Chapter 6

Analysis Of Minor Structures Of The Imphal Valley

Earth felt the wound, and Nature from her seat
Sighing through all her works gave signs of woe
That all was lost

Milton (Paradise Lost)
6 ANALYSIS OF MINOR STRUCTURES OF THE IMPHAL VALLEY

Large scale structures are commonly accompanied by simultaneous development of a number of small structural elements. A large scale first order fold, say for instance, may have a number of associated small scale second order folds. So, analysis of minor folds may provide good information about the nature and other geometric properties of the large fold. In the same manner, if the fold is large and non-observable in an outcrop, by analysing the dip-strike values and plotting them in the form of $\pi$ or contour diagram, the geometric properties of the large fold can also be evaluated. On the same diagram by superposing the minor fold axes as lineation, the relationship can be examined whether the minor folds are compatible or incompatible to the larger fold. Similarity in the geometric properties of the major and minor folds suggests common deformation mechanism and history. On the other hand, incompatible relationship may suggest independent deformation mechanism and/or history.

Likewise, analysis of minor fractures and joints can also be carried out in order to decipher the correlatibility between the minor fractures and the tectonic lineaments of the region. Because, close compatibility between the minor and major structures will suggest a common deformation mechanism and history as mentioned above. So, in this chapter, attempt to analyse certain minor structures is made in order to know their geometric, kinematic and tectonic significances. However, in-depth studies on mechanical properties of the rocks, frequency of joints in the rocks as a function of rock competency and other physical properties, mechanics on buckling and fold development will not be included since it is beyond the scope of the present work. Observations made in the field are simply analysed and interpreted in terms of the deformation mechanism discussed in chapter 3 with a special reference to the
kinematic and tectonic significances which directly or indirectly contribute to the major objective of the present work, “evolution of the Imphal Valley”.

6.1 FOLD ANALYSIS

Extensive field observations and studies in the Imphal/Manipur Valley and its adjoining areas reveal widely variable geometric properties of the folds. In the outcrop scale exposures, angular synforms, broad (box shaped) as well as angular antiforms are found in various parts of the valley. However, in general the folds are angular in nature characterised by narrow hinge zone and slightly asymmetric, marked by one steeper but short and the other gentler but longer limbs. Dip and strike of beds usually follow the regional trend although, localised swings are common. Dips of beds are generally moderate to high towards E or W directions. But, quite often low dips that resulted from the creeping phenomenon, specially in the upper part (shallower) of outcrops are common, sometimes even causing dip reversal. So, utmost care is needed while recording the dip-strike data of these beds during mapping. To minimise the errors, it is usually recommended to take dip-strike data on the competent sandy and silty layers/bands associated with the shales as well as at the lower part of the exposures if possible.

6.1.1 Major Folds

The nature, form and geometry of folds that are not observable in a single outcrop can be established by geologic and structural mapping. Single or multiple fold(s) of a particular area can be analysed using simple statistical techniques and equal area projection. From these analyses, the geometry, form, orientation, homogeneity and symmetry as well as preferred orientation of the minor structures (folds) with respect to the major/macroscopic folds can be established. The outcomes of these analyses can further be studied to establish the compatibility with tectonic framework of the state. So, in this section we analyse the planar surface (bedding planes) data of the Imphal Valley in order examine and understand the nature and geometry of the large folds that characterise rocks of the valley. General
comprehensive accounts on the analyses of both mesoscopic and macroscopic folds and their implications can be referred to Turner and Weiss (1963).

Dip-strike data, all over the valley region, have been collected during geologic and structural mapping. About 200 dip-strike data (poles to bedding) have been analysed and plotted in the form of π or pole and contour diagrams (Fig. 6.1A, B). Analysis, counting and contouring of poles have been conducted using Schmidt or Grid Method and equal area projection. Details of this method is not discussed here and can be referred to any structural geology practical text book e.g. Marshak and Mitra (1988), Ragan (1985), Turner and Weiss (op.cit.), etc. Figure 6.1A is the pole (π) diagram of the bedding planes displaying good concentrations of the poles in the WNW-ESE (roughly E-W) direction indicating fair compatibility with the regional compression axis. This further suggests the kinematics of the region that WNW-ESE shortening and approximate N-S (NNE-SSW) lengthening or extension, resulted from the plate interactions discussed in chapter 4, is true and the deformation undergone by the rocks of the valley are well in agreement with the regional mechanics/stress field. Figure 6.1B is the contour diagram of the poles to bedding and shows two points of maximum concentration. It gives rise to a π - girdle or S-pole girdle running nearly E-W. The pole to this girdle is the position of the regional fold axis (π or β-axis) which plunges at 7° towards N6°E (horizontal to sub-horizontal). From the diagram it appears that the large scale folds are, as if, cylindrical in nature. Such a nature may be due to the scale of the fold i.e. large where the dip-strike data were principally collected from the central parts of the fold(s). Because, in case of minor folds plunging towards N or S is quite common (see next section).

