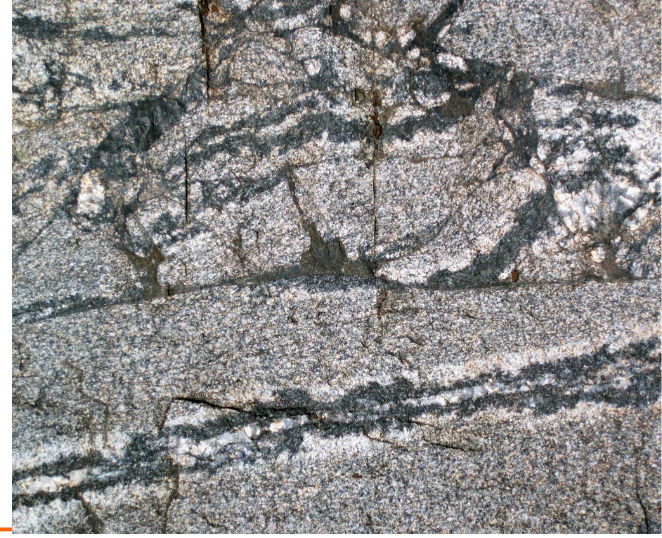
Shear Zones and Crustal Blocks of Southern India

vol 3



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Department of Geology
University of Kerala
Trivandrum, India

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& University of Kerala

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Preface

Preface

The Department of Geology, University of Kerala established in 1963, is one of the pioneering educational institutes, imparting studies in earth system sciences, in Kerala, India. The department has entered the third year of the UGC-SAP-DRS (*University Grants Commission-Special Assistance Program-Departmental Research Support*) Phase II (2013 to 2018) with the thrust area of research being 'Shear zones and crustal blocks of south India with special emphases on fluid inclusions and tectonics'. The Southern Granulite Terrain is composed of a collage of blocks exposing mid- and lower-levels of the continental crust, dissected by crustal-scale shear zones among which the Palghat-Cauvery Shear Zone (PCSZ) in the north and the Achankovil Shear Zone (ACSZ) in the south have been interpreted as suture zones. The faculty of the department have been part of the research that established the existence of the Coorg microcontinent.

Under this project detailed investigations have been carried out on the metamorphic rocks, shear zone rocks, kinematics of shear zones and the tectonics of the crustal blocks on the basis of petrography, geochemistry, fluid inclusions. As part of the ongoing research initiatives, the first UGC–SAP– DRS Phase II conference was held on 29 March 2014 and the second on 31 March 2015. It brought together experts in the thrust area leading to very vibrant presentations and discussions. In this third edition of the seminar series, supported by UGC and also the University of Kerala through the funding for the lecture series under 'Current Trends in Earth System Sciences (CTESS)' well-known experts as well as budding geoscientists from various scientific organizations/universities/research centers in petrology, tectonics and geochemistry have come together to present their research work. Additionally, the University of Kerala is building a new museum of geology, and a session of the seminar is devoted to discuss how geological museums can be built up. It is hoped that the outcome and deliberations of the conference would give a strong foundation for the department to go forward with the phase II research program as well build a geological museum in a well-planned and systematic manner. We are extremely happy to bring out this volume, which contains the full papers and abstracts of the papers presented in the conference. The contributions received from the experts and the students are greatly appreciated and acknowledged. ***The financial support received from the University Grants Commission has helped this department aspire for excellence in research and this is gratefully acknowledged.*** The department is on the anvil of building up a strong petrological and fliud inclusion lab with the UGC SAP financial support. This will benefit the students and faculty of this University as well as neighbouring ones and will be open to all researchers of this country.

E. Shaji
Dty coordinator, UGC-SAP-DRS II

A. P. Pradeepkumar
Coordinator, UGC-SAP-DRS II

UGC SAP DRS II 3rd yr seminar and CTESS2015 with Museum Session			
Date and time	Event	By	Topic
15 Feb 2016	**DAY 1 Dept of Geology, Uni of Kerala Seminar Hall**		
10:00	Invocation	Masters student	
10:05	Welcome	Dr AP Pradeepkumar, UGC SAP DRS II coordinator and Org Scty CTESS2015	
10:10	Presidential address	Dr SN Kumar Director, School of Earth System Sciences	
10:15	Felicitations	Dr PM Radhamony Prof of Botany & Syndicate Member	
	Felicitations	Dr VM Tiwari Director, NCESS	
10:30	Release of seminar proc vol by handing over to Dr RS by Dr VM Tiwari & Inaugural keynote 1	Dr R Srinivasan Editor, Current Science, Bangalore *(former Scientist, NGRI)*	1. A critique of sutures in the Neoarchean Dharwar craton, southern India 2. IASc, *Current Sci.*, and internships
11:15	**Tea break & Group photo**		
11:30	Invited lecture 1	Biju John, Yogendra Singh, E. Praseeda NIRM	Neotectonic evidences associated with shear zones of south India
11:50	Invited lecture 2	R.T. Ratheesh-Kumar	Definition and tectonic evolution of the Biligiri Rangan

		IISc	Block, southern India
12:20	Invited lecture 3	DP Mohanty Uni Pune	Study of mesoscopic structural features along the margins of Cauvery Suture Zone, Southern India
12:40	Invited lecture 4	R Bhaskaran GSI Trivandrum	
13:00	**LUNCH**		
14:00	Keynote lecture 2	Ernst Hegner LMU Munich	Geological clocks for dating the pace of crustal assembly
14:45	Keynote lecture 3	Dr SG Viladkar Mumbai	REE-status in Indian carbonatites
15:15	Invited lecture 4	A Krishnakanta Singh WIHG	Ophiolites of the Indo-Myanmar Orogenic Belt, Northeast India: Petrogenesis and Geodynamic implications
15:45	UGC SAP Keynote Lecture 1	Satish Sangode Uni Pune	Anisotropy of Magnetic Susceptibility: A Comparative Analysis of Lava Flow and Sediment bed load fabrics based on some case studies
16:15	**Tea break**		
16:25	Invited lecture 5	G.R. Ravindra Kumar N-CESS	Arrested charnockite formation in southern India
16:50	Invited lecture 6	Ajay KK & Chaubey AK Govt College, Nattakom	Continental crustal blocks and reactivated structural lineaments of Laccadive Ridge, SW continental margin of India
17:00	Invited lecture 7	Rajesh VJ IIST	Mars analogue studies

16 Feb 2016	DAY 2 Dept of Geology, Uni of Kerala Seminar Hall		
10:00 Day 2	Keynote lecture 4	TRK Chetty NGRI	The Southern Granulite Terrane of India: Shear Zone Systems and crustal blocks
10:45 Day2	Invited lecture 8	Rajneesh Bhutani, Maya JM & Balakrishnan S Pondicherry Uni	Mantle heterogeneity during early Earth history: clues from $^{146-147}Sm$-$^{142-143}Nd$ studies on komatiites
11:30	**Tea break**		
11:45 Day 2	Invited lecture 9	P Ajayakumar & KR Baiju CUSAT	Crustal structure across Periyar Plateau, Southern Granulite Terrain (SGT): Inferences from Gravity data
12:00 Day 2	UGC SAP PhD talk 1	Amaldev T CUSAT	High grade metamorphism and subduction related arc-magmatism in the Mercara Shear Zone, southern India
12:15 Day 2	UGC SAP PhD talk 2	P.V. Thanooja, C. Ishwar-Kumar, K. Sajeev IISc	Geology and petrography of major rock types from Madras Block, southern India
12:25 Day 2	UGC SAP PhD talk 3	Manju Narayanan CUSAT	Fluid Inclusion Study on the Wynad and Attappadi Gold mineralization in Southern Granulite Terrain, India
12:35 Day 2	UGC SAP PhD talk 4	Sajna S NCESS	Tectonic and metamorphic evolution of Nagercoil block through in-situ trace element studies on accessory minerals
12:45 Day 2	UGC SAP PhD talk 5	Manu Raj R Uni Kerala	Miarolitic cavities in Granitic Pegmatites of Nagamalai – Pudukottai area, Madurai district, Tamil Nadu, India.
13:00	**Lunch**		
	Afternoon session		
14:00	UGC SAP Keynote	Abdul Matin	The structural anatomy of Cuddapah basin --- a

Day 2	Lecture 2	Uni Calcutta	Proterozoic fold-thrust belt from Peninsular India
	GEOLOGICAL MUSEUMS SESSION		
14:30 Day 2	Introductory remarks 1	KS Gopakumar Syndicate Member (Planning)	Geological Museum of Univ of Kerala
14:40 Day 2	Introductory remarks 2	K Sobha University Engineer	Plan and progress of the geological museum, U Kerala
15:00 Day 2	Geological museum lecture 1	Dr SG Viladkar Mumbai	Geological museums: Carbonatite museum of Amba Dongar
15:30 Day 2	Geological museum lecture 2	Dr SK Parcha WIHG	Museums - Vistas of Knowledge
16:00 Day 2	Heritage museum lecture 3	S Raimon Museum, Trivandrum	Setting up of heritage museums: an experience
16:00	**Tea break**		
16:45 Day 2	Summing up session & Vote of thanks	E Shaji Dty Coordinator UGC SAP II Uni Kerala	
17:00 Day 2	***Visit to the site of the geological museum***		

A critique of sutures in the Neoarchean Dharwar craton, southern India

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Abstract

Dharwar craton which was considered as a single terrane based on geological mapping and structural studies was suggested to be composed of more than one terrane based largely on geochemistry and geochronology. Initially individual schist belt- Kolar schist belt- was suggested to be an Archean suture. Later it was suggested that crustal scale fault along the eastern margin of the Chitradurga schist belt constitutes a suture that juxtaposes the Archean nucleus in the west and Early Proterozoic mobile belt on the East.These two terranes have come to be known as Western Dharwar craton and Eastern Dharwar craton . Recently based on SHRIMP Zircon U-Pb age data, it has been suggested that the Mercara massif in the SW Karnataka and North Kerala is an exotic palaeoarchean (Haedean) terrane to which the Ca.3.3-3.6 Ga Dharwar craton was sutured (Santosh et al., 2014). Similarly based on SHRIMP and laser ablation U-Pb geochronology it has been proposed that the Dharwar craton is actually a patchwork of four terranes, not two.

The southern boundary of the Dharwar craton has also been controversial. The Palghat -Cauvery lineament was proposed as a terrane boundary between the Archean craton and the Proterozoic mobile belt of sothern Tamilnadu and Kerala. However based on model Nd ages and zircon geochronology the boundary between the two terranes was shifted far to the south of Palghat -Cauvery lineament to Karur-Kambham-Painavavu-Trichur shear zone. High pressure and high temperature metamorphism in the Kambham region is presented in support of this zone being a suture.

The structural unity in the Dharwar craton, Laser ablation zircon lead isotopic geochronology, unpublished SHRIMP U-Pb ages of zircons from felsic volcanic rocks of the Dharwar Sequence with the author , provide evidence for similar structural evolutionary history, similar antiquity and co-eval felsic volcanism in the WDC and EDC. These observations are not compatible with the division of the Dharwar craton into two or three terranes. Further the sedimentary volcanic assemblages in the Dharwar craton provide evidence for accumulation in magmatic arc and back-arc, not a setting for a suture. Accidental discovery of a Haedean zircon in Mercara massif and their non-discovery in other regions cannot be adequate evidence for erecting a new terrane. Zircon geochronology on Dharwar craton is only in initial stage and more data base is essential to propose or deny new terranes in the craton on the basis of geochronology.

There is a major structural and metamorphic break across the P-C lineament a few kilometres south of Namakkal, which could be a terrane boundary between Archean and Neoproterozoic terrane. Structural studies show that the NS fabric seen in the amphibolite facies gneisses south of the lineament, is absent in the Archean granulites north of the lineament. In the contact zone between the granulites and gneisses coinciding with the lineament, granulites are retrogressed to amphibolite facies rocks. The sense of movement along the fault although is oblique slip, has a large dip-slip component and smaller strike-slip component. Kinematic indicators show that the northern granulite block is thrust over the southern amphibolite block. Remelting of the southern subducted block has apparently given rise to the chain of potassic granitoids in the northern granulite terrane, between Bhavani and Coimbatore.

Neotectonic evidences associated with shear zones of south India

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Abstract

The southern granulite terrain is composed of a collage of Precambrian crystalline terrains which are separated by shear zones. All thermo-tectonic events in these terrains occurred well before the split of Gondwana around 120 Ma. However, the studies on active tectonics in Peninsular India indicate a north directed movement of Indian plate and the plate interior is experiencing compression. In continuation with the ongoing studies, this paper reports observations from the southwestern part of Palghat-Cauvery shear zone and southeastern end of Achankovil shear system, in-terms of tectonic geomorphology.

The E-W trending Palghat Gap, which follows Palghat-Cauvery shear zone, is one of the most significant geomorphic discontinuities in Westerm Ghats. The E-W trending main trunk of Bharathapuzha River is considered as influenced by the structures related to this shear zone. The NW-SE trending Desamangalam fault, which is identified as active, changes the Bharathapuzha River course near its vicinity. The studies also identified continuity of NW-SE trending Periyar lineament into the E-W trending Palghat-Cauvery shear zone which is influencing the drainage system of the area. A recent study considered Periyar lineament as a part of another shear zone.

The NW-SE trending 15-20 km wide, Achankovil shear system is identified as prominent structural and geomorphic features in Western Ghats. The studies found that the geomorphic and structural signatures of the lineaments associated with this shear zone are extending further into the flat land east of Western Ghat. The traces of these are identified as multiple slip planes with varying style of brittle deformation. The slip planes observed in this area are mostly dipping south. These observations suggest that these shear zones may be week and the discrete faults with in them are responding to the present stress regime.

Key words: *Palghat-Cauvery shear zone, Achankovil shear system, tectonic geomorphology, Brittle deformation*

1.0 Introduction

The Southern Peninsular India consists of high grade Precambrian crystalline terrains which are separated by shear zones. These terrains are well studied to understand the various thermo-tectonic events that occurred (Santosh et al., 2003; Ghosh et al., 2004). The youngest of the events was occurred around 550 Ma which were associated with the pegmatite intrusions (Soman et al., 1990). The shear zones play an important role in the reconstruction of the East Gondwana and are identified based on discontinuities in lithologic and structural units, metamorphic P-T conditions, and geochronology and are considered as of Pan-African origin. Though the origin and kinematics of some of them are still debatable, they are associated with distinct geomorphic features. Some of these structures are also associated with seismicity (Fig.1).

This region, however, is considered as stable (Stable Continental Region) in the context of earthquake occurrences (Johnston and Kanter, 1990). The sparse occurrence of seismicity however indicates that the Peninsular India is under compressional tectonic regime owing to the northward movement and can generate moderate earthquakes (Gowd, et al 1996 and Rajendran, et al 1992). Studies in various stable continental regions indicate that the earthquakes are occurring in preexisting zones of weakness (e.g. Sykes, 1978; Crone et al., 1997; Rajendran et al., 1996).

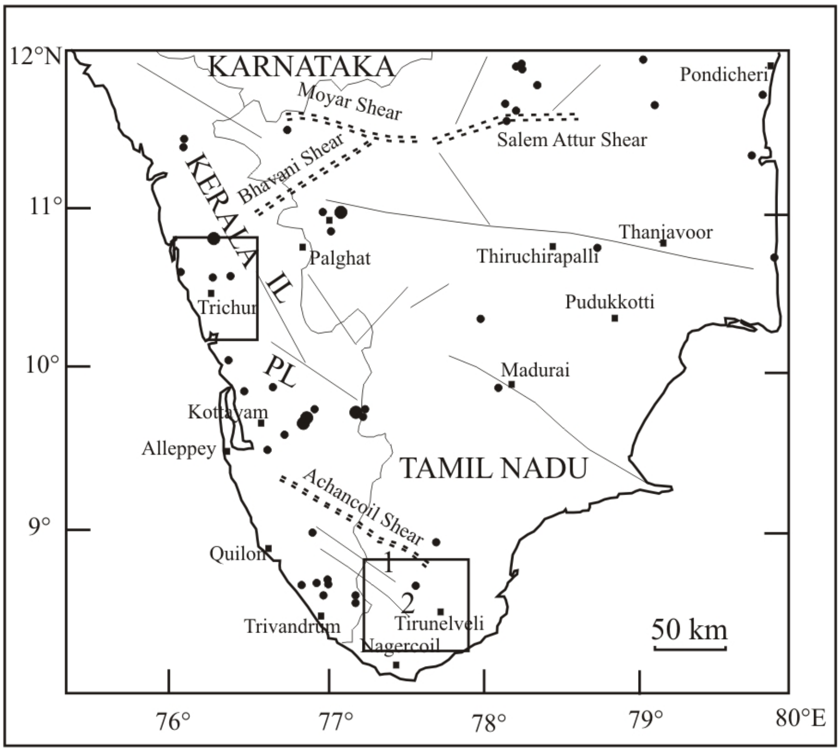

Fig.1 Seismotectonic map of South India adopted from SEISAT (GSI, 2000).
The study areas are shown in rectangles; PL is Periyar lineament; IL is Idamalayar lineament fault marked as 1 is Thenmala Fault and 2 is Thenmala South Fault.

The active fault identification studies in Peninsular India are mostly based on regional geomorphic and local fault zone evaluation (e.g. John and Rajendran 2008; John and Rajendran 2009; Ramasamy et al, 2011, John et al., 2013; Praseeda et al., 2015). These studies show that the regional geomorphic analysis can identify anomalies induced by active faults. The geologically young deformation/faulting are identified based on the textural variations, deformation processes and rheology (John and Rajendran 2009; Praseeda et al., 2015; Singh et al., 2016). A crustal scale fault is dominated by brittle deformation that involves cataclasis and frictional sliding and produces incohesive breccias or gouge at shallower levels (Fig.2) and cohesive cataclasis at greater depth (Scholz1988; Sibson 1977). This paper reports observations from the southwestern part of Palghat-Cauvery shear zone and southeastern end of Achankovil shear system, which can be considered as neotectonic.

2.0 Observations from Western terminus Palghat Cauvery shear zone

The Palghat-Cauvery Shear Zone (PCSZ) is an E–W trending shear zone following the Palghat Cauvery Lineament extending from the east coast to the west coast of India (Drury and Holt, 1980; Ramakrishnan, 1993; GSI and ISRO, 1994). The 1900 (M=6.0) and 1975 (5.5) Coimbatore earthquakes are two important events occurred within this shear zone. The 1994, Wadakkancheri earthquake (M=4.3) promoted several studies in the epicentral area. The area, which continued to experience tremors intermittently, lies around the Bharathapuzha and Chalakkudi Rivers and northern half of it is a part of the PCSZ (Bhaskar Rao *et al* 1996)

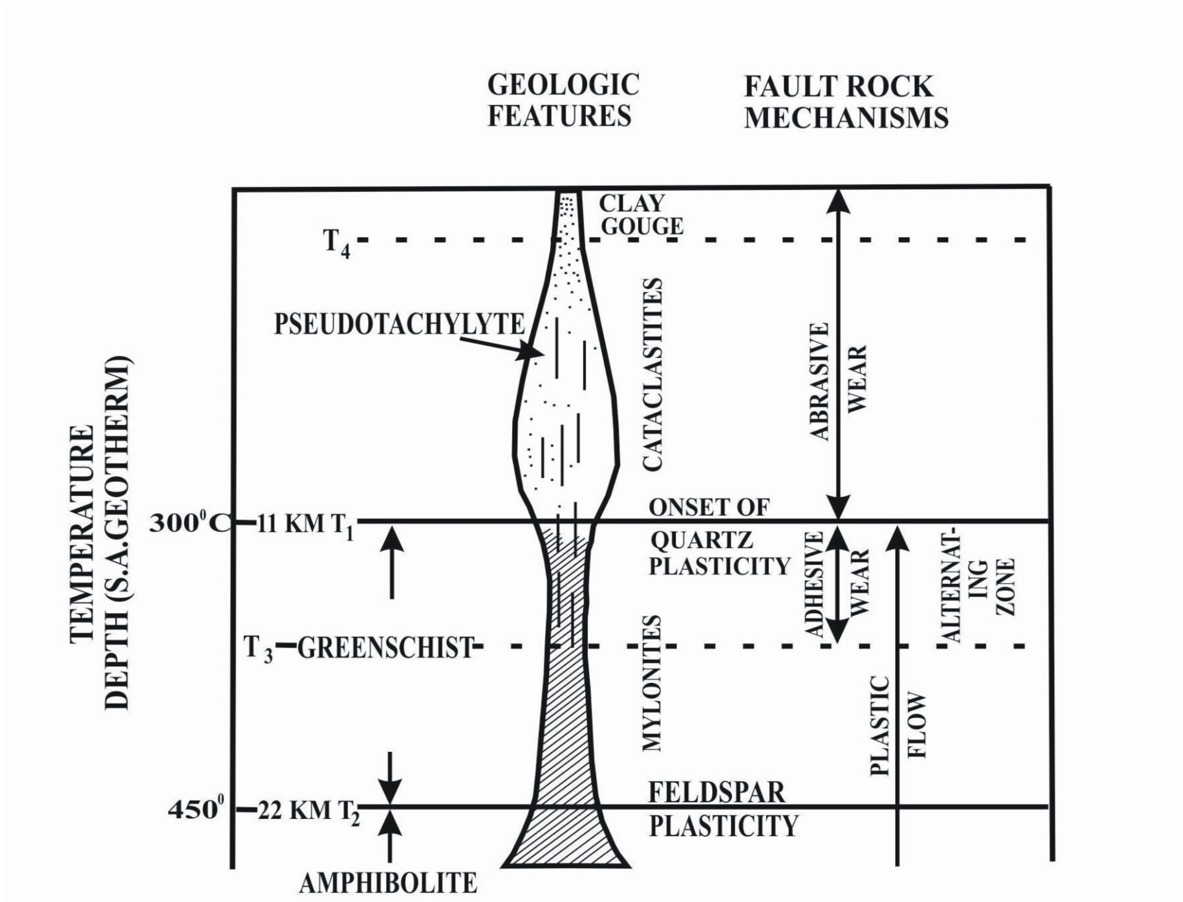

Fig. 2 Conceptal model of crustal scale faultand shear zone; modified after Scholz 1988. Not that the clay gouge is observed at the tip of the fault zone.

2.1 Structural and geologic setup

The local geology is dominated by a metamorphic suite of charnockite and khondalite group of rocks (GSI, 1992). The charnockitic suite of rocks (consisting of granular quartz, feldspar and hypersthene) forms the basement in the area, and is characterized by well-developed foliation, at many places, striking NW-SE with a southward dip of 30°-50°. Quartzo-feldspathic gneiss, pink granite and hornblende biotite gneiss are the other major crystalline rocks in the region (GSI, 1992).

The Periyar river lineament, which controls the course of the Periyar River for a longer distance (Rajendran *et al* 2009), is also enters through the southern part of the study area. Ghosh *et al* (2004) considered this as a Precambrian structure and named it as Karur- Kambam-Painavu-Trichur Shear Zone (KKPTSZ), which suffered more than one phase of shearing and granitic activity. According to them the KKPTSZ is a V-shaped shear zone extending from south of Karur in the east, with a NE–SW trend to just north of Kambam and with a sharp turn towards Painavu and trissur in the NW direction.

2.1 Observation on neotectonism

The Bharathapuzha River sourced at the Western Ghat and its tributaries constitute the drainage network in the gap area, which is generally controlled by E–W trending lineaments. However, the Desamangalam fault and the Periyar lineament influence the drainage network of the area. Both these structures also show association of seismicity and brittle deformation.

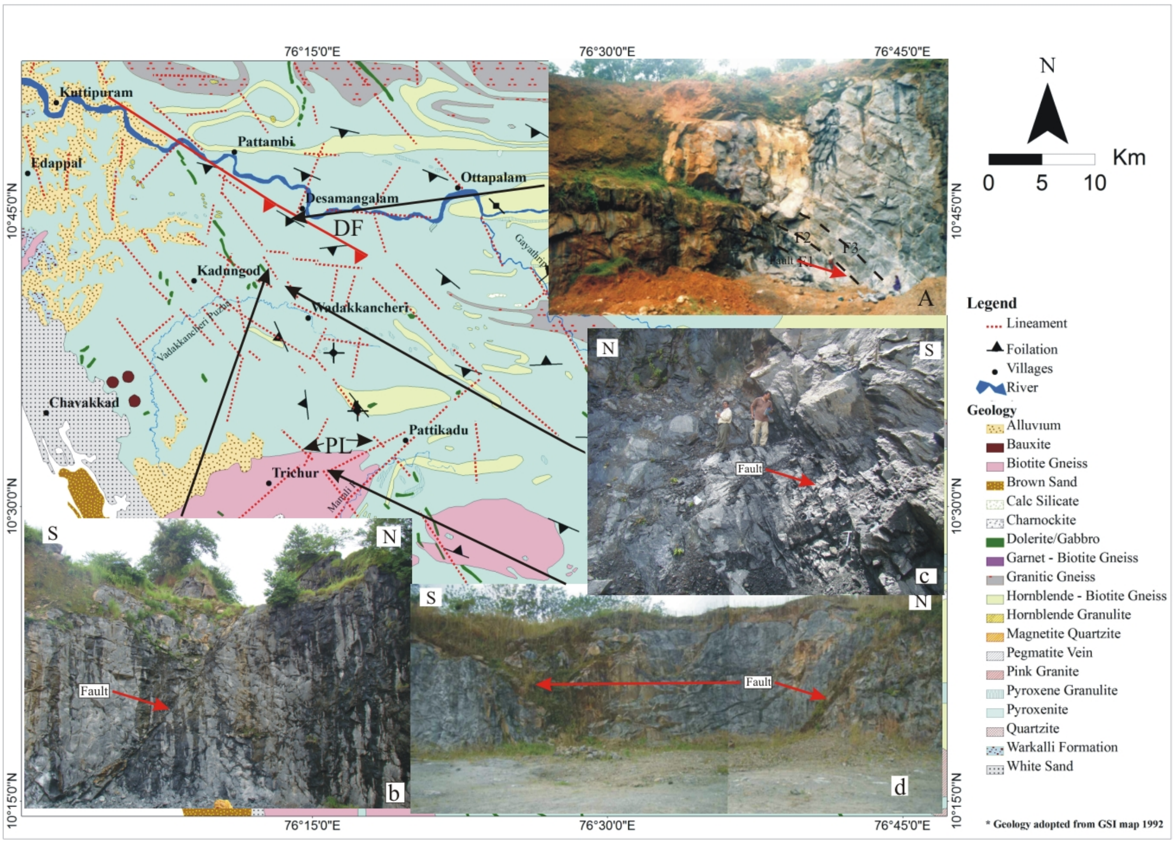

Figure 3 Geological map of the area; note the NW-SE trending lineaments and dykes. DF and PL are Desamangalam fault and Periyar lineament respectively. Inset: 3a shows the Desamangalam fault exposure; 3b shows the vertical quarry section showing a brittle fault found near Erumapetti; 3c fault exposure near Teyyur; 3d fault exposure near Mannuthi.

2.1.1 Desamangalam fault. The Desamangalam fault controls the main trunk of Bharathapuzha River downstream from Desamangalam (John and Rajendran 2008). The fault follows an elongated hill ridges and created a waterfall with a board upstream valley and a narrow downstream valley. The isoseismal elongation of 1994 earthquake is also coinciding with this fault. The evidence of brittle faulting was obtained from a quarry section exposed in the WNW–ESE-trending hillock within the seismic source zone (Fig. 3a). This brittle fault zone was developed by the progressive incorporation and amalgamation of newly formed and preexisting subsidiary shears and fractures of varying size and orientation (John and Rajendran 2009). Detailed morphological, textural and mineralogical studies indicate episodic nature of fault growth where the major displacement imprinted on the quartz grains within the loose gouge is dated at around 430 ka (Rao et al., 2002).

2.1.2 Periyar Lineament. The drainage system of the area is also controlled by the NW-SE trending lineaments corresponding to Periyar lineament that enters into Palghat-Cauvery shear zone. Singh et al., (2016) identified that these lineaments are segmented and have induced drainage anomalies in the area. Their studies identified subtle landform modifications induced by ongoing tectonic adjustments in the area. Southeastern end of this lineament is associated with seismicity (e.g. 1988 Idukki M=4.5 earthquake). Signature of the NW-SE trending lineament is traced as faults at three locations viz., Erumapetti, Tayyur and Mannuthi (Fig. 3b,3c,3d). The brittle deformation exposures are associated with damage zone, gouge formation and slickensides. The vertical and lateral extend of the fault zone display variations in thickness of damage zone. It is also noted that all of them dipping southwest.

