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Map patterns produced by thrusting and subsequent superposed folding: Model experiments and example from the NE Kumaun Himalayas

By Ashok K. Dubey and Sudip K. Paul [1]

ABSTRACT

Multilayer modelling clay models were compressed in orthogonal directions for simultaneous early folding and thrusting and subsequent superposed folding. In all the experiments, the initial layering was horizontal in the press but the overall shortening varied during the two stages of deformation for obtaining a variation in the structural features. After the completion of an experiment, a horizontal slice was cut and removed from the model to expose the internal structural pattern (i.e. the map pattern). The experiments revealed a variety of structural patterns depending upon the thrust geometry, amount of displacement along the basement thrust, the presence or absence of a plane of décollement at the basement cover interface and geometries of the early and the superposed folds. The patterns included inliers characterized by domal structures. A similar map pattern is described from the NE Kumaun Himalayas.

ZUSAMMENFASSUNG

Die im Experiment untersuchten Mehrschichten-Tonmodelle wurden in orthogonalen Richtungen gepresst, um frühe Phasen von Faltung und Überschiebung und anschliessende überlagernde Faltung zu simulieren. Zu Beginn aller Experimente war die Lagerung der Tonschichten jeweils horizontal. Während zweier Deformationsphasen wurde die Gesamt-Verkürzung jeweils variiert, um Unterschiede der strukturellen Merkmale zu erzielen. Nach Beendigung jedes Deformationsexperimentes wurde jeweils mit einem Horizontalschnitt ein Teil vom Modell abgetrennt, um das innere Strukturmuster, das sog. «Kartenmuster», offenzulegen.

Eine Vielzahl von Strukturmustern konnte auf diese Weise sichtbar gemacht werden abhängig von der Überschiebungsgeometrie, vom Verschiebungsbetrag entlang der basalen Abscherungsfläche, der An- oder Abwesenheit einer Scherfläche zwischen Sockel und überliegenden Schichten sowie der Geometrie der frühen Falten und später überlagernden Faltungen. Die Muster enthalten auch domartige Strukturen mit Fenstern. Ein ähnliches Kartenmuster wird aus dem Gebiet des nordöstlichen Kumaun-Himalaya beschrieben.

Introduction

It is a well known fact from the Himalayas that fold hinge lines formed at different times during the Himalayan orogeny have a consistency in their orientation (Le Fort 1975; Thakur 1980; Dubey & Bhat 1990). The hinge lines of the early folds (i.e. coaxial F1 and F2) trend E-W to NW-SE, roughly parallel to the strike of the major Himalayan thrusts (i.e. the Main Frontal Thrust, the Main Boundary Thrust, the Main Central Thrust etc). The only exception is the early sheath folds where the fold hinge lines have been rotated to NE-SW orientation as a consequence of large shear strain associated with the thrusts (Cobbold & Quinquis 1980; Jain & Anand 1988). The hinge lines of the superposed folds (i.e. F3) trend nearly N-S to NE-SW i.e. normal to the trend of the early

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fold hinge lines and the major thrusts. These superposed folds have formed at a late stage of orogeny probably after the locking of the thrusts since they are unaffected by the thrust related strains (Dubey & Bhat 1986, 1991). The map patterns of the Himalayas thus needs to be interpreted in terms of thrust tectonics with early fold formation followed by superposed folding.

The available literature on the subject deals with one aspect at a time, i.e. either the map patterns have been interpreted as a result of various thrust geometries and thrust propagation (e.g. Dahlstrom 1969; Boyer & Elliott 1982; Williams & Chapman 1983; Boyer 1986; Woodward et al. 1989) or the effect of superposed fold geometry on the early fold geometries has been studied (e.g. Ramsay 1967; Thiessen & Means 1980). Hence it was decided to perform a series of experiments in order to understand the map patterns resulting from superposed deformation on an earlier folded and thrusted sequence.

The multilayer models

The experiments were carried out by using multilayer modelling clay models. The multilayer packet consisted of five layers, each approximately 2 mm thick, and the interlayer boundaries were lubricated by talc powder to allow interlayer slip during deformation. The alternate layers were of contrasting colours so that the layering is prominent in the photographs. The multilayer packet was sandwiched between two slabs of modelling clay. The top slab was a continuous block whereas a fracture was induced in the bottom slab to act as a plane of weakness at the onset of deformation. The fracture simulated a basement fault formed during the pre-orogenic extensional deformation (Bhat 1987; Dubey & Bhat 1991). The fracture extended into the multilayer packet as well in some of the experiments. The geometry of the fault surface was either planar or listric. The fault surface was lubricated by talc powder to reduce frictional effects. The external dimensions of the models ranged from 15 × 11 × 7.5 cm to 15 × 12 × 7.5 cm.

At the start of the experiment, the axis of maximum compression was parallel to the layering and normal to the strike of the basement fault. After few stages of deformation, the axis of maximum compression was changed to an orthogonal direction so that the new direction was parallel to the initial strike of the basement fault. This was done in order to produce the superimposed folding. The axis of minimum compression was normal to the initial layering and it remained unchanged throughout the deformation. The different models were subjected to different amounts of shortening during the two stages of deformation so that the developing structures are arrested at different stages of evolution. After the completion of an experiment the upper part of the folded multilayers was cut by using a thin wire so that the internal structure of the model is revealed on a flat surface.

The biaxial press used for deformation was similar to the press described earlier by Dubey & Cobbold (1977). The layering was horizontal in the press and the models were compressed parallel to the layering. The resulting extension took place along the vertical axis.

