CHAPTER V

STRUCTURAL GEOLOGY

The structure of the area has been worked out mainly on the basis of a detailed lithological and structural mapping of all outcrops of the various rocks formations in the area (Fig.V.1 & 2).

As already mentioned earlier, the Ramgarh/ Mukteswar area comprises two tectonically distinct units. The rocks of the Upper Schistose group, Mukteswar gneissic group and Bhulmaria schists and phyllonites form a part of the Almora nappe of Heim and Gansser (1939). The older crystalline rocks are separated from the underlying younger quartzites and phyllites of the Krol nappe by the South Almora thrust. The author's investigations have revealed that the rocks of the two tectonic units contain distinctive structural characters. The various structural elements - both planar as well as linear, show definite genetical relationship with the major structures. Each of the different tectonic episodes, has left some marks on the rocks, and thus the sequences of various episodes have been worked out for both the units separately on the basis of a detailed and systematic analysis of the various structural elements (Table.V.1.).

The author, before proceeding with the systematic discussion of the structural characters of the rocks, has preferred to give below, a summary of the main structural events of the area.

(1) Isoclinal folding (F_1) of the geosynclinal (perhaps already metamorphosed) sediments with the development of the axial plane foliation (S_1), which now characterises the main schistosity of the rocks. The related fold axis lineation (L_1) is characterised by axes of minor folds, striping due to cleavage-bedding intersection, quartz rods and mineral orientation etc.

TABLE V.1

MINOR STRUCTURES DEVELOPED DURING DIFFERENT TECTONIC EVENTS IN THE ROCKS OF THE RAMGARH-MUKTESWAR AREA

TECTONIC EVENTS		ALMORA NAPPE PLANAR STRUCTURES		ALMORA NAPPE LINEAR STRUCTURES		KROL NAPPE PLANAR STRUCTURES		KROL NAPPE LINEAR STRUCTURES	
I ISOCLINAL FOLDING	(F_1)	Schistosity and gneissic foliation; Axial planes of minor folds	(S_1)	Axes of minor folds on S; Quartz rods & boudinage; Mineral orientation; Striping or ribbons; Axes of folded quartz veins	(L_1)	--		--	
II DEVELOPMENT OF ALMORA THRUST		Phyllonitic cleavage; Axial planes of drag folds	(S_2)	Axes of drag folds; Kink bands	(L_2)	Slaty & phyllitic cleavages	(S_2)	Occasional drag folds	(L_2)
III SYNFORMAL FOLDING	(F_2)	Axial planes of crenulation and microfolds and the related strain-slip cleavages	(S_3)	Axes of the microfolds and puckering; Intersection of S_1 & S_2	(L_3)	Strain-slip cleavage developed due to crenulation and crinkling of S_2	(S_3)	Fold axes of crinkles, crenulation and puckers; Intersection of S_2 & S_3	(L_3)
IV E-W FOLDING	(F_3)	--		--		Axial planes of a few stray minor folds in quartzites	(S_4)	Axes of minor folds	(L_4)
V RAMGARH THRUST		--		--		Strain-slip cleavage in the crinkles due to drag	(S_5)	Slickenside 'a' lineation	(L_5)
								Axes of micro-folds and crinkles, puckering and boudinage; Intersection of S_2 & S_5	(L_6)
VI NNE-SSW FOLDING	(F_4)	--		Axes of flexures, minor folds puckering	(L_7)			Axes of flexures, minor folds & puckers	(L_7)

(2) <u>Culmination of isoclinal folding into the Almora thrust</u> due to continued deformation accompanied by slipping and shearing resulting into a phyllonitic cleavage (S_2) and drag folding of the foliation (S_1). Axes of these drag folds mark the linear structure (L_2). The strong slaty and phyllitic cleavage in the underlying rocks of Krol nappe developed during this movement.

(3) <u>Synformal folding (F_2) of the Almora thrust</u> accompanied by microfolding and crinkling of the schistosity (S_1). The axes of these microfolds and crinkles, seen as distinct puckering characterise the related lineation (L_3). This folding gave rise to the anticline at Bhowali, and also to some small anticlines and synclines in the Krol nappe rocks near Khairna. Only microfolds and puckers related to this fold episode are seen in the rocks of the study area.

(4) <u>Superimposition of an E-W folding (F_3)</u> on the Krol nappe rocks of Naini Tal and Bhowali area, resulting into considerable distortion of the syncline of Naini Tal and the anticline of Bhowali.

Effects of this folding are not much recorded in the study area.

(5) Development of the Ramgarh thrust cutting the F_2 and F_3 structures obliquely. It is a high angled dislocation, bringing older Deobans over Nagthats. Intense shearing accompanied by the development of a strong 'a' lineation (L_5) of the nature of slickensides, is the most conspicuous feature of the thrust.

(6) NE-SW to NNE-SSW open folding (F_4) of the entire terrain. Regional flexures related to this fold episode are seen in rocks of both the tectonic units, and the related microfolds and crinkles (L_7) are sporadically developed. The axial planes of these folds are almost upright and the axes plunge due NNE to NE.

STRUCTURAL ELEMENTS OF THE ROCKS OF ALMORA NAPPE

The Almora nappe rocks lying within the study area, comprise a portion of the southern flank of the synformally folded nappe. The two gneissic (migmatitic) bands perhaps indicate the existence of atleast two isoclinal folds (F_1), the gneisses occurring in the fold cores. The rocks of Almora nappe contain structural elements related to F_1, Almora thrust, F_2 and F_4 only.

Planar structures related to the isoclinal folding (F_1)

Schistosity and gneissic foliation (S_1): The main foliation of the schists and migmatites characterises the axial-plane of the isoclinal folding. The schistosity typically shows the axial-plane relationship with small folds, and it is thus obvious that the same relationship exists between the regional schistosity and the major (F_1) structures. The parallelism of bedding and foliation (S_1) is due to the isoclinal nature of F_1 folding. This S_1 schistosity however, has not developed directly from the unmetamorphosed state as suggested by Merh and Vashi (1965 p.56) and Merh (1968 p.3) and it has been observed by the author that the S_1 is derived by a very tight microfolding of an earlier load schistosity (S). Textural evidences of a pre-existing metamorphic cleavage, have been discussed elsewhere in this thesis. Similar phenomenon has been observed by Desai (1968) in the Majkhali area near Ranikhet and by Das (1968) in the Chaukhutia area. A.N. Shah has also recorded mica orientation in gneisses of Almora indicating an early foliation crinkled on F_1 folding. Petrographic studies have further revealed that the foliation (S_1) is not a phenomenon of simple compression alone, but the shearing stresses have also played a role in its development. The rotated garnets of the schists indicate differential slipping along the foliation during their crystallisation. This dynamic phase of regional metamorphism was closely related with the migmatisation, and as a result the schists were transformed into gneisses. Thus, the gneissic foliation and the schistosity are genetically identical.

Axial-planes of minor folds (S_1): Thin quartzitic layers and quartz veins occuring within the schistose mass show 'intra-folial' minor folds (Turner and Weiss 1963, p. 117) in all parts of the Mukteswar area. These minor folds are seen in quartzitic layers and quartz veins. The schistosity shows axial-plane relationship with these folds and the minor folds reflect the geometry of the major structures. It is recorded that the minor folds to the north of the gneissic bands generally show 'S' shape while those to their south are of 'Z' shape, indicating that the gneisses form fold cores.

<u>Linear structures related to the isoclinal folding F_1</u>

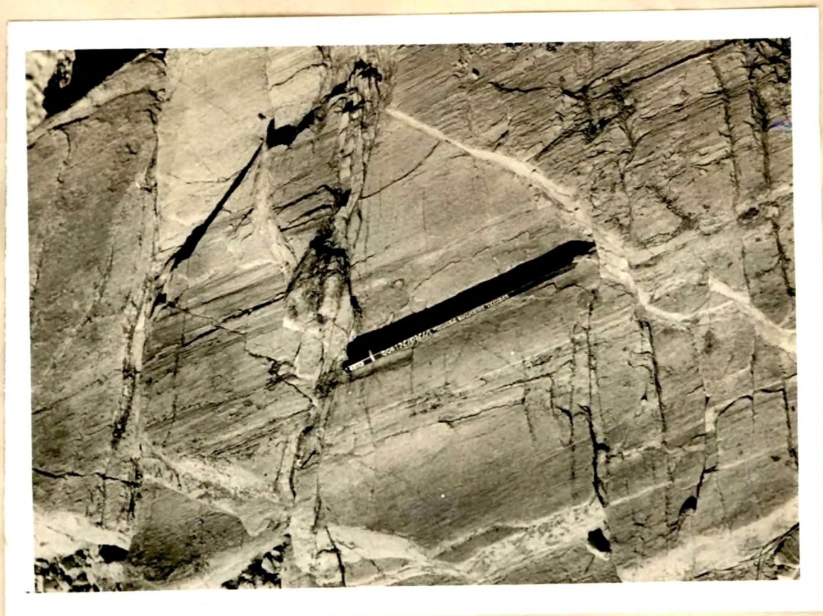
The various lineations related to F_1 folding and described below show identical orientation and plunge moderately due N to NNE.

<u>Axes of minor folds including mullions (L_1)</u>: The axes of the almost reclined minor folds shown by the thin layers of quartzites and quartz veins in schists characterise the lineation (L_1). At some places quartzite bands have been repeatedly so folded that they have developed fold mullions.

<u>Quartz rods and boudinage (L_1)</u>: Quartz rods and boudins occur very frequently in the schistose rocks. These never exceed a few centimetres in length. The quartz rods have developed due to the involvement of quartz veins in F_1 folding, and they typically represent 'rootless intrafolial folds' of Turner and Weiss (1963 p. 117). Boudinaging is an indication of the stretching to which thin quartzite layers were subjected during the differential slipping of the schistose matrix.

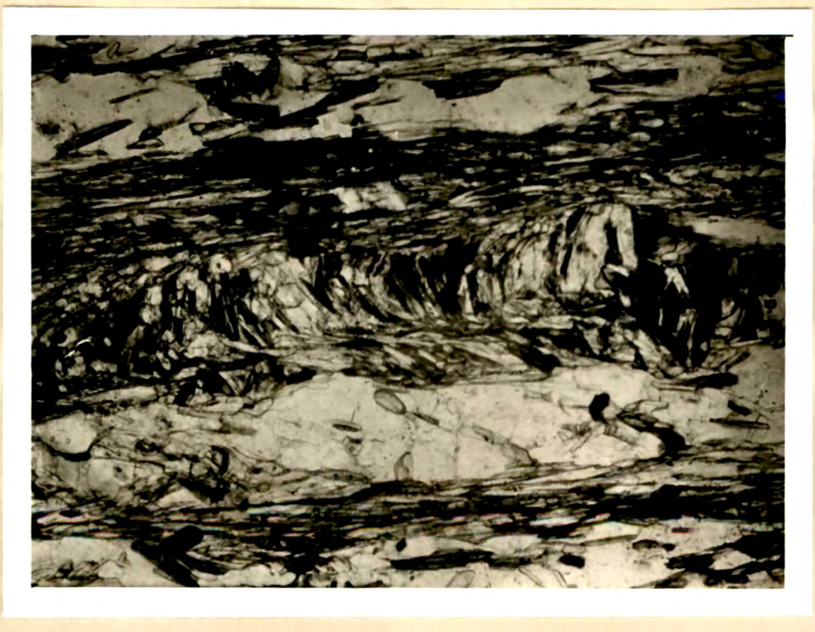
<u>Lineation due to striping (ribbons) (L_1)</u>: This type of lineation is often recorded in flaggy quartzites and has developed on account of the intersection of cleavage (S_1) and bedding (Plate V.1A).

PLATE V.1A



Ribbon lineation (L_1) in flaggy quartzites of Almora Nappe (Loc. Half a mile east of Bhulmaria).

PLATE V.1B



Drag fold in phyllonites (L_2).
(Photomicrograph X60)

Mineral orientation (L_1): This lineation is parallel to the fold axis, characterised by a fine linear arrangement of mica flakes in schistose and gneissic rocks. It appears that these elongated flakes of mica have originated along the beddings and S_1 intersection.

Planar structures related to the South Almora thrust

Phyllonitic cleavage (S_2): The isoclinal folding culminated into the Almora thrust and the sudden dislocation caused intense shearing and crushing in the vicinity of the thrust. The resulting retrograde phyllonitic rocks are characterised by the formation of a fine shear cleavage (S_2) which almost coincides with the main schistosity (S_1).