3.0 Observations from South eastern terminus of Achankovil shear zone

The Achankovil shear system is one of the major crustal scale structures in Peninsular India. This NW-SE trending shear zone stretches across the Western Ghats for a strike length of 120 km. This feature is identified as a shear zone based on the change in rock types to the north and south, and by the sharp change from NE trending structures north of the shear zone to NW trending structures within and south of the zone (e.g Rajesh and Chetty, 2006). The northern boundary of the shear zone is considered to be coinciding with the straight course of the Achankovil River while the Thenmala fault is confined to a long narrow valley passing through the Thenmala village. Chacko et al. (1987), Ramakrishnan (1993), Rogers and Mouldin (1994), Braun and Kriegsman (2003), Kumar et al. (2009) considered these two boundaries as two individual shear zones viz., Achankovil Shear and Thenmala Shear, and the region bounded by them as Achankovil Unit. A number of parallel lineaments demarcate this 15-20 km wide shear zone. Gravity signature across the Achankovil shear characterized by sharp velocity contrast indicates that the shear is a crustal scale zone of deformation reaching up to mid-crustal level (Sunil et al., 2010).

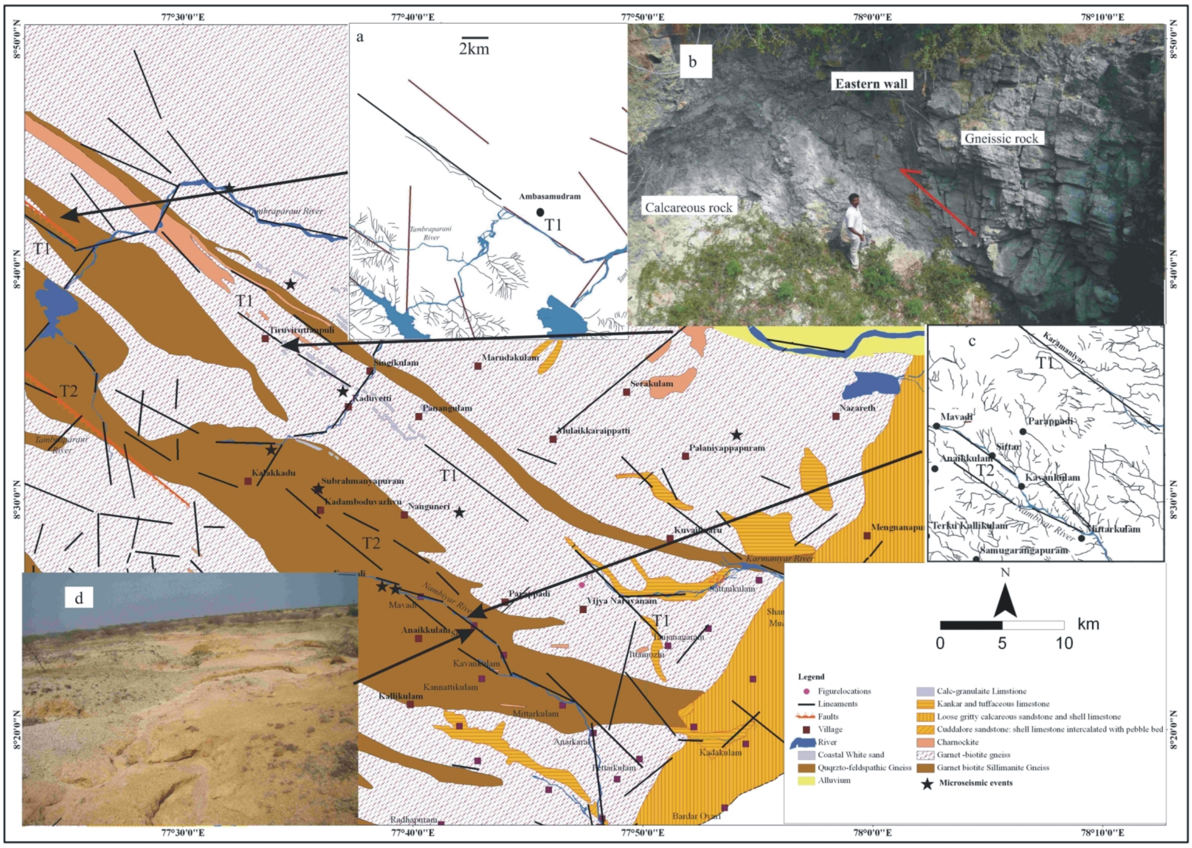

Figure 4 Geological map of the area. Note the NW-SE trending primary structural features. (Geology adopted from Quadrangle Geological Map (1989). T1 and T2 are Thenmala and Thenmala south fault respectively. Inset: 4a shows the drainage anomaly northwest of ambasamudram; 4b shows the faulting observed along Thenmala fault; 4c river pattern influenced by T1 and T2; 4d shows the geomorphic feature associated with Thenmala south fault (Praseeda dt al., 2015).

3.1 Structural and Geologic Set up

Achankovil shear zone represents a number of parallel lineaments within Western Ghats. Thenmala fault forms the SW boundary of this ~ 15-20 km wide shear system (Rajesh and Chetty, 2006). In Seismotectonic Atlas of India and Its Environs (SEISAT) there are two faults (one named as Thenmala and another unnamed) marked south of Achankovil shear zone (GSI 2000). The present paper further describes the unnamed fault as Thenmala south fault. Even though these faults were demarcated in hilly terrain of Western Ghats, its expression into the plain area east of the mountain terrain were not identified during the earlier studies.

3.2 Observations on neotectonism

The present study identified the Thenmala fault as a prominent lineament in the Western Ghats and is demarcated by the straight course of Kallada and Chendurni rivers (west of the present study area). At the southeastern end within the hill ranges it shows discontinuous features (Fig.4). The signature of this fault is further traced in the plain area based on the tonal change observed in the Landsat image. Closely spaced parallel drainages observed as drainage anomay northwest of Ambasamudram (Fig. 4a). The straight course of Karamaniyuar River between Nanguneri and Vijaya Narayanam (Fig 4c) is along this lineament.

The study also identified Thenmala South Fault as a discontinuous feature within the Western Ghats. It passes through NW trending reservoir of Karayar Dam (Hope dam). The southern fault is matching with an en-echelon pattern in the plain area after slight offset where it shows a left stepping of lineaments (Fig.4). It also forms part of two parallel flowing tributaries of Nambiyar River (Fig. 4c). Active erosion within the vicinity of these lineaments may indicate neotectonic adjustment (Fig. 4d).

3.2.1 Thenmala fault. Field observations were made about 50 km in to the plain area around the Thenmala fault. The faults are identified at several locations along the lineaments. A wide range of faulting, characteristics to brittle deformation, are observed in different exposures. The dip amount of the NW-SE trending fault/slip planes also changes from place to place.

A brittle fault trending N 300^0 dipping 45^0 southwest is exposed near Thiruviruthanpuli (Fig.4a). Here the gneissic rock appears to have over raided on calcareous rock. The hanging wall (gneissic rock) is highly jointed and the slip plane is demarcated with open cracks (Fig. 4a). Multiple slip planes are observed in the hanging wall. In nearby area relatively thick calcareous deposit is observed over the basement crystalline rocks. The footwall is highly crushed and it is difficult to determine the original rock structure.

3.2.2 Thenmala South fault. The faults are identified at several locations along this lineament. A wide range of fault related damage pattern are observed in different exposures. The dip amount of the NW-SE trending fault/slip planes also changes from place to place. The area around Anikulam shows badland topography due to intense erosion Fig. 4d. This could be due to the local base level change induced by the neoteconic movement along the lineament.

The fault observed near Kadamboduzazhu appears as thick crushed zone separating the faulted blocks (Fig.5). The movement across the slip plane is evident from the distinct joint pattern observed on either side of the fault. Vertical joints are observed in the hanging wall whereas inclined joints are observed in footwall. None of these sets of joints continued across the slip plane, suggesting an appreciable slip. The cross cutting relationship may indicate that the faulting is the youngest deformation.

4.0 Concluding remarks

PCSZ and AKSZ are two major shear zones in Peninsular India. Some recent studies consider Periyar lineament as a part of KKPTSZ. Some part of these shear zones show geomorphic anomalies. Some of them are associated with seismicity. The faults in these areas are identified as brittle deformation zones and must be geologically young and formed in the shallow levels. Three types of lithologies can also be distinguished in each of the fault exposures, namely, 1) protolith or host rock 2) damage zone, and 3) a fault core (e.g. Caine *et al* 1996; John and Rajendran, 2009). Protolith is the undeformed host rock surrounding the fault rock and the damaged zone. The damage zone consists of a network of fault related subsidiary structures that bound the fault core. The fault related subsidiary structures in the damaged zone include small offsets, veins, fractures and cleavages (Bruhn *et al* 1994). Fault core is the portion of a fault zone where much of the displacement is accommodated (Caine *et al* 1996).

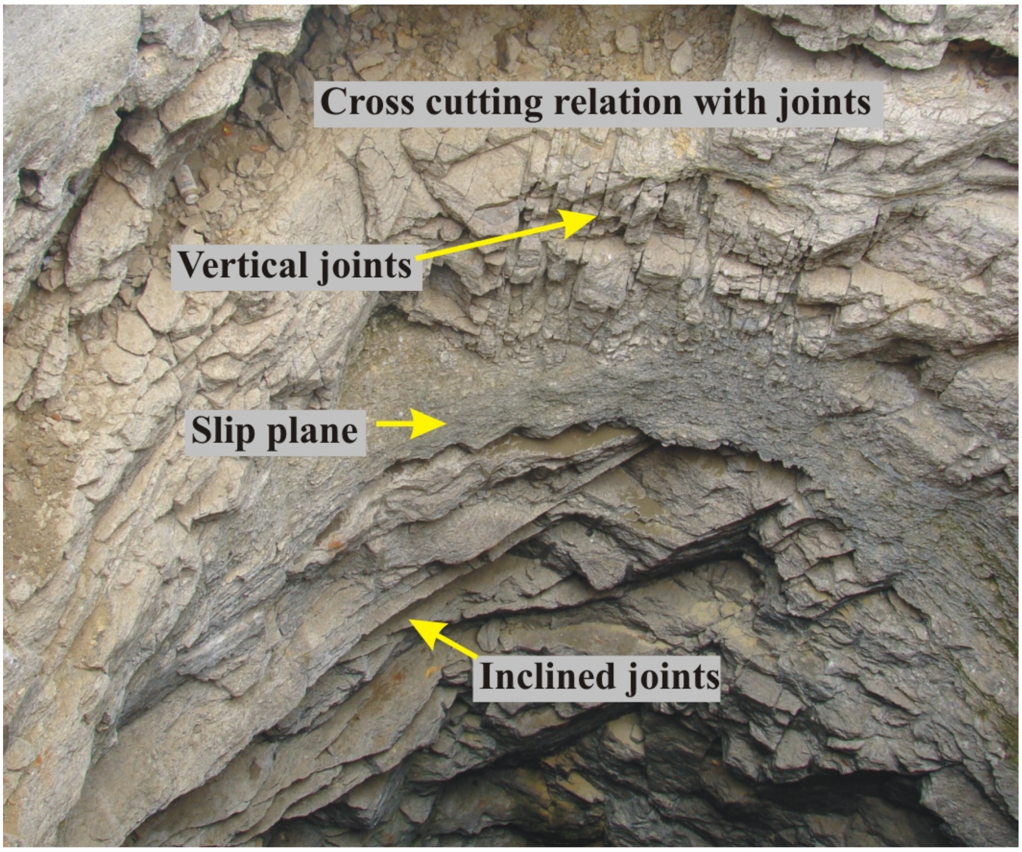

Fig. 5 Gentle NW-SE trending south dipping fault observed in the well section near Kadamboduvazhvu. Note the rocks on either side of the slip plane shows different joint pattern

The association of geomorphic anomalies, brittle deformation and seismicity in the shear zones may indicate that these structures are week and the discrete faults within them are responding to the ongoing compressional tectonic regime of Peninsular India. Thus a relook at these shear zone is important in the context of active tectonics.

Acknowledgement

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Definition and tectonic evolution of the Biligiri Rangan Block, southern India

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The Southern Granulite Terrain (SGT) in India is a collage of crustal blocks ranging in age from Archean to Neoproterozoic. This study investigates the tectonic evolution of one of the least studied terrain in the northern part of the SGT comprising Biligiri Rangan (BR) – Male Mahadeshwara (MM) Hills domain (**Fig. 1**), which was previously considered as the part of the Salem Block. A multidisciplinary approach has been implemented for this study that integrates field relations, petrography, mineral chemistry, thermodynamic modeling of metamorphic *P-T* evolution, and LA-ICPMS U-Pb and Lu-Hf analyses of zircons on representative rocks from the BR Hill-MM Hill domain together with crustal thickness model derived using gravity inversion and flexure inversion geophysical techniques. The results suggest Meso- to Neoarchean tectonic evolution of this terrain as a discrete crustal block, and we name this terrain as Biligiri Rangan Block (BRB).

The BRB is identified as one of the ancient high-grade granulite terrains of southern India, characterized by distinct lithology and geochemical and isotopic signature. The block is bounded by the EW-trending Moyar-Attur shear zone in the south, in the west by NNE-trending Kollegal shear zone against the Western Dharwar Craton (comprising the mafic-ultramafic suites and metasediments of the Sargur Group), and in the east by the NE-trending Mettur shear zone against the Eastern Dharwar Province (comprising the Shevaroy Block). Systematic field investigations (**Fig. 1**) have been carried out in and around the BRB that reveals Charnockite as the major rock-type that are in association with mafic granulite, granites and metapelites. The westernmost periphery of the BRB, adjacent to the Kollegal shear zone, is characterized by the occurrence of enclaves and lenses of ultramafics, gabbro and amphibolites oriented along the Kollegal shear zone. Metasedimentary rocks including quartzo-feldspathic gneisses, quartzite and banded iron formation (BIF) are exposed in several localities in and around the Kollegal shear zone. Representative samples from the BRB selected for the present study including the charnockite, pink granite and garnet bearing gneiss samples (exposed within the terrain), quartzite and metagabbro samples (from the Kollegal shear zone), and mafic granulite sample (from the Mettur shear zone).

Zircons in the quartzite from the Kollegal shear zone show a wide range of ages between 3315±24 and 2972±20 Ma. The data indicate different zircon populations with a wide range of εHf(t) values from negative to positive (-6.4 to 5.1). The distribution in age and Hf isotope values are suggestive of multiple sources of both juvenile and reworked components. Zircons in the garnet-bearing gneiss (sample BR-5) show upper concordant age at 3207±22 Ma and lower concordance at 2806 Ma (**Fig. 2d**). The spread in ages may suggest a sedimentary protolith for this garnet-bearing gneiss. The age ranges obtained from this sample can be correlated with the similar age range yielded by the zircons in quartzite (sample BR-1). This may indicate that both the garnet-bearing gneiss and the quartzite represent contemporary sedimentary units, with detritus derived from the continental crust that existed during Mesoarchean. The age of TTG (3100-3360 Ma) reported from this region (Peucat et al., 2013) and the high positive εHf isotope values of the zircons from quartzite (εHf(t) ~ +5.1) and garnet-bearing gneiss (εHf(t) ~ +2.7) obtained in the present study are suggestive of a primitive juvenile continental crust with ages between 3100 and 3400 Ma. The LA-ICP-MS analysis of a charnockite sample (BR-22) yield an upper intercept age of 2650 Ma and lower intercept at *ca.* 2500 – 2550 Ma (Fig. 2c). The age data from charnockite reveal 2600 Ma as the age of charnockite formation and 2513±5 Ma as the granulite-facies metamorphism in the BR Hill. The age estimates of other samples including pink granite that yields an upper intercept age of 2490±13 Ma, and the mafic granulite (BR-35) that shows a wide range of discordant ages between 2632 to 2498 Ma are also broadly consistent with the age range obtained from zircons in the charnockite, suggesting that the protoliths of these rock types are cogenetic (at. *ca.* 2600 Ma) and witnessed a common metamorphic event (at *ca.* 2500 Ma).

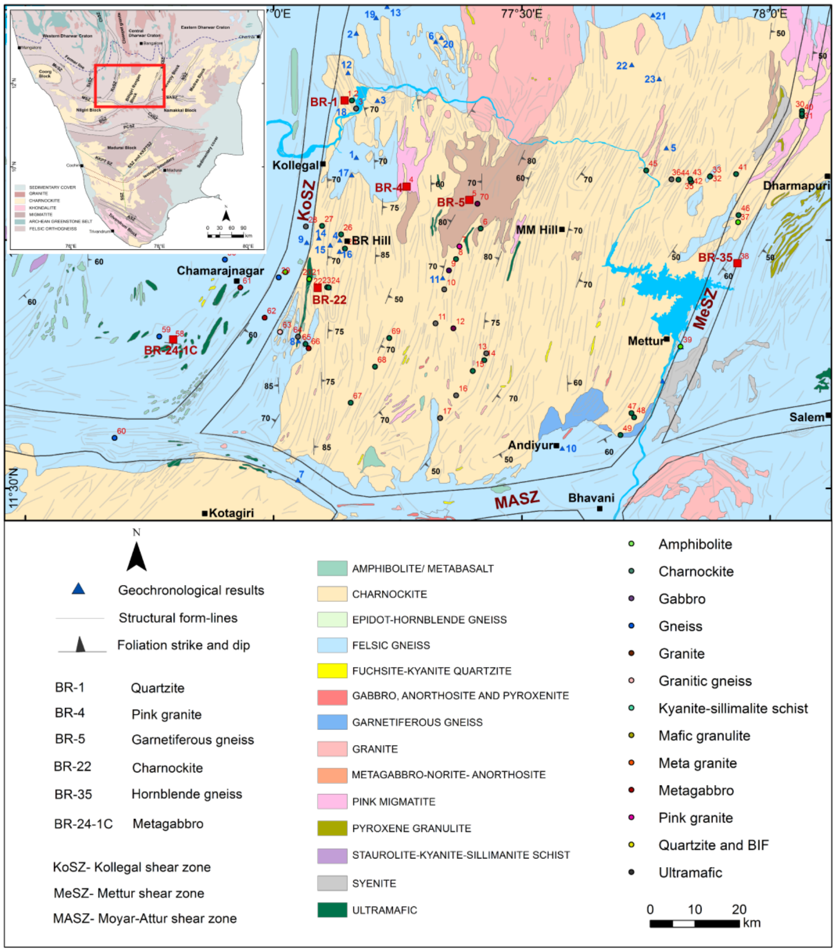

Fig. 1. Geological map of the Biligiri Rangan Block (BRB) showing general tectonic setting and sample distributions (filled circles). The filled red squares (BR-1, 4, 5, 22, 24-1c, 35) are the samples selected for the present study. The inset map shows location of the present study area. (*Ratheesh-Kumar et al., Precambrian Research, In Press*).

The occurrence of quartzite-iron formation intercalation as well as ultramafic lenses along the western boundary of the BRB is interpreted to indicate that the Kollegal structural lineament is a possible paleo-suture. Phase diagram computation (using mineral chemistry data and thermodynamic modeling) of a metagabbro from the western periphery of the Kollegal suture zone reveals a clockwise P-T path with a peak pressure~18.5 kbar and temperature~840 °C (**Fig. 2e**), clearly suggest high-pressure granulite facies metamorphism in a subduction setting, and subsequent exhumation. Based on these results, this study proposes a new tectonic model for the evolution of the BRB (**Fig. 2b**) that envisages eastward subduction of the Western Dharwar oceanic crust beneath the BRB along the Kollegal suture zone resulted in the arc magmatism during the Neoarchean. This model better explains existing chaos in the plume model (Jayananda et al. (2000) and westward subduction of the Eastern Dharwar Craton beneath the Western Dharwar Craton as proposed by Chadwick et al. (2000) and Chardon et al. (2008).

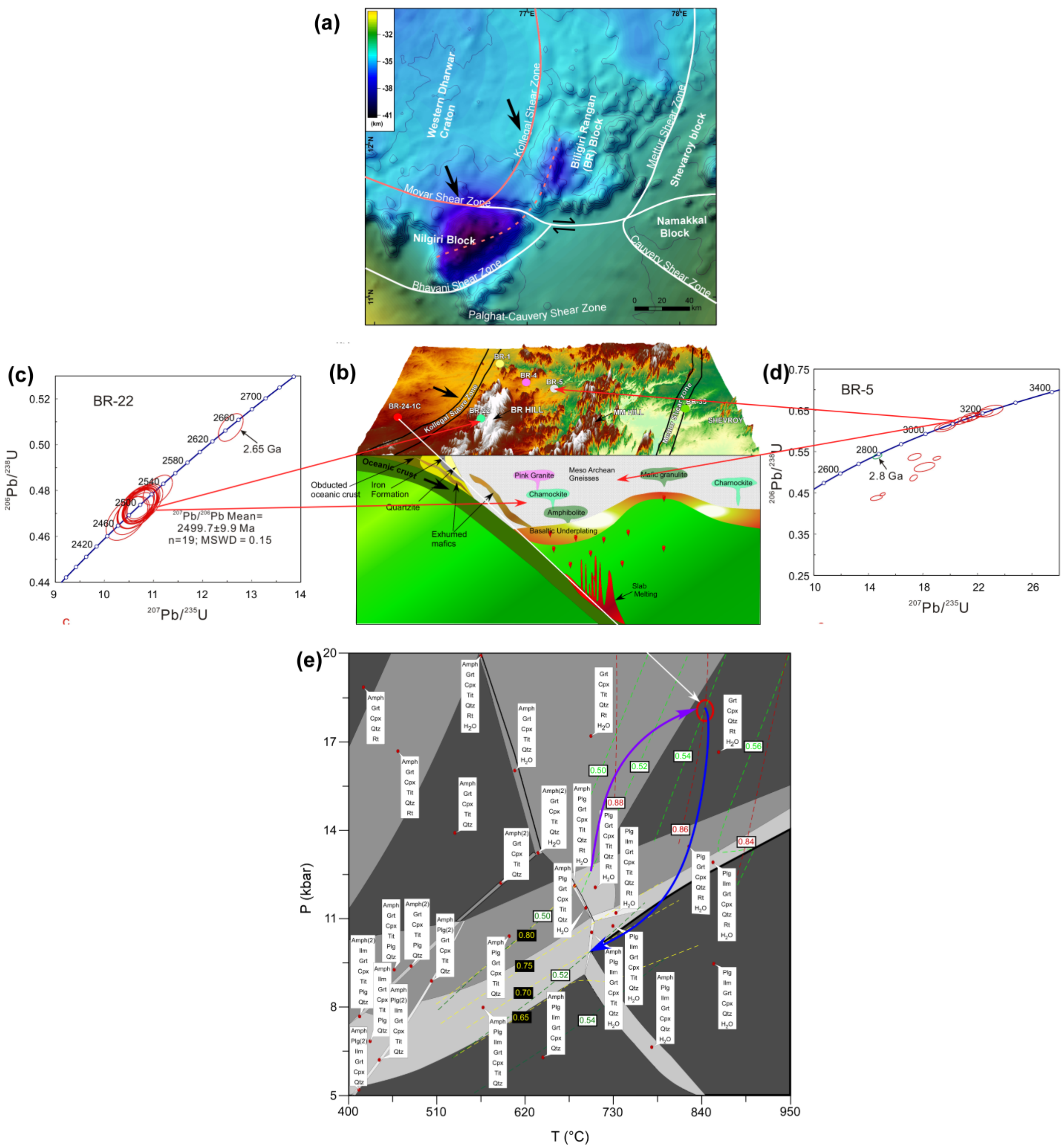

Fig. 2(a) Crustal thickness map showing the subduction polarity of the western Dharwar oceanic crust beneath the BRB and Nilgiri Block along the Kollegal-Moyar suture zone and the resulting high-crustal thickness patterns (b) A schematic tectonic model depicting the subduction of the Western Dharwar Oceanic crust and associated slab melting and arc magmatism in the BRB (c) Age of the charnockite indicating the age of arc magmatism (d) Age of the garnet bearing gneiss indicating Meso Archean primitive crust in the BRB (e) *P-T* phase diagram showing the high-pressure

(18-19 kbar) and medium temperature (~840˚C) metamorphic evolution of metagabbro in the Kollegal suture zone. (*Ratheesh-Kumar et al., Precambrian Research, In Press*)

This model assumes Mesoarchean crust in the BRB which probably built the core of this crustal block, as inferred from the 3100 to 3300 Ma emplacement ages from magmatic zircons in the garnet-bearing gneiss. After *ca.* 2970 Ma, eastward subduction of the Western Dharwar oceanic crust beneath this Mesoarchean continent occurred along the Kollegal suture zone. The subduction-related slab melting and underplating of the basaltic magma beneath the lower crust of the BRB, and associated partial melting of the Mesoarchean crust generated charnockitic rocks at *ca.* 2650 Ma. This crustal reworking can be inferred from the negative εHf isotope values (-8.2 to -4.7) of the zircons in the charnockite. The ages obtained for the mafic granulite (*ca.* 2550 Ma) and the positive εHf isotope values suggest predominantly juvenile crustal addition simultaneously with the arc magmatism. The spatial variation of crustal thickness (**Fig. 2a**) (computed using gravity inversion and flexure inversion techniques) reveal a comparatively high crustal thickness beneath the Nilgiri Block (~41 km), and in the western part of the BR-Block (~38 km). We attribute this anomalously high crustal thickness patterns in Nilgiri and in BRB as a more competently thickened crust resulted by the subduction of the western Dharwar crust. Earlier studies proposed Moyar shear zone as a suture zone along which the Nilgiri Block was thrust onto the Dharwar Craton, synchronous with the arc magmatism in the Neoarchean. The correlation of the timing of arc magmatism (*ca.* 2700-2500 Ma), connectivity of the Moyar and Kollegal suture zones, and high crustal thickness patterns suggest the possibility that both the Nilgiri and BR Blocks accreted on the western Dharwar Craton during Neoarchean. However, the variation in crustal thickness, structural deformation trends, and lithological variations may indicate difference in subduction polarities of the western Dharwar oceanic crust that caused a steeper subduction in the Nilgiri Block, and a shallow subduction in the Biligiri Rangan Block.

Thus, the evolutionary models presented in this paper revise the existing ideas on the tectonic framework of the Archean terranes of southern India. The accretionary tectonics of the Biligiri Rangan Block and Nilgiri Block presented in this study suggest that the Western Dharwar Craton acted as a continental nuclei on to which different crustal blocks including the Coorg and Karwar Blocks, were amalgamated to form the present tectonic framework.

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Study of mesoscopic structural features along the margins of Cauvery Suture Zone, southern India

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Abstract
Suture zones are the collision boundaries connecting two continental plates having miscellany of former oceanic lithosphere in them and are intensely deformed by the tectonic movements of the two continental blocks. These are also zones of occurrences of high grade metamorphic rocks associated with ophiolitic suits. Such assemblages are considered to be well preserved in case of Phanerozoic age orogenic belts. However, there are also occurrences of oceanic remnants which are of Precambrian ages. Cauvery Suture Zone (CSZ) of Southern Granulite Terrane (SGT) is an excellent example of such types of tectonic settings. The marginal parts of the suture zone are very interesting to study in terms of structural aspects as the rocks show excellent exposures of megascopic as well as mesoscopic features. Mesoscopic structures include small scale shear zones, S-C fabrics, deformed boudins, lift-off folds, deformed sheath folds, small scale faults etc. have been studied from different localities of marginal parts of CSZ. These features are very important to determine the deformation stages and sense of shearing of the major shear zones. Such typical structural geometry has helped to understand the subduction-collision-accretion tectonics of southern India and its tectonic implication of Gondwana amalgamation.

Keywords: Southern India, Cauvery Suture Zone, Shear Zones.

Introduction
The first steps in the study of geological structures are largely geometrical and this concern for geometry includes the methods of describing and illustrating the form and orientation of geological structures, and the solution of various dimensional aspects of these structures (Ragan, 2009). Scale is a very important parameter in case of structural geological investigations. Evaluating the mesoscopic structures, especially in high grade rocks, are very significant as they were formed at deep crustal levels. Since dislocation creep, diffusion creep and grain boundary migration are dominant in these conditions, the flow in deep crust affecting high-grade rocks may be partitioned less and on a larger scale than in the upper crustal scales. These structures of between one meter and hundreds of meters scales are important for a variety of applications viz: ore deposits, rheological/mechanical behavior of folds or faults, tectonic implication of the region. The mesoscopic structures examined include centimeter to hundred meter scale folds, faults, fractures and veins. These types of structural features often demonstrate remarkable complexities when they are reactivated in the reverse sense of kinematics leading to contradictory interpretations.

Mesoscopic structures analyzed from the study area include disharmonic folds, S-C fabrics, lift-off folds, inclined folds, superposed folds, small scale faults, nano duplexes, deformed sheath folds, centimeter to meter scale shear zones, riedel shears etc. (Mohanty and Chetty, 2014). The distribution, density, and orientation of outcrop-scale structures have been investigated from northern as well as southern margins of CSZ, related to the subduction-collision-accretion mechanism in Southern Granulite Terrain (SGT), an exhumed ancient trace of the Gondwana, in order to determine the structural and tectonic evolution of the region.

Suture zones in southern India
Southern India has been divided into different crustal blocks which are experienced with multi

phases of deformations and are distinguished by major shear zones. These crustal blocks and shear zones have been studied extensively by different researchers, from India as well as abroad, to find out the different stages of magmatism, metamorphism and deformations. Different Suture zones from southern India from are Kumta Suture Zone (KSZ) (Ishwar Kumar et al., 2014), Coorg Suture Zone (CoSZ) (Santosh et al., 2013), Kollegal Suture Zone (Ratheesh et al., 2016), Cauvery Suture Zone (Chetty, 2015) and Archankovil Suture Zone (ASZ) (fig. 1).

