CHAPTER 2

STRUCTURAL FEATURES OF THE ROCKS OF THE AREA

2-1. INTRODUCTION:

The regional foliation of the gneissic complex is relatively simple with a NE-SW dominant trend. Variations in this trend to E-W and locally but rarely to NW-SF are noticed. This foliation is represented by the gneissosity, schistosity and composition layerings in the rock. The presence of tight isoclinal and asymmetrical folds and other linear structures are also characteristic. These structures show a distinct relationship to each other (see following pages). Regularity of banding in the metasediments, banding, streakiness, and contortion of foliation in the quartzofeldspathic gneiss are also characteristic. In addition to these structures, the rocks are also characterised by well developed joints.

The rocks affected by deformations are the biotite-sillimanite-cordierite schist and gneiss, mica schist, banded quartz-magnetite rock, calc-silicate rocks, quartzofeldspathic gneiss and amphibolite. They are found to contain both penetrative and non-penetrative planar structures (Turner and Weiss, 1963, pp. 21-31) and linear structures of various types. The granodiorite and blastomylonite have shown development of
only weak planar structures. These are, as will be shown later, younger in relation to the planar structures of the above rock units. Ultramafic rock occurring in the area is non-foliated.

2-2. METHODS OF STUDY:

The structural study was carried out by mapping the area on a 1:4" mile scale topographic map. Systematic mapping involved in the collection of data relating to different structural elements (cf. chapter 1-A2). These were later studied in terms of mesoscopic and microscopic structures (petrofabric analysis) in the laboratory. The individual methods for these structural studies in the laboratory and the results obtained therefrom are described separately.

2-3. TERMINOLOGY AND STRUCTURAL ELEMENTS:

While describing the sequence of development of the structures of the area, instead of using the terms like the main, mid, and late phases of deformation of Bowes and Bhattacharjee (1967, pp.7-60), Bhattacharjee (1968, pp.235-264) and Keppie (cf. 1969, pp.171-185), the terms such as F₁, F₂, F₃ used by Turner and Weiss (1963, pp.91-143), Turner (cf. 1968, pp.369-374) and Dawes (cf. 1970, pp.5-121) have been employed.

The following abbreviations are constantly used while describing the S-surfaces, lineations and folds:

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a. Planar structures include schistosity or neissosity or both.

- $S_1 = \text{It is older than } S_2$, as $S_2$ is axial planar to the folds that folded $S_1$.
- $S_2 = S_2$ is axial planar to $F_1$ folds.
- $S_3 = \text{It is younger than } S_1$ and $S_2$ and axial planar to the fold formed on $S_1$ and $S_2$.
- $S_4 = \text{It is of local occurrence and mimicks the older planes } S_2$ and $S_3$.
- $S_5 = \text{It is younger than } S_1, S_2, S_3$ and $S_4$ and affects all of them. It is related to $F_3$ fold.

b. Linear structures include minor folds or other linear structures or both.

- $L_1 = \text{formed during } F_1$ fold.
- $L_2 = \text{formed during } F_2$ fold.

c. Folds

- $F_1 = F_1$ fold is formed when $S_1$ is folded and produced $S_2$ parallel to the axial plane of the fold.
- $F_2 = F_2$ fold is developed when both $S_1$ and $S_2$ are folded with the development of $S_3$ as the axial planar foliation.
- $F_3 = \text{The fold affects both } F_1$ and $F_2$.

The following terms are also used in statistical analysis of the structures:
2-4A. Foliation (S₁) = This is the oldest recognisable planar structures in the metamorphites. It is represented by the compositional layerings in the metamorphites like quartzofeldspathic gneiss (Fig. 2 a and Pl. XXIV), mica schist and biotite-sillimanite-cordierite schist and gneiss. This S₁ is also characterised by the individual bands or lenses rich respectively of quartz and magnetite in the banded quartz-magnetite rock (Fig. 2 b; Pl. XVII b-c; XIX a). In case of calc-silicate rock, the S₁ foliation is marked by the bands consisting of diopside, garnet, clinozoisite often with quartz (Pl. XXI, a,c).

This foliation is generally tightly folded, rendering it parallel to the axial plane foliation (S₂) of the (F₁)
folds, the discordant between the two can be seen only at the axial regions of the folds (Fig. 3 a & c; 5 g & h; 6 b, d & f; & Pl.IV b & c; V b & VI a). Elsewhere, however, the lithological layerings is parallel to and cannot be separated from the dominant ($S_2$) foliation in the rocks.

2-4B. Structural elements of the first phase ($F_1$):

The dominant foliation in the metamorphites of the area is parallel to the axial planes of the generally small, tight isoclinal folds ($F_1$). The penetrative nature of the foliation and associated lineation, and the form of the folds indicate that intense tectonic deformation was in operation during their development. Both the structural readjustment and mineral reconstitution producing the dominant fabric of the rocks took place during this phase of deformation. The foliation developed during this phase is very persistent and is consistently the most dominant planar element. Because of this, it can be used as reference plane in the structural sequence (cf. Choudhury, 1969).

2-4B.1. Folds ($F_1$): Folds of this phase of deformation are well displayed in the banded quartz-magnetite rock, micaschist and quartzo-feldspathic gneiss occurring at Mawkhrangdubi, Aradonga, Lejadubi, Buspani and Rangsapara areas. They affect the compositional layerings in these rocks and are
mostly characterised by longer and shorter limbs and penetrative planar foliation (Fig. 2 a, 3 a & c, 6 f and Pl. IV b, c; V a, b & VIII a & b). The folds are small scale folds: the size generally do not exceed 25 cms. across. The folds are mostly isoclinal, intrafolial and asymmetrical, although open and/or symmetrical folds are also noticed.

The folds in the banded quartz-magnetite rock are mostly tight isoclinal and are characterised by thickened hinges and thinned limbs (Fig. 3 e; 5 b-h and Pl. IV a, c; Pl. Vc). The limbs are generally of unequal length, the longer limbs always remain parallel to the axial plane foliation (S₂), while the shorter limbs are arranged at variable angles to this foliation. Some of these folds are so tightly appressed that the either of the limbs coincide with the other, the intervening magnetite or quartz rich bands or both being arranged as isolated elliptical lenses between the limbs (Fig. 5 h), or the limbs are sheared off parallel to S₂ into thin lenses, while the noses remained unaffected (Fig. 3 c; Pl. IV c; V c & VI a).

Tight and open asymmetrical folds with short and long limbs (Fig. 6 a, 7 a) are also rarely noted in the quartz rich bands of the rock.

Intrafolial/interformational folds (Pl. VI c), between the parallel bands of the banded quartz magnetite rock, characterised by randomly oriented axes, are observed
at Mawkhrangdubi area on the right bank of the Sinera river.

The isoclinal folds in quartzo-feldspathic gneiss are generally open. These folds are better displayed and the axial planar foliation is better developed in the quartzo-feldspathic gneiss than those occurring in banded quartz-magnetite rock, where the folds usually have highly appressed limbs. Open folds, sometimes with the development of slip planes parallel to the axial plane of the folds, are also noted (Fig. 3 b & 7 c and Pl. IV d).

The tight isoclinal folds are also common at Drongda, Buspani, Lajadubi, Rangsapara, and Mawkhrangdubi areas (Fig. 3 a; 6 b-f; 7 a & d; 9 b and Pl.IV b; V b; VII a-b & VIII b). Some of them are often dissected into isolated lenticles, knots and masses, while the fold noses and one of the limbs remained intact (Fig. 6 b).

The plunge of the folds is either to the NE or to the SW, with the angle of plunge varying from 60° - 90°. The formation of these isoclinal folds, open folds and asymmetrical folds was essentially co-oval with the development of the dominant foliation (cf. Bhattacharjee 1968, p. 238) in the rocks.