From the figure 6.1B, another interesting feature observed is the geometry of the fold that the folds in the region are usually angular with narrow hinge (not necessarily angular and sharp hinge) and may be similar to the nature and geometry shown by the figure 6.2A (see also Fig. 6.3A). The folds are generally asymmetric in nature with one limb relatively short and dipping steeply while the other limb longer and dipping gently. But the axial surface represented in the figure 6.1B created by joining the axis and the bisector of the two maxima may have variable attitudes since
Fig. 6.1. A. Pole or \(\pi\)-diagram of about 200 poles to bedding planes of the rocks of the Imphal Valley. B. Contoured diagram of the poles showing two maxima and the \(\pi\)-girdle or s-pole girdle which gives rise to \(\beta\)-axis (7\(^\circ\)/006\(^\circ\)). Axial plane is nearly vertical (007\(^\circ\), 87\(^\circ\)/277\(^\circ\)).
the hinge points on different layers (axial plane trace) not necessarily bisect the fold always, but oriented nearly sub-vertical in majority of the cases.

6.1.2 Minor Folds

The form, geometry and orientation of minor folds are widely variable unlike the major/macro folds analysed above. Although, a very extensive and in-depth study of these minor folds are not made, some of the limited studies conducted here reveal that the folds usually show low to moderate plunges towards NNE or SSW. These are found basically associated with and as second order folds to the large ones. In addition to these, a number of other minor folds also do occur in the rocks of the valley having variable geometry and orientation.

Figure 6.2B represents minor fold axes as lineations with respect to π-girdle and β-axis of the macro folds. It is observed that minor folds usually concentrate around NNE and SSW directions with low to moderate plunges. These folds could, therefore, be coaxial to the regional folds and may occur as second order to the large ones. Their plunging nature is quite common and evidently observed in the field (Fig. 6.3B). In addition to these minor coaxial folds, a number of other minor folds oriented and plunging in NW, SE, NE quadrants are also found. Whether these folds were produced as a function of different phases of deformation/folding is a matter of conjecture. Assignment of different phases of folding based on fold tightness/geometry (e.g. Chattapadhyay and Agarwal, 1983; Ghosal, 1983; Setty and Raju, 1990) is also questionable. Because, tightness or openness of folds may be resulted from competent contrast of the folded beds. In the valley, the shales (Disangs) generally show delicate as well as tight folding mainly due to its low competency. On the other hand, sandy bands as well as the Barails usually show open nature of folds due to its higher competency. Another important point of little liability of different phases of folding in the rocks of the Imphal Valley is the relatively young age of the IMR tectogenesis. Whatever may be the condition, four types of minor folds are observed in the valley. They are:
Fig. 6.2.  A. Possible geometry of fold as inferred from figure 6.1. The fold is asymmetric and angular with narrow hinge zone having one steeper but short and the other gentler but longer limbs. B. Minor fold lineations with respect to the \( \phi \)-axis (regional fold axis).
1. Minor folds oriented parallel to the regional axis, probably coaxial to the large folds,

2. Minor folds oriented and plunging in the NW, SE, and sometimes NE quadrants,

3. A third group of minor folds that are generally horizontal i.e. axis and axial plane are sub-horizontal but nearly parallel to the regional trend.

