Folds in multilayered rocks of Proterozoic age, Rajasthan, India

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First phase folds F_1 developed in polydeformed Ajabgarh Group rocks of Proterozoic age are studied using various geometrical methods of analysis for compatibility of homogeneous strain in both class 1–3 pairs by correlating t'_α/α plots with existing curves for competent layers and matching t_α/α plots with the flattening curves for the incompetent layers.

F_1 folds were initiated by the process of buckling but underwent $[(\lambda_2/\lambda_1) = 0.2 \text{ to } 0.7]$ for competent layers and R -values of 1.1 to 5 for incompetent layers. The varying flattening is also revealed by the geometry of folds. The apparent buckle shortening of folds which ranges between 49 and 67 per cent with a majority of the folds having shortening values between 50% and 55% (exclusive of layer parallel strain) and inverse thickness method strain up to 50%. Besides flattening, the fold geometry was also modified by the pressure solution. This is borne by the presence of dark seams rich in phyllosilicates and disseminated carbonaceous material offsetting limbs of buckled quartz veins in slates.

1. Introduction

The geometric properties of folds are considered to be of prime importance for the analysis of natural folds and their linkage with theoretical and experimental work. Various methods of analyzing geometric forms of folds in profile section include: orthogonal thickness measurement, thickness measurement, parallel to axial surface and the dip isogon relationship which are interdependent and hence, folds can be studied quantitatively.

Most of the work based on the mentioned methodologies focused on the shapes of modified parallel folds. However, if modifications taking place in original class 3 layer with class 1 layer are studied simultaneously, this would provide a better check on the homogeneity of strain (Ramsay and Huber 1987).

Field studies in orogenic belt indicate that homogenous flattening due to ductile deformation

within individual layers can produce marked thickness variations of layers in overall fold geometry (*cf* Ramsay 1967; Davis 1984). As the bulk strain increases, the folds undergo progressive modification in geometries, which results in a variation of interlimb angle and layer thickness. The transformation takes place from parallel folds (1B) to flattened parallel folds (1C).

The vast amount of existing work on folding processes (Biot 1961; Ramberg 1964; Sherwin and Chapple 1968; Hudleston 1973; Hudleston and Stephenson 1973; Ramsay and Huber 1987; Tripathi and Gairola 1999; Jeng *et al* 2002 and Johnson and Johnson 2002 etc) shows that the fold shape modification may be brought about by buckling and flattening operating simultaneously throughout the development of fold.

In the present paper a series of F_1 folds developed in slates with interlayered alternations with quartzite of Proterozoic age and unaffected by later deformations are analysed by shape modifications

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in both competent and incompetent layers and for their possible mechanism.

2. General geology

The Delhi Supergroup rocks form a part of NNE-SSW Aravalli mountain belt which extends from Delhi in the north through Ajmer and Mewar to Idar and Palanpur in the south covering approximately 800 km. Heron (1917) proposed threefold and later (Heron 1953) two fold classification of the Delhi Supergroup which rests unconformably over pre-Delhi schists and gneisses; Ajabgarh series and Alwar series. Subsequently Roy (1988) renamed that as a separate lithostratigraphic unit, as rayanhalla group at the base of the Delhi Supergroup. Considering these revisions the stratigraphic succession of the Delhi Supergroup as developed in the Alwar and Bayana basins in the northeastern part of Delhi Fold Belt is as follows:

Delhi Supergroup	Ajabgarh Group (3000–4000 m appx.)	dominantly pelitic and volcanics
	Alwar Group (1500 m appx.)	dominantly arenites and volcanics
	Rayanhalla Group	dominantly carbonates and volcanics

The entire succession of the rocks of the Delhi Supergroup is folded/metamorphosed and affected by igneous intrusives viz., amphibolite sills, granite bosses and pegmatite veins. These rocks in the northeastern part of the belt are metamorphosed in medium grade in the western part and low grade in the eastern part. Crawford (1970) based on whole rock Rb-Sr age determined the age of the Delhi Supergroup rocks between 900 Ma and 1650 Ma whereas Gopalan *et al* (1979) determined the age of granite (Rb-Sr) intrusive in Delhi Supergroup of Udaipur and Saladipura between 1480 ± 40 Ma. The Rb-Sr age data provided by Chaudhary *et al* (1984) seems to be the criteria of assumption about the diachronous evolution of the Delhi Fold Belts. On the basis of ages of granitoids, the North Delhi Fold belt and younger South Delhi Fold Belt are distinguished with an assumed dividing line lying south of Ajmer (Sinha Roy *et al* 1998; Roy and Jakhar 2002).

