaean and Proterozoic granulite terranes in the north during the Pan-African orogeny (Choudhary *et al* 1992; Harris *et al* 1994). The southernmost tip of India is composed of charnockites and charnoenderbites (Nagercoil unit), and geochronologic studies suggested that they experienced a similar crustal history to the KKB. Nd modal ages from the Achankovil metasediments range from 1.3–1.5 Ga, from the KKB range from 2.1–3 Ga, and from the Nagercoil unit range from 2.1–2.57 Ga (Harris *et al* 1994; Brandon and Meen 1995; Warriar *et al* 1995; Bartlett *et al* 1998).

3. Salient field and petrographic features of the charnockite massifs

From north to south, the charnockite massifs considered here are the Pallavaram, Shevroy hill,

Biligirirangan hill, Nilgiri hill, northern Kerala, Cardamom hill, and Nagercoil massifs (figure 2). Most of the exposed rocks of these massifs comprise intermediate type (enderbites) and/or felsic type (charnoenderbites to charnockites). Together they cover a substantial portion of the continental crust in southern India. Their greenish to greenish-yellow colour in fresh outcrops, unusual for granitic rocks, is due, at least in part, to fine alteration and fracture fillings in the feldspars. Both types usually have a dark greasy homogenous and massive appearance in quarry exposures. Some of the massive charnockite exposures show streaky gneissic foliation and signs of retrogression (retrogressed portions are lighter in colour). On weathered surfaces, the essentially gneissic nature of the rocks becomes evident. The lineation, generally parallel to the foliation, observed in some of the massifs is made conspicuous by the differential weathering of feldspars and quartz. Although all the massifs show overprints of subsequent granulite facies metamorphism, the igneous nature of their protoliths is evident from a combination of some or all of the following features: outcrop pattern, intrusive relationship with the surrounding rocks, homogeneity at outcrop scale, presence of enclaves and xenoliths, cross-cutting charnockitic dikes, *in situ* development of ($\pm$ orthopyroxene bearing) pegmatoids, granitic textures, observed order of crystallization of primary minerals, as well as distinct chemical features (see below).

The Pallavaram massif consists mainly of felsic charnockites (charnoenderbites to charnockites) and minor intermediate charnockites (enderbites). Garnet is present in the felsic charnockites. Both the Shevroy hill and Biligirirangan hill massifs consist of intermediate charnockites (enderbites), with the former bearing garnet and the latter garnet-free. When present, garnet usually shows inhomogeneous distribution, sometimes occurring in local lenses and bands. Dark gray bands and lenses of mafic charnockite occur within the Shevroy hill charnockites. The Nilgiri hill massif is composed of intermediate charnockites (minor, but distinct, non-garnetiferous enderbites to dominant garnetiferous enderbites). The garnetiferous enderbites show prominent gneissic layering and are characterized by the compositional and structural uniformity throughout the massif. Dolerite dykes cut across both the Nilgiri hill and Biligirirangan hill massifs. Neoproterozoic shear zones partly bound and separate the Shevroy, Biligirirangan and Nilgiri hill massifs (figure 2). Continuous layers of metasedimentary gneisses (garnet-sillimanite gneiss and minor garnet-biotite gneiss) bound the Pallavaram and Shevroy hill massifs. Within these gneisses, lensoid masses of mafic granulites and calc-silicate rocks, and boudinaged alkali

pegmatites are common. Boudinaged enclaves of mafic granulites are common in the massifs, whereas ultramafic and Fe-rich layers are found only in the intermediate massifs. Except the Biligirirangan hill massif, other massifs contain less significant amount of metasedimentary layers/swathes. The rare metasedimentary intercalations in the Nilgiri hill massif include banded magnetite quartzites, kyanite and garnet bearing quartzites, and garnetiferous gneisses. The occurrence of xenoliths (basic (pyroxene- or garnet-bearing) granulites, pyroxenites) in the charnockite massifs and the presence of dykes of pyroxene-bearing granite cutting amphibolite facies rocks suggests hot, dry magmas.

Dark greenish-gray colored intermediate charnockites (enderbites) form the dominant rock type in the northern Kerala massif. The spatially associated felsic charnockites (charnoenderbites to charnockites) form a minor, but distinct, rock type in the northern Kerala massif. Basic rock enclaves are present in both charnockites. Granitic veins cut across several exposures of the northern Kerala massif, causing retrogression of the host charnockites. The rocks along the retrogressed areas are lighter in color and are mostly devoid of orthopyroxene. They contain amphibole and biotite, which impart gneissosity to the rocks. The northern Kerala massif is bounded by biotite-hornblende gneiss/hornblende-biotite gneiss, often carrying boudins and bands (dykes) of amphibolite, and mica schist. Dolerite dykes cut across all the rock types including charnockite.

Like the northern Kerala massif, the Cardamom hill massif is also composed of intermediate and felsic charnockites. A very weak foliation trending NW-SE, imparted by biotite, is seen in some of its charnockite exposures. Metasedimentary rocks in the south and hornblende-biotite gneiss/biotite-hornblende gneiss in the north, bound the Cardamom Hill massif. The gneissic exposures in the south show variations from garnet-biotite gneiss to migmatitic garnet gneiss to cordierite gneiss. Some of the gneissic exposures exhibit incipient (metamorphic) charnockitic patches. The Nagercoil charnockite massif is composed of garnetiferous and non-garnetiferous felsic charnockites and is bounded by garnet-biotite gneiss and minor garnet-biotite-sillimanite $\pm$ graphite gneiss. Apart from a weak foliation developed at places, the charnockite generally shows a massive texture. Pyroxene granulite bands, mafic dykes, and metapelite or calc-silicate enclaves occur within the charnockite massif. Some metapelite lenses show very diffuse margins, laterally grading into the host charnockite. Garnet is present only in those areas where the charnockite encloses supracrustal lithologies, and shows pronounced foliation. The gneissic rocks

show variations from a predominant garnet-biotite gneissic rock, through an intercalated rock of garnet-biotite gneiss and garnet leuco-gneiss, to bands of augen gneiss. Irregular patches (~ 0.5 to 20 cm) and veins of charnockite (incipient (metamorphic) charnockite) are spectacularly exposed in some of the garnet-biotite gneiss exposures.

