CHAPTER 3

STRUCTURE

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3. STRUCTURE

3.A. Structural Elements

Planar Structure

(1) Bedding: Compositional bending can be recognised in the banded ferruginous chert/quartzite in which the individual bands of ferruginous matter and chert/quartzite range in thickness from fraction of a centimetre to a few centimetres. North of K.M. Kere village, red jasper bands alternate with ferruginous bands.

Banding can also be recognised in some of the slaty and argillaceous rocks interlayered with banded ferruginous quartzites and within some of the chlorite schists, generally associated with conglomerate horizons. Bending is defined by variation of colour. The thickness varies from less than a centimetre to a centimetre.

To the east of K.M. Kere village, at a few places, bedded tuffs have been observed where the bending is defined by variation in the grain size as well as in the concentration of the volcanic fragments within a matrix of chlorite schist (Fig. 2.5). These probably represent water-worked volcanic materials.

(2) Schistosity/Slaty cleavage: The most prominent schistosity/slaty cleavage in the area is parallel to the axial plane of the second phase folds and is generally oblique to the
bedding (Fig. 3.1). Under microscope, this regional second phase structure displays a domainal fabric, that is, this is composed of small lenticular silica rich domains surrounded or separated by dark lines/films (Fig. 3.2). The lenticular domains include both matrix of the rock and clastic grains, aggregates of grains and volcanic lapilli, and are composed dominantly of cryptocrystalline aggregates of quartz with phyllosilicates mixed in various proportions. The dark lines/films are of ferruginous material and/or of chlorite, sericite and biotite. Usually there is no preferred orientation of the grains within the lenticular domains, that is, neither the quartz grains are flattened nor do the phyllosilicates show a parallel arrangement. However, in strongly deformed volcanic lapilli, the phyllosilicates within the lapilli show a preferred orientation parallel to the schistosity defined by the micaceous films (Fig. 3.3). The dark lines or films curving round the lenticles probably represent solution planes.

In some schistose rocks, this domainal fabric is absent and the phyllosilicates show a strong preferred orientation defining an uniformly developed schistosity (Fig. 3.4).

In some silica bands within the banded ferruginous quartzite and also in silica rich bands of some slaty rocks, the second phase planar fabric is represented by dimensional preferred orientation of flattened quartz grains, at low angles to the bedding (Fig. 3.5).

The first phase planar fabric is rarely preserved in the rocks and when present, it is defined by preferred orientation
of phyllosilicates while the second phase planar fabric takes the form of crenulation cleavage (Fig. 3.6). The anastomosing dark lines/films representing solution planes, in such cases, are parallel to the axial planes of the minute crenulations. This is best illustrated in Figure 3.7 where alternate quartz-rich and mica-rich layers form a second phase fold. In the mica-rich layer, the parallel arrangement of mica flakes define the first phase schistosity, while the second cleavage, which is axial planar to the fold, has crenulated the schistosity; in the quartz-rich layer, the first fabric is absent and the second cleavage forms discrete planes separated by bands of flattened quartz grains.

In some slates and argillites, an alignment of the phyllosilicates parallel to the lamination is found, which probably represents a first phase planar fabric though the possibility of its being a primary depositional feature (001) of the clastic grains of phyllosilicates lying on the depositional plane cannot be ruled out.

The regional schistosity/cleavage represents the XY (X > Y > Z) plane of the strain ellipsoid rather than a plane of shear. It is axial planar to the second phase folds and these second folds, as will be discussed later, are of flexural type modified by flattening and are indicative of shortening perpendicular to the axial plane. Therefore, the schistosity, being parallel to the second phase axial plane, represents development normal to $\lambda_3$. 
The shortening perpendicular to the schistosity is evidenced from other observations also. The lapilli in the basic volcanics are, at places, deformed with the longest and intermediate axes lying on the schistosity plane. If the schistosity represented a plane of shear strain, the long axes of the ellipsoids would be at an angle to the schistosity. The flattening perpendicular to the schistosity is also indicated by similar other observations, viz., elliptical prophyroblasts of quartz with the longest axes lying on the plane of schistosity; flattening of quartz grains in some silica bands parallel to the axial plane of the second phase fold as well as in the direction of slaty cleavage (second phase); highly strained clastic quartz grains with development of deformation banding sub-parallel to the schistosity (Fig. 3.8).

The curved schistosity/cleavage surfaces (represented by fine dark lines/films of pressure solution plane curving around lenticular domains of matrix material as well as deformed volcanic lapilli and clastic grains) indicate variations of strain parameters on a microscopic scale (cf. Ramsay, 1967, p.181). The variation of the volcanic lapilli from undeformed, nearly spherical type to strongly deformed ellipsoidal type indicates inhomogeneity of strain on mesoscopic scale.

The pressure solution planes in the matrix occasionally straightway pass into the clastic or volcano-clastic fragments without any change in orientation (Fig. 3.9). This suggests that the fragments have not undergone any rotation relative to the matrix because in that case the pressure solution planes would
assume sigmoidal form near their passage from the matrix into the fragments.

The pressure shadows (the pressure 'fringes' according to the nomenclature of Spry, 1969, p. 240 - 247) filled with straight fibrous mineral growth against euhedral pyrite cubes, not only indicate flattening perpendicular to the schistosity but also suggest a non-rotational pattern of strain during flattening. The pyrite crystals within the chlorite schists acted as mechanically rigid grains (due to the higher competency than the matrix) during flattening and uneven strains were set up around the crystals. As a result, the matrix pulled away from the crystals in the direction of maximum elongation sheltering a low pressure region (the pressure shadow zone) around the crystals. Silica from the neighbouring matrix migrated to the shadow zones and grew in the fillings in fibrous habit facing the direction of maximum elongation (Durney and Ramsay, 1973). The fibres are oriented perpendicular to the crystal faces of pyrite cubes, and, therefore, are not parallel to the extension-direction (i.e., schistosity trend), except in the special case where the crystal face of pyrite is perpendicular to the extension-direction (Fig. 3.10). Here the fibres do not grow on the faces parallel to the schistosity as the direction of maximum compression acts perpendicular to the face. On the other pair of faces, fibres develop as the direction of fibre-growth is perpendicular to the compression direction. If both the pairs of faces are at angles to the extension direction, fibres grow on both pairs of faces and as a result two domains of fibre-orientation are formed on each side of the shadow zone (Figs. 3.11 & 3.12). The partition line of the two domains is
parallel to the schistosity. The fibre-growth, on the face which is at low angle to the schistosity, is usually narrow or partial and smaller in length compared to that in the other face lying at high angles to the schistosity (Fig. 3.11). Thus the fibre-growth on the two sides of partition line is asymmetrical here. But if the crystal faces of the cube are at 45° with the schistosity, the fibre-growth is usually symmetrical on either side of the partition line (Fig 3.12). In all cases, however, the partition line is parallel to the schistosity. The straight nature of the fibres as well as the straight partition line suggest co-axial deformation path (non-rotational) during second phase strain. If the principal incremental elongation had changing orientations, the fibres and the partition line would have been of sygnoidal shape.

(3) Crenulation Cleavage: These are discrete planes that separate portions of puckered schistose rocks. Usually the crenulation cleavage is parallel to the axial plane of the puckers of third phase on the second schistosity. At many places conjugate sets are present. As has been mentioned above, the second phase planar structure also has rarely the appearance of crenulation cleavage.

(4) Fracture Cleavage/Close spaced joints: These are close spaced, discrete, parallel fractures or joints and are found in the slaty rocks and banded ferruginous quartzites (Figs. 3.48 to 3.51). Usually these are parallel to the axial planes of the second and third phase folds. On the hinges of the folds, they commonly show a radial arrangement (fanning).
(5) Axial planes of folds: These are geometrical planes and in many rock types, no penetrative planar structure has developed parallel to them. Because of the polycrinal nature of folding in the banded ferruginous quartzite, the axial planes of the minor folds show variation in attitude and are not always strictly parallel to the axial planes of lower order folds with which they are associated. However, a broad regularity in orientation is always observed.

The dip of the axial plane is generally very steep and as a result, reversals in the direction of dip are frequent while the strike-direction remains more or less the same.

Linear Structure

(1) Minor fold axes: Minor folds related to the first, second and third phases of deformation are common. In banded ferruginous quartzite, minor folds include folds with wave length varying from the scale of outcrop-size to as small as 0.3 cm. and small puckers appearing as fine ribbings on the bedding plane. Folds of larger wave-length generally have the same attitude as the minor folds on their limbs, though occasionally a divergence is noted. Amplitude also varies and as a result the folds belonging to the same phase may show different shapes from very gentle warps (low amplitude-wave length ratio) to very tight folds (high amplitude-wave length ratio) (Figs. 3.13 & 3.14).

Except on the hinges of larger folds, the minor folds show distinct asymmetry in the length of their limbs and the folds are dextral (or Z-shaped, that is, right hand shift of the limbs of the folds) or sinistral (or S-shaped, left hand shift of the long
limbs). On the hinges of the larger folds, the minor folds are symmetrical or M-shapod.

Puckers on the schistosity are found throughout the area but are more strongly developed south of Ingaldhal and west of Kasavanahalu. Intersecting sets of puckers are also found at a place east of Kasavanahalu.

(2) Striping: This results from an intersection of the compositional bands on the schistosity surface and is found in some argillites and slaty rocks. These are usually parallel to the fold axes of second phase.

(3) Elongation of deformed lapilli: At places the original spherical lapilli are strongly deformed into ellipsoidal shape, the long axis of which show a preferred orientation on the schistosity surface and this defines a lineation (Fig. 3.15). This is related to the second phase deformation.

