Some structural observations in the Eastern Ghats Mobile Belt surrounding Visakhapatnam, South India

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Abstract

The Eastern Ghats Mobile Belt is an arcuate belt of the high-grade terrain located along the east coast of Peninsular India. This mobile belt is considered to lie between the Archean Indian Craton and the East-Antarctic Craton in Gondwanaland. Therefore, this mobile belt played an important role in the construction of Gondwanaland. However, geologic studies, especially structural ones in the Eastern Ghats Mobile Belt, are still insufficient.

Detailed work was carried out in the Eastern Ghats Mobile Belt area around Visakhapatnam in order to evaluate the possible deformational history in the light of recent studies. Deformational structures occurring along the route from Kottaplem to Gollapalem, north of Visakhapatnam, are described in this short note. This selected route is situated in the northern marginal area of the macroscopic domal structure known as the 'Madhuravada Dome'. Well-developed compositional banding, foliation parallel to the compositional banding, pinch-and-swell structures, lineations and several type of folds can be observed on this route. These structures can be classified into the D_L, D_M, and D_N deformational stages, from the earliest to latest. The D_L deformation is characterized by a flattening event, identified by the foliation which is composed of garnet grains (or aggregates) showing the oblate strain ellipsoid. The D_M deformation is considered to form the mesoscopic, intrafolial, isoclinal to tight folds, pinch-and-swell structures, lineations and several type of folds can be observed on this route. These structures may also be due to a compression event.

The preliminary structural interpretations in this study area appear to be dissimilar to those of previous works. It is emphasized, therefore, that regional and local structural data are necessary for a better understanding of structural evolution of the Eastern Ghats Mobile Belt around Visakhapatnam.

Key words: deformational structures, Eastern Ghats Mobile Belt, Visakhapatnam, India, Proterozoic.

1. Introduction

The Eastern Ghats Mobile Belt (EGMB) is a high-grade terrain distributed along the east coast, facing the Bay of Bengal, of Peninsular India (Fig. 1). On a reconstruction map of East Gondwanaland, the EGMB lies between the Indian cratons of Dharwar and Bastar, and the East Antarctica Craton during the middle Proterozoic to Paleozoic and the Mesozoic Eras (Fig. 2). Thus, the EGMB might have played a significant role in the formation of East Gondwanaland. This mobile belt is also considered to preserve structural and metamorphic evidences for their behaviour during the exhumation of granulites from deep crustal levels (Chetty, 1995). However, geologic studies of the EGMB are insufficient, and the characteristics of this mobile belt are still indistinct.

Some contributions concerning the lithology and deformation of the rocks in the EGMB around Visakhapatnam have been published (e.g.,
Sriramadas and Rao, 1979; Fonarev et al., 1995). The petrological features were well described in these works, but deformational and kinematic interpretations, on the basis of detailed structural data, as well as investigation of the deformation mechanisms of the structures, were not examined. Considering the importance of the Visakhapatnam area in evaluating the structural and tectonic evolution of the EGMB, a detailed geological survey much needed. The present study aims to establish detailed lithological and structural maps, to characterize the lithological and structural features of the rocks in this area, and to discusses the structural and tectonic evolutions of the EGMB in and around Visakhapatnam.

This note introduces the structural outline of the area around Visakhapatnam and some observations on the deformational structures in the area.

2. General features of the Eastern Ghats Mobile Belt

The EGMB is a curvilinear mobile belt of less than 60 km width and more than 700 km length (Fig. 1). The western margin of this belt is in contact with the Archean Bastar Craton in the southern part and the Dharwar Craton in the northern part (Fig. 1). The Archean Singhbhum Craton is adjacent to the northern margin of the EGMB (Fig. 1). It is considered that the boundary between the EGMB and Bastar-Dharwar cratons is marked by a thrust, with the former's superposition on the latter (Fig. 2).

In the EGMB, metamorphosed supracrustals showing granulite-facies grade, granites, charnockites, anorthosites and alkaline rocks occur with minor amounts of calc-silicate rocks, mar-
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ble and quartzite. Migmatitic rocks are also observed in some regions (e.g., the Tekkali area, Yamamoto et al., 1998). Pressure-temperature (P-T) path studies from the different areas of the EGMB generally show a near-isobaric cooling path, followed by a near-isothermal decompression, from a peak temperature-pressure condition around $\sim 950^\circ$C at $\sim 9$ kbar (e.g., Dasgupta et al., 1995; Shaw and Arima, 1997). Sanyal and Fukuoka (1995) have suggested a near-isothermal decompression path, followed by a near-isobaric cooling path from the P-T co-ordinates of 8.4 kbar and 900$^\circ$C.

