CHAPTER V

STRUCTURAL GEOLOGY

SCOPE OF STUDY

No one in the past has attempted to study the structural geology of this part of Midlands in detail. As a matter of fact, the entire Nepal still remains unexplored from the point of view of systematic structural analysis. As a result, a host of problems related to the structural and stratigraphic framework have remained unsolved. So far as the study area is concerned, only broad structural details are found in the works of the various geologists who have worked in Midlands of Central West Nepal (Nadgir & Nanda, 1966 ; Frank & Fuchs, 1970 ; Fuchs & Frank, 1970, Sako et al., 1973 ; and Pecher, 1977). The present author, however, found that the previous work was not only inadequate but it also required drastic modifications. It was therefore essential that a critical analysis of all available structural data be made to properly understand the structural geology of the area. To a casual observer, the area might look structurally simple, but on detailed investigation, it was found that the rocks here have preserved within them a complex deformational history, the imprints of successive tectonic events having been adequately preserved.

The present author has very carefully observed and recorded a variety of planar and linear structures, belonging to more than one generation. A critical analysis of all the available structural data has revealed an interesting sequence of deformational events. The present study has enabled the author to chronologically arrange the various fold events and relate them to the regional dislocations typical of this part of the Himalaya.

In his structural analysis, the author has also taken into account the information collected by Toran Sharma (personal communication) from the rocks to the north beyond the study area.

MAIN DEFORMATIONAL EVENTS

Before proceeding with the systematic discussions of the different structural characters of the rocks and characteristics of individual sub-areas, the author would like to summarise the main structural events as under :

1. <u>Isoclinal folding (F_1)</u> is quite conspicuous in the area to the south of Phalebas Thrust. The folds show N-S axial planes dipping due E at varying angles, but in the north it is represented by numerous mesoscopic folds showing diverse trends. These F_1 folds have developed prominent axial-plane cleavage (S_1) which now characterises the main foliation of the area. The minor fold axes (related to F_1), quartz roddings, stripings due to cleavage-bedding intersection, mullions and mineral orientation, are the best recorded linear structures (L_1) related to this earliest event of folding. Folds of later generations have acted upon these early folds resulting into reclined folds (F_1) at places and also in changing the orientation of their axes.

2. Superimposed over the isoclinal folds are the comparatively open and macroscopic <u>folds</u> (F_2). The foliation trend on the map (Fig. V.1A) clearly

shows the pattern and nature of these F_2 folds. They trend N-S to NE-SW. Only a few lineations (L_2) related to this folding have been recorded.

3. Development of <u>Phalebas Thrust</u>.

4. <u>The third generation folds</u> (F_3) are widely encountered showing WNW-ESE to E-W axial traces, and with subvertical axial planes. These F_3 folds are of open, minor undulation type, the amplitude being very low. This F_3 folding has produced a widespread E-W pucker lineation (L_3).

5. <u>The last deformational event</u> is the development of F_4 represented by prominent N-S open undulations and micropuckers (L_4), which show a consistently northerly trend. The L_4 micropuckers are found to have been superimposed over all the earlier structural elements but no major folding related to this lineation is observed.

   The transverse faults observed in the Kusma area also belong to this generation of deformation.

STRUCTURAL ELEMENTS

The rock types, have preserved within them an ~~int~~ interesting record of successive deformational events and the various structural elements belonging to different events, provide valuable clues to the structural history of the area. It is observed that the major and minor structures related to the successive foldings, are characteristic of the relevant deformation and are of considerable diagnostic value. A brief account of the structural elements, deformation wise is given below, and the same is summarised in the accompanying table (Table V.1). Figure V.2 shows the various linear structures related to different fold events.

Structures related to Folding F_1

This fold event is adequately recorded in the rocks of Sirkang Unit, and is seen at all scales (Plate V.1A, 1B; V.2A, 2B). Large-scale macroscopic almost N-S folds of this generation are shown by the dolomitic rocks (Fig. III.2), and in fact the tongue like shapes are due to this isoclinal folding. The axial planes are seen dipping moderately to the east (i.e. overturned to the west) and sometimes they are almost recumbent (Plate V. 3A). The fold axes are always seen plunging very low angles due N or NNE. Sometimes, they are almost subhorizontal or seen plunging southerly also.