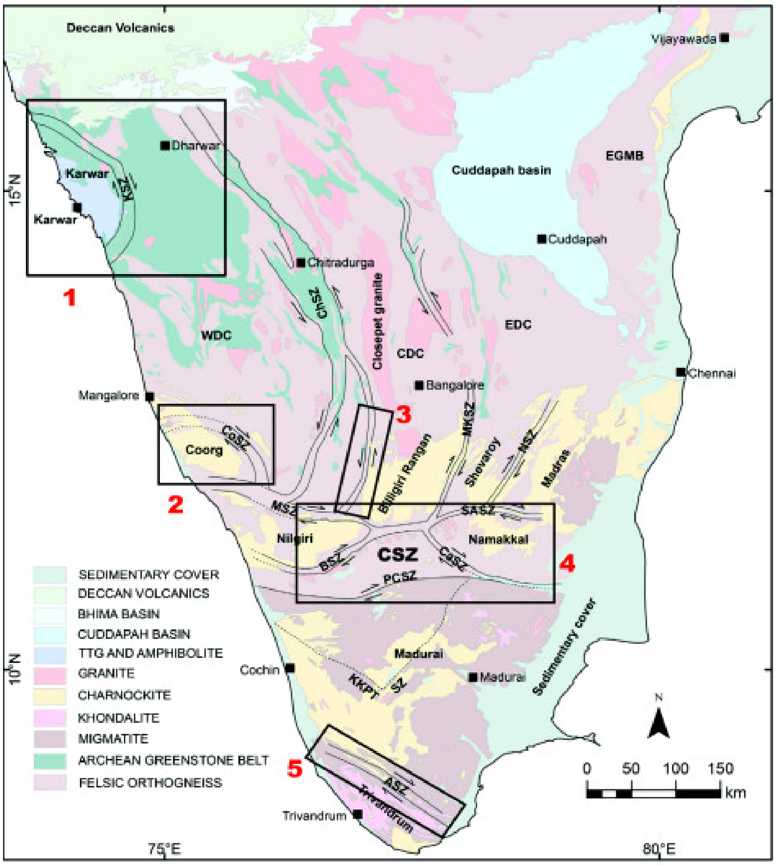

Fig. 1: The regional geology and tectonic framework of southern India. Geology modified after Geological Survey of India (1995) and shear zones after Ishwar-Kumar et al. 2014. The rectangle shows location of the study area. Acronyms: TTG-Tonalite-trondhemite-granodiorite, 1. KSZ – Kumta suture zone. 2. CoSZ – Coorg suture zone, ChSZ –Chitradurga shear zone, 3. Kollegal Suture Zone, MKSZ – Mettur-Kolar shear zone, NSZ – Nallamalai shear zone, MSZ – Moyar shear zone, BSZ – Bhavani shear zone, SASZ – Salem-Attur shear zone, 4. CSZ – Cauvery suture zone, PCSZ – Palghat-Cauvery shear zone, KKPT – Karur-Kambum-Painavu-Trichur shear zone; 5. ASZ – Achankovil suture zone, WDC – Western Dharwarcraton, CDC – Central Dharwar craton, EDC – Eastern Dharwar craton, EGMB – Eastern Ghats mobile belt.

Cauvery Suture Zone. Cauvery Suture Zone (CSZ), the most important tectonic feature within the Southern Granulite Terrain (SGT), separating the Archean Dharwar craton to the north and the Proterozoic granulites to the south. The Moyar-Bhavani-Salem-Attur Shear Zone (MBSASZ) marks the northern boundary while the Palghat-Cauvery Shear Zone (PCSZ) the southern boundary of the CSZ. The CSZ has been variously described and interpreted by different researchers as: (i) A collision zone and cryptic suture, with remnants of probable ophiolitic sequence (Gopalakrishnan, 1994), (ii) A dextral shear zone as exemplified by the deflection of north–south Archean fabrics to near east–west disposition along the Moyar-Bhavani Shear Zone (MBSZ) (Drury et al., 1984; Chetty et al., 2003), (iii) An analog of the central part of the Limpopo mobile belt (Ramakrishnan, 1993), (iv) The Archean–Proterozoic Terrane boundary (Harris et al., 1994), (v) A zone of Palaeo- and Neoproterozoic reworking of Archean crust (Bhaskar Rao et al., 1996; Raith et al., 1999), (vi) A Neoproterozoic dextral–ductile transpressive tectonic zone

(Meissner et al., 2002; Chetty et al., 2003; and (vii) Neoproterozoic crustal-scale 'flower structure' (Chetty and Bhaskar Rao, 2006b). Structural features at the marginal parts of the CSZ are more interesting with migmatisations, mylonitisation and retrogression of the granulite facies rocks.

From the review on the published geochronology, it is clear that the rocks from CSZ vary from 3010 Ma (Archean) to 550Ma (Neoproterozoic) in age. The rocks dated by different workers include charnockites, gneisses, granite gneisses, migmatites, Plageogranites, quartzites, trondjhemaites, gabbro anorthosites, felsic gneisses etc. from different parts of the CSZ. In the last one decade, there has been a steady increase in the accumulation of age data from different localities of CSZ, through various dating techniques, reflecting the complexity of crustal evolution of the CSZ. Geochronological, metamorphic and isotope evolution studies have brought out that the region, south of CSZ, has a geological history distinctly different from that of the Dharwar craton. From the study of different age data, it is shown that the crustal growth of northern part of the CSZ has occurred predominantly during Neoarchaean (~ 2500 Ma) (Clark et al., 2009; Sato et al., 2011b; Yellappa et al., 2012; Ram Mohan et el., 2013). The SGT might have witnessed several cycles of metamorphism, the most pervasive and youngest being the 550Ma Pan-African granulite facies event as constrained by isotopic systematics (Sato et al., 2011a; Santosh et al., 2012; Plavsa et al., 2014).

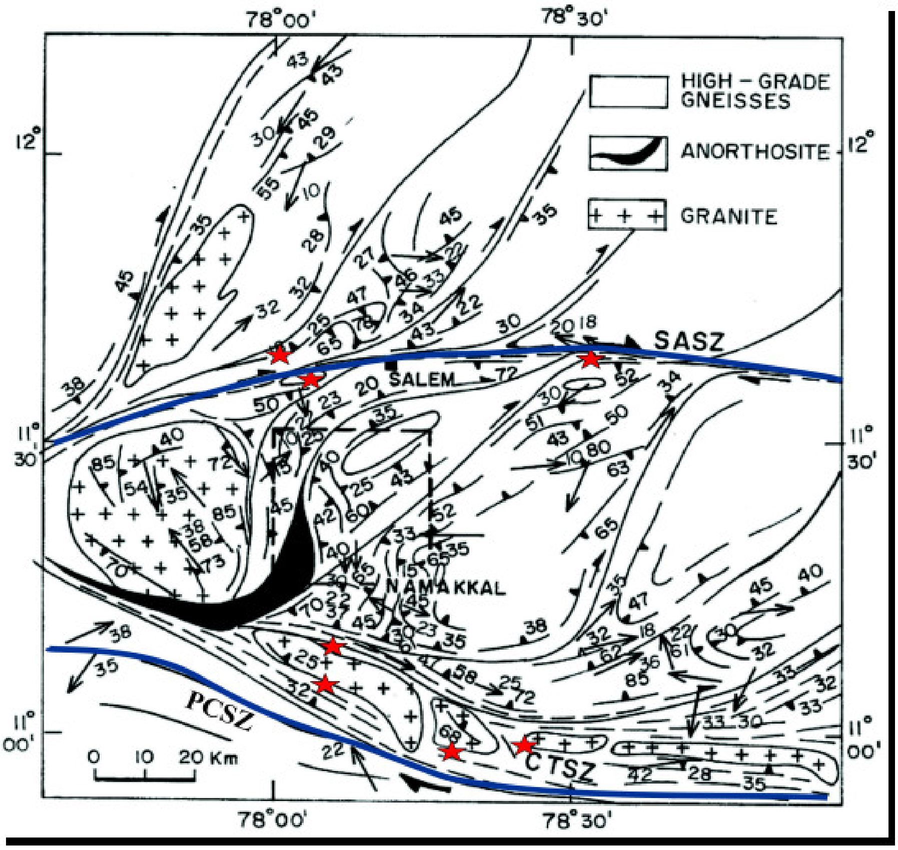

Fig. 2: Foliation trajectory map of eastern part of Cauvery Suture Zone showing locations of field observations (star marked) (Modified after Chetty and Bhaskar Rao, 2006a).

Northern margin

Northern margin of the CSZ is marked by east-west trending Salem Moyar-Bhavani-Salem-Attur Shear Zone (MBSASZ) (Fig. 2). Along this trend a number of closed circular hills are present aligning the shear zone. These hills are associated with bounding shear zones and form the kanjamalai hills, is such an excellent example, located at the northern margin of the Cauvery Suture Zone (CSZ), Southern India, is characterized by the high grade metamorphic rocks exhibiting strong foliations in them. The entire Kanjamalai hill is enveloped by mylonitic fabrics. The shear zones are, in general, characterized by a wide range of well developed mylonites and a variety of shear sense indicators such as S-C fabrics, C'-type of shear band cleavages, asymmetric porphyroclasts and rigid rock fragments, and micro-, to mega scale deflection of foliations, which indicate dextral sense of movements. Recently, a detachment zone has been reported from the northwestern margin of the hill near Elampillai village (Mohanty and Chetty, 2014). The well developed fold structures at the foothill regions are very significant in understanding the mechanism of the detachment fold zone. The foliated rocks at the foot of the hill vary in thickness and are represented by parasitic folding and penetrative strain. These might be the reflections of the differences in mechanical stratigraphy, relative thicknesses of the competent and incompetent units, and structural relief of the underlying basement. This zone spatially coincides with growth of a mylonitic foliation and associated mineral stretching lineation in the lower part, while the early fabrics are still persistent in structurally higher units. The post peak cooling path of the high grade metamorphic rocks from Kanjamalai which might characterize the exhumation tectonics associated with the Neoarchaean tectonic event in the sourthern margin of the Dharwar craton. Recent studies about the Neoarchaean subduction tectonic processes within the CSZ and the P-T data from Kanjamalai rocks provide insights into the reconstruction models of pre-Gondwana events in the region.

In Fig. 3, representative field photos from Kanjamalai and its surrounding are presented to show the mesoscopic structural behavior of the different rock types. Fig. 3a & 3b are from the felsic gneisses of Kanjamalai Hills, showing S-type fold geometry (fig. 3a) of the competent bands with intense foliations. In fig. 3b, well developed crenulation cleavages and extension cleavages can be seen in the felsic gneisses which can is reported here as microlithon type structures. Garnet bearing pyroxene granulites (mafic granulites) in this area are very well deformed as well. Rotation of garnet clasts and banding of garnet and pyroxenes are observed to be showing open folding patters. Fig. 3c shows ellipsoidal blocks of garnet rich segregations within the granulite rocks showing reactions with pyroxenes in the form of rims where as the fig. 3d is from Noack et al, 2013 which is interpreted as a megacrystic garnet aggregate and melt segregation within the strongly garnet pyroxene granulites. Not only the gneissic rocks, but also the Banded Magnetite Quartzites (BMQs) show intense foliations and complex structural patterns. The BMQs in this area marks the shear zones with well developed mylonitic foliations within them. (Fig. 3e & 3f). Complex fold styles and centimeter scale shear zones are observed and reported in the small boulders, as shown in the fig. 3e. Developments S-C fabrics and Extension Crenulation Cleavages (ECC) with sinistral kinematics can be studied very well in these outcrops (fig. 3f).

The surrounding regions to these hills, in the northern margin of CSZ, are mostly bounded by shear zone networks. This can be studied with the investigations on the basement gneisses which are mylonitised in most of the places. The basement gneisses are mainly of compositions Quartzo feldspathic gneisses, Charnockites, Biotite-Amphibole gneisses and Mylonites. The qartzo feldspathic gneisses from the basements of northwestern part of Kanjamalai hills, which is interpreted as a detachment zone by Mohanty and Chetty (2014), show typical structural geometries like, Lift-off folds, plunging inclined folds, small scale faults, flow of matters, refolded sheath folds and nano-duplexes. The fig. 4 shows some deformational features within the basement gneisses from the northern part of the CSZ.. Fig 4a shows the occurrences of mafic boudins within quartcofeldspathic gneisses which are deformed and sheared by the mesoscopic shear zone along the hammer. There are ductile shear zones of dextral kinematics are common in this region (fig. 4b). The fig. 4c shows that there are also brittle shearing occur in these localities with diverse trend which are much younger in age to the ductile shearing.

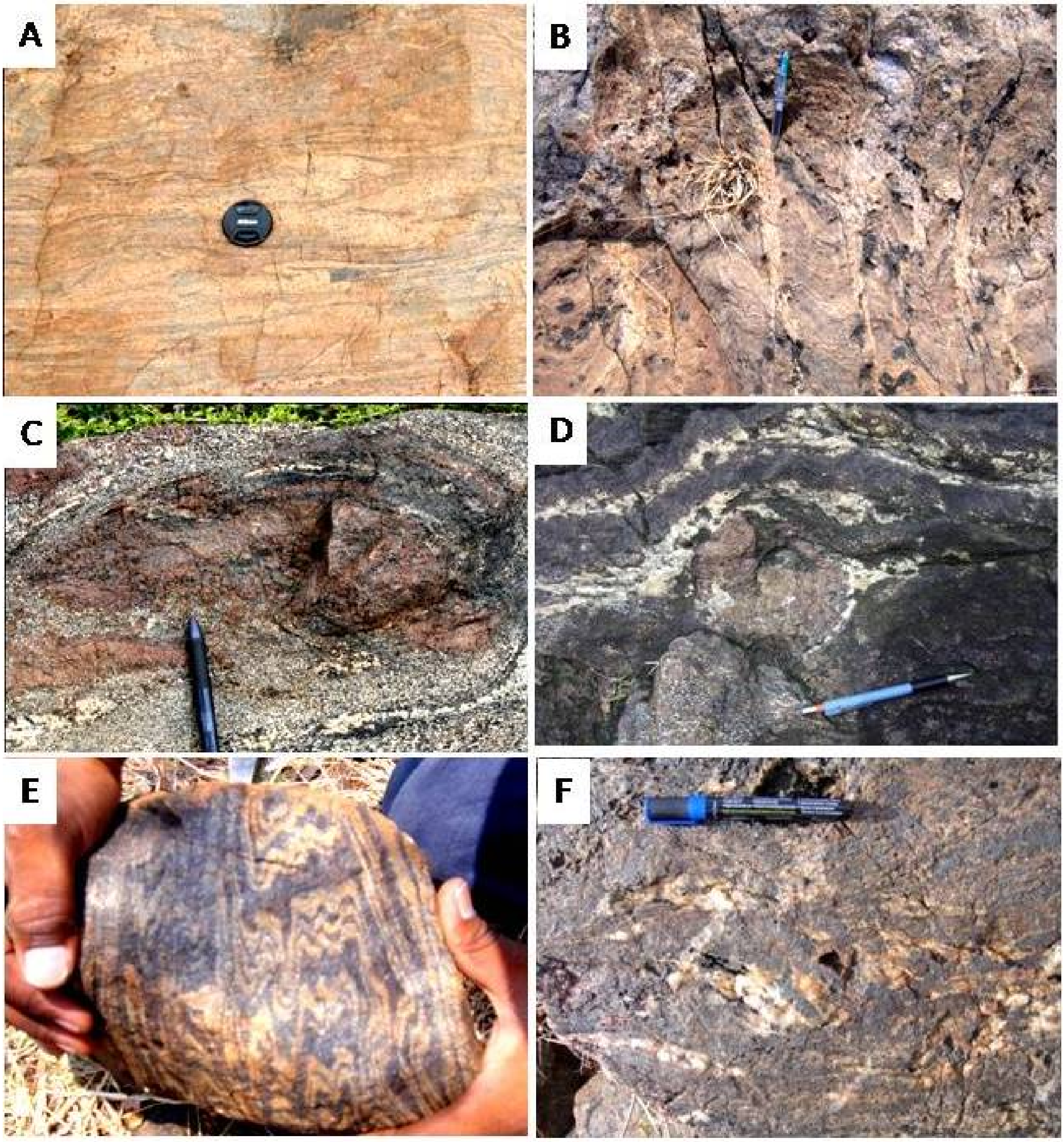

Fig. 3: Field photos from northern margins of Cauvery Suture Zone: A. Felsic gneisses showing S-type structures , B. Microlithon type structures within granite gneisses, C. Ellipsoidal blocks of garnet rich segregations within the granulite rocks showing reactions with pyroxenes in the form of rims, D. Megacrystic garnet aggregate and melt segregation in a strongly garnetiferous mafic granulites (photo from Noack et al., 2013), E. BMQ boulder showing refolded isoclinals folds with shearing effect, F. Sinistral kinematics within the bands of BMQs.

Southern Margin

The Southern margin of the CSZ is marked by the E-W trending Palghat Cauvery Shear Zone (PCSZ) (see fig. 2). This margin of the CSZ is very important and have been studied extensively by researchers from different parts of the world. Occurrences of ophiolites of two distinct ages: Neo Archean Devanur Ophiolite Complex (Yellappa et al., 2012) and Neo Proterozoic Manamedu Ophiolite Complex (Yellappa et al., 2010; Santosh et al., 2012) are the most important findings in the recent past from this region. There are also occurrences of circular hills like in northern margin which have been studied and interpreted in different way. Manamedu Ophiolite Comples (MOC) (Yellappa et al., 2010; Santosh et al., 2012) and Devanur Ophiolite Complex (DOC) (Yellappa et al., 2012) are the most important findings in the recent few years from this region.

Mahadevi hills from this region has been reported as a Mega Sheath Fold by Chetty et al., 2012 is an very important finding to understand the accretion tectonics of the CSZ. The mesocopic structures has been well studied from these areas. There are occurrences of migmatites, qartzofeldspathic gneisses, biotite amphibole gneisses and mylonites all along the southern margin of CSZ. These rocks show excellent outcrop patterns showing complex structural geometries.

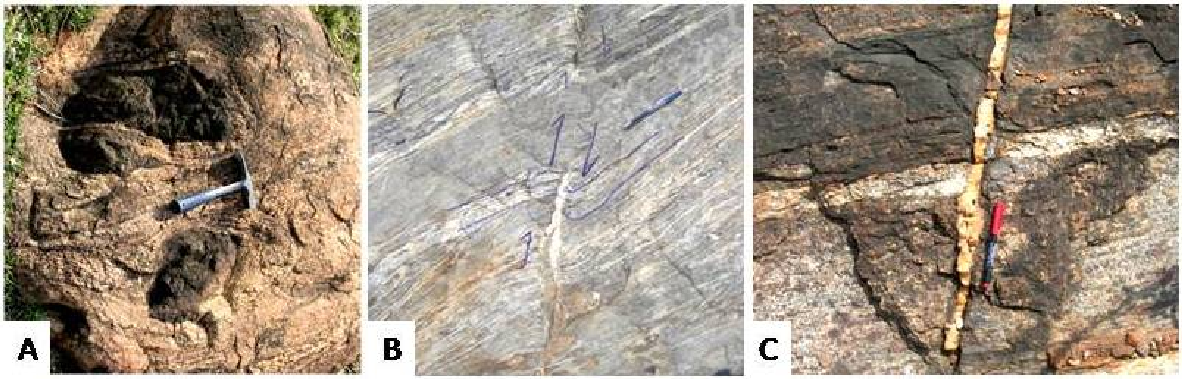

Fig. 4: Field photos of the basement gneisses in the northern margin of CSZ; A. Mafic boudins within the quartzofeldspathic gneisses showing deformations, B. Ductile shear zone within the mylonites with dextral behavior, C. Brittle shearing with sinistral kinematics.

Fig. 5 shows few field photos showing mesoscopic structural geometries from the SE part of the CSZ. Fig. 5a shows an excellent example of ductile shear zone within the migmatites exhibiting dextral sense of shearing. Within these migmatites there are different fold patterns could be observed. The tight isoclinals folds (F1) (fig. 5b) are refolded by a second generation of folding (F2) giving rise to interference fold patterns. Along this margin there also occurrences of calc gneisses which show intense foliation patterns and gentle to open folding within them (fig. 5c). Banded gneissic rocks are common in the marginal parts often show annealed mylonitic foliations (fig. 5d; Yellappa et al., 2014). Competency contrasts within the mafic and felsic layers can be well examined in this area. Fig. 6a&b shows bukling effect of the felsic band (competent layer) showing development of asymmetrical fold patterns and flow nature of the mafic materials (incompetent layer) best explaining mechmanism of folding.

Discussions and Conclusion

The geological investigation in this paper presents the complexities in structural geometry in the marginal parts of CSZ, are mainly based on the field structural interpretations in mesoscopic scales. CSZ is a focal point for all geoscientists working in the field structural geology, metamorphic petrology, geochronology and geochemistry, has been studied and analyzed in different aspects and interpreted in different ways. Gondwana amalgamation, major shear zones, subduction tectonics, Precambrian ophiolites, suture zones are the key terms which draw attention to the researchers. Drury and Holt, 1980 were the first to give the northward subduction of the entire SGT into the Dharwar Craton, which is now been updated by the subsequent researchers saying the southward subduction. Santosh et al., 2009, considering the ‘flower structure’ model of Chetty and Bhaskar Rao, 2006, suggested the closure of the Mozambique Ocean and the subduction of Dharwar Craton along the CSZ. The CSZ is also marked by the collision of the Archean Craton to create a Himalayan-type Cambrian orogenic belt and accompanied by regional high grade metamorphism. The final stage of subduction is marked by post-orogenic extension and emplacement of minor late stage intrusive granitic and alkaline plutons widely occurring in various blocks and shear zones. Post-collision Barrovian hydration is also widely noticed, particularly in the PCSZ with the development of lower grade assemblages dominated by hydrous minerals.

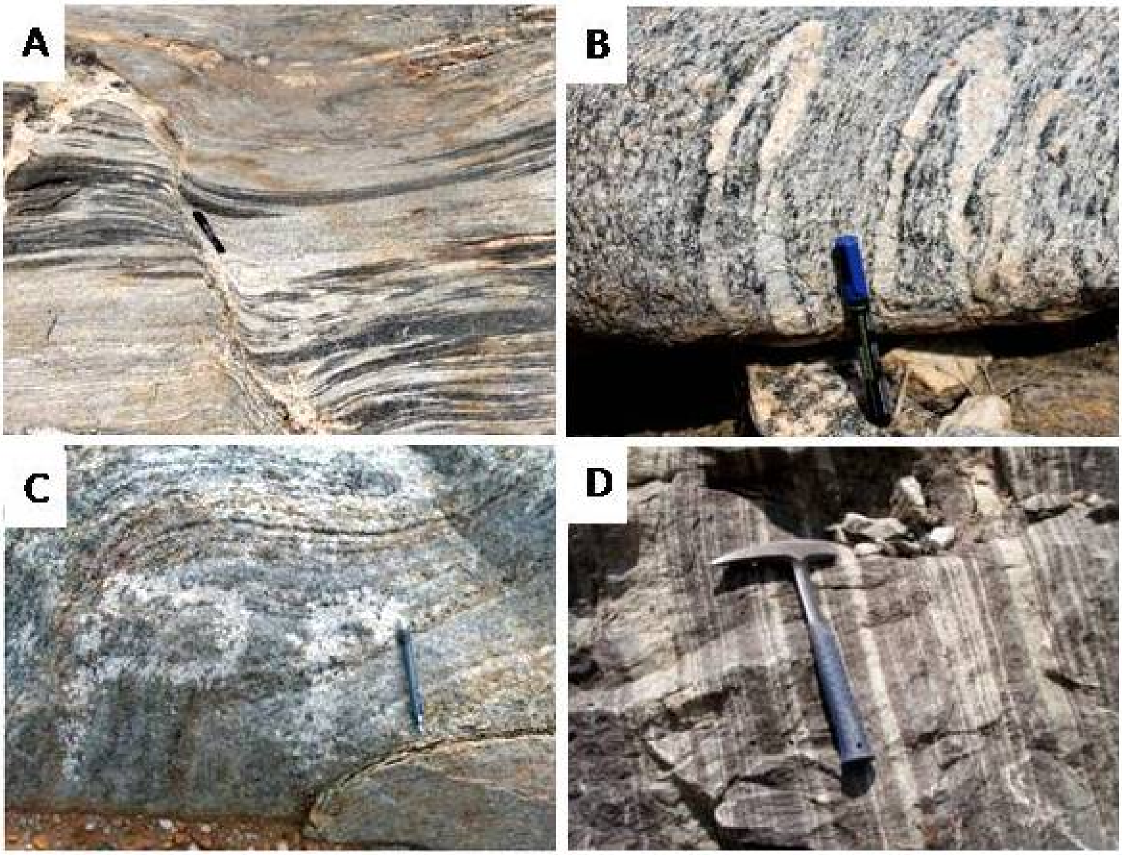

Fig 5: Field photos from sourthern margin of Cauvery Suture Zone: A. Migmatites with well developed mylonitic foliation exhibiting ductile shearing and dextral nature, B. Migmatite gneiss showing tight isoclinal (F1) folds with narrow limb and broad hinge patterns, C. Gently folded calc granulites near Manamedu hills (photo from Chetty et al., 2011) and D. Banded gneissic rock showing annealed mylonites near Aniyapuram area (photo from Yellappa et al., 2014).

Recently, the results from the study of Kanjamalai Hills (Mohanty and Chetty, 2014) at the northern margin of CSZ, indicate the existence of well exposed detachment zone at Elampillai, which can be regarded as a classic example of detachment zone in a Precambrian high grade terrane. It is also pertinent to note that the detachment feature is not an isolated feature connected to the development of Kanjamalai Hills, but is also related to the evolution of the CSZ, in particular, and the SGT in general. The lithological characteristics and the broad structural form of Kanjamalai Hills can be correlated with the mega sheath fold structure (MSF) of Mahadevi Hills, located in the SE part of the CSZ (Chetty et al., 2012) implying their significance in understanding the accretionary tectonics in the region. From their results obtained from the two study areas (one from northern and one from southern margin of CSZ) in conjunction with the available structural, petrological, geochemical and geochronological data, they had also proposed an improvised tectonic model (Fig. 7) for the evolution of the CSZ as well as the SGT. The detachment surface from at the northern margin is exposed in the frontal thrust zone of the crustal scale 'flower structure' model suggested by Chetty and Bhaskar Rao (2006b) where as the MSF of Mahadevi Hills lies in the back thrust zone.

Structural styles from northern margin of CSZ are best described as the rotation of rigid balls, rotation of garnet crystals within the high pressure rocks (Noack et al., 2013; Anderson et al., 2012). The granitoids and felsic gneisses show mylonitic foliations and typical stuctural geometries like S-C fabrics, microlithons. The BMQs show the mylonitic fabrics and developments of extensional crenulation cleavages within them. The shearing patterns within them are dextral which follows the trend of Salem-Attur Shear Zone.

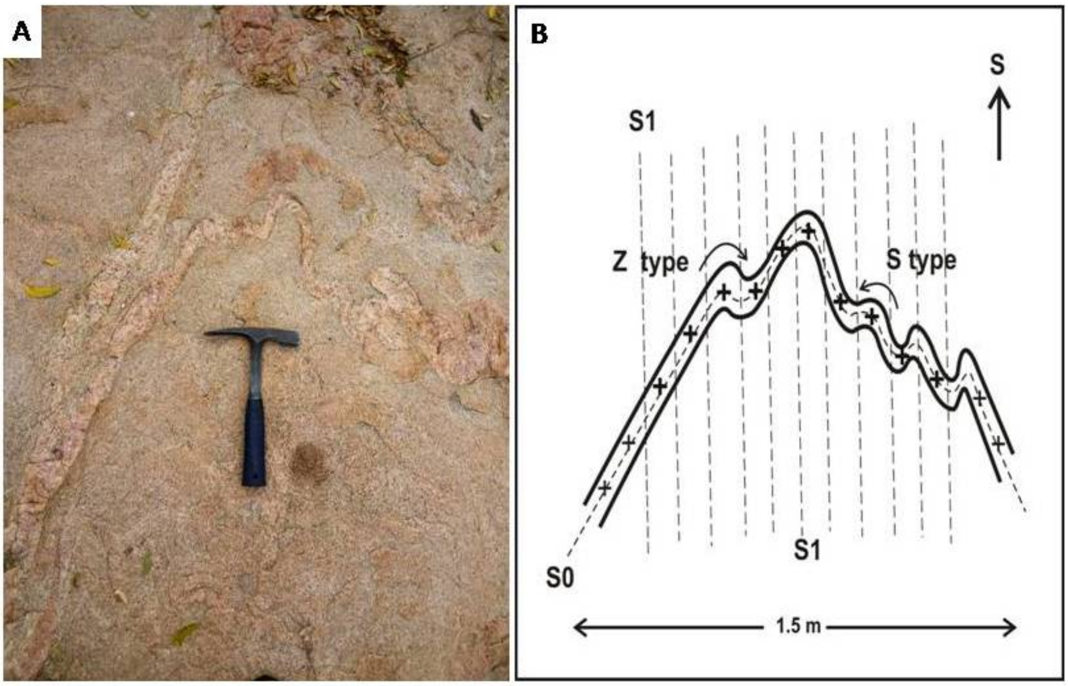

Fig 6A&B: Field photo and sketch showing buckling effect of competent layers and parasitic folding with the development of Z- & S-type folds.

