CHAPTER V
STRUCTURAL ANALYSIS
It is now well-known that most of the Precambrian terrains in the world have been involved in more than one phase of deformation and metamorphism. They exhibit therefore a complex deformational and metamorphic history. The different structures exemplified by these rocks may all be the result of a single orogeny or may have been produced in more than one orogeny. The Aravalli mountain range has also undergone a complex structural and metamorphic history. The area under study forms only a part of the Aravalli belt and the structural history has been discussed in the previous chapter. Whether all the deformatonal structures seen in the rocks of the present area belong to one episode related to Delhi orogeny or different orogenies cannot be said conclusively. But since no younger movement is known in the rocks younger than Delhi, it may be possible that these rocks have suffered deformation, perhaps only in one orogeny related to Delhi orogeny.

The structural map of the poly-movemented area should sufficiently suggest different fold trends. Though there may be different fold trends, they may not be uniformly developed all over the area.
et al., 1970). As mentioned in the previous chapter, the folds of different episodes are developed in localised domains in the area under study. Different parts of the area may therefore exhibit one of the movements more distinctly than others. In such areas, it may not be meaningful to treat the entire available data as one unit. For a proper appraisal and understanding of the geometry of folds, the area should be divided by careful scrutiny and by trial and error method into small domains in which the folding can be considered to be statistically cylindroidal (McIntyre and Weiss, 1957; Weiss, 1951). Such domains have to be made out, indeed on an arbitrary basis for the full utilisation of the data. It is necessary at times to combine the data of two or more domains and treat the same in a semi-synoptic manner. It is, however, extremely dangerous to look into the stereoplots and interpret the structure. Such study is only made to support the observations already made in the field. The deficiency becomes all the more serious in poly-folded areas where interference patterns on minor scale are ubiquitous. The plots of data on planar elements may show clear girdles and fold axes but it may not
be possible to know which particular fold axis is brought out in the plots. By considering the closure patterns and minor structures of that domain, this difficulty can be solved. Even when the stereoplots show cylindroidal fold, it does not mean that the domain is strictly cylindroidal but it is only statistically so. The advantage of synoptic diagrams is that they bring out the prominent features and ignore the insignificant ones which are readily seen in the plots of individual domains.

Taking all the factors into consideration, the area was divided into ten tectonic domains of apparently cylindroidal folding (Plate 43).

TREATMENT OF DATA

The treatment is essentially dependant upon the need and scope. The term S-pole diagram (Turner and Weiss, 1963) is frequently used than the term W diagram (Sander, 1948). The S-pole diagrams have been drawn for the planar elements bedding and bedding foliation of each domain. Since bedding and regional foliation have together behaved as a single planar feature during all movements, they have been treated together.
\(\beta\) diagrams have not been drawn in view of the serious limitations they have got (Ramsay, 1964; Turner and Weiss, 1963). It is too well-known that the \(\beta\) intersection does not always point to a fold axis and can be taken to be fold axis when confirmed from field data. Sometimes the use of such diagrams can lead to misinterpretation. Apart from this it is absolutely necessary in a \(\beta\) diagram to treat the planar elements of the same generation. If the structure is essentially cylindroidal, \(\beta\) diagram gives fairly good results. When the folding is not cylindroidal, the \(\beta\) diagram gives rise to spurious concentrations of fold axes. Such diagram also suffers from the drawback that a large number of intersections are obtained for a very relatively few surfaces. For example, 50 traces of S-surfaces in a stereogram would yield as many as 1225 intersection points which would be difficult to contour. It also tends to create a false sense of dealing with a great amount of data. Because of such limitations, the \(\beta\) diagrams have not been drawn in the structural analysis of the area discussed in this chapter. Only S-pole diagrams have been drawn for the planar elements of different domains.
Geometry of Bedding and Regional Foliation

The most important planar structure in the area is bedding which is easily recognisable in most cases. Since this is the earliest planar element and a primary feature, it displays all the categories of folds. Because of the complexity of folding movements, the bedding attitudes show diversified trends which at first look appear irregular. Refolded folds on minor scale are common and suggest a non-cylindroidal character of major folds. The strike of vertical beds and the least dip of beds at right angles are both indicators of axial trend. These axial trends are not much regular. The S-pole diagrams of various domains show either non-cylindroidal or apparently cylindroidal character. This is because minor folds in most cases are non-cylindroidal. In domains in which folds are really cylindroidal, it is possible that the domain is only statistically cylindroidal although minor folds are non-cylindroidal.

