MODEL DEFORMATION STUDIES TO SIMULATE PERI-BASINAL DEFORMATION OF VINDHYAN BASIN OF INDIA.

GENERAL STATEMENT:

In the present study experiments were performed to simulate the present state of finite strain of Vindhyan Basin of India through model deformation techniques. The study reveals that when the model is deformed under the influence of centrifugally directed stress field the stress concentrates along the periphery of the model having rigid margins generating compressive stress regime ($\lambda_1 > 1 > \lambda_2$) and the central part exhibit mild deformation in the layer in tensile stress field ($1 > \lambda_1 > \lambda_2$). The folds have developed along the margin and fractures of different orientation can be seen in the central part of the model, in conformity to the compressive and tensile stress fields of the model. The simulated model deformation exhibit, good correlation with the spatial spread of the structural fabric of Vindhyan Basin of India (see Ramasamy, 1985).

FIELD INVESTIGATIONS:

The finite strain in the Vindhyan Basin of Rajasthan exhibit following structural features.
1. The northwestern margin is characterized by a major fault extending from Chittorgarh in the south to Machilpur in the north having a strike length of about 400 km trending roughly in NE-SW direction. The fault has been designated as Great Boundary Fault of Rajasthan (see, Pascoe, 1968; Prasad and Sharma, 1977; Ramasamy, 1985).

2. The strike continuity of Great Boundary Fault has been punctuated at several places by left and right lateral wrench faults which occur as secondary fault in relation to Great Boundary Fault (Iqbaluddin, et al., 1978).

3. Central part of the basin has almost horizontal beds with open joints and fracturing indicating tensile stress regime in the central part of the basin (see Ramasamy, 1985).

4. Recent work carried out by the author indicate the Great Boundary Fault is a composite surface, in Chittorgarh and Mandalgarh sectors it is a thrust while in the Barundni sector it is developed as a wrench (Fig. 7).

5. In the proximity of thrust the sedimentary pile of Suket Shale and Akoda Mahadev Sandstone formations indicate development of a-lineation which suggest centrifugally directed tectonic transport towards basin margin (Pt. V, Fig. b)

6. The folds have developed in sedimentary pile and show progressive tighten-
ing from axial zone towards the basin margin (Fig. 10). Table 10 presents the interfacial angle of folds developed in the axial, peribasinal and marginal portions of the Vindhyan Basin of Rajasthan.

Table 10

<table>
<thead>
<tr>
<th>Folds</th>
<th>Interfacial angle</th>
<th>Classification</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bijolia Anticline</td>
<td>172°</td>
<td>Open</td>
<td>Axial zone</td>
</tr>
<tr>
<td>2. Parosi-Bichor Syncline</td>
<td>63°</td>
<td>Tight</td>
<td>Pari basinal</td>
</tr>
<tr>
<td>3. Sigoli Syncline</td>
<td>30°</td>
<td>Tight</td>
<td>Marginal</td>
</tr>
<tr>
<td>4. Gowta Anticline</td>
<td>36°</td>
<td>Tight</td>
<td>Marginal</td>
</tr>
</tbody>
</table>

7. In the Chitorgarh sector the Great Boundary Fault is present as a thrust (Pl VI, Fig. a). The sympathetic structures developed on the mesoscopic scale indicate development of folds which as a result of progressive deformation have been ruptured and the steeper limbs have undergone failure by thrusting (Pt. XIII, Fig. a & b). Locally the failure plane developed as high angle reverse fault in the folded limbs (Pl V, Fig. a). At some places the faults have developed as thrust with a well developed slip lineation along the failure surface.
FIG. 10 : STEREOCGRAM SHOWING INTERLIMB ANGLE OF -
   a) BIDOLIA ANTICLINE
   b) PARSOI-IIIVOR SYNCLINE
   c) SIGOLI SYNCLINE
   d) GOWTA ANTICLINE
STRAIN IN EXPERIMENT:

The development of folding and fracturing in the model studies has been attempted by several workers (see Willis, 1891-92; Biot, 1961; Paterson and Weiss, 1966; Cobbold, et al., 1971; Cobbold, 1975 & 1976). The finite strain in model studies was evaluated to determine the spatial location of fold nucleation, the dimension of fold structures and relationship of folding to fracturing to develop a correlated model of strain in nature and experiment in respect of cratonic regime with particular reference to the Vindhyan Basin of Rajasthan.

