J. Ind. Geophys. Union (January 2014)
v.18, no.1, pp:19-56

Deep crustal Shear Zones in the Eastern Ghats Mobile Belt, India: Gondwana correlations

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ABSTRACT
Shear zones are significant in understanding the physicochemical processes, such as mineralization, magmatism, metamorphism, and deformational patterns and bear remarkable influence on many aspects of earth system science. We present here the structural framework of the Eastern Ghats Mobile Belt (EGMB) that constitutes a net work of deep crustal shear zones. It was possible to identify and recognize these shear zones by involving different spatial data sets, field observations along regional traverses and detailed structural analysis in selected critical areas and outcrop mapping and in conjunction with the available published geological maps. We review and present here field description, distribution, geometry and the kinematics of different shear zones of the EGMB and emphasize their significance in terms of tectonic models and Gondwana correlations.

The shear zones at the cratonic margins such as the Sileru shear zone, Koraput - Rairakhol shear zone and the Northern boundary shear zone represent a long and continuous suture zone extending for over a few hundreds of kilometers and upto lithospheric depths. All the shear zones witnessed multiple events of magmatism, metamorphism and deformation. The stretching lineations show different orientations in different segments and divide the EGMB into several distinct structural domains. All the shear zones are found to be transpressive in character and subjected to repeated reactivation in space and time. Oblique collision and long lived transpressional tectonic regime during Gondwana amalgamation seem to be responsible for the present structural architecture of the EGMB.

The shear zones 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. There is a strong need for detailed field based studies involving modern mapping techniques with current tectonic perspectives before we attempt any advanced laboratory based measurements for useful and meaningful interpretations.

INTRODUCTION

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 (Sibson,1977; Hanmer, 1988; Chardon et al., 2008) and much wider zones in the deeper parts of the crust (e.g., Coward and Park, 1987; Myers,1987; Drury et al.,1980). The middle to deep crustal shear zones are being increasingly recognized only in the last 2-3 decades from several high grade metamorphic terranes (e.g., Bak et al.,1975;Drury et al., 1980; Coward and Park,1987; Myers,1987; McCourt, and Vearncombe,1992; Daly, 1986; Chetty and Murthy, 1994; Chetty, 1996; Smit and Van Reenen, 1997). Deep crustal shear zones are usually associated with continuous strain gradients (Nadeau and Hanmer, 1992) comprising kilometer wide ductile shear zones with substantial internal ductile deformation in the proximity. The structural and metamorphic relationships in such deep crustal shear zones are more complex due to the possible interactions of high temperature fluids with superposed tectonics during their formation. Deep crustal shear zone systems are an example of dissipative structure developed in response to rheological heterogeneities in the crust, particularly the presence of melt and the superimposed far field tectonic stresses. The resulting finite strain field is heterogeneous, large variations in strain are possible and complex kinematic patterns may occur (Brown and Solar, 1998).

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. Therefore, the study of shear zones is fundamental and essential because of their profound influence on the interpretation of any branch of earth science; be it geological, petrological, geochemical, isotopic or geophysical data sets. There is a strong need for detailed field based studies of shear zone systems involving modern mapping techniques with current tectonic perspectives in mind before we attempt any advanced laboratory based measurements for useful and meaningful interpretations of any Precambrian terrane.Further, there has been lot of confusion and the ambiguity in the classification and characteristics of shear zones exposed at different structural and crustal levels. Therefore, it is felt necessary to provide below some fundamental aspects about the definition, classification, characteristics and the significance of deep crustal shear zones in general.

It has been recognized in the last 2-3 decades that large tracts of Archean terrains were reworked during the early Proterozoic in many parts of the world. In many cases, the reworking occurred essentially along linear zones in the earth's crust, found to be made up in detail of many shear zones, often recording large amounts of overthrust or transcurrent displacement. Individually, shear zones like faults may be compressional (thrust), extensional (normal or lag), strike-slip or oblique-slip. The determination of the movement direction, not always obvious, is critical to the kinematic interpretation. The most useful guide to the movement direction is the orientation of elongation lineations (parallel to the axis of greatest extension) in zones of high strain. Some revolutionary concepts have emerged and changed the earlier thinking significantly and have important implications in understanding the scenario of global geodynamics. In view of this, several areas are being revisited, studied and reinterpreted.

Shear zones are by definition much more strongly deformed than the surrounding rocks. It is a zone of faulting in which the displacement is accommodated across and along a zone rather than on a single plane. In other words, it is a planar zone of concentrated (dominantly simple shear) deformation which by itself, or in association with other zones, helps to accommodate, or wholly accommodates an imposed regional or local, strain rate beyond the strength of the country rock. These are typically produced when volumes of rock, metamorphosed or intruded at high temperatures, are reworked under lower temperature conditions. Previously, ductile shear zones were only described as shear zones to distinguish them from clean-cut faults. Off late, the term shear zone encompasses both clean-cut faults and ductile shear zones as the two end members of the same spectrum (Ramsay, 1980). The shear zones range in scale from microscopic or grain scale to the scale of a few hundred kilometers in length and a few kilometers in width, as reported for the first time, from the Precambrian gneisses of Greenland (Bak et al .,1975). Shear zones are long relative to their width, generally in the aspect ratio of 5:1.

Traditionally, shear zones are believed not to show any loss of coherence, between the wall rock and the shear zone itself. A marker layer, though deflected in the shear zone, should not be broken at the contact. Therefore, a ductile shear zone cannot be regarded as a fault in the ordinary sense of the term. However, as pointed by Wise et al (1984), the distinction is difficult, if not impossible, for most field examples especially when the tangential displacement is very large in comparison with the width of the ductile zone. In such shear zones marker units may undergo extensive boudinage and the continuity of the markers may be unrecognizable in the mylonite belt. Following Ramsay (1980), we can designate this entire class of structures as shear zones, with faults and ductile shear zones as the end members. It also depends on the scale we are looking at these structures. A line, for instance, on a million-scale map represents nearly 1 km width, which indicates that it is a zone of planar elements or crushed material. Even on outcrop scale, although we find it as a line in the field, it would invariably be a fault/ shear zone on a microscopic scale. Therefore, it is justified to refer to the entire spectrum of faults as 'shear zones'.

Shear zones are significant in several ways. They are: (i) the prime targets for mineral exploration. Mineralisation is commonly associated with specific geometrical features such as bends and intersections, (ii) the sites of very large strain and that they offer some of the strongest tools to unravel the complex deformation features of the Earth's crust, (iii) the sites for igneous intrusions like alkaline rocks and anorthosites, etc; (iv) the only permeable pathways for the large continental crust and they act as effective fluid conduits during active deformation, (v) the potential hazardous sites because of enhanced concentration of radon gas in soils, some times related to the uranium concentration. (vi) the belts of extensive mylonitisation, repeated reactivation and chemical transfer and (vii) they can also act as important piercing points into adjacent continental fragments or different plates which would be helpful in reconstructing the supercontinental models.

The shear zones can be classified into three classes: (1) Faults / Brittle shear zones are a special variety of shear zones where a clear discontinuity exists between the sides of the zone and the shear zone walls are almost unstrained or perhaps brecciated. Gouges and cataclasites are often produced. As a rule of thumb, brittle shear zones develop in the upper crust at temperatures below about 300° C. (2) Brittle-ductile shear zones are associated with some ductile deformation in the walls, which show permanent strain for a distance of up to 10 meters on either side of the fault break. There is a possibility that the ductile part of the deformation history formed at a different time from that of the fault discontinuity. Another type of brittle-ductile shear zone is the extension failure. The deformation zone shows an en-echelon array of extension openings, usually filled with fibrous crystalline material. The openings usually make angle of 45 degrees or more with the shear zone and some times the openings develop into sigmoidal forms. (3) Ductile shear zones are those in that the deformation and differential displacement of the walls is accomplished entirely by ductile flow. No discontinuities can be observed on the scale of the rock outcrop. Marker layers in the country rock can be traced through the shear zone; they are deflected and may change in their thickness, but they remain unbroken. Ductile shear zones are extremely common in deformed crystalline basement rocks (granites, gabbros, gneisses, etc.) of all grades of metamorphism. Crystal plastic deformation processes, e.g.: pressure solution, dislocation creep, grain boundary sliding and diffusion, along with recrystallization and neomineralization, dominate to make mylonites; which are typical of ductile shear zones. In general, ductile –, and brittle-ductile varieties are the deep level counterparts of brittle shear zones and brittle faults occur at higher levels in the crust. These shear zones may range in scale from the microscopic or grain scale to the scale of a few hundred kilometers in length and a few metres or a few tens of kilometers in width. e.g. Precambrian gneisses of Greenland (Bak et al., 1975); crustal shear zones in Africa (Daly,1986; Coward and Park, 1987). Ductile shear zones can further be classified into two types: (a) discrete shear zones which cut across rocks, otherwise undeformed by the particular phase of deformation; and (b) shear zones located at the margins of mobile belts or at the margins of sub zones within the belts (Coward, 1980). The former are unrelated to the local tectonics and the latter develop necessarily to maintain compatibility between zones of different intensities of deformation. Ductile shear zones are formed at mid-crustal levels of around 15-20 km depth as indicated by the high metamorphic grade of the associated fabrics. There is increasing evidence from deep seismic reflection surveys and theoretical considerations of crustal rheology that major detachment horizons of this kind exist within middle and lower crust. Further, deep crustal shear zones are important in tectonic reconstructions as a source of information regarding the relative motion of large crustal blocks or plates in the geological past. The deep crustal shear zones in high grade orogenic belts are distinct deformational markers, which are characterized by the following: (a) typically by the development of mylonitic fabric – in granitic material for instance, the closely spaced foliation is defined by alternating layers of recrystallized quartz grains, milky ribbons of fine grained, recrystallized feldspar and fine platy biotite, (b) the foliation surfaces contain a very strong lineation (stretching lineation) defined by the elongation (and / or boudinage) of minerals like hornblende, micas, quartz, feldspar, etc. as well as mineral aggregates, (c) the development of S-C mylonites is very common, indicating non-coaxial deformation history, (d) the amount of strain is highly variable resulting in the occurrence of a spectrum of mylonites (Proto- to ultramylonite), (e) grain size reduction is typical, (f) retrogression of metamorphism is usual, (g) the development of new grain-growth, particularly biotite, kyanite, staurolite and muscovite, (h) the shear zones occur in the form of intersecting and anastomosing pattern, (i) generally associated with large geophysical anomalies, and (j) associated with igneous intrusions (white et al.,1986; Bell and Hanmond,1984; Passchier and Trouw, 1996; Simpson, 1983; Hanmer,1986).

Identification and recognition of shear zones especially in high-grade gneisses is a challenging task because of multiple deformation cycles and complex fabric geometries of high grade environments. It is emphasized here that simple extrapolation of structural analysis from low grade rocks to high grade gneisses may often lead to misinterpretations. Therefore, multi-scale structural studies are warranted since the deep crustal shear zones in high grade metamorphic terranes are larger and wider. In contrast to traditional approach and with the availability of modern tools like Remote Sensing data and GPS and GIS , new modern mapping techniques were found to be extremely useful in obtaining entirely new structural and tectonic perspectives which were hither to unknown.

The Eastern Ghats Mobile Belt (EGMB), occurring at the east coast of India, represents an important part of the Great Indian Proterozoic Fold Belt and a critical sector of global Neoproterozoic orogenic belts. The EGMB is crucial in supercontinent reconstruction models, attracting the attention of national and international geoscientists. This is evident from several recent exhaustive reviews about the EGMB-regarding the general geology (eg., Ramakrishnan and Vaidyanathan, 2008; Gupta, 2004; Nanda, 2008), shear zone network (Chetty and Murthy, 1998; Chetty, 2010), geochronological history (e.g., Shaw et al., 1997; Paul et al.,1990; Biswal et al., 2007; Dharma Rao et al.,2011;Dasgupta et al ., 2013; Vijayakumar et al.,2013) and a comprehensive overview of thermochronological history and the constituent domainal architecture of the EGMB (Dobmier and Raith, 2003; Mukhopadhyay and Krishnapriya basik, 2009). Recently, Paleoproterozoic to Neoproterozoic evolution of the EGMB has been critically described in terms of plate tectonic perspectives (Vijayakumar and Leelanandam, 2008; Dharma Rao et al., 2011; Vijayakumar et al., 2013; and the references there in). However, adequate field description of the fundamental structural architecture and the constituent network of shear zones and their kinematic history have been lacking to have a complete understanding of tectonic evolutionary history of the EGMB. In this contribution, we review and analyze the nature and spatial distribution and the geometry of deep crustal shear zone frame work of the EGMB involving essentially field based and multi-scale structural analysis with a focus on the 3D-geometry, kinematics, and the significance of different shear zones involving satellite images, field traverses, and detailed structural mapping of rocks and regions.

THE EASTERN GHATS MOBILE BELT

The Eastern Ghats Mobile Belt (EGMB), a Mesoproterozoic collisional orogen, extends along the east coast of India for over 900 km with varying width from 50km in the south to a maximium of 300 km in the north (Fig.1). The margins of the EGMB are characterized by lithosphere shear zones at the contact with the Archean cratons of Dharwar, Bastar in the west and the Singhbhum craton in the north. The EGMB is transected by two important NW-SE trending Mesozoic rifts with suspected Precambrian ancestry ocupied by Permo-carboniferous coal bearing sediments namely Godavari rift (GR) in the south and the Mahanadi rift (MR) in the north. The later has been correlated with the Lambert rift of east Antarctica in the Indo-Antarctica correlations (eg.Federov et al., 1982; Hofmann, 1996). It was also described as a pre-Gondwana continuous tectonic feature during early Mesozoic Gondwana (Horrowfield et al., 2005).Some workers have proposed that Mahanadi rift was formed as a consequence of strike –slip motion along the Precambrian shear zones at the northern boundary of the EGMB (Chetty, 1995b; Nash et al., 1996). It represents an important Precambrian orogenic belt of global significance and plays a key role in the reconstruction models of east Gondwana. The EGMB principally consists of high grade metamorphic gneisses viz.,khondalites (garnet-sillimanite gneisses), charnockites (hypersthene bearing granites) and porphyritic gneisses. The khondalitic group of rocks include khondalites, quartzites and calc granulites, while charnockitic group of rocks include mafic granulites, enderbites and variably retrograded charnockites. All the rocks have been metamorphosed to granulite facies metamorphism exhibiting excellent metamorphic gneissosity.

