CHAPTER - I

1.1. INTRODUCTION

Granulite facies rocks constitute an important litho unit of lower to mid-continental crust, occupying most of the Precambrian terrane in different continents. Their study has attracted the attention of many geoscientists to understand the formation and evolution of the continental crust. Granulites which represent the high grade metamorphic rocks are generally agreed to originate in the lower to mid continental crust (Fountain, 1989, Newton and Perkins, 1982), at an average formation temperature range of 700-850°C and pressure range 7-10 kbar. Such P-T condition is observed at the deeper crustal level, approximately equivalent to 25 to 30 km depth. The granulites represent a cross section of the deep continental crust, now exposed to the surface in many continents; offer a unique opportunity in understanding the composition and evolution of the lower continental crust.

The granulite facies rocks are classified as two types, they are Archaean and Phanerozoic granulites. The largest are the Archaean Ashuanipi complex of north-eastern Canada (Percival et al., 1992); Wheat belt of Western Australia (Wilson, 1978) and the southern Dharwar craton, South India (Radhakrishna and Naqvi, 1986; Janardhan et al., 1982; Raith et al., 1999). Few Phanerozoic terranes also contain granulite facies rocks, which are of smaller extent like the Moldanubian zone of central Europe (Petrakakis, 1997); Fiordland of southwest New Zealand (Oliver, 1980) and the Ivrea zone of northern Italy (Mehnert, 1975).

The Precambrian terrane in southern India is predominantly composed of granulites, occupying more than 70% of the area and are traversed by many shear zones with complex structural styles and grades of metamorphism. The south Indian Precambrian terrane is composed of a variety of lithologic assemblies, structural pattern, textural and mineralogical features and distinct geochemical and geochronological signatures associated with intrusive rocks and the net work of shear zones which provide excellent case studies for the deep crustal and crust-mantle interaction processes.
1.2. GEOLOGY OF SOUTHERN INDIA

The high-grade metamorphic rocks of the Precambrian terrain of south India is predominately composed of orthopyroxene bearing, greenish grey to brownish grey coloured, greasy looking rocks, generally termed as charnockites (Holland 1900). Based on petrographic and mineralogical studies, these rocks have been classified as charnockitic, charno-enderbitic and enderbitic granulites which show major and trace element composition of granitic, tonalitic to trondhjemitic composition. Associated with these rocks are numerous basic granulites (two pyroxene-plagioclase ± garnet granulites) and ultramafic rocks. Quartz-plagioclase-sillimanite/kyanite-k-feldspar-garnet (khondalites); quartz-plagioclase-k-feldspar -garnet bearing gneisses (leptynites) and other metasedimentary units like banded magnetite quartzite, marbles and quartzite occur associated with charnockites.

The southern Indian peninsular shield has been divided into the Dharwar cratonic nuclei, surrounded by mobile belts of varying ages (Radhakrishna and Naqvi, 1986). The granulite facies rocks in southern India is divided into two distinct crustal blocks viz., Northern Granulite Terrain (NGT) and Southern Granulite Terrain (SGT), separated by a major E-W trending Palghat Cauvery shear system (PCSS) (Fig.2.1). The Archaean Dharwar craton (DC) is essentially composed of granite-greenstone belts within the peninsular gneissic complex in the central part with granulite facies rocks occurring all along the western and southern margins of the craton. These granulites are distinctly of Archaean age and considered to be post-accretional type granulites (protoliths age of 3.400.m.y) and metamorphosed around 2500.m.y. (Peucat et al., 1989). These granulites are variously termed as Biligiri Rangan granulites (BRG), Satnur-Halagur granulites (SHG), Male Mahadeshwara granulites (MMG), including the Mercara granulites (MEG).

In addition to these, the late Archaean syn-accretional type of granulites (accreted and metamorphosed around 2500 m.y. ago), termed as the Nilgiri granulate (NG) and Salem-Madras granulites occur within the NGT. The Moyar-Bhavani shear zone (MBSZ), which separates the early-Archaean DC with the late Archaean NG is considered as a major terrane boundary in southern India (Srikantappa et al., 1986; Raith et al., 1990; 1999).
The southern granulite terrain (SGT), also termed as Pandiyan mobile belt, (PMB; Ramakrishnan, 1993 and 1998) include charnockites, both banded/gneissic and massive types, two pyroxene granulites interlayered with high grade hornblende-biotite gneisses. Pre-deformational, pre-metamorphic intrusives of dunite-peridotite-pyroxenite gabbro anorthosite complexes are significant. Post-deformational, post-metamorphic intrusives vary from gabbro-anorthosite plutons to alkali carbonate complexes and granite plutons as well as dolerite dyke (Gopalakrishnan, 1994). Within the SGT, different granulite blocks like Madurai granulite block, Kodaikanal granulite block bounded by Palghat Cauvery shear zone in the north and Achankovil shear zone (ACSZ) in the south occur. The Kerala khondalite belt (KKB), south of the ACSZ upto Kannyakumari is composed of two granulite block viz., Trivandrum granulite block and Nagercoil granulite block (Srikantappa et al., 1985; Yoshida and Santosh, 1996). The southern granulite terrain (SGT) comprises an crustal domains of contrasting composition and tectonothermal evolution (Buhl, 1987; Peucat et al., 1989; Choudary et al., 1992; Harris et al., 1994; Raith et al., 1999).

