7

STRUCTURAL HISTORY

STRUCTURAL HISTORY

PREAMBLE

As already mentioned, the area under investigation is a typical example of polymetamorphic terrain. The metamorphism is obviously developed in response to tectonic episodes witnessed by the rocks of the study area. The principal lithological types are of calcareous and pelitic parentage. The process of migmatization and Post-kinematic granite activity has further rendered the deciphering of various minor structural elements rather complex. The previous workers have considered this area to be a part of Ajabgarh Group obviously involved in a complex Delhi deformation. To the north of present area, the Pre-Delhi metamorphism was for the first time suggested by Desai et al., (1978) on the basis of granulite facies metamorphism in Balaram - Abu Road area and because these high grade rocks were separated from the true Delhi Supergroup rocks by prominent lineaments (Patel et al., 1985) while Sychanthavong and Merh (1984) consider these granulite facies metamorphism to be due to their tectonic setting during Delhi orogeny. No radiometric age data is available to authenticate any of these above observations.

Before dealing with the details of the development of structural elements in relation to various tectonic events, the author has preferred to give a brief account of the structural interpretations suggested by previous workers. Sychanthavong and Merh (op. cit.) have attempted to explain the three fold episodes, developed during Delhi orogeny, in terms of protoplate tectonics by producing a series of rheologic models. These three foldings affected both the BGC and the Aravalli rocks (in Rajasthan) and have regional folds trending NNE-SSW. According to them the second folding also strikes NNE-SSW and F_1 and F_2 are thus cofolded. The third folding (F_3) is WNW-ESE trending. So far as the time span is concerned, these fold episodes range in age from 600 to 1650 Ma. The mesoscopic (F_1) folds show diverse orientation of axial planes ranging from subhorizontal to almost vertical. The (F_2) folds show upright axial planes and are exhibited by their folding of (F_1) axial plane. The (F_3) folds trending WNW-ESE resulted into conical and heart shape F_1, F_2 fold cores with their axes plunging at different angles mostly due southwest. Such (F_3) folds, which are regional in extent, are almost isoclinal with axial planes overturned due NNE but become tight and show subvertical axial planes. Further they have classified mafic rocks into fold core ortho-amphibolites and granulites and fault zone amphibolites, granulites, gabbros and peridotites.

Powar and Patwardhan (1984) have suggested that the rocks of Delhi Supergroup have been subjected to complex history of folding and dislocation. The early folds (F_1) are W to WNW plunging and F_2 and F_3 folds trend N to NNE and are coaxial. According to them (F_2) and (F_3) folds are the most persistent and mild cross folding on EW to WNW-ESE trending axes (F_4) has resulted in the development of doubly plunging structures.

From the above data it can be inferred that in the Delhi Supergroup of Danta area and its surrounding, Powar and Patwardhan (op.cit.) suggest both E-W to WNW-ESE late folds while Sychanthavong and Merh (op.cit.) considered E-W as corresponding to Aravallis of (Naha and Halyburton, 1974b) and WNW-ESE as late Delhi (F_3) folding. Thus there is no general agreement amongst these workers about the trend of (F_3) folding.

Bhan (1972) described earlier folds (F_1) Delhi folding as tight, isoclinal, asymmetrical and overturned. The axial planes of such folds dip at steep angles towards ESE to ENE and the fold axes of (F_1) plunge at moderate angles in the directions NNE to NNW and SSW to SSE but mostly towards southern directions. According to him, the (F_2) folds of Delhi are open upright folds with fold axes plunging at high angles (40^o to 53^o) towards WSW or WNW. He considers WNW being the (F_3) folding of Delhi.

Keeping in view the structural data in the neighbouring regions in the north and west of Danta and the grade of regional metamorphism, the tectonic framework worked out for the study area is proposed as under.

Tectonic episodes.	Regional trend of folds.	Linear structures.	Planar structures.	Grade of metamorphism.
F_3	N-S	L_3	S_3	Amphibolite facies (Delhi).
F_2	NNW-SSE NW-SE WNW-ESE	L_2	S_2	
F_1	NE-SW NNE-SSW	L_1	S_1	
F_0	obliterated	?	?	Granulite facies (Pre-Delhi).

Further, he has classified planar structures and the linear structures coeval with various tectonic episodes as under

STRUCTURAL ELEMENTS IN THE STUDY AREA

The planar structures are mainly bedding in calcareous members and the foliation in pelitic members. The linear structures are represented by mullions (Plate VII.1), quartz rodding, mineral orientation, axes of boudins and minor folds developed more commonly in pelitic members. The calcareous rocks, being more plastic show complex deformation and the lineations corresponding to mineral orientation and quartz rodding etc. Although the area shows complex fold interference patterns, the foliations do not show any visible microfolding but variation in fold axes wherever observed and the quartzofelspathic bands within pelitic members show various fold axes. The axes of microfolds and the fold patterns present in calc gneisses have been helpful in deciphering the fold patterns. Sometimes the axial planes in mesoscopic folds in both the calcareous and pelitic members have been of great help in elucidating the fold generations.

From Danta towards Ambamata, the calc gneisses show NE-SW, N-S and NNW-SSE bedding with dips varying between 50° to 80° towards W and E to almost vertical.

Plate VII.1 Field photograph showing fold mullions in calcgneisses (Loc. Kanbiavas).

Plate VII.2 Field photograph showing refolding (flow folding) in calcareous rocks (Loc. Kuvarsi).

This variation in bedding of the calcareous rocks indicates F_1, F_2, F_3 fold generations. The fold axes of minor folds trend 165 with a plunge of 25° to 30°. The author is of the opinion that this ESE trending fold axes is related to (F_2) folding and is refolded (L_2). On the other hand, the quartz rodding or mullions in the calc gneisses show southerly trend with a plunge of about 24° and this is related to (F_3) folding of the author. At places, the ribbon lineation in calc gneisses show WNW trend (280°) with a plunge of about 55°. This is (L_2) lineation (Fig. VII.1). It is observed that a swing in bedding from NE-SW to N-S indicates the presence of two fold generations.

The pelitic members on either side of the road from Danta to Ambamata show NNE-SSW to NNW-SSE strike with steep angles of 62° to 70° to SW or SE. The ribbon lineation shown by preferred orientation of biotite in the cordierite - biotite gneisses shows a trend of SSW (215°) with a plunge of about 45°. This lineation is refolded (L_1) and this refolding is attributed to late (F_2) fold (Fig. VII.2). The striking variation within small distances can be explained with the help of bedding in calc-gneisses and foliation in cordierite biotite gneisses.