4. A fourth group of minor folds showing delicate nature/geometry but widely variable orientation.

The first group of minor folds coaxial to the regional folds, as already mentioned above (Fig. 6.3B), might have been produced as a function of regional WNW-ESE compression along with the associated large folds. The second group of folds (Figs. 6.3A and 5.7A) that plunge in different quadrants, other than the regional strike, might have been produced by secondary or second order (localised phenomenon) stress field derived from the regional compression at an angle of about 45° with respect to principal compression direction (about secondary or second order shear, see Badgley, 1965). This idea is strengthened further by field observations, for these types of folds are relatively common in the western and eastern peripheries of the valley. In these peripheral areas, the rocks undergo tremendous strain due to shearing along the Thoubal thrust on the east and Churachandpur-Mao thrust on the western side. These create a secondary stress field having a compression along the NE-SW direction thereby producing folds oriented in these quadrants. However, these kinematic and dynamic implications need further detailed investigations as well as analyses.

The third group of minor folds (Fig. 6.4) usually have low plunge towards NNE or SSW parallel to the regional strike. These are mainly displayed by the incompetent shale beds. Sometimes they occur as large and open warps. They are probably produced by action of gravity i.e. the steeply dipping (sometimes vertical) shales folded into warps with nearly horizontal axial surfaces. Figure 6.4A is an outcrop of dark grey splintery shales in the excavation of Khuga dam, Churachandpur district. It shows well developed rock/hill creep induced by gravity action. The photograph is taken facing north and the outcrop is on the eastern bank of the river,
Fig. 6.3 A. Photograph showing angular asymmetric nature of folds (Thongaorok stream). Note the steeper but short and gentler but long limbs of the fold. B. Photograph showing steep plunging nature of the minor antiform (Thanga hills).
Fig 6.4 Photographs showing variable nature of folds resulted from gravity action. A. Rock/hill creep resulted from gravity. Note the eastward dipping nature of the dark grey splintery Disang shales in the upper part and high angle westerly dip in the lower part (Khuga dam, Churachandpur). B. A minor fold having nearly horizontal axial plane (Ningombam hills north of Hiyangthang).
so, the topographic slope is towards west. As a result of creep, the upper part of the outcrop appears dipping towards east at a gentler dip while the lower part is subvertical. Similarly figure 6.4B is a fold developed in an incompetent shale bed due to gravity. The adjoining, more competent layers don’t suffer such deformation. The fourth group of minor folds have most widely variable plunge amount and direction. Their morphologic and geometric properties are, not only widely variable, but also highly delicate. From the peculiar nature and behaviour of these folds, it is very unlikely that they were produced by tectonic processes. For instance, figure 6.5 represents such typical example of folds (see also Fig. 2.12). Moreover, gravity sliding and slumping are common features in the flysch basin depositional environment. Figure 6.5A is a delicate fold in silty band of Disang Shales where the axis is roughly horizontal while figure 6.5B is another fold similar to an isoclinal fold plunging 36°/165° but the limbs run nearly N-S dipping steeply towards east. Interesting nature of these folds (Fig. 6.5) is that the delicate nature of the fold is confined to a few layers or bands only and doesn’t extend to the adjoining layers. Such nature of fold, therefore, may not be produced by post depositional tectonic phenomenon. So, these structures can be treated as slump folds.

6.1.3 Fold Geometry

In the two foregoing sections we have seen various nature and geometry of folds. It has also been mentioned that the folds are asymmetric with angular and narrow hinge in general. However, geometry of folds, as observed in the field, are widely variable. Although, not as frequent as the usual asymmetric angular folds, symmetric, rounded, disharmonic, parallel, concentric types of folds are found at different places. All these variable geometry of folds seem to be closely related to the competency of the layers. But in addition to these types and geometry, some of the commonly observed natures of fold are the angular synforms and broad and rounded sometimes boxed shaped antiforms (Fig. 6.6) and vice-versa. In the peripheral regions of the valley, broad box shaped antiforms and sharp and angular synforms are common. Figure 6.6A and B represent such type of folds well developed along the Thongjaorok stream in the foothill regions of Bishnupur. Similar type of folds i.e.
Fig. 6.5 Photographs showing delicate nature of folds probably resulted from slumping and gravity sliding as syndepositional phenomena. A. Slumplike folding (isoclinal) in silty bands of Disang rocks (Sendra hills). B. Isoclinal type of fold in the shale and silty bands of Disangs (Kthing hills). Ironically the fold is confined in a few bands only.
broad box shaped antiforms are also found at some places on the western side of Thoubal river (Thoubal thrust). On the other hand, broad and rounded synforms, but angular antiforms are common in the western part of the state as already pointed out in the previous chapters. This geometry of fold in the western part of Manipur was known as early as Oldham (1883). Sarkar and Nandy (1976) also observed and analysed these types of fold style and geometry in Tripura-Mizoram area of Surma basin. They tried to explain the development mechanism of these folds in terms of layer-parallel compressive strain and buckle shortening to a constant rate until counterbalanced by the upward pulling force due to buoyancy. Although, layer parallel compressive strain is an ideal mechanism for fold development, the model cannot visualise properly the geometry of the structures. For example, under such compressive strain equally angular or rounded folds e.g. chevron/fan folds or box folds may develop. Angular antiforms separated by broad synforms will not necessarily develop, and gravity, buoyancy as well as isostasy have very little role in shaping the geometry of folds. Moreover, in folding (buckling) mechanics it is generally assumed that role of gravity is negligible. Therefore, the geometric characteristics of these folds require some explanations providing reasonable justifications. There are two possible reasons as mentioned below.