The rocks exposed in the area around Tasing in Alwar district are slates interlayered with quartzite and are part of the Ajabgarh Group, the younger member of the Delhi Supergroup. Slate covers almost the whole of the studied area in the form of NNE-SSW striking ridges from Banharh in the north to Morand in the south through Tasing and Khapariya (figure 1)). It is the prominent lithological unit and has well developed slaty cleavage due

to which it breaks easily. However, the competency of the rock varies. The rock at places is fairly compact. The primary stratification in slates is identified in certain outcrops by variation in color and composition.

3. Structural history

The rocks have been deformed by three phases of folding (F_1 , F_2 and F_3). F_1 folds are well preserved and affected the bedding S_0 and have coevally developed slaty cleavage, S_1 which dips north-eastward (figure 1). F_2 folds have variable geometry and deform both S_0 and S_1 . These are of chevron type folds in slates but in quartzite intercalated with slates, they are open folds having high wave length/amplitude ratio. These maintain ENE-WSW axial trend and have steeply plunging axes. A set of planar surface S_2 occurs parallel to their axial planes. F_3 folds occur as kink bands of dextral and sinistral nature. The kink axes plunge in NE direction and kink band boundaries also dip NE. The angle α (angle between unlinked lamellae and kink plane) and β (angle between kinked lamellae and kink plane) varies from 70° to 80° .

3.1 First phase folds (F_1)

F_1 folds are preserved in slates and slates intercalated with quartzite layers. The folds follow competency law with large wavelength folds confined to competent layers in multilayer sequence. These are open to tight and their interlimb angle varies 92° to 24° . Open folds in quartzite layers have almost constant orthogonal thickness and radial fractures, which converge in core (figure 2) whereas the tight folds have thickened hinge zones and high amplitude to wave length ratio and have convergent radial fractures (figure 3) in folded competent layer but do not maintain normal orthogonal relationship to the layers. Some folds have cusped and lobate nature whereas others affecting multilayers show development of pinch and swell, boudinage structures along the limbs. Quartz veins in slates show F_1 folds. Slaty fabric on the inner arc of the folded quartz veins shows strict parallelism to the axial plane whereas on the outer arc it shows divergent nature. Some of the veins along the axial planes of microfolds show pinch and swell structure.

F_1 fold axial planes steeply dip southeastward and their fold axes moderately plunge between NNE and NE and rarely SSW. The folds are associated with slaty cleavage which occurs parallel to their axial planes. It is well developed on the inner arc of the folds and shows divergent pattern on

Figure 1. Structural map of the area around Tasing, Alwar district, Rajasthan.

the outer arc. The general strike of the cleavage is NNE-SSW (figure 1) and transects bedding.

Lineations formed during the first phase of deformation are the axis of minor folds, intersection lineation due to the intersection of bedding S_0 and the slaty cleavage S_1 , mineral lineation. S_0 and S_1

intersection lineation occurs as striping and parallel to the F_1 fold axes. The lineation plunges from 10° to 50° towards NNE to NE direction. Mineral lineation is defined by the linear alignment of mica flakes, chlorite and rhombic pyrite crystals and steeply plunges southeastward.

Figure 2. First phase open shallow plunging fold in quartzite interlayered with slates, has radial fractures and almost constant orthogonal thickness of layers (locality: Tasing).

3.2 Geometric analysis of F_1 folds

Geometrical analysis of F_1 folds as related to dip isogons and combination of layer thickness with limb dip variation of folds, based on Ramsay classifications are studied. Dip isogon analysis of F_1 folds traced from outcrops, hand specimens (profile sections) in multilayers viz., quartzose and pelitic bands show moderately to strong convergent and divergent isogon patterns, respectively, which fit into subclass 1C in quartzose layers and class 3 in the pelitic layers (figures 4 and 5). The variation in the convergent and divergent patterns could be produced by flattening on initially buckled layers (*cf.* Ramsay 1967).

In order to know more clearly the difference in fold styles the folds that are subjected to dip isogon analysis are also studied for layer thickness variation (t) at various limb dip (α) at 10° intervals (after Ramsay 1967). The thickness variation (t) limb dip (α) plots reveal that folds traced by competent quartzitic layers fall in a majority of instances in 1C type but at limb dip ($\alpha = 20^\circ - 30^\circ$) fall in 1B category.

