Chapter V

MOPHOLOGY AND GEOMETRY OF THE STRUCTURAL FABRIC

In the present study the morphology and geometry of the folds, planar tectonic anisotropy, linear fabrics associated with fold generators, joints and faults in the area are described and discussed. For a better understanding of the structural evolution of the area in space and time, the nomenclature adopted for describing the structural fabric of the study area is based on the position of structural elements in the regional tectonic sequence. The structural elements associated with the Udaipur and Lunavada groups have been assigned to the AD$_2$, AD$_3$ and AD$_4$ deformative episodes of the Aravalli Tectonic System (1981).

NOMENCLATURE OF THE STRUCTURAL FABRIC :

Tectonic System :

The Precambrian rocks of the northwestern part of the Indian Shield have been assigned to the Bhilwara, Aravalli and Delhi Tectonic Systems (1981). The basic assumption in this grouping has been that the rocks of the
Bhilwara Supergroup became cratonised prior to the Aravalli sedimentation and were exposed during the Aravalli sedimentation. Similarly, the Aravallis were exposed at the time of Delhi sedimentation. The rocks of the Bhilwara, Aravalli and Delhi supergroups exhibit evidence of plastic deformation. It is, therefore, obvious that they were deformed prior to their cratonisation, because, surface rocks behave as brittle elastic substances and would not have elasticoviscous flow. As a corollary, it may be assumed that the structural elements which are spatially associated with the Bhilwara, Aravalli and Delhi supergroups are temporally related to the Bhilwara, Aravalli and Delhi Geological Cycles. Hence, the structural elements associated with the Bhilwara, Aravalli and Delhi supergroups have been included into Bhilwara, Aravalli and Delhi Tectonic Systems. However, there are certain exceptions where the younger orogenies are overprinted in the older sequences.

Deformative Episode:

It has been observed that within a particular geological cycle the older rocks involved in the cycle have more deformative imprints than the younger ones. The total deformation of a tectonic system represents separate pulsations of compressive stresses with \( \sigma_1 \) trajectories either remaining constant or at times changing. The
deformations manifesting individual pulsations have been assigned to separate deformative episodes within the tectonic system. The structural elements such as folds and planar and linear tectonic anisotropies, which are kinematically related, have been accommodated within the same deformative episode. The style, morphology, and the intensity of the elements vary, depending upon the strain rate and physical state of the rock during deformation, but they show general correlation in local orientation and temporal distribution within an episode.

Alpha numeral scheme of nomenclature has been adopted for describing the tectono-chronology of the deformative episodes in a tectonic system. It takes into account the tectonic system to which it belongs and its temporal status in the deformative events of the system for example AD₁; where 'A' stands for Aravalli Tectonic System, 'D' for deformative episode and '1' signifies the position of the episode in the tectono-chronology of the Aravalli Tectonic System. The succeeding deformative episodes representing later pulsations of the compressive stresses of the Tectonic System have been designated as AD₂, AD₃ and AD₄ respectively.

Nomenclature of Elements:

The nomenclature introduced for folds, cleavages and lineations that are kinematically related with the folds of different deformative episodes, are AF₃, AS₃, A½₃, etc.
The letters F, S and  i refer to the structural elements concerned i.e. F for folds, S for planar tectonic anisotropy and  i for lineations having tectonic anisotropy with the fold axes. The prefix 'A' refers to the tectonic system i.e. Aravalli Tectonic System. The suffix '3' refers to the deformative episode with which the element is kinematically and dynamically related. The elements that constitute the structural fabric of the area comprise foliations, lineations, folds, joints and faults which are referable to AD₃ and AD₄ deformative episodes of the Aravalli Tectonic System.

MORPHOLOGY OF STRUCTURAL ELEMENTS:

Foliation

Many terms such as foliation (Darwin, 1846 in Whitten, 1969; Fairbairn, 1935); rock cleavage (Mead, 1940; Swanson, 1941; Billings, 1954); fissility (Van Hise, 1896 in Whitten, 1969); flow cleavage; fracture cleavage (Leith, 1923); axial plane cleavage; strain slip cleavage (Ramsay, 1967); slaty cleavage (De Sitter, 1954); schistosity (Darwin, 1846 in Whitten, 1969; Harker, 1932) have been used in literature to describe planar tectonic anisotropy in tectonites. These terminologies imply genetic connotation. However, in the present study to avoid the genetic
implications, the planes of mechanical inhomogeneity have been described under the general term foliation, which represents planar structures defined by the preferred orientation of component grains or fragments (micro-lithons) in deformed rocks (see Whitten, 1969; Spencer, 1977) and designated as 'S' planes following Sander (1930). Depending upon their mutual cross-cutting and temporal relationships, the different 'S' planes have been designated as $AS_2$, $AS_3$, $AS_4$ etc. in conformity to the norms of nomenclature adopted in the present study.

$AS_2$ Foliation:

The pervasive and penetrative fissility in the rocks of the Vareth Formation of the Udaipur Group, kinematically related to $AF_2$ folds and dynamically associated with $AD_2$ deformative episode, has been recorded on map as $AS_2$ foliation. It is defined by the preferred orientation of sericite and chlorite porphyroblasts which have their flat faces aligned parallel to $\{1\} \{2\}$ plane of strain, corresponding to the axial plane of $AF_2$ folds. The mean orientation of the $AS_2$ foliation is $N26^\circ W - S26^\circ W$, dip $76^\circ /N64^\circ W$; poles to $AS_2$ foliation occur as point diagram (Fig. 18 a) in the area. The genesis of this foliation possibly involved mechanical flattening of quartz grains, which show strain shadows and undulose extinction, recrystallisation and growth of chlorite along $\{1\} \{2\}$ plane.
The orientation of sericite possibly reflects combination of mechanical rotation of the allogetic flakes and recrystallisation along the plane of flattening. Occasionally, this foliation is manifested as transposition cleavage, defined by laminations of quartzose layers, which by mechanical rotation and attenuation have aligned with the planar tectonic anisotropy e.g. in the area around Vareth and Ukreli.

\[ \text{AS}_3 \text{ Foliation :} \]

In the rocks of the Wardia Formation a foliation is developed parallel to the bedding. This plane of mechanical inhomogeneity which exhibits parallelism with the bedding in rocks of Lunavada Group (AS\(_0\)) has been mapped as AS\(_3\) foliation. It is kinematically related with the AF\(_3\) folds in the area. This foliation is defined by preferred orientation of sericite and elongation of quartz grains in the plane of fissility. Some of the biotite grains are aligned with the foliation, others are isotropic in disposition. The foliation is superposed over the bedding surfaces and in most of the places it has either obliterated the bedding or coincides with it.

\[ \text{AS}_3 \text{ Foliation :} \]

The most pervasive and penetrative set of foliation,
that strikes parallel to the axial plane of \( AP_3 \) folds, is defined as \( AS_3 \) foliation. This foliation is highly variable in its exogenic expression and morphology. It appears as a closely spaced fracture cleavage (in the rocks of Bhukia and Bhawanpura formations) in the areas around Bhukia and Simlia villages. It occurs as flow cleavage (in the rocks of Bhawanpura and Chandanwara formations) near Bhawanpura and Dad. It is developed as slaty cleavage (Hills, 1963) in Nahali, Chandanwara, and Kadana formations, in areas around Arthuna, Chandanwara, Nahali, Bhatar and Kadana and as schistosity (in the rocks of the Kadana Formation) around Divda and Rajanpur villages. The foliation strikes generally from N-S to NNE-SSW and dips steeply towards West or WNW. It, however, exhibits azimuthal rotation about \( AP_4 \) generator (Fig. 18b), in areas of superposed deformation, as in Shergarh Synform.