2-4B.2. Foliation (S₂): The foliation (S₂) developed in the metamorphites is very prominent and is well exhibited throughout the area. This highly penetrative planar element is well
displayed by the parallelism of the platy or prismatic minerals like the micas (Fig. 2 d; 18 a, b, c and Pl. VIII a; VII b) and the amphiboles and the alternate bands of quartzo-feldspathic and mafic minerals (Fig. 2 a and Pl. XXIV a & c; XV b). This foliation (S2) is parallel to the lithologic layerings (S1) and the limbs of the folds (F1), except at the fold closures (Fig. 3 a & c; 6 b & d, and Pl. IV b & c; V b & VIII b). It is most prominent in the quartzo-feldspathic gneiss, biotite-sillimanite-cordierite gneiss, mica schist, amphibolites and anthophyllite-tremolite schist and partly in calc-silicate rocks.

The foliation in the quartzo-feldspathic gneiss is produced by the alternating quartzo-feldspathic and micaceous layers (Fig. 2 a and Pl. XXIV a, b & c). In the biotite rich quartzo-feldspathic gneiss, the gneissosity is better developed (Fig. 2 a & d; Pl. XXIV a,b,c), than in the biotite poor variety (Fig. 2 e & f). In biotite-sillimanite-cordierite gneiss (Pl. XV a), the gneissosity is marked by the mica together with fibrous sillimanite alternating with bands of quartzo-feldspathic and cordierite. The well displayed planar structure in the amphibolite is exhibited by the grains of amphibole and by the elongate aggregates of quartz and feldspars (Pl. XXII b; XXIII a). In anthophyllite-tremolite schist, the schistosity is defined by the parallel to subparallel arrangement of the amphibole grains (Pl. XXIII c). This foliation, as
seen at Mawkhrangdubi area, is also defined by the slip plane developed parallel to the axial planes of the open folds (Fig. 3b and Pl. IV d).

As this foliation is axial planar to the folc (F₁), it is also called axial planar foliation.

The dominant trend of this foliation (S₂) in the host rock (quartzofeldspathic gneiss), together with that in the metabasic and metasedimentary inclusions, is NE-SW. Local variations from NE-SW to E-W and rarely to NW-SE are also noted. The dip of the foliation, which is steep to vertical, is from SE to S and often SW (see also Fig. 12).

2-4a.3. Lineation (L₁): The early lineation (L₁) is represented by mineral lineation, intersection lineation (S₁ S₂) rodded lineation and minor fold and crenulation axes.

The best developed and the most abundant lineation present in almost all the metamorphites is the mineral lineation. It is defined by the parallel orientation of platy and elongated minerals and streaks of biotite.

The type of lineation that is second in abundance is the rodded lineation. It is marked by the rods of quartz and is generally well developed in quartzofeldspathic gneiss, banded quartz-magnetite rock and often in biotite-sillimanite-cordierite gneiss.
Where the intersections of S-planes \((S_1\&S_2)\) are developed, these provide excellent lineation. This lineation is generally very conspicuous on the hinge zones of the minor folds \((F_1)\), where the relations of \(S_1\) and \(S_2\) are pronounced (Fig. 2 a & c; 6 d; and Pl.IV b, c; V b; VIII b).

The lineation \(L_1\) represented by the axes of the minor folds and crenulations are also present and well exhibited at Aradonga, Mawkhrangdubi, Lejadubi, Rangsapara and Buspani areas. This lineation is imparted by the \(F_1\) folds.

The trend of the lineation generally parallels the \(S_2\) foliation, with steep to vertical plunge towards NE or SW (Fig. 13).

2-4C. Structural elements of the Second phase \((F_2)\):

This phase of deformation is characterised by folds that affect the structural elements of the first phase of deformation. These are again, in their turn, affected by the third phase \((F_3)\). The folds of this phase are not as abundant as the \(F_1\) folds.

2-4C. 1. Folds \((F_2)\): The \(F_2\) folds are common in Aradonga, Lejadubi, Rangsapara and Mawkhrangdubi areas. No major folds are recorded. These small scale folds are not larger in size than 40 cms. across. The style of the folds is also variable. Many are asymmetrical (Fig. 3 d; 7 a & d; 8 a, b & c and Pl. IV a; Va,b) and a few are monoclinal (Pl. IV a; IV a, b).
There are variations from monoclinal to asymmetrical forms with the development of axial planar shears (Fig. 8 a, b & c). Asymmetrical folds with the development of strain slip cleavage parallel to the axial planes of the folds are also noticed (Fig. 8 c). The quartzo-feldspathic bands in the folded rocks often show dislocation and these dislocated bodies are aligned parallel to the axial planes of the folds (Fig. 8 c).

The folds of this generation are slightly rounded with uniform thickness of hinge and limbs of the fold.

The deformation of pre-existing planar fabric is shown down to the microscopic scale by folding of biotite flakes in mica schist, in micaceous layers of quartzo-feldspathic gneiss, and by folding of bands in banded quartz-magnetite rock. In the latter case, porphyroblasts of garnet (Fig. 17 a and Pl. XVII b) also show deformation consistent with the deformation of the bands.

The trend of the axes of these folds varies from N 30° - 65° E - S 30° - 65° W, locally but rarely to S-W, with steep to almost vertical plunge towards the either ends of the axial planes of the folds.

2-4C.2. Foliation (S₃) : The occurrences of this foliation are better displayed in the quartzo-feldspathic gneiss, mica schist and banded quartz-magnetite rocks at Mawkhrandubi,
Lejadubi and Aradonga area. It is defined by the orientation of the biotite flakes parallel to the axial planes of the \( F_2 \) folds (Fig. 8 c). It is distinct in microscopic scale in almost all the rocks of the area and is marked by the growth of mica and quartz (Fig. 4; 18 a, b & c and Pl. XVI b & c) and often hornblende and epidote (Fig. 20 c), parallel to the axial plane of the \( F_2 \) folds that inclines to the \( S_2 \) foliation.

\( S_3 \) planes are only of local occurrence and are not as well developed throughout the rocks as the \( S_2 \) planes. The trend of this foliation varies from N 30\(^\circ\) - 65\(^\circ\) E - S 30\(^\circ\) - 65\(^\circ\) W to E-W with vertical to steep dip towards southeast.

2-4C.3. Lineation (\( L_2 \)) : The linear structures of this generation are not abundant as the earlier one (\( L_1 \)).

The best exhibited \( L_2 \) lineation is the intersection lineation of \( S_2 \wedge S_3 \) at the hinge zones of \( F_2 \) folds (Fig. 3 d and Pl. IV a; V a, b & VI b). The flakes of biotite and elongated quartzo-feldspathic bodies oriented parallel to the axes of the \( F_2 \) folds also express a mineral lineation and a mided lineation, respectively.

The \( L_2 \) lineation represented by the axes of the minor folds \( F_2 \) plunges steeply towards SW and often to NE. The details of the folds are given above (see \( F_2 \) folds).

The lineation (\( L_2 \)) plunges mostly to SW and often to NE with varying angles from 60\(^\circ\) to almost vertical.
2-4D. Foliation (S4): This foliation is locally developed and is confined only to granodiorite. This foliation may also be termed mimick foliation on the plea that it mimicks the earlier foliations (S2) and (S3) of the gneiss. This is quite apparent from (1) the streaks comprising of biotite with quartz and plagioclase which mark the foliation of the gneissic rock also mark the foliation of the granodiorite (Pl. XXVII a), (2) streaks comprising of biotite with or without hornblende and epidote marking the foliation of the gneissic rock also define the foliation of the granodiorite (3) there is a gradational contact from gneiss to granodiorite (Pl. XXVIIia) through migmatite and augen gneiss, and (4) the porphyroblast of microcline develops almost parallel to the foliations (S2) and (S3) (Fig. 3 e). The fabric of mica and quartz also indicate the similar idea (see chapter 2, -9B. 3 &-9B.5).

The dominant trend of this foliation varies from NE-SW and often to E-W with steep dip towards SE.

2-4E. Structural elements of the third phase (F3):

This phase of deformation is characterised by (1) a few open folds of smaller amplitude (2) presence of boudinage, and (3) of crush zones.

2-4E.1. Folds (F3): Sporadic occurrences of the F3 folds are seen only at the Aradonga, Lejadubi and Mawkhrangdubi and
Rangsapara areas. The folds are open folds that refolded the axial planes of $F_1$ isoclinal folds (Fig. 9 a & b, and Pl. IV - & VI c). This type of folding is also indicated by the buckling of flakes of biotite and often bands of quartz defining the $S_2$ and the $S_3$ foliations (Pl. VII b). These small scale folds are only a few cm. across.

