PART II: STRUCTURE OF THE AREA
5.01 In his map (Plate 3, inset) on Eastern Part of Rajasthan (Central Mewar) that includes the present area, Gupta (1934) has shown two main fold closures - one to the west of Pur (25°18'00"N : 74°32'45") and the other to the west of Pandal (25°21'00"N : 74°34'45"), the former defined by the Aravalli quartzite and the latter by the Ralialo marble. Both close towards south. A small northerly closure in a quartzite band is also shown in his map south of Salampa (25°19'30"N : 74°31'00") . There are, besides these, a number of quartzite bands that extend in a NNE-SSW direction.

5.02 The present structural analysis incorporating all these closures along with the long running bands has been carried out on two scales - macroscopic and mesoscopic. Microscopic fabric has not been studied. Macroscopic analysis includes the study of map pattern, form, orientation, geometric relation and sequence of formation of the different sets of folds, study of linear structures and S - surfaces which pervade the domain. For detailed study of the geometry and orientation of the linear (generally folds) and planar elements, the map area has been divided into a number of
subareas. In mesoscopic analysis, the geometry of various structural elements, such as lineations and folds in the mesoscopic domain (hand specimens to single exposures) has been described and their interrelation, spatial and temporal, and relative ages established. Measurement of different geometric elements has been carried out on individual mesoscopic folds for a possible appreciation of the fold mechanism (Chapter VII). A kinematic interpretation of the structures is attempted in Chapter VIII.

MACROSCOPIC STRUCTURAL ANALYSIS

Rock boundaries

5.03 Lithologic boundaries are broadly conformable. However, sometimes the rock units are lenticular in occurrence; several such large scale lenses of quartzite and mica schist have been found around Balyakhera (25°13'00" : 74°30'25''). Two lenses of quartzite are noted 2 km northeast of Kiratpura (25°22'15" : 74°32'15''). In the western limb of the Jipi antiform (the western antiform) the banded ferruginous quartzite pinches out at Suras; the same rock is folded in the core of the Pur synform (the synform lying immediately west of the village Pur, 25°18'00" : 74°32'45''); its eastern limb almost immediately pinches out within the calc-silicates. The marble
band in the western limb of the Pandal synform pinches out around 1 km south of Dhulkhera (25°24'00" : 74°35'00") ; the eastern limb disappears under an alluvium cover to the north.

5.04 For the major part of the area, the contact relation between the adjacent lithounits is regular and normal. In the eastern part, the contact of a band of marble with the garnetiferous mica schist that occurs to its west and south poses some problems. The metapelite here is very thin and is irregular in width. If it forms the core of an antiform (Dantar antiform) as anticipated, the narrow occurrence of the schist must represent the narrow apical portion of a tightly appressed antiform. There is a possibility that the contact between the pelitic schist and the marble is of a tectonic nature produced either by a shearing off of the antiform or by a comparatively long - distance travel of the marble unit along a thrust over the schist. The thinning of the mica schist may also be due to the capacity of the rock to flow comparatively easily. However, the first group of explanation (sheared contact) seems more probable as there is considerable evidence of shearing at the base of the marble besides occurrence of thin lenticular bodies of impure quartzite which shows shearing of its constituent laminae and bands. Intense flowage has sheared out thin quartzite bands into small lenses that roll up ultimately to appear as "pebbles" in an autoclastic conglomerate. A systematic
study reveals their tectonic origin proving them to be tectonic or pseudoconglomerate. Gupta (1934) considered these pseudoconglomerates as true conglomerates of sedimentary origin marking an unconformity between the marbles of the eastern part of the area with the other metasediments of the west.

5.05 The eastern contact of the marble with the amphibolite near Lakshmipura is also sheared with a small lenticular garnet bearing amphibolite at the contact where the slicing of the rock is clearly visible. Shearing of garnet and hornblende is apparent even under the microscope (Fig. 3).

Map pattern and the Folds

5.06 Of the rock units, a thick band of quartzite with a closely associated band of ferruginous quartzite and a less persistent band of marble occur almost continuously exposed, often as hill formers, to serve as distinct key beds that could be traced for considerable distances. They yield a map pattern that is an expression of the regional fold recognised here as of the \( F_2 \) generation. The rock units run in a generalised NNE-SSW direction, swerving to the NE in the northern part of the map area (Plate 3). The marble yields a south closing fold of complex shape, west of Pandal. Just west of Lakshmipura, from near the nose of the north plunging synformal fold, a tongue like band extends north which is a surface expression
of a short, appressed, narrow antiform that rides on this synform which constitutes the easternmost fold unit of a succession of closures found in this region. West of this "compound" synform of marble (Pandal synform) a band of quartzite gives a repetitive fold pattern. Starting from near Dentar (25°25'00" : 74°37'15") in the northern part of the map area and running in a SW to SSW direction for around 14 km, the quartzite band first swings to WSW and then to N to NNE to define a marked regional synformal closure (Pur synform). This western limb then runs through Malikhera (25°18'25" ; 74°31'30") in a NNE direction for about 13 km and swings back on itself with a rather thick nose region giving rise to a north facing complex closure near Jipi which includes a small antiform (Jipi antiform). From south of Jipi, the quartzite band then runs in a SW direction and swings to SSW direction near Suras and continues further south; the band pinches out near Salampura within calc-silicate rocks.

5.07 Another quartzite band occurs in the western part of the map area structurally below the quartzite band as described above. This band runs in a NNE direction from north of Balyakhera. This band actually forms two limbs of a regional tightly appressed antiformal fold (core of the Jipi fold) which closes at 1.5 km east of Kotri.
5.08 A small isoclinal closure defined by a quartzite band is found 1.5 km west of Balyakhera (25°18'00" : 74°30'25")
This may present an earlier rootless fold. Quartzite also occurs as lenticular bands around Balyakhera and 2 km northeast of Kiratpura.

5.09 Calc-silicate rocks occur mainly as two distinct bands, one structurally above and the other below the main quartzite band already described \( p_{\text{para}} \). Near Salampura (25°19'30" : 74°31'00") where the quartzite band pinches out, these two bands of calc-silicate rock merge and form a single wide band.
Otherwise, these two bands are folded into an antiformal fold (Jipi fold) and into a synformal fold (Pur synform).