The early-formed structures have been overprinted by the fabrics of subsequent successive deformational events. For a detailed description of lithology and general geology, the reader is referred to the regional review published by Ramakrishnan et al., (1998), presenting geological evolution of the EGMB. Considering the broad structure, lithological assemblages and shear zone network, Chetty (2001) has described the EGMB as a collage of juxtaposed terranes (Chetty, 2001), while Rickers

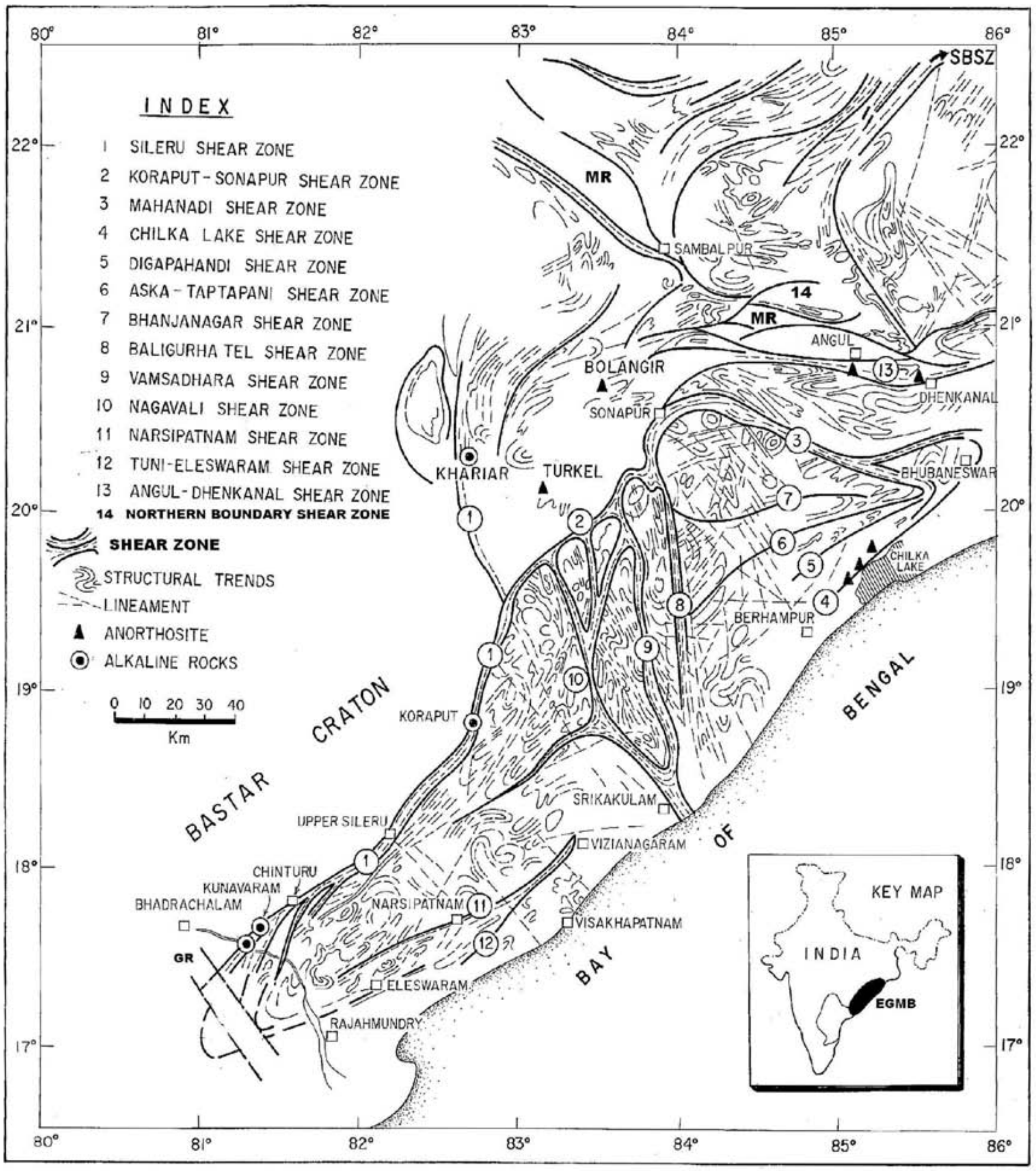


Figure 1. Map of the Eastern Ghats Mobile Belt (EGMB) showing the disposition and orientation of network of deep crustal shear zones and associated fold styles, structural fabrics and other lineaments, derived from structural interpretation of multi-scale Satellite data: MR – Mahanadi Rift, GR – Godavari Rift, SBSZ-Sighbhum shear zone (modified after Chetty, 1992)

et al., (2001) as a belt of distinct crustal provinces based on isotopic signatures. This is in variation with the longitudinal classification and division made by Ramakrishnan et al., (1998). Recently, a plate tectonic perspective involving two cycles of rifting and convergence has also been proposed to understand the tectonothermal evolution of the EGMB (Vijayakumar and Leelanandam,2008; Dharma Rao et al.,2011).

A network of deep crustal shear zones (Fig.1) was first recognized and described from the EGMB (Chetty, 1992; Chetty and Murthy, 1992; 1993; 1994; 1998a) that stimulated new discussions and researches. The shear zones vary in their extension and orientation, which are not often consistent with the regional NE-SW trend of the EGMB. The shear zone orientations are: NE-SW and conformable to the regional trend in the southern part; N-S in the

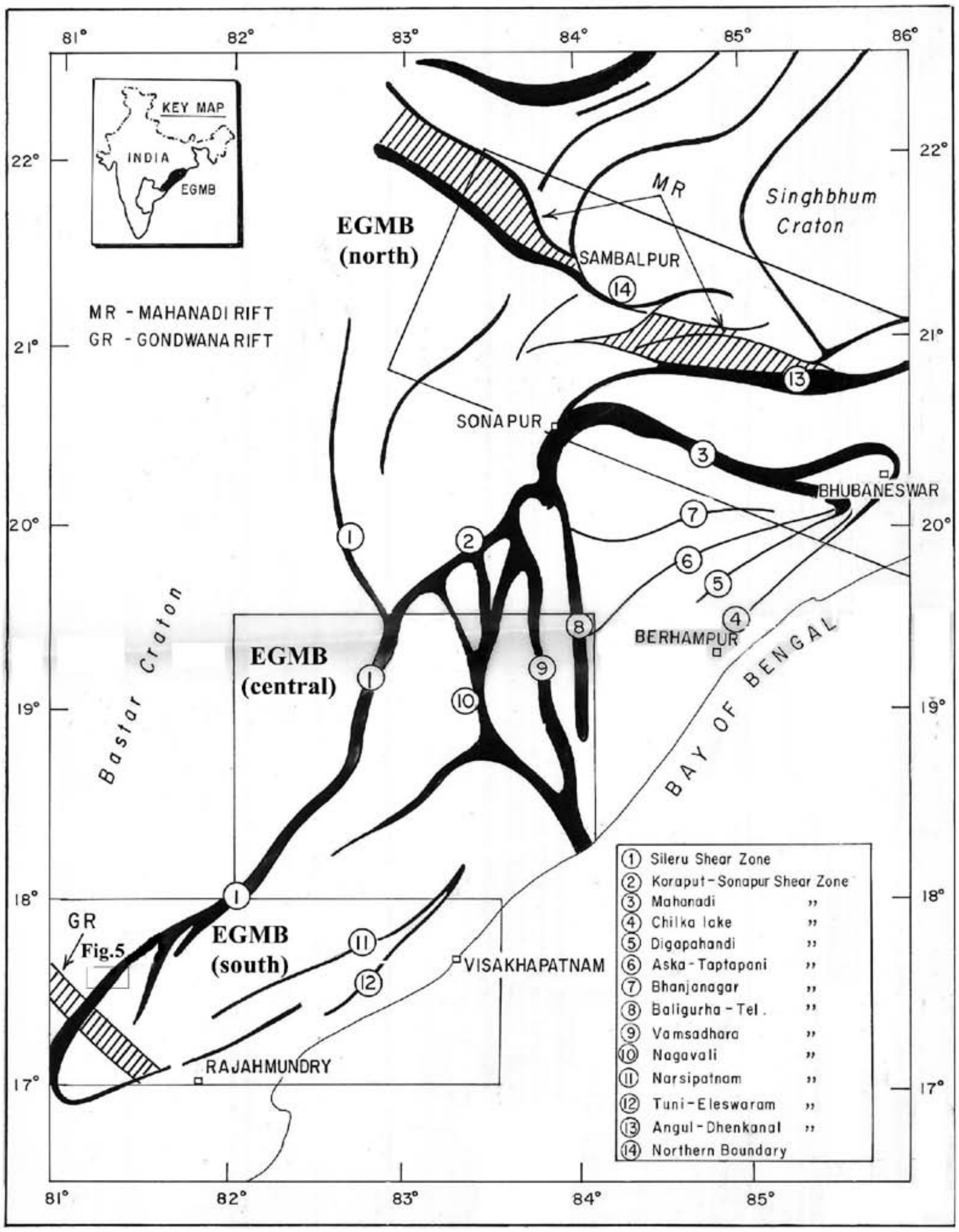


Figure 2. Map of network of deep crustal shear zones in the EGMB showing the division of southern, central and northern parts. The shear zones are numbered.

central part and orthogonal; and E-W in the northern part. The lithological contacts and the foliation trajectories are, in general, conformable to the shear zones in the proximity. In this contribution, the nature, disposition, geometry and kinematics of shear zones are described below by dividing the EGMB into southern, central and northern parts for the sake of brevity and convenience and on the basis of the geometry of shear zones (Fig.2).

EGMB (south)

The area lying between N.17°-18° and E.81°-83°, extending up to the Godavari rift in the south is considered here as the southern part of the EGMB (Fig.3). The granulite facies rocks continue further south of Godavari rift and are described separately as Terrane Bounadary shear zone. Regional structural interpretation of Landsat TM data, followed by geological field observations along a few chosen traverses and selected outcrop mapping reveal a set of subparallel NE-SW trending shear zones in the region (Chetty and Murthy, 1994; 1998). A number of major ductile shear zones occur both at the margins and within the EGMB (Chetty and Murthy, 1993; 1994) These shear zones vary in their nature, scale and geometry. The shear zones in the region trend NE–SW, sub parallel to the regional trend of the EGMB. Amongst them, the most striking is the Sileru Shear Zone (SSZ) that occurs at the western contact zone between the Archaean cratonic rocks of Dharwar and Bastar cratons and the granulite facies rocks of the EGMB (Fig. 3). The east dipping major thrust reported by Kaila and Bhatia (1982) coincides with the SSZ.The rock units in the shear zone include a variety of migmatitic gneisses of granite, biotite, quartzofeldspathic, charnockite and amphibolite. These rocks preserve intensely developed foliations giving rise to a complete spectrum of mylonites varying from proto- to ultramylonite (Chetty and Murthy, 1993; 1998b). The rocks also preserve well developed stretching lineations with a dominant plunge of ~30° to south west. The mesoscopic structures such as high asymmetrical fold structures, S-C fabrics and deformed augen gneisses indicate dextral sense of strike-slip movements. However, the behaviour of stretching lineations and the heterogenety of foliation fabrics indicate that the rocks in the shear zone witnessed transpressive tectonic regime (Fig.3). The SSZ varies in width from 3 to 10 km and extends over a strike length of ~ 500 km with an average dip of about 50° to south east (Chetty and Murthy, 1993, 1994), which is interpreted as a northwest verging thrust.

Apart from the boundary SSZ, there are other internal shear zones that occur at the contact between the two major rock suites, viz; khondalitic group and Charnockitic group of rocks. The width of the zone varies from a few meters to a few hundred meters. They occur as parallel shear zones with in the granulite facies rocks and are characterized by (i) a change in the character of the rocks from coarse grained, folded and banded gneisses to finer grained, thinly banded quartzofeldspathic gneisses with dominant transposition fabrics, (ii) characteristic presence of migmatitic rocks, resulting in the emplacement of neosomes such as

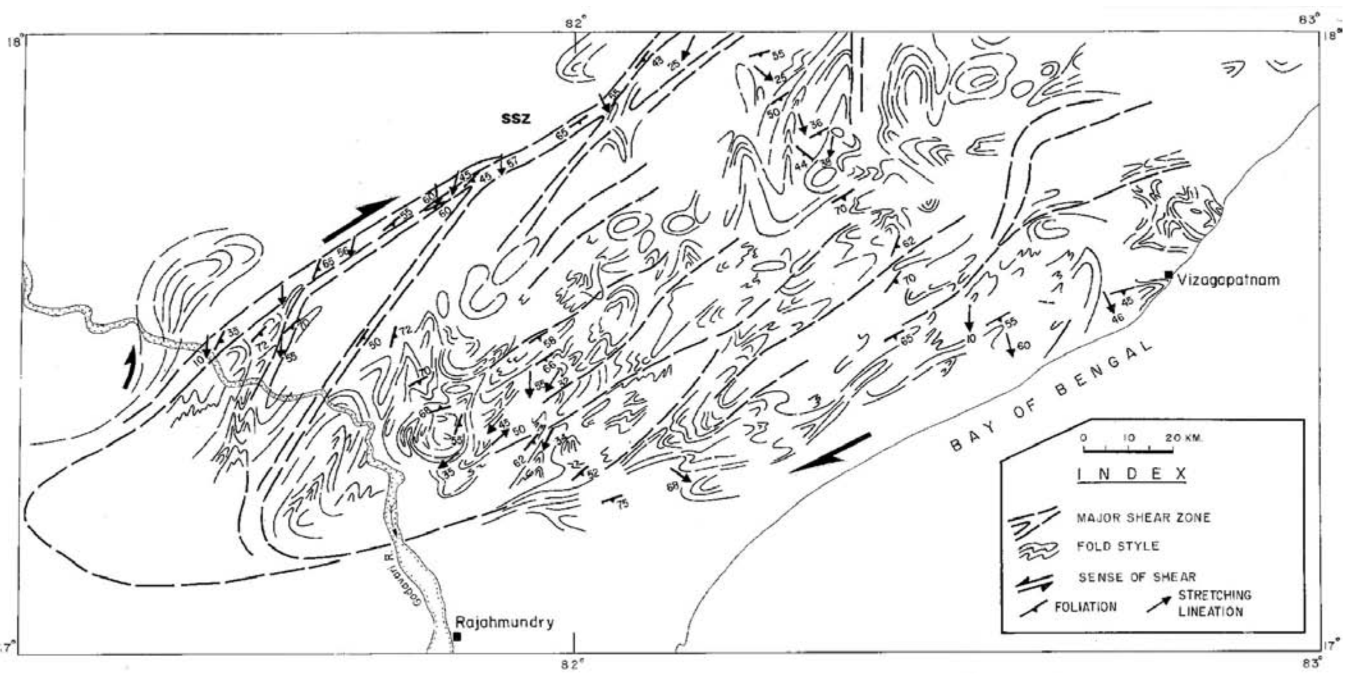


Figure 3. Simplified structural framework of the EGMB (south), based on the image interpretation together with regional geological field traverses, exhibiting boundary as well as internal shear zone network. Note the structural measurements of foliation and stretching lineation confirming the interpretations from Satellite data. SSZ-Sileru Shear Zone. Note the presence of refolded fold structures of different orientation and closed structural forms of varying sizes. Also, notice the presence of shear zones in the limb regions displaying displacements (after Chetty and Murthy, 1994).

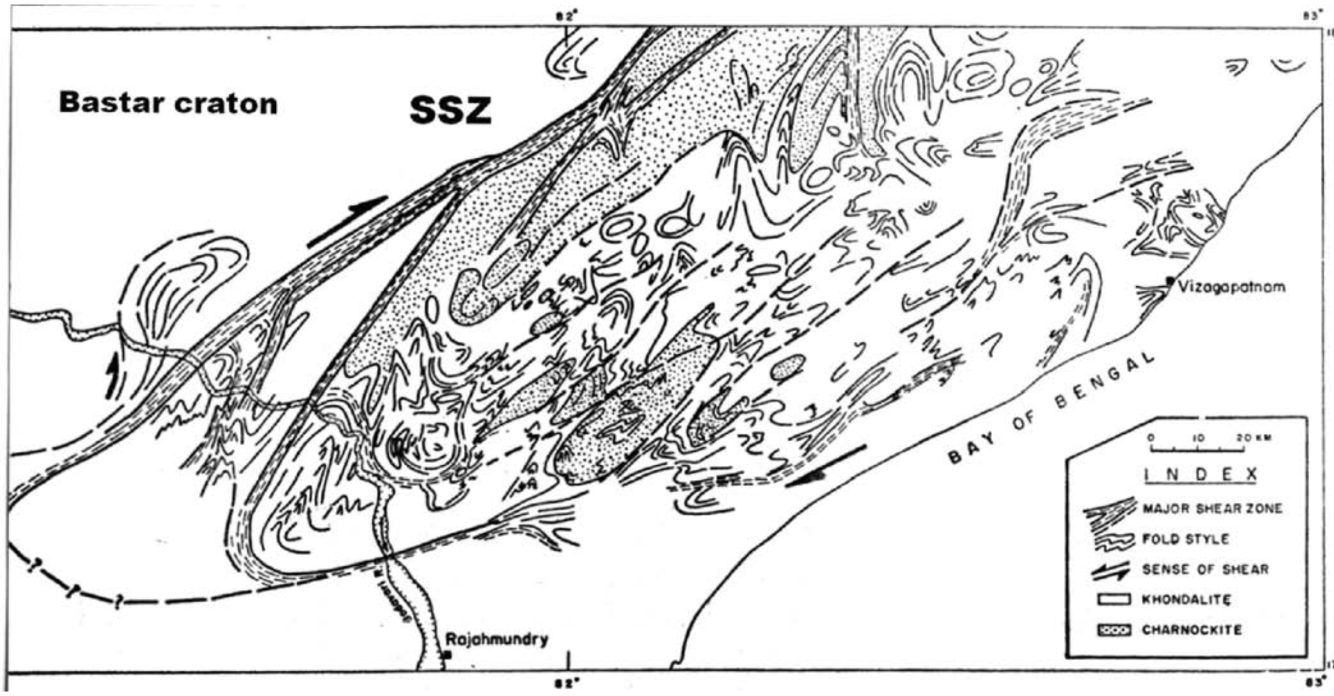


Figure 4. Simplified structural framework of the EGMB (south) along with superimposed geological formations. Shear zones follow the lithological contacts and the complex fold styles with varied orientation of axial plane, which are dominantly exposed in incompetent metasedimentary rocks. Note the presence of southwesterly plunging regional antiformal fold closure in the south. Also, note that the distribution of lithologies is influenced and controlled by the shear zone network. (Lithologies are borrowed from published geological maps of the GSI)

leptynites (pyroxene free garnetiferous granitic rocks) quartzofeldspathic gneisses , pegmatites and vein quartz showing syn-or late tectonic deformation, and (iii) development of stretching lineations, boudinaged rocks and occasional sheath folds. Amongst them, the two important zones are Narsipatnam shear zone and Tuni-Eleswaram shear zone (see Fig.1).