FIG. V.2

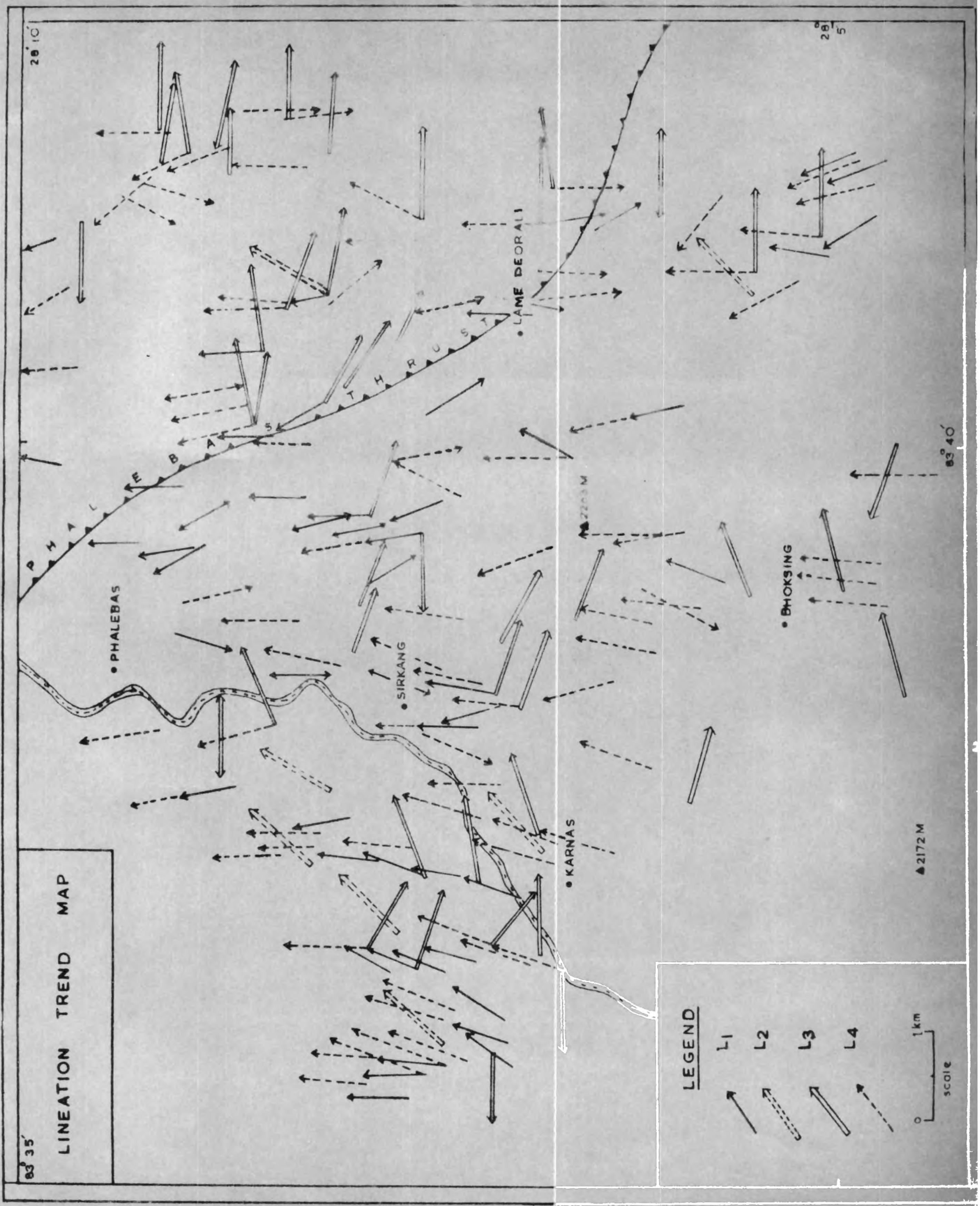
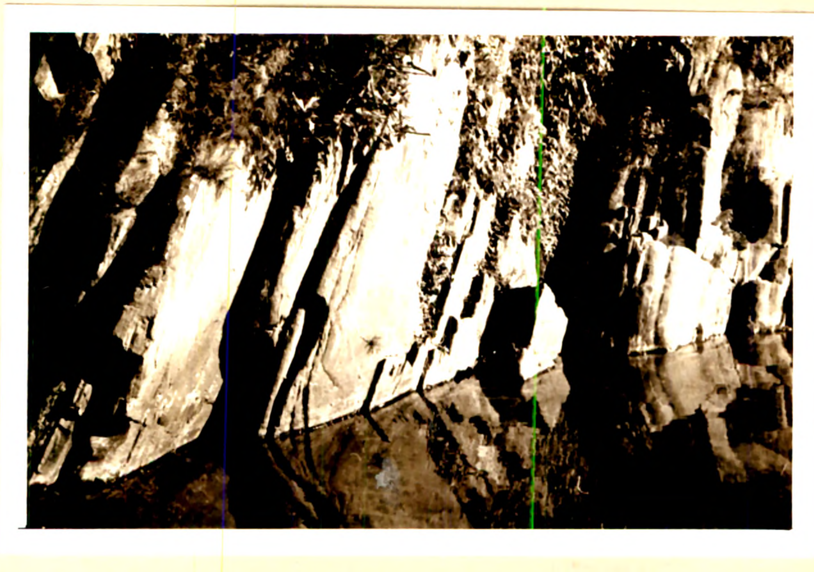

LINEATION TREND MAP
28°10'
28°5'
83°35'
83°40'
PHALEBAS THRUST
LAME DEORALI
PHALEBAS
SIRKANG
KARNAS
BHOKSING
2172 M
LEGEND
L1
L2
L3
L4
0
1km
scale

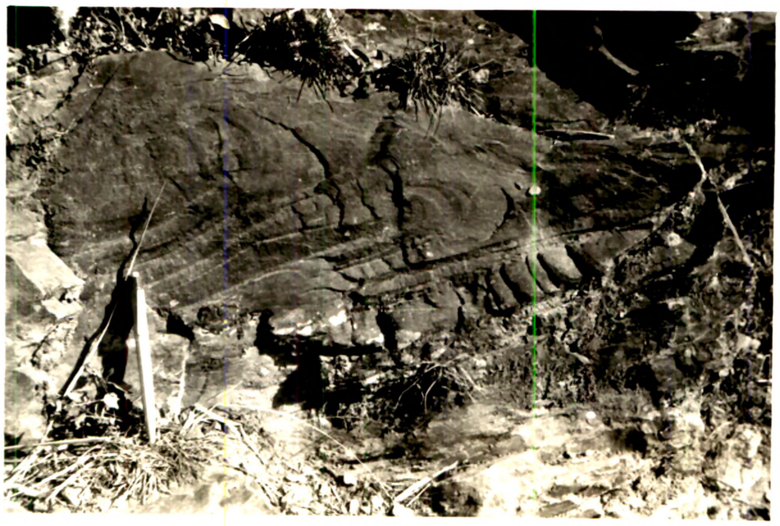
Plate V.1A Nearly recumbent isoclinal fold (F_1) in Sumsa Formation. Axis - N 33° E/6°.