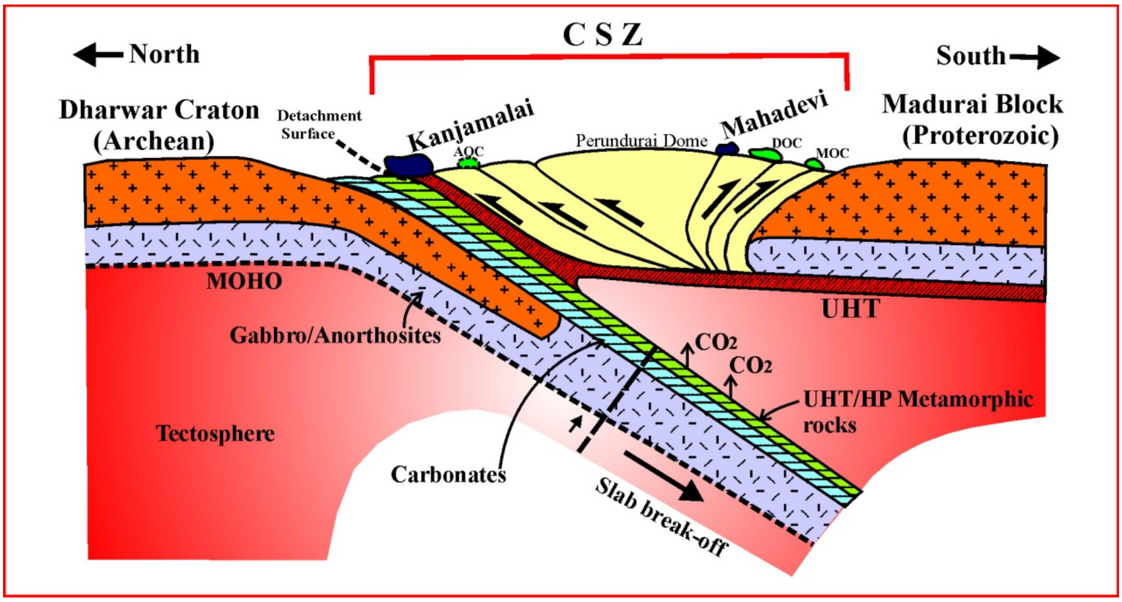

Fig. 7: Tectonic model suggesting the southward subduction of Dharwar Craton into the SGT, implicating accretionary tectonism displaying the detachment surface at the north and ophiolite bodies (AOC, DOC &MOC) in the central and southern part of the CSZ: AOC-Agali Ophiolite Complex, DOC-Devanur Ophiolite Complex, MOC-Manamedu Ophiolite Complex, UHT-Ultra High Temperature and HP-High Pressure. (After, Mohanty and Chetty, 2014)

Along the southern margin of the CSZ, the structures are more complex than that in case of northern margin. Here the migmatites along the PCSZ exhibit high strain zones where superposing of folds are observed. The F1 tight isoclinals folds show narrow hinge and broad limb folds and are refolded by the F2 folds which are more often open in nature. This best explains the Type-3 interference pattern or Hook-pattern (Ramsay, 1967). Results provided in the present study offers some important clues on the tectonic history of the CSZ, the trace of the Gondwana suture associated with ocean closure and the final amalgamation of the Late Neoproterzoic-

Cambrian Gondwana supercontinent involving subduction-accretion-collision history.

Acknowledgements

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Ophiolites of the Indo-Myanmar Orogenic Belt, Northeast India: Petrogenesis and Geodynamic implications

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Abstract

Crustal rocks and mantle sequence of the ophiolites of Indo-Myanamr orogenic belt in Northeast India have been studied to understand their petrogenesis and geodynamic evolution. Mantle peridotites consist mainly of lherzolites with lesser amounts of Cpx-bearing harzburgites and characterized by high contents of low Cr# of Cr-spinel (0.11–0.27); low Mg# of olivine (Fo_{90}) and high Al_2O_3 in pyroxenes (3.71–6.35 wt.%). They have very low REE concentrations and display LREE-depleted patterns (La_N/Sm_N = 0.14–0.45) with a flat to slightly fractionated HREE segments (Sm_N/Yb_N = 0.30–0.65). Mineral and whole rock major and trace element compositions of peridotites are generally comparable to those of abyssal peridotites that represent mantle residues produced by partial melting beneath mid ocean ridges. Thus evaluation of mineralogical and petrological characteristics of these peridotites suggests that they represent the residual mantle section left after partial melt due to decompression of mantle in the spinel stability field in a mid-oceanic spreading environment. Correspondingly most of the mafic volcanic rocks also show tholeiitic normal mid-ocean ridge basalt (N-MORB) - type characteristics, showing almost flat REE patterns with slightly depleted LREEs [$(La/Sm)_N$ = 0.62–1.03]. Petrogenetic modeling suggests that ~20% partial melting of depleted mantle within spinel stability facies zone (shallow depth) is responsible for generation of these N-MORB tholeiites. However, few mafic volcanic samples exhibit plume induced ocean island basalt (OIB) character. They have very high TiO_2 (1.7–3.5 wt. %) concentrations as compared to N-MORB samples (TiO_2 = 0.6–1.6 wt.%). These alkaline OIB-type samples are also characterized by highly enriched LREE pattern as compared to their HREE [$(La/Sm)_N$ = 2.27–3.44, $(Sm/Yb)_N$ = 2.56–3.29]. It is also evidenced that 5–10% partial melting of enriched mantle or plume material at garnet facies stability zone (deeper depth) is responsible for their production. There are also another group of mafic volcanic rocks that show moderate enrichment in LREE [$(La/Sm)_N$ = 2.83–2.95] which is the typical composition of P-MORB. Considering these three different sets of basalt composition, it is strongly suggestive that mafic volcanics of the ophiolites of Indo-Myanamr orogenic belt were derived from chemically heterogeneous mantle sources. Depleted source at shallow depth gave rise to N-MORB samples at the spreading zone. Enriched/plume source at deeper depth gave rise to OIB samples that was formed at the proximity of the spreading axis. Mixing of these two melts was responsible for production of P-MORB.

Further this ophiolite complex also hosts both the refractory grade high-Al chromitites and metallogenical grade high-Cr chromitites. The Cr# varies from 0.46 to 0.59 and Mg# from 0.55 to 0.72 in the high-Al type chromitites. Such compositions and estimated Al_2O_3 parent melt value (14.00-16.34 wt.%) for the high-Al type are consistent with tholeiitic melt that form at the mid-oceanic ridge tectonic environment through partial melting. In contrast, the high-Cr chromitites have high Cr# (0.77-0.79) and low Mg# (0.44 and 0.71) with Al_2O_{3melt} (10.62-11.22 wt.%) and FeO/MgO_{melt} (0.58-1.54 wt.%), which may reflect the crystallization of high-Cr chromitites from boninitic magmas in supra-subduction zone (SSZ) environment, which could be possible when the Tethyan MORB slab of the Indian plate underwent subduction initiation underneath Myanmar plate and generated boninitic magmas within the mantle wedge. After the removal of boninitic melt, extensively depleted mantle was left behind, and the high-Cr chromitites crystallized from the melts. The distinct gap observed between the chemical compositions of high-Al and high-Cr chromitites, together with the estimated compositions of the parental magmas for high-Al

chromitites (Al_2O_{3melt} = 14.00-16.34 wt.%; FeO_{melt}/MgO_{melt} = 0.72-1.35 wt.%) and high-Cr chromitites (Al_2O_{3melt} = 10.62-11.06 wt.%; FeO_{melt}/MgO_{melt} = 0.55-1.78 wt.%), indicates that these two types of geochemically different chromitites did not crystallize by differentiation of the same magma source. Thus it is suggested that the ophiolites of Indo-Myanmar orogenic belt in northeast India are fragments of oceanic lithosphere initially formed in a mid-ocean ridge tectonic environment and plume environment and later incorporated by supra-subduction zone components. Later, due to prolonged subduction of the Indian plate beneath the Myanmar plate and afterward collisional activity, they might have accreted along the Indo-Myanmar Orogenic Belt as upthrust oceanic crust.

Anisotropy of Magnetic Susceptibility: A Comparative Analysis of Lava Flow and Sediment bed load fabrics based on some case studies

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Abstract

The lava flow as well as the fluvial channel bedload both representing non-newtonian and hyperconcentrated flows can have several similarities in the flow dynamics. Fabrics developed after the solidification can be characteristic of the processes experienced by these two physical conditions. The ferrimagnetic compounds act as indicator minerals developing the fabrics that can be accurately detected by using the advanced and precise method of Anisotropy of Magnetic Susceptibility (AMS) and is attempted here for the comparative evaluation of both these conditions using geological records in order to test its future utility for determination of the lava flow direction, rate of transport (/effusion) as some of the significant aspects in the Deccan Volcanism of the Indian Subcontinent. Oriented samples were collected from various localities in the Deccan Volcanic Province of Maharashtra (representing pahoehoe), the Siwalik fluvial paleochannel sandstones of Uttaranchal and the Middle-Upper Bhuban deltaic paleochannel sandstones of Mizoram, all comprising dominantly ferromagnetic mineralogy. The pāhoehoe type flow shows planar to oblate fabrics without any preferred orientation depicting crystal settling (of magnetic grains) as the primary mechanism of magnetic fabrics formation. The rubbly pahoehoe type flow showed prolate fabrics with well clustered maximum susceptibility axis (K1 = σ1) within horizontal planes probably governed by viscosity shear. The dykes across lava flows showed well clustered K1 axis parallel to the plane of dyke controlled by contractional cooling planes. The typical fluvial channel sand shows the K1 parallel to the flow direction in contrast to K3 parallel to flow in the piedmont type flow regime depicting that the fabrics in channel are formed by a delicate equilibrium amongst gradient, grainsize and stream power.

Continental crustal blocks and reactivated structural lineaments of Laccadive Ridge, SW continental margin of India

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Abstract

Laccadive Ridge is a major aseismic ridge along Southwest Continental Margin of India (SWCMI) evolved as a result of rifting between India and Madagascar during the Late Cretaceous (~88 Ma) under influence of the Marion Hotspot, and subsequent activity of Réunion Hotspot which emplaced numerous igneous intrusives and extrusives during Early Tertiary (~65 Ma). Analysis of 2D Multi-Channel Seismic (MCS) reflection profiles across the ridge reveal numerous structural and tectonic features, associated with the sediment units as well as underlying basement, formed as a result of the rifting, hotspot episodes and reactivation of structural lineaments. Density of faults and horst-graben structures in the seismic profiles indicate heavily faulted and uplifted crystalline basement beneath sediment cover of the ridge. A zone of well developed horst-graben structures associated with numerous faults and tilted crustal blocks, interpreted from a seismic profile of southern part of the Laccadive Ridge, suggests that sediments deposited in the pre-Middle Miocene are more intensively affected by those complex structures rather than the post-Middle Miocene sediments deposited more or less continuous with least disturbance by later subsidence. The structural zone characterized by intensively faulted pre-Middle Miocene sediment, and coincides with offshore extension of the Bhavani Shear zone, indicates reactivated structural lineaments as a result of hard collision of India with Eurasia in the Middle-Miocene raising Himalayas. Seaward Dipping Reflectors (SDRs), identified from the seismic profiles, along the western flank of the Laccadive Ridge suggest incipient volcanism during India-Madagascar rifting episode, and occurrence of oceanic crust of the Arabian Basin to the west of the ridge. Although the ridge is characterized by relatively positive but subdued free-air gravity anomalies, correlation of high amplitude free-air gravity anomalies over the ridge indicates more or less NNE-SSW trending structural lineaments intruded by numerous igneous intrusives. The Steep fault scarp and SDRs interpreted along western flank of the Laccadive Ridge, subdued free-air gravity anomalies, gravity anomaly lineaments more or less parallel to the Precambrian structural trends of the Peninsular India, and offshore extension of major inland structural trends affirm continental affinity of Laccadive Ridge.

The Southern Granulite Terrane of India: Shear Zone Systems and crustal blocks

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Shear zone systems are the controlling factors for any mineralization, igneous activity, migmatization and retrogression and that they represent 'key laboratories' for understanding the geological processes and ultimately the earth's history. Geological observations and geophysical signatures suggest that large scale-strain of the continental lithosphere is accommodated by networks of relatively narrow shear zones in the upper crust and much wider zones in the deeper parts of the crust. The middle to deep crustal shear zones are being increasingly recognized only in the last 2-3 decades from several high grade metamorphic terrains. The structural and metamorphic relationships in such deep crustal shear zones are more complex due to the possible interactions of high temperature fluids with high grade tectonics during their formation. The resulting finite strain field is heterogeneous, large variations in strain are possible and complex kinematic patterns may occur. Multi-scale structural analysis from satellite scale to outcrop scale studies offer a comprehensive understanding of the evolutionary history of the shear zones and associated geological processes in any high grade terrane. We discuss here about the distribution, geometry and kinematics of the shear zones of the Southern Granulite Terrane (SGT) with typical examples and emphasize their significance in terms of their geodynamic implications.

The Southern Granulite Terrane (SGT), an important part of the Proterozoic orogens of India, occurs at the southern tip of the Indian shield. Being at the intersection of two global orogenies of East African Orogen and the Kuunga orogeny, the SGT is crucial not only in understanding the geodynamic history of the orogens, but also central to many reconstruction models of Rodinia and Gondwana supercontinents. The SGT has been one of the most intensely studied orogen in the last two decades by several national and international groups encompassing all aspects of geology and geophysics. Innumerable publications have brought out large volumes of data with several modern concepts and innovative ideas, but with variable and contradicting interpretations. However, many of the controversial topics still remain debatable even today, despite the accumulation of significant amount of geological, geochemical, geochronological and geophysical data. The debatable points include: the definition of SGT and its extensions; transition zone where the low grade tonalitic and granitic gneisses gradually transformed into granulite facies metamorphic charnockitic rocks; division and extensions of different tectonic blocks, suture zone/ shear zones and their kinematics; existence of terrane boundaries; timing of subduction, accretion and collisional processes and so on. The plethora of these contrasting interpretations and the evolution and subdivision of crustal blocks within the SGT are a direct consequence of limited field observations, lack of field and structurally constrained geochronological data, limitations of accessibility to high elevated and densely vegetated areas.

Considering the recent developments and significant advances, the SGT can be divided into five distinct crustal/tectonic units based on lithological assemblages, structural styles, geochronological characteristics and geophysical signatures. From north to south, they are: (i) Northern Granulite Block (NGB) (ii) Cauvery shear/suture zone (CSZ), (iii) Madurai Granulite Block (MGB), (iv) Achankovil shear/suture zone (AKSZ), and (v) Trivandrum Granulite Block (TGB) (Fig.1).

In the present discussion, I would be highlighting some of the characteristics of these tectonic elements and their geodynamic significance. I shall also discuss some of the basic geological issues as described below that need to be attended by future researches:

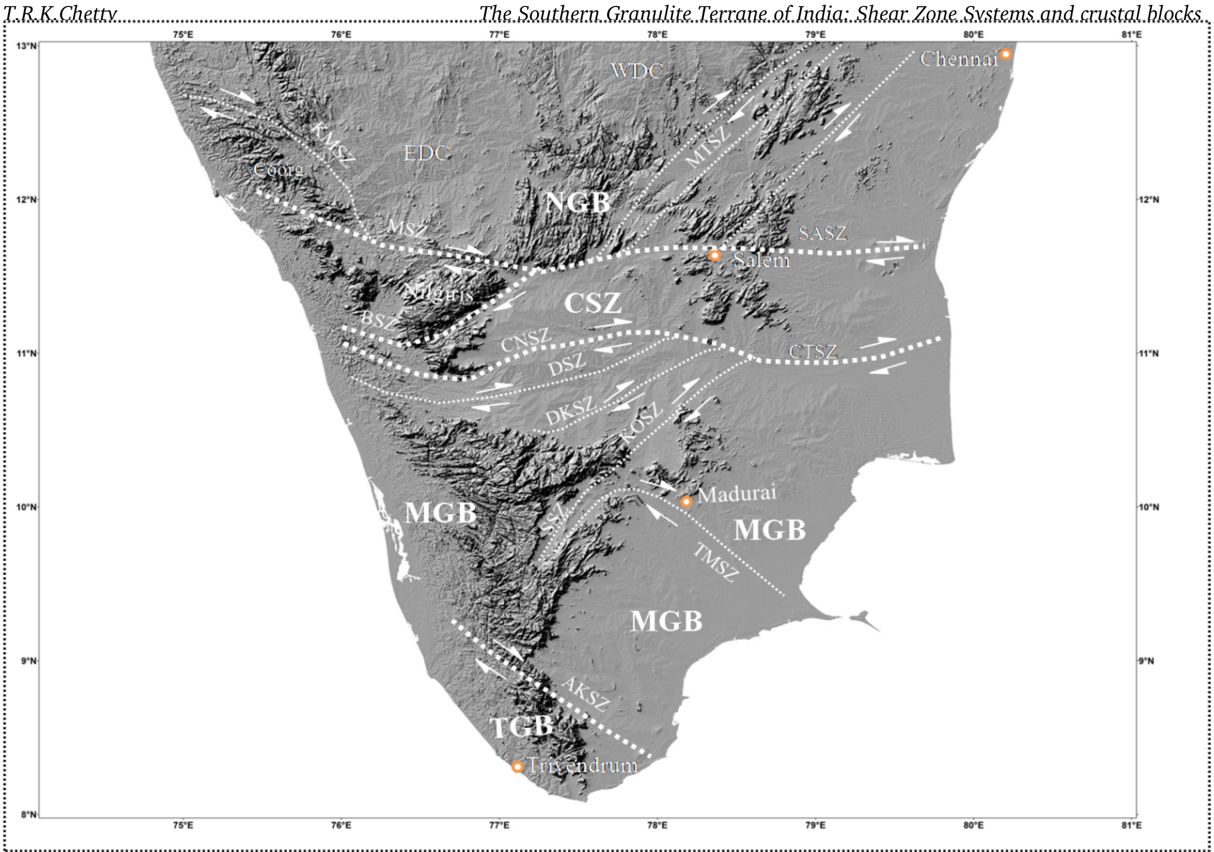

Fig 1. Digital elevation model of the southern granulite terrane showing shear zone systems and crustal blocks: NGB- Northern Granulite Block; CSZ- Cauvery shear zone; MGB- Madurai Granulite Block; AKSZ- Achankoil shear zone; TGB- Trivendrum Granulite Block;EDC- Eastern Dharwar craton; WDC- Western Dharwar 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-Tiruchinapalli shear zone; DSZ- Dharapuram shear zone; DKSZ- Devathur-kallimandayam shear zone; KOSZ- Kodaikanal Oddanchathram shear zone; SSZ- Suruli shear zone; TMSZ- Theni-Madurai shear zones

- ❖ There is a strong need for detailed field based studies of suture/ shear zones involving modern mapping techniques with the current tectonic perspectives before we embark on the advanced and sophisticated laboratory studies.
- ❖ Detailed studies regarding structural and kinematic analysis of shear zones together with interpretative structural cross- sections would provide insights into geodynamic implications.
- ❖ Integrated geological, structural, petrological and geochemical characteristics and isotopic signatures of ophiolites are essential in understanding the spatial and temporal patterns of Wilson cycle.
- ❖ In view of the recently published abundant data of Zircon geochronology and their conflicting interpretations pertaining to the Madurai block, the following suggestions are proposed to resolve some of ambiguities and complexities: (i) Multi-scale structural analysis of Madurai block to obtain a comprehensive map of structural architecture, (ii) The existence, nature and the geometry of the KKPT shear zone and its linkage with the Suruli shear zone warrant detailed field based investigations.
- ❖ The answers to the following queries related Madurai block would lead to exciting possibilities: (i) Are the High land massifs of Charnockites large scale nappes?, (ii) Do the migmatites in Low land areas represent the zone of thrusting and the structures in migmatites reflect syn-metamorphic or pre thrusting?, (iii) Is the Kadavur Dome , a 'true structural dome' or a deeply eroded and thrust related antiformal fold structure exposing the basement?, and (iv) Do the sedimentary packages of Kadavur dome represent a nappe complex?.

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Mantle heterogeneity during early Earth history: clues from $^{146\text{-}147}$Sm-$^{142\text{-}143}$Nd studies on komatiites

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^{146}Sm is a short-lived, and now extinct, radioactive isotope (Half life estimates range from 68 Ma to 103 Ma, Kinoshita et al, 2012) whose presence can be inferred from a slight excess in its daughter ^{142}Nd compared to the normal (chondritic) abundance. Chondrites represent the undifferentiated starting composition of the Earth and provide reference for estimating the extent of differentiation. During the differentiation, Nd being slightly more incompatible than Sm gets enriched in melt leaving a residue of higher Sm/Nd ratio. With time, residual solid would have higher ratio of ^{143}Nd/^{144}Nd due to decay of long-lived isotope of ^{147}Sm (half life 106 Ga) and higher ratio of ^{142}Nd/^{144}Nd if the differentiation occurred within life-time of ^{146}Sm.

The studies looking for this excess ^{142}Nd, a positive anomaly in ^{142}Nd/^{144}Nd ratio with respect to sample formed after decay of ^{146}Sm, targeted the oldest rocks present on the Earth and demonstrated it successfully in Isua greenstone belt of 3.8 Ga age (Caro et al., 2003). This excess is interpreted to indicate that source of Isua rock has undergone a differentiation event during the life-time of ^{146}Sm, i.e., within 30-100 Ma of formation of the Earth. Boyet and Carlson (2005) re-measured ^{142}Nd/^{144}Nd ratios in chondrites with technologically advanced mass-spectrometers and showed that chondrites ratios are actually, 18 ± 5 ppm lower than the terrestrial samples. This means that all terrestrial samples today are sourced from an early depleted reservoir formed, within 30-100 Ma of Earth's formation, due to global differentiation of the silicate Earth. This discovery has given rise to the search for a complementary early enriched reservoir with negative ^{142}Nd/^{144}Nd anomaly (Rizo et al., 2012; Upadhyay et al. 2009). Early enriched reservoir has been hypothesized to be either hidden near the core-mantle boundary and has not been tapped by mantle-plumes, or lost from the Earth by collisional erosion during early history of the Earth in events similar to the moon-forming impact (Jellinek and Jackson, 2015). Recently, it has also been suggested that during anoxic environment core could accommodate Nd leaving mantle with superchondiritc ratios of Sm/Nd (Wholers and Woods, 2015).

Besides the implications for the trace-elements' budget, a related question is about the preservation of early heterogeneities as evidenced by higher anomaly in the Isua source at 3.8 Ga. Even younger rocks, such as ~2.8 Ga old Kostomuksha komatiites are reported to have preserved anomaly in ^{182}W which is a product of ^{182}Hf with a half life of 8.9 million years (Touboul et al. 2012) . On the other hand, studies with long-lived isotope systems such ^{176}Lu-^{176}Hf and ^{147}Sm-^{143}Nd, have shown that mantle has been homogenously depleted in Archean though the depletion decreased with time (Blichert-toft and Puchtel, 2010).

It is in this context that we studied komatiite samples of Sargur group, collected from near Banasandra, that are known to be the oldest in Dharwar craton. The whole-rock ^{147}Sm-^{143}Nd results yielded an age of ~3.14 Ga consistent with earlier studies, with an initial ε_{Nd} of +3.5. We also carried out high precision measurements of ^{142}Nd/^{144}Nd using new-generation Thermal Ionization Mass Spectrometer (TIMS) and found no detectable anomaly in these rocks compared to a terrestrial standard. However, these results when taken together, provide constraints on the nature and evolution of the mantle-source of these komatiites. No anomaly in ^{142}Nd/^{144}Nd ratio indicates the source of these rocks would have formed after the decay of ^{146}Sm, i.e. younger than ~4.3 Ga, but has been depleted to +3.5 ε_{Nd} at ~3.14 Ga. These boundary constraints help calculate time-integrated Sm/Nd ratio of the source-mantle which turned out to be higher than that of contemporary mantle-sources. We, therefore, propose that these results indicate preservation of spatial heterogeneities in the Archean mantle which have arisen due to more than one differentiation events, either local or global in nature.

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Crustal structure across Periyar Plateau, Southern Granulite Terrain (SGT): Inferences from Gravity data

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Abstract
Significant geological problems in a Precambrian terrain are metamorphism, magmatism and tectonism. The inter-relationship of these three can be elucidated to a great extent by detailed gravity analysis. A gravity anomaly results from the inhomogeneous distribution of density, dimension and depth of the anomalous body beneath. The study region forms the western part of the Madurai block (southern block) and shares several lithological characteristics of the Proterozoic exhumed South Indian Granulite Terrain (SGT). Based on the detailed gravity observations a Bouguer anomaly map of the region has been prepared and shows a prominent gravity low along the Periyar plateau, it coincides with Munnar granites. A crustal structure across the Periyar plateau has been modelled and the crustal models indicate that the upper layer containing exhumed lower crustal rocks (2.76 gm/cc) is almost homogeneous, most part of the gravity field resulting from variations in intracrustal layers of decharnockitised hornblendic gneisses and granite bodies. Below it, a denser layer (2.85 gm/cc) of unknown composition exists with Moho depth ranging from 36 to 41 km. This crustal model, which can be expected to be a major heterogeneity in the overall crustal structure of the terrain.

Key words: Gravity anomalies; Crustal structure; Periyar plateau; Southern Granulite Terrain;

1. Introduction
Geophysical methods play an important role in understanding the subsurface geology and solving the related problems. Gravity and magnetic methods are the most effective tools among them that can be used to study the regional geology, crustal structure, nature of large scale geologic/tectonic features, sedimentary basins and problems related to engineering geology. The gravity anomaly map can be used to understand the spatial variations of the gravity field and their correlation with the surface and subsurface geology. Subsurface mass distribution can be inferred by a qualitative analysis of the trend, amplitude and wavelength of free-air and Bouguer anomalies. Krishna Brahmam and Kanungo, (1976); Subba Rao, (1988); Krishna Brahmam, (1993) have carried out gravity studies of the south Indian shield on a regional basis. The present study brings out the broad geological features of the region in more detail than ever before. In order to understand the nature of crust and the attendant tectonics, we carried out detailed gravity surveys in the Periyar plateau and the adjoining areas.

2. The Geological framework of the Study Area
The Periyar Plateau is a horst like regional feature at an elevation of 500 m above MSL in the Southern Granulite Terrain (SGT) bounded by the EW trending Palghat-Cauvery lineament (PCL) in the north, and the NW-SE trending Achankovil-Thenmalai lineament (ATL) in the south. The NE-SW trending Kambam lineament delimits the region to the SE and to the west is bounded by West Coast fault which is related to late Phanerozoic rifting and Deccan magmatism. The area falls in the western part of the Madurai Granulite Block. The major geological formations in the area comprise members of charnockite suite with minor bands of leptynites, corderite granulites, garnet-free mafic granulites, migmatitic gneisses, garnet corderite gneisses, garnet corderite sillimanite gneisses and quartzites (Fig.1.).

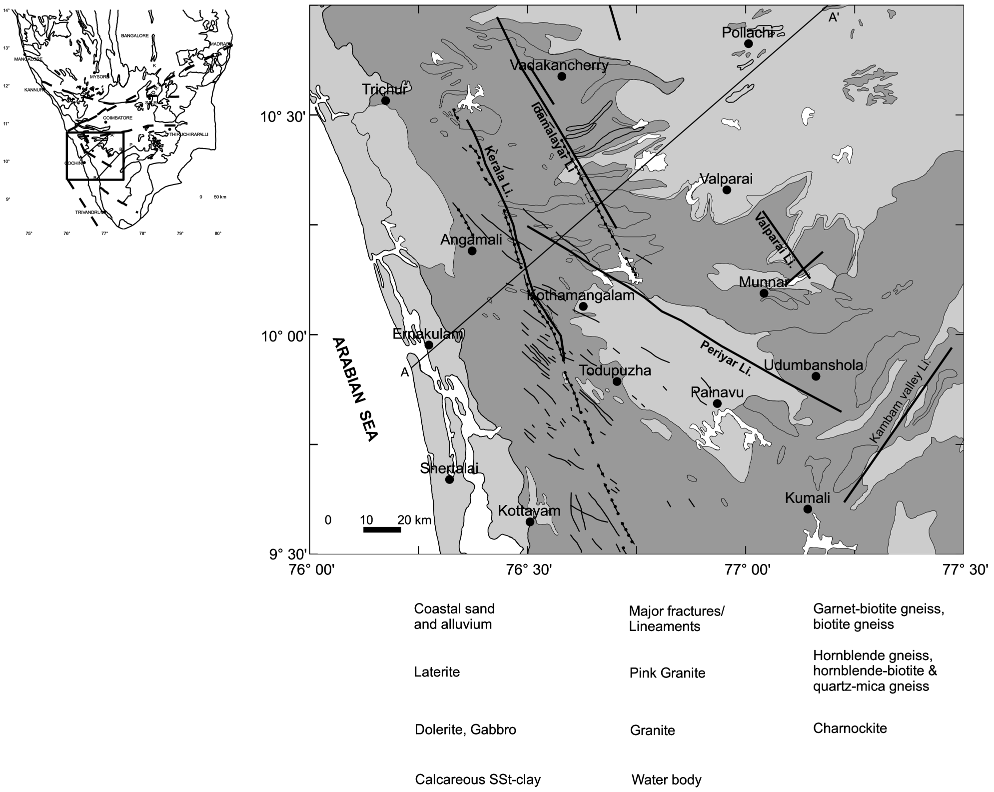

Fig.1. Geological map of the study area (after GSI, 1995). Lines AA′ show the location of the regional gravity profile considered for modelling. The south Indian geology map and present study area shown with in the rectangular as inset.

