CHAPTER V

STRUCTURAL GEOLOGY

GENERAL

Structurally, the area can be divided into two tectonic units, separated by Phalebas Thrust, a prominent dislocation which has been variously interpreted by previous workers. Detailed structural studies have revealed that this dislocation is separating two units which appear to show quite diverse patterns, but essentially contain rocks of a connected depositional sequence which have preserved an identical structural history. As such, the Phalebas Thrust, has much less regional significance than that envisaged by some workers like Fuchs and Frank (1970).

A detailed and critical mapping of the structural elements as well as their analysis have revealed an interesting sequence of tectonic events with a time span ranging from Pre-Himalayan to as late as Quaternary. None of the earlier workers have attempted to go into the structural complexity of the area, and in their works, mostly brief references to Pre-Himalayan folds and anticlines - synclines related to Himalayan uplifts are found. The present author has been able to work out the chronology of the various fold events and establish their relationship with the major dislocations of this part of the Himalaya.

STRUCTURAL PATTERN

From the structural point of view, the study area comprises three sub-divisions as under:

Sub-division I	Rocks to the south of Phalebas Thrust (Sirkang Unit).
Sub-division II	Rocks between the Phalebas Thrust and the Kusma Reverse Fault (Kusma Unit).
Sub-division III	Rocks to the north of the Kusma Reverse Fault (Kusma Unit).

All over the area, effects of four episodes of folding are recognised. Linear and planar structures related to the various fold events in the two units have been recorded, and on the basis of this data as well as the outcrop pattern and foliation trends the structural history of the area has been worked out (Table V.1).

Structural characters of sub-division - I

The rocks below the Phalebas Thrust show clear imprints of all the fold episodes. The F_1 (isoclinal to reclined) folds are quite conspicuous all throughout the Sirkang Unit. Of course, they are better developed in the slates and dolomites further south outside the study area. These folds show N-S axial planes dipping due E at varying angles, and have developed axial-plane cleavages very prominently. Being the earliest of all the fold events, the lineations related to this folding are not well preserved. The quartz roddings and cleavage-bedding intersections are probably the best record of the 'b' lineation (L_1) produced by this folding. Folds of later generations have acted upon these early folds resulting into reclined (F_1) folds at places and also in changing the orientation of their axes.

Superimposed over the isoclinal folds are the comparatively open and macroscopic folds F_2. In the area to the south and west mapped by B.N. Upreti (personal

Table V.1 : The successive fold eve

Fold events		ıctures	
		Natu	Orientation
1. N-S Isoclinal folding	F_1	Developmen cleavage (. cleavage o $_1$ isoclinal throughout	NNW-SSE to NNE-SSW
2. NNE-SSW to SE-NW moderately open large scale regional folds	F_2	Not observe-	--
3. WNW-ESE to WSW-ENE open folds and minor undulations	F_3	Crenulatio developed nally $_3$	WNW-ESE to WSW-ENE
4. N-S open folds, and minor undulations	F_4	Strainslip developed $_4$ nally	NNW-SSE to NNE-SSW

communication), the foliation trend clearly shows the pattern and nature of these F_2 folds. They extend N-S to NE-SW. These folds have considerable impact on the isoclinal (F_1) folds. Very few lineations (L_2) related to this folding have been recorded.

The third generation folds (F_3) are sporadically encountered showing WNW-ESE to E-W axial trend and with sub-vertical axial planes. The F_3 folds are of open, minor undulation type, the amplitude being very low. This folding has produced a widespread E-W pucker lineation (L_3). F_3 folding appears to be related to the movement along the longitudinal dislocations viz. the Phalebas Thrust and the Kusma Reverse Fault.

The last event of deformation (F_4) is represented by prominent N-S open undulations and micro-puckers (L_4), which show a consistently northerly trend. These micro-puckers are found to have been superimposed over all the earlier structural elements, but no major folding related to this lineation is observed.

Structural characters of sub-division - II

Comprising the middle portion of the study area, just to the north of Phalebas Thrust, this sub-division is structurally most interesting. On a regional scale, the rocks here are seen to form a number of synforms and antiforms and from W to E show quite divergent trends (Fig. V.1). The westernmost part constitutes a very open synform with axial plane broadly E-W. Eastward along the Kali Gandaki Valley, a N-S trending antiform with a northerly plunge is seen. To its east, lies a much distorted curviplanar synform whose axial plane shows southeastward, a variation in trend from almost N-S to NW-SE. In the east are seen a few E-W to WNW-ESE folds.

