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Geology

A CONCEPT ON THE ORIGIN OF SIMILAR AND THE RELATED FOLDS BASED ON THE STUDY OF HIMALAYAN TECTONITES*

A. R. BHATTACHARYA

Department of Geology, Lucknow University, Lucknow, U.P.

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Detailed study of the folded tectonites of the Himalaya, in relation to major thrust planes, especially the Main Central Thrust, has revealed some interesting results on the genetic relationship between the development of similar folds and thrusting. As a result, the maximum value of flattening in similar folds and the corresponding minimum value of ϕ (the angle between the tangent on any limb and the axial race of the fold) are obtained at the thrust plane. These values, on the other hand, show a sympathetic decrease (flattening) and increase (ϕ) away from the thrust on either side. Thus, the nature of variation in the styles of similar folds comes out to be a second-degree curve of the type : $y = ax^2 + bx + c$. For a parallel fold, on the other hand, the relationship between the orthogonal thickness (t) and hinge thickness (T) is always a straight line : $t = T$. Further, during similar folding, the distribution pattern of strain is such that the orthogonal thickness (t) bears a parabolic relation

$$(t - k)^2 - 4a\,(T - h)$$

with the hinge thickness (T). It has also been shown that higher the degree of thrusting, higher is the value of flattening, and vice versa. Thus, the present method can not only be applied to locate precisely the thrusts in a tectonically disturbed area, but also to compare the relative degrees of thrusting for several thrusts.

INTRODUCTION

A DETAILED study of the folded tectonites in the Himalaya has indicated some interesting relationships between the magnitude of flattening in similar folds and the proximity, or otherwise, of the major thrusts. Thus, a genetic link between fold development and thrusting is established. As a special case, the tectonites around the Main Central Thrust (MCT) in the Kumaun Himalaya have been studied in detail. The MCT is an important geotectonic element in the Himalaya, on which the Central Crystalline Zone of the Higher Himalaya has been thrust over the sedimentary belt of the Lower Himalaya. The tectonic pattern of the MCT has been compared with the Pennine thrustfolds of the Alps, and the gneisses of the Central Crystalline Zone bear similarities with those of the Saint Bernard Gneiss of the Pennines (Heim & Gansser, 1939). The MCT has an E-W to ESE-WNW trend, and is everywhere associated with a high degree of structural complexity in both the crystallines and the sedimentaries, detailed accounts of which have already been published (Misra & Bhattacharya, 1972, 1973, 1976; and Bhattacharya, 1974).

The present paper pertains to a study of the flattening of folds on the mesoscopic scale across the MCT, as well as in relation to some other subsidiary or relatively less prominent thrusts in the Kumaun Himalaya. In this context, Ramsay (1967, p. 421) has observed that similar folds "are generally found in the central parts of

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belts of regional folding and metamorphism. The zones of the crust where these folds are most common were probably in a very ductile state during fold formation. The rocks were probably positioned at some considerable depth below the surface when folding took place and subjected to high temperatures and pressures (both hydrostatic and deviatoric)". According to Biot (1965), similat folds are formed where viscosity contrasts are very small; otherwise the embedding medium acts as a strong confinement, which prevents similar folding and leads to internal buckling. Carey (1962) suggested the formation of similar folds by flow across a set of layers or beds. However, Ramsay (1967, p. 431) raised objections to this view maintaining that similar folds are more or less the result of buckling. The present author has, however, observed a definite relationship especially between the development of similar folds and of thrusting. The observations are based on the nature of folds as they typically occur in the field.

ORTHOGONAL THICKNESS AND FLATTENING

The cross-sections of profiles of folds have been studied (Fig. 1). Two parallel tangents are drawn on a selected bedding plane on one of the limbs, and their normal, i.e., orthogonal thickness (t) measured. The angle ϕ, which these tangents subtend with the axial trace of the fold, is measured. At the hinge zone, the thickness (T) of the folded material is also measured along the axial trace of the fold. The ratio of these two thicknesses gives the parameter $t' = t/\mathrm{T}$. In fact, this is a modification of Ramsay's (1962) graph in which, instead of dip on the limb of the fold, the angle between the axial trace of the fold and the bedding plane on the limb has been measured. In the present case, the parameter t' defines the proportional change in orthogonal thickness throughout the fold. In other words, t' is an expression of the distribution pattern of strain in the fold.