The most prominent structural features of the Periyar Plateau are the steeply dipping Periyar and Idamalayar faults (often reported as lineaments) with the Periyar lineament trending NW-SE and the Idamalayar lineament trending NNW-SSE. The Periyar lineament/fault system is traceable over a length of 90 km between NE of Angamali and SE of Udumbanshola and the Idamalayar lineament is traceable over a length 80 km between NW of Vadakancherry and SW of Valparai. The south-eastern part of the Periyar plateau is sharply dissected by the Vaigai River draining the area along a prominent NE trending valley well known as Kambam valley. This is the most significant NE trending geomorphic feature in the area and also in the southern Indian Shield.

3. Gravity data analysis and its derivates

A Lacoste–Romberg (Model G) gravimeter with an accuracy of 0.01 mGal was used for the data acquisition and nearly 1200 gravity measurements were made at an average station spacing of 1–2 km in the study region. The measurements were made utilising already available base stations and by establishing additional secondary base stations. The elevation data has been considered from spot heights, benchmarks and toposheets. The 1930 international gravity formula and the surface rock density of 2.67 gm/cc were used for the purpose of gravity data reduction. The density and magnetic susceptibility of various rock types of the region were determined by collecting a good number of rock samples.

3.1. Bouguer anomaly map

There are many approaches to interpret the gravity anomalies, which are explained in Dimri (1992, 1998), Blackly (1995), Dimri et al. (2012), Bansal et al. (2006) and Chamoli et al. (2006) etc. The

Bouguer anomaly map prepared for the study region at a contour interval of 5 mGal is shown in Fig. 2. In the figure, regions of Bouguer high and low are clearly demarcated. Detailed interpretation of Bouguer anomaly map over this region has already been presented in Ajayakumar et al., (2006). The Bouguer contour map shows good correlation with the surface geology and the minor geological structures of the area. The anomaly map suggests that the gravity field in the NE of Periyar lineament is distinctly different from that of SW part. It separates a strong gravity gradient tending to be positive towards the coast from the significant gravity lows ranging from -85 to as low as -150 mGal covering a larger part in the Periyar plateau.

Under the general assumption that no lateral in homogeneities exist below the Moho, the Bouguer anomalies would generally reflect the variation in the crustal thickness, the intra-crustal structures and lithologic changes, the near surface geological structures and changes in surface geology. The Bouguer anomaly map shows some major trends as follows.

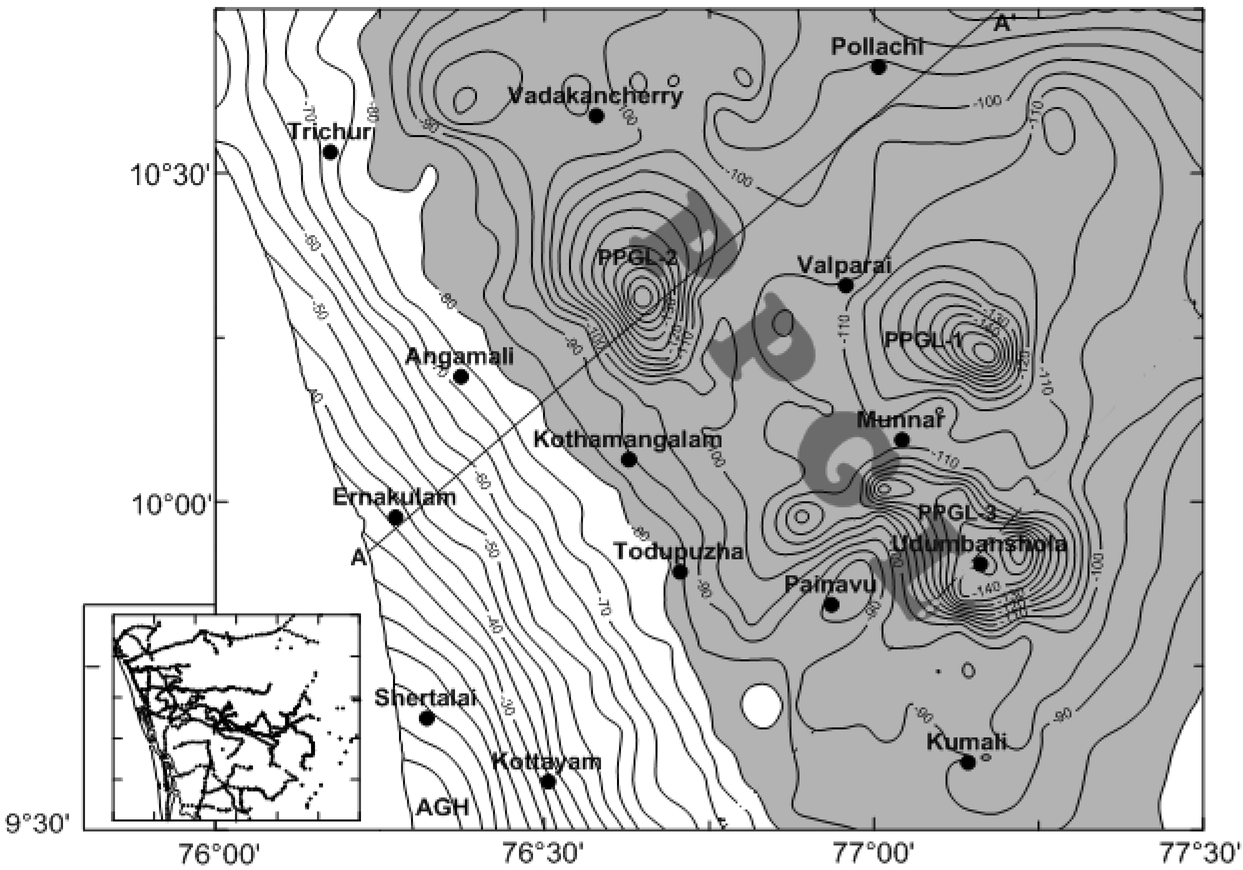

Fig.2 A generalized map depicting gravity and magnetic (both total field and analytic signal) anomaly trends and patterns in the study area. Details are discussed in the text. PPGL1, 2 & 3 are small gravity low closures in the Periyar plateau (Ajaykumar et al., 2006).

- The Bouguer anomaly values in general range from 0 to -155 mGals
- A series of negative closures of ≥ 120 mGals (Periyar Plateau Gravity Low, PPGL-1, PPGL-2 and PPGL-3) coincides with the Munnar granitic region.
- Two isolated anomalies -85 mGal closures in the southern most central part of the map are correlated with the small granite bodies.
- The Bouguer anomaly map shows a gravity gradient across the Periyar lineament. The Periyar lineament (LM1) is oblique to the gravity trends and runs NW-SE. It broadly separates a region of gravity low in the NE from one of gravity high in SW. The gravity signature of this fault is one of a

moderate to sharp gravity gradient. The Idamalayar lineament (LM2) marks a region of gravity low but has no expression otherwise. The Kerala lineament (LM3) runs oblique to the anomaly contours and has therefore a poor expression. The LM4 runs parallel to positive gravity gradients between Kottayam-Angamali-Trichur. It is noteworthy that Kottayam-Angamali-Trichur lineament (LM4) has also been inferred from the earlier magnetic map. It limits a broad gravity high increasing from -35 to 0 mGals at AGH - Alleppey Gravity High (which falls just outside the study area) in the southwestern portion of the map and may be the boundary of a distinct gravity field.

4. Gravity modelling and Model Implications

In order to obtain the crustal structure in the region, 2-D modelling was carried out using the SAKI program of USGS (Webring, 1985). A representative gravity modeling results along a section across the Periyar Plateau (profile AA') is shown in Fig.3 (Ajayakumar et al. 2006).

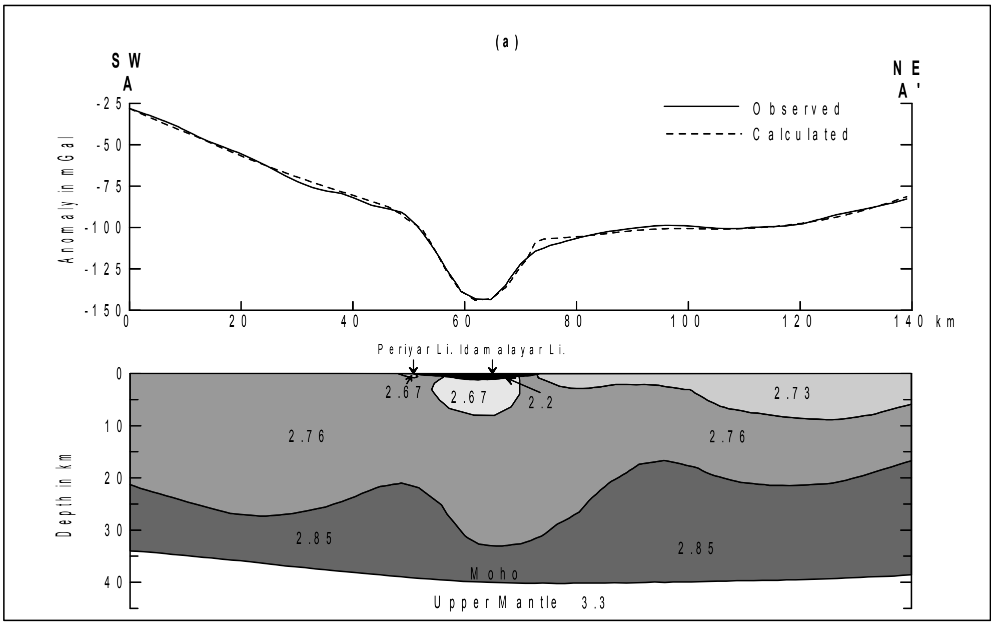

Fig. 3. Interpreted crustal model along profile AA' in the Periyar plateau region.

Considering the average densities for the surface rocks and the mid-to-lower crustal exhumation in the SGT, a two-layer crustal model consisting of high density lower crustal rocks (charnockites 2.76 g/cc) as the upper crustal layer and a 2.85 g/cc density lower crustal layer below it. The upper mantle below these two layers is assigned a density of 3.3 g/cc. This two-layer density model for the crust is consistent with the simplified two-layer crustal model proposed for the SGT based on velocity–density relation of the major rock types (Ramachandran, 1992). In addition to these two layers, the other surface rock exposures become a part of the crust as localised bodies or as thin layers. Gravity modelling along the profile AA' (Fig.3) in the region reveal crustal thickness of the order of 40–41 km below the Periyar plateau and a tendency to thin up to 34–37 km along the fringes of the plateau bounded by rift zones of different ages. The models show that the thickness of the lower crustal layer (dominated by charnockites) is different on either side of the Periyar lineament. An interesting feature is the presence of localised highly weathered surface rock extending down to a depth of 500 m in the area between Idamalayar and Periyar lineaments bringing out a steep gravity low. A granitic body with a small outcrop length extending down to a depth of 8 km has been inferred below it. Towards northeast of the profile, hornblende gneisses extend down to depths of 4–8 km as a top layer. The upper crustal layer consisting of charnockites extends down to a depth of 27 km in SW part of the profile and 21 km in NE part of the profile and shows an irregular wavy layered shape. The Moho depth extends to 34 km in the SW part of the profile and deepens down to 41–42 km in the central part of the profile and again thins to 39 km in the NE part of the profile.

6. Conclusions

The following broad conclusions have been arrived from interpretation of gravity field in the Periyar plateau.

- The Periyar lineament more or less defines the NE limit of the strong gravity gradient tending to be positive towards the west coast; it is bounded by a region of low gravity gradient covering a larger part of the Periyar plateau.
- Three near domical high gradient negative anomalies (PPGL-1, PPGL-2 and PPGL-3) emerge out of the broad negative Bouguer field over the Periyar plateau. The above three localised gravity lows are due to the Munnar granite massif in this province.
- The positive gravity anomaly gradient towards the coast near Alleppey (AGH, just outside the study area) in the southern part of the study area can be attributed to the crustal thinning and a unique coastal structure.
- Deep weathering of the rocks (< 300 m) inferences the gravity field giving rise to sharp local negative anomalies.
- Trichur–Udumbanshola province in the NE and (ii) the Trichur–Ernakulam–Kottayam province in the SW. A prominent NW–SE trending belt of magnetic low separates the two provinces of magnetic high.
- The results presented in this paper underline the fact that the SGT, though comprising largely of exhumed lower crust of the Indian Shield in the Proterozoic, comprises segments, which have been affected differentially by tectonic and magmatic events of both the Proterozoic and Phanerozoic that have brought about distinctive continental structure below the Periyar plateau.

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High grade metamorphism and subduction related arc-magmatism in the Mercara Shear Zone, southern India

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Abstract

Mercara Shear Zone is sandwiched between the Western Dharwar Craton and Coorg Block, marked by steep gravity gradients interpreted to suggest the presence of underplated high-density material in the lower crust. Here we present a synoptic view about the metamorphism and related events from Mercara Shear Zone, Southern India. Geochemical data on the magmatic suite suggests formation through subduction-related arc magmatism, whereas the metasediments represent volcano-sedimentary trench sequences. Phase equilibrium modeling of mafic granulites and metapelites from the Mercara Shear Zone suggests that the rocks undergone high-grade metamorphism.

Introduction

The process of stabilization or cratonization of continental blocks/mobile belts includes juvenile crustal growth, deposition of supracrustal rocks and orogenic processes normally at the continent margins, anorogenic plutonism and deposition of platform sediments in the associated sutures/shearzones. Thus the identification and recognition of new shear zones and understanding their geometry and kinematics provides critical information on regions of large strain and reactivation, locale of igneous intrusions and important economic mineral deposits which in turn is helpful for paleogeographic correlations between discrete crustal blocks. The elucidation of P-T-t path (pressure and temperature variation with time) of crustal plates or cratons on either sides and within the associated sutures would provide new insights on the timing of magmatic and metamorphic events, magma sources and crust mantle interactions, whereas the geochemical systematics can constrain petrogenetic mechanisms of the material underwent subduction and exhumation.

Geological Setting of the Mercara Shear Zone

The Southern Indian Shield comprises the Archean granite–greenstone terrains of Dharwar Craton in the north and the high-grade granulite facies crustal blocks of the Southern Granulite Terrain (SGT) in the south (Fig. 1). The Mercara Shear Zone is a curvilinear transpressional shear zone exhibiting dextral displacements, sandwiched between the south-western part of Dharwar Craton and Coorg Block in the Southern Granulite Terrain (Fig. 2). The shear zone having a strike length of more than 100 km and with a width of 20-30 km extending from the western coast of southern India and converging with the Moyar Shear Zone in the east (Chetty et al., 2012; Santosh et al., 2015, 2016). Major rock types in the shear zone include charnockite, TTG (tonalite - trondhjemite

- granodiorite) gneisses, metagabbros, mafic granulites, kyanite-sillimanite bearing metapelites (khondalite), metagabbros and quartz mica schists (Fig. 3). The Mercara Shear Zone hosts younger intrusive bodies like that of Angadimogar syenite, Thalur granite and Sulliya syenite bodies. Chetty et al. (2012) observed that the foliations in general have steep dips (70-80^{0}) and the plunges are mostly to southeast subparallel to the trend of the shear zone.

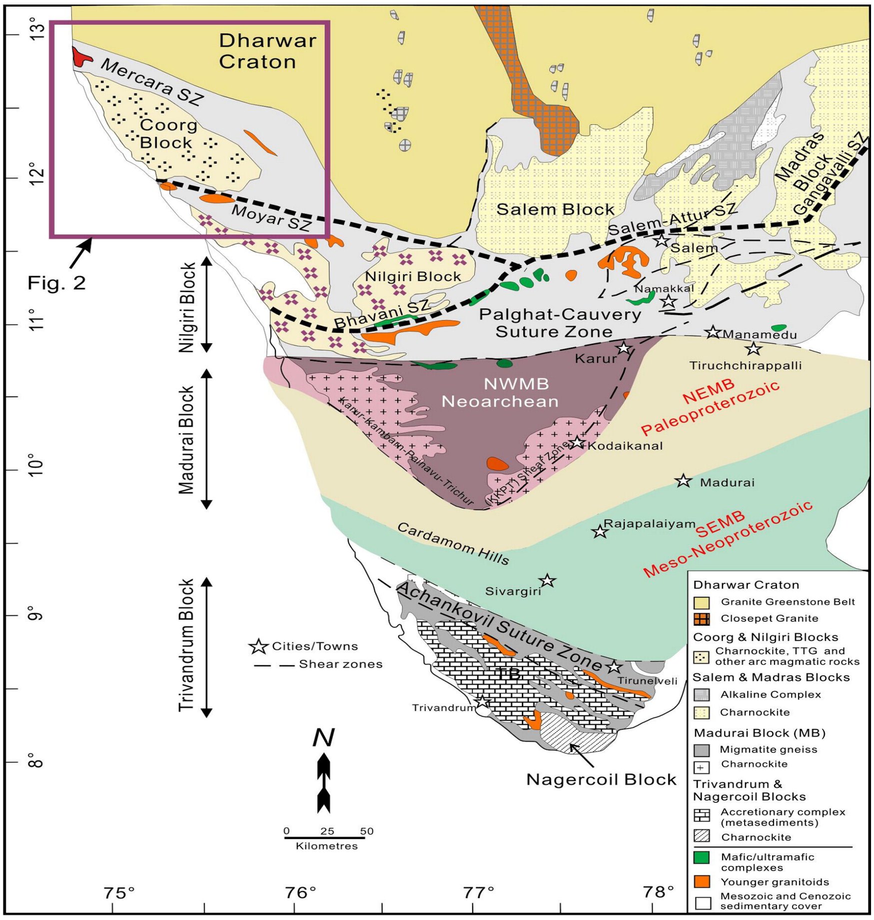

Fig. 1. Generalized geological and tectonic framework of southern India showing major crustal blocks and intervening shear/suture zones. The Mercara Shear Zone is marked as box and shown in Fig. 2. (after Santosh et al., 2015, 2016)

Methodology

Detailed field work was carried out in and around Mercara shear zone and samples were collected. Polished thin sections were prepared for all the samples collected for detailed petrographical study. Mineral chemical analyses were carried out using an electron microprobe analyser (JEOL JXA8530F) housed at the Chemical Analysis Division of the Research Facility Center for Science and Technology, the University of Tsukuba, Japan.

The stability of mineral assemblages in pelitic gneiss and metagabbro was constrained using THERMOCALC 3.33 software. The pseudosection calculations were undertaken in the systems Na_2O-CaO-K_2O-FeO-MgO-Al_2O_2-SiO_2-H_2O-TiO_2-Fe_2O_3 (NCKFMASHTO) for pelitic rocks and Na_2O-CaO-FeO-MgO-Al_2O_2-SiO_2-H_2O-TiO_2-Fe_2O_3 (NCFMASHTO) for metagabbro. Bulk rock compositions for the rocks were determined by FUS-ICP/MS at Activation Laboratories, Canada.

Whole rock geochemistry including the major, trace and REE data were obtained. Major elements were analysed using a Phillips® MagiX PRO Model 2440, X-ray fluorescence (XRF) spectrometer (Philips, Eindhoven, The Netherlands) and the trace elements including rare earth (REE) and high field strength elements (HFSE) were analysed by PerkinElmer® Model ELAN®

DRCTM II, ICP mass spectrometer (PerkinElmer, Inc., Shelton, CT, USA) at the CSIR-National Geophysical Research Institute, Hyderabad, India.

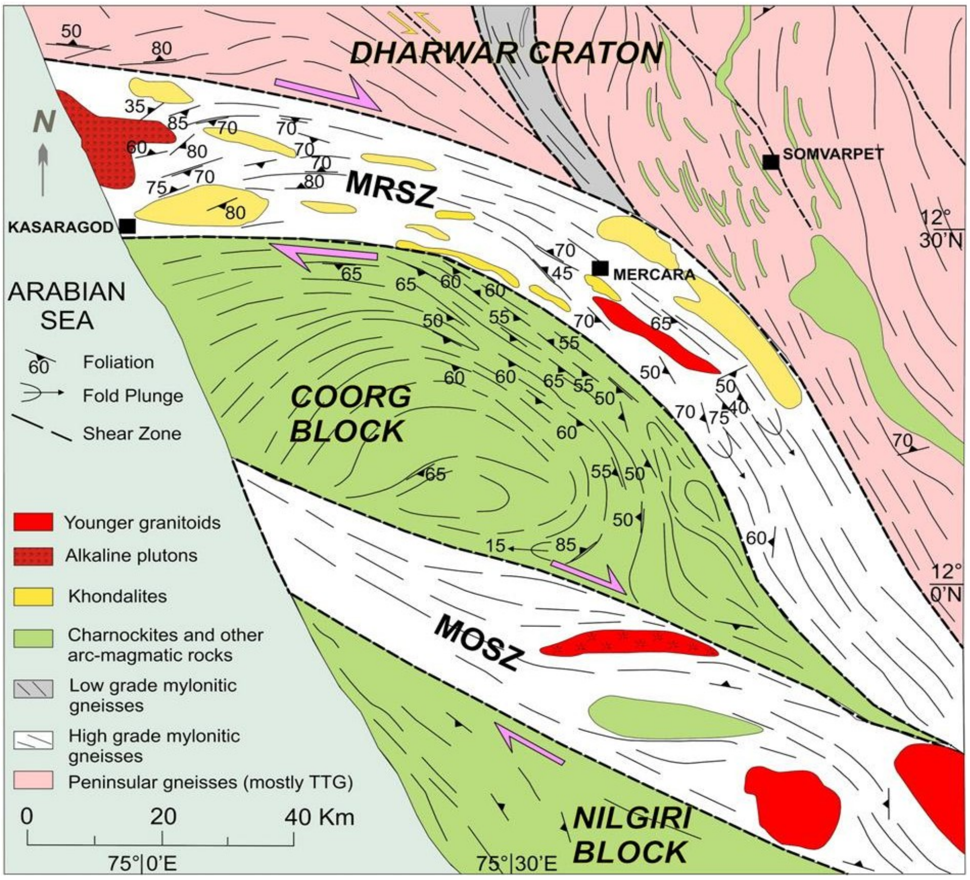

Fig. 2. Geological map of the Mercara Shear Zone (Modified after Chetty et al., 2012; Santosh et al., 2015)

Results and Discussions

Major rock types in the shear zone includes metaigneous suite corresponding to arc magmatic rocks (charnockite, TTG gneisses, metagabbros, mafic granulites) and metasediments (Kyanite-sillimanite bearing metapelites, leptinite gneiss, garnet biotite gneiss, quartz mica schist) representing volcano-sedimentary trench sequences accreted onto the continent.

The metapelites contains prograde to peak mineral assemblage of Grt + Bt + Ky + Kfs + Pl + Qtz + Rt, from which *P–T* is estimated as 5.5 kbar to 10 kbar and 600°C to 800°C respectively (Fig. 4). The Retrograde temperatures calculated based on garnet-biotite assemblages in metapelite ranges between 600-610°C and garnet-hornblende assemblage in mafic granulite at 600-620°C. The metagabbro which contains peak mineral assemblage of Grt + Opx + Cpx + Opx + Hbl + Pl + Qtz + Rt suggests a wide *P–T* range of 10 kbar at 700°C and 12 kbar at 900°C. The peak *P-T* condition was further constrained by temperature calculation based on the Grt-Cpx geothermobarometry of Ellis and Green (1979) for a mafic granulite as 760-780°C and 10.3-11.2 kbar, which corresponds to upper amphibolite to granulite facies metamorphism. Similar temperatures were also obtained from hornblende-plagioclase assemblage of metagabbro (740-780°C) and the peak P-T condition of 760-780°C and 10.3-11.2 kbar. One of the most notable aspects that can be highlighted from the petrography, mineral chemistry and P-T estimates is that the rocks represent a deeply eroded zone of paleo-subduction and collision.

Fig. 3. Representative field photographs of the major rock types in the Mercara Shear Zone

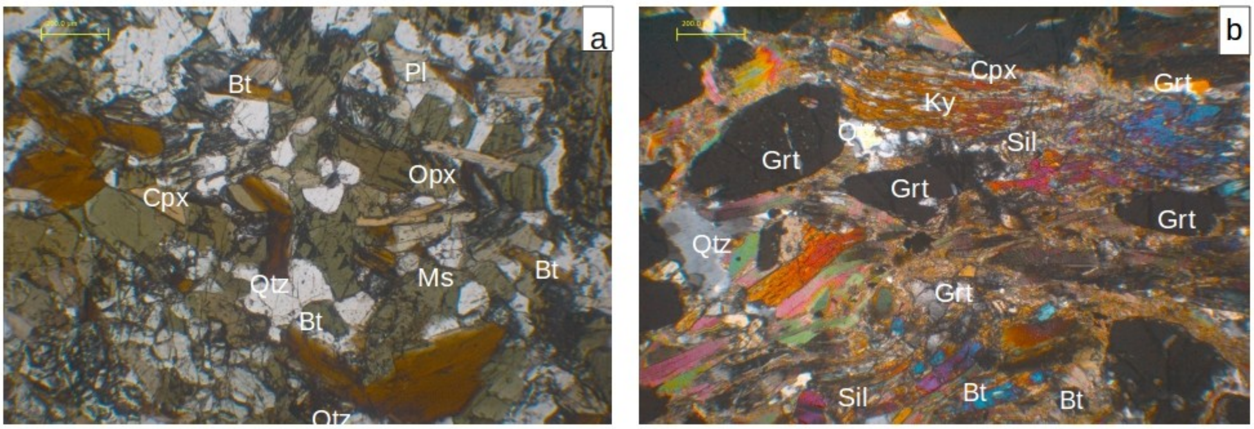

Fig. 4. Representative photomicrographs (a) Two pyroxene bearing mafic granulite comprises clinopyroxene + orthopyroxene + biotite + plagioclase + quartz assemblage (b) Well-foliated kyanite + sillimanite + garnet + quartz assemblage in the metapelite.

The whole rock geochemistry (major, trace and REE) of the meta-igneous suite of rocks from the area suggest magma generation in a convergent margin setting (Fig 5a-5d). In order to differentiate the petrogenetic mechanisms of the charnockites and granitoids from Mercara, we compare our data with those on the Mesoarchean charnockites of Coorg Block (Santosh et al., 2015), Mesoarchean TTG rocks of the adjacent Dharwar Craton to the north (Naqvi et al., 2009) and also the world average TTG data compilation of Martin (1994).The charnockites and gneisses show typical calc-alkaline nature whereas mafic granulites were plotted in the field of arc tholeiites (Fig. 5a). In the basalt discrimination diagram after LeBas et al. (1986) (SiO_2 Vs Na_2O+K_2O), the mafic granulites plot within the field of basalt to andesite and classifies the protolith of this rock as basaltic to andesite type magma (Fig. 5b). The magmatic parentage for the charnockite and gniesses is evident from the chemical features including the metaaluminous nature, lower K_2O/Na_2O ratios, similarity to high Ba-Sr granitoids, and plots confined to the igneous field of K_2O/Al_2O3 vs. Na_2O/Al_2O3 diagram (Tarney, 1976) (figure's not shown). The charnockites, granitoids and mafic granulites from the Mercara zone fall in the subduction field (Thieblemont and Tegyey, 1994) (Fig. 5c) suggestive for subuction related arc-magmatism. In the geotectonic environment discrimination diagram of Wood (1980), all the magmatic rocks from Mercara plot within the field of Arc basalts and plot within the field of E-MORB and OIB in the Th/Yb–Nb/Yb diagram of Pearce et al. (2005) (Fig. 5d). The chemical characteristics based on the major and trace element systematics and key isotopic ratios are consistent with their evolution in active convergent margin setting.