Grew and Manton (1986) indicate 979 Ma for zircon from charnockites of Visakhapatnam and a similar age for sapphire-bearing granulites from Anakapalle. Paul et al. (1990) also report U-Pb zircon and monazite ages of 990-950 Ma from the charnockites of the Visakhapatnam and Phulbani areas. Aftalion et al. (1988) considered that the charnockites might have formed between 1100-950 Ma in the EGMB.

The obtained ages, ranging from 1500 to 1400 Ma, appear to be the ages for an alkaline magmatism or an anorthositic activity (Sarkar et al., 1981; and Sarkar et al., 1994). An U-Th-Pb age of 2600 Ma, and a Nd model age of TDM 2600 Ma for the charnockites of Vsakhapatnam, are also reported (Vinogradov et al., 1964; and Paul et al., 1990). Unnikrishnan-Warrier et al. (1993) compiled the geochronological data of southern India and concluded that the EGMB is characterized by charnockite formation at ca. 1000 Ma over precursor granulites of 2000 Ma and/or 2500 Ma. On the other hand, minor data showing a $\sim 500$ Ma Pan-African thermal event are also known (see Fig. 4 in Yoshida, 1995). Thus, geochronological works have proposed $\sim 1500$-1400 Ma and $\sim 1000$ Ma for the major events of the EGMB, while the relict ages reflect Archean and minor amounts of $\sim 500$ Ma Pan-African activities.

3. Structural outline of the present study area in and around Visakhapatnam

The study area is mostly composed of garnet-sillimanite (-biotite) gneiss (Khondalites) and garnet-biotite or biotite gneisses (Leptynites), as well as minor charnockite-enderbite rocks and basic pyroxene granulites (Fig. 3). Quartzite layers are often interbedded with the garnet-sillimanite (-biotite) gneiss. The lithological boundaries between the quartzite and garnet-sillimanite (-biotite) gneiss are generally parallel to the major compositional banding (Fig. 4). Basic pyroxene granulite and enderbite-charnockite rocks are distributed within the leptynites. Enderbite-charnockite rocks are characteristically exposed in the crestal and axial parts of the macroscopic overturned folds (Fig. 4, Sriramdas and Rao, 1979).

Macroscopic, overturned isoclinal synforms are well reported in the EGMB around Visakhapatnam by Sriramadas and Rao (1979) (Fig. 3). The axial traces of the macroscopic overturned folds trend E-W and plunge towards the east in the coastal area. On the other hand, the overturned isoclinal folds in the inland area show NE-SW-trending axial traces (Fig. 3). According to Sriramadas and Rao (1979), the arcuated shape of the axial traces of the macroscopic overturned folds are considered to be the result of the superposition of later folding on the macroscopic overturned folds (Figs. 3 and 4). In
spite of the development of the macroscopic overturned isoclinal synforms, overturned isoclinical antiforms, which should have been formed simultaneously with the synforms, were not reported by Sriramadas and Rao (1979). A macroscopic domal structure with upright axial plane can be recognized in the Madhuravada area (Figs. 3 and 4). This domal structure is well known as the 'Madhuravada Dome' (Rao et al., 1994) and is occupied mostly by quartzo-feldspathic rocks (Fig. 4).

Fonarev et al. (1995) discussed the tectono-thermal history of the granulite terrain around the Visakhapatnam area and identified at least four different phases of ductile deformation (Table 1). However, their description of the structural data is not enough for the establishment of the regional structural evolution of this area. Hence, their interpretation of the deformational part needs to be reinterpreted, using additional detailed structural and kinematic analyses.

4. Deformational structures in the area between Kottapalem and Gollapalem, northern Visakhapatnam district

The selected route is situated in the northeastern marginal region of the Madhuravada Dome (Fig. 4). It is thought that this macroscopic domal structure is reflected in the map as a topographic basin (Fig. 5). In this area, garnet-sillimanite (-biotite) gneiss constitutes the dominant rock type. Compositional banding, foliation, folding structures, pinch-and-swell structures and minor linear structures are well observed in this area. However, features indicative of a ductile shear zone, such as a mylonite zone and a brittle shear zone, could not be found. The deformational structures in the area between the Kottapalem and Gollapalem villages are described below.
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Legenda
- Garnet-sillimanite (-biotite) gneiss (Khondalites)
- Basic pyroxene granulite
- Quartzite
- Quartzo-feldspathic rocks (Leptynites)
- Chamokite
- Strike and dip of foliation
- Overturned isoclinal synclinal fold
- Axial trace of F2 fold
- Axial trace of F3 fold
- Axial trace of F4 fold

Fig. 4. Geological map around Visakhapatnam (modified after Rao, A.T. et al., 1993).