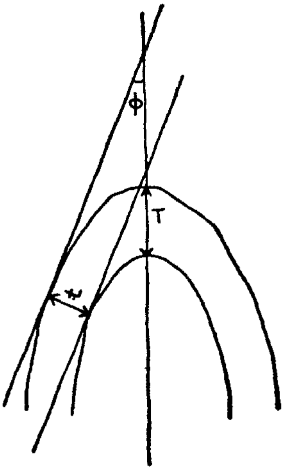

FIG. 1. Cross-section of a fold showing the various parameters used. t is the orthogonal thickness, i.e., the normal distance (thickness) between the two tangents drawn on the limb of the fold. T represents the hinge thickness as measured along the axial trace. ϕ is the angle which the above-mentioned tangents subtend with the axial trace of the fold.

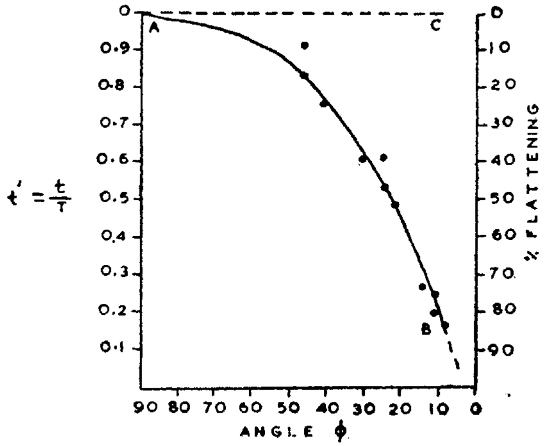

FIG. 2. Plot of $t' = t/T$ versus ϕ in degrees for the various similar folds around the Main Central Thrust and away (south) from it. AB represents the curve obtained for similar folds of the area. The point B corresponds to the MCT and its vicinity. AC represents the theoretical curve (straight line) for the parallel folds of the area, because for all such folds $t' = 1$, as $t = T$, for all the values of ϕ. Note the maximum values of percentile flattening, with corresponding minimum values of ϕ, near the MCT.

The relationship between $t' = t/T$ and angle ϕ has been plotted on a graph, together with flattening as ordinate (Fig. 2). This graph can easily be applied to reoriented as well as folded structures. A number of fold profiles have been measured in the field as also from the oriented field photographs. As a result, a succession of representative folds, from the *MCT* and away from it, has been sketched and plotted (Fig. 3). The respective values of ϕ, t' and percentile flattening have also been given alongwith.

It is obvious from the graph of Fig. 2 that for a parallel fold, t being equal to T, t' will have a value of unity. Thus, depending upon the value of ϕ, the graph will follow a straight line parallel to the abscissa (AC in Fig. 2). Further, the t-T relationship, when plotted for the parallel folds of the area, also comes out to be a straight line (Fig. 4) : $t = T$ passing through the origin, because for all values, $t = T$, and hence the gradient of the curve ($\tan \theta$) $= 1$.

On the other hand, for similar and other related folds, like Ramsay's (1967) class 1C and 3 types, there will be varying values of t'. Thus, the points, in such cases, will show scattering throughout the graph, below the straight line AC (from A to B). It can easily be seen from the graph, that the folds with increasing values of flattening show a tendency of clustering on the right portion of the graph.

