3.1 Introduction

The study of structures is fundamental to any historical understanding of the crustal geodynamics through time. Speck-sized to continent sized masses of crustal rocks have been shifted, rotated, uplifted and internally distorted as a response to Earth forces. An universal compromise that the crustal rocks make with the Earth forces lead to a jargon of architectural features like folds, faults, joints, foliation and lineation etc. Thus a student of structural geology is always greeted in nature by architectures which look like a finished product and, is challenged as well as compelled to ask questions and logically surmise their genesis.

Observations of the varying structural features and their measurements, interpretations, geometric analyses both in the field and in the laboratory are carried out after the methods suggested by de Sitter (1958), Turner and Weiss (1963), Ramsay (1967), Ramsay and Huber (1987), Ghosh and Chatterjee (1985), Twiss and Moore (1992), Ghosh (1993) and Passchier and Trouw (1996). As genetic interpretations of the structural features like folding and foliations (or S-surfaces) are imperfectly understood, and are a difficult task to work out from the end products of deformational events, therefore, the descriptive / morphological study of such deformational imprints are mostly made use of in the following discussions. Every attempt is made, wherever possible, to deduce the regional structural pattern based on the study of minor structural elements observed in the hand specimen scale. Special attention has been paid to integrate all such observations, descriptions and measurements in the area of study. Lithological map profile acts as the indicator of regional structural configuration. However, for the purpose of structural analysis, the studied area is divided into two broad sectors viz., north-eastern sector named as Tatimara sector and south-western sector is named as Narengi sector (Fig. 3.1).
3.2 Regional structural setting

The present area comprises of a chain of continuous hills with varied lithology, and is a northeasterly extension of the “Assam Meghalaya Plateau”. Beyond the study area toward north, all the lithoassociations are submerged into Brahmaputra alluvials and nowhere exposed till Himalayan foothills - an effect by virtue of the Indian Plate’s northward subduction beneath the Himalayas.

The present study area is an integral part of the Gneissic Complex composed dominantly of quartzofeldspathic gneiss, amphibolite, hornblende biotite schist, calc-silicate rock, biotite schist and later intrusives in the form of pegmatite and other vein rocks including basalt and dolerite. The gneisses appear to be remnants of the remobilised primordial crust forming the basement. The different lithounits exposed in the study area are characterised by the concordant association of two distinct compositions - basic and felsic - and is designated here as ‘banded gneiss’ for onward discussion.

The quartzofeldspathic gneiss is the most dominant rock type and the generalised trend of the lithological layerings is NE-SW. Basic enclaves show concordant relationship with the regional foliation cum layering of quartzofeldspathic gneiss. The hornblende biotite schist, calc-silicate rock and biotite schist are limited to small dimensions and occur mostly as big lensoid bodies or as discontinuous layers maintaining parallelism with the general trend of the associated quartzofeldspathic gneiss. Amphibolite is comparatively a thinly layered rock quite persistent in occurrence but discontinuous in the direction of tectonic transport bearing the imprints of all the deformational phases and behave like a form surface, the way regional \( S_1 \) foliation acts. They are interlayered with the more ductile quartzofeldspathic gneiss and can also be utilised as the marker horizon.

The generalised trend of the lithological layerings is NE-SW. The axial planar \( S_1 \) foliation is of regional extent and is the most pervasive planar fabric. The foliation is considered as a reference plane or form surface to work out the regional structural configuration. The \( S_1 \) is highly perturbed because of superposition of later deformations.
and is invariably parallel to the lithological layer boundaries on the regional scale but
make some angles on the centimeter scale probably because of shearing.

3.3 Notations used in the text

The different symbols used in the text are listed below for convenience of references.

First phase deformation - $D_1$
Second phase deformation - $D_2$
Third phase deformation - $D_3$
Fourth phase deformation - $D_4$
First phase folding - $F_1$
Second phase folding - $F_2$
Third phase folding - $F_3$
Fourth phase folding - $F_4$
Lithological layering - $S_0$
First phase foliation - $S_1$
Second phase foliation - $S_2$
Third phase foliation - $S_3$
First phase lineation - $L_1$
Second phase lineation - $L_2$
Third phase lineation - $L_3$
Folding angle - $\Phi$
Interlimb angle - $\gamma$
Angle between an isogon and the normal to the parallel tangents of the folded surfaces
of a layer (for strain analysis of folds) / angle between the fault plane and the layer - $\phi$
Dip of the fold limbs - $\alpha$
Orthogonal thickness of a folded layers - $t_O$
Layer thickness parallel to a fold axial surface - $t_0$ or $T_0$
Apparent strain ratio $\sqrt{\lambda_2/\lambda_1}$ of the folded layers - $R$
Thickness of the layer - $t$
Length of the boudin - $L$
Width of the boudin - \( W \)
Shear angle - \( \psi \)
Direction of maximum extension - \( \hat{e}_1 \) (= direction of maximum stretch)
Direction of intermediate extension - \( \hat{e}_2 \)
Direction of minimum extension - \( \hat{e}_3 \)
Fold amplitude - \( A \)
Distance between the two inflection points of a fold along the base - \( M \)
Aspect ratio - \( P \)
Bluntness of folding - \( b \)
Wave length - \( \lambda \)
Intrados curvature - \( i \)
Extrados curvature - \( e \)
Arc length - \( a \)

3.4 Homogeneous structural domains

The rocks of the present area suffer from multidimensional episodes showing extreme inhomogeneity and to decipher them complexities arise to a maximum extent. Therefore, to maintain minimum homogeneity and easy reference, the entire area has been broadly divided into two domains viz., north-eastern domain (= Tatimara sector) and the south-western domain (= Narengi Patthar quarry sector) along the generalised trend of the lithology. For better convenience and simplicity the northeastern domain has been further subdivided into the Tatimara subdomain (A) and Chandrapur thermal station subdomain (B) while the south-western domain has been subdivided into Bonda subdomain (C), Forest gate (D), Narengi Patthar quarry (E) as shown in Fig. 3.1. Although the physical continuity of the outcrops between the subdomains is lost in some cases under a vast expanse of wetlands and alluvials, yet enough care has been taken to delineate them.

Fig. 3.1 · Domain map of the study area
from both petrological and structural point of views. Numerous blasted surface, several tens of meter high, show almost continuous exposures for many hundreds of meters which have helped to unravel the complex structural history of the area. The structural map of the area is presented in figure 3.2.

3.5 Structural elements and sequence

A structure based chronology of events has been established in the area using the standard criteria and the different lithoassociations have been affected by at least three phases of ductile followed by another phase of brittle deformations. The ductile phase deformations are essentially identified by the folds, reference S-planes (foliations) and lineations, whereas the brittle phase is marked by faults, fractures and joints.

The successive stages of deformation, for convenience of reference, are designated as $D_1$, $D_2$, $D_3$ and $D_4$. The diagnostic characters of these deformations are enlisted under foliation, fold and lineation and have been given numerical values which represent a time sequence and are denoted as $F$ for folds, $S$ for foliations and $L$ for lineations.

The different aforesaid structural elements can be chronologically tabulated below:

First phase: $D_1$ $F_1$ $S_1$ $L_1$
Second phase: $D_2$ $F_2$ $S_2$ $L_2$
Third phase: $D_3$ $F_3$ $S_3$ $L_3$
Fourth phase: $D_4$ $F_4$ $S_4$ $L_4$

3.6 Geometry of Mesoscopic Structures

3.6.1 First phase deformation ($D_1$)

The earliest recognisable deformation ($D_1$) records the intensive shearing mechanism under layer parallel shear couple operative of in the initial horizontal or near horizontal predeformational lithosetting and results rootless, intrafolial, $F_1$ folds with attendant axial plane foliation ($S_1$) and lineations of different types. The foliation ($S_1$) is of regional extent and bears the imprints of most of the later deformations and helps in studying the map profiles of the area.
Rarely a pre $S_1$ planar structure in the form of straight trails of inclusions could be identified within some of the garnet porphyroblasts of calc-silicate rock which might have resulted from an earlier (?) episode of deformation cum metamorphism or may represent an earlier stage of the $D_1$ deformation itself (cf Bowes and Wright, 1975). Relatively small, unidentified grains are also aligned around the $F_1$ fold hinge curvatures being transected by pervasive axial planar foliation ($S_1$) to $F_1$ folds. These two evidences are clear indicative of a pre $D_1$ phase which might have obliterated due to intensive recrystallisation and restructuring during $D_1$ deformation phase leaving a few relict features in the undoubted metasediments.

3.6.1.1 Lithological layering ($S_0$)

The lithological layering is designated as ($S_0$) and is documented by persistent but discontinued layers and lenses of alternate dark and white coloured rocks. Such gneissose layering may be a primary features of sedimentary or igneous origin or may be secondary origin developed by extreme flattening of compositional inhomogenities to the original rock under ductile environment. Such layered sequences may represent as the earliest recognisable planar structure in the area. Intense folding and metamorphism during different phases probably have obliterated stratification to a maximum extent making the individual lithological layers discontinuous and at places thickened and thinned, but the end-products still bear the testimony of initial stratification (Plates 3.1, 3.2ac).