The common mineral assemblage of the Pallavaram and Shevroy hill massifs is $\text{qtz-kfs-plg-opx} \pm \text{cpx} \pm \text{grt} \pm \text{hbl} \pm \text{bt-ap-zr-mt-il-ru-pyrr}$. The mafic charnockite from the Shevroy hill massif has a dominant mineralogy of $\text{plg-cpx-opx-hbl-mt-il-ru} \pm \text{kfs} \pm \text{bt-ap-zr}$. The non-garnetiferous enderbites from both the Biligirirangan and Nilgiri hill massifs have a similar mineralogy of $\text{qtz-plg-kfs-cpx-opx} \pm \text{hbl} \pm \text{bt-ap-zr-mt-il-ru-pyrr}$. The most commonly encountered mineral assemblage of intermediate type northern Kerala massif is $\text{qtz-plg-opx-cpx-mt-il-ap-zr} \pm \text{kfs} \pm \text{hbl} \pm \text{bt} \pm \text{grt}$, and that of felsic type northern Kerala massif is $\text{qtz-kfs-plg-opx} \pm \text{cpx-hbl-bt-zr-ap-ru-ti}$. Garnet accompanies the intermediate type northern Kerala massif occasionally. The felsic type Cardamom hill massif has a dominant mineralogy of $\text{qtz-kfs-plg-opx-mt-il-zr-ap} \pm \text{hbl} \pm \text{bt}$, while the intermediate type Cardamom hill massif has mineralogy of $\text{qtz-plg-kfs-opx-cpx} \pm \text{hbl} \pm \text{bt-mt-il-ru-zr-ap}$. Nagercoil massif charnockites show a common mineral assemblage of $\text{qtz-plg-kfs-opx-bt-il-zr-ap} \pm \text{grt}$. In general the intermediate charnockites are distinguished from felsic charnockites by their relatively low K-feldspar contents, and greater mafic mineral contents. Garnet is usually absent or of small abundance in intermediate charnockites than in the felsic charnockites. The ubiquitous (but quite unevenly distributed) occurrence of perthite, antiperthite and/or coarse mesoperthites, clinopyroxene exsolution and/or pyrrhotite in these rocks is suggestive of the crystallization of the host rock at elevated temperatures.

Compositionally the intermediate Shevroy hill charnockites range from quartz monzodiorite to tonalite and granodiorite, the intermediate Biligirirangan hill and Nilgiri hill charnockites show similar compositional range from tonalite to granodiorite, the intermediate Nilgiri hill charnockites range from quartz diorite to tonalite to granodiorite, the intermediate northern Kerala charnockites range from quartz diorite to tonalite, whereas the intermediate Cardamom hill charnockites range from diorite to quartz monzodiorite in the normative $\text{Qz-Or-Ab} + \text{An}$ ternary plot. Regarding the felsic charnockites, those from the northern Kerala and Cardamom hill massifs show similar compositional range from granodiorite to monzogranite, while those from the Pallavaram and Nagercoil massifs show similar compositional variation from quartz monzodiorite to granodiorite to

monzogranite. In the Q - P cationic classification of Debon and LeFort (1988), they show similar compositional range with the exception of the most felsic samples falling in the granite field; the overall trend of intermediate charnockites being calc-alkaline and felsic charnockites tholeiitic.

4. Whole-rock geochemical variations

Howie (1955), Howie and Subramaniam (1957), Subramaniam (1959), Weaver *et al* (1978), Weaver (1980), Condie *et al* (1982), Condie and Allen (1984), and Griffiths *et al* (1987) presented geochemical data on the Pallavaram and Shevroy hill massifs. Except a few intermediate samples ($\text{SiO}_2 \sim 54$ to 59 wt%), the Pallavaram felsic charnockites show high silica content from ~ 64 to 77 wt%. The Shevroy intermediate charnockites ($\text{SiO}_2 \sim 54$ to 72 wt%) are characterized by higher contents of TiO_2 , Al_2O_3 , total Fe, MgO, CaO, Na_2O and P_2O_5 , but lower K_2O contents than the Pallavaram felsic charnockites. In the normative An-Ab-Or triplot, intermediate charnockite compositions (Shevroy hill and Pallavaram massifs) fall mainly in the tonalite field, while the felsic charnockite compositions (Pallavaram massif) show an extended compositional range up to the granite field (figure 3). Condie and Allen (1984), Janardhan *et al* (1994), Srikantappa (1996) and Raith *et al* (1999) presented geochemical data on the Biligirirangan hill and Nilgiri hill intermediate charnockite massifs. The non-garnetiferous charnockites ($\text{SiO}_2 \sim 57$ to 61 wt%) from the Nilgiri hill massif are characterized by higher contents of TiO_2 , Al_2O_3 , CaO, Na_2O , P_2O_5 , Sr, and Ba, but lower Rb contents than the garnetiferous charnockites ($\text{SiO}_2 \sim 63$ to 71 wt%). Raith *et al* (1999) suggested that the garnetiferous charnockites exhibit dominant compositional features of S-type granitoids, while the non-garnetiferous charnockites exhibit compositional features of I-type granitoids. The overlapping nature of the compositions of I-type and S-type granitoids is now evident worldwide. Even the I-type and S-type granitoid types in the Lachlan Fold Belt, which was originally used by Chappell and White (1974) to propose the S- and I- type granitoid classification, form an overlapping chemical and isotopic array (Collins 1996). Our geochemical discrimination points to the dominant I-type affinity of the Nilgiri hill intermediate charnockites (figures 4a, 4c and 4d). In this context, it is important to point out that Rajesh (2004b) illustrated the similarity of some intermediate charnockites to the geochemical characteristics of fractionated I-type granitoids, while the geochemical characteristics of felsic charnockites are more comparable to that

