Deformation history of the NW salient of the Eastern Ghats Mobile Belt, India

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Abstract

The Eastern Ghats Mobile Belt of India displays fold-thrust belt structure with a prominent salient on its NW margin. The salient consists of Lathore nappe and Turekela klippe that have overthrust the craton to NW. The rocks of the nappes have undergone granulite facies metamorphism and multiple phases of folding corresponding to the Eastern Ghats orogeny, prior to thrusting. As a result the granulites along the thrust are retrograded to amphibolites and the axial traces of the folds have been truncated against the thrust plane. The basal decollement of the fold-thrust belt is represented by the Terrane Boundary Shear Zone that defines the tectonic margin between the craton and the mobile belt. It occurs as a ductile thrust affecting the cratonic basement as well as the mobile belt suggesting that the basement did not behave as a rigid body during thrusting. Thus the study area is comparable with the Caledonide fold-thrust belt. Further, two large lateral ramps namely Khariar and Paikamal lateral ramps have been developed on the decollement at the lithological contact between tonalite–trondhjemite gneisses/granite gneisses and the latetectonic potassic granites of the craton. Fault-bend folds associate with these ramps too. It is suggested that the salient structure of the fold-thrust belt is the combined result of (1) lateral ramps on the decollement and (2) differential displacement along the sole thrust due to lateral variation in detachment strength.

Keywords: Proterozoic fold-thrust belt; Eastern Ghats Mobile Belt; Nappe; Lateral ramp; Rheological contrast

1. Introduction

Fold-thrust belts (FTB) are characteristic features of convergent mobile belts. Though they are commonly reported from Phanerozoic mobile belts like the Himalayas (Valdiya, 1984), Alps (Dewey et al., 1973), Zagros (Bird, 1978) and Taiwan fold belts (Davis et al., 1983), they have also been observed in Proterozoic mobile belts like Grenville (Davidson, 2001), Broken Hill (White et al., 1995) and Churchill province (Gibb, 1978). The FTBs consist of stack of enechelonly arranged nappes showing vergence towards the foreland. The frontal thrust marks the sole thrust or decollement that forms the leading imbricate structure with the splay thrusts behind (Ramsay and Huber, 1987). The thrusts are normally listric in nature and adopt a ramp-flat geometry while cutting across different rock types in the stratigraphic section. The hanging wall rocks produce fault-bend folds over such ramp-flat parts while gliding over the thrust planes. This results in thickening and a large amount of shortening of the thrust wedge leading to the development of parallel folds and axial planar cleavage. Hence the thrust structure guides the structural style of the overriding block (Fig. 1(a)) (McClay and Coward, 1981; Suppe, 1983). However, the basement remains undeformed. Contrary to this, another model postulates that thrusting takes place much after folding and metamorphism of the cover rocks and the thrusts cut across the preexisting structures of the nappes. Moreover, the basement is deformed along with the cover (Fig. 1(b)) (Fischer and Coward, 1982; Ramsay, 1997). The FTBs on the map display a curvilinear geometry because of the salient and recess structures (Marshak and Tabor, 1989; Macedo and Marshak, 1999; Spraggins and Dunne, 2002).

In this paper we describe the FTB structure from the northwestern margin of the Proterozoic Eastern Ghats Mobile Belt of India (Fig. 2). The sole thrust is exposed at the surface as a well defined ductile shear zone that demarcates the terrane margin between a low grade cratonic foreland and a highly deformed granulitic mobile
belt. A prominent salient structure is observed on the northwestern part of the mobile belt, which has been investigated in this paper with regard to the structural geology, and a model has been proposed to explain its origin.

