Evidences of polyphase deformation and retrogression in high-grade metamorphic rocks – a case study from the Western Madurai Block, Southern India

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***Abstract:** The deformation history of the Southern Granulite Terrain is as complicated one as its metamorphic evolution is polyphased with multiple thermal events. In this present study detailed lithological mapping and analysis of structural fabric of the Precambrian metamorphic rocks in and around Erattupetta area, Western Madurai Block, Southern Granulite Terrain. The different tectonic impulses varying in magnitude and direction have left their imprints in the tectonites in the form of the mesoscopic and macroscopic structures. Systematic analysis of structures reveals that the area has been affected by polyphase deformation. The textural and mineralogical evidences suggest that rocks undergone high grade metamorphism and influenced by different tectono-metamorphic events. It is suggested that, these multiple and complex structural and metamorphic events could be chronologically constrained for better perception and evaluation of the tectonic history of this terrain.*

***Keywords:** Deformation, retrogression, Western Madurai Block, southern India*

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1. Introduction

The South Indian shield represents one of the shield areas of the world that has preserved an early formed crust (prior to 2500Ma). Following the pioneering classification by Fermor [1936], the south Indian shield has been traditionally divided into the Dharvar craton and the Southern Granulite Terrain (SGT). The SGT forms the southernmost part of the peninsular India is one among the prominent granulite terrains of the world which constitutes deformed and metamorphosed assemblages with complex lithological inter relationship (Ramakrishnan et al., 1993, 2003). The SGT is characterized by the association of upper-amphibolite's and granulite facies lithologies along with rocks of syn-post events of plutonism, volcanism, sedimentation and several periods of deformation and metamorphism. In the SGT, the granulite rocks are well exposed except along the linear stretches of the coasts where they overlain by Mesozoic and Tertiary sediments. The most characteristic feature of the SGT is that the entire terrain is dissected by various crustal scale shear zones (Chetty et al 1995). Major shear zones, the prominent crustal discontinuities in SGT include, Mercara Suture Zone, Moyar–Bhavani shear zone, Palghat Cauvery Shear System and Achankovil Suture Zone (Amaldev et al., 2016; Santosh et al., 2015) (Fig. 1). Systematic studies of the rocks in these Proterozoic crustal units had provided a valuable insight to the tectonic history of the south Indian shield (Hariss et al., 1994; Jayananda and Peucat, 1996; Braun and Kriegman, 2003).

2. Regional geology

The Southern Granulite Terrain (SGT) forms the southern part of the South Indian Precambrian shield and is comprised of high-grade metamorphic rocks such as charnockites and gneisses. The prominent crustal blocks in the SGT from the north to south are the Mesoarchean Coorg Block (Santosh et al., 2015), dominantly Neoarchean Nilgiri Block (Samuel et al., 2014), the NW and SW segments of Madurai Block dominated by Neoarchean-Paleoproterozoic and Meso-Neoproterozoic rocks respectively (Plavsa et al., 2012 and Collins et al., 2014), Late Neoproterozoic-Cambrian Trivandrum Block (Santosh et al., 2005, 2006). The Madurai block is the largest granulite block in Southern granulite terrain bounded by Palghat-Cauvery shear zone in the north and Achankovil shear zone to the south. The major rock types in the area include charnockites, mafic granulites, hornblende-biotite gneiss, biotite gneiss, garnet-biotite gneiss, other quartzo-feldspathic gneisses and granitoid intrusives. Some of the petrological features like sapphirine bearing granulites; occurrence of graphite in charnockites and the extensive areas of massive charnockite occurrences etc. make this block petrologicaly significant.