Figure 3. Comparison of southern Indian charnockite massifs compositions in normative An-Ab-Or ternary diagram. Glasses from various dehydration-melting studies of alkali basalt are plotted in the first plot. The dashed arrow pointing upward is the trend of glass compositions with increasing temperature. The dashed arrow pointing downward is the trend of glass compositions with increasing X_{CO_2} in the system alkali basalt- H_2O - CO_2 . Experimental melt compositions (Sen and Dunn 1994) from amphibolite dehydration (vertically ruled field) at 1.5 and 2.0 GPa, with the arrow (solid line) showing the change in composition of melts with increasing temperature is also shown. The corresponding experimental starting composition (source) is indicated by the star symbol.

Figure 4. (a) Na_2O vs. K_2O plot illustrating the dominant I-type affinity of both non-garnetiferous and garnetiferous intermediate charnockites from Nilgiri hill massif. The dividing line between I-type and S-type granitoids is from White and Chappell (1983). (b) Bar diagram illustrating the variation in $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of southern Indian charnockites. In the case of northern Kerala and Cardamom hill massifs, the range to left represents intermediate charnockites while the range to the right represents felsic charnockites. (c) and (d) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs. SiO_2 and $\text{Fe}^*/(\text{Fe}^* + \text{MgO})$ vs. SiO_2 plots illustrating the similarity of southern Indian charnockites to intermediate and felsic charnockites worldwide. The ranges of I-type and S-type granitoids are from the compilations of Frost *et al* (2001). The ranges of intermediate and felsic charnockites are from Rajesh (2004b). Intermediate charnockites are shown by filled symbols and felsic charnockites are shown by open symbols.

of A-type granitoids, and is often referred to in the literature as A-type charnockites (e.g., Zhou *et al* 1995). Compositionally, the non-garnetiferous intermediate charnockites from the Nilgiri hill massif fall in the tonalite field while the garnetiferous intermediate charnockites fall in the tonalite-granodiorite fields (figure 3). They exhibit calc-alkaline affinities, with the garnetiferous intermediate charnockite samples falling close to the field boundary of the tholeiitic series. The older non-garnetiferous intermediate charnockites from Biligirirangan massif ($\text{SiO}_2 \sim 68$ to 75 wt%) have lower contents of TiO_2 , total Fe, MgO, Zn, V, Cr, and higher Al_2O_3 , $\text{Na}_2\text{O} + \text{K}_2\text{O}$, Rb than the Nilgiri intermediate charnockites (Condie and Allen 1984; Raith *et al* 1999). Compositionally, the Biligirirangan intermediate charnockites cluster across the trondhjemite-tonalite field boundary (figure 3) and display a calc-alkaline trend.

Nambiar *et al* (1992) and Rajesh (2004b) presented geochemical data on the northern Kerala charnockites. Chacko *et al* (1992) presented geochemical data on the Cardamom hill charnockites. Both the intermediate ($\text{SiO}_2 \sim 53$ to 59 wt%) and felsic ($\text{SiO}_2 \sim 66$ to 69 wt%) Cardamom hill charnockites show similar major and trace element trends as well as compositional ranges (tonalite (intermediate charnockites) to granodiorite-granite (felsic charnockites)) as their northern Kerala massif counterparts (intermediate type ($\text{SiO}_2 \sim 55$ to 67 wt%); felsic type ($\text{SiO}_2 \sim 68$ to 75 wt%)) (figure 3). They display a typical calc-alkaline trend close to the field boundary to the tholeiitic series. Srikantappa *et al* (1985) and Santosh *et al* (2004) presented geochemical data on the Nagercoil felsic charnockites. Both the garnetiferous ($\text{SiO}_2 \sim 61$ to 71 wt%) and non-garnetiferous ($\text{SiO}_2 \sim 62$ to 72 wt%) charnockites show similar compositional ranges of tonalite-granodiorite-granite, with the non-garnetiferous charnockite compositions showing an extended range (figure 3). They typically display a calc-alkaline to tholeiitic trend.

In general the intermediate charnockites fall mainly in the tonalite field, while the felsic charnockite compositions show an extended compositional range up to the granite field. Both the intermediate and felsic charnockites from each massif have quite different $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios, with the latter having a higher and extended range than the former (figure 4b). In terms of Fe-number all the intermediate charnockites are magnesian, with felsic charnockites showing magnesian to dominantly ferroan compositions (figure 4c). Although intermediate samples show calc-alkalic to calcic affinity (in terms of the modified alkali-lime index), felsic samples show variations from alkali-calcic to calc-alkalic to calcic (figure 4d).

In terms of alumina saturation index, all the charnockite massifs are metaluminous to peraluminous with peraluminous compositions in the high SiO_2 samples. The major element characteristics of these charnockite massifs are similar to intermediate and felsic charnockites worldwide (Rajesh 2004b).

