CHAPTER VII

FOLD MECHANISM

7.01 Some fold specimens were measured in the laboratory and in the field in order to suggest the fold mechanisms that have played part in the present area. The results are discussed in this Chapter.

7.02 Attempt has been made in recent years to infer the mechanism of folding from geometric characters of the structures. Among more important contributions are those by Ramberg (1963), Ramsay (1963, 1967), De Sitter (1956), Biot (1957, 1961, 1964, 1965) and Currie, Patnode & Trump (1962).

Measurement of mesoscopic folds

7.03 A number of folds (all $F_2$ folds except fold 5 which is an $F_1$ fold) have been measured and are described below:

Fold - 1

7.04 This fold (Fig. 61) is developed in the calc-silicate rocks near Jipi (Loc: 515, Plate 5). The orthogonal thickness ($t$) and the thickness parallel to the axial plane of the fold ($T$) of the stippled band are measured and yield the following results -

(a) the orthogonal thickness $t$ remains constant
throughout the band and

(b) the thicknesses parallel to the axial plane, 
T, changes and have higher values in the left limb of the fold.

The regularity in the orthogonal thickness points 
to its origin through flexure - slip mechanism.

Fold - 2

7.05 This fold (Fig. 62) is found to develop to the south 
of the Teranga hills at Loc : 732 (Plate 5). The bands I and 
II are measured. The observations in case of band I are -

(a) orthogonal thickness t throughout the band (in 
both antiform and synform) is almost constant,

(b) thickness T varies and is minimum along the 
axial planes and

(c) the axial planes of the antiform and synform 
meets at a low angle.

In band II, in the synformal part,

(a) T remains constant along the band and

(b) t changes with maximum value parallel to the 
axial plane.

It is apparent from the above study that the two bands 
vary in geometric properties and the band I presents a concen-
tric geometry whereas the band II presents a similar geometry. The band I represents a comparatively competent band being composed chiefly of calc-silicate minerals whereas band II is a nearly pure marble band resulting in incompetency. In flexure-slip mechanism, the competent bands usually yield to concentric type and the incompetent bands flow and may present similar geometry. In the present case, the folds have originated through flexure-slip mechanism attributing different geometry to the competent and incompetent bands.

Fold - 3

7.06 This is a fold (Fig. 63) developed in a calc-silicate rock near the Teranga hills, to its north, at the location point 620 (Plate 5). The stippled band is measured, and

(a) the orthogonal thickness t is nearly constant throughout the band except at the hinges where a little thickening is seen,

(b) Z-shaped minor folds are developed in the western limb of the fold and

(c) thickness parallel to the axial plane T varies and is higher in the limbs.

The mechanism suggested is flexure-slip with little flattening (Pur^2-shear), the latter increasing the orthogonal thickness along the hinges.
Fold - 4

7.07 This fold (Fig. 64) is found within the banded ferruginous quartzite in the Jipi area at the location point 555 (Plate 5). The measurements give the following results -

(a) $t$ is highly variable along the folded band and increases towards the hinge.

(b) $T$ is higher in the limbs and gradually decreases towards the hinge.

This fold has originated through the possible mechanism of flexure-slip aided by intense flattening.

Fold - 5

7.08 This is the fold (Fig. 65) found in the banded quartzite at about 1.5 km east of Kotri (Loc : 885, Plate 5). This fold assumes the geometry of a similar fold with axial plane thickness $T$ remaining fairly constant. The dip isogons (Ramsay, 1967, p. 363) are drawn and they are found to converge weakly to the core of the fold. Ramsay (1967, p. 365-367) has classified this type of folds as 1C. In this sub-class $t'\kappa = t\kappa / t_0$ is always less than 1 ($t\kappa = \text{thickness of the material measured between two folded surfaces by constructing tangents to each surface making an angle of } 90^\circ - \kappa \text{ with the axial trace of the fold} - \text{Ramsay, 1967, p. 360}; t_0 = \text{proportional thick-
ness measured at the hinge zone of the fold. Fig. 68 may also be seen). This fold may be described as a flattened parallel fold. Strictly parallel folds (Class 1B of Ramsay, 1967) being superimposed by homogeneous strain (flattening) gives rise to fold 1C of this type; the geometry approaches to the Class 2 (similar) fold of Ramsay (1967).