Northeast of Danta near Kanbiavas, the calc gneisses show fairly consistent NE-SW to ENE-WSW strike

Fig. VII-1

EFFECT OF F_2 FOLDING ON L_1 LINEATIONS

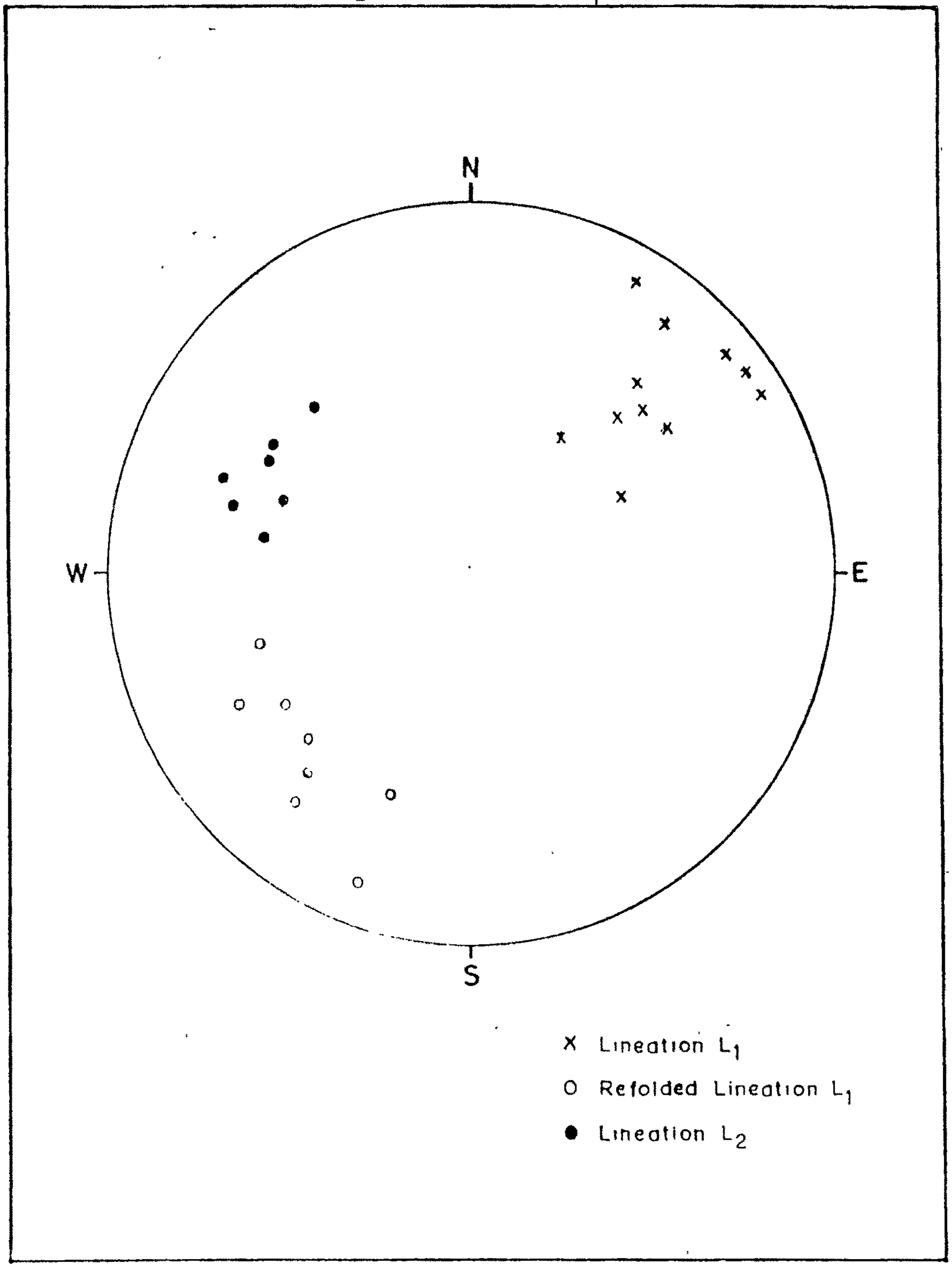
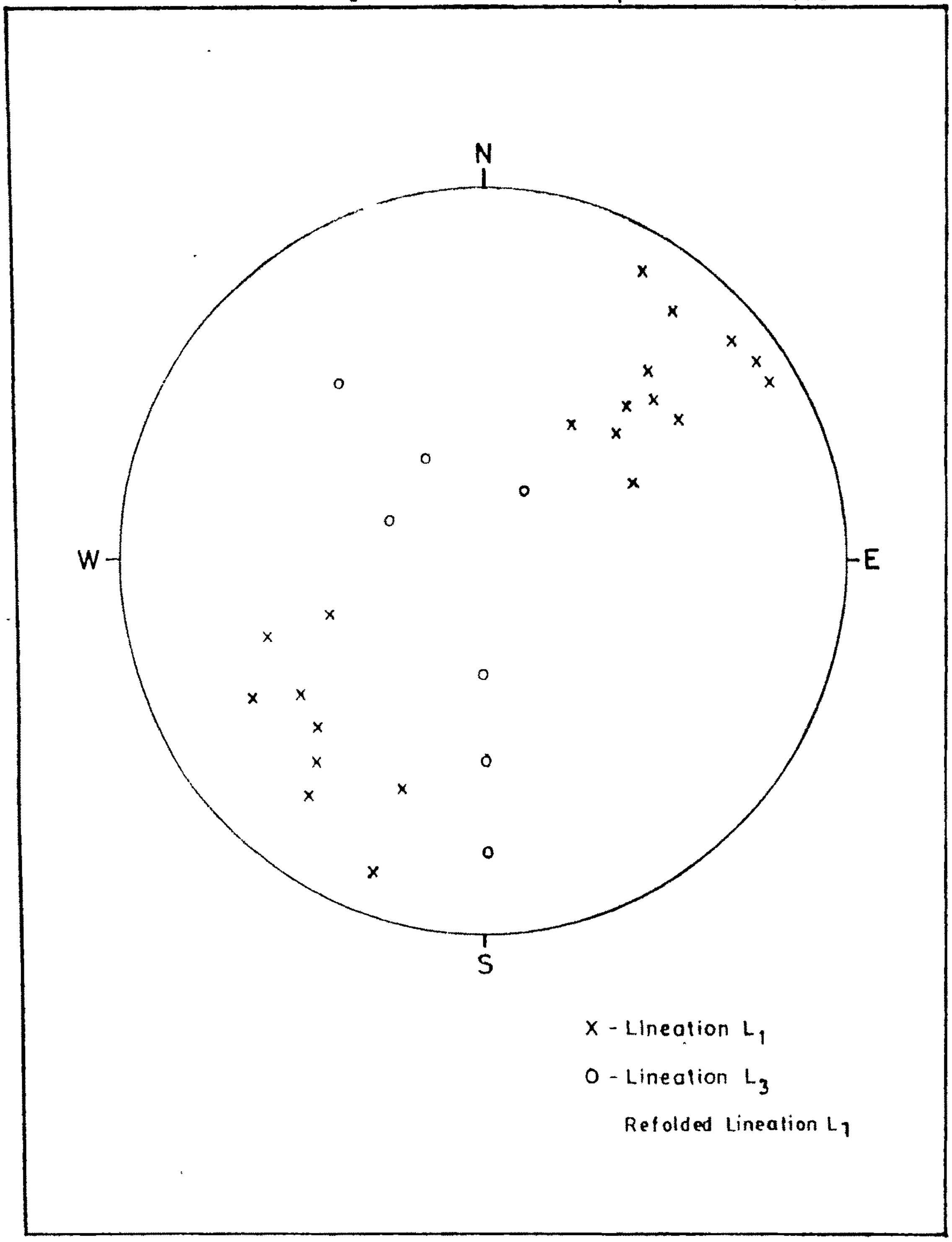