Paucity of these folds in megascopic scale makes it difficult to determine the trend of these folds, although in the limited number of exposures the trend seems to have a near perpendicular relation to the earlier fold axes ($F_1$ and $F_2$)(Fig. 9 b, & 10 & Pl. IV a; VI b & VII a). The angle of plunge largely depends upon the earlier foliation ($S_2$).

Mineral growth co-oval with this phase of deformation is rare. Undeformed biotite flakes developed cutting across the $S_2$ and $S_3$ maintain a parallel to subparallel relationship with the axial plane of the $F_3$. This attitude of biotite flakes suggests their growth in subsequent static conditions (chapter 2,-9B,3). The presence of weak girdles shown by the plots of quartz axes (Fig. 15 a, b & c) parallel to the axial planes of the $F_3$ folds can apparently be taken as $S_5$.

2-4E.2. Boudinage: Occurrence of boudinage is well displayed in the quartzo-feldspathic gneiss at Buspani (along the road to Sonapahar from Hahim) (Fig. 9 c), at Ranighat and at Wawkh-
Boudinages are characterised by their development parallel to the axes of the $F_3$ folds.

The following features are shown by the boudins:

1. Thickening and thinning and often separation of the quartz veins into elliptical segments (Fig. 9c).

2. Fracturing of the folded quartz-feldspathic veins (Fig. 9c).

3. Pinch and swell structure in pegmatite vein ($P_1$) (Fig. 2 e, f & 7b, and Pl. IIIa).

4. No mineral is recrystallised between the individual segments of the boudin (Fig. 9c).

5. The trend of the boudin line is perpendicular to the $F_1$ and $F_2$ fold axes.

6. Boudinised veins occur mostly parallel to $S_0$ (Fig. 2 e & f, and Pl. IIIa).

7. Fractures are developed at the hinge of the folded quartz-feldspathic vein that are subsequently boudinised (Fig. 9c).

It becomes obvious from the above characters that the earlier quartz and pegmatite veins ($P_1$ & $P_2$) formed during the first and second phase deformations were boudinised during the later folding. As the boudin line is perpendicular to the $F_1$ and $F_2$ fold axes and almost parallel to the local ($F_3$) fold axis, it can be suggested that the development of boudinage is
co-oval with the formation of the $F_3$ folds. This view is also supported by the above points 2, 4 and 7.

The main reason for the development of these boudins might have been the stretching produced at right angles to the boudin lines (Billings, 1960, pp. 354-355).

Similar type of boudinised structures have been reported by Ramberg, (1952, p. 124-126), and Dawes (1970, p. 54), but these authors did not try to correlate them with different phases of deformation.

2-4E.3. Crush zones: These are represented by rare occurrences of mylonite band at Mawkhrangdubi (Pl. III b & IV c) and at Rangsapara areas. Their location is controlled by NW-SW fractures that are parallel to the dominant foliation ($S_2$) in the host rock.

The crush zones are small, varying from a few centimeters to more than a metre in thickness. Two bands occurring at Mawkhrangdubi (Pl. III b & IX c) on the right bank of the Singra river are 40 cms. to 1½ metre thick. The dominant mineral fabric and consequently the colour of the host rock along the crush zones are greatly affected. The individual minerals in the bands are characterised by mineral granulation, breaking and fracturing (Fig. 18 d, and Pl. XVIII a & b). Some of these crushed bands cut across a single crystal and other contains block of host rocks (Fig. 18 d).
These crush zones are also the zones of development of epidote veins, and as a consequence of the epidote veins, the rocks of the crush zones are dirty-green to dirty grey in colour. Some angular blocks of the host rock are also seen to be included within the body of the veins (cf. Fig. 18 c. and Pl. XXIX b).

2-5. PTYGMATIC FOLDS:

The ptygmatic folds occurring in the gneissic rocks of the area, also represent a type of lineation which post date all other linear structures of the rocks. This can well be judged from the following features.

The folds occur in the quartzo-feldspathic gneiss and are well observed in Buspani and Rangapara area (Fig. 8 e & 9 d, and Pl. IX c). These are small-scale folds and apart from having no constant relation to the dominant foliation ($S_2$) of the host rock, show the following features:

1. the ptygmatically folded veins are invariably either pure quartz or quartzo-feldspathic in composition.

2. the grains composing the veins show no sign of cataclasis.

3. the vein themselves do not show any directional or flowage structure.

4. the foliation of the host gneiss remains absolutely undisturbed and unaffected by these folds (Fig. 3 d).
5. the contact zone of the host gneiss with the vein does not show any visible evidence of deformation (Fig. 9 d, and Pl. IX c).

6. the plunge of the individual fold has no constant directional relation to either \( S_2 \) or \( S_3 \), although folds plunging along the foliation planes \( (S_2) \) of the host rock are also noticed (Fig. 9 d, and Pl. IX c).

7. the style varies greatly (Fig. 9 d).

8. the tightness of the fold forms is also variable.

9. the axial directions are variable.

10. the thickening and thinning of the folded veins are also noticed (Fig. 9 d, and Pl. IX c).

These observations are helpful for suggesting that ptygmatically folded veins of the area are of replacement rather than of injection origin. Therefore, it is considered that the folds might have been formed during the growth of the veins in their plastic state.

The occurrences of identical type of veins are reported by Mishra, Mahapatra and Bagchi (1960, pp. 57-60). The works of Read (1927), Wilson (1952) and Goodfey (1954) were also considered in the study of the veins of the area.

2-6. GENERAL CHARACTERISTICS OF THE FOLDS:

Most of the \( F_1 \) folds are of similar type with thickened hinges and thinned limbs, and axial planar foliation
(Ramsay, 1962a, pp. 309-10, and de Sitter, 1956, pp. 214-215, Billings, 1960, p. 56, and Turner and Weiss, 1963, p. 113). The tight nature of the folds and the strong penetrative nature of the foliation indicate that the folds developed under a strong compressional stress. The isolated nature of the folds may suggest that the shear movement was locally dominant during the deformation, that is, consequent to the severe shearing, most of the folds, either wholly or partly obliterated from the rocks.

Some of the $F_2$ folds are characterised by nearly uniform thickness of the folded lithological layerings. This is the characteristic of flexural (= concentric) type of folds (de Sitter, 1956, pp. 182-185, Turner and Weiss 1963, pp. 470-471). The new foliation ($S_3$) exhibited by the biotite flakes in the biotite rich band is developed parallel to the axial plane of the $F_2$ folds. The fold shown by the quartzo-feldspathic bands is often fractured and deformed. This character indicates that while a flexure mechanism was dominant, the deformation was not purely flexural but of modified type (Ramsay, 1962a, pp. 309-16). The characters of the folds suggest that they developed in a stress-field with local variation.

The $F_3$ folds are generally open folds. These are associated with unoriented/or weakly oriented mineral growth (quartz), developed under weak directed pressure. Development of mylonite enhanced by the epidote veins which developed
towards the end of the $F_3$ deformation indicates a rather cool and rigid state of the rocks during the deformation. As there is no clear evidence of regional axis of folding and dominant directed pressure during the brittle deformation, it can be taken to indicate that the complementary stress (cf. King and Rast, 1955, p. 265) developed in the orogenic belt might have been operative in the development of the folds of this phase.

2-7. RELATIONSHIP OF PEGMATITES TO STRUCTURES:

Two types of pegmatites have been recognised in relation to structures in the field. They are:

Pegmatite-I occurs as small veins, lenses and streaks which rarely reach more than 5 cm. in width. The trend of these veins are controlled by the dominant foliation ($S_2$) of the host gneiss (Fig. 2 e & f; 6 d and Pl. III a & c).

Pegmatite-II is in the form usually of thicker veins or layers of few centimetres to a metre or sometimes more in width. They bear either concordant or discordant relationship to the structures in the host rocks. The same vein may also occur in both the forms. Some of them are controlled by the axial plane and fold form of the $F_2$ folds (Fig. 2 e; 3 e; 6 d; 7 b; 9 b and Pl. IIB b & III c). The trend of the pegmatite-II varies from NE-SW to E-W, and NW-SE.