5.10 Two distinct bands of banded ferruginous quartzite have been found in the area. One occurs intimately associated with and structurally above the main quartzite band extending in a general NE direction from Suras to Jipi (5 km) where it forms a large scale Z - shaped regional fold with an antiform and a synform (Jipi folds). The other, occurring in the northern part of the map area just about 250 m east of the eastern limb of Jipi synform and within two calc-silicate bands structurally above and below it, runs in a general SSW direction for a distance of 12 km and is then folded in the core of Pur synform; the eastern limb described by this ferruginous quartzite pinches out within the calc-silicates immediately after the folding.
5.11 The narrow, elongated, NNE-SSW trending light coloured calc-silicate band occurring within the Pandal synform is folded by the same synform; the western limb of the fold defined by this lithounit is very short.

5.12 Starting from south of Pur, a band of garnetiferous mica schist extends in a general NNE direction, and from 500 m west of Lakshmipura (25°19'45" N; 74°33'45") becomes very narrow and continues upto Dantar in the north; the total stretch of the rock is about 16 km. In the northern part, this rock is highly migmatised and is invaded by quartz and quartzo-feldspathic veins and pegmatite bodies. This unit presumably represents the core of a tightly appressed antiform, namely, the Dantar antiform, the complementary synforms on either side being the Pur synform and the Pandal synform. The closure of this antiform expected near Dantar is not traceable because of intense pegmatite permeation. The eastern contact of the garnetiferous schist with the marble band, and occasionally with a thin quartzite band, is sheared (para 5.04).

5.13 The greater thickness of the calc-silicate bands in the western part of the area, that is around Kiratpura-Kotri area, may be due to the presence of early folds. Presumably such an early fold closure (earlier to the regional fold) in calc-silicate rock is seen just north of Salampura. It is a
tightly appressed isoclinal fold. Thickening of the ferruginous quartzite band in the Teranga hills is also due to presence of early folds.

5.14 Summarising, four distinct regional folds (named $F_2$ folds) have been established in the present map area - Jipi fold (broadly an antiform) Pur synform, Dantar antiform and Pandal synform. The following is a brief description of these folds.

5.15 The Jipi antiform is a tightly appressed overturned fold (overturned to the west). The bands occurring structurally at a higher level including the banded ferruginous quartzite shows a reversal of curvature, breaking up into two antiformal closures in the shape of a Z-fold instead of one as in the bands of calc-silicate at a structurally lower level. This closure in the calc-silicate band, about 2 km north of Samodi, is seen to plunge 32° towards N29°E, with the axial plane dipping at steep angles to the ESE.

5.16 In the Pur synform the western limb is almost straight whereas the eastern limb is curved giving rise to the appearance of a snake head. The western limb near the closure region strikes NNE - SSW with high values of dip ranging from 52° to 86° towards ESE; the eastern limb curves gradually and ultimately parallels the western limb, having a strike swing from
WNW - ESE, NE-SW to NNE-SSW; the amount of dip varies widely from 42° to 88° towards NNE to WNW respectively. This is a tightly appressed fold, but with a broader hinge than the other regional folds of the map area; stereographic plotting of the $S_2$ planes of the folded quartzite band in the nose area yields a beta axis plunging 40° towards N35°E.

5.17 With the closure region of the Dantar antiform obscured (para 5.12), the attitude of the beds, because of their very steep dips, do not give any indication of the overall geometry of the antiform. Existence of congruous small scale folds is indicated by the systematic oscillation of the foliation dips with the strike running in a general NE-SW direction.

5.18 The Pandal synform which closes further south near Lakhmipura is a complex synform with a tongue shaped, elongated riding over it (para 5.06). It is a tightly appressed fold with a round hinge; the western limb of the fold in the closure area strike NNE-SSW to NE-SW with high amounts of dip (64°-80°) towards ESE to SE respectively, and the eastern limb strikes NNE-SSW with high amounts of dip (54°-85°) towards western directions. The plunge of this fold has been worked out stereographically at 30° towards N19°E.

5.19 Apart from this regional set of folds, three other sets of folds are recognised in the present map area; these
are (a) an isoclinal rootless intrafolial set of folds $F_0$, 
(b) a tight to isoclinal set $F_1$ which has clearly been bodily 
rotated by the regional set $F_2$ in the Pur synformal area and 
(c) a later set of gentle fold or warp, $F_3$, which causes the 
frequent swerve of the general strike of the rock units. $F_0$
and $F_1$ sets are earlier to the regional $F_2$ set of folds whereas
$F_3$ is syn- to late-$F_2$ in origin.

5.20 The $F_0$ folds are rare and occur only as small scale 
mesoscopic folds; these folds are found in garnetiferous mica 
 schist and occasionally in thinly layered quartzite west of 
Pur (Figs. 2a & 2b); large scale $F_0$ fold is not seen anywhere 
in the map area. These $F_0$ folds are the oldest folds observed 
in this area and the axial surface $S_2$ is defined by a well 
marked schistosity particularly in the pelitic schists which 
serve as one of the most important form surface for all the 
other later sets of folds $F_1$, $F_2$ and $F_3$. The $F_1$ folds are 
particularly well developed in the quartzite band west of Pur.
Sporadic occurrence of $F_1$ folds in mesoscopic scale is also 
seen at places, and the folds often form interference patterns 
with other later sets of folds. In the quartzite band west of 
Pur, $F_1$ folds occur in mesoscopic scale and are tight to 
isoclinal; the regional synformal fold $F_2$ here has rotated 
these minor $F_1$ folds (para 5.60). The $F_1$ fold limbs together 
with the axial surface usually trend parallel to the lithologic 
boundary.
5.21 The F₃ warp brings about the frequent changes in the general strike direction of NNE-SSW to NE-SW. The axial trend of the warp is generally NW-SE.

5.22 Sector-wise structural analysis to ascertain the geometry, orientation and interrelationship of the various sets of folds described above has been done and is described in the later part of the present chapter.