Fig. VII-2

EFFECT OF F_3 FOLDING ON L_1 LINEATIONS

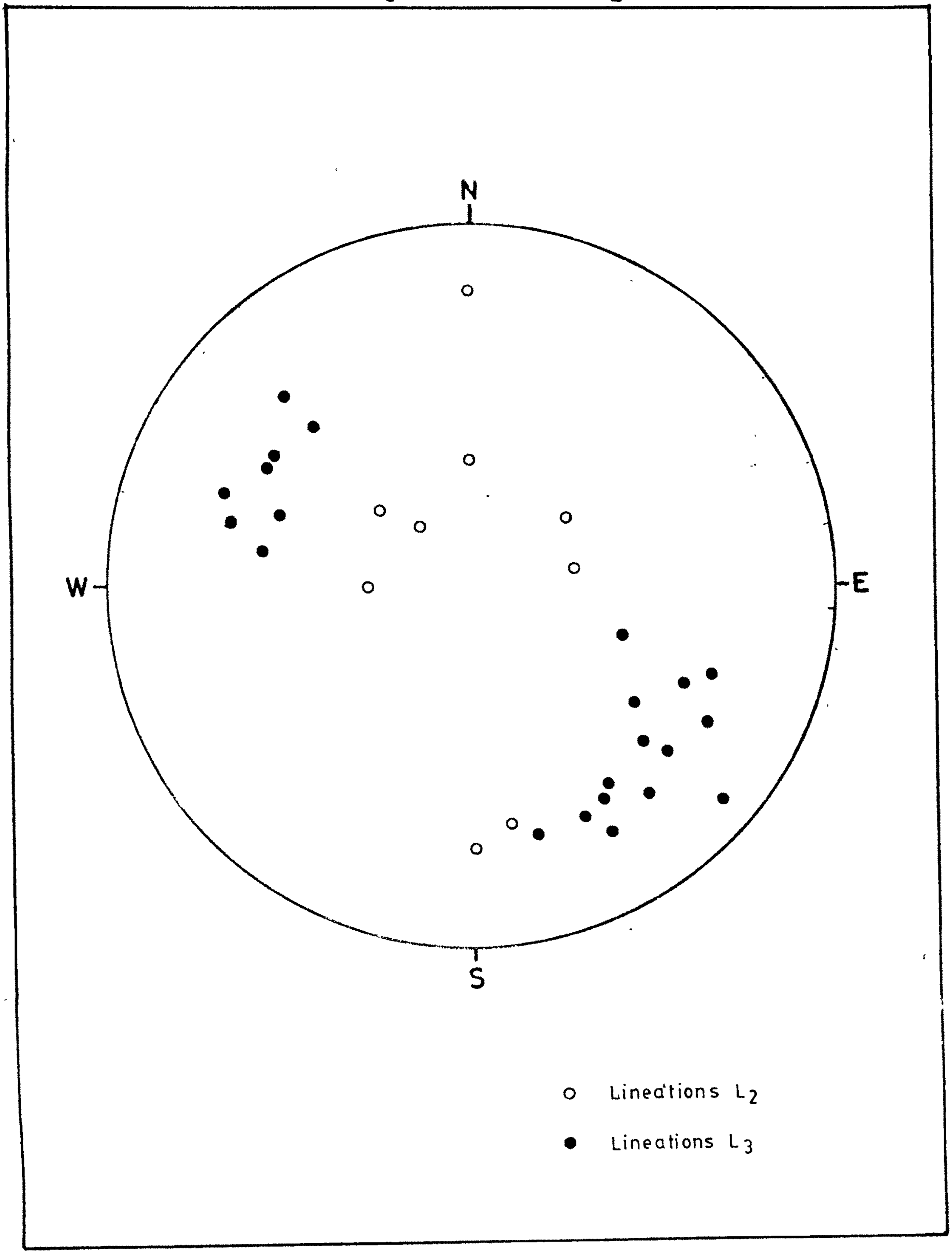


and with dips variation between 20° to 62°. The ribbon lineation in calc gneisses is southwesterly (200°) with the plunge of about 35° and thus is refolded (L_1) (Fig. VII.2). At places the calc-gneisses show bedding swinging to ENE-WSW and dip of 62°. It exhibits ribbon lineation WNW (310°) with a plunge of 55° to 60°. This is (L_2) lineation related to (F_2) folding of the present author (Fig. VII.1). The basic rocks near Kanbiavas show a foliation of 15° with a dip of 10° to 15° due NW. Strikingly, these basic rocks show quartz veins ptygmatically folded but it is difficult to measure their trend on the road side exposures.

On proceeding south and southeast of Danta, the calc gneisses and the biotite gneisses show significant variation in their trends. The strike varies between NNE-SSW to NNW-SSE and even N-S in some cases with amount of dip varying between 35° to 55° towards east and west. The ribbon lineation in calc gneisses trend towards NNE or SSW (Fig. VII.1) with a plunge of 15° only. The opposite trends of (L_1) lineation is on account of NNW-SSE trending (F_2) folds. The biotite gneisses as well as calc gneisses show the fold axes and the related lineations trending between south and southeast directions with 50° to 65° trend. It is possible to measure the (L_2) lineation plunging towards NW or SE with a plunge about 60° (Fig. VII.3). This is

Fig. VII-3

EFFECT OF F_3 FOLDING ON L_2 LINEATIONS



obviously on account of (F_3) folding. Near Vajapur village beautiful examples of folded calc gneisses have been observed and the measurement of two limbs (Fig. VII.4) indicates the trend of fold axis towards NE with almost subhorizontal plunge.