Axial planes of the drag folds (S_2): Numerous drag folds have developed in the vicinity of the thrust. These drags have folded the schistosity (S_1) during the sudden movement of the rocks along the thrust plane. The axial-plane of these drag folds have the same orientation as that of the phyllonitic cleavage (Plate V.1B).

Linear structures related to the S. Almora thrust

Axes of drag folds (L_2): This fold axis lineation is widespread in the immediate vicinity of the South Almora thrust where the rocks show intense drag folding on megascopic as well as microscopic scale.

Kink bands (L_2): The Kink bands are developed in phyllonites in the vicinity of the South Almora thrust and are obviously related to drag effects along the thrust. These are seen as fine puckering of the phyllonitic cleavage (S_2). The Kinks are angular, step-like monoclinal folds with narrow hinges formed due to angular deflection of the foliae. Genetically, these kinks are identical to the drag folds (Plate V.2).

Planar structures related to the folding of the Almora thrust (F_2):

Strain-slip cleavage (S_3): The widespread micro-folding of S_1 schistosity into crinkles of herringbone and chevron type, has taken place during the folding of the thrust. At some places the micro-folding is so sharp and angular that hinges have broken giving rise to a strain-slip cleavage along the axial plane of the folds. This cleavage strikes E-W to WNW-ESE, shows steep northerly dips and cuts across the (S_1) foliation. Thin sections show recrystallised fractured hinges with new mica flakes growing along the new cleavage, oblique to the schistosity.

Linear structures related to the folding of the Almora thrust (F_2):

Axes of microfolds (S_3): The axes of crinkles and the herringbone and chevron type minor folds characterise the

PLATE V.2

Drag puckers (kinks) in phyllonites (Loc. Near Bhulmaria).

lineation (L_3). Generally it is seen as a very fine and distinct puckering. The lineation (L_3) is mostly sub-horizontal or shows very gentle plunge either due WNW or ESE.

Planar structures related to the NNE-SSW folding (F_4)

This folding (F_4) has affected the rocks by gently flexuring them into a number of regional folds. Few planar structures have developed during this folding, though microfolds and crinkles related to it are sometimes encountered. Desai (1968) has reported stray occurrences of a strain-slip cleavage related to this fold episode from the nearby Majkhali area.

Linear structures related to the NNE-SSW folding (F_4)

Axes of microfolds (L_7): This folding has given rise to a faint and sporadic puckering (L_7) which shows a gentle plunge due NNE to NE.

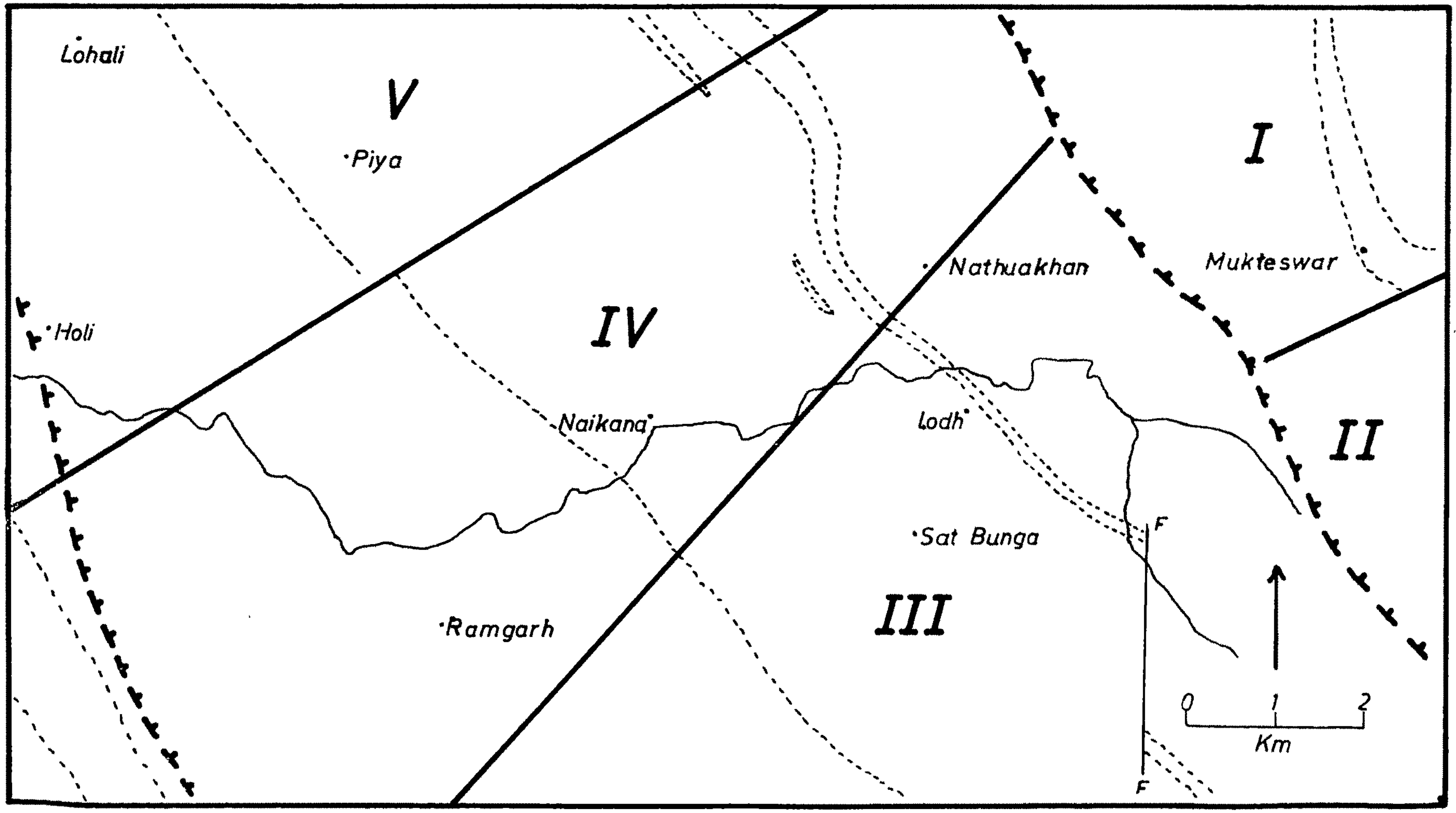
Structural Analysis

For the purpose of a detailed structural analysis of the various mesoscopic structures, the techniques adopted by Ramsay (1958,1960) and Turner & Weiss (1963) have been generally followed. The scope of the analysis is based on the assumption that the minor structures, both planar and linear observed in a small area reflect the broad structural pattern on regional scale. The author divided the terrain occupied by the Almora nappe into two Sub-areas, and the various linear and planar structures of different generations encountered in the respective Sub-areas were analysed. The different structural elements were plotted on Schmidt's Equal-Area Net and several stereograms (mainly π , β and Collective diagrams) prepared. These stereograms have borne out the structural characteristics of the two Sub-areas very well, and proved very useful in working out the tectonic pattern and the structural history.

Sub-area I: This sub-area comprises the ground around Mukteswar and to its north (Fig.V.3) and includes almost all types of rocks of the Almora nappe. Planar and linear structures related to the various fold episodes are quite distinctly preserved and are easily recognised and distinguished. Bedding schistosity (S) is nowhere recorded and the most conspicuous foliation is the schistosity (S_1). Nearer to the thrust, shearing along S_1 has given rise to the phyllonitic cleavage (S_2), both having identical orientation. Effects of F_2 and F_4 are distinctly recorded. The S_1 shows variable moderate dip due NE, but the strike fluctuates from as much as WNW-ESE to almost NS. The variation in the amount of dips is due to the effect of F_2, and that

Fig.V.3.

Sketch map showing the sub-areas



in the strike trend is due to F_4. Crinkling and microfolding of S_1 during F_2 is present but not widespread. Only a few exposures show tiny chevron folds quite often with an associated strain-slip cleavage (S_3). This cleavage is seen to be steeply dipping due north. Textural studies have revealed that strain-slip cleavage is due to the fracturing of the chevron type microfolds and subsequent recrystallisation. The lineation (L_1) related to F_1 comprises minor fold axes of reclined folds in quartzites and quartz veins, quartz rods, boundins, mineral orientation and striping. This lineation shows a gentle to moderate plunge due N to NNW. The (L_2) lineation confined to phyllonites consists mostly of axes of tiny kinks. Drag folds are scarce. The orientations of L_1 and L_2 are identical. The lineation L_3 which is not very common but sporadically recorded all over as axes of F_2 microfolds, is almost sub-horizontal showing plunge of a few degrees only in the NW-SE sectors. The actual plunge direction fluctuates between NNW-WNW and SSE-ESE. This variation in the plunge direction appears to be due to F_4 folding. As the flexures related to F_4 are open, the strike of S_1 varies gently between NNW-SSE to WNW-ESE. The stereogram showing

L_3 and L_7 in relation to the orientation of various S_1 planes, clearly explains the scattering of L_3 (Fig.V.4). The variation in the amount of dip of S_1 is obviously an effect of F_2 flexures, but this effect does not come out clearly in the stereograms. The fluctuation in strike direction, however, is very clearly due to F_4 folds. In the π S_1 diagram the poles lie on a girdle whose β coincides with the L_7 (Fig.V.5).

Sub-area II: The rocks to the S and SE of Mukteswar lie within this Sub-area. The rock types and various structural elements belonging to the different tectonic episodes are same as those recorded in the Sub-area I. F_2 crinkles are sporadic but conspicuous, while large flexures on F_4 are almost absent. The L_1 is more of the nature of ribbons or stripes, due to S and S_1 intersection. The L_2 is represented by mesoscopic drag folds instead of tiny kinks L_7 comprises axes of tiny F_4 flexures and forms a faint puckering with a north-easterly plunge. The stereograms do not reveal much except the variation in the L_3 direction. The S_1 poles however show a tendency to form a girdle whose β coincides with F_2 fold axis (Fig.V.6).

Fig.-V.4.

Stereogram showing the relationship between L_3 and L_7 in the sub-area I.