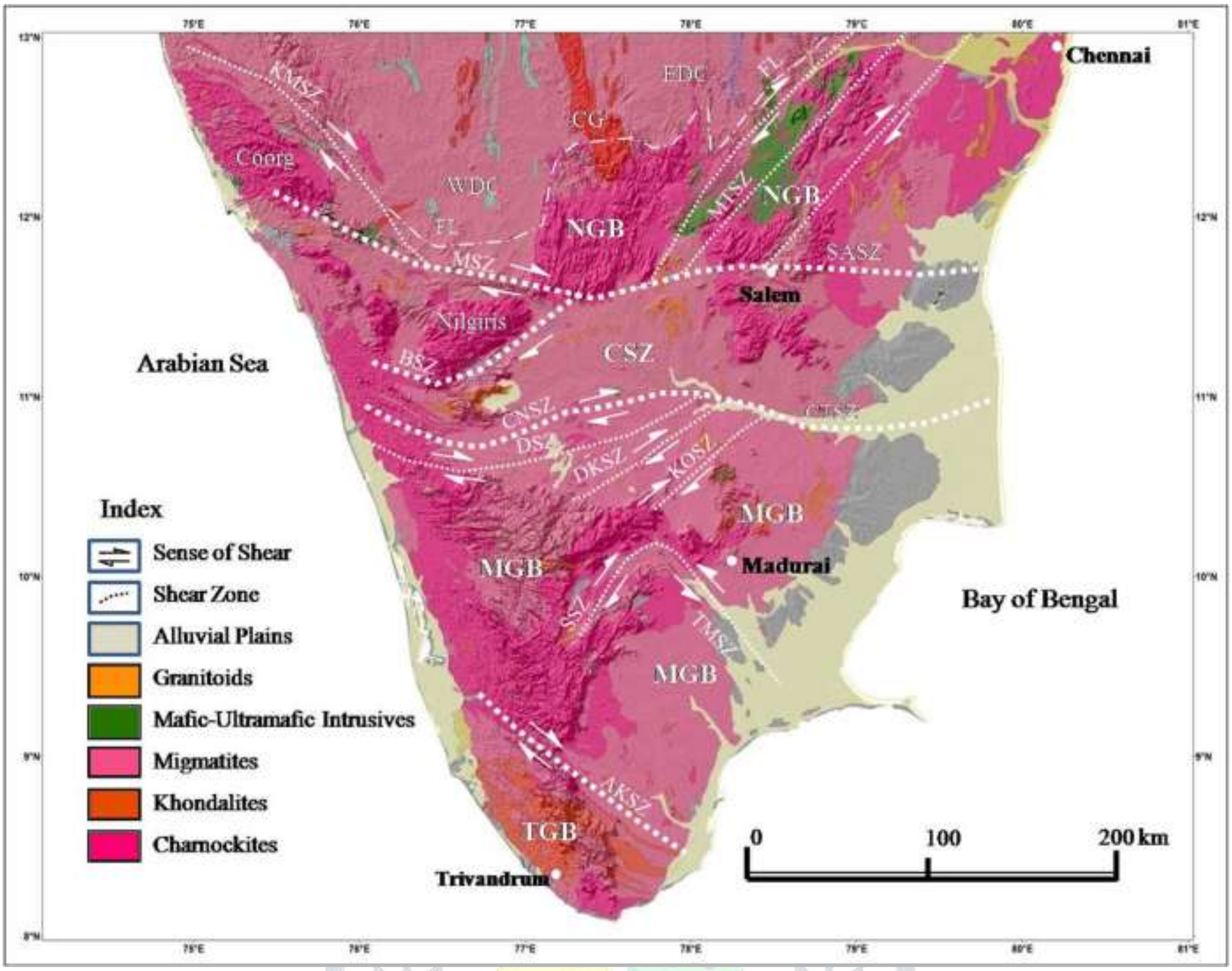

Fig.1. Geological and Tectonic map of the Southern Granulite Terrane showing major rock types and tectonic features along with the digital elevation model—NGB, Northern Granulite Block; CSZ, Cauvery shear zone; MGB, Madurai Granulite Block; AKSZ, Achankoil shear zone; TGB, Trivandrum Granulite Block; EDC, Eastern Dharwar craton; WDC, Western Dharwar craton; CG, Closepet Granite; FL, Fermor's line; MTSZ, Mettur shear zone; KMSZ, Kasargod- Mercara shear zone; MSZ, Moyar shear zone; BSZ, Bhavani shear zone; CNSZ, Chennimalai Noil shear zone; SASZ, Salem-Attur Shear Zone; CTSZ, Cauvery-Tiruchirappalli shear zone; DSZ, Dharapuram shear zone; DKSZ, Devattur-Kallimandayam shear zone; KOSZ, Kodaikanal Oddanchathram shear zone; SSZ, Suruli shear zone; TMSZ, Theni-Madurai shear zone (After Chetty. (2017)).