(4) Ribbing (Micro-mullion): These are micro-corrugations on the bedding surface of banded ferruginous quartzites and are mostly found on the western limb of the Chitradurga Fold. Usually these have a down dip or very steep plunging orientation, similar to the axes of the second phase minor folds and therefore probably belong to the second phase deformation.

The following two features distinguish these ribblings from the first phase linear structure:

(a) The first phase fold axes usually have low to moderate values of plunge whereas these ribblings are steeply plunging.
(b) The first phase fold axes usually trend sub-parallel to the regional strike of the bedding. But these ribbings are usually along the dip direction of the beds or are at high angles to the bedding strike.

Locally these ribbings are found to be refolded by second phase warps or folds. For these reasons, these can be regarded as belonging to the earlier stage of second phase deformation. These were refolded by larger folds belonging to the later stage of second phase deformation. Evidence in support of the idea that the smaller folds have developed earlier and larger folds later during progressive deformation is presented in a later section Sec 3 F (i).
3. B. General Outcrop Pattern

Two sub-parallel hill ranges formed by banded ferruginous quartzite clearly define a U-shaped closure (Plate 1). The swing in strike of bedding plane of the banded ferruginous rocks confirms this U-shaped structure as a broad southerly closing fold (Plate 5). This is the largest mapable fold in this region, and, as will be discussed later, this fold is a second phase structure. In the north-eastern corner of the map (Plate 1) another hill range of banded ferruginous rocks trends north-south; its southern continuation beyond Kallehadlu has not been mapped by the present author. But it is apparent from the earlier geological maps of this area (Sampat Iyengar, 1905, plate III; Smeeth, 1915, Geological Map of Mysore; Naqvi, 1973, Fig. 1; see also Figs. 1.2 & 1.3 of the present text) as well as from the aerial photographs that this band continues southward with north-south trend.
3. C. Structural History and Interference

Pattern of Different Fold Phases

Careful investigation of the geometry of the folds and the inter-relation among the different structural elements reveal the existence of three principal phases of deformation in the area. Evidence of superposition of the different fold phases comes from the following lines:

(a) Relation between the major and minor folds:

The largest fold in the area is a southerly closing fold (the Chitradurga Fold) with north-northwesterly trending axial plane. Schistosity and slaty cleavage as well as a group of minor folds in the banded ferruginous quartzite are congruous with it. Besides these congruous minor folds, there are some other minor folds whose axial planes are parallel to the general attitude of the bedding at the point of observation. When the attitudes of these axial planes are plotted on the map, they are seen to be folded by the major fold (Plate 7). Therefore, these minor folds belong to an earlier phase of deformation - the first phase \(F_1\). On the other hand, the axial planes of still another set of folds cut across the major fold (Plate 7). Therefore, these belong to the third phase of deformation \(F_3\) post-dating the formation of the major fold. The late folds are generally incongruous on both the limbs of the major fold. These have developed on northeast-southwest to east-west trending axial planes on the eastern limbs and west-northwest — east-southeast trending axial planes on the
western limb of the Chitradurga Fold. These two trends form a conjugate set and sometimes both the trends can be observed at the same spot.

(b) Interference pattern on mesoscopic scale:

(i) Hook-shaped pattern: This is the simplest type of interference pattern observed in the area (Figs. 3.16 to 3.22). As discussed by Ramsay (1967), such patterns are produced when early and late axes are parallel or at low angles to one another, the early axial plane is bent and the early hinge line intersects the surface of observation only once. If the early axis happens to intersect twice the surface of observation, the pattern will be crescent shaped and will be discussed later. When a number of axial traces of early and late phases are involved in the interference and the relative scale of the two phases are nearly same, patterns as in Figure 3.23 are produced, in which, a late S-shaped fold (of second phase) has been superimposed on early Z-shaped fold (of first phase).

In the present area, when hook patterns are produced by interference between the first and second phases, the second phase fold is characterised by parallelism of its axial plane (and associated fracture cleavage at places) with the schistosity or cleavage in the argillites and this planar structure shows congruous relationship with the major fold. When the interference is between the second and third phase folds, the later fold is identified as a third phase structure by parallelism of its axial
plane with the strain-slip or crenulation cleavage in the neighbouring schists and by its incongruous relationship with the major fold. In such second and third phase interference patterns, the early fold is commonly identified as belonging to the second phase on the basis of several criteria, viz., style of the fold, congruous relationship with the major fold, general orientation of the axial plane etc. However, the possibility of some of the earlier folds as belonging to the first phase instead of second cannot be totally ruled out.

Interference pattern of this type between first, second and third phase folds and the congruous/incongruous relation of the folds in relation to the major fold is schematically shown in Figure 3.25. On the western limb, S-shaped folds are congruous $F_2$ and Z-shaped folds are incongruous $F_3$. $F_1$ has no definite shape. So in the interference pattern on the western limb, if the late fold is S-shaped, we can conclude that to be an interference between $F_1$ and $F_2$ (Figs. 3.26, 3.27 & 3.28). If the late fold is Z-shaped, it is an interference involving $F_3$ and either $F_1$ or $F_2$; if in these examples the early fold is Z-shaped (i.e. incongruous with the $F_2$ fold) it is an interference between $F_1$ and $F_3$; if it is S-shaped, the early fold may be either $F_1$ or $F_2$ (Fig. 3.21) and in such instances criteria other than the shape of the fold are to be used (see section 3.D) to identify the early fold as $F_1$ or $F_2$. On the eastern limb congruous $F_2$ folds have Z-shape while incongruous $F_3$ folds are S-shaped. So, here, in the interference pattern, if the late fold is Z-shaped, it is between $F_1$
and $F_2$ (Fig. 3.29). If the late fold is S-shaped (i.e. $F_3$ fold) and the early fold is also S-shaped it is between $F_1$ and $F_3$, but when the early fold is Z-shaped it is between $F_3$ and either $F_1$ or $F_2$. On the hinge zone, the shapes of the folds by themselves do not have much significance in identifying the particular phases of interference pattern. In many instances, a single early fold has been affected by a pair of asymmetrical late folds. The shape of the late fold, its congruous - incongruous relation with the $F_2$-structure and its style may identify the fold-phases involved in the interference pattern. For example, in Figure 3.24, a tight, low-plunging antiform has been refolded by a late S-shaped fold on the eastern limb of the Chitradurga Fold. Since S-shaped fold is incongruous on the eastern limb, the late fold is $F_3$. The tight nature and low plunge of the early fold suggest the early fold to be a $F_1$ structure. So the interference is between $F_1$ and $F_3$. The interference pattern in Fig. 3.30 shows an early fold refolded by late S-shaped fold. It is located on the western limb of a broad southerly closing $F_2$-warp from the hinge-zone of the major fold (the warp is shown in Fig. 3.63). So the late fold is a congruous $F_2$-structure, and the interference is between $F_1$ and $F_2$. The above relations of the fold shapes in the interference patterns on the different limbs of the major fold are shown in Table 3.1.
Table 3.1
Relation of the fold-shape with different phases of interference pattern on the two limbs of major fold.

<table>
<thead>
<tr>
<th>Western limb</th>
<th>Early fold</th>
<th>Interference between</th>
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<tbody>
<tr>
<td>Late fold</td>
<td></td>
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<tr>
<td>S-shaped</td>
<td>Any shape</td>
<td>$F_2$ and $F_1$</td>
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<tr>
<td>Z-shaped</td>
<td>Z-shaped</td>
<td>$F_3$ and $F_1$</td>
</tr>
<tr>
<td>Z-shaped</td>
<td>S-shaped</td>
<td>$F_3$ and $F_1 / F_2$</td>
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<table>
<thead>
<tr>
<th>Eastern limb</th>
<th>Early fold</th>
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</tr>
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<td>Any shape</td>
<td>$F_2$ and $F_1$</td>
</tr>
<tr>
<td>S-shaped</td>
<td>S-shaped</td>
<td>$F_3$ and $F_1$</td>
</tr>
<tr>
<td>S-shaped</td>
<td>Z-shaped</td>
<td>$F_3$ and $F_1 / F_2$</td>
</tr>
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</table>

(ii) "Eyed folds" and crescent-shaped pattern: In the present area, small "eyed folds" or completely closed elliptical structures have been found only at a few localities (Figs. 3.31, 3.32 and 3.33). These "eyes" are closely associated with tight to isoclinal $F_1$-structures and the long axes of the ellipses are parallel to the bedding as well as the $F_1$-axial traces. These suggest that the "eyed folds" belong to the first phase of deformation. The regional $F_2$-trend is oblique to the long axes of the ellipses. However, no later folds occur on the limbs of the "eyes".

Ramsay (1962) has explained the formation of similar "eyes" on a model of later shear folding. But in the present area, the mechanism of folding is flexural accompanied by considerable
(iii) Other types of interference pattern:

In many instances, hook shaped patterns have not been produced, though the geometric conditions are satisfied, because of much difference in the scale of folds of the two phases involved in the interference. If the scale of the early fold is much smaller than that of the late fold, the whole series of early folds will be refolded by the late fold and will show incongruous relation on one limb of the latter. Figure 3.36 shows the example in which a series of small early S-shaped folds has been refolded by a relatively large late S-shaped fold. On the long limb of the large S-shaped fold, the early smaller S-shaped folds appear to have a congruous relation but on the short limb incongruous nature of these folds becomes evident. The late S-shaped fold in this example belongs to the second phase, as indicated by the parallelism of its axial plane with the second phase schistosity. The smaller folds probably belong to the first phase. But since both have the same form of asymmetry (sinistral or S-shaped) the possibility of their formation during early and late stages of a continuous deformation cannot be altogether ruled out.