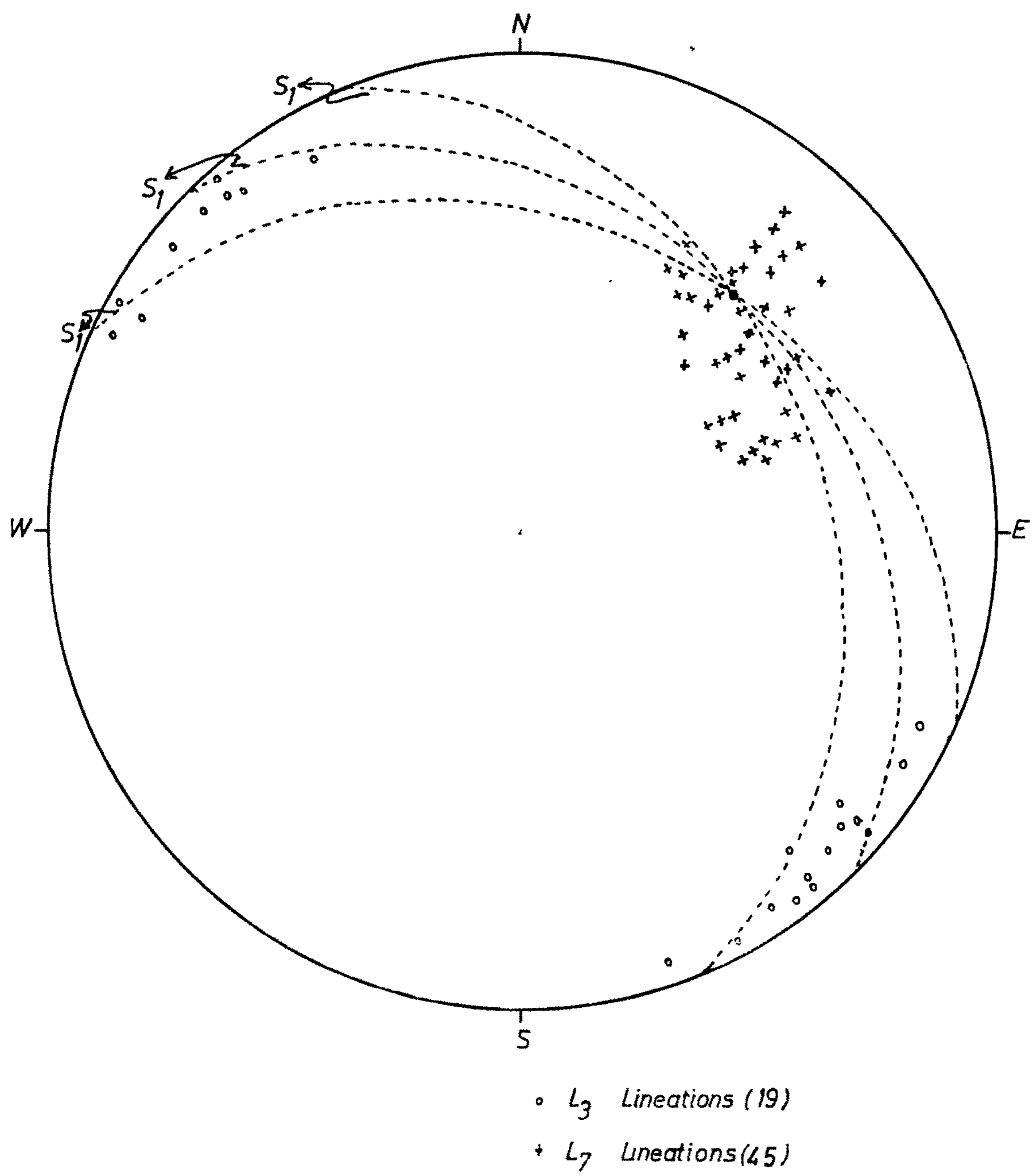
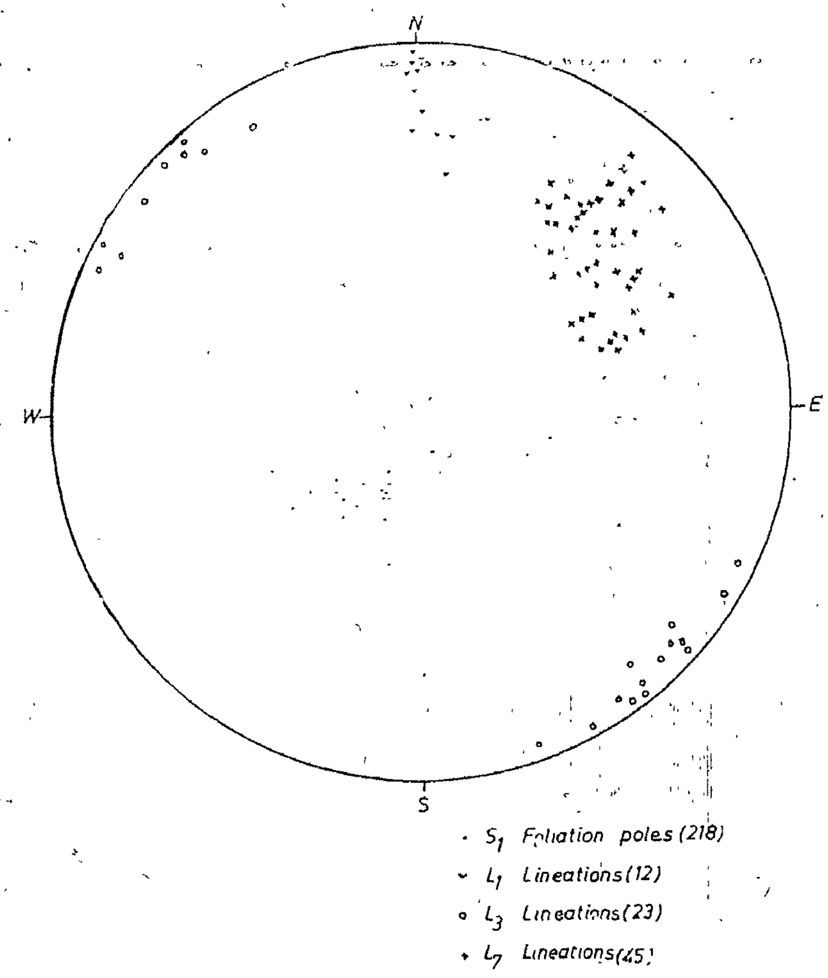


Fig.-V.5.

Stereograms showing the structure of the sub-area I.

A

Various structural elememts.



B

Effect of F_4 on S_1

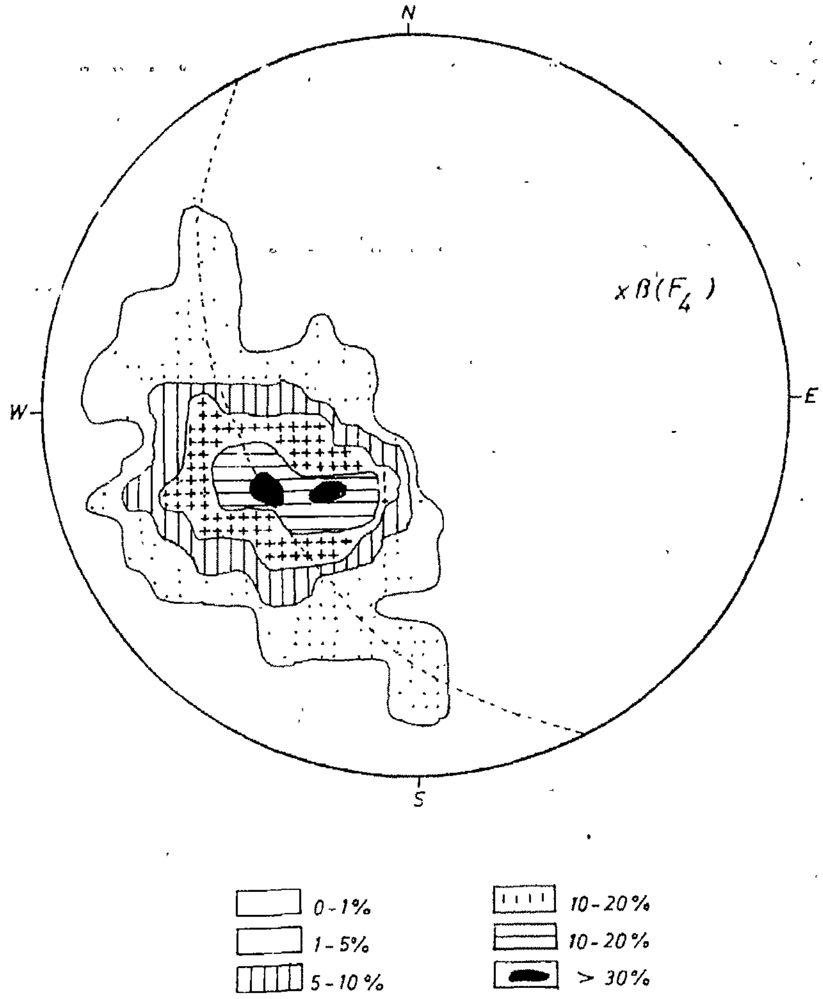


Fig.- V. 6.

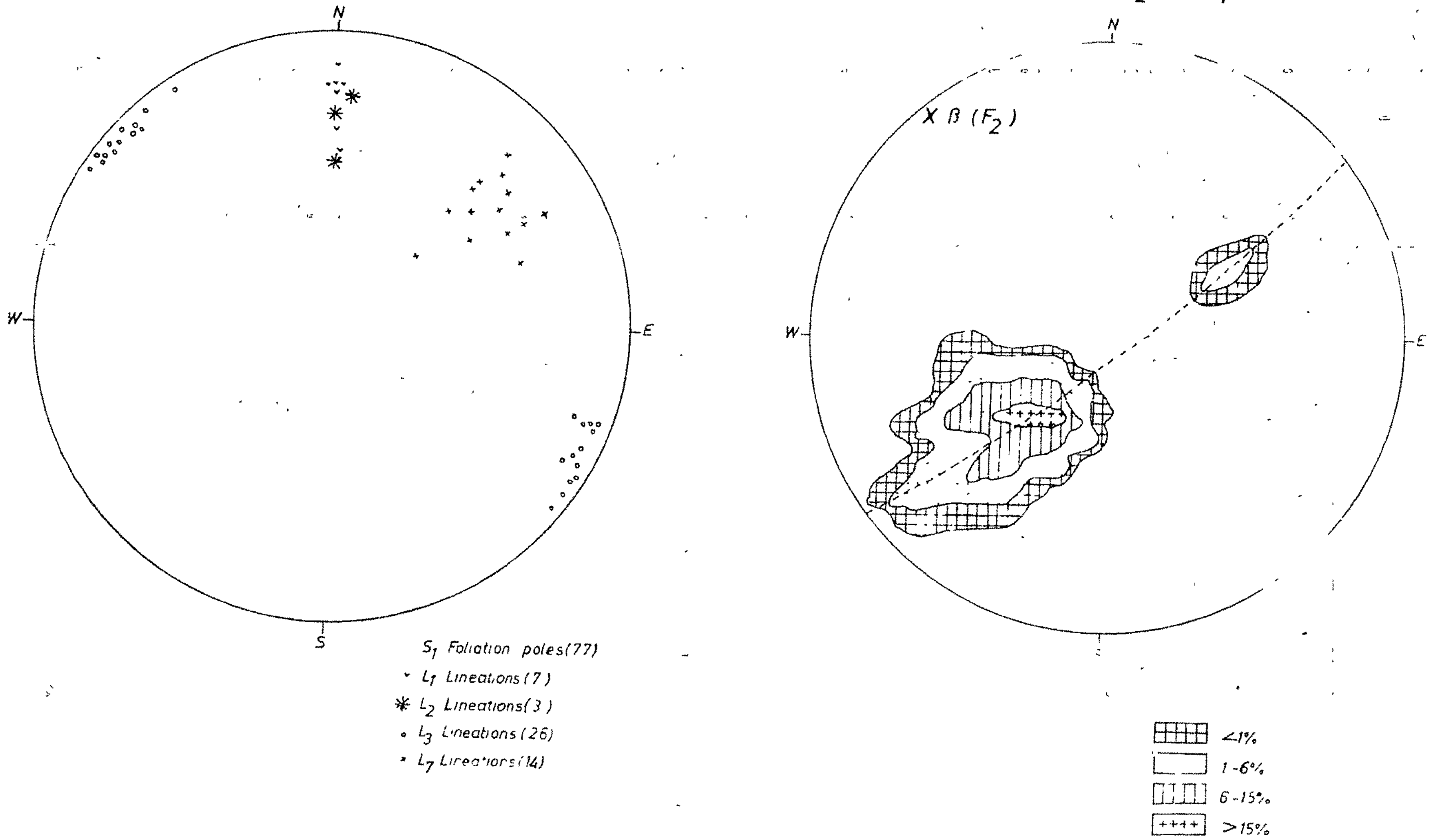
Stereograms showing the structure of the sub-area II.

A

Various structural elements

B

Effect of F_2 on S_1.



Structural Synthesis

The critical analysis of the structural elements of the two Sub-areas,of Almora nappe reveal that (1) S_1 is the axial plane cleavage of F_1, (2) S_1 is folded by F_2 into crinkles and related S_3 strain-slip cleavage has developed, (3) S_1 and S_3 are folded by F_4 into gentle flexures, and (4) the scattering of the sub-horizontal L_3 is due to F_4.

STRUCTURAL ELEMENTS OF THE ROCKS OF KROL NAPPE

The rocks of Krol nappe, lying beneath the South Almora thrust, can be said to form the north-eastern limb of the Bhowali anticline. All the formations show a north-easterly dip. Mesoscopic flexures and the resulting variation in the strike trend are due to F_4 folding. The most conspicuous regional structure in the rocks is the NW-SE extending Ramgarh thrust, which has pushed the Deobans over the Nagthats. The rocks of Krol nappe have preserved within them structural elements related to almost all the major events except F_1.

Planar structures related to the South Almora thrust

Phyllitic and slaty cleavage (S_2): The slaty or phyllitic rocks that occur interbedded with quartzites below the South Almora thrust show a well developed metamorphic cleavage which is parallel to the bedding. This metamorphic cleavage appears to have developed during the Almora thrust movement. On entering the Krol nappe from Almora nappe, it is found very difficult to demarcate the contact between phyllonite and phyllite. The phyllitic and phyllonitic cleavages are contemporaneous, having developed by slipping and shearing related to the Almora thrust. It is however quite likely that this S_2 cleavage became more pronounced during the flexural slip along folds that developed during the synformal folding (F_2).