Two types of charno-enderbitic granulites have been recorded in the Precambrian terrane of south India viz., Massive/banded charnockite (MBC) and incipient charnockite (IC).

"Massive/Banded" Charnockite (MBC): The medium to coarse grained, massive/banded charnockite (MBC), which are generally massive (look homogeneous in outcrop occur as mappable units) covering large areas and generally occupy upland regions (could be uplifted masses during neotectonism). Numerous basic enclaves occur as boundins or layers parallel to foliation planes imparting banded structures in the field. These rocks show evidence of at least two periods of deformation as seen in Biligiri Rangan granulite and Nilgiri granulite in the northern granulite terrain (NGT). Typical examples of massive to banded charnockites (MBC) occur in the Biligiri Rangan granulite (BRG), Nilgiri granulites (NG), Mercara granulites (MEG) and Kerala khondalite belt (KKB).

"Incipient" charnockite (IC) are orthopyroxene bearing acid granulites which have been developed locally as veins, patches or lenses within the predominately amphibolite facies gneisses. IC are considered to represent an arrested stage of transformation of an
amphibolite facies gneiss to granulite. Two typical examples of IC formation documented in the Precambrian terrane of southern India viz., The protoliths for the Kabbal type incipient charnockite veining is an ortho-gneiss (Pichamutu, 1960; Janardhan et al., 1979; Stahle et al., 1987), whereas in the Ponmudi type, it is a para-gneiss (Srikantappa et al., 1985; Ravindra Kumar et al., 1985; Hansen et al., 1987; Santosh et al., 1991).

1.3. GEOLOGY OF THE AREA AROUND BHAVANI

1.3.1. Lithology: The high grade metamorphic rocks exposed around Bhavani is predominantly composed of charno-enderbitic granulites, retrogressed charno-enderbitic granulites, fissile biotite gneiss (Bhavani gneiss); numerous dismembered, layered anorthositic, two-pyroxene-plagioclase; garnet-two-pyroxene-plagioclase bearing basic granulites occur. The various meta-sedimentary rocks like biotite gneiss, garnet+kyanite/sillimanite+biotite gneiss, calc-silicates and quartzites belonging to Sathyamangalam Group are exposed in the area (Gopalakrishnan, 1994).

Towards northern part of the area, N-S trending, massive-banded charnockitic granulites (MBC) of the Biligiri Rangan granulite (BRG) occur. The N-S structures of the BRG are truncated by the late N60°E to E-W trending ductile, ductile/brittle shears along the Moyar-Bhavani shear zone (MBSZ). Towards south of Bhavani, massive to banded charnockite of the Chennimalai area are exposed. These rocks are interbanded with various meta-sedimentary rocks like calc-granulites and banded magnetite quartzite.

Three types of gneissic rocks viz., epidote-biotite gneiss, fissile biotite gneiss and hornblende biotite gneiss, are exposed in the area (GSI map, Fig.2.1). The boundary between various types of gneisses is vague and their genetic relationship is not well established.

Fine to medium grained nepheline syenites as seen near Vellar, Jalakandapuram and Nangavalli syenites are undeformed igneous rocks, represent post-kinematic intrusives into the DMSZ during an extensional tectonic regime. The Pakkanadu and Elagiri syenites emplaced into the DMSZ yield the whole rock Rb-Sr ages of 900±37 and 757±32 Ma
respectively (Krishna Rao and Nathan, 1991; Miyasaki et al., 2000). Coarse to medium grained, pink foliated granites with highly irregular boundaries named as Sankari, Tiruchengodu and Punjai-puliyampatti granites are exposed in the area. These granites yield the whole rock Rb-Sr ages of 390±40 Ma (Nathan et al., 1994). Numerous pegmatite and quartz veins intrude various lithologies. A set of late dolerite dykes trending N 40°W to E-W occurs towards northern part of the area.