Similar to these pegmatite veins, quartz veins are also noted in relation to the above structures (cf. chapter I, 1-C2; Fig. 3 c; 8 b and Pl. IV c; V b & IX c).
2-8. RELATIONSHIP OF JOINT PLANES TO STRUCTURES:

Joints are well developed in all the rock types of the area. They are best developed in quartz-feldspathic gneiss. In the gneiss, these are more prominent in the pink variety than in the grey type (Pl. XIA a, b & YIB). In granite-diorite, these are widely spaced.

These joints are recognised as cross joints (bc), longitudinal joints (bc), diagonal joints and horizontal sheetings in relation to the dominant structures (F1 and S2) of the rock types of the area (Billings, 1954, pp. 106, 124. de Sitter, 1956, pp. 122-134, and Badgley, 1965, pp. 98-152). The detail description of the joints are given in the structural analysis (chapter 2-9 A.4).

2-9. STRUCTURAL ANALYSIS:

2-9A. Mesoscopic structures:

This study includes the statistical analysis of the dominant structural elements like foliation (S2), lineation (L1) including minor fold axes and joint planes.

2-9A.1. Method of study: The attitude of foliations, lineations and joint planes were collected from different localities of the area during the field work. A maximum of 200 and a minimum of 100 readings on each of the elements were collected at each of the location (table 1, 2 and 3).
PLATE IV

a. The fold in banded quartz-magnetite rock occurring at RangsaPara, showing three phases of deformation. The similar fold (F₁) is associated with monoclinal (F₂) folds and open (F₃) folds. Development of fractures parallel to the F₃ fold axis is noticed.

b. Well developed foliation in quartz-feldspathic gneiss developed parallel to the axial plane of isoclinal folds (F₁). The isoclinal fold is characterised by a shorter and longer limbs. The shorter limbs are at an angle to foliation while the longer limb are parallel to the foliation. A parasitic fold is seen at the centre of the photograph.

c. Similar fold (F₁) of B.Q.M. bands (dark grey) with thicken hinge and thin limbs are affected by open (F₃) folds in quartz-feldspathic gneiss. The longer limbs are often sheared out into elliptical bodies.

d. F₁ open fold in Q.F.G. shows axial planar slip. (Left hand part is loose sand in river bed).
a. Tight isoclinal ($F_1$) folds in association with asymmetrical ($F_2$) folds in quartz-feldspathic gneiss at Lejadubi on the bed of the Umsynthi river.

b. Tight isoclinal ($F_1$) fold occur in association with asymmetrical ($F_2$) folds in Q.F.G. at Mawhran-dubi. Quartz vein (light grey) mimick in fold.

c. Tight isoclinal ($F_1$) fold in B. A. M. rock are extremely destructed and dislocated, but fold noses remained intact. Pencil indicate the direction of axial plane.
PLATE VI

a. Q.F.G. shows the development of axial planar foliation (11 hammer) parallel to the axial plane of tight isoclinal fold.

b. Isoclinal (F₁) fold in B. Q. M. is affected by open (F₃) folds (H 85 a).

c. Interfolial folds in B. Q. M. (H 86)
PLATE VII

a. Tight isoclinal ($F_1^1$) fold (top, clinometer) is affected by open fold ($F_3$).

b. Well banded B.Q.M. with isoclinal folds ($F_1$) refolded by $F_2$ folds. The bands, together with the $F_1$ and $F_2$ folds are folded by $F_3$ folds.
Plate VII
PLATE VIII

a. Biotite-rich quartzo-feldspathic gneiss with well-developed foliation plane.

b. Tight isoclinal folding of compositional layering (S₁) by isoclinal folds (F₁), with axial plane foliation (S₂).

c. Augen gneiss with augens of felspar with quartz in quartzo-feldspathic gneiss. The augens are elongated on the dominant foliation (S₂).
PLATE IX

a. Monoclinal (F2) folds in Q.F.G. occurring in Mawkhrangdubi. It folds the dominant foliation \((S_g)\).

b. Similar to a. Quartz vein mimicks the fold structures.

c. Ptygmatic fold shown by a quartz vein \((Q_V)\) in quartz-feldspathic gneiss at Buspani along the road to Sonapahar on the thickening of hinge and thinning of the limbs.
a. Granodiorite with streaky lenses of quartzofeldspathic materials and mafic minerals defining weak foliation.

b. Migmatitic veins mimicking the dominant foliation ($S_2$) of the gneiss. $S_2$ is affected by $F_3$ open folds ($H\ 86$).

c. Band of mylonitic rock traversed by epidote veins (dark) along the fractures ($H\ 79$).
PLATE XI A

a. Development of joints in the pink gneiss at Mawkhrangdubi.

b. Similar to a and b at Aradonga.

c. Exposure of the rocks at Tutia bazar on the river bed of the Singra shows the development of joints in dolerite dyke. The river flows (top right) over the dyke along the dip of the horizontal sheeting.
a. Exposure of the pink gneiss within the grey Q.F.G. at Bandaraja Parbat shows the occurrence of joints (longitudinal, cross and diagonal).
Explanation of figure 2:

a. Disposition of mafic (biotite rich) band in quartzo-feldspathic gneiss indicating $S_1 = S_2$.

b. Alternate bands rich in quartz and magnetite with garnetiferous bands in banded quartz-magnetite rock. The individual bands indicate compositional layering ($S_1$).

c. Lenticular streaks of quartzo-feldspathic horn in Q.F.G. defining $S_2$.

d. Preferred orientation of minerals defining $S_2$.

e. Concordant pegmatite ($P_1$) show pinch and swell structure in Q.F.G. at Ranighat.

f. Microcline in pegmatite ($P_1$) which occurs in Q.F.G. at Mawkhrangdubi shows rotation.
Fig. 2.

- Magnetite rich band
- Quartz rich band
- Quartzofeldspathic gneiss
- Garnetiferous band
- Biotite rich band
- Pegmatitic vein
- Microcline
Explanation of figure 3:

a. Isoclinal fold (F₁) characterised by thickening of nose and thinning of limbs and growth of axial planar foliation, developed affecting compositional layering S₁ at the bed of river Singra at Aradonga.

b. Axial planar slip shown by one limb of an open fold parallel to S₂ in Q.F.C. at Mawkhrandubi.

c. Tight isoclinal fold with shorter and longer limbs, the longer one is parallel to S₂ and sometimes shear out into thin lenses, while the shorter and the nose remain intact, the quartz vein (S₄) mimicking the fold structures, at Mawkhrandubi left bank of the Singra river.

d. Axial plane of F₁ is folded with the development of F₂ fold in the same locality as c. F₂ vein develops along the axial region of the F₂ fold.

e. Granodiorite shows planar structures (S₄) with the streaks of biotite and amphibolite bands.
**Fig. 3.**

- **a**
  - $S_1$
  - $S_2$
  - 0 CMS

- **b**
  - $F_1$
  - 0 CMS

- **c**
  - $S_1$
  - $F_1$
  - $S_2$
  - 0 CMS

- **d**
  - $F_2$
  - $P_2$
  - 0 CMS

- **e**
  - $S_4$
  - 0 CMS

Legend:
- **MICA SCHIST**
- **QUARTZ RICH BAND**
- **MAGNETITE RICH BAND**
- **GNEISSIC BAND**
- **MICROCLINE**
- **MICA + HORNBLende STREAKS**
- **QUARTZ + PEGMATITE VEIN**
Explanation of figure 4:

Relation of mineral growth to the fold structures (Camera lucida drawing)

a. Section perpendicular to the axis of a tight isoclinal fold ($F_1$) in banded quartz-magnetite rock showing the relations of different planar elements. Scale: field of view (length) = 4 mm.

b. Section perpendicular to $S_2$ showing the orientation of biotite in biotite rich quartz-feldspathic gneiss in relation to planar structures. Scale: field of view (length) = 4 mm.