Linear structures related to the South Almora thrust

Axes of drag folds (L_2): The phyllitic rocks show drag folds at some places just below the South Almora thrust. The orientation of the fold axes L_2 of these drag folds coincides with that of drag folds of the Almora nappe in the vicinity of the thrust.

Planar structures related to the folding of ~~South~~ Almora thrust (F_2)

Axial planes of chevron folds and strain-slip cleavage (S_3): Effect of F_2 folding is generally recorded in the phyllitic rocks lying between the South Almora thrust and the Sayalgad limestone, in the form of tiny chevron folds. The fracturing of hinges of these microfolds has resulted into a strain-slip cleavage S_3. The southern limbs of these micro-folds are steeply dipping while the northern limbs dip rather gently, such that the axial plane (S_3) is steeply inclined due NE.

Linear structures related to the folding of ~~South~~ Almora thrust

Axes of microfolds (L_3): These are developed mostly in the phyllites that occur in the Lusgaini and Sayalgad formations. Sometimes small folded quartzitic layers indicate this fold axis lineation, but the most common variety, however, is the distinct puckering. This puckering is distinguished from that related to the Ramgarh thrust (L_6) by the scrutiny of axial planes.

Planar structures related to the E-W folding (F_3)

Axial planes of small folds (S_4): But for a few minor folds in the Titoli quartzites to the west of the Ramgarh thrust, no structures related to this fold episode are recorded in major part of the area. The axial planes S_4 of these small folds can be considered as the only planar structure of F_3 origin.

Linear structures related to the E-W folding (F_3)

Fold axes of minor folds (L_4): Fold axes of stray F_3 minor folds in the above quartzites, west of Ramgarh thrust, comprise the only lineations L_4 recorded.

Planar structures related to the Ramgarh thrust

Strain-slip cleavage (S_5): During the Ramgarh thrust movement the phyllitic rocks above the dislocation developed monoclinal flexures on all scales, obviously due to some kind of drag effect.

These are seen to vary in size from mesoscopic to microscopic scale. The most characteristic features of these folds are their angular hinges and SW dipping axial planes. Extensive slipping along numerous shear planes (somewhat parallel to the axial planes of these flexures) has in turn crinkled the schistosity and given rise to a crenulation and a strain-slip cleavage. The fractured axial planes of the monoclinal angular folds and the associated strain-slip planes comprise the dominant planar structure (S_5).

Linear structure related to the Ramgarh thrust

Slickenside (L_5): Extensive slickensides have developed due to the slipping of the foliae during the

Ramgarh thrust movement. This slickenside lineation (L_5) indicates the actual direction of slipping, and is of the nature 'a' lineation (Plate III.8A).

Axes of tiny crinkles (L_6): Axes of the tiny monoclinal crinkles and microfolds related to the drag folding comprise a distinct puckering and show widespread development in the vicinity of the Ramgarh thrust. The orientation of these puckers is the same as of those related to F_2, but the former are distinguished by their very gentle SW dipping axial planes and strain-slip (S_5).

Lineation due to S_2 and S_5 intersection (L_6): Wherever the strain-slip cleavage (S_5) is prominent, its intersection with the main cleavage (S_2) has given rise to fine striations. This type of lineation shows same orientation as the other related types.

Bou~~n~~dinage (L_6): Differential slipping along the foliation planes (S_2) have sometimes stretched and bou~~n~~dinaged thin quartzite layers (Plate III.8B). Axes of these bou~~n~~dins marks another variety of lineation parallel to the fold axis (L_6).

Planar structure related to the NNE-SSW to NE-SW folding(F_4)

The author did not come across any planar structure that could be assigned to this episode. Perhaps they have scantily developed in the study area. But Desai (1968) has reported crinkling and stray development of a strain-slip cleavage related to this folding.

Linear structures related to the NNE-SSW to NE-SW folding(F_4)

Axes of crinkles (L_7): Faint puckers (L_7) characterising the axes of crinkles related to this folding are not very abundant but common enough to be recorded.

Structural Analysis

The structural pattern of the Krol nappe rocks is significantly different from that of the Almora nappe. Though a considerable portion of the structural history is common to both the units the Krol nappe shows much more diversity of structural elements. The major structures of the nappe enumerated above, are each represented by the respective minor structures and critical analysis of the attitude and behaviour of the various structural elements, has led the author to a complete unravelling of the complex structural history. For this analysis the area of Krol nappe was divided into 3 sub-areas (III, IV and V) (Fig.V.3) and each sub-area was investigated in detail, the results of which are given below.

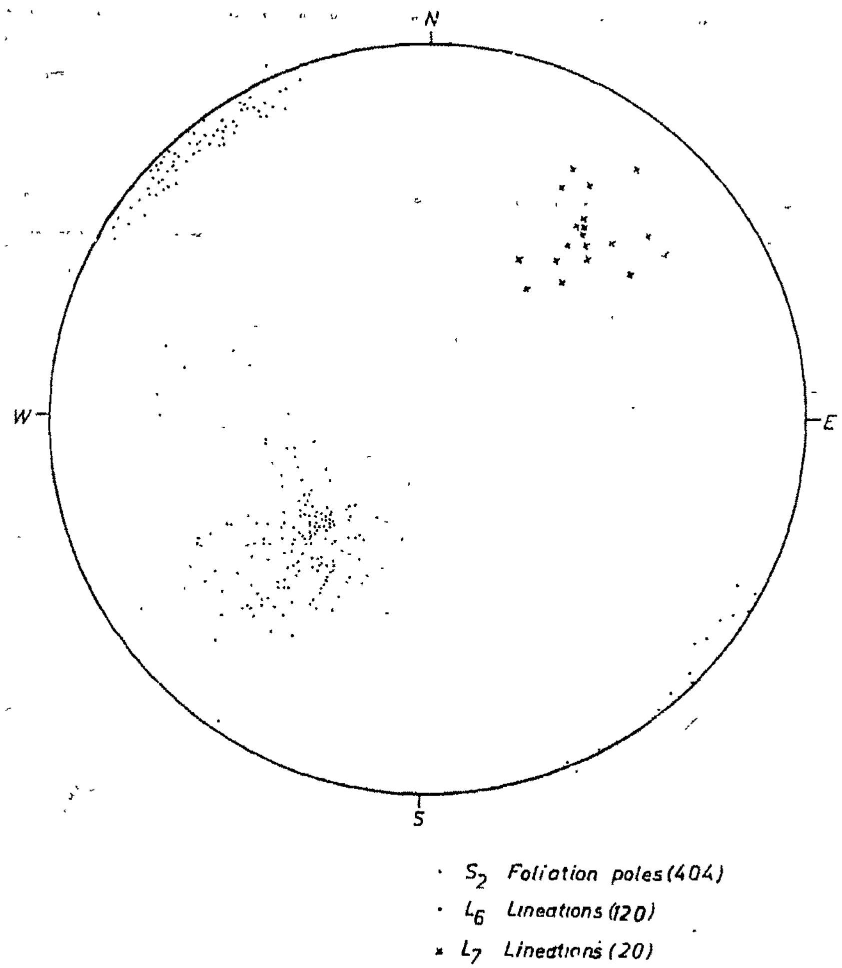
<u>Sub-area III</u>: The ground to the south of Nathuakhan makes up this Sub-area in which almost the entire sequence of Krol nappe is present. Structures related to the South Almora thrust, dominate and comprise the main foliation (S_2) which essentially is a shear cleavage developed during thrusting. As the slipping took place in the incompetent layers, this cleavage is parallel to the bedding seen in quartzite and limestone. Microfolds and crinkling on S_2, developed during F_2 are well represented. An almost identical crinkling, related to the Ramgarh thrust movement, is also equally abundant. But the two could be easily distinguished on the basis of the dip of the axial planes (and the associated strain-slip cleavage). While S_3 dips rather steeply due NE, the S_5 dips very gently due SW. This criteria is also helpful in sorting out the fold axis lineation L_3 and L_6 related to the two respective tectonic events; though both show close similarity and identical sub-horizontal trend which fluctuates between ESE-WNW to SE-NW. The 'a' lineation (L_5) related to the Ramgarh thrust movement and indicating the slip direction, shows, a sporadic development. It is seen as a conspicuous slikenside (L_5) type striation developed on S_2 and plunging moderately, almost at right angles to the trace of the Ramgarh thrust. The overall fluctuation in the orientation of S_2 planes is obviously due to the flexuring by F_4 (Fig.V.7).

Fig.-V.7.

Stereograms showing the structure of the sub-area III.

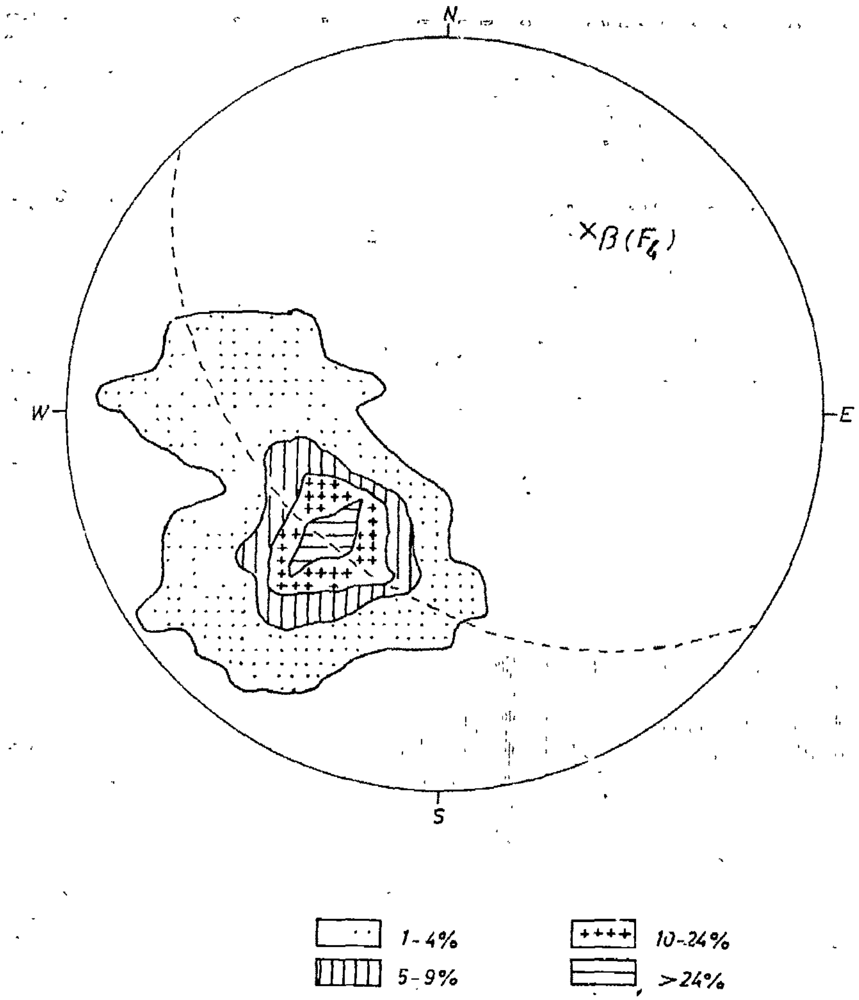
A

Various strctural elements (except L_5).



B

Effect of F_4 on S_2



<u>Sub-area IV</u>: Containing all the formations of the area, this Sub-area lies in the central part of the Krol nappe. The foliation S_2 though mostly dipping due NE, show much variation in dip and strike, and this variation is evidently due to the effect of F_2 and the monoclinal flexuring during Ramgarh thrust. The π S_2 diagram (Fig.V.8) clearly shows the trace of the girdle on which the formation poles lie on account of the above two foldings; strain-slip cleavage (S_3) is common but not as abundant as S_5. As usual, the S_3 dips due NE while S_5 dips due SW. The traces of S_2-S_3 and S_2-S_5 intersections, together with the connected puckers comprise the lineation L_3 and L_6; of the two L_6 predominates. Both the lineations show identical orientation. The slicken-side type 'a' lineation (L_5) is widespread on S_2 and shows NE to NNE plunge. A careful scrutiny has shown that this northerly swing, is on account of the lineation belonging to the early and late phases of the Ramgarh thrust movement.