The first cleavage or the regional foliation is quite predominant and everywhere lies parallel to bedding. In all the deformations, this foliation and bedding have together behaved as a single planar structure. A lot of field measurements show that this
foliation and bedding are parallel. The general trend of this cleavage, like bedding is irregular. In the structural analysis of individual domains, the bedding and regional foliation have been treated together.

Geometry of fold axes and related lineations

In regions of complex superposed folding, the fold axes and related linear structures have no unique direction. The early fold axes are rotated into different positions in subsequent deformations and hence are diversely oriented. The later fold axes cannot have a unique direction as the later folds are developed on already folded surfaces. It is now well-known that later fold axes and related lineations are coincident with the line of intersection of later fold axial surface with surface undergoing deformation (Weiss and McIntyre, 1957; Weiss, 1959; Ramsay, 1960; Johnson, 1969). So in an area of polyphase deformation the fold axes and linear structures have highly diversified trends, more particularly when two or three fold systems are equally intensely developed (Johnson, 1969) as seen at the western extremity of the area under study (Plate ). But in the rest of the area, the fold axes
and linear structures are not so irregular. Although no special plots have been made in the present study for the linear structures, they are plotted in the S-pole diagrams of each domain. In these diagrams, there can easily be seen some order in the orientation of linear structures. It may be pointed out that not all lineations in a domain in question have been plotted but only the orientations of the linear structures which appear to be representative for the domain in question have been plotted.

Domain I

The total area covered by this domain is about 9 kms. sq. and the rock types in it are banded gneisses, migmatites, granite and amphibolite. This domain is sub-divided into three sub-domains strictly on lithological basis; each covering an area approximately 3 kms. sq. Plate II-Fig. I is the lower hemisphere equal area projection (hereafter referred to as S-pole diagram) of poles to gneissic foliation in granite in sub-domain I A. There is a point maximum in the northwest quadrant which represents either a homoclinal series, the limb of a fold or a series of isoclinal folds. In the field,
this domain covers part of the southeastern limb of F-2 fold in which occur isoclinal F-I folds. These F-I folds are either reclined or upright depending upon the steepness of the limb of F-2 folds which in turn depends upon the degree of tightness of the F-2 fold. Some splay of low density contours permits drawing of a girdle with axis $\beta$ plunging moderately to ESE. Some F-I lineations plotted in the diagram cluster around $\beta$, the pole of the girdle. The pegmatites intruded into gneissic granite along its foliation planes are sometimes observed tracing minor F-I reclined folds. Therefore the S-pole diagram in Plate II-Fig.I confirms the observation made in the field.

Plate II-Fig.2 is the S-pole diagram of gneissic foliation, schistosity and bedding in sub-domain I B. The rock types in this sub-domain are banded gneisses, migmatites, schists and quartzites. The three planar elements have been treated together since they all lie parallel to each other. The southeastern limb of F-2 fold is represented by the maximum in the NW quadrant and a few poles falling in the SE quadrant represent the northwestern limbs of small to medium scale F-2 folds. The girdle is reasonably well-defined
with pole $\beta$ emerging near the northeastern periphery. The concentration of F-2 lineations around $\beta$ confirms that this girdle is obtained as a result of attitudinal variation caused by F-2 folding. Another relatively less well-defined girdle can be drawn with its pole $\beta'$ corresponding with the trend of F-I lineations. Note the change in the position of F-I lineations from Plate II-Fig.1 to Plate II-Fig.2. This rotation is caused by F-2 folding. The original $\beta$ axis of F-I reclined folds has shifted more towards left in Plate II-Fig.2 now, and F-I folds have been positioned into upright folds with moderately or steeply plunging axes due to the tightening of F-2 fold. The apparently cylindroidal nature of F-2 folding is suggestive of the fact that F-2 folds are developed on earlier isoclinal folds with very narrow hinge zones.