The metamorphic evolution of the MGB has been the focus of a number of recent studies spurred by the occurrence of UHT metamorphic assemblages from a number of localities (Brown & Raith, 1996; Mohan & Windley, 1993; Shimpo et al., 2006). The host rocks in the northern part of MGB include quartz free Mg-Al rich rocks often containing aluminous minerals such as saphirine, spinel, and corundum. The southern part of MGB is characterized by bluish cordierite-bearing granulites occasionally intruded by pink alkali feldspar granites. Mineral assemblages considered as diagnostic indicators of ultrahigh-temperature (UHT) metamorphism occur commonly in this block include sapphirine + quartz (e.g., -Tsunogae and Santosh, 2007; Braun et al., 2007), spinel + quartz (e.g., Morimoto et al., 2004; Tang Li et al., 2017), and orthopyroxene + sillimanite + quartz (e.g., Tateishi et al., 2004; Sajeev et al., 2004-). The influx of CO_2 -rich fluids significant in UHT metamorphism under dry conditions were also reported (Tsunogae and Santosh, 2011; Santosh et al., 2004; Amaldev and Baiju, 2017; Tsunogae et al., 2008; Santosh and Omori, 2008).

The deformation history of the Southern Granulite Terrain is as complicated one as its metamorphic evolution is polyphased deformation with multiple thermal events. The present work aimed on the detailed lithological mapping and structures of the rocks in and around Erattupetta, Kottayam, southwest of Madurai block (Fig. 2). The main objective of the present work is to delineate the structural signatures of the area and to interpret the various deformational events which have a significant role in the tectonic history of the area. The detailed petrography of granulites was also studied to evaluate the metamorphic evolution of the terrain.

