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Significance of forelimb folds in the Shumar allochthon, Lesser Himalaya, eastern Bhutan

SUMIT KUMAR RAY

Geological Survey of India, C. & P. Division, 27, J. L. Nehru Road, Calcutta 700016, India

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Abstract—The Shumar allochthon is the most widespread of all the thrust sheets constituting the Lesser Himalaya of eastern Bhutan. The pre- to syn-thrusting folds of the allochthon have been affected by an unusual type of superposed folding (called here forelimb folding). In this type of superposed folding the alternate limbs of pre-existing folds are buckled and thickened, while the other set of limbs is stretched and thinned. The hinges of these pre- to syn-thrusting folds are also bent, producing plane non-cylindrical folds. Analysis of these fold structures within the allochthon indicate simple shear strain, generated in the course of forward movement of the thrust sheet. Within the shear zones some of the larger folds were oriented such that one set of limbs (the forelimbs) were inclined towards the shear direction and the other set (the backlimbs) were inclined in the opposite direction. In the course of progressive shearing, the forelimbs were shortened and buckled producing the forelimb folds and the backlimbs were stretched and thinned. The forelimb folds also indicate the shear sense. In the course of progressive shearing, the forelimb folds have been boudinaged and rotated, producing rootless folds with axes parallel to the thrust direction.

INTRODUCTION

SEVERAL mesoscopic scale folds with an unusual geometrical pattern occur within the Shumar allochthon in the Lesser Himalaya of eastern Bhutan (Fig. 1). One set of limbs of these folds is planar and straight, whereas the other set is closely folded (Fig. 2). Moreover, the layers in the straight planar limbs are thinner compared to the layers in the other set of limbs. The origin of this unusual refolding pattern (called here 'forelimb folding'—defined later) has been discussed in this paper. The present study also analyses the other fold structures within the Shumar allochthon, which is a composite thrust sheet traversed by several interconnected subsidiary thrusts (Janpangi 1974, Ray *et al.* 1989), and which bears imprints of multiple deformation.

THEORETICAL CONSIDERATIONS

Simple shear model

Oblique planar markers within a simple shear zone are either compressed or stretched depending on whether the plane is inclined towards or opposite to the shear direction, respectively (Fig. 3). The limbs of pre-