When \( AS_3 \) foliation is represented by fracture cleavage it has usually 30 to 50 planes per centimeter. The fractures are distinct and separated from one another by thin microlithons having no mineral anisotropy along these failure surfaces. Under microscope the fracture surfaces appear rough, irregular and discontinuous. Sericite exhibits feebly developed parallelism with the fracture surfaces, possibly due to slip along the fracture planes.
POLES TO $A_3$ FOLIATION, CONTOURS
$\sigma_1$ TRAJECTORY, $A_2$ EPISODE 4, 8, 10 AND 32 %, KADANA RESERVOIR

Axial trace of $A_5$ Shergarh Synform
Angular rotation
of $A_5$ due to $A_4$ folding

POLES TO $A_3$ FOLIATION, CONTOURS
1, 5, 10 AND 15 %, SHERGARH SYNFORM

AP$_2$ CIRCLE EXHIBITING PLUNGE VARIATIONS AND AZIMUTHAL DISPERSAL OF AP$_2$ LINEATION BETWEEN VARETH AND UKRALI

FIG 1B
Where AS\textsuperscript{3} foliation is developed as slaty cleavage, flow cleavage or schistosity, it is defined by the anisotropy of mineral fabric which exhibits parallelism with the plane of mechanical inhomogeneity. The slaty cleavage, flow cleavage and schistosity are differentiated on the basis of their exogenic morphology. The three types of planar tectonic anisotropies have been distinguished, on the basis of the effect of mechanical shearing, slipping and the extent of recrystallisation. In areas where mechanical effects are predominant over the recrystallisation, the fissility appears as slaty cleavage; where the degree of recrystallisation is higher and the fissility is defined by the lepidoblastic structure of sheet minerals (biotite, sericite and chlorite) and slight elongation of quartz grains, it is introduced as flow cleavage. The flow cleavage has been referred to as schistosity when there is an increase in grain size of porphyroblastic minerals. Thus, the slaty cleavage, flow cleavage and schistosity, which are the manifestation of degree of recrystallisation represents various stages in the evolution of the plane of mechanical inhomogeneity developed in kinematic harmony with the AF\textsubscript{3} folds of the area.

AS\textsuperscript{3} Foliation:

It is a crenulation cleavage (see Knill, 1960; Richard, 1961) developed parallel to the axial plane of
AF\textsubscript{3} folds, which occur as puckers over AS\textsubscript{3} foliation. It is exogenically manifested as close spaced fractures at places penetrative but generally discreet. Locally, at outcrop level e.g. around Peisawara village, it becomes pervasive and penetrative obliterating the earlier foliation (AS\textsubscript{3} flow cleavage) and rendering the schist and phyllites of Bhawanpura Formation to the status of slate. This provides an interesting example of tectonic retrogression with progressive structural deformation. The AS\textsubscript{3} foliation is developed along the hinge of AF\textsubscript{3} puckers. At places, the attenuation of fold limbs has resulted in orienting the sheet minerals (chlorite and sericite) parallel to the plane of mechanical inhomogeneity defining the AF\textsubscript{3} foliation. Morphologically, it is the same as slip cleavage (White, 1949; Brace, 1953; Billings, 1954); shear cleavage (Mead, 1940; Wilson, 1946); strain-slip cleavage (Bonney, 1886 in Whitten, 1959); cataclastic cleavage (Knopf, 1931) and transposition cleavage of Weiss (1949).

AS\textsubscript{4} Foliation:

The closely spaced fracture cleavage, kinematically and dynamically related to AF\textsubscript{4} folds, has been designated as AS\textsubscript{4} foliation. This foliation at the outcrop level is pervasive and penetrative in the rocks of Shergarh synform. To an unaided eye it is morphologically expressed as closely spaced (1 mm and less apart) planes of mechanical
inhomogeneity. However, under microscope, the cleavage exhibits films of sericite showing preferred orientation at low angles to the plane of mechanical inhomogeneity. The foliation strikes WNW-ESE, and dips steeply to subvertically towards NNE. Sometimes it exhibits vertical dips. However, locally the strike is NW-SE with steep northeasterly dip (Fig. 18 c). This foliation is superposed over the earlier $AS_3$ foliation in the area.

**Lineation:**

Cloos (1946; 1953) and McIntyre (1950) used lineation as a descriptive and non-genetic term to connote external and internal linear fabrics of rocks. Jones (1959), Turner and Weiss (1963) and Whitten (1959) favour usage of the term to linear fabrics penetrative in hand specimens as well as in small exposures. Hills (1963) considered all linear components, *sui generis* having linear habit as lineation. Cogenetic linear elements may have variable morphology, geometry and orientation in poly-deformational regimes (see Ramsay, 1967). Therefore, in the present study, the linear elements having with variable morphology but exhibiting tectonic anisotropy with the fold axes, with which they are kinematically and dynamically related, have been regarded as lineations, independent of scale and penetrative character of the fabric. In conformity to
Sander's usage (Spencer, 1977) the lineation disposed parallel to b-axis of fold \( (b = \beta) \) has been recorded as \( \beta \) lineation and designated as \( \beta_2, \beta_3, \beta_3', \) and \( \beta_4 \) in conformity to the norms of nomenclature adopted in the present study.

\( \beta_2 \) Lineation:

The linear components of the tectonic elements, kinematically related to b-axis of \( \beta \) fold have been designated as \( \beta_2 \) lineation. It is manifested as b-axes of the mesoscopic folds and defined as intersection of \( \alpha_2 \) foliation with the bedding \( (S_0) \) in the ultrabasic rocks as well as in the metasedimentary sequence of the Vareth Formation around Kochri, Vareth, Dad and Ukreli. The lineation has an average plunge, \( 75^\circ/N14^\circ W \) and limit of variability of plunge of \( \beta_2 \) is from \( 56^\circ \) to \( 86^\circ \) and azimuthal dispersal lies between \( N65^\circ W \) to \( N40^\circ E \) (Fig. 18 d).

\( \beta_3' \) Lineation:

The \( \beta_3' \) lineation is developed as b-axis lineation of \( \beta_3 \) folds in the rocks of Wardia Formation. Being a non-penetrative element in the tectonic fabric of the area, it occurs as isolated linear element defined by the b-axes of mesoscopic \( \beta_3 \) folds in the area south of Wardia around Kadana dam and north of Harjoria. Locally, this lineation
is defined as the intersection of bedding \((S_0)\) with \(AS_3''\) foliation at the interface between the limbs and hinge of \(AF_3''\) folds exposed in the stone quarries at Wardia. \(AB_3\) plunges gently towards southeast in the area between Wardia and Khokarwa, towards north around Kadana Dam and towards north-northwest in Barjoria (Fig. 19 a).

\(AB_3\) Lineation:

The linear structure which are kinematically and geometrically related and disposed parallel to the b-axes of \(AF_3\) folds, have been mapped as \(AB_3\) lineations. Morphologically, they are expressed as the intersection lineation of bedding \((S_0)\) with \(AS_3\) foliation and the b-axes of the \(AF_3\) mesoscopic folds. They are locally penetrative at outcrop level. \(AB_3\) lineation is conspicuously developed in the Bhukia area and plunging moderately to gently towards the north or south in the area (Fig. 19 b). In the hinge zone of Shergarh synform (\(AF_4\) fold), it exhibits an azimuthal rotation about \(AF_4\) generator (Fig. 19 c).

\(AB_3'\) Lineation:

The lineation, which is developed as crenulation lineation on \(AS_3\) foliation is defined by the b-axes of \(AF_3'\) folds and by the intersection of \(AS_3'\) foliation with the bedding. It is generally developed in the limbs of \(AF_3'\) folds.
AP3 LINEATION FIELDS,
1. KADANA DAM
2. BARJORIA
3. WARDIA

AP3 LINEATION FIELDS,
BHUKIA AREA

ROTATION AND STEEPENING
OF AP3 LINEATION ALONG
AF4 GENERATOR
SHERGARH SYNFORM

NOTE THE AXIAL DIRECTION
STABILITY, KADANA RESERVOIR

Fig. 19
The \( A^2_3 \) plunges gently to sub-horizontally and exhibits low axial direction stability of \( A F_3 \) puckers in the area (Fig. 19 d).