All these folds have been found to belong to more than one generation. Based on the systematic structural analysis of the foliation trends and lineations, the various folds have been classified as under:

1. E-W synform in the west - F_3
2. N-S antiform and adjoining distorted synform - F_2
3. E-W to WNW-ESE folds in the east - F_3

The F_1 folding does not form any major structures, but is fully represented by numerous mesoscopic tight folds all over the area, showing a variety of orientations on account of the effects of F_2 and F_3. Fine northerly

1. Area to the north of Kusma Reverse Fault - Sub-area I to III.
2. Area between the Kusma Reverse Fault and the Phalebas Thrust - Sub-area IV to XIII
3. Area to the south of the Phalebas Thrust - Sub-area XIV

In the following lines a brief analytical account of the structural characters of the various sub-areas is given.

Sub-area I

This sub-area is just north of Kusma Reverse Fault. The dominant rocks are quartzites, and bedding (S) is clearly recognised. Minor folds are nowhere recorded. Lineations on the whole are scarce. The contoured π - S diagram shows only a fragmentary girdle reflecting dip values due to F_3. Here the F_3 axis is almost horizontal trending N85°W. Also there are some indications of a girdle on F_4, the fold axis of F_4 pointing to 26° due NNW (Fig. V.3).

Sub-area II

Again made up exclusively of Kusma Quartzites, just flanking the Kusma Reverse Fault, its structure is reflected in the trends and dips of the bedding (S) only. On the map, a very open but narrow F_3 antiform is clearly recognised. Minor folds of any generation are scarse, but lineations related to F_1 (L_1 Quartz rods), F_3 (L_3 puckers) and F_4 (L_4 puckers and undulations) are occasionally observed. The contoured - S diagram reveals fragmentary girdle related to F_3 and F_4 (Fig. V.4).

<u>Sub-area III</u>

Lying to the north of sub-area I and II, the rocks partly belong to Kusma Quartzites and partly to Balewa Formation. The Modi Khola Transverse Fault is cutting almost middle of this sub-area. The dips are almost sub-horizontal at many places. The strike trend of S points to an open F_4 antiform. F_3 is nowhere observed. Lineations are also not so common, except for a few L_1 quartz rods pointing due NNE, and scattered puckers related to F_3 and F_4. The - S diagram reveals a girdle on F_4 and a faint tendency on F_3 (Fig. V.5).

<u>Sub-area IV</u>

Lying just to the south of the Kusma Reverse Fault, this sub-area forms the north-western corner of the study area. Comprising entirely of the Balewa Formation, here the rocks show both S and S_1, which are almost parallel.

Sub-area VI

This sub-area extends almost N-S from the Kusma Reverse Fault to Phalebas Thrust, and lies just adjacent to sub-area IV and V to their east. The rocks here belonging to both the formations, show regional folding in almost N-S direction and form a large antiform. Mapping has established this fold to be earlier to the two dislocations, and is obviously an F_2 structure. Very few lineations related to this folding are recorded. Quartz rods represents L_1, while the fine northerly puckers comprise the usual L_4. F_3 folding is not so conspicuous on the map, ~~but~~ except in the vicinity of Phalebas Thrust, where they are seen as drag folds with axes plunging very gently due WNW. Superimposition of F_3 on F_2 is responsible for the plunge of L_3 in both quadrants. This phenomenon is ideally seen in the π ($S-S_1$) diagram, which shows one conspicuous girdle on F_2 and two fragmentary girdles on F_3 - each having developed on the two limbs of F_2 (Fig. V.8).

Sub-area VII

Comprising almost the central part of the study area, the rocks here, made up of Balewa Formation, forms a regional distorted synform of F_2 generation. The dips are very gentle, but the strikes of foliation very clearly reveal the structure.

The foliation trend map (Fig. V.1), which shows the shape of the synform, has been reconstructed on the basis of the field observations and the structural analysis of the different parts of this fold. In the south-eastern part, the fold trend is almost NW-SE (Fig. V.9.A), the axis plunging very gently due NW. Further north-west, the fold takes a northerly swing, and the axial plunge is almost due NNW (Fig. V.9.B and Fig. V.9.C). Finally, in the extreme northern part of the sub-area, the synform becomes almost N-S (Fig. V.9.D), with a conspicuous F_3 (E-W) antiform superimposed over the F_2 fold (Fig. V.9.E).

Sub-area VIII

Just adjacent to the Phalebas Thrust to its north the rocks here, made up of Kusma Quartzites, show a much distorted fold pattern which is rather difficult to analyse. An E-W antiform with a gentle easterly plunge is seen on the map. It is interesting to observe that on the two limbs of this fold, are superimposed folds with NW-SE trend. The northern limb shows narrow elongated flexures, plunging very gently to the NW to NNE. The southern limb also shows folding on NW-SE, but here the folds are very open flexure type (Fig. V.10.A and Fig. V.10.B). The stereograms are difficult to interpret except that a broad framework is recognised. These superimposed folds have been doubtfully taken as F_4.

