SECTION III - MEGASCOPIC STRUCTURAL DATA

A. General statement

The lithological units in this area have undergone at least three phases of deformation which gave rise to planar and linear structures termed in the thesis as structures of the first, second and third generations respectively. The three sets of structures in the rocks have been studied in the field. The field data have been recorded in the lithological and structural maps (Map 1 and Map 2). The field slips used by the author are of scale 4" = 1 mile.

Structural investigation by the author includes mapping of the main rock types, measurement and recording of bedding, schistosity, cleavages, linear structures and axial planes of minor folds (Map 1 to Map 13).

For detailed analysis of structural elements the area has been subdivided into twenty seven subareas. The data of planar and linear structures have been analysed separately for each subarea (Fig. 105).

The poles to bedding or bedding-schistosity from different subareas show patterns of scattering which suggest that the main planar structure of the rocks has been distorted on NNW/NW - SSE/SE and NNE/NE - SSW/SW axes.

The poles to the axial planes of minor folds have been plotted to show the distribution of axial plane structures (Map 4).
The structures of the different generations have been described first. This description is followed by discussion on geometry of folding of the area.

The minor structures have been grouped into different generations on the following basis:

1) structures of similar style and patterns of orientation are likely to be of the same generation,

2) structures of one style and pattern of orientation overprint and distort the structures of another style and pattern of orientation,

3) structures belonging to different generations may have similar pattern of orientation but differ in style; for example folds of different generations may be coaxial but may be of different style,

4) episodes of repeated metamorphism indirectly help to differentiate among the sets of structures generated during separate phases of movement and corroborate the established sequence of development of structures.

B. Classified Megascoptic Structures

Four sets of minor structures have been observed in the area. These differ from one another in style, or orientation or both. Of these, three sets can be arranged in their order of development and termed structures of first,
second and third generations respectively. Some structures in Ajabgarh mica schists in subareas I and XIII could not be assigned specifically to the above category of structures. The schistosity and lineations in the mica schists are earlier than structures of second generation and have been described as "the structures of uncertain age" in the present thesis.

In the following paragraphs structures of different generations have been described, their development in different rock-types traced, and the possible movements required for the generation of these structures and distortion of one structure by another discussed.

(1) **Structures of the first generation**

The following elements are among the structures of the first generation:

a) Tight to near isoclinal folds, $F_1$ (Fig. 95). recorded on minor scale.

b) Bedding-schistosity, $S_1$.

The minor $F_1$ folds are noted mainly in Kushalgarh limestones and Ajabgarh calc-silicate rocks. These have not been observed in Alwar quartzites and Ajabgarh mica schists. The folds are very tight in nature varying in apical angle from $8^\circ$-12$^\circ$ degrees with a steep axial plane.
dipping about 70° and axes plunging 60°-70° towards NW. The orthogonal thickness of the layers involved in this folding nearly remain constant with slight thickening at the hinges, giving a style of parallel folding (Ramsay, 1967). They are nearly isoclinal folds with long limbs. The schistosity, $S_1$, is the dominating bedding-schistosity of the whole area, which is parallel to the bedding plane, $S$. Folds of second generation (termed $F_2$) and third generation (termed $F_3$) are raised on this $S_1$ plane. As observed in Ajabgarh calc-silicates and Kushalgarh crystalline limestones the bedding schistosity, $S_1$ is made of recrystallized granular mosaic of quartz, calcite and biotite; the recrystallized minerals reemphasize the trace of original bedding, $S$. It is to be mentioned here that the minor $F_1$ folds observed so far do not disclose any cleavage or schistosity cutting across the bedding even at the hinges of $F_1$ folds. At the hinge areas of folds there may be slight swerving of $S_1$ but $S_1$ remains essentially parallel to $S$ (Fig. 96). The recrystallized minerals along $S_1$ constitute a granular mosaic and no remarkable flattening or elongation of minerals along $S_1$ has been observed.

It has been mentioned previously in Section II and also subsequently in the present Section that $S_2$ (axial plane cleavage related to fold of second generation, $F_2$) cuts across bedding schistosity, $S_1$. The recrystallized granular minerals along $S_1$ have been crushed and realigned along $S_2$ in rocks where such superposition of $S_2$ on $S_1$ has
occurred. In the field, $S_2$ and $S_1$ can be distinguished from one another. Only in Bairawas valley region where major $F_2$ folds (Bairawas synforms and Bairawas antiforms) occur, $S_2$ and $S_1$ are virtually parallel on the limbs of these folds in subareas VII, XIII, XIV and XVI (Fig. 105). In this region, distinction between $S_1$ and $S_2$ is difficult particularly in recrystallized Ajabgarh calc-silicates and marbles.

A large-sized near isoclinal fold has been mapped near Nanglheri village within subarea I in an outcrop of Ajabgarh calc-silicate rocks. In the same outcrop, minor isoclines refolded by folds of second generation have been observed (Fig. 52).

South of Shirunda, a form surface in Alwar quartzite has been traced by following continuously a lithological band about one hundred feet wide (Fig. 91). The direction of younging as indicated by deltaic current bedding in this quartzite band has been noted. The structure can be interpreted as a synformal anticline. The anticline, whose axial plane and limbs are refolded, may represent a major $F_1$ fold. The position of this structure has also been noted in Map 5.

In the minor near isoclinal folds of first generation, $S_1$ does not cut across the nose of folds but indicates a tendency to converge. A possible explanation of this feature may be as follows. Photoelastic experiments (Sen, 1969) indicate that such bedding schistosity or concentric cleavage
follows the direction of minimum compressive stress which converge near the hinge of tight folds. It is suggested that due to simple flexure the minimum compressive stress directions converge near the hinge whereas the same remain parallel in other parts of the fold (vide Fig. I, in Sen, 1969).

(2) Structures of the Second Generation

The structures of this generation are -

(a) Major and minor open, asymmetrical folds, \( F_2 \) (Plate I).

(b) Axial plane cleavage, \( S_g \).

(c) Cleavage-bedding intersection, mullions and mineral lineation. The linear structures of the second generation have been collectively referred to as \( L_2 \) – lineation.

The major and minor folds of the second generation have been observed in Alwar quartzites, Kushalgarh crystalline limestones and Ajabgarh rocks throughout the area. Hornstone breccias do not possess any planar structure and hence folds could not be recognized in these rocks. However, the outcrop pattern of Hornstone breccias do follow the regional folds indicated by distribution of other lithological units of Kushalgarh and surrounding areas (cf. Heron, 1917).
The axial traces of the major folds of second generation have been shown in Map 3. The folds have been named after the localities in the area as follows. The antiform at Talbriksha is referred to as T-antiform, synform at Bairawas as B-synform, antiform at Bairawas as B-antiform, antiform at Kalachhara as K-antiform, antiform at Kushalgarh as K'-antiform. In the text of the thesis these major folds have often been referred to after the localities mentioned for convenience of description. All these folds are open and concentric in nature with varying wavelength. The main feature of these major structures is that the fold axis is variable both in amount and in direction of plunge. This is brought out in the analysis of subareas stated later in this section. An example is mentioned here. If major $F_2$ axis is traced continuously from Talbriksha down to Duharmala and then to east in the Bairawas valley, it shows variation in amount and direction of plunge (Maps 2 and 3). This variation in the axis may be either due to the superposition of the later folds ($F_3$) of third generation or due to the development of $F_2$ on already folded surface or both. A consistent feature of major $F_2$ folds is that the folds are overturned to the easterly direction with axial plane dipping steeply westwards. The general attitudes of major fold axes as deduced from subarea analysis are briefly stated here. The T-antiform shows
a plunge of 40° towards 4° while the B- synform plunges 58° towards 345°. The B- antiform, which is complementary to the B- synform, plunges 27° towards 341°. The B- synform and the complementary B- antiform together constitute a large-scale box-like structure. The K- antiform plunges 35° towards 330° while the K'- antiform plunges 65° towards 160°. The folding pattern shown by individual form-surfaces (Map 5) of Alwar quartzites around Duharmala and Shirunda indicate moderately plunging (30 - 35 degrees) open folds with a variable direction of plunge ranging from N 15° W to N 15° E.