Although Condie *et al* (1982), Condie and Allen (1984), Janardhan *et al* (1994) and Raith *et al* (1999) reported significant depletion of Rb in Archaean charnockites from the northern part of the southern Indian granulite terrain, Subramaniam (1959), Weaver *et al* (1978) and Weaver (1980) reported Rb enrichment from the Archaean Pallavaram massif. Further Raith *et al* (1999) also reported Rb enrichment (with significant Rb depletion with increase in silica content) from the Archaean Biligirirangan massif, implying that Rb depletion is not unique in Archaean southern Indian charnockites. The younger charnockite massifs from the Madurai and Trivandrum blocks invariably show Rb enrichment. Significantly all the charnockite massifs from southern India are rich in Ba and Sr, similar to high-Ba-Sr granitoids (Tarney and Jones 1994) (figure 5). Generally, the traditional I-, S- and A-type granitoids possess low Ba and Sr concentrations (hence, denominated together as low-Ba-Sr granitoids) (figure 5a). However, Tarney and Jones (1994) identified an additional type, named high-Ba-Sr granitoids, that exhibits many trace-element characteristics distinct from the low-Ba-Sr granitoids. In general intermediate charnockites show similarity to high-Ba-Sr granitoids with low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios, similar to adakites, while felsic charnockites show similarity to high-Ba-Sr granitoids with high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios, which are different from adakites (figure 5b; Rajesh 2004b).

Rare earth element patterns are similar for the different charnockite massifs with slightly fractionated, LREE enriched, and HREE depleted patterns; the main difference being the presence or absence of (positive and/or negative) Eu anomaly. Some of the Biligirirangan hill massif samples show positive Eu anomalies, while the Shevroy hill massif samples show both negative and positive Eu anomalies. The Nilgiri hill non-garnetiferous intermediate charnockites are characterized by the absence of an Eu anomaly, while the garnetiferous variety is characterized by a slightly negative Eu anomaly. Although overall rare earth element concentrations of charnockites from the northern Kerala and Cardamom hill massifs are similar, the latter are distinguished by pronounced negative Eu anomalies, while Eu anomalies are modest in the former and range from slightly negative to slightly positive.

Figure 5. (a) Sr–Rb–Ba and (b) Na–K–Ca triplots for the charnockite massifs from southern India. Same symbology as in figure 4, with intermediate charnockite from different massifs, except Shevroy hill (filled triangle) and Biligirirangan hill (filled down triangle) massifs, shown by open symbols for clarity. Fields of high-Ba–Sr and low-Ba–Sr granitoids are based on data from Fowler and Henney (1996) and Fowler *et al* (2001). See Rajesh (2004b) for the references on adakite compositions. The dashed line in figure 5b running upward indicates calc-alkaline trend, while that running sideways indicates trondhjemitic trend.

5. Conditions of crystallization

The higher Ti and P, in comparison to spatially associated granitoids (e.g., Rajesh *et al* 1996; Rajesh 1999, 2000, 2003, 2004a, b) correspond to higher saturation temperatures for Fe–Ti oxides

and apatite in the charnockites (Watson and Harrison 1983; Green and Pearson 1986). Temperature estimates based on zircon solubilities in felsic liquids (Watson and Harrison 1983) range from ~ 953 to 679°C for the Pallavaram massif, ~ 850 to 800°C for the Biligirirangan hill massif,

~ 857 to 776°C for the Shevroy hill massif, ~ 1036 to 778°C for the Nilgiri hill massif, ~ 940 to 700°C for the northern Kerala massif, ~ 920 to 750°C for the Cardamom hill massif, and ~ 936 to 813°C for the Nagercoil massif. Crystallization temperatures of ~ 900 to 1000°C are supported by the high TiO₂ and/or P₂O₅ contents of the least evolved samples of these massifs. Application of QUILF calculation (Andersen *et al* 1993) on co-existing pyroxenes (Weaver *et al* 1978; Rajesh 1999) yielded crystallization temperatures of 840 to 710°C and 960 to 860°C for the Pallavaram and northern Kerala massifs respectively. Available pressure estimates from these massifs range from 6 to 9 kbar (Condie and Allen 1984; Raith *et al* 1990; Nambiar *et al* 1992; Rajesh 1999; Santosh *et al* 2003).

When compared with liquidus phase relations in the system Q-Ab-Or, the felsic charnockite compositions spread around the minimum. Whilst intermediate charnockitic melts are clearly not minimum melts, they occur parallel to the Q-Ab sideline in the Q-Ab-Or plot. The non-garnetiferous intermediate charnockites occur towards the Ab corner and garnetiferous intermediate charnockites occur towards the Q corner parallel to the Q-Ab sideline. The shift of the minima (from intermediate charnockite compositions) toward the Q-Or sideline allows more potassic non-minimum melts (felsic charnockites) to be generated. Further various experimental studies have shown that, with decreasing aH₂O there is a decrease in Ab/Or ratio of the melt (e.g., Holtz *et al* 1992). The melt compositions become enriched in normative orthoclase at the expense of plagioclase (e.g., Holtz and Johannes 1994). The magnesian intermediate charnockites probably show a close affinity to relatively hydrous, oxidizing magmas, while the ferroan felsic charnockites probably show a close affinity to relatively anhydrous, reduced magmas.