In the study area at few places, the interference of various fold generations has led to the development of structural basins and domes (Fig. VII.5, Fig.III.1).

Near Vajasan, south of Danta, the calcareous rocks show (F_1) folds such that these axes plunge at about 50° to 85° in NE and SW directions. Almost at right angles to this direction, the late (F_2) folds are developed with fold axis plunging in WNW and ESE directions. This is indicative of third fold episode (F_3) and the interference of two fold episodes has given rise to domes and basins and this corresponds to "Type I" folds of (Ramsay, 1967) (Fig. VII.5).

East of Nedardi, the calcareous rocks show 70° to 75° dips in SW and SE directions. At places even the vertical dips are recorded. These radial dips are suggestive of domal structure (Fig. VII.5) present in this area. The metagabbros within calc gneisses show both cryptic layering and granoblastic texture suggesting the granulite facies metamorphism as already discussed in chapters IV and VI. The author has

Fig. VII-4

STEREOGRAM SHOWING TREND OF F_1 FOLD AXES

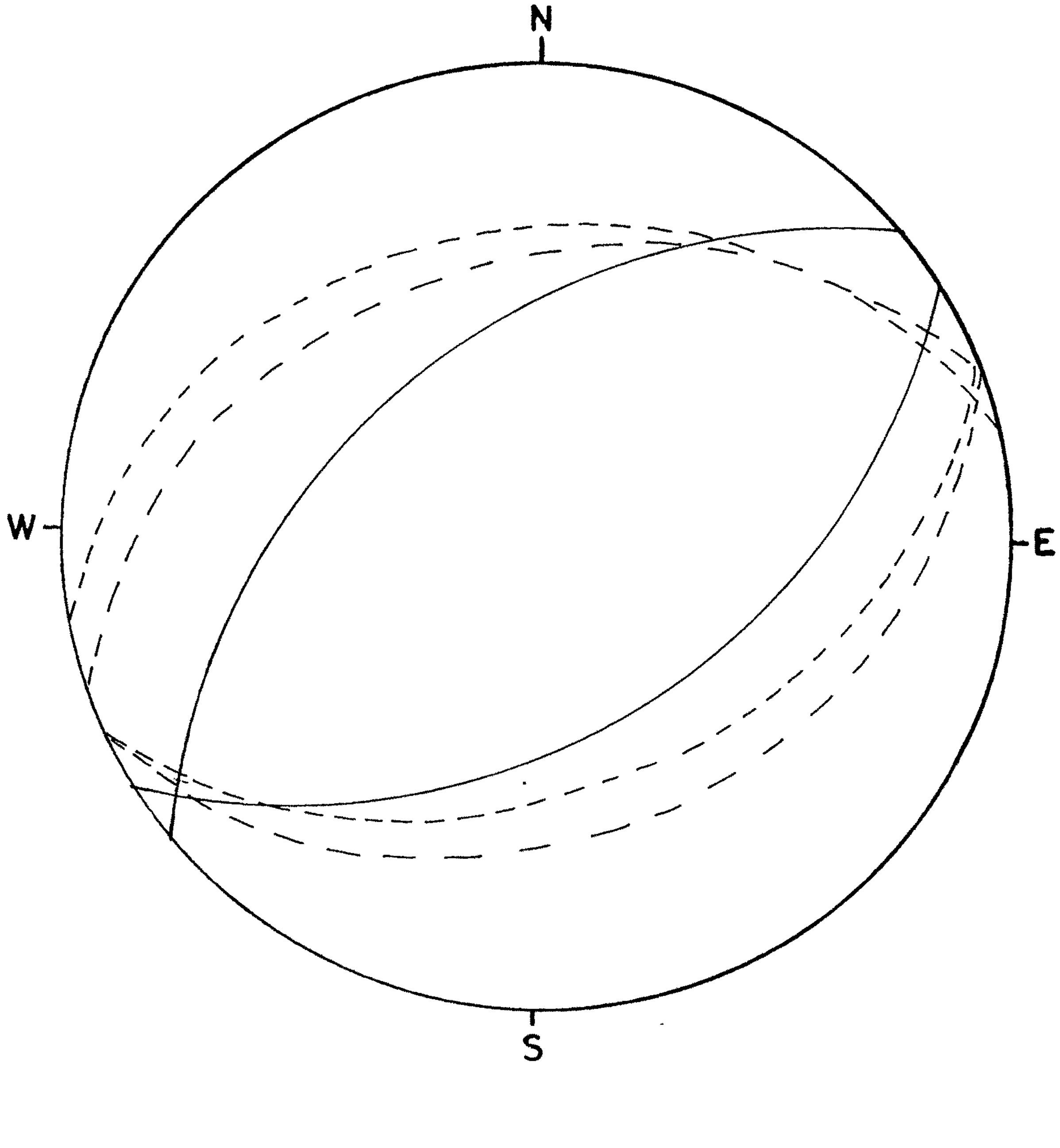
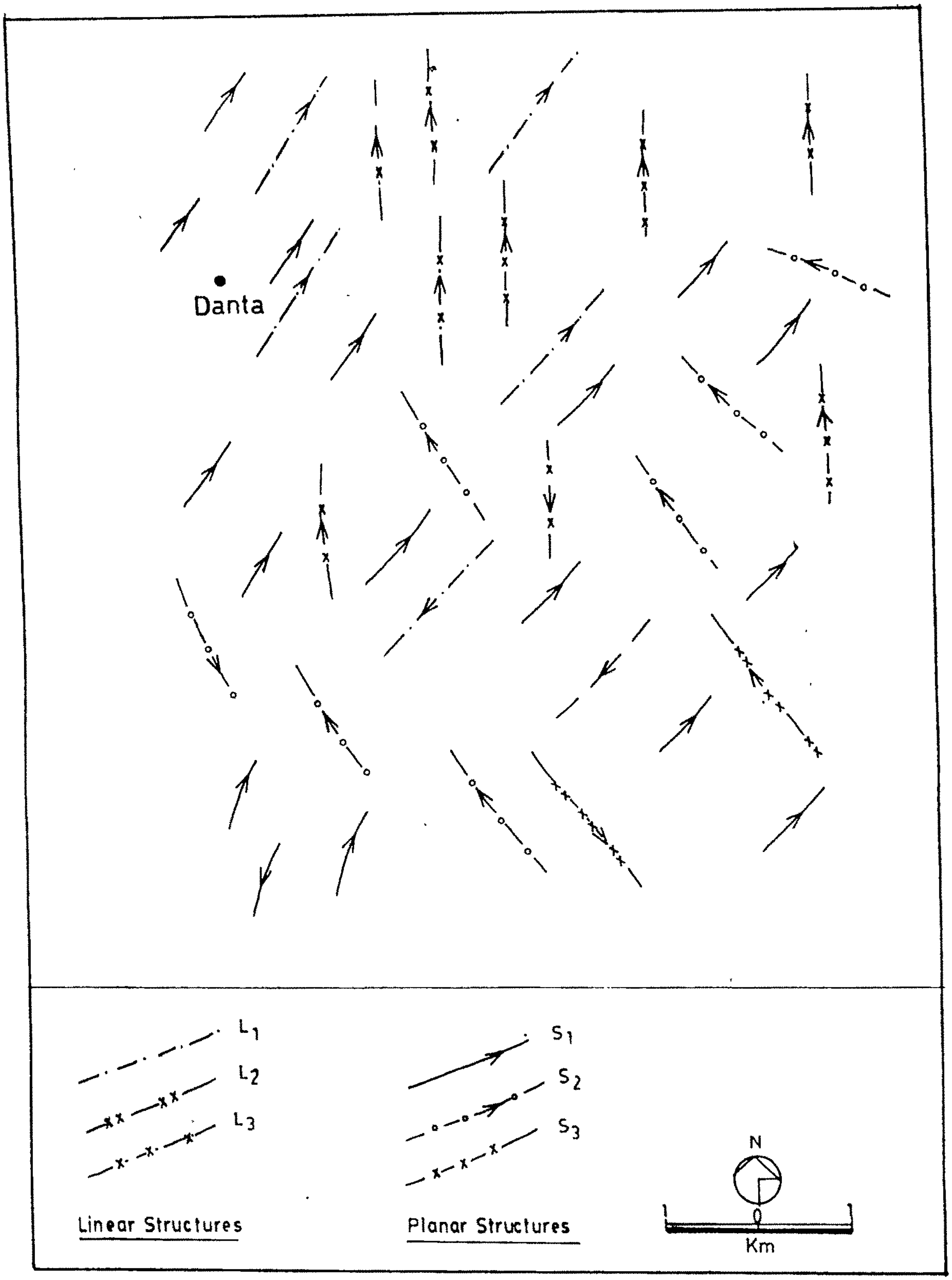


