CHAPTER 4

STRUCTURAL FRAMEWORK

Structural mapping was done in regional-scale around Phulbani town (Fig. 4.1) in order to understand the variations of the planar and linear fabric elements. This was followed by outcrop-scale mapping of some selected areas (rectangular areas marked in Fig. 4.1). The detailed litho-structural mapping suggests that the studied area has been affected by five stages of deformations which are designated as D_1 to D_5 (corresponding to S_1 to S_{5S} fabrics). Depending upon the presence of deformation fabrics, the study area is subdivided into two sectors: (1) the southern sector, located at the southern part of the Phulbani town, and (2) the northern sector, situated at the northern part of the Phulbani town. At the southern sector, imprints of D_2, D_3 and D_4 deformation phases (S_2, S_3, S_4 and S_{4S} fabrics) are prominent whereas at the northern sector the imprints of D_4 and D_5 deformations (S_4 and S_{5S} fabrics) are noteworthy. At the southern sector, the D_2 and D_3 deformations produced megascopic folding in which aluminous granulite bands serve as the marker horizon. On the other hand, folds related to the D_4 deformation are also locally present and marked by folded aluminous granulite and calc-silicate granulite bands. In spite of the presence of D_4 deformation, D_5 deformation and related fabric occupies the major portion of the northern sector. The latter is notably confined along the Ranipathar shear zone (maximum width is up to 4 km). It is important to mention that the imprint of D_1 deformation (S_1 fabric /F_1 fold) is present only in grain-scale within the porphyroblastic phases such as garnet, corundum and spinel present in the aluminous granulite of both sectors. The deformation phases, related fabrics and resultant fold interference patterns are discussed below in detail.

4.1 Developments of structural fabrics in regional scale

4.1.1 Structural fabrics at the southern sector

At the southern sector, the earliest recognizable planar fabric is S_2 which resulted during D_2 deformation and dominantly present at the western part of this sector. S_2 fabric is gneissic in nature and developed preferentially along the axial plane of folded inclusion trails (F_2: folded S_1) present within garnet, corundum and spinel of aluminous granulite. In most cases, this S_2 fabric is present locally in outcrop-scale and represented by discontinuous fold trains. The S_3 fabric has been developed axial planar to the tightly folded S_2 surfaces (F_3; Fig. 4.2a) during the D_3 deformation and in most of the places, barring the fold hinges, is parallel to the earlier formed S_2 fabric. At the western part, this F_3 fold is present both in macro- to mesocopic-scale and because of its tight geometry, it becomes difficult to differentiate the S_2 and S_3 fabrics separately at least in outcrop-scale. This suggests that the D_2 and D_3 deformations were possibly successive in nature producing a composite S_2/S_3 gneissic fabric which is identified as the dominant planar fabric of the study area. In mesoscopic-scale, the F_3 fold is defined by aluminous granulite bands having broadly E-W trend. The mean orientation of the composite S_2/S_3 gneissic fabric is 083/77S (Fig. 4.1). Gneissic fabric in the aluminous granulite is defined by alternate spinel-bearing and quartz-feldspar-bearing layers. It is important to mention that although best preserved in the aluminous granulite, the composite S_2/S_3 fabric is also present in fine-grained charnockite gneiss and migmatitic felsic gneiss too (Fig. 4.2b, c). In the fine-grained charnockite gneiss, this fabric is characterized by alternate pyroxene-rich and quartz-feldspar-rich layers whereas in the migmatitic felsic gneiss, it is defined by alternate garnet-biotite-rich and quartz-feldspar-rich layers.

