The present chapter deals with the description and analyses of the various structures encountered in the rocks of the present area. It is an established fact that the arrangement of the small scale structures like foliation, lineation, fold etc. are genetically related to the large scale structures. The careful recording of the geometrical arrangements of these small scale structures help in establishing the large scale structures present in the area.
The study of the small scale structures and many of the directly observable structures of sedimentary, igneous or metamorphic origin yields information which helps to study the arrangement of structures in the area together with the time sequence in which the structures developed and the geological processes responsible for their formation. The most important outcome of these phases of crustal movements may be of orogenic dimensions or may be the result of the small pulses of deformation within the framework of single orogeny.

The field observations reveal that the area under investigation has witnessed at least three phases of deformation i.e. \(D_1, D_2\) and \(D_3\). As each successive deformation developed, it affected the rocks in two ways: a new set of structures was formed in the rocks and the earlier structures were deformed.

The structures present in the area have been described under two headings.

A) Structures associated with country rocks
B) Structures associated with the granitic rocks.

A. STRUCTURES IN THE COUNTRY ROCKS

The various structures which have been observed, recorded and studied in the country rocks are as under.

I) Primary structures
   a) Bedding
   b) Cross bedding
II) Secondary structures
   a) Planar structures
   b) Linear structures
   c) Mesoscopic folds

3.1 PRIMARY STRUCTURES

Primary structure is the structure that originates during the formation of the rocks through depositional processes (Davis, 1984). These structures show the physical environment of processes operating at the time of deposition of sediments. Since the country rocks happen to be metamorphic ones, only the relicts of the primary structures are present. The primary structures, wherever possible, have been used to workout the younging direction.

3.1.1 Bedding $S_0$

Bedding ranging from layering to delicate lamination is the basic primary structure present in the country rocks. According to Pettijohn (1984) 'bedding or stratification is expressed by rock units of general, tabular or lenticular form that have some lithological or structural unity distinguishing it from other strata with which these are interlayered. Mckee and Weiss (1953) have used the term 'lamination' for a unit less than 0.1 cm thick and for units greater than 1 cm used the term 'bed'.

Bedding ($S_0$) has been recognised in the field by colour, texture, composition and resistance to erosion. The bedding planes are smooth and straight, and in cross-section
range in thickness from a millimeter to more than a meter. Bedding is quite common in the metapsammites of the area. In the metapelites of the area, the bedding has been recorded from the places, where there is a lithological contacts between the two different compositional bands. Wherever possible, bedding was recognised and mapped carefully and its relationship with the rock cleavage was used to work the younging direction.

3.1.2 Cross Bedding

A set of sedimentary origin layers within a bed making some angle with the horizontal bedding plane is called cross bedding. Pettijohn et al., (1972) have termed it to be a single sedimentary unit characterised by internal bedding called 'forset bedding' inclined to the principal surface of accumulation. In their most useful and diagnostic form, the cross beds or cross laminations are tangential to the lower bedding surface and they are sharply truncated along the upper surface.

In the area under study, cross bedding has been observed in the metapsammites and has been used for finding the top and bottom of the beds. Care was taken to separate the true cross bedding from the pseudo-cross bedding produced by the transposition and small slides during kinematic deformation.

3.2 SECONDARY STRUCTURES

Structures which reflect the subsequent deformation or metamorphism after the deposition are the secondary
structures. Secondary planar and linear structural elements formed due to successive tectonic activity were recorded and analysed. These structures form an important tool for the geologists because of their genetic relation to the major structures. The structures produced during the three phases of deformation have been classified as under.

a. Planar structures
b. Linear structures
c. Mesoscopic folds
d. Macroscopic folds

3.2.1 Planar Structures

All the deformed rocks are characterised by one or more type of penetrative planar structure. All penetrative planar surfaces are called \textit{S-surfaces} (Turner and Weiss, 1963). In the present work, all S-surfaces including schistosity, rock cleavage, fracture cleavage, etc. have been included under the planar structures. Surfaces of metamorphic origin such as cleavage, schistosity and layering due to metamorphic differentiation, shall be referred under the general term \textit{foliation}. Foliation may be defined by layering of contrasting mineralogy (gneissosity), by planar preferred orientation of individual grains (schistosity), by planar fracture surface (cleavage) or by any combination of these three.

Different foliations are associated with different phases of deformation. The various types of foliation
associated with folding phases and deformation have been summerised in table 3.1.

Table 3.1: Various types of foliation associated with different stages of the deformation.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Foliation Type</th>
</tr>
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</table>
| Phase I foliation $S_1$ (Axial planar to F1 fold) | 1. Schistosity $S_{1s}$  
|                | 2. Mylonitic foliation $S_{1m}$ |
| Phase II foliation $S_2$ (Axial planar to F2 fold) | 1. Crenulation cleavage $S_{2c}$  
|                | 2. Shear zone cleavage $S_{2sz}$ |
| Phase III foliation $S_3$ (Axial planar to F3 fold) | 1. Fracture cleavage $S_{3f}$ |

3.2.1.a Schistosity $S_{1s}$

The rocks of the area exhibit a prominent schistosity defined by preferred orientation of micaceous minerals or by alternating metapelitic and metapsammitic bands (Plate 3.1.A). This type of foliation is associated with $F_1$ folds and is parallel to their axial planes and cuts across the hinges of $F_1$ folds and is folded by the later folds ($F_2$ and $F_3$). Thus, they are syn to late $F_1$ folds. It is the first secondary planar structure to be formed in the rocks which is the main foliation of the country rock. Price and Cosgrove (1990) suggested that schistosity may develop with the removal of quartz, felspar from the cleavage domain with the progressive deformation. This foliation is seen cutting the original bedding ($S_0$) only at the hinges of $F_1$ folds and seem to be parallel to subparallel to the limbs (fig. 3.1). Its relationship with $S_0$ has helped in working out the
The stratigraphy of the area which in turn helped to mark the trace of the axial plane of the $F_1$ folds.