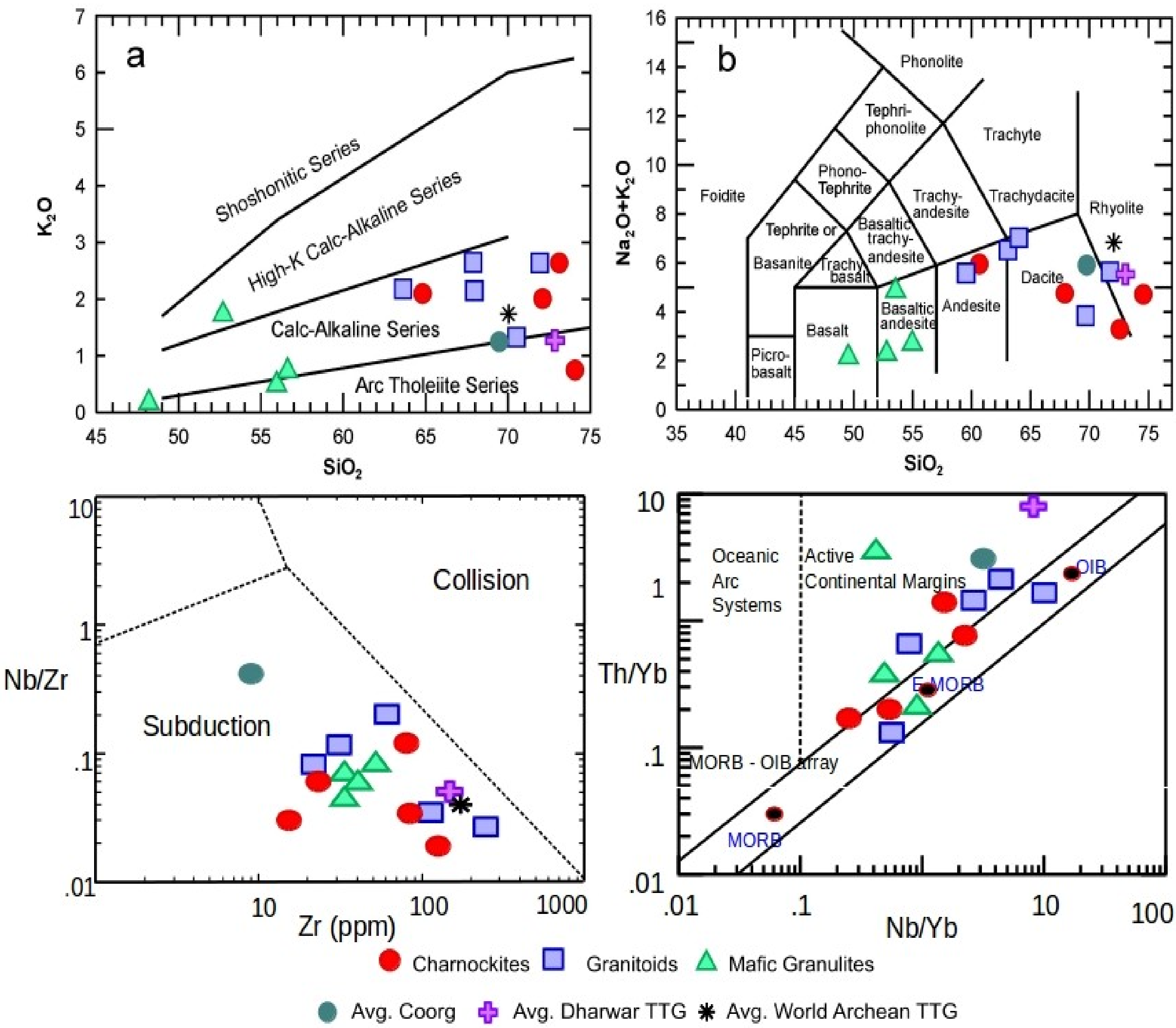

Fig. 5. Geochemical differentiation diagrams. (a) SiO_2 vs. K_2O Diagram after Peccerillo and Taylor (1976). (b) Basalt discrimination diagram after LeBas et al. (1986). (c) Zr vs. Nb/Zr diagram to show the nature of tectonic setting. All the lithologies of present study are confined to the subduction field, similar to most of the charnockites of southern India. Discrimination fields are after Thieblemont and Tegyey (1994).(d) Geotectonic environment discrimination diagram after Pearce et.al. (2005).

An integration of geochemistry, petrology and geochronological data from the Coorg Block and the Western Dharwar Craton suggest that the derivation of Mesoarchean charnockites and TTG's from a subducting geodynamic setting (Santosh et al., 2015, 2016; Shaji et al., 2014; Samuel et al., 2014; Jayananda et al., 2015). The Mercara Shear Zone welds the Coorg Block with the Dharwar Craton to the north and is marked by steep gravity gradients interpreted to suggest the presence of underplated high density material in the lower crust (Sunil et al., 2010). A near-vertical conductive structure extending from the lower crust into the upper mantle was identified in magnetotelluric study by Abdul Azeez et al. (2015), which coincides with the geologically marked transition zone between the Coorg Block and the Western Dharwar Craton confirming that this zone is a suture between two Archean terrains. Our present study also defines Mercara Shear Zone as a possible suture formed as a collisional event between the Coorg Block and Western Dharwar Craton.

Conclusions

The geochemical signatures of the magmatic suites within the Mercara Shear Zone show features typical of subduction - related arc magmas in a convergent margin setting and the occurrence of arc magmatic rocks together with high P/T metasediments, represent the deeply eroded zone of subduction. Thermodynamic modeling by pseudosection calculations indicates that the metapelites and mafic granulies from the Mercara Shear Zone had undergone high grade metamorphism.

Acknowledgements

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Geology and petrography of major rock types from Madras Block, southern India

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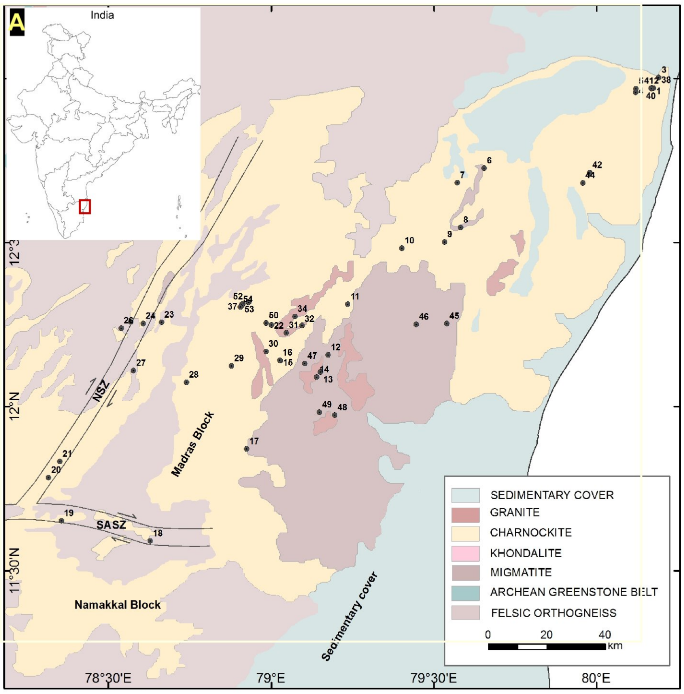
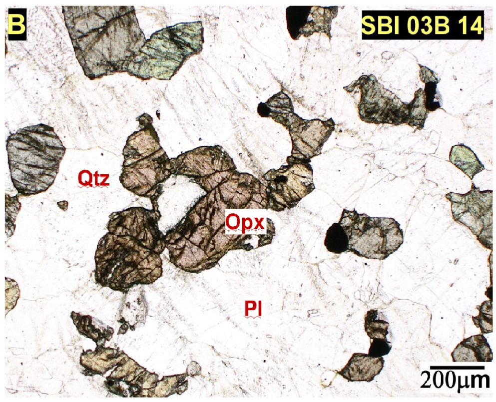
Southern part of Dharwar Craton represents a college of crustal blocks transected by several deep crustal shear zones. This includes Coorg, Nilgiri, Namakkal, Madras, Madurai, Trivandrum and Nagercoil. Each of these blocks has distinct lithology, age and tectono-thermal histories. These differences among them show that it is important to explore each of these blocks separately to reconstruct their tectonic evolution. In this Madras Block, southern India represents a significant exposure of lower Archean crust. This block is present towards the south-east of Dharwar Craton and north-eastern margin of southern granulite terrane. This block is demarcated by Nallamalai shear zone in the west and Salem-Attur shear zone in the south. A preliminary field work has been done to identify major rock types in this block. Field observation revealed that major rock types in this block are charnockite, felsic ortho-gneiss, granite, migmatite and two-pyroxene granulite. Charnockite represents the major rock type in this terrain which is widely exposed in the north, south and west. This charnockite is closely associated to Felsic ortho-gneiss along the western margin. Another major rock type in this terrain is migmatite which is mostly present towards the central to eastern margin. We have also observed granitic outcrops in between charnockite and migmatite. Following this petrographic analysis of all the rock types is done. The major rock type charnockite is mainly made up of orthopyroxene + Biotite + plagioclase + K-feldspar + quartz ± garnet (Fig. 1B). Orthopyroxene and biotite defines the foliation in these





samples. Both primary and secondary biotite is present in these charnockite samples. Secondary biotites are common along the pyroxene boundary. In some samples garnet is absent and clinopyroxene is present as a major mineral. Quartz is mostly subhedral in the matrix and rarely platy in nature. In some areas quartz has myrmekitic texture shows exsolution of plagioclase in them. Plagioclase is characterized with polysynthetic twinning. Sulfide minerals like pyrrohotite, chalcopyrite and pyrite are common in the collected charnockite samples. A variety, Oscillation texture can be seen in the pyrrhotitie. Oxides like ilmenite and cubical magnetite are also present in the rock samples. Major accessory minerals in charnockite are zircon and apatite. Previous geochemical studies carried out on the charnockites indicate that, they consist mainly AI2O3 – K2O – FcO – MgO – SiO2 – H2O, where SiO2 can be taken as an excess component. (Howie, 1955, Subramanian, 1959, Sen, and Sahu, 1970, Sen, 1970, Sen, et al., 1970). Previous geochronology studies show that these charnockite formed and metamorphosed in the Precambrian age. St. Thomas mount charnockite has an age of 1650Ma (Poornachandra Rao et al., 1999). Ages from the shear zones signify Neoproterozoic to Cambrian reworking during the assembly of Gondwana supercontinent (Santosh et al., 2009, Meert et al., 1997, Roy, 1999, Braun et al., 2003, Collins et al., 2014, Yoshida et al., 1996). Adetailed petrographic, geochemical and geochronological studies can give vital clues on Gondwana congregations.

Fluid Inclusion Study on the Wynad and Attappadi Gold mineralization in Southern Granulite Terrain, India

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Abstract

The Wynad Gold Field (WGF) and Attappadi Province are the main gold prospects in Southern Granulite Terrain, India. Gneisses are the predominant rock type in these areas and auriferous veins intruded within the country rocks. Fluid inclusions in vein quartz are abundant in these areas. The present work including fluid inclusion petrography and microthermometry of auriferous quartz veins in different parts of Wynad and Attappadi. Fluid inclusion studies of vein quartz gives an idea of the nature of the ore forming fluids and fluid involved in gold mineralization is of low saline and aqueous-carbonic in composition and quite similar to the orogenic lode gold deposits reported world-wide. Micro-thermometric data indicates fluid immiscibility (phase separation) during trapping of fluid inclusions and this must have played an important role in gold deposition.

1. Introduction

Majority of the gold occurrences in India are concentrated in the peninsular part of India, especially around shield areas of south India, Bastar in central India, Rajasthan and Singhbhum of eastern India Terrain (Biswas and Gangopadhyay, 2009; Krishnamurthi, 2012; Krisnamurthi et al., 2014). Important gold deposits are located in Eastern Dharwar Craton (Kolar, Hutti and Ramagiri) and in Western Dharwar Craton (Kempinkote, Gadag, Ajjanahalli, Chinmulgund and Ganajur area (Krishnamurthi et al., 2010). The Southern granulite terrain, south of Dharwar Craton hosts numerous gold occurrences such as Wynad, Malappuram and Attappadi provinces. Records of ancient mining activities (Radhakrishna andCurtis,1999), illegal gold mining by local people and, ongoing research work related to gold mineralization and geotectonic context of SGT by number of workers (Binu Lal et al., 2003; Krishnamurthi et al., 2010; Santosh et al., 2013)gives an indication of new discoveries in this part of the country. This paper focuses on fluid inclusion characteristics of vein quartz of WGF and Attappadi to provide evidences of ore forming fluid about genesis of deposit.

2. Geological setting

The SGT is one of the Proterozoic orogens in southern Peninsular India, comprising high grade metamorphic rocks like charnockite, khondalite and migmatite invaded by younger pegmatite intrusives (Chetty and Santosh, 2013). The terrain is transected by four regional shear zones such as the Moyar (MSZ), Bhavani (BSZ), Palaghat-Cauvery (PCSZ) and Achankovil (ASZ) shear zones (Drury and Holt, 1984) (Fig 1).

WGF is located immediately south of the MSZ. The area comprises mainly migmatitised hornblende gneiss, amphibolite, biotite gneiss, garnet–biotite–sillimanite gneiss, pyroxene granulite, magnetite quartzite and talc-tremolite- actinolite schist (Binu Lal et al., 2003; Pruseth et al., 2011). This sequence is intruded by pegmatites and quartz veins. The veins generally strike along NE-SW direction and cut the regional trend of foliation. The dominant sulfide minerals associated with auriferous quartz veinsare pyrite, pyrrhotite, arsenopyrite and chalcopyrite.

Attappadi is located in the western termination of BSZ. Gneisses are the predominant rocks in Attappadi. All rock types of Attappadi other than supracrustals could be categorized into seven broad types. They are charnockite, hornblende gneiss, migmaititic amphibolite, quartz biotite gneiss, quartz-feldspathic gneiss, biotite granite gneiss, and pegmatite. Metavolcanics and metasedimentary rocks designated as the "Attappadi supracrustals" are found as enclaves and remnants within the gneisses.the auriferous quartz veins are confined to a 25 km long and 10km wide, NE trending regional shear zone within the gneiss and amphibolite. The associated sulide minerals are pyrite, chalcopyrite, galena, covellite and malachite.

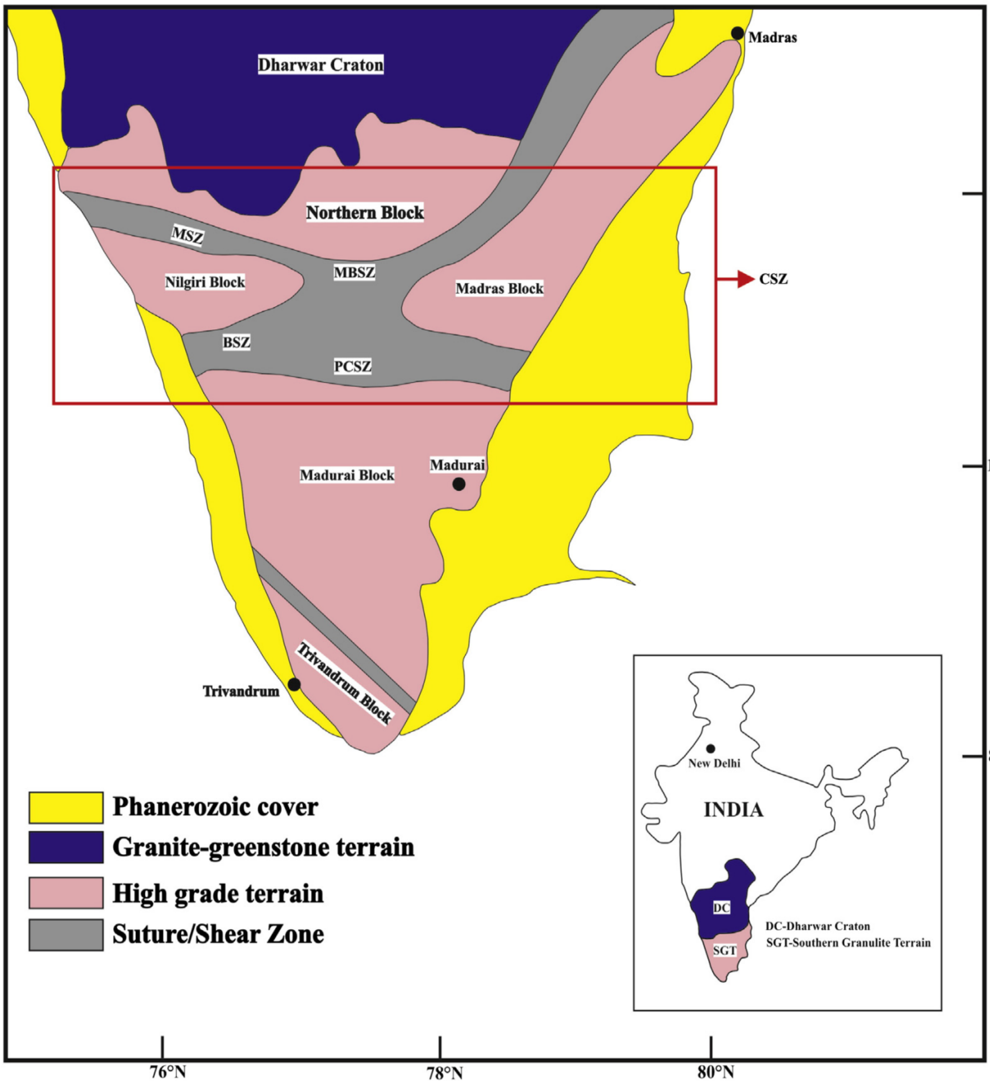

Fig 1: Generalized geological map ofSouthernGranulite Terrain(modified after Santosh etal.,2012). BSZ—Bhavani Shear Zone, CSZ—Cauvery Suture Zone, MSZ—Moyar Shear Zone, PCSZ—Palghat Cauvery Shear Zone. b. Map of the Cauvery Suture Zone (CSZ. Map showing gold occurrences in the Southern Granulite Terrain: 1. Manantody; 2.Tariyod; 3.Chundale; 4.Vayittri; 5.Meppadi; 6.Maruda; 7.Nadugani ; 8. Rousdenmalai ; 9. Glenrock ; 10. Kotagiri; 11. Kadannamanna and Mankada ; 12. Valambur ; 13.Kappil; 14. Attappadi. The boxes represent three gold provinces: 1 to 10 are in Wynad- Nilgiri province, 11 to 13 are in Malappuram province and 14 is in Attappadi province. (Krishnamurthi et al., 2010)

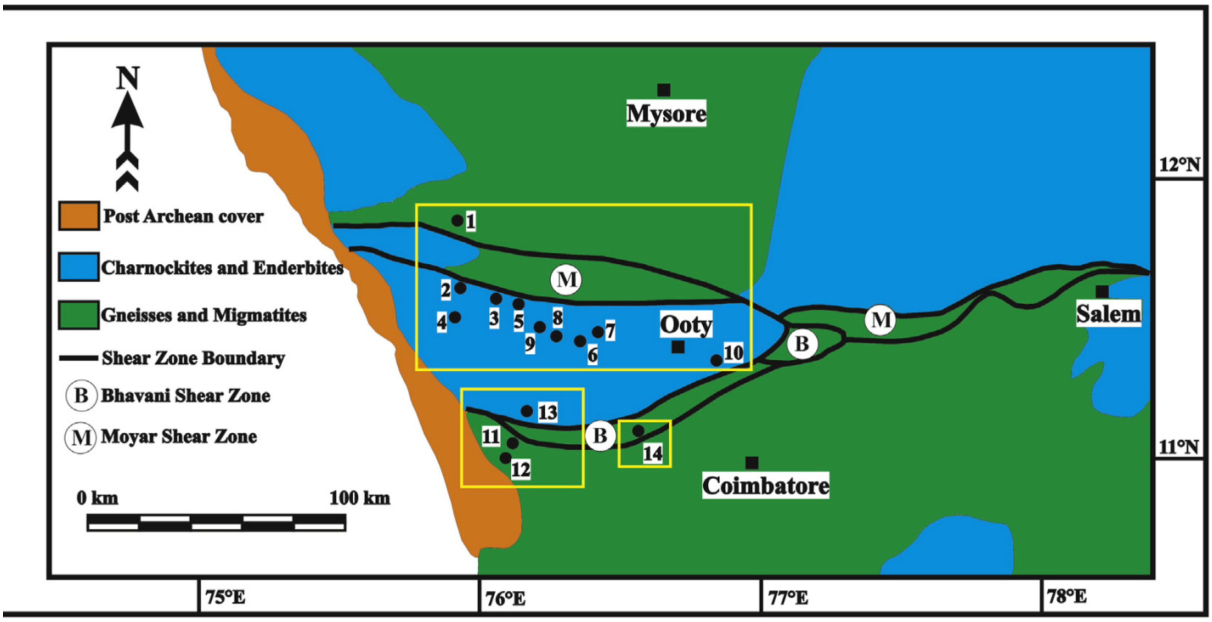

Fig.1 (continued).

3. Fluid inclusions

Samples for fluid inclusion study were collected from the two deposits. Samples showing evidences of deformation and recrystallization were avoided. Only primary inclusions (5–15 μm) were studied to understand the nature of mineralizing fluid. Microthermometric measurements on the fluid inclusions were carried out using a Linkam THMSG 600 Heating-Freezing stage fitted on a LV 100 Pol Nikon microscope at the Department of Earth Sciences, IIT Roorkee. The unit operates in the temperature range of -196°C to + 600°C. The stage was periodically calibrated by synthetic pure CO_2inclusions (triple point = -56.6°C) in quartz.

3.1 Fluid inclusion petrography and microthermometry

3.1.1 Wynad Gold Field. Three different compositional types of fluid inclusions are distinguished: H2O-CO2 (Type I), CO2 (Type II), and aqueous (Type III) inclusions based on the combination of petrography at room temperature and phase transition observed during microthermometric investigations.

Type I inclusions are composed of H_2O and CO_2 phases. At room temperature, the Type I inclusions consist of two phases i.e., water and liquid CO_2, but during freezing a new phase appears with in the liquid CO_2 and becomes an assemblages of three phases i.e., H_2O, CO_2 and gaseous CO_2. Inclusions of this type exhibit rounded tubular or irregular shapes and are 5-15μm in size. These are the most abundant variety of primary inclusions observed in the doubly polished wafers.

Type II inclusions appear as monophase at room temperature but gas bubble appears during freezing. Fluid inclusions with in this group are generally between 2-10μm in size and show rounded, elongated or irregular morphologies. This type of inclusions is as abundant as Type I inclusions.

Type III inclusions are biphase with a gas bubble in aqueous phase. These inclusions are varying in size from 4-12μm and show oblate or spheroidal morphologies.

Melting temperature of CO_2 (Tm CO_2) for Type-II and Type-I inclusions occurred between -55.5°C and -60°C which indicate the presence of other gases like CH_4 and N_2. The homogenization of the carbonic phase ($ThCO_2$) occurs always to the liquid state in a wide range of temperature, from -4°C and 28°C indicates bulk densities between 0.64 g/cm^3 to 0.95 g/cm^3. The first melting of ice

(Tfm ice) in Type-I and Type-III inclusions occurred between −18 °C to −27 °C. Final melting of ice (Tm ice) in Type-III inclusions fall in a temperature range of −1 °C to −5 °C. Based on these freezing data, the salinity values of fluids present in Type-III inclusions have been found to be of the order of 2 to 8 wt.% NaCl equivalent (Fig 3). For type I inclusions, clathrate dissociation temperatures (Tmcl) were recorded between 2°C to 8°C and salinity deduced from such clathrate melting is within 4 to 14 wt% NaCl equivalents (Fig 3). The total homogenization temperature (Th TOT) of Type-I inclusions range from 200° C to 300° C whereas Type-III inclusions show a range of 180°C to 290°C. Type-III inclusions homogenize in liquid state, whereas Type-I inclusions homogenize in both liquid- and vapour- state.

The intersecting isochores method was used to estimate the P–T condition of fluid entrapment, as the co-existence of Type-I and Type-II inclusions is common in the samples and estimated temperature and pressure condition ranges from 240 to 330 °C and 1.4 to 2.4 kbar respectively.

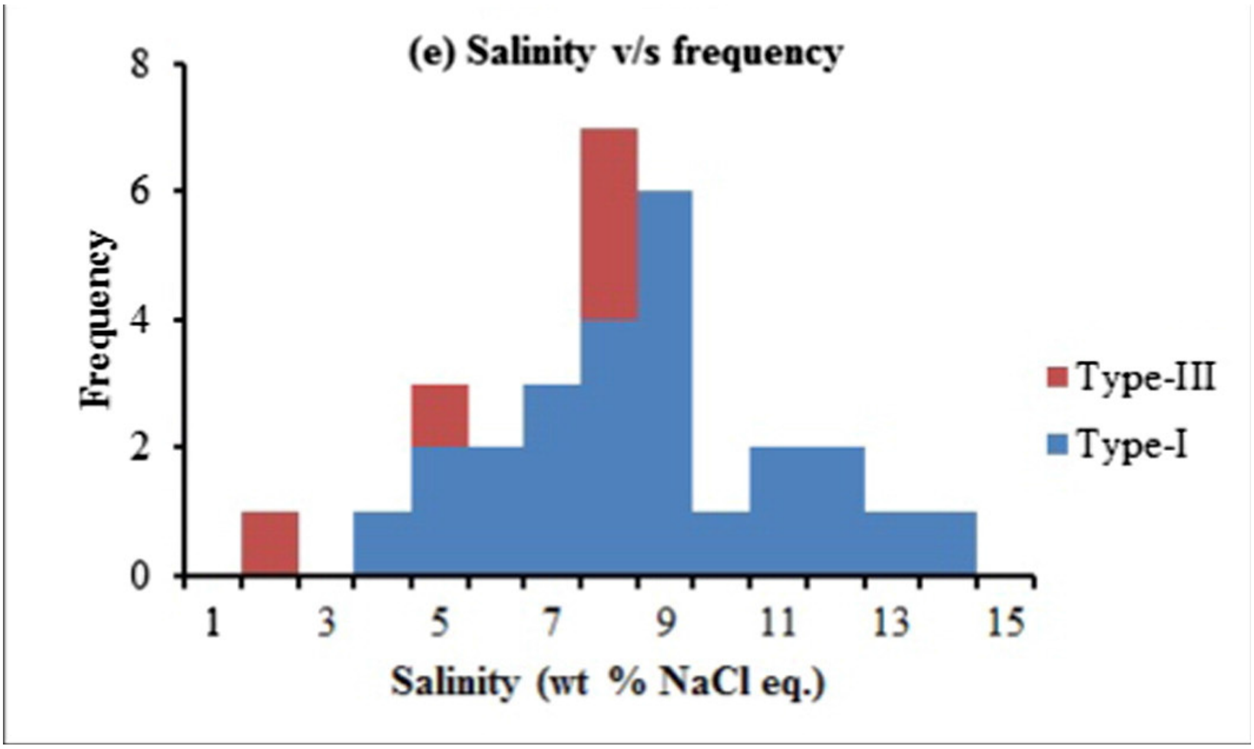

Fig 3: Histograms of primary inclusions obtained during freezing- Salinity v/s frequency (Type I and Type III inclusions)

3.1.2 Attappadi Province. Four different types of fluid inclusions are distinguished: aqueous-carbonic (Type 1), carbonic (Type 2), aqueous inclusions with daughter minerals (Type 3) and aqueous inclusion (Type 4) (Krishnamurthi et al., 2010).

Type 1inclusions is isolated in nature and size ranges from 10-15μm. All of them are bi-phase in nature and considered as primary with respect to quartz vein.

The type-2 inclusions are similar to type-1 inclusions in terms of distribution. They range in size from 5-15 μm. They are occurring within the quartz veins and quartz biotite gneiss.

Type 3 inclusions are multiphase inclusions observed in the quartz veins and are restricted to Kottathara area of Attappadi and size ranges from 10 to 30μm. These are three phase inclusions consisting of liquid, vapor phase and daughter mineral.

Type 4 inclusions are aqueous biphase inclusions, present in quartz veins, size varying from 5 to20μm. They are occurring in trails /clusters and appeared to be a later fluid.

It was observed that type-1 and type-2 inclusions do not co-exist in auriferous quartz samples and so the intersecting isochore method was not followed to estimate the P–T condition of entrapment of fluid inclusions. Due to lack of geo-thermobarometric data, the maximum temperature of homogenization (~300 °C) has been considered as the minimum temperature of entrapmentof fluid inclusionsand mineralization.

4. Summary

Gold mineralization at WGF and Attappadi of SGT is associated with a subparallel quartz vein system. The fluid inclusion study indicates the fluid was subjected to immiscibility (or phase separation) within temperature and pressure range of 240 to 330°C and 1.4 to 2.4 kbar. Gold along with other constituents could have precipitated in response to phase separation of the ore fluid. The phase separation of original homogeneous gold bearing ore fluid could be due to drop of pressure and temperature as it entered the fractures developed during the late phase of Neoproterozoic (Pan-African) deformation event.

In Attappadi area, the fluid inclusions can be classified into four different types, aqueous-carbonic (type 1), carbonic (type 2), aqueous inclusions with daughter minerals (type 3) and aqueous inclusion (type 4). The type-1, type-2 and type-3 inclusions are primary with respect to formation of quartz in auriferous veins. However, the type-3 inclusions are considered to have no direct linkage with gold mineralization in the Attapadi prospect as they are restricted to the samples of only one area. As the auriferous veins in this area are proximal to pegmatite bodies, the type-3 inclusions could be related to the fluids released from the pegmatites. In Attappadi, the maximum temperature of homogenization (~300 °C) has been considered as the minimum temperature of entrapment of fluid inclusions and mineralization. The fluid involved in gold mineralization is of low saline and aqueous-carbonic in composition and quite similar to the orogenic lode gold deposits reported world-wide.