Regarding the present configuration of the lithological layering, however, there are two possibilities:

(i) the layering represents the original stratification or,

(ii) it is the product of transposition of the original stratification under an intense tectonic set up (King and Rast, 1955, Turner and Weiss, 1963) The second possibility is apparently the right one in the present area as is indicated by the following features: (a) discontinuity of layers (Plates 3.1, 3.2), (b) complete absence of sedimentary structures and (c) medium to high grade metamorphism to which the rocks were subjected to (d) presence of intrafolial $F_1$ folds as tectonic fish in an incompetent quartzofeldspathic matrix (Plates 3.1, 3.2bc, 3.12ab; Figs 3.5, 3.9).
This lithological layering may thus represent the stratification after transposition and the original attitudes of the lithological layering cannot be ascertained due to overprinting of the impacts of subsequent deformations.

**3.6.1.2 Folds (F₁)**

Folds of this deformation although infrequently observed but consistent and bear the testimony of the earliest deformational impact. They are intrafolial, rootless, tight to isoclinal ($\phi = 160°$ to $180°$) in habit (Plates 3.1, 3.2bc, 3.4ac; Figs. 3.3-3.5). The tightness and bluntness ($b$) of the folds are rock selective depending upon the competency of the rock and the size does not exceed a few meters across. The interlimb angle ($\theta$) of these folds developed in quartzofeldspathic gneiss is relatively greater than those developed in amphibolite (Plates 3.1c, 3.2b). It is also observed that, higher the $\theta$ angle lower is the $\phi$ angle and such phenomenon is competency controlled. The $F₁$ fold shows ‘S’ shaped sinistral sense of rotation with characteristic thinning and thickening habits of the limbs and noses respectively indicating similar type of fold (Plate 3.2c; Fig. 3.4). Dextral vergence or ‘Z’ sense of rotation as well as M-type are also equally noticed all throughout the area (Plates 3.1cd, 3.3a, 3.4a, 3.6a; Figs. 3.5, 3.9). In quartzofeldspathic gneiss and amphibolites these $F₁$ folds are more often mimicked by quartz as aplitic veins but less common in quartzofeldspathic gneiss (Plate 3.2d). Each of them are invariably associated with contemporaneous axial plane foliation ($S₁$) which cuts the hinge zone of the folds at maximum angle but made parallel with the limbs in case of isoclinal folds, and where these are not parallel, they normally make acute angle with respect to that of hinge zone (Plates 3.4a, 3.12a; Figs. 3.3, 3.5, 3.17). The folded layers of $F₁$ folds are designated as $S₆$ (lithological layering) and they are also transposed into planar fabric - $S₁$ (Turner and Weiss, 1963). The arc length ($a$) measured from $F₁$ folds is highly rock selective and varies largely due to competency of the different lithounits. The $F₁$ folds are seen in the form of discontinuous lenses enclosed within the host rock, lenses being tectonically sheared out in the direction of tectonic transport (Plates 3.5d, 3.6c) Such lenses could be termed as “tectonic fish” (Ghosh, 1993) swimming within the more ductile quartzofeldspathic gneissic matrix where the flow rate is higher. The geometry of $F₁$
folds is approximately that of class 2 similar folds (Ramsay, 1967) although variations are noted from class 1C to 3 (Fig. 3.24) and the wide range of orientation of $F_1$ fold axes suggests that $F_1$ folds are deformed by subsequent deformations. The aspect ratio of $F_1$ folds ($P = A/M$) in case of amphibolite is higher than the computed nature in case of quartzofeldspathic gneiss. The axial surfaces of $F_1$ folds are generally parallel to the lithological banding or are oblique to the banding with a relatively low angle. Occasionally parasitic folds are seen in the hinges of $F_1$ folds in quartzofeldspathic gneiss (Plates 3.3a, 3.4a). The inhomogeneity is marked both by the planar and the products of non-linear transformation. The stereo plots of the axes of $F_1$ show wide dispersion which indicate that the influence of the later deformations is notable to a large extent (Fig. 3.20v).

3.5.1.3 Foliation ($S_1$)

The $S_1$ is axial planar to $F_1$ and is the most pervasive planar fabric of this deformation. The $S_1$ is defined by elongate, flaky minerals like biotite and hornblende in hornblende biotite schist and amphibolite, while in the quartzofeldspathic gneiss they are dominantly marked by the growth of the flaky mineral biotite and rarely hornblende (Plates 3.1b, 3.4a, 3.12ab). Flattening habit of quartz also take part in the formation of $S_1$ fabric (Plate 3.1b). Such foliation are sometimes diffused in quartzofeldspathic gneisses. They are invariably parallel to the lithological layer boundaries on the regional scale but sometimes make low angles on the centimeter scale probably because of shearing. Morphological study of foliation indicates the following types - (a) diffused foliation (b) axial plane foliation and (c) anastomosing foliation. In the migmatitic rock the $S_1$ is defined by quartz rich, quartzofeldspathic (neosome) and melanocratic to mesocratic palaeosome bands.

This foliation is considered as a reference plane (or form surface) to work out the regional structural configuration. The $S_1$ is highly disturbed because of superposition of later deformations (Plates 3.2ab, 3.4bc; Figs. 3.5, 3.7, 3.11). The generalised trend of the $S_1$ foliation is NE-SW (varies from NW-SE to almost E-W) showing dip either towards NW or SE at low to moderate angles. This diversified attitude is because of interference of later $F_2$ or $F_3$ foldings. Such tectonic flowage of planar fabric is deflected
around the boudins and form neck folds in the separation zones between the boudins (Figs. 3.9, 3.30, 3.32; Plate 3.9). The S\textsubscript{1} foliation is further transected by shear foliation during subsequent deformations.

3.6.1.4 Lineation (L\textsubscript{1})

The L\textsubscript{1} lineation is marked by minerals, fold axes, intersection lineation (S\textsubscript{0} ^ S\textsubscript{1}), striation, slickensides, pinch and swell structures and boudins, out of which mineral lineation is common (Fig. 3.28). Such mineral lineation makes different angle with F\textsubscript{2} fold axes (Fig. 3.10). Striations are marked on the foliation planes indicating the direction of slip and make acute angle with the strike of the foliation. The long orientation of the lenticular boudin axes of amphibolite on the XY plane coincides with the L\textsubscript{1} (\approx F\textsubscript{1} axes) lineation.

Various measurements of L\textsubscript{1} ^ F\textsubscript{2} are taken and their interference patterns are worked out as type 2a, 5b of Ghosh and Chatterjee (1985). Pinch and swell structures are common linear manifestation of this deformation and they are more common in quartzofeldspathic gneiss where migmatisation and shearing are conspicuous (Figs. 3.9 and 3.29).

3.6.2 Second phase deformation

The second phase of deformation is a major tectonic process of crustal shortening which controls the regional configuration of the lithological layerings and regional foliation. This phase of crustal shortening is marked by the development of F\textsubscript{2} folds on different scales from centimeter to hundreds of meter, and occasional development of cleavage (S\textsubscript{2}) of non pervasive characters and associated lineation (L\textsubscript{2}).

3.6.2.1 Folds (F\textsubscript{2})

Folds of this deformation in a multilayered sequence show varied geometry and accordingly the reference plane S\textsubscript{1} is folded to a maximum extent. The F\textsubscript{2} folds are the dominant structural feature and are predominantly of asymmetrical type (Plates 3.2ab; Fig. 3.7, 3.12) with long and short limb, the long limb being gently dipping while the short limb dip steep to near vertical. The short limbs are rotated more than 90° and made the fold as overturned or near recumbent in the hinge zones of the outcrop scale folds (Plate 3.2a; Fig. 3.18). Thus the F\textsubscript{2} folds show extreme variation in intensity of tightness.
The sense of shear is worked out and reveal top right bottom left shear sense and belongs to Ramsay's class 1B to class 1C types (Plates 3.4d, 3.5b). The curvature of the intrados (i) and extrados (e) part of the mesoscopic folds is same in some cases (Plates 3.12d, 3.13c; Fig. 3.11), while in others the curvatures of the folds in the intrados is less than the curvature of the extrados and vice versa (Plate 3.2bc; Fig. 3.18). Hence the divergency of the dip isogon is quite obvious from the fold morphologic study (discussed later in the chapter) (Fig 3.23). The F2 folds are plunging NE and / or SW at a subhorizontal to moderate angle ($\sim 30^\circ$) showing monoclinic to triclinic symmetry (Ghosh, 1993) and are of upright nature (Plate 3.2a) with characteristic subvertical dip of the axial plane. The axial plane of these folds are dipping towards the longer limbs. There are evidences of coaxial nature of F1 and F2 indicating type 3 (hook shaped) interference pattern of Ramsay (1967), but they are rock and site selective and no way related to regional shearing / tectonic flow during this deformation (Plates 3.6c, 3.7d; Fig. 3.11) In still some other cases, it is observed that the eastern limb of some F2 folds when overturned resembles isoclinal F1 folds but the reference S1 plane is folded by the former and L1 makes acute angle ($< 45^\circ$) with respect to F2 fold axes (Fig. 3.18). The F2 folds show small digitations on their limbs indicating dextral and sinistral senses and this is a good example of flexural slip mechanism (Plate 3.12d). Some of the F2 folds also show conjugate type. Such conjugate, double hinged type merged into single hinge in the intrados parts of the folds (Plates 3.3bc; Fig 3.10) The wavelength / amplitude ($\lambda / A$) ratio of the F2 folds are rock and site selective and not constant. Some F2 folds vary from chevron to concentric type and nearly isoclinal (Fig 3.18) Discordant quartz aplitic veins across the regional foliation show ptygmatic folding which marks the direction of shortening in the subsequent deformations (Plate 3.4d, Fig. 3.14) In many F2 folds marked by quartz veins show pinch and swell and boudin structures which suggest extension before the development of F2 folding (Plate 3.11ab). In biotite schist and highly biotised amphibolite, small scale digitations (crenulatons) maintaining enéchelon pattern are observed and the axial curvatures of such digitations are caused by later D1 deformation (Plates 3.5a, 3.8c)
3.6.2.2 Foliation (S2)