During the second stage of deformation, the model was rotated by 90 degrees along the vertical axis of the press. After each stage of deformation, the model was taken out of the press for photographing the geometrical shape modifications.

Three experiments of this series are described here.

Experiment One

In this experiment the basement was cut by a planar fault before the onset of deformation. The dip of the fault was 15 degrees.

Successive stages in the deformation of the model are shown in Fig. 1 A to 1 E.

At the start of the experiment (Fig. 1 A), there was a prominent plane of décollement at the matrix-multilayer interface. The displacement along the thrust was insignificant and the folds initiated as buckle folds. The folds were asymmetric and the axial surfaces were dipping in the dip direction of the thrust. After 27 per cent overall shortening (Fig. 1 B), the basement fault was folded and a conjugate set of thrust faults initiated in the matrix. The multilayer folds became nearly upright with small interlimb angles and the fold geometries varied with depth along the axial surface. On tracing these folds in the third dimension, they were noncylindrical with curved fold hinge lines (Fig. 1 C). The hinge line curvature may be attributed to fold initiation at different points and oblique linking of the fold hinge lines during the longitudinal fold propagation (i.e. extension of fold hinge line by amplification) (Dubey & Cobbold 1977). The matrix-multilayer interface was also folded.

The model was then compressed in the orthogonal direction, parallel to the early fold hinge lines. The superposed folds became prominent after 10 per cent shortening. These folds were upright and the wavelengths were larger as compared to the early folds. The interference pattern was marked by curvature of the early fold hinge lines, and dome and basin pattern. The initial basement fault was folded harmonically with the superposed folds. The model was compressed up to 33 per cent shortening during the second phase of deformation (Fig. 1 D) and then a thin horizontal slice was cut and removed from the model. The internal structure of the model is shown in Fig. 1 E and the structural details in Fig. 1 F. The basement occurs at four isolated domes (Fig. 1 F). The first one occurs in front of the thrust and the other three in the tilted basement wedge. Two of the exposures (no. II and III) have a thrusted contact on one side and a normal contact on the other sides, with the overlying layers. The exposure no. IV occurs as a noncylindrical dome which is an inlier having a normal contact with the overlaying layers. The structure is cut by two sets of faults which strike parallel to the early and the superposed fold hinge lines.

Experiment Two

The model material, construction of the model and the mode of deformation were similar to that of Experiment One. However, the initial basement fault had a listric geometry and it extended into the multilayers.

The stages in the deformation of the model are shown in Fig. 2 A to Fig. 2 E.

After 7 per cent overall shortening an asymmetric fold was prominent above the basement fault (Fig. 2 A). The layer surface revealed that the fold was cylindrical. Internal deformation within the layers was less and the folding involved bending and subsequent yielding at the fold hinges. Folding did not initiate from other possible irregularities on the layering or by transverse fold propagation (i.e. lateral spreading of a fold as a periodic structure). Overturning of the fold gradually increased and it was pronounced after 13 per cent overall shortening (Fig. 2 B). The transverse fold propagation was not