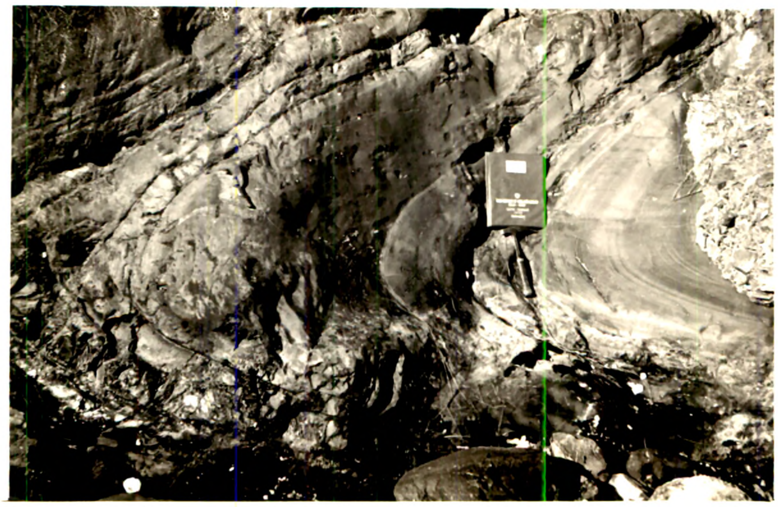
Location: Near Sirkang (0.8 km NE of Pangran).

Plate V.1B Mullions comprising tight isoclinal fold (F_1) with vertical axial planes in slates of Sumsa Formation. Axis - N 20° W/50°.

Location: About 1 km E of Shera.







Excellent occurrences of mesoscopic F_1 folds are recorded in the slates, where the slaty cleavage (S_1) typically marks the axial plane of F_1. The dolomites also show fairly wide-spread F_1 minor folds (Plate V.3B). At such places where the F_2 folding is prominent, these F_1 folds have become almost reclined. (Plate V. 4A). In the Kusma Unit, beyond the Phalebas Thrust, F_1 folds on a mesoscopic scale are frequently encountered, but here they do not show any definite trend, because of their extreme involvement in the various subsequent foldings.

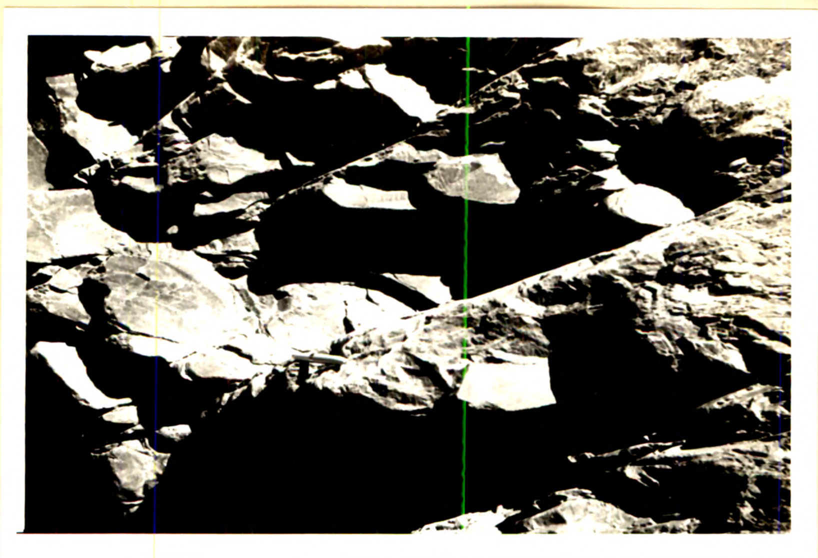
Linear structure related to F_1(L_1) comprise mostly the axes of minor folds in dolomites and sandy layers in slates. Quite often, repeated folding in a rapidly alternating slaty-sandy sequence, has given rise to a mullion structure (Plate V.4B). The involvement of quartz veins in this folding has resulted into a conspicuous quartz rodding or striping (Plate V. 5A). In quartzites and quartzose phyllites, the lineation is characteristed by a fine orientation of quartz grains, sericite and chlorite in the fold axis direction. The slaty rocks quite often exhibit a fine striping due to cleavage-bedding intersection (Plate V.5B).