D_3 deformation was succeeded by D_4 deformation that produced the mesoscopic-scale S_4 fabric. Folds related to this deformation (F_4) are best presented by folded aluminous granulite and calc-silicate granulite bands respectively at the western and at the south eastern part of the sector where composite S_2/S_3 fabric is folded. Outcrop-scale folds (F_4) represented by folded aluminous granulite bands do not contain any axial planar foliation (S_4) at the western part of the sector but it is distinctly notable in aluminous granulite and calc-silicate granulite outcrops (Fig. 4.2d) located at the southeastern part. In the latter case the F_4 folds are dominantly intrafolial and tight in nature and S_4 fabric develops as axial planar foliation of the folded S_3 fabric to form hook-shaped fold patterns (Fig. 4.2e). The mean orientation of this S_4 fabric is 320/75NE (Fig. 4.3a). The hook-shaped F_4 folds are moderate to steeply northeasterly plunging (Fig. 2; mean orientation of the fold axis is 074→035) and absence of considerable variations in the plunge amount of such folds suggest the cylindrical nature of the same. Additionally, the dip direction of the axial plane (S_4) broadly coincides with the plunge direction of the F_4 fold suggesting the reclined nature of the same at least in outcrop-scale. The coarse-grained charnockite which appears to be intruded within the aluminous granulite, calc-silicate granulite and the fine-grained charnockite possesses only the S_4 fabric (Fig. 4.2f) at places, which indicates that the charnockitic intrusion was post-D_3 and pre- D_4 in nature.

Discrete small-scale N-S trending vertical to steeply dipping ductile shear zones are present at low angle with the S_4 fabric and confined mostly at the central part and few other places of the southern sector (Fig. 4.1). Localization of mylonitic fabric (S_{4S}) along the ductile shear zones is conspicuous in the migmatitic felsic gneiss, the aluminous granulite and the associated coarse-grained charnockite (Figs. 4.2 g, h, i). Detail mapping suggest that the mean orientation of such mylonitic foliation is 180/89 W (Fig. 4.3b). Fold trains (F_4) defined by S_2/S_3

fabric are present in these shear zones and the mylonitic foliation (S_{4S}) preferably develops along the axial plane of such folds (Fig. 4.2h). Sheared migmatitic layers of the aluminous granulite, present at the vertical sections within the ductile shear zone (Fig. 4.2 j) confirm that the shear zone development occurred after the high-grade metamorphism. Shearing produced the S-C fabric in the aluminous granulite and the migmatitic felsic gneiss (Fig. 4.2k) with sinistral sense on plan view which is also confirmed by the asymmetry of garnet and feldspar porphyroclasts (Fig. 4.2l). Aluminous granulite and migmatitic felsic gneiss locally preserve steeply southward plunging stretching lineations (Fig. 4.2m). Presence of shear fabrics in both the horizontal and the vertical sections suggests an oblique movement during development of these ductile shear zones.

It is important to note that although the S_{4S} mylonitic fabric lies at low angle to the S_4 fabric and both the fabrics formed along the axial plane of the F_4 fold, these fabrics possibly not developed during a single phase of deformation (discussed later in detail). However, as both the fabrics are axial planar to the F_4 fold, the deformation which was responsible to produce the S_{4S} mylonitic fabric is designated here as $D_{4'}$ and possibly was a discrete phase of deformation that followed the main D_4 event.

4.1.2 Structural fabrics at the northern sector

A broadly E-W trending brittle-ductile shear zone occurs at the northern part of the study area (Fig. 4.1) where mylonitic fabric and associated pseudotachylite veins are conspicuous in aluminous granulite, migmatitic felsic gneiss, felsic augen gneiss, coarse-grained charnockite and mafic granulite. This shear zone has been named as the Ranipathar shear zone (RSZ) by the earlier workers (Dobmeier and Raith, 2003; Chetty, 2010). Structural mapping of this shear zone has been done from the Charichak area at the east to the Putudi water falls at the west covering almost 27 km in length and have maximum width of 4 km (Fig. 4.1). It is important to note that the shear zone shows a broad warping (Fig. 4.1) which resulted in a southward shift of it at the western part. At the eastern part of the RSZ, an earlier NW-SE trending S_4 fabric with mean orientation of 329/90 shows folding (F_5) to form an axial planar mylonitic fabric (S_{5S}) with mean orientation of 279/77NE (Fig. 4.1). The folded S_4 fabric is best preserved at the close proximity of the western part of the same shear zone and the trends of the axial planes of such mesoscopic folds vary from 280°-317° (Fig.4.4a). Mafic granulite lenses occurring within the migmatitic felsic gneiss are also occasionally folded (Fig. 4.5a). Detailed mapping suggests that these folds are overturned in nature as both limbs of these folds appear to be dipping towards east (Fig.4.4a). Poles to the form surface of these overturned folds (S_4 fabric) form girdle have the mean orientation of 171/65SW while the intersection lineations on the limbs of these folds (Fig. 4.5b) present in the migmatitic felsic gneiss have the mean orientation of 039→072 (Fig. 4.4a). It is noteworthy that the orientations of the calculated beta axis of such folds have similar values (023→082) with respect to the mean orientation of the intersection lineations mentioned above. This indicates that these intersection lineations are actually the fold axes developed during folding of S_4 fabric (F_5).