c. Section cut perpendicular to $S_2$ in mica schist showing crenulation of axial planar biotite with planar orientation. Scale: field of view (length) = 4 mm.
Fig. 4.
Explanation of figure 5:

Fold structures in Q.F.G. and quartz-magnetite rock.

a. Relationship of dominant foliation and lineation to F₁ folds, in Q.F.G. with quartz vein (Mawkhrangdubi).

b. Isoclinal folds with long and short limbs and prominent intersection lineation in B.Q.M.

c, d, e and f. Tight isoclinal folds with thickened hinges and thin limbs in B.Q.M.

g. Isoclinal fold with attenuated and slipped core limbs in B.Q.M. parallel to S₂.

h. Tight structures represented by elliptical lenses of magnetite and quartz parallel to S₂ in B.Q.M.
Fig. 5.
Explanation of figure 6:

a. Asymmetrical fold in B.Q.M.

b. Relict nose and one limb of a fold in F with the development of S2.

c. Refolded tight isoclinal fold in biotite rich quartz-feldspathic gneiss.

d, e and f. Tight isoclinal folds in G with dominant foliation axial planar to folds. Biotite pegmatite (P1) and (P2) develop in e.
FIG. 6.
Explanation of figure 7:

Fold structure in quartzo-feldspathic gneiss.

a. Tight isoclinal and open folds ($F_1$) with the development of $S_2$, Mawkhrangdubi.

b. Earlier concordant pegmatite vein ($P_1$) is cut by later pegmatite vein ($P_2$), Malsapara.

c. Open fold ($F_1$) in Q.F.G.

d. Asymmetrical fold in Q.F.G.
Fig. 7.
Explanation of figure 8:

a. Asymmetric $F_2$ fold with folded $S_2$.

b & c. Asymmetrical $F_2$ fold with folded $S_2$ foliation in biotite rich quartzo-feldspathic bands also often show boudin like structures whose axis is also parallel to $F_2$ axis.

d. Quartz vein ($Q_g$) oriented parallel to $F_2$ axis.

£. Quartz vein ($Q_2$) develops ptygmatically in amphibolite.
Explanation of figure 9:

a. Banded Q.F.G. shows open folds (undulatory) ($F_3$), Mawkhrangdubi.

b. Tight isoclinal folds ($F_1$) are affected by open (undulatory) folds of $F_3$ phase of deformation, Aradonga.

c. Boudinised quartz vein folded and fractured, Buspani.

d. Ptygmatic fold in foliated Q.F.G., Rangsangar.

e. Discordant pegmatite vein ($P_2$) with slightly folded foliation of the country rock, Mawkhrangdubi.
Fig. 9.

- **S₁ = S₂**
- **70°**
- **65°**

**Figures**

- **a.**
  - **F₃**
  - **1 METER**

- **b.**
  - **F₁**
  - **55°**

- **c.**

- **d.**
  - **50°**

- **0 CMS 15**

**Legend**

- **III** MICA SCHIST
- **Banded Quartz Magnetite**
- **Quartz Feldspathic Gneiss**
- **Quartz Feldspar Veins**

**Annotations**

- **N**
- **0 CMS 10**
- **P₂**

**Fig. 9.**
Explanation of figure 10:

Almost perpendicular relation of the axes of the two phases (F\textsubscript{1} and F\textsubscript{3}) of deformation.
The poles of the foliation planes were plotted on the lower hemisphere of the Schmidt equal area projection. The poles were counted and contoured by the free counter method and is used for contours equal to or greater than 3-4°, such that the locus of the centre of the counting circles includes as great an area possible within the contour. In contoured diagram (* diagram of Sander), the poles of the circles in each case, is plotted as $\beta S_2$.

In case of linear elements, the measurements in the field and laboratory analyses were carried out following the methods of Turner and Weiss (1963, pp. 80-85).

Both, the plotting and counting as well as contouring of joint planes were also carried out similarly to foliation planes (Billings, 1954, pp. 111-115, Turner and Weiss, op. cit.).

2-9A.2. Analysis and interpretations of planar structures:
The statistical representation of the poles ($\beta S_2$) to foliation from four sub areas (Table 1) falls into near perfect point maxima with slight spread to form imperfect girdles, the poles of which are marked as $\beta S_2$ in the diagrams (Fig. 12).

In Aradonga, Mawkhrangdubi, and Lejadubi area, the poles of the $S_2$ foliation show a slight spread pattern in the northeastern sector and a few of the poles also fall on the periphery of the southeastern sector. In Tutiabazar area, the poles of $S_2$ foliation tend to spread over to northeastern
sector. This indicates that the dip of the foliation, which is steep to vertical, is toward SE and aften toward SW. The $\beta S_2$ shows a variation in trend S 20°E to S75°E with a plunge of 80°. This variation of trend of $\beta S_2$ is consistent with the planar and linear elements of the F$_3$ (third phase deformation). The presence of F$_3$ folds is locally observed at Mawkhrandubi, Lejadubi, Aradonga and Rangsapara areas. Therefore, the dominant foliation might have been affected by the F$_3$ fold movement.

2.9A.3. Analysis and interpretations of linear structures: The concentration of the plots of the linear elements reveals that in each case (Fig. 13), they trend both to the northeastern and to the southwestern directions with steep to vertical plunge (table 2). The maxima of the poles of linear structures falls on the northeastern sector, while the pole of $\beta S_2$ falls on the southeastern sector. This indicates that there is no coincidence between pole of $\beta S_2$ and the maxima of lineation ($L_1$).

In view of the above analyses, it becomes apparent that the structural elements of the first phase deformation were affected by the later fold movements (F$_2$ and F$_3$). The following points make such an observation much clearer:

1. the change in the strike direction of $S_2$ from NE-SW.
2. non-coincidence between the maxima of lineation with $S_2$ of the dominant foliation ($S_2$).
3. Spread pattern of poles of foliation (S₂).

4. Triclinic or near triclinic pattern of orientation of quartz axes bear no distinct relation to dominant foliation (S₂) and mica cleavages (Fig. 12, 14, 15).

2-9A.4. Analysis and interpretations of joint planes: The contour diagrams (Fig. 11 a-f; table 3) reveal the presence of four major sets of joint planes, and in relation to the local (F₁) fold axis, these can be termed as cross joints, (ac), longitudinal joints (bc), diagonal joints, and horizontal sheetings.

The pattern of orientation of the joints varies from diagram to diagram (i.e. locality to locality) (Fig. 11). The orientation is sometimes regular and systematic and sometimes it is erratic.

The most important sets of joints are the cross joints (Set I) and the longitudinal joints (Set II) which are perpendicular and parallel to (F₁) fold axis respectively (table 3). They are well developed in all the stations (Fig. 11, a-f). Except at Aradonga, the cross joints are more prominent than the longitudinal joints. Both sets of joints are vertical.

The next important set of joints in order of abundance is the horizontal sheeting (Set IV). These are conspicuous at Tutiabazar and Aradonga. In other localities these are less well developed or almost absent (Fig. 11, b, c & f).
Fig. 12.
Fig. 13.
The horizontal sheetings do not bear any relation to the planar and linear structures in the rocks (table 3). This becomes apparent because while the attitude of \((F_1)\) foliation varies from steep to vertical, the attitude of sheetings is always or nearly so \((0^\circ\) to \(10^\circ\)).

The least abundant joints are the diagonal joints which make acute angles with the ac joints and obtuse angles with the bc joint. It is also observed that the bisector of the acute angle formed by the diagonal joints is being the direction of ac joints. The relation of these joints to \((F_1)\) fold axis is incline. There may be one, two or more sets of these joints. These joints are of moderately steeply dipping \((40^\circ-60^\circ)\).

From the above descriptions, it becomes clear that the number of joints developed and their relation to the structural elements like foliation \((S_0)\) and lineation \((L_1)\) are variable from place to place. In most cases \((Fig. 11, a, b, d)\), the horizontal sheetings are well developed and these occur with variable angular relationship with the lineation \((F_1)\) fold axis indicating that the structural set up during the development of foliation differ from that of the development of sheeting. As the sheetings affected the fabric elements, like the lineation, that developed on the foliation planes, therefore, the sheetings, are taken to be of much later origin \((Niyogi, 1966, pp. 65-88; Price, 1966, p. 128)\).
The erratic distribution of poles of joints, the variation in the prominence and also the variation in the orientation of the joints in relation to the (F₁) fold axis from locality to locality are taken to be indicative of the fact that the development of joints in these rocks was induced by more than one tectonic setup, otherwise they would have similar, or nearly so, orientations in all the localities.