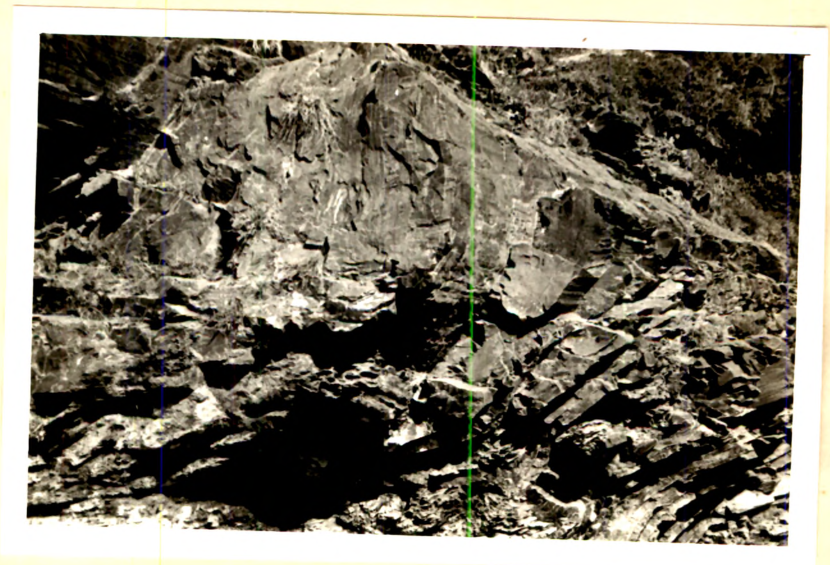
Structures related to folding F_2

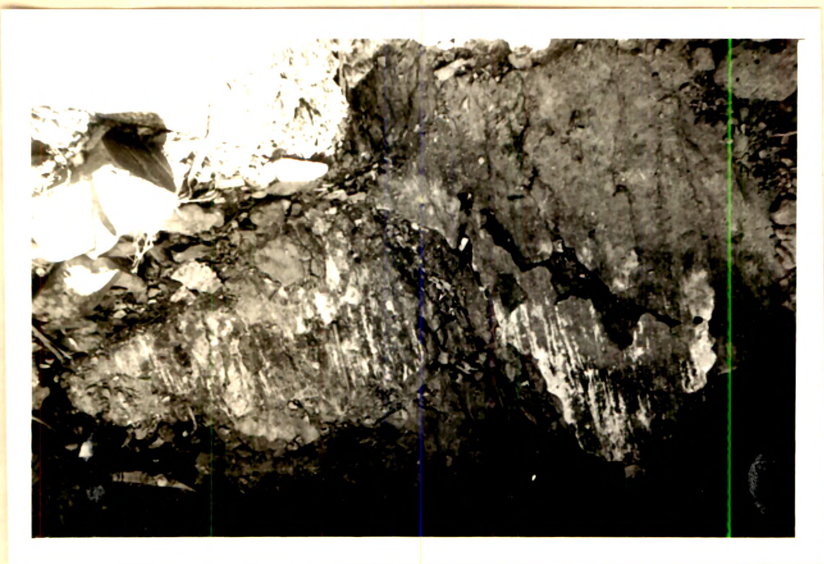
This fold event is almost co-axial with F_1 , but rather open and with a sub-vertical axial plane, striking

Plate V.4A Isoclinal - reclined folds (F_1) in Sumsa Formation; the fold closure are in the left. Axis - N 20° E/26°. <u>Location</u>: 0.8 km S of Baon village along the stream section.

Plate V.4B Mullion structures (L_1) in Sumsa Formation. Axis - N/5°. <u>Location</u>: About 0.5 km SE of Phalebas village in Lamai Khola section.







NNE-SSW. In the Sirkang Unit, this folding is ideally represented by a large antiformal structure in the north-western part of the area, just to the west of Phalebas (Fig. V.1). Another conspicuous fold in the SE, south of Lame Deorali, also perhaps belongs to this generation, but here its axial plane strikes almost NNW-SSE (Fig. III.2). A few folds of this generation are doubtfully recognised just to the north-east of the Phalebas Thrust, in the Kusma Unit.

This folding has not given rise to any planar structure like cleavage etc. The linear structure (L_2) comprises a sporadic microfold axes and a fairly widespread puckering.

Structures related to folding F_3

This folding which is almost E-W is observed in both the structural units, but it is better developed in the Kusma Unit. This folding which shows considerable disharmony in details, has been found to be related to the movement along the Phalebas Thrust and the Kusma Reverse Fault (Fig. III.1).

In the Sirkang Unit, F_3 is marked by a gentle fluctuation in the foliation trends (Fig. V.1) and is easily recognised in the area around Karnas and Bhoksing. Across the Phalebas Thrust, in the Kusma Unit, F_3 folds are more tight but considerably deformed by the later fold event (F_4).

Minor structures related to this F_3 folding comprise a prominent puckering due E and W, depending on the orientation of the foliation plane on which they have developed. This puckering forms the dominant lineation L_3 . Occasional development of a crenulation cleavage due to fracturing on the microfold hinges marks the only planar structure (S_3).