NUCLEATION OF FOLD:

The nucleation of fold takes place where inhomogeneities exist either in the layer or in the stress distribution. The development of folds involves distortion in the layer at places where inhomogeneities are present. The inhomogeneities in layers or the stress field may be inherited or generated (see Paterson and Weiss, 1966). In Vindhyan Basin the inhomogeneities are present in layers near the basin margin and in the stress distribution which was maximum at the margin of the sinking basin, thus nucleation of folds in the basin was maximum in the peripheral zone.

DIMENSION OF FOLDS:

The concept of dominant wavelength presume the existence of small sinusoidal irregularities in layer subjected to deformation (see Biot, 1961; Ramberg, 1959,
1961, 1963, 1964). Bijlaard (1946) considered the dominant wavelength 'L' will be dependent on thickness of the stiff layer and the elastic modulus of stiff layer and confining medium, where dominant wavelength can be expressed as:–

\[
L = 2\pi t \sqrt{B/6B_0}
\]

Where

- \(L\) = dominant wavelength
- \(t\) = thickness of stiff layer
- \(B\) = Elastic modulus of stiff layer
- \(B_0\) = Elastic modulus of confining medium

Currie, et al. (1962) suggested the Young's modulus of the stiff layer and confining medium play dominant role in determining the dominant wavelength of folds and they suggested the equation:–

\[
L = 2\pi t \sqrt{E/6E_0}
\]

Where

- \(E\) = Young's modulus of confining medium
- \(E_0\) = Young's modulus of stiff layer
- \(t\) = Thickness of the stiff layer
Biot (1959) and Ramberg (1959) studied the folding in perspective of viscous deformation and suggested the role of the coefficient of viscosity of the layer and the confining medium to determine the dominant wavelength. They gave the mathematical analysis for the dominant wavelength of elastic deformation as:

\[ L = 2\pi t \sqrt[3]{\frac{n}{6n_0}} \]

Where

- \( n \) = coefficient of viscosity of stiff layer
- \( n_0 \) = coefficient of viscosity of confining medium
- \( t \) = thickness of stiff layer

Scherwin and Chappel (1968) have suggested the amount of layer parallel strain before buckling controls the dominant wavelength. Huddleston (1973) rewrote the Sherwin-Chappel equation as:

\[ L = 2\pi t \sqrt[3]{\frac{n(5-1)}{6n_0(2S^2)}} \]

Where

- \( S = \sqrt[3]{A_1/A_3} \)
\( \lambda_1 \) = quadratic elongation perpendicular to shortening
\( \lambda_3 \) = quadratic elongation parallel to shortening
\( n \) = coefficient of viscosity of stiff layer
\( n_0 \) = coefficient of viscosity of confining medium
\( t \) = thickness of stiff layer

Thus the dominant wavelength are determined by the thickness and the quadratic elongation perpendicular and parallel to the shortening.

In the Vindhyan Basin small scale structures are conspicuous by their paucity. Large wavelength structures are developed in the peripheral zone as gentle to open folds. The development of the dominant wavelength in the basin is characterized by the thickness of the competent layers of sandstone which have determined the structural architecture in the area.

The development of the concentric folds has been explained by Ramberg (1963) as function of boundary conditions. Chevron folds form about the middle of the model while concentric folds developed near the boundaries. Ghosh (1968) has demonstrated that the kink bands developed in imperfectly lubricated layers and concentric folds with rounded forms developed in well lubricated layers.

Thus the development of concentric folding with rounded hinges (PL VI, Fig. b) in the Vindhyan rocks suggest well lubricated layer boundaries, possibly pore
water was controlling the lubrication between the layers and to an extent the deformation of the basin margin was syn-tectonic to late-tectonic to sedimentation.