\( A^2_4 \) Lineation:

The b-axis lineation of \( A F_4 \) folds has been designated as \( A^2_4 \) lineation. For the purpose of analytical rigour, the intersection lineation of bedding and \( AS_4 \) foliation has been taken geometrically iso-azimuthal to b-axis lineation of \( A F_4 \) fold in the area. The \( A^2_4 \) shows low axial direction stability in the area around Bhukia and plunges moderately towards west-northwest or east-southeast depending upon the slant of the limbs of earlier \( A F_3 \) folds over which the \( A F_4 \) fold is superposed (Fig. 20 a).

Geometry and Style of Folds:

The rocks of the area were folded on mesoscopic and macroscopic scales. These folds have been classified and termed as \( A F_2 \), \( A F_3 \) and \( A F_4 \) corresponding to the three deformative episodes of the Aravalli Tectonic System on the basis of their mutual cross-cutting relationship in the regional tectono-chronology (1981). The \( A F_3 \) folds, which are dynamically and kinematically related to \( A D_3 \) deformative episode, have been further defined as \( A F_3'' \).
AF3 LINEATION FIELDS EXHIBITING 
LINEAR AXIAL DIRECTION STABILITY, 
SNERGAM SYNEORE 

ORTHOGONAL RELATIONSHIP 
BETWEEN MEAN PALAEOSLOPE 
DIRECTIONS AND AF3 LINEATIONS 
FIELDS, 1-BARJORIA, 2-KADANA DAM, 3-WARDIA 

DEFINITION OF FOLD ATTITUDES 
OF AF3 FOLDS
AF^1 and AF^- on the basis of their style, geometry, temporal relationship and orientation.

AF^2 Fold:

The AF^- folds have been recorded from the rocks of the Vareth Formation of the Udaipur Group. In the regional tectono-chronology these are deemed to be the oldest folds mapped in the area. The geometry of these folds is manifested on macroscopic scale in the deformed ultrabasics.

These folds have cylindrical plane geometry with rectilinear hinges. But in areas where they are cross-folded, the geometry changes to non-cylindrical, non-plane with curvilinear hinge. The interlimb angle varies from 20° to 60°, thus in terms of tightness they may be grouped into tight to open fold (see Fleuty, 1964). The attitude of these folds conforms to steeply inclined to upright and sub-horizontal to moderately plunging folds (see Fleuty, 1964). The orthogonal thickness of the folded layer is more in the hinge region than in the limbs. The relative behaviour of the outer, and inner arcs of these folds varies, in some cases the rate of change of curvature is uniform in others, the inner arcs are more acute than the outer arcs of the folds. Thus the behaviour of the form surface of AF^- folds conforms to Class 1C folds and Class 2 folds of the fundamental classes of folds (see Ramsay, 1967).
FAMOCILE OF AF₃ FOLDS SHOWING CONVERGING ISOGONS, WARDIA. (a)

(a)

(b)

(c)

FIG 21
The first folds of the Lunavada Group referred to as $AF_3$ have been recorded from 2 km. southeast of Wardia, Barjoria and the right abutment of Kadana Dam. The geometry and orientation of $AF_3$ folds show extreme variations in the area though they are characterised by homogeneity of style localised axial direction stability, which is nearly normal to the local direction of palaeoslope in the area (Fig. 20 b).

These folds occur as rootless intrafolial folds (Turner and Weiss, 1963) within the older lithounits and as intraformational folds (Hills, 1963) within the younger lithounits of the Lunavada Group.

In the older lithounits of Lunavada Group southeast of Wardia, the variable attributes of $AF_3$ folds corresponds to moderately to gently inclined and sub-horizontal to gently plunging folds (Fig. 20 c). Locally, they have acquired reclined geometry (Naha, 1959; Sutton, 1960; Turner and Weiss, 1963). They are tight to isoclinal folds (see Fluety, 1964; Tremlet, 1976) with cylindrical plane geometry, occurring as tectonic inclusions of isolated closures in structural harmony with bedding foliation ($AS_o = AS_3$). The geometry of the folded arc exhibits weakly converging isogonal pattern (Fig. 21 a); $t'$ is less than 1 but exceeds $\cos\alpha$ in the limbs (Fig. 22). The $t'$ and $\alpha$ plots of the folds lie within the field of subclass 1C (Fig. 21 b).
$t' \cos \alpha$ plots for AF3, FOLD LIMBS A, B, C and D OF FIG. 21(a)
but $T'$ and $\alpha$ plots of these folds lie within the field of Class 3 and then swing to the field of Subclass 1C (Fig. 21 c) of fundamental classes of folds (see Ramsay, 1967).

The position of the curves of $T'$ and $\cos \alpha$ corresponding to $AF_3$ folds in the rocks of Wardia Formation is also anomalous. The plots for the limbs A, C and D follow the relationship $T'$ exceeds $\cos \alpha$ but in the hinge zone $\cos \alpha$ exceeds $T'$. The $T'$ and $\cos \alpha$ plots of limb B follow a constant relationship, i.e. $\cos \alpha$ exceeding $T'$ (Fig. 22). The overall geometry of the $AF_3$ folds shows that the curvature of the inner arc is more acute than the outer arc and the orthogonal thickness $T'\alpha$ is less than $T_0$. However, these folds do not exhibit any known text-book pattern corresponding to a definite class of the fundamental classes of the folds.

The initial geometry of $AF_3$ folds corresponds to parallel fold model, as exhibited by the petrified geometry of the intraformational folds (Hills, 1963) near Barjoria and the right abutment of Kadana Dam. The variable attributes of these $AF_3$ intraformational folds correspond to sub-horizontal to gently plunging and steeply inclined geometry (after incorporating dip correction in the tectonites). These folds exhibit progressive tightening from open to close and overturning of their limbs in the direction of tectonic transport which show parallelism with the $a$-axes of cross bed dip azimuth in Barjoria and Kadana Dam areas. The fold arcs follow convergent dip isogons, with nearly uniform
orthogonal thickness along the folded arc. The dip isogons are normal to $S_0$ and makes angle $\alpha$ with $AS_3$ plane at Kadana Dam. The isogonal characteristics of $AF_3^"$ intraformational (open, steeply inclined to upright) folds in Kadana Dam and Barjoria follow parallel fold model corresponding to Subclass 1B of fundamental classes of folds (see Ramsay, 1967).

The overall geometry of the $AF_3^"$ folds as seen at Wardia could be assigned to flattened parallel fold model (see Ramsay, 1962). The plots of the $AF_3^"$ fold represented by limbs C & D in famscile (Fig. 21 a) suggest variations in $\sqrt{\alpha_2/\alpha_1}$ from limb to hinge, when $\alpha$ becomes $\angle 40^\circ$ the plots lie beyond the curve where $t' = \cos \alpha$ (Fig. 23). The compound geometry of these early folds in the Lunavada Group is possibly due to the combined effect of shear stress parallel to stratification, caused by creep/epidermal glide due to the instability of the basin margin and lithostatic stress contributed by the body forces of the superincumbent strata over the epidermally glided tectonic inclusions of $AF_3^"$ folds.

**AF_3 Fold:**

The $AF_3$ is dominant fold element recorded on a macroscopic scale from Bhiliri, Bhukia, Bhana Simla, Kadana Dam, etc. Absence of these folds on mesoscopic scale is rather significant. The $AF_3$ folds have been imprinted on all formational units of the Lunavada Group. The slip folds
FIG. 23

After Ramasamy (1967)
(Hill, 1953; Turner and Weiss, 1963) recorded from Salakari on mesoscopic scale are perhaps younger and appear to be kinematically related to wrench fault tectonics in the Kadana Reservoir area.

The $AF_3$ folds are cylindrical, plane folds with rectilinear hinges. In areas where they have been cross folded by later $AF_4$ folds, the geometry changes to noncylindrical nonplane fold with curvilinear hinge. They are open to close folds with interlimb angle varying from $40^\circ$ to $100^\circ$ (see Fleuty, 1964).