2. Regional geological setting

The Eastern Ghats Mobile Belt (EGMB, Fig. 2 inset) of the east coast of India represents a regional granulite belt belonging to a wide spread of ages from Archaean to Upper Proterozoic (Sarkar and Paul, 1998 for review; Rickers et al., 2001). Continental collision between India and Antarctica during Mesoproterozoic time, however, marks the most significant event in the evolution of the belt. The belt comprises a host of granulitic supracrustals such as khondalites (garnet–sillimanite–graphite gneiss), charnockitic gneisses, calc granulites, quartzites and banded iron formations that have been intruded by mantle derived intrusive suites such as charnockites, basic granulites, enderbytes, I type of granites, anorthosites and alkali granites and rocks derived from the partial melting of the supracrustals such as leptynites. S-type granites and migmatites. These rocks have been grouped into four zones namely the western basic charnockite zone, the western khondalite zone, the central migmatite and charnockite zone and the eastern khondalite zone (Fig. 2) (Ramakrishnan et al., 1998). A linear transition zone consisting of amphibolite facies rocks occurs along the western margin of the belt, derived from the retrogression of the granulites. The rocks of the EGMB show polyphase folding (Natarajan and Nanda, 1981; Halden et al., 1982; Bhattacharya et al., 1994; Mahalik, 1994; Nash et al., 1996; Biswal et al., 1998a,b; Biswal and Sahoo, 1998) and metamorphic history (Grew and Manton, 1986; Lal et al., 1987; Dasgupta, 1995). Ductile and brittle shear zones have been reported from the length and breadth of the belt (Chetty and Murty, 1994; Biswal et al., 2000, 2002). The most prominent ductile shear zone lies at the western and northern margin of the EGMB, demarcating the terrane margin with the surrounding cratons (Fig. 2). Designated as Terrane Boundary Shear Zone (TBSZ, Biswal et al., 2000), it shows a curvilinear geometry with a WNW–ESE strike and a strike–slip character in the north, and NNE–SSW strike with a thrust character in the west. However, it shows dip towards the mobile belt. The surrounding cratons namely Dharwar, Bastar and Singhbhum cratons consist...
of greenstone belts, granulites, tonalite–trondhjemite gneisses and a suite of intrusive rocks that include latetectonic potassic granites, riebeckite granites, dolerite, albitite, microsyenite and micromonzonites (Ramakrishnan, 1990; Nanda et al., 1998). The craton shows a prolonged history of cratonization ranging in age from 4.0 to 2.5 Ga (Sarkar et al., 1993). Platform sequences known as Puranas belonging to Cuddapah, Bastar and Chhattishgarh basins (Fig. 2 inset) and ranging in age from 1.6 Ga (Cuddapah, Meijerink et al., 1984) to 0.7 Ga (Chhattishgarh, Kreuzer et al., 1977) unconformably overlie the craton. The craton is very low in gravity compared to the mobile belt. A sharp rise from $-80$ to $-10$ mGal is witnessed across 60 km width of the TBSZ. Deep Seismic Sounding (DSS) study reveals three seismic reflectors in the EGMB crust, of which the uppermost one at 8 km depth marks a sharp change in velocity from 6 to 8 km. This is attributed to a marked change in composition as well as state from brittle to ductile. The shear zones including the TBSZ bend downward in a listric nature and merge with the above reflectors forming a detachment or decollement in the EGMB crust (Nayak et al., 1998). Therefore the TBSZ is considered in this paper as a decollement between the cratonic foreland and the EGMB, at least in the NW part of the belt.

A series of alkaline rocks have been emplaced into the TBSZ (Leelanandam, 1993). These intrusive rocks bear a magmatic fabric consistent with the shear fabric of the TBSZ, thus suggesting the synkinematic nature of their intrusion with thrusting (Biswal et al., 2000). The age of these intrusive bodies has been estimated to be 1.5 Ga (Sarkar et al., 1989; Aftalion et al., 2000), which, thus, is taken to be the age of thrusting. However, the northern part has been reactivated subsequently during Grenville and Pan African orogeny by means of strike–slip faults (Mahalik, 1994; Nash et al., 1996; Crowe et al., 2001). The TBSZ in the southern part is very ambiguous because of its splaying nature and presence of large scale rigid blocks between the splays.

The study area lies in the NW part of the mobile belt where the TBSZ shows an arcuate pattern with convexity towards the Bastar craton (Figs. 2 and 3). The TBSZ is nearly 2 km wide and dips southeasterly towards the EGMB. Based on the geophysical interpretation (Nayak et al., 1998) the TBSZ is considered to become gentler downward. Consistent with this explanation, the structural data from the southern part of the TBSZ, west of Dharamgarh (Fig. 3) where the deeper levels of the Eastern Ghats crust is exposed, reveals the gentle nature of the mylonitic foliation (Biswal et al., 2002). The EGMB rocks are further split by the Turekela thrust into two nappes that are characterized by distinct lithological assemblages and deformational history. On the basis of this structural
configuration, the study area was described to be a fold-thrust belt of the EGMB (Biswal, 2000; Biswal et al., 2001) similar to the model given by Ramsay (1997) and the TBSZ was said to demarcate the decollement between the cratonic basement and the overlying Eastern Ghats rocks (Fig. 4). The convexity in the NW front is referred to be a salient structure in the fold-thrust belt (Fig. 2).