The grain size of the schistose rocks near the granite contact shows a better development. In these better grained rocks at places, porphyroblasts of garnet and staurolite are seen across the main $S_1$ foliation as the result of emplacement of the granitic rocks. In the metapsammites the $S_1$ foliation is marked by development of small tabular bodies of mica. The trend of these small tabular bands in the metapsammites are parallel to $S_0$ in the metapelites.

3.2.1.b Mylonitic Foliation $S_{1m}$

The country rocks in immediate contact with the granites are mylonitised. The mylonitic rocks occur as narrow zones and are characterised by intense deformation. The rocks in these zones are generally fine grained, crushed and resemble the adjacent occurring rocks. The reduction in grain size is due to cataclasis and recrystallisation. These
crushed rocks show typical mylonitic fabric. In these mylonites, a preferred dimensional orientation of quartz defines the schistosity \( S_{1s} \). Elongate and deformed quartz grains occur as distinct ribbon, surrounded by a mantle of fine recrystallised grains. These deformed quartz grains are small relics of older detrital grains and are characterised by undulose extinction and subgrain development. Mylonites of the study area have typically a strongly layered appearance, the layering being due to the variation in the composition (Plate 3.1.B). A lineation is developed within the foliation which is defined by elongate rods of felsic mineral aggregates.

3.2.1.c Crenulation Cleavage \( S_{2c} \)

Crenulation cleavage varies considerably in morphology, but is very distinctive in that, it cuts a host rock that possess a preexisting continuous cleavage (\( S_{1s} \)), which is typically crenulated into microfolds. (Plate 3.1.C). These microfolds are symmetrical or asymmetrical, but later are more common in the metapelites of the area under study. With the increasing fequency of development of the crenulation cleavage, the width of the microlithons decreases, and the rock start showing prominent parting parallel to the crenulation. The attitude of the crenulation cleavage is controlled by the orientation of the preexisting foliation.

This type of foliation has been recorded in various types of schist of the area and are developed parallel to
the axial planes of the $F_2$ folds by crenulating the axial planes of the foliation (Schistosity $S_{1s}$) of $F_1$ fold in the metapelites (Fig. 3.2). The $S_{2c}$ foliation has an average dip of 70°-80° due eastwards. It is composed of uniform distribution of quartz and mica. The mica rich layers coincide with both the limbs of symmetrical crenulation and alternate limbs of asymmetrical crenulation, the micas within these layers are aligned approximately parallel to the length of the layer. The micas, in fact, are still parallel to the earlier foliation but have been rotated towards parallelism with the new foliation.

Microlithons in rocks of the area marked by crenulation cleavage are rich in quartz and felspar but very poor in mica. Cleavage domains in these rocks marked by crenulation cleavage are very rich in micas but very poor in quartz and felspar. To be precise, the segregation in crenulation cleavage of mica rich domain and domain rich in
quartz-felspar is strikingly conspicuous, reflecting a strain induced differentiation.

Cosgrove (1976, 1989) and Price and Cosgrove (1990) suggested that at some stages of folding in a multilayer consisting of quartz and mica rich layers, crenulation cleavage may develop due to stress concentration at hinges of folds. Gray and Durney (1979) who gave one of the most enlightening papers about the strain significance and mechanism of formation of crenulation cleavage, emphasized that the development of crenulation cleavage involves a physical/chemical redistribution of minerals as a function of relative solubilities and chemical mobilities.

3.2.1.d **Shear Zone Cleavage S\textsubscript{2sz}**

This type of foliation has been noticed in shear zones. These structures occur in narrow zones across which markers are displaced by faulting. They are simply zones of large ductile shear strain with or without a component of shortening perpendicular to the zone. The foliation is more or less parallel to the zone but near the contact it trangresses. Restriction of the foliation to the zone around immediately adjacent rocks indicates that it is a product of the deformation that produced the zone. These zones in the area of study are parallel to subparallel to the S\textsubscript{2c} schistosity and may be associated with development of Jutogh Thrust.
3.2.1.e **Fracture Cleavage \( S_{3f} \)**

Fracture cleavage is a parting defined by closely spaced discrete parallel fracture, ideally independent of any planar preferred orientation of grain boundaries that may exist in the rocks. This is best developed in thin quartzite bands within the metapelites and its trend is more or less parallel to the axial plane of \( F_3 \) folds (Fig. 3.3). Thicker the quartzite bands, widely spaced is the fracture cleavage. This structure is non-penetrative and no metamorphic recrystallisation has been noticed with this type of structure.

![Fig. 3.3: Field sketch showing the development of fracture cleavage present in quartzite band within the metapelites exposed near Kungal.](image)

The fracture cleavage is developed in metapsammites and metasemipelites of the area which exhibits a prominent fracture cleavage near Jarasi. The cleavage cuts the schistosity at angles varying from \( 30^\circ \) - \( 70^\circ \). Quartzite and schistose quartzites are also characterised by fracture cleavage, but sometimes it becomes difficult to distinguish
it from the jointing, since the distance between the cleavage planes gradually increases.