The tightly appressed nearly isoclinal folds of the first generation are seen to be refolded on F2 axes. The style of the refolded folds is open (Fig. 52). In these examples the axial plane and limbs of F1 folds and bedding-schistosity, S1 have been distorted on F2 axes.

The F2 minor folds display on axial plane cleavage, S2. This planar structure is well developed in outcrops of Kushalgarh crystalline limestones and Ajabgarh rocks. In the Alwar quartzites the cleavage is occasionally observed and in these rocks it megascopically appears like closely spaced joints about 1/8" to 1/4" apart. The axial plane cleavage, S2, cuts across the bedding schistosity, S1 and often displaces the latter (cf. Figs. 50, 53, 54 to 63 and Plate 4. Fig. 2).
On the western limb of B- antiform (Bairawas antiform) the following mineral lineations have been observed in Kushalgarh limestones -

(a) lineation formed by scapolite (Fig. 86)
(b) lineation formed by actinolite-tremolite

In both cases the lineation is defined by parallelism of long dimensions of ovoidal aggregates of respective minerals. The structural position of this limb of B- antiform is such that cleavage, $S_2$, is nearly parallel to bedding-schistosity, $S_1$. However, the recrystallized minerals occur along $S_2$, axial plane cleavage of $F_2$ folds and the lineations conform to the $F_2$ axes plunging $50^\circ - 60^\circ$ towards $345^\circ$. The carbonate grains in the matrix constitute a granular matrix along $S_1$ and thus contrast in arrangement with the minerals which form the lineation.

Lenticular elongated calcite and quartz and biotite are also seen to be flattened and elongated along $S_2$ in both the Kushalgarh crystalline limestones and Ajabgarh calc-silicate rocks and marbles. Here $S_2$ is recognised in the field cutting across the $S_1$ (bedding-schistosity) on which $F_2$ has developed. It is suggested that constituent minerals have recrystallised and realigned with elongated shape along $S_2$ when $S_2$ has been superposed on an already recrystallized granular matrix of minerals which define $S_1$ structure in recrystallized rocks.
The above relationships indicate that the bedding-schistosity, $S_1$, is of earlier generation than $F_2$-folding with which cleavage, $S_2$, is developed. In the field $S_1$ and $S_2$ can be distinguished from one another and mapped separately (Map 1 and Map 4). It is only on the eastern limbs of Bairawas synform and Bairawas antiform, which are major folds of the second generation, that the schistosity seen in Ajabgarh calc-silicates and marbles is apparently of uncertain status because $S_1$ and $S_2$ are very close to one another here. However, $S_2$ is developed on the hinges of the major folds and this cleavage can be traced continuously to the limbs. In outcrops where such continuous tracing of $S_2$ cleavage is not possible the status of visible schistosity in the recrystallized calc-silicates and marbles is difficult to establish. Even then the remarkable flattening and elongation of constituent minerals along $S_2$ may be used as a guide in these recrystallized rocks as explained earlier in Section II. In outcrops where minor $F_2$ folds are developed the $S_2$ cleavage can be readily detected. In the particular outcrop of calc-silicates mentioned above the presence of ptygmatic veins suggest strong compression normal to observed schistosity. Due to this strong compression the two planes $S_1$ and $S_2$ have possibly been brought closer together than elsewhere in the area.
The minor folds and associated structures of the second generation observed and mapped in the area are -

(i) Asymmetrical open folds (Figs. 53, 54, 55, 58, 75, 92).
(ii) Disharmonic box-shaped folds (Fig. 71).
(iii) Polyclinal and conjugate folds (Figs. 60, 61, 62).
(iv) Mullions; these are mainly fold mullions, some are accentuated by the cleavage, S₂ (Fig. 104).
(v) Cleavage, S₂ parallel to axial plane of F₂ folds; a slight fanning of the cleavage with respect to the actual axial plane of folds may be present (Figs. 63, 72, 97).
(vi) Bedding-cleavage intersection lineation; where the rock possesses bedding-schistosity, S₁ this lineation is determined by intersection of S₁ and S₂.

Minor folds of the second generation are common in outcrops of Kushalgarh crystalline limestones and Ajabgarh rocks. A few folds with associated cleavage have been noted in Alwar quartzites in subareas I, II, III, IV, V and VI.

Minor 'S'- and 'Z'- shaped folds are found to occur mainly on the limbs of B- synform and B- antiform. Both these folds plunge NNW. 'S'- shaped folds are recorded on eastern limb of B- synform and western limb of B- antiform whereas 'Z'- shaped folds on the western limb of B- synform and eastern
limb of B- antiform. These minor folds conform to the major folds in style, orientation and sense of movement. Similar relationship has been observed among major and minor folds of the second generation elsewhere in the area.

The disharmonic style of folds of second generation is reflected on all scales - major, minor and microscopic. On outcrop scale this disharmonic style of $F_2$ folds is well displayed. An outcrop of Kushalgarh crystalline limestone in subarea XXIII has been mapped on a large scale to illustrate the pattern of $F_2$ - folding (Map 7). The topography of the exposure is nearly flat. Here the form surfaces in the crystalline limestones have been traced by continuously following bedding ($S$) or bedding-schistosity ($S_1$) of thin layers in order to obtain the style of $F_2$ folds at different structural levels on the scale of the outcrop. The data obtained are stated below :-

(a) The fold on outcrop scale (including all form surfaces) plunge about 50° north-north westwards as determined by plots of poles to $S$ and $S_1$.

(b) The smaller scale minor $F_2$ folds and related lineations plunge north-north-westwards but the amount varies from about 20° to 60°.

(c) The form surfaces traced from northeast to southwest in the outcrop, that is, from higher structural level to lower structural level differ from one another although the gross open, concentric style of folding is maintained.

(d) The fold on outcrop scale is polyclinal in nature.
The plunges of curvatures on each form-surface can be compared with those in the other. It is seen that fold plunge for one layer differs from another.

(e) The constant orthogonal thickness of layers suggest that the folding is parallel and that the limestone layers behaved as competent units within the scale of folding considered.

(f) Fold mullions occur in this outcrop and are parallel to the fold axes of the layers on which they lie.