DISCUSSION AND CONCLUSIONS

Various types of plottings for a number of folds from the several structurally deformed areas of the Himalaya, have been carried out. As a special case, the MCT has been selected, as the respective values of flattening in folds associated with it are much

ORIGIN OF SIMILAR AND THE RELATED FOLDS

Fold Profile	ϕ	t T	% Flattening
	10°	0-19	81
	14°	0-26	74
	21°	0-48	52
	24°	0-53	47
	30°	0-60	40
	40°	0-75	25
	47°	0-83	17

FIG. 3. Sketches of a succession of folds from the MCT and away (south) from it across the strike of the rock formations. The associated values of ϕ, t/T and percentile flattening for each fold are also given. In the figure, the fold lying at the top, with maximum value of percentile flattening and minimum value of ϕ and t/T, corresponds to the MCT and its vicinity.

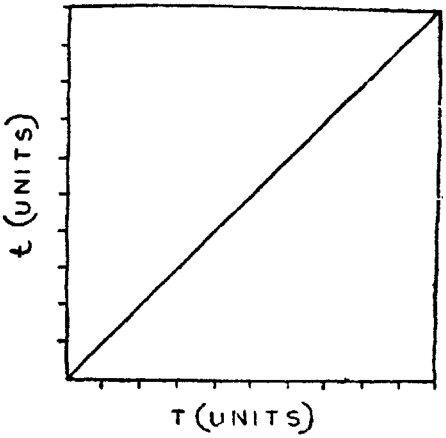

FIG. 4. t : T relationship for the parallel folds of the area. Since $t = T$ for all such folds, the relationship represents a straight line passing through the origin with a gradient of unity.

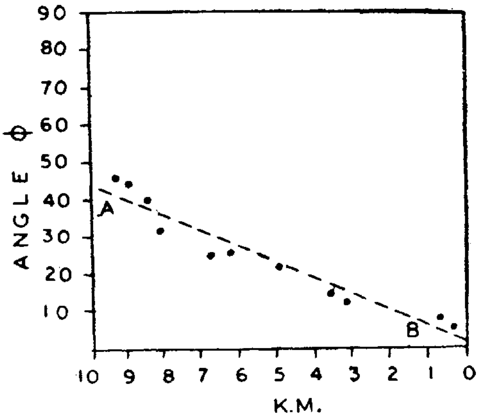

FIG. 5. Plot of the angle ϕ versus the distance (in kilometres) from the MCT for the various similar folds related to the MCT. As the MCT is approached, ϕ shows a gradual decrease. Point B in the graph corresponds to the MCT and its vicinity, where ϕ reaches its minimum value. The sedimentary strata dip consistently north to north-northeast, at angles from 15° to 40°.

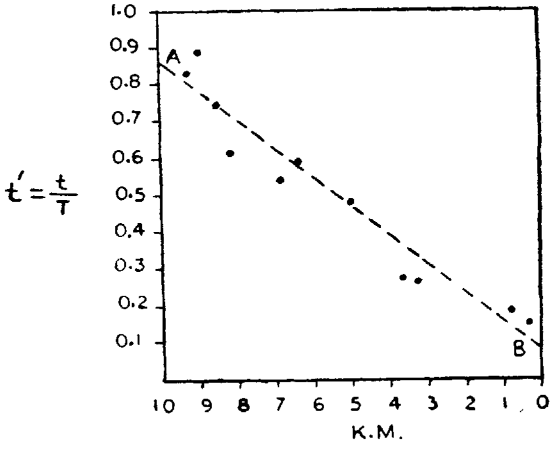

FIG. 6. Plot of the various $t' = t/T$ data for the similar folds against the distance (in kilometres) from the MCT. A gradual decrease in t' values, like ϕ, is observed as the MCT (point B) is approached. The sedimentary strata, as mentioned above, dip consistently north to north-northeast, at angles from 15° to 40°.

higher than those with other thrusts, thus facilitating a better presentation of the data. The various fold data from the MCT toward south in the sedimentary belt as well as in the north in the Central Crystalline Zone, have been collected and plotted (Figs. 2, 3, 5 to 7). The results indicate that :

(1) When the plottings in Fig. 2 are successively extended towards the MCT, the points gradually move from A towards the lower right portion of the graph (curve (AB), showing an increasing value of flattening. As a rule, the maximum values of flattening (upto 84 per cent or even more), and the corresponding minimum values