Fold - 6

7.09 This fold (Fig. 66) from the location 84 (Plate 5) and from a calc-silicate rock also assumes the shape of a similar fold with the axial plane thicknesses remaining almost constant along the folded bands; the dip isogons in a similar way converge weakly to the inner parts of the fold. This may belong to the Class 1C of Ramsay. This fold is a flattened parallel fold and is similar to the Fold 5 above. The geometry approaches Class 2 (similar) type of fold of Ramsay (1967).

Fold - 7

7.10 This presents an interesting fold (Fig. 67) found within the banded quartzites at the location 63 (Plate 5). Here the fold offers the following results -

(a) the curvature of the fold decreases away from the core, that is, acuteness increases to the outer part of the fold,
(b) the axial plane thickness $T$ is constant for an intermediate band but is having higher value in the hinge zone of the outer folds such as at $H_0$ and $H'_0$.

(c) orthogonal thickness $t$ is always higher in the hinge zones and gradually decreases towards the inflection point of the limbs and

(d) dip isogons drawn show peculiar features; they weakly diverge from the parts $H_0$ and $H'_0$ and almost parallel in the intermediate layers; isogons in the zone $A$ and $A'$ are seen to converge weakly.

The intermediate layers have a geometry of similar fold (Class 2); the outer layers in the antiform present Class 3 folds with weakly divergent dip isogons, and the inner layers of the antiform show Class 1C geometry with weakly convergent isogons. The author thinks that this fold may well be generated when a bending fold (Ramberg, 1963) is flattened.

Fold - 8

7.11 This is a hand specimen fold in banded quartzite (Fig. 68) collected from an area around 1 km west of Lakshmi-pura. The dip isogons for the stippled band are drawn. The thicknesses $t$ and $T$ are measured. The following observations
are noted -

(a) T varies constantly, and increases gradually away from the axial plane,
(b) t gradually decreases away from the axial plane, but at a lower rate,
(c) The bands in the core are crumpled and give rise to reverse curvature and
(d) the dip isogons converge towards the core of the fold.

These observations indicate that it is a flattened parallel (concentric) type of fold. Ramsay classifies this type of folds as Class 1C.

Fold - 9

7.12 This fold (Fig. 69) is also collected from the same area occurring in the same rock type as Fold 8. The following are the observations with the fold -
(a) T gradually increases away from the axial plane and at a higher rate than seen in case of fold 8,
(b) t decreases gradually away from the axial plane at a much greater rate than found in fold 8, and
(c) the dip isogons weakly coverage to the core of the fold.
MEASUREMENT OF MESOSCOPIC FOLDS

FIG. 61

FIG. 62

FIG. 63

FIG. 64
MEASUREMENT OF MESOSCOPIC FOLDS

FIG. 65

Fold 5

FIG. 66

0 - 30 cm

FIG. 67

Fold 6

Fold 7

Fold 9

(True to scale)

FIG. 68

Fold 8

FIG. 69

Thickness

Distance

Thickness

Distance
This fold falls in Class 1C of Ramsay (1967) with the weakly convergent isogons. The thickness measurements point to their flattened parallel character and must have been originated through the flexure-slip mechanism in combination with flattening of a higher degree.

7.13 To find out the ratio of quadratic extension $\sqrt{\lambda_2/\lambda_1}$ in the directions normal and parallel to the axial surfaces of the folds ($\sqrt{\lambda_2}$ and $\sqrt{\lambda_1}$ respectively) $t'\kappa = t_\kappa / t_o$ values ($t_\kappa$ and $t_o$ are defined under fold 5 above; Fig. 68 may also be seen. Also, Ramsay, 1967, pp. 360-361) have been plotted against angle of dip $\kappa$ for the folds Fold 8 and Fold 9. The measurements relating $\kappa$ and $t'\kappa$ are tabulated (Table III, p. 99). In case of Fold 8, it is observed that the curve joining the $t'\kappa$ plots for the left limb (Fig. 70) is parallel for certain range to the curve with $\sqrt{\lambda_2/\lambda_1}$ value of 0.4 (from Ramsay, 1967) and then swerves to cut across the curves with the values 0.5 to 0.7. The plots at values of 0.5, 0.6 and 0.7 lie on the limb of the fold. The plots of $t'\kappa$ for the right limb of the fold also generate a curve cutting gently the standard curves for the $\sqrt{\lambda_2/\lambda_1}$ values of 0.9 and 0.8.