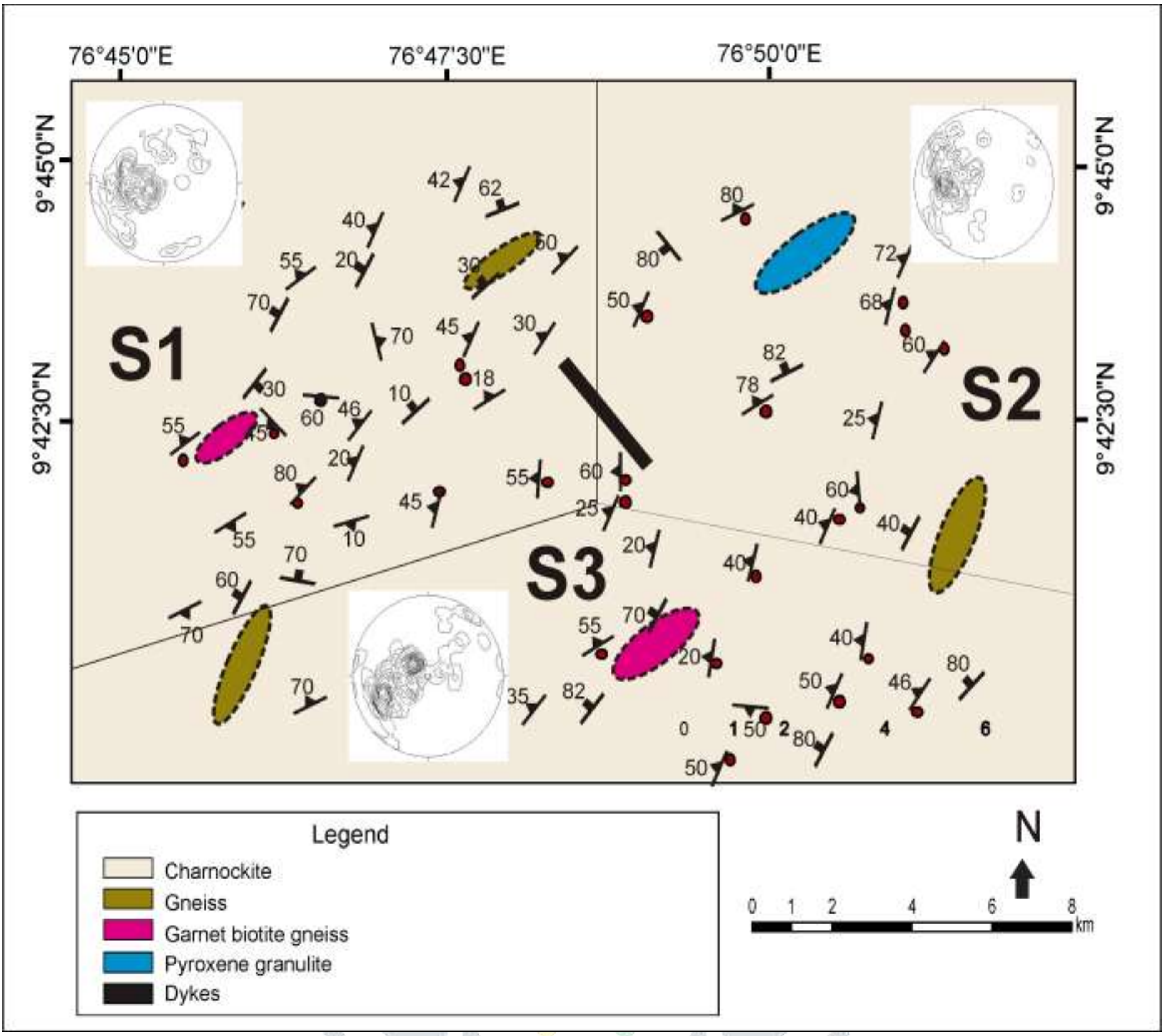

Fig.2 Geological map of the study area, in and around, Erattupetta, Kottayam

3. Field relations and petrography

Charnockite, hornblende biotite gneiss and pyroxene granulite are the major rock types of the study area with some granitic and pegmatitic intrusions (Fig. 3). Due to extensive weathering and thick vegetative cover, the exact contacts between the rocks of different lithology has been exterminated and is difficult to delineate the exact contacts between different litho types in the study area. Fresh exposures of crystalline rocks are limited to working and abandoned quarries. Dolerite and pegmatite veins are found as later intrusives into the dominant rock types. Most of the area is characterized by intense shearing and these are indicated by deformed structures like minor folds, augen structures, boudinage etc.