(g) Axial plane cleavage, \( S_2 \), is well developed. The cleavage-bedding intersection (\( L_2 \) - lineation) conforms to \( F_2 \) axes in plunge and direction.

Minor polycrinal folds (cf. Greenly, 1919) have also been recorded elsewhere in the area and mainly in the outcrops of Kushalgarh crystalline limestones (Figs. 60, 61, 62). The same style of folding has been noted on a larger scale in Ajabgarh phyllites (Map 10).

The linear structures of second generation usually plunge towards NW/NNW direction in the Bairawas valley and the same plunge towards SE/SSE direction in the Kushalgarh valley. A zone of culmination trending roughly NE-SW from Kalachhara to Andoon is thereby indicated for these linear structures (Fig. 74 and Map 8). The role of folds of third
generation (F3 folds) in determining this zone of culmination has been discussed later in this Section of the thesis.

The axial plane cleavage, S2, is often seen in direct association with folds of second generation (Figs. 71 and 72). The cleavage usually trends NNW-SSE and dips steeply southwestwards. Crystallization of flattened and elongated calcite, quartz and biotite along S2 plane has been observed in thin sections of rocks (vide Section II). The cleavage S2 can be megascopically and microscopically traced in the rocks especially in Kushalgarh limestones, Ajabgarh calc-silicates and Ajabgarh phyllites. They are physically very clear cut in appearance cutting across S1 plane in the above rocks and displacing latter (Fig. 82). Displacement is $\frac{1}{2}$" - 1" as seen in the field; displacement may also be of microscopic dimension (<1 mm.). This displacement is more prominent when S1 is folded by F2 to give rise to disharmonic folds (Figs. 50, 69). There is a fanned arrangement of S2 preferably when they are developed with polycrinal F2 folds as observed in Kushalgarh limestones and Ajabgarh calc-silicates (Figs. 57, 69). When F2 folds in these rocks are tighter the fanning of S2 is less.

The Ajabgarh mica-schists have been puckered on F2 axes (Fig. 92). The axial planes of the puckers develop into 'strain-slip cleavage' (Turner and Weiss, 1963) and discrete fractures may be observed under the microscope (Fig. 84).
This cleavage has been superimposed on earlier recrystallized matrix of the rock. The previously crystallized muscovite, biotite, quartz and garnet in the rock have suffered mechanical deformation. Few micas have developed along $S_2$ subsequent to post-crystalline deformation.

The trace of cleavage, $S_2$ on bedding ($S$) or bedding-schistosity ($S_1$) is parallel to $F_2$ fold axes. This is a prominent linear structures observed throughout the area. These plunge usually in NNW direction in Bairawas valley and in SSE direction in Kushtagarh valley as do the minor $F_2$ axes and other linear structures of second generation ($L_2$). This aspect of $L_2$ - lineations has been previously mentioned. The subject is discussed later in the present Section under "Interference between fold of second generation and fold of third generation".

The gross style of folds of second generation can be stated to be open, asymmetrical and disharmonic. The box-shaped geometry and disharmonic nature of the folds can be observed on major as well as minor scales. The variation in direction and amount of plunge of folded layers in different structural levels is a notable feature of the folds of this generation. Because of this variation the author has attempted to trace the major $F_2$ folds continuously in the field as far as possible. The thicknesses of beds deformed by $F_2$ are nearly constant. It suggests that flexural
slip was the main mechanism for generation of $F_2$ (Ramsay, 1967). Displacement of folded layers along axial plane cleavage, $S_2$ indicates that restricted movement occurred along $S_2$ at a stage during deformation.

**Deformation of $F_1$ by $F_2$**

In subarea I southwest of Nanglheri occurs a well defined Ajabgarh calc-silicate horizon with numerous thin, relatively resistant, impure siliceous layers interbanded with marble. Structurally the rocks occupy the core of a major $F_2$ fold termed B-synform or Bairawas synform. This horizon discloses two sets of minor folds: one set comprises of open asymmetrical folds ($F_2$) which are related to Bairawas synform and another set comprises of long-limbed isoclinal folds ($F_1$). The two sets of folds are nearly co-axial. The attitudes of the structural elements of this locality are shown in plots for structures of subarea I in Fig. 105. The best examples of $F_1$ refolded by $F_2$ have been observed in the calc-silicate rock of this locality (Figs. 48, 49, 59). It has been observed that the limbs and axial plane of isoclinal fold ($F_1$) have been bent partly into open asymmetrical fold ($F_2$). The refolded fold belongs to the category of minor folds related to Bairawas synform in style and orientation. The hard, siliceous layers in calc-silicates disclose cleavage, $S_2$, which is parallel to the axial plane of the superimposed $F_2$ fold. The cleavage cuts across the limbs, hinge and axial plane of deformed
isoclines. Some examples of refolding from this locality had been previously described by the author in a publication (Gangopadhyay and Sen, 1968).

South of Shirunda tracing of form surfaces in quartzite with younging direction suggest the presence of a major isoclinal anticline. The limbs and axial plane of this fold have been distorted (Fig. 91). The refolded structure is synformal. The refolded fold (synform) can be traced northwards into Bairawas synform, a major fold of second generation. This may be an example of refolding of $F_1$ by $F_2$ on a major scale.

(3) The Structures of the Third Generation

The structures of the third generation are -

(a) Major and minor open, asymmetrical folds $F_3$ (Plate I and Fig. 102b)

(b) Fracture cleavage, $S_3$ (Fig. 103).

$S_3$ is developed parallel to axial plane of minor $F_3$ folds and observed only locally (Map 4). The cleavage can be best observed in outcrops of Kushalgarh crystalline limestones near Andoon. Megascopically the cleavage is a clean-cut fracture. In a few thin sections of Kushalgarh crystalline limestones some recrystallized calcites with elongation parallel to $S_3$ have been observed (vide Section II).

The $F_3$ folds are generally developed on NNE/NE - SSW/SW axes; the axial planes of folds are inclined steeply westwards.
A few minor, disharmonic $F_3$ folds have been observed in subarea XVII near Andoon. These folds plunge 12°-60° either north-northeastwards or south-southwestwards. Their axial planes, however, consistently dip steeply westwards. Larger $F_3$ folds on outcrop scale have been observed in this subarea. The minor folds conform to the larger folds in style, orientation and sense of movement.

The axial traces of major $F_3$ folds in the area are shown in Map 3. The antiform ('Raikho antiform' of Heron, 1917) occurring on the northern side of Kushalgarh-Talbriksha road is called here $N$- antiform or Nanglheri antiform. To the east of Nanglheri antiform other major folds of third generation have been traced in the Alwar quartzites north of Kalachhara. These major $F_3$ folds are superimposed on the limbs and hinge of a major $F_2$ fold called Kalachhara antiform or $K$- antiform. The region from Kalachhara to Andoon is marked by the development of folds of third generation. It is across this region that the linear structures of second generation disclose a culmination (Fig. 74).