These folds are sub-horizontal to moderately plunging and steeply inclined to upright around Bhukia but becomes steeply plunging to vertical around Kadana Dam (Fig. 24 b), and the fold arcs exhibit high wave length/amplitude ratio. Like $AF''$ fold the form surface of these folds is defined by $S_0$ (bedding); but they are distinguished from $AF''$ folds by their larger interlimb angle and higher wave length/amplitude ratio.

$AF'_3$ Fold:

The $AF'_3$ folds are developed on mesoscopic scale as puckers with form surfaces defined by $AS_3$ or $AS''_3$ foliations. These are temporally post-tectonic to $AF_3$ folds as exhibited by the mutual cross cutting relationship between $AS_3$ foliation and $AS'_3$ crenulation cleavage (see Knill, 1960). Geometrically, the $AF'_3$ folds are
DEFINITION OF FOLD ATTITUDES OF AF₄ FOLDS

(a)

DEFINITION OF FOLD ATTITUDES OF AF₃ FOLDS

(b)

FIG 24
asymmetric to overturned, with steeper limbs having positive geotropy. They are cylindrical plane folds with rectilinear hinges; in terms of tightness they are close to open with inter-limb angle varying from 35° to 100° (see Fleuty, 1964). The puckers exhibit uniformity of curvature in the form surfaces, defining the outer and inner arcs of these folds and correspond to Class 2 folds (Ramsay, 1967). The fold attitudes (Fig. 25 a) vary from gently plunging and gently inclined to reclined (see Fleuty, 1964).

The axial direction stability of these folds is low in areas of superposed deformation (Fig. 19 d).

AF4 Fold:

The AF4 folds are temporally post-tectonic to AF3 folds and are kinematically related to the WNW-ESE trending ChampanerS (see Gopinath, 1977). These have been tentatively assigned to the AD4 deformative episode of the Aravalli Tectonic System (1981). The imprints of this deformation are manifested on macroscopic scale in the Lunavada Group of the Kadana Reservoir area.

Geometrically, the AF4 folds have noncylindrical plane geometry, with curvilinear hinge. The folds are open with higher ratio of length of the projection of limb to length of the projection of the hinge zone, on the join of the adjacent inflexion points, than in case of AF3 folds (see Ramsay, 1967). Thus for the same inter-limb angle the parameter $P_1$
(see Ramsay, 1967) will be higher for AF<sub>4</sub> fold than for AF<sub>3</sub> fold. The form surface of these folds is defined by bedding and AS" foliation. The profile section is asymmetric with polycilinal box geometry (see Hills, 1963; Ramsay, 1967). The polycilinal style changes to single hinge type along the hinge zone towards the outer arc of a synform. The plunge of the fold axes and dip of the axial surface lie within moderately plunging and steeply inclined to upright field (Fig. 24a).

**Macro-Fabric & Orientation of Folds in Kadana Reservoir Area**

The major architectural pattern of the structural fabric of the Kadana Reservoir area is brought out by AF<sub>3</sub> (Fig 34) and AF<sub>4</sub> macrofolds. The style and geometry of folds corresponding to AD<sub>3</sub> and AD<sub>4</sub> deformative episodes have already been described. The orientation and spatial disposition of the major structural units have been synthesised which for descriptive purpose have been named after the villages/localities where they are fairly well developed. The important structural units of the macrofabric in the area are defined as follows:

- AF<sub>3</sub> folds of the Kadana Dam area,
- AF<sub>3</sub> folds of Shergarh area,
- Bhana Simal synform,
- Minagarh antiform,
- Shergarh synform
AF<sub>3</sub> Folds of Kadana Dam Area:

The quartzite ridges, which occur as natural fortification fringing the Kadana Lake display the morphology of the AF<sub>3</sub> folds on the right abutment of the Kadana Dam. The Kadana Dam folds are kinematically related to the major synformal structure. Their geometry correspond to asymmetric, tight cylindrical nonplane surfaces with rectilinear hinges. Their axial surfaces are curviplanar in acc section and axial traces trend NNE-SSW. The limbs trend NNW-SSE to NNE-SSW, dip subvertically at steep angles of 75° to 85° towards ESE and WSW. These are steeply inclined, upright to near neutral folds (Fig. 24 b) plunging 78° to 85° towards S10°E to S4°W (Fig. 25 b). Their profile sections represent non-periodic asymmetric waves with curved median surface. The folds exhibit sinistral drags. By virtue of their location in the hinge zone of a synformal structure it is unlikely that the shear stress of AD<sub>3</sub> deformation could have modified the geometry of these folds, as the shearing stresses would have been zero at the hinge. The asymmetricity of these folds is possibly the result of the shearing stress with sinistral movement, kinematically related to AD<sub>4</sub> deformative episode.
DEFINITION OF AF3 FOLD ATTITUDES, KADANA DAM

AF3 LINEATION FIELD, KADANA DAM

Fig. 25
AF$_3$ Folds of Shergarh Area:

The AF$_3$ folds developed in the Shergarh Synform, have been studied in three sub-areas namely (i) Davera sub-area, (ii) Bhilfri sub-area and (iii) Bhukia sub-area. The sub-area boundaries have been drawn on the basis of homogeneity of structural trends of stratification, which constitute the form surface of AF$_3$ folds in the area.

AF$_3$ Folds of Davera Sub-Area:

Holomorphic folds (see Belousov, 1962) referrable to AF$_3$ are discernible in the area around Davera. They are present on the macroscopic scale as plane cylindrical folds with monoclinic symmetry. In closures the folds exhibit non-cylindrical geometry. The profile sections are asymmetric, amplitude and wave length ratio is low, the folds are open with inter-limb angle varying from 90° to 100°. The axial plane has N5°W - S5°E to N-S trend and the folds are steeply inclined to upright and gently plunging (Fig. 26 a). The structural trend of the form surface (bedding) is N-S with moderate dips of 30° to 60° in westerly and easterly directions. The fold axes plunge 24° in N3°W direction (Fig. 26 a).
AF₃ Fold of Bhilāri Sub-Area:

Between Bhilāri and Markhola, the AF₃ folds are located in the hinge zone of the Shergarh Synform. These folds, like those of Davera sub-area, are seen on macroscopic scale as holomorphic, parallel, plane cylindrical elements which tend to be non-cylindrical at closure. The profile sections are asymmetric (see Turner and Weiss, 1963) with low amplitude wave length ratio; the form surface (defined by the bedding) is non-periodic asymmetric with curved median surface (Ramsay, 1967) in the area around Markhola (Fig. 26 b). The form surface exhibits open to close profile with inter-limb angles varying between 60° and 110°. The tightness of these folds increases towards the inner arc of the Shergarh Synform. The folds are steeply inclined and sub-horizontal to gently plunging (Fig. 26 b). The orientation of the axial surface veers from the North-South trend in the Davera sub-area to N16°E - S16°W in this sub-area. The strike of the form surface varies from N10°E - S10°W to N30°E - S30°W and the dip amounts from 20° to 70° in westnorthwesterly and eastsoutheasterly directions. Around Markhola these folds appear doubly plunging with Aβ₃ plunging 2° to 30° towards northnortheast and southsouthwest (Fig. 26 b).
AF₃ Folds Bhukia Sub-Area:

In Bhukia sub-area AF₃ folds are present on macroscopic scale as holomorphic elements. The sub-area is characterised by Northeast-Southwest trending structural fabric. Bhukia Synform and its complimentary antiform south of Bhukia constitute the macrofabric of the sub-area.