Table 1. Structural evolution in and around the Visakhapatnam area (Fonarev et al., 1995).

<table>
<thead>
<tr>
<th>Deformation stage</th>
<th>Deformational structures</th>
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<tbody>
<tr>
<td>D₁</td>
<td>Strong foliation (S₁) parallel the compositional banding Strong stretching lineation</td>
</tr>
<tr>
<td>D₂</td>
<td>Tight to isoclinal fold (F₂) with axial planar cleavage (S₀)</td>
</tr>
<tr>
<td>D₃</td>
<td>Macroscopic open to tight fold (F₃) showing often doubly plunging shape (domal structure)</td>
</tr>
<tr>
<td>D₄</td>
<td>SE-plunging open upright fold (F₄) characterized by prominent axial planar shears</td>
</tr>
<tr>
<td>Post-D₄</td>
<td>NNE-trending kink bands Brittle shear on a minor scale</td>
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</table>

Planar structures

Compositional bandings, identified by the alternation of garnet-rich layers and quartzo-feldspathic layers, are well developed within the garnet-sillimanite (-biotite) gneiss (Fig. 6A). This compositional banding is distinguishable from other minor compositional banding structures in this area and is termed the 'major compositional banding'.

Although the garnet grains often have rounded shapes, lenticular garnet grains (or garnet aggregates) can be observed both on the
horizontal and vertical rock surfaces in some localities (Fig. 6B). This observation indicates that these garnet grains (or aggregates) are the shape of the oblate strain ellipsoid which might have been formed by flattening (Davis, 1984). This preferred orientation of lenticular garnet grains form a foliation, generally paralleling the major compositional banding. On the other hand, this foliation is deformed by an isoclinal folding, as explained below.

The major planar structures, consisting of the major compositional banding and foliation parallel to the major compositional banding, trend NW-SE and have moderate to high NE dipping in the outcrops located near Kottapalem (Fig. 7). On the other hand, the N-S-trending and E-dipping planar structures, with moderate dip angles, are common in the outcrops situated near Gollapalem (Fig. 7). On the basis of the major planar structures, the survey area is divided into two structural domains (Structural domains A and B, Fig. 7).

The major planar structures are deformed by pinch-and-swell structures in some localities (Fig. 6C). The direction of the necks of the pinch-and-swell structures show various orientations, but the data are not enough to confirm this (Fig. 8).

Steeply dipping cleavages associated with leucocratic veins are locally observed in this area (Fig. 7). These cleavages cut the major compositional banding and trend E-W (Fig. 6D). As the outcrops are highly weathered, the minerals in these leucocratic veins are indistinct.

Fold structures
Deformed, major compositional banding structures often show mesoscopic intrafolial folds of isoclinal to tight type, with asymmetric or symmetric types in some outcrops. These fold structures are generally non-rootless and show nearly similar shapes. However, the intrafolial tight folds, observed at outcrop No. P96091011, are nearly of the chevron type (Fig. 6E). An axial
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Fig. 6. Field photographs showing the deformational structures in the area between Kottapalem and Gollapalem. A: intrafolial isoclinal to tight fold, showing rootless type. B: Foliation formed by oblate strain ellipsoid. C: pinch-and-swell structure. D: leucocratic veins. E: intrafolial tight fold showing nearly chevron style. F: isoclinal to tight fold showing asymmetric shape.

planar foliation, composed of weakly flattened garnets, is rarely observed in some intrafolial folds (Fig. 9A and 9B). The equal-area stereographic projections illustrate that the hinges of the intrafolial, isoclinal to tight folds have various directions (Fig. 8).