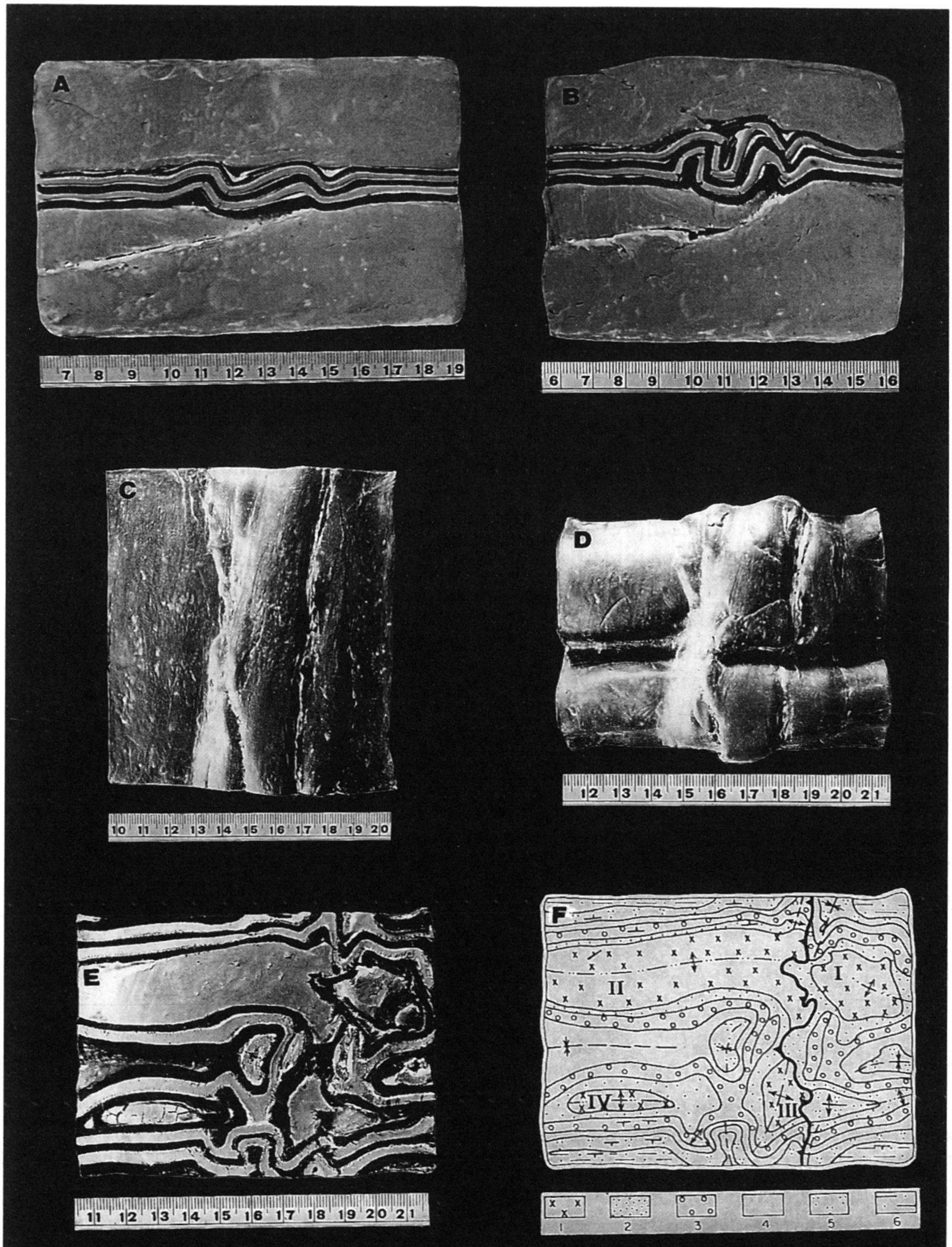

Fig. 1. Stages in the deformation of a multilayer model: A- Cross-sectional fold shapes after 10% overall shortening; B- Cross-sectional fold shapes after 27% overall shortening; C- The top layer surface at stage B; D- The top layer surface after 27% shortening in the first phase and 33% shortening in the second phase of deformation; E- Internal structure of the model at stage D, after removing a horizontal slice from the upper part of the model; F- The structural features at stage E. 1 is basement. 2 to 6 represent successively overlying layers in the multilayer packet.

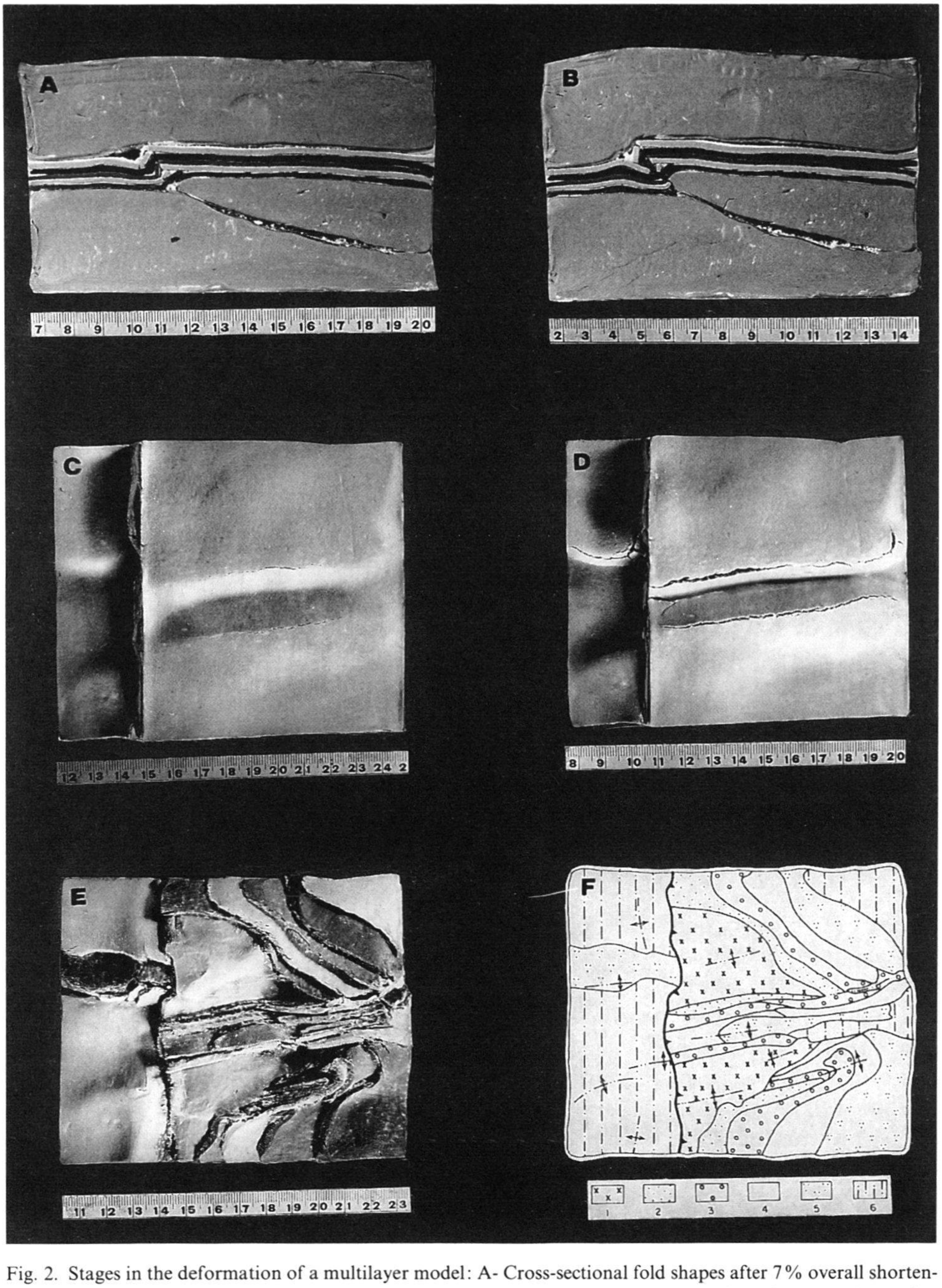

Fig. 2. Stages in the deformation of a multilayer model: A- Cross-sectional fold shapes after 7% overall shortening; B- Cross-sectional fold shapes after 13% overall shortening; C- The top layer surface after 13% shortening in the first phase and 4% shortening in the second phase of deformation; D- The top layer surface after 13% shortening in the first phase and 12% shortening in the second phase of deformation; E- Internal structure of the model at stage D, after removing a horizontal slice from the upper part of the model; F- The structural features at stage E. 1 is basement. 2 to 6 represent successively overlying layers in the multilayer packet.