Plate II-Fig.3 is the S-pole diagram of the gneissic foliation in banded gneisses and migmatites and schistosity in schists and amphibolites in sub-domain I C. The diagram is similar to Plate II-Fig.2 the only difference being that the F-2 fold is much tighter here. The girdle is well-defined with $\beta$ emerging near the periphery and F-2 lineations cluster around this pole.
Plate II-Fig. 4 is the synoptic S-pole diagram of bedding in psammite, gneissic banding in gneisses, migmatites and granite and schistosity in pelitic schists and amphibolites in domain I. The overall plunge here suggested by $\beta$, the pole of the girdle appears to be steeper. This is the cumulative effect of the variable plunges of F-2 axes due to the development of F-2 folds on the en the limbs and hinge zones of early F-I folds.

**Domain II**

The total area covered by this domain is approximately 6 kms. sq. and it is constituted by the rock types-composite gneisses, garnet-staurolite-mica schist with intercalated psammitic bands. Plate II-Fig. 5 is the S-pole diagram of gneissosity, schistosity and bedding in this domain plotted together. The girdle is well-defined and $\beta$ plunges rather steeply. The F-2 lineations, however show a scatter but radial to the centre($\beta$ falling on this radius) and shows the non-cylindroidal character of F-2 folds. Considerable splay of poles is probably the effect of F-3 folds which are prominently developed in this sector. F-4 folds are
also developed in abundance especially towards the western part of the sector. F-3 folds are co-axial with F-2 folds and F-3 lineations have gentle or moderate plunge amounts. Slight split in the maximum in the NW quadrant is probably the effect of F-3 folding causing the overturning of the southeastern limb of F-2 fold. F-3 lineations show a scatter because F-3 folds are developed on the variably oriented surfaces rotated by earlier F-2 and F-I folds. Well-defined girdle corroborates the small scale F-2 closures seen in this domain. Scatter of F-2 lineations is also due to the effect of F-4 folding.

**Domain III**

The total area covered by this domain is about 6 kms sq. and the rock types in it are amphibolite and quartz-mica schist with intercalated psammitic and calcareous bands. This domain is sub-divided into two sectors, III A and III B, each covering an area of approximately 3kms sq. Plate II-Fig.6 is the S-pole diagram of schistosity in sub-domain III A. Two girdles related to F-2 folding with poles $\beta'$ and $\beta''$ are quite conspicuous. There is considerable
splay of poles around each maximum which is due to the
effect of F-5 folding and this permits drawing of two
more girdles with poles $\beta^\prime$ and $\beta^\prime\prime$ representing F-5
axes. The lineations related to F-5 folding fall near
these poles of the girdles.

Plate I2-Fig.1 is the S-pole diagram of bedding
and schistosity in sub-domain III B. Two girdles
related to F-2 folding are conspicuous but the
rotation of F-2 axis from NE in Plate II-Fig.6 to
almost NNE in Plate I2-Fig.1 is noticed and this is the
effect of F-4 folding which forms a prominent closure
in this domain. The split in each of the maxima may
be the effect of F-54 folding as seen by any F-54 folds
developed in this domain.

Plate I2-Fig.2 is the synoptic S-pole diagram
of bedding and schistosity in domain III. Two girdles
related to F-2 are well-defined but splay of contours
suggests the effect of F-4 folding. Moreover, the
F-2 lineations show variable orientations which is
also the effect of F-4 folding. The axial planes of
F-1 folds have been separately treated and discussed
later in this chapter.
Domain IV

The total area covered by this domain is 1.5 kms. sq. approximately and the rock type in it is mainly sheared quartzite and partly impure limestone. Plate I2-Fig.5 is the S-pole diagram of bedding in this sector. The F-2 fold girdle is not a well-defined one. But girdles representing F-I and F-5 folding are suggested. This supports the field observation that F-I and F-5 minor folds are ubiquitously developed in this part of the area. F-I lineations show a slight scatter because of the effect of F-5 folding but the linear structures related to F-5 folding itself have a more or less consistent trend.