If the early fold is much larger than the late folds, the latter will fold the planar limbs of early fold only and will show incongruous relation on one limb. Figs. 3.37 to 3.45 show several examples of later incongruous minor folds occurring on the limb of a relatively large early fold.
At a locality on the southern ferruginous band, a little south of 3778 peak, (sector 3 in Plate 6) folds of all the three phases have been observed in a single exposure. On the limb of a (macroscopic) second phase fold, there is a mesoscopic fold of first phase whose limbs and axial plane are sub-parallel to the bedding (Figure 3.46). On both the limbs of this first phase fold are found incongruous minor folds; one has north-northwesterly trending axial plane and is congruous with the larger second phase fold; the other has east-northeasterly trending axial plane and belongs to the third phase.

It is interesting to note that in spite of polyphase deformation and the presence of minor folds belonging to each individual phase, refolded folds in mesoscopic scale is relatively scarce. Minor folds of the second and third phases have usually developed where the bedding has a general planar attitude. In other instances the later folds have affected only the individual limbs of earlier folds, i.e. they are also confined within domains of planar bedding (Figs. 3.37 to 3.45). In the opinion of the author, this can be attributed to the dominantly flexural mechanism of the folding and also to certain mechanical behaviour of the rock under the given environment of deformation. As will be discussed later (see Section 3.6), the geometry of the folds suggests that the rocks were folded in an environment where the overall ductility of the rock was low and the viscosity contrast between the layers was high (cf. Donath and Parker, 1964).
Fig 3.46 Macroscopic M-shaped fold of second phase (sector 3) and occurrence of folds of all the three phases in a single exposure on one of its limb.

Fig 3.47 Sketch from a field photograph showing NNE'ly trending set of conjugate pair of strain-slip cleavage (third phase) has been folded by WNW'ly trending set of the pair.
In superposed folding, unless the early fold is isoclinal, the late axes would have different orientations on the two limbs of the former. Hence if the later fold is flexural, the loci of a deformed line parallel to the early fold axis would be represented by two different small circles on the two limbs of the early fold. This geometrical condition can be satisfied only if sliding occurs along the axial surface of the early fold (Ramsay, 1967). If the strength of the rock prevents such rupturing, it becomes difficult to refold both the limbs together by a later fold. However, the problem does not arise if the late fold affects only the limb of the early fold (Mukhopadhyay, 1965b).

Theoretical considerations help to explain why it is difficult to refold an earlier fold by a later buckling. As is well known for an elastic strip, the following relation holds:

\[ p = BI \left( \frac{2 \pi}{L} \right)^2 \]

where \( p \) = force to buckle, \( B \) = elastic modulus of the material, \( I \) = moment of inertia and \( L \) = wave length of the buckle-ed fold. Now if the plate is previously buckled on a transverse axis, the cross-section has a sinusoidal shape and the moment of inertia of such sinusoidal section is greater than that for a rectangular section; hence the force necessary to cause buckling also increases. It is a common experience that to buckle a thin sheet, requires much less force than to buckle a sheet corrugated on a transverse axis. Therefore it is apparent that in flexural refolding it is
easier to fold only the planar part of a limb of an early fold than to fold together both the limbs. So in regions where the mechanism of late folding is essentially flexural, refolded fold is expected to be infrequent, except where the earlier folds are isoclinal making the bedding effectively planar in these domains.

The question of relative scale of the early and late folds is also important. If the early folds are very small, the beds behave effectively as a planar bedding during late buckling and earlier small folds, behaving essentially as lineations, get refolded. On the other hand, if the early folds are larger than the late folds, the late folds affect only the limbs of the early folds which are essentially planar surfaces (Nukhopedhyay, 1965b).

(c) Relation of the schistosity / slaty cleavage with the major and minor folds:

The schistosity and the slaty cleavage in the schists, argillites and slaty rocks are congruous with the second phase major fold. It is parallel or sub-parallel to the axial planes of the second phase minor folds. This is seen to cut across the early folds (Figs. 3.48 to 3.51). Subsequently during the third phase of deformation, the schistosity has been folded into smaller folds and pucker with development of a strain slip/crenulation cleavage. The third phase has been developed along two conjugate planes having (i) north-northeast/east-northeast trend and (ii) west-northwest trend. East of Kasarmahalli village, the north-northeast trending strain-slip cleavage has been folded on west-northwest trending axial plane (Fig. 3.47). This suggests a small time gap between the two component planes of the conjugate set.
Interference patterns between folds of different phases are not frequently observed and the task of assigning a minor fold to a particular phase often presents a serious problem. At some places, fracture cleavages or close spaced joints having an attitude parallel to the general trend of $F_2$ axial plane cut across both the limbs of minor folds (Figs. 3.48 to 3.51). This indicates that these minor folds belong to $F_1$-phase. However, if such cleavage is related to $F_2$-deformation, the problem arises whether to assign the minor folds to $F_1$ or $F_2$.

The criteria which have been used for assigning an individual fold to a particular phase are, the shape of the minor folds and their congruous-incongruous relationship with the major Chitradurga Fold or with the higher order folds related to this major structure, their styles, the attitudes of the axial planes and the axes.

First phase folds generally have the following characteristics

(i) Tight to isoclinal nature
(ii) Sub-parallelism of the axial planes with the general attitude of the bedding
(iii) Low wave-length/amplitude ratio.
(iv) Commonly low to moderate plunge of the axes.

Figures 3.52 and 3.53 show mesoscopic $M$-folds on the western
limb of the Chitradurga fold and their tight to isoclinal nature, sub-parallelism of the axial planes with the bedding and low plunge of the fold-axes suggest these to be first phase folds. However, any one of these characters individually or by itself is not a sufficient criterion to assign a fold to the first phase, e.g. a first-phase fold might have a steep plunge or locally an isoclinal fold may belong to the second phase (Fig. 3.54). But if all these features are considered in combination, a relatively reliable identification of the first folds can generally be made.

The second phase folds can be identified by their congruous relation with respect to the major Chitradurga Fold (i.e. Z-shaped on the eastern limb, S-shaped on the western limb and H-shaped on the hinge), north-northwest to northwesterly trend of the axial planes and parallelism of the axial planes with the schistosity in the neighbouring schists and argillites. On the eastern limb of the Chitradurga Fold, axial planes of the congruous F₂ folds are at a very small angle to the bedding and the folds usually have moderate (30° - 60°) plunges (Fig. 3.55). On this limb it is often difficult to separate the folds of the first phase from those of the second.

The third phase folds are developed only on mesoscopic scale. On the eastern limb, the general trend of the axial planes of the F₃ folds varies from northeast-southwest to east-west; the folds are S-shaped and are incongruous in contrast to the general Z-shape of the F₂ minor folds on this limb. Thus the third phase folds are distinguished by their attitude of the axial plane,
incongruous shape and steep plunge. On the western limb, the axial plane of the F3 folds have west-northwest - east-southeast trend and the folds are Z-shaped, incongruous with the S-shaped F2 folds.

On the eastern limb of the major fold, the incongruous S-shaped folds are either F1 or F3. In such cases, the attitude of the axial plane and axis help in differentiating them. For example, many of the large S-shaped folds on the eastern limb of the major fold have been identified as F1 because of their low plunge (usually towards north) and small angle between the attitude of their axial plane and the general bedding trend (Figs. 3.56 and 3.57). The S-shaped fold of F3-deformation, on the other hand, have usually steep plunge and northeast-southwest to east-west trending axial plane; these are also of more open type (Fig. 3.58). At places, where the F3 axial plane happens to be nearly at right angles to the bedding-trend, the F3-folds are broad warps or M-shaped folds (Fig. 3.59) instead of being S-shaped.

On the western limb, the incongruous Z-shaped folds are either F1 or F3. The attitude of the axial plane itself or the angle between the bedding and axial plane trend is not of much use in distinguishing between the F1 and F3 in this part because the general bedding has northwest-southeast trend and the F3 axial plane also has the general trend of west-northwest - east-southeast. Hence, the F1 axial plane trend is nearly parallel to F3-trend. However, tight nature, angular hinge, low asymmetry index (ratio between the length of long limb and short limb) suggest that many of the incongruous Z-shaped folds belong to F1 rather than F3.
(Fig. 3.60). The Z-shaped \( F_3 \)-folds are more open with sub-rounded hinge and higher asymmetry index (long limb is much larger than the short limb) (Fig. 3.61). The S-shaped folds on the western limb are either congruous \( F_2 \) or \( F_1 \); \( F_1 \)-folds have axial planes parallel or sub-parallel to the bedding at the place of observation while \( F_2 \)-folds have axial planes at moderate angles to the bedding at that locality. Also the \( F_1 \) folds are more tight, more angular at the hinge and have lower asymmetry index than \( F_2 \)-folds.

On the hinge zone of the Chitradurga Fold, the \( F_3 \) axial planes have north-northeasterly and west-northwesterly trend and depending on the relative attitude of the bedding and the axial planes, the folds are Z- or S-shaped or symmetrical warps. Therefore, here, the trend of the axial planes distinguishes the folds of third phase from those of the first or second phase.

On the western end of the hinge zone of Chitradurga Fold (east of Kasavanahalli village, southern part of sector 11 in Plate 6), pelitic schists show development of strain-slip cleavage (belonging to the third phase) along two conjugate planes - north-northeasterly and east-southeasterly. It is possible that in the banded ferruginous rock along with the principal east-southeasterly trend of the \( F_3 \) axial planes, the north-northeasterly trending folds of the conjugate set have also developed. But in the absence of refolding relation, these cannot be distinguished from the second phase folds as they both have similar shape (sinistral or S-shaped) and the orientation of the axial plane of the two are also close to one another. Hence, some
of the folds from this sector assigned as \( F_2 \) folds in Plates 3 & 4 and in Figs. 3.72(v) & 3.76(iii) may actually belong to the third phase.