Lineations and Linear Structures

5.23 Gloos (1946) defined a lineation as "a descriptive and nongenetic term for any kind of linear structure within or on a rock. It includes striae on slickensides, fold axes, flow lines, stretching, elongate pebbles or ooids, wrinkles, streaks, intersection of planes, linear parallelism of minerals or components, or any other kind of linear structure of megascopic, microscopic, or regional dimensions". Turner and Weiss (1963, p. 101) advocate a restricted usage of the term 'Lineation' only for those linear structures which are "penetrative in hand specimens or in small exposures". Thus slicken-side striae are excluded and only those fold axes are to be "treated as a lineation in a body that is homogeneous with respect to folding on a small scale. Larger-scale linear features such as mullion, rods, and elongated pebbles" are treated by them as linear structures.
5.24 The lineations and linear structures in the present area include mainly mineral lineation (defined by parallel to subparallel arrangement mostly of amphibole, puckers, minor fold axes, intersection of two sets of planar surfaces, orientation of elongated superindividuals and boudin lines. Detailed description of these lineations and linear structures is given in a later chapter (Chapter VI) under the heading mesoscopic structural analysis. In the present chapter, these lineations are plotted vis-a-vis the S-surfaces in the stereograms for better understanding of the relations of the macroscopic folds with the other types of lineations and linear structures.

**Penetrative planar structures**

**Bedding S₁**

5.25 Unequivocal primary sedimentary bedding is rare except for some relict "cross-bedding", a few showing the full set of topset, foreset and bottomset cross-laminations preserved in banded quartzite forming hills west of Pur. The interfaces between the topset - foreset and the foreset-bottomset measures 10 to 30 cm and the angle formed at the interface between the topset and foreset ranges from 8° to 20°.

5.26 The conspicuous structure that seems to be a composite of more than one set of planes that form the basis of recons-
struction of the form surface is a mineral-cum-colour banding that reasonably parallels the boundary of the lithological units. The banding, most of the time, runs continuous sometimes across single exposure, and usually maintain regular thickness. Such type of banding is seen in the banded ferruginous quartzite with alternate brown to grey coloured iron-rich and dull white coloured iron-poor bands; in calc-gneisses, also, alternate bands display both colour and compositional contrasts, the dull white bands made up almost wholly of calcite crystals, and the dark grey bands of a high proportion of mafic minerals. The banding sometimes is expressed as alternations of distinctive lithologic units such as quartzites with alternations of mica schists or marbles with alternate bands of calc-silicates.

Planar structure \( S_2 \)

5.27 The schistosity \( S_2 \) is widespread and acts as the form surface for the \( F_1, F_2 \) and \( F_3 \) folds. This surface is represented in different forms in different rock types. It occurs as fine bands or laminations in the calc-silicate rocks and banded ferruginous quartzites. In the pelitic schists \( S_2 \) is represented by the regionally widespread schistosity which is sensibly parallel to thin quartzite bands sometimes present in these schists. The fine banding or lamination in the rocks have probably originated through metamorphic differ-
entiation (Turner and Verhoogen, 1960; Turner and Weiss, 1963). Close examination of the bands has revealed that flat discontinuous lenses (Turner and Weiss, 1963) occur as overlapping units to give rise to the foliation (Fig. 4). This $S_2$ surface is, at places, represented by a fracture cleavage.

5.28 In the banded alternation of quartzite and mica schist, the schistosity in the latter is almost parallel to the banding in quartzite except in a few places where the angle between the two planar surfaces goes up to $10^\circ$. The banding in the quartzites in these cases probably represents the original bedding $S_1$ and the schistosity, the foliation $S_2$ which is definitely of metamorphic origin. The relation between the $S_1$ and $S_2$ surfaces is better understood at places in the garnetiferous mica schist. At few places west of Pur, the pelitic schists show small scale dead folds recognised as the earlier phase of folding and designated in this report as $F_0$ (Fig. 2). Such folds are also seen in some other types of rocks such as quartzites and calc-silicates. In the pelitic schists, these dead intrafolial $F_0$ folds are defined by thin bands or laminae of quartzite; the nose regions are preserved and the limbs of the folds are totally transposed along the axial plane schistosity. Thus, the planar structure along the nose of the dead folds or tectonic inclusions represent an earlier foliation surface, probably $S_1$ and so the axial plane schistosity
to these folds may be designated as $S_2$. The $F_0$ structures are seen only to develop in smaller scales and are also scanty. Unequivocal occurrence of $S_1$ planar surfaces along the major part of the exposures, because of a nearly perfect transposition, is rare. The surface $S_1$ is practically parallel to $S_2$.

Planar structure $S_3$

5.29 A set of fracture cleavage forms locally along the axial surface of the $F_1$ folds. This is designated $S_3$. It is not as widespread as either $S_1$, $S_2$ or other later planar structures (described below). The cleavage developed in the quartzite hills west of Pur provides an example. Fig. 5 shows the surface in a quartz-mica schist in an area 1.5 km SE of Dhulkhera; the quartz crystals with some feldspars are flattened parallel to the cleavage showing some incipient flow along the structures. A later crenulation cleavage is found to intersect $S_3$ at a high angle. In some highly appressed structures, the surface $S_1 = S_2$ becomes nearly parallel with $S_3$ and the latter is often transposed and made coincident making this planar structure a composite of the three (Fig. 6).

Planar structure $S_4$

5.30 A set represented by various types of foliation, such as, fracture cleavage, schistosity and crenulation cleavage develops parallel to the axial surface of $F_2$ regional folds.
Fig. 7 shows a set of $S_4$ cleavage intersecting an earlier presumably $S_1$-$S_2$ surface at an angle of around 15°. It occurs in a marble exposure about 800 m southeast of Samodi. Two sets of fracture cleavages intersect and produce angular cleavage blocks in the banded ferruginous quartzite exposures north of Suras. Near Jipi, the mesoscopic $F_2$ folds present this type of cleavage along which partial transposition of calcareous bands occur. Transposition along $S_4$ surfaces is also exemplified by an exposure of quartzite-mica schist alternated rock at a place about 1.5 km east-north-east of Dhulkhera (Fig. 8). Here the foliation $S_1$ is transposed along the $S_4$ schistosity defined by subparallel arrangement of the flaky minerals, the micas. Dead intrafolial folds belonging to $F_2$ set is seen to the right lower corner of the figure. The intersection of the banding and the schistosity makes an angle of about 30°.