Domain V

The area covered by this domain is approximately 3 kms sq. and the rock types in it are impure limestone, many impersistent bands of quartzite and amphibolite occurring as thin intercalations within quartz-mica schist and calc schist. Attitudinal variation is mainly found between Khedela and Chipala owing to the effect of F-5 folding. The two limestone bands representing two limbs of isoclinal major F-I fold show attitudinal
variation equally. This means that both the limbs
dipping steeply start dipping at moderate or gentle
angles at the same spot where probably is located
axis of F-5 folding. This is quite clear from the
structural map (Plate 43 ) especially south, SE and
east of Kchedela. Plate 12-Fig. 4 is the S-pole
diagram of total bedding in this domain. There is
a point maximum but considerable spread of low
density contours towards NE and SW quadrants thus
permitting the drawing of a girdle with its pole β
plunging at steep to moderate angle to WNW. The
concentration of F-5 lineations around the pole

β indicates that the spread of contours is the
effect of F-5 folding. A few F-I lineations have also
been plotted in this diagram and these show a scatter
from NNW to WSW and this rotation is the effect of
F-5 folding. A few poles fall on the western periphery
or near it. This is because of the development of
medium scale F-4 folds in limestone. Another girdle
can possibly be drawn with its axis or pole at β'.
The F-4 lineations though mainly clustered around
this yet show some scatter owing to the effect of
the youngest deformation.
Plate I2-Fig.5 is the S-pole diagram of the first cleavage (S-2) or regional schistosity in this domain. The split in the maximum and the spread in the contours on either side of it is the effect of D-5 deformation. A girdle is reasonably well-defined with its pole emerging at $\phi'$ near the centre and evidently corresponds with F-5 axis. Another girdle, approximately EW can be drawn which describes the F-4 axis emerging at $\phi'$ near the northern corner. This is the effect of F-4 folding recognisable south of Chipala (Plate 43 ).

The two diagrams Plate I2-Fig.4 and Plate I2-Fig.5 are quite similar and this supports the field observation that the bedding and first cleavage are parallel to each other and have behaved as a single inseparable planar feature during all the deformations. However, the girdles are more well-defined in Plate I2-Fig.5 than in Plate I2-Fig.4 which indicates that the folds are relatively more close or tiés in pelitic than in psammitic rocks and that therefore the style of folds is a function of the competency of the rock undergoing deformation. The amphibolite band in this domain mostly shows minor F-2, F-4 and F-5 folds.
Domain VI

The area covered by this domain is approximately 7.5 kms. sq. and it includes the rock types: calc schist, biotitic limestone and quartz-mica schist with its impersistant bands of quartzite, limestone and amphibolite. This domain is divided into two sub-domains, VI A and VI B, the former covering an area of about 1.5 kms. sq. and the latter about 6 kms. sq. Each lithologic unit covers an approximately equal area (about 2.5 kms. sq.) in this domain. Plate 13-Fig.I is the S-pole diagram of bedding in sub-domain VI A. There is a point maximum but slight split at the southern end of the lowest contour, suggests slight rotation about F-5. The point maximum suggests either a homoclinal series limb of a fold or a series of isoclinal folds. The field observation indicates that this domain falls in the northwestern limb of major F-2 fold containing F-I isoclinal folds and on this limb are developed at places F-4 and F-5 folds. In the sub-domain in question, F-I folds seem to be predominant. F-I lineations exhibit slight scatter because of the slight effect of F-5 folding. A somewhat less defined girdle can be drawn with its pole $\beta$ near the centre. F-4 lineations also show slight scatter as a result of F-5 folding.
Plate I2-Fig.6 is the S-pole diagram of first cleavage (schistosity-S-2) in sub-domain VI A. It is quite similar to Plate I3-Fig.I except for a few poles falling on the western periphery due to vertical foliation. It is commonly observed in field that the effect of F-5 folding causes verticality of foliation. Foliation dipping steeply to NW becomes vertical and then gradually changes strike and begins dipping steeply to southwest. The similarity of two diagrams corroborates the field observation that bedding and first cleavage are parallel. Bedding in psammites does not attain much verticality because of the competency of the rock but the schistosity does.