At Andoon area, especially within subarea XVII, minor folds of both second and third generations can be observed in outcrops of Kushalgarh crystalline limestones (Map 9). $F_3$ fold axes trend NNE-SSW and the $F_2$ fold axes trend NW-SE. Refolding of $F_2$ folds on $F_3$ axes is seen on small scale. Due to distortion on $F_3$ axes minor $F_2$ folds in
this subarea vary in plunge from low to high angles and in direction from NW to SE (vide plots of structural elements for subarea XVII in Fig. 105). Axial plane cleavage of second generation, \( S_2 \), has been twisted on \( F_3 \) axes (Fig. 102). The cleavage of third generation, \( S_3 \), cuts across \( S_2 \) as well as bedding, \( S \) (Fig. 103). The intersection of \( S_3 \) and bedding in the rocks define a lineation, termed by the author as \( L_3 \), which is parallel to \( F_3 \) fold axes. These trend NNE/NE - SSW/SW; the amount of plunge varies from 50° to 60° and directed either northwards or southwards (Map 9).

The thickness of folded layers on the hinge and limbs of \( F_3 \) folds remains nearly constant, suggesting that the folds are developed due to flexural slip (Ramsay, 1967).

**Interference between fold of second generation and fold of third generation:**

The region between Kalachhara and Andoon offers opportunity to study the effect of superposition of third generation folds on second generation folds as seen on major and minor scales.

The three dimensional form taken up by planar surfaces as a result of superposition of two sets of folds is actually replicas of interference pattern caused by two sets of waves (Ramsay, 1967). The nature of the interference
patterns depends on the orientation relationships of the component fold systems (Fig. 106). The orientations of the second and third generation folds are such that \( \alpha \) is about \( 70^\circ \) and \( \beta \) is about \( 60^\circ \). The interference has occurred on \( F_2 \) and \( F_3 \) fold axes directed at high angles to one another; axial planes of \( F_3 \) folds are also at high angle to the limbs and axial planes of \( F_2 \) folds. The result will be the production of domes and basins of various shapes in outcrop patterns of rocks (cf. Ramsay, 1967; O'Driscoll, 1962; Carey, 1962; deSitter, 1964). Wherever antiformal \( F_3 \) folds are superimposed on antiformal \( F_2 \) folds there is a mutual culmination of both sets of folds resulting in the formation of dome. Similarly crossing synforms produce mutual depressions in both sets of fold axes with the development of basin. Where antiform of one set crosses the synform of another set, the antiformal hinges are depressed while the synformal hinges show a culmination. Where this occurs 'saddle' or 'col' structures develop. When the third generation folds have caused tightening of second generation folds the domes and basins assume elongate shape and have relatively sharper apical regions. These features of interference have been diagrammatically represented in Fig. 107.

In order to analyse the structural geometry the entire area has been subdivided into 27 subareas (vide Section III. C). For the purpose of this chapter subareas X, XI, XVII, XVIII, XX, XXI, XXII, XXIV, XXV, XXVI and XXVII
will be considered because interference between the folds of second and third generations can be observed in these subareas better than in other subareas (Fig. 105; Maps 1, 2 and 3).

In subarea X folding involves mainly the Alwar quartzites. Although \( F_2 \) is dominant and plunges northwestwards the southern part of the subarea is distorted on \( F_3 \) axes. The plunge of the \( F_3 \) axes is \( 50^\circ - 60^\circ \) and directed either northeastwards or southwestwards. The bedding locally discloses domal or basin-like structure. In subarea XI, which adjoins subarea X to the northeast, a major domal structure with quaquaversal bedding dips occurs in the Alwar quartzites. Here two sets of major folds - \( F_2 \) on NW-SE trend and \( F_3 \) on NE-SW trend - are likely to have crossed one another nearly at right angles, resulting in the formation of the dome.

In subareas XX, XXI and XXII, which are adjacent to one another, both \( F_2 \) and \( F_3 \) occur on minor and major scales. Bedding plane is distorted to assume domal or basin-like structure. The plots of poles to bedding planes in Kushalgarh limestones and Alwar quartzites indicate a ring-shaped pattern (cf. Fig. 105).

Continuous exposures of Alwar quartzites occur in subareas XXIV, XXV, XXVI and XXVII north of Kalachhara/the Ruparel river. Major \( F_3 \) and \( F_2 \) folds have been mapped in these
subareas. A major $F_3$ fold, termed Nanglheri antiform, dominates the structural pattern in subarea XXIV. The fold plunges $20^\circ$ towards $224^\circ$ and has axial plane dipping steeply northwestwards. Subsidiary synforms and antiforms ($F_3$) have been traced to the east of Nanglheri antiform in adjacent subareas XXV, XXVI and XXVII. These subsidiary $F_3$ folds possess the same general axial trend as the Nanglheri antiform. In subarea XXV the hinge and limbs of Kalachhara antiform, which is a major $F_2$ fold, are exposed. The fold plunges $35^\circ$ towards $330^\circ$ and its axial plane dips steeply southwestwards. This major $F_2$ fold has been traced continuously into subareas XXVI and XXVII. Across the hinge and limbs of Kalachhara antiform ($F_2$) the $F_3$ folds mentioned above have been superimposed, resulting in the formation of interference structural patterns on a large scale (Map 6).

In the southern part of subarea XXV a synform of third generation occurs across the southern limb and hinge of Kalachhara antiform ($F_2$). The bedding of the quartzite has been distorted to assume a saddle-like structural shape. In the northern part of subarea XXV several antiforms and synforms ($F_3$) occur across the hinge and northern limb of Kalachhara antiform. The bedding of Alwar quartzite has been deformed to assume shapes of dome-, basin-, saddle-, and col-like structures. The superimposed $F_3$ folds vary in plunge and direction as they are followed from one limb to another across the hinge of Kalachhara antiform ($F_2$).
On the southern limb of Kalachhara antiform the plunge of $F_3$ folds may be as high as $75^\circ$ and directed southwards. On the hinge the $F_3$ axes plunges as low as $10^\circ$ or may be nearly horizontal. On the northern limb the $F_3$ fold axes are again steeply plunging but the direction of plunge is northwards. The features of interference observed in subarea XXV can be observed in subareas XXVI and XXVII. In the eastern part of subarea XXIV the Nanglheri antiform ($F_3$) crosses the northern tip of Kalachhara antiform ($F_2$). Here a large-scale domal structure is disclosed by the bedding plane of quartzite. As wavelength is relatively larger than amplitude in both $F_2$ and $F_3$ folds in these subareas the domes, basins and related features are gently curved and are not markedly elongated in shape.