The mylonitic foliation (S_{5S}) of the migmatitic felsic gneiss, felsic augen gneiss and the coarse-grained charnockite at RSZ is defined by elongated feldspar grains which are set in dark-colored fine-grained quartz-rich matrix (Fig. 4.5c). Alternate mylonitic and ultramylonitic bands are present in such rocks (Fig. 4.5d) and these alternate bands are defined by differences in the matrix proportion. The aluminous granulite present at RSZ is fine-grained and appears as phyllonitic in most instances (Fig. 4.5e). Stretching lineations are present on S_{5S} mylonitic fabric

(Fig. 4.5f) and is defined by elongated quartz and feldspar grains in the migmatitic felsic gneiss, felsic augen gneiss and by elongated quartz, feldspar and sillimanite grains in the aluminous granulite. At the eastern part of RSZ, these stretching lineations are moderate to steeply northeasterly plunging with mean orientation of 071→056 (Fig. 4.1). At the western part of RSZ, the stretching lineations are notably doubly plunging (Fig. 4.5g) and both steeply easterly and westerly plunging stretching lineations are present in migmatitic felsic gneiss. It is however important to note that locally horizontal stretching lineations are also present both at the eastern and the western part of the RSZ. Although rare, the calc-silicate granulite shows outcrop-scale sheath folds both on the horizontal and the vertical sections within the RSZ (Fig. 4.5h). Detailed mapping at the western part of RSZ additionally reveals the presence of a partially preserved mesoscopic-scale sheath fold in the migmatitic felsic gneiss and the mafic granulite (Fig. 4.4b). Although having similar trends, the mylonitic foliations related to this fold have variations in dip directions which is manifested by northerly dipping foliations at the northern part and southerly dipping foliations at the southern part. Poles to this mylonitic foliation form a girdle and the mean orientation of this girdle is 045/20SE. This fold has a closure along E-W direction and best preserved at the western part of the detailed map. Foliations present in the migmatitic felsic gneiss at the area of the detailed map are folded (Fig.4.5i) and the axial plane of the fold is approximately E-W trending. It is worth mentioning that the folds defined by the mafic granulite bands also have closure along E-W direction (Fig.4.5j) which resembles the fold pattern present in the migmatitic felsic gneiss mentioned above. Meter-scale blocks/xenoliths of migmatitic felsic gneiss having an earlier fabric are present at the same area and hosted by migmatitic felsic gneiss having the mylonitic fabric (Fig. 4.5k). Although similar in appearances these two rocks are temporally different and the latter is characterized by a conspicuous mylonitic fabric which is totally absent within the former.

Millimeter-scale pseudotachylite veins are present in the RSZ that usually are parallel to the (S_{5S}) mylonitic foliation (Fig.4.5l). Detailed mapping suggests that the pseudotachylite veins are ubiquitous where mylonitic to ultramylonitic gradation is present (Fig.4.4c). Such pseudotachylite veins are always associated with injection veins which are stemmed to the original pseudotachylite veins running parallel to the mylonitic foliation (S_{5S}). Mylonitized wall rock fragments are visible in outcrop-scale where the thickness of the pseudotachylite veins appears to be high (Fig. 4.5m). Fragments present within the pseudotachylite veins which are parallel to the mylonitic foliation are dominantly stretched but elliptical to sub-rounded fragments are also present at some locale. In all instances, the pseudotachylite veins appear to be black and characterized by dull to sub-vitreous lustre. Pseudotachylite veins at high angle to the mylonitic foliation (S_{5S}) are also present at RSZ. It is important to mention that this latter type of veins are always associated with shear fractures at high angle to the mylonititc foliation and has visible offset in outcrop-scale (Fig. 4.5n).