2-9B. Microscopic structures (Petrofabric analysis):

The study of the microstructures of the rocks of the area was undertaken to supplement the analysis of the mesoscopic structures. Q.F.G., mica schist, B.Q.M., granodiorite and blastomylonite were taken for this study. Both the mica cleavages and the quartz c-axes were studied.

2-9B.1. Method of study: This study was carried out with the help of Leitz 4-axes universal stage. The thin sections for this study were prepared from the oriented handspecimens cut perpendicular both to the foliation and the lineation, (table 4). The orientation and measurements of the quartz (0001) axes and mica (001) cleavages were made using the standard method of Turner and Weiss (1963, pp.195-231). A maximum of 200 and minimum of 100 measurements were made from a slide and plotted on the lower hemisphere of a Schmidt equal area net of 20 cm. diameter. The contour represents the percentage of the total number of points per 1% area. The
contouring was done using the free counter method for contour
equal to or greater than 3% (for quartz) and 4% (mica) in most
cases, such that locus of the centre of the counting circle
includes as great an area as possible within the counter
(Turner and Weiss, 1963, p. 62). Each diagram is presented
with the plane of the thin section with the plane of the paper,
the strike of the foliation coinciding with the field orienta-
tion.

The variation in the orientation of quartz (0001) axes and the (001) of mica over the area are the important
presentation made by this petrofabric study.

The fabric dominated by a prominent planar structure
is designated as ab and the lineation on the ab plane as b
but in the absence of any visible lineation on the ab plane
is arbitrarily designated as b. The intersection of any S-
surfaces in a common axis is also termed as b. Here, in the
diagrams, the L1, L2 and L3 are referred to as b1, b2 and b3.

2-9B.2. Mica-subfabric : Mica occurs in the rocks in four
different varieties; biotite-I, biotite-II, biotite-III and
biotite-IV (chapter 3). The latter three varieties of biotite
are represented in the diagrams (Fig. 14) and were taken to
determine the time of growth of the micas and the variation
in the metamorphic conditions in relation to the structural
sequence as well as the affects of a subsequent phase of
deformation and metamorphism upon the inherited mica-subfabric.
The data relating to this analysis and the location of samples are given in table 3.


Each of the mica petrofabric diagrams (Fig. 14 a-r) of the rocks of the area is characterised by a strong maximum perpendicular to $S_2$ and absence of submaxima corresponding to $S_3$. The strong maximum developed corresponding to $S_2$ represents the tabular habit of mica developed parallel or sub-parallel to this surface. This suggests the absence of influence of other associated minerals and also that the effects of later folding on mica were less effective (cf. Keppie, op. cit. Chatterjee, 1970, pp. 75-95). Had there been any noteworthy influence of other minerals and later folding, the degree of pattern of orientation would have been reduced. The orientation of muscovite cleavages (Fig. 14 b) also exhibits identical strong pattern of orientation. The few randomly oriented scattered $S^\bot$ poles unrelated to any mesoscopic fabric ($S$ or $L$) elements (Fig. 14 d, e & f) represent the decussate mica (biotite-$IV$) crystals. The $S^\bot$ contour in
Fig. 14 d, e & f shows tendency to form complete girdle around b. This suggests that the platy mica were slightly subjected to folding.

The lack of any strong mica concentrations around $S_3$ poles confirms the textural observations (chapter 3) that there was very little recrystallisation during $F_2$ deformation and whenever there was recrystallisation, it is now superimposed on the earlier one. This is presumed because the angle between $S_2$ and $S_3$ is less than 20° and sometimes more.

The orientation pattern of biotite cleavages from granodiorite (Fig. 14 h) is almost identical to the pattern of orientation revealed by the quartzo-feldspathic gneiss and the mica schist. This might indicate that mica represents a pre-existing S-surface in the granodiorite.

From the above analysis, it becomes obvious that the strong maximum is mainly due to the platy mica (biotite) that defines the dominant $S_2$ foliation. This orientation also indicates that the growth of these platy mica is controlled by the active S-surfaces. Hence, the growth of most of the micas was syntectonic. The micas defining the $S_3$ post date the above platy micas (because of their cross-cutting relationship), that both these micas were deformed during the $F_3$ folding is evident from the bending, kinking, and buckling of the flakes normal to the $S_2$ foliation. However, this deformation was very mild and the recrystallisation is also not
so well marked. The decussate micas (biotite-IV) post date the platy micas (biotite-II) because they developed across the $S_2$ and $S_3$. That the crystallisation of this late mica outlasted even after the $F_3$ deformation is evident from its undeformed nature. Therefore, it can be suggested that the growth of the decussate mica (biotite-IV) might have occurred during the static conditions attained during the $F_3$ deformation.

The weak recrystallisation or absence of recrystallisation during $F_2$ and $F_3$ deformations indicates that mica might have played a passive role during these periods of deformation (Keppie, op. cit; Crampton, 1958, pp. 28-34; and Chatterjee, op. cit.).

The most important feature shown by this analysis is the coincidence of the girdle axes of mesoscopic fabric and the mica subfabric and thus they are homotactic (Turner and Weiss, 1963, p. 439). This also coincides with and lies on the maximum concentration of $L_1$. However, this coincidence is lacking with quartz subfabric (chapter 2-9B.5).

2-9B.4. Quartz subfabric: Quartz occurs in three varieties (Quartz-I, quartz-II and quartz-III) and varies from comparatively coarser to elongated and to almost polygonal medium-to fine grained (chapter 3).

In thin section, no other well defined orientation is shown by the quartz grains, except, at places an elongation parallel to $S_2$. The prominent orientation revealed by
the diagrams are related to S₂ (mica schist, Q.F.G. and B.Q.M.) and S₄ (granodiorite), orientation parallel to S₃ is rarely noticed. It is attempted here to correlate the growth of quartz in relation to a structural sequence and also to find out the affects of subsequent phases of deformation and metamorphism on them.

The data relating to the analysis and the sample locations are given in table No.4.

2-9B.5. Analysis and interpretations: Most of the quartz diagrams show well defined girdles with the most prominent lineation (L₁) as the girdle axes. Both the cleft and peripheral girdles are present. However, the cleft girdles are more pronounced than the peripheral girdles (Fig. 15 a-f, i & j). Figs. 15 h & g are characterised by peripheral maxima and absence of cleft girdles, whereas Fig. 15 e shows a combination of two great circle girdles intersecting at the periphery.

The diagrams Fig. 15 c-d & f are characterised by maximum VII, and Fig. 15 f is characterised by maximum i of Fairbairn (1949, p. 10, Fig. 2-1). In most of the diagrams (Fig. 15 a-i) the maxima and submaxima occur asymmetrically, lacking any strict plane of symmetry, indicating triclinic symmetry for the diagrams (Turner and Weiss, 1963, p. 233). But, one diagram from mica schist (Fig. 15 f) shows a pair of maxima in a cleft girdle.
of a radius of 75°; and also two other diagrams from B. J. M. (Fig. 15, g & h), show peripheral girdles each with a pair of maxima of near orthorhombic symmetry (Turner and Weiss, op. cit.).

The diagrams from granodiorite (Fig. 15, k & l) show well developed girdles indicating that quartz has crystallised mimicking the $S_2$ and $S_3$ planes of the quartzfeldspathic gneiss (Saha, 1959 a, p. 109).

The quartz c-axes of the blastomylonite (Fig. 15 b) develop a cleft girdle with a radius of 70°. The two maxima on the cleft girdle are symmetrically arranged on either side of the $S_2$, indicate a difference in orientation of the quartz axes with the host rock, mica schist, B. J. M. and granodiorite. This indicates that the quartz of the rock are the product of recrystallisation.