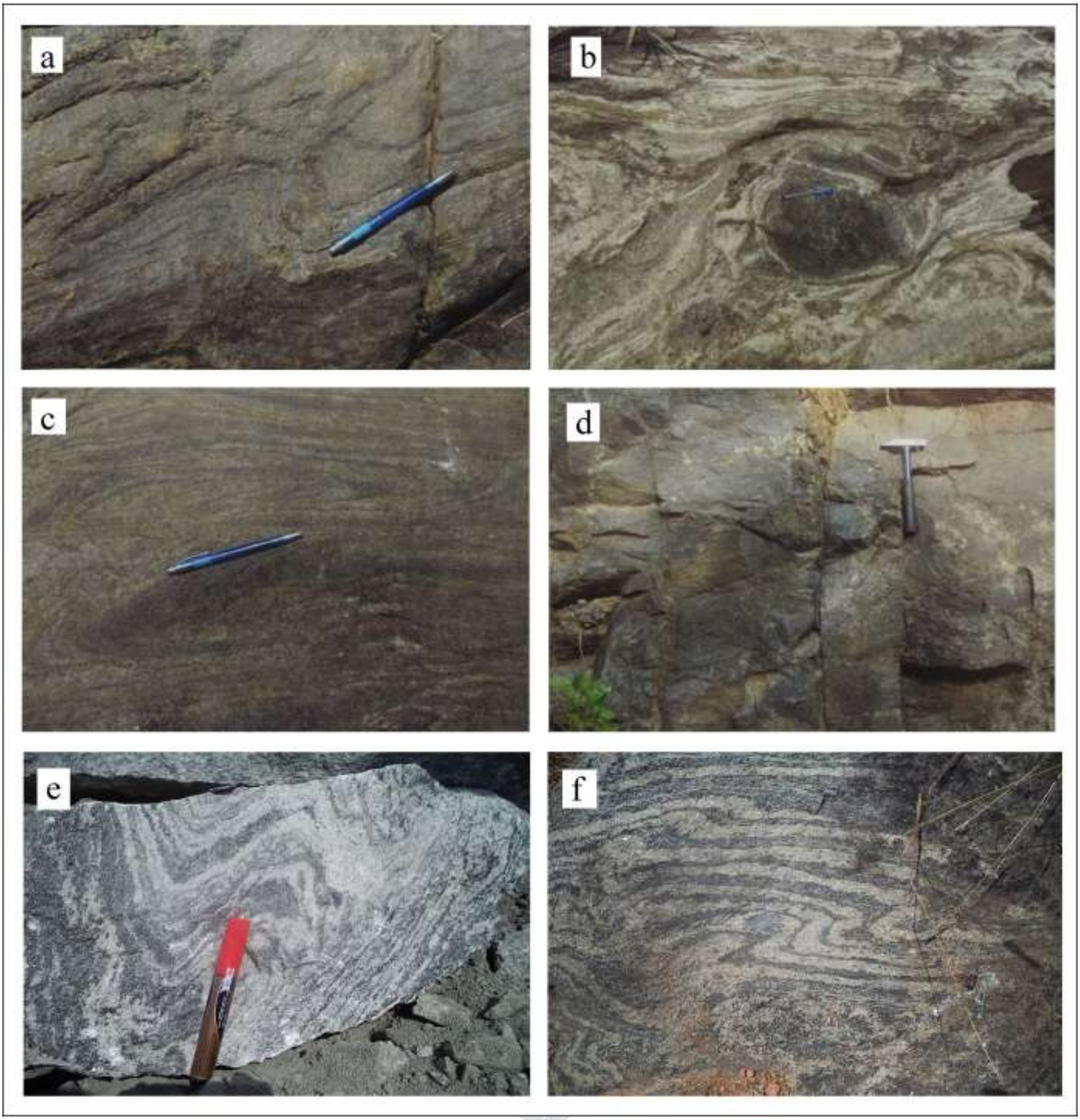

Fig. 3 Deformational structures in the field, a) Minor folds, b) Assymetric rotated boudin in gneiss showing dextural shear sense, c) Sheath folds in gneiss, plan view, d) Vertical joints in charnockite, e&f) Inclined folds.

3.1. Charnockite

Charnockite is the dominant rock type in the study area with wide extends in the mapped area. The rock is medium to course grained with irregular to prismatic grains of orthopyroxene, in greenish grey colour. Quartz occurs as colourless and xenoblastic grains with occasional bluish tint exhibiting vitreous luster and conchoidal fracture. Structures like folds, augens and boudins are observed in Moopanmala and adjacent areas. Vertical as well as dipping joints are also noticed in this rock. The main exposures are found in near Ayyambara, Edameruka, Theekoyi, Kaipalli, and Aruvithura.

The mineral assemblage found in the thin section of foliated charnockite is:

Plagioclase + hypersthene + quartz+ orthoclase + biotite + opaques

In thin section, the rock is medium to coarse grained, subhedral grains with interlocking and granoblastic texture (Fig. 4). Most of the grains of charnockite are subjected to strain effects and show undulose extinction. The grain boundaries are curved, straight as well as irregular in nature. Plagioclase grains are medium to coarse grained and are subhedral, inequigranular and have sharp grain boundaries. K-feldspars are medium grained with curved to embayed grain boundaries. The grains of hypersthene are inequigranular, medium to coarse grained, subhedral in nature with curved grain boundaries. Quartz grains occur as colourless, subhedral, medium sized grains showing irregular grain boundaries. Triple junctions among grain boundaries are observed. Myrmekitic textures are also noticed. Biotite grains are dark brown to pale brown in colour. The foliation defined by the mafic minerals is discontinuous. In the sections which show retrogression, orthopyroxene exhibits alteration to biotite along cleavage planes. Secondary opaques are quite abundant and are formed due to exsolution from retrogression of pyroxene or hornblende.