Fig. VII-5

TRENDS OF MINOR STRUCTURES IN DANTA AREA



refrained from using the term Basic charnockite' for these metagabbro bodies because of very sporadic development of hypersthene.

From the foregoing account, it is clear that NE-SW trending Delhi fold episode has left very strong imprint on the orientation of the outcrops. The earlier workers have indicated that (F_1) and (F_2) Delhi folding is synchronous. The consistencey of this fold episode and very strong development of mullions or quartz rodding lineations in calcareous rocks and the presence of only two dominant lithologies (calcareous members and pelitic members) has prompted the author to introduce in the study area, the concept of "flow folding" putforth by Wynne-Edwards (1963). This concept is not new in high grade metamorphic rocks and the structures suggesting pervasive movement (flow) have already been referred to in the literature as creep, plastic folds, rheid flow or viscous flow. Griggs and Handin (1960, p.348) have suggested three ways in which rock flow may take place :

(1) by cataclasis and intergranular movement,

(2) by intragranular gliding and twinning, and

(3) by melting, solution and diffusion.

Regardless of the interplay of these processes, they individually or collectively produce flow. From the structural map (Fig. VII.5) it will be revealed that refolding of L_1, L_2, L_3, does indicate the presence of cross folding or superimposition related to other deformations. However, the author has preferred to apply the simple principles of fluid mechanics in terms of nonuniform, unsteady viscous flow to rock deformations because the principle of fluid mechanics explains many complex features in high grade metamorphic terrains such as present one.

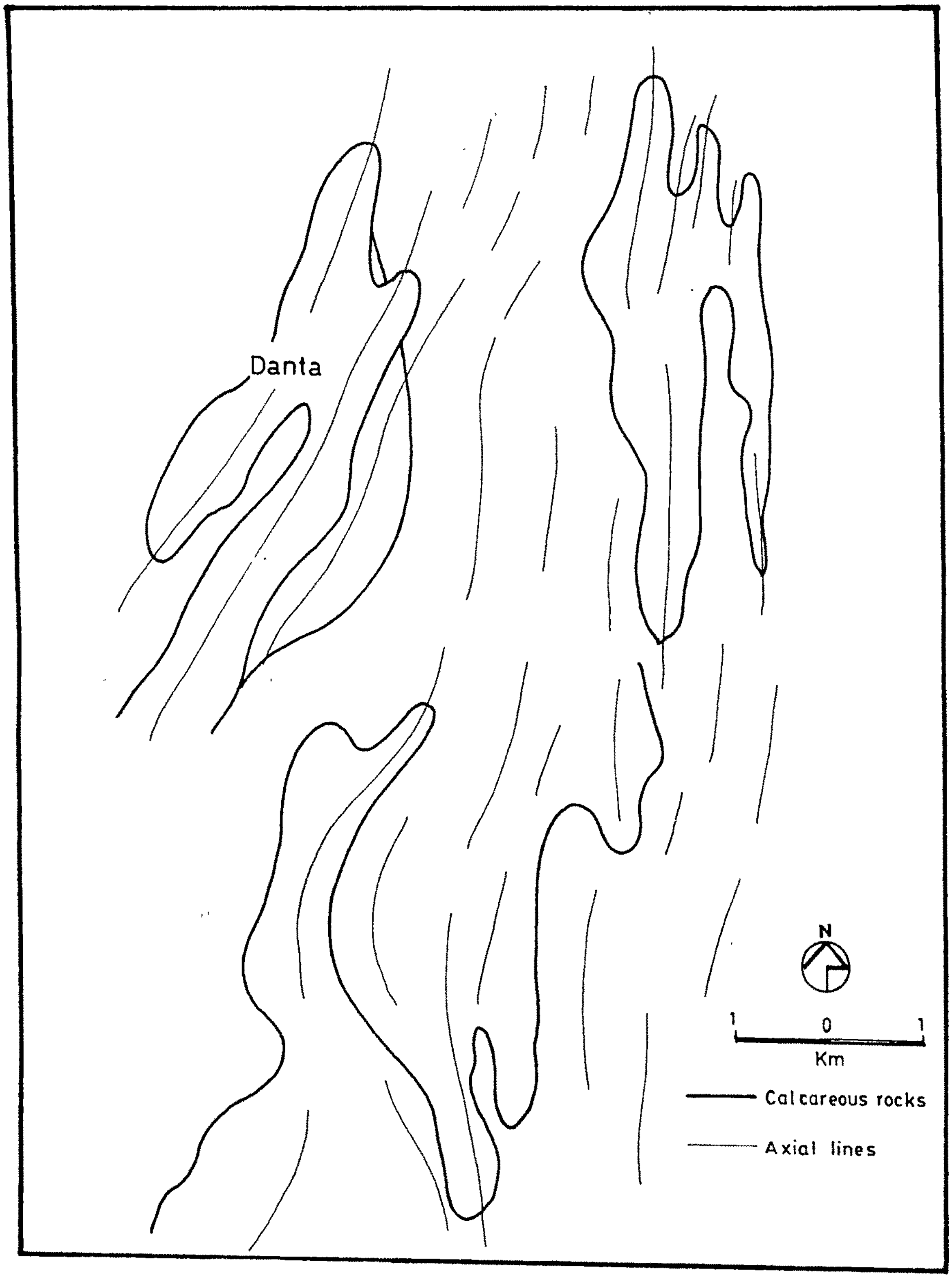
These high grade metamorphic rocks belonging to granulite to upper amphibolite facies show persistent NNE-SSW foliation that traces out the fold (Fig. VII.6) and is parallel to the original bedding. The structural pattern in the area also indicates isoclinal and upright folds (roughly similar folds) in which calcareous horizon is represented at different structural levels by refolding about the same axis (Plate VII.2). The major folds also continue for long distances and have parallel axial planes that represent flow laminae.