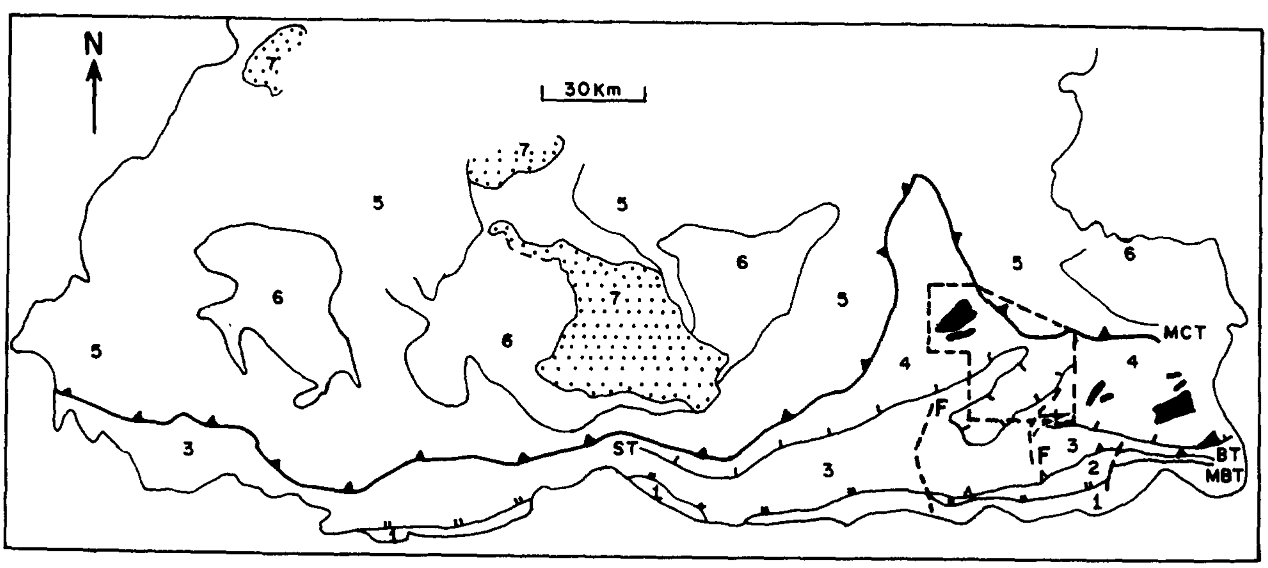

Fig. 1. Sketch geological map of the Bhutan Himalaya. MBT—Main Boundary Thrust, BT—Buxa Thrust, ST—Shumar Thrust, MCT—Main Crystalline Thrust (= Thimpu Thrust). 1, Siwalik Group (Tertiary). 2, Gondwanas. 3 and 4, Precambrian–Palaeozoic rocks of the Lesser Himalaya (3, Daling and Buxa Groups, Thungsing and Duiri Formations; 4, Shumar Group). 5, Thimpu Gneissic Complex (Precambrian). 6, large enclaves of metasedimentary rocks within the Thimpu Gneissic Complex (Paro and Chekha Groups). 7, fossiliferous Palaeozoic–Mesozoic rocks. The area studied is outlined by the dashed line.

existing folds within a shear zone may thus be either shortened (and buckled) or stretched (and thinned/ boudinaged) depending on their orientation with respect to the shear direction. Open to tight (but not isoclinal) folds with axes trending at high angles to the XZ plane of finite strain may thus have one limb (called here the forelimb, Fig. 4) inclined towards the shear direction, and the other (called here the backlimb) inclined in the opposite direction. In the course of progressive simple shear deformation, the forelimbs will be shortened and buckled, and the backlimbs will be stretched and remain straight, producing the fold pattern observed within the Shumar allochthon (and described in the preceding section). This superposed folding phenomenon, resulting in buckling of alternate limbs of pre-existing folds, has been designated here as *forelimb folding* and the folds developed on the forelimbs have been designated as *forelimb folds*. The terms forelimb and backlimb may thus be defined as: if two limbs of a fold undergoing simple shear deformation are oriented such that the traces of these two sets of limbs on the XZ plane are inclined in opposite directions with respect to the shear direction, the limb represented by the line dipping towards the shear direction is the forelimb and the other limb is the backlimb.

Obviously, forelimb folding is not possible if the early folds are isoclinal, because in that case, both the limbs will have similar responses to the bulk deformation and will either be stretched or compressed depending on their orientation with respect to the shear plane. Moreover, superposed forelimb folds will be developed only if the pre-existing fold hinges make moderate to high angle with the XZ plane of the superposed strain. A prominent axial planar foliation will impede development of forelimb folds.

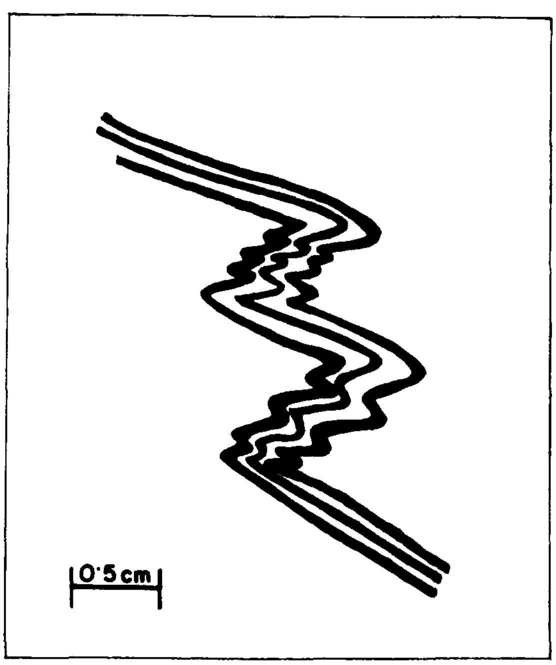

Fig. 2. Diagram showing the features of forelimb folds within the Shumar allochthon. One set of limbs of the larger order folds is thickened and buckle folded, and the other set of limbs is thinned and planar.

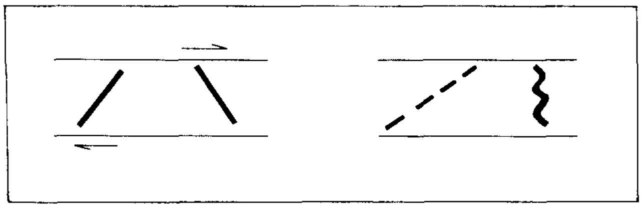

Fig. 3. Diagram showing that planar markers within a simple shear zone may be stretched and boudinaged, or shortened and buckled, depending on the orientation in the simple shear field. The plane of drawing is the XZ plane of strain.