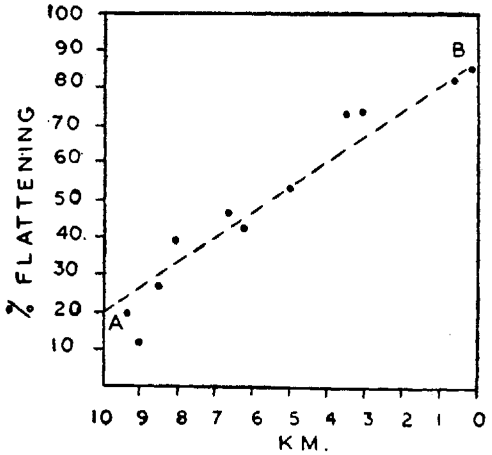

FIG. 7. Presentation of percentile flattening data against the distance (in kilometres) from the MCT. Note the gradual increase in the flattening values towards the MCT (point B), which is represented by the maximum flattening values.

of angle ϕ (as low as 5°) are obtained at the MCT, irrespective of the lithology of the folded tectonite. The successive values of ϕ, as well as t', when plotted against the distance from the MCT (Figs. 5 and 6) clearly indicate a gradual decrease in both these parameters, as the MCT is approached, where these values reach their minimum. Further, the successive flattening values of individual folds when plotted against the distance from the MCT (Fig. 7) clearly show a gradual increase towards the MCT, where the flattening reaches its maximum value. All the above-mentioned values, on the other hand, show a sympathetic decrease (flattening) and increase (ϕ, t') as one proceeds southwards or even northwards of the MCT. Thus, the highly flattened and tight similar folds around the MCT changes their attitude to open folds away from the thrust, and ultimately merge into zones of parallel folds with zero to negligible flattening.

(2) The nature of variation in the styles of similar folds (from A to B in Fig. 2) represents a second-degree curve of the type

$$y = ax^2 + bx + c, \qquad \ldots(1)$$

where a, b, c are parameters. In the above equation, the angle ϕ is represented by x and t' by y.

$$\text{Let, } S = \sum_{i=1}^{n} \left[y_i - (ax_i^2 + bx_i + c) \right]^2 . \qquad \ldots(2)$$

In order that the curve (Fig. 2, eqn. 1) is a "best-fit" curve, the values of S should be minimum. It thus follows that

$$\frac{\delta S}{\delta a} = 0 \qquad \ldots(3)$$

$$\frac{\delta S}{\delta b} = 0 \qquad ...(4)$$

$$\frac{\delta S}{\delta c} = 0 \qquad ...(5)$$

The least square equations, as obtained from (3), (4) and (5) are as follows :

$$a\sum_{i=1}^{n} x_i^4 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} y_i\, x_i^2 \qquad ...(6)$$

$$a\sum_{i=1}^{n} x_i^3 + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i\, x_i \qquad ...(7)$$

$$a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i + nc = \sum_{i=1}^{n} y_i \qquad ...(8)$$

The values of x_i and y_i are known from the graph, when Σx_i, Σy_i, Σx_i^2, Σx_i^3, Σx_i^4, $\Sigma y_i x_i$, and $\Sigma y_i\, x_i^2$ can be calculated, and their values inserted in eqns. (6), (7) and (8). In the present case, n represents the number of data in the curve (Fig. 2). Thus, the parameters a, b, c are calculated and the exact and accurate nature of the curve (Fig. 2) for the MCT can be determined.

By following this method, the exact equation as well as the nature of the "best-fit" curve for any thrust and the associated similar folds with it can be obtained.

(3) The rate of change of hinge thickness (T) of the folds with respect to their orthogonal thickness (t), has been studied by plotting for t and T (Fig. 8). The resultant graph comes out to be a parabola, of the type

$$(t - k)^2 = 4a\,(T - h). \qquad ...(9)$$

In other words, it may be said that during similar folding, the distribution pattern of strain in the folded tectonites is such that the orthogonal thickness (t) bears a parabolic relation with the hinge thickness (T).