The Narsipatnam shear zone is relatively a narrow belt (~1km wide) and extends for about 200km along NE-SW direction. It joins the tungsten bearing graphite deposits of Burugubanda-Tapasikonda in the south, restricted to a shear zone (Chetty and Murthy, 1992). In the north, it merges with Tuni-Eleswaram shear zone and terminates near Vizianagaram. Presence of mylonites is a characteristic feature of the shear zone. The Tuni-Eleswaram shear zone trends NE-SW and occurs in the east, parallel to the coast. It dips dominantly to east and merges with the SSZ in the south defining southerly closure of a regional fold.

Basaltic rocks equivalent to Deccan traps (65Ma) occur in the east adjacent to the shear zone near Rajahmundry. Fig.4 shows simplified tectonic framework of the EGMB (south) displaying the pattern of distribution of major rock units and associated structural trends. Examination of general trends and dips of foliations, map pattern and the distribution of rock types, geometry and disposition of folds and ductile shear zones suggest an over all shortening of rock units by means of imbricate thrusting. Apart from the shear zone network, large scale refolded structures are evident in the central part of the region. Several closed structural forms of varying dimensions and NE-SW elongation in the form of structural domes and basins and are interpreted as possible sheath geometries (Chetty and Murthy, 1993). The presence of large scale refolded fold structures at the SW margin of the region and associated conformable structural fabrics indicate the presence of major fold closure, which may be closely related to major low angle thrusting. The south westerly fold closure together with the dominant plunge direction of stretching lineations and mesoscopic fold axes suggest the presence of a major antiformal fold developed due to NW verging major thrust. Areal photo studies across a small segment of the SSZ show the presence of folded

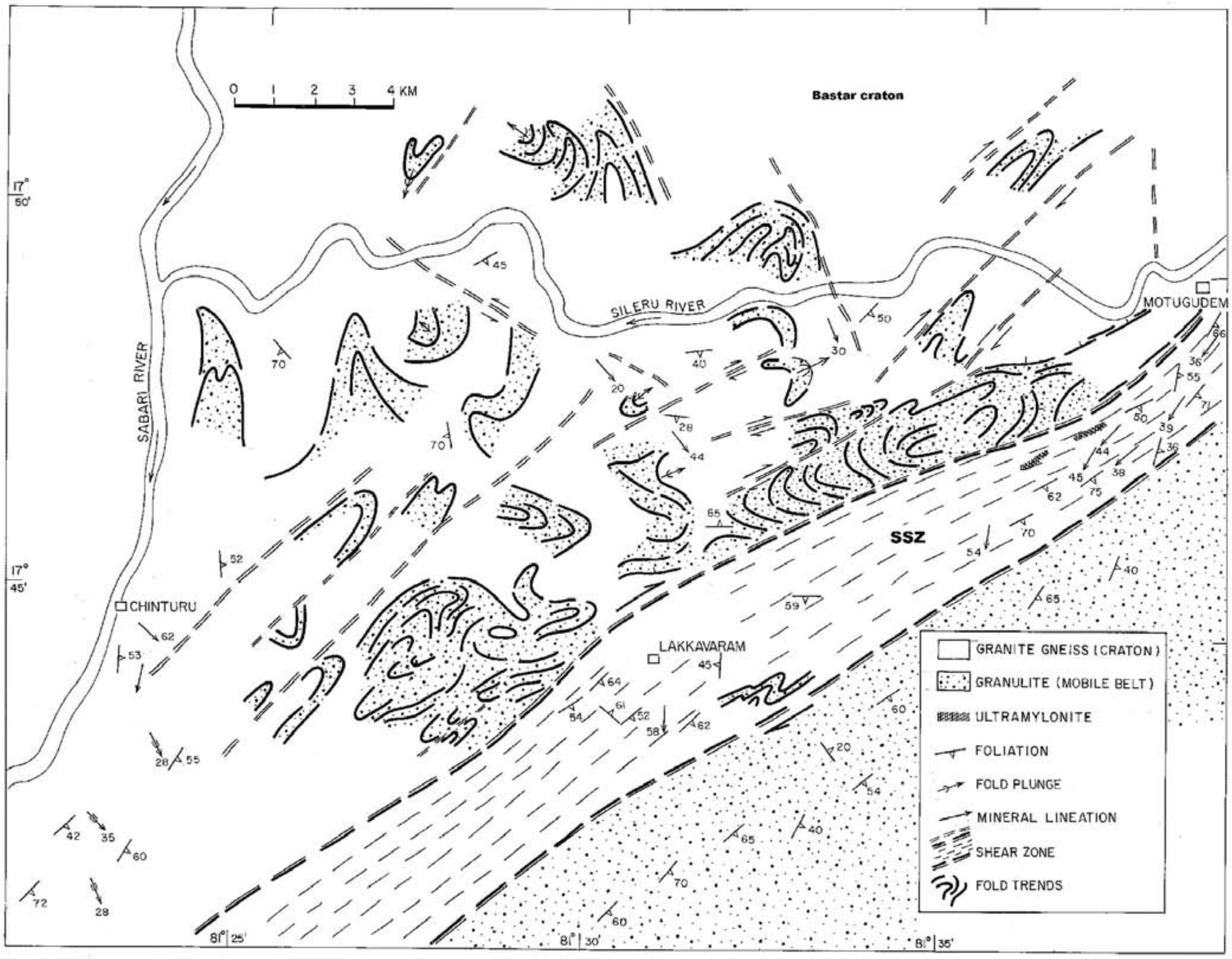


Figure 5. Map showing structural interpretation of areal photos in a segment across the SSZ around Lakkavaram. Note the presence of scattered granulite facies rocks lying over the craton, and the isolated exposures of ultramylonites with in the SSZ-Sileru Shear Zone (modified after Chetty and Murthy, 1998b)

granulite facies rocks to the west of SSZ (Fig.5) imply that they have been thrusted on to the craton from the east (Chetty and Murthy, 1998b). Alkaline magmatism ranging in age from 1450 Ma to 850 Ma is restricted to the SSZ and is emplaced at a few places within the span of the total length of the SSZ. Gravity anomalies over SSZ are strongly negative, rising sharply up to the axial zone and then becoming increasingly positive towards the eastern boundary (Subramanyam and Verma, 1986) suggesting that the SSZ is a Precambrian suture zone.(Subramanyam, 1978; Chetty and Murthy, 1998b). The Sileru shear zone is also marked by the presence of a chain of nepheline syenite plutons (DARCs) indicating deep sections of a suture zone. Considering the structural styles within the shear zone, contrasting geological features on both sides and association with alkaline magmatism, the SSZ has been described as a major Precambrian suture zone (Chetty and Murthy, 1998b).

Two E-W trending interpretative structural cross sections, separated by about 70km, were constructed (Fig.6) along (i) Upper Sileru-Dharakonda-Chintapalle-Narsipatnam-Vizag (A-A1); and (ii) Chinturu- Maredumilli-Rampachodavaram-Addatigala-Eleswaram (B-B1) in view of accessibility and outcrop availability. While charnockites dominate in the western part , khondalitic group of rocks form major rock unit in the eastern part of the cross sections. The SSZ and other inferred shear zones are marked by the occurrence of migmatites and quartzofeldspathic rocks (leptynites) with strong mylonitic fabrics (Chetty and Murthy, 1993), which

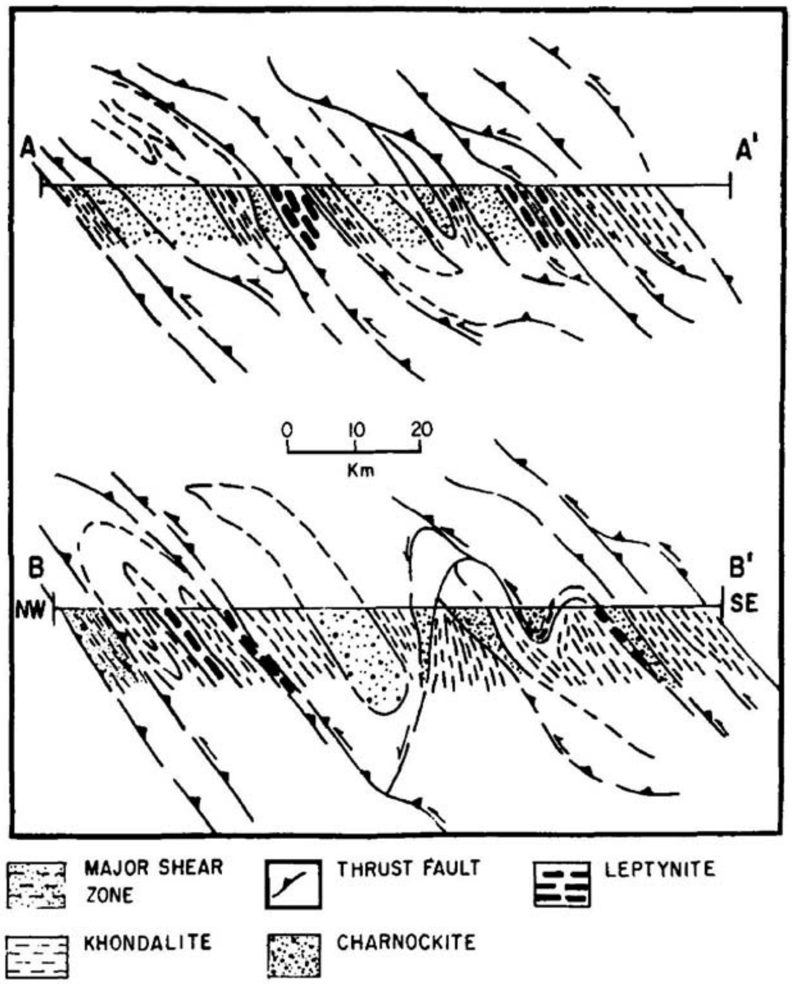


Figure 6. Interpretative regional structural cross sections along (i) Upper Sileru-Visakhapatnam (A-A1), (ii) Chinturu-Eleswaram (B-B1), suggesting north- westward verging imbricate thrusting (after Chetty and Murthy, 1994)

occur along geomorphologically low lying linear belts. Features like ribbon type quartz, recrystallization around the margins of mafic minerals are also recorded under the microscope. Profuse development of garnets and intense migmatisation are well recorded in these rocks. Away from the shear zones, rootless mesoscopic fold hinges with moderate southerly plunges and flat lying metamorphic foliations are often well preserved. Both the traverses are interpreted interms of major duplex structures and associated shear zones related to imbricate thrust structures. All the observations described above suggest NW verging thrusts during D1 (Fig.6). The steep shear zone fabrics (50°-70°) and the presence of oblique stretching lineations point to the subsequent transpressive deformation during D2 deformation.

South of Godavari rift

The granulite facies rocks of the EGMB extend further south of Gadavari rift upto Ongole in the form of a broad linear zone, which are described here as an extended EGMB (south). A wide zone of mixed lithologies consisting mainly of migmatitic gneisses punctured by plutonic bodies of gabbros and granites are mapped with several isolated hills of granulite facies rocks at the eastern segment (e.g., Sesha Sai, 2013 and the references there in). The zone between the eastern margin of the Cuddapah basin and the granulite facies rocks is reported here as a crustal-scale Terrane Boundary Shear Zone (TBSZ) ; (Nagaraju and Chetty, 2005; Nagaraju et al., 2008). Based on the gravity data, some workers believe that the western contact of the EGMB in the region coincides with the eastern margin thrust of the Cuddapah basin and thus including the Nellore-Khammam schist belt and the surrounding low to medium grade gneisses as a part of the EGMB (e.g. Naqvi and Rogers, 1987). Sengupta et al., (1999) documented UHT metamorphism in these granulites during Late Archaean time and also recorded the Mesoproterozoic (1600 Ma) granulite facies metamorphism. The available U-Pb cooling ages of minerals also indicate no significant high-grade metamorphic event subsequent to 1600 Ma (in Kondapalle) and ~1300Ma (in Ongole) except for late shear zones. However, so far, there are no reports of evidences for Grenvillian granulite facies metamorphism in this part of the EGMB, which is widespread in the northern part. The metamorphic history of this part of the EGMB is also correlated with the Napier complex, Enderby Land. The granulite facies rocks of the TBSZ, south of Godavari rift, are distinctly different in their thermotectonic evolution in comparison to their northern counterparts.

The TBSZ is strikingly marked by extensive alkaline magmatism, dotted by several alkaline plutons of different sizes and shapes, which yielded ages of 1240Ma, 860Ma, and 620Ma over extremely long intervals during a protracted period A detailed review describing the geology, petrology, genesis and nature of these plutons is presented recently (Leelanandam,1989; Upadhyay et al., 2006). Alkaline magmatism has been reported to be confined to the TBSZ that lies at the junction between the cratonic and mobile belt regimes. The low $^{87}Sr/^{86}Sr$ ratios of the rocks from alkaline and carbonatite complexes of the EGMB suggests a mantle origin. The role of deep crustal tectonic features controlling the ascent and emplacement of magma can well be determined with the help of kinematic indicators both inside and at the margins of plutons. For instance, structural mapping of a gabbro-anorthosite pluton near Pasupugallu reveals concentric, helicoidal and inward dipping magmatic/tectonic foliations suggesting syn-tectonic nature of emplacement involving dextral transpressional tectonic regime (Nagaraju and Chetty, 2005). The geochemical characteristics of the pluton indicate that they belong to low potassium island arc tholeites supporting the subduction related magmatism (Nagaraju and Chetty, 2006). Further, AMS studies together with field structural observations of the pluton suggest that the magma has been emplaced into a chamber (dilational jog) induced by crustal-scale dextral transpressional tectonic regime (Nagaraju et al., 2008). Recent geochemical studies of granite plutons of the TBSZ point to a significant event of Precambrian crustal growth and accretion in a late orogenic to anorogenic set up to a possible collision boundary (Sesha Sai, 2013). It is also suggested that plutonism is favoured when the tangential component of convergence is large.

The TBSZ has been considered as the southern extension of the SSZ and a cryptic suture with an eastward dipping thrust (Subrahmanyam, 1978; Chetty and Murthy, 1998b; and the references there in). The TBSZ is characterized by bipolar gravity anomaly with a relative gravity high over the EGMB and a low over the eastern part of the Cuddapah basin (Singh and Mishra2002). The available seismic profile across the TBSZ is along Alampur-Koniki, which reveals major east dipping thrust. Based on geophysical signatures, the Moho is estimated at a depth of 35km in the region and that it increases to 39-40km in the west underneath the Cuddapah basin.