LITHOLOGY

The calcareous members are invariably characterised by the presence of bedding and the gneisses show irregular spacing and the individual layers between the foliation planes are massive and homogeneous but show variable thickness. The granitic rocks form concordant plutons and follow the linear

Fig. VII-6

MAP SHOWING AXIAL TRENDS



belts of calcareous and pelitic gneisses. The author thinks that these are thought to occupy what Wynne-Edwards (1957) described as "vortices" and linear belts in the flow pattern developed during later stage of deformation.

STRUCTURAL ELEMENTS

In the study area two major structural elements that merit attention in the calcareous as well as pelitic members are

(1) Ripples or corrugations on foliation surfaces (mullion structure) which are commonly accentuated by mineral segregation (Plate VII.1). They are parallel to the major and minor folds and are thus b' lineations.

(2) Stratiform foliation -prominent foliation i.e. bedding is shown by changes in lithology and at few places by the presence of undisturbed bedding in homogeneous layers (Plate VII.3). Stratiform foliation develops along bedding planes which are interfaces between the layers of different composition having different rates of flow. Such folds result from changing nature of strain from solid shear to viscous flow with increasing metamorphic grade and not from different types of stresses. The foliation is not only parallel to bedding but coincides with the actual bedding

Plate VII.3 Stratiform foliation in calcareous rocks (Loc. Divri).

Plate VII.4 Field photograph showing drag folds in calcareous rocks (Loc. Piplavali Vav).

planes where this marks changes in lithology. Deformation aided by differentiation and migmatization later on accentuated existing stratification but created no new layering.

Structure

In the study area, the rock shows folding of two major types (F_1) folds are mostly tight and isoclinal in nature with NNE-SSW trending axial planes parallel to the bedding and the (F_2) folds are upright. (F_1) folds are approximately similar folds and the fold axis of these folds plunge 55° to 60° towards NE or SW but in a general way the northeasterly trend is persistent in the entire area (Fig. VII.1). During the first stage, the similar folds were formed and all the rocks were deformed by essentially pervasive movement (flow). During the successive stage, the gneisses also stopped responding to stresses and the flow continued in the linear zones of calcareous rocks producing either mylonite or large drag folds in the gneisses at its boundaries and creating "vortices" in the flow pattern of calcareous rocks in these linear zones.

In the study area, the presence of drag folds (Plate VII.4) and the fault zone parallel to the linear belt near Nedardi supports this observation Sychanthavong and Merh (op. cit.). Ideally these vortices (low pressure structures) became the sites of granite emplacement. From the map (Fig.VII.5) it is obvious that the granites are essentially intruded or emplaced parallel to this flow direction i.e. NNE-SSW to NE-SW direction are linear and elongated. The last stage was marked by the prevention of flow in calcareous rocks. These stages are produced by changes in the competency of the rocks undergoing deformation rather than by changes in the system of stages. Although the folds appear quite regular, it is observed that the calcareous rocks are repeated at successive structural levels and several times within a single major fold (Fig.VII.6). Thus the folds have consistent northeasterly trend and appear refolded but it is possible that the refolding about the same axis i.e. synchronous refolding (Plate VII.5) is also an inevitable part of flow process and is the result of unsteady flow. The author has already stated that there is superimposed folding or crossfolding in the study area.

In order to appreciate this concept of "flow folding" putforth by Wynne-Edwards (1963) in Canada, the author has made an attempt to invoke this "flow folding" in the study area by considering two main parameters 1) Non-uniform laminar flow 2) Unsteady flow and synchronous refolding because they have analogy to structures found in the flow viscous fluids.