Foliation of second deformation is not of regional extent and is infrequently developed along certain slip zones of strain. They are rock selective and designated as S2 and mostly follow the axial planes of F2 folds and rarely along the short and steep limbs of the mesoscopic folds. They are also marked by reorientation and slip of the earlier minerals along the strain zones and as such termed as strain-slip foliation. Incipient recrystallisation along these zones could be seen. Crenulation cleavage is characteristically developed in mica schist and highly sheared amphibolites. Such S2 crenulation cleavage varies from zonal to discrete types (Gray, 1979). Crenulation cleavage (S2) and in some cases widely spaced cleavage have also been developed axial planar to F2 folds. The strain zones of such F2 folds are occasionally associated by fractures but such fracturing are more conspicuous in competent rocks and less conspicuous in quartzofeldspathic gneiss (Plates 3.3a, 3.4b; Fig. 3.7) and are well marked by quartz vein in dark coloured metabasites. Along the short limbs of the F2 folds vein rocks are emplaced (Plates 3.13d, 3.8c; Fig. 3.8). In the mesoscopic folds, S2 is made curviplanar (Plate 3.13c, Figs. 3.6, 3.15) due to interference of later D3 deformation. The trend of the S2 plane is NE-SW with a slight deviation on either sides and dominantly show NW dip at moderate to high angle.

3.6.2.3 Lineation (L2)

The L2 is designated by the crenulation / small scale fold axes lineation, intersection lineation (S1 ^ S2) and infrequent mineral lineation of which the first type is more common and well defined. They are well preserved in almost all rock types but more frequently observed on mesoscopic scale in amphibolite and calc-silicate rock (Plate 3.5a, Fig. 3.15). The attitudes of L2 varies largely because of interference of later folds. The L1 ^ L2 is measured in different exposures and is plotted in the stereoplots which shows well pronounced maxima in SW quadrant (Fig. 3.20v).

3.6.3 Third phase deformation

Refolding of second phase deformational fabrics give clue of the existance of third phase deformation. The third phase deformation is also a crustal shortening deformation resulting
the development of folds (F₃) on varied scales and associated nonpervasive planar (S₃) and linear fabrics (L₃), but the direction of shortening is roughly perpendicular to the earlier crustal shortening direction during D₂ deformation (Plate 3.6d).

3.6.3.1 Folds (F₃)

Folds of this generation are formed on the minor scale as well as major scales. The minor folds are asymmetrical, with long and short limbs, to overturned showing right vergence. The axial trend (S₃) of this fold is NW-SE with a moderate dip towards SW (Plates 3.2a, 3.5a; Fig. 3.6). The / varies from 35° to 65°, and Φ varies from 105° to 145°. The intensity of flattening of such folds are relatively less than the folds of the second deformation. The fold hinges are rounded to sub-rounded and rarely sharp to angular in type. The intensity of curvature gradually decreases towards the extrados side and accordingly the single hinge becomes double hinged outward in case of upfacing folds. Such F₃ folds are of low amplitude and high wavelength relative to the F₂ folds.

3.6.3.2 Foliation (S₃)

The S₃ planar fabric, although rare, are not inconspicuous and wherever present are invariably formed along the axial plane of the F₁ folds (Fig. 3.6). Such syngenetic planar fabric is also marked by re-orientation of early formed minerals as a result of strain along slip planes or axial plane fracture (Plate 3.8b). Cleavage (S₃) occasionally filled up by migrating quartz or calcitic solution from the stressed zones.

The trend of S₃ is NW-SE showing dip at a high angle towards SW (Fig. 3.6). In more ductile quartzofeldspathic gneiss, crenulation cleavage (S₃) is developed by reorientation of the preexisting platy micaceous minerals or quartz filled axial plane fracture cleavage.

3.6.3.3 Lineation (L₃)

Infrequent development of intersections of S₁ and S₃ marks as L₃ lineation in addition to the development of small scale fold axes lineation in case of micaceous schist at the peripheral zones of amphibolite. The linearity marked by L₃ is obviously unaffected by later deformation and trends NW-SE.
3.6.4 Fourth phase deformation

The presence of $D_4$ structures is marked by faults, large scale fractures and joints. Minor shear zones were observed in surface outcrops and such shearing are related to the emplacement of pegmatitic veins almost across the lithological layering. Conspicuous presence of both normal fault and reverse fault, are noted from Forest gate, Narengi Patthar quarry and Tatimara areas (Plates 3.3d, 3.5c, 3.8abd). Most of the fault planes trend roughly N-S or NNE-SSW directions. The angle between the plane and the layer varies from 26° to 45° and amount of displacement is 20 cm to 110 cm. The shortening is worked out by the equation $\Delta L = d \cos \phi$, where $\Delta L$ is the finite length of shortening, 'd' is the distance of displacement and $\phi$ is the angle between the fault plane and the layering (Plate 3.8). There is an increasing complexity in the geometry of faults as one moves to the south western part of the area. The emplacement of porphyritic granite further south westward beyond the study area has some impacts over the dominance of faulting in the south western sector of the study area (cf summary and conclusion - chapter 7). The conspicuous presence of both normal and reverse faults is indicative of crustal instabilities and is representative of the brittle stage towards the waning stage of $D_3$ ductile deformation or during $D_4$ deformation itself (Plates 3.8, 3.10ab; Fig. 3.16). A major fault zone can be speculated from its vicinity and probably the Brahmaputra valley can be inferred as a fault zone although this aspect is not incorporated in the present study.

3.7 Interference pattern of folds

Each deformation structure has its own special geometric characteristics which helps in assigning structures to a definite phase in some areas where interference relations are not obvious. Interference of three phases of folding affects the rocks of the area. Original attitudes of the $F_1$ folds being intrafolial and isoclinal in nature cannot be determined precisely because of successive superimposition of at least two phases of folding - $F_2$ and $F_3$. The $F_1$ and $F_2$ folds are often coaxial in nature and so, overprinting of $F_2$ folds on $F_1$ has resulted in the hook shaped type 3 interference pattern of Ramsay (1967) as shown in Plates 3.6c, 3.7d; Figs. 3.7, 3.11. The geometry of superposed folds involving $F_1$ and
\( F_2 \), can also be described as non plane cylindrical folds (cf. Turner and Weiss, 1963). The tightness of the hook depends on the intensity of second generation folds and accordingly where the \( F_2 \) folds are tight or isoclinal, the axial planes of \( F_1 \) and \( F_2 \) become parallel or nearly so. The axial planes of the \( F_2 \) folds are generally steep or even near vertical. On the other hand \( F_1 \) folds, because of superimposition, have lost the original attitude of axial plane and at present disposition show moderate dip, direction being controlled by \( F_2 \) folds. The successive stages of interference of \( F_1 \) and \( F_2 \) maintaining coaxiality, result open to tight through moderate hook shaped folds as shown in Figs 3.13. The superposition of \( F_3 \) folds on earlier \( F_2 \) folds has resulted in the formation of type 1-dome and basin structure (Plate 3.6d; Fig. 3.13) and eyed fold (Ramsay, 1967). Eyed folds are also developed due to superposition of \( F_1 \) and \( F_3 \) (Plates 3.6b, 3.7a b c). The interference of \( F_2 \) and \( F_3 \) also developed another pattern designated here as plier fold (Sarma and Dey, 1999) (Plate 3.6a).

### 3.8 Statistical analysis of structural elements

The study area exhibits polyphase fold sequence consisting of three different generations and they are associated with planar and linear structures. In banded gneisses, fold morphology is not complex as complex they are in case of migmatites. Study of overprinting relationship made this complex task a bit easier. For statistical analyses the inhomogeneously deformed area has been divided into sectors (of page 25) and each sector further being subdivided into different sub areas (Fig. 3.19) so that minimum homogeneity prevails. Plots are made on the lower hemisphere projection on equal area net and contoured by the grid method. Interpretations are based on the traditional approaches since the days of Turner and Weiss (1963).