From (9)

$$t^2 - 2kt + k^2 = 4aT - 4ah$$

or

$$4aT = t^2 - 2kt + k^2 + 4\,ah$$

This simplifies to

$$T = a't^2 + b't + c', \text{ (say)} \qquad ...(10)$$

$$\text{Let,}\quad S' = \sum_{i=1}^{n}\left[T_i - (a't_i^2 + b't_i + c')\right]^2 \qquad ...(11)$$

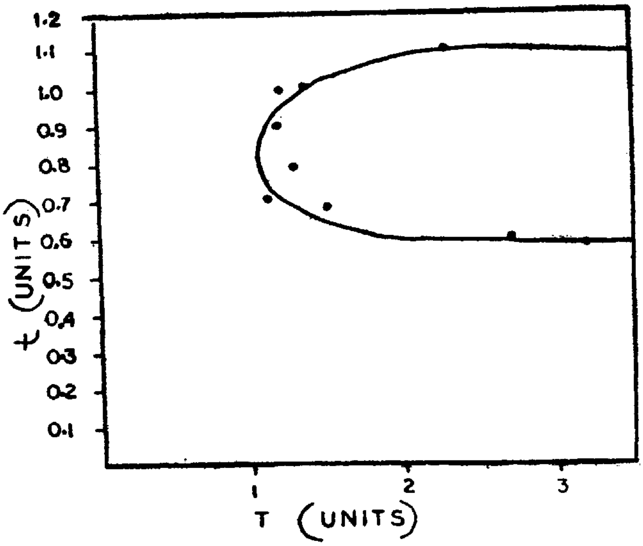

FIG. 8. Plots of the values of orthogonal thickness (t) and hinge thickness (T) for the similar folds of the area. The relationship, as can be seen from the graph, comes out to be a parabolic one.

In order that the curve (Fig. 8, eqn. 9) is a "best-fit" curve, the value of S' should be minimum, which follows that

$$\frac{\delta S}{\delta a'} = 0 \qquad \ldots(12)$$

$$\frac{\delta S'}{\delta b'} = 0 \qquad \ldots(13)$$

$$\frac{\delta S'}{\delta c'} = 0 \qquad \ldots(14)$$

The least square equations from (12), (13) and (14) can be obtained, whence the parameters, a', b', c' can be calculated, as outlined earlier.

(4) In the case of other relatively less prominent thrusts also, the magnitude of flattening shows a sympathetic low value (for example, up to 62 per cent in the case of the Kaphauli Thrust of northern Almora district of Kumaon (Misra & Bhattacharya 1972). Further, it has also been observed that lithology of the beds involved in similar folding is not a (major) factor in the development of flattening; instead, it is minor parameter in this milieu. However, only a difference of up to 5 per cent in the flattening values has been obtained when the same is individually measured for shale, limestone and quartzite beds. This observation is exclusively based on field data. Thus, on the basis of various measurements and plottings of the field data, the following scheme of increasing susceptibility to flattening has been tentatively obtained :

shale → limestone → quartzite

At a particular flattening level, say 30 per cent, the values for different lithologies, as given above, vary within a range of maximum 5 per cent only, i.e., say between 27 per cent and 32 per cent, but they never show such figures as 52 per cent or 73 per cent or 11 per cent. In other words, one can visualise the existence of some sort of "iso-flattening lines", whose percentile flattening values successively go on increasing towards the thrust plane, where the values become maximum ; beyond which the values again shown almost sympathetic decrease (unless and until some other thrust plane is approached). For obvious reasons, higher the degree of thrusting, higher is the value of flattening, and vice versa. In the particular case like this, the higher values of flattening themselves speak of the significance of the MCT in the Himalayan region as a whole. *Thus, the present method can not only be applied to locate major thrusts in tectonically disturbed areas, but also to compare the relative degree of thrusting for many thrusts.*

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