3.3 Homogeneity of strain in class 1–3 pairs

An idea of apparent strain ratio in flattened parallel folds can be deciphered by t' versus α plots

(Ramsay 1967). It is observed that most of the folds t' versus α plots fit reasonably well on Ramsay's curves. The value of different competent layers in folds show a range from 0.2 to 0.7, indicating that folds underwent varying amounts of flattening and that flattening followed, rather than accompanied, buckling in most instances (*cf.* Hudleston 1973). Most of the folds analysed have layers with low viscosity contrast (i.e., viscosity ratio between 2.5 and 16 estimated by procedure laid down by Biot (1961) and Ramsay (1967)).

F_1 folds show flattening between 49% and 67% with a majority of folds having shortening values between 50% and 55% (exclusive of layer parallel strain).

3.4 Homogeneity of strain in class 3 layers

In order to evaluate the homogeneity of strain in incompetent layers, curves with various values of superimposed strain ' R ' with respect to t'/α values develop the same pattern as in the case of competent layers in multilayer sequence. Ramsay and Huber (1987) have given an equation by applying which theoretical curves with variation of ' R ' could be produced for incompetent layers. Hence these values could be matched with the competent layers to know the compatibility of homogeneity of strain class 1–3 pairs. The theoretical curves between t'/α'

Figure 3. Flattened parallel F_1 fold distinctly folding bedding in quartzite interlayered with slates (locality: Tasing).

versus α' in modified incompetent layers in class 1–3 pairs have been produced by using equation (Ramsay and Huber 1987):

$$t'\alpha' = 1/n[(n+1)\cos\alpha' - (\cos^2\alpha' + \sin^2\alpha'/R)^{1/R}].$$

where n = thickness ratio of competent to incompetent layer at the hinge ' R ' is the value of superimposed strain. The value of ' n ' for one set of curves of incompetent layers is constant whereas ' R ' values are varied. This equation gives the solution of superposed strain ' R ' on the class 1–3 pairs because all other variables besides ' R ' are measurable. The $t'\alpha'/\alpha'$ plots of incompetent layers associated with three sets of folds (figure 4) are matched with the $t'\alpha'/\alpha'$ curves with variation of superposed strain (figure 6 and 7). By doing so, the plots for the left and right limbs of folded incompetent layers would give the same value of superimposed strain

' R ' which could be correlated with the ' R ' values obtained for the competent layer. The ' R ' value obtained for incompetent folded layers in three sets of folds range from 1.1 to 5. This brings forth a better check to know if the folds in the multilayered mass underwent varying flattening.

The strain estimation of folds by inverse thickness (Lisle 1992) which is considered complementary t'/α method, also reveals that these folds have undergone strain up to 50% (figure 8). The amount of flattening in class 1–3 multilayer, viscosity ratio and shortening of fold is shown in table 1.

4. Origin of F_1 folds

Interpretation of F_1 folds in terms of folding processes has been made by analogy with theory and results of experiments (Hudleston 1973). In

Figure 4. Dip isogon analysis and layer thickness variation (t) with respect to limb dip (α) in F_1 folds affecting slate-quartzite multilayers. Dot (•) represent right limb of antiform and synform and circle (o) represent left limb of antiform and synform.

Figure 5. Dip isogon analysis and layer thickness variation (t) with respect to limb dip (α) in (A) F_1 folds affecting quartzite multilayers (stippled) and pelitic layer (dashed). (B) value of t'/α plots of the F_1 folds (from a to f). Dot (.) represents right limb antiform and circle (o) represent left limb antiform.

Figure 6. Diagram showing values of $t'\alpha'$ in modified incompetent layers with variation of 'R' values for different 'n' values.

this consideration, the characteristic features of F_1 folds are appended. The following features associated with F_1 folds prove that they were initiated by layer-parallel compressive strain (buckling):

- Some folds show cusplate and lobate forms. These develop in the rock of low viscosity ratio and form as a result of contraction along an interface between competent and less competent material,

the cusplate folds having cores of less competent material.

- An axial plane cleavage, (S_1) is intimately associated with F_1 folds. The studies have confirmed that slaty cleavage usually develops normal to the direction of maximum compressive strain (Siddans 1972). The strong coevally developed S_1 cleavage thus points to compressive strain normal to the axial plane of the F_1 folds in their

Figure 7. Diagram showing values of $t'\alpha'$ in modified incompetent layers with variation of ' R ' values for different ' n ' values.

original orientation. The slaty cleavage in thin section is absolutely axial planar to the buckled quartz vein in the inner arc but on the outer arc shows divergent nature, again indicates that cleavage geometry arising from a homogenous strain with shortening normal to the axial plane (*cf.* Dietrich 1969). Pinch and Swell structure in quartz veins parallel to the axial planes of folds

also provide evidence of shortening normal to the axial planes of the F_1 fold.