The Forest gate and Narengi Patthar quarry areas (Sub sector D and E cf. Fig. 3.1) are subdivided into 5 sub areas (A to E) and each
sub area maintains classic evidences of planar, linear and fold fabrics. On the regional scale, lithological layering (S₀), axial plane foliation (S₁) and bedding joints are parallel to each other and that is the reason why for statistical analyses of the reference plane, all the three categories are considered together. Stereo plots of the poles of S₁ (= S₀) from all the 5 sub areas show several maxima of widely scattered habit which indicate that the reference planar surface is perturbed by multi phase deformation (Fig. 3.20). The map pattern of the area is controlled by second and third phase folding and that the conical nature of such folding is indicated by the presence of incipient small circle girdle.

Six diagrams have been prepared (Figs. 3.20_v-v) from the forest gate area where poles of S₁ planes are plotted in Figs. 3.20_v-v. They represent a synformal fold structure where 3.20_v represents the north western limb while 3.20_w the south eastern limb, 3.20_w being the hinge zone of the major fold. Fig. 3.20_v from sub area (A), shows βS₁ plot in south eastern quadrants of the circle with elongate maxima, πS₁ being in the NE-SW direction. The plots of the βS₁ of sub areas (B) roughly corresponds with the generalised plunge of the Forest gate synformal structure (Fig. 3.20_v) and lies essentially in the south western quadrant. Similarly sub area (C) shows elongate maxima in the south eastern sector and the βS₁ falls in the north western quadrant of the circle (Fig. 3.20_v). Thus, it is apparent from the sum up values that the Forest gate synformal structure is a SW plunging synform at 35° towards 220°.

The plots of L₁ lineation show highly scattered nature while L₂ (= F₂ axes) falls essentially around the statistically defined b-axis of the Forest gate synformal structure (Fig. 3.20_v). The plots of the F₂ fold axes (= L₂) are shown in Fig. 3.20_v and they lie approximately at right angle to the F₂ (= L₂) plots. The scattered nature of linear and fold structural plots of second deformation is caused due to interference of third phase deformation. The physiographic expression of the Forest gate hill shows NE-SW trend with a curvilinearity and represents a south westerly plunging synformal structure. The occurrence of S₂ and S₃ which is rock and site selective in nature is limited and hence not plotted in the stereonet.

The Narengi Patthar quarry area is sub divided into 3 sub areas namely C, D and E.
and the sub area C represents the north western limb of the Patthar quarry antiform (or the south eastern limb of the Forest gate synformal structure). Stereoplots of the poles of \( S_1 \) planar fabric which is used as a reference plane to delineate the major fold structure is shown in Fig. 3.20, while the plots of the poles of \( S_1 \) from the other limb of the antiformal structure (sub area E) show similar elongate maxima fall in the north western quadrant, diversity of concentration is largely caused due to superposition of later deformation (Fig. 3.21). Sub area (D) is the closure of the antiformal structure and the plots of the poles of the \( S_1 \) plane show maxima at north eastern quadrant, \( \beta S_1 (= B_2) \) indicate about 28° plunge towards SW (Fig. 3.21a). \( S_2 \) and \( S_3 \) foliations are also plotted in the stereonet and they are shown in Fig. 3.21. Similarly \( L_1 (= F_1) \) is plotted from this area and they correspond with the plots of the poles of \( L_1 \) of Forest gate area (Fig. 3.21b). The widely scattered pattern of \( L_1 (= F_1) \) plots is apparently due to the combined result of the major influences of the non cylindrical \( F_2 \) and \( F_3 \) folding. Plots of \( L_2 (= F_2) \) and \( L_3 (= F_3) \) are shown in Fig. 3.21 and it is observed that the plots of the linear and fold fabrics of \( D_2 \) deformation are centrally located around \( \beta S_1 \) of sub areas (D) which indicate that they are synchronous with the formation of large scale \( F_2 \) folds of the region. A synoptic diagram is prepared where linear, planar and fold fabrics of all the related deformatinal phases of the Narengi Patthar quarry and Forest gate areas are plotted (Fig 3.21).

In Thakurkuchi and Bonda areas of central sub sector (C), the Railway line is passing through the NE-SW trending valley which takes a turn towards SE with a sinusoidal nature. The generalised trend of the \( S_1 \) plane is NE-SW showing dip towards NW at moderate angle. The plots of \( S_1 \) is shown in Fig. 3.22. Lack of exposures in the valley region due to wet land and thick vegetation hinder the investigation to locate the other limb of the major fold. There is every possibility that the valley represents an antiformal core and that, the south eastern limb of the antiform is exposed only in the present area. The lineations/fold axes of all the three generations are shown in Fig 3.22. The plots shows maximum concentration of \( L_2 \) in both the NE and SW quadrants and this indicates that they are doubly plunging in nature and, is apparently due to superposition of \( F_3 \) folding. Although there is a physiographic discontinuation of the
exposures of the Forest gate and Narengi Patthar quarry areas of the south western sector due to wet land and thick piles of alluvials, but it can be assumed from the similar and single linear trend of the Patthar quarry hills further towards Bonda and Thakurkuchi that the inferred fold is the continuation of the south eastern limb of the major antiformal (Patthar quarry antiform) structure.

The third isolated but elongate hill ranges around Tatimata (Sub sector A of the north eastern sector) where a series of ongoing blasted quarries are netwith which reveal the geometry of interferences of folding and show unique dip direction towards SE with minor local variation due to fold interferences.

Around a dozen of quarries in one linear belt showing approximately 200 to 300 meter thick transverse sections (XZ section). All the data relating to reference surface \( S_1 \) when plotted in the stereonet reflect an elongate but prominent girdle with pronounced maxima and confined within the north western quadrant. The mean \( \beta S_1 \) falls at 32° towards SE (Fig. 3.22v). The girdle pattern bears similarity with the \( S_1 \) girdle of Narengi Forest gate area (cf. Fig. 3.20u) and the physiographic expression of the linearity of the hill trends corresponds with the north western limb of the Forest gate synformal structure. The plots of \( L_1 (= F_1) \) from this area also show widely scattered distribution while \( L_2 (= F_2) \) show high concentration both in the NE and SE directions (Fig. 3.22w). The rate of dispersion of \( F_2 \) plots is higher than the plots of the \( L_1 (= F_1) \), the latter falls exclusively in the SE quadrant of the stereonet (Fig. 3.22x).

Near Chandrapur (Sub sector B of the north eastern sector) the lithounits are showing opposite dip towards NW, strike being still NE-SW, which is a clear indicative of the presence of a relatively large scale synformal structure. The plots of the poles of \( S_1 \) is shown in Fig. 3.22y and apparently \( \beta S_1 \) plots are lying in the NW quadrant at relatively low angle. The closure of the fold nowhere can be traced as the hills gradually merge into mighty river Brahmaputra to the north. It is apparent from the study that the general north eastern inclination of the trend line of the different lithounits (from both the Tatimara and Chandrapur sections) and the north easterly plunge of the layers indicate the presence of a large scale synformal structure plunging towards NE at a relatively
low angle. The $F_2 (= L_2)$ plots from Chandrapur Sub sector (B) also show similar nature as in the case of Tatimara area, but $F_3 (= L_3)$ plots show clustering at NW quadrant i.e. opposite to that of Tatimara section which indicate that the original attitude of the Tatimara synformal structure has not been modified to a large extent by the interference of $F_1$ fold, rather the initial geometry is still retained by the former (Fig. 3.22v). Thus, the physically separated block of the Tatimara section representing a synformal structure may be evidences of continuation of the Narengi Forest gate synformal structure.

3.9 Geometry of Macroscopic structures

The regional fabrics incorporating the lithological layering ($S_0$) and regional foliation ($S_1$) play an important role which bear the testimony of intensive multideformational history and their associated metamorphic episodes. It is generally accepted that in a high grade metamorphic terrain where the dominant rock type is gneissic, the effect of shearing on various scales / zones become difficult to identify precisely as could be identified in case of low grade metamorphic terrain. Even the dominance of the linear fabrics becomes less obvious and less penetrative. Moreover, tectonically attenuated hornblende biotite schist, calc-silicate rock and amphibolite lenses within the more ductile gneissic host indicate intensive deformation and they may represent the tectonic relict of early supracrustal rocks (?). The map profile, small scale folds, lineations, variation in the sense of shear both in the extrados and intrados part of the folds, variation in the attitudes of the $S$-planes, topographic configuration in the form of elongation and sinusoidal patterns all indicate the presence of a km sized antiform and a synform around Forest gate and Narengi Patthar quarry areas in the south western sector and Tatimara and Chandrapur in the north eastern sector (cf. discussion under statistical analyses, pages 35 - 39).

That the major folds belong to second and third generations can be suggested from the following observations:

(a) $S_0$ and $S_1$ are parallel to each other on the regional scale but the regional distribution of the $S_1$ foliation which is related to $D_1$ deformation, and hence $F_1$ folds, is controlled mainly by $F_2$ and, to a somewhat lesser extent, by $F_3$ only.