On the hinge-zone of the Chitradurga Fold, the trend of the \( F_3 \) axial planes, as has already been stated, range from north-northeast - south-southwest to east-southeast - west-northwest whereas the range in trend of \( F_2 \) axial planes is between northwest - southeast to about north - east - 15° east - south 15° west. Hence, here also, because of fairly wide range in the orientation of the axial planes of the minor folds of each phase in the banded ferruginous rock, in the absence of other decisive factors (e.g. refolded relation) it is difficult to assign a fold to a particular phase on the basis of orientation of the axial plane alone.
3. E. General structural pattern

The most prominent macroscopic structure in the area is the large southerly closing fold (the Chitradurga Fold) clearly defined by the two ferruginous quartzite bands. The Chitradurga Fold with its very broad rounded hinge zone can be termed as a vertical fold because of its subvertical axis (on the hinge zone) and axial plane. In between the two bands of ferruginous quartzite and to the north of the northern ferruginous band occur the basic volcanics which have also suffered deformation and have acquired the north-northwesterly trending schistosity (the "Darwarian strike").

Compared to the southern band, the northern band has a much smaller extent along the strike. It starts from about 2 miles southwest of K.M. Kere village with a northeast-southwest trend and finally swings to the west-northwest - east-southeast direction on the western limb of the fold. The southern band starts from south of Ingaldhal village with a general north 15° east-south 15° west strike and passes southward through K.M. Kere and Kallchadi village south of which it takes a gradual swing towards south-southwest, southwest and then west-southwest and finally shows, from south of Kakkeharavu village, a northeast-southwest strike which continues to the east of Banjagondanahalli village.

On this Chitradurga Fold, there are smaller macroscopic folds which are congruous with the larger fold and belong to the same phase. These are asymmetrical (Z-shaped or S-shaped) on the limbs. Thus on the macroscopic scale, the eastern limb shows a few gentle dextral swings (Z-shaped) of the bedding strike (second order folds, Ramsay, 1967, p. 355). Gentle to open asymmetrical warps and close
symmetrical folds are present on the hinge zone and open to close sinistral folds (S-shaped) on the western limb. This generalised pattern, of course, gets more complicated when viewed in more detail due to the development of folds of still higher order.

The hinge zone of the southern band (southern part of sector 1, sector 6 and eastern part of sector 7 in Plate 6) shows moderately open M-shaped folds with three southerly closing antiformal hinges and the complementary synforms (Fig. 3.62). These folds are disharmonic in nature and the inner part of this band shows M-shaped folds of much smaller wave-length. A ferruginous argillite layer intervenes between these two parts of the quartzite band and this incompetent material probably facilitated the ferruginous quartzite layers in the two parts to fold independently of one another.

Further westward (western part of sector 7 and eastern most part of sector 10, plate 6) the strike of the enveloping surface on the third order folds changes from east-northeast - west-southwest to west-northwest - east-southeast direction and this defines the second order warps on the hinge region of the Chitradurga Fold (Fig. 3.63). The third order folds are symmetrical and of two types; on the inner side of the band (i.e., towards the centre of curvature) the folds are tight and have low ratio of wave length/amplitude; on the outer side, these are more open, have relatively high wave length/amplitude ratio and are often polyclinal with wide hinge zone; often they show negative interlimb angles (Ramsay, 1967, p.349). Because of the presence of these minor folds,
where continuous exposures are absent, a bewildering variability of the strike-directions can be observed within a small area.

The area to the west of the hinge (sector 10 excepting the eastern most part, in Plate 6) shows a sinistral pair of fold. The northwesterly closing hinge of this pair displays a number of close to tight folds with low wave length/amplitude ratio. The continuity of the beds is lost across the hinge of the southeasterly closing fold.

Further to the west, on the western limb (sector 11 in Plate 6) there is another sinistral fold pair. On the middle limb of this pair, the outcrops are detached from one another which may be due to faulting or tearing apart of the beds as a result of stretching parallel to the axial plane of the folds. A number of small \( M \)-shaped folds characterises the hinge zone of the southerly closing fold of this pair.

Compared to the southern ferruginous band, the northern band has fewer higher order macroscopic folds and the map-pattern shows gentle undulations of strike-direction both on the limbs and on the hinge (Plate 6); however, the inner part of the band on the hinge zone shows a sinistral fold pair with west-northwesterly trending axial trace (Sector 8 in Plate 6).

Thus the macroscopic fold pattern on the Chitradurga Fold immediately reveals the disharmonic nature of the folding. As already described, such disharmonic nature is present also on the
hinge zone of the southern band itself (southern part of sector 1, sector 6 and eastern part of sector 7 in Plate 6 and Fig. 3,62). The basic volcanics in between the two ferruginous bands behaved as incompetent material and facilitated independent folding of the two ferruginous bands on either side of it.

Earlier phase mesoscopic folds are present nearly all over the area in the two ferruginous bands, but there is no unequivocal direct evidence (such as change in the shape-asymmetry of the minor folds, or reversal in the direction of younging) to establish the presence of any major fold. On the western extremity of the southern ferruginous quartzite band, a tight U-shaped ridge is seen which might lead one to suspect the presence of an early major fold closure at that locality. But a close investigation reveals that here two parallel bands are present which are not connected with one another. However, most of the relatively large mesoscopic folds of this region (sector 13 in Plate 6) probably belong to the first phase. Near the western termination of the northern band also, a good number of relatively large, first phase mesoscopic folds are seen.
3. F. Macroscopic Structural Geometry

(i) Bedding plane

For geometrical analysis of the structural data, the area has been divided into 13 sectors (Plate 6) on the basis of homogeneity of the pattern of bedding plane ($S_0$) poles on equal area projection diagrams. Initially the sub-division was made from a visual inspection of the structural data into very small sectors and where neighbouring sectors showed similar patterns, they have been combined together. An initial sector showing irregular distribution pattern was further subdivided to get a regular pattern. The structural patterns in the different sectors are shown in Figure 3.64 and described in Table 3.2.

From the projection diagrams, it is seen that on the eastern limb of the Chitradurga Fold (sector 1), there is a spread of $S_0$-pole on two girdles (Fig. 3.64(i) and Table 3.2). One has northern inclination and the other is peripheral. The northerly inclined girdle indicates the presence of southerly plunging folds. Since the mesoscopic and macroscopic folds congruous with the Chitradurga Fold also show a dominant southerly plunge in this area (Plates 4 & 8) the southerly plunging $\beta$ is taken to represent the second phase of deformation. The peripheral girdle reflects gentle warps of the beds on sub-vertical axes ($\beta'$). On the eastern limb of the Chitradurga Fold, the third phase minor folds with sub-vertical east-northeasterly to east-southeasterly trending axial planes and steep to sub-vertical axes have been
Fig 3.62 Detailed trend map of bedding on the hinge zone of southern b.f.q. band (southern part of sector 1, sector 6 and eastern part of sector 7) showing moderately open M-shaped folds.

Fig 3.63 Detailed trend map of bedding showing broad warp on the hinge of southern b.f.q. band (western part of sector 7 and eastern most part of sector 10).
Fig 3.6: Equal-area projection diagrams of bedding plane (S_0) planes in different sectors. Contours at 1% - 3% - 5% - 10% - 15% per 1% area. \( \beta \)-pole to the \( S_0 \)-girdle, \( \beta_a \)-pole to the approximate \( S_0 \)-girdle, \( \chi \)-axis of cone.
observed and hence it appears that these gentle warps of the beds are also an effect of the third phase of deformation.

In many sectors on the hinge and to its west (sectors 4, 6, 7, 8, 9, 10, and 11, Figs. 3.64(iii) to 3.64(ix)) there is only one dominant girdle which is very gently inclined or almost horizontal. These peripheral girdles are considered to be due to second phase folds, and their poles represent steeply plunging or sub-vertical $\beta$. There are two reasons for arriving at this conclusion:

(1) The $F_2$-minor folds in these sectors are steeply plunging, sub-parallel to the steeply plunging $\beta$ in the projection diagram.

(2) The third phase compression acted on a nearly north-south direction (as indicated by the general east-west trend of the axial planes) and hence on the hinge-zone and to its west, the direction of compression was perpendicular or at very high angles to the regional bedding. In other words, in these sectors, the attitude of the regional bedding fell within the zone of elongation of the third phase strain ellipsoid and hence larger third phase folds are unlikely to have developed here (Fig. 3.65). So $S_p$ girdle due to third phase deformation is not expected in these sectors. However, due to the presence of smaller $F_1$ and $F_2$ folds, locally the attitude of bedding may deviate from the general east-west trend. In such places, mesoscopic $F_3$ folds are quite common (Figs. 3.82(ii) & (iii) and 3.83(ii) & (iii)), but on a macroscopic scale, the effect of $F_3$-folding is negligible.
Fig 3.65 Relation between the orientation of bedding on the Chitradurga Fold and the third-phase strain-ellipse section. The inset shows the trace of bedding in lower order fold from the hinge-zone and its low-angle relation with the compression direction of third-phase.
In sector 13, on the western limb, the southern ferruginous band shows a profusion of first phase tight folds with gently plunging axes and steeply dipping axial planes having west-northwest to north-northwest trend /"Fig. 3.64(xi)\/. Because of the presence of these first phase folds, northeasterly and south-easterly inclined bedding plane poles are noticeable in Figure 3.64(xi) and the partial spread of the poles on a sub-vertical great circle with northwest-southeast axis is a reflection of the first folds.