Within the RSZ, S-C fabric and asymmetric tails of rotated porphyroclasts having dextral sense of shearing are present on horizontal sections (Figs. 4.5o, p). Stretching lineations in such cases are also horizontal. In the outcrop-scale, vertical sections containing the steeply plunging stretching lineations do not contain any structure that could indicate asymmetry. Detailed mapping of the eastern part of the RSZ indicates presence of alternate mylonitic and ultramylonitic bands which are cross-cut by subsequently developed N-S oriented fracture planes (Fig.4.4c). The felsic gneiss and the coarse-grained charnockite in such mylonitic bands have augen shaped feldspar grains set in the fine-grained quartz rich matrix.

4.2 Synthesis of the structural elements and deformation phases

Regional- to outcrop-scale mapping and microstructural studies suggest that five deformation phases affected the presently studied area. The first deformation (D_1) has no regional significance as the imprint of the same (S_1 fabric) is confined only within the porphyroblastic phases of aluminous granulite. The regional-scale structural characters of the Phulbani domain however are interpreted to be the result of four deformation phases (D_2-D_5) which followed D_1.

The earliest recognizable planar fabric of the study area is of composite nature (composite S_2/S_3 gneissic fabric) which developed during D_2-D_3 deformations. Being preserved at the western part of the study area, this fabric is broadly E-W trending and is defined by folded aluminous granulite bands. This fabric is also present in the fine-grained charnockite and the migmatitic felsic gneiss which are found to co-occur with the aluminous granulite. An earlier N-S compression is responsible to produce this fabric present at the Phulbani domain.

D_2-D_3 deformations were followed by D_4 deformation which folded earlier formed S_2/S_3 gneissic fabric to form mesoscopic-scale hook-shaped fold interference patterns which are best documented in the calc-silicate granulite outcrops present at the south eastern part of the study area. The axial planar foliation (S_4) of such folds are broadly NW-SE trending. The plunge direction of the fold axes of these folds are almost similar to the dip direction of the axial planar foliation (S_4) indicating reclined nature of the same. The orientation of the folds and their axial planes suggest a NE-SW compression during development of S_4 fabric.

The N-S trending ductile shear zones of the study area are characterized by mylonitic foliation (S_{4S}). This mylonitic fabric has developed as axial planar foliation of the folded S_2/S_3 fabric, similar to the resultant fabric (S_4) of the previously mentioned D_4 deformation. However, the deformation phase which is supposed to be responsible for the development of such mylonitic foliation possibly was a discrete phase of deformation ($D_{4'}$) that followed D_4. Existence of such a latter deformation phase can be speculated if the sense of the N-S shearing is considered. Rotated porphyroclasts and the S-C fabric suggest that on horizontal section the shear sense was sinistral and the compression direction was broadly along NW-SE direction. Development of a shear zone with sinistral shear sense during D_4 deformation is theoretically not possible as the compression direction during this deformation was along NE-SW direction. If any shear zone developed during D_4 deformation the sense of shear of that shear zone would have been dextral on horizontal section which is absent in the present scenario.

D_5 deformation is confined along the RSZ located at the northern extremity of the presently studied area and has broadly E-W trending conspicuous mylonitic foliation (S_{5S}). This S_{5S} fabric developed during folding of earlier formed S_4 foliation. In most cases, the stretching lineations associated with the S_{5S} mylonitic fabric are moderate to steeply-plunging but horizontal and doubly plunging stretching lineations are also notable at some places. Such variations in the orientation of the lineations could be the result of macro- to mesoscopic-scale sheath folds which is present in the calc-sillicate granulite and migmatitic felsic gneiss located at RSZ.

Pseudotachylite veins present within the RSZ are usually parallel to the mylonitic foliation (S_{5S}) but veins at high angle to the mylonitic foliation (S_{5S}) are also common. This latter type of veins is associated with shear fractures which occur at high angle to the mylonitic foliation of RSZ and offset such foliation in outcrop-scale.