EGMB (central)

The central part of the EGMB represents the widest and the most complex part of the belt marked by the presence of three important crustal-scale shear zones viz; Nagavali shear zone (NSZ) and Vamsadhara shear zone (VSZ) besides the SSZ at the western margin (Fig.7). The shear zones are prominently observable on the satellite images and are marked by closely spaced lineaments with distinct tonal variations and linear alignment of structural fabrics. While the VSZ is a straight feature, the NSZ is sinuous, swerving to southeast to merge with the VSZ in the south before they disappear in the Bay of Bengal. Both the shear zones trend N-S at an angle to the regional trend of the EGMB and vary in their width from 2 to 10 km. They extend for about 150km strike length and coalesce with the SSZ in the north. The SSZ is well defined in the southern part exhibiting sharp boundaries and it is diffused in the north by the presence of upthrusted granulite facies rocks of the EGMB. The NSZ and VSZ comprise voluminous occurrence of megacrystic gneisses, quartzofeldspathic gneisses respectively with mappable enclaves of charnockites, khondalites and mafic granulites. The

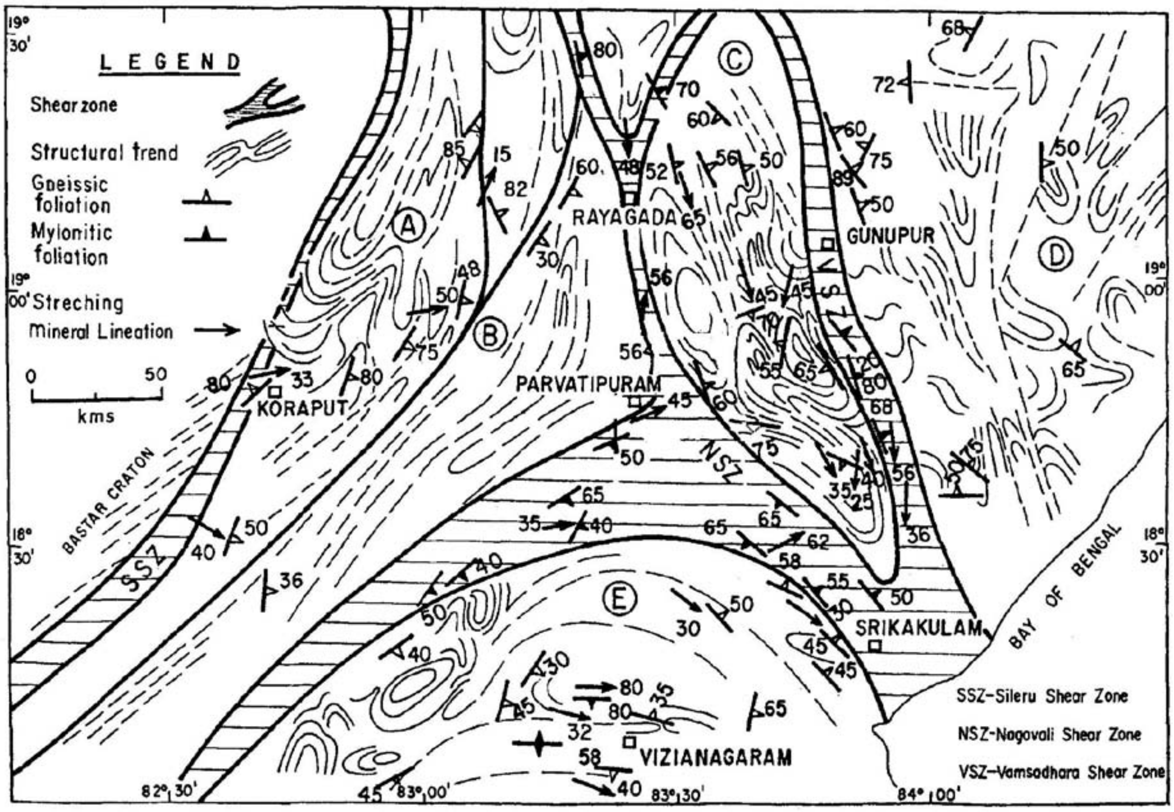


Figure 7. Regional tectonic framework of the EGMB (central) showing the major shear zones: Sileru shear zone (SSZ), Nagavali shear zone (NSZ), Vamsadhara shear zone (VSZ). Note the variation in the thickness of shear zones and their mutual connections. Please note the variations of fold styles and the geometry of structural trends in different structural domains. (See the text for details) (modified after Chetty et al., 2003)

enclaves are mostly deformed and aligned sub-parallel to the regional gneissic foliation. The leucogneisses occur as thin parallel bands, small lensoid bodies and sometimes as small mounds and ridges. Interestingly the leucogneisses are predominant in the central part of the NSZ and the foliations wrap around these bodies. The isolated and fragmented bodies of charnockitic and khondalitic group of rocks occur as enclaves on all scales from meso- to as large as mappable extension within the megacrystic gneisses suggesting their intrusive nature. Complex fold forms and curvilinear structural trends mark the presence of major non-cylindrical folds in the southwestern sector across the NSZ around Parvatipuram (Chetty et al., 2003). The structural trends mainly conform to the lithological contacts between the folded quartzite horizon and the migmatitic/ megacrystic gneisses (both hypersthene and biotite bearing) in the widened part of the NSZ around Parvathipuram. The early formed gneissic foliation is well preserved with the alignment of megacrysts (dominantly K-feldspar), generally lying parallel to the boundaries of shear zones. The gneissic foliation shows moderate to steep dips and the mylonitic foliation is invariably steep suggesting its development later superimposed on the earlier fabrics. However, both of them often lie subparallel to each other indicating the role transpositional fabrics. Mesoscopic shear zones are common in megacrystic gneisses. The feldspar porphyroclasts exhibit rotated and winged shape of kinematic indicators suggesting dextral kinematic sense of movements (Fig.8). The VSZ is characterized by the presence of quartzofeldspathic gneisses in the form of linear alignment of ridges with typical metamorphic foliation/lithological banding.

The terrane between the two shear zones occurs in the form of a lensoid form, the longer axis being in north-south direction. A variety of highly asymmetrical fold forms and elongated closed structural forms occur between the two shear zones (see Fig.7). Both the shear zones are marked by tight to isoclinal folds, steeply dipping mylonitic foliations

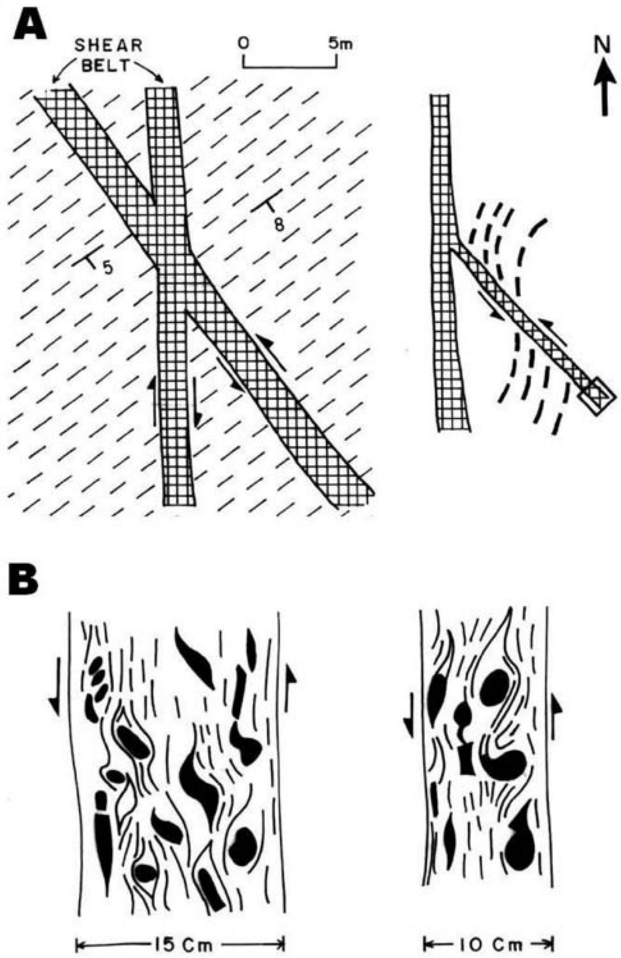


Figure 8. Field sketches showing (A) mesoscopic shear zones and (B) deformed porphyroclasts , exhibiting dextral sense of kinematics from the northern part of Nagavali shear zone.

and gently plunging stretching lineations and show dextral sense of regional transpressive deformational history of the EGMB (Chetty et al., 2003). The megacrystic gneisses and quartzofeldspathic gneisses in these shear zones are characterized by high-degree of parallelism between compositional layering and foliation, "σ" type polymineralic aggregates etc. These kinematic features indicate non-coaxial dextral shear sense of movements along the shear zones during transpressive orogenesis. The close association of megacrystic gneisses and quartzofeldspathic gneisses from the NSZ and VSZ with the metasedimentary rocks like khondalites, quartzites and calc-silicate granulites, alignment of the metasedimentary enclaves parallel to the foliation of the host gneisses indicate the derivation of the high-grade gneisses due to partial melting of the metasedimentary assemblage. The melts introduced during the hydrothermal phase of intrusion has migmatized the metasedimentary assemblage resulting in the formation of megacrystic gneisses and quartzofeldspathic gneisses. The central part of the EGMB can be divided into five distinct structural domains (A-E) separated by shear zones (see Fig.7). Each domain is characterized by distinct styles of folding and the geometry of structural fabrics. The domains are characterized by closed structural fold forms and flat to moderately dipping gneissic foliations.

A few other important and relatively narrow shear zones are also delineated in the block between the VSZ and the Mahanadi shear zone (MSZ) (see Figs.1&2). They include: (i) Baligurha-Tel shear zone, (ii) Chilka lake shear zone, (iii) Digapahandi shear zone, (iv) Aska-Taptapani shear zone, and (v)Bhanjanagar shear zone, and the details are described below. The Baligurha-Tel shear zone

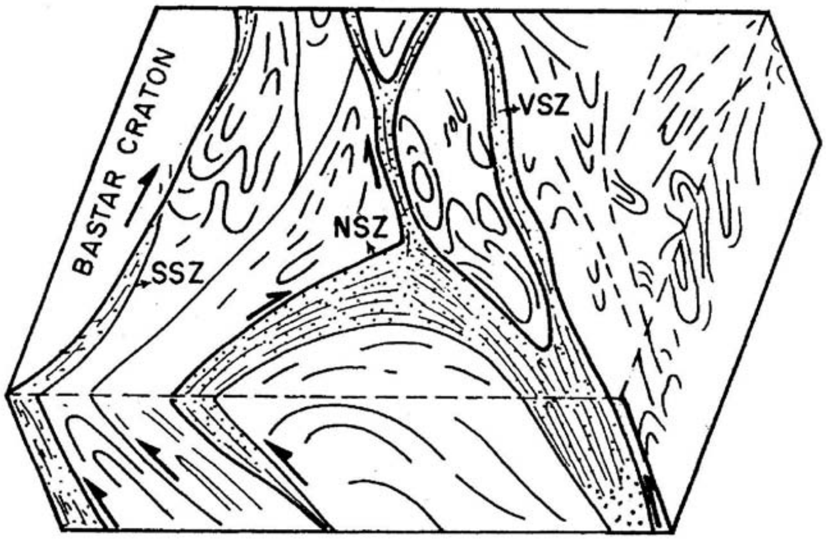


Figure 9. Field sketches showing (A) mesoscopic shear zones and (B) deformed porphyroclasts , exhibiting dextral sense of kinematics from the northern part of Nagavali shear zone.

(BTSZ) , subparallel to the VSZ, occurs to the east of VSZ and merges with the SSZ near Sonapur. It is typically dominated by brittle shearing. In general, the triangular block lying between the VSZ and the MSZ is dominated by migmatitic gneisses, retrogressed charnockitic rocks, megacrystic gneisses and isolated and intensely deformed khondalitic group of rocks in the order of abundance. The early formed structures in the region seem to be near east-west or NE-SW, which are overprinted by N-S brittle shearing.

Chilka lake shear zone strikes NE-SW with a length of about 100km passing through Chilka lake igneous complex and extends upto Cuttack to join with the MSZ (No.4, Fig.1). According to Moharana (1982), all the anorthosites bodies are confined to the shear zone. Mesoscopic shear zones and localized zones of intense deformation and boudin formations are common with in these rocks (Bhattacharya et al., 1994). Digapahandi shear zone, subparallel to Chilka lake shear zone, also follows similar geometry and joins the MSZ (No.5, Fig.1). Porphyritic megacrystic gneisses are predominant along this zone. Aska-Taptapani shear zone (No.6, Fig.1) also trends NE-SW and merge with MSZ similar to other shear zones, but ends against the BTSZ in the west. Bhanjanagar shear zone (No.7, Fig.1) seems to be relatively thinner compared to other shear zones. It trends near E-W and underlies the Phulbani charnockite block together with the MSZ. Brittle deformation appears to be dominant in Phulbani block. All the above shear zones dip NW or north wards. These observations can be interpreted as a stack of thrust sheets. Interestingly all these are connected and genetically interlinked to the east-west trending MSZ. However, it is challenging to determine the roots of these shear zones and their vergence which need further focused multi-scale structural studies.

Structural cross section

A three-dimensional block diagram (Fig.9) based on multi-scale structural observations exhibits the nature and geometry of all the shear zones in the central part of the EGMB. While the SSZ strikes NE-SW and dips to southeast (50^0-60^o), both NSZ and VSZ trend near N-S with steep dips. The NSZ is marked by the presence of voluminous megacrystic gneisses while intensely sheared quartzo-feldspathic gneisses define the VSZ. Both the shear zones show dextral sense of movements and merge together at both the ends. Lithological and structural variations across the shear zones exhibit distinctly different features suggesting a division of the central part of the EGMB into a number of structural domains bounded by major shear zones. The rocks in the interlying region between NSZ and VSZ show refolded isoclinal folds. It is interesting to note that the charnockites structurally overlie khondalites in the central part, while they underlie khondalites and megacrystic gneisses at the western boundary of the VSZ. These

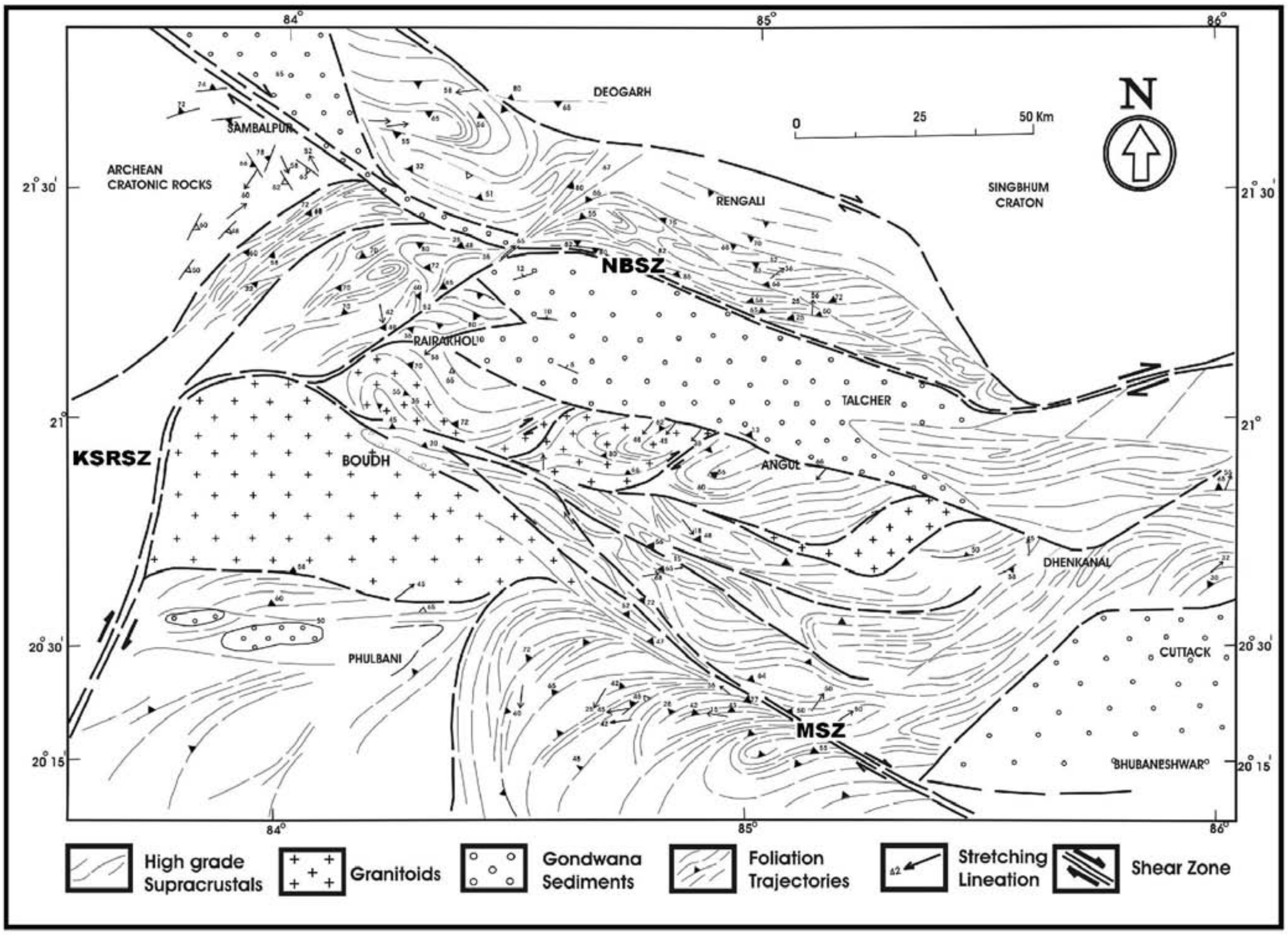


Figure 10. The structural architecture of the EGMB (north) showing regional lithological distribution, shear zone network, distribution and trends of structural fabrics and kinematic displacements. Note the consistent dextral displacements along E-W shear zones as well as along the NE-SW striking Riedel shear zones. NBSZ – Northern Boundary shear zone; KSRSZ – Koraput- Sonapur- Rairakhol Shear zone; MSZ – Mahanadi Shear zone and the other link shear zones (after Chetty, 2010).

observations clearly suggest all these rocks are folded together exhibiting thrusts and nappes and related complex fold structures suggesting thrust related tectonics involving collisional processes. Further, the domain lying between NSZ and VSZ has been interpreted to represent a possible mega-duplex (Chetty et al., 2003). All the features described above suggest west directed thrusting in the early part of the tectonic history of the EGMB.