(b) The reference surface ($S_1 = S_0$) is folded on the regional scale and hence, the
regional folds are later than \( F_1 \) fold. Even if the area belongs to a part of the fold nappe structure under \( D_1 \) deformation itself, the present study reveals no such indication, nor is seen the presence of any sheared thrust sheet from the adjacent areas of the banded gneissic complex.

(c) The presence of 'Z' and 'S' vergences on the opposite limbs of the mesoscopic folds and the development of 'M' and 'W' on the up and down facing fold closure zones are indicative of the presence of antiformal and synformal fold structures on the regional scale. These folds belong to \( F_2 \) generation which fold the \( S_1 \) form surface.

Thus, the orientation of the highly pervasive foliation and associated lithological layering in the enveloping banded gneissic complex indicate presence of elongate synformal and antiformal folds named as Forest gate synform and Narengi Patthar quarry antiform in the south western sector (Sub sector D and E). Similar synformal structure is mapped in the north eastern sector (Sub sector A and B) and is named as Tatimara synform. Details of the fold structures are discussed under statistical analyses.

3.10 Morphological study of folds

Folds are the most common non-linear transformation observed in the Precambrian tectonites which exhibit morphological variation to a large extent. Such variation is controlled probably by competence, thickness and other rheological/physical properties of the rocks. These geometrical properties are of prime importance in fold classification and in the analysis of natural folds. Since the days of Van Hise (1896) who recognised parallel and similar folds in geologic literature, a lot of workers have suggested various methods of geometrical and genetic classification of folds and a systematic study of fold analysis were done by many workers in recent times (eg. Ramsay, 1960, 1967, Ramberg, 1963; Hudleston, 1973 a,b,c; Hobbs et al., 1976; Treagus and Treagus, 1981; Ramsay and Huber, 1987; Ghosh, 1993).

3.10.1 Theoretical background

It is well known that most of the natural folds owe their development to compressive stresses parallel to the length of the layers. In a sequence of layers of different viscosity
contrasts, an instability is initiated by such stresses and buckling is produced in more competent layers resulting in a train of folds (Biot, 1961, 1964, 1965, Ramberg, 1960, 1961, 1963a, 1964). Biot (1961) predicted that wave length to thickness ratio of buckled layers would be constant if the viscosity ratio of the folded layers and the host medium are constant. Layer parallel shortening during buckling has been predicted in low viscosity contrasts (Sherwin and Chappie, 1968; Fletcher, 1974; Fletcher and Sherwin, 1978). Hudleston (1973 a,b,c) and Hudleston and Stephansson (1973) observed that buckling is more conspicuous after the limb - dip of 10° to 20° is attained. It can, therefore, be concluded that in a layered sequence of comparable viscosity ratio, folding is developed by buckling, if the ratio of dominant wavelength to thickness of the competent layer in the folds of different orders is constant.

In ductile environments it is common for the buckled layers to become modified by superposition of a fairly homogeneous strain. de Sitter (1958) suggested that the compressive strain leads to the modification of the parallel shape by the process of flattening and folds formed in this way are flattened parallel folds.

In the present study, folded layers of varied composition and thickness have been used in estimating the finite strain in the rocks. Care has been taken in choosing the profiles of the folds for analysis. Ramsay’s classification has been used for correlating purposes (Ramsay, 1967) and to determine the amount of compressive strain in naturally formed folds.

3.10.2 Analysis of folds

In the study area, folds are best displayed by amphibolite, hornblende biotite schist and calc-silicate rocks infrequently associated with thin layers of quartzofeldspathic gneiss. Such relatively thin layers are encased within the quartzofeldspathic gneissic host. Fundamental elements of strain analyses are shown in Figs 3.24 and 3.26. A few representative folds of F₁ and F₂ deformations of single and multilayered sequences have been selected (Figs. 3.23) for strain analysis and it is considered that the viscosity contrast of the layer are comparatively low. A few folds on outcrop scale have been photographed facing the axial direction and are analysed following the methods suggested by Ramsay.
t'α/α and φ/α plots have been prepared for F₁ and F₂ folds as shown in Figs. 3.25 and 3.27. Figures reveal that there is not much variation in extrados and intrados curvature of F₁ folds indicating similar nature and almost all F₁ folds exhibit class 1C to class 2 geometry.

3.10.2.1 F₁ folds

A few representative F₁ folds have been selected for their geometric analysis (Figs. 3.23a-g). Orthogonal thickness \( t'_n \) for different values of \( α \) have been worked out and plots of \( t'_n = \frac{t_n}{t_0} \) against \( α \) show a total variation in the fold geometry from limbs to the hinges. Dip isogons are of weak to moderately convergent types but a few are showing near parallel habit. \( t'_n / α \) plots for different values of \( \sqrt{\lambda_2 / \lambda_1} \) where \( \lambda_2 \) and \( \lambda_1 \) are quadratic strain parallel and perpendicular to axial plane of folds, show variation from 0.2 to 0.9 (Fig. 3.25, folds a to g) and such variation is indicative of flattening (Roy, 1978, Sharma et al., 1988).

The \( φ \) is defined as the angle between the normal to the tangents drawn to either fold surface at angle of (apparent) dip, \( α \) and the isogon. If the isogon from i to e is deflected clockwise or counter clockwise relative to the normal, \( φ \) is considered as positive or negative respectively (Figs. 3.24ii, iii). Similarly, \( α \) is considered as positive for right limb of upward facing fold (= left limb of downward facing fold) and negative for the other limb of the fold (Hudleston, 1973a).

The plots of \( φ / α \) for the same folds have been shown in Figs. 3.27a-g. It is apparent from the plots that most of the folds are showing combined geometry of two or three classes i.e. there is a variation from class 1C to class 3 through class 2 types of Ramsay, 1967. The variation is also noted from limb to limb and limb to hinges.

3.10.2.2 F₂ folds

The geometrical analysis of F₂ folds are shown in Figs. 3.25h-n, 3.27h-n. Plots of orthogonal thickness \( (t'_n) \) against different values of \( α \) (limb dip) indicate that rarely folds show \( t'_n \cdot 1 \) and fall in the field of class 1A, specifically 1A₃ of Zagorchev, 1993 (Fig. 3.24iv) and most of the folds plot are confined within the fields of Class 1B-1C-2-3 (Figs. 3.25h-n).
Ramsay’s curves have been used for determining apparent strain ratio $\left(\sqrt[3]{\lambda_i/\lambda_j}\right)$ and it is seen that plots varies from 0.4 to 1.2.

The plots of $\phi/\alpha$ show a wide variation in fold geometry and plots of $F_2$ folds fall in the field of 1B (parallel), 1C (flattened parallel), 2 (similar) and rest mostly fall in the field of class 3 (modified similar). It is apparent from plots of both $t'/\alpha$ and $\phi/\alpha$ that most of the folds are found to occur in combination of two or three classes and vary from parallel to modified similar through flattened parallel and similar types (1B-1C-2-3).

3.11 Boudin analysis - a theoretical background

Boudinage, unlike folding, is not recoverable. This develops where prevalence of competence contrast between light and dark coloured rock units results tectonic attenuation and fragmentation of the competent units encased within the ductile quartzofeldspathic gneiss in the field of extensional tectonism during the earliest phase of deformation. Boudins are a common feature of tectonites which record the strain components of penetrative deformation. Boudinage is a process involving extension of a stiff layer enclosed by a ductile medium (Ranberg, 1955; Sanderson, 1974; Mitra, 1979). Layer extension is due either to tensile failure producing fractures (discontinuous boudinage) or to differential thinning producing pinch - and - swell structures (continuous boudins). The genetic hypothesis of the boudins is very difficult to be formulated unless a greater understanding of the geometry and kinematics of the structures that occur in nature is achieved. Important consideration in boudin development include hardness differences between layer and matrix, fracture toughness, timing of fracturing and the relative role of brittle vs ductile processes (Lloyd and Ferguson, 1981).

3.11.1 Elements of boudin

The various elements of boudin are referred to and described here after Wagmann (1932), Wilson (1961) and Ghosh (1985, 1993). Length (L) of the boudin is the distance along the long direction of the boudin on a plane view. Width (W) is the distance of the boudin along layer parallel extension in a transverse profile. Thickness (t) is measured as the thickness of the boudinised layer, perpendicular to the layer boundary. Long direction of
boudin is the boudin axis which may be longitudinal or transverse. Distance between the two boudins in a profile section is the separation. In the separation zone of the boudins, the more ductile material usually flow to the direction of low stress and form oppositely directed bending character. This is called bending / scar / necking fold. Transverse boudin axis is the shorter direction (⊥ to long axis) of the boudin in a plane view, while longer direction is the longitudinal boudin axis separated by a transverse separation zone. The above elements are shown in Figs. 3.28a,b,c.

3.11.2 Boudin shapes and their significance

In the study area, the quartzofeldspathic gneissic host is usually intercalated with amphibolites, hornblende biotite schist and calc-silicate rock. The amphibolites and hornblende biotite schist layers are found in the form of bands of different dimensions ranging in width from a few millimeters to several meters. The bands of metabasic rocks (amphibolite and hornblende biotite schist) show folds of varied scale and geometry along with pronounced boudinage structures. In transverse section, the shapes of boudins are rectangular, barrel-shaped, fish-head, lensoid (Plates 3.9, 3.10c,d, 3.11c; Figs. 3.29-3.33). The boudins are often rotated, folded and faulted and essentially synmigmatitic (Plates 3.10a, 3.11d).