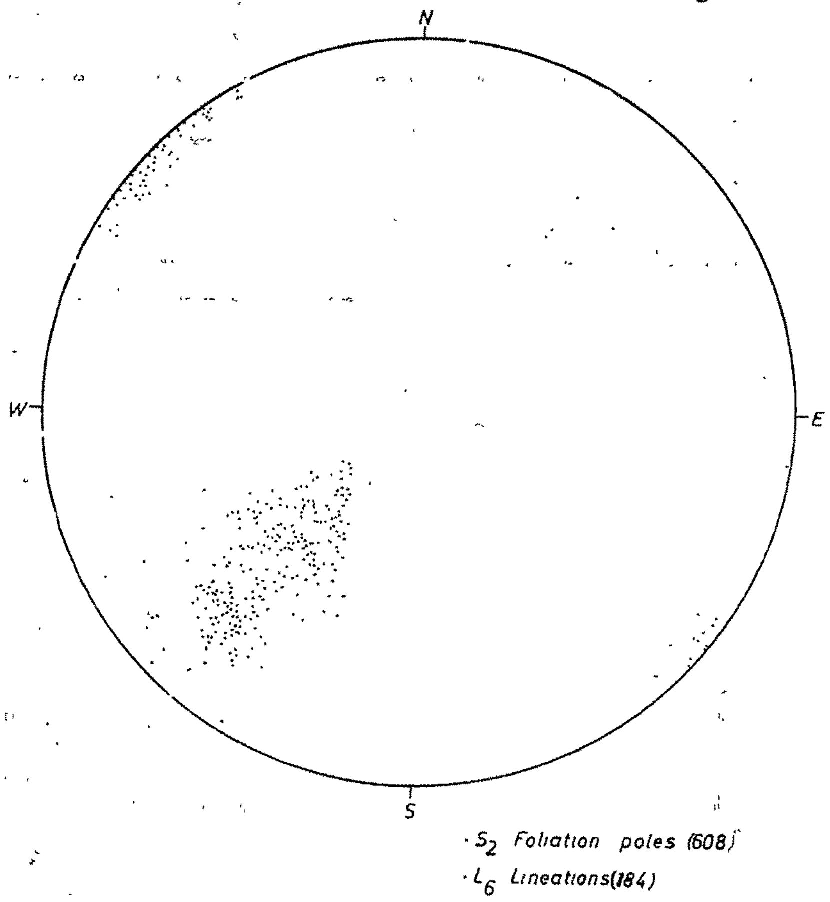
<u>Sub-area V</u>: This Sub-area includes the north-western corner of the area. The rocks occurring within the sub-area are sheared granites and phyllites. The main foliation(S_2) is related to the South Almora thrust. The bedding and S_2 all show a fairly constant dip of moderate angles due NE except at some places where F_2 folding has given rise to dips due SW (Fig.V.9). The most conspicuous and striking planar and

Fig.-V.8.

Stereograms showing the structure of the sub-area IV.

A

Various structural elements (except L_5).



B

Effects of F_2 and monoclinal flexuring on S_2.

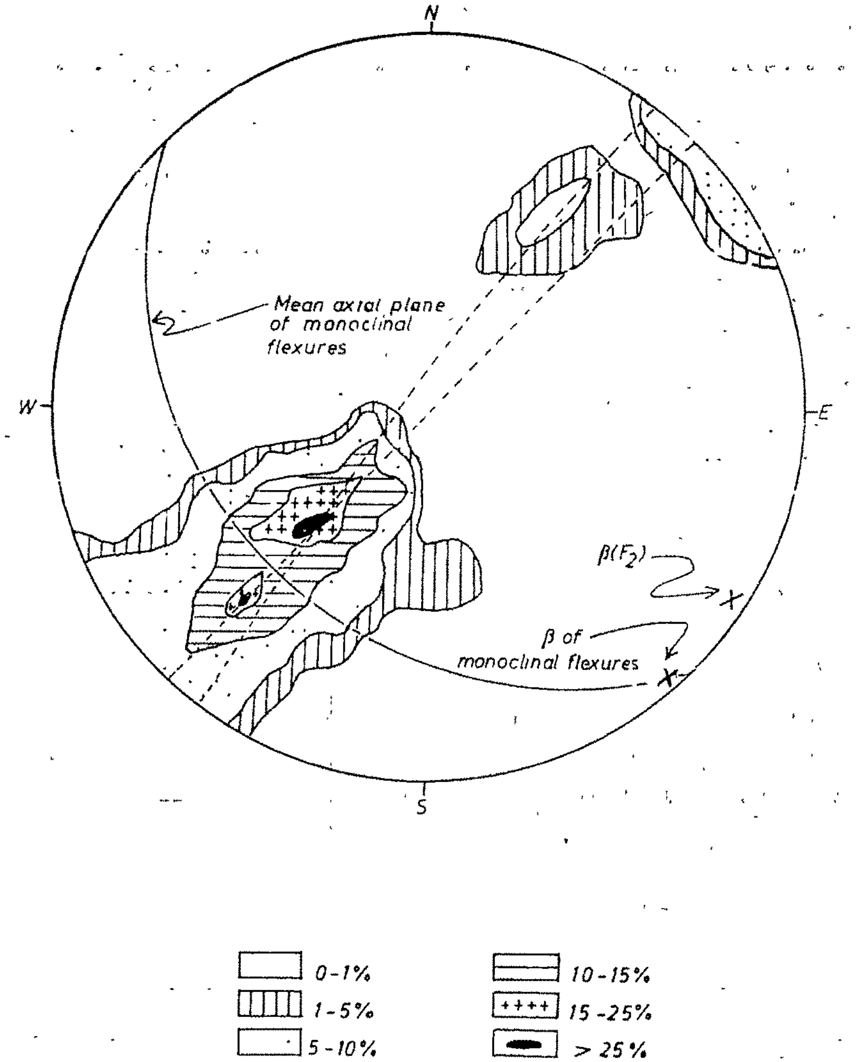
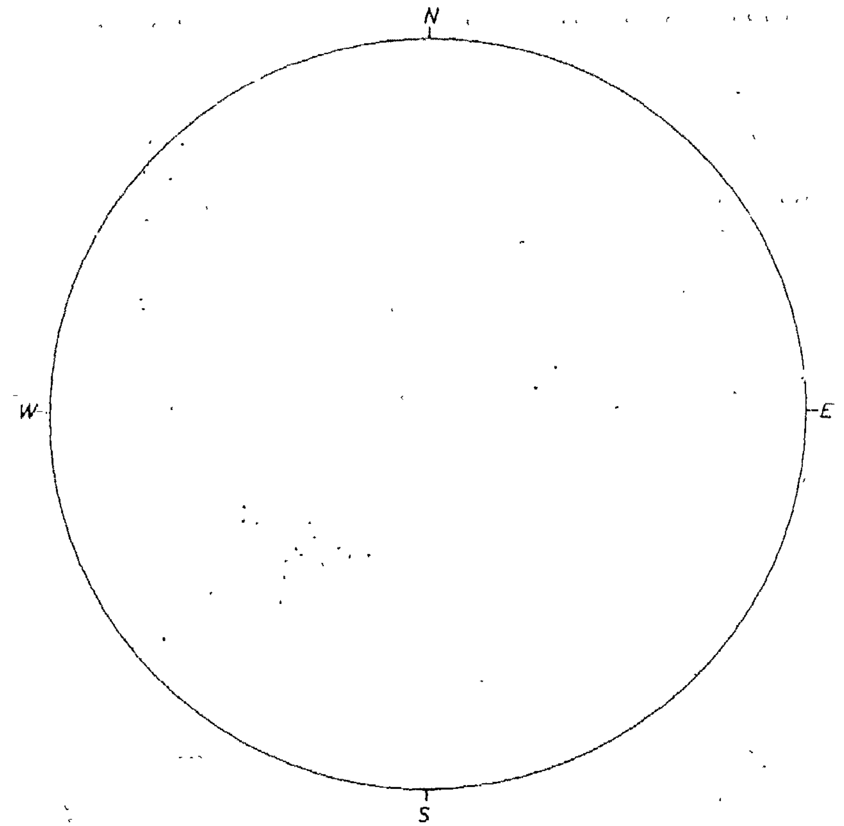


Fig.-V.9

Stereograms showing the structure of the sub-area V

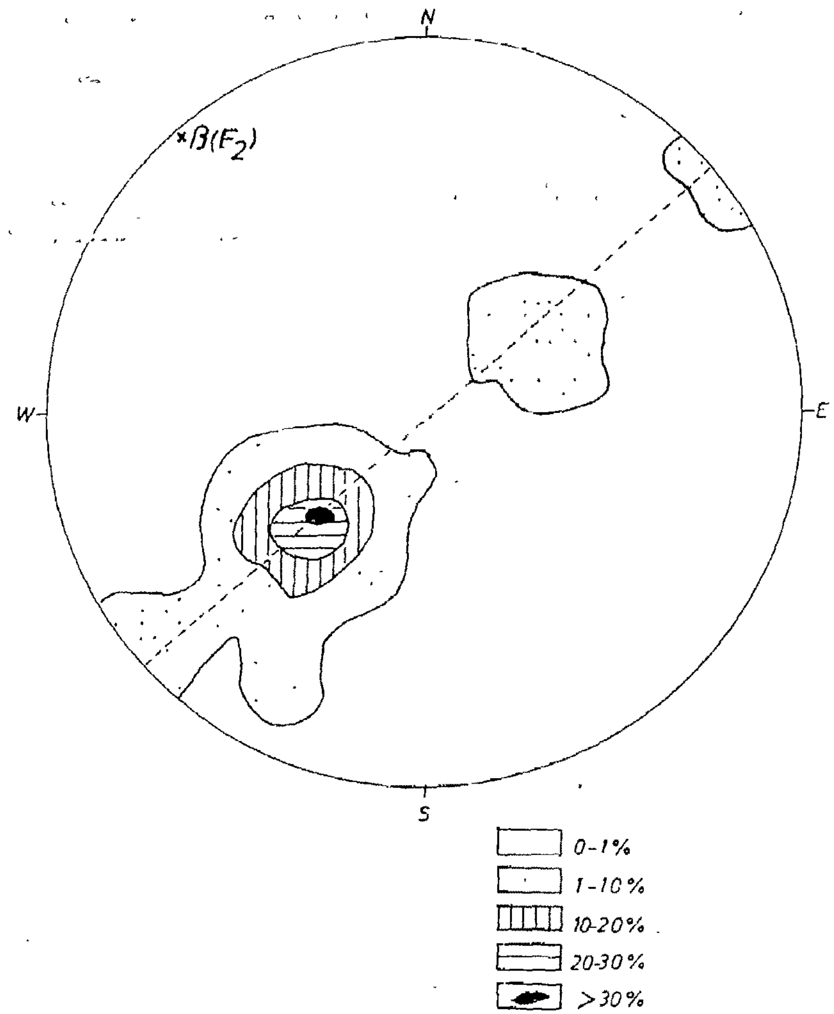
A

Various structural elements (except L_5)



B

Effect of F_2 on S_2.



linear structures developed in the rocks are those related to the movement during the Ramgarh thrust. The slickensides show a very strong development on S_2 and this typical 'a' lineation is seen plunging due NE to NNE. The S_2 further shows extensive crinkling on account of drag effect of Ramgarh dislocation. The individual micro-folds are mostly monoclinal with sharp hinges, and SW dipping axial planes. Extensive micro-shear planes have developed in this axial plane direction, and slipping along these planes has further crinkled the 'microlithons' (Di Sitter, 1961, p.97). The net result is the formation of a conspicuous strain-slip cleavage (S_5). This cleavage is seen dipping due SW. The axes of the crinkles, puckering, S_2 and S_5 intersection and bouding of quartz veins together comprise the lineation L_6, and this lineation is almost sub-horizontal, trending NW-SE. In this Sub-area, pucker lineation L_3 related to F_2, is almost absent.

Structural Synthesis

The results of the analysis of the structural data, when put together, reveal an interesting structural pattern. The successive tectonic episodes of folding and fracturing have left permanent imprints on the rocks. These have been found valuable in working out the structural history of the area as a whole. The salient structural features of the Krol nappe, that have developed in the course of it entire tectonic evolution, have been summarised as under:

(1) The main foliation (S_2) of the schists and phyllites is essentially of shear type and developed at the time of the Almora thrust movement. The sedimentary bedding is obliterated in the softer and incompetent rocks while in quartzites and limestones, it shows good preservation. The S_2 is mostly parallel to the bedding.