The Bhukia synform is non-plane non-cylindrical fold with curviplanar axial trace extending from Tembu to Nano Bhukia over a length of 4 km. The envelop of the axial surface trends N55°E - S55°W. The synform corresponds to close geometry with inter-limb angle 50°-60°. The limbs follow strike N55°E - S55°W and N60°E - S60°W dipping 75°/S35°E and 55°/N30°W. The synform plunges 40°/S53°W. The profile section is asymmetric with higher amplitude wave length ratio than in the AF₃ folds of the adjacent Bhilri sub-area. Though the Bhukia synform in its totality exhibits non-plane, non-cylindrical geometry, yet its individual segments exhibits cylindrical plane geometry. The synform is moderately plunging and steeply inclined (Fig. 26 c).

The complimentary Bhukia antiform has been mapped south of Bhukia. The geometry of the fold is brought out by the closure where the fold is open with inter-limb angle of 95°. The antiform is subhorizontal and steeply inclined, AF₂ plunges 9°/S48°W and axial plane trend N50°E-S50°W, dipping 80°/S40°E (Fig. 26 d). The morphology of the
antiform has been obscured by alluvial cover. However, there are indications to believe that the axial trace of the antiform possibly extends up to Ubapan over a strike length of about 1.5 km. in the northeast.

**Bhana Simal Synform:**

The quartzite band that constitutes natural fortification around Bhana Simal valley with a closure towards south, defines the geometry of the Bhana Simal synform. The synform is gently plunging, upright, close fold with inter-limb angle varying from $50^\circ$ to $70^\circ$. The tightness of the fold decreases towards its nose. The axial surface strike N5°W - S5°E, dipping 86° towards N85°E with generatrix plunging 30° towards N3°W (Fig. 27 a). The profile section is asymmetric, the western limb dipping at 60°-80° towards east and eastnortheast. The eastern limb has moderate dips of 30°-50° towards westnorthwest. In the hinge zone the dips become shallow (20°-30°). The axial trace of the Bhana Simal synform, which is traceable from Bhana Simal to Mahi river over a strike length of about 5 km; the continuity of the structure north of Mahi river has been brought out northwards through Salakari forest over a strike length of another 10 km. up to east of Kochri. In the regional tectonochronology, the position of the Bhana Simal synform is uncertain. On the basis of spatial
disposition and apparently complimentary relationship with adjacent $AF_3$ Minagarh antiform, in the present work the synform has been tentatively assigned as $AF_3$ fold.

**Minagarh Antiform:**

To the east of Bhana Simal synform and north of the Salakari lineament an antiformal axial trace has been mapped between Kunda and Minagarh Dungar. The antiform exhibits non-plane cylindrical geometry with curvilinear axial trending N10°E − S10°W around Kunda, which veers to NE-SW at Minagarh Dungar. The antiform is steeply plunging and upright. The limbs exhibit asymmetric profile, the western limb dips 70°-80° towards WNW and the eastern limb dips moderately 45°-55° towards ESE. At closure in Minagarh Dungar the limbs become tight with subvertical dips. This tightening of the Minagarh antiform is possibly the result of the superimposition of $AF_4$ strain of Shergarh synform. The flexure-slip of Shergarh synform ($AF_4$) operated on the Minagarh antiform ($AF_3$), the slide was restricted and the strain was adjusted by the tightening of the limbs; $\beta_3$ fabric is not developed in the antiform to demonstrate development of the oblique shear, in all probability during $AD_4$ deformation at hinge of the Minagarh antiform oblique shear operated together with the simple shear which resulted in the tightening of the fold at closure (nose) and folding of $AF_3$ axial trace about WNW-ESE axis at Minagarh Dungar (Fig. 27 b).
STEREOGRAM OF ASO POLES IN BHANA SIMAL SYNFORM, 75 ASO POLES

SCHEMATIC SYNOPTIC VIEW OF MINAGARH ANTIFORM

Fig 27
The major structural feature of the Bhukia subsector is a AF$_4$ synform having hinge at Shergarh. The synform has been evolved about a N70°W-S70°E axial trace. The geometry of the fold is defined by quartzite hills and strike ridges of meta-subgraywackes and meta-protoquartzite. The northern limb of the structure has been traced from Arthuna to Shergarh in N16°W-S16°E direction, dipping 48° towards S74°W (Fig. 28 a). The southern limb of the fold continues from Shergarh to Minagarh hill in N80°W-S80°E direction, dipping 48° towards N10°E (Fig. 28 b). The hinge zone of Shergarh synform trend N50°E-S50°W, dipping 48° towards N40°W (Fig. 28 c). At Minagarh the continuity of the fold is punctuated by the AF$_3$ closure of Minagarh antiform. The Shergarh synform is having polyclinal box geometry, the axes are seen at Tinira and Shergarh plunging 34° towards N26°W and 32° towards N48°W respectively (Fig. 28 d). It is open cylindrical plane fold with rectilinear hinges. The hinge is broad and rounded and hinge zone extends from Chhapra to Tinira. The inner arc of the folded surface is more acute than the outer arc, giving a converging isogonal pattern, corresponding to class-I fold (Ramsay, 1967).

Effects of superposed deformation in Shergarh Synform:

The AF$_3$ folds have generally north-south to NNW-SSE
OBJECT: ON OF BEADING

LOWER HEMISPHERE
PROJECTION OF BEDDING
POLES OF THE NORTHERN
LIMB OF SHERGARH SYNFORM
CONTOURS 1/2, 1 AND 2°

(1)

(2)

(3)

(4)

LOWER HEMISPHERE
PROJECTION OF BEDDING
POLES OF THE SOUTHERN
LIMB OF SHERGARH SYNFORM
CONTOURS 1/2, 1 AND 2°

ORIENTATION OF
POLYCLINAL AXES OF
SHERGARH SYNFORM.

Fig. 28
trending axial traces, having double closures towards north and south plunging at low angles of $6^\circ$-$30^\circ$. The axis trace of the AF$_3$ gets rotated from N-S to N60$^\circ$E - S60$^\circ$W about AF$_4$ generator of Shergarh synform (Fig. 29 a). Spatially the rotation from north-south to NE-SW is discernible south of the line joining Shergarh and Bhilri. In the area south of this line in the hinge zone of Shergarh synform (AF$_4$), the AF$_3$ folds due to superposed deformation, becomes non-cylindrical, non-plane with curvilinear hinge. The AF$_3$ show rotation from N3$^\circ$W to N65$^\circ$E due to superposition of AF$_4$ folds in the area around Bhukia (Fig. 29 a). The superimposed shear has led to tightening of the AF$_3$ folds, the dihedral angle vary from 100$^\circ$-120$^\circ$ in Davera sub-area to 50$^\circ$-60$^\circ$ in Bhukia sub-area. The imprint of later AF$_4$ fold over earlier AF$_3$ folds having easterly and westerly dips has resulted in opposing plunges of AF$_4$ with low axial directional stability (Fig. 29 b). No major interference patterns of multilobe forms are seen in the area, perhaps due to the fact that AF$_4$ folds are developed as very large scale structure as compared to AF$_3$ folds. Their wave lengths have ratios varying 1 : 20 to 1 : 25. This disparity in their wave lengths possibly prevented development of complex interference patterns though the geometry of the two sets of folds correspond to type 2 interference patterns of Ramsay (1967).
SYNOPTIC DIAGRAM OF SHERGARH SYNFORM SHOWING SCATTER OF \( a \beta_3 \) DUE TO ROTATION ABOUT \( a \beta_4 \) GENERATOR

LOCUS OF \( a \beta_3 \) LINEATION ABOUT \( a \beta_4 \) WEST AND \( a \beta_4 \) EAST OF SHERGARH SYNFORM

Fig. 29
Joints:

The joints encountered in the area, occur more commonly than any other structural element and are almost ubiquitous in their distribution. They represent petrified geometry of brittle failure in the rocks of all the formations and are manifested most prominently in the quartz-arenite beds. They are studied in order to find out any possible genetic connection between strain pattern and stress distribution. However, no genetic distinction has been possible, for separating tension and shear joints because of superposed deformation. It could neither be ascertained which joints were in existence when the rocks were subjected to cross folding. As parts of the area would go under submergence, it was felt desirable to document the joint sets, as the details might be useful with improved understanding of the stress distribution of the area.