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Tectonic and metamorphic evolution of Nagercoil block through in-situ trace element studies on accessory minerals

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Abstract

The proposed study is mainly focused on Nagercoil Block, one among the discreet terrains (blocks) in Southern Granulite Terrain (SGT). Unlike the other blocks in SGT, the Nagercoil Block at the southernmost tip of the Indian peninsula has received comparatively little attention and its role and significance in the evolution of the region are uncertain. The area predominantly consists of massive charnockite-pyroxene association, together with igneous intrusives of norite and syenite. The main goal of the study will be to constrain tectonometamorphic evolution of the Nagercoil Block through analysing accessory minerals such as Garnet, Zircon, Monazite, Apatite, Ilmenite etc. The results expected to be derived from systematic field and laboratory work will include

- 1) structural and petrological observation of different rock types.
- 2) P-T conditions of peak and retrograde metamorphism is derived via forward modelling of phase equilibria.
- 3) Quantitative constraints on the timing and duration of crustal metamorphism (t) will be derived by in-situ U-Pb dating of accessory minerals using LA-ICP-MS coupled with trace element analysis of these accessory phases.
- 4) These data will be used to constrain pressure-temperature-time (P-T-t) evolution of the Nagercoil Block and place the findings within the context of the geological evolution of southern India.

Miarolitic cavities in Granitic Pegmatites of Nagamalai –Pudukottai area, Madurai district, Tamil Nadu, India

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Abstract

The A-type granites of the Nagamalai- Pudukottai area lie within the Madurai block of Southern Granulite Terrain. Pegmatites in this area are closely associated with granites and are of two types-gray feldspar bearing and pink feldspar bearing. Field investigation reveals the presence of mineralised cavities in these pegmatites. This paper is based on a preliminary investigation of the miarolitic cavities and associated mineralization in these granitic pegmatites. Although the two varieties of pegmatites of the area contain mineralised pockets, the cavities in the gray feldspar bearing pegmatites are larger, and richer in mineral diversity. The important minerals present in these cavities include quartz, feldspar, calcite, beryl (?), and sulphides. The miaroles in the granitic pegmatites can be interpreted as resulting from separation of fluid bubbles through melt crystallisation enriched in volatile components within the pegmatite bodies. From the presence of miarolitic cavities and related mineralization, it is inferred that the granitic pegmatites of the study area, as per depth classification, comes under the miarolitic NYF type pegmatites.

Introduction

The study area is a part of the Madurai Block of Southern Granulite Terrain. The Madurai Block is located between the Palghat Cauvery shear zone in the North and Achankovil shear zone in the South (Fig.1). The Madurai block is typically a high-grade Charnockite-Khondalite terrain comprising of granulite facies rocks (Mohan, 1996). Several granite bodies of Late Proterozoic to Early Palaeozoic age have been reported from Madurai block (Subramanian et al., 2001).

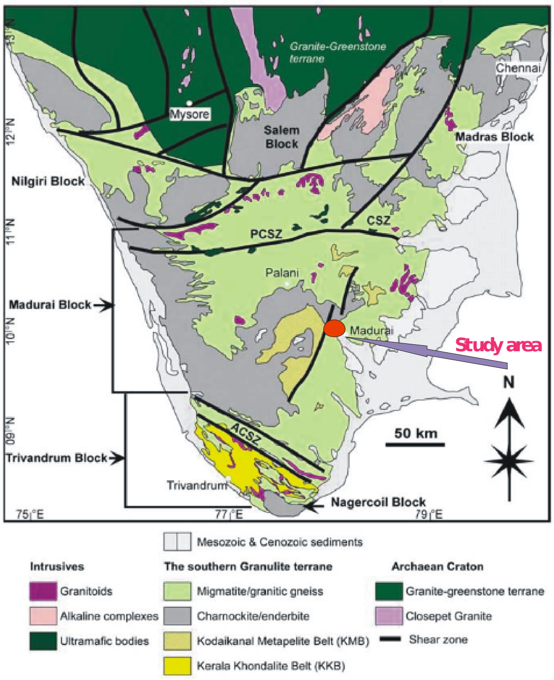

Fig.1. Simplified geological map of South India (After Sajeev, et al..2006)

The major rock types identified in the study area are gneisses, quartzites, charnockites, granites, pegmatites and dolerite. Quartzites form continuous hills whereas the gneisses and charnockites mainly cover the plains.

The granites in the study area occur as small isolated hillocks. Based on colour they can be grouped into two: gray granites and pink granites. These granites lie close to the NW-SE Vaigai lineament/fault zone. The granites are essentially made up of alkali feldspar, quartz and biotite. Accessory amounts of zircon, apatite and opaques are also noticed. Migmatized zones are seen associated with the granites at places. The geochemical data of these granites point to their A-type nature (Remya,2011) and Rb-Sr geochronological dating have given them an age of 837±34Ma (Pandey et al., 1994).

The term 'Pegmatite's is given to any exceptionally coarse grained phase of rock and when these bodies have an association with granite, they are of greatest interest by means of their various geological aspects. One such important feature is the presence of miarolitic cavities. These are cavities of irregular shapes, bordered with idiomorphic crystals of quartz and feldspar which project into vacant spaces and occur in some granites and granophyres. The spaces represent places where pockets of residual magma highly charged with volatile fluxes remained after the bulk of the rock had crystallized. From these mobile liquors, good crystals grew out from the walls and by the escape of the final remnant of liquid or vapour, the interstitial cavities which they originally occupied, were left (Holmes,1930).According to Sinkankas (1969), the term miarolitic pegmatites are used to describe the pegmatitic granitic rocks more or less honey combed by gas openings. Berry et al. (2004) feel that miarolites are cavities formed by the late stage crystallisation of magma. Recently Kurosawa et al., (2010) opine that miarolitic cavities are typically associated with granitic pegmatites and are formed due to the entrapment of mineral-rich fluids which have segregated by vesiculation of granitic magma during its final stage of crystallization. Miarolitic cavities typically contain granitic as well as rare minerals resulting from the concentration of trace-elements by hydrothermal activity (Johnsan, 2014).

A few granitic pegmatites in the area belong to the miarolitic type pegmatites and the cavities in these rocks are diverse in their mineral assemblages. In this study, an attempt is made to understand the nature of these miarolitic cavities and their origin.

Miarolitic Pegmatites of the study area

The pegmatites in the study area are closely associated with the granites. These pegmatites contain mainly feldspar, quartz and biotite. Based on the colour and abundance of feldspars, the granitic pegmatites of the study area can be divided into two- gray feldspar bearing and pink feldspar bearing pegmatites. Miarolitic cavities are found in both the pegmatites [Fig. 2(A) and (B)].

The cavities in the gray feldspar pegmatites are comparatively larger. They range in size from 15cm ×5 cm. The void area is large enough to carry a 3-5cm sized crystal. Most of the cavities in these pegmatites are partly filled. The minerals present in the miarolitic cavities are mostly coarse and euhedral. Quartz, feldspar, calcite, beryl (?) and associated sulphides are the most important minerals present in these cavities. Quartz in the cavities is of different types- euhedral quartz with typical prisms, milky quartz, and smoky quartz and amethyst crystals. Quartz crystals show well developed rhombohedral faces and prisms. Twinned amethyst crystals as per Japan law with twin plane ($11\bar{2}2$) is noted. Rarely anhedral quartz is also present. Many quartz crystals show horizontal striations. Feldspar in the cavities appear to be colourless to gray and mostly anhedral. Calcite crystals present are euhedral and prismatic; rhombohedral forms are rare. Growth layers are seen on the surface of the calcite crystals. The sulphides include pyrite, chalcopyrite, bornite and pyrrhotite (Manu Raj and Kumar, 2015). Typical euhedral pyrites and chalcopyrites are seen on quartz and calcite crystals [Fig. 3 (A) and (B)].

The miarolitic cavities in pink feldspar pegmatites are smaller in size and lesser in number. The cavities are almost completely filled with quartz, feldspar, calcite and sulphides. The minerals present within these cavities are subhedral to anhedral and medium to fine grained. Sulphide crystals are rare and when found, are very small.

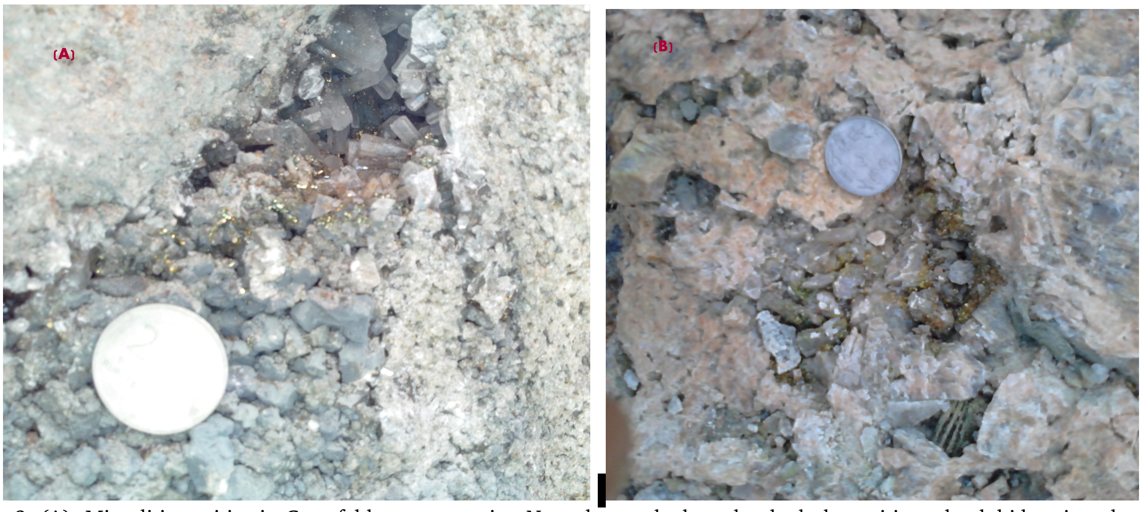

Fig. 2. (A). Miarolitic cavities in Gray feldspar pegmatite. Note the comb shaped euhedral granitic and sulphide minerals. (B). Small miarolitic cavities in Pink feldspar Pegmatites. Note the subhedral to anhedral mineral grains.

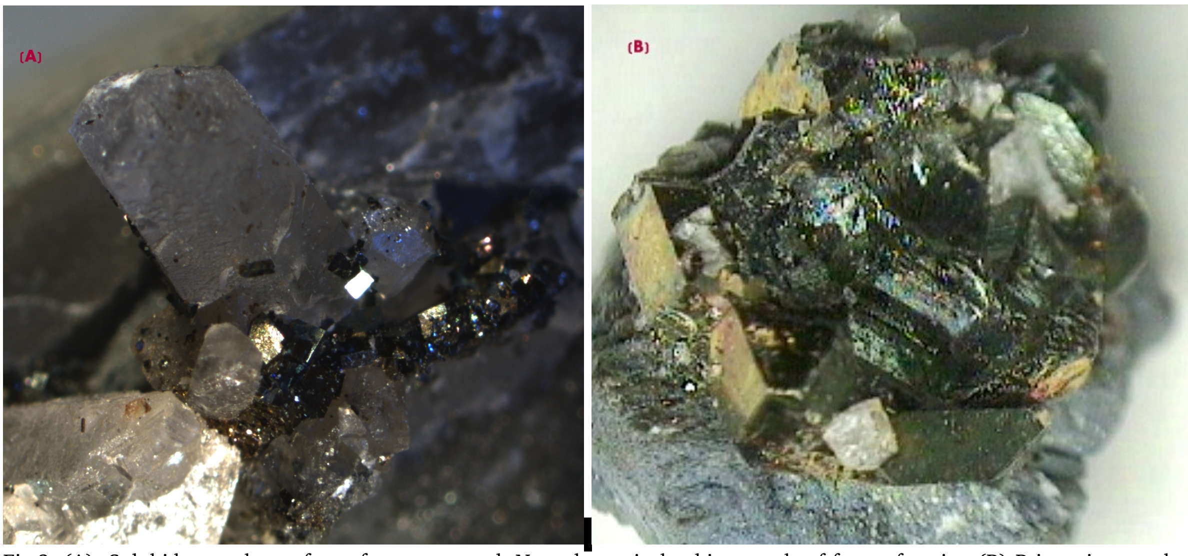

Fig.3. (A). Sulphides on the surface of quartz crystal. Note the typical cubic crystals of form of pyrite. (B) Prismatic crystals of sulphides separated from miarolitic cavities.

Discussion and Conclusion

In pegmatites, primary cavities may result from trapping bubbles of an exsolved gas phase inside the parent magma. The term 'miarolitic is used as an additional characteristic of granitic pegmatites, when they contain mineralised cavities. The conditions under which miarolitic cavities form in granitic pegmatites have not been fully understood. According to Jahns and Burnham (1969), the miaroles can be formed during the accumulation of fluid phases in pegmatite chambers during the crystallization of melts enriched in volatile components. This concept is widely accepted among petrologists. Miaroles have been inferred to form from vapours released from granitic magma (Candela, 1997). Vapour (superficial fluid) bubbles form as locally water saturated magma rises and crystallizes in response to decompression, which causes vapours to escape. This decreases the concentration of water in the melt, which raises its liquidus temperature and effectively undercools the melt. The result is a fine grained granite with granophyric intergrowths. At the same time crystals grow in the cavities by precipitating from the vapour phase (Vernon, 2004).Recent studies point to the presence of immiscible silicate melts and large fluid segregations of various compositions in granitic magmas that lead to the formation of miaroles in granitic pegmatites (Peretyazhko, 2009). The miarolitic pegmatites of the study area indicate the presence of abundant volatiles in the parent magma and associated fluids with varying compositions.

One of the most widely accepted classification scheme for pegmatites is by Cerny (1991) and it is more or less related to the depth of formation. In this classification, the different pegmatite classes are grouped into five based on their order of increasing depth and they are miarolitic, rare-element, muscovite, rare-element muscovite and abyssal. The miarolitic pegmatite class is subdivided into families, in which one family is called the NYF family -NYF stands for Niobium, Yttrium and Fluorine (Cerny, 1991; Simmons et al. 2003, Rakovan, 2008). These NYF type pegmatites are of poorly mineralised and gemstock. Typical elements associated with these pegmatites are Be, Y, REE, Ti, U, Th, U, Zr, F, Nb>Ta. Pandey et al. (1994) have reported rare earth and rare metal mineralization represented by similar pegmatites in the nearby areas. Rakovan, (2008), feel that the NYF type pegmatites of miarolitic class form under shallow to subvolcanic P-T conditions. The NYF type pegmatites represent anorogenic tectonic settings (Wise, 1999). The granites of the area belong to the A-type category (Pandey et al., 1994) and the major minerals in the pegmatites associated with granites are similar indicating anorogenic settings. Thus the miarolitic pegmatites of the study area may be classified under the NYF family. The detailed field and petrological studies of the granitic pegmatites of the Nagamalai-Pudukkottai area have shown the presence of miarolitic cavities. The miaroles indicates the abundance of fluid phases during the last stage crystallization of the volatile rich pegmatites. The divergent mineral assemblage in the miaroles points to the compositionally different fluid segregations. The occurrences of sulphides in the cavities convey the hydrothermal activity in the mineralized cavities. Based on the occurrence and mineralogical characteristics, the Nagamalai-Pudukottai granitic pegmatites may be fitted into the NYF type of miarolitic pegmatites.

Further detailed chemical analysis of the pegmatites and associated minerals will provide more insights into the origin of miarolitic cavities and nature of mineralization.

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The structural anatomy of Cuddapah basin --- a Proterozoic fold-thrust belt from Peninsular India

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Identification of Precambrian fold-and-thrust belt is challenging due to deep incised erosion of the belts. The Proterozoic Cuddapah Basin of Peninsular India, which hosts the Cuddapah Supergroup and the Kurnool Group of rocks, represents the frontal part of a larger fold–thrust belt, formed in response to the Neoproterozoic orogenesis in East Antarctica and India that led to the amalgamation of northern Prince Charles Mountains-Rayner complex of Antarctica with the Krishna Province of India along the present eastern coast of India with the development of ~990-900 Ma old fold - thrust belt. Therefore, the intercratonic deformation now preserved in the Palaeoproterozoic-Neoproterozoic Cuddapah Basin is related to the collision of the Indian shield to the Antarctic block during the amalgamation of the Rodinia Supercontinent. The Cuddapah fold–thrust belt (CFTB), bounded by the Nellore–Khammam schist belt and Eastern Ghats terrane in the east and Peninsular Gneissic complex of the Dharwar Craton to the west, includes two frontal thrusts and foreland of an orogen. The frontal Nallamalai thrust structurally separates the Cuddapah basin into two blocks – the eastern Nallamalai fold belt and the western foreland. The CFTB, forming the front-most segment of a larger orogen associated with the intercratonic deformation related to the formation of the Rodinia Supercontinent, is the result of fault-propagation folding, forming an overturned anticline–syncline pair at the tip of the propagating Velikonda thrust which later cuts through the common limb of the fold pair. The CFTB includes two frontal thrust sheets carried by the eastern Velikonda and the western Nallamalai thrusts, along with a part of the undeformed foreland. It constitutes part of a larger fold-thrust belt now fragmented and separated in different continents of Gondwanaland. CFTB is dominated by quasi-plastic deformational structures, representing exhumed deeper level fault-propagation folding related to the Velikonda thrust, while the Nallamalai thrust represents the foreland word thrust of the CFTB dominated by elastico-frictional deformation structures.

Museums - Vistas of Knowledge

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The word museum owes its origins to the Greek 'mouseion" meaning 'seat of muses', and was used to denote a philosophical institution or a place of contemplation. It was used for the first time by Ptolemy for the great museum created by him in the third century at Alexander. It was only in the 17th century that the term extended all around Europe to describe collections of inquisitiveness.

One can associate the primary idea of museum to human desire for knowledge. People have always been interested in understanding the nature, environment and the people those with whom they are associated. One of the most motivating methods to achieve this is to study the objects everyone creates. Traditionally, the beginning of acquiring and displaying objects of inquisitiveness and scholarly importance can be traced to the Renaissance in Europe in the fourteenth Century. Since it was the period when the whole world was becoming more accessible with the opening of new routes from Europe to other parts of world. The idea of acquiring objects from these regions came up. People now started purchasing and getting objects for demonstration at home and in their parks, thus laying the foundation for private collections, which eventually led the creation of museums. These collections also ascertained to be an appealing and satisfying means of learning about the world. The desire to spread knowledge to the public through private collections took shape in 1523 when the Grimani brothers donated their collections to the City of Venice.

When one visits a museum and looks at substances exhibited within the glass showcases, some observing you with a desolate expression, you might have wondered how they came there and who is responsible for picking these samples of such beautiful objects and choosing how to display them? No one might have imagined that a small text was adequate to describe them? Who thought first about the wooden cabinets of display and then glass showcases. When the idea of a museum took shape in India.

In India the European idea of the museum peculated in 18th century. In 1784 Sir William Jones, a British historian formed the Asiatic Society at Kolkata then (Calcutta) in order to study and disseminate the India's socio-cultural and historical heritage. It was the turning point were from the idea gave birth to have a permanent space dedicated for exhibiting objects. It was after that the Asiatic Society members in 1796 accepted the suggestion to start a Museum. In this way India's first museum was set by Asiatic Society in 1814 at Kolkata (Calcutta) which was named as 'Imperial Museum', later on renamed as Indian Museum which is still one of the largest museums in India.

A museum is an institution that cares for collection of artifacts and other objects of scientific importance or other objects of artistic, cultural and historical importance and makes them available for public viewing through exhibits that may be permanent or temporary. Museums have varying aims, ranging from serving researchers and specialists to serving the general public. It is one way of scientific outreach programme. The goal of serving researchers is increasingly shifting to serving the general public to make them aware about the nature, environment and about the universe and other things. Science museums are institutions of authoritative incontestable knowledge, places of collecting, seeing and knowing, places where anyone can come and see the evidences of science.

The museum also serves the repository of mineral, rocks, fossils. It promotes India's mineral, fossil heritage and equally promotes its importance. It aims to inspire scientific curiosity through education and research while encouraging appreciation of the earth and responsibility for its mineral, fossil, mining and other treasures. The many exhibitions of the Geological museum relate to the importance of Geology in all details, large and small. From the beginning of universe to fossilisation, drifting of continents and mountain building and the origin of life etc.It is a learning centre that provides a valuable resource for the students of schools and colleges research workers enthusiastic with an interest in or desire to learn about geological processes. The museum of geology supports teaching and research in the earth sciences and natural history. The fossil collections are important both scientifically and historically to understanding the origin and evolution of life. Similarly the collection of different rock types minerals among them are some are rare and of economic importance which fascinates the students and public.

Museum planning involves planning design the actual mission along with the planning is the space that the collection of the material of the museum will be housed in. Museums need to be planned according to the need of the students, researchers and public since it is a knowledge hub. The museums are planned and designed according to the collection they house, with the displays and exhibits easily accessible to the public. Museums are being made more accessible to the public by resorting to open storage which elicits more public interest. Modern museums now include contents in the form of images, audio and visual effects and interactive exhibits. Virtual Museums have gained importance in the current online era, wherein photo-galleries of minerals, fossils, rock types and other scientific achievements can be viewed by the people living far away using their internet capable devices. Museum planning process must include feasibility study, analysis of comparable facilities, resources and interpretive plan.

A chemico-mineralogical study of granites of Perinthalmanna area, Malappuram District, Kerala, India

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Abstract.
The Kerala region, forming part of the South Indian Precambrian terrain, preserve major units of the Archean continental crust, such as granulites, granites, gneisses, and greenstones. The study area, forming part of the Southern Granulite Terrain (SGT) is pierced by a number of plutons. Acid plutons are the dominant among them. Detailed studies of a few granite bodies like that of Chengannoor, Munnar, Ambalavayal and Kalpatta areas have been carried out. In the present study a comprehensive account of field relations, petrography and geochemistry of Perintalmanna granite, a small granite bodylocated in Malappuram district, is attempted. Granite in the study area has concordant relationship with the country rocks indicating its igneous parentage and some structural control in its origin. It is devoid of deformational structures or textures. Mainly two types of granites are found viz. pink and gray, the former being the dominant one. The texture, structure and field relations of the two granite variants show their post-kinematic nature. The mineralogical characteristics support A-type and peraluminous nature, alkalic-subalkalic character and within-plate origin. The study indicates that the two variants of Perintalmanna granite had probably formed by the partial melting of granulites in the lower crust by mantle derived volatiles.

Keywords: Southern Granulite Terrain, Achankovil Shear Zone, granite variants, A-type granite.

Introduction

The Kerala region is an important segment of the South Indian Precambrian terrain, where major units of the Archean continental crust, such as granulites, granites, gneisses, and greenstones are preserved (Fig.1). The Precambrian granulite terrain of this region is pierced by a number of plutons. Granite plutons are dominant among them. Post-collisional alkaline magmatism with Pan-African affinities has been reported in a number of locations in the Southern Indian Granulite Terrain (SGT) (Santosh and Drury, 1988; Rajesh et al. 1996).Several alkali granite and syenite plutons intrude the South Indian shield that preserves evidence of prominent felsic magmatic events (Santosh and Drury, 1988). Most of these plutons are spatially associated with major Late Proterozoic lineaments (Ratnakar and Leelanandam, 1989; Santosh et al. 2005; Ratnakar, 2006). These intrusives are considered to represent anorogenic A-type magmas generated in rift related environments of high heat flow and abundant volatile activity.

Detailed studies of a few granite bodies in Kerala, like that of Chengannoor, Munnar, Ambalavayal and Kalpatta areas, have been carried out in the late 1980's and 1990's (Santosh and Nair, 1983; Nair et al., 1983; Santosh et al., 1986; Satish Kumar and Santosh, 1994; Kumar et al., 1998). These plutons are generally considered to be anorogenic or post orogenic (Rajesh, 2000). The present study aims to give a comprehensive account of field relations, petrography and geochemistry of Perintalmanna granite, a small granite body located in Malappuram district.

Geology of the Area

An area of about 40 km^2bounded by 10˚59'40" and 11˚0'N latitudes and 76˚11'50" and 76˚15'57"E longitudes,was studied for deciphering the extension of Perintalmanna granite body(Fig.2). Biotite gneiss (BG) is the most widespread rock type in the study area, followed by hornblende biotite gneiss (HBG),charnockite, dolerite and hornblende biotite schist (HB Schist) in abundance. The pervasive gneissic banding in the rock, ranging in width from <1 cm to 25 cm, is defined by the alternate quartz-feldspar rich and ferromagnesian minerals-rich layer(Fig.3a).The general trend of the most prominent foliation is NW-SE with steep dip. Relict foliation is also observed on weathered surfaces. Augens of feldpars and enclaves of biotite are noticed at places. Pegmatite veins, bearing pink feldspar and quartz, parallel the foliation. Charnockite, which is seen as a massive and well- jointed rock, is cut across by pegmatite veins. Large abandoned quarries of charnockite are acting as water harvesting structures in many parts of the area(Fig.3b). Dolerite dykes are exposed as boulders trending NW-SE. The occurrence of HB schist is very much limited.

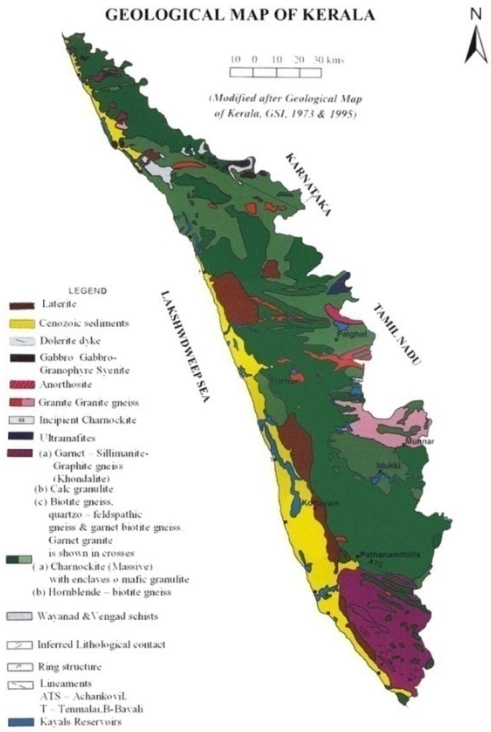

Fig.1. Geological map of Kerala (After GSI, 1973 & 1995)

Perintalmanna Granite

Granite of the area occurs as small hillocks. They area are of two types-pink granite and grey granite. Among the two, the pink variety predominates over the other. These massive rocks, showing grain size variation from fine to medium, have sharp concordant contact with BG, HBG and charnockite. These contacts are mostly parallel to the general NW-SE foliation trend in gneisses and gneissic charnockite. The granites exhibit crude gneissosity and foliation near the contacts. The granites, which are well jointed, are cut across by feldspar + quartz pegmatite veins, ranging in width from 15 cm to 50 cm, at many places. Enclaves of ferromagnesian minerals are noticed in granite(Fig.3c).

Petrography

Field relations and texture clearly establish the presence of two variants of the granite. However these two varieties exhibit many textural and mineralogical similarities. Both are light coloured, holocrystalline, hypidiomophic, nearly equigranular and free of deformation. However the content of potash feldspar and opaque are more in pink granite compared to that in grey granite. The biotite content of pink granite is less than in the grey granite. The magmatic nature of the granite variants is revealed by the subhedral to euhedral form of plagioclase and biotite and the anhedral to subhedral character of K-feldspar and quartz (Pitcher, 1993).