Plate I3-Fig.2 is the S-pole diagram of bedding and schistosity of sub-domain VI B. The girdle related to F-5 folding is more obvious than the one related to F-4 folding. F-4 lineations show a slight scatter due to the effect of F-5 folding but F-5 lineations seem to possess a consistent trend. The sub-vertical S-4 cleavage is nicely developed in this sub-domain but is not separately treated for this sub-domain but treated together for the whole area. Structural map (Plate 43 ) shows swings in the trend of this due to F-5 folding.
Domain VII

The area covered by this domain is approximately 6 kms. sq. and the rock types in it are biotitic limestone, impure limestone and calc gneisses. Plate I3-Fig. 3 is the S-pole diagram of bedding, gneissosity and schistosity in this sector. A clear well-defined girdle can be drawn with its pole $\beta$ emerging near the periphery. The effect of F-5 folding is not very prominently noticed. The girdle describes the F-4 fold on major scale seen in the structural map (Plate 43). The well-defined girdle gives an impression that F-4 folds are cylindroidal in character. The map of lineations (Plate 44), however, shows a disarray of attitude of F-4 axes. Since axial planes of F-4 folds are sub-vertical at large and since F-4 axes lie at the intersections of axial planes of F-4 folds with already folded surfaces, this variation is due to the development of F-4 folds in the limb and hinge regions of F-2 folds of medium or large scale. This apparently cylindroidal nature of F-4 folds is suggestive of the narrow hinge zones of both F-1 and F-2 folds. This is clearer from the structural map and some photographs. The variation in the amount of plunge of F-4 axes is attributable to three reasons:
(i) because F-4 folds are developed on earlier folded surfaces, (ii) because of the effect of F-5 folding and (iii) because of the complex geometry of F-4 folds due to inhomogeneous flattening.

**Domain VIII**

The total area covered by this domain is about 2.5 kms. sq. and the rock type in it is calc schist. Plate I3-Fig.4 is the S-pole diagram of the schistosity (S-2) in this sector. A low or gentle F-4 fold is indicated by the EW spread of contours. The girdle is not very well-defined. Slight effect of F-5 folding on F-4 lineations is noticed. Minor folds of all the generations are rather rare in this sector.

**Domain IX**

This domain covers an area of approximately 1.5 kms. sq. and the main rock type in it is calc gneiss. Type-I interference pattern is noticeable on medium scale. Plate I3-Fig.5 is the S-pole diagram of bedding (in thin intercalated calcareous bands) and gneissosity (in calc gneiss) in this sector. Clear girdles cannot be drawn as there is considerable interference between F-4 and F-5 folds. F-4 lineations occupy N and S ends. This is clearly the effect of F-5 folding.
Domain X

The total area covered by this domain is about 6 kms. sq. and the rock types in it are calc schist, biotitic limestone and impure limestone. Plate 13-Fig. 6 is the S-pole diagram of bedding and regional schistosity(S-2) in this sector. Two girdles are well-defined one approximately EW and the other approximately NS with their poles emerging at $\beta$ and $\beta'$ respectively. The former girdle is related to F-4 and the latter to F-5 folding. The spread of F-4 lineations is due to the effect of F-5 folding. It is clearly noticed in the map of lineations(Plate 44) that the axes of F-4/lineations associated with them gradually take sinuous turns between NNE and NNW. This swing is evidently an imprint of F-5 folding.

Geometry of Axial Surfaces of Minor Folds

Axial surfaces of minor folds were excluded by many workers and were considered insignificant in the analysis of structurally complicated terrains. But recently, they have been considered as important non-physical planar features. Axial surfaces of minor folds are quite significant since they do not show as much variation as the fold axes and associated
lineations. The axial surfaces of early folds are always affected by later deformation (except in type-I pattern of interference, Ramsay, 1962). In an area having undergone deformations in two successive events, the plots of axial surfaces of early folds in the S-pole diagram should give a clear girdle pointing to second deformation.