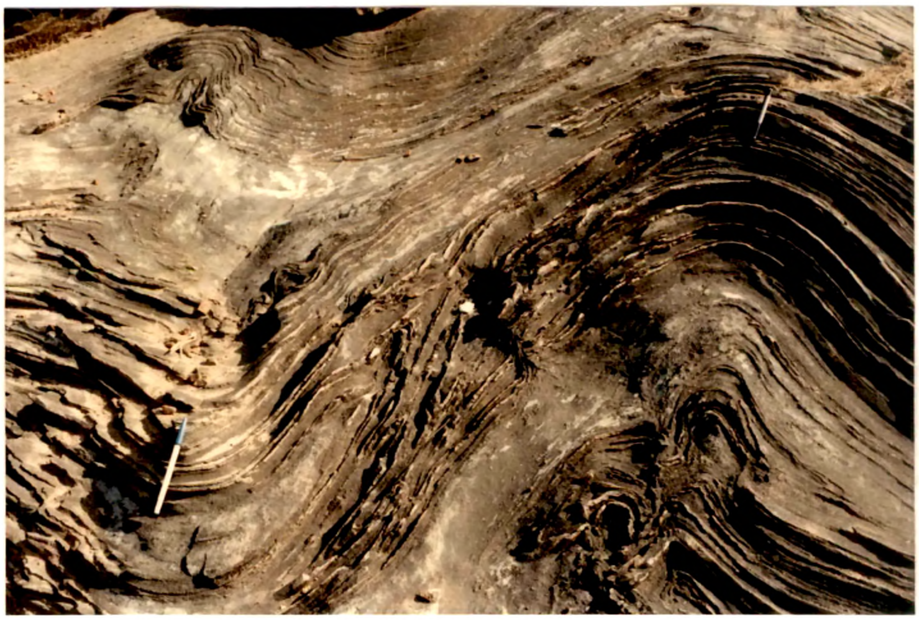


Plate VII.5 Field photograph showing synchronous refolding in calcgneisses (Loc. Vajasan).

Plate VII.6 Calcgneisses showing flexural slip (flow) foldings. (Loc. Vadvera).

Non-uniform laminar flow

According to Carey (1954), the materials which show fluid characteristics without being in a fluid state are termed as "rheid". He suggested that most rocks, especially held at elevated temperature, would have rheidities well within span of orogenesis and that they could be treated as viscous fluids. In the case of non-uniform laminar flow, the axial planes are roughly parallel and persist for considerable distances. If these axial planes are taken as representing flow planes, the pattern is one of laminae flow with a direction of movement being consistent i.e. NE in the present case. The flow takes place along closely spaced laminae which are planes of viscous shear in this type of flow folding. There is no lateral compression of the layers to produce these folds of similar type, where the layers are thickest at the nose of the folds and markedly thinned on the limbs. So in such case not only flow but contrasting lithologies also play an important role. The flow is mechanically independent of these layers and as long as flow is laminar there is no movement between them. Each layer possesses a different competence or viscosity and will therefore flow at a different rate. Therefore each composition boundary becomes surface of differential movement and the foliation is produced on actual bedding plane but not between them and not in original massive units. The least competent layers get concentrated in the trace of the folds because of variation in different rates of flow and indicates flexural slip folding (Plate VII.6). From the map (Fig. VII.5) it is clear that the least competent calcareous rocks have thickened and thinned throughout the study area. This variation in competence or the viscosity of the rocks is also controlled by their positions, compared to enclosing rock sequence, e.g. the pelitic gneisses in the study area are discontinuous, broken and deformed by flexural slip creating small concentric folds (Plate VII.7). Layers of relatively high competence may be segmented by this process. Wynne-Edwards (op.cit.) has suggested that concentric folds, similar folds and disharmonic fold may all originate by unsteady flow and synchronous refolding. The unsteady flow implies that the shapes of the folds (Plate VII.8a,b) change because of variation in flow rate and flow direction with time. In viscous materials, although the lengthening of the limb may be accompalished by stretching of the layers involved, the main effect is to force material across the general direction of flow.

Unsteady laminar flow

The movement of material at some angle to the general direction of flow becomes important and brings

Plate VII.7 Well developed concentric folds in calcgneisses (Loc. Vajapur).

Plate VII.8a Field photograph showing various shapes of folds in calcgneisses (Loc. Vajapur).