In subareas XVII and XVIII the Kushalgarh crystalline limestones show the development of $F_2$ and $F_3$ folds on minor and outcrop scale. The plots of bedding and linear structures indicate that the bedding surfaces are shaped like basins or domes. The folds of second generation plunge $10^\circ$-$65^\circ$ towards either NNW or SSE directions and folds of third generation plunge $10^\circ$-$60^\circ$ towards either NE or SW directions. The axial planes of fold of second generations are inclined steeply southwestwards and axial planes of folds of third generation are inclined moderately.
steeply northwestwards. In subarea XVII occurs an excellent exposure of Kushalgarh limestones where the interference between the second and third generation folds have been studied by means of outcrop mapping on large scale (1" = 10'). The data are plotted in Map 9. The topography can be considered in the outcrop to be nearly flat. On the surface exposure several marker beds in the black crystalline limestones have been traced continuously in order to study the outcrop pattern of fold forms. Three such patterns are marked A, B and C in Map 9. In outcrop A three form surfaces traced indicate closed shapes. The innermost form surface suggests a dome. The two outer form surfaces show the replica of the dome and confirm that this is elongated in a NE-SW direction; as a whole the dome is overturned to the east. Minor folds of both second and third generations are present and their low wavelength/amplitude ratios indicate that the interference has been due to meeting of relatively tight folds of second and third generations on outcrop scale. Outcrop B can be interpreted to represent a basin overturned to the east. It is elongated in the NE-SW direction. The form surfaces in outcrop C indicate a closed shape elongated in the NE-SW direction. At the present level of exposure the form surfaces of outcrop C do not definitely indicate whether it is a dome or a basin. Nevertheless it is clear that the closed structural form is overturned to the east.
It has been previously mentioned that the folds and related structures of the second generation plunge generally northwestwards in Bairawas valley and southeastwards in Kushalgarh valley. A zone of culmination, which trends NE-SW from Andoon to Kalachhara, is thereby indicated (Fig. 74). It is seen that this zone is dominated by the development of major F₃ folds. The range in direction of plunge of linear structures of second generation from NW to SE is mainly due to superimposition of F₃ folds which have distorted the former. The linear structures of second generation can be unrolled about NE-SW trending F₃ axes. The large scale systematic variation in trend and plunge of second generation folds and associated linear structures have been represented in an isogonial map (Map 8). The isogons are drawn through locations where the linear structures have the same pitch or rake which is noted on the contours (cf. Elliot, 1965).

The distribution and orientation of axial plane cleavages of two generations, S₂ and S₃, together with axial planes of F₂ and F₃ folds are shown in Map 4. Throughout the area S₂ is more prominently developed than S₃. As already described in Section II cleavage, S₂, is often accompanied by recrystallization of flattened and elongated constituent minerals in the rocks along its direction (Fig. 46). On the otherhand cleavage, S₃, is usually a discrete fracture plane along which post-crystalline deformation of minerals are
observed. In the samples of Kushalgarh crystalline limestones from Andoon area it is seen that there is a restricted crystallization of some elongated calcite grains along $S_3$ (Fig. 32). Thus there are two phases of crystallization associated with $S_2$ and $S_3$ cleavages and a time gap between them is suggested.

(4) The Structures of Uncertain Age

In Bairawas valley within subarea XIII, which structurally occupies the core of Bairawas synform ($F_2$), occur several scattered and isolated outcrops of Ajabgarh mica-schists (Map 1). Due to paucity of exposures continuous mapping of structural elements from adjacent quartzites, calc-silicates, marbles and phyllites into these isolated mica-schists has not been possible. The mica-schists exhibit -

(a) Schistosity defined by muscovite, biotite and quartz,

and (b) Mineral lineation defined by dimensional parallelism of elongated micas and quartz.

As explained later the above structures are earlier than structures of the second generation. However, no tight, isoclinal fold of first generation has been observed in these rocks. The status of schistosity and lineation is, therefore,
not clear. The structures are tentatively classified as "Structures of Uncertain Age".

In some isolated outcrops the mica-schists are interbanded with Ajabgarh garbenschiefer and calc-silicates (Map 11). In these outcrops the schistosity is parallel to lithological banding. The schistosity strikes nearly N-S and dips steeply (60°-70°) both eastwards and westwards although westward dip is more common. The structural position of the outcrops of mica-schists is shown in Fig. 93. These occur above the Ajabgarh phyllites and occupy partly the western limb and core of Bairawas synform (Fg). This major Fg fold has developed on S and Sg should be present. The mica-schists are puckered on Fg axes (Fig. 21). Discrete fracture planes develop parallel to axial plane of puckers and represent Sg. Elongated micas and quartz, which define a planar as well as linear arrangement, have been deformed by Fg puckers (Figs. 21 and 92). The cleavages of micas are bent, and quartz and micas exhibit strained extinction. Discrete S2 cleavages occur across schistosity and may cause small scale displacement. Some garnets are also disrupted along S2 (Fig. 84). Traces of fracture are also seen on quartz and micas (Fig. 94). The Fg puckering may develop as conjugate sets with complementary sets of S2 cleavages. Along with the distortion of schistosity on NNW trending Fg axes the mineral lineation of the schist has been folded. In the
outcrops observed the plunge varies from $0^\circ$ to $65^\circ$ and may be directed either WNW or ESE.

The above observations confirm that the schistosity and lineation in the Ajabgarh mica-schists are earlier than structures of the second generation. If there is no other structural set other than 'Structure of the first generation' which is earlier than 'Structures of the second generation' the schistosity and lineation may belong to the former category. Southwest of Nanglheri village outcrops of mica-schists are very close to adjacent Ajabgarh calc-silicates where $S_1$ and $S_2$ could be traced separately. Here the schistosity of mica-schist and bedding-schistosity, $S_1$, of calc-silicate are nearly parallel and traceable into close proximity of each other. However, the calc-silicates and mica-schists occur in separate outcrops and continuous tracing of the planar structures could not be done. The observation, however, strongly suggests that schistosity of mica-schist may be $S_1$.

C. Discussion on Style of Structural Geometry

As mentioned earlier the whole area has been divided into 27 subareas and poles to the planar and linear structures in each subarea are plotted on the equal area net (Fig. 105). The planar structures are bedding-schistosity ($S_1$) and bedding ($S$). While describing the subareas the
term foliation has been used to include both $S$ and $S_1$. $S$ and $S_1$ are parallel to each other as stated in Section III B.

The lithological units of this area have been affected by first, second and third generations of folds - the first fold is isoclinal, and the second and third folds are open, asymmetrical with axes at high angle to each other. The first and second folds are nearly co-axial. It is now proposed to discuss the relative dominance of different generations of structures in different subareas and the resulting structural geometry.

The general procedure in megascopic analyses (Turner & Weiss 1963) of superposed fold-systems is to recognise and define domains each of which is homogeneous with respect to $\beta_2$, $S$ being any prominent $'S'$-surface. From the geometrical relation among $\beta_2$ is different domains emerges a picture of the total geometrical configuration of $'S'$-plane and of the stages of folding by which $S$-plane has been affected.

Before going into details of the subareas it is relevant to state that the geometry of the combined antiforms and synforms in the Bairawas valley shows a concentric box-shaped fold which is disharmonic in nature while the combined synforms and antiforms in the Kushalgarh valley and Kalachhara ridge disclose domes, basins and 'saddle' and 'col'-like features.
Details of Subareas (vide Fig. 105)

In subarea I the lithological units consisting of Kushalgarh limestones, Ajabgarh calc-silicates and phyllites have been folded to form the hinge area of Bairawas synform (F₂). The poles to foliation spread on a great circle having its pole plunging about 58° towards 345°. The minor folds of second generation cluster around the pole, P, of the circle. Minor isoclinal folds (F₁) have been observed to be refolded by F₂ folds in this subarea. The plots of axes of F₁ folds occur close to those of F₂ folds. In the outcrop where minor F₁ folds occur a larger sized F₁ fold has been mapped in Ajabgarh calc-silicates (Map 12).