In sectors 4 & 6, close to the hinge zone of the Chitradurga Fold, the $S_0$-poles show a small circle pattern with steep $x$ (axis of cone). The absence of a unique $\beta$ in these sectors is probably due to the presence of a number of large mesoscopic and macroscopic folds whose axes are not mutually parallel. However, an approximate great circle can be drawn in both these sectors and orientation of these approximate $\beta$'s ($\beta_a$) have been considered in the following discussion on the nature of regional variation of $\beta$ in the two ferruginous quartzite bands. It is to be noted that the significance of $x$ is different from that of $\beta$ which represents the axis of cylindrical folds. Similarly $\beta_a$ is a line lying on the folded surface whereas $x$ is a geometrical direction representing the axis of cone and does not lie on the folded surface (Fig. 3.66). It is obvious that, as the fold approaches a cylindrical form (where apical angle is zero) the angle between $\beta_a$ and $x$ decreases. This relation is clearly reflected in the orientation diagrams of bedding plane poles for sectors 4 & 6 /"Figs. 3.64(iii) and 3.64(iv)\/. In sector 4, the apical angle is $10^\circ$ (the apical
Fig 3.66  Difference between $\beta$ of a cylindrical fold and $\chi$ of a conical fold.
angle of the complementary cone made by bedding-pole surface being $80^\circ$) and $\beta_a \wedge x = 6^\circ$. In sector 6, with increase of apical angle to $26^\circ$, $\beta_a \wedge x$ also increases to $14^\circ$.

The dispersion of bedding-poles in the orientation diagrams from each sector is due to the presence of small scale Fg-folds in each sector (in some sectors also due to Fg-folds). Hence the $\beta$ in each individual sector gives the axis of the second and higher order folds congruous with respect to the major Chitradurga Fold (first order fold). The major Chitradurga Fold has a steep plunge as indicated by the steep dip of beds on the hinge. To determine the overall geometry of this major fold, bedding-plane pole maxima from the individual sectors have been plotted in a synoptic diagram (Fig. 3.67). They fall on a small circle around a vertical axis. This indicates that the major fold approximates a conical fold with vertical cone axis ($X$). The apical angle of the conical major fold is $7^\circ$ and such a small value of apical angle indicates that, though the folded surface has strictly speaking a conical form, it closely approaches a cylindrical surface (zero apical angle). The $\beta$'s from different sectors on the northern and southern ferruginous bands are also plotted in another synoptic diagram (Fig. 3.68) and they show a systematic pattern of variation. The loci of $\beta$ from different sectors on the northern and southern band are two complex spiral lines around the vertical cone axis, and these depict the relation of the axes of the higher order folds to that of the first order Chitradurga Fold. Ramsay (1967, p. 468 - 469) has shown that if a surface containing early rectilinear structures is deformed into a circular conical fold, the deformed
early lineation forms a complex spiral locus on the cone-surface. The present spiral loci are very similar to the pattern described by Ramsay which suggests that the $\beta$'s represent the axes of the folds which are later refolded by the large Chitradurga Fold (first order fold). This can be confirmed by unrolling the major conical fold and noting if the $\beta$'s after unrolling assume a parallel rectilinear orientation. Figure 3.69 shows the orientation of $\beta$'s after unfolding the conical surface to an east-west trending vertical plane. (For details of the method of unfolding of conical fold-surface and restoration of $\beta$ on it, see Appendix - I). The $\beta$'s, after unrolling, are found to be almost parallel to each other which confirms the idea that the first order large Chitradurga Fold formed later and refolded the earlier formed smaller folds whose axes are represented by $\beta$. Since, the large fold and the smaller folds both belong to the second phase deformation, they represent development during different stages of progressive deformation. It is therefore suggested that the smaller folds (with smaller wave-length) developed at the early stage and larger folds (with larger wave-length) developed at the later stage of a progressive deformation. Ramberg (1963) has shown that at the initial stage of layer parallel compression, thin and competent layers get shortened by buckling component and develop smaller folds while in thicker and relatively incompetent layers, this buckling component is insignificant and these layers get shortened only by thickening (due to uniform compressive strain) and minor folds are not formed in these layers. During later stage of deformation, shortening by the buckling component becomes more
the volcanics immediately west of the southern ferruginous band indicates an eastward younging direction i.e. away from the supposed syncline. Moreover, the conglomerate lenses to the south and southeast of the southern ferruginous band contain pebbles of banded ferruginous quartzite which must have been derived from the ferruginous bands occurring north of the conglomerate horizon. Therefore, this also indicates a southward and eastward younging direction. So the assumption of the existence of any synclinal structure inbetween the two ferruginous bands can be rejected.

Hence, in the author's opinion, an original slight non-parallelism of the bands irrespective of any early major fold structure is a more likely feature of the structure of the area prior to the second phase deformation. The two ferruginous quartzite bands would then represent separate stratigraphic horizons, both of which contained early minor structures and were folded together during the second phase deformation.

(2) Variation of $\beta$ on the different bands resulting from variation in strain pattern in different parts of the major fold

It has been shown earlier in this section that though the $\beta$'s assume a sub-parallel attitude after the unrolling of the major conical fold, lack of strict parallelism indicates slightly differing initial attitudes of $\beta$. In section 3.F. (iii), it has been shown that in different sectors, the axes of the second phase minor folds show a large scatter around $\beta$. The role of progressive deformation and variation of strain pattern in causing the variability of orientation of $\beta$ and axes of second phase minor
folds have been discussed in section 3.F. (iii).

The present author holds that the pre-second phase variation in the orientation of bedding and inhomogeneous strain pattern have both contributed towards causing the diverse orientation of \( \beta \) in the area, particularly near the hinge-zone where \( \beta \)'s on the northern and southern ferruginous bands show differing orientation.
(ii) **Variability of the axial planes and axes of the first-phase folds ($F_1$).**

$F_1$-axial planes: Axial planes of the $F_1$-folds have been refolded along with the bedding plane ($S_0$) during the second phase deformation and because of the tight to isoclinal nature of the $F_1$-folds, their axial planes usually follow the pattern shown by the bedding plane.

As data of $F_1$-axial planes in many sectors are scanty, these are shown in four synoptic diagrams; for eastern limb (sectors 1 & 3), hinge (sectors 4, 6, 7 & 8), west of hinge (sectors 9, 10 & 11) and western limb (sectors 12 & 13) \( \text{Fig. 3.70(i) to 3.70(iv)} \). On the limbs of the Chitradurga Fold, the $F_1$-axial planes have the same trend as the regional bedding. On the eastern limb, the axial planes have steep dips with trends varying between north-northwesterly and north-northeasterly \( \text{Fig. 3.70(i)} \). On the western limb, the $F_1$-axial planes have northwest-southeast trend \( \text{Fig. 3.70(iv)} \). On the hinge zone, the $F_1$-axial planes along with the bedding have been folded by $F_2$-folding and the $F_1$-axial plane poles lie here on girdles around subvertical axes \( \text{Fig. 3.70(ii)} \). West of the hinge-zone, the girdle is around a steep north-northwesterly axis \( \text{Fig. 3.70(iii)} \).

The attitude of the $F_1$-axes are also represented in four similar synoptic diagrams \( \text{Fig. 3.71} \). On the planar limbs of the Chitradurga Fold, the $F_1$-axes lie on subvertical girdles; it is north-northeasterly trending for the eastern limb \( \text{Fig. 3.71(i)} \).
Fig 3.70 Synoptic diagrams showing equal-area plots of poles to the $F_1$-axial plane.
Fig 3.71 Synoptic diagrams showing equal-area plots of $F_1$-axis.
(iii) **Second phase planar structures**

Planar structures belonging to the second phase deformation ($S_2$) include schistosity and related slaty and fracture cleavage and axial planes of minor folds in the schists, argillites and basic volcanics and banded ferruginous quartzites. $S_2$-planes from adjacent sectors which show almost identical orientation have been plotted together. Their patterns are shown in Figure 3.72 and are described in Table 3.3. In the projection diagrams, different symbols have been used for the schistosity/slaty cleavage and the axial plane of minor folds because in some sectors a little angular relation exists between the two but broadly they have parallel orientation. The variation of the $S_2$-pattern over the whole area is shown in Plate 7.

The strike of the $S_2$-planes makes a low angle with the bedding-strike on the limb of the major fold and a high angle near the hinge; the acute angle relationship between the strikes of the $S_2$ and $S_0$ (bedding) is always congruous with the major southerly closing fold.

The west-southwesterly to west-northwesterly trending attitudes of the schistosity in a few sectors are due to third-phase folding ($F_3$). The interbanded argillites associated with banded ferruginous quartzite have been affected by $F_3$-folding, and the $S_2$-cleavages in the argillites are folded along with the bedding and this causes a variation in their orientation. In sector 2, immediately to the east of the northern ferruginous band,
There is a small angle in between them, see Fig. 3.72(i), the relation being such that the former makes a smaller angle with
S₀-strike than the latter. This angular relation, usually known as cleavage refraction is probably due to the variation of strain pattern in the competent and incompetent layers (Ramsay, 1967; Dietrich, 1969). Since the measurements of the schistosity planes are from less competent unit and those of the axial planes are from more competent unit, it may be concluded that the largest axis of the strain ellipsoid makes a smaller angle with the bedding in the less competent rock (Fig. 3.73). On the hinge, there is much variability in the trends of schistosity and F₂-axial planes, but the range of variation is same for both the schistosity and axial plane trends; in other words, there is no systematic difference in the trends of schistosity and F₂- axial plane on the hinge zone.