3. Geological setting of the craton in the foreland

Fig. 5(a) and (b), respectively, show the False Colour Composite and generalized geological map of the NW salient of the FTB (Fig. 5(b) is to be compared with Fig. 3 for detailed geology). The Bastar and Singhbhum cratons lie to the west and north, respectively. The salient has a flat convex outline with broad apex and nearly orthogonal end points (EP in Fig. 5(b)). As many authors have dealt with the geology of the cratons extensively (Ramakrishnan, 1990 and references therein), the description in this paper is restricted to the area adjoining the TBSZ. Granite gneisses and tonalite–trondhjemite gneisses dominate both Bastar and Singhbhum cratons. However, the craton near the apex

![Fig. 3. Generalized geological map of the NW salient showing various nappes and lateral ramps (modified after Biswal et al., 2002).](image)

![Fig. 4. Schematic profile view of the fold-thrust belt of the EGMB showing Lathore nappe and Turekela klippe overthrusting the craton. The fold axial traces truncate against the thrust. This is comparable with Caledonide model.](image)
is dominated with latetectonic potassic granites, which occur as intrusive into the above mentioned gneisses (Fig. 3).

3.1. Granite gneisses and tonalite–trondhjemite gneisses

These are medium to coarse grained rock carrying a coarse gneissic foliation. The foliation is defined by metamorphic banding with thick quartzo–feldspathic layers alternating with thin biotite–hornblende rich layers. The granite gneisses sporadically enclose pockets and slivers of schists, amphibolites and metabasics which have been concordantly folded. The schists and amphibolites share a migmatitic front with the host rock. Petrographic study reveals that the minerals are medium to coarse grained exhibiting strong preferred orientation defining the gneissosity in the rock. The minerals show the effect of postcrystalline strain as indicated by the undulose extinction in quartz and kinks in the plagioclase. Biotites and amphibole in many instances are kinked with sweeping extinction. Feldspars are more dominating than quartz in the rock. While tonalite–trondhjemite gneisses carry more plagioclase feldspars, potash feldspars dominate the granite gneisses.

3.2. Latetectonic potassic granites and dykes

The latetectonic potassic granites occur as intrusive inside the gneisses. Compared to the host gneisses, the granites are very coarse grained to pegmatoidal and are relatively rich in quartz. The rock shows a homophanous texture, completely devoid of deformational fabric. Under microscope they show xenomorphic to hypidiomorphic granular textures with K-feldspar phenocrysts showing porphyritic texture. Graphic and myrmekitic intergrowth are very common in the rock. The craton is cut by a set of NNW–SSE to N–S trending dolerite and diorite dykes that truncate against the TBSZ in the east (Fig. 5(b)).

3.3. Purana rocks

Isolated outcrops of platform deposits belonging to the Chhattishgarh Group occur unconformably on the craton surrounding the Eastern Ghats front. These deposits are horizontally bedded and comprise alternate sequence of shale, sandstone and rarely carbonate rocks without any folding. The EGMB terrane is devoid of such Purana outcrops.

3.4. Structure

The granite gneisses and tonalite–trondhjemite gneisses show the presence of gneissosity resulting from synkinematic deformation and metamorphism. The mineral assemblage and the migmatitic structures suggest an upper amphibolite facies of metamorphism for the rocks. However, the fold related to peak metamorphism is not identified. The gneissosity is involved in multiple generations of latefolding that include open to tight folds, kinks and chevron folds. However, no significant recrystallization is associated with them. Mesoscopic ductile shear zones are observed along the limbs of the minor folds. In many instances pinch-and-swell and boudin structures

![Fig. 5. (a) False Colour composite (FCC) of the salient. (b) Structural interpreted map of the salient.](image)
are prominently developed in the concordant amphibolite bands. The gneissosity shows variable strikes due to multiple folding. However, they are oriented NNE–SSW in the south (west of Dharamgarh) and E–W in the north (Singhbhum craton) near the TBSZ due to dragging effect of the thrust (Fig. 3). In contrast to this the latetectonic potassic granites lack deformational fabric, suggesting that the granites have intruded latekinematically with respect to the main deformation in the craton. Further, the folding in the EGMB has not even influenced the granites and gneisses which leads to the inference that the craton behaved as a stable land during Eastern Ghats orogeny. However, the TBSZ which has juxtaposed the EGMB against the craton has affected both the terranes. Further, late stage brittle conjugate strike-slip fractures and faults have dissected the craton as well as the EGMB in two predominant directions, NW–SE and NE–SW. The stress pattern of these fractures varies considerably, though the line of intersection between them always remains steep (Fig. 6(a)).