1. The fold geometry - broad/box shaped antiforms and angular synforms or vice-versa may be produced by buckling i.e. compressive strain provided the whole sequence behaves as a multilayered anisotropic system. Because, anisotropic multilayered sequence can give rise to large kink folds under certain physical condition and shortening rate (see Price and Cosgrove, 1990; Hobbs et al, 1976). The angular synforms and broad antiforms or vice-versa might have developed as a result of about 30-40% shortening of the rocks (see Paterson and Weiss, 1966). In the region since shale and sand/silt alternations are common, the whole sequence may behave as a multilayered anisotropic complex giving rise to these typical fold geometry. One problem in this assumption is that, if such assumption is true, then the fold magnitude and wavelength should be nearly constant. Along the Thongjaoorok stream, these features are observed in the outcrop scale (Fig. 6.6) but, in the western part of the state, these are practically large scale structures
Fig. 66. Typical nature of folds found along the Thongjaorok stream of Bishnupur foothills. A. Angular synform where both the limbs dip at relatively high angles. In the foreground are the students of Earth Sciences Dept., Manipur University. B. Broad and rounded (box shaped) antiform that occurs nearby the synform represented in figure A above.
measuring sometimes 100’s of meters and rarely observable in the outcrops. So, this explanation has certain drawbacks.

2. The fold geometry is controlled by the nature of the thrust tectonics of the region, as nowadays, it is becoming one of the most widely observed phenomena in the thrust and fold orogenic belts. Wherever the thrust climbs over a small step called ramp, a box shaped antiform may be produced while the intervening parts remain as angular synforms. A good kinematic model of this type has been provided by Schonborn (1992). Another possibility of this type of folds may be the result of antiformal stacks arising from one thrust sheet piling over the other. For these type of features see McClay (1992), Boyer and Elliot (1982), Suppe (1983). So, in the eastern part of the state where majority of the thrusts has emerged on the surface, these features may be common. On the other hand, in the western part, the geometry of folds might have been influenced by a system of blind imbricate thrusts or duplex (see also Soibam, 1993). Where and around the tip lines of these thrusts lie, angular antiforms are formed, the intervening space being left as relatively less disturbed broad synforms. Since the thrusts still remain buried, they are unable to observe in the field. This type of fold and thrust relationship is also quite common in the foothills of northern Rocky Mountains of Canada (Thompson, 1981). The idea is also quite conformable to the observations made by Evans (1964) in the “Belt of Schuppen” of Nagaland where the thrusts occupy sharp antithetic axial planes. The thrusts in this belt are no more blind due to high shortening of the IMR resulted from thrusting against the Shillong-Mikir massif. Whereas on the southern side of Dauki fault, they remain mainly as a blind imbricate system possibly due to low shortening.

The idea given above is purely based on surface observations and mapping as well as based on similar and applicable models worked out elsewhere in different parts of the world. Detailed analysis and confirmation can be done only through extensive subsurface studies using seismic profiles, gravity anomaly studies, etc. So, more studies and investigations are needed.
6.2 FRACTURE (JOINT) ANALYSIS

Joints and fractures, by far, are the most widely occurring small scale structures in the rocks of the Imphal Valley. Various sets of joints/fractures are known in the valley rocks having variable dimension and orientation. Basically, fractures are closely spaced in shales and weaker rocks while in sandstone and siltstone bands, they are widely spaced. Tensional as well as shear joints are known to occur in these rocks. The joints are sometimes characterised by secondary infill materials (silicification) reflecting their tensional nature while others are marked by smooth surfaces without any silicification revealing their shear origin (see Figs. 3.7 and 3.8).