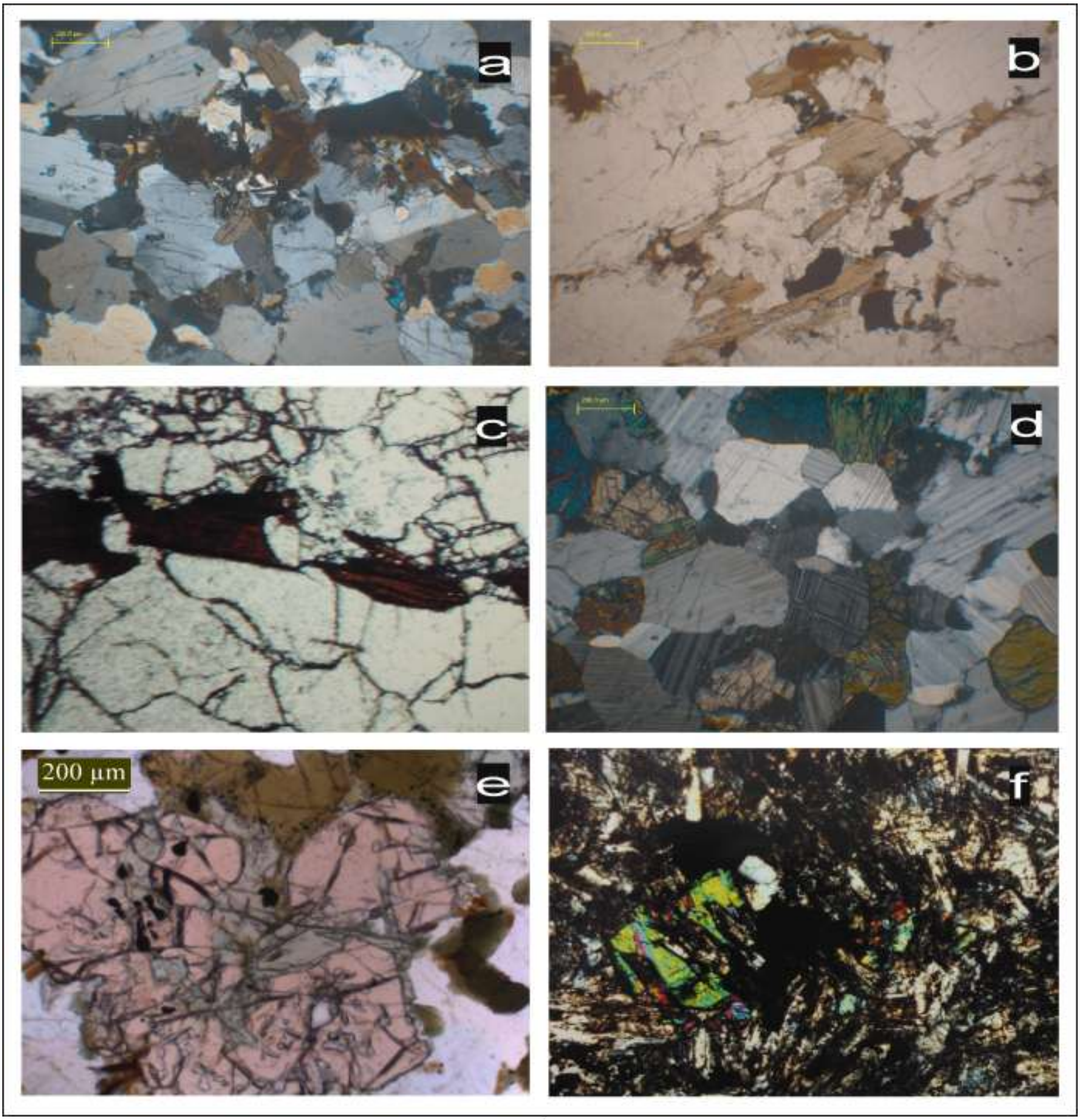

Fig. 4 Photomicrographs of a) charnockite, b) biotite gneiss, c &d) hornblende biotite gneiss, e) mafic granulite, f)dolerite dyke.

The peak mineral assemblage present in charnockite is

K-feldspar + hypersthene + plagioclase + quartz + opaque + biotite

Most of the mineral constituents are subhedral. Lobate, curved and straight grain boundaries are noticed between the mineral grains. Grains show effects of strain. Pyroxenes found in the rock include hypersthene and diopside. Hypersthene is the most dominant orthopyroxene present in the charnockite and can be easily recognized by its green colour, pleochroism, high relief, typical pyroxene cleavage and parallel extinction. The grains of hypersthene are inequigranular, medium to coarse grained, subhedral in nature with curved grain boundaries.

Feldspars include plagioclase and orthoclase. Plagioclase is the most dominant feldspar in charnockite and is medium to coarse grained in nature with well-defined two directional cleavage and closely spaced twin lamellae. Orthoclase is cloudy in appearance and has well-developed cleavage. K-feldspars are medium grained with curved to embayed grain boundaries. In some sections, plagioclase shows deformation twinning. Opaques are generally found associated with hypersthene.

3.2. Hornblende biotite Gneiss

Hornblende biotite gneiss is the next important litho unit of the study area. The rock composed essentially of quartz and orthoclase feldspar. It is a pink, coarse to medium grained rock. A grey variety of granite is also noticed. Most of the grains are subhedral with straight, curved, irregular or embayed boundaries. Myrmekitic intergrowth of vermicular quartz in plagioclase is noticed.

The mineral assemblage identified is

Hornblende+quartz + orthoclase + plagioclase + + biotite + opaques

The major felsic minerals are quartz, k-feldspar, perthite and plagioclase. Felsic minerals dominate the mineral assemblage. Two generations of quartz grains seen. Plagioclase showing the characteristic polysynthetic twinning according to albite law is noticed. K-feldspar occurs as medium to large sized grains showing inclusions of quartz, biotite and opaques. Antiperthitic intergrowth of orthoclase in plagioclase is noticed. Biotite occurs as short broken flakes and is characterised by distinct dichroic and basal cleavage. Accessory minerals include sphene and zircon.