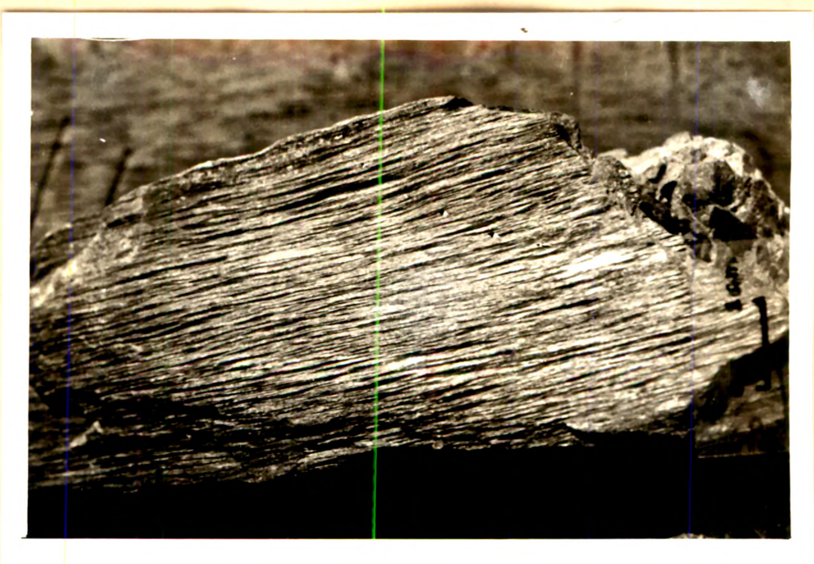
Structures related to folding F_4

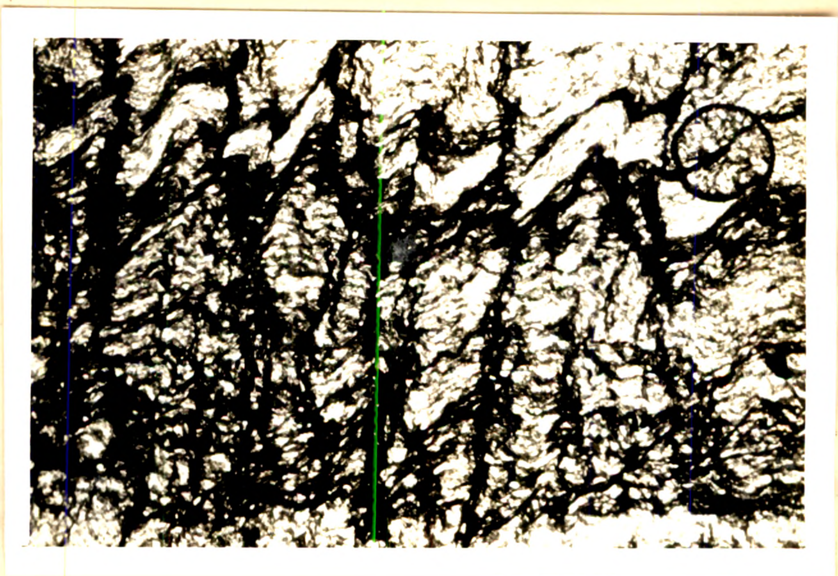
This folding is a prominent event affecting almost the entire Himalaya, and is responsible for the extensive N-S or NNE-SSW flexing of the regional Himalayan trend. This fold event is extensively recorded all over the Himalaya in the form of open N-S flexures. Associated microfolding and puckering is also observed by many workers.

It is interesting to observe that F_4 folding is nowhere represented in the study area by any significant and well defined macroscopic folds, but instead, an extensive and widespread fine puckering (Plate V.6A) and very open mesoscopic folds consistently plunging due north at various angles characterises this fold episode. The amount of plunge varies from moderate to almost subhorizontal, thus again depending on the orientation of the puckered surface. Crenulation cleavages (S_4) are also occasionally developed (Plate V.6B).

Plate V.6A Fine N-S pucker lineation (L_4).
Location: 1 km west of Thana village.

Plate V.6B Photomicrograph of crenulation cleavage in phyllite developed along the crests of N-S puckers (L_4). (crossed nicols, x50).





Another indirect evidence of F_4 folding is seen in the development of open dome and basin like structures in Kusma Unit on account of the interference of F_3 and F_4 (Plate V.7A , 7B).

STRUCTURAL ANALYSIS

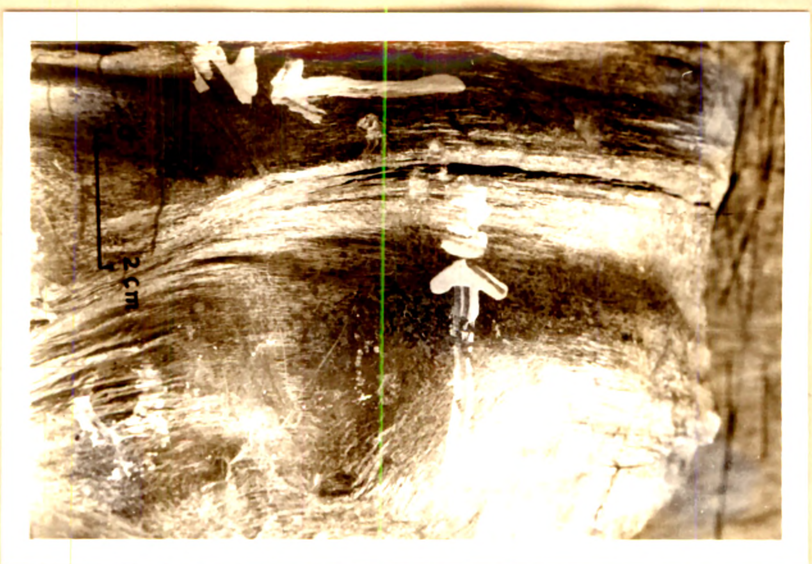
The various structural elements of the study area were critically analysed and sorted out stereographically. For the purpose of such a detailed geometric analysis, the techniques adopted by Turner & Weiss (1963) and Ramsay (1967) were followed. The analysis is based on the assumption that the minor structures, both planar and linear observed in a small area reflect the broad structural pattern on a regional scale. The various structural elements were plotted on Schmidt's Equal-Area Net, and a number of stereograms were prepared. The mapped terrain was divided into nine sub-areas, of which two lie in the Kusma Unit while the remaining seven are included in the Sirkang Unit (Fig. V.3).