4. Structure of the TBSZ, the decollement

The deformation structures of the TBSZ have been described in reference to apex and end points of the salient (Figs. 3 and 6).

The TBSZ in the apex part shows a thrust character. It has a width of nearly 2 km and shows linear geometry with NNE–SSW strike. The dip varies from 45 to 60° towards SE (Fig. 6(b)). In an overall listric geometry of the decollement, the above high dip corresponds to the frontal ramp of the decollement. The thrust is marked by quartzofeldspathic mylonites, showing a down-dip stretching lineation (Fig. 6(c)) and various simple shear strain fabric like S–C fabric (Fig. 7(a)), sigmoidal porphyroclasts and mica fishes which unequivocally point to the overthrusting of the mobile belt on the craton. The thrust has placed higher grade assemblages of the mobile belt on the low grade rocks of the craton. Biswal et al. (2000) calculated nearly 4.7 km of displacement along the thrust based on the S–C angle (Ramsay and Huber, 1987). Further, the strain in the mylonites is more at the center of the thrust and drops gradually towards the margin. As a result the mylonites and latetectonic potassic granites share a gradational contact to the west. This leads to the inference that the cratonic granites, by and large, have served as the protolith of the mylonites and the basement behaved in a ductile manner during thrusting. However, a thin edge of the TBSZ occurs inside the EGMB where amphibolites are developed from the retrogression of basic granulites during thrusting. Hence, the TBSZ is considered to be a retrograde shear zone.

Microfaults are an important microfabric in the mylonites of the apex part (Fig. 7(b)). These are developed in conjugate fashion in the feldspar rich layers. The dominant set lies subparallel to the S– fabric. It has fractured the feldspar grains into several rectangular clasts, called ‘shear microlithons’. The fractures are independent of the orientation of the mineral cleavage. The microlithons have assumed elliptical shape and formed winged porphyroclasts with progressive shearing. When these microfaults occur as brittle faults inside the feldspar porphyroclasts, the acute angle remains horizontal and where they occur as ductile faults (Fig. 7(c)) in the quartz ribbons the obtuse angle is horizontal. Hence, a clear refraction is observed in their trend. From the equal-angle plot of such conjugate microfaults from the edge of the shear zone where the rotation of the porphyroclasts is to be the least, it has been deduced that the σ1 is subhorizontal and directed in WNW–ESE direction (Fig. 6(d)). This is parallel to the azimuth of the slip line of the main thrust. Considering the shearing and fracturing to have taken place in a single event, an orthogonal convergence between the craton...
and the mobile belt is inferred from the above parallelism (Ramsay and Lisle, 2000). However, the strain ellipse for the above stress does not coincide with the strain ellipse of the bulk simple shear as indicated by the S–C fabric in the quartz ribbons. Probably this is due to strain partitioning into pure shear and simple shear between the feldspar and quartz rich layers, respectively, during same stage of deformation (Goodwin and Tikoff, 2002).

The deformation pattern changes near the end point of the salient. The TBSZ assumes an E–W trend, transverse to that of the apex (Fig. 3). Moreover, the sense of shear changes from thrust to strike–slip. These transverse structures show the features of lateral ramps and not merely of a normal- or strike–slip fault (Biswal and Jena, 1999). These are named as Khariar lateral ramp in the south and Paikamal lateral ramp in the north. The important features of the ramps are

(i) Most importantly, they join the end points of two segments of the TBSZ. Therefore, in three dimensions
they work a link between two segments of the frontal ramp.

(ii) The strike of the lateral ramps is parallel to the thrusting direction of the apex part.

(iii) The slip direction changes from strike–slip to thrust–slip gradually from lateral ramp to the apex.

(iv) Rocks of different structural levels are juxtaposed against the lateral ramp. The gabbro–norite-basic granulite suite of the western basic charnockite zone that constitutes the lower crustal rocks of EGMB is exposed to the south of Khariar lateral ramp (Fig. 3).