At the outcrop No. P96091011, it can be observed that the foliation, composed mainly of shape preferred orientation of garnet aggregates showing an oblate strain ellipsoid, is deformed by the isoclinal folding event (Fig. 9C and 9D). The foliation marked by garnet is observed in the limbs as well as in the hinge areas of the isoclinal folds (Fig. 9C and 9D). This indicates that the isoclinal folding might have occurred after the formation of the garnet foliation, which
Fig. 7. Route map showing structural data in the area between Kottapalem and Gollapalem.
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• B...tion of these asymmetric folds are almost similar with that of the NNW-SSE-trending macroscopic close fold (Fig. 8). Their vergence, defined by the fold asymmetry, is concordant with vergence of the parasitic folds of the macroscopic close fold. Hence, it is possible that these asymmetric, non-rootless folds are parasitic folds of the macroscopic close fold mentioned above.

c Phai (TT)-pole of major compositional banding (MCS) and major foliation (MF).

o Minor foliation cutting the MCS.

• Hinge of intratolial isoclinal fold (symmetric shape).

• Hinge of intratolial isoclinal - tight fold (asymmetric shape).

• Long axis of elongated quartz.

• Long axis of elongated garnet.

• Long axis of sillimanite and crenulation lineation.

• B-maximam of TT-poles of the MCS and MF.

Fig. 8. The equal-area stereographic projections (lower hemisphere) of L and S structures in the area between Kottapalem and Gollapalem. A: structural domain A; B: structural domain B; C: major planar structures in domains A and B.

...was probably associated with the flattening event.

Any shear-zone features, such as mylonite and fault zones, which could change the structural orientation, were not identified in this area (Fig. 7). The variation of the orientation of the major planar structures suggests that a macroscopic fold structure possibly lies in this area (Fig. 7). Structural data of the major planar structures are plotted on an equal-area stereographic projection (Fig. 8C). This shows that the macroscopic fold is a NNW-SSE-trending close fold, with overturned axial plane. The hinge of this macroscopic fold is moderately dipping toward ENE and moderately plunging toward ESE. However, more structural data are necessary to establish the macroscopic fold completely.

Two asymmetric non-rootless folds (Fig. 6F) of isoclinal to tight type can be observed in structural domain A (Fig. 7). The hinge direc-

tion of these asymmetric folds are almost similar with that of the NNW-SSE-trending macroscopic close fold (Fig. 8). Their vergence, defined by the fold asymmetry, is concordant with vergence of the parasitic folds of the macroscopic close fold. Hence, it is possible that these asymmetric, non-rootless folds are parasitic folds of the macroscopic close fold mentioned above.

Lineations

Although lineation constitutes a very minor structural element in this area, crenulation lineation, mineral lineation and mineral-stretching lineation can rarely be observed in a few localities. Mineral lineation is defined by the long axis of sillimanite. This lineation is generally associated with the crenulation lineation parallel to the mineral lineation, and trends ENE.

In an exposure situated near the outcrop No. P96091011, garnets show granular or weakly elongated shapes on the vertical section, in spite of the lenticular shape on the horizontal surface (Fig. 9E and 9F). This observation may indicate that these garnets probably give an outline of the prolate strain ellipsoid, related to a stretching deformation (Davis, 1984). Elongated quartz grains, showing the prolate strain ellipsoid, are also observed in some localities where the pinch-and-swell structures can be well identified (locality No. P96090902 and No. P96091011, Fig. 7). These elongated shapes of minerals are considered to be the stretching lineations. Although stretching lineation is locally developed, almost all these lineations trend E-W in this area (Fig. 8). These are, in general, eastward-trending lineations.

5. Discussion

A schematic illustration of the outcrop No. P96091011 is given in Figure 10, together with an equal-area stereographic projection. Judging from the geometrical relationship and the field observations, the following interpretations can be considered: (1) the intrafolial, isoclinal to tight folds were formed after the formation of the major compositional banding; (2) the mineral-stretching lineation and the pinch-and-swell structures might have been formed by extension, parallel mostly to the hinges of the isoclinal to tight folds. This extension may be due to the
post-buckling compression of the intrafolial, isoclinal to tight folds.

On the other hand, the major foliation, composed of the preferred orientation of lenticular garnet grains or aggregates showing the oblate strain ellipsoid, is deformed by the isoclinal folds in a few localities. This observation may give rise to the following interpretation: (3) the intrafolial, isoclinal to tight folds might have occurred after the formation of the garnet foliation. A mineral grain or a mineral aggregate showing the oblate strain ellipsoid is generally formed by a flattening mechanism (Davis, 1984). Thus, it is possible to consider that, (4) a flat-
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Table 2. Preliminary interpretation of the relationship between the structures in the area between Kottapalem and Gollapalem (this study).