observed along the layering. The amount of fault displacement increased with increase in shortening and this led to tilting of the layers in the dip direction of the fault.

The model was then compressed in the perpendicular direction. Superposed noncylindrical folds became pronounced after 4 per cent shortening (Fig. 2C). Fractures along the fold hinge lines formed and became prominent after 12 per cent shortening (Fig. 2D). Since the layering was confined from the sides, the compression also resulted in the formation of folds near the boundaries of the model (Dubey & Bhat 1986). Interference of these newly formed folds with the folds of the second generation produced orthogonal linking which was marked by curvature of the superposed fold hinge lines and the accompanying faults (Fig. 4).

A horizontal slice was then removed from the model (Fig. 2E). The structural features of the exposed internal part of the model are shown in Fig. 2F. The basement is exposed as two isolated domes separated by a superposed synform, along the initial basement fault. Since the multilayer sequence was tilted, successively overlying layers occur in the dip direction of the initial fault. Thus, the basement domes had a thrusted contact with the overlying layers on one side and a normal contact with the overlying layers on the other sides.

Experiment Three

This experiment was similar to Experiment Two as the multilayers were also cut by the initial basement listric fault. The only difference lies in the amount of deformation it underwent during the two phases. Successive stages in the deformation of the model are shown in Fig. 3A to 3E.

Displacement along the basement fault quickly led to initiation of a fold in the multilayers (Fig. 3A). Increase in the shortening led to pronounced asymmetry and the axial surface became nearly parallel to the thrust after 10 per cent overall shortening (Fig. 3B). On the layer surfaces these folds were nearly cylindrical. An upright fold developed at the foot wall side as a result of layer parallel shortening (Fig. 3C).

After 20 per cent total model shortening, the axis of maximum compression was changed in the orthogonal direction to produce superposed folding. After 4 per cent shortening of the second phase, noncylindrical superposed folds appeared on the layer surfaces (Fig. 3D). Since the amount of shortening was less, these folds do not refold the early fold. At this stage of deformation a horizontal slice was cut from the model surface. The internal structure of the model is shown in Fig. 3E and 3F. A noncylindrical antiformal fold is exposed in front of the basement thrust at the foot wall. Tilting of the hanging wall layers, as a result of the thrust displacement and subsequent removal of the top part has arranged successively overlying layers away from the thrust. The basement has a thrusted contact with overlying layers on one side and a normal contact on the other sides. Thus, the isolated basement exposure is not a klippe in the true sense.

A Summary of the Experimental Results

At the onset of deformation, displacement along the thrust fault led to the initiation of a fault propagation fold at the thrust tip. The fold axial surface dip in the dip direction of the thrust fault. The fold amplified and propagated along the layering. It was observed