The boudins with rectangular cross section indicate brittle behaviour of the layer (Plate 3.10d). This morphology indicates that the competence contrast between the quartzofeldspathic gneissic host rock and the boudins is very large. The barrel-shaped boudins with curved edges (Plate 3.9a) indicate plastic deformation of the outer layers after the phase of fracturing i.e. post - boudinage plastic deformation (Wegmann, 1932; Ghosh and Ramberg, 1976). This curving of edges of the barrel-shaped boudins takes place owing to the more competence of the boudins relative to the ductile host rock and development of high shear strain at the longer edges of the boudins. The boudins being more competent deform more slowly than the enclosing gneissic host and the shear strain and the associated effective lengthening decreases towards the mid-level of the boudinaged layer giving the curve edges to the barrel - shaped boudins (Ghosh, 1993). The fish - head boudins (Plates 3.9d, 3.10c, 3.11c; Figs. 3.31, 3.32) show an extreme
case of such post boudinage plastic deformation of the outer shells (Wegmann, 1932; Ramberg, 1955). The lens shaped boudins (Plates 3.9b, 3.10b; Figs. 3.29, 3.33) indicate the competence contrast between the boudinaged layer and the enclosing gneissic host decreases and as a result a very large amount of plastic stretching takes place by necking.

3.11.3 Boudinage in relation to folding episode

In a multilayer sequence of alternate dark and light coloured rocks, it is often observed that the former namely amphibolite and hornblende biotite schist show the imprints of different degree of tectonic attenuation followed by layer parallel shortening under different tectonic setting. Layer parallel extensional tectonism under layer normal compressive stress leads to the development of continuous and discontinuous boudinages (Plates 3.9ab). Pinch and swell structures, barrel, rectangular, parallelogram, tile like imbricate and lenticular types are some of the structures which indicate tectonic attenuation and fragmentation of the initial layering in the continuum of $D_1$ deformation alone (Plates 3.9, 3.10; Figs. 3.29-3.33). Such fragmented parts of the layers are floated within the more ductile quartzofeldspathic - migmatitic host. The $F_1$ fold is marked by amphibolite layer with characteristic right and left vergences and associated axial plane cleavage ($S_1$). They are intrafolial, axes being plunging at varied angles and directions. The long orientation of the lenticular boudins of amphibolite on the YZ plane coincides with the $L_1 (= F_1)$ lineation which is a clear indicative of tectonic origin syngenetic to $F_1$ folding movement (Fig. 3.29). The separation zones of boudin are mostly occupied by pegmatitic and migmatitic infilling and host rock planar fabric favour the formation of scar fold (Plate. 3.9bcd, 3.10bcd; Figs. 3.30, 3.32). The associated banded migmatitic material also show affinity towards such pressure gaps (Plate 3.10c, 3.11b). The effect of subsequent deformation is more conspicuous in the form of folded boudins in case of lenticular and fish head types (Plates 3.5d, 3.9d, 3.10cd; Figs. 3.29-3.33) while the barrel, rectangular, parallelogram type of boudins are highly rotated under simple shear mechanism, angle varies from 20° to 50°. Rigid body rotation leads to the development of bulging at the two wings of the rounded boudins (σ type) showing dextral shear movement (Plate 3.13a). Imbricate or tile like piling up feature is also observed in the
area but they are not marked by straight boudins as is the common case reported by Sengupta (1983) from Sweden, in fact they are essentially marked by lenticular boudins partly deformed in the study area.

The initial fragmentation mechanism during $D_1$ deformation has been modified due to superposition of later deformations - $D_2$ and $D_3$, both being affected by layer parallel shortening and is best displayed in XZ sections of the study area. The effect of $D_2$ deformation over the $D_1$ boudins result up or down facing upright folds mostly of half wave (Fig. 3.33). The lenticular type show asymmetric folded boudins indicating right lateral or dextral vergence, axes of such boudins are plunging either NE and / or SW. This observation is best displayed by layered rocks in the YZ section in specific but some competent layers immediately develop extensional fractures and gradually detached from each other in the tectonic stretch direction. Rectangular, barrel type of boudins of asymmetric and symmetric nature are thus developed during this process and they are best studied in $\hat{e}_1$, $\hat{e}_3$ principal section of finite strain ellipsoid. Towards the late stage of this deformation granitisation acts as a synkinematic episode and the detached zones of the boudins are occupied by infilling of pegmatitic materials (Plate 3.10c, Figs 3.30, 3.32, 3.33). The development of scar fold marked by both migmatitic bands and the regional cleavage planes also suggest such kinematic growth (Plate 3.11b). The effects of subsequent folding mostly of asymmetric type and rotation of the boudin might be due to non-coaxial simple shear mechanism. Though it has been accepted that extensional fractures and shear fractures are the causes of initial fragmentation under layer normal compressive stress, but there is every possibility that such force is inapplicable in a sequence of near horizontal stratified layering where extensional reworking is hardly possible in layer normal or layer oblique direction. In contrast the initial sub horizontal sedimentary sequence with igneous intrusives in the form of sills and dykes, when will be affected by layer parallel shear couple, the resulting planar fabric, after intensive shear transposition in the field of tensile stress, will maintain almost identical initial configuration and the initial folding will remain as remnant type after thorough readjustment. The subsequent layer parallel shortening effects along $\hat{e}_1$, $\hat{e}_2$ directions are
best observed in the boudins. The skeletal boudin clusters enclosed within the pegmatitic or granitised host (Plates 3.9c, 3.10c) can be termed as ghost boudin (Sarma and Dey, 1997), scar fold with oppositely directed bending, emplacement of pegmatitic or migmatitic material along axial surfaces of F, folding (Plate 3.10c, Figs. 3.30, 3.32, 3.33), dextrally and sinistrally moving boudins and / or shear banding of contractional habit (Plate 3.10a, Figs. 3.29), foliated boudins in quartzofeldspathic gneiss (Plates 3.11a) are some of the characteristic feature observed in the area (Sarma and Dey, 1997).

3.12 Finite memory structures

Memory structures of finite extent have been delineated from the Precambrian basement gneissic complex of the Narengi area, Guwahati, Assam and observed that the rock associations have been inhomogeneously deformed under different sets of ductile and brittle environmental stress fields.

Memory structures of undeformed rocks have a little bit of complexity as compared to a high to medium grade gneissic terrain where memory structures have been either destroyed or obliterated to a maximum extent due to repeated deformation and effective restructuring. Such restructuring and readjustment lead to the development of partial melting of the gneisses and as such the behaviour and attitudes of most of the memory structures of finite extent have to be deduced with much complexities through a system of integration from the relicts or ghost fabrics both in the fields of positive and negative approaches.

The different rock units display evidences of greater crustal instability or mobility leading to the formation of folds, foliation, lineation, joints, fractures and faults of both extensional and contractional tectonism. These structures can be categorically grouped into ‘memory structures of finite extent’.

From the foregoing observations and integration of the planar, linear and fold fabrics, it can be inferred that the F₁ folds predate other deformational events. This statement is valid because their attendant planar fabric - S₁ which is the most dominant feature and on the regional scale maintains parallelism with the lithological layering (Sₙ).
is deformed by all other structures in the region. Discontinuation of the competent layers encased within the ductile QFG, their tectonic attenuation leading to thickening and thinning behaviour during the earliest D$_1$ framing reflect higher level of strain and PT field of metamorphism and the subsequent deformations deformed the preexisting structural setting in the field of shortening but failed to bring out any significant metamorphic changes excepting retrograde path of transformation. The delineated fabrics (Figs. 3.34abc) clearly demonstrate an anisotropic multilayered media with a notable rheological variations, where inhomogeneously deformed fabrics are arrested and reflect the nature of superpositions (Sarma and Dey, 1999).

3.13 Experimental models

Folds are the most obvious common structural manifestation that demonstrate the existance of ductile deformation (Hobbs et al., 1976) and develop widely in naturally deformed rocks of all ages. They provide a good record of tectonic processes involving in the earth as well as reflect both the physical conditions and mechanical properties of the lithologies predating folding. The interpretations of such folds in nature are usually made from the end products of deformation documented in deformed tectonites. The common approach in which the initial geometry of the earlier configuration of the structures is assumed and deduced from the end products or relict features if any, is an open question (Sarma, 1998). The mechanism of naturally buckle folds depends upon a few parameters like viscosity contrast, ratio of incompetent to competent layer thickness, initial fold morphology, arc length / wave length ratio, initial wavelength to competent layer thickness ratio, amplitude / wave length ratio of the layers etc. The shape of the competent and incompetent layers varies widely during the development of folding. Thus folding and subsequent refolding modify most of the initial parameters and, therefore by a reverse process, it is hardly possible to compute the initial configuration prior to folding.