**MODELLING MATERIALS:**

A variety of materials have been used to simulate naturally occurring rocks in model studies. Hall (1895) used cloth and clay to represent geological strata. Daubree (1878, 1879 in Hubbert, 1937) used glass, plaster of paris, wax and metal as modelling materials. Cadell (1889) experimented with plaster of paris and damp sand to generate the geological structures. Willis (1891, 1892) employed different grades of wax and plaster of paris in model deformation studies conducted to generate Appalachian structural fabric. Kunen and De Sitter (1938) performed series of experiments using paper sheets, rubber plates, paraffin wax and clay to generate folds. Bucher (1956) used stiching wax (Shoe maker pitch) to experiment on role of gravity tectonics in orogenesis.

In recent years, modelling clay, Dow Corning silicon Putty plastic base Painter's Putty, stiching wax, collophony-ethylene phthalate mixtures, various wax-oil mixtures, various mixtures of heavy powder and silicon Putty or stitching wax, plates of concrete and aqueous solutions have been employed to simulate rocks of dissimilar competency and fluid magma (see Ramberg, 1981).
CHOICE OF MODELLING MATERIAL:

In the experiment to simulate the competent strata of Vindhyan Basin which had low yield strength in the initial stages of deformation and increased ultimate strength generated due to strain hardening with progressive deformation, a material was required which may yield at low stress but may eventually increase in strength due to strain hardening.

Several materials were tried to simulate the physical behaviour of Vindhyan sandstone which has controlled the structural architecture of the Great Boundary Fault and its accompanying fabric. The materials such as modelling clay, plasticine were used. These materials could not respond to centrifugal stress field due to their lack of cohesion with the basement layer through which stress field was simulated in the machine. The Painter's Putty was experimented, which is a mixture of linseed oil and white pigment. The Painter's Putty exhibit the desired quality of low yield strength and pronounced strain hardening with progressive deformation. It had the quality of sticking with the rubber base through which the centrifugal stress field was generated in the machine designed for the model experiment.

Readymade dirty yellow Painter's Putty available in the market was used. It was mixed with grease to make it soft for rolling it in layers of desired thicknesses and to impart it adhesive quality.
THE MACHINE:

The machine used in model deformation studies was designed to generate centrifugal stress field with the stress concentrating along the periphery of the model in line with the stress distribution in Proterozoic Cratonic basins (see Turcotte, et al., 1977; Iqbaluddin, 1979; 1981). The machine had a iron tripod (a), main frame with a ring having 30 cm diameter (b). The frame was designed with a height of 90 cm. The experimental platform for keeping the model was attached to the ring with 4 supporting rods (c). The experimental platform has a rigid base (d) of circular iron sheet 28 cms in diameter. The outer circular ring of the machine is fitted with ten pullies (e) and 4 threaded bolts (f) (PL VII, Fig a). A top glass plate (g) is used to fix the model in position of the experimental platform. The glass plate (g) is attached to the machine with 4 threaded bolts (f). The model is placed over an elastic rubber sheet (h) spread between the model and experimental platform. The rubber sheet with a diameter of 10 cm was connected by 10 strings (i) which passed through the pullies and were tied into a knot and attached to a weighing assembly (j). The pull was generated in the elastic rubber sheet by placing weight in the assembly (j). The force was transmitted through strings on to the rubber sheet which transmitted it to experimental 'medium' (Painter's Putty). The rigid margin of the model led to stress accumulation in the 'medium' and generated deformation. The rigid margin of the Vindhyan Basin were simulated in the model using hard transparent plastic sheets (k).
EXPERIMENTAL DETAILS:

To simulate the structural fabric of Vindhyan Basin experiments on model deformation were performed using the machine designed to generate centrifugal stress field with stress concentration along the basin margin, in line with the conceptual model evolved for the Vindhyan Basin of India (see Iqbaluddin and Mughni, 1976; Srivastava, and Iqbaluddin, 1981). These experiments were designed to study the strain, generated in the basin. The basin boundaries were generated as rectangular and circular in conformity with the various possibilities of basin configuration.