The regional pattern of variation of S₂- plane within the relatively less competent rock is illustrated by the variation in orientation of the schistosity within the basic rocks. It is very well-developed in the basic volcanics on the eastern limb. Around the hinge-zone, the thick basic volcanics in between the two ferruginous bands as well as other thin interbands are mostly massive with local development of cleavage. As a result the cleavage pattern could not be studied in detail, but an overall divergent pattern in the schistosity trend (including cleavages in the pelitic schists, argillites) exists throughout the fold. Around the hinge-zone, the pattern is sub-parallel with a general trend of N30°W - S30°E. However, north of the northern ferruginous band, this parallel set takes a small swing towards west, the trend there being N50°W - S50°E. Just east of the hinge, south of
layer and the latter in the competent one. Therefore, divergent type cleavage develops in incompetent layers and convergent type in competent layers in a multilayered sequence. However if the competent layers are separated wide apart (more than one initial wave-length of the fold) by incompetent material, the effects of inhomogeneous strain set up around the buckled competent layer (known as zone of contact strain) diminishes away from either side of the competent layer and beyond one initial wave length distance, the incompetent material suffers homogeneous strain (Ramsay, 1967, p.416 - 417); as a result, in the incompetent band, divergent cleavages only exist in the zone of contact strain and outside that, the cleavages are parallel to each other (in the zone of homogeneous strain).

In case of the Chitradurga Fold, two competent ferruginous quartzite bands are separated by the less competent basic volcanic rock; though the thickness of the basic band is greater than the two ferruginous quartzite bands on either side, it is much less than the wave length of the Chitradurga Fold. Therefore the divergent cleavage fan within the basic rocks is as predicted by the theoretical study.

The swerving of the schistosity on the eastern limb towards centre of curvature is interesting. Mukhopadhyay and Sengupta (1967) made a theoretical analysis of the internal strain of flexural slip type and have shown that the long axes of the strain ellipses develop divergent pattern on the hinge,
at lower values of bedding dip and progressively towards limb with decrease of bedding - axial plane angle, the angle of divergence increases and ultimately, after being parallel on some part of the limbs, a convergent pattern appears (Fig. 3.74). In other words, the long axis of the strain ellipse rotates towards centre of curvature of the fold with decreasing values of bedding - axial plane angle. Therefore, the present swerving of the schistosity trend from hinge towards limb may be regarded as due to flexural-slip type of internal strain. Mukhopadhyay and Sengupta (1967) have further shown that the ratio of principal strains $Z/I$ is higher on the limb than on the hinge and since it is likely that cleavage develops only after the ratio $Z/X$ reaches a certain value (Cloos, 1947), the cleavage would be well developed on the limbs and may be ill-developed or absent on the hinge zone. The well developed schistosity on the eastern limb and massive to crude cleavage structure on the hinge zone in the basic volcanics support this theoretical inference.

The convergent pattern of $F_2$-axial planes in the banded ferruginous quartzite and the divergent pattern shown by $S_2$-planes in the schistose rocks are due to different orientations of the longest axes of finite strain ellipsoids within the competent and incompetent layers respectively. Competency variation in alternate layers causes cleavage-refraction even in smaller scale as seen in Figure 3.75.
(iv) Axes of the Second-phase minor folds (F₂).

The data for the F₂-axes are presented in four synoptic projection diagrams Figs. 3.76(i) to 3.76(iv). The F₂-axes show a large scatter around the β's in different sectors as evidenced in these diagrams.

On the eastern limb of the Chitradurga Fold sectors 1 and 3; Fig. 3.76(i), the axes show a southerly plunging scatter having a southward, moderately plunging average attitude. The poor northward distribution is mostly due to gentle, northward plunging striping lineation in the pelitic schists.

On the hinge zone sectors 4, 6, 7 and 8; Fig. 3.76(ii), the F₂-axes vary in plunge direction from south to west. Some have northwesterly to northerly plunge. The scatter has a central value of steep southwesterly plunging attitude. However, the deformed volcanic lapilli show a moderate to steep northward plunge of their longest axes and hence are not parallel to β.

West of the hinge zone sectors 9, 10 and 11; Fig. 3.76(iii), the F₂-axes have northerly plunge with concentration around a central value of steep northerly plunging attitude.

On the western limb sectors 12 and 13; Fig. 3.76(iv) the axes have variable orientations. The maximum concentration has a steep northeasterly plunge. A poorer distribution of south and southwesterly plunging axes is also present. The northeasterly and southwesterly plunge directions are due to superposition of F₂-axes on the northeasterly and southwesterly dipping limbs of the F₁-folds as seen in Fig. 3.64(xi).
Fig 3.76 Synoptic diagrams showing equal-area plots of $F_2$-linear structures. Contours at 1% - 3%, 5%, 10%, 15% per 1% area. $\phi_1, \phi_2$ etc. represent orientation of $\phi$ in the respective sectors, dots - elongation lineation by deformed volcanic lapilli.
The volcanic lapilli and spherical variolites are undeformed in most of the places except at two places near the hinge zone of Chitradurga Fold (shown in Plates 4 & 8) where the lapilli are strongly deformed into ellipsoidal shape, the longest axes of which show a preferred orientation towards northwest with moderate plunge. This localised deformation of the lapilli at the hinge zone indicates regional inhomogeneity of the strain during second-phase deformation.

Axial ratios of a number of deformed lapilli from five specimens of schistose metavolcanics have been measured. X and Y have been measured on the schistosity surface and Y and Z have been measured on the plane normal to the schistosity and to the elongation lineation. The ratios of X/Y and Y/Z have been determined from the X - Y and Y - Z plots for these five samples (Figs. 3.77(i) to 3.77(v)). The plot of X/Y values against Y/Z values of these five samples fall near the line k = 1 (Fig. 3.78). But it is not certain whether the shape of the lapilli defines the finite strain ellipsoid in the rock. It is possible that before tectonic strain, the lapilli were deformed, during compaction, into oblate ellipsoidal shape (in which \( X_0 = Y_0 > Z_0 \)) with shortest axis \( Z_0 \) normal to the bedding (cf. Oertel, 1970). During tectonic strain of the second phase deformation (with \( X_t ; Y_t ; Z_t \) axial ratio of the tectonic strain ellipsoid), near the hinge zone of the Chitradurga Fold where bedding is vertical and normal to XY principal plane, only one co-axial combination of the original oblate ellipsoids and tectonic ellipsoid is possible, i.e., \( X_0 \)
Fig 3.78 Filtn diagram showing plots of the five samples of Fig 3.77 falling near the line k = l

Fig 3.77 X-Y and Y-Z plots of deformed volcanic lapilli from five handspecimens
coincides with $X_t$, $Y_o$ coincides with $Z_t$ and $Z_o$ coincides with $Y_t$ (Fig. 3.79). So, $X_f : Y_f : Z_f$ being the axial ratio of the final shape of the tectonically deformed lapilli, $X_f = X_o X_t$, $Y_f = Z_o Y_t$ and $Z_f = Y_o Z_t$.

Now

$$a_f \left( \frac{X_f}{Y_f} \right) = \frac{X_o X_t}{Z_o Y_t}$$

Since

$$X_o > Z_o, \quad \frac{X_o X_t}{Z_o Y_t} > \frac{X_t}{Y_t} \quad (= a_t)$$

Therefore, $a_f > a_t$.

Similarly,

$$b_f \left( \frac{Y_f}{Z_f} \right) = \frac{Z_o Y_t}{Y_o Z_t}$$

Since

$$Z_o < Y_o, \quad \frac{Z_o Y_t}{Y_o Z_t} < \frac{Y_t}{Z_t} \quad (= b_t)$$

Therefore $b_f < b_t$.

So, the final ellipsoid $(a_f, b_f)$ that is derived from the initial oblate ellipsoid (lying on abcissa in $X/Y$ - $Y/Z$ graph) by a tectonic strain ellipsoid $(a_t, b_t)$, shifts towards constrictional field though the strain ellipsoid lie on the flattening field (fig. 3.80).

So, in the present area, though the deformed lapilli give the value of $k$ near to 1, the tectonic strain may be of flattening type of deformation $(1 > k > 0)$.
The orientation of fold axes developed at any particular stage is dependent on the relative attitude of bedding with reference to the three dimensional strain ellipsoid. At a particular instant of time, the intersection of the bedding plane with the strain ellipsoid of that particular instant is an ellipse. The principal axes of this strain-ellipse section give the direction of maximum and minimum elongation on that plane and fold axes would be parallel or sub-parallel to the longest axis of the ellipse at that instant of deformation (Flinn, 1962).* It is evident therefore, that the orientation of the fold axes would depend on the attitude of bedding on which folds are developed and on the orientation of strain-ellipsoid during deformation. Within a single phase of deformation, the fold axes normally should have variable orientations because of the following factors:

i) Variation of strain pattern in different parts of the major structure

ii) Variation in the orientation of strain-ellipsoid at a particular spot during the successive stages of progressive deformation.

iii) Variation in the attitude of bedding in the successive stages of progressive deformation.

*However, at the present state of knowledge, it is not certain whether the fold axis at its initiation would be parallel to the long axis of the finite strain ellipse section, or the long axis of the infinitesimal strain ellipse section, though the latter seems to be more likely.
Since the strain field over the total domain of a large fold is generally inhomogeneous (Ramsay, 1967), the smaller folds that develop in different parts of the larger fold are likely to have axes showing different orientations amongst themselves as well as from the axis of the larger fold.