EGMB (north)

The northern parts of the EGMB, covering the Mahanadi rift structure and the adjacent regions, forms significantly a composite terrane of high grade metamorphic rocks (Chetty, 2010). In contrast to the regional NE-SW trend of the EGMB, the rocks in the region trend east west in the form of a major block structure (120x50km) with a composite network of shear zones (Fig.10). The region comprises high-grade orogen core and the Permo-carboniferous Gondwana sedimentary basins. The major rock units include charnockitic and khondalitic gneisses , which have been variably migmatised and retrogressed. These are separated from the 3.4 Ga old rocks of the Singhbhum craton in the north by a crustal- scale shear zone described here as Northern Boundary Shear Zone (NBSZ). The NBSZ has been earlier described differently by different workers: Kerajung fault (Nash et al., 1996), Northern Orissa Boundary fault

(Mahalik, 1994).The NBSZ extends and coincides with the popularly known chromite bearing Sukinda thrust in the east. This zone is well known for its close proximity with Lower (Permo-carboniferous) Gondwana basins of Talcher and Ib River. The Koraput-Sonapur-Rairakhol shear zone separates the Bastar craton in the west while Mahanadi Shear Zone (MSZ) marks the boundary of the composite terrane in the south. The other important shear zones that traverse the region include the domain boundaries as well as the oblique Riedel shear zones and are described here as link shear zones, which are spatially connected to the boundary shear zones. Protracted deformational history ranging from Neoarchaean to Permo-carboniferous/ Cretaceous is well preserved along the boundary shear zones (Lisker and Fachmann, 2001; Chetty, 2010). The details of each shear zone are described below.

Northern Boundary Shear Zone (NBSZ)

The NBSZ marks the northern boundary of the EGMB and separates the Singhbhum craton (3.4Ga) to the north. It extends along near east-west direction with over 250km strike length and varying width (2-5km), often extending to ~15km in the central part (Fig. 11). The northern margin of the widened part has been earlier described as Riamal fault while the southern margin as Kerajung fault (Crowe at al., 2003). In the east, it coincides with Sukinda thrust hosting chromiferous- ophiolite dominated lithologies (Prasada Rao et al., 1964). A suite of ophiolitic differentiates in island arc environment that include gabbro-orthopyroxene-peridotite –dunite bodies with podiform to stratiform chromite occur along this suture zone (Banerjee et al., 1987). In the west, the NBSZ deviates from its main trend and extends in NW-SE direction and is closely associated with Lower Gondwana coal bearing sediments of Ib River to its north. In the central part it strikes east –west with a maximum width of ~15km and separates the Talcher Lower Gondwana basin to the south and the Rengali granulite facies rock domain to the north (Fig. 11b).

The NBSZ is characterized by sharp and conformable but intensely deformed quartzite ridges with a strike length of a few tens of kms and intense deformational features. The quartzites are, in general, cherty type and are closely associated with sericite schists, exhibiting intense folding, mylonitisation and intense fracturing. While the gneisses show gentle to moderate dips to south, mylonitic fabrics display steep and southerly dips. North verging tight to isoclinal folds with gentle plunges on either side are common. Thin linear bands of basement slivers sandwiched between two bands of cherty quartzites exhibit high strain fabrics. East-west kinematic displacements are often marked by dyke emplacements. Gondwana basins that are associated with the NBSZ are inferred to be the resultant product of dextral displacement kinematics and the development of pull apart type basins (Chetty, 1995b).

The NBSZ could represent a lateral ramp allowing the granulite facies rocks of the EGMB to be transported north wards on to the Singhbhum craton giving rise to Rengali domain (Chetty, 2010). The presence of K-feldspar phenocrystic granite and k-feldspar augen gneiss along the NBSZ suggests the ca 980Ma representing the minimum time constraint for the initiation of the NBSZ (Crowe et al.,2003).This implies that the NBSZ must have been initiated as dextral transpressional shear zone during Grenvillian time. Reactivation deformational event during 490-470Ma along the NBSZ was inferred based on Ar-Ar plateau ages for white mica and biotite derived from pervasively retrogressed mylonites (Dobmier and Raith,2003). This event must have been dominated by transcurrent dextral shearing, subsequent faulting and displacement in coal deposits of Lower Gondwana basins of Talcher and Ib River, which confirms brittle reactivation of the NBSZ during Permo-carboniferous period. Available AFT ages of zircons along the NBSZ suggest a long residence time and slow cooling of the metamorphic basement rocks during 400-300Ma (Lisker and Fachmann, 2001)

Mahanadi Shear Zone (MSZ)

The MSZ, a first order tectonic feature, represents the southern boundary of the EGMB (north) (see Fig. 10). It trends for over 150km (2 to 8km wide) in WNW-ESE direction , subparallel to NBSZ, and occurs all along the Mahanadi River course, which is well reflected in Satellite image (Fig. 12a) in the form of a series of parallel strike ridges of spectacular outcrops of ultramylonites. The predominant rock types along the MSZ include khondalites and charnockites which are invariably retrogressed, migmatised and mylonitised. Pseudotachylite veins of

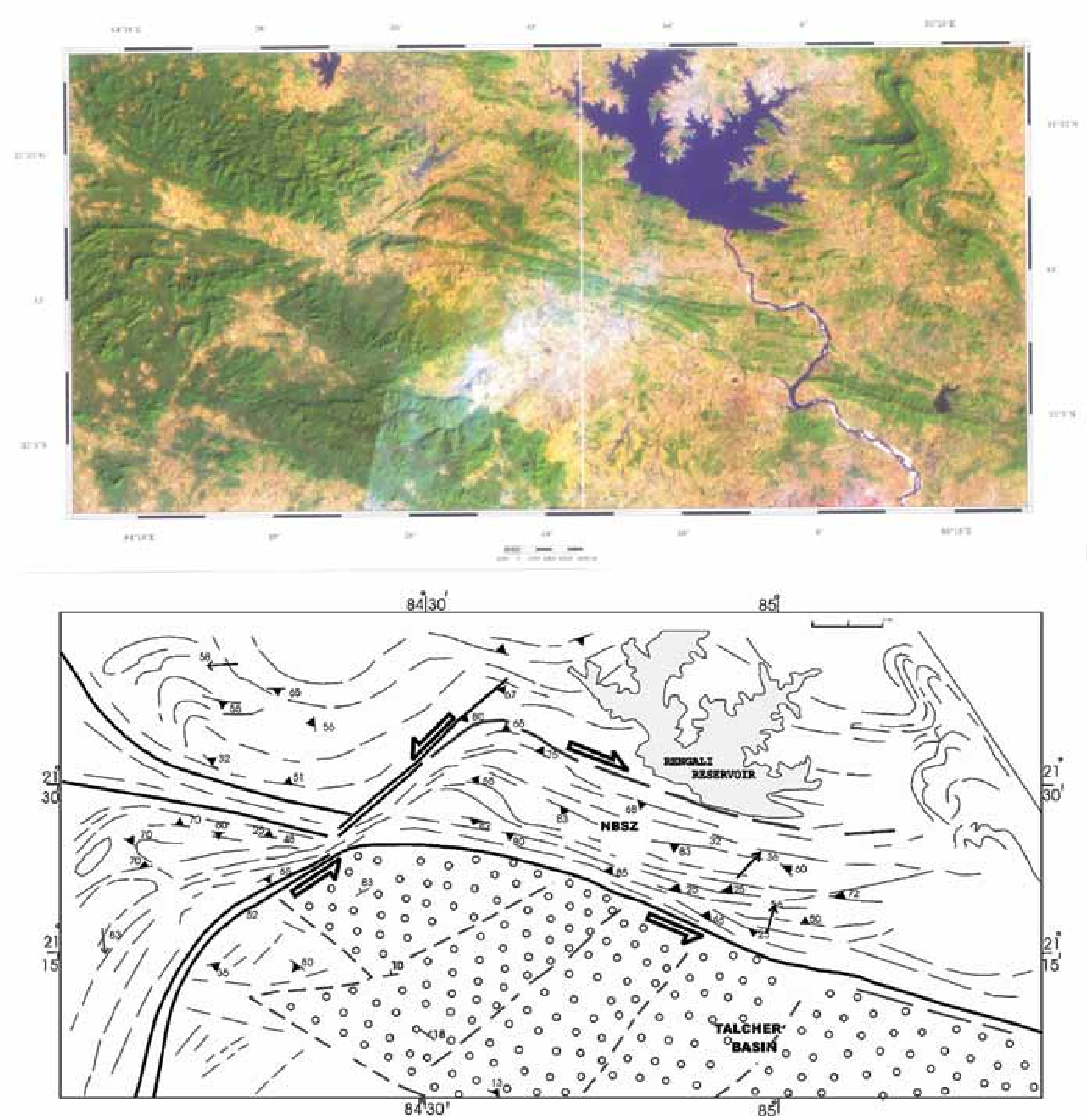


Figure 11. Map showing (A) Northern Boundary Shear Zone (NBSZ) as reflected in Landsat Thematic Mapper data; and (B) the structural interpretation derived from the satellite image given in (A). Note the tonal characteristics of Rengali reservoir and the Talcher basin.

10cm wide criss-cross the outcrops of ultramylonites (Chetty, 2010 , Mahapatro et al.,2012). The field observations indicate that the MSZ extends along WNW-ESE direction and dips around 50º to north (Fig.12b). However, the dips vary from relatively gentler (30º-50º) in the eastern part to steep values in the western part. The stretching lineations are well developed and are predominantly down-dip in nature. The early fold structures with N-S trending axial planes (F1/F2), which can be ascribed to 2.8 Ga event, have been rotated to near E-W and finally converging with the WNW-ESE trend of MSZ. This kind of deflection of fabric trajectories strongly indicates large strains of dextral kinematic displacements (Fig. 12b).

(A)

(B)

Figure 12. (A) Landsat Thematic Mapper data image along the Mahanadi Shear Zone (MSZ). Note the river course of Mahanadi and the structural fabrics in rocks on either side; (B) Structural interpretation of the Satellite data around the MSZ. The dotted ornamentation indicate metasediments, dots with thicker dots indicate metaigneous and the rest shows migmatites. Note the deflection of foliation fabrics becoming sub parallel to the mylonic fabrics of the MSZ, suggesting dextral kinematics.

The orientation and geometry of fabrics on either side of the MSZ are distinctly different with characteristic fabrics defining sigmoidal lenses indicative of a dextral component of shearing.

The MSZ branches off into several splay shear zones in the west; the dominant one along NW-SE direction wrapping round the northern boundary and the others extend towards west, joining the southern boundary of a large megacrystic granitoid body at Boudh (see Fig.10) The later shear zone has been described as Ranipathar shear zone (Nash et al., 1996). It is interesting to note that this granite body appears more massive and internally less deformed and envelopes all the splay shear zones that emerge from the MSZ. This granite body has yielded a SHRIMP Zircon age of ca 980Ma (Crowe et al., 2003), which is consistent with similar ages for megacrystic granites elsewhere in the EGMB (Kovach et al.,1998). Intense overprinting reactivation was recorded along the Ranipathar shear zone indicated by $^{40}Ar/^{39}Ar$ biotite date of 504 Ma (Crowe et al., 2001). Two isolated and E-W oriented Upper Gondwana basins occur in between two major fracture zones in the close proximity of Ranipathar shear zone (see Fig. 10). However, it is interesting to note that all the splays of the MSZ coalesce finally with the KSRSZ in the west. In the east, it is relatively narrow and well defined extending upto the east coast. A few NE-SW trending oblique shear zones emerge in the east apparently controlling the development of rhombohedral shaped upper Gondwana Athgarh basin. Interestingly, 117 Ma old mafic dyke located at Naraj, intrudes these sediments (Lisker and Fachman, 2001).

Koraput- Sonapur-Rairakhol Shear Zone (KSRSZ)

The KSRSZ forms the northern extensions of the Sileru shear zone of Chetty (1995a) and marks the western boundary of the study region. It strikes for over 70km long in NNE direction with a width of 1-3km and traverses further through Rairakhol. The KSRSZ exhibits an eastward dextral shift of ~10km and restricts the western extensions of Sonapur megacrystic granite as well as the western contact of Talcher basin (see Fig. 10). The rocks to the west of Rairakhol are described as Badarama complex which show similar characteristics as those of Rengali province. The structural fabrics of contrasting geometries occur on either side of the KSRSZ.

At the northern end of the shear zone, foliations show remarkable deflections mimicking the sinistral character with a displacement of a few km. Further north, the presence of shear zone gets diffused along the western contact of the Rengali domain and finally disappear further north in the Singhbhum craton. The shear zone, in general, dips at moderate to steep angles to southeast with strike parallel to oblique stretching lineations. A few small nephelene syenite bodies (1413 Ma, Rb-Sr) associated with non-feldspathoidal syenites are located in the proximity of KSRSZ around Rairakhol (Panda et al., 1993). The country rocks around these bodies include the interbanded sequence of quartzites, khondalites and charnockites.

Link shear zones

The link shear zones occur between the boundary shear zones of NBSZ and MSZ (Fig. 10) and are described here as the domain boundary shear zones and a distinct oblique set of NE-SW trending Riedel shear zones, which are interlinked together. The domain boundaries are characterized by intense shearing and migmatisation. Angul-Dhenkanal shear zone, the most striking domain boundary, occurs at the southern contact of the Talcher basin. The shear zone is 2-3km wide and ~200km long with broad southerly steep dips hosting many satellite bodies of alkaline rocks (Panda et al., 1993). Reactivated basement lithologies and a few preferably located dykes are also exposed along the zone. The time of granitic intrusive activity along the zone is around 850Ma (Rb-Sr muscovite mineral age, Halden et al.,1982).

The shear zones within the Tikarapara domain coalesce with the MSZ and KSRSZ in the west, while they get deflected towards NE converging with the geometry of Riedel shear zones and finally get terminated against the NBSZ in the east. These zones are relatively narrow and the strain partitioning is well reflected in the form of distinct sigmoidal foliation geometries, consistent with the dextral displacements. Intense recrystallization and reorganization of foliation and associated pegmatitic activity is often recorded. While the shear zones at the domain boundaries are steep, the shear zones in Tikarapara domain show moderate to steep dips to north. These are characterized by well developed early high grade ductile mylonitic fabrics with quartz and feldspar aggregate ribbons. They are superimposed by brittle shearing at several places often displaying fault gauge and fault breccia. All these observations suggest that repeated reworking had been a common feature of these shear zones with varied deformational environment. The geometric relationships of foliation trajectories, sigmoidal shaped enclaves and other kinematics indicate dextral shearing.

Lithostructural domains

The EGMB (north) constitutes many lithostructural domains of basement rocks separated by east-west trending shear zones described above. From north to south, the distinct domains include: Rengali domain, Angul domain, Tikarapara domain, and Phulbani-Daspalla domain (Fig. 10). The geology of each domain is detailed below.

Rengali domain

The Rengali domain, a triangular shaped region north of the NBSZ, is bound by shear zones on all sides. It comprises granulite facies metamorphic rocks namely charnockites, orthogneisses, khondalites, quartzites, and a few small occurrences of isolated basic granulites exhibiting E-W trending tight to isoclinal folds with gentle to moderate dips to south. The pervasive gneissic foliation in the rocks has been superimposed locally by mylonitic secondary foliations recording lower amphibolite to greenschist facies metamorphism. The identical Pb-Pb zircon age of 2802+3Ma and SHRIMP age of 2801+10Ma, obtained for hornblende bearing orthogneiss have been interpreted to indicate crystallization of precursor granitoids suggesting the extensive magmatism at 2.8Ga within Rengali domain (Crowe et al., 2003). Syntectonically emplaced N-S and E-W oriented narrow dykes are common. Fachmann, (2001) reported Nd-isotopic signatures of TDM=2.1-2.7 Ga and a mineral isochron age of 792± 85Ma for the emplacement of later mafic dykes and interpreted them in terms of varying contamination of the primary basaltic melts with Archaean crustal material. The Ar-Ar plateau age for hornblende indicates cooling below 500ºC at 699 ± 8Ma indicating retrogression to amphibolite facies (Crowe et al., 2001). The available age data shows that the protoliths of Rengali domain yielded Archean ages (~3.o Ga) and the event at 2.8Ga denotes a major tectonothermal event, followed by isolated mafic dyke activity around 0.8Ga. The 2.8Ga metamorphism had a peak P-T regime of 9.5Kb at 950ºC followed by post-peak isobaric cooling through 200º-350ºC at 8.5-9.5Kb (Kar, 2007). Fission Track ages between 270±13Ma and 252±9Ma suggest that Rengali domain entered the partial annealing zone for apatite (120º-160ºC) during Late Permian (Lisker and Fachmann, 2001).

Angul domain

The Angul domain, bound by shear zones on either side, extends in an east-west direction, south of Gondwana sediments of Talcher basin. A distinct oblique set of NE-SW trending shear zones, akin to Riedel shear zones, links the domain boundary shear zones defining dextral regional scale lozenge shaped geometries, which are often occupied by coarse grained granitoid bodies. The host rocks include khondalites, charnockites and basic granulites accompanied by extensive migmatisation. Detailed geology around Angul can be found in Halden et al (1982). The early L-S fabrics of 2.8Ga are best preserved locally in high grade assemblages where coaxially refolded compositional layering is evident. The initial subhorizontal foliations are largely obliterated by intense transposition and folding into steeper mylonitic fabrics. A few narrow (1x10m) mafic dykes are also recorded which are restricted to narrow shear zones within the domain. Megacrystic granitic gneisses with enclaves of charnockitic and khondalitic rocks are also common displaying dextral transpressional kinematics.