1. The rectangular boundaries of the model in the first experiment were adopted to simulate the fault bounded basin.

2. The circular model was adopted to consider a basin geometry generated as a result of sagging of the basement.

Experiment 1: Model of Fault Bounded Basin

Step-I:

The machine was set for Experiment-I. The rubber sheet (h) was stretched over the experimental platform (d) through the strings (i). An initial weight
of 1.25 kg was placed over the weighing assembly (j) to provide initial stretching of rubber sheet (the initial weight may vary depending upon the elasticity of the rubber sheet being used).

The fresh Painter's Putty was rolled into approximately 2 mm thick layer of nearly uniform thickness over the rubber sheet placed over the experimental platform of the machine. A rectangular model made up of plastic sheet measuring 11 cm x 7 cm dimensions was placed over the Putty layer. The Putty layer outside the rectangular frame was removed. The frame was fixed in position through glass plate (g) and adjusted by the threaded bolts (f) of the machine. The putty layer had initial wrinkles in line with the basement irregularities reflected by the model (PL VIII, Fig. a).

Step-II:

A weight of 4.4 kg was added to the weighing assembly (j). The wrinkles in the model were smoothened and the model started deforming with two sets of tensile fractures in the central part of the model and perimarginal folding in the model under a centrifugal stress field transmitted by a total weight of 5.65 kg. The rate of deformation in the initial stages was more, it gradually decreased, after about 20 minutes the model got stabilised. The model was photographed using black and white Panchromatic film with camera axis vertically disposed (PL VIII, Fig. b).
Step-III:

The weight of 2.5 kg was added to the weighing assembly (j) and the effect on the model was studied. Tensile fractures in the central part of the model increased in opening. The folds in the peripheral part started growing both in amplitude and wavelength under the stress field transmitted by a total weight of 8.15 kg. The growth of the folds towards the model margin led to steepening of the limbs. Later the wavelength of the folds increased towards the axial zone of the basin. Thus compressive regime transgressed over tensile regime embracing the early formed tensile fractures within the fold structures. The model was deformed for about 20 minutes. After 20 minutes no appreciable change in the model was perceived. The model was photographed by keeping camera axis vertical (PL VIII, Fig. c) using the B & W panchromatic film.

Step-IV:

The weight of 3 kg was added to the weighing assembly (j). The model responded by opening up of the fractures in the central part and growth of folds in wavelength towards the basin. The dips steepen towards the margin of the model and towards the axial zone of the model the dips remained gentle. In the central part the dips remained nearly horizontal. The model was deformed for about 30 minutes under a stress transmitted by a weight of 11.15 kg and after which
it was photographed by keeping the camera axis vertical (PL IX, Fig. a) using B & W panchromatic film.

**Step-V:**

The weight of 5 kg was added to the weighing assembly (j). This weight was placed in steps, initially 2 kg of weight was added and response of the model was noted. The model did not responded to the weight. Another weight of 2 kg was added to the model. The rubber stretched slightly and the effect in the model was, slight opening in tensile fractures already in existence in the model. There was no change in the geometry of the marginal folds. Another 1 kg was added and there was no response in the model, at this stage the model was photographed by keeping the camera axis vertical (PL IX, Fig. b) and the experiment was disconnected after 30 minutes observations with the total weight of 16.15 kg.

The above experiment with single layer of Painter's Putty was repeated and similar observations were recorded. The only changes were in the shape and extent of fracturing and folding. The basic geometry of strain remained same, that is tensile stress regime in the central part with open fracturing and compressive stress regime in marginal part with folds having parallelism with the margin. In the corners the structures became curvilinear due to changes in $\tau_1$ trajectories.
Experiment II - Model Simulating Sagging Basin Geometry:

Step-I:

The machine was set for experiment II. The rubber sheet was stretched over the experimental platform through strings. An initial weight of 1.25 kg was placed over the weighing assembly (j) to provide initial stretching of the rubber sheet.