5.31 Crenulation cleavage is particularly well developed in the pelitic and psammo-pelitic metasediments. This is a variety of fracture cleavage usually forming in the apical region of the puckers as axial plane cleavage to these minor folds which belong to $F_2$ fold set. Sen (1971) also describes similar type of cleavages from Rajgarh area, Central Aravalli, Rajasthan.
Planar structure $S_5$

5.32 The axial surface of the warp $F_3$ is also represented by a cleavage surface to be described as $S_5$. This is a fracture cleavage which at places grades into a joint. This structure is rare in occurrence and is seen mostly in banded ferruginous rocks. Fig. 9 shows this planar structure in the same rock near the village Jipi. The surface is subvertical with a ESE-WNW strike.

Systematic structural analysis

5.33 The map area has been divided into 14 subareas (Plate 5) to analyse systematically the distribution of the various structural elements present. The methods employed have been discussed by many and considerable work has been done on this problem. Turner and Weiss (1963) incorporated the principles and procedures advocated by Sander (1930, 1948, 1950). Excellent accounts on geometric analysis of superposed cylindrical and non-cylindrical folds have been given by Weiss (1958), Weiss and McIntyre (1967), Ramsay (1958, 1960, 1963), Tobisch (1967), Ross (1962), Rickard (1963), Wilson (1967) and others. Stauffer (1964) analyses the behaviour of early lineations folded by later conical folds.

5.34 The choice of the subareas is made with an objective to find out statistically homogeneous domains with respect to
any of the structural elements such as $B_1, B_2$ or $B_3$, the axes of the fold systems $F_1, F_2$ and $F_3$ respectively (cf Turner and Weiss, 1963, pp 175-185). The order of homogeneity of a domain for a particular fold axis depends on the order of interference of the other fold axes in the domain. Thus, when more than one of these elements are equally dominant in a subarea, their interference will produce considerable inhomogeneity causing difficulties in analysis. In the present area, high pervasive-ness of more than one event of folding makes the problem difficult. Considerable precaution has thus been taken in analysing and processing the data.

5.35 The geometric analyses of the defined subareas are described systematically in the following pages. The poles of the penetrative structural planes ($S_1 = S_2$) are plotted and pi-diagrams (S-pole diagrams) are prepared. As beta-diagrams are liable to give a large number of spurious intercept points, the analysis has been carried out mostly by pi-plots. The pi-diagrams are considered to be the most satisfactory method of analysing field data and in many cases they give us greater information about the fold geometry (cf Ramsay, 1964 and Weiss 1958, p. 135; Turner and Weiss, 1963, p. 158).

5.36 Plotting of the S-pole for the various subareas has yielded data on the macroscopic folds; cylindrical to non-cylindrical fold geometry has been established. The following
is the description of the subareas:

Subarea I (Pur synform - $F_2$)

5.37  The poles of the bedding and the foliation ($S_1 = S_2$) within the sector are plotted together with linear structures that include puckers, minor folds, mineral lineations and stretching. The contour pattern of the pi-poles (Fig. 10) shows a thick irregularly diffuse girdle distribution through which a large number of great circles could be drawn. The pi-poles also show scatter along two small circles one in the western and the other in the southeastern part of the diagram. From this diagram, the following inferences can be made:

(1) Local concentration of the pi-poles in two opposite parts of the diagram indicates straight limbs of a tight fold with probable subvertical steep axial plane trending NNE-SSW. The average pi-girdle gives rise to an average beta which plunges $37^\circ$ towards N35$^\circ$E. The scatter of the beta-axis appears to be real representing the restricted scatter of the $F_2$ fold due to superimposition of the small circle rotation.

(2) Scattering of the pi-poles into two different small circles in the western and southeastern part of the diagram indicate rotation of the incipient S-surfaces into two cones with vertex axes plunging towards each other at high angles to the horizontal. The vertex axes D and D' plunge at $67^\circ$ towards
N43°W and 62° towards S83°E respectively. This scattering of the pi-poles in two small circles in probably due to a later fold superposed on the earlier F2 fold with straight limbs.

Irregular scattering of the pi-poles may also be the effect of an early fold, earlier to the F2 fold set.

(3) As the pi-poles are, thus scattered due to an earlier and/or a later fold, the beta (37° towards N35°E) becomes comparatively diffused.

(4) Most of the minor folds along with other types of lineations lie with varying amount of plunge in a subvertical westerly dipping and NNE-SSW trending plane. A majority of them obviously belong to the regional set of fold, F2 (supported by geometry and orientation of the structures in their mesoscopic occurrence). The scatter of these folds in the NNE-SSW plane may again be due to an earlier fold structure and/or rotation by a later structure.

Thus the possibility of three sets of fold structures in this sector may arise - the regional F2 set, a set earlier to the F2 and, third, a set later than the F2 fold.

5.38 Some mesoscopic folds within the quartzite band defining the Pur synformal structure are plotted in a diagram, Fig. 11. These fold axes are found to lie in a small circle around an axis marked Lq, the angle between the fold axes and Lq is
around 46°. The fold axes plotted, plunge at 1° towards N63°E (from exposure 714), 21° towards N82°E (exposure 798), 85° towards N68°E, 5° towards S45°E (exposure 695), and 2° towards S40°W (exposure 698). From this study, the following inferences may be drawn:

(a) An early set of fold is rotated by a later superposed fold with a rotation axis \( L_2 \).

(b) The later fold (the Pur synformal fold, \( F_2 \)) is a concentric cylindrical fold. The early folds are designated as \( F_1 \) (with axes \( B_1 \)) and the rotation axis \( L_2 \) is the axis of the regional fold \( F_2 \) (axis \( B_2 \)).

5.39 The early \( F_1 \) folds described above are seen to develop in the quartzite band in the nose region of the Pur closure. This part of the quartzite band lies within the domain marked \( l_b \). To find out the beta = \( B_2 \) defined by this quartzite band within this domain (\( l_b \)), poles of \( S_1 = S_2 \) surfaces are plotted in a pi-diagram (Fig. 10b). The following results are obtained from the diagram:

1) S-poles concentrate in a great circle girdle.