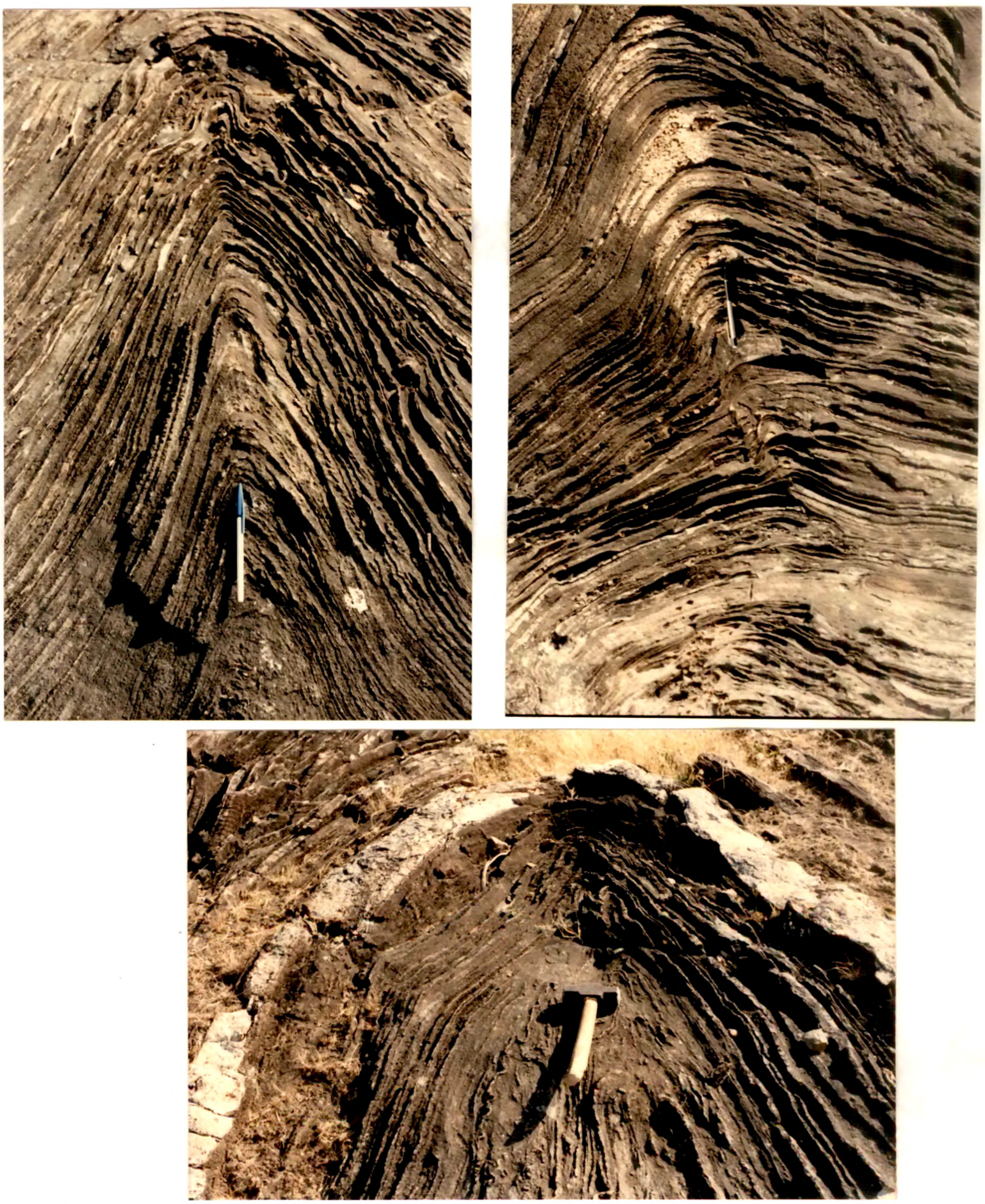


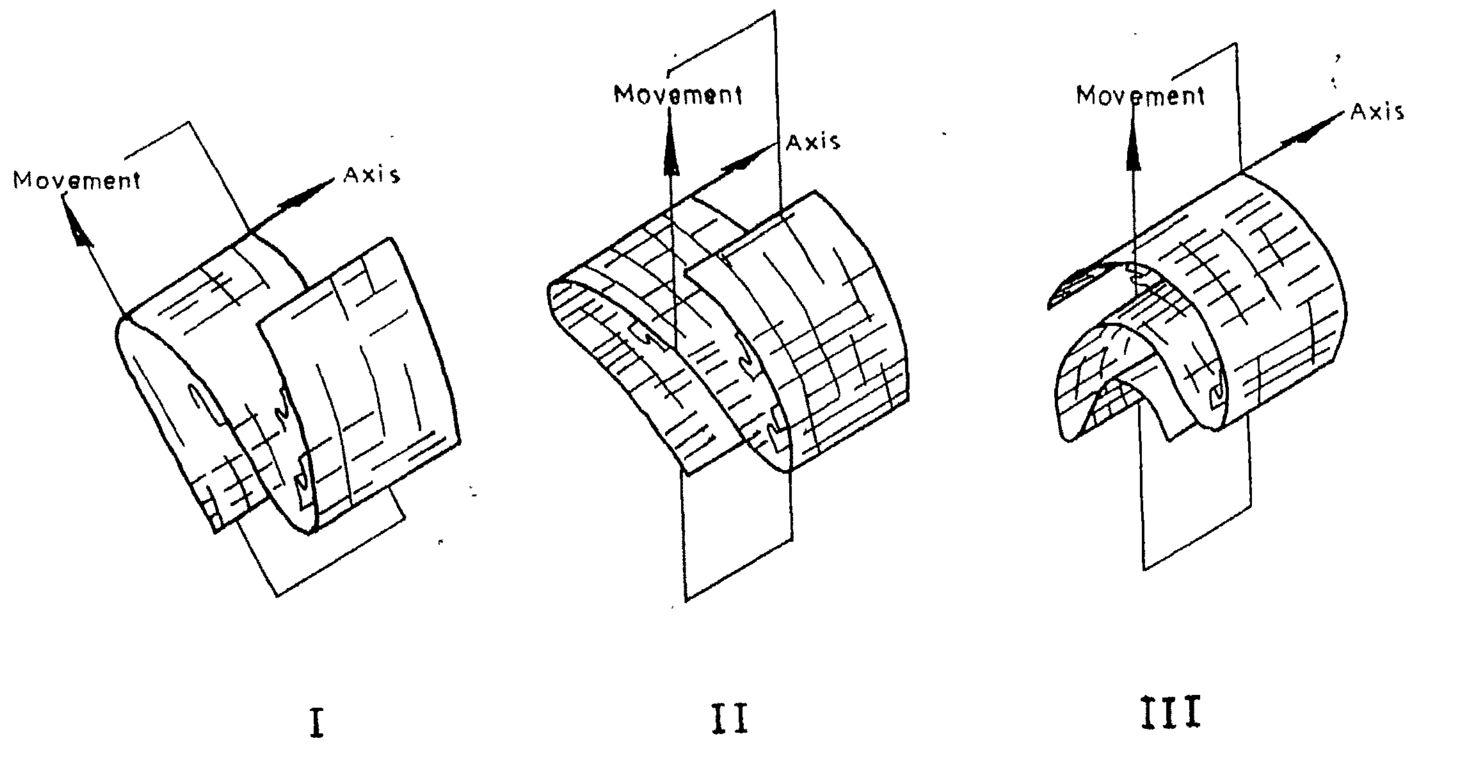
Plate VII.8b Field photograph showing various shapes of folds in calcgneisses (Loc. Kantivas).

about refolding as an integral part of the flow process. Due to unsteady nature of flow on account of presence of competent and incompetent layers, refolded folds are produced, such that there is uniform direction indicated by fold axis. Such refolding explains the formation of stratiform foliation because flow takes place along it. Refolded folds are also produced by small fluctuations in direction of flow. Any change in the direction will result into development of axial planes transverse to the new movement direction and hence they will be refolded by continued flow (Fig. VII.7). In the study area, the parallelism between fold axes of (F_1) and (F_2) folds (of previous workers) and overall isoclinal and upright folds may indicate the role of flow folding. In high grade metamorphics, the folds result from combination of concentric and shear folding. The development of stratiform foliation, and dominant NE fold axis in the present case have led the author to surmise that these structures have resulted from non-uniform laminar flow process. Whether this feature in the present case is the product of single protracted period of deformation or indicates refolding known as synchronous folding is a mute question.

It is not the intention of the present writer to suggest that there is no cross folding in the area under discussion. The opposite directions of L_1,L_2 lineations

Fig. VII-7

SUCCESSIVE STAGES OF THE DEVELOPMENT OF FOLDED FOLDS IN UNSTEADY FLOW BY A CHANGE IN THE DIRECTION OF MOVEMENT



(After Wynne-Edwards, 1967)

and the development of L_3 lineations, cannot be explained only by flow folding but wherever, there is coaxial folding it has to be explained by invoking this flow phenomena of Wynne-Edwards (op. cit.) but the development of the other late foliations and related lineations has to be explained by considering late deformation.

The previous workers have advocated two to three fold episodes during Delhi deformation but instead of connecting all these fold episodes to Delhi deformation, the present author thinks it more logical to suggest that in the earliest deformation [Pre-Delhi (?)] such flow folding cannot be ruled out and even the grade of metamorphism is upper amphibolite to granulite facies. Moreover, the parallelism between (F_1) and (F_2) fold axes envisaged by previous workers as well as the variation in shapes of the folds can also be explained by invoking flow folding. What one encounters today is the total causative factors related to Pre-Delhi and Delhi deformation.