Sub-area IX

Structurally, this sub-area is very interesting. Lying to the NE of Sub-area VII, it shows flexures that have been classified as F_3. These are not exactly E-W, but trend almost ESE-WNW, and could be easily confused with the adjacent F_2 structure. But a careful analysis of L_3 lineation and the trends of F_3 folds in the adjoining sub-areas (X,XI,XII and XIII), clearly establish these flexures to be F_3. L_3 lineations are most abundant, while a few L_4 puckers are recorded. L_1 is not observed (Fig. V.11). The girdle on contoured π diagram is not so well defined, but this phenomenon is better understood in the adjoining areas where it is found that F_3 folds show a fanning and this fact is reflected in the stereogram.

Sub-areas X,XI,XII and XIII

All these sub-areas forming the eastern part, essentially show a number of F_3 folds, which vary in trends from WSW-ENE to WNW-ESE, pointing to a tendency of fanning of axial planes. All the folds plunge westerly at very low angles. On account of the fanning, the girdles on π diagrams are somewhat less well defined (Fig. V.12; Fig.V.13; Fig. V.14 and Fig. V.15). The lineations belong to three generations - L_1, L_3 and L_4. L_3 and L_4 show considerable fanning. In the sub-area X, some effect of NE-SW flexuring is seen. Perhaps this flexuring is local phenomenon as it is not reflected in any lineation trends, but related to some possible lateral movement along the thrust.

Sub-area XIV

Lying just to the south of the Phalebas Thrust, this sub-area forms the south-western corner of the study area. Comprising entirely of Sumsa Formation, here the rocks show both S and S_1, which are almost parallel. Minor folds related to F_1 are occasionally encountered. The open flexures related to F_3 and F_4 folds are very common. The foliation trend is almost E-W with moderate to high dips to the north. The foliation map clearly shows very broad N-S antiformal and synformal structures. The lineations L_3 and L_4 are quite common, and are the nature of fine puckers. The π-(S-S_1) diagram shows a conspicuous girdle on F_4 (Fig.V.16).

DEFORMATIONAL HISTORY

A critical evaluation and analysis of the structural data point to a long deformational history, going back at least to the early Palaeozoic. The present study has amply revealed that the structural evolution of the area consists of two distinct phases - Pre-Himalayan and Himalayan, perhaps with a considerable time gap. The two earlier fold events F_1 and F_2, which are transverse to the main Himalayan trend, are obviously very early structures, unconnected with the main Himalayan orogeny. The F_1 is invariably represented by tight isoclinal N-S trending folds. These are better represented in the Sirkang Unit, while in the Kusma Unit, they do occur as numerous mesoscopic folds, but show diversity in trends. Of course, their axes almost invariably point northward. An interesting feature of 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. The dominant metamorphic foliation of the rocks i.e. slaty and phyllitic cleavages, is a product of this metamorphism. The F_2 is also a fold event that pre-dates the Himalayan thrusting and longitudinal faulting. Its axial trend is also northerly, but its folds being quite open and affected by F_3, show considerable variation, ranging from NW-SE to as much as NNE-SSW.

The F_1 and F_2 folds pre-existed the Himalayan thrusting and nappe movements, and appear to be related to compressional stresses operating at right angles to the Himalayan strike. These events, unrelated to the Himalayan orogeny, might belong to some earlier deformational event during Precambrian or early Palaeozoic times.

The F_3 fold is the most dominant and conspicuous structure connected with the Himalayan uplift. It is evident that this folding is genetically related to the Phalebas Thrust and Kusma Reverse Fault, the two longitudinal fractures that developed during the southward nappe movement. The Himalayan thrust movement, which generated stresses in the underlying rocks, appear to have been responsible for the development of numerous local thrusts, and these in turn have folded the rock masses bounded by such fracture planes. It is significant to observe that there are no metamorphic changes associated with the F_3 folding. On account of unequal distribution of stresses within such fault-bound blocks, the F_3 folds show considerable diversity in size, shape and orientation.

The last folding F_4, again trending N-S, 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

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; Bordet ~~et al.~~, 1961; Hagen, 1969; Valdiya,1976). Though Ohta & Akiba (1973) have not observed any Pre-Himalayan folding, they have referred to a strong mineral lineation related 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 view 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. Such behaviour of F_1 folds is ideally seen in the Sub-division II of the study area.

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 comprise Pre-Hercynian deformational events.

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 puckerings affecting entire Lesser 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 structures to the differential advance of crystalline thrust sheets which according to them was an 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 depositis, viz. Siwaliks and Sub-Recent formations in the south, across the Main Boundary Fault.