3.2.1.f Joints

Joints are fracture surfaces along which there has been imperceptible movements. Davis (1984) suggested that the density of joints increases as we go towards hinge zone of related folds. Price and Cosgrove (1990) used aspect ratio as criteria for differentiating between syntectonic and post tectonic joints. In the present area, joints are well developed in the metapsammites (PLATE 2.1.B) while they are poorly represented in the marble and metapelites. The best developed joints in the area are eye-catching systematic joints with planar or curved surfaces which cut across other joints. These systematic joints occur in the field as sets, each set being characterised by parallel to subparallel joints. Nonsystematic joints traced in the area do not cut across other joints and terminate at the bedding surfaces.

Fig. 3.4: Genetic orientation of longitudinal and diagonal joints relative to $F_2$ fold axis and to principal stress axis.
The relationship of systematic joints to regional structures has been worked out. The predominant trend is parallel to the fold axis \( (F_3) \) which runs in N55W-S55E direction. The diagonal joints occur in paired sets arranged systematically with respect to longitudinal joints. They generally intersect to form an obtuse angle about \( S_2 \) foliation and the longitudinal joint sets (Fig. 3.4). Diagonal joints are also present which trend NE-SW.

3.2.1.g Faults

Faults are fractures along which there is visible offset by shearing. Faults are noticed at some places in the area. These are minor distortion and as such are not mappable. Reverse type of faults are the most common type present, which run parallel to the major foliation \( (S_{1s}) \) of the country rock. The fault planes of these faults dip at low angles. Normal faults are less common and dip at high angle. These are often seen cutting the earlier reverse faults and seem to be younger than the reverse faults.

3.2.2 Linear Structures

The term lineation has been used to describe any linear structure that occurs within or on a rock. It includes striae on slickensides, fold axes, flow lines, stretching, elongated pebbles or ooids, intersection of planes, linear parallelism of minerals.

Lineation is the subparallel to parallel alignment of elongate, linear elements in a rock body, elements that are penetrative at the outcrop and handspecimen scale.
observation. Just like foliation, lineation has many physical expression and can form in metamorphic, igneous and sedimentary rocks (Weiss, 1972).

Lineations are very much common in the deformed rocks of the present area and sometimes more than one lineation are visible in a given foliation plane. The dominant classes of lineations are intersection lineation, mineral lineation which are so penetrative that the lineated rock looks like fibrous wood. Other lineations are coarse and described in the form of linear structures which include rodding, mullion, boundins etc. The linear structures are systematically related to the local fold structures. This is because linear elements resulted from stresses dependent of those produced folding. These linear structures are generally, but not invariably either parallel to the fold axes or inclined at an angle approaching 90°, when related to the group of folds.

The linear structures in the area of study show great variation in their attitude because the rocks which have undergone polyphase deformation are related to the tectonic movements prevailed during various phases of orogeny. The linear structures formed during earlier phases of orogeny were either obliterated or modified by later tectonic movements with the development of new linear structures. The lineation in the area of study have been distinguished on the bases of their character and particular phase of deformation, in which they were formed. The linear elements
representing intersection of S-planes form an important set of linear structure that are well preserved in the metapelitic or metasemipelitic rocks of the area. Lineation due to mineral (biotite, felspar) orientation is also well marked. Different types of lineation associated with different phases of deformation have been summerised in the table 3.2.

Table 3.2: Linear structures occurring in different stages of deformation.

| Phase I Lineation          | 1) Fold axes lineation $L_{1f}$ |
|                           | 2) Intersection lineation $L_{1I}$ |
|                           | 3) Mineral lineation $L_{1m}$ |
|                           | 4) Boudinage and pinch & swell structures $L_{1b}$ |
|                           | 5) Rodding and mullion structure $L_{1r}$ |

| Phase II Lineation         | 1) Fold axes lineation $L_{2f}$ |
|                           | 2) Striation $L_{2S}$ |
|                           | 3) Pucker axis lineation $L_{2p}$ |
|                           | 4) Intersection lineation $L_{2I}$ |
|                           | 1) Kink fold axis $L_{3k}$ |

| Phase III Lineation        | 2) Intersection lineation $L_{3I}$ |

3.2.2. a Fold Axis Lineation $L_{1f}$

The metapelites of the study area show corrugations and microfolds which run as linear elements over the bedding planes. The corrugations show a small wave length ranging from 0.2 to 0.5 cms. Some of them show a wave length of more
than 0.5 cm, running for a distance of more than a meter. These linear structures are associated with the first phase of folding and the plunge and attitude of these fold axes vary from place to place (Fig. 3.5). They plunge at an average angle of about 20° in N35°E and S35°E

3.2.2.b Intersection Lineation \( L_{II} \)

This lineation is composed of geometric lines created by the intersection of two or more foliations or the intersection of foliation with the outcrop surface. This linear structure in the present area which is related to \( F_1 \) fold has been formed by intersection of bedding \( (S_0) \) and foliation parallel to the axial plane and \( F_1 \) fold (i.e., \( S_{1s} \)) (Fig. 3.5). This type of intersection lineation is displayed by the metapelites. The trend of the lination shows a variation from place to place.
3.2.2. Mineral Lineation $L_{1m}$

Mineral lineation is defined by the preferred dimensional orientation of inequant grains. Mineral elongation in the rocks of the area is marked by lenses, augens, porphyroblasts of biotite and quartz on $S_0$ and $S_{1s}$ surfaces of mica schist (Plate 3.1.D.E). The growth of mineral lineation is attributed to the growth of these minerals in the direction of least resistance. The trend of mineral lineation is more or less parallel to the fold axes of first phase deformation.

Much of the expression of mineral lineation is of preferred directional crystallisation of minerals. However, the linear alignment of minerals and mineral aggregates can in part be derived by mechanical breakdown, that is, comminution of once larger elements. The relative roles of recrystallisation and comminution are a function of the mineralogy of the rock and the condition under which the deformation was achieved. (Davis, 1984).