6. Tectonic scenario

It is now widely accepted that trace element components of granitoids are a function of the sources and crystallization history of the rock; the tectonic environment is secondary. Hence no traditional trace element discrimination (e.g., Rb vs. Y+Nb; Pearce *et al* 1984) was attempted to delineate tectonic environments. Charnockites are likely to have formed in collision settings where substantial crustal thickening occurs (e.g., Zhao *et al* 1997; Percival and Mortensen 2002; Rajesh 2004b). Many collision zones display associations of calc-alkaline to alkaline magmatism, which are closely related in space and time. Pearce *et al* (1990) used the composition of volcanic rocks from

eastern Anatolia to argue that derivation from the mantle above an earlier subduction gives a calc-alkaline character and derivation from the lithosphere beneath the passive margin gives an alkaline character. In southern India intermediate charnockites generally display a calc-alkaline trend whereas felsic charnockites show a trend of iron-enrichment, comparable to that displayed by alkaline rocks.

In collisional tectonic settings where island arc material has been thrust into deeper levels of the crust or simply accreted from beneath, the formation of tonalite melt and hbl-bearing, opx-bearing charnockites is likely. If higher pressures are achieved, garnet will also be a part of these charnockites. In the case of southern India, geochronologic data from the Dharwar craton indicate a major thermal and accretional event close to 2.5 Ga, where 3.0–3.4 Ga protoliths (post-accretional) and 2.5–2.6 Ga protoliths (syn-accretional) were involved (Jayananda and Peucat 1996). The older non-garnetiferous and garnetiferous charnockites probably represent the accretion of the Madras–Northern–Nilgiri blocks to the Archaean craton in the north. This corresponds to the major thermal and accretional event close to 2.5 Ga (see geologic setting section). In the case of Biligirirangan hill massif, the time gap between crust formation and regional high-grade metamorphism characterizes it as post-accretional (Peucat *et al* 1989) and probably represents the deeply buried southernmost extension of the Dharwar craton (Pichamuthu 1965). The younger charnockites, covered in this study, from Madurai and Trivandrum blocks are considered in a supercontinent framework and were probably related to the collision between crustal fragments of East and West Gondwana (~ 700–650 Ma; Stern 1994), as this event most likely resulted in substantial crustal thickening (Rajesh 2004a). This period is probably characterized by basaltic underplating (Rajesh 2004a), hence the ponding of magmas at the base of the crust, resulting in the formation of anorthosites (e.g., Ashwal *et al* 1998; Jacobs *et al* 1998) and/or igneous charnockites (e.g., Kröner *et al* 2000; Rajesh 2004a, b) at different parts along the Gondwana suture (the continuation of the East African orogen (Stern 1994) into the East Antarctic orogen (Jacobs *et al* 1998)).

7. Petrogenesis of charnockites

7.1 Nature of the source and petrogenetic process

The composition of the source plays a critical role in determining the major-element chemistry

of the melt. Partial melting experiments have shown that granitoid magmas can be produced from a wide range of common rocks at geologically realistic temperatures and pressures, and are characterized by distinct chemical signatures that allow for discrimination between compositionally different protoliths (figure 6). The chemical compositions of the least evolved samples from the southern Indian charnockites seem to be broadly compatible with a basaltic source (figure 6). Ferrodiorite is probably a more likely protolith for the petrogenesis of charnockites by crustal melting than basalt because it has a lower melting point than basalt, and ferro-basalts are found in many extensional settings (Frost and Frost 1997). Scoates *et al* (1996) showed experimentally that melts of ferrodioritic source compositions are monzonitic. But opx-bearing monzonites (mangerites; Le Maitre *et al* 2002) have not been found among the southern Indian charnockites considered in this study.

Although all the southern Indian charnockite massifs, considered here, are thought to be of igneous parentage there is an exception in the literature. Condie and Allen (1984) and Peucat *et al* (1989) suggested an igneous parentage for the Nilgiri charnockites, while Raith *et al* (1999) indicated a sedimentary parentage for the precursor rocks of the garnetiferous intermediate charnockites of this massif. Raith *et al* (1999) used major element discrimination ($ASI > 1.1$; negative values of discriminant factor (DF) of Shaw (1972)) and oxygen isotope data to suggest a sedimentary (psammite and pelite-dominated greywacke-type) provenance for the garnetiferous intermediate charnockites. Although strongly peraluminous ($ASI > 1.1$) melts, like Nilgiri garnetiferous intermediate charnockites, are commonly taken to have formed from a sedimentary source (Chappell and White 1974), they may also form by melting of biotite-bearing metaluminous felsic rocks (Miller 1985) or even by water-excess melting of mafic rocks (Ellis and Thompson 1986). The use of a different set of geochemical discrimination factors (other than the DF factor) does not rule out the igneous affinity of the source rock of Nilgiri enderbites (figure 7). Further, igneous enclaves present within both garnetiferous and non-garnetiferous enderbites from the Nilgiri hill massif indicates that more mafic magmas and/or other igneous sources may have been involved in the origin of both types of magma.

From a geochemical point of view, metapelites, metagreywackes, felsic orthogneisses and amphibolites all constitute possible sources for the production of peraluminous garnetiferous Nilgiri intermediate charnockites. Melting experiments on pelitic sediments show that they tend to produce

Figure 6. Major element compositions of the southern Indian charnockite samples plotted as a ratio between two variables versus the sum of the same variables. Compositions of melts generated experimentally by dehydration melting of a wide range of bulk compositions are also shown (see Patiño Douce (1999) and Rajesh (1999) for the compilation and sources of data). Same symbology as in figure 5, with non-garnetiferous and garnetiferous intermediate charnockites from Nilgiri hill massif represented by filled and open circle, respectively. All the values are in wt%.