These shear zones are mostly marked by pegmatites and associated migmatites. Muscovite from such pegmatites has yielded Rb-Sr age of 854±6Ma (Halden et al., 1982) and amphiboles gave rise to ^{40}Ar-^{39}Ar age of 854±4Ma (Lisker and Fachmann, 2001), which can be related to granite magmatism and migmatisation in the domain. The Grenvillian peak metamorphism (M2) in the basement rocks was followed by slow cooling and thermal overprinting during the Pan-African event and represented by the development of 512 Ma old psuedotachylites (Lisker and Fachmann, 2001). This event, which is extensively recorded in the entire EGMB, perhaps represents reactivation of regional shear zones in the region.

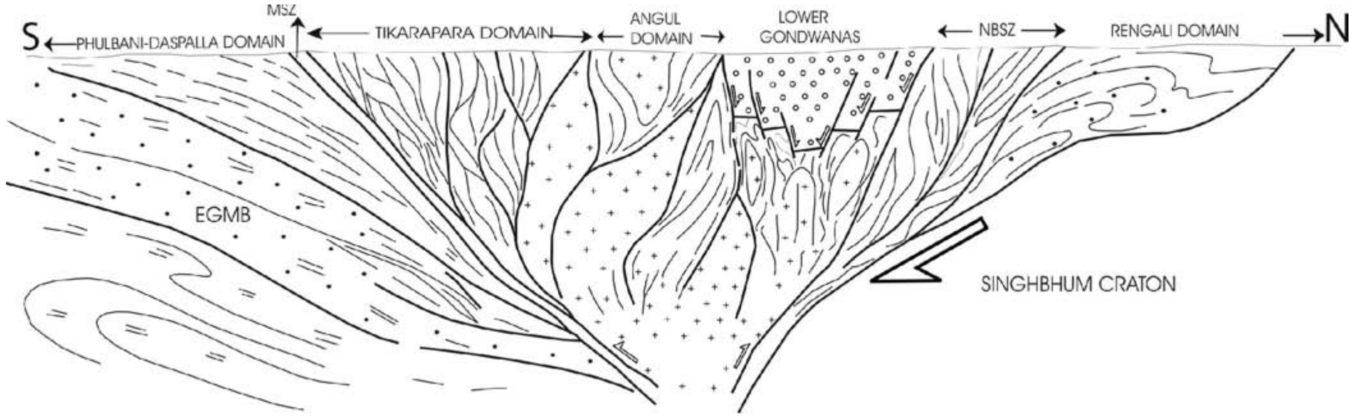


Figure 13. An interpretative north-south structural cross section across the different structural domains of the EGMB (north) displaying a crustal - scale' flower structure'. Note the change in geometries of shear zones and the variation in structural fabrics, emplacement of granitoids and extensional faults associated with the Gondwana sediments of Talcher basin. (after Chetty,2010).

Tikarapara domain

This domain occurs between the Angul domain and the Mahanadi shear zone. The major rock types include khondalites, charnockites, basic granulites, quartzites and calc-silicate rocks with occasional Pegmatites and quartz veins. Pseudotachylites of the domain yield ages of 550Ma representing large scale transcurrent shearing. Unlike in other domains, the foliations in this domain dip with moderate to steep angles to north. Stretching lineations and mesoscopic fold axes consistently show ESE gentle to moderate plunges with open to tight folding subparallel to the trend of major shear zones. Reorientation and reorganization of foliation geometries into sigmoidal shapes are the characteristic features indicating consistent transpressional dextral displacement history in the domain. Broadly, the internal fabrics and the boundary shear zones of the Tikarapara domain define a south verging 'half flower structure'. The occurrence of upper Gondwana Athgarh basin in the eastern part of the domain seems to be strongly controlled by NW-SE trending MSZ and NE-SW trending Riedel shear zones.The AFT ages from the eastern part of the domain yield 318±18Ma and 315Ma point to a continuous slow cooling without any major influence during Gondwana rifting/basin formation (Lisker and Fachman, 2001).

Phulbani –Daspalla domain

This domain, an integral part of the EGMB, occurs to the south of the MSZ and to the east of the KSRSZ. The domain extends in an east-west direction but lithological and structural characteristics differ in the east and in the western parts. The western part is dominated by quartz-pyroxene-granulite grade association, mafic granulites, charnockites and migmatites. They display near NE-SW trends with steep westerly dips, often associated with domal structures in the central part. Two small isolated upper Gondwana basins also occur a few km west of Phulbani. The rocks in the eastern part of the domain are mostly migmatitic and seem to be structurally underlying the rocks of the western part. While retrogressed migmatites and megacrystic granitoids are common in the region, large scale folds defined by the gneissic foliations are predominant with fold axes plunging at gentle to moderate values towards northwest. The stretching lineations plunge westwards and gradually change to SW. The early folds have been dragged, rotated and stretched parallel to the MSZ, indicating dextral transpressional tectonics.

Crustal cross section

A north-south trending crustal cross section across the composite terrane of the EGMB (north) (Fig. 13) reveals the geometry, disposition and nature of shear zones, and the distinct lithological domains. North verging nappes and related fold structures are common in Rengali domain with horizontal to gently dipping structures to south. Although , the nature of this domain is debatable, the field observations suggest that the Rengali domain must have been a part of the EGMB and that it is transported on to the Singhbhum craton from south through north verging NBSZ thrust that acts as a ramp (Chetty, 2010). The Talcher basin is in contact with the Angul domain in the south, which is characterized by intense migmatisation and steep dips, intruded by 980Ma old megacrystic granitoids. The basement seems to have been reworked giving rise to syntectonically emplaced and deformed oval shaped granitoids displaying dextral kinematics. The Angul domain, the axial part of the orogen core, forms the central part of the cross-section overlying the granitic magmatism where the shear zones seem to merge together at depth.

Tikarapara domain is characterized by intricately folded and intensely imbricated south verging structures with dominant northerly dips. This domain is bound by south verging thrust, described here as the MSZ. Considering the geometry and disposition of NBSZ and the MSZ and other complimentary shear zones and their temporally consistent dextral kinematics, it can be inferred that the study region of EGMB (north) represents a typical crustal-scale 'flower structure'.It is inferred that the Rengali domain represents north verging collisional front beyond the NBSZ. The NBSZ has been reactivated in a dextral transpressional tectonic regime, which perhaps continued upto Pan-African times. Subsequently, the first phase of rifting must have developed giving rise to progressive evolution of Gondwana basins in the region. The north dipping MSZ and north verging NBSZ merge together at depth in the form of a detachment zone giving rise to extensive granitoids in the axial zone of the composite terrane. The MSZ must have been initiated initially as a south verging complementary thrust emanating from the south dipping NBSZ. Both the shear zones have been subjected to protracted dextral transpressional tectonics during Grenvillian and upto the Pan African period. It is emphasized here that the NBSZ and MSZ may represent the boundaries of the broad structure of Mahanadi rift where rifting processes were superimposed over the preexisting tectonic zone giving rise to the development of normal faulting, sedimentation, deposition and magmatism.

REGIONAL SYNTHESIS

Shear zones

The net work of shear zones is strikingly the most prominent deformational feature in the EGMB. They occur both at the margins as well as in the internal parts. They represent wide and linear geomorphic expressions mostly coinciding with the major river courses and hence they are named after them (Chetty and Murthy, 1993; 1994; 1998a). The shear zones are well reflected in satellite images with closely spaced lineaments and characteristic tonal variations. Field observations such as the presence of mylonites, highly asymmetrical folds, S-C fabrics and well developed stretching lineations confirm the presence of shear zones. The margins of the EGMB are marked by major ductile shear zones hosting alkaline magmatism, anorthosites, and extensive migmatisation and retrogression. These zones vary in width from 2 to 20km and extend along the strike length for a few hundred km. The Sileru shear zone (SSZ) occurring at the western boundary of the EGMB, varies in width from 3 to 10 km and extends to a strike length of 500 km. (Fig. 2). The SSZ shows foliation with an average dip of about 50º to SE and is interpreted as a northwest verging thrust. Alkaline magmatism ranging in age from 1250 Ma to 650 Ma (Upadhyay, 2008) along the SSZ is centred at a few places along the SSZ covering the total length. All the alkaline plutons are confined to the SSZ and its extensions to north and southwards. The emplacement history of these plutons has been widely debated. Some workers (eg., Chetty and Murthy, 1994, 1998; Biswal et al.,2007) believe that the alkaline plutons are syntectonically emplaced, while others describe post emplacement deformation and shearing developing solid-state metamorphic fabrics (eg.,Gupta, 2004; Upadhyay and Raith, 2006). Vijayakumar et al., 2008; reported that the parental magma must have been derived from partial melting of the enriched mantle sources. Gravity anomalies over SSZ are strongly negative, rising sharply upto the axial zone and then becoming increasingly positive towards the eastern boundary (Subramanyam and Verma, 1986). Geological and geophysical characteristics suggest that the SSZ could be a Precambrian suture zone (Subramanyam, 1978; Chetty and Murthy, 1998b), extending to lithospheric –mantle depths. The SSZ also extends northwards to join the NBSZ and southwards to join the CSZ. It also implies that there must have been multiple events of accretion, which is a common feature of many ancient accretionary systems. However, the present structural architecture represents final amalgamation history related to the assembly of Gondwana super continent during Neoproterozoic-Cambrian period (Chetty and Santosh, 2013).

The shear zones in the EGMB (south) trend NE-SW, subparallel to the regional trend of the EGMB. The shear zones, while in the EGMB (north) they srike east-west exhibiting sharp change from that of the southern part. The northern boundary shear zone of the EGMB is characterized by strike-slip movement which has led to the evolution of Mesozoic Gondwana basins (Chetty, 1995b). In contrast to the boundary shear zones in the west and the north, the shear zones in the EGMB (central) are unique and trend nearly north-south hosting the granitoids of ~900 Ma age (Kovach et al., 1997). It is not clear, however, as to whether the steeply dipping (at the surface) shear zones (NSZ and VSZ) pass down into a flat lying thrust system. This can be resolved only by deep reflection seismic profile studies. Considering the lithotectonic trends and metamorphic history, these shear zones are interpreted to have been extended into the Enderby Land of east Antarctica (Chetty, 1995a). In view of the significance of the shear zones , integrated geophysical studies including the seismic reflection studies are essential to have comprehensive geodynamic understanding of the EGMB. This is only region suitable for such studies because of the accessibility exposing major geological and tectonic features.

The deformational history of the EGMB can be divided into two major events: the first, is marked by northwest verging thrusts giving rise to large-scale recumbent fold structures and other flat lying fabrics associated with crustal thickening and granulite facies metamorphism around 2800Ma (Chetty and Murthy, 1994). The second event is recorded in the form of shearing preferably along the pre-existing thrust planes leading to magmatism and migmatisation around 1250-950 Ma. Pan-African event recorded around 500 Ma could possibly represent a reactivation event, most probably restricted to shear zones.

The reactivation tectonics in space and time seemed to have occurred along the major shear zones taking the advantage of their steep geometry associated with mylonitic fabrics. They have also helped in accommodating progressive transformation from transpression to transtension, particulary in EGMB (north). However, transpressional orogenesis seems to be a crucial common factor for later reactivation by rifting during Gondwana dispersal (Goscombe and Gray, 2008). The kinematic changes from a long lived transpressional tectonics to transtensional regime are consistent with a change in global geodynamics and pattern of mantle convection, responsible for the reconfiguration of Rodinia and its transformation into Gondwana (Brown, 2007).

Two contrasting data sets exist regarding the P-T-t history of the granulites of the EGMB. One, based on isobaric cooling paths that show anticlockwise trajectories, suggests magmatic underplating (e.g., Sengupta et al., 1990; Dasgupta, 1995; Shaw and Arima, 1996). The other, decompression paths showing clockwise trajectories imply models of collision tectonics (e.g., Lal et al., 1987; Mohan et al., 1997). However, it is not clear about the precise location of the analysed rock samples with reference to shear zones that provided these P-T-t histories. It is also not surprising to have contrasting P-T trajectories preserved in different orogenic belts (Brown, 1993). It is also possible to obtain a similar P-T trajectory from different tectonic settings in the same orogenic belt (cf. Dasgupta et. al. 1994). However, it should be noted that divergent opinions of P-T-t histories may be factual and may represent different terranes, which is supported from the P-T-t trajectories obtained from the rock types of Rayagada of the EGMB (Shaw and Arima, 1996). It has been well established that the rocks in the shear zones are affected by several processes such as partial melting, mixing of fluids that come from deeper levels, and strain variations. Geochemical and mineralogical changes are inevitable (Beach, 1976) and distinct differences may emerge between the sheared and non-sheared rock domains. This needs to be borne in mind while carrying out sampling and further laboratory studies.

Terranes

Terranes are the building blocks of orogenic belts. Their modern analogues include microcontinents, magmatic arcs, intraplate volcanic chains, accretionary subduction complexes and oceanic plateaus which are brought together by plate motions. Their motions are seldom simple orthogonal convergence envisaged in the Wilson cycle. The motions involve complex patterns, not haphazard but dictated by the changing vectors associated with lithosphere motion oblique to the plate boundaries and migrating triple junctions (Jones, 1990). Identification of fundamental crustal blocks has increasingly gained importance in reconstructing the sequence of events in the evolution of an orogenic belt. In recent years, several Precambrian orogenic belts were described as the constituents of juxtaposed terranes. For example: the Archaean southern west Greenland (Friend et al., 1988); Grenville Province of southeast Canadian shield (Rivers et al., 1989); Arunta Inlier high grade complex of Australia (Collins and Teyssier, 1989); Mesoproterozoic Sveconorwegian orogenic province of Scandinavia (Park et al., 1991); Superior province of Canada (Percival, 1990); Archaean Limpopo belt of South Africa (Rollinson, 1993); Lewisian complex of northwest Scotland (Kinney and Friend, 1997) etc. Recognition of terranes requires descriptive data on several aspects such as stratigraphy, petrological, geochemical, structural, geochronological and geophysical characteristics that define a tectonostratigraphic terrane. A terrane is a fault bounded package of rock of regional extent with distinctive geologic history (Coney et al., 1980; Schermer et al., 1984). It is recognised that the present spatial juxtaposition of terranes does not necessarily reflect their relative position prior to assembly.

For the first time, Chetty (2001) came out with the concept that the EGMB is a collage of juxtaposed terranes on the basis of network of shear zones, fold styles and stretching lineations and broad lithologies. The mineral stretching lineations, mostly defined by the elongation of mineral grains such as mica, hornblende, feldspar, sillimanite, quartz etc., display a systematic variation over distances across a few tens of kilometers). However, a closer examination reveals some regional consistency in the orientation of lineations bordered by the shear zones demarcating the individual tectonic domains (Fig. 14). These features suggest that the EGMB has not behaved as a single homogeneous unit of rock assemblages but as a few structural domains, distinguishable on the basis of orientation of stretching lineations. Different tectonic domains are characterized by distinct orientations of gneissic foliation exhibiting different fold styles, axial surfaces of early formed folds F1/F2, and stretching lineations. This further division of the EGMB is further substantiated by Rickers et al.,(2001) in identifying different crustal domains with distinct isotopic characteristics. The divergent P-T-t histories, the broad spectrum of geochronological data and our observations on contrasting structural orientations from different domains may support the applicability of terrane concept to the EGMB. Each terrane displays wide penetrative metamorphic fabric and development of metamorphic minerals to such a degree that original stratigraphic features and relations are obscure. The terranes in the EGMB are characterized by internal homogeneity and continuity of structure and independent tectonic style and history. The boundaries between terranes are fundamental discontinuities and are manifested with later magmatic activity. These boundaries provide linkages, constraining the age of terrane amalgamation. The characterization and description of these terranes/lithostructural domains/ crustal domains and their amalgamation history have been recently reviewed by many workers (Dobmier and Raith, 2003; Mukhopadhyay and Basak, 2009; Dasgupta et al.,2013). Another perspective has been proposed by Mahadevan (2013) that the EGMB may have been initiated by either a process of rifting or delamination of the SCLM exposing the crust to high thermal regimes in the asthenoshperic mantle.