The above analysis reveals that the orientation pattern of quartz axes produces peripheral to cleft girdles and near orthorhombic to triclinic patterns. The mineral also shows orientation rarely in relation to $S_3$ and $S_5$ (Pl. VII) in addition to $S_2$ and $S_4$. This pattern of orientation is slightly different from those displayed by mesoscopic structures and mica-subfabrics (Fig. 12 & 14). Even in the same thin section (Fig. 15 d & 14 c), when quartz shows a triclinic pattern of symmetry, the mica subfabric exhibits higher symmetry. This may be due to the fact that even while micas were passive.
the quartz played an active role (recrystallisation) which outlasted the deformation ($F_3$), (cf. Keppie, op.cit., Frampton, op.cit., and Chatterjee, op.cit.). It is also no less conspicuous that the banded quartz magnetite rock and mica schist show quartz orientation which is strictly different from that of the host gneiss. This may possibly be due to the fact that the degree of recrystallisation of quartz in the former was less in comparison to the latter (quartz-feldspar gneiss) during $F_2$ and $F_3$ deformations. All these characteristics are, therefore, taken to indicate that the rocks of the area underwent repeated deformations, with alternating episodes of deformation and recrystallisation (Turner and Weiss, op.cit., p. 429).

2.10. DISCUSSION AND CONCLUSION:

The rocks of the area have revealed three phases of deformation which are referred to here as $F_1$, $F_2$ and $F_3$. At least five S-surfaces, $S_1$, $S_2$, $S_3$, $S_4$ and $S_5$; three linear elements (including minor fold axis) $L_1$, $L_2$ and $L_3$ and four sets of joints have been recognised.

These three phases of deformation, together with the effects of high grade of regional metamorphism (chapter 6) have made to the determination of the original structural forms of the rocks, difficult. However, the compositional layerings in the metamaterials and Q.F.G. are identified here as the earliest structure ($S_1$) of the complex, which might
have been the relics of the original bedded structures in a sedimentary rock complex, partially or even at places, wholly altered and obliterated by later folding and metamorphism.

The deformation of this $S_1$ (compositional layering) has resulted in the formation of $F_1$ folds. The main recognizable phase of this deformation ($F_1$) resulted in the development of axial planar foliation ($S_2$) and the lineation ($L_1$). The isoclinal folds ($F_1$) and lineation ($L_1$) are syntectonic (Turner and Weiss, 1963, p. 125, and cf. Bhattacharjee and Barua, 1970, pp. 1-8). The plots of planar ($S_2$) and linear elements ($L_1$) show non-coincidence with $S_2$ and the concentration of poles of $L_1$ (Fig. 12 and 13). This might be due to the affect of $F_2$ and $F_3$ deformations (Dash, 1969, pp. 347-374).

The metasedimentary bands (rocks) particularly the folded B.Q.M. show dislocation, deformation and destruction of either of the bands (Fig. 3 c, and Pl. V c), where the dislocation planes are always parallel to $S_2$. As the dislocated bands are arranged in the form of lenses or thin bands parallel to $S_2$, it is supposed that these planes were not only the planes of movement of the dislocation that dissected the bands in the B.Q.M., but they also acted as the planes of movement of the dissected parts. This together with the tendency, in certain cases, of the separated lenses or bands to arrange themselves in such a way so as to indicate their con-
tinuation in the form of folded structures, is taken to indicate that the compositional layerings in the B.N. and in the same sense in the other metamorphites also, were once continuous. Their dislocation and separation now become the product of tectonic disturbance and transposition (Kinny, 1966, and Turner and Weiss, 1963) caused during intense folding.

The similarity of structural elements in the rock units (table 5) and their strikewise extension/continuation are considered that the compositional layerings and the boundaries of the rock units were originally parallel or nearly so (cf. Bhattacharjee, 1968, p. 248, cf. Hopgood, 1960). It can also be supposed that as some of the rock units are of sedimentary origin, the bands of amphibolite and Q.F.G. are originally horizontal or nearly so and parallel or sub-parallel to sedimentary bands. The presence of axial planar foliation (S2) to isoclinal folds, and of dominant lineation indicates emplacement of amphibolite not later than early stages of deformation during which these structural elements were developed.

The main stress component during this phase of deformation (F1) was oriented NW-SE. Slight variation to N-E is indicated by the presence of small scale isoclinal folds that have ENE-E axes. This view is also corroborated by the statistical studies of planar and linear structures with their
concentration of poles (Fig. 12 and 13) consistent with a NW-SE stress field. The (001) of mica and (0001) of quartz which show their maxima corresponding to \( S_2 \) suggest the existence of the similar pattern of stress field. The presence of triclinic pattern of stress field is also indicated by the triclinic pattern of orientation of quartz c-axes, although, this shift of stress field most probably was due to imposition of \( F_3 \) on \( F_2 \) deformation.

During this (\( F_1 \)) folding minor shearing in the F.F.C. (Fig. 2 b and Pl. IV d) probably occurred and might have produced the shear planes parallel to \( S_2 \), elsewhere in the F.F.G. (chapter 2,-4B.2). This, of course, indicates a tectonic transport towards NE (cf. Dawes, op.cit.).

The \( F_1 \) phase of intense folding was followed by another phase of folding (\( F_2 \)). Associated planar and linear structures (Strain slip cleavages, \( S_3 \)) and linear elements (\( L_2 \)) were developed locally. Recrystallisation of mica corresponding to \( S_3 \) although wide spread but very weak. This weak recrystallisation is indicated by the lack of maxima corresponding to \( S_3 \) (Fig. 14, chapter 2,-9B.3). In accordance with the planar \( S_3 \) the recrystallisation of quartz was also weak (Fig. 15).

In the later half of this deformation and with the accession of potassium, the metasediments and Q.F.G. gave rise to granodiorite (chapter 6,-3C &-4C), where \( S_4 \) (minick
foliation) was developed almost parallel to the $S_2$ and $S_3$ planes. Quartz c-axis orientation (Fig. 15 k & e) indicates that the rock formed as a result of mimetic crystallisation of pre-existing rocks (Saha, op.cit.), that is, post tectonic in relation to $F_1$ and pre-tectonic in relation to $F_3$. The similar pattern of orientation is also indicated by the $(001)$ of mica, because the orientation of $(001)$ of mica does not reveal any difference in relation to $F_1$ deformation.

The main stress field component during this $F_2$ deformation might have acted from NW-SE. This is evident from (1) the trend of planar and linear structures of the $F_2$ deformation (chapter 2, -4B & -4C) (2) the angle between $S_2$ and $S_3$ which is about $20^\circ$ or sometimes more and (3) the absence of maxima corresponding to $S_3$ in the diagrams either of quartz c-axis or of $(001)$ of mica (Fig. 14 & 15).

At the end of the $F_2$ deformation, the rocks became non-plastic and consequently brittle (cf. Bhattacharjee, 1963, pp.31-60), Bhattacharjee, 1968, pp.235-264; Bhattacharjee, 1966, pp. 42-50, and Dawes, 1970, p.61) as shown by the presence of open folds, mylonitic bands and boudins. No planar structures can be recognised that are consistent macroscopically with this deformation. The rarely observed weak orientation of the quartz c-axes parallel to the axes of open folds indicates a tendency to develop a planar surface parallel to the axes of $F_3$ folds (Turner and Verhoogen, op.cit.).
Recrystallisation of mica is not indicated and whatever developed is post tectonic in relation to $F_3$ (cf. Keppie, op. cit.) because none of them show orientation parallel to the axial planes of $F_3$ folds (Fig. 14).

The orientation of quartz c-axes (Fig. 15) corresponding to the axial planes of $F_3$ folds and the plunge and trend of $\beta S_2$ (Fig. 12, chapter 2, 2-4E.1) indicate that the $F_3$ folds formed under a NE-SW compressive force.

Even after this deformation ($F_3$), the quartz shows strong recrystallisation. This is clearly shown by the quartz surfabric of a blastomylonite developed during $F_3$ deformation. This may be assumed that the quartz axes of the rock, after prolonged deformation might have tried to reorient themselves in a NEE-E direction (Fig. 15 i) during a late phase ($F_4$), although the presence of such a late phase deformation is an assumption.