only small quantities of strongly peraluminous melts with $A/CNK > 1.3$, and they cannot be suggested as the dominant source for the large volumes of garnetiferous Nilgiri intermediate charnockitic melts with lower A/CNK values (~ 1.1 – 1.28). Furthermore, Montel and Vielzeuf (1997) showed that the K_2O/Na_2O ratio of melts from a pelitic source

Figure 7. Plots illustrating the igneous affinity of both the non-garnetiferous (filled circle) and garnetiferous (open circle) intermediate charnockites from Nilgiri hill massif. The igneous-sedimentary dividing lines in the TiO_2 - SiO_2 plot and $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ - $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ plot are from Tarney (1976) and Barrels and MacKenzie (1971). The igneous trend line and the arkose compositional range in the SiO_2 - Al_2O_3 - (total Fe + TiO_2 + CaO) triplot are from Roche (1972).

is significantly higher (average 4–24) than the ratio in the least evolved samples of Nilgiri garnetiferous enderbites (0.13–0.59; see figure 4b). The more feldspar- and quartz-rich metagreywackes and orthogneisses are potentially fertile sources and could give rise to comparatively large volumes of moderately peraluminous melt. In figure 6, the compositional difference of partial melts produced from sources, such as greywackes, pelites, and amphibolites, can be visualized. It follows from figure 6 that the original melt of the Nilgiri

enderbites may be derived from an amphibolitic source.

The similar affinity of the parent rock for the intermediate charnockites from the Biligirirangan hill, Shevroy hill, Nilgiri hill and northern Kerala massifs is substantiated by their similarity to high-Ba-Sr granitoids with low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (see figure 5) and other elemental characteristics (e.g., high Sr, Ba and LREE, low Y and HREE, elevated La/Yb and Sr/Y ratios) that are typical of adakites and Archaean TTG (trondhjemite,

tonalite and granodiorite) suites (e.g., Martin 1986; Drummond and Defant 1990). This character is different from those of felsic charnockites, like those of the Pallavaram massif, which show a similarity to high Ba–Sr granitoids with high K_2O/Na_2O ratios (see figure 5).

To place additional constraints on the possible source rock(s), total Fe–Na+K–Mg contents of the southern Indian charnockites were compared with some of the available experimental data on compositions of partial melts derived from a variety of crustal rocks (figure 8). Fluid-absent melting of F-rich tonalitic gneiss yields strongly peraluminous melts, in contrast to the least evolved samples of the intermediate charnockites. The low normative corundum contents of the intermediate charnockites rule out a pelitic source rock. Although most experimental dehydration melts from metabasaltic sources are strongly peraluminous (Patiño Douce and McCarthy 1998), at very high degrees of partial melting ($> 1000^\circ\text{C}$) dehydration melts produced from metabasaltic sources start to become metaluminous (e.g., Rapp *et al* 1991). Further their low- K_2O contents, relatively high contents of Na_2O and low values of Mg#, regardless of the degree of partial melting, make metabasaltic rocks suitable source rocks for intermediate charnockites.

Amphibolite dehydration melting experiments conducted at $750\text{--}1000^\circ\text{C}$ (over a wide variety of pressures) generate granite-granodiorite-tonalite magmas (e.g., Rushmer 1991; Beard and Lofgren 1991; Patiño Douce and Beard 1995), which are similar to or indistinguishable from charnockite compositions considered in this study. Heat ultimately controls the degree of partial melting, and consequently the residual mineral assemblage. During dehydration melting experiments, hornblende is totally consumed at $925\text{--}1000^\circ\text{C}$, leaving a granulitic residue of clinopyroxene, orthopyroxene, plagioclase and Fe–Ti oxides with garnet at higher pressures (Rushmer 1991; Beard and Lofgren 1991). Melting to higher temperatures partially consumes the remaining minerals. Although partial melting during the latter stage is volumetrically dominated by plagioclase, the residual mineral assemblage remains unchanged for a considerable isobaric temperature increase.

Beard and Lofgren's (1991) dehydration melting experiments using basaltic and basaltic andesitic starting materials yielded melts similar to southern Indian charnockites (figure 8). Springer and Seck (1997) experiments using basaltic starting material showed that with rising temperatures at constant CO_2 content, melts become richer in normative anorthite content similar to the intermediate charnockites from southern India (see figure

3). Kaszuba and Wendlandt (2000) showed that with increased amounts of CO_2 at constant temperature, melts become richer in normative orthoclase content similar to the most evolved intermediate charnockite samples (see figure 3). In addition, CO_2 -rich melt is likely to be enriched in K, Ba, and Zr (Eggler 1987), which is characteristic of charnockites like those from southern India (e.g., figure 9; CO_2 -rich fluid inclusions have been reported from some of the charnockite massifs; e.g., Touret and Hansteen 1988; Srikantappa 1996; Santosh *et al* 2003; Rajesh 2004a). The lack of K depletion and extreme Rb depletion in some of the high pressure Archaean charnockites from southern India may also reflect the presence of a fluid phase with relatively high CO_2/H_2O ratios (Weaver 1980; Condie and Allen 1984).