From the available geological and geophysical information, it is possible that different terranes could represent different thrust nappes as allochthonous tectonic sheets representing a tectonostratigraphic terranes. The Balangir terrane has already been interpreted as a sheet of nappe emplaced onto the margin of a craton (Rath et al., 1994; Biswal et al., 1998). The marginal shear zones of the EGMB appear analogous in geometry to higher level structures developed in a thin-skinned thrust tectonic regime (Chetty and Murthy, 1998a). Many different geological and geophysical approaches are required to prove or to disprove the applicability of the terrane concept to the EGMB and the answers remain more in the field and in experimental laboratories.

The Eastern Ghats Mobile Belt (EGMB) of India is an important Precambrian orogenic belt and constitutes several major ductile shear zones both at the margin and within the EGMB as described above. Divergent P-T-t histories have been recorded leading

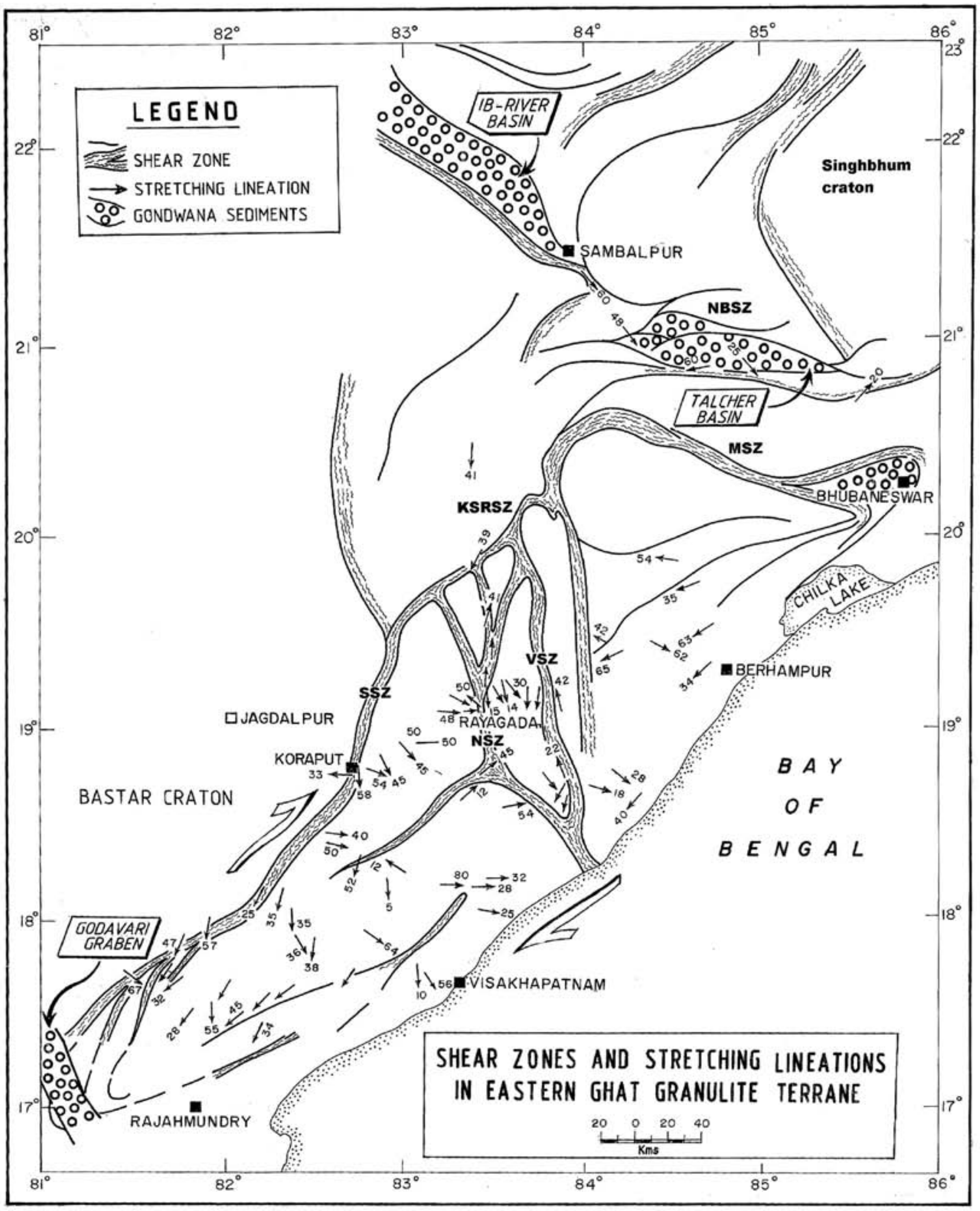


Figure 14. A network of deep crustal shear zones and the orientation of stretching lineations with in the EGMB. Note the consistent behaviour of stretching lineations in each of the lithostructural domain. Map showing the distribution of shear zones and stretching lineations (modified after Chetty, 2001)

to the interpretation of different tectonic histories (Dasgupta, 1995; Shaw and Arima, 1998; Mohan et al., 1997). Analysis of structures from different parts of the EGMB has resulted in the interpretation of structures as complex (Bhattacharya, 1996). Available geochronological data shows a broad spectrum of ages varying between 3000-450 Ma. However, a Grenvillian event of ~1Ga has been widely recognised throughout the belt (Grew and Manton, 1985; Paul et al., 1990; Shaw and Arima, 1996). Recent results also show significant tectono-thermal imprints of Pan-African age at several places (Yoshida, 1997; Bindu et al., 1998; Simmat and Raith, 1998). It is possible that different domains of the EGMB might have followed distinct evolutionary patterns during the early history, but share a common deformational history during the end Neoproterozoic, associated with the assembly of Gondwana.

GONDWANA CORRELATIONS

The EGMB forms a significant part of larger global orogenic belt system, considered to have developed as a result of the 1000 Ma collision between eastern India and a part of East Antarctica during the amalgamation of Rodinia (Hoffman, 1991; Fitzsimons 2001).

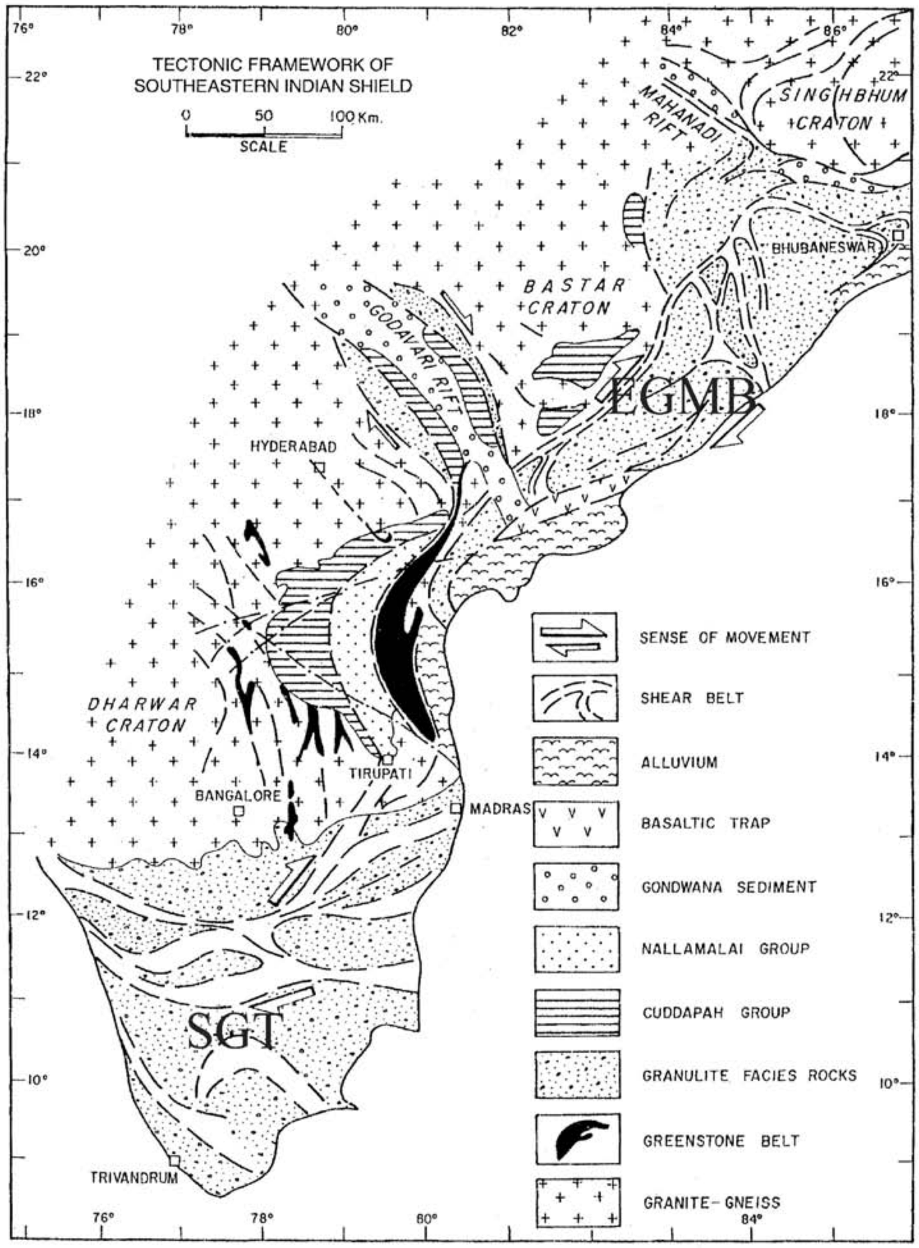
In the east Gondwana supercontinent, the Indo-Antarctic reconstruction model was essentially based on correlatable/extendable potential geologic piercing points across the conjugate continental margins. They include: major Neoproterozoic ductile shear zones (Chetty, 1995a; Chetty et al., 2003), Mahanadi rift and Lambert rift (eg., Federov, 1982) magnetic anomaly trends (eg.,Golynsky, 2007) and the Permian-Triassic ages and trends (Lisker, 2004). Detailed ocean floor topography through satellite altimetry (Sandwell and Smith, 1997) also supported this model.

Shear zones

The extension and the continuity of major shear zones through the EGMB and the Southern Granulite Terrain (SGT) is shown in Fig.15. The shear zones also pierce through the adjacent continents like Antarctica and Madagascar in a semicircular network interlinking all the Proterozoic orogenic belts around the Archaean Dharwar craton (Fig. 16). The prominent shear zones that connect the continuous network include the Nagavali-Vamsadhara Shear Zones (EGMB-central), Napier-Rayner Boundary Fault (Enderby Land, Antarctica), Cauvery Shear Zone (southern India) and Betsimisaraka Suture Zone (southern Madagascar). These shear zones are marked by Neoproterozoic (Pan-African) events of metamorphism and/or rejuvenation of pre-existing Archaean crust. These are characterized by the preexisting thrust structures, emplacement of granite and syenite plutons, and compressive convergent tectonics (Yoshida et al., 1996). Important observations of each shear zone are described below. The Nagavali-Vamsadhara shear zones (NVSZ) strike NNW-SSE and broadly divide the EGMB (central) into two parts. While the eastern part is correlatable with the Rayner Complex , the western part is with the Napier Complex of Enderby Land of east Antarctica (Chetty 1995 a). The NVSZ is also described as a major tectonic boundary separating the two crustal domains of distinct isotopic crustal history of Nd-model ages (Rickers et al., 2001). The granitic magmatism along these zones yielded 980-955 Ma (Kovach et al., 1997) while the Pan-African thermal overprint has been recorded in the rocks of NVSZ in the northern part (Shaw et al., 1997). The NVSZ represents piercing point and extends to the other Gondwana fragments to join the with the Napier-Rayner Boundary Fault (NRBF), Enderby Land, the interface of Napier and Rayner complexes in the structural frame work of Gondwana supercontinent. There are several geological similarities between the NVSZ and the NRBF. The NRBF trends nearly east-west and represents a shear zone (Kelly et al., 2002), predominantly comprising of migmatitic gneisses and granitoids of ~960 Ma and a reworking event of 500-550 Ma (Black et al., 1987). The NRBF also divides the Enderby Land into two terranes: the Napier Complex with Nd-model ages between 3.2 Ga and 4.2 Ga and the Rayner Complex with Nd-model ages lie between 1.4 and 2.4 Ga. However, the kinematic sense of the NRBF is not known. The Rayner Complex is also often compared with the EGMB (north of Godavari rift) of India based on geochronological signatures.

The NVSZ and NBRF continue to extend further to coincide with the Cauvery Suture/Shear Zone (CSZ) Southern Granulite Terrain , which is a 350 km long and 65 km wide east-west trending transpressional - dextral shear zone system (Drury and Holt, 1980; Chetty and Bhaskar Rao., 2006). Neoproterozoic reworking (ca. 730 Ma) has been reported along the CSZ based on a whole-rock-garnet-plagioclase-hornblende Sm-Nd isochron age from garnet granulite from Sittampundi anorthositic complex (Bhaskar Rao et al., 1996). The CSZ separates the Archaean Dharwar Craton to the north and Neoproterozoic granulites to the south and is marked by granitoids of ~780 Ma. Further, the CSZ and its extension into Madagascar in the form of Betsimisaraka suture zone (BSZ) , which were recently proposed as the trace of the Mozambique Ocean suture (Collins et al., 2007; Raharimahefa and Kusky, 2009; Santosh et al., 2009). The CSZ has also been correlated with the NRBF of east Antarctica (Harris et al., 1994; Yoshida 1995; Chetty 1995a).

The continuity of NVSZ–NRBF–CSZ–BSZ envelopes the Dharwar Craton in a semicircle fashion as prominently outward dipping shear zones suggesting the polarity of subduction to be away from the Dharwar Craton at least during the Neoproterozoic



After Chetty, 1999

Figure 15. Tectonic frame work of the southern Indian shield displaying the connectivity of the Proterozoic orogenic belts and associated shear zones of the EGMB and the SGT. Note the presence of Proterozoic and Gondwana sediments, schist belts and the Archaean cratonic rocks in the vicinity of orogenic belts (after Chetty, 1999).

(Chetty et al., 2003; Chetty and Santosh, 2013). The associated accretion and collision history suggest a possible east–west convergence between Dharwar and Tanzanian cratons leading to the shortening of hotter and softened lithosphere beneath (Martelat et al., 2000), controlling the strain partitioning at the scale of supercontinents (Rodinia and Gondwana). However, the differential kinematics along the shear zones and the precise timings need to be addressed in future studies. The common manifestation in the continuity of shear zones and associated structural fabrics and magmatism imply subduction–collision process in an oblique convergence associated with the assembly of Gondwana.

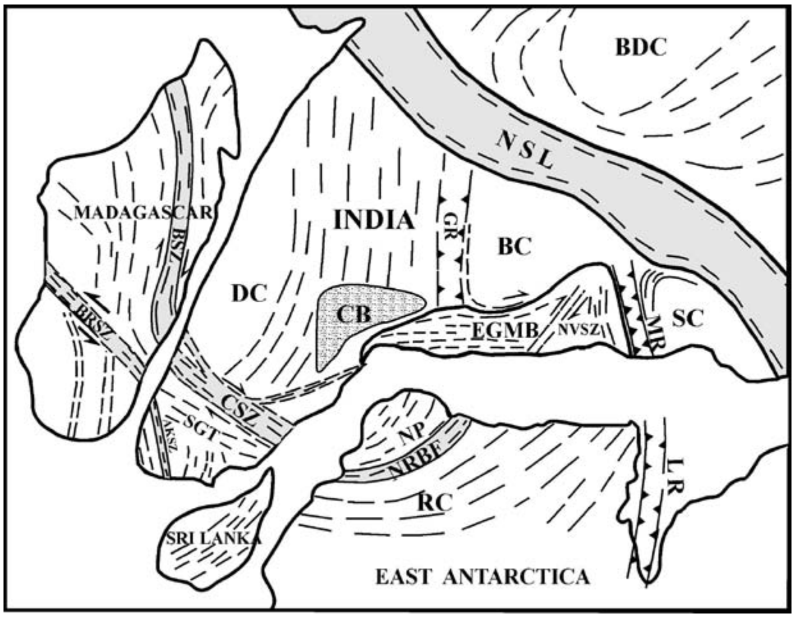


Figure 16. Reconstruction of East Gondwana supercontinent and the continuous shear zone network: NVSZ – Nagavali–Vamsadhara Shear Zone; NRBF – Napier- Rayner Boundary Fault; CSZ – Cauvery Shear Zone; BSZ – Betsimisaraka Suture Zone; BRSZ – Bongolava–Ranotsara Shear Zone; BDC – Bundhelkhand Craton; BC – Bastar Craton; SC – Singhbhum Craton; DC – Dharwar Craton; CB – Cuddapah Basin; NSL – Narmada–Son Lineament; GR – Godavari Rift; MR – Mahanadi Rift; LR – Lambert Rift; NC – Napier complex; RC – Rayner complex; EGMB – Eastern Ghats Mobile Belt; SGT – Southern Granulite Terrane (modified after Chetty ,1995a).