Statistical analysis of about 400 fractures collected from different locations of the valley reveals some interesting preferred orientation pattern (Fig. 6.7A). In the figure, it is observed that maximum concentration of fractures occur around N85°W-S85°E (E-W) close to the regional compression direction (N75°W-S75°E) as mentioned in chapter 3. The excessive concentration and abundance of joints around E-W may be principally due to scattering and overlapping of the extension fractures developed around N75°W-S75°E and the synthetic shear (Riedel, R) fractures developed around N75°E-S75°W. In addition to these fractures, P shears and Y shears may also develop between the compression direction and 45° from the compression axis i.e. between N75°W and S50°W (see Fig. 3.2 also). The heavy abundance around this E-W azimuth further confirms the explanation given in chapter 3 that, even if, lineaments are relatively less in this direction, minor fractures develop widely in the rocks of the valley. Although, less in number, and outnumbered by the joints trending E-W, figure 6.7A shows other preferred orientation azimuths around N5°E-S5°W, N35°W-S35°E and N75°E-S75°W. All these orientation trends have definite angular relationship and correlatable to that of the lineaments, even though, there is a minor variation of about ±10° in case of some group of joints. This further strengthens the idea that these fractures probably originated under a fairly uniform stress field as found in the case of structural and tectonic analysis.
Fig. 6.7. Graphic representation of analysed fractures/joints of rocks of the Imphal Valley. A. Rosette of the fractures representing number vs. trend. B. Bar histograms of fractures representing number vs. dip angle.
Figure 6.7B depicts the relationship between number and dip angles of the joints present in the rocks of the valley. There is also a very interesting distribution pattern of the dip angles that nearly 75% of the joints belong to high to very high category (60°-90°) and approximately a third of them to the sub-vertical to vertical class (80°-90°). All these features may be related to the origin and formation mechanism of these joints. And practically such large number of high angle fractures can normally be produced when S3, the minimum principal stress is horizontal and remains oriented in one particular direction. Possibly high angle fractures might have been produced under the following two conditions:

1. Firstly, they could be originated under the mechanism of normal faulting where the joints will develop at about 60° to the horizontal.
2. Secondly, the fractures may develop under the mechanism of strike-slip faulting where nearly vertical and very high angle joints may be produced.

The low abundance of fractures compatible to the origin by thrusting mechanism may be due to subsequent rotation of them during progressive compressive strain of the region. Or otherwise, the mechanism itself restricts wide development of fractures. However, high abundance of the steep angle fractures in the rocks of the valley is largely controlled by the two deformation mechanisms pointed out above which is evidently seen in section 6.3 later.

6.2.1 Fracturing Pattern

Widely variable fracturing and jointing patterns are observed in the shales of Disangs of the Imphal Valley as well as in the shales contained within Barail sandstones of the adjoining region. It is rightly termed as splintery nature of the Disang shales but without much physical and mechanical significance. And still a detailed physical, mechanical and strain analyses of the deformation characteristics of these shales are needed. The author, however, here tries to present some of the observations made in the field during his field works and further tries to give the possible significances.
Spacing or frequency of joints/fractures is a function of rock competency that is, competent rocks show widely spaced (low frequency) joints while incompetent rocks are marked by closely spaced (high frequency) fractures (see Price, 1966). In the Imphal Valley where there is intercalations of silt/sand and shale bands, the silty/sandy bands are generally characterised by relatively widely spaced fractures while the shales show closely spaced fractures that give rise frequently to the splintery nature of these rocks. Such features are exemplified by figure 6.8A.