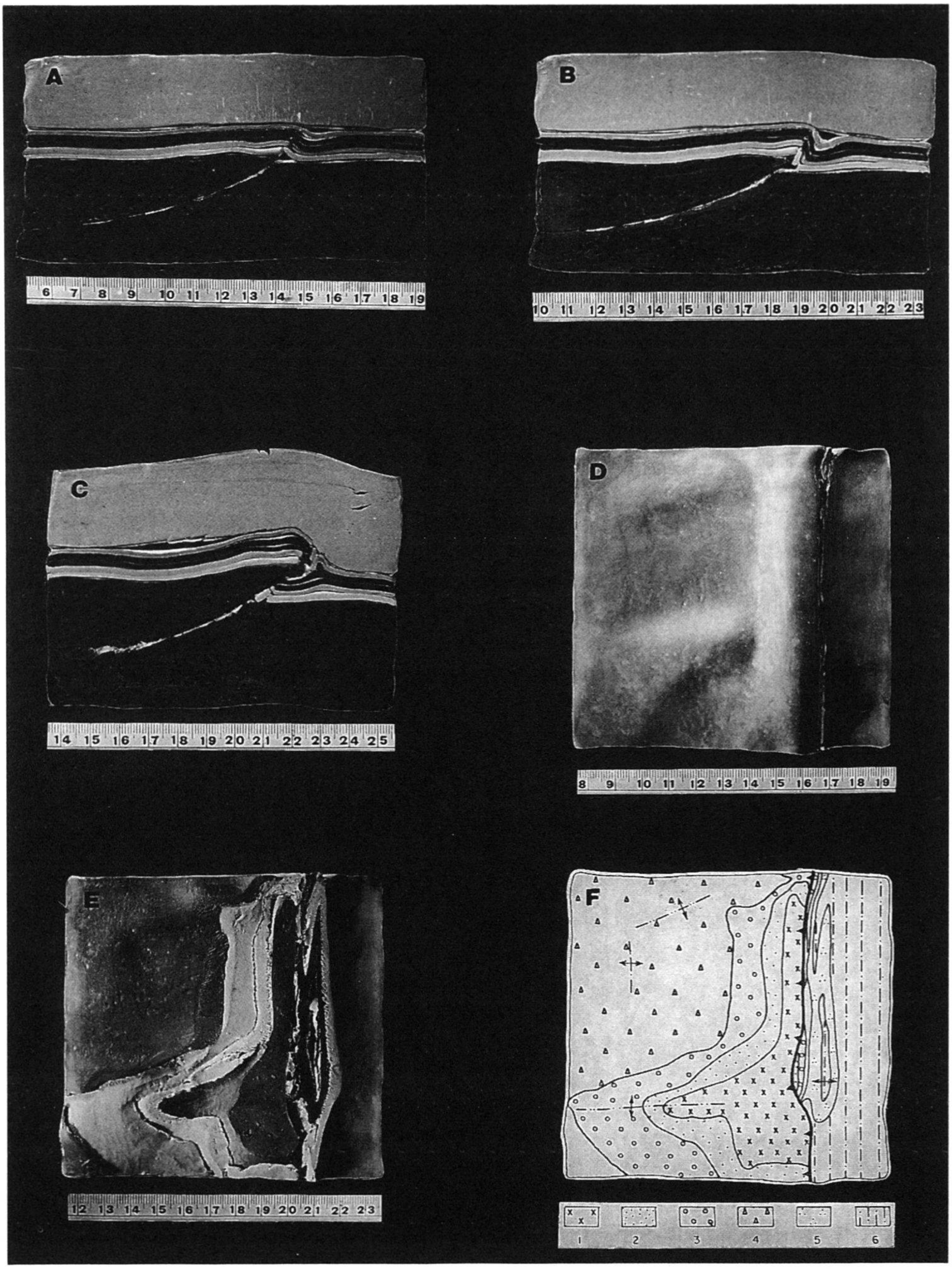

Fig. 3. Stages in the deformation of a multilayer model. A- Cross sectional fold shapes after 7% overall shortening; B- 10% shortening: C- 20% shortening; D- The top layer surface after 20% shortening in the first phase and 4% shortening in the second phase of deformation; E- Internal structure of the model at stage D, after removing a horizontal slice from the upper part of the model; F- The structural features at stage E. 1 is basement. 2 to 6 represent successively overlying layers in the multilayer packet.

that the transverse fold propagation was more prominent in the presence of a plane of décollement at the matrix-multilayer interface and in absence of a fracture in the multilayers. The plane of décollement also led to an early modification of a few folds to an isoclinal style (cf. Dubey 1980). Initially, the folds were noncylindrical but later they modified to cylindrical folds. The noncylindricity of folds was more pronounced during the second phase of deformation (i.e. superposed deformation). These superposed folds propagated by longitudinal fold propagation and interfered with the early folds. The resulting fold interference pattern depended on whether the early folds had a cylindrical or noncylindrical geometry. When the early folds were cylindrical the interference pat-