In subarea II the hinge of Bairawas synform is exposed in Alwar quartzites. The plunge is northwards and the exposures reveal the hinge at a structural level lower than that in Subarea I. At this level the hinge of the main fold is seen to be subdivided into subsidiary folds. Minor F₂ folds and cleavage-bedding intersection (L₂) are few and their plots cluster around the pole of the circle.

The major F₂ fold traced in subareas I and II continues into subarea III. The linear structures of second generation here plunge north-northwestwards in conformity with the general attitude of the same in adjacent subareas I and II. However,
the plots of poles to foliation scatter in a ring-like pattern and do not lie strictly on a great circle with $F_2$ axis as its pole. The bedding of quartzites here are, therefore, arranged into a domal structure. Superimposition of a NE-SW trending $F_3$ axis of distortion on the northerly trending $F_2$ fold may account for the observed structural pattern.

In subarea III the form surfaces in Alwar quartzite beds have been traced (Map 5). The attitudes of bedding and the direction of younging suggest the occurrence of a major nearly isoclinal anticline ($F_1$) which has been refolded on $F_2$ axes. The refolded fold is a synform. The plunge of the isoclinal fold could not be determined.

The variation in direction and amount of plunge of major $F_2$ fold (Bairawas synform) when traced continuously from subarea I to III, that is, from higher to lower structural levels, is notable. In subarea I the axis plunges about 58° towards 345°, in subarea II 38° towards 356° and in subarea III 36° towards 17°. At the highest structural level (northern limit of subarea I) the Ajabgarh phyllites indicate that the $F_2$ axis plunges 60° towards 350°.

In subarea IV $F_2$ is dominant with an axis plunging about 20° degrees towards 7°. This is also a variance in the
trend of $F_2$ having a NNE-SSW trend instead of a NNW-SSE trend as seen in subarea I. The form surfaces in the quartzites in the region have been traced and they show open asymmetrical folds. The apical angle of the folds (measured from the traced surface) varies from 50° to 70° and the thickness across bedding of the bands is nearly constant. The curvature of the $F_2$ fold has a wavelength of about one and a half mile (Map 5).

Subarea V also shows open folds, $F_2$, in the northern continuation of subarea IV. $F_2$ folding involves Alwar quartzites here. A form surface in quartzite has been traced to determine the open, asymmetrical style of folding. The wavelength is nearly one mile as recorded on map no. 5 and the fold axis has a low plunge of 15°-20° towards NNE. The fold is slightly overturned to the east.

In subarea VI the $F_2$ folds have axial planes which trend NNE-SSW and dip steeply westwards. Form surfaces in quartzites have been traced, which show open nature of $F_2$ folds with large wavelength. 

In subarea VII the hinge and limbs of a major $F_2$ fold (Talbriksha antiform) occur. The main rock type is Alwar quartzite and outcrops of Kushalgarh limestones are few. The poles to the bedding in Alwar quartzite only spread on a ||-circle with pole plunging 40° towards 4°. If the poles to bedding of both Alwar quartzite and Kushalgarh
limestones are considered the plunge is calculated to be $40^\circ$ towards $356^\circ$. The minor $F_2$ folds, cleavage-bedding lineation ($L_2$), mullions in Kushalgarh limestones plot close to the pole of $\mathcal{W}$ - circle.

The Bairawas synform traced in subarea I is followed to the east by Bairawas antiform ($F_2$) which is the dominant major structure in subarea VIII. From the plots of poles to foliation the axis is calculated to be plunging $27^\circ$ towards $341^\circ$. The linear structures of second generation cluster around the pole of $\mathcal{W}$ - circle. The folding involves Kushalgarh limestones, Ajabgarh calc-silicates and phyllites. A few minor, tight, long-limbed folds ($F_1$) occur in the Kushalgarh limestones and Ajabgarh calc-silicates; these are nearly co-axial with $F_2$ folds.

Subarea IX consists of Alwar quartzites. In the plot of poles to foliation a slight scattering is noticed; the pole of the $\mathcal{W}$ - circle plunges $50^\circ$ towards $325^\circ$. This indicates the attitude of major $F_2$ fold in the subarea.

Subarea X adjoins subarea IX to the south and contains outcrops of Alwar quartzites only. There are some $F_2$ folds on NNW axes, which are developed on outcrop scale. In the $\mathcal{W}$ - diagram a partial spread of poles to bedding is observed. The manner of spread indicates warping on NW-SE and NE-SW axes. The presence of large-scale $F_2$ folds on NNW trend indicates dominance of this set in this subarea.
Subarea XI shows a domal structure in Alwar quartzite. The poles to foliation are scattered but do not spread on a great circle. The warping of the bedding is likely to be due to $F_2$ and $F_3$ axes which trend NW-SE and NE-SW respectively. A few $F_3$ minor folds plunge northeastwards in the subarea.

Outcrops of Kushalgarh limestones occur in subarea XII. The scattering of poles to foliation suggests warping on axis plunging $20^\circ$ towards $135^\circ$.

In subarea XIII outcrops of Kushalgarh limestones, Ajabgarh calc-silicates and Ajabgarh mica-schists are exposed in the core of Bairawas synform. The outcrops are scattered and isolated from one another. The mica-schists contain interbanded amphibole garbenschiefer and calc-silicates. The schistosity and lithological banding are parallel. The plots of poles to schistosity suggest that it is warped on gently plunging NNE-SSW axes. Minor $F_2$ puckers of this attitude have observed and these contort the schistosity.

In subarea XIV the rocks are mostly Ajabgarh calc-silicates. These rocks occur on the eastern limb of Bairawas synform. As previously mentioned $S_1$ and $S_2$ are very close here and cannot be readily distinguished in the field. The observed schistosity is nearly parallel to lithological banding. These are inclined steeply westwards. The plots of poles to foliation indicate $F_2$ axis of warping, which trends NNW. Axes of minor $F_2$ folds and related linear structures of second generation
plunge towards NNW/NW. A few tight near isoclinal, minor $F_1$ folds occur in the subarea and are nearly co-axial with $F_2$.

Kushalgarh crystalline limestones in subareas XVII and XVIII disclose domes and basins due to interference of $F_2$ and $F_3$ folds. The examples of the structures from these outcrops have been stated in Section III B. The poles to foliation in both these subareas show ring-like scattering, suggesting warping of foliation on a large-scale on $F_2$ and $F_3$ axes. Minor $F_2$ folds and $F_3$ folds are present. The plots of axes of $F_2$ folds show a systematic variation in direction and amount of plunge and suggest distortion on NE-SW trending $F_3$ axis.

In subarea XIX, east of subarea XVII, the scattering of poles to the foliation indicates interference of NE-SW $F_3$ folds and NW-SE $F_2$ folds. The linear structures of second generation are distorted by $F_3$ and plunge either NW or SE. The rock in this subarea is Kushalgarh limestone.