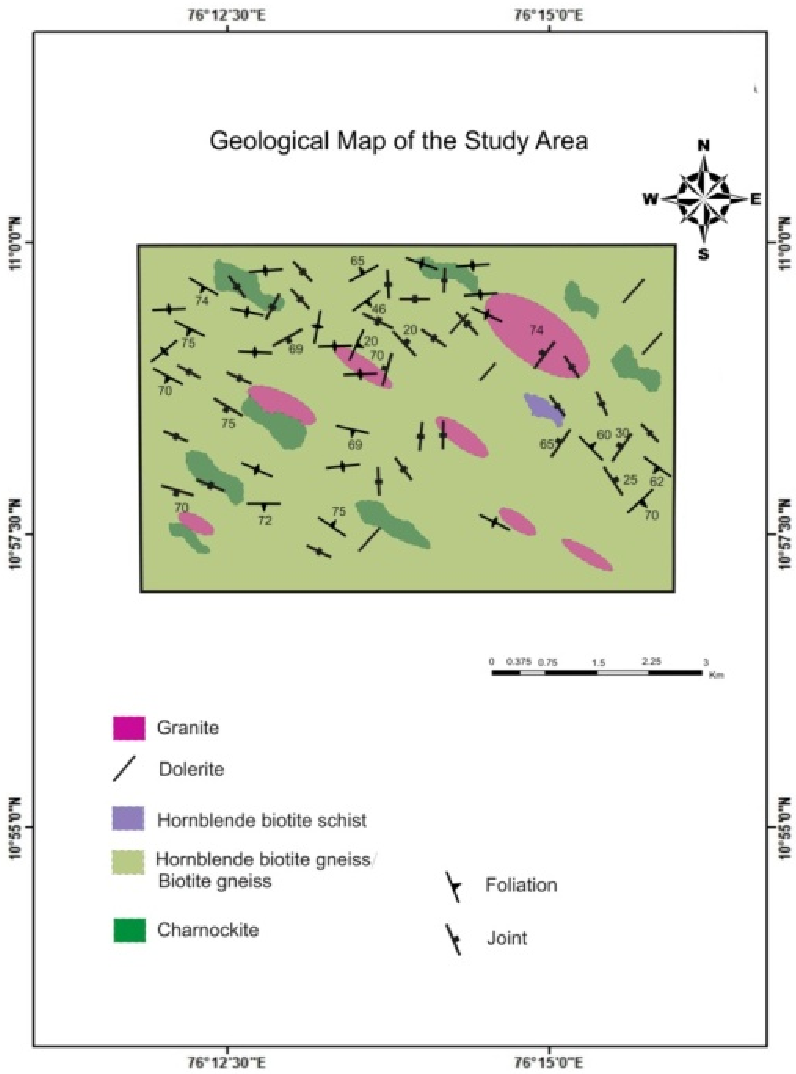

Fig.2. Geological map of the study area

Grey granite

The presence of abundant grey feldspar imparts grey colour to the rock. The rock is essentially made up of perthite, orthoclase, plagioclase, quartz and minor amounts of biotite and hornblende. Zircon and opaques are also found in very small amounts. The most abundant mineral present in the rock is perthite. Orthoclase grains, which are subhedral, show the effects of sericitisation. Myrmekitic intergrowth is noticed in some sections(Fig.3d).Quartz grains, which are anhedral, are seen both as independent grains and as inclusions in perthite (Fig.3e).Biotite is strongly pleochroic(light yellow to brown). Hornblende grains exhibit strong pleochroism. Zircon grains are nearly elliptical. Zircon inclusions with pleochroic haloes are noticed in perthite (Fig.3f). Opaques, mainly reddish brown rutile, are of various size and shape.

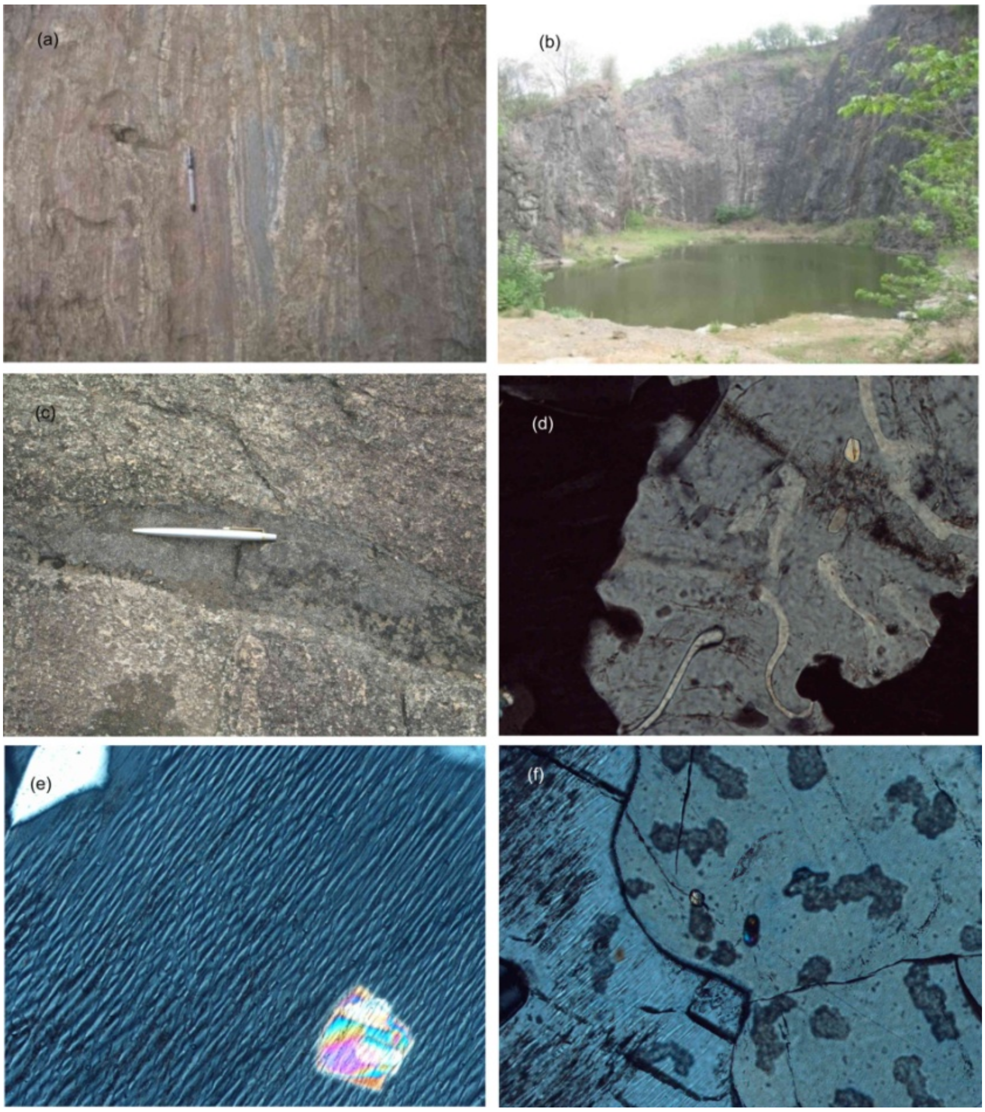

Fig 3. a. Well foliated and well banded hornblende biotite gneiss (plan view);b.Abandoned charnockite quarry used as water harvesting structure;c.Enclave of ferromagnesian minerals in weathered granite;d.Myrmekite in grey granite (crossed nicol, 10X);e.Inclusion of quartz in perthite in grey granite(crossed nicol, 10X);f.Zircon inclusion in perthite in grey granite (crossed nicol,10X).

Pink granite

These are leucocratic, fine grained rocks with well - developed joints. The essential minerals present in pink granite are similar to that in grey granite. The content of potash feldspar and opaque are more in pink granite compared to that in grey granite.

The magmatic nature of the granite variants is revealed by the subhedral to euhedral form of plagioclase and biotite and the anhedral to subhedral character of K-feldspar and quartz (Pitcher, 1993). The perthitic intergrowth is mostly controlled by cleavages and fractures. This may be due to feldspar -fluid interaction at subsolidus temperature (Parson, 1980; Yund and Ackermand, 1979) that leads to the replacement of albite at the margin of perthite. The development of myrmekite in both variants may be due to the subsolidus reaction that had taken place during the cooling stage of magma. The close association of zircon and apatite with biotite suggests early crystallization of biotite around apatite nuclei from a melt (Schermerhorn, 1956).

The texture and mineralogy of the granite variants of Perintalmanna area indicate a common source of magma. They may be considered as products of polyphase late magmatic crystallization.

Geochemistry

The major and trace element content of five representative samples of the granite, which were analysed by X-ray Fluorescence (XRF) in the laboratory of Centre for Earth Science Studies, Thiruvananthapuram,is provided in Table 1.

Table1: Chemical Analysis of Granite Samples

Sample No.	RE 24(grey)	RE 51(grey)	RE 22(pink)	RE 41(pink)	RE41(2)(pink)
SiO_2 (%)	71.027	74.232	70.17	74.382	72.239
TiO_2	0.369	0.102	0.324	0.125	0.227
Al_2O_3	13.516	13.688	14.135	13.76	13.838
MnO	0.02	0.024	0.026	0.009	0.014
Fe_2O_3	2.935	1.768	2.01	0.97	1.422
CaO	2.299	0.602	2.137	1.412	1.848
MgO	1.363	0.092	1.076	0.438	0.885
Na2O	2.585	3.311	3.013	2.795	2.778
K2O	4.751	5.352	5.143	5.451	5.201
P2O5	0.255	0.009	0.129	0.035	0.073
Total	99.12	99.18	98.163	99.377	98.525
Co(PPM)	5	3	3	1	2
Ni	14	6	8	9	11
Ga	11	16	13	18	15
Rb	99	94	99	105	124
Sr	974	309	476	0.11%	0.15%
Y	ND	4	ND	ND	ND
Zr	37	181	ND	ND	ND
Nb	ND	1	ND	ND	ND
Ba	0.27%	0.11%	935	0.28%	0.34%
La	26	64	11	ND	11
Ce	39	103	25	ND	3
Sm	3	7	3	1	2
Th	ND	4	ND	ND	ND

The granites are rich in SiO2, Al_2O_3, Na_2O and K_2O and poor in CaO, MgO, Fe_2O_3 and TiO_2. In K_2O-Na_2O-MgO diagram (Andreoli, 1984)(Fig.4a) all the granite plots are located in the igneous field. In K_2O-Na_2O-CaO diagram (Fig.4b), both the granites show calc-alkaline trend. In Na_2O-CaO-K_2O diagram, all granite plots fall in the granite field(Fig.4c).

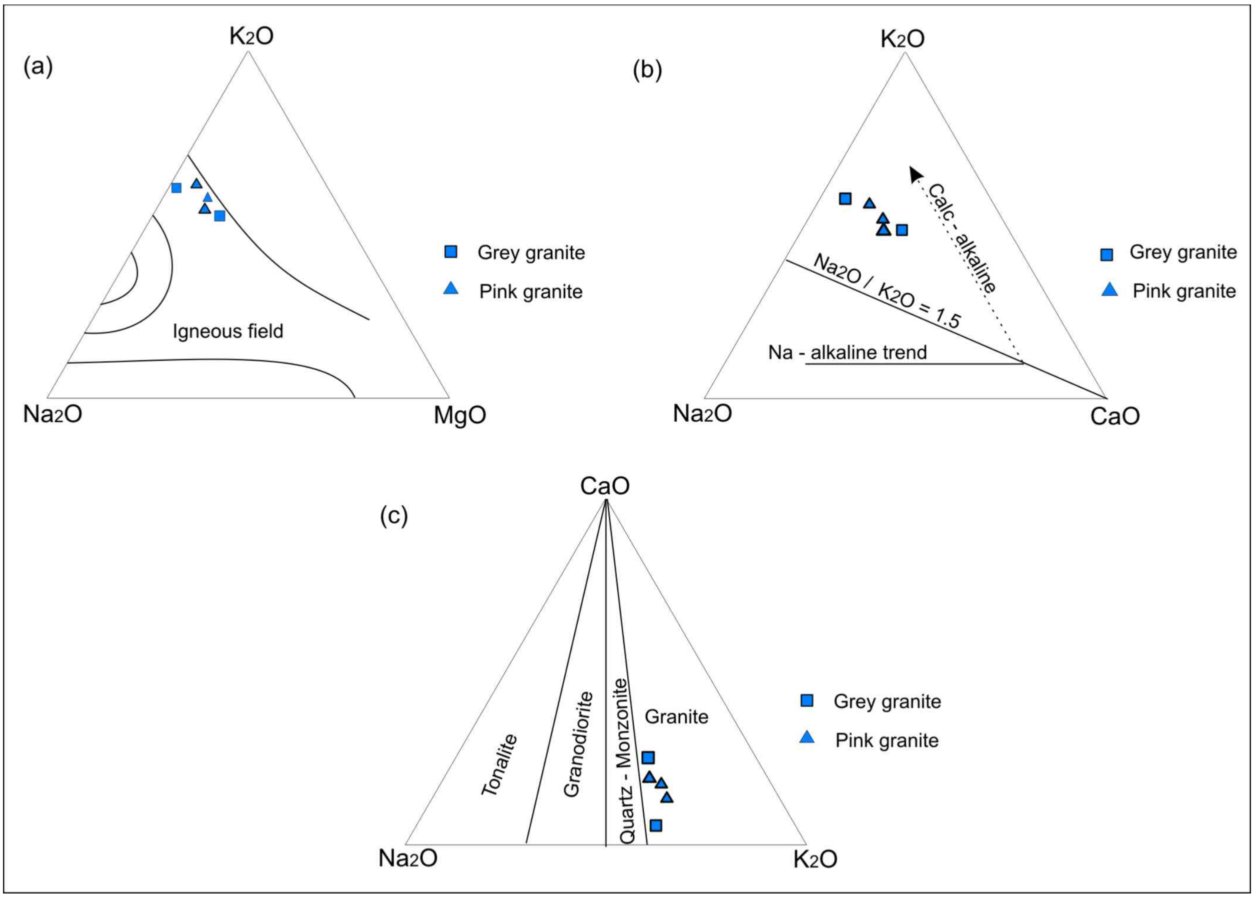

Fig.4 a. K_2O-Na_2O-MgO diagram (after Andreoli, 1984); **b.** K_2O-Na_2O-CaO diagram [Na2O/K2O=1.5 line (after Babock et.al;1979),Calc-alkaline trend (after Longstaffe et.al;1980),Na-alkaline trend (after Barker and Arth,1976)]; **c.** Na_2O-CaO-K_2O diagram

The CIPW norm for the granites is given in table 2. All the samples are quartz normative showing the high silica content. The normative corundum in all the samples point to their peraluminuous nature. The Differentiation Index (DI), after Thornton and Tuttle (1960), ranges from 81.7-92.4 for the granites. The high DI points to the salic nature of the rocks. The Larsen Index for the granite variants range between 23.51 and 28.64.

Table 2: CIPW Norm for Perintalmanna Granite

MINERAL	RE-24(GRAY)	RE-51(GRAY)	RE-22(PINK)	RE-41(PINK)	RE-41(2)(PINK)
QUARTZ	31.3	32.9	27.4	33.6	31.3
ORTHOCLASE	28.4	31.7	30.6	32.2	30.6
ALBITE	22	27.8	25.7	23.6	23.6
ANORTHITE	9.5	3.1	8.6	6.95	8.3
CORUNDUM	0.6	1.3	0.4	0.71	0.6
HYPERSTHENE	3.7	0.7	2.8	1.23	2.2
MAGNETITE	2.3	1.4	1.6	0.7	1.2
ILMENITE	0.8	0.2	0.6	0.3	0.5
APATITE	0.7	-	0.7	-	0.3

In An-Ab-Or normative diagram (Fig.5a) all the samples are confined to the granite field. In SiO_2vs total alkali variation diagram (Irvine and Baragar, 1971)(Fig.5b) the gray and pink granites are located both in the alkalic and subalkalic fields. The calc-alkaline nature of the Perintalmanna granite is evident in AFM diagram (Fig.5c).Here all the plots are located in the calc-alkaline field.

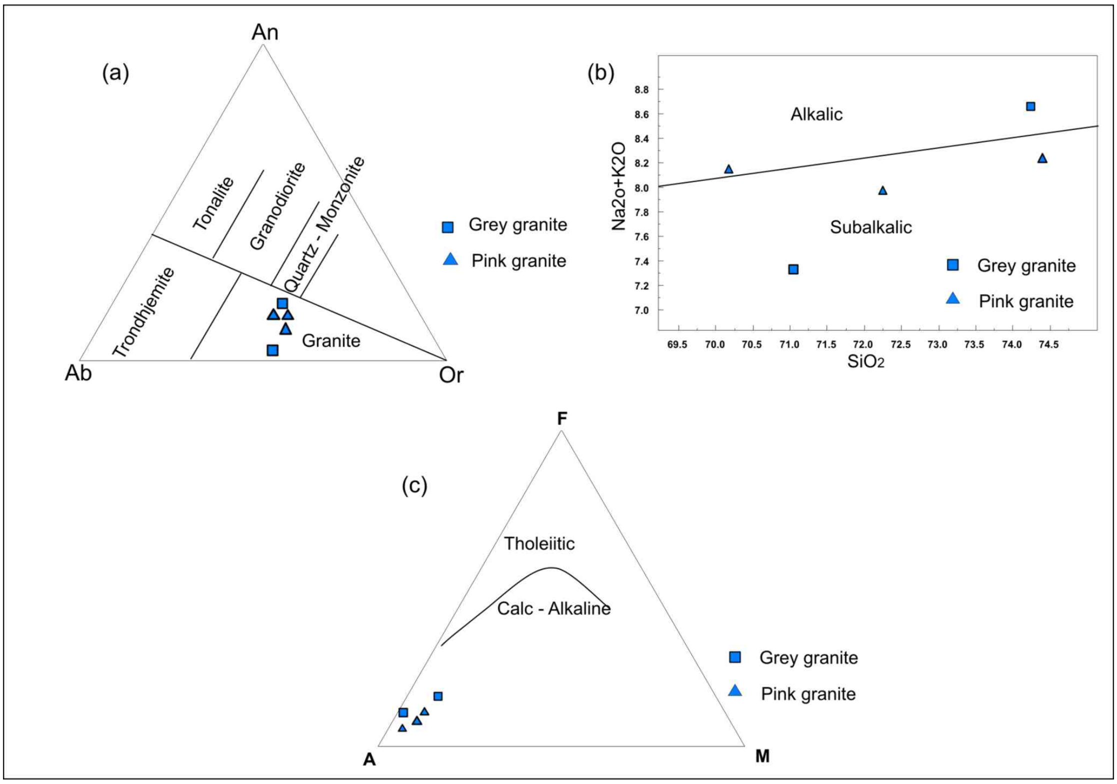

Fig.5 a. An-Ab-Or normative diagram; **b.**SiO_2vs total alkali variation diagram (Irvine and Baragar, 1971); **c.**A-F-M diagram.

Thus the major element content and ratios indicate that the Perintalmanna, granites are peraluminous and strongly potassic. The various discrimination diagrams point to the overall granitic nature of rocks.

The granites have high content of Ba and Sr. In SiO_2vsRb diagram, all the granite plots fall in the within-plate field (Pearce, 1984)(Fig.6a).The depth of formation of granite is between 15 and 30 km as is shown in log Rbvs log Sr diagram (Condie, 1973) (Fig.6b). The overall content and ratios of the trace elements support the magmatic and A- type character and within- plate setting for Perintalmanna granites.

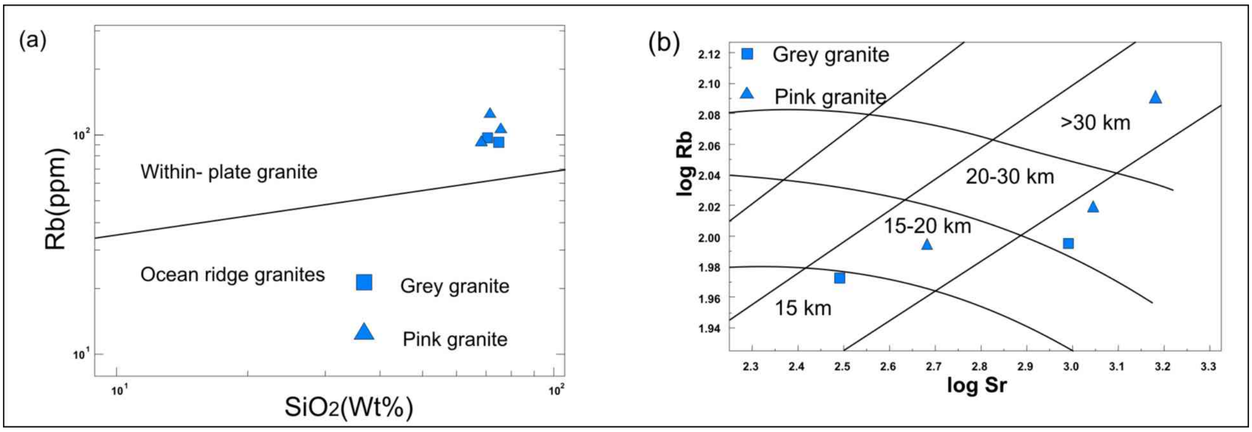

Fig.6 a. SiO_2vsRb diagram (Pearce, 1984); **b.** log Rbvs log Sr diagram (Condie, 1973)

Discussion and conclusion

The rocks of Perinthalmanna area do not preserve any primary planar structures due to high grade metamorphism undergone by them. The secondary planar structures observed in the gneisses and charnockite are deep penetrating foliations and well-developed joints. The fabric of the rocks, except that of granite and dolerite, reflect intense deformation and metamorphic recrystallization. Biotite gneiss, hornblende biotite gneiss and hornblende biotite schist are characterized by deep penetrative foliations, well developed gneissosity and schistosity.

Granite in the study area has concordant relationship with the country rocks indicating its igneous parentage and some structural control in its origin. The rock does not exhibit deformational structures or textures pointing to the post-orogenic nature. Mainly two types of granites are found viz. pink and gray, the latter being the dominant one.The holocrystalline,coarse grained and interlocking grains suggests igneous origin. The texture, structure and field relations of the two granite variants show the post-kinematic nature of Perintalmanna granite. The mineralogical characteristics also support A-type character.

The major element data of gray and pink granites have strong geochemical similarities. The DI values are also similar. Both granites have low CaO, MgO and high FeO/MgO values indicating their A-type character. The high SiO_2 and alkali content, Na_2O/K_2O ratio, weak peraluminous nature and subalkalic character of the two variants are similar to that of many A-type granites. Thus the major element characters show the post-orogenic, magmatic and calc-alkaline to alkaline nature and A-type affinity of Perintalmanna granites.

The trace element content and ratios of gray and pink varieties of Perintalmanna granite show magmatic differentiation to be a major process in their formation. The high Ba/Sr ratios are typical of early crystallization of plagioclase. The high K/Rb values suggest Rb-depleted source. High Sr and low Rb show that they have not evolved from sedimentary rocks. The discrimination diagrams indicate that the granites belong to the within-plate type and the depth of formation is between 15 and 30 km. The concentration and ratios of trace elements indicate the A-type character of the two variants.

A number of models are suggested for the formation of A-type granites. The most popular genetic model is the formation of magmas by partial fusion followed by fractional crystallization. Metasomatism, fractional crystallization and partial melting are the possible theories on the origin of alkali granites (Whalen et al., 1987). Sylvester (1989) and Eby (1990) suggest the formation of anorogenic granites from primary magmas produced by partial melting of dry lower crustal rocks. Mantle derived volatiles rich in CO_2 might have driven hydroxyl minerals and fused the lower crustal rocks resulting in the generation of granite magmas. Perinthalmanna granite is located in an area of thick continental crust with granulites. Here the A-type granite magma might have formed by the partial melting of granulites by the influx of CO_2-rich fluid. The most probabale mechanism of melting in plate interior is by mantle upwarping producing rapid decompression melting. Crustal distension might have led to mantle degassing and localized melting of lower crust (Bailey,1974; Harris and Marriner, 1980; Whalen et al 1987; Sylvester, 1989). Perunthalmanna is located in a region of thicker continental crust. It may be concluded that the two variants of Perintalmanna granite had formed by the partial melting of granulites in the lower crust by mantle derived volatiles.

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Petrology and geochemistry of mafic granulite dyke within the metasedimentaries of Trivandrum block, South India

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Abstract

Mafic granulite dykes occur widely as dismembered units within the metasedimentary units of Trivandrum block, southern India. Field relations, petrology and geochemistry of these rocks were studied. The dykes occur as boudinaged layers, bands and enclaves within the gneissic units. Mineralogically two distinct domains are observed in the mafic band. (1) dark-coloured fine-grained core consists of equigranular mosaic of xenomorphic grains of ortho and clinopyroxenes, plagioclase feldspar, hornblende, ±biotite and quartz; and (2) medium grained rim with orthopyroxene, garnet, plagioclase , biotite and quartz. Petrological studies revealed that mafic granulite shows relict ophitic texture, the pyroxenes enclosing laths of plagioclase and the presence of two-pyroxenes suggest peritectic segregations. Geochemical studies show that these rocks have an igneous protolith and were derived from sub alkaline tholeiitic magma. These dykes were emplaced into the accretionary sequence of the khondalite belt and metamorphosed during the final collisional stage of Gondwana assembly. Zircon U-Pb age data show the dykes were emplaced during late Neoproterozoic-Cambrian during the tectonics associated with the final assembly of the Gondwana supercontinent.

Key words: mafic granulites, Trivandrum block, two-pyroxene granulites, Gondwana

Shaji E 2011 Petrology and geochemistry of pyroxene granulites within the metapelites of Trivandrum Block, south India. Indian Mineralogist, 45/2,31-47

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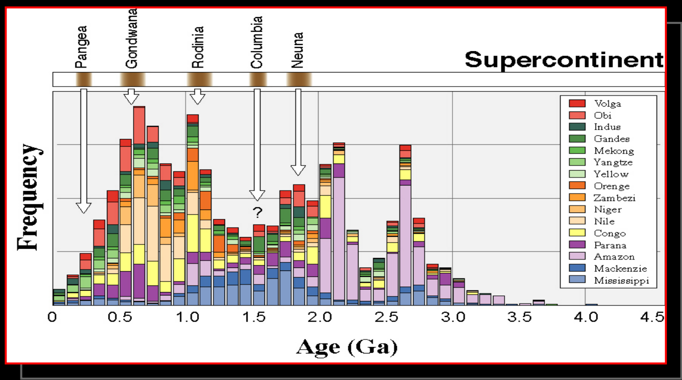

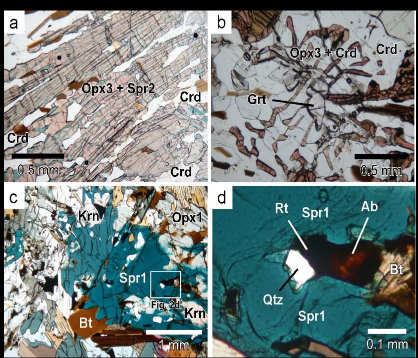

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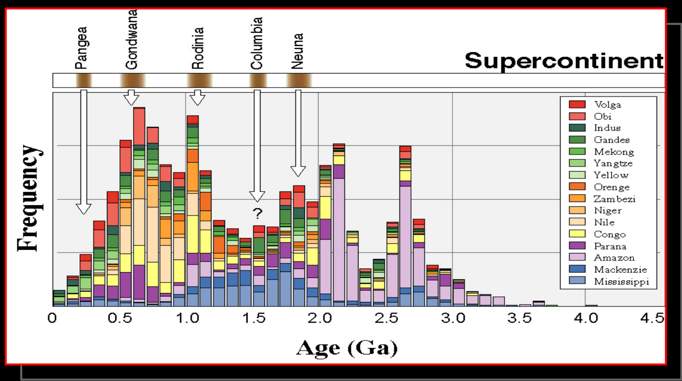

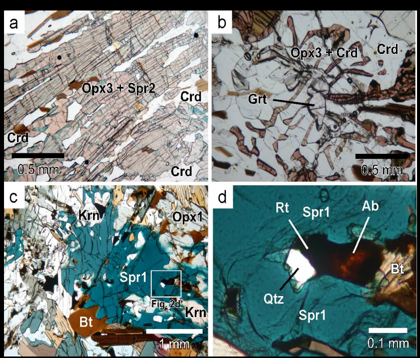

The role of fluids and melts in crustal processes, crust-mantle interaction and mantle dynamics is a topic of global interest

Fluids and melts play a critical role in the geochemical differentiation and element distribution in the Earth

The Current Trends in Earth System Sciences (CTESS 2015) lecture series, sponsored by University of Kerala brings experts in the area to a common platform. The lectures are aimed at students and research scholars, providing them an opportunity to learn from established authorities in the field and to help them establish a rapport with them.

Confirmed speakers

Dr R Srinivasan Current Science
Dr TRK Chetty NGRI
Dr M Satyanarayana NGRI
Dr VJ Rajesh IIST
Dr GR Ravindrakumar NCESS
Dr Sajeev Krishnan IISc
Dr Rajneesh Bhutani Pondicherry University
Dr Abdul Matin Univ of Calcutta
Dr Satish Sangode Univ of Pune
Dr Biju John NIRM
Dr Ernst Hegner LMU Munich
Dr Krishna Kantha Singh WIHG
Dr SK Parcha WIHG Museum
Dr RT Ratheeshkumar IISc
Dr R Bhaskaran GSI
Dr DP Mohanty Pune University
Dr SG Viladkar Ahmedabad

The UGC – SAP DRS Phase II conference will bring together experts in petrology, tectonics, fluid inclusions, geochemistry, geophysics to a common platform where the latest research in the area will be discussed. Outstanding research questions would be identified and newer methodologies discussed to tackle them. CTESS2015 will have a session on Geology Museums which can help in the moulding of the new museum that is about to be set up within the University of Kerala

Please e-mail your full papers/extended abstracts before 8 Feb 2016 to esnure publication in an ISBN volume, to:

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Proc volumes of last two seminars available at

https://www.researchgate.net/publication/264046221_Shear_zones_crustal_blocks_of_southern_India_Vol_1_Fluid_Inclusions_Tectonics_Petrology_UGC_SAP_DRS_Phase_II_Seminar

https://www.researchgate.net/publication/275408679_Shear_Zones_and_Crustal_Blocks_of_southern_India_Vol_2_2015