*Splintery nature* of the Disang shales is principally produced by intersection of fracture cleavage with the bedding fissility although, shape, size and dimension of the splintered fragments are highly variable. In Disang shales of the Imphal Valley, this intersection relationship is ill preserved, probably due to intense fracturing. But in the shale beds of Barails, they are sometimes well preserved as shown in figure 6.8B. Here, the steeper planes (white pen) are cleavages rather fracture cleavages while the gentler planes (white pen with blue cap) represent the beddings. They intersect in an angular relationship and so, the splinters are usually given off in the form of rhomb chips or fragments. The regularity in shape and size of the chips is a function of the closeness and evenness of the beddings and the cleavages. The length of the chips is determined by the spacing of another fracture/cleavage that develops roughly normal to these two planes i.e. parallel to the plane of the photograph. The dimension of the chips is also widely variable, sometimes as small as 2 to 3mm and sometimes as large as 2 to 3cm. Pencil shaped chips to flaky or platy shaped chips of about 2 to 3cm size are common at different places. But, small chip splinter nature is the commonest type in majority of the outcrops in the valley. Sometimes the whole exposure of shale looks like a heap of gritty sand (Fig. 6.9A). Although, ideal slaty cleavages are not common in these shales, the fracture cleavages are highly pervasive and penetrative in almost all parts of the Disang shales. Hence, probably these features suggest a relatively high degree of strain and a shortening of about 40-50% or more parallel to the tectonic transport direction (see also Ramsay and Huber, 1983).

*Pencil structure* is another important fracturing pattern found in the rocks of the valley. These are generally well developed and preserved in the mudstones
Fig. 6.8. A. Photograph showing varying degree/intensity of fracturing in different rock layers. The competent sand layer (light grey) is characterised by low frequency, while the incompetent shales (dark grey) by intensely and closely spaced cleavages/fractures. B. Photograph showing angular relationship between bedding and fracture cleavage in the shale beds of Barails along NH 53 (near Tupul). The steeper surfaces represent cleavage planes.
Fig. 6.9 A. Photograph showing splintery shales in the form of gritty sand heap. Brown colour is due to weathering (Pechi hills, near Yairipok). B. Pencil structures in Disang shales/mudstones (Itthing hills, Loktak lake).
lacking well defined bedding fissility (Fig. 6.9B). One of the best developed outcrops is in the Ithing hills of Thanga and Karang regions of Bishnupur district. The dimension of the pencils is however, highly variable having a width of about 0.5cm to 1.5cm and a length of about 6 to 10cm. The length is sometimes as short as 2cm and sometimes as long as 15 cm. It is believed that at such stage of pencil formation the strain condition may be similar to that of a prolate strain ellipse and may have a tectonic shortening of about 10-25% (Ramsay and Huber, op.cit.). Reks and Gray (1982), similarly pointed out a tectonic shortening of about 9-26% based on the studies of pencil structures.

In addition to the above fracturing patterns discussed, other patterns generally observed are the irregular conchoidal to regular or irregular polygonal patterns (Fig. 6.10). Figure 6.10A is a pattern displaying irregular conchoidal to semicircular fractures. These types of fracturing have been reported as early as 1876 by Mallet. Possibly these fractures develop when the environment lacks a well defined stress system to produce either the pencil structures or the splintery fractures. So, the fractures orient themselves randomly being originated through various mechanisms. Figure 6.10B, on the other hand, represents a regular polygonal fracturing pattern developed in shales interbedded with sandstone beds. This pattern is most probably produced by a layer normal compression and equal extension in all directions perpendicular to the compression direction. The condition may be comparable to that of the chocolate structure formation and strain state may be equivalent to a pancake model. The tectonic significance and shortening is yet to explore and still further detailed study and analysis of these fractures are required.

6.3 PALEOSTRESS ANALYSIS

Analysis of joints/fractures in the previous section and that of the lineaments in chapter 3 reveal that there is good compatibility in the stress field producing both the joints, and the structural and tectonic lineaments though, there is a minor directional variation. So, in this section, it is attempted to analyse the paleostress conditions of the rocks of the Imphal Valley using conjugate joints or other
Fig. 6.10. Photographs showing various nature and forms of fracturing in shale beds (Soura, near Khongjom). A. Randomly oriented conchoidal fractures. B. Regular hexagonal to polygonal fractures.
Fig. 6.11. Photographs showing conjugate fractures/joints. A. Conjugate shears from an outcrop near Tenth village. B. Conjugate shears from an outcrop near Thouhal Lourembam (Pechi hills).
systematically developed fractures. Theoretical background of the analyses is based on the physical and mechanical laws of brittle failure theory that shear fractures develop at certain angular relations with the maximum principal stress ($S_1$). The practical procedure of evaluating the principal stresses in space can be referred to practical structural geology texts such as Ragan (1985), Hobbs et al (1976), Badgley (1965), Phillips (1971), etc.