Subarea XX shows outcrops of Alwar quartzites distorted by $F_2$ and $F_3$ folds. $F_3$ folds with axes nearly at right angles to those of $F_2$ folds have interfered with the latter and as a result elongated basin-like structure is formed in the subarea. The poles to the foliation form a ring-shaped pattern on $\hat{\mathbf{I}}$ - diagram. Due to superimposition of $F_3$ at high
angle to $F_2$ linear structures of second generation have been rotated so as to plunge towards SE or SW instead of NW.

The structural pattern of Alwar quartzite in subarea XXI is determined by $F_2$ and $F_3$ folds. The poles to bedding show ring-shaped scattering on $\Sigma$-diagram. Minor $F_3$ folds plunge northeasterly. Minor $F_2$ folds plunge southeasterly due to distortion on $F_3$ axes.

In subarea XXII the rocks are Kushalgarh limestones. Here major $F_3$ fold axis plunging $38^\circ$ towards $194^\circ$ is indicated by plots of poles to foliation. $F_3$ minor asymmetrical open folds plunge SW and cluster around pole to $\Sigma$-girdle. There are some 'S' and 'Z' - shaped minor folds showing range in the direction of plunge from WNW to SE. These are interpreted as minor $F_2$ folds rotated by later major $F_3$ fold.

In subarea XXIII occurs the Kushalgarh crystalline limestones. The rocks display disharmonic folds ($F_2$) on minor and outcrop scales (Map 7). The pole to the $\Sigma$-girdle plunges $45^\circ$ towards $41^\circ$. This indicates that $F_3$ is present and controls folding of rock on a major scale although minor $F_3$ are not present. Minor $F_2$ folds and related mullions and cleavage-bedding intersection lineation plunge north-northwestwards. Although a $\Sigma$-girdle is drawn through the poles to the foliation the girdle pattern is actually
ring-shaped, suggesting influence of both $F_2$ and $F_3$ axes in warping foliation of the rock. This is expected because this subarea occurs in the zone of interference between $F_2$ and $F_3$ extending through subareas X, XI, XVII, XVIII, XXIV, XXV.

The interference patterns developed due to superimposition of major $F_3$ folds on Kalachhara antiform ($F_2$) in subareas XXIV, XXV and XXVI have been described in detail in Section III B. Hence only some relevant points are mentioned here. In subarea XXIV the plots of poles to foliation indicate that the axis of Nanglheri antiform ($F_3$) plunges 20° towards 224°. Its axial plane is inclined steeply westwards. Nangalheri antiform ('Raikho antiform' of Heron, 1917) is not a complementary antiform to Bairawas synform ($F_2$) as suggested by Heron (vide Fig. 4). It is a fold of later generation than Bairawas synform.

Subarea XXV has Kushalgarh limestones and Alwar quartzites as rock types and contains the hinge of Kalachhara antiform - a $F_2$ fold plunging about 35° towards 330°. A NE-SW trending $F_3$ fold interferes with $F_2$ here, producing saddle- and col-structure on outcrop scale. The poles to foliations give a ring-shaped pattern indicating interference between $F_2$ and $F_3$ folds. Linear structures of second generation are few in the Kushalgarh crystalline limestones and these plunge towards NW, NE and SE directions.
Subarea XXVI has the same structural pattern as subarea XXV but here \( F_2 \) is more dominant. The limbs of Kalachhara antiform (\( F_2 \)) are warped by later \( F_3 \) folds. The linear structures of second generation show the same orientation as in subarea XXV. The rocks here are Kushalgarh limestones and Alwar quartzites.

Subarea XXVII consists of Alwar quartzites and Kushalgarh limestone and is structurally a repetition of subarea XXVI. The poles to the foliation gives major fold axis plunging about 30° towards 330°. This is in conformity with the \( F_2 \) trend of Kalachhara antiform in subareas XXV and XXVI. This means that in spite of superimposition of \( F_3 \) folds the Kalachhara antiform (\( F_2 \)) mainly controls large-scale fold geometry in these subareas.

Note on the status of Kushalgarh antiform (Map 13)

If the foliation of Kushalgarh crystalline limestones in northern part of subareas XXII and XVIII is considered along with the same in southern part of subareas XXVI and XXVII an antiform is suggested (called Kushalgarh antiform) with a plunge of about 65° south-eastwards. Thus Kushalgarh limestones in the Kushalgarh valley occupy the core of an antiform. The Kushalgarh antiform is interpreted to be a major fold of the second generation. The above structure suggests that the Kushalgarh limestone occurs structurally below the Alwar quartzites. But Heron (1917) suggested
that the structural and stratigraphic succession of Delhi System of rocks is such that Alwar quartzites overlie the Kushalgarh limestone here. The present author suggests that there may be a decollement between Alwar quartzite and Kushalgarh limestones. This plane of decollement possibly is lying on the contact of the Kushalgarh limestone and Alwar quartzites in subareas XXIV, XXV, XXVI to the north and in subarea XXII to the south of Kushalgarh valley. This discontinuity (decollement) in structure has developed in the incompetent Kushalgarh limestone between two competent quartzite bands north and south of Kushalgarh valley. Thus the Kushalgarh limestone might have been detached from underlying basement of Alwar quartzite in this area.

D. Ptygmatic Folds

Ptygmatic folds are represented by quartz veins seen in the Ajabgarh calc-silicate rocks exposed west and east of Nangalheri village and are scarcely found in Kushalgarh crystalline limestones.

These folds have been studied to see how rocks behave under compression maintaining law of competency in miniature scale. Secondly these are analysed to make a quantitative estimate of strain in the rock.

The formation of ptygmatic folds represent a phase of deformation of country rocks and here it is possibly related to Fg mainly because the ptygmatic folds maintain a NW-SE trend like the F2 folds in their vicinity.
The style of folding of the quartz veins, which vary in thickness from fraction of an inch to four inches, are shown in Fig. 64 (a to h) and Fig. 101. They show thrusting on small scale and the plane of thrust is parallel to $S_2$ in enclosing calc-silicate rocks. The folds are sinusoidal in shape with round hinge. The quartz veins also show boudinages parallel to $S_2$ (Fig. 66). The nature of source for the quartz veins is open to discussion. As there is no evidence of igneous activity it is suggested that during lateral compression silica from the original layering in rocks is segregated and becomes folded following the rule of competency (cf. Ramberg, 1955).

Layer parallel compression of more or less straight layered rocks causes some layers to shorten essentially by more or less uniform compressive strain and thickening of less competent and thick layers. Thin and most competent layers shorten essentially by buckling. In course of time, however, the rate of buckling of thick layers becomes significant relative to the rate of $x_2$-shortening and the thin layers with the early formed short buckles are forced to mimic the larger folds ($F_2$ here) of the thick layers more or less passively (cf. Ramberg, 1962). Thus the ptygmatic folds in the area under investigation are likely to be related to $F_2$ folds and they actually do resemble them as seen from their orientations in the field.

Both lenticular and sharp-edged boudins (Ramberg, 1955) are found in the area together with ptygmatic folds.
It has been observed that quartz veins, which trend at high angles to visible schistosity (S2) in calc-silicates, are ptygmatically folded. Quartz veins, which trend at low angles (less than 30°) to schistosity form boudins. Axial planes of ptygmatic folds are nearly parallel to schistosity of calc-silicates. All these features mentioned above indicate compression normal to schistosity.