The joints are both open and tight. The open joints are common in the quartz arenite beds specially in the peripheral ridge of the Kadana Reservoir. At places the displacements measuring 1-5 cm. along the joint planes were recorded. It may possibly be the effect of cross folding over existing joint sets, which are kinematically related to earlier deformation. The density and spatial continuity of the joints show considerable variation. They are more pronounced in the quartzite; spatially some
JOINT POLES, KADANA DAM

(a)

(b)
CARDINAL POLES AND TRACER OF JOINTS, KADANA DAM
Fig 31
of the major joints are traceable from 30 m to 100 m, whereas minor joints die out within 1 m to 2 m. The nature of joints surfaces varies from smooth to undulose and some of the surfaces developed slickensides and plumose structures.

The spacing, orientation and density of the fractures occurring as joints exhibit random fabric. To bring out some pattern out of the isotropic picture emerging from the plotting of joint data for different areas namely, Shergarh, Bhana Simal, and Kadana (Figs. 30 a, 30 c & 31 a), maxima of polar concentration of joints were plotted and planes corresponding to these maxima were constructed to obtain the joint sets. (Figs. 30 b, 30 d & 31 b).

The sets obtained for the structural units of the area possibly belong to more than one system, but lack of data for interpreting tectonochronology of joint sets inhibit any attempt on chronology of these microlineaments into joint systems. The prevalent sets developed and recorded in the area are given in Table-7.

<table>
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<th>Structural Unit</th>
<th>Joint set</th>
<th>Dip Amount</th>
<th>Dip Direction</th>
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<td>80°</td>
<td>N84°W</td>
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<td>do</td>
<td>N41°E-S41°W</td>
<td>24°</td>
<td>N49°W</td>
</tr>
<tr>
<td>do</td>
<td>N70°E-S70°W</td>
<td>86°</td>
<td>N20°W</td>
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contd........
Fig. 30

JOINT POLES, BHANA SIMAL SYNFORM

CARDINAL POLES AND TRACE OF JOINTS, BHANA SIMAL SYNFORM

JOINT POLES, SHERGARH SYNFORM

CARDINAL POLES AND TRACE OF JOINTS, SHERGARH SYNFORM
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<th>Joint set</th>
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<td>Amount</td>
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<tr>
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<td>do</td>
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<th>Strike Direction</th>
<th>Joint set</th>
<th>Strike Direction</th>
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<td>10°</td>
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Fault & Shear controlled Linears:

In the area under report four major tectonic linears are present, which have been designated as Salakari, Sarmi Muvada, Dhani Choti Pass and Nawagaon linears (Fig. 32).
Morphotectonically these linears are controlled by faults and shears in the area.

Geomorphically expression of these tectonic linears are straight drainage channels, wind gaps, topographic depressions, linear ridges and minor fault and fault line scarps in the area. Structurally these are characterised by shift in trends and lithology along the strike slip component of the faults e.g. along Salakari and Sarmi Muvada linears. The photographic expression of the faults and shears in the area are linears, which are indiscreet, non-penetrative, straight or curvilinear. The linears cross even rough topography without any deflection because of the vertical to sub-vertical dips of faults and shears.

Salakari Linear:

It is traceable as continuous linear between Salakari and Dungar over a strike length of about 16 km. It trends roughly N60°W-S60°E between Salakari and Dhani Choti Pass. In Dhani Choti Pass the trend veers to N65°W-S65°E which further eastwards near Dungar becomes N75°W-S75°E.

The linear is developed as wrench in the area between Dhani Choti Pass and Sarmi Muvada but further east and west it is developed as a shear. In the area examined no distinct tearing of beds was discernible. The termination of lithology across the Salakari linear around Bhana Simal is function of sedimentation and not of tectonics (Iqbaluddin, 1977a).
Between Dhani Choti Pass and Bureti the Salakari linear is represented by 300 m wide fractured zone in quartzite but in incompetent meta-semipelites it narrows down to about 10 m. The effect of wrench and shear in the quartzite is manifested by joints, developed as close spaced fractures. The bisectrics of their dihedral angle roughly conform to the trend of Salakari linear (Fig. 33 a). The genetic relationship between the joints and wrench in the area can be brought out by the intensity and close spacing of joints in the vicinity of the linear.

Locally, in the fractured zone along Salakari linear development of fault breccia is seen. It comprise of randomly oriented irregular fragments of quartzite, varying in size from less than a centimeter to over 6 centimeter. These autoclasts are cemented by medium to coarse grain admixture of quartz and silica. The breccia represents a jumbled mass of quartzite fragments with high percentage of voids. Generally in this breccia no rotational movement is discernible. Only in few outcrops the autoclasts appears to have been slightly rotated under a shear couple. It may be stated that though evidence of shearing is seen in a few outcrops manifested by slight rotation of fragments but evolution of breccia has basically been controlled by opening of tension gashes and is genetically different from Crush Breccia and Crush Conglomerate (see Hills, 1953).

Southeast of Bhilbar along Salakari linear, enchelon failure zones occurring 4 m to 6 m apart are present.
STEREOGRAM OF TENSION JOINT SETS ALONG SALAKARI LINEAR

STEREOGRAM OF JOINT SETS ALONG DHANICHOTI PASS LINEAR

FIG 33
These failure zones exhibit a sort of zoning with about 1 m thick brecciated core surrounded by a 2 m wide fractured zone. Locally in these failure zones tension gashes are developed trending NW-SE dipping 70°/NE. The acute angle relationship of the tension gashes with the shear zone suggest a sinistral sense of movement of the couple.

The wrench daylighted in a road cutting near Bhilbar is developed as 10 m wide shear zone in meta-semipelite. In this zone a locally penetrative fracture cleavage has superposed bedding, it trends N60°W-S60°E, dipping 70°-80°/S30°W. Field observations do not provide any conclusive evidence to suggest if it represent 'Sheeting' or close spaced 'Pinnate shears' (see Hills, 1953).

Morphotectonics of Salakari linear between Salakari and Sarmi Muvada and west of Dungar is controlled by thin shear zones. In Mahi river section near its confluence with the nala from Sarmi Muvada the geology controlling the Salakari linear is exposed. Here the linear show spatial correlation with fault zone trending N70°W-S70°E, dip 60°/S20°W. Along this fault, locally, displacement of beds is seen with a strike slip component of 30 cm; in this outcrop as elsewhere, in the area, the sense of relative movement along the failure surface is sinistral.

The morphotectonics of Salakari linear between Salakari and Sarsodi is controlled by the axial direction of AF4 folds. In this area no wrench and shears were observed.
The extension of the Salakari linear in the area west of Dungar along Walai nala is controlled by joint set trending WNW-ESE, dipping 70°-80°/NNE.

From the above description it will be seen that it is a physically ill-defined zone. The trend is well established, both structurally and geomorphologically, but the dip of the failure surface controlling the linear is matter of conjecture. Cardinal direction of dip of the shear zone has been conceived towards NNE i.e., upstream of Mahi river, on the basis of local geomorphology and it has been inferred to be sub-vertical due to rectilinearity of its trace in areas of uneven topography.

Nawagaon Linear:

It is traceable as geomorphic linear between Nawagaon and Dhani Choti Pass over a strike length of about 8 km, roughly trending WNW-ESE enechelon to the Salakari linear. The trend of this linear is not absolutely straight, local changes in relief have caused slight undulations, however, broadly it is rectilinear.

On ground the linear is defined by the local development of a micro-scarp, trending N65°W-S65°E, dip 65°/S25°W around Jher. The scarp face is a composite surface carved out in quartzite by East-West, 60°/South and N60°E-S60°E, 65°/S30°W trending joint sets. In the area
around Jher no brecciation is seen along the Nawagaon linear. However, higher recrystallisation slickensides along joint planes and physiographic break in the quartzite in north of Jher manifested as micro-scarp, are suggestive of structural failure along the linear.