The forelimb folds may be superposed on pre-existing larger folds, or both may be formed in the course of single continuous deformation. Accordingly two separate sub-models may be considered. In the first sub-model, where the shearing movement is superposed on pre-existing folds, the forelimb folds may or may not be developed depending on whether the geometric conditions mentioned in the preceding paragraph are satisfied or not. Moreover, whether the axes of the forelimb folds will be parallel or oblique to the axes of the pre-existing folds depend on whether the latter are initially parallel or oblique to the shear plane. Initial parallelism of the fold axes and the shear plane is not likely as these two are unrelated, and hence in this sub-model, the axes of the superposed forelimb folds will generally be oblique to the axes of the pre-existing folds. In the course of progressive shear movement, however, the axes of the pre-existing folds and the forelimb folds will rotate towards the plane of shear. In the second sub-model, where the forelimb folds and the larger folds are product of a single continuous movement, axes of both the sets of folds will be parallel. They will also be parallel to the shear plane and will remain so in the course of progressive deformation. Development of the forelimb folds only on one set of limbs of the larger folds indicates that the forelimb folds are formed later. Hence, in this sub-model, it is likely that the larger folds are formed at an early stage of the shear movement that at a later stage produces the forelimb folds.

Pure shear model

Refolding of alternate limbs of pre-existing folds may also occur in the domains of pure shear. In these domains one set of limbs may be parallel to the principal

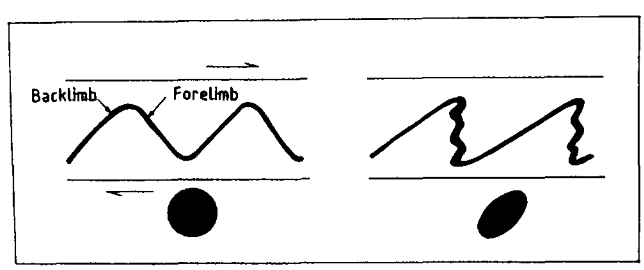

Fig. 4. Diagram showing refolding and shortening of only the alternate limbs of pre-existing folds within a simple shear zone. The limbs undergoing refolding are the forelimbs. The other limbs are backlimbs (for definition see text). These two limbs are orientated in the shortening and stretching sectors, respectively.