2) The pi-girdle (great circle) is well defined and its pole define a beta = \( B_2 \) axis with a plunge of 40° towards N28°E. This is nearly parallel to the \( L_2 \) rotation axis of the earlier diagram (Fig. 11).
3) Slight scattering of S-poles on both sides of the girdle may be the influence of early folds F_1 present in the form of minor folds in the domain which are statistically isoclinal.

4) Effect of the F_3 warp is minimum or none within the scale represented by this diagram as a regularity of the S-poles about the pi-girdle is maintained.

5) Finally, this defines a cylindrical fold of the quartzite band within the domain Ib where the early folds F_1 are rotated in a small circle around B_2 (Fig. 11).

5.40 In contrast, when the broader subarea I (including the domain Ib) is considered, non-cylindrical F_2 folding becomes apparent. It may now be concluded that in the Pur synformal closure area, the quartzite band representing a restricted area is cylindrically folded whereas the main fold is broadly non-cylindrical.

Subarea II

5.41 This subarea covers an elongated tract north of Pur village as well as a part of the eastern limb of the Pur synform (Plate 5). It includes a number of structural elements such as S_1 = S_2 surfaces, puckers, minor folds and intersection of two planar surfaces S_4 with S_1 = S_2. The linear elements are found to spread in the first and third quadrant.
of the stereogram (Fig. 12). The S-poles ($S_1 = S_2$) are scattered and form a single maximum; through the scattering, a partial girdle with a beta-axis plunging $75^\circ$ towards NW can be drawn; cylindrical to partly non-cylindrical rotation of the S-planes around this subvertical axis is indicated. The minor folds and puckers scatter mostly in the first and third quadrant, and mainly represent the regional $F_2$ folds. The scatter is probably due to the presence of still earlier folds ($F_1$?) and also partly to the later $F_3$ warp. The regional fold $F_2$ probably a highly appressed structure with straight limbs, and does not yield a full girdle.

Subarea III

5.42 An area around the Teranga hills (Plate 5) is analysed. The S-surfaces $S_1 = S_2$, and mesoscopic folds, mineral lineations and a striation (non-penetrative) are plotted in a stereogram (Fig. 13). The rocks covered in this sector include banded ferruginous quartzite and calc-silicate metasediments. The S-poles concentrate is a single maximum with of course, a small spread giving rise to elliptical contours. No definite great circle (pi-girdle) can be drawn through the S-poles; however, roughly NNE-SSW trending vertical to steeply dipping (easterly or westerly) S-planes are indicated with minor variation of their attitude. This may indicate either very tightly appressed folds or very gentle folds. A partial girdle yields
a beta plunging 48° towards N27°E. Two groups of minor folds are seen in the first quadrant; one group lies in a partial small circle and the other group is arranged haphazardly near the rotation axis; a single fold is found to lie in the third quadrant. The first group of folds may denote $F_1$ (lying in a small circle), and the second group and the single occurrence may represent regional $F_2$ folds. The spread of the S-poles in elliptical contour form (yielding a subvertical beta-axis) may also be due to the latest fold $F_3$ of the area. Thus this sector may present all the three folds $F_1$, $F_2$ and $F_3$ though the features are not very clear from the diagram.

Subarea IV

5.43 This sector encompasses a larger area incorporating the subareas I and II and covering a greater part of the Pur synform (Plate 5). Minor folds, puckers, intersection of $S_1 = S_2$ with $S_4$ surface and pole of S-planes ($S_1 = S_2$) are plotted in an orientation diagram (Fig. 14). 125 S-planes are plotted and contoured; the following informations can be gathered from the pi-diagram:

(a) S-poles give a more complete pi-girdle which is thick and dispersed. Average girdle yields an average $beta_{B_2} = 40^\circ$ towards N26°E.

(b) Greater concentration of the S-poles towards the
edges of the diagram indicates that the \( F_2 \) fold (with \( B_2 \) axis) is tight and has straight limbs.

(c) Scattering of the S-poles and the greater thickness of the pi-girdle is due to an early fold and partly due to a later fold which rotates the S-poles in a small circle (vide d below).

(d) Rotation of S-pole maxima in a small circle in the SE quadrant is due to a later fold with D (Vertex axis) plunging at \( 52^\circ \) towards N52°W. This is a conical rotation of the initial surfaces probably by the \( F_3 \) fold (warp).

(e) Scattering of the S-poles has also affected the scattering of regional beta-axis. This is supported by the plotting of minor folds and puckers related to regional fold set \( F_2 \). The diagram shows a scattering of these linear elements in the first and the third quadrant; the earlier and the later sets of folds have influenced the scattering of these \( F_2 \) folds.

5.44 The minor folds and puckers (50 lineations) are plotted and contoured in a separate diagram (Fig. 15). Besides generally lying in a NNE-SSW trending subvertical plane a cone is described with three maxima in the first quadrant of the diagram. This cone is formed around a central axis with an angular relation of about 19°. This may suggest a rotation of \( B_2 \) around a cone axis K in effect of superposition of the \( F_2 \)
folds (with axis $B_2$) on an earlier set of $F_1$ folds at moderately high angles (vide Chapter VIII also). Rotation of $B_2$ in another partial cone is also seen in the diagram.

Subarea V

5.45 This sector (Plate 5) covers the closure region of the Pandal synform defined by the marble band just west of Lakshmi-pura. This synform actually is a complex synform with a tongue-shaped tightly appressed antiform riding over it (vide Plate 3). $S$-poles ($S_1 = S_2$) and minor folds are plotted in a stereogram (Fig. 16); the minor fold axes are found to scatter in the first quadrant only. A better pi-girdle is formed, but is thick and scattered. The average great circle passing through the contoured diagram gives an average beta = $B_2 = 30^\circ$ towards N22$^\circ$E. Also three maxima in the southeast quadrant lie in a small circle indicating a conical rotation of the $S$-poles; the vertex axis $D$ for this small circle girdle plunges 50$^\circ$ towards N52$^\circ$W. This conical rotation of the $S$-poles is most likely to be due to $F_3$ fold (warp). The scattering of the minor folds ($F_2$) in the northeast quadrant may also be due to the $F_3$ fold. The variable incipient planar surfaces arising out of earlier folds on which the $F_2$ folds formed might have also taken part in the scattering of the minor fold axes and the $S$-poles as described above. The latter view gets support when it is seen that most of the minor
folds lie in a cone around the central axis K very near the statistical beta-axis.