Therefore, a lot of workers have proposed different models with known required parameters to account for the development of folds and delineated the entire progressive deformational path at different stages and then compare the characteristics of the
model folds with natural folds.

An attempt has been made to study buckle folds through modeling prepared in the personal laboratory developed by my supervisor (K.P. Sarma) at his residence. The intention is to study such folds and establish absolute resemblance of both natural and model folds with much limitations.

3.13.1 Experimental study

All the experimental models have been prepared in a pure shear box. The pure shear box is made up of wooden frame and various parts are shown in Fig. 3.35. The front side of the shear box is covered by thick transparent glass plate so that the progressive development of the fold structures can be observed, sketched them and photographed. Two movable walls are fitted with hand rotated long screws to shortened the model as per requirement. Plasticine or grease moulded talc powder, painters putty, lubricating oil or petroleum jelly are used in the models. McClay (1976) has studied the physical properties of plasticine in detail and suggested as rock analogue and hence it is used in the models. Different colours of plasticine are used and sometimes some plasticine layers are made more ductile to develop a good contrast of competency. A relatively thick block of painters putty is cut into a rectangular block as per shape of the pure shear box. A thin slab of plasticine is prepared on a thick glass base plate by pressing a small block of plasticine with the help of a hand roller. To maintain uniform thickness, two pieces of glass plates of required thickness are kept on two sides while rolling (Fig. 3.36a) and the slab is then cut into required size by a sharp but very thin knife or pointer (Fig. 3.36b). Similarly a few slabs of plasticine of different thickness have also been prepared and pasted over the other layers, interfaces being lubricated by petroleum jelly or in some cases, ordinary liquid detergent is used to reduce the cost of price (Fig. 3.36c). Thus a multilayered sequence is prepared and placed them into the shear box. The base of the shear box and the surrounding walls are lubricated to avoid frictional force. The initial length of the layers and their related thicknesses are noted and then allowed to deform by layer parallel shortening. The layer parallel force is designated as $P_1 (\sim \lambda)$ and gradually compressed by rotating the screws from both sides (force is not considered as measurable
unit). The model is then allowed to extend in the vertical direction only i.e. layer normal extension ($\lambda_z$) keeping the other horizontal direction ($\lambda_x$) fixed (Fig. 3.35). The layers start buckling and developing up and down facing folds of varied geometry at different stages of shortening say 6% to 61% (Plate 3.14a-c, Figs. 3.37). At all the stages, fold profiles are drawn on transparent overlays. The folds thus produced are labelled as $F_1$ in case of experimental modelling which is equated with $F_2$ of natural folds (The plasticine layers are considered as lithological layering after transposition during $D_1$ deformation and hence post $F_1$ fabric). It is observed that in most of experiments, folds behave cylindrically in the initial stage but as shortening increases, some folds behave like noncylindrical (Plate 3.14a,b). Also the shape of the competent and incompetent layers varies during the process of development of folds with increasing shortening (Plate 3.14c). The drawn out profiles of the shapes of folds when analysed they fall in class 1C and class 3 with a few exceptions in class 1B. This observation matches with the fold analyses of natural $F_2$ folds of the present area. Interference of folding is a common feature in a polydeformed terrain but the genetic interpretations of such interference patterns are still awaited for a crystal clear solution. A few experiments have been conducted in the line suggested by Sarma (1998). The experimental models prepared under layer parallel $P_1$ force as stated above, are transferred and pasted over another rectangular block of painter’s putty and placed them again in the pure shear box with the orientation of earlier $F_1$ fold axes parallel to the $P_2$ horizontal force at 90° with the initial setting and the models are allowed to suffer from compression in the axial direction. Thus axial culminations and depressions are developed and result type 1 interference pattern (Plate 3.14d). It has been observed that the complexities of the interference patterns as well as failure of the modelling increase with the increase in the angle between the $P_1$ and $P_2$ forces. Hence, the prepared models with all known parameters may bear maximum similarity with the natural folds and as such it can be observed that thickness of the folded layers, competency of the stack of layers and layer parallel or layer oblique non-balanced compressive forces are the main controlling factors for the development of buckle folds (Sarma, 1998).
Fig. 3.3: Tight nearly isoclinal $F_1$ fold (Z-pattern) with attendant axial plane foliation $S_1$. The fold noses are partially disharmonic showing thickened hinges and thin limbs. Location: Forest gate area.

Fig. 3.4: S-pattern $F_1$ fold with thickened hinge and thin limbs. The associated $L_1$, lineation is syngenetic to $F_1$ fold axis. Location: Tatimara area.

Fig. 3.5: Sheared out lenses of dark layers are intrafolial within the foliated $S_1$ quartzofeldspathic gneissic matrix. The $F_1$ folds are folded by $F_2$ folds. Development of scar folds are observed. Location: Narengi area.

Fig. 3.6: Interference of $F_1$ and $F_2$ folds are observed in quartzofeldspathic gneiss from area. The associated $S_2$ planes to $F_1$ folding are of conjugate nature. Location: Narengi area.

Fig. 3.7: Hook shaped interference pattern (Type III interference) is reflected by amphibolites interlayered by quartzofeldspathic gneiss layers. Partial development of $S_2$ along the axial plane of $F_2$ fold is observed. Location: Thakurkuchi area.

Fig. 3.8: Emplacement of pegmatitic vein along the short limbs of $F_2$ folds are observed in alternate bands of dark and white banded gneiss. Location: Narengi Patthar quarry area.

Fig. 3.9: Intrafolial $F_1$ folds (= tectonic fish) are floated on the migmatitic gneiss. They are tectonically sheared out and form pinch and swell structure as well as boudins. The effect of $F_1$ is observed. Location: Narengi Patthar quarry area.
Fig. 3.10: A conjugate $F_1$ fold in alternate thin quartzofeldspathic gneiss layers. The fold hinges are semi rounded and gradually double hinge become single hinged downward. Location: Hajongbari area.

Fig. 3.11: Hook shaped interference pattern (Type III) is observed from Forest gate area. The $F_1$ closure are sharp and gradually decreases upward.

Fig. 3.12: A 3-d basinal $F_1$ upright fold showing variation in the extrados and intrados curvatures. Location: Panikhaiti area.

Fig. 3.13: 3-d view of type I interference pattern (dome and basin structure) observed in metabasites. The fold may be referred to as cross fold also. Location: Naerengi area.

Fig. 3.14: A ptygmatic vein within the migmatitic host. The shortening direction is NE-SW and probably is related to $D_3$ deformation. Two eyed folds (interference of $F_1$ and $F_2$) are seen. Location: Tatimara.

Fig. 3.15: A set of enéchelon folds are observed in the quartzofeldspathic gneiss with the conspicuous development of axial plane foliation ($S_1$). The $F_1$ fold axes on the $XY$ plane are discontinued maintaining non-cylindricity. Location: Hajongbari.
Fig. 3.16: Amphibolite layers are showing the development of $F_1$ and $F_2$ folds with notable development of faults of extensional habit. A pegmatite vein transects the layered sequence at high angle. Location: Forest gate.

Fig. 3.17: Tight $F_1$ fold associated with contemporaneous axial plane foliation $S_1$ which cuts the hinge zone of the folds at certain angles but are made parallel with the limbs. Location: Bonda.

Fig. 3.18: Interference of $F_1$ over $F_2$ folds of tight nature. Both the type show dextral vergence. The thickness of the hinge zone is much higher than limbs in case of $F_2$ fold. Locality: Thakurkuchi.
Fig. 3.20: (i-vi) Stereoplots of the poles of the $S_1$ plane, (i-iv) and plots of the $F_1$, $F_2$ and $F_3$ fold axes ($= L_1, L_2$ and $L_3$), (v-vi) of the Forest Gate area. Contour: 2, 5, 5, and 7%.
Fig. 3.21: (i-vi) Stereoplots of the poles of the $S_1$ plane; (i-iii) and plots of the $F_1$, $F_2$, and $F_3$ fold axes ($= L_1, L_2$, and $L_3$); (iv-vi) of the Narengi Patthar Quarry area. Contour 1, 2, 5, 5 and 7%
Fig. 3.22: (i-ii) Stereoplots of structural elements of different generations from the Thakurkuchi -Bonda area. (iii-vi) Plots of the poles of $S_1$ and plots of $F_2$ and $F_3$ fold axes (= $L_2$ and $L_3$) of the Chandrapur-Tatimara area.
Fig. 3.23: Dip isogons of different single and multilayered $F_1$ (a to g) and $F_2$ (h to n) fold profiles.
Fig. 3.28: Different elements of boudins, description, and terminology are in current use after Wilson, 1961; Ghosh, 1985.
Fig. 3.29: The more competent and comparatively thin layers are showing pinch and swell and boudin structures. Boudins are folded by \( F_3 \) folds and scar folds are observed in the boudins gap, from Tatimara area.

Fig. 3.30: \( F_2 \) fold with attendant down dip \( L_1 \) marked by amphibolite layer. Associated regional \( S_2 \) plane differentiates overturned \( F_1 \) from \( F_2 \); dextrally moving parallelogram type of boudins is seen to the left, from Forest gate area.