In the area under study, the axial surfaces of conjugate F-5 folds only, show a consistent trend. The axial surfaces of F-1, F-2, F-3 and F-4 folds show variation in attitude because of their having been involved in later movements. Axial surfaces of F-2 minor folds have not been subjected to structural analysis because of the paucity of development of F-2 folds on minor scale. Therefore the S-pole diagrams have been prepared only for the axial surfaces of F-1, F-3 and F-4 folds. Out of these three, the F-4 folds are best developed in the area under study. Plate 14 however shows the attitude of minor F-2 folds in the whole of the area and striking changes in the attitude can be noticed, especially in the closure regions of F-4 folds. Plate 14 shows the attitude of axial planes of only some minor folds in the area.
Plate I5-Fig.1 is the S-pole diagram of the axial planes of F-I minor folds in the whole of the area. A clear girdle with its pole $\beta$ represents the effect mainly of F-2 and subordinately of F-4 folding. Two somewhat less well-defined girdles related to F-5 folding are also suggestive. It may be mentioned here that F-I folds have been involved in some areas in predominant F-2 or F-4 folding, in others only F-5 folding.

Plate I5-Fig.2 is the S-pole diagram of the axial planes of F-4 minor folds in the whole of the area. A clear girdle is suggested with axis $\phi$ near the periphery. This describes the F-4 axis only and is obtained because of fanning. Two girdles running approximately from northern to souther corner are suggested and describe the rotation of F-4 folds about F-5 axes.

Plate I5-Fig.3 is the S-pole diagram of the axial planes of F-3 minor folds which are only restricted to domain II. Since axial surfaces are gently or moderately dipping, their rotation about F-4 and F-5 axes is common and is suggested by the two possible girdles drawn.
Geometry of S-4 Cleavage

The *strong* cleavage(S-4) is very well developed in parts of the area(see chapter III) and lies parallel to the axial planes of F-4 folds. Sometimes it is a well-developed axial plane schistosity, at other times a crenulation cleavage and at still other times only a fracture cleavage. Many measurements were made of this cleavage in the present study. This cleavage invariably shows considerable fanning. This cleavage is rotated at places about F-5 axis of folding.

Plate 15-Fig.4 is the S-pole diagram of S-4 cleavage in the whole of the area. The fanning of S-4 cleavage is clearly noticed in the diagram by the prominent EW girdle. Two NS trending girdles are suggestive of the rotation of this cleavage about F-5 axis. Such a clear rotation is also seen in the structural map(Plate 43).
LEGEND FOR STEREGRAMS

- GIRDLE

- POLE OF THE GIRDLE (p)

- F-1 LINEATIONS

- F-2 LINEATIONS

+ F-3 LINEATIONS

△ F-4 LINEATIONS

△ F-5 LINEATIONS
Fig. 1: Sub-Domain IA
82 S1 and S2 Poles
Contours: 1-5-10-15%

Fig. 4: Domain I
402 S1 and S2 Poles
Contours: 0-25 - 1-4-8-12-16%

Fig. 2: Sub-Domain IB
233 S1 and S2 Poles
Contours: 0-4-8-16-24%

Fig. 5: Domain II
198 S1 and S2 Poles
Contours: 0-3-6-9-15-18%

Fig. 3: Sub-Domain IC
85 S1 and S2 Poles
Contours: 1-5-10-15-20%

Fig. 6: Sub-Domain IIIA
98 S1 and S2 Poles
Contours: 1-3-6-9-12-15%
Fig. 1. Sub-domain III-B
III 5₁ and 5₂ poles
Contours: 1-3-6-9-12%

Fig. 2. Domain III
209 5₁ and 5₂ poles
Contours: 0-5-2-4-6-12-18%

Fig. 3. Domain IV
60 5₁ poles
Contours: 1-6-5-8-11%

Fig. 4. Domain V
126 5₁ poles
Contours: 0-8-4-8-12%

Fig. 5. Domain V
97 5₂ poles
Contours: 1-5-10-15%

Fig. 6. Sub-domain VI-A
186 5₂ poles
Contours: 0-3-5-10-15-20%
Fig. 1. 166 POLES TO AXIAL PLANES OF FIRST GENERATION MINOR FOLDS
CONTOURS: 0-6-3-6-9-12°/

Fig. 2. 289 POLES TO AXIAL PLANES OF FOURTH GENERATION MINOR FOLDS
CONTOURS: C: 0-3-6-9-15-18%

Fig. 3. 76 POLES TO AXIAL PLANES OF THIRD GENERATION MINOR FOLDS
CONTOURS: 1-3-3-4-8-12%

Fig. 4. 309 POLES TO S2 CLEAVAGE
CONTOURS: 0-3-3-5-9-18%