3.2.2.d Boudinage and Pinch and Swell Structures $L_{1b}$

Where unconsolidated layers of strongly contrasting strength properties are permitted to stretch as they compact, pinch and swell structure and boudins can form.

Pinch and swell structure in the present area is characterised by the gentle pinching of the quartzite layer within the rock sequence of Khadrala Mica Schist Member (Fig. 3.6). Boudins are formed by attenuation of the more competent layer of quartzite bed and concomitant flow of
Fig. 3.6: Pinch and Swell structure developed by quartzite in mica schist near Bhali.

less-competent adjacent unit (Mica Schist) into the neck zone resulting from the attenuation (Plate 3.2.A). Continued deformation/attenuation commonly results on the separation of the competent rock into isolated oval-shaped unit.

The form of boudins are endlessly variable depending on the ductility contrast between the layers that are flattened and stretched. In the present area, it is possible to find boudin lines or axes in particularly one direction at low angles (4° - 8°) to the mineral lineation $L_{1m}$ and axes of mesoscopic fold $L_{1f}$. The boudins are restricted to $F_1$ folds only and are stretched at right angle to the direction of maximum compression.

3.2.2.e Rodding and Mullion Lineation $L_{1r}$

Rodding is a linear structure that is defined by a penetrative array of straight, parallel, highly elongated rodlike bodies of minerals. Rods are essentially mono-mineralic and are composed of material different from that of the main mass of rock in which they occur. In the area
these rocks are mostly made of milky or icy quartz. Good developments of this structure are exposed in Sharman Quartzite Member near Bhallun, where quartz segregation are developed along bedding surfaces and schistosity $S_{1s}$. They are also seen in the rocks of the Khadrala Mica Schist Member. The general trend of these linear structures are conformable with the $F_1$ fold axes.

Mullions are structures that generally form from the country rocks. They form in a competent layer where they occur as elongated bodies bounded partly by bending planes or other preexisting surfaces, and partly by new surfaces such as joints or cleavages. Alternately they form in a surface rather than a layer. Mullions are well developed in schistose quartzite of the area. These are also observed in the rocks of the Khadrala Mica Schist Member. Mullions in the area are remarkably cylindrical and have a ribbed appearance and individual surface features are very persistent along the length of the mullion. Bedding mullions occur where folding is less intense so that undulation of individual bedding planes are prominent.

Phase II lineation

3.2.2.2 Fold Axes Lineation $L_{2f}$

This linear structure is associated with second phase of folding and the plunge and attitude of these fold axes vary from place to place, which may be due to the effect of $F_3$ folding (Fig. 3.7).
3.2.2.g Striation $L_{2s}$

Striations are direct product of frictional sliding on faults. But, these surface marking are not present on all faults, either because they never formed or because they were removed by weathering at the level of surface exposures. They are non-penetrative, linear structures found in the area as parallel to subparallel markings on $S_0$ and $S_{1s}$ planes of carbonaceous schist which have a shining appearance.

There are surfaces of easy parting (slickenside) on the smooth and polished surfaces of schistose quartzite near the fault plane in Khadrala (Fig. 3.8). These slickensides display prominent ribbing or striation. They are believed to be parallel to the direction of relative movement during their formation. These striae are the grooves scoured on one side of the fault by hard particles drawn over it by the
Fig. 3.8: Field sketch showing the development of striation $L_{2s}$ in schistose quartzite exposed near Bahlun.

other side. These striations occur normal to the $F_2$ fold axes and run almost to the northsouth direction.

3.2.2.h Pucker axis $L_{2p}$

The pucker lineation in the area is produced when individual metapelitic or metasemipelitic layers move past over another. These linear structures especially occur on the limbs of $F_2$ folds in the present area and are associated with second phase of deformation. The puckers are well developed in the carbonaceous schist as well as in the mica schist and the attitude and plunge of these puckers is highly variable. (Plate 3.2.B).

3.2.2.i Intersection Lineation $L_{2i}$

This type of intersection lineation has been formed by the intersection of $S_2$ with $S_0$ and $S_1$. This lineation $L_{2i}$ is parallel to the mineral lineation $L_{2m}$ and fold axes ($L_{2f}$) of $F_2$ fold (Fig. 3.7). This is more common in the present area and plunges due NNE in most part of the area.
Phase III Lineation

3.2.2. Kink Fold Axis \( L_{3k} \)

The hinge lines of the kink folds define the \( L_{3k} \) lineation. Kinking is best developed in the metasemipelitic sediments. At places, kinking occurs as a conjugate sets of fold (Fig. 3.9). These structures show constant trend in the present area.
3.2.2.k **Intersection Lineation L\textsubscript{3k}**

This structure is produced by the intersection of \( S_3 \) foliation with \( S_1 \) foliation. Invariable \( L_{3k} \) intersection is parallel to \( L_{3k} \).

3.2.3 **Folds**

Folds are the most obvious evidence of the permanent deformation. The metamorphic rocks of the area show complex folding as a result of repeated deformation of more than one generation. On the bases of variation in style orientation and the nature of the \( S \)-surfaces affected by folding, three generations of folds, (also their phases of deformation) have been established.