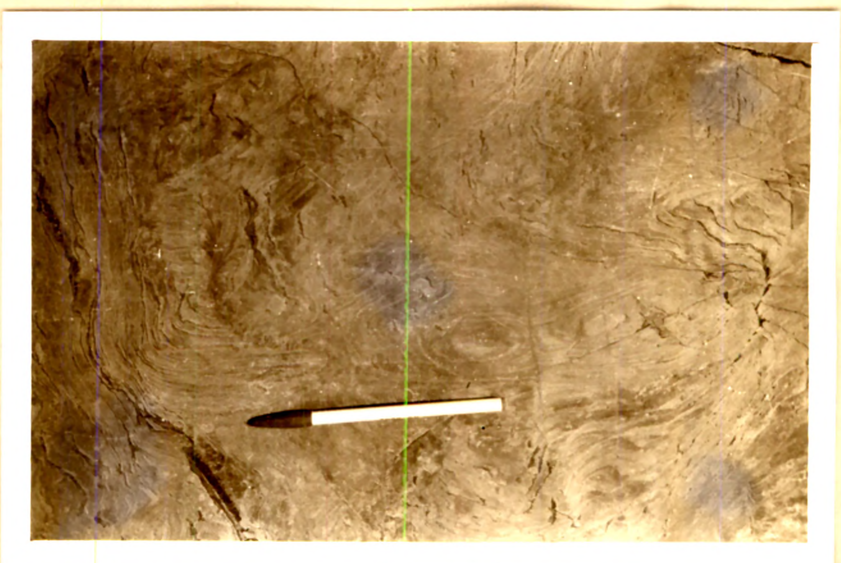
In his analysis, the author was handicapped mainly by following complications:

1. Low to almost subhorizontal dips at many places. This made the exact measurements of structural elements somewhat difficult. Also, the π-S diagrams of such foliations tend to give a wide

Plate V.7A A specimen showing domal structure due to the interference of F_3 and F_4 folds. L_4 lineation conspicuous. Location: Abcut 0.4 km N of Thana.

Plate V.7B Field photograph of mesoscopic domal and basinal structures in Sumsa Formation due to interference of F_3 and F_4 folds.
Location: At the confluence of Kali Gandaki and Lamai Khola, South of Phalebas (x 1/5).


2 cm



scatter such that it is difficult to obtain well-defined girdles. Quite a few stereograms indicate domal and basinal structures.

2. The mixing up of L_1 , L_2 and L_4 which show almost identical orientations, and they have to be sorted out on the basis of their styles and nature.

Sub-area I

Sub-area I, which is a complimentary part of sub-area VII, occupies the northwestern portion of the map, and lies to the West of Kali Gandaki river. This sub-area lies almost entirely in the Sumsa Formation except for a small part which includes Phoksing Dolomite. The foliation map (Fig. V.1) clearly shows that this sub-area constitutes the western limb of a large F_2 antiform. There are also other smaller antiforms and synforms belonging to the same generation. The majority of the foliations have E-W to WNW-ESE trend with a northerly dip direction. However, in the southeastern part of the sub area, a few foliations strike N-S with an easterly dip.

The π-diagram of the foliation poles (Fig. V.4) shows a fragmentary girdle on F_2 , the mean F_2 axis being in a direction N 45° E , plunging at 30°. Some related puckers (L_2) are sporadically recorded. Isoclinal fold axes (L_1) are quite common, and show in a general way northerly plunge L_3 is not observed.

Sub-area II

Sub-area II lies to the south of sub-area I. The rocks are mainly of Sumsa Formation, but a small part of Phoksing Dolomite also falls within it. The N-S striking and easterly dipping foliations in the eastern part change gradually to NW-SE and NNW-SSE to E-W towards western side forming a NE plunging antiform.

The π-diagram (Fig. V.5) points to a fold whose mean axis is due N 50° E, with a plunge of 26°.

In fact, structurally the sub-area I and II are quite identical. Lineations belonging to L_1 (minor fold axes, quartz rods etc.), L_2 (puckers), L_3 (only a few puckers) and L_4 (fine puckers) are observed.

Sub-area III

Lying further south, this sub-area forms the south-western corner of the study area. It is confined to Phoksing Dolomite of Sirkang Unit. In the northern part around Karnas and Amrigaon, a small portion is occupied by the Sumsa Formation. More or less, here the strike of the foliations is N-S with a easterly dip. But, it is quite conspicuous from foliation map that there are good indications of the effects of F_3 folding on these foliations which are represented by the undulations in the foliation trends. The tongue of Sumsa Formation protruding in the dolomite constitutes the northerly plunging synclinal isoclinal fold, and the adjacent dolomite tongue to the east forms the corresponding anticline where the effect of E-W folding (F_3) is quite obvious. The lens of carbonaceous slate in dolomite also shows the effects of F_3 near △ 2172 m (Gorland Danda). The dolomites compared to other rock types have preserved very few planar and linear structures.