7.14 In case of Fold 9, the $t'\kappa$ plots against the angle of dip generate a curve for right limb sloping at a slightly
TABLE III

Measurements on Fold 8 and Fold 9 (see Figs. 68 and 69)

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<th>Fold No.</th>
<th>Limb</th>
<th>Sl. Points</th>
<th>α (in degrees)</th>
<th>t_α (in mm)</th>
<th>t_0 (in mm)</th>
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(contd....)
Figure 70

Diagram showing ratios of Quadratic Extension in minor folds 8 and 9.
TABLE III (Contd.)

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<th>Fold No.</th>
<th>Limb</th>
<th>Sl. No.</th>
<th>Points</th>
<th>( \alpha ) (in degree)</th>
<th>( t_\alpha ) (in mm)</th>
<th>( t_0 ) (in mm)</th>
<th>( t'<em>\alpha = \frac{t</em>\alpha}{t_0} )</th>
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<td>66.5</td>
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<td>0.56</td>
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</table>

higher rate than the standard curves for the values 0.3 to 0.7; the plots for the left limb are very near to the standard curve with value 0.1 with a single value near 0.3.

**Discussion**

7.15 On analysis of the nine folds, it becomes apparent that most of these are flexure folds (Fairbairn, 1942) or
flexural-slip folds (Billings 1954, Ramsay 1967, Turner and Weiss 1963, Turner and Verhoogen 1960) superimposed by homogeneous flattening (pure shear). Some of these (Folds 5, 6 and 9) are tight to isoclinal and approach the similar fold model (Class 2 of Ramsay, 1967). A single fold (Fold 7) shows a peculiar variation in geometry, the outer antiformal or synformal folds are more acute and simulate the fold model Class 3 of Ramsay (1967).

7.16 Several mechanisms have been advocated for the generation of various fold geometry in natural rocks or produced artificially in the laboratory models. Ramberg (1963) redefines bending and buckling folds, and suggests how to differentiate them in the field. The generation of these two different types of folds is attributed to different mechanisms. Bending folds are formed when the forces act perpendicular to the layers, and the Buckling folds are originated by a compressive deviatoric stress acting parallel to the layers. Competent layers are buckled while no competency contrast is necessary for the bending folds. Ramberg (1963) shows that the change in the thickness of the layers in case of bending folds is different from that in case of the buckling folds, and the order of change is just reverse (Fig. 71 after Ramberg, 1963). This idea regarding the change in thickness in the two
basic type of folding phenomena is necessary in understanding some of the fold geometry as discussed early.

7.17 Ramsay (1967) advocates the processes or mechanisms of buckling and shear folding. Buckled folds are developed through layer parallel slip or tangential longitudinal strain or in combination of both. The most important fold form generated through the mechanism of layer parallel slip or shear is a Class IB fold (parallel fold). Class IA may also develop. When thick nonstratified sheets are buckled, tangential longitudinal strain is developed within them; the principal axes of this internal strain are arranged tangentially and perpendicularly to the folded layers. The important result found out of this sort of strain in a layer is that the outer arc is stretched whereas the inner arc of the folded layer is compressed. Transmission of the strains of this folded competent layer produces inhomogeneous strain within the incompetent layers on either side of it for certain distance (about one initial wavelength of the folded competent layer). This zone of contact strain (inhomogeneous strain) develops folds in the incompetent layers which is otherwise homogeneously strained and produces no fold. In most of the buckled folds, both the layer parallel shear and the tangential longitudinal strain are operative giving rise to more complicated geometry to the folds thus produced.
7.18 Superimposed homogeneous strain or the flattening modifies the fold geometry to a large extent. The parallel folds when modified by the homogeneous strain has been called "flattened parallel folds" (Ramsay, 1962). Ramsay (1967) propounds that with intensive compressive (flattening) modification, the flexure folds approach the model for similar folds (Class 2). He demonstrates his idea by a graph the coordinates being $t' \alpha = t_\alpha /t_0$ and the angle of dip $\alpha$. The ratio of quadratic extensions parallel to and perpendicular to the axial surface of the folds ($\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$) with various amounts of superimposed compressive strain are found out and curves are drawn (for different values of $\sqrt{\lambda_2/\lambda_1}$). This graph prepared by Ramsay is very useful in determining the amount of the homogeneous strain (flattening) superimposed on a parallel type of fold. The mechanism of heterogeneous simple shear (non-affine slip on a single set of slip planes) is not a likely mechanism for the development of folds in the present area. Ramberg (1963) also criticises this mechanism as a likely mechanism for fold formation.