3.2.3.a **First Phase Folds \( F_1 \)**

This is the oldest recognisable secondary structure present in the area and has developed on the stratification planes (\( S_0 \)). These folds have been developed on mesoscopic scale and have been observed on the outcrop level only ([Plate 3.2.C](#)). On a bigger scale they have not been observed nor their presence is reflected by the outcrop pattern. Strong axial plane cleavage (schistosity \( S_{1s} \)) is associated with these folds which is the main foliation of the country rocks ([Fig. 3.2](#)). The fanning out of this schistosity is slightly convergent in the direction opposite to the fold closures suggests that, schistosity developed in later stages of this folding. The \( F_1 \) folds are tight to isoclinal in nature. As a result of successive foldings, the \( F_1 \) fold at some places have acquired reclined nature. The interlimb
angles varies from $0^\circ$ to $25^\circ$. Transposed bedding in garnetiferous mica schist is also observed at one or two places. It is developed due to extreme flattening and thinning of the limbs of $F_1$ folds. The folds show a varying amount of plunges both in northerly and southerly directions. The variation in fold style and plunge is due to superimposition of later deposition.

Since the metamorphism has destroyed the original stratification to various degrees, it is with great difficulty that one recognises $F_1$ folds on a small scale. Bedding, axial plane cleavage have been used to trace the axial plane of the major $F_1$ folds in the map area, which have been associated under secondary planar and linear structures in the following pages.

3.2.3.b Second Phase Fold $F_2$

They are developed both in micro and macro dimensions and are coaxial with the $F_1$ folds. During this folding slippage on $S_1$ planes has occurred and as a result striation are seen on $S_1$ planes (Fig. 3.7). The $F_2$ folds are also isoclinal in nature with variable interlimb angles (Plate 3.2D,E,F). Towards the eastern side the axial plane cleavage i.e. crenulation cleavage ($S_{2c}$) is associated with this type of folds. This crenulation cleavage is prominently developed in the pelitic rocks. The crenulation cleavage in the present case is of penetrative type and very insignificantly developed in the metapsammites. The interlimb angle decreases and they become overturned, and the dip of the
axial planes of these folds decrease towards the eastern side. The general strike of the axial plane is NE-SW. The parallelism of $S_0$ and $S_1$ development of axial plane cleavage ($S_2$), folding of axial plane ($S_1$) of $F_1$ fold hence suggest that $D_2$ structures were overprinted on the $D_1$ structure. Mineral lineation, intersection lineation, pucker axes run parallel to $F_2$ folds. The axes of these fold have easterly or westerly plunge with varying amount of $25^\circ$-$35^\circ$. These folds are also well developed in carbonaceous schists and metasemipelites.

3.2.3.d **Third phase fold ($F_3$)**

The $F_3$ folds trend in the SE direction. These were produced where the rocks were in brittle stage and they are open folds and fracture cleavage is associated with them (Fig. 3.10) The fracture cleavage is very well exhibited by quartzite bands within the metapelites. Fracture cleavage is non penetrative in nature and is axial plane to $F_3$ folds. The $F_3$ folds are the youngest folds in the Himalaya. They affect even the younger sediments like Upper Siwalik of Upper Pliocene to Middle Pleistocene age.

![Fig. 3.10: Field sketch showing the development of kink band near Katedi](Image)
3.3 INTER-RELATION AND VARIATION IN THE ATTITUDE OF PLANAR AND LINEAR STRUCTURES IN THE COUNTRY ROCKS

On the bases of homogenity and the trends of the various structures present, the area has been divided into two structural domains (SD_1, SD_2), (Fig. 3.11). The varied style in the orientation of folds of three generations and their relations with different S-surfaces help in establishing the chronological order of formation of structures. The map (Fig. 3.11.a) shows the various planar and linear structures present in the area.

The first deformation (D_1) has folded stratification (S_0). The F_1 fold thus produced are characterised by development of strong foliation (S_1) which is axial planar to these folds. This S_1 foliation is the main foliation of the country rocks and has been described as schistosity. Trend of the schistosity (S_{1s}) of the country rock is parallel to the stratification (S_0) in the area. Only at few places where the hinges of the folds are present, this schistosity cuts across the original bedding (S_0). The poles to S_0 and S_1 planes have been plotted (Fig. 3.12A,B). These diagrams show marked concentration of points at two places which correspond to domains I and II. In domain I, the general trend of S_0 is NS, it varies between N15° E - S15°W and N20W - S20E with an average dip of 40°-60° eastward, whereas its trend in domain II is E-W and varies between S60E - N60W and N70E - S70W. In both the cases the rocks dip eastward at an average angle of 50° (Fig.3.12.A).
Fig. 3.12: Equal area projections of planar elements (country rocks)
A) 74 poles to $S_0$ foliation;
B) 70 poles to $S_1$ foliation
C) 28 poles to $S_2$ foliation
D) 30 poles to $S_3$ foliation
E) 76 poles to joints
The concentration at places fall on a great circle (girdle). The girdle is almost complete and well defined. The poles of this great circle defines the B axis. In the present case, the B axis defines F₃ fold which plunges at an angle of about 40° in S40E direction. The F₃ fold, thus has developed at right angle to F₁ and F₂ fold which are coaxial in nature. Figure 3.12B brings almost the same type of result in case of S₁ foliation. The S₁ foliations have more or less the same strike trend but their dip angle is little less than that of S₀ foliation. The B axis worked out, runs in S60E and plunges at an angle of 30°. The B axis also represents the general trend of the F₃ folds. The variation in the worked out direction attitude of the F₃ fold axis of S₀ and S₁ is due to the fact that S₀ and S₁ are neither exactly parallel to each other nor have the same dip throughout the area.

The parallelism of S₀ and S₁ even at the hinges of F₂ folds indicates that F₂ folding has affected both the S₀ and S₁ and therefore is later than F₁ folding. Nowhere in the area F₂ folds have been seen folding F₁ hinges. Which suggests that F₁ and F₂ folding are coaxial.