Stereograms (Fig. V.6) do not reveal much. On the π-diagram, a probable F_3 girdle ($88^{0}/33^{0}$) can be drawn. On the whole, lineations related to F_1, F_2 and F_3 are scarce. Only a few puckers of L_4 are observed. The F_1 folding being isoclinal, is not revealed on the stereogram.

Sub-area IV

This sub-area lies on the southern flank, and the rocks exposed are both of Sumsa Formation and Phoksing Dolomite. The foliations show NW-SE to WNW-ESE trend with northeasterly dip. The dolomite exposures clearly show their folded nature. The foliation map indicates that this sub-area consists of two major folds - an artiform and a synform with north-northeasterly trend.

The -diagram (Fig. V.7) reveals effects of superimposition of F_3 on F_2. The main structures are of F_2 generation, the girdle pointing to an almost northerly fold axis(trend 3° E, plumge 26°). F_3 is represented by two very fragmentary girdles--one each developed over the easterly and westerly dipping limbs of F_2 fold. Lineations related to F_3 and F_4 (both puckers) are sporadically developed.

Sub-area V

To the east of sub-area IV, it includes Phoksing Dolomite and Sumsa Formation. The planar and linear structures related to different structural events are mainly recorded from the Sumsa Formation, as the dolomites have not preserved these structures so well. The rocks show more or less E-W trend with fluctuations of a few degrees on either sides. They all have northerly dip. This sub-area constitutes the easterly limb of the adjacent F_2 antiform.

Effects of F_2 (N 14° W/30°) and F_3 are reflected in the -diagram (Fig. V.8) and show structural character almost identical to those of sub-area IV. Some L_1 (isoclinal fold axes), L_3 (puckers) and L_4 (puckers) are observed.

Sub-area VI

This sub-area, together with the sub-area VII, forms the eastern limb of a large F_2 fold. Structurally, least interesting, it does not show any conspicuous features. The main rocks are slates, phyllites, siliceous dolomite of Sumsa Formation. The strike of foliations show fairly uniform orientation of N-S with a easterly dip. Some effect of F_3 folding is seen in the trend of the foliations. The stereograms (Fig. V.9) do not reveal anything, except a few sporadic lineations L_1 , L_3 and L_4 .

Sub-area VII

Lying to the north of sub-area VI and east of sub-area I, it is entirely confined within the Sumsa Formation. This sub-area comprises the eastern limb of an F_2 antiform. Nearly all the foliations have N-S strike and easterly dip. But, near the closure of the antiform, the strike of foliations swing to almost E-W having northerly dip. Planar and linear structures are better developed in this area.

The π-diagram (Fig. V.10) is identical to that of sub-area VI, except that it shows a fairly conspicuous tendency of F_2 girdle, with fold axis due N 7^0 E , with a plunge of 26^0 . Lineations L_1 , L_3 and L_4 are recorded.

THRUSTS AND FAULTS

The Phalebas Thrust, separating the Southern Unit from the Northern Unit, appears to be quite an important tectonic contact. It has been variously interpreted by previous workers. Fuchs (1967) has attributed considerable significance to this dislocation and has taken it to be a regional thrust related to large-scale nappe movement separating his Chail Nappe (Kusma Unit) from the Krol or Tansing Unit (Sirkang Unit). On the other hand Nadgir & Nanda (1966) as well as the Japanese geologists Ohta & Akiba (1973) have recognised this plane only as a steeply dipping reverse fault connected with vertical block movenents.

According to the present author, this thrust is not very steep, and is inclined moderately due NE. It also does not involve any large-scale horizontal displacement. A few drag folds observed in the vicinity of this thrust show their axial planes dipping about 30^{0} to 40^{0} to the NE.

The Kusma Reverse Fault (outside the study area in the north) on the other hand, has been recorded to be a steep fracture striking almost WNW-ESE, roughly parallel to that of the Phalebas Thrust, with the northern side having been uplifted. Previous workers like Nadgir & Nanda (1966), Talalov (1972), and Ohta & Akiba (1973), have shown this dislocation to extend for long distances following almost a straight course.

This fault is recognised by a prominent scarp of quartzite that broadly follows the valleys of Kali Gandaki and Modi. The quartzites, abutting against the quartzose phyllites to the south of this dislocation have been taken to be the oldest rock formation of the Kusma Unit.

The two dislocations (Phalebas Thrust and Kusma Reverse Fault) appear to be of same age and genetically related, having developed due to a north-south compression. It was during this compressional movement perhaps from the north, that the WNW-ESE to E-W folds (F_3) were also generated.

A few transverse faults of local significance, striking NNE-SSW , NE-SW and NNW-SSE are also recorded. These appear to be the youngest, cutting across all the previous structures. Such transverse faults have been recorded from all over the Himalaya and could be related to tectonism during the Quaternary.

DEFORMATIONAL HISTORY

Folds of various generations together with the faults, longitudinal as well as transverse, all point to a long deformational history, going back at least upto the early Palaeozoic times. From the present study, following facts have emerged:

1. F_1 and F_2 folding, both almost N-S, pre-existed the Himalayan thrust and the nappe movements.

2. The F_1 folding resulted due to compressional stresses operating at right angles to the direction of the Himalayan orogenic movements.

3. The F_1 and F_2 compressional events, unrelated to the Tertiary Himalayan orogeny, belong to some earlier movements during Precambrian or Early Palaeozoic period.