3.3. Pyroxene granulite

Pyroxene granulite is variably termed as basic charnockite, two pyroxene granulite etc. Pyroxene granulites are observed in Aniyillappu and adjacent areas. They are typically medium to coarse grained melanocratic rocks (dark greyish black). Pyroxene granulites comprise an assemblage of orthopyroxene, plagioclase, clinopyroxene, biotite, Fe-Ti oxides, garnet and quartz with accessory zircon and apatite. Pyroxene grains are identified by their dark colour, subvitreous luster and good prismatic cleavage. Quartz grains are distinguished by their fresh appearance, smoky colour, vitreous, luster, conchoidal fracture, absence of cleavage and high harness. The feldspar grain in the rock is distinguished by their white to light grey colour, subvitreous luster, good prismatic cleavages and hardness. Biotite grains present in small amount are recognised by flaky habit, brownish colour, perfect basal cleavage, pearly luster and low hardness.

Under the microscope pyroxene granulite exhibits granoblastic texture. The rock consists of minerals such as diopside, plagioclase, hypersthene, orthoclase and opaque. The grain boundaries include lobate, straight, curved and also embayed. The mineral assemblage observed is

Hypersthene + diopside + plagioclase + orthoclase+quartz

Hypersthene occurs as subhedral grains. It shows a set of prismatic cleavages traversed nearly at right angles by fractures. Diopside it is colourless to pale green with little pleochroism, prismatic cleavage, inclined extinction.

3.4. Garnet biotite gneiss

Garnet biotite gneiss present in the study area is migmatised and sheared. It is a medium to coarse grained rock exhibiting xenomorphic granular texture. Quartz occurs as anhedral grains whereas feldspar grains are subhedral to anhedral. At many places, the gneiss contains lenticular megacrystals of feldspar. Garnet varies in proportion and occurs as irregular, rounded grains and as scattered porphyroclasts. Biotite occurs as flakes and specks in the rock.

The mineral assemblage present in garnet biotite gneiss is

Quartz + K-feldspar + plagioclase + biotite + garnet + opaques

The rock is inequigranular, medium to coarse grained with granoblastic texture and shows the characteristic gneissosity defined by alternating layers of quartzo-feldspathic and ferromagnesian minerals. The various minerals present in the gneiss show irregular, embayed, curved and sinuous grain boundaries. Quartz grains show the characteristic wavy extinction indicating the strain effects. Fractured quartz grains with secondary infillings are also seen. Both orthoclase and plagioclase feldspars are noticed. Plagioclase is subordinate to orthoclase. Garnet is generally almandine-rich and occurs as irregular, rounded or semi-rounded grains and as scattered porphyroblasts. Opaques are found associated with garnet.

3.5. Dolerite

Dolerite occurs as small dykes which are relatively younger formations and cross cut granulites in the study area. They are fine-grained dark colored in nature. A major dyke found in a quarry exposure near Alana area. It is a mesocrystalline rock that shows equigranular, hypidiomorphic texture. In thin section the rock shows subophitic texture,, in which laths of plagioclase in larger grains of pyroxenes can be observed. The rock shows spherulitic texture. Plagioclase spherulite can also be observed in dolerite. The spherulite comprises of elongated crystals of plagioclase, each having different optical orientation.

4. Mesoscopic analysis of structural elements

The studies of the geometrical dispositions are mainly done by the observation of structural fabric. Mesoscopic structural analysis is primarily concerned with the structures visible in hand specimens and exposures. The area under investigation undergone high-grade metamorphism and was subjected to polyphase deformation. Hence it is difficult to observe primary structure such as bedding planes. Such primary structures are designated as S_0. The primary structures such as bedding planes (S_0) in the study area are often tilted and folded. Because of this deformation it is very difficult to infer the original stratigraphy of the terrain.

Hornblende biotite gneiss in the study area shows alternate light layers (quartzo-feldspathic minerals) and dark layers (ferromagnesian minerals) due to compositional layering. Compositional layering is the characteristic feature of these gneissic banding. These gneissic layering can form by metamorphic differentiation, by transportation and recrystallization of original bedding, by partial melting. The compositional banding in metamorphic rocks can be either primary or secondary in origin. This feature is common in high-grade southern granulite terrain. In majority of the deformed metamorphic rocks parallel alignment of elongate grains is visible in hand specimen. In the study area, foliation in hornblende biotite gneiss is well defined by the planar preferred orientation of hornblende and biotite. The other rock type that shows a planar preferred orientation is the mylonite. The foliation in the study area generally strikes WNW-ESE.