<table>
<thead>
<tr>
<th>Deformation stage</th>
<th>Structures</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>( D_L )</td>
<td>Major compositional banding</td>
<td>Flattening</td>
</tr>
<tr>
<td></td>
<td>Foliation composed of lenticular garnet grains or garnet aggregates</td>
<td></td>
</tr>
<tr>
<td>( D_M )</td>
<td>Mesoscopic intrafolial isoclinal to tight fold</td>
<td></td>
</tr>
<tr>
<td>( D_M )</td>
<td>Pinch-and-swell structure</td>
<td>Post-buckling compression</td>
</tr>
<tr>
<td></td>
<td>Some stretching lineations</td>
<td></td>
</tr>
<tr>
<td>( D_N )</td>
<td>Macroscopic close fold with overturned axial plane (?)</td>
<td>possible compression</td>
</tr>
<tr>
<td></td>
<td>Mesoscopic isoclinal to tight fold</td>
<td></td>
</tr>
</tbody>
</table>

tening deformation might have affected the rocks in this area before the isoclinal folding event.

The intrafolial structures between the major compositional banding are deformed by the macroscopic close fold with overturned axial plane (Fig. 4). Hence, it is possible to consider that the macroscopic close fold and its associated mesoscopic fold might have been formed after the formation of the intrafolial, isoclinal to tight folds and their associated structures, mentioned before. However, the mechanism and kinematics of this macroscopic folding event is not clear. To sum up, a preliminary interpretation showing the relationship among the deformational structures in the area between Kottapalem and Gollapalem is given in Table 2.

The \( D_L \) stage is characterized by a flattening deformation, which is identified by the major foliation composed of garnet grains (or aggregates) showing the oblate strain ellipsoid. The \( D_M \) deformation is also considered to form the mesoscopic intrafolial, isoclinal to tight folds, pinch-and-swell structures, and some stretching lineations, as the result of a compression perpendicular mostly to the axial plane of the mesoscopic intrafolial folds. Moreover, the \( D_N \) structures, such as the possible macroscopic close fold with overturned axial plane and related mesoscopic structures, may also be due to a compression event. Thus, the structures observed in the area between Kottapalem and Gollapalem are possibly the result of three stages of compression, including the first flattening deformation.

The first stage of deformation (\( D_L \)) is possibly equivalent to the \( D_1 \) stage of Fonarev et al. (1995). They concluded the strong foliation was accompanied by a strong stretching lineation. However, some stretching lineation is developed after the formation of the strong foliation, as discussed in this paper. On the other hand, it seems that the \( D_M \) deformation is not comparable to the \( D_2 \) deformation of Fonarev et al. (1995), because the hinges of mesoscopic intrafolial folds generally show random orientation, which is entirely different from the linear features of the macroscopic \( F_2 \) folds, illustrated in Figures 3 and 4. The \( D_N \) deformation may be equal to the \( D_2 \) deformational stage of Fonarev et al. (1995).

6. Concluding remarks

The results of the structural analysis carried out locally are not harmony with the structural history proposed by previous contributions (e.g., Sriramadas and Rao, 1979; and Fonarev et al., 1995). Such a disharmonic interpretation can also be recognized at the macroscopic scale. Rao et al. (1993) and Fonarev et al. (1995) illustrate the clear domal structure in and around the Madhuravada area (see Figs. 3 and 4). It is true that the topographic characteristics and some planar structural data of the Madhuravada Dome area suggest the presence of the domal structure in the southeastern part of the Dome area (Fig. 5). However, it appears that the northwestern part of the Dome area shows a plunging syn-
form rather than a plunging antiform, although the data are insufficient for a macroscopic analysis of this Dome area (Fig. 5).

It is emphasized that we need more micro-, meso-, and macroscopic structural data collected regionally from the study area, for a better understanding of structural evolution of the EGMB around Visakhapatnam.

**Acknowledgments**

We wish to express our sincere gratitude to Dr. K. Srinivasa Rao, Mr. S. Srinivas, and Mr. P. Saradhi of Andhra University, India, for their assistance and hospitality during the field work. We would like to thank Prof. V. Glebovitsky and Dr. A.B. Kovach of Institute of Precambrian Geology and Geochronology, St Petersburg, Russia for their fruitful discussions in the field. We are thankful to Mr. H.M. Rajesh of the Department of Geosciences, Osaka City University, for valuable review and discussions. This paper is a contribution to IGCP 368.

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