Uemura (1965) while describing boudins from the Muro group of rocks, southwest of Japan, suggests the occurrence of two types of boudins genetically-extensional and shearing. The present area shows parallel folding. As boudins are not noted on the limb of similar type of fold here, their origin referred to extensional the force on the limb of similar type of folding is excluded. Thus the origin of the boudins here is best interpreted as due to the tensile stress along the bedding plane. The stress probably came from the compressive force normal to schistosity.

Mechanical analysis and tectonic considerations (Ramberg, 1955, Uemura, 1965, Gvozdy, 1960, Luchitskiy, 1962) show that the formation of the boudins are generally controlled by both lithologic and tectonic factors as well as the strength of the brittle layer and the viscosity of the ductile layer. The tectonic force which formed the boudins here is probably attributed to the phase of F2 folding of the Delhi group of rocks which caused the
main structure in the Balrawas valley.

Amount of shortening in a direction parallel to the originally more or less straight veins have been measured for the ptygmatic veins as given in Table 6. As the shortening has occurred normal to the axial plane of $F_2$ folds of the enclosing calc-silicate rocks it also represents the measure of strain in the country rock here. This assumption is valid for buckling folds unless the vein has been rotated from the segment of compression into the segment of extension in the strain ellipsoid (Ramberg, 1959).

The shortening is also recognised by structural features like rotation of schistosity and occurrence of boudins in the surrounding country rocks of Ajabgarh calc-silicate type. The pattern of the contact strain in rocks adjacent to the competent layers has possibly influenced the schistosity to rotate (cf. Mukhopadhyay, 1965). It is also noted from the photo-elastic experiments (Sen, et. al, 1969) that the convergence or divergence of the plane of foliation in the tight folds around the hinge is due to the fact that the minerals, in the foliation plane align themselves on the loci of minimum compressive stress-directions which coincides here with the $x$ direction of strain ellipsoid. The schistosity developed by elongated calcite grains in Ajabgarh rocks parallel to axial plane of ptygmatic folds (Figs. 26, 27) appears to lie along to the plane of maximum
Table 6
(Showing results of measurements on ptygmatic folds)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Length of arc (L) (inches)</th>
<th>Wavelength (l) (inches)</th>
<th>Amount of shortening $\left(\frac{L-l}{L} \times 100\right)$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ptg. 30</td>
<td>18</td>
<td>5.5</td>
<td>69%</td>
</tr>
<tr>
<td>Ptg. 15b</td>
<td>18.4</td>
<td>7.4</td>
<td>59%</td>
</tr>
<tr>
<td>Ptg. 15b</td>
<td>3.6</td>
<td>1.7</td>
<td>52%</td>
</tr>
<tr>
<td>Ptg. 11</td>
<td>3.45</td>
<td>2.5</td>
<td>25%</td>
</tr>
<tr>
<td>Ptg. 13</td>
<td>5.6</td>
<td>1.65</td>
<td>71%</td>
</tr>
<tr>
<td>Ptg. 14</td>
<td>4.2</td>
<td>2.1</td>
<td>50%</td>
</tr>
<tr>
<td>Ptg. 12</td>
<td>6.0</td>
<td>1.3</td>
<td>78%</td>
</tr>
<tr>
<td>Ptg. 10</td>
<td>3.15</td>
<td>1.8</td>
<td>41%</td>
</tr>
<tr>
<td>Ptg. 17</td>
<td>3.2</td>
<td>1.15</td>
<td>65%</td>
</tr>
<tr>
<td>Ptg. 8</td>
<td>2.3</td>
<td>2.05</td>
<td>13%</td>
</tr>
<tr>
<td>Ptg. 3</td>
<td>2.25</td>
<td>1.45</td>
<td>35%</td>
</tr>
<tr>
<td>Ptg. 7</td>
<td>2.4</td>
<td>2.1</td>
<td>12%</td>
</tr>
<tr>
<td>Ptg. 6</td>
<td>2.55</td>
<td>1.65</td>
<td>35%</td>
</tr>
<tr>
<td>Ptg. 2</td>
<td>18.7</td>
<td>11.6</td>
<td>37%</td>
</tr>
<tr>
<td>Ptg. 1</td>
<td>25.5</td>
<td>13.1</td>
<td>48%</td>
</tr>
</tbody>
</table>
extension \( (x) \) in the strain ellipsoid because there is one such plane only. The force of extension sometimes becomes so strong that overthrust parasitic folds appear (Fig. 65 a, b) as suggested by de Sitter (1965). According to the present author there is also a shear component coupled with normal compression which produces these features (Sen, et al, 1969).

A close-spaced fracture has occasionally developed cutting across the folded veins from limb to limb and the schistosity of rocks (Plate 4 Fig. 1). It may be just one set of a conjugate set of fractures. The compression responsible for ptygmatic folds could produce such fractures at a later stage when the rock becomes rigid. The other complementary set is apparently not developed.

An attempt is made to reconstruct the possible geological history of ptygmatic folds in this area.

Due to compression the silica material in the calc-silicate rocks may have melted out from the parent rock and segregated to form veins in the rocks. With the continuation of the strain the changes take place in the veins in the following order:

a) The veins are buckled, giving a sinusoidal pattern. Sections normal to the axis of a single ptygmatic fold have been prepared to study the style of folding (Fig. 67). The style varies from open, asymmetrical to very tight shape as fold form is followed along the axis.
b) During compression the schistosity/country rock is also compressed. Some quartz veins are stretched to form boudins. The presence of lensoidal and sharp-edged boudins in different parts of the same area indicates that compressive strain was not uniform throughout (Sen, et al., 1969).

c) As the rock is gradually more and more compressed the rock possibly gives way to plastic flow and then gradually becomes rigid. But the continuous compression produces a fracture cleavage which cuts across the folds and the schistosity.

Possible Strain-Pattern of the Ptygmatic Folds

The east-west profile views of the ptygmatic folds in the Ajabgarh calc-silicate rocks have been considered to reconstruct the 'x', 'y' & 'z' (maximum, intermediate and least strain directions of strain ellipsoid) directions following Ramberg's hypothesis (Fig. 44 a, b).

It is noted that in all cases the maximum strain direction (x) parallels the axial plane of ptygmatic folds and schistosity of calc-silicate rocks. This geometry of the strain here fits in with the experimental fact which has been found from the flexural folding of competent layers in an incompetent groundmass (Ramberg, 1959). It indicates that the axial plane and schistosity occur parallel to xy and normal to the direction of maximum compression.
Therefore the direction of maximum strain (x) in the calc-silicate rocks with ptygmatic veins has a spatial orientation of N-S while the least strain direction (z) is E-W. Thus maximum compression from east-west in the area rendered a maximum extensive strain parallel to North-South, which facilitated recrystallization of elongated minerals along x.

In the flexural fold, there is always a two-dimensional movement in the same plane. These two component movements are not constant in relation to each other and vary from level to level. Thus in Figs. 68 and 100 the different geometric style shown by the same ptygmatic vein (with constant composition) in different levels can be ascribed to the different componental movements at the same point of the layer which is folded in different levels.