The effect of progressive deformation has been discussed by Ramsay (1967, p.174 - 175) who has shown that the principal directions of a finite strain ellipsoid at a certain stage of deformation (say, at \( t_1 \)) will not coincide (because of rotational component of natural deformation) with those of the infinitesimal strain-ellipsoid during next increment of straining (say, at \( t_2 \)). As a result the changes in length that are going on during the process of deformation at a particular instance (during \( t_2 \), for example) do not coincide with those finite changes already established prior to that particular instance (at \( t_1 \)) and depending upon the nature of superposition of the finite and infinitesimal strain-ellipsoid, lines that have elongated (at \( t_1 \)) might undergo (at \( t_2 \)) elongation or contraction or no change in length. Eventually structures formed during one part of the deformation will be deformed or re-oriented differently as successive new strain-increments are superimposed and Ramsay (1967, p. 175) has stated: "It is extremely unlikely that the minor structures formed during the progress of deformation will ever be arranged symmetrically with respect to the axes of the finite strain ellipsoid". Moreover, while the earlier formed folds are undergoing modifications by each succession of infinitesimal strain increment,
new fold axes, initiated at these successive stages of progressive deformation, will have different orientations from the earlier formed ones. This is illustrated in Figure 3.81. A layer 'A' at time \( t_1 \) on a progressive deformation-path starts to form a warp with axis parallel to 'a' \( \text{Fig. 3.81(i)} \). This fold axis 'a' at its initiation is perpendicular to the maximum shortening direction of the infinitesimal strain ellipse section on the plane 'A' at time \( t_1 \). At a later stage \( t_2 \) of progressive deformation, the orientation of the layer with reference to the principal strain ellipsoid changes as a result of rotation of that plane and the axes of the strain ellipse section on the rotated plane have orientations different from those at \( t_1 \), and the direction of maximum incremental shortening at \( t_2 \) will be oblique to that at \( t_1 \), (i.e., not perpendicular to 'a' axis). So at \( t_2 \) depending on its infinitesimal strain ellipsoid orientation, new folds \( \text{"b"} \) in Fig. 3.81(ii) initiate at right angles to the maximum shortening direction at \( t_2 \). At the same time the early fold with axis 'a' continues its development (a') by taking up the oblique shortening at \( t_2 \) \( \text{Fig. 3.81(ii)} \) and it may also be deformed by the new fold with axis 'b'. Therefore several directions of minor fold axes are developed by growth of new folds having mutually non-parallel axes at successive stages of deformation and by continuous modifications of the earlier axes by oblique shortening of later strain increment during a single path of a progressive deformational history.
(v) Variability of the axial planes and axes of the third-phase folds ($F_3$).

The data for the $F_3$-axial planes as well as the $F_3$-axes are presented in four synoptic diagrams (Figs. 3.82 and 3.83).

On the eastern limb $\angle$ sectors 1 & 3, Fig. 3.82(i), the trend of most of the $F_3$-axial planes ranges between north-northeast — south-southwest to east-southeast — west-northwest and the dips are steep. However, the maximum has a trend of northeast-southwest. A subordinate maximum shows an east-southeast — west-northwest trend. On the hinge zone $\angle$ sectors 4, 6, 7 & 8, Fig. 3.82(ii), the trend varies from east-northeast — west-southwest to east-southeast — west-northwest and the dips are steep. To the west of hinge zone $\angle$ sectors 10 & 11, Fig. 3.82(iii), the $S_3$ maximum has a trend of northeast-southwest with steep northwesterly dips; another subordinate maximum has the trend of east-southeast — west-northwest. On the western limb $\angle$ sectors 12 & 13, Fig. 3.82(iv), the trend is east-southeasterly with steep dips. Probably the northeasterly and east-southeasterly trends together constitute a conjugate set; the north-easterly trend is predominant on the eastern limb and the east-southeasterly trend on the western limb; on the hinge and to its west, these two trends have nearly equal frequency. The development of the conjugate set of crenulation cleavage in the schists can be seen well to the east of Kasavanahalli village where the north-northeasterly trending strain-slip cleavage, at one place, has been folded by east-southeasterly trending set. Thus, there may be a slight difference in the time of formation of the two sets.
F3-fold axes usually have moderate to very steep plunge and show wide variability of the plunge direction. The orientation of F3-axes is controlled by the orientation of bedding. On the eastern limb (Fig. 3.83(i)), a concentration of F3-axes in the northeastern quadrant of the projection diagram is noticed. On the hinge zone (Fig. 3.83(ii)), a similar concentration in the southwestern quadrant, to the west of the hinge zone (Fig. 3.83(iii)) a concentration in the northwestern quadrant, and on the western limb (Fig. 3.83(iv)) a concentration of easterly plunging axes are found. This broad generalised pattern of variation of F3-axes is related to the variation of the regional attitude of bedding which is easterly dipping on the eastern limb, southerly on the hinge zone, northerly to the west of the hinge zone and northeasterly on the western limb.
3. G. Mechanism of folding

Frequent disharmony in fold-style and dependence of the wave-length on the thickness of the competent bands indicate that the folds have been initiated by buckling. But considerable thickening of the bands at the hinge-zones indicates the role of strong compression in modifying the buckle folds.

To get a quantitative idea of the compressive strain and to study the variation in response of the layers of differing composition, namely quartzite and ferruginous bands, changes of orthogonal thickness of different bands across the fold have been studied on eight profile sections of handspecimens (a) parts of Figs. 3.84 to 3.91.

The intensity of compressive strain (the ratio of \( \lambda_1 / \lambda_2 \)) can be measured by plotting \( t' = 2 \lambda \) against \( \cos^2 \lambda \) (Hudleston, 1973) and drawing the line of best fit through the points. The ratio \( \sqrt{\lambda_1 / \lambda_2} \) can be estimated from the slope of the line.

Measurements have been made on enlarged photographs of handspecimens. Orthogonal thickness on hinge and on planar parts of the limbs has been measured. To avoid the irregularities in bedding plane, the thickness has been measured where the limbs remain planar over a long distance. Where minor wrinkles are present, the median surface has been used for measurement of the thickness.

In fold forms, where hinge-point tangents are not normal to the axial trace, for example, band no. 4 of specimen no. 536, Fig. 3.86(a), the zero degree datum has been fixed at the point where the tangent to the bedding is normal to the axial trace (Hudleston, 1973).
The data have been plotted on graphs \((b)\) parts of Figs. 3.84 to 3.91 and the patterns have been described in Table 3.4. From the different specimens, it is found that the thick, massive quartzite bands or quartzose multilayers with thin ferruginous laminae show Class 1C geometry (Ramsay, 1967). In two cases only, the quartzite bands show Class 2 or Class 3 geometry. In specimen No. 536, the quartzite band showing Class 2 geometry separates two multilayered units of Class 1C geometry. In specimen No. 318, the outermost quartzite band which has smaller thickness than the inner quartzite band, shows Class 2 geometry. The magnetite layers, on the other hand show Class 2 or Class 3 geometry. This indicates greater competency of the quartzite band compared to the magnetite band. The greater competency of the quartzite band is also evidenced from frequent rupturing of the quartzite bands (Fig. 3.92). The ruptured bands and fragments follow the second-phase folds (Fig. 3.93). This indicates that the rupturing preceeded the second-phase folding. This rupturing may be pre-tectonic or contemporaneous with the first-phase of deformation. The less competent behaviour of the ferruginous bands is indicated by frequent squeezing of the ferruginous matter from limb into hinge. Due to excessive thickening at the hinge and when the flattening is oblique, one limb of the fold in the ferruginous layer may be very much reduced in thickness and consequently adjacent to that limb, the antiformal or synformal hinge of the competent (quartzite) layer on one side of the ferruginous layer comes close to the synformal or antiformal hinge respectively of the competent layer on the other side of the ferruginous layer (Fig. 3.94).
Quartzose bands showing Glass 1C geometry are usually separated by ferruginous bands with Glass 3 geometry. Because of this geometry of the fold, the curvature in the lower part of the upper quartzite band is greater than the curvature in the upper portion of the lower quartzite band underlying the intervening ferruginous band. In other words, in the multilayered sequence of quartzite and ferruginous band, the quartzite layer in the antiform hinge zone has greater curvature in the upper part and smaller curvature in the lower part. In extreme cases a ferruginous band separates chevron shaped fold in immediately overlying quartzite layer from the broad, rounded-hinge fold in immediately underlying quartzite layer (Fig. 3.95, the fold in the lower part of the photograph).

Johnson (1970) has shown that transition from rounded hinge-fold to angular hinge-fold is related to yielding of the material during buckling. He has also shown that the amount of strain a material can withstand before yielding is proportional to the yield strength and inversely proportional to the elastic modulus of the material. During early stage of buckling, the quartzite and ferruginous layers assumed Glass 1C and Glass 3 geometry respectively. The lower portion of the quartzite band immediately over a ferruginous band would have greater curvature and consequently would have greater fibre strain and so would yield earlier than the material at the upper part of the lower quartzite band, immediately underlying the ferruginous band, where the curvature is less (Fig. 3.96(i)).

As a result, the fold in the quartzite band immediately over the ferruginous band gets sharp and develops chevron type of fold.
while the quartzite below the ferruginous band remains a rounded-hinge-fold as seen in Figure 3.96(ii). In other words, yielding would start first at the core of the antiformal hinges and continued yielding produces sharpening of the folds there, while the outer part, i.e., away from the core, maintains its rounded to sub-rounded hinge zone.