(2) During the F_2 folding (which gave rise to the Bhowali anticline and the Almora synform), microfolding of S_2 sporadically took place. The related strain-slip S_3, only occasionally recorded, is seen steeply dipping due NE.

(3) Effects of differential slipping at the time of the Ramgarh dislocation, are most prominent. The wide-spread crinkling and crenulation of S_2 is related to the movement along the Ramgarh thrust. The actual dislocation was preceded by large-scale differential slipping along S_2 which has given rise to a strong 'a' lineation (L_5). The movement along the dislocation, drag folded the S_2 into monoclinal crenulation, thus superimposing a puckering L_6 on S_2 and L_5.

Nature of the South Almora thrust

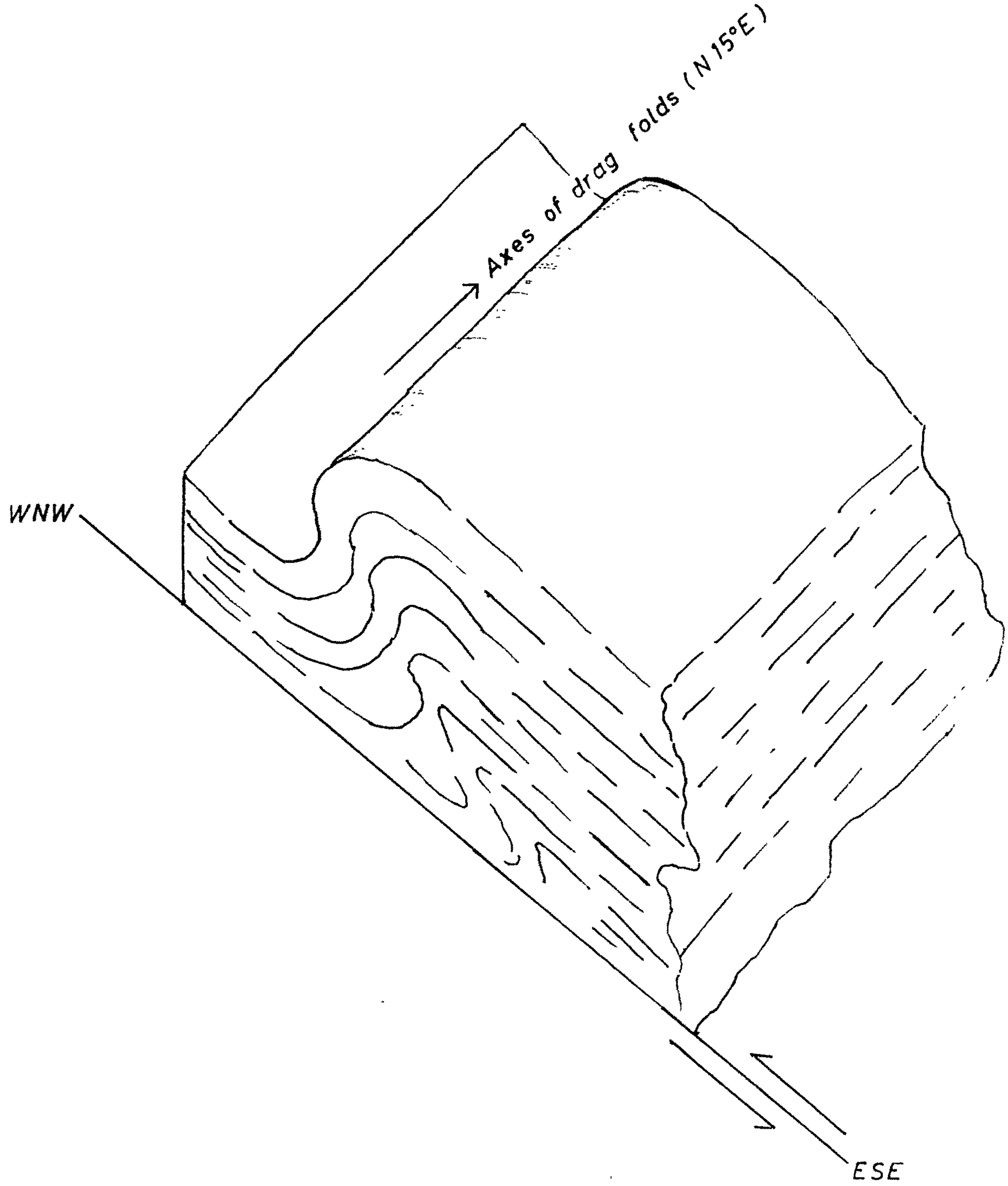
The thrust which is encountered in the eastern part of the area and separates the crystalline rocks of the Almora nappe from the underlying Krol nappe rocks. The author has found this major dislocation to run from SSE to NNW, the town of Mukteswar lying just to its E. The physiographic expression of the South Almora thrust is not very conspicuous, but it has been systematically traced on the basis of a constant presence of a phyllonitic zone all along its strike. Further N and NW, Vashi and Merh (1966, p.13-16) have described it as Upradi thrust. The author has preferred to call this dislocation as South Almora thrust only, rather than giving it any local name. The thrust obviously forms the southern flank of the synform into which the Almora nappe was folded during F_2. In its existing folded position only the local geometry of the thrust and the sense of movement along it could be deciphered.

As stated above, a narrow zone of highly cleaved phyllonites characterises the thrust, and as the phyllonitic cleavage is the result of intense shearing during the thrust movement, it is quite reasonable to visualise the thrust plane to be parallel to the cleavage. If it is so, the thrust plane, like the phyllonitic cleavage, dips gently due NE. A slight variation in the dip and strike could be due to the effects of F_2 and F_4. The drag folds and kinks, developed in the immediate vicinity of the thrust, provide a very useful clue in knowing the sense of movement along the thrust. Drag folds always develop in a direction at right angles to that of movement. Hence, considering the axes of the drag folds and kinks associated with the South Almora thrust, which plunge due NNE, the movement direction works out to be due WNW, somewhat in the direction of the trace of the thrust itself (Fig.V.10).

The Almora thrust, being the culmination of the isoclinal folding (F_1) and a product of the same deformational stresses, appears to have closely followed the folding (and the related metamorphism). There is considerable metamorphic downgrading associated with this thrusting, and migmatitic gneisses too have been affected by it. Obviously the thrust thus formed an integral part of the orogeny, comprising isoclinal folding, regional metamorphism and granitisation. According to Sarkar et al. (1965,p.668) the metamorphism and migmatisation took place during Lower Oligocene. The thrust could also be assigned approximately the same age.

Fig. -V 10.

Sketch diagram showing the sense of movement along the South Almora Thrust.



Nature of the Ramgarh Thrust:

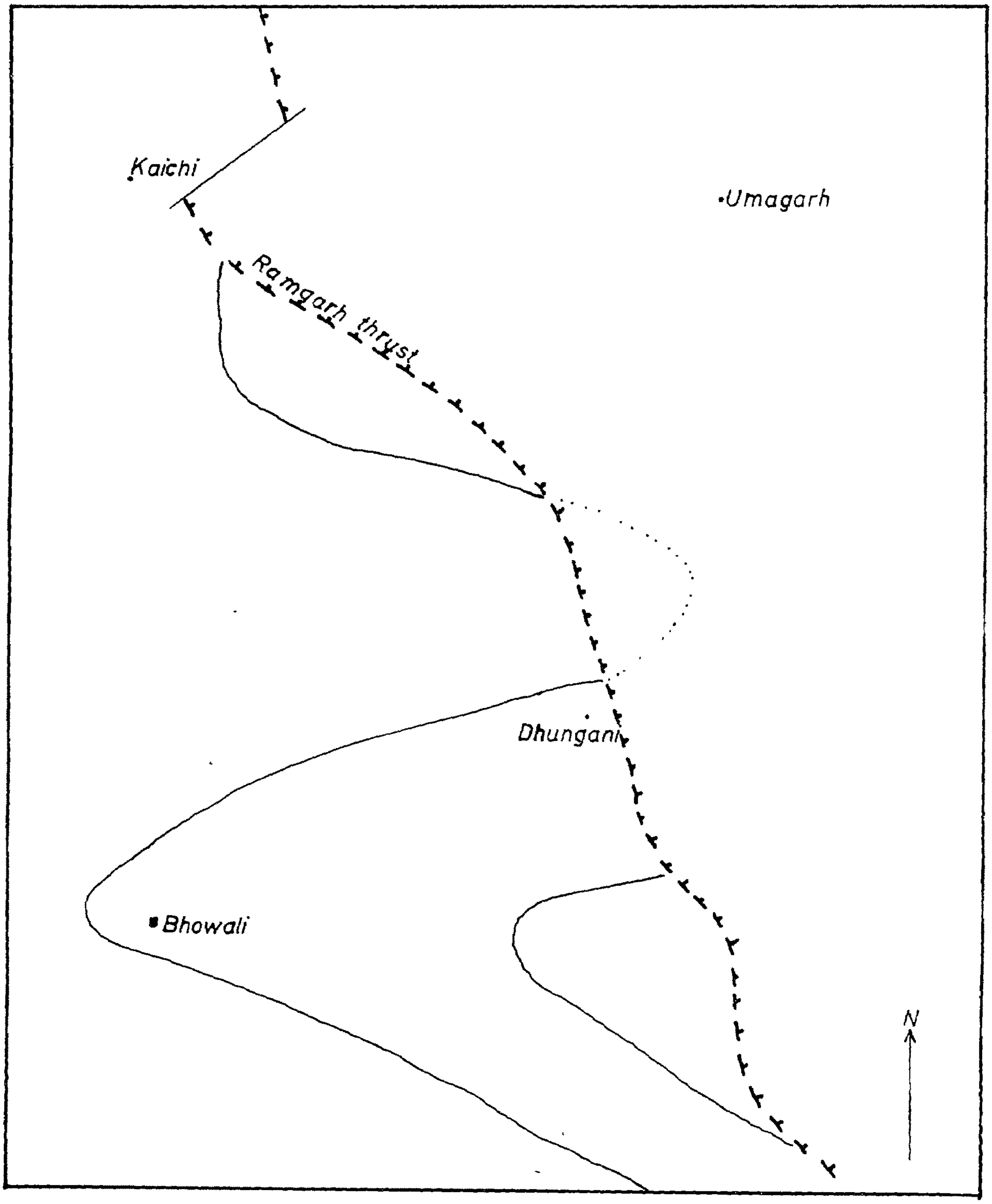
The Ramgarh thrust extends almost NW-SE and is encountered in the SW part of the area. The thrust and the rocks resting immediately over it have intrigued almost all the previous workers. Heim and Gansser (1939), Gansser (1964), Pande (1950) and Valdiya (1962), all have considered this dislocation to be a folded continuation of Almora thrust. Although none of the previous worker have unequivocally mentioned this fact, but their maps and accounts, have implied that the Ramgarh thrust is only yet another folded remnant of Almora thrust. Heim and Gansser (1939) have termed the thrust flanking the Almora nappe synform in north as North Almora thrust. They are however, not clear about the exact location of the southern flank of the folded Almora thrust. Between Bhowali and Mukteswar, they have shown two thrusts dipping NE; the one near Ramgarh (=Ramgarh thrust) in their opinion joins up with the North Almora thrust, though thrust near Mukteswar has been called by them as South Almora thrust. Pande (1950,p.21) also considers the Ramgarh thrust as an eastern continuation of the Garhwal thrust (=Almora thrust) or equivalent to it in age. In the same paper, he has further stated that the metamorphics lying over the Ramgarh thrust, form a syncline. According to Heim and Gansser

(1939, p.28) the region between Bhowali and the South Almora thrust comprises a recumbent syncline overturned to the NE. Merh (1968,p.6) however, for the first time pointed out that the Ramgarh thrust and the Almora thrust were two quite distinct dislocations, and the former did not constitute the southern flank of the synformally folded Almora thrust as postulated by Gansser (1964); nor do the rocks above the Ramgarh thrust form a syncline, recumbent or otherwise. Further, Merh suggested that the Ramgarh thrust is subsidiary dislocation related to the Krol thrust. The present investigations have partly supported the findings of Merh, and the author too has come to the conclusion that (1) the entire succession from Bhowali northward upto the South Almora thrust constitutes an uninverted and unfolded sequence, and (2) the Ramgarh thrust is more of the nature of a big reverse fault or high angled thrust, that originates from the Krol thrust. The author, however, disagrees with Merh in considering the Ramgarh thrust in any way related to the F_2 folding that gave rise to Almora nappe synform and Bhowali anticline etc. The mapping by the author in the Ramgarh-Mukteshwar area, and by O.K. Shah in the Bhowali-Bhimtal area (personal communication) has very clearly established that there was a considerable time gap between the F_2 folding and Ramgarh thrust, and the latter dislocation is seen obliquely cutting not only the F_2 structures but also the east-west trending F_3 structures (Fig.V.11). Of course the Ramgarh thrust which originates from the Krol thrust, is genetically related to the latter and both came into existence at a date much later to F_3 folding.