Subarea VI

5.46 A narrow, elongated, NNE-SSW trending area of garnetiferous mica schist west of the marble closure at Lakshmi pura is covered under this sector (Plate 5); the most prominent S-surface in this part of the area is the schistosity S₂ in the pelitic schist. To analyse the area, minor folds, puckers and the S-poles (S₂) are plotted (Fig. 17). Contouring of the S-poles presents a single maximum near the western edge of the diagram. However, an elliptical extension of the contours may allow a great circle to pass through them and a beta = B₂ with a plunge of 70° towards N52°E is indicated. The low scattering of the S-poles indicate that the F₃ fold (with axis B₃) is a gentle one. Scattering of the S-poles in two opposite edges of the diagram may also indicate the regional fold F₂ (axis B₂) as a tightly appressed fold with straight limbs; however, beta = B₂ cannot be fixed from this pi-diagram.

5.47 The axis of puckers and minor folds spread mostly in the first quadrant, a single axis lies in the southern part of the diagram. These lineations are identified as belonging to F₂ set (with B₂ axis). The scattering is probably due to (a) variable orientation of surfaces over which F₂ is superposed
and (b) effect of a later fold $F_3$ rotating the earlier planar and linear elements. The incipient variable surfaces may again owe their origin to a probable early $F_1$ fold.

**Subarea VII**

5.48 A regional closure defined by a quartzite band near Suras is included in this sector (Plate 5); other lithologic units included in this are calc-silicate and banded ferruginous rocks. The structural elements analysed are minor folds and poles of $S$-planes ($S_1 = S_2$). The pi-diagram (Fig. 18) for this sector is similar to those for the subareas II and III. The contoured $S$-poles here give rise to a single maximum in the western edge of the diagram, with an elliptical elongation. No definite incipient girdle for $\beta = B_2$ is generated by the contoured diagram; this may be due to tightly appressed nature of $F_2$ folds (with axis $B_2$) with subvertical NNW-SSW trending axial surfaces. The spread of the contours in an elliptical form may, however, indicate a more or less cylindrical rotation of the $S$-planes around a subvertical axis ($B_2$?) with a plunge of $80^\circ$ towards $S70^\circ E$.

5.49 The minor fold axes $B_2$ scatter in the first quadrant of the diagram and plunge at low to very steep angles. This is primarily due to an earlier structure folding $S_1 = S_2$. 

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and (b) effect of a later fold $F_3$ rotating the earlier planar and linear elements. The incipient variable surfaces may again owe their origin to a probable early $F_1$ fold.

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Subarea VIII

5.50 An area of calc-silicate rocks north of Kiratpura is covered under this sector (Plate 5). A few lineations including mineral lineation, intersection of $S_1 = S_2$ with $S_4$ and minor fold axes, and poles of the planar surfaces $S_1 = S_2$ are plotted in a diagram (Fig. 19). The contoured $S$-planes yield a small circle girdle and a less perfect great circle girdle; the small circle girdle in the third quadrant of the diagram gives rise to the vertex axis $D$ with a plunge of $42^\circ$ towards $84^\circ E$. This rotation of the $S$-planes in a conical surface is most probably due to the $F_3$ fold.

5.51 The less well-defined pi-girdle gives rise to a southerly plunging beta ($20^\circ$ towards $S6^\circ W$). The lineations plotted are seen to cluster very near to this beta which is the regional fold axis $B_2$.

Subarea IX

5.52 A small area north of Suras is analysed (Plate 5); calc-silicate metasediments cover the area. Poles of the $S$-planes ($S_1 = S_2$) are plotted and contoured; lineations plotted in the same diagram (Fig. 20) include minor fold and pucker axes and mineral lineations. Point maxima are generated in the north-western quadrant; $n$ - number girdles can pass through
the contours. Highly appressed nature of the \( F_2 \) fold is expressed in the diagram. The minor \( F_2 \) fold and pucker axes (\( B_2 \)) are subvertical and approximately 90° away from the \( S \)-pole contours. The scattering of the lineations as well as the foliation poles may be due to early folds or rotation by later folds.

**Subarea X**

5.53 This sector (Plate 5) covers a small area around the village Jipi; the rocks occurring in the area are quartzite, banded ferruginous quartzite and the calc-silicate metasediments which are curved into a large regional Z-shaped fold with a definite antiformal and a synformal structure. Minor fold and pucker axes, intersections of \( S_4 \) (cleavage) with \( S_1 = S_2 \) surfaces and poles of \( S \)-planes (\( S_1 = S_2 \)) are plotted over stereographic net (Fig. 21). Lineations cluster in the first quadrant (except one fold axis which lies in the second quadrant) with high angles of plunge. A more complete significant pi-girdle is generated through the contours of \( S \)-poles and a beta with a plunge of 60° towards N61°E is formed. This beta-axis is the regional fold axis \( B_2 \); the minor \( F_2 \) fold axes with other types of lineations cluster around this beta. Influence of earlier or later sets of folds is very insignificant in this subarea.

**Subarea XI**

5.54 This includes a small area in the extreme northeastern
part of the map (Plate 5) consisting of pelitic schists which are highly migmatised and are invaded by pegmatite bodies. The structural elements plotted in Fig. 22 include minor fold and pucker axes, intersection of $S_4$ surface with $S_2$ (schistosity) and poles of $S$-planes ($S_2$). Contouring of the $S$-poles gives rise to a single maximum indicative of subparallel surfaces. However, a partial girdle gives a beta with a plunge of 76° towards N43°E. The lineations scatter in the first quadrant and a single minor fold axis almost coincide with the beta; the lineations and the beta with all probability represent the $F_2$ fold axis, $S_2$. The scatter of the lineations and also the high plunge of the beta may be, of course, an influence of early fold $F_1$ and/or rotation by the later warp $F_3$.