1.3.2. Shear Zone: The southern granulite terrain (SGT) is subdivided into large crustal blocks, which are transected by crustal scale shear zones as Proterozoic shears dominated by strike slip/oblique slip shearing and faulting (Drury and Holt 1980; Drury et al., 1984; Chetty, 1996 Bhaskar Rao et al., 2000; Chetty et al., 2000 and Srikantappa et al., 2000 and Srikantappa et al., in press). The major shears are Moyar-Bhavani shear zone, Palghat Cauvery shear zone and Achankovil shear zone. The associated minor shears are Moyar shear zone, Bhavani shear zone, Dharmapuri-Mettur shear zone, Chennimalai shear zone, Dharamapuram shear zone and Devattur-Kallimandayam shear zone.

Dharmapuri-Mettur shear zone is termed as the Dharmapuri suture rift zone by Gopalakrishnan (1994). Deep faults extending to the mantle, containing ultrabasic intrusions and carbonatites are present which are seismically active around Mettur. These deep faults contain carbonatite complexes.

Whether the Biligiri Rangan granulite (BRG) extend further south into to Moyar-Bhavani shear zone (MBSZ) or this shear zone represent a tectonic suture is not clear. The type of deformation in the shear zone, and the length and breadth of these shear zones is not properly understood.

Information on the field relationship of various rock types, modern petrographic description, P-T conditions of regional metamorphism, nature and composition of granulite facies fluids have not been well documented in the area around Bhavani. The type of shear deformation like ductile, ductile-brittle or brittle nature and the length and breadth of shear zone is not properly understood. Mineral kinematic indicators and sense of movement
of rocks is not properly understood. The field relationship of different igneous bodies like syenites and granites is not well established. The nature of shear deformation, type of mineral assemblages developed during retrograde metamorphism is not well documented.

1.3.3. Metamorphism: The granulites exhibit different types of P-T-t trajectories implying various tectonic processes like collisional, extensional and thrust type of tectonic regimes. The P-T conditions of metamorphism, evaluated based on various inter-crystalline cations exchange reactions in the co-existing mineral phases in granulites, using refined thermodynamic models will help to evaluate the different grades of metamorphism (M1, M2, M3 etc.). The different periods of metamorphism of the granulites like M1, M2 and M3 are noticed in south India (Touret and Hansteen, 1988; Srikantappa et al., 1992; Srikantappa, 1996 and 2001; Santosh, 1991; Santosh et al., 1991); Southern Alps of New Zealand (Johnson and Hollister, 1995), Finland (West Uusimaa Complex, Touret and Hartel, 1990); Central Kola peninsula, northern Baltic Shield (Fonarev et al., 1998).

A number of metamorphic petrologists have been trying to understand the various tectonic environment of granulite formation (Bohlen, 1987; 1991; Harley, 1989). Harley (1989) based on the P-T-t paths, distinguished between isothermally decompressed (ITD) and isobarically cooled (IBC) granulites. Most of the granulites exposed in the NGT, show a isobaric cooling P-T-t paths (IBC) with peak T followed by peak P (Srikantappa, 2001). In contrast, most of the granulites in the southern granulite terrane (SGT) as well as the incipient charnockite (IC) show isothermal decompression (ITD) paths, with peak P followed by peak T (Santosh et al., 1991; Srikantappa, 2001). Thermobarometric studies in the E-W trending MBSZ indicate a general P-T conditions $T=760^\circ\pm40^\circ$C and $P=8.3\pm1.0$ kbar (Harris et al., 1982) and $T=730^\circ\pm30^\circ$C and 7.5 to 9.2 kbar (Raith et al., 1983 and 1990). Apart from these scanty P-T data, no detailed work on the P-T estimates of different litho units in the area is available. Some of the basic rocks within the MBSZ are described as eclogites by Subramanian (1956) and the P-T estimates of 10 kbar and 850°C is estimated (Janardhan and Leake, 1975).
Metamorphic evolution of granulites around Bhavani and retrogressed rocks within the shear zone is poorly understood and no modern petrological data, micro-textural studies and mineral P-T estimates is available.