- The thin section of F_1 folds cut normal to fold axes clearly shows quartz grains in the outer arc of microfolds, traced by quartzose layer alternating with slate, are polygonal and strain free, whereas in the inner arcs they are flattened and aligned parallel to S_1 slaty cleavage. In the outer

Figure 8. Strain estimation of F_1 folds, analysed for dip isogons and layer thickness variation, by inverse thickness methods (Lisle 1992).

Table 1. Showing amount of flattening, different values of 'n' (thickness ratio of competent to incompetent layers), viscosity ratios, shortening values in folds in multilayers.

Fig. no.	Layer no.	Amount of flattening in competent layer		Layer no.	Amount of flattening in incompetent layer		n	Viscosity ratio	Shortening %
5	1	0.5-0.6	0.4-0.6	2	5	4.5	0.92	2.8	51
6	1	0.5-0.6	0.3-0.4	2	5	4.0-4.5	1.7	2.7	49
	3	0.2	0.2						
7	2	0.5-0.6	0.4	1	5	5	0.25	2.5	52
8	2	0.5-0.6	0.4-0.5	1	4.5-5.0	3.5-4.5	1.22	2.9	50
9	2						0.37		
	(Antiform)	0.2-0.3	0.4	1	5	5			
				(Antiform)					
	4								
	(Antiform)	0.2	0.3	3	5	4-6	0.61	2.6	67
				(Antiform)					
	1	0.2-0.3	0.2						
	(Synform)								
	3								
	(Synform)	0.6-0.7	0.2-0.4						
10	1	0.4-0.6	0.6-0.7	2	1.1-1.5	2.0-2.5	1.78	6.0	50
	3	0.2	0.3-0.4	4	2.0-2.5	1.1	3.7		
	5	0.4-0.6	0.3-0.4						

arcs of some quartz grains fractures are seen and some show strong undulose extinction. This also proves the folds are zones of extensional and compression respectively which is expected in buckle folding.

- The dip isogon analysis shows that the folds to be of class 1–3 geometry. Further, their analysis of thickness variation with respect to limb dip shows that the folds are combination of class 1B near the hinge and of class 1C at the limbs. Dependence of their shape is a viscosity contrast between layers.
- That slip on bedding (flexural slip) was operative during buckling of more viscous materials in layered meta sediments is evidenced by: (a) Striae at the limb of the F_1 folds.
- The F_1 folds showing thickened hinges and thinned limbs with high amplitude/wavelength ratio, however, cannot be explained only by buckling. This is very well borne by the $t'\alpha/\alpha$ plots of these folds with varying amounts of flattening. This indicates that compressive strain also operated after buckling and the folds experienced flattening.
- The post-buckling compressive strain on folds had not been uniform for both limbs. Instead folds experienced differential flattening as deduced from the values of λ_2/λ_1 determined from $t'\alpha/\alpha$ plots and the constructed curves for the incompetent layers.
- Some of the $t'\alpha/\alpha$ plots showing points gradually transecting the flattening curves suggest that during the formation of folds volume changes are involved. The λ_2/λ_1 curves were constructed with assumption $\delta = 0$. That there had been some volume changes during F_1 fold formation is also brought out by the microstructures/fabric. In thin sections of microfolds shown by quartz vein or quartzose layers, quartz is seen to have solution truncation, embayed boundaries and sharp boundaries with phyllosilicates. The rock in the vicinity of these grains is more rich in phyllosilicates and dark seams, suggesting that pressure solution phenomena was operative during fold formation. Such features are more commonly noticed in the limbs of microfolds.

5. Conclusions

The study of the mesoscopic features, geometric analysis and microstructures of F_1 folds indicate that these were initiated by buckling. The folds experienced post-buckling compressive strain, flattening. It is borne by the geometry of folds having thickened hinges and thinned limbs and being a combination of class 1B near hinge and class 1C at the limbs as is analysed by dip isogon and $t'\alpha/\alpha$

methods. The post buckling compressive strain had been non-uniform for both limbs assessed by matching $t'\alpha/\alpha$ plots with $t'\alpha'/\alpha'$ curves with variation of ' R ' for both competent and incompetent layers. During the fold development and associated slaty fabric pressure solution further modified their geometry bringing about mineral redistribution. The geometry of F_1 fold axes, their axial planes and associated structures linear and planar it could be deduced that these folds were formed by layer parallel compressive stress from $N70^\circ W - S70^\circ E$ direction.

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