Rift structures

Mahanadi rift, India and the Lambert rift, East Antarctica represent two crustal- scale rift structures that were considered to represent a single Intra-Gondwana rift (eg.Hofmann, 1996). They show strikingly similar characteristics such as crustal thickness, sedimentation pattern, architectural features in the adjacent basement, kinematic and paleocurrent indications, stratigraphic and Palynological features and contemporaneous 500 Ma dyke magmatism (Lisker and Fachmann, 2001). The Mahanadi rift (MR), a part of ~600km long Son-Mahanadi valley, trends WNW-ESE and lies orthogonal to the east coast of India. The MR is associated with two Gondwana basins located on either side of the NBSZ. The southern basin is called as Talcher while the northern basin is termed as Ib River basin. The former is an east-west elongated basin with coal bearing Gondwana sediments. The basin is bound by longitudinal faults (normal type) parallel to the NBSZ and shows cross cutting NE- SW trending faults parallel to Riedel shear zones. There are also other small, isolated and elongated Mesozoic upper Gondwana basins that occur in the vicinity of MSZ. The occurrence of all these rift related basins, made this belt locally known as 'Mahanadi rift'. Two contrasting opinions exist regarding the origin and evolution of these Gondwana basins: one, as a consequence of strike-slip tectonic regime along a pre-existing shear zone in the basement (Nash et al., 1996; Chetty, 1995b) and the other non-tectonic regime where the basins are preserved as the faulted remnants of former widespread depression (Ahmad and Ahmad, 1976).

The Lambert rift (LR), a typical half-graben structure in a thin continental crust of ~25km, is associated with meridional fault systems at the margins (Federov et al., 1982). Similar to MR, the LR is also surrounded by Neoproterozoic granulites, which have undergone a multi-stage tectonometamorphic history and the final metamorphic event was during Neoproterozoic time (500Ma, Boger et al., 2000). In both the regions of MR and LR, the basement shear zones and their association with the Permian-Triassic coal bearing sedimentary sequence are closely correlatable.

After the cessation of transpressional tectonics during the Pan African orogeny, the basement around MR remained relatively stable until the late Carboniferous. The rifting was initiated taking the advantage of preexisting tectonic frame work reactivating the major shear zones. Deposition of Gondwana sediments started simultaneously during late Carboniferous and continued through the Permian into the Early Triassic (eg.Veevers and Tewari, 1995). A new set of brittle fractures were also developed in a later stage of reactivation associated with rifting. This kind of superposed brittle faulting and fracturing over the ductile fabrics of pre-existing ductile shear zones were interpreted from SRTM data (Chetty, 2010). A new set of E-W trending large scale fracture pattern, parallel to the MSZ, are mapped in the Phulabani-Daspalla domain, hosting the isolated small Gondwana basins. The development of upper Gondwana basins such as Athgarh basin along a new set of fractures along the MSZ suggests a renewed rifting activity since early Cretaceous (~140Ma). The Athgarh basin was later intruded by a 117 Ma mafic dyke near Bhubaneswar.

Considering the standard reconstruction models, the position, orientation and timing, the Mahandi rift strongly corresponds to the Lambert rift of east Antarctica during pre-Gondwana break up. Both of them are characterized by asymmetric half- graben structure, homoclinal basin tilts and Permo-Triassic growth faulting and are formed in the anisotropic basement.

DISCUSSION

Satellite image interpretation supported by multi-scale field observations indicate that some of the fragments of granulite facies rocks seen on the craton beyond the SSZ and the NBSZ indicate that they are upthrusted and transported masses of granulites. These shear zones also represent sole thrusts and are considered as the sites of suture zones across which the EGMB was accreted to India. The presence of thrust systems and associated structures, large recumbent folds and the network of shear zone systems suggest that the tectonic history is similar to that described for continent-continent collisional belts (Dewey and Bird, 1970, Chetty and Murthy, 1994). The deep crustal shear zones of the EGMB , described above, reveals the disposition, geometry and relative displacement of shear zones and the distribution of sub domains with distinct characteristics of lithology, metamorphism , geochronology and deformational styles. The prominent boundary shear zones and the internal as well as link shear zones are spatially and genetically connected affecting the EGMB spatially and temporally. The early thrusting and transpressive nature of boundary shear zones, the extrusion of granitic material, specially along NSZ and VSZ in the central part, high angle thrusting and the crustal - scale 'flower structure' in the northern part of the EGMB - all together make the EGMB a classic orogenic belt of oblique convergence during Neoproterozoic. It is proposed here that ,while the SSZ in the western margin of the EGMB acted as a frontal ramp , the NBSZ in the northern margin probably acted as a lateral ramp giving rise to intense and complex structural architecture.

The earliest deformational event that could be recognized in the granulite facies rocks of the EGMB is the development of the compositional fabric or the gneissic banding, which can be related to 2.8Ga deformational event during Neoarchaean (eg., Sarkar et al., 2000; Ramakrishnan and Vaidyanathan, 2008). This event must have been associated with north-west directed thrusting generating NE-SW trending fabrics with gentle to moderate dips at the western margin juxtaposing the Bastar craton and ENE-WSW fabrics at the northern margin juxtaposing the Singhbhum craton. This is consistent with several thrust zones that were demarcated in the northwestern part of the EGMB (Biswal et al., 2001). The subsequent and significant Grenvillian orogenic event (1100-800Ma) was marked by the development of shear zones associated with reworking and reorientation of fabrics. This event was also associated retrogressive metamorphism, granitic magmatic activity and intense migmatisation (Aftalion et al., 1982; Chetty and Murthy, 1994). The 2.8 Ga gneissic fabrics were also superimposed by ~1Ga mylonitic fabrics during the Grenvillian shearing event. As described earlier, the emplacement of megacrystic granitoids along NSZ as well as MSZ and the region in between during 980 Ma provides undisputable evidence for the Grenvillian orogenic event. This deformational event could be related to Mesoproterozoic oblique convergence between the Indian shield and the East Antarctica, broadly coinciding with the formation of Rodinia supercontinent (~1Ga, eg., Grew and Manton, 1986; Yoshida et al, 1996). Dextral transpressional kinematics seem to be the dominant tectonic scenario during this period. These events are also reflected throughout the EGMB clustering around 960Ma (Aftalion et al 1988; Mezger and

Cosca 1999; Paul et al; Shaw et al., 1997; Kovach et al., 1998).

Intense strain partitioning is typical of transpressional orogens in generating highly elongated domains and laterally extensive crustal-scale shear zones. (Goscombe and Gray, 2008). Further, the prolonged (~400Ma long) transpressional tectonic history helps in not only in reorientation but also in changing the initial low angle structures into subvertical features , which would be conducive to reactivation tectonics. The dextral transpressive kinematics seem to have continued until the end of Neoproterozoic giving rise to pull-apart Gondwana basins along the NBSZ taking the advantage of preexisting major ductile shear zones in the basement (Chetty, 1995b). This interpretation is corroborated by the emplacement of 520-510Ma old pseudotachylites. The associated thermal overprint of the immediate host rocks has been regarded as the direct expression of Pan-African event in the region, dominated by a cluster of Neoproterozoic ages, mostly restricted to major shear zones (Crowe et al., 2001; Lisker and Fachmann, 2001; Yoshida et al., 1996; Shaw et al., 1997; Mezger and Cosca, 1999). Based on ^{40}Ar-^{39}Ar analyses of biotites (530-470 Ma) from pervasively retrograded rock samples as well as from an amphibolite (700 Ma, Crowe et al., 2001) opined that rocks from the EGMB (north) have undergone non-uniform thermal overprinting implying intense reworking along the shear zones. Interestingly, both the Grenvillian and the Neoproterozoic orogenic events were restricted to the granulite facies rocks of the EGMB and failed to significantly in affecting the neighbouring marginal cratonic regions. Fitzsimons (2003) reported well spread occurrence of the Neoproterozoic history in different constituents of the neighboring Gondwana fragment of East Gondwana Land that include Prytdz Bay and Dunman glacier regions of East Antarctica.

Crustal- scale 'flower Structures' are typical features of modern collisional belts. Although, they have been commonly described from modern orogenic belts, only recently, these are recognized from Precambrian terrains (eg. Goscombe et al., 2003, 2008; Chetty and Bhaskar Rao, 2006), providing significant insights into the tectonic perspectives of ancient orogenic belts. Detailed structural studies in the EGMB (north) reveal the disposition of shear zones , consistent transpressive dextral kinematics, similar thermochronological history and the complementary nature of dipping geometry of shear zones represent a positive crustal-scale 'flower structure', analogous to many modern oblique convergent orogens (Chetty, 2010). It is pertinent to note the existence of Neoproterozoic crustal- scale 'flower structure', based on geological as well as geophysical signatures of the Cauvery shear zone system (Chetty and Bhaskar Rao, 2006) that occurs at the interface between the Archean Dharwar craton and the Neoproterozoic Southern Granulite Terrain (SGT) in southern India. Recently, Chetty and Santosh (2013) described that EGMB and the SGT were continuous and wrapping round the Archean Dharwar craton, exhibiting several similarities such as shear zones, thrust-fold structural styles, metamorphic history, magmatic intrusives of alkaline and anorthositic complexes, granitoids and ophiolitic complexes of Precambrian age. Both EGMB and the SGT maintain structural continuity and must have been subjected to oblique collsional processes. The subtle variations in lithologies and intensity of deformation in these two terranes could be the manifestations of distinct strain variations and different structural levels that are now exposed (Chetty and Santosh, 2013).

Tectonic models

New tectonic models were proposed by many workers, in recent years, based on geological, geophysical and geochronological data sets. Importantly, all the models involved subduction-accretion and collision as the major processes of the evolution of the EGMB. Vijayakumar and Leelanandam (2008) delineated two episodes of convergence with initial onset of continental rifting. The first rifting was at ~2.0Ga and culminated through continent –continent collision at 1.55 Ga. The second rifting was at 1.5 - 1.35Ga facilitating the emplacement of alkaline rocks and carbonatites (ARCs). They have also opined that the polarity of subduction changed at around 1.5Ga from the earlier westward to eastward subduction and that emplacement of Kandra ophiolite (1.85 Ga) and Kanigiri ophiolite mélange (1.35Ga) belong to the former westward subduction. It is also known that Pan African tectonics were restricted to major shear zones irrespective of their spatial association in the EGMB. This is evident from many isotopic ages on monazites and biotites of alkaline plutons and cratonic rocks that cluster between 600-450Ma. It was also argued that the final amalgamation of the EGMB with the Indian plate along the east dipping SSZ took place during the Pan-African period (Dobmier et al.,(2006), Biswal et al., (2007), Das et al., (2008), Simmat and Raith, (2008). Dharma Rao et al., (2011) also envisaged that the subduction was initiated as early as 1.8Ga and continued for over 500 million years. Based on the wide gap in ages of ophiolites of Kandra (1.85 Ga, Vijayakumar et al.,2011) and Kanigiri (1.35 Ga, Dharma Rao et al, 2011) that occur in the region accretion tectonics were proposed in SE margin of southern India during a prolonged history of convergence. Dobmier and Raith (2003) proposed that the collision of the Napier complex with the Eastern Dharwar craton resulted in E-W convergent tectonics and thrust stacking between 1.7 and 1.5 Ga. However, the subduction polarity in the model of Dharma Rao et al., (2011), shows westward subduction in contrast to eastward subduction as proposed by Vijayakumar et al., (2008). The present day structural architecture of the EGMB in conjunction with the geometry of the shear zones suggests eastward subduction polarity. Based on the geophysical characteristics such as receiver function analysis, Ramesh et al., (2011) identified westerly dipping interface between 160-200km reflecting a subduction related relict associated with westward subduction polarity. This kind of ambiguity about the subduction polarity can be resolved by further detailed geological and geophysical studies. The EGMB must have possibly witnessed a Pacific-type orogeny during Paleoproterozoic and Mesoproterozoic culminating in Himalayan - style collision in the Neoproterozoic (Dharma Rao et al., 2011), similar to the Plate tectonic architecture proposed for the Gondwana assembly in southern India (Santosh et al., 2009). This hypothesis is further supported by the contiguity of the EGMB and the SGT indicating similar orogenic processes at least during the Neoproterozoic period (Chetty and Santosh, 2013).The operation of two complete Wilson cycles in the Eastern Ghats Belt were suggested by Vijayakumar et al ., (2013) based on the new SHRIMP-RG zircon U-Pb ages and opined that Paleoproterozoic crustal growth along the SE margin of India is similar to that of the Trans-Hudson orogen involving ocean closure, arc accretion, and final continent-continent collision.

CONCLUSIONS

1. The Eastern Ghats Mobile Belt (EGMB) constitutes a network of deep crustal shear zones, which are fundamental in providing the structural architecture, understanding the comprehensive tectonic evolution, and influencing the interpretations of any data related to petrology, geochemistry, geochronology and geophysics.

2. The shear zones are recognized and identified involving structural interpretation of multi-scale Satellite data in conjunction with field observations including critical mapping of rocks and regions.

3. The details about the field characteristics, disposition and the geometry of deep crustal shear zones in the EGMB are compiled and reviewed.

4. The shear zones are variable in thickness, orientation and geometry and are typically characterized by the development of mylonitic rocks in association with magmatic intrusions and migmatitic gneisses. These zones act as laboratories and provide opportunity to study deeply eroded remnants of the EGMB.

5. The boundary shear zones like SSZ, KSRSZ and NBSZ, representing suture zone , are marked by alkaline magmatism ranging in age 1250 Ma 650Ma suggesting that they are reactivated in space and time.

6. The northern boundary shear zone (NBSZ) dips steeply to south, while the Mahanadi shear zone (MSZ) and other domain boundary shear zones dip to north with moderate to steep angles and are characterized by consistent dextral kinematics- all define a typical crustal- scale 'flower structure', akin to modern convergent zones.

7. The presence of shear zones and associated stretching lineations and the structural architecture point to the hypothesis that the EGMB could be a collage of juxtaposed terranes of distinct structural history.

8. The EGMB constitutes fold-thrust system developed during its early stages of evolution involving the accretionary processes and has witnessed prolonged dextral transpressional tectonics during the Meso- to Neoproterozoic period related to oblique convergence.

9. The EGMB has evolved through subduction-accretion and the final collisional processes during Neoproterozoic indicating Himalayan style Plate tectonics.

10. The Nagavali-Vamsadhara shear zones (NVSZ) and Mahanadi rift structure act as piercing points of Gondwana correlation from the EGMB with the Lambert Rift and the Napier-Rayner boundary fault (NRBF) of the Enderby Land of east Antarctica, representing pre-Gondwana continuous tectonic markers for the reconstruction models of east Gondwana.

ACKNOWLEDGEMENTS

This review is a compilation of my efforts for more than 15 years, between 1985 and 2002, in understanding the evolution of the EGMB. Deviating from traditional approaches of mapping techniques, I have made use of modern mapping tools involving Satellite image interpretation, geological field traverses, structural analysis of selected segments and critical outcrop mapping. Dr.D.N.Kanungo taught me the fundamentals of structural geology while I was working for my Ph.D in Nellore schist belt. I am thankful to all directors of NGRI and all my colleagues who supported my novel approach and interpretations despite initial criticism by some workers. I had the benefit of discussions in the field with my senior colleague Dr.D.S.N.Murthy during the initial years of mapping of the EGMB (south). Part of field work in the EGMB (central) has been carried out with my colleague Dr.B.L.Narayana and my students Mr. P. Vijay and Mr. M. Giridhar. The study of the EGMB (north) was possible through Indo-German collaborative project (1997-2002) with German colleagues Prof. Hofmann, Mr. Fachmann and Mr.Frank Lisker. I thank all those above colleagues for their unstinted support and encouragement. However, I am responsible for all the conclusions and inferences made in the present contribution. This paper has been finalized during my Emeritus Scientist scheme at CSIR-NGRI. I acknowledge the financial support from CSIR, New Delhi and thank the Director, CSIR-NGRI, for his cooperation in providing facilities. I thank Dr.P.R.Reddy, Editorial advisor, for inviting me to contribute this review article for the Journal of Indian Geophysical Union. I am also thankful to anonymous reviewers for their constructive and helpful comments in improving the paper.

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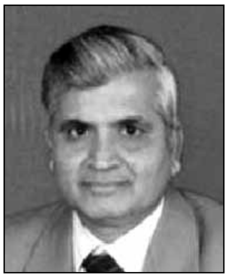

Dr. T.R.K. Chetty, currently CSIR -Emeritus scientist at NGRI, is a leading expert in structural geology and Tectonics with four decades of experience in multi-scale structural analysis to understanding the larger tectonic perspectives of several Precambrian terranes of India. He was instrumental in the discovery of the richest diamondiferous Venkatampalle Kimberlite pipe-7.

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