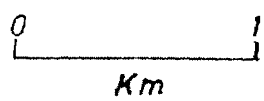
The Ramgarh thrust, as mapped by the author, shows some fluctuation in its strike trend. Though the dip of the thrust plane is always north-easterly, its amount varies between 60° to 80° and the variation of strike and dip is obviously an effect of flexuring by F_4. The slickenside lineation (L_5) which has abundantly developed on S_2 due to differential slipping at the time of the thrust movement, points to a southwesterly push of the Deobans almost at right angle to the dislocation. Analysis of this 'a' lineation shows two major directions NNE and NE. It appears that during the initial stages the differential slipping along S_2 was due SSW-NNE, but with increasing stress when the actual rupture took place, the movement direction swung to SW-NE. It was during this stage that monoclinal flexures with angular hinges, and associated crenulations of S_2 were brought about. The widespread strain-slip cleavage (S_5)

Fig.-V.11.

Sketch-map showing how Ramgarh thrust is cutting F_3 structures.



(Based on the work of O.K.Shah)



dipping gently towards the thrust plane, originated due to the drag effects. The spatial relationship between the S_5, L_5 and L_6 - the three structures related to the thrust, is shown on the enclosed stereograms (Fig.V.12, V.13 & V.14).

STRAIN-SLIP (CRENULATION) CLEAVAGE IN ALMORA AND KROL NAPPES

From the preceding account, it is seen that the rocks of both Almora and Krol nappes have extensively developed strain-slip cleavages. While in schist and phyllonites of the Almora nappe, this microstructure (S_3) is a product of F_2 folding, the similar cleavage (S_5) in Krol nappe is related to the crumpling caused by the Ramgarh thrust movement. Both the cleavages, are of strain-slip type, but a critical study has revealed that their respective mechanism of development are characteristically different from each other.

According to Turner & Weiss (1963,p.99) strain-slip cleavage commonly develops in rocks with superposed deformation, and like slaty cleavage, it may take the form of a late axial-plane cleavage cutting earlier folded S surfaces. But it is invariably a late structure, and the folded S surface to which it has the axial plane relation may itself

Fig.- V.12.

Stereograms showing the lineations related to Ramgarh thrust.

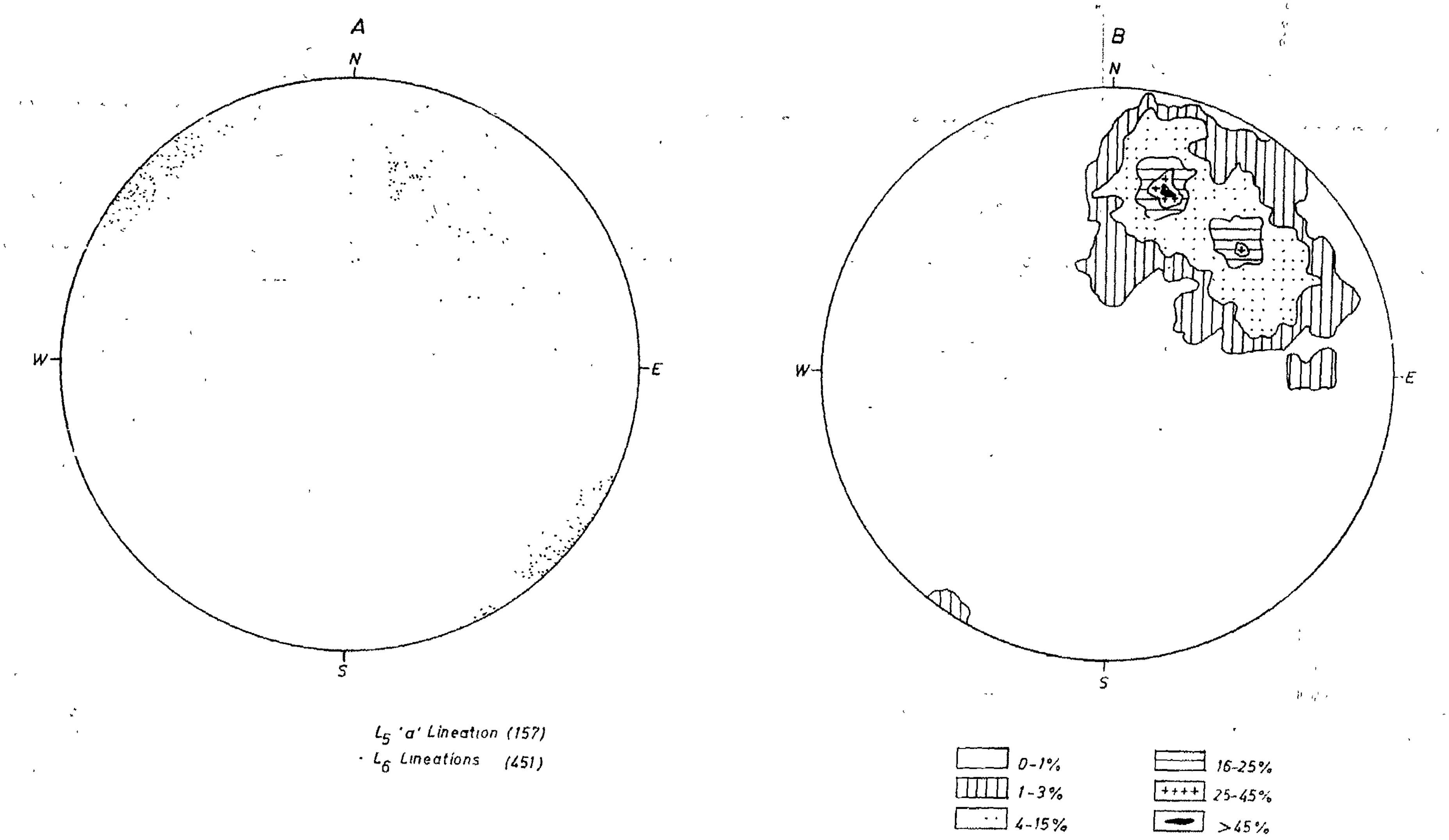


Fig.- V.13.

Stereograms showing the axial planes of monoclinal flexures.

A

B

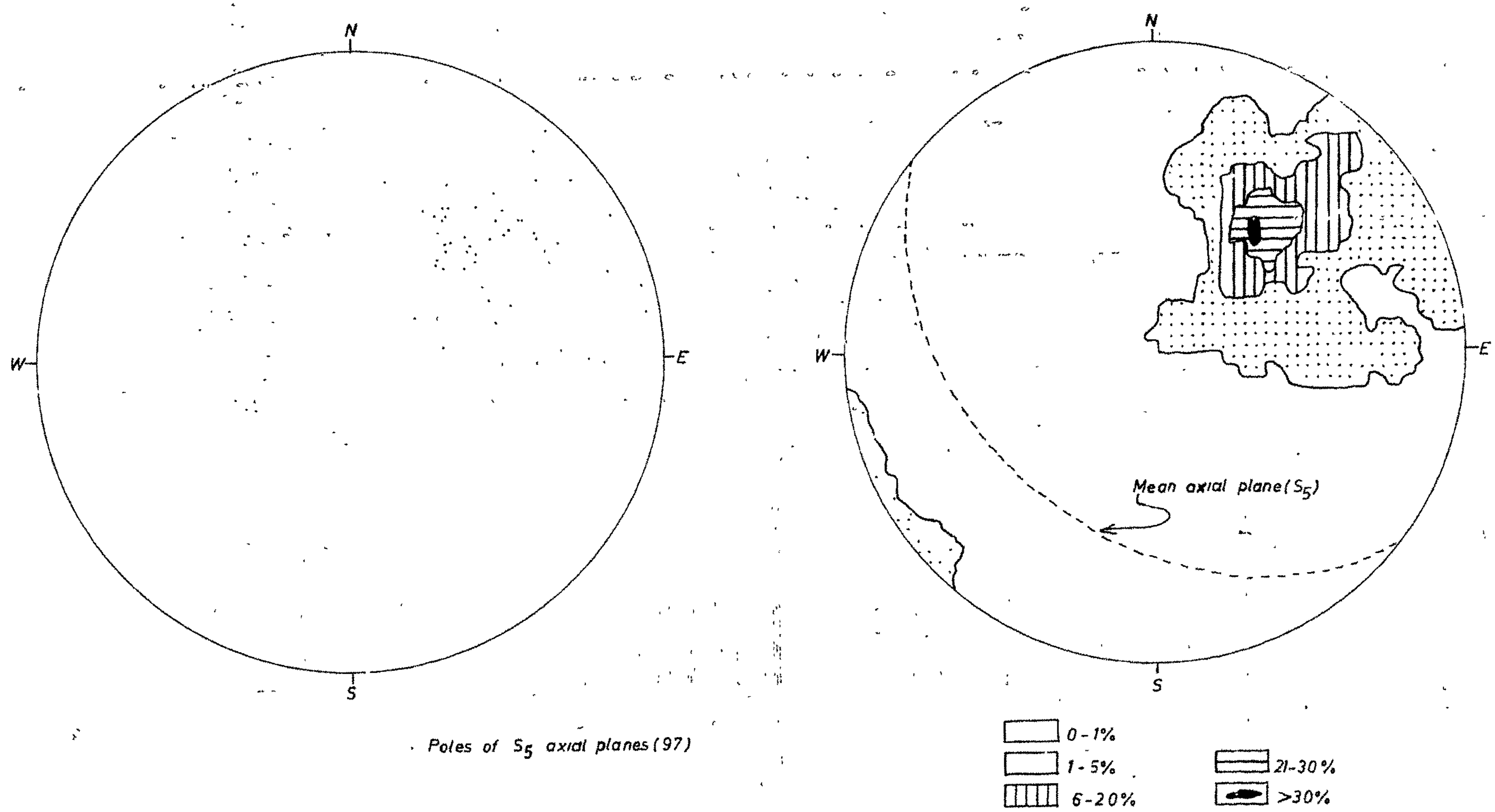
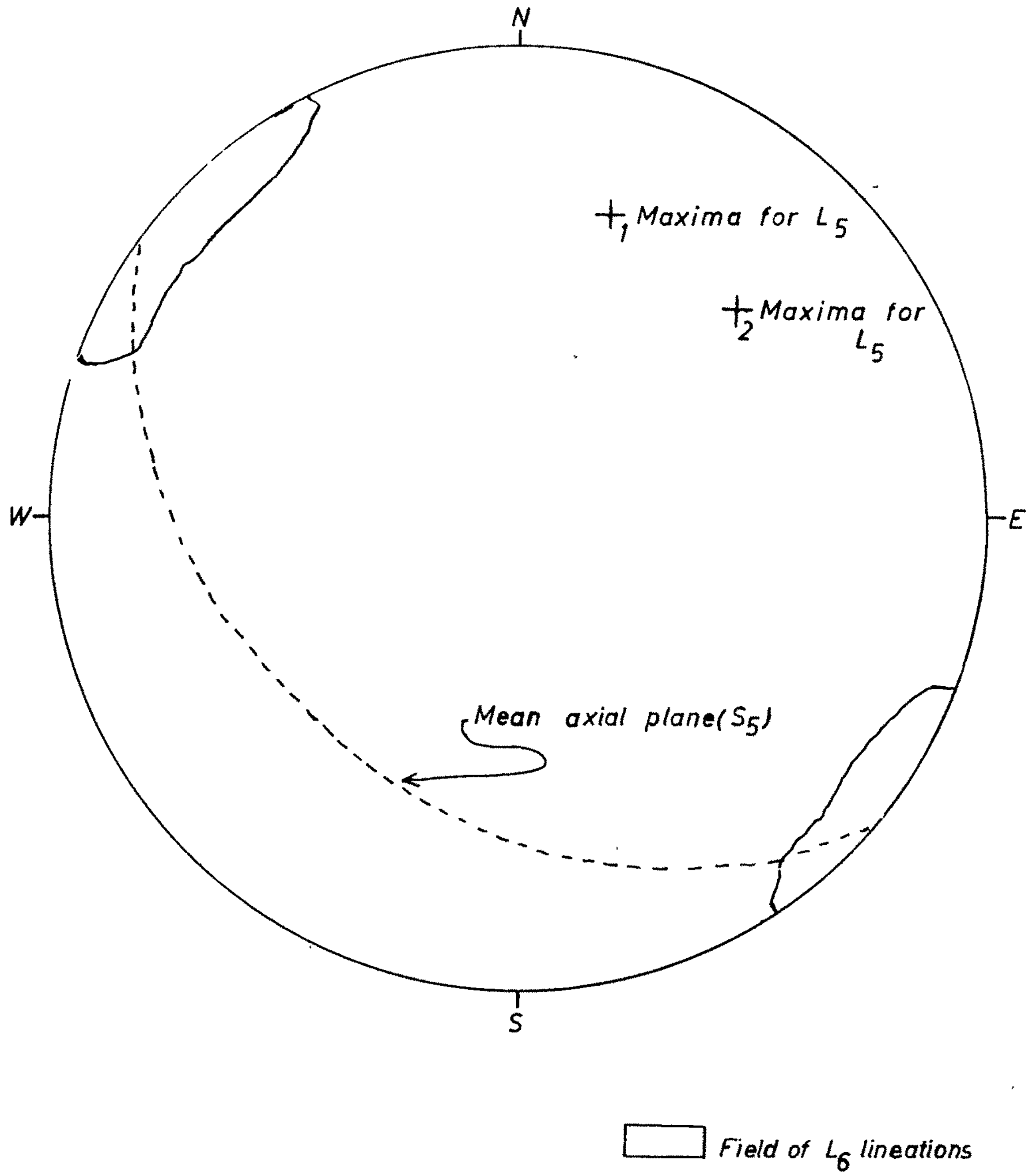