The S₂ foliation (crenulation S₂c) is almost parallel to axial planes of F₂ fold axis. Since the F₁ and F₂ folds are coaxial, the trend of the crenulation cleavage (S₂c) is almost parallel to the main schistosity (S₁s). This foliation has an average dip of 58° - 74° due eastwards in both the domain since this is not a penetrative structure on
regional scale it has been observed only in the metapelites of both the domains.

The regional variation in attitude of stratification $S_0$ and the axial plane foliation ($S_1$) is explainable in terms of folding of $S_0$ and $S_1$ around an axis $B$. The poles of $S_0$ and $S_1$ plotted in equal area do not suggest that $F_3$ folding has affected both the $S_0$ and $S_1$. Since $S_0$ and $S_1$ are almost parallel to each other, $B$ axis worked out in both these cases more or less coincide with each other. The girdle axis of $S_0$ poles plunges about $38^\circ$ in S45E direction whereas girdle axis of $S_1$ poles plunges about $30^\circ$ in S60E direction. Thus the $B$ axis, which defines the $F_3$ fold, in both cases comes to have more or less the same proposition (Fig. 3.12).

The fracture cleavages ($S_3$) associated with $F_3$ folds have regional NW-SE direction and dipping at high angle in both the directions throughout the area.

Throughout the area prominent joints have developed. Langitudinal joints strike parallel to $S_3$ have developed, which are parallel to $S_3$ foliation. These are high angle joints which dip in both the directions. Associated with these are two sets of shear joints. $S_1$ foliation bisects the angle between the two sets of joints (Fig. 3.12E), which suggests a close genetic relationship among the longitudinal joints, shear joints, $F_3$ fold, and $F_2$ foliation. It occurs at places that fracture cleavage has been taken as the longitudinal joints because their orientation coincide with each other.
Fig. 3.13: Equal area projections of linear elements (country rocks)

A) 23 fold axis lineations, $L_{lf}$ domain I,
B) 23 fold axis lineations, $L_{lf}$ domain II,
C) 42 intersection lineations, $L_{ll}$ in domain I and II,
D) 48 mineral lineations, $L_{lm}$ in domain I and II,
E) 35 boudinage lineations, $L_{lb}$ in domain I and II,
F) 36 rodding and mullion lineations, $L_{lr}$ in domain I and II.

The phase I lineations $L_1$ (Fig. 3.13) (Fold axis lineation $L_{lf}$, intersection lineation $L_{ll}$, mineral lineation $L_{lm}$, boudinage and pinch and swell $L_{lb}$, Rodding and mullion
lineation L_{1r}) have almost the same orientation as the F_1 fold axis in both the domains. The F_1 folds plunge at an average angle of about 35-40° in N80°E in domain I and S10°E in domain II.

The variation of the linear structures associated with in a domain is due to the effect of F_2 folding. In domain I, the trend of S_2 varies between S28E to N10E having 58-74° easterly dip. In domain II, the strike of S_2 runs between S70E- N72E to EW with dip of 60° - 78° towards the eastern side.

The variation in the general trend of L_2 lineation in both the domains is due to the effect of F_3 folding. The corresponding L_2 lineation are parallel to F_2 folds. The F_2 folds are also isoclinal and coaxial with F_1 folds in nature with having an axial plane dipping at an average angle of 70° towards East. During this folding there has been some slippage on the S_1 planes, as shown by the striation on the S_1 planes. The attitude of these striations is almost at 90° to the F_2 folds and these striations lie in S_1 planes.

Third phase of deformation has produced F_3 folds which has not been seen on the outcrop level but has been worked out with the help of planar structures (S_0 and S_1) in both the domains. The worked out attitude of F_3 fold plunges at an angle of about 28° in S50E. The kink folds which are present only in thinly bedded rocks seem to have been formed during F_3 folding. The varied orientation of L_3 is mainly due to the conjugate nature (Fig. 3.14).
Fig. 3.14: Equal area projections of linear and planar elements

A) 51 intersection lineations $L_{21}$, domain I,
B) 42 intersection lineations $L_{21}$, domain II,
C) 40 fold axis lineations $L_{4f}$ domain I & II,
D) 32 poles to kink fold axis lineations $L_{3kf}$.

73
Figure 3.15 Shows the statistical maxima for all the planar and linear structures present in the country rocks of the area.

Fig. 3.15: Synoptic diagram showing statistical maxima and girdles of all the planar and linear elements in the country rocks.
B. STRUCTURE IN THE GRANITIC ROCKS

The structures found in the granites are generally divided into:

I) Flow stage structures

II) Solid stage structures

Structures of the flow stage appear to have originated when the host rocks were largely in the semi-liquid and crystalline state. Structures of solid state develop in the outer shell of the pluton after this portion has completely consolidated but while the interior of the pluton was still mobile. Pitcher and Berger (1972) used the term deformation, meaning simply, change in shape and they further emphasized that the term 'flow' should not be restricted to movements in fluids, since it describes any deformation without loss of cohesion on the scale observed. Keeping in view this statement, the use of terms primary and secondary which have been used to describe the structures in igneous rocks has been avoided, because these are misleading and fulfil no useful function and instead the evolution of these structures as a separate case discussed.

3.4 Foliation in Granitic Rocks

3.4.1 Gneissosity $S_{1g}$

Although the central part of the western granite pluton is composed of massive granite, a foliation is commonly developed towards its margin with the country rock. This foliation which is termed as gneissosity is defined by the alignment of ferromagnesian and felsic constituents.
(Plate. 3.3.A). Towards the core from the contact there is a general increase in the grains size of both the ferromagnesian and felsic constituents. The development of this foliation is closely related to the formation of schistosity \((S_{1s})\) in the country rocks associated with \(D_1\) deformation. Such structures develop when country rocks are capable of deforming plastically under the influence of temperature and pressure appropriate to the regional metamorphism.