In the example shown in Figure 3.95, it is also possible that the upper quartzite band has different rheological property than the lower one caused by differences in grain-size, in the proportion of the ferruginous matter etc., as a result of which it has started yielding before the lower band and causes angular hinge-zone in the former.

\[ \sqrt{\frac{\lambda_1}{\lambda_2}} \] values for most of the quartzite layers showing Class 1C geometry range between 1.5 to 4.5 which indicates that the folds are flexural-flow folds of Donath and Parker (1964). They have shown that the flexural-flow type of mechanism will operate in a rock-sequence where the mean ductility is moderate and the ductility contrast is moderate to high. High ductility contrast in the present area is evidenced from the variable fold geometry and contrasting fold-classes in the quartzite and ferruginous bands respectively. So deformation in the present area took place in an environment where the mean ductility was moderate and the ductility contrast high.
3. H. Structural Conclusions

Three phases of deformation have been recognised in the present area. The major U-shaped structure, south of Chitradurga town is a second-phase southerly closing fold defined by the swing in strike of the b.f.q. bands. The most prominent schistosity with a general north-northwest — south-southeast trend is related to this phase. The first-phase structures are generally represented by minor folds only. Pervasive planar structure related to this phase within the metapelites is rarely preserved and in such case, the second-phase structure appears as crenulation cleavage. The third phase structures are crenulation cleavage and minor folds on a general east-west trending axial plane.

The Chitradurga Fold with subvertical axis and axial plane is nearly a vertical fold. The geometrical analyses of the bedding plane data from different small sectorial domains show that in most of the sectors, there is a considerable spread along a gently inclined great circle indicating a subvertical or steeply plunging \( \beta \). In the synoptic diagram, the bedding-pole maxima from the individual sectors fall on a small circle around a vertical axis, indicating that the major fold approximates a conical fold with vertical cone axis (\( x \)). The small apical angle (7°) further suggests that, though the folded surface has strictly speaking a conical form, it closely approaches a cylindrical surface (apical angle = 0).
The Chitradurga Fold is an anticline as indicated by the easterly younging pillows on the eastern limb of Chitradurga Fold, thereby suggesting the basic volcanics occurring at the core of the fold as the oldest unit in this folded sequence.

The first phase folds are present only on mesoscopic scale. There is no evidence to indicate that the individual ferruginous bands (viz., the northern and southern b.f.q. bands) represent early major anticlinal or synclinal fold-cores (Naqvi, 1973) nor do the two b.f.q. bands represent two limbs of any early major fold. The two b.f.q. bands represent two different stratigraphic horizons. The F$_1$-axial planes on the limbs of the Chitradurga Fold are parallel or sub-parallel to the general attitude of bedding on the limbs. On the hinge-zone, the F$_1$-axial planes are involved in a number of mesoscopic and macroscopic second phase folds. On the limbs of the Chitradurga Fold, the F$_1$-axes show variation of plunge on an uniform attitude of F$_1$-axial plane and on the hinge-zone of the Chitradurga Fold, the F$_1$-axes show wide variability both in direction and amount of plunge because of the presence of a number of F$_2$-folds.

The schistosity and the slaty cleavage related to F$_2$-deformation show divergent fan pattern within the basic volcanics. The strike of the schistosity/slaty cleavage are not strictly parallel to the axial plane of F$_2$-minor folds in b.f.q.. The schistosity makes smaller angle with bedding than the F$_2$-axial planes in b.f.q.. The F$_2$-axial planes in b.f.q. show convergent fan pattern in
Chitradurga Fold. Such variations of $F_g$-structures in the volcanics-pelites and in b.f.q. are due to different orientations of the longest axis of finite strain ellipsoid within the incompetent and competent layers.

The axes of $F_g$-minor folds show a wide scatter around the $\beta$'s of individual sectors. There is a distinct variation of the overall plunge direction of $F_g$-axes from the eastern limb through the hinge to the western limb. It is generally southward on the eastern limb, south-westward on the hinge, northward to the west of the hinge and northeasterly on the western limb. The synoptic diagram showing plots of $\beta$'s from the individual sectors shows spiral loci on both the northern and southern ferruginous bands. On unfolding the conical surface of the major fold to an east-west vertical plane, the $\beta$'s assume an almost parallel orientation. This indicates that the first order major Chitradurga Fold formed later and refolded the earlier formed smaller folds whose axes are represented by $\beta$. Since the major folds and the smaller folds both belong to the second phase deformation, they represent development during different stages of progressive deformation.

The $F_3$-axial planes are developed on two conjugate trends; the northeasterly trend is most prominent on the eastern limb and the west-northwesterly trend is well developed on the western limb. On the hinge zone, both the trends exist in equal frequency.

The quartzite bands are more competent than the ferruginous bands and usually show Class 1C geometry of folding, while the
ferruginous bands show Class 2 or 3 geometry. The values of $\sqrt{\lambda_1/\lambda_2}$ ratio for the the quartzite bands, computed from the orthogonal thickness variations range between 1.5 to 4.5. This indicates flexural flow type of folding in the competent band in an environment of moderate mean ductility and high ductility contrast.

The plot of $X/Y$ against $Y/Z$ for the deformed volcanic lapilli from the hinge-zone of the Chitradurga Fold lie close to the line $k=1$. It is likely that, before the tectonic strain, which is of flattening type as evidenced from the well developed schistosity in the basic and pelitic rocks, the lapilli might have been deformed into oblate ellipsoids during compaction, and were later subjected to tectonic strain, and thus the shape of the deformed lapilli does not give true idea of the tectonic strain.

The author's structural interpretations differ in several respects from that presented earlier by Naqvi (1973). Some of these have already been pointed out in the discussion of Naqvi's article by Mukhopadhyay and Baral (1974). The main points of difference are summarised below:

1. The Chitradurga Fold has been shown as a syncline in the profile CC' of Figure 6 of Naqvi (1973), though according to his description, the fold has a southward plunge and hence should be an antiform because of its southerly closure. According to the present author, this is a vertical fold with nearly vertical axial plane and axis.
(2) On his map, Naqvi, (1973, Fig. 1; Fig. 1.3 of this text) has drawn a number of arcuate axial traces of major folds which, according to him, are of first generation. He further concluded that these early folds are synclinal in hills and anticlinal in valleys; the two ridges of banded ferruginous rocks (unit 14 of Naqvi, 1973) represent two early synclines, the median valley representing the intervening anticline. Though early minor folds are present throughout the area, the present author does not find any structural evidence to establish the presence of early major folds. Naqvi (1973) regarded the two maxima in the bedding-pole plots in his projection diagrams (Fig. 2 of Naqvi, 1973) to represent the two limbs of the early fold, whose axis is given by the pole of the great circle passing through the two maxima. But in his Reply (Naqvi, 1974) to the Discussion of Mukhopadhyay and Baral, he suggested that these two maxima are due to twisting of the individual steep-dipping limb of the early folds. In his own words, "the same limb of first generation fold at different topographic levels of observation show twist in the dip-direction. The topographic changes along the hill ranges bring the same limb of the fold before the observer with a change in the dip direction of totalling 30°, that is 15°on either side of the vertical (Naqvi, 1973, Figs. 1, 2B)" (Naqvi, 1974, p. 1501). If this be the case, the intersection between the two maxima (τ-axis) would not represent axis of the early overturned fold, as shown in Figures 2B & 2C of Naqvi (1973), but the axis of the subsequent twist. The present
author has not observed any such twist in the attitude of the bedding plane.

(3) The η-diagrams given by Naqvi show two clear-cut maxima of bedding-plane poles in each domain with a slight spread. But the present work shows that the η-diagrams within sectors of much smaller area/extent than Naqvi's domains, show more complex patterns. In most of the sectors there is a girdle on steeply plunging axis (β) giving the axis of second phase fold.

(4) In each domain, Naqvi shows that the axes of early folds (F₁) have a single maximum and these have been refolded by the second-phase Chitradurga Fold. The present work shows the axes of F₁ minor folds had initial variations of plunge indicated by the spread of the F₁-axes on a plane representing the average F₁-axial plane on the limbs of the Chitradurga Fold. They show wide variability in both direction and amount of plunge in the hinge area of the Chitradurga Fold.

(5) Naqvi has shown that in each of his domains, the F₂-axes show a single maximum. However, according to his own interpretation of early fold, i.e., the two maxima of bedding-planes represent the two limbs of early fold, the F₂-axes should have two maxima corresponding to the two limbs of the early fold. The present work shows a great variability of F₂-axes, though they cluster around the β's of individual sectors. This variability of F₂-axes is partly a result of progressive deformation.
possibilities about the origin of the coarsely crystalline amphibolites containing large actinolite needles in Barberton type basaltic komatiite of Onverwacht Group — growth during the period of regional greenschist metamorphism under condition of greater volatile activity or growth during subaqueous extrusion of the lava due to rapid cooling or quenching in presence of water. It is not possible to choose between the two alternatives for the present area on the basis of textural criteria only.

The massive type, at places contain well developed spherules consisting of radiating aggregates of very fine fibrous antigorite with a little altered felspar and epidote granules (Fig. 4.4). The spherules are set in a very fine grained cryptocrystalline mosaic of slightly devitrified glass. Vesicles filled with quartz and epidote granules have been noted both within the spherules and the host rock.

The pillowed types have the same petrography and texture as the unpillowed massive type. In one case, the rim of the pillow has been noted to have a more felsic composition consisting of relatively coarse grained aggregates of quartz and felspar within a devitrified glassy matrix of dominantly epidote and chlorite.

The massive volcanics, at many places contain pea-shaped spherical nodules or varioles. These varioles are composed of randomly oriented microphenocrysts of dominantly tremolite needles and subordinate plagioclase laths set in a very fine