Unlike the apex part, the TBSZ at the ramp is developed on the tonalite–trondhjemite gneisses, granite gneisses and other supracrustals of the craton. As a result, the mylonites vary from quartzofeldspathic to amphibolite to calcareous in composition. Further, the TBSZ in these zones branches into a number of synthetic shear zones enclosing rigid amphibolite enclaves, thus making the mapping of the entire width of the shear zone difficult. In addition to these, the simple shear strain is superimposed over the pre-existing strain of the granite gneisses and therefore, the strain fabric in the mylonites differs much from the simple shear fabric of the apex part. The pre-existing planar fabric defined by the preferred orientation of the quartz, feldspar and amphibole grains is deflected along the small-scale shear planes (C band) (Fig. 7(d)). This is in contrast to the mylonites of the apex part where the rock is differentiated into alternate layers of ductile quartz ribbon and brittle feldspars; the quartz ribbons carry grain shape fabric corresponding to simple shear strain (Figs. 7(a) and 8(a)) and the feldspars carry the microfractures (Fig. 7(b)).

5. Structure of the Lathore nappe

Immediately overlying the decollement, the Lathore nappe occurs as a huge tectonic slab occupying 80% of the area of the salient (Fig. 4). The charnockitic gneiss is the main rock type in the nappe (Fig. 3) followed by basic granulites, khondalites (near Gandhmardan Hill) and calc granulites which carry the signature of multiple generations of folding. The folds include coaxial F₁ and F₂ that are developed along NNE–SSW axes. These folds are classified as parallel to highly flattened parallel folds having all attributes of buckling origin. These have been transformed into sheath folds at many places due to axial planar inhomogeneous flow. Detailed structural analysis of the closed outcrop of garnetiferous quartzite to the east of Lathore has indicated the presence of map scale sheath fold in the area (Biswal et al., 1998a). The fold axes of these folds remain strung over a great circle coinciding with the axial plane of the F₂ fold (Fig. 6(e)). Mullion, boudin and pinch-and-swell structures are associated with F₁ and F₂ folds and developed prominently in the quartz and pegmatite veins emplaced in the calc granulites.

The granulite metamorphism is synkinematic to the F₁ folding. This is borne out by the cross cutting relationship between the bedding plane (S₀) and the gneissosity (S₁) at the hinge of the F₁ fold. Thin section study of the charnockitic gneisses reveals the presence of highly flattened quartz grains producing ribbon structure parallel to the gneissosity. Size measurement of these quartz grains indicates flattening strain in the rock (Fig. 8(a)). Dome-and-basin structures are produced due to the interference of F₂ folds with F₁ folds. The Lathore nappe close to the TBSZ displays realignment of the folds parallel to the shear direction of the TBSZ. Furthermore, the granulites have been retrograded into amphibolites. The amphiboles have grown parallel to the XY plane of the strain ellipsoid. This clearly proves thrusting post dated folding and granulite metamorphism. In and around the Khariar lateral ramp, many alkali granite dykes have been emplaced into the granulites synkinematic to thrusting.

The granulites of the Lathore nappe are prominently marked by gneissosity fabric which strikes NE–SW in
the major part of the area (Fig. 3). However, towards the end point, it takes a swing to the E–W direction. The above swing is more uniform in the northern end point (Paikamal lateral ramp) as the structural trend inside the nappe remains parallel to the TBSZ. Contrarily, a sharp kink is observed over the Kharian lateral ramp in the south. These broad warps and kinks are in fact fault bend folds (Suppe, 1983) produced during thrusting of the EGMB rocks over lateral ramp of the decollement. The Lathore nappe is affected by brittle deformation in the form of sinistral NE–SW and dextral NW–SE faults. Traced towards east, the NE–SW faults cut across the Turekela thrust. This suggests two generations of growth of faults (Biswal and Sahoo, 1998).