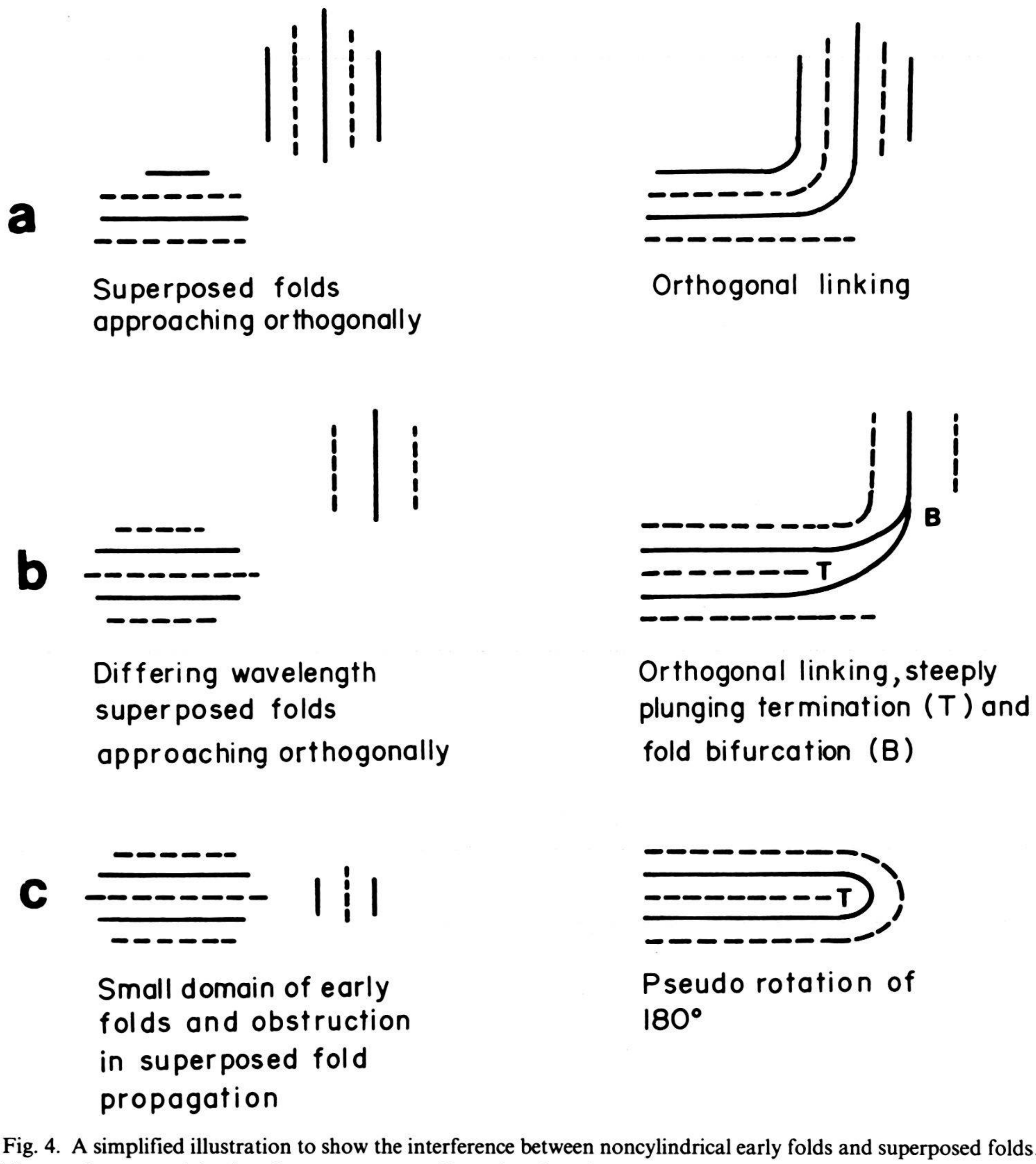

Fig. 4. A simplified illustration to show the interference between noncylindrical early folds and superposed folds. The continuous and broken lines represent antiformal and synformal hinge lines respectively. The vertical lines represent early folds and the horizontal lines represent superposed folds (Dubey 1984).

tern was mainly marked by; (i) termination of superposed folds at the early fold surface (i.e. superposed folds of the first type; Ghosh & Ramberg 1968), and (ii) curvature in the hinge of the early folds (i.e. superposed folds of the second type; Ghosh & Ramberg 1968). Interference between the noncylindrical early and superposed folds resulted mainly in dome and basin pattern or orthogonal linking (Fig. 4). It was also observed that different patterns resulted simultaneously across the model, e.g. dome and basin pattern in the basement, and curvature of fold hinge lines in the multilayer cover. The layers showed a dip in the dip direction of the thrust and successively overlying layers occurred away from the thrust. The inclination of the layers was modified during the superposed deformation which also produced domal structures in the basement. The subsequent removal of the top of the model (erosion!) revealed inliers where the overlying sequence partially or completely encircled the underlying basement.

Field example

A natural example from the NE Kumaun Himalayas with a similar sequence of development of structures is described in this section. The area forms a part of the Lower Himalayas and the Central Crystallines (Gansser 1964). A geological map of the Kumaun Lower Himalayas, compiled by Valdiya (1980) depicts a number of thrusts resting over the Lower Himalayan sedimentary sequence. The NE part of the region was remapped by Paul (1985) on 1:50000 scale during the years 1978 to 1981. For details of the structural features the reader is referred to the original work, however, a reduced version of the map showing the salient features and a cross-section are shown in Fig. 5 and Fig. 6 respectively. It is to be noted that the extension of the thrusts underneath in Fig. 6 is speculative due to lack of geophysical data. The lithotectonic set-up of the area is shown in Table 1. The finer details of the stratigraphic succession and correlation are controversial primarily because of absence of geochronological data from different litho-units. However, all the rock types are regarded as Precambrian in age (Valdiya 1980). Some of the significant structural features of the region are mentioned here.

There are two prominent thrust sheets, viz. Vaikrita thrust sheet and Munsiari thrust sheet of the Central Crystalline rocks that have translated in a southerly direction to overlie the younger sedimentary rocks of the Lower Himalayas. The geological mapping reveals that the Munsiari Formation is not a continuous unit immediately south of the Vaikrita Thrust but a thin lensoidal wedge of the sedimentary sequence divides it into two. Thus the contact (i.e. Munsiari Thrust) where the older Munsiari Formation overlies the younger sedimentary sequence occurs at Munsiari Thrust I and Munsiari Thrust II (Fig. 5). The two thrusts may have formed as a result of thrust splay. The width of the outcrop incorporating the Munsiari Formation increases in the SE part of the map exhibiting a prominent domal structure.

The early folds from the region that have formed simultaneously with thrusting can be classified into three, F 1 a, F 1 b and F 2. The F 1 a folds are tight to isoclinal, reclined with a plunge variation of 30–40° due ENE to NE. The F 1 b folds are open to tight, upright or overturned plunging 25–70° due WNW to NW. The formation of the F 1 b folds can be explained by a maximum compression along the NE-SW axis and this is compatible with the movement of the Indian plate. The ENE to NE orientation of F 1 a folds is probably the result of reorientation of the early fold hinge lines due to large shear