Fig.-V.14.

Synoptic stereogram showing the relationship between S_5, L_5 and L_6.



be a slaty (axial plane) cleavage of an earlier deformation. The above two authors do not subscribe to the view that slaty cleavage or schistosity and associated transverse strain-slip cleavage are broadly synchronous strain structures. Rather it would seem that when a finely foliated and mechanically anisotropic rock such as slate or phyllite is stressed so that the greatest principal stress (σ_1) is inclined at a high angle to the plane of foliation, failure is achieved by slip on surfaces cutting across the foliation. The surfaces of slip i.e. strain slip cleavages, are not discrete features but rather "laminar domains" of intense strain. The domains may become foci of syntectonic or post-tectonic recrystallisation of mica, so that ultimately the strain slip structures evolve into foliation.

The author finds himself in agreement with the above mentioned views of Turner and Weiss, and his observation in the study area substantiate the above statement, to some extent. The present area throws much light on the actual mechanism of the evolution of strain slip cleavage. The cleavages (S_3) in Almora nappe and (S_5) in Krol nappe - both the strain-slip cleavage types, reveal almost diametrically opposite mechanisms of evolution. While the former reveals its origin due to the fracturing of the hinges of microfolds and subsequent recrystallisation, in the case of the latter, microfolding followed the evolution of discrete slip planes.

The (S_3) strain-slip cleavage shows all stages of its evolution in thin sections. The earliest stage is a gentle crinkling of S_1; the next stage being tightening of these crinkles into chevron or accordion folds showing sharp and broken hinges (Plate V.3). The final stage is shown by the recrystallised hinges and frequent growth of tiny flakes of mica across the broken hinges. Another important feature of the cleavage is the indication of some slipping during the growth of new mica.

In contrast, the strain-slip (S_5) in Krol nappe, is more or less a simple slip structure, maintaining a constant sense of displacement. The slip surfaces, parallel to each other, developed at a wide angle to the Ramgarh thrust plane. With progressive strain, the microlithons of S_2 between adjacent strain-slip surfaces of (S_5) themselves became deformed by a progressive folding of (S_2) (Plate.V.4).

It is thus obvious that the evolution of strain-slip (S_3) followed the microfolding (of S_1), while that of (S_5) preceded the microfolding (of S_2). The accompanying figure illustrates the two mechanisms (Fig. V.15).

PLATE V.3

Strain-slip cleavage (S_3) in Almora Nappe
(Photomicrograph X120)

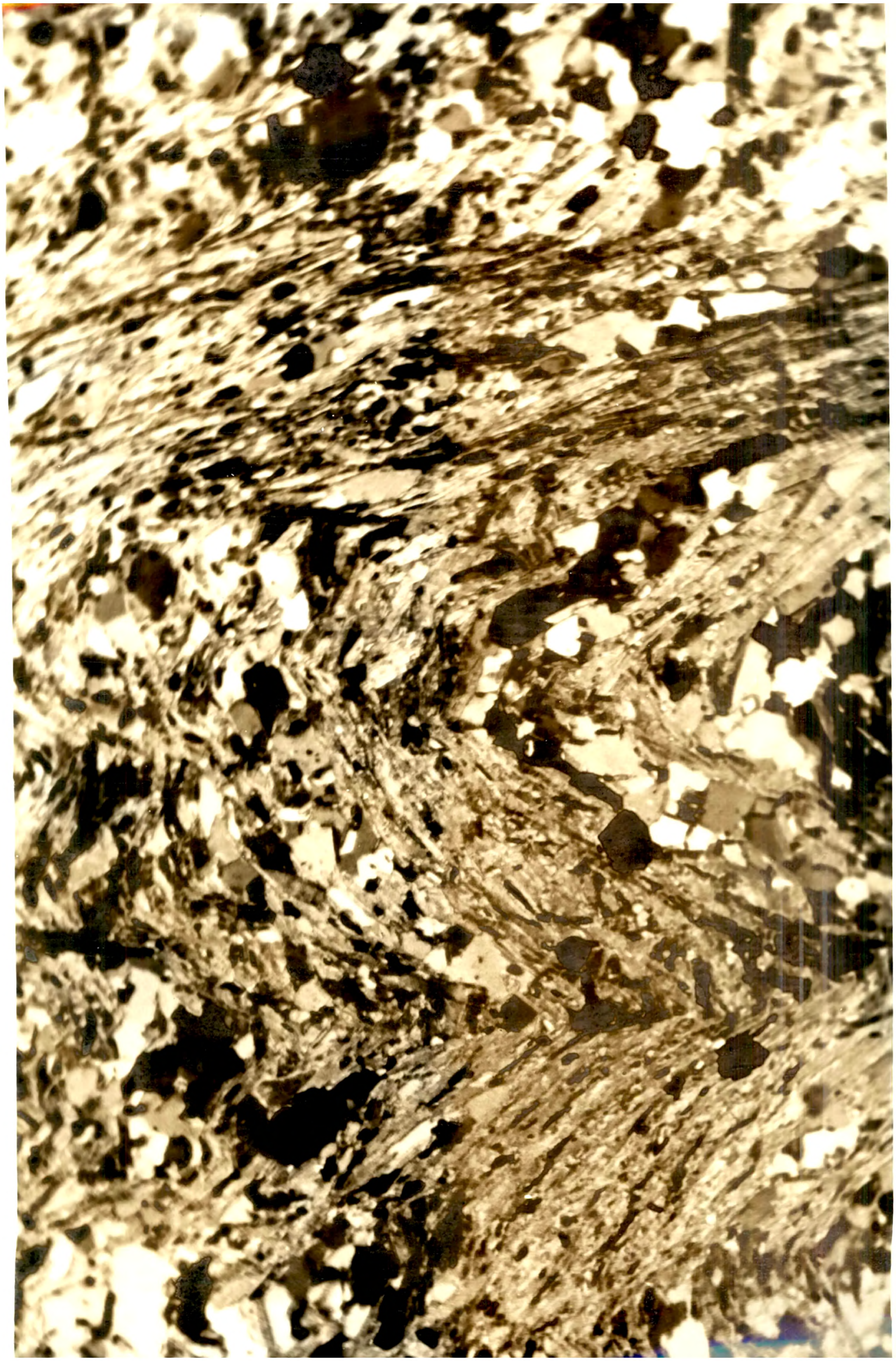


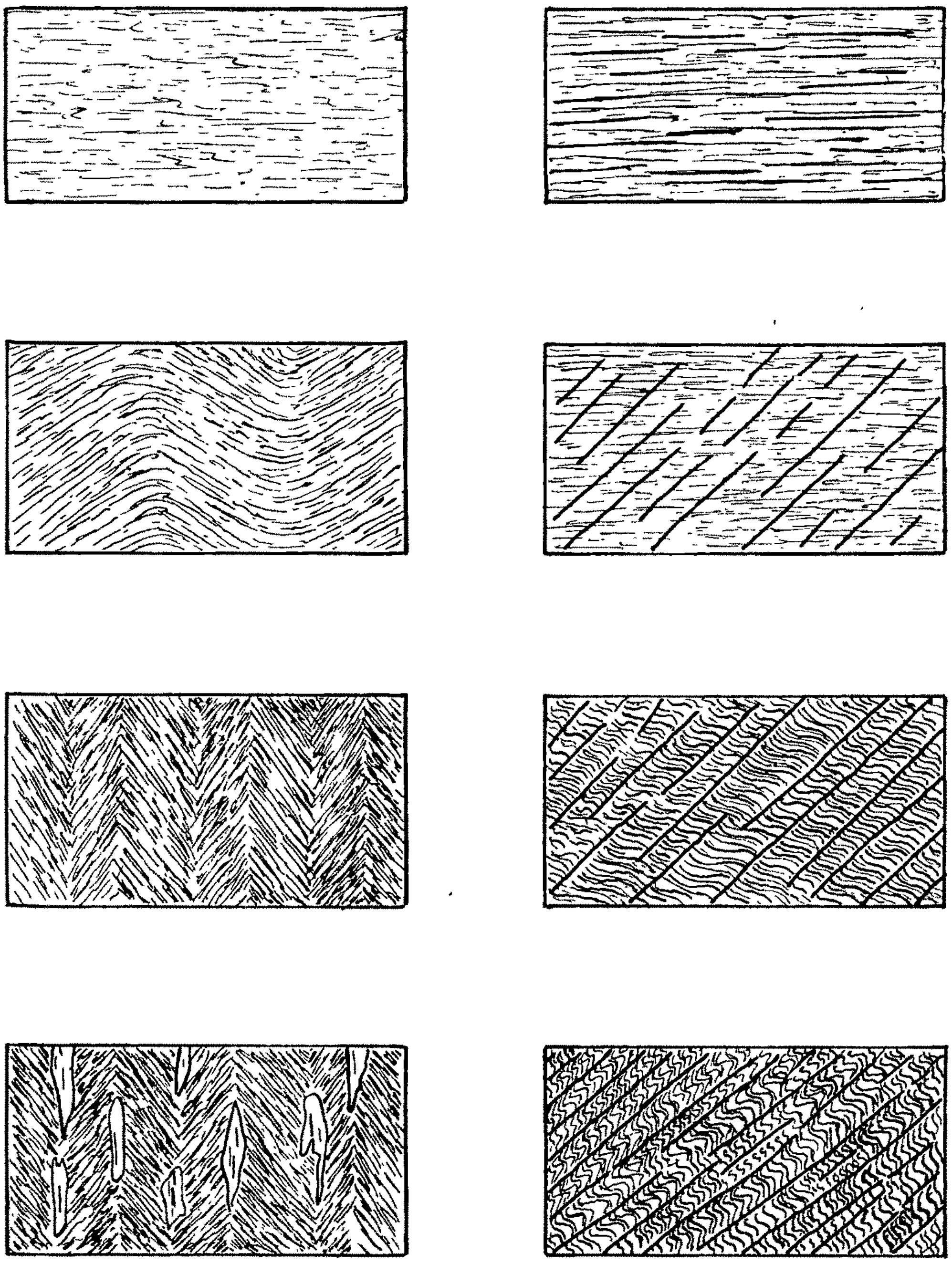
PLATE V.4

Strain-slip cleavage (S_5) in Krol Nappe.
(Photomicrograph X120)

Fig.-V .15.

Types of strain-slip cleavage.

(Almora Nappe) (Krol Nappe)



Strain-slip cleavages followed the microfolding

Strain-slip cleavages preceded the microfolding