Conjugate fractures (Fig. 6.11) as well as non conjugate but, systematically developed fractures found in the same outcrop, from different parts of the valley, have been analysed using stereographic or equal area projections and presented in figures 6.12 to 6.14. The figures provide definite orientation positions of the three principal stresses of the faults or fractures in space. Sometimes text book type fracture systems are found well in accordance with the mechanical laws.

Figure 6.12A shows orientation of principal stresses of a particular fracture system in the Ithing hills of Thanga region while figure 6.12B is obtained from the foothill regions of Bishnupur area. Both the figures represent relatively high angle orientation of the maximum principal stress ($S_1$) reflecting the possible origin of these fracture systems under the condition of normal faulting. Figure 6.13 shows the orientation of principal stresses in the central eastern part of the valley. Figure 6.13A is from Chingkham hills near Lilong where 6.13B is from Khoirom hills near Yairipok. Special features of these fracture systems are the presence of a third fracture in addition to the conjugate one. This third fracture has a point of common intersection with that of the conjugate fractures revealing common origin or deformation mechanism. But the fractures represented in figure 6.13A are produced by normal faulting mechanism while the ones represented in 6.13B by strike-slip faulting as evident from their respective orientations of the maximum principal stresses, $S_1$. Similarly figure 6.14 represents paleostress conditions in the Kakching hills on the south-eastern side (Fig. 6.14A) and Langol hills on the northern side (Fig. 6.14B) of the valley. Both the fracture systems seem to have originated through strike-slip faulting as evident from the relatively high angle orientation of $S_2$, the intermediate principal stress. In all the analyses, the internal friction angle ($\phi$) ranges
Fig. 6.12. Orientation of principal stresses ($S_1 =$ maximum, $S_2 =$ intermediate, $S_3 =$ minimum) deduced from conjugate as well as systematically developed fractures. A. Ithing hills, $\theta$, angle between $S_1$ and fault plane = 32°, $\phi$, internal friction angle = 26°. B. Western foothills near Bishnupur, $\theta$ = 29°, $\phi$ = 32°.
Fig. 6.13. Orientation of principal stresses deduced from conjugate fractures. All the three fractures having common intersection point indicate identical mechanism of origin. A. Chingkham hills near Lilong, $\theta = 30^\circ$, $\varphi = 30^\circ$. B. Khoirom (Pechi) hills near Yairipok. $\theta = 27^\circ$, $\varphi = 36^\circ$. 
Fig. 6.14. Orientation of principal stresses deduced from conjugate fractures. A. Tenthā hills near Kakching, $\theta = 29^\circ$, $\varphi = 32^\circ$. B. Langiing Achouba hill near Langol hills, $\theta = 27^\circ$, $\varphi = 36^\circ$. 
$30^\circ$-$36^\circ$, where $\theta = 45^\circ - \phi/2$, since $\theta$ is the angle between the maximum principal stress ($S_1$) and the fracture/joint. This relatively high value of $\phi$ is due to the fact that the fractures were measured from the siltstone or sandstone bands associated with the shales. Otherwise the angle could have been smaller for the shales.

The paleostress analyses carried out with randomly selected fracture data from different parts of the valley reveal one ironic but interesting information. That, in all the analyses, only the orientations of $S_1$ and $S_2$ change i.e. there is interchanging position of the maximum principal stress ($S_1$) with the intermediate principal stress ($S_2$) quite frequently. But the position of $S_3$, the minimum principal stress remains more or less constant oscillating around N-S. And the orientation of $S_3$, is well conformable with the regional extension direction, NNE-SSW as evaluated in chapter 3. Even when we apply the tilt corrections for the bedding dips, only the positions of $S_1$ and $S_2$ interchange and that of $S_3$ remains quite undisturbed since the bedding strike is roughly parallel to the regional trend (NNE-SSW) as well as to the orientation pattern of $S_3$. From the above it can, therefore, be inferred that the rocks of the Imphal Valley and its adjoining regions have suffered nearly NNE-SSW extension at least, since the later stage of the IMR evolution. So, such a phenomenon, might have played a very important role in the evolution of the valley, in the recent geological past.