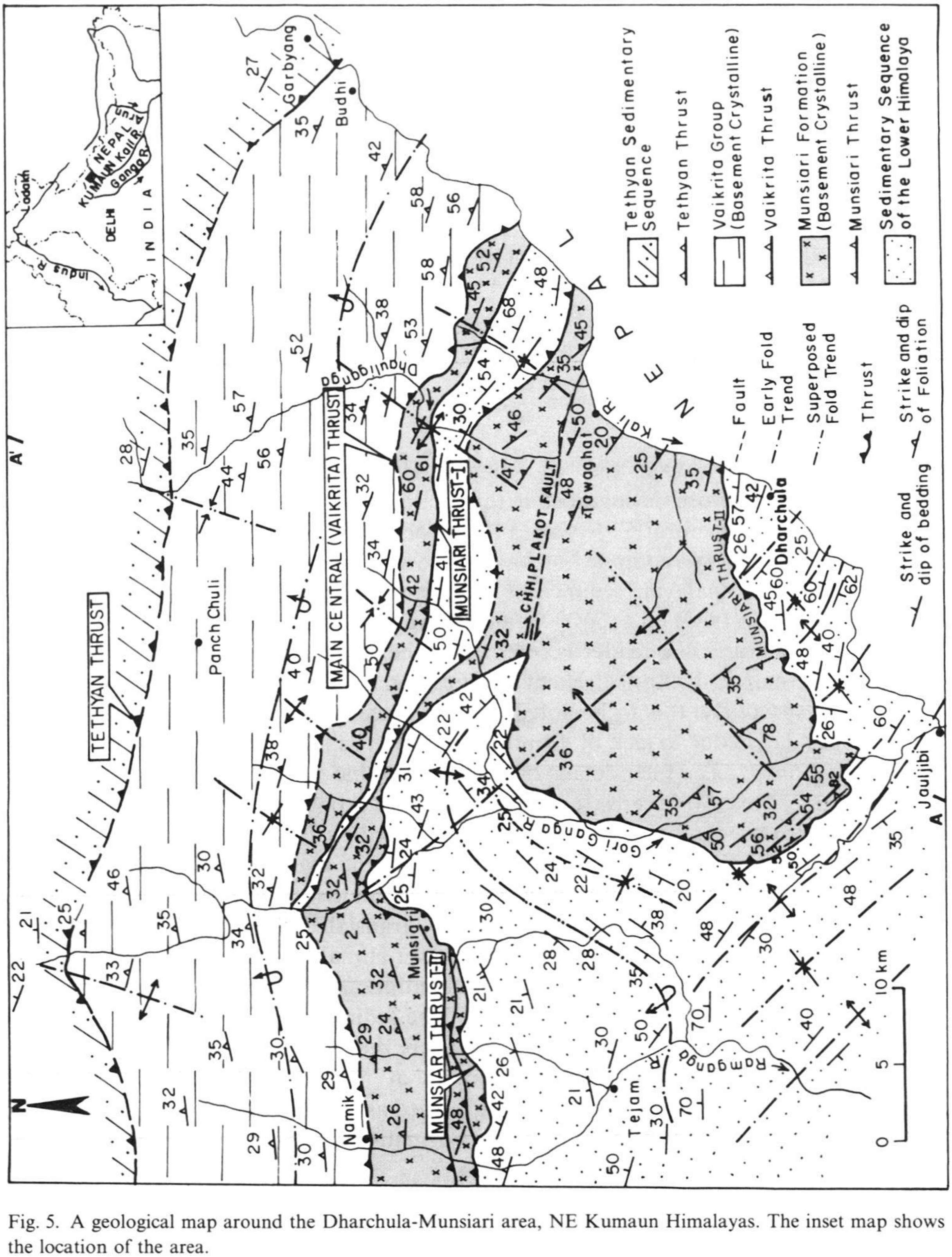

Fig. 5. A geological map around the Dharchula-Munsiari area, NE Kumaun Himalayas. The inset map shows the location of the area.

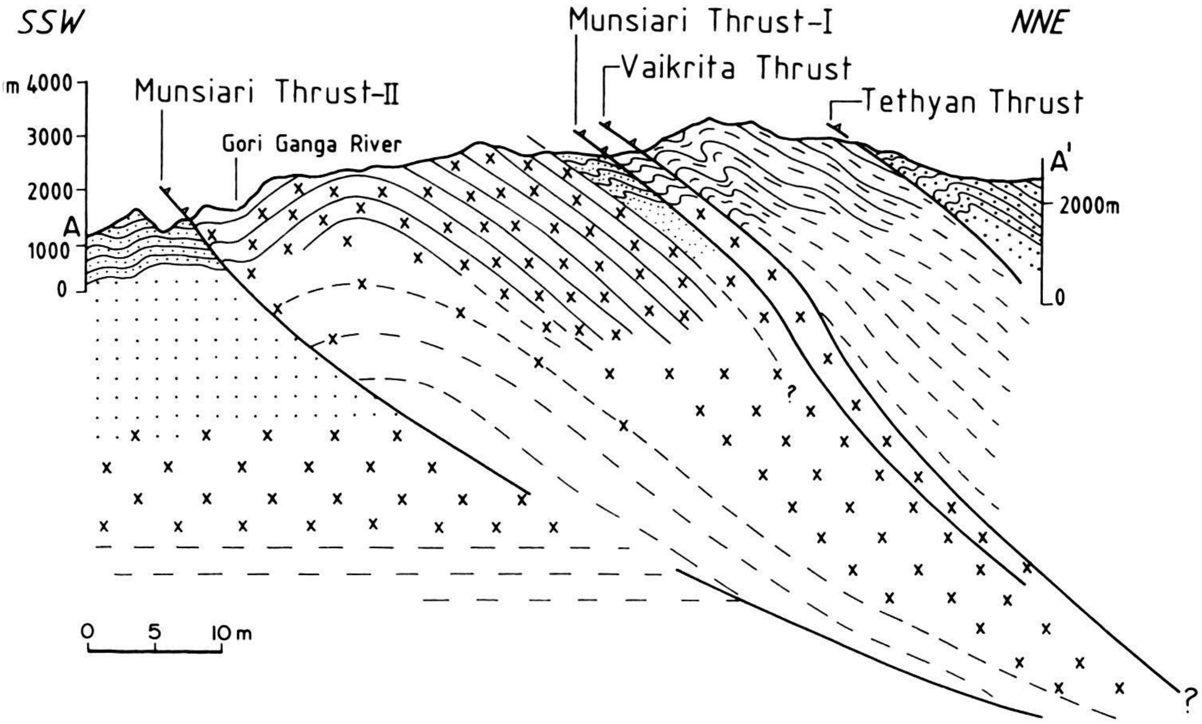

Fig. 6. A geological cross-section of a part of the NE Kumaun Himalayas along the line AA′ in Fig. 5. Symbols same as Fig. 5.