This \(S_{1g}\) foliation is very prominent at the margins or near the contact with the country rocks. Towards the core, the foliated granite is emplaced by nonfoliated one. It is suggested that the emplacement of the nonfoliated granite took place after \(D_1\) deformation. Since the main schistosity of the country rock \((S_{1s})\) and foliation \((S_{1g})\) in the granitic rocks are parallel to each other, it is concluded that the emplacement of foliated component was syntectonic or late tectonic with \(D_1\) deformation.

The foliated components of the granitic bodies in both the plutons are not seen cutting across the main \(S_{1s}\) foliation of the country rocks, it is likely that the emplacement took place after the country rocks had acquired their main foliation. Moreover, \(S_{1s}, S_{1g}\) and the contact planes are parallel to one another, it is evident that the granitic bodies were emplaced as sheet like bodies in the country rocks.
3.4.2 **Mylonitic Foliation S_{1mg}**

The granitic rocks near the margin with the country rocks are intensely deformed producing a foliation or fluxion structure. Foliation here is defined by mylonitic banding which is defined mainly by compositional layering so that mica rich layers, alternate with layers rich in quartz and felspar (Plate 3.3.B). In the zone immediately adjacent to the contact with the country rock, the mylonitic banding trend is parallel to the wall and the foliation in the country rocks. The regional trends of the foliation S_{1} in the country rock and that of the mylonite banding in granitic bodies is nearly the same.

It is suggested that these rocks owe their texture to pervasive crushing or comminution of mineral grains achieved through penetrative frictional sliding along network of microcracks. Although these mylonitic rocks partly reflect the influence of cataclastic flow, they are dominantly formed through crystal-plastic dislocation creep. In other words, the grain size reduction in the mylonites of the area is mainly due to the dynamic recrystallisation of original grains that deformed by dislocation creep (Tullies and Schmid 1982) not simply to comminution accompanying cataclastic. Mylomites display a planar parallel arrangement of broken mineral grains and shear surfaces. Viewed microscopically the mylonites of the area display beautiful lensoidal fabric. Quartz typically look like it has flowed like butter, whereas felspar obviously have behaved brittlely breaking into chips, which sometimes become
oriented within the fluxion structure (Chapter four). The trend of the \( S_{1mg} \) is almost parallel to that of \( S_{1g} \), which is further parallel to the main foliation \( (S_1) \) of the country rocks and to the contact between the granitic bodies and country rocks. It can be safely concluded that granitic material was emplaced along the \( S_1 \) planes (i.e. axial planes of \( F_1 \) folds and the structures were formed during the same phase of the deformation.

3.4.3 Mineral Lineation \( S_{1m} \)

Mineral lineation is the product of deformation. It is due to the crude alignment of biotite and felspar megacrysts in the granites of the area. Lineation present in these granites is defined by elongate aggregates of mica and quartz lenses (Plate 3.3.C). However, elongate quartz and felspar grains which have been elongated in the plane of mylonite banding also defined lineation. The quartz lenses are aligned in the plane of the mylonite banding, thus contributing to the lineation, whereas individual felspar lenses tend to break up into fragmental trains which are megascopically expressed as mylonite lineation. The alignment of the minerals become less and less prominent towards the central part and it ultimately dies out in the nonfoliated granite.

The mylonitic banding and associated lineation present in the granitic bodies are geometrically related to \( F_1 \) folds. Mylonite banding is axial planar to these fold and mineral elongation lineation is parallel to the axis of \( F_1 \)
fold. No where the mineral alignment cuts across the foliation of the country rocks. In fact, this lineation is parallel to the mineral lineation of the country rock and is syntectonic with $D_1$ phase of deformation.

3.4.4 Inclusions

Inclusions are most commonly interpreted as xenoliths or fragments of the surrounding country rocks. These are very common in the granitic magmas, and their orientation can provide a glimpse of the internal structure even when the rock matrix does not disclose foliation or lineation. The margins of both the granitic bodies of the present area contain numerous fragments of the country rocks, the distribution of which have an important bearing on the genesis of the granitic body (Plate 3.3.D,E). Inclusion in these granites vary in size which are sharply bounded to the enclosing granitic rock. Their shape varies considerably depending partly on their lithology and partly on the position within the granitic body. All but a few of the inclusions lie with their longer axes parallel to the host granite foliation. The inclusion exhibit an internal foliation which lies parallel to their long dimensions and thus to the host foliation (Fig. 3.16). There are exceptions when the longer axes of the inclusions and the internal foliation of the inclusion donot coincide. The foliation in the metasedimentary inclusions is axial planar to tight internal folds though it has certainly accentuated during
the later deformation. The orientation of the inclusion has been controlled by the flow and indeed, it is certainly the

Fig. 3.16: Field sketch showing the foliation and flattening of xenoliths in the granites at Tutupani. Note the internal foliation in the xenoliths lie parallel to their long dimensions.

case that they are generally aligned parallel to the mineral orientation of the host.

In a general irrotational strain such as that resulting from the flattening of a consolidating magma already in place, all inclusions with continued deformation would relate to X-Y plane, while those already in this position would remain so. Since the inclusion were not rigid they got flattened regardless of their attitude. Those lying parallel to the X-Y planes are most deformed. This is also supported by the general parallelism between the trend of inclusion and that of the linear elements of the country
rocks. A remarkable concordance between the inclusions and the country rock structure is also observed at eastern side of the Khadrala. These comprise a group of metasedimentary inclusions, observed within the granite, in which the internal bedding and foliation are markedly concordant to the moderately dipping host granite foliation. These xenolithic elements dip at shallow to moderate angles in precisely the same attitude as the corresponding structures in the adjacent garnet mica schist. It can therefore, be concluded that inclusion in the granite had developed $S_1$ foliation along with the development of $F_1$ folds prior to the emplacement of the granites.