A few quartz veins and pegmatite veins ($P_1$ and $P_2$) are seen to have developed in relation to $F_1$ and $F_2$ deformations (chapter 2, 2-7). The ptygmatic folds bear no relation to any of the deformational phases. These might have developed during the static conditions, attained after the plastic deformations ($F_1$ and $F_2$) synchronous with the development of the quartzo-feldspathic veins (chapter 2-5).

Although, cross joints, longitudinal joints and diagonal joints are related in their orientation, to the
structural elements of the $F_1$ deformation, still these were not affected by the $F_1$ and $F_2$ deformations. Therefore, these were thought to have originated during or at the beginning of the brittle deformation ($F_3$) (cf. Bhattacharjee, 1965, pp. 54-57, Turner from Price, 1966, p. 129, and Price, op. cit. and Saha 1959, p. 97). This view is quite conclusive as (1) no joint can develop during plastico-viscous deformation (Turner, see in Price, op. cit.), (2) joints are not affected by earlier $F_1$ and $F_2$ plastic deformations and (3) these are not filled up with pegmatitic matters. The horizontal sheetings are considered to have postdated all the other structural elements. Further evidences can be cited from the fact that these joints (horizontal sheetings) affect all the other rock types right from pre-cambrian to post Archaean dykes occurring in the area.

It becomes clear from the study of the different structural elements of the area that the rock types of the Pre-Cambrian of the Hahim area underwent alternate periods of deformation and recrystallisation.

The style and general characteristics of the folds indicate that the first two deformations were plastic to semiplastic, while the third one was brittle.
The sequence and style of the structural development of the rock types of the area are comparable to the Simultala area, Bihar, India (Bhattacharjee, 1966, pp. 42-50), Tariussaq area, south Greenland (Dawes, op. cit.) and different parts of the Lewisian rocks of Scotland (Bowes and Bhattacharjee, op. cit., Bhattacharjee, op. cit.; Dash, op. cit. and Choudhury, op. cit.).
### Table 1. Description of foliation diagram.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Locality</th>
<th>No. of readings</th>
<th>Concentration of maxima % per 1% area</th>
<th>Amount and direction of plunge of $\beta$</th>
<th>Contour % per 1 % area</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>Tutiabazar</td>
<td>100</td>
<td>9%</td>
<td>$80^\circ - 70^\circ$ \ S $20^\circ$ E</td>
<td>1-2-3-5-8 %</td>
</tr>
<tr>
<td>b.</td>
<td>Aradonga</td>
<td>200</td>
<td>11%</td>
<td>$80^\circ - 75^\circ$ \ S $60^\circ$ E</td>
<td>1-2-4-6-9 %</td>
</tr>
<tr>
<td>c.</td>
<td>Mawkhrangdubi</td>
<td>200</td>
<td>13%</td>
<td>$80^\circ - $ \ S $50^\circ$ E</td>
<td>1-3-6-9-12 %</td>
</tr>
<tr>
<td>d.</td>
<td>Lejadubi</td>
<td>100</td>
<td>10%</td>
<td>$80^\circ - 80^\circ$ \ S $75^\circ$ E</td>
<td>1-5-6-9-12 %</td>
</tr>
</tbody>
</table>

### Table 2. Description of lineation diagrams.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Locality</th>
<th>No. of readings</th>
<th>Concentration of maxima % per 1% area</th>
<th>Amount and direction of maxima</th>
<th>Contour % per 1 % area</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>Tutiabazar</td>
<td>100</td>
<td>9%</td>
<td>$60^\circ - 85^\circ$ \ N $70^\circ$ E</td>
<td>1-4-9 %</td>
</tr>
<tr>
<td>b.</td>
<td>Aradonga</td>
<td>150</td>
<td>11%</td>
<td>$60^\circ - 85^\circ$ \ N $55^\circ$ E</td>
<td>1-4-9(11) %</td>
</tr>
<tr>
<td>c.</td>
<td>Mawkhrangdubi</td>
<td>150</td>
<td>10%</td>
<td>$65^\circ - 85^\circ$ \ N $55^\circ$ E</td>
<td>1-4-9(10) %</td>
</tr>
<tr>
<td>d.</td>
<td>Lejadubi</td>
<td>100</td>
<td>6%</td>
<td>$75^\circ - 85^\circ$ \ N $50^\circ$ E</td>
<td>1-3-6 %</td>
</tr>
</tbody>
</table>
Table 3. Description of the joint diagrams.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Locality</th>
<th>No. of readings</th>
<th>Attitude of foliation ($S_2$)(average)</th>
<th>Trend of lineation ($L_1$) (average)</th>
<th>Sets of joint developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>11a.</td>
<td>Tutiabazar</td>
<td>200</td>
<td>85°/85° SE</td>
<td>85° NE</td>
<td>1. N 35° W - S 35° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 60° E - S 60° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 30° E - S 30° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. N 40° E - S 40° W</td>
</tr>
<tr>
<td>11b.</td>
<td>Ranighat</td>
<td>200</td>
<td>80°/80° SE</td>
<td>80° NE</td>
<td>1. N 30° W - S 30° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 70° E - S 70° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 30° W - S 80° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. N 40° S - S 40° W</td>
</tr>
<tr>
<td>11c.</td>
<td>Aradonga</td>
<td>200</td>
<td>60°/75° SE</td>
<td>60° NE</td>
<td>1. N 45° W - S 45° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 45° E - S 45° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 30° W - S 30° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. N 80° W - S 80° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5. N 15° E - S 15° W</td>
</tr>
<tr>
<td>11d.</td>
<td>Aradonga</td>
<td>200</td>
<td>70°/70° SE</td>
<td>70° NE</td>
<td>1. N 35° W - S 35° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 45° E - S 45° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 30° W - S 30° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. N 30° W - S 30° E</td>
</tr>
<tr>
<td>11e.</td>
<td>Mawkhrangdubi</td>
<td>280</td>
<td>70°/80° SE</td>
<td>70° NE</td>
<td>1. N 35° W - S 35° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 50° W - S 50° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 75° W - S 75° E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. N 30° W - S 30° E</td>
</tr>
<tr>
<td>11f.</td>
<td>Bandaraja</td>
<td>100</td>
<td>65°/70° SE</td>
<td>65° NE</td>
<td>1. N 35° W - S 35° E</td>
</tr>
<tr>
<td>Parbat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. N 65° E - S 65° W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. N 30° E - S 30° W</td>
</tr>
</tbody>
</table>

Table 5. Relation of structural elements of different rock units of the Hahim area.

<table>
<thead>
<tr>
<th>Type of structures</th>
<th>Metasediments</th>
<th>Metabasics</th>
<th>Q.F.G.</th>
<th>Granodiorite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P1 deformation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-deformation structure</td>
<td>Compositional layering</td>
<td>Banding</td>
<td>Banding</td>
<td>-</td>
</tr>
<tr>
<td>Isoclinal and associated folds</td>
<td>Common in B.Q.M.</td>
<td>-</td>
<td>Common</td>
<td>-</td>
</tr>
<tr>
<td>Planar structures associated with isoclinal folds</td>
<td>Well defined (Schistosity)</td>
<td>Well defined (foliation)</td>
<td>Well defined (foliation)</td>
<td>-</td>
</tr>
<tr>
<td>Linear structures</td>
<td>Mineral-, Intersection-, Fold axes- and rodded lineation</td>
<td>Mineral-, and rodded lineation.</td>
<td>Mineral-, Intersection-, Fold axes- and rodded lineation</td>
<td>-</td>
</tr>
<tr>
<td>Small scale folds (asymmetrical, monoclinal, and rare isoclinal)</td>
<td>Common in B.Q.M.</td>
<td>-</td>
<td>Common</td>
<td></td>
</tr>
<tr>
<td>Planar and linear structures</td>
<td>Present</td>
<td>Rare</td>
<td>Common</td>
<td>Weak foliation (mimick) represented by streaks and lenses of mafic bodies.</td>
</tr>
</tbody>
</table>

Almost all the rock types