Between Jher and Dungar the quartzite is much fractured due to intense and close spaced tension joints trending N30°W-S30°E and N65°W-S65°E. In the area the intensity of jointing decreases away from the linear. Spatial correlation between the tension jointing and Nawagaon linear can perhaps be taken as evidence of genetic relationship between them.

In Jher a line of four springs is seen along this linear within a distance of about 30 m. These springs had a total discharge of about \( \frac{1}{2} \text{ Cu/sec} \) in the month of May, 1976. It is interesting to record that the western most spring had luke warm water (35°C). Though in summer months the temperature difference between the spring water and stream water is not much but it is said that contrast becomes significant in winter months.

Locally in Dungar the fractured zone along this linear is developed as topographic depression, along which linear development of trees is seen. At places change in soil texture from dark loam to sandy loam and rubble covered soil is seen across the Nawagaon linear under stereo-models.

Between Bureti and Dungar this linear has controlled development of shallow water-table conditions.
The rectilinearity of Nawagaon linear, tension jointing in quartzite along the linear, presence of springs, one with luke-warm water and shallow water-table conditions along the linear are suggestive of a zone of structural failure. Through no definite sense of dislocation is seen in the area, but enough evidences in the form of differential recrystallisation, quartz veins (sweat in type) and tension jointing are present, which support strain development in a tensile stress field. The plane controlling the evolution of Nawagaon linear trend roughly WNW-ESE dip 60°/SSW and geometrically is an antithetic element to the failure surface controlling the Salakari linear.

Sarmi Muvada Linear:

It is developed as micro-linear in Sarmi Muvada along the eastern limb of Bhana Simal synform extending over a strike length of 1 km trending in WNW-ESE direction. The linear is controlled by a N70°W-S70°E, dip 70°/N20°E fault plane.

The fault is characterised by the development of 3 m to 4 m thick fault breccia and fractured zones of even thickness both along the foot wall and hanging wall sides of the fault plane. The strike slip component of the fault is about 50 m. The fault is normal with down-throw towards north and it exhibits a dextral sense of movement. The fracturing and fault breccia along this fault were evolved
due to development of tension gashes in a strain field characterised by $\lambda_1 > \lambda_2 > 1$. The fault breccia comprise irregularly shaped fragments of quartzite, occurring as jumbled mass cemented by silica and quartz grains, with a high percentage of voids. The autoclasts in the breccia have acquired different geometric shapes depending upon the prominence of the local fractures. The development of this fault zone is characterised by positive dilation which suggest tension has been the predominant factor in the evolution of this element.

Geometrically it occurs as second order fault in relation to Salakari linear which occurs as first order structure.

Dhani Choti Pass Linear:

It occurs as micro-linear emerging from Salakari linear from near Dhani Choti Pass extending over a strike length of about 2.8 km in N80°E-S80°W direction.

Exogenically, the linear is generally covered by rubble and is expressed as gullies and saddle across quartzite ridges in the area. Ground-truth checked in a nala near Kuhda revealed it to be morphotectonically controlled by a 2 m to 3 m thick fractured zone. The strain effects in the area are manifested by close spaced irregular tension fractures, internal recrystallisation of silica, at places
forming sweat-in type of quartz veins, which occur along fractures and joints (Fig. 33 b) in the zone.

Crudely defined slickensides are seen in the outcrop near Kunda, but it is not clear enough to give any directional sense of movement. The slickensides indicate that slight movement has taken place during process of fracturing but by and large strain release has been the dominant factor in the development of the fractured zone controlling the geomorphic evolution of Dhani Choti Pass linear.

Geometrically it occurs as second order fault like Sarmi Muvada in relation to the primary first order Salakari linear.

KINEMATIC MODEL FOR STRUCTURAL FABRIC OF LUNAVADA GROUP:

The rocks of Lunavada Group were deposited in a marginal basin successor to AD\textsubscript{2} deformative episode of the Aravalli Tectonic System. The structural fabric comprising AF\textsubscript{3}, AF\textsubscript{3}, AF\textsubscript{3} and AF\textsubscript{4} folds and their accompanying foliations and lineations were evolved during AD\textsubscript{3} and AD\textsubscript{4} deformative episodes of the Aravalli Tectonic System (1981).

Four successive phases of deformational episode have been identified and described as follows:
First Phase:

The earliest deformation in the Lunavada Group is manifested as $A^F'_3$ folds, $A^S''_3$ foliation and $A^B''_3$ lineation. These have been recorded from Wardia, Kadana and Barjoria. The $A^S''_3$ foliation is present in the area as bedding foliation ($A^S''_3 = A^S''_3$). The $A^F''_3$ folds are upright to overturned in the Kadana area (see Iqbaluddin and Shah, 1976) while around Wardia they occur as flattened parallel folds corresponding to class 1C (see Ramsay, 1967). The $A^S''_3$ foliation is present as axial plane foliation around Wardia. The $A^B''_3$ exhibits orthogonal relationship with palaeoslope in the Kadana Reservoir area (Fig. 20 b).

The orientation and geometric relationships of the $A^F''_3$, $A^S''_3$ and $A^B''_3$ fabric elements in the Lunavada rocks indicate that the movement plane was initially controlled by flexural bending of $A^S''_3$ (bedding) initiated by basinal instability, triggered by synsedimentational palaeoseismic activity (Iqbaluddin and Shah, 1976; Iqbaluddin, 1978b). The seismicity in the initial stages developed seismites (Pl. 11 a) and subsequently generated sliding process in the sediments. The slide was controlled by palaeoslope direction, initially the slide generated upright to asymmetric folds with $A^B''_3$ having orthogonal relationship with local palaeoslope direction (Fig. 20 b), in extreme cases the cohesion was lost resulting in the development of olistostromes (Pl. 10 b).
The folds were gradually overturned down the palaeoslope. The slide mechanism led to progressive tightening and increase in amplitude of the folds. The AF''3 eventually became unstable under gravity and acquired reclined geometry (Fig. 20 c). The progression of slide generated slip along ASO (bedding) which led to attenuation of limbs, resulting in the development of rootless as well as disjunctive geometry of AF''3 folds. The rotation of sheet mineral in the direction of slip led to the development of AS''3 foliation.

The strain geometry of AF''3 and AS''3 was subsequently modified by superimposed pure shear, corresponding to field 3 of the strain ellipse (see Ramsay, 1967), as a result the rootless AF''3 folds were flattened in the $\lambda_1\lambda_2$ plane of finite strain ellipsoid under the impact of lithostatic stresses. The superimposed pure shear modified the AF''3 buckle folds to flattened parallel fold model of class 1C (see Ramsay, 1967). The effect of pure shear on AS''3 foliation was rotation of sheet minerals in the $\lambda_1\lambda_2$ plane of the strain ellipsoid as a result of which the shear cleavage acquired attributes of axial plane foliation.

Second Phase:

The second phase of deformation in the Lunavada Group is manifested as AF3 folds, AS3 foliation and AB3 lineation. The AF3 folds have developed as flexure slip folds, the folds are generally open, upright with moderate plunge of AB3.
except in Kadana area where $A_{3}$ acquired sub-vertical disposition due to superimposed strain of $A_{4}$ deformative episode (Fig. 24 b). The folding was accompanied by the development of $A_{3}$ (axial plane) foliation.

The bedding ($A_{0}$) acted as slip surface during the genesis of $A_{3}$ folds. The $A_{3}$ foliation is developed as axial plane foliation of $A_{3}$ folds, morphologically expressed as slaty cleavage and schistosity. The kinematics of $A_{3}$ foliation involved mechanical rotation and flattening of the mineralogic population and recrystallization of new minerals with fabric anisotropy in the plane of fissility. The tectonic fabric involved solution in $\lambda_{3}$ direction and recrystallisation and flattening in $\lambda_{1} \lambda_{2}$ plane of strain ellipsoid.