In the case of charnockite massifs showing close spatial association (and possibly temporal) of intermediate and felsic varieties (the northern Kerala and Cardamom hill massifs), their near continuous variations in major and trace element compositions probably point to a genetic link between them. If both types of charnockites were differentiated from similar parental magmas, the felsic charnockites would presumably represent a greater degree of fractional crystallization. The lack of systematic K/Rb variation, similar levels of incompatible trace elements in both the intermediate and felsic charnockites, and absence or low Eu anomalies in felsic charnockites do not favor the large amount of fractionation required for the formation of most of these charnockites (e.g., Rajesh 2004a). Constancy of trace element ratios (e.g., Zr/Nb, Ce/Zr, Rb/Zr) is often cited as evidence that fractional crystallization has been the dominant process in the evolution of particular suites (e.g., Wilson 1989). If trace element ratios are constant within a suite, significant crustal melting and contamination are unlikely to have occurred. In the southern Indian charnockites, however, the above mentioned trace element ratios vary in both intermediate and felsic charnockites. Further bimodality of some of the charnockite suites (with basic member; e.g., Pallavaram massif) can be used to argue against a fractional crystallization model. Fractional crystallization might be responsible for contrasts among intermediate and felsic charnockites of the same massif. This would explain, for example, the decrease in $(Eu/Eu^*)_N$ and increase in REE abundances that correlate with increasing SiO_2 in some charnockite massifs. Alternatively, such contrasts may reflect differences in the degree of melting with lower degree melts having higher SiO_2 and higher REE contents. It is also possible to explain the spatial association of intermediate and felsic charnockites by a two-stage model, which

Figure 8. (a) AFM (wt%) plot of the southern Indian charnockites and (b) experimental data on compositions of partial melts derived from a variety of crustal and mantle rocks by water-under saturated melting. The different rocks and respective experimental P-T conditions are: Dacite (850–950°C, 10 kbar; Conrad *et al* 1988); Basalt (850–950°C, 3–6.9 kbar; Beard and Lofgren 1991); Basaltic andesite (900–1000°C, 3–6.9 kbar; Beard and Lofgren 1991); Tonalitic gneiss (875–1050°C, 10 kbar; Skjerlie *et al* 1993); Metapelite (900–950°C, 10 kb; Skjerlie *et al* 1993); Tonalitic gneiss (F-rich) (900–1075°C, 6–10 kbar; Skjerlie and Johnston 1993); Charnockite (850–950°C, 6.9 kbar; Beard *et al* 1994); Charnockite (CO₂-rich) (950°C, 6.9 kbar; Beard *et al* 1994); Quartz amphibolite (900–1000°C, 5–10 kb; Patiño Douce and Beard 1995); Tonalite (950°C, 4–8 kbar; Patiño Douce 1997); Granodiorite (950°C, 4–8 kbar; Patiño Douce 1997); #Charnockite (950–1150°C, 15 kbar; Litvinovsky *et al* 2000); Alkali basalt (1000–1025°C, 7 kbar; Kaszuba and Wendlandt 2000). The respective compositions of the starting material (indicated by arrow) and the product(s) of water-under saturated melting of some of these rocks are shown (by similar symbols). For figure 8(a) same symbology as in figure 4.

assumes an initial low degree of partial melting and subsequent fractionation. The possibility of fractional rather than batch melting for the for-

formation of those charnockite massifs having REE patterns with a slight positive Eu anomaly cannot be discounted.

Figure 9. Chondrite-normalized REE patterns showing the similarity of the average felsic (AFCM) and intermediate (AICM) charnockite samples from the Cardamom hill massif (Chacko *et al* 1992) to CO₂-rich charnockite sample (HP30) used in Beard *et al* (1994) experiments. HP32 is a charnockite sample used in the Beard *et al* experiments.

7.2 The influence of temperature and water fugacity

Regarding the charnockite massifs, which show a spatial association of intermediate and felsic charnockites, different experimental studies have shown that different melts embracing the variation range of the particular charnockite massif can be generated from a single source material under different conditions (e.g., temperature, water fugacity). As far as temperature is concerned, for e.g., 10 kbar experimental data of Conrad *et al* (1988) show the possibility of generating both metaluminous partial melts and peraluminous melts from the same dacitic source material. The former, obtained at low $a_{\text{H}_2\text{O}}$ (0.50–0.25), high temperatures (900–975°C), and high melt proportions (> 75%), would be in equilibrium with restitic cpx+opx+plg. At similar $a_{\text{H}_2\text{O}}$ and slightly lower temperatures (825–875°C) peraluminous melts are obtained that would be in equilibrium with cpx+opx+plg±qtz. Although a close similarity exists between the two melting residues obtained, the different phase proportions may account for the different chemical compositions found in the parental melts in the two-granitoid sequences. Data from the melting experiments of Beard and Lofgren (1991) also support production of intermediate magmas at 950–1000°C, and felsic magmas at 850–950°C. However, fluid-absent melting of slightly metaluminous, metavolcaniclastic rocks at 10 kbar yields high-K tonalitic and/or granodioritic melts at 1050°C and high-K peraluminous granitic rocks at about 975°C (Skjerlie and Johnston 1996).

Experimental studies have shown that water fugacity strongly influences melt composition and residuum mineralogy during partial melting of basaltic compositions at mid- to lower-crustal pressures (e.g., Holloway and Burnham 1972; Beard and Lofgren 1991). The main effect of increased $f_{\text{H}_2\text{O}}$ during melting is to increase the amount of amphibole and decrease the amount of plagioclase in the residuum. Depending on the bulk composition, dehydration melting of amphibolite yields 6–60% melt at 900–1000°C, while vapor-saturated melting yields similar amounts of melt at slightly lower temperatures, 800–950°C (Beard and Lofgren 1991; Rushmer 1991). Further liquids produced by dehydration melting are tonalitic and coexist with a residuum dominated by plagioclase, pyroxene, and Fe-Ti oxides (Beard and Lofgren 1991; Rushmer 1991). In contrast, melts generated in the presence of an H₂O-rich vapor phase are high in silica and alumina, low in magnesium, and coexist with a residuum of amphibole, clinopyroxene, Fe-Ti oxides and minor plagioclase (Beard and Lofgren 1991).