4.1. Geometric Analysis of Planar Structures

Geometry of the fabric elements reflects the geometry of movements responsible for deformation. Geometric analysis is the best tool in analysing data on spatial orientation of planar and linear structural elements collected in the field and for drawing conclusions on the geometry and mutual relations of structures. Construction of π- diagrams is the most satisfactory method for the analysis of S-plane data from folded terrains.

Foliation forms the predominant planar fabric in the study area. It shows variation in different parts of the study area. Since the primary planar fabrics have been modified to a great extent by metamorphic recrystallization and S_0 and S_1 are effectively parallel, the dominant planar fabric in the rock types of the study area can be considered as S_1 for the purpose of geometric analysis. A structural map of the study area was prepared based on the attitude of foliation (Fig. 2). For convenience, the area was divided into three sectors based on homogeneity/inhomogeneity of the attitude of structural elements.

Sander (1970) has recommended cyclographic plotting of all syngenetic S-planes as a method of tectonic analysis of macroscopic scale structures. Ideally, these planes should intersect in a common line or lines that cluster around a centre of gravity which is termed as β–axis. In general, the poles to the S-planes are plotted, which are contoured or a great circle of best fit is drawn through them to derive the macroscopic fold axis. This method of structural analysis is widely followed in the analysis of structures. Sectorwise π S_1 diagrams were prepared using computer software STEREO 2.46.

Sector	Orientation of π-maximum	Orientation of submaximum	Orientation of Axis of rotation	Nature of distribution of S_1 poles
1	48^0/N270^0	50^0/N360^0	12^0/N150^0	Incomplete great circle girdle
2	45^0/N260^0	32^0/N112^0	45^0/N150^0	Incomplete great circle girdle
3	72^0/N300^0	25^0/N252^0	28/N110^0	Incomplete great circle girdle

Table. 1 *Summarised account of the characteristics of sectorwise S_1 pole diagrams*

Sectorwise π S_1 diagrams

Sector - I

The S_1 poles of sector I form an incomplete great circle girdle, with two slightly elongated concentrations and a compact concentration. Here, the π-maximum and submaximum plunges 48^0/N270^0 and 50^0/N360^0 respectively. The pole to the great circle, passing through the two maxima, represents the axis of rotation, plunges 12^0/N150^0. The tendency of the poles to spread along an incomplete great circle girdle can be attributed to later F_3 folding.

Sector – II

The poles to S_1 surfaces of the sector-II form an incomplete great circle girdle, with an extremely elongated concentration. The π-maximum plunges 45^0/N255^0 and the sub-maximum plunges 32^0/N112^0 . The pole to the great circle, passing through the two maxima, represents the axis of rotation, plunges 45^0/N150^0. Spread of the concentration, containing the sub-maximum, along an incipient girdle can be related to superpose cross folding during the F_3 event.

Sector – III

The S_1 poles of sector III form an incomplete great circle girdle with an elongated concentration and a peripheral one. The maximum plunges 72^0/N300^0 and the sub-maximum plunges 25^0/N252^0 respectively. The pole to the great circle, passing through the two maxima, represents the axis of rotation, plunges 28^0/N110^0. The spreading of poles along incipient great circles is due to the rotation of poles as a result of F_3 folding.

6. Discussions

The study area is a high grade metamorphic terrain as evidenced from the presence of charnockite and pyroxene granulites. The presence of hornblende-biotite gneiss along with the charnockites points towards the retrogressive metamorphism undergone due to the granitic and pegmatitic intrusions. Biotite found developing at orthopyroxene rims together with magnetite and quartz. Similarly biotite inclusions are found within garnet, which are indicative for retrograde reactions. Therefore it can be concluded that the present study area had witnessed a regional granulite facies metamorphism which has retrogressed to the amphibolite facies at places.

The primary planar structures are not well preserved in the region due to intense metamorphism and subsequent deformation. The principal planar fabric i.e., foliation defines a regional fabric, the curving of which gives rise to tightisoclinal fold (F1) having a prevalent southerly sub-vertical dip. The systematic analysis of structural fabric delineates the deformation associated with high grade metamorphism. Polyphase deformed rocks display multi-directional tectonic trends and general trending towards WNW-ESE and this indicates superimposed folding. The pole diagrams of the area indicate polyphase deformation at least two phases of folding in response to deformation on regional scale forming linear ridges, residual hills and pediment plains imparting an uneven topography. These multiple and complex structural and metamorphic events could be chronologically constrained for better perception and evaluation of the tectonic history of this terrain.

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