Table 1. Lithotectonic units in the NE Kumaun Himalayas (after Paul 1985).

Lithotectonic units	Lithology	Metamorphic grade
Lower Himalayan sedimentary sequence	Quartzite, phyllite, slate, limestone and dolomite	Green schist facies
	Munsiari Thrust	
Munsiari Formation	Granite, schist and gneiss with bands of amphibolite and ultramylonite	Green schist to epidote amphibolite facies
	Vaikrita Thrust	
Vaikrita Group	Schist and gneiss with interbedded quartzite, granite and aplite	Amphibolite facies

strain along the thrusts (cf. Carmignani et al. 1978; Cobbold & Quinquis 1980; Jain & Anand 1988). The F 2 folds are recognized by refolding of the F 1 a and F 1 b folds. These F 2 folds are open to tight plunging 30–50 degrees due NNE or NNW. The superposed F 3 folds have formed at a later stage and are represented on a small scale by kinks and on a large scale by broad open folds. The orientation and the amount of plunge vary considerably as it involves refolding of the non-planar surfaces. The general trend of the folds is due NNE. These folds have also been described as cross-folds since their orientation is at 90 degrees to the early folds.

The orientation of folds does not differ significantly in the sedimentary and metamorphic rocks except for the fact that the F 1 a folds are absent in the sedimentary rocks. If the formation of the F 1 a folds is attributed to a large amount of simple shear then it may be inferred that the amount of shear was probably of lower magnitude in the overlying sedimentary sequence.

The map pattern and the structural data reveal that there is a marked difference in the fold interference patterns in different rock units. The Vaikrita Group of rocks exhibit curvature of the early fold hinge lines as a result of superposed folding (cf. Ghosh & Ramberg 1968). The Munsiari formation, west of Tawaghat (SE part of Fig. 5) exhibits a domal structure as a result of crossing of two antiforms of different generation folds (Ramsay 1967, chapter 10) whereas the sedimentary rocks east to Tejam (SW and central part of Fig. 5) exhibit an antiform with a curved axial trace. The pattern in the sedimentary rocks may be interpreted in terms of coalescing of the early and the superposed fold hinge lines, i.e. orthogonal linking (Fig. 4). Hence, a part of the fold exhibits an early fold whereas the other part exhibits a superposed fold. The other peculiar feature of the fold is that the culmination is characterized by an overturned fold and away from the culmination the fold has an upright geometry (Dubey 1977).

Conjugate set of strike slip faults affect all the rock types as well as the thrusts showing that they are the younger structures. Chiplakat fault (N and NW of Tawaghat) is one of the most important strike slip fault as it is responsible for a large number of catastrophic earthquakes in the region (Kumar et al. 1981; Paul 1986). It is to be noted that the recent seismic activity in the Himalayas is confined along the strike slip faults (Khattri & Tyagi 1983) thereby suggesting that the thrust faults have already been locked (Dubey & Bhat 1986).

The field data cited above indicate that the early and the superposed fold hinge lines have an orthogonal relationship. The later superposed folds interfere with the early folds and the interference patterns are marked by linking of the folds of different generations, curvature of the early fold hinge lines and domal structure. The outcrop of the Munsiari Formation (north of Munsiari Thrust II, west of Tawaghat) is one of the examples of the domal structure which has formed by stacking of the thrust sheets and superimposed folding as described in the experiments. The structure is neither a klippe as it is not an isolated block of rocks detached from its roots nor an inlier as the older rocks are not completely surrounded by the younger rocks. The domal structure may be described as a partial inlier. In the experiments these structures were not always surrounded by a thrust fault but they also had a normal contact with the overlaying sequence, in the dip direction of the thrust. This observation tempts to propose that the original contact of the sedimentary rocks with the underlying Munsiari Formation (between Munsiari Thrust I and Munsiari Thrust II) (Fig. 6) was transitional and subsequently modified by the thrust.

Conclusions

The different orientation of folds may form in a single deformation as a result of; (i) geometrical accommodation to the changes in thickness between the two thrust sheests and differential movement of the thrust nappe (Elliott & Johnson 1980), (ii) oblique and lateral thrust ramps (Coward 1982), (iii) interference of tip strains of two separate thrusts (Coward & Potts 1983) and (iv) folds in the lower thrust sheet affecting the higher thrust sheet containing the older structural elements (Coward 1984). All these mechanisms have characteristic map patterns. Superimposed folding involving a change in the nature and orientation of strain increments during the deformation may also result in different orientation of folds. These superimposed folds also have characteristic fold interference patterns (Ramsay 1967, chapter 10; Thiessen & Means 1980). The present experiments deal with simultaneous thrusting and folding followed by superposed fold formation. The experimental results reveal a variety of map patterns including inliers and partial inliers where the older rocks are completely or partially encircled by the younger rocks and part of the contact may be a thrust. One example is described from the Himalayas and it is expected that similar structures may exist in other orogenic belts as well.

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