Subarea XII

5.55 A small elongated area (Plate 5) in between the villages Dhulkhera and Jodhras including quartz - mica schist, partly migmatised, has been analysed. Minor fold axes and poles of $S$-planes ($S_2$) are plotted in Fig. 23. The maxima of the contoured $S$-poles lie near the northwestern and southeastern edge of the diagram and a number of girdle can be drawn through them. This indicates that the regional $F_2$ folds are tight appressed and are flattened perpendicular to the NNE-SSW trending high easterly dipping axial surfaces; these folds also have straight
limbs. The minor fold axes occur in the northeastern and southern part of the diagram; these are $F_2$ folds and their scattering may be due to the influence of earlier and/or later folds.

**Subarea XIII**

5.56 This sector (Plate 5) covers a small area around the village Ruppura and include the rocks - garnetiferous mica schists and calc-silicate metasediments. Poles of $S_2$ surfaces are plotted and contoured; the lineations plotted in the same diagram (Fig. 24) include pucker and minor fold axes, and intersections of $S_4$ with $S_2$ surfaces. The $S_2$ distribution gives rise to a single maximum at the northwestern and southeastern edges of the diagram and thus a single perfect girdle cannot be conceived. However, the elongated contours may define partial girdles giving rise to beta-axes plunging at low angles to NNE or SSW. The linear elements defining $E_2$ (axes of regional fold) are seen to plunge at low to moderate angles towards NNE and SSW or south. The influence of earlier folds may give rise to such dispersion of fold axes.

**Subarea XIV**

5.57 This sector (Plate 5) includes the rock types quartzite, banded ferruginous quartzite and calc-silicate rock around Dhulkhera; minor fold axes, mineral lineation and poles of $S$-
Explanation of Figures 10-20

Fig. 10 : Subarea I, 105 S-poles, contours 1-2-3-5-8-10-13% per 1% area.

Fig. 10b : Domain Ib, 25 S-poles, 4-8-12-16-20% per 1% area.

Fig. 11 : Cylindrical rotation of B₁ around B₂ within the domain Ib.

Fig. 12 : Subarea II, 56 S-poles, contours 2-6-10-20-30% per 1% area.

Fig. 13 : Subarea III, 42 S-poles, contours 2.5-5-7-12-21-30% per 1% area.

Fig. 14 : Subarea IV, 100 S-poles, contours 1-3-5-8-10-13-15-18% per 1% area.

Fig. 15 : Subarea IV, 50 fold axes and puckers, contours 2-4-6-10% per 1% area.

Fig. 16 : Subarea V, 120 S-poles, contours 0.8-2.5-5-10-12% per 1% area.

Fig. 17 : Subarea VI, 36 S-poles, contours 5.5-11-22-33% per 1% area.

Fig. 18 : Subarea VII, 25 S-poles, contours 4-8-12-16-20-24-33% per 1% area.

Fig. 19 : Subarea VIII, 20 S-poles, contours 5-10% per 1% area.

Fig. 20 : Subarea IX, 20 S-poles, contours 5-10-15-20% per 1% area.
Explanation of Figures 21-27

Fig. 21: Subarea X, 50 S-poles, contours 2-6-8-10-12-14% per 1% area.

Fig. 22: Subarea XI, 27 S-poles, contours 4-11-22-33% per 1% area.

Fig. 23: Subarea XII, 20 S-poles, contours 5-10-15-20% per 1% area.

Fig. 24: Subarea XIII, 25 S-poles, contours 4-8-12-16-20% per 1% area.

Fig. 25: Subarea XIV, 30 S-poles, contours 3.3-6.5-10-13-16-20-30% per 1% area.

Fig. 26: Synoptic diagram for the Subareas I-XIV.

Fig. 27: 220 minor folds and pockers for the whole area, contours 2-4-10-12-20-24-30-38% per 1% area.

Symbols for the lineations:

Fold axis - Black dot, pucker axis - open circle, mineral lineation - triangle, intersection of two planar surfaces - cross, other lineations including boudinage etc. - cross with circumscribed circle.
planes \((S_1 = S_2)\) are plotted (Fig. 25). On contouring the poles of S-planes, a single point maximum is formed in the fourth quadrant of the diagram; innumerable great circles can pass through the contours; however, a girdle can pass through the maximum and an isolated lowest contour giving rise to a beta plunging 46° towards N34°E. The lineations plotted in the diagram cluster around this beta-axis and actually define \(B_2\), the axis of \(F_2\) fold. The clustering of the S-poles around a single maximum also indicate that the \(F_2\) fold is tightly appressed with straight subparallel limbs; the scatter of \(B_2\) may be the effect of an earlier or a later fold.

**Summary of the macroscopic structural analysis**

5.58 The three sets of folds \(F_1\), \(F_2\) and \(F_3\) are established from the structural (geometrical) analysis, their interference has made the overall structure of the area much complicated. The impact of the earliest folds \(F_0\) which occur rarely and in the form of tightly appressed, isoclinal, rootless, minor dead folds is probably very little compared to the other three sets of folds as mentioned above.

5.59 A synoptic diagram (Fig. 26) is prepared showing all the statistical beta = \(B_2\) axes (from the pi-diagrams, Figs. 10 to 25); the vertex axes \(D\) for \(F_3\) fold set (which generates
conical fold surfaces) are also plotted. The $F_1$ folds (with $B_1$ axes) seen in the mesoscopic scales in the quartzite band of Pur closure and from other areas are also shown in the diagram. A model diagram showing the interrelationship of the three fold sets is also presented (Fig. 60).

5.60 In the map area, the $F_1$ folds are seen only in the mesoscopic scale and most of them could be identified in the quartzite band in the Pur closure area. However, the repetition of the quartzite and calc-silicate bands in the structural sequence may also be due to this $F_1$ folding in macroscopic scale. This could not be established as regional closures of the $F_1$ folds could not be traced within the map area. Transposition of the quartzite and other rock bands in the western part of the map (around Balyakhera) may have destroyed a regional $F_1$ closure. The $F_1$ minor folds could be best studied in the Pur closure area; these folds are rotated around the regional fold axis $B_2$; the $B_1$ axes are rotated around $B_2$ with an angular relation $B_1 \wedge B_2 = 46^\circ$ (Fig. 11). The quartzite band in this closure area is cylindrically folded (Fig. 10b); thus, $B_2$ has a constant value. The $F_1$ folds are in general tightly appressed folds and are usually isoclinal. These folds are further described in Chapter VI.