The fresh Painter's Putty was rolled into 1 mm to 2 mm thick layer of nearly uniform thickness and placed over the rubber sheet fixed over the experimental platform of the machine. A rigid margin made up of hard plastic sheet moulded into a circle of 7.5 cm diameter, simulating the peripheral boundary of the sagging basin, was placed over the Putty layer. The Putty layer outside the circular frame was removed. The frame was fixed in position through glass plate (g) and adjusted by the threaded bolts (f) of the machine. The Putty layer had initial Wrinkles in line with the basement irregularities reflected by the model (Pl X, Fig. a).

Step-II:

The weight of 4.4 kg was added to the weighing assembly (j). The inhomogeneities present were stretched out and model responded with initiation of Peribasinal folding and tensile fracturing in the central part under centrifugally directed
stress field generated by a total weight of 5.65 kg. The fractures are essentially extensional. The peribasinal folding has been selective, restricted to margins where stress concentration was more and initial nucleation was well defined (see inset c Pl. X Fig. a & b). The model was deformed for about 20 minutes after which it got stabilised and was photographed by keeping camera axis vertical (Pl. X, Fig. b).

Step III:

The weight of another 2.5 kg was added to the weighing assembly (j) and responses in the model were recorded to the increased stresses transmitted by a total weight of 8.15 kg. The marginal folds accentuate in amplitude and progressively decreased in wavelength and also increased in spatial distribution along the periphery of the model. The accentuation of the amplitude led to tightening and fracturing along the hinge of the marginal fold and overturning of the external limb. The fractures developed in radial pattern corresponding to centrifugal stress distribution in the basin. The radial fractures propagate towards model margins and they open up with progressive deformation. The model was observed for about 25 minutes and when no significant change was noticed it was photographed with camera axis vertically disposed (Pl. X, Fig. c).

Step IV:

In the fourth step of the experiment a weight of another 3.0 kg was added
to the weighing assembly (j). The model responded with fracturing along the hinge line of the marginal folds (Fig. 11) followed by over thrusting of the internal limb over external limb (see inset Y Pl. XI, Fig. a). The tensile fractures developed in the model form polygonal cracks and continued to grow towards model margin under a centrifugal stress field generated by a total weight of 11.15 kg in the weighing assembly of the machine. The model was kept under pull for about 20 minutes when it got stabilised, it was photographed with camera axis vertical (Pl. XI, Fig. a).

Step-V:

The model was subjected to release of stresses (of the deformation achieved in step-IV). The weights of 9.9 kg were removed from the weighing assembly of the machine. The response to the release of centrifugal pull was observed. The model responded by decreased in the openings of the tensile fractures and amplitude of the fold decreased with the corresponding increase in wave length of the structures. The folds nucleated along the margin grew in aerial extent, generating enechlon pattern (see inset Z, Pl. XI, Fig. b). The fold which underwent fracturing and thrusting of the limb did not exhibit any significant changes as the stress accumulated in the hinge has possibly be released by failure along the hinge zone of the fold. The fold with thrusted contacts possibly simulate the present state of finite strain along the Great Boundary Fault of Rajasthan.
FIG. 11: SCHEMATIC DIAGRAM SHOWING OVERTHRUSTING OF INNER LIMB OVER THE EXTERNAL LIMB. NOTE THE OVERTURNING OF EXTERNAL LIMB BEFORE RUPTURE.
During the last stages of deformation, the secondary field developed due to redistribution of stress led to strike slip faulting. Note the displacement along an earlier fractures by growth of secondary faulting due to right lateral and left lateral movements in the model (see inset Z & W, Pl. XI, Fig. b & c).

The Experiment was repeated and similar observations were recorded. In the end phase of the repeat experiment the closing of the tensile fractures was followed by development of dome and basin structures (Pl. XII, Fig. b). These features simulates the present state of finite strain as recorded by Ramasamy (1985) from the Ramgarh Dome area in the Kota district of Rajasthan. The structures represents 1st order interference patterns evolved in a constructive strain field (see Ramsay, 1967; Sengupta & Mukhopadhyay, 1979).