1.3.4. Fluid Inclusion Studies: Another challenging problem in understanding the evolution of Precambrian granulites, apart from P-T-t paths, is the role of fluids in deep-crustal metamorphism. The various mineral assemblages in the granulites may be stabilised in either "fluid-absent" or "fluid-present" metamorphic process. The CO₂-rich fluid inclusions have been the dominant fluids to be present in granulate facies rocks in contrast to H₂O-rich fluids in amphibolite facies rocks. However, the recent experimental data has shown that the CO₂-rich fluids, because of their low wetting property and low solubility with the silicate minerals in granulate facies rocks have casts doubt on the importance of carbonic fluids in deep crustal metamorphism. Presence of brine inclusions, immiscible with CO₂-rich inclusions in high-grade metamorphic rocks appears to be the common the fluids in granulites (Newton et al., 1998). Characterisation of nature and composition of fluids in granulites is important as they play key role in controlling mineral stability, heat-flow, element transport, melting and deformation rocks.

Hypersaline solution of granulate facies fluids are believed to have played a major role in the evolution of gabbro rocks (Pasteris et al., 1995), alkaline volcanic rocks (Lowenstern, 1994), carbonatites (Samson et al., 1995), some of the alpine eclogites (Philippot and Selverstone, 1991) and the super-high-pressure coesite-bearing metasediments (Philippot et al., 1995). Recent studies of brine-rock interaction at high temperatures and pressures demonstrate additional properties of concentrated alkali chloride solutions, which support renewed consideration of such fluids as important agencies in the evolution of the deep continental crust.

The recent experimental work by Vityk and Bodnar (1995) on fluids has indicated that a careful documentation of textural study of fluids and the host minerals is very important in the study of granulites. Based on experimental work they have shown that despite of high
degree of deformation and high grade metamorphism, at least 10 to 20 percent of fluid inclusions record the original densities, representing peak-metamorphic pores fluids.

High density carbonic fluids have been recorded in minerals like garnet, plagioclase and quartz in all the massive/banded charnockites as well as in the incipient charnockites both in the NGT and the SGT (Hansen et al., 1984; Srikantappa, 1987; 1996 and 2001; Srikantappa et al., 1985; 1992; 2000 and 2002 (in press). However, to find out whether the CO$_2$ fluids were present during peak-granulite facies metamorphism ("fluid present") or they have been trapped at a later stage ("fluid absent"), during uplift/cooling history of these rocks. Precise information on the chronology of fluid inclusion entrapment in minerals in granulites is required to solve above problem.

No data is available on the types of fluids in the massive to banded charnockites exposed around Bhavani as well as in the retrograde rocks, granites and syenites in the study area.

1.3.5. Geochemistry and Geochronology: Geochemical study of granulites is significant as they provide important clues on the nature and composition of the lower continental crust and particularly whether the granulites are igneous or sedimentary protoliths characters. The Biligiri Rangan granulite in the Dharwar craton represent the igneous protoliths metamorphosed around 3.3 Ga (Basavarajappa, 1992; Jayananda and Peucat, 1996; Raith et al., 1999), whereas the Nilgiri granulites in southern India has been classified as belonging to greywacke type of sediments metamorphosed around 2.5Ga (Raith et al., 1999). Many of the granulites show both depleted and non-depleted geochemical signatures with respect LIL elements like K and Rb (Condie and Allen, 1984; Frost and Frost, 1988; Barbey and Cuney, 1982 and Janardhan et al., 1982).

Two types of Archaean granulites facies terranes are recognised: depleted granulites are typified by Scourian granulites from Scotland (Pride and Muecke, 1980; Holland and Lambert, 1965; Sheraton et al., 1973 and Tarney, 1976) and undepleted granulites as typified by charnockites near and within the low to high grade transition zone of southern India (Condie et al., 1982).
The study of geochemistry is lacking in the study area, but the geochemistry and geochronological study of pegmatoidal granites of Sankari and Tiruchengodu region were studied in detail by Nathan et al., (1994).

The granitic rocks of southern India are equivalent to Pan-African event reported from different parts of Kerala (Santosh and Drury, 1988; Rajesh, 2000) and Tamil Nadu (Balasubrahmanyam and Sarkar, 1981 and Narayana et al., 1988). The Sankari-Tiruchengodu granite emplaced in a high grade terrain represented by amphibolite facies gneisses and the associated Sathyamangalam supracrustals of Archaean-Proterozoic age in central Tamil Nadu. Rb-Sr whole rock isochron data of granite yields 390±40 Ma, which are resulting in crustal instability and generation of S-type granite (Nathan et al., 1994).

The recent geochronological data have indicated at least three granulite forming events viz., 2500 Ma, 1000 Ma and 550 Ma (Jayananda and Peucat, 1996 and references therein). The Moyar-Bhavani shear zone (MBSZ) which separates the early Archaean DC with the late-Archaean NG is considered as a major terrane boundary in southern India. The Archaean granulites have been extensively reworked mainly along the ductile, ductile/brittle shear zones and appear to have been subjected to various stages of retrograde metamorphism from 0.73 to 0.55 Ga (Meissner et al., 2002). The relative timing of deformation and related metamorphism is not clearly established along Moyar Bhavani shear zone (MBSZ).