5.61 The regional $F_2$ folds have variable beta = $B_2$ axes, lying mostly in the first and third quadrant of the orientation
diagram. This is reflected in the synoptic diagram where $B_2$ axes lie in a NNE-SSW trending zone bounded by two planar surfaces dipping 70° easterly and 78° westerly respectively. Thus, the $B_2$ axes plunge at various angles and to various directions lying on the NNE-SSW trending $F_2$ axial surfaces dipping at very steep angles ESE or WNW. Occasionally the $F_2$ axial surfaces swing from NNE-SSW to NE-SW. The variations in the amounts of dip of the axial surfaces are due to the gradual overturning of the $F_2$ folds in the west; the Pur synform has an axial surface dipping subvertically to WNW whereas the synform near Salampura is overturned to the west and the axial surface dips at high angles to ESE. The variation in strike of the $F_2$ axial surfaces from NNE-SSW to NE-SW is mainly due to the $F_3$ folds with the flow direction of the superimposed $F_3$ movements at very high angle to the axial surface of $F_2$ folds. All these explain the variations in strike and dip of the axial surfaces of $F_2$ fold set in regional scale. The variable position of the $B_2$ axes on the $F_2$ axial surfaces need be accounted for. Variation of the axes of the late folds by influence of the early structures has been explained by many workers (Ramsay, 1958; Tobisch, 1967). In the present case also, the earlier fold $F_1$, though usually isoclinal, has offered variable planar surfaces (the limbs and the hinges) for $F_2$ folding. It is also possible that the $F_1$ folds were less appre-
ssed at the time of superposition of $F_2$ rotation presenting a wider variation of orientation of the $S$-surfaces. The $F_1$ structures could have been appressed and made isoclinal in course of $F_2$-rotation. This could explain the variable plunge of the $F_2$ fold axes. In some statistical domains (cf. in Subarea IV), the $B_2$ axes (axes of puckers and minor folds) lie mostly in a cone and thus define a conical fold in the domain. Folded surfaces by $F_1$ being superposed by a later fold ($F_2$) may generate either cylindrically or conically folded surfaces (cf. Ross, 1962). This is further described in detail in Chapter VIII on structural synthesis.

5.62 The $F_3$ fold axes (vertex axes D) are plotted and are found to lie on and very near to the axial plane trending N47°W - S47°E. Superposition of the $F_3$ axial surfaces on the regional $F_2$ folds have also generated $F_3$ conical folds though with large $D/2$ and comparatively smaller $K/2$ angles (that is, elliptical conical folds with the longer axis horizontal, Haman, 1961). The variable plunge (high angle of plunge is usually noticed) is due to the variability in attitude of the form surfaces attained through $F_2$ folding.

The higher concentration of the $B_2$ axes are shown as a dashed area in the diagram (Fig. 9.26).

5.63 A synoptic diagram with the plotting of 200 puckers
and minor folds is prepared (Fig. 27). Most of the lineations concentrate in few areas in the northeastern and southwestern quadrant and lie in planes dipping at very high angles with the approximate direction of strike N35°E-S35°W which corroborates well with the average axial surface of the regional fold $F_2$; this indicates that most of the puckers and minor folds belong to the $F_2$ fold set, and the minor representatives of $F_1$ and $F_3$ folds are rare. Of course, there may be a possibility that some of the $F_1$ minor folds might have been rotated around $B_2$ axis and have taken identical position as $F_2$ folds and lost their identity.

**Joints**

5.64 The joints or the non-penetrative planar structures are developed in comparatively brittle rocks such as in quartzites and in marbles. In the quartzites (mostly in the banded ferruginous quartzite), the following types of joints are developed:

1) **Bedding joints** - These joints are parallel to the original bedding planes $S_1$ and also at places parallel to the surfaces $S_2$ where $S_1 = S_2$ are developed.

2) **Transverse joints** - These joints are perpendicular to the regional fold axis $B_2$ and may be called as joints or extension joints (Billings, 1962). This set of joints strike
approximately NW-SE and dip 60° to 70° SW.

3) Axial plane joints - Joints are formed parallel to the axial surfaces of the earlier folds $F_1$, the regional folds $F_2$ and the warp $F_3$ at places. Such joints are seen to develop in the Teranga hills where a group of subvertical joints trend NNE-SSW (parallel to the axial surfaces of the mesoscopic folds $F_1$) and also a second group dipping at high angles to the NW with a strike of NE-SW. Joints parallel to the axial surfaces of the $F_3$ folds are seen near the village Jipi (Figs. 9 & 29). These are subvertical, and strike NW-SE.

4) Subhorizontal joints - A set of joints with subhorizontal planes are developed in the northern part of the area.

Three sets of intersecting joints, at places, give rise to cubical blocks of the rocks.

5.65 The marbles are also highly jointed; the joint systems include bedding joints, transverse or $ac$ joints (dipping 50° to 60° towards SW) and conjugate or $h01$ joints (with respect to $B_2$ axis); the conjugate joints dip at high angles from 50° to 70° easterly or westerly with a strike varying from NNE-SSW to NE-SW.

Shear Zones

5.66 Shear surfaces are developed at some places and at
least two such zones are found to have some impact on the metamorphic event in the area. These are represented by close spaced fractures along which some movement is indicated by slickensiding, crushing or slicing (Plate 4). At the base of the marble exposures west of Pandal, thin bands of quartzite with considerable crushing is observed. The shearing was probably contemporaneous with the $F_2$ folding. Another shear zone occurs in the northern part, to the northeast of the village Dhulkhera; the shear surfaces trend NE-SW and seem to be related to the $F_2$ folding. The shear zone trending N60°E-S60°W to the west of the village Pur across the 1767 hill does not extend for long distances. The surfaces dip northerly at high angles and are nearly parallel to the axial surface of the $F_1$ folds which occur in the same quartzites in which these shear surfaces are developed. The shearing causes retrograde development of chlorite producing thin bands of chlorite schists along these planes.