Fig. 3.31: Fish head boudins are folded by \( F_3 \); the nodal zones are occupied by pegmatitic materials (peg.), from Narengi Patthar quarry area.

Fig. 3.32: The nodal zones of fish head boudins are occupied by pegmatitic materials carrying remnant boudins. Comparatively thin hornblende biotite schist layers are showing scar folding, from Tatimara area.

Fig. 3.33: Boudins of different patterns and effect of subsequent deformations are seen, from Narengi Patthar quarry area.
Fig. 3.34a Generalised map of Narengi area showing mafic layers within the quartzofeldspathic host. The trajectories of the mafic layers are drawn from the outcrops as well as field photographs taken systematically covering the whole area.

Fig. 3.34b Finite strain generalised map of the Narengi area. The foliation is highly perturbed due to repeated folding.

Fig. 3.34c Map of joints in the Narengi hills (Forest Gate and Patthar Quarry). The trajectories are constructed parallel to the major strike and the trend of joints measured in well exposed outcrops throughout the area.
Fig. 3.35 A schematic sketch of the pure shear box

Fig. 3.36 (a-c) Various steps implemented for model construction

(Rao & Sivadas, 1998)
Fig. 3.37: (a-e) Sketches of buckle folding of a multilayered sequence of varied thickness (2 to 4 mm) embedded in painter's putty. The layers are composed of modelling clays, interfaces are greased by petroleum jelly. A sequential development of folds of varied nature is exhibited at different amount of shortening: (a) initial setting of the layers in pre-deformed stage; (b) At approximate 6% shortening; (c) At 20% shortening; (d) 30% shortening; (e) The final configuration of the buckle folding is shown at 61% shortening.
Plate 3.1 The different lithoassociations showing their relationships to structures from Forest gate areas. (a): Alternate layers of mafic and felsic indicating evidences of intrafolial, tight, isoclinal F (Z pattern) folds. The layers are dipping inward (SE) the hill; (b): More felsic layers are showing the evidences of F and F, folds. (c): Same as (a), F, folds are of similar pattern and intrados-extrados curvatures are almost identical. (d): Tight F, fold with parasitic fold noses marked by alternate amphibolite layers. Felsic materials are passing through axial plane of F, folds.
Plate 3.2  Field photographs showing complex patterns of natural folds from Forest gate area. (a): Complex folds marked by amphibolite and quartzofeldspathic gneissic layer with curved axial surfaces and steep dip due to $D_3$ phase. Fold axes are plunging at high angle. (b): Same as (a), biotite flakes are stretching parallel to axial plane of $F_4$ at the fold hinges. (c): $F_4$ ('$S$' pattern) folds with axial planar $S_4$, deformed by $F_3$ folds. The dark layers are affected by conjugate extensional faults. (d): Felsic veins mimicking folds and passing roughly parallel to axial planar direction. A minor reverse fault is marked by hornblende biotite schist.
Plate 3.3  (a) : 'M' pattern fold in calc silicate rock from Bonda area. Axial plane fracture is seen. M pattern is mimicked by a quartzose vein maintaining uniform thickness. (b) : Sharp hinged F, fold is refolded by F,, the latter shows open, box type (top). Locality : Narengi Patthar quarry. (c) : Concordant metabasite, both being folded and refolded by F, and F,. Discordant look of the metabasites are essentially due to joint planes observed in quartzofeldspathic gneiss. Locality : Tatimara quarry. (d) : Sinistrally rotated F, folds with well developed rounded to sharp hinges are marked by alternate felsic and mafic layers of Tatimara quarry. The
Plate 3.4  
(a) : Tightly appressed ‘Z’ pattern F, folds with attendant axial planar S; (b) : F, folds in migmatite, folds are tight and oppositely curved, feldspathic vein approximately parallels the axial planar from left to right is seen; (c) : Same as (b) disharmony is observed, ‘Z’ pattern fold to the right is refolded by F, later deformation; (d) : Ptygmatic folds marked by quartz veins within quartzofeldspathic gneiss showing dextral motion. 

Locality : Forest gate and Narengi Patthar quarry areas.
Plate 3.5  
(a): Rolled over crenulation lineation \((L_2 = F_2)\) in micaceous schist along the border zone of amphibolite (XY section), crenulations are of \textit{en echelon} pattern. Pen marks the \(F_1\) axes of the fold trending NW-SE.  
(b): \(F_2\) folds with dextral motion mimicked by quartz veins. Mafic veins maintain variation in orthogonal thickness while felsic veins almost show identical thickness.  
(c): Tectonically attenuated and sheared out amphibolite layer marks the extensional fault (Fault plane trends NNE-SSW). Separation zone is occupied by pegmatitic materials.  
(d): Highly boudinised, folded, rotated mafic bodies are enclosed within highly migmatised quartzofeldspathic gneiss. Change in orientation is largely due to viscous flow of the migmatised materials.  
Locality: Narengi Forest gate and Tatimara.
Plate 3.6 Interference patterns of folds from Tatimara and Forest gate areas: (a) Plier fold (Sarma and Dey, 1999) marked by amphibolite layer showing much thickened hinges and thin limbs (M pattern). Scarp folding effect is observed to the right. (b) Quartz veins within amphibolite showing evidences of interference of $F_1$ and $F_2$ folds. Shadow zone (right top to left bottom) marks the axial planar direction. (c) Type 3 - hook shaped interference pattern is marked by amphibolite. (d) Interference of $F_1$ and $F_2$ folds (almost $\perp$ to each other). In the outcrop dome and basinal structure (type 1) is inferred.
Plate 3.8  

(a): Boudins of hornblende biotite schist showing contractional fault with sinistral geometry from Narengi Patthar quarry area. The E-W fault plane is occupied by pegmatitic materials. To the left fault - bend fold is observed.

(b): Extensional fault (normal) trending NW-SE in banded gneiss. Fault plane shows moderate angle. The fault plane makes low angle with the axial plane fracture cleavage ($S_1$) of $F_1$ fold (left). Locality: Thakurkuchi area.

(c): A low angle thrust along the short limb of a near recumbent ($F_1$) fold refolded by $F_1$. The fault plane is marked by quartzofeldspathic veins. An eyed fold is seen at the bottom. Locality: Forest gate area.

(d): Highly sheared amphibolite with lots of ribbon quartz is sinistrally shifted fault plane trending E-W and occupied by pegmatitic material. Partial fault bend fold is seen. Locality: Narengi Patthar quarry area.
Plate 3.9  Boudins of varied shapes and sizes in Forest gate and Narengi Patthar quarry areas.  
(a) : Barrel type;  
(b) : Lensoid type with the development of scar folding;  
(c) : Ghost boudins (after Sarma and Dey, 1997);  
(d) : Fish headed, separation zone is occupied by pegmatitic materials.
Plate 3.10 Photographs from Narengi Patthar quarry area showing the development of boudins and related shifting. (a): Sinistrally moving low angle thrusted boudins, the displacement plane is E-W, φ angle 25°, shortening (ΔL) 40%; (b): Post F, boudins, separation zone is occupied by pegmatitic materials and faulted; (c): Fish head boudin; pegmatitic materials in the separation zone contain relict boudins (Ghost boudin); (d): Parallelogram fish head, lensoid group of boudins.
Plate 3.11 (a): Foliation boudinage structure marked by gneissic foliation with the formation of scar folding. The lower part is highly sheared. (b): Same as above, but highly migmatised. (c): Fish head boudin is marked by amphibolite and is enclosed within the pegmatitic groundmass. (d): Folded boudins marked by amphibolite is dextrally rotated and preserved within the quartzofeldspathic gneiss. Locality: Nareni Patthar quarry (a, b) and Tatimara (c, d).
Plate 3.12 Hand specimen photographs showing F, folds (a) and (b) and F, folds (c) and (d) from Talmara area. Both (a) and (b) show the development of attendant axial planar S, foliation while (c) and (d) although closed type planar photo (d) shows the development of excellent clockwise and anticlockwise senses of rotation on the two limbs of the fold indicating flexural slip mechanism.
Plate 3.13 Handspecimen photographs from Forest gate and Tatimara areas showing (a) : $\sigma$ type rotation of a rigid mafic body enclosed within quartzofeldspathic gneissic host. (b) : High angle normal fault. (c) : Curved axial surface of $F_1$ fold due to interference of later $F_2$ folding. Closure being sharp, bluntness becomes zero (0). (d) : $F_1$ fold showing injection of small granitic vein along the short and steep limb of the fold.
Plate 3.14 (a) Cross section (⊥ to F₁ fold axis) of a Model. Individual layers were initially of uniform thickness, varies largely, fold morphology also varies (37.5% shortening). (b): Folds showing Enéchelon tendency. Enéchelon, fractures across the F₁ fold hinge is observed. (c): Multilayered sequence of varied competency and thickness showing the development of folds of varied nature. F₁ and F₂ folds in case of experimental models coincides with the F₁ and F₂ of natural folds; (d): Interference of two phases of deformation (F₁ and F₂). Fractures parallel to F₁ and F₂ hinges are seen.