For the above reasons, a detailed study has been carried out on the metamorphic evolution of high-grade rocks and fluid regime around Bhavani.

1.4. AIM AND SCOPE
It is difficult to carry out detailed geological mapping of the area, because most of the northern part of the area around Mettur is a hilly terrain, generally covered by thick vegetation with reserved forests infested with wild animals like elephant and tigers. For the above reasons, geological information is gathered mainly from rocks exposed along hill slopes and small mounds, active and abandoned quarries around Mettur, Bhavani, Vellar,
Andipalyam, Andiyur, Erode and Chennimalai areas (Fig.2.2). A strip of high-grade metamorphic area, covering an area of 285 sq. km around Bhavani within the MBSZ in Tamil Nadu is selected for present investigation (Fig.2.1). Numerous massive granulites have been exposed around Mettur and Chennimalai.

An attempt is made in the thesis to bring out field relationship between various rock types, detailed petrological, micro-textural and fluid inclusion studies including geochemical studies on rocks exposed around Bhavani in Tamil Nadu, southern India (Fig.2.1).

Following are the objectives of the present investigations:
1. To bring out geological map of the area around Bhavani and to study the nature of shear deformation in the areas and to record sense of movements across the crustal blocks.
2. To record metamorphic evolution in the area and retrograde metamorphism in the shear zone by studying mineral reactions in different litho units.
3. To know the nature and composition of inter-granular fluids during high-grade metamorphism and during retrograde metamorphism.
4. To characterise the composition of protoliths for granulites and elemental depletion during high-grade metamorphism and during retrograde metamorphism in shear zones.

A synthesis of above data will help to understand the metamorphic evolution and fluid regime of the deep crustal rocks exposed around Bhavani in Tamil Nadu. The data obtained during the present investigation and interpretation of the results has been presented in SIX different chapters.

1.5. LOCATION
The study area is situated between the latitude 11° 5’ to 12°0’ longitude 77°15’ to 78° 0’ and fall in the toposheet number 58E. The study area in and around Bhavani town in Tamil Nadu lies within the Moyar-Bhavani shear zone (MBSZ) (Fig.2.2). Topographically, the area around Bhavani is an undulating terrane with elevation of about 200 mts above MSL with isolated hills rising 500 to 800 above MSL. The highest elevation is about 1430 mts above MSL near Mettur. The Bhavani town is well connected by roads from Bangalore, Salem, Erode, Coimbatore and Chennai. The nearest railway station is Erode.
1.6. METHODOLOGY

Fieldwork has been carried out for about 125 days. The geological map published by Geological Survey of India (1:25,000 scale) in the year 1995 is being utilised for mapping purpose. Mapping was carried out in active quarries to study field relationship between different rock types and to understand the process of shear deformation and retrograde alteration of granulites. Representative rock samples were collected from fresh exposures along road cutting in hilly terrane and in active quarries in the shear zone. Care was taken to collect less deformed and highly deformed rocks in shear zones. Petrographic study was carried out to document micro-textures, mineral reactions related to granulite facies metamorphism and retrograde metamorphism.

Chemical analyses of various silicate and oxide minerals were obtained using CAMECA SX50 at the Department of Geology, University of Mysore, Mysore. The analyses were carried out at 15KvA and with a beam current of 20nA. The standards used for calibration includes both pure synthetic and natural elemental / mineral standards supplied by CAMECA, France. The following standards were used for calibrations: Si-natural quartz, Ti-rutile, Fe-elemental Iron, Al-kyanite, Mg and Ca-diopside, Mn-rhodonite, K-microcline feldspar, Na-jadeite, Cr-chromite and F-fluorite.

Doubly polished plates of 100 to 300 µm in thick were used for fluid inclusion study. Phase transitions in fluid inclusions were made on a temperature calibrated, LINKAM and CHADXMCA microthermometry apparatus with a range of -180°C to 600°C at Department of Studies in Geology, Manasagangotri, University of Mysore, Mysore. The density data have been calculated using LINKSYS program. Fluid inclusion petrography were done using high power objective (40x and UT 40) in LEITZ (Laborlux 12 POL) petrological microscope.

The major and trace element data were obtained using X-ray fluorescence employing well established methods on a Philips automated XRF spectrometer equipped with on-line computer at Institute for Mineralogy and petrology, University of Bonn, Germany.