It follows from these experimental data that the intermediate and felsic charnockites can be derived from similar basaltic sources, with the intermediate charnockites originating by dehydration melting and the felsic ones by melting under higher $f_{\text{H}_2\text{O}}$. This does not require that the felsic charnockites crystallized from water-saturated magmas, because as recognized by Helz (1976) and others, melt composition in this case is dependent primarily upon $P_{\text{H}_2\text{O}}$ rather than P_{total} . The compositional similarity between intermediate charnockites and the experimental glasses produced by 20–50% melting of basaltic source rocks at 900–1000°C and low $P_{\text{H}_2\text{O}}$ supports dehydration melting (figure 10). Felsic charnockites, when compared with intermediate charnockites at equal SiO₂, are higher in Al₂O₃ and lower in MgO. Similar trends are observed with increased $f_{\text{H}_2\text{O}}$ among the experimental glasses (Beard and Lofgren 1991). Generation of felsic charnockites at higher $f_{\text{H}_2\text{O}}$ is also suggested by their closer resemblance to glasses formed at 1 kbar $P_{\text{H}_2\text{O}}$ than to those formed by dehydration melting (figure 10). Thus dehydration and vapour-saturated melting of basaltic rocks is a possible primary mechanism in the formation of southern Indian charnockite massifs.

7.3 A plausible model

A possible model is suggested for the formation of intermediate and felsic charnockites from southern India, as an extension of the one proposed by Rajesh (2004b). It is argued that their sources were roughly similar, and that the change from calc-alkaline (magnesian) to alkaline (ferroan)

Figure 10. MgO vs. SiO₂ plot illustrating the comparison of southern Indian charnockite compositions with glasses produced by melting of greenstone and amphibolite at different $f_{\text{H}_2\text{O}}$. Glass analyses (dehydration melting (darker field) at 950–1000°C; water-saturated melting (lighter field) at 1 and 3 kb P_{total}) are from Beard and Lofgren (1991), Rushmer (1991), and Wolf and Wyllie (1989). Same symbology as in figure 4.

charnockitic magmatism was caused by increasing water contents. Rajesh (2004b) suggested that the southern Indian charnockites were produced by partial melting of amphibole-bearing mafic lower crust that formed by underplating of basaltic magmas. Here the crust probably would have acted as a barrier to basaltic magmas ascending from the mantle, causing them to pond and crystallize, and leading to the development of a zone of lower crustal melt generation. Melting of this lower crust already close to or slightly below its solidus, forming charnockites, was probably driven by the intrusion of mantle-derived basaltic magmas. Importantly variations in the water contents of these basalts exert a strong influence on the resulting charnockitic melt compositions. Intrusion of relatively anhydrous basalts resulted in dehydration melting of the lower crust and production of intermediate charnockites (trondhjemites to tonalites). In contrast, intrusion of hydrous basalts resulted in production of felsic charnockites (granodiorites to granites).

This model outlines a chemical as well as physical role for basalts in the production of charnockites, and implies that a thick lower crust is a requirement for large-scale generation of charnockites. It attributes much of the lithologic diversity within some charnockite massifs (intermediate to felsic) to differences in melting reactions. The model does not preclude the possibility that crystal fractionation, assimilation, and/or mixing may have modified individual magma batches, but such processes may be of secondary importance

in determining the general lithology of charnockite massifs. In the case of spatially associated charnockite massifs, the possibility of an initial low degree of partial melting and subsequent fractional crystallization for their petrogenesis is not excluded.

The suggested two-stage model relates the generation of older charnockite massifs to the dynamic underplating of the southern Indian crust during late Archaean to early Proterozoic time. During the first stage partial melting of slightly enriched upper mantle creates a mafic underplate. In the second stage this newly accreted material is itself partially melted, giving rise to the non-garnetiferous intermediate charnockites, and subsequently after the underplate has thickened through the garnet-in transition, the more voluminous garnetiferous felsic charnockites were formed. The younger charnockite massifs were probably related to the collision between crustal fragments of East and West Gondwana, as this event most likely resulted in substantial crustal thickening.

8. Conclusions

- Among the charnockite massifs from southern India, the older Biligirirangan hill, Shevroy hill and Nilgiri hill massifs are intermediate charnockites, with the Pallavaram massif consisting dominantly of felsic charnockites. The charnockite massifs of northern Kerala and Cardamom hill show a spatial association of intermediate and felsic charnockites, with the youngest Nagercoil massif consisting of felsic charnockites.
- The southern Indian charnockite massifs show a similarity to high-Ba–Sr granitoids, with intermediate charnockites showing a similarity to high-Ba–Sr granitoids with low K₂O/Na₂O ratios, while felsic charnockites show a similarity to high-Ba–Sr granitoids with high K₂O/Na₂O ratios.
- A two-stage model is proposed here for the formation of southern Indian charnockites. The first stage involved a period of basalt underplating, with the ponding of alkaline mafic magmas. Partial melting of this mafic lower crust formed the charnockitic magmas. Emplacement of basalt with low water content would lead to dehydration melting of the lower crust forming intermediate charnockites. Conversely, emplacement of hydrous basalt would result in melting at higher $f_{\text{H}_2\text{O}}$ favoring production of more siliceous felsic charnockites.
- It is inferred that the southern Indian crust was affected by at least two crustal thickening

phases, one during late Archaean to early Proterozoic and one during late Proterozoic. The first one was related to the accretion of the older crustal blocks (Madras–Northern–Nilgiri blocks) with the Archaean craton to the north. The second crustal thickening stage occurred in a supercontinent formation process, probably during the collision between crustal fragments of East and West Gondwana along the Gondwana suture.

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