3.4.5 Joint pattern

Jointing is very well developed in the granitic rocks of the area. Major joints are noted and the poles to the joints have been plotted on the equal area net (Fig. 3.19E). The following sets of joints are recognised in the area.

I) N 50 W-S 50 E dipping at 50°-60° in both the directions

II) N 40 E - S 40 W and dipping southeast

The first ones are close spaced longitudinal joints and are persistent throughout the granitic body and the country rocks and are parallel to the $F_3$ fold axis. There is another sets of shear joints with the same trend but dipping at an angle of 40°-50° in both the directions. These are comparatively less common. The cross joints run in N40 E - S 40 E and are almost vertical. The mutual relationship has been shown in figure 3.17.
Fig. 3.17: Block diagrams to show the joint developments and other minor intrusives in the granites of the study area

3.4.6 The Dykes

Marginal zones of the granitic bodies in the study area are characterised by numerous dykes and veins (Plate 2.3.C,E). These dykes may be grouped into three more or less distinct categories, partly on the basis of mineral
composition and partly on structural grounds. These are I) early pegmatites II) late pegmatites and aplites III) quartz veins. Cross cutting relationship at several places indicates that early pegmatites are older than late pegmatite, aplite and that the quartz veins are the youngest of these minor intrusions (Fig. 3.17).

3.4.6.1.a Early Pegmatite

Pegmatites are by far the most common discordant bodies present in the granitic body and are especially abundant in the marginal zones of the granitic bodies in the area. These are large continuous bodies with a fairly constant width (about 1-3 mts) and are traceable for long distance and run almost parallel to the $S_1$ foliation of the rocks.

![Schematic diagram showing chronological relationship of various structures in the granites.](image)

Fig. 3.18: Schematic diagram showing chronological relationship of various structures in the granites.
These are coarse grained friable rocks having large crystals of tourmaline and felspar set in a relatively finer groundmass.

The dykes are characterised by the presence of internal mineral foliation which lie oblique to both the dyke walls and host granite alignment. These oblique foliations are the result of lateral movements of the dyke walls in such a way that the acute angle between the walls and the internal fabric points in the direction in which the walls were moving (Berger 1971). The fact that oblique foliation have been formed even where the dykes pinch out and end abruptly suggests that the dykes have come along narrow shear zones in a much larger and rigid host.

3.4.6.b Late Pegmatite and Aplite

Late pegmatites and aplites invariably occur as irregular discordant bodies. The internal mineral alignment, where present, is generally oblique to both wall and host foliation. The dykes are irregular and vary in width from 0.5 to 1.5 mts. The contact with the envelop rock is sharp.

3.4.6.c Quartz Vein

This group of minor intrusives constitute thin veins or lenses of quartz of about 1-10 cms in thickness which cut across the granites at random. These can be traced for distance up to 15 meters. These veins cut all the other dykes at various angles and show no sign of deformation.
Quartz vein may sometimes be localised along small scale shear zones in the host granite. This is particularly common in the margins of both the granite plutons. It clearly indicates the operation of structural control, even at this main stage.

**Figure 3.18** brings the relationship of various minor intrusives within the rocks of the area.

### 3.5 INTER-RELATION AND VARIATION IN THE ATTITUDE OF PLANAR AND LINEAR STRUCTURES IN GRANITIC ROCKS

The various structures encountered in the granite of the study area have been plotted in the map (**Fig. 3.11.a**). The interrelationship and variation in the attitude of various planar and linear structures help in establishing a sequence of formation of these structures. The figures **3.19.A,B** show that the main foliation of granite ($S_{1g}$) and mylonite foliation ($S_{1m}$) are parallel to each other and both of them are parallel to the schistosity in the country rocks.

Mineral lineation and inclusions in the granites have also been plotted (**Fig. 19.C,D**) As mentioned earlier, inclusions (xenoliths) lie in the main foliation plane ($S_{1g}$) of the host granite. It suggests that the emplacement took place in a partially consolidated condition. They were subjected to great pressure and squeezing at 90° to the direction of the flow resulting in ruff parallelism of the felspar phenocrysts. The inclusion shows well developed foliation $S_1$. At places, $F_1$ folds are also present in the...
Fig. 3.19: Equal area projections of planar and linear structures present in the granitic rocks of the study area

A) 42 poles to foliation $S_{1g}$ of foliated granite,
B) 23 poles to mylonitic foliation $S_{1m}$ of foliated granite
C) 43 mineral lineations $L_{1m}$ of the granites
D) 15 inclusion lineations $L_{1in}$ in the granites
E) Poles to joints in the foliated and non-foliated granites
inclusions which imply that prior to inclusion of foliated granite \( F_1 \) folds and \( S_1 \) foliation have already developed in the country rocks. The general trend of lineation produced by these inclusions and mineral lineation is parallel \( S_1 \) foliation in the country rock.

Fig. 3.20: Equal area projection (statistical maxima only) of various structures of the granitic rocks of the study area

by these inclusions and mineral lineation is parallel \( S_1 \) foliation in the country rock.
Throughout the area, prominent joints are present in both the foliated and nonfoliated granites. Longitudinal joints show a genetic trend of N50W-S50E dipping vertical (Fig. 3.19E). Since the development of joints in the granites and country rocks have genetic relationship with F₃ fold, it is concluded that joints developed during F₃ fold both in the granite and the country rocks. The statistical maxima of various structures present in the granitic rocks of the area have been shown in figure 3.20.