6. Structure of the Turekela thrust

The Turekela thrust underlies the Turekela nappe (Fig. 4). The thrust in the western margin dips gently to SE and shows NW vergence. The Turekela nappe in the study area is extremely eroded and has been left out as a klippe. Similar to Turekela klippe there could be few other klippes in the area tectonically resting over the Lathore nappe. These are yet to be mapped. The Turekela thrust is very conspicuous at Dholmandal where the khondalites of the Turekela klippe are extremely sheared and show close spaced mylonite foliation and down dip stretching lineation. The leptynite veins are sheared into lensoidal patches, which are arranged in enechelon manner resembling small scale schuppen structure (Fig. 8(b)). Narrow mylonite zone is invariably present between the lenses. The fold and the gneissosity on either side of the thrust show gradual realignment towards the shear direction as one moves from the core of the nappe to the thrust plane. The calc granulites of the Lathore nappe, which are otherwise steeply dipping to SE, become gradually gentler near the thrust. Similarly the NE–SW intersection lineations of the Turekela Group become down dip and TF1 folds are modified into sheath folds.

7. Structure of the Turekela nappe

The Turekela nappe represents the top most nappe in the NW salient. It occurs as a klippe surrounded by the rock of the Lathore nappe (Fig. 3). The root zone of the klippe lies further towards east. The klippe is dominated by khondalites followed by calc granulites. Mineralogically khondalites consist of sillimanite, garnet, feldspar and quartz. Leptynite veins derived from the melting of the above assemblage occur concordantly in the khondalites. Turekela nappe exhibits multiple stages of folding consisting of coaxial folding between first three folds namely F1′, F3 and F2 along NNE–SSW axis. These are followed by NW–SE trending F3 folds which have produced mirror image structures in interference with F2 fold. These structures are observed from small to map scale in the area. A large scale mirror image structure is observed in the calc silicate outcrop to the east of Turekela (Jena, 2000). The plot of the fold axes and the intersection lineation of such large-scale interference pattern shows a small circle distribution of the early fold axes (Fig. 6(f)). The gneissosity in the Turekela klippe shows overall trend in NE–SW direction (Fig. 3). Thin sections of the khondalites show the preferred orientation of sillimanite, garnets and quartz parallel to such gneissosity. Quartz grains are distinctly lensoidal and the size analysis of these grains shows constrictional type of strain in the Turekela klippe (Fig. 8(a)). The Turekela klippe has been traversed by many close spaced NW–SE trending brittle dextral faults, which cut across the Turekela thrust and the Lathore nappe.

8. Mechanism of formation of the salient

The formation of the salient is to be discussed in light of the FTB structure of the EGMB. It has been mentioned earlier that the thrusting took place subsequent to folding and granulite metamorphism which happened during Eastern Ghats orogeny in Mesoproterozoic period (Ramakrishnan et al., 1998). Thrusting juxtaposed the mobile belt against the craton forming FTB on the NW front, subsequent to the orogeny. The TBSZ acted as the decollement for the Eastern Ghats rocks which have been split up into Lathore nappe and Turekela klippe by the Turekela thrust. Hence the TBSZ, Lathore nappe, Turekela klippe and Turekela thrust constitute the main architecture of the FTB.

Various tectonic models have been suggested for the development of the salient structure in an FTB (Macedo and Marshak, 1999). These are (1) when the sediment thickness varies in a basin along strike due to basement highs, the thicker part gets displaced more towards the foreland compared to the thinner part (Fig. 9(a)) as for example in the Rocky and Appalachian mountains (Marshak and Wilkerson, 1992; Boyer, 1995); (2) when the thrusting occurs in front of a hinterland indenter, as in case of the Himalayas (Fig. 9(b)) (Tapponnier and Molnar, 1976); (3) When the frontal thrust is dissected by late transverse strike–slip faults (Fig. 9(c)) as in Sevier fold-thrust belt (Paulsen and Marshak, 1997); and (4) when the strength of the glide horizon varies laterally along strike as in the case of salt bed pinching out (Fig. 9(d)) in the Franklin mountain of NW Canada (Davis and Engelder, 1985).

The FTB in the study area is developed in a highly metamorphosed and deformed terrane of the EGMB and hence variation in basin thickness as a cause for differential displacement along the sole thrust does not arise. Secondly, the composition of the nappes in the salient part is similar to the other part of the mobile belts and the hinterland is not observed. Thirdly, the study area shows the presence of ramp structures. These are not late structures as required (Fig. 9(c)) to develop a curved outline on the frontal thrust.
However, the lateral ramps could produce a curved outline as they connect the two segments of the TBSZ occurring at two different structural levels. In light of this, it would be more significant to discuss the mechanism of the development of TBSZ at two different structural levels. Further, the fourth option that the gliding horizon varies in strength along the strike is to be evaluated.