The cardinal orientation of $A_{3}$ foliation in the area is NNE-SSW with subvertical disposition. The axial plane foliation has orthogonal relationship to $\sigma_{1}$ trajectory in tectonites (see Sharpe, 1947; Born, 1929; Fourmarier, 1951 in Whitten, 1969; De Sitter, 1954; Goguel, 1962). From the NNE-SSW cardinal orientation and sub-vertical disposition of $A_{3}$ foliation, the following stress plan will emerge which controlled the kinematic evolution of $A_{3}$ folds and related structural fabric.

\[
\begin{align*}
\sigma_{1} & \quad \text{WNW-ESE subhorizontal} \\
\sigma_{2} & \quad \text{NNE-SSW horizontal} \\
\sigma_{3} & \quad \text{WNW-ESE subvertical}
\end{align*}
\]
The east-south-easterly directed sub-horizontal trajectory led to the buckling of bedding with slip surface lying in the bedding plane. The progressive deformation of AS\(_0\) led to changes in the \(\lambda_1\lambda_2\) plane of incremental strain ellipsoid, facilitating mechanical rotation of sheet minerals and recrystallization in \(\lambda_1\lambda_2\) plane in accordance with Riecke's principle. The flattening strain resulted in tightening of AF\(_3\) and rotation of AS\(_3\) foliation in the \(\lambda_1\lambda_2\) plane of finite strain.

**Third Phase:**

The third phase of deformation is manifested as AF\(_3\)' puckers, AS\(_3\)' crenulation foliation and \(\lambda_3\)' lineation. The development of the crenulation foliation has the same kinematic significance as axial plane foliation (see King, 1956).

The dying out of the stresses responsible for AF\(_3\) folding led to the generation of a secondary stress field possibly caused by release of the elastic component of the flattening strain of AF\(_3\) folding. In the secondary field the \(-1\rightarrow 2\) and \(-3\) coincided with the \(i'_{1,i'2}\) and \(i'3\) directions of the strain ellipsoid corresponding to AF\(_3\) folding (as the direction of maximum positive elongation of the primary AD\(_3\) field coincided with the maximum negative elongation of secondary AD\(_3\) field).
The directional correlation between $A_F^3$ and $A_F^{3'}$ and near parallelism in the strike of $A_S^3$ and $A_S^{3'}$ foliations suggest that the strain ellipsoid corresponding to $A_F^{3'}$ puckering had coincidence in the $\lambda_2'$ direction and $\lambda_1'$ and $\lambda_3'$ directions of $A_F^{3'}$ coincided with $\lambda_3$ and $\lambda_1$ directions of $A_F^3$ strain ellipsoid. The $A_F^{3'}$ puckers which are developed as kink bands and chevron folds, developed as flexure slip folds in a strong anisotropic medium characterised by closely developed $A_S^3$ foliation which acted as glide surface during compression (see Peterson and Weiss, 1966). The sharpening of hinge and asymmetry of the limbs of $A_F^{3'}$ puckers facilitated the shearing of the limbs where $A_S^3$ subtended near orthogonal relationship with $\lambda_1'$ (of $A_F^{3'}$ field). The flexure slip mechanism which initiated the $A_S^{3'}$ crenulation foliation became dead and was replaced by shear mechanism (see Fairbairn, 1949; Wickham and Anthony, 1977; Anthony and Wickham, 1978; Sarkar, 1982) during the third phase of deformation in the Kadana reservoir area. The kinematic plan was such that the $b$-kinematic axes of second and third phase were co-directional while $a$-kinematic axis of third phase was parallel to sub-parallel with the $c$-kinematic axis of the second deformative phase during the structural evolution of the Lunavada Group.

Fourth Phase:

The last phase of structural deformation in the area is
dynamically related to the $A D_4$ deformative episode of the Aravalli Tectonic System. It is manifested as $A F_4$ folds, $A S_4$ foliation and $A L_4$ lineation.

The fourth phase in the structural evolution of the Lunavada Groups has following characteristic features:

i. The $A F_4$ folds are developed only on macroscopic scale, having polyclinal box geometry.

ii. The $A F_4$ folds are developed strongly in the quartzite bands and are significantly absent from meta-subgraywacke, schist, phyllite, etc. The dip of $A S_0$ is steep in the quartzite and gentle to moderate in the meta-subgraywacke, schist and phyllite sequence.

iii. $A S_4$ foliation is developed at angles to axes of $A F_4$ fold (Shergarh synform). The foliation exhibit variation in the dip and strike within the structural unit (Shergarh synform).

The kinematic plan of the $A D_4$ deformative episode correspond to near surface deformation under low tectonic regime as manifested by morphology of $A S_4$ foliation. In the near surface conditions the shearing stresses will be zero, and $\tau_1$ will be horizontal (see Anderson, 1951).

The $A F_4$ folds are developed in the quartzite while $A S_4$ foliation is strongly developed in the associated meta-subgraywacke, schist and phyllites. The selective development of the fabric elements in different lithologies is possibly related to the viscosity contrast and competence differences.
of the layered rocks. The quartzite bands define the geometry of $\text{AF}_4$ folds in the Lunavada Group. The viscosity contrast in the quartzite and the enclosing medium (meta-subgraywacke, phyllite and schist) led to buckling of competent beds (see Dieterich and Carter, 1969; Dieterich, 1970). The enclosing medium lacked the contrast within itself, which possibly explains absence of $\text{AF}_4$ folds in the meta-subgraywacke, schist and phyllite sequence in the area. The absence of low wave length structures corresponding to $\text{AD}_4$ deformative episode is possibly controlled by the orthogonal thickness of the quartzite. The wave length of folds in buckling are controlled by the thickness of competent layer (see Biot, 1964; Ramberg, 1964). The $\text{AD}_4$ deformation possibly took place at low strain rate, as suggested by the behaviour of Lunavada rocks as viscous fluids during the deformation (see Ramsay, 1967).

The kinematic plan of $\text{AD}_4$ deformation as inferred from the orientation of the $\text{AF}_4$ fold will correspond roughly to north-northeasterly horizontal trajectory. The viscosity contrast in the rocks led to variations in the intensity and orientation of $\text{AS}_4$ foliation, under deformation controlled by flexure slip mechanism. The angular relationship of $\text{AS}_4$ foliation with polyclinal axes of cogenetic $\text{AF}_4$ fold is due to tectonic milieu of the Lunavada Group (deformation at low strain rate under near surface condition). In areas of superposed deformation the later foliation is always crenulation foliation (see Ramsay, 1967). During the $\text{AD}_4$ deformation the Lunavada rocks were subjected to flexure
slip folding. The lack of viscosity contrast in the meta-subgraywacke, schist and phyllite sequence restricted slip along buckled layers. The strain increments were adjusted by development of slivers at small angles to \( \lambda_1 \lambda_2 \) plane of strain ellipsoid (see Ramsay, 1967; Whitten, 1969; Williams, 1977). The slivers which developed as planes of mechanical inhomogeneity, acted as slip surfaces for the incremental strain, which is manifested by fabric an isotropy of sericite flakes at acute angle to \( A S_4 \) foliation. The development of strain slip along the slivers resulted in the change of flexure slip folding to strain slip mechanism in the less viscous sequence. During the deformation the movement picture progressively changed but the intersection lineation of bedding (\( A S_0 \)) and \( A S_4 \) foliation coincided with the \( b \)-kinematic axis of strain ellipsoid.

The steepening of dips in the competent quartzite beds is due to development of oblique flexural slip under horizontally directed \( \sigma_1 \) trajectory with the progressive deformation the kinematic plan gradually altered, generating oblique flexural slip in the competent quartzite bands. It resulted in rotation of \( b \)-kinematic axis in the \( \lambda_1 \lambda_2 \) plane of strain ellipsoid leading to steepening of dips in the flexural slip regime, while in the strain slip regime the shear was accommodated along the slivers without disturbing the directional stability of \( b \)-kinematic axis during the \( A D_4 \) deformation.