4. An interesting feature of the F_1 folding is the low metamorphic grade of the deformed rocks. Evidently, the rocks were subjected to strong compressional stresses under low temperature, typically characterising epizonal conditions.

5. The folds of F_3 generation comprise the typical Himalayan orogeny structures, having resulted due to the movement or push from the north. A close genetic relationship exists between the F_3 folds and the movement along the Phalebas Thrust and the Kusma Reverse Fault.

6. During the last folding F_4, again trending N-S, the most interesting feature is the development of numerous shallow basins and low dome-like structures

in the study area. This is due to interference of F_4 with F_3. This N-S (F_4) folding is somewhat difficult to explain. But this fold event is recorded all over, cutting across transversely all the Himalayan and Pre-Himalayan structures. This folding has been reported from all over Himalaya, even in the Siwaliks, and it is therefore quite likely that F_4 as well as the various transverse faults belong to a Quaternary deformational event.

DISCUSSION

According to the present author, the rocks of the study area comprise a Late-Precambrian sequence, (? Proto-Tethyan deposits fringing the Indian Peninsula), and these were folded by compressional stresses normal to the trend of the F_1 and F_2 folds. These orogenic stresses could be taken as Pre-Himalayan. The next fold episode F_3 and the thrusting came in the Tertiary time related to the Himalayan orogeny. The F_4 and the transverse faults are quite recent and the author considers them to have developed during the Late Quaternary and Sub-Recent times, on account of the generation of differential stresses due to unequal northward movement of the Indian continental mass.

The above conclusions arrived at by the author are strongly supported by the work of Mehta (1976) in Kulu-Mandi Belt of Indian Himalaya. Mehta has, mainly on the basis of the geochronological studies, also envisaged four fold events viz. F_1 (isoclinal and Recumbent), F_2 (close, overturned, co-axial to F_1), F_3 (open or concentric, locally overturned) and F_4 (gentle warps and cross folds). Of which, F_1 & F_2 were Pre-Himalayan, F_3 being synchronous with thrusting & nappe movements and F_4 (NE-SW) post dating the thrust movements and affecting all the earlier structures.

Most of the previous workers in Nepal Himalaya have observed folds parallel to the Himalayan strike and also those transverse to it. N-S folds have been reported by many workers, but the mention of their isoclinal nature has been only sporadically made. That these transverse structures (F_1 and F_2 folds of the present author) are Pre-Himalayan, has been suggested by many workers (Auden, 1935 ; Hagen, 1969 ; Mehta, 1976 ; Valdiya, 1976). Though Ohta & Akiba (1973) have not observed any Pre-Himalayan folding, they have referred to a strong mineral lineation relation to Aravalli orogeny.

Fuchs & Frank (1970) have on the other hand, explained the transverse folds rather differently, and according to them, the formation of these structures was synchronous with the nappe movements, having developed on account of "Compression along 'B' which becomes effective during the deformation of deeply buried parts of an orogen." The present author however does not agree with the views of Fuchs & Frank. The mechanism suggested by them is not at all convincing. The metamorphic grade does not support deep burial, and moreover, such an isoclinal folding can hardly be explained by a limited compression along 'B' if at all such a stress is feasible.

The present study has revealed that the Pre-Himalayan folds belong to two generations - the early (F_1) tight isoclinal to reclined and late (F_2) rather open and seen on both macroscopic and regional scale. The F_1 is not always N-S, and its trend and orientation considerably vary, depending on the effects of the superimposition of F_2, F_3 and F_4.

The various large scale transverse structures referred to by Auden (1935) and Hagen (1969), according to the present author, belong to F_2. It is quite likely that F_1 and F_2 were genetically related and formed two successive events of the same stress field. It is difficult to assign definite date to these fold episodes but in all probability they could comprise Pre-Himalayan deformational events. The Pre-Himalayan (Precambrian) deformational events giving rise to isoclinal-reclined and recumbent folds and other transverse structures have also been reported and discussed by many previous workers

(Auden, 1935 ; Valdiya, 1964b , 1976 ; Hagen, 1969, Ohta & Akiba, 1973 ; Ganesan et al., 1978). The presence of Pre-Himalayan metamorphism and deformation is also suggested in the works of Krummenacher, 1966 , 1978, Ashgiree et al. 1975, Mehta, 1975 ; Ravindra Kumar et al. 1978, ~~and~~ Karanth (1977) and Karanth & Shah (1977).

The F_3 folds were generated during the main Himalayan uplift. This folding was obviously caused by the southward pushing of the rocks along the longitudinal thrusts and faults. The nature and amount of slipping must have been variable from one dislocation to the other and this gave rise to a sort of compressional folding in the various faulted slices.

The F_4 folds-almost normal to the Himalayan strike, have to be explained by a mechanism related to the last phase of the Himalayan orogeny. Gentle undulations and the related strong puckering, affecting the entire Less~~h~~er Himalaya, must have formed by the differential stresses generated in the rocks, on account of unequal slipping along the various longitudinal thrusts and fault planes. Ohta & Akiba (1973) attributed the younger transverse structure to the differential advance of crystalline thrust sheets which according to them was essential feature of the Himalayan schuppen and nappe. The present author however, is more inclined to attribute these F_4 folds and the various transverse strike-slip faults to the differential movements of the underlying mass, rather than that of the overlying crystalline mass, because these flexures and faults have been recorded even in the Post-Tertiary deposits, viz. Siwaliks and Sub-Recent formations in the south, across the Main Boundary Fault.