The lateral ramps are developed at the contact between latetectonic granites and the granite gneisses/tonalite–trondhjemite gneisses. It has been mentioned earlier that the foreland adjoining the apex is composed of latetectonic potassic granites which are massive and lack deformational fabric. These are very coarse grained with the minerals showing straight grain margin and no intracrystalline deformation. As against this, granite gneisses/tonalite–trondhjemite gneisses contain various strain fabrics including gneissosity, folds and small scale ductile shear zones. The gneissosity is defined by metamorphic banding with quartz-feldspar rich layers alternating with biotite-amphibole rich layer. The minerals exhibit preferred orientation defining the gneissosity in the rock. The minerals show the effect of postcrystalline strain as indicated by the undulose extinction in quartz and kinks in the plagioclase. Biotites and amphibole in many instances are kinked with sweeping extinction. The above difference in the rock fabric is believed to have brought variation in the strength of the rock because of the following reasons.

1. The granite gneisses and tonalite–trondhjemite gneisses including the metamorphic enclaves have been dehydrated during amphibolite facies of metamorphism and repeated deformation. However, the late tectonic granites are likely to contain water rich fluid. Therefore quartz behaves as a stronger phase in gneisses compared to that of the latetectonic granites. Rocks attaining strain hardening with deformation and metamorphism have been advocated by Schweickert et al. (1984) and Naha et al. (1987).

2. Further, latetectonic granites are comparatively rich in quartz than the granite gneisses and tonalite–trondhjemite gneisses. Quartz in the presence of water could provide extreme ductility to the rock (Goodwin and Tikoff, 2002). Therefore, the mylonites in the apex part carry very large quartz ribbons even at the lowest strain while the gneisses do not contain such structure.

3. During ductile deformation the grains develop dislocations, which pile up to produce strain hardening and resist further strain. If the stress was withdrawn at this position, the material would require higher stress to undertake ductile deformation further (Dieter, 1961). The gneisses exhibit umpteen evidences of such strain hardening like undulose extinction and deformation lamellae in quartz. These features indicate post-crystalline deformation. Furthermore, the rocks are not annealed to free those dislocations. As a result, the gneisses would act as rheologically stronger rock than the latetectonic granites. There exists experimental study of granites to show the strain hardening effect at certain temperature and pressure ranges (Griggs et al., 1960). Further, the granite gneisses/tonalite–trondhjemite gneisses are characterized by crystallographic fabric. If a rock deforms by ductile flow and develops a crystallographic fabric, this can also cause hardening and transition to brittle deformation without a change in external condition (Passchier and Trouw, 1996).

4. The granite gneisses/tonalite–trondhjemite gneisses show metamorphic banding, which varies in orientation due to repeated folding. The orientation of the fabric will influence the nature of late deformation to a great extent (Dieter, 1961; Donath, 1961). However, this is not the case with latetectonic granites.

5. The granite gneisses and tonalite–trondhjemite gneisses carry inclusion of amphibolite and metabasic pockets which act as rigid bodies during thrusting (Passchier and Trouw, 1996) and contribute to increased strength.
Variation in rheological property of the basement causing variation in the structure of the frontal shear zone is emphasized by Simony and Carr (1997). They have interpreted the formation of Valkyr shear zone at different levels of the crust due to the contrast in the rheological property of the granites belonging to different ages (Fig. 9(e)). They explain that if a shear zone encounters harder rocks laterally it shifts its position to a higher structural level. The shear zones at different levels join up by lateral ramps. As the latetectonic granites and the granite gneisses/tonalite–trondhjemite gneisses pose dissimilarities in the rheological properties it is likely that the basal decollement of the EGMB-FTB has developed at different levels of the crust and the Khariar and Paikamal lateral ramps have been developed as links between them (Fig. 10). The thrust at the apex part corresponds to a lower structural level while the thrusts to the north and south of it belong to the higher structural levels.

Contrast in lithological associations on either side of the Khariar lateral ramp supports the above interpretation of a difference in structural level (Biswal and Jena, 1999). To the south of the northerly inclined Khariar lateral ramp the lower crustal rocks of EGMB such as gabbro-norite-basic granulite suite (western basic charnockite zone) are exposed. This zone is evidently very thin in the apex part. Further, the gentle dip of the thrust in the southern segment has contributed to the larger outcrop width of the formations.