7.19 In the present area, Fold 1 and Fold 3 (Figs. 61, 63) are simple parallel folds originating through the processes of buckling (flexural slip). A small increase in thickness in the hinge area in Fold 3 may be due to flattening or the
tangential longitudinal strain. The Z-shaped left limb (Fold 3) supports the idea of buckling phenomenon.

7.20 In Fold 2, the calc-silicate layers I and III show little disharmonic relation, and the marble layer, band 'II', is folded to form a similar geometry. The bands I and III (III not measured) being the competent layers are folded in a concentric manner. Ramsay (1967, p. 417-418) suggests that this type of disharmonic folds generate when the layers are separated at a distance greater than their initial wavelengths. The fold form in the incompetent marble layer (similar type) is guided by the competent layers and the type generated is quite possible through the overall process of buckling.

7.21 Fold 4 is typical with rapid increase of the orthogonal thickness towards the axial surfaces. This may be due to either of the sets of mechanisms -

(a) the fold was formed initially through buckling phenomenon and was then highly flattened, or

(b) the fold started as a bending fold and then flattened.

7.22 Fold 5 and Fold 6 are highly flattened buckle folds. Fold 7 is a complicated fold presenting similar geometry (Class 2) in the central part, and geometry of Class 3 and
Class 1C in the outer part and inner part of the antiform respectively. The bending fold by Ramberg, 1963 (Fig. 71) when superimposed by homogeneous flattening may generate the typical fold form. This type of complicated fold has hardly been recorded. The bending fold in the quartzite layers in present case probably generated in an environment where these layers behaved as ductile layers with minimum or no contrast in competency. The forces which threw these layers (plastic layers) into bending folds acted perpendicular to the layering in the manner shown in Fig. 71. These folds, no doubt, are passive; still, the folding mechanism through shear or slip across the layering need not be called for as an explanation for these bending folds.

7.23 Fold 8 (parallel fold basically) shows less flattening in the right limb whereas the left limb is much flattened. In case of left limb, the flattening is also not uniform (Fig. 70). This may be due to one or more of the following reasons:

(a) the thickness of the layer was originally (prior to folding) not uniform, the part now forming the left limb was thinner;

(b) asymmetry of the fold may influence the thickness data, or
(c) the amount of flattening is not uniform (differential flattening, Ramsay, 1962a, 1967).

7.24 Fold 9 is more flattened with the dip isogons almost parallel to the axial trace. This is also reflected in the Fig. 70. The left limb of the fold is intensely flattened, the $\sqrt{\frac{S}{\lambda}}$ values being around 0.1 while the right limb show variable $\sqrt{\frac{S}{\lambda}}$ values from 0.7 to 0.4. The reason for this variation is again may be one or more of those mentioned for the Fold 8. However, the probability (c) above seems to be more valid; differential flattening which is more common in natural rock deformation as Ramsay (1962a, p. 320) states that "the deviation in the measurements of T in natural and ideal similar folds suggests, however, that the flattening is unevenly developed throughout the rocks, and that the fold hinges represent the zones of maximum or minimum flattening". This variability of flattening (differential flattening) in a fold whether it is of similar type or of flattened parallel type is usually probably much more common in nature than uniform flattening.

7.25 Recently, flattened parallel folds are described from Rajasthan area by Roy (1978) where $\sqrt{\frac{S}{\lambda}}$ value is determined to be 0.3.
Summarizing, the important mechanisms which operated in deforming the rock layers in the present area are buckling (with layer parallel shear strain and tangential longitudinal strain), flattening (pure shear; affine slip along two conjugate slip planes, Turner and Verhoogen, 1960) and to some extent bending. Heterogeneous simple shear across the layered rocks was not an important mechanism for folding in the present map area. Of course, rare instances of similar folding through the shear mechanism can be cited. The pegmatite veins in the Dantar area are, at places, shear folded (Fig. 72). Movements of the pegmatite layers along cleavage surfaces are apparent. Buckling may be considered the most dominant mechanism in the present area, and becomes understandable in field when huge numbers of S- and Z-shaped folds are developed in various rocks types, the layers in the core of the folds are much crumpled giving reverse curvatures, and are faulted and thrusted. In a large mesoscopic fold, the closely packed competent layers are seen to buckle with the formation of curved, open fissures (Fig. 30, cf. Ramsay, 1967, p. 416-419). The phenomenon of buckling is, thus, highly indicated when the outer areas of the large mesoscopic folds are fragmented and form boudins (pseudoconglomerate is thus formed) due to extension parallel to layering characteristic of buckle folds (Fig. 58).