Based on this contrast in rheological property, the strength of the mylonites of the TBSZ is to be assessed, which could bring variation in amount of displacement. If the gliding horizon encounters a soft bed like clay or halite that pinches out laterally, the transportation is enhanced over the soft bed. Since the study area represents a metamorphic terrane, association of above mentioned rocks do not arise. However, the mylonites in the apex part might be more ductile due to the presence of more quartz and water. This has facilitated more transportation. Mylonites in the gneisses would resist shear due to dry condition and presence of rigid amphibolite and metabasic enclaves. Though the amount of transportation is not calculated for the granite gneisses/tonalite–trondhjemite gneisses due to preexisting strain, the displacement (minimum value) is about 4.7 km over the mylonites of the latetectonic granites.

Hence at this stage it is not possible to distinguish the effect of two tier development of thrust from the unequal displacement along it. It is quite likely that both the phenomenon have occurred together. Therefore it is suggested that the NW salient of the EGMB-FTB is a combined product of two-tier development of the sole thrust as well as difference in displacement.

9. Conclusion

The NW salient of the EGMB is characterized by episodic deformational history largely belonging to two distinct events. While the earlier phase is marked by polyphase folding (F₁, F₂ and F₃) and synkinematic granulite metamorphism the later includes thrusting, thrust related folding and retrogression of granulites into amphibolites. The folds noticed in both the nappes, as part of the earlier phase of deformation, are attributed to a buckling origin which is obviously the result of subhorizontal compression during Eastern Ghats orogeny. That, the granulite metamorphism has occurred in a compressional setting, is borne out from its synkinematic nature with F₁ folding. However, granulite metamorphism in extensional setting has been reported from some part of the EGMB (Dasgupta, 1995). This leads to the interpretation that the tectonic setting of the granulite metamorphism varies both temporally and spatially across the EGMB. Similar variation is also observed in the strain pattern as indicated by flattening type of strain in Lathore nappe and constrictional type of strain in Turekela nappe. All these features are suggestive of extreme heterogeneity in the EGMB.

The second phase of deformation in the EGMB is dominated by thrusting which has produced FTB on its foreland margin like that of Grenville belt. The granulites have been sliced off by these thrusts into nappes and have been thrust over the craton. The TBSZ serves as the basal decollement of the FTB. At the present level of erosion the TBSZ shows moderate to steep dip corresponding to the frontal ramp part of the decollement. The sole thrust is predominantly quartzofeldspathic in composition as a wider part of the sole thrust is developed on the basement granites and the mylonites possess a transitional margin with the granites of the craton. Hence it is believed that the foreland did not behave as a rigid body during thrusting. It deformed in a ductile manner producing mylonites and other ductile fabrics. As the shear strain is as low as 6.0, the deformation could not penetrate deeper into the basement, but is confined to the contact between the craton and the mobile belt. However, the pre-existing large scale folds of the EGMB are truncated by the thrust plane.
and the granulites have been retrograded to amphibolites. From the above discussion it is obvious that the major structural features such as fold pattern and gneissosity in the nappes are controlled by the early phase of deformation in the EGMB and not guided by the thrusts. Therefore, the FTB of the EGMB is comparable with Caledonide FTB as reported by Ramsay (1997) (Fig. 1(b)). Hence the model given by Suppe (1983) where the structures in the overriding plate are guided by the thrust (Fig. 1(a)) does not hold good for the study area. However, the thrusting has produced broad fault bend folds on the granulites which are manifested as large open warps at the end points of the salient (Fig. 3).

Large lateral ramps are developed on the basal decollement as a result of the rheological contrast between granite gneisses/tonalite–trondhjemite gneisses and the latetectonic granites of the craton (Fig. 10). The FTB shows a salient structure on the NW front of the EGMB. Various models have been proposed for the development of salient structures. However, one that involves the variation in the rheological properties of the basement seems to be valid for the study area as the foreland shows variation in rock types from massive granite at the apex to granite gneisses/tonalite–trondhjemite gneisses at the end points. The lateral ramps have developed exactly where the lithological contrast appears (Fig. 10). The variation in the rheological property has either induced the decollement to develop at two structural levels or produced variation in the amount of displacement along the thrust. Hence it is concluded that the NW front of EGMB represents the salient part of a FTB that resembles Caledonide type of fold-thrust belt where the thrusting is post tectonic to folding and metamorphism of the cover rocks and the basement has deformed in ductile manner during thrusting.

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