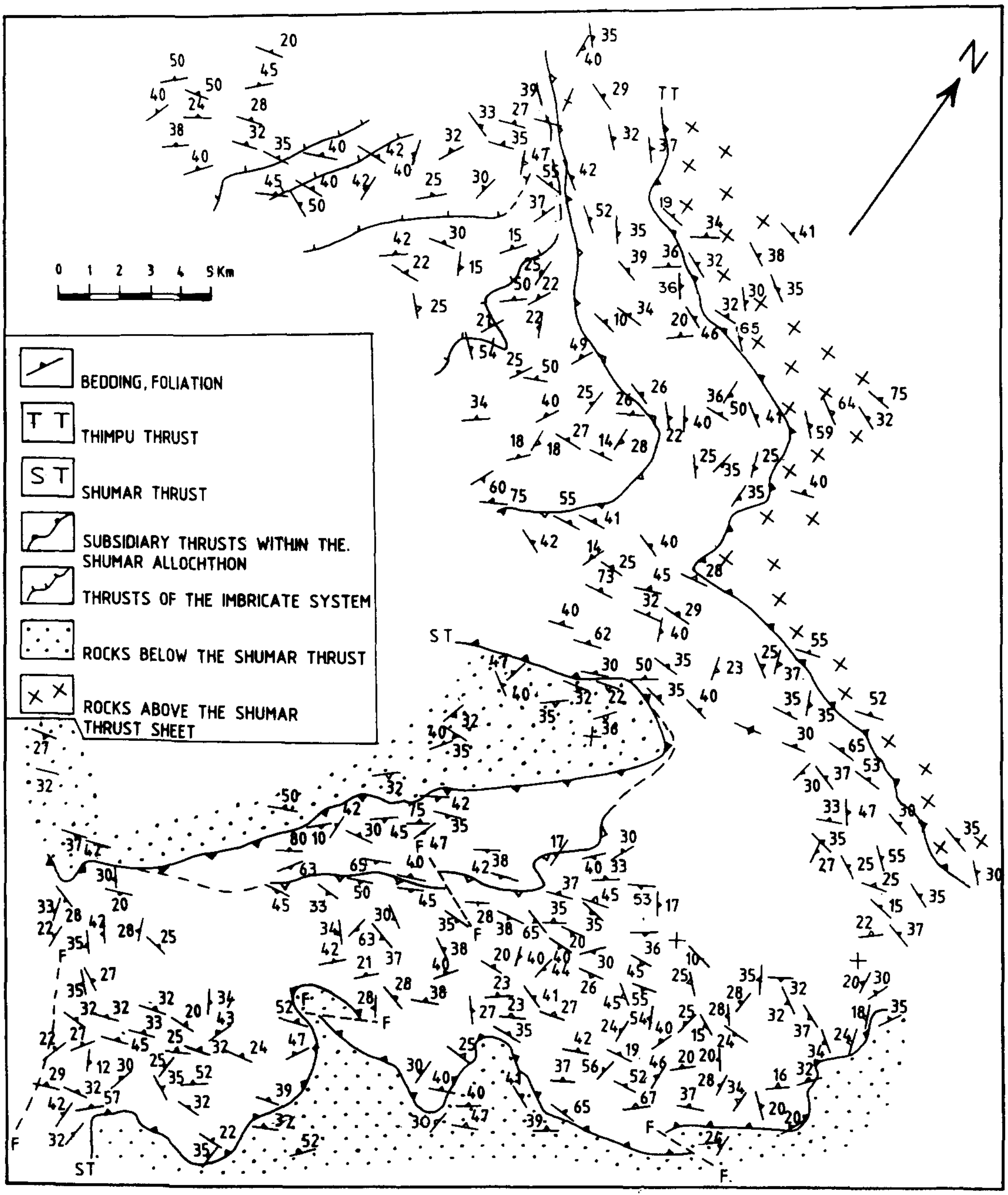

Fig. 5. Planar structures and subsidiary thrusts within the Shumar allochthon, Lesser Himalaya, eastern Bhutan.

extension and the other parallel to the principal contraction direction of the superposed non-rotational strain ellipse on the profile plane of the pre-existing folds. In this pattern of deformation also, one set of limbs will be stretched and the other will be buckled.

Thus it is seen that forelimb folds do not indicate a particular type of strain and may be developed in domains of rotational as well as non-rotational strain. In all the models discussed above, the forelimb folds are produced by layer-parallel shortening and hence have the characteristics of buckle folds.

FOLDS WITHIN THE SHUMAR ALLOCHTHON

The examples of forelimb folding presented here were observed in the Shumar thrust sheet of the Lesser Himalayan zone in eastern Bhutan (Fig. 1). As in other parts of the Himalayas, the Lesser Himalaya of eastern Bhutan is made up of a pile of thin thrust sheets stacked on one another and the Shumar thrust sheet lies at the top of this pile. Interpretation of detailed maps (Figs. 5 and 6) (also see Janpangi 1974, Ray *et al.* 1989) indicate that the Shumar thrust sheet has moved SSE by body translation along a thrust plane. In the course of forward propagation, the thrust sheet has accreted material from the underlaying thrust sheet and the Precambrian gneissic foreland (Ray *et al.* 1989) by means of a stack of imbricate thrusts, which define a hinterland-dipping duplex and an antiformal arch at two places.

The earliest folds (F_1 folds) within the Shumar allochthon are tight to isoclinal with large amplitude to wavelength ratio. A set of lineations, dominantly puckers, is parallel to the axes of the F_1 folds. A large number of mesoscopic scale F_1 folds are plane non-cylindrical type with gently to moderately curved fold hinges (transitional to sheath folds, Fig. 7a) and the hinges of these folds can be traced only for short distances. Regional variation in orientation of the axial surfaces of these F_1 folds from a large part of the Shumar allochthon is shown in Fig. 6. The axes and the poles of axial surfaces of these folds have been plotted (equal-area stereographic projection) in Fig. 8. The axes show a wide scatter, almost along a girdle. But the poles of the axial surfaces show comparatively less scatter, and a large number of poles are concentrated within a small area in Fig. 8 (the point maximum). This point maximum coincides with the axis of the girdle containing the fold axes. This relationship of the fold axes and the axial surfaces (i.e. the diversely oriented axes lying in a plane parallel to the dominant orientation of the axial surfaces) indicates mesoscopic and macroscopic scale sheath folding within the Shumar allochthon. A small scatter in the orientation of the poles of the F_1 axial surfaces is an effect of the later folds which are generally open folds with small amplitude. The later, open, low amplitude folds have two dominant trends (E–W and N–S) with low plunge in either direction.

Mesoscopic scale forelimb folds

In addition to the sheath folds described above, the F_1 folds also bear imprints of superposed forelimb folding. These forelimb folds are not so common and a few examples are given below.

Forelimb folds are best studied in profile planes. Photographs of the profile planes of three different samples of forelimb folds within the Shumar allochthon are presented in Figs. 7(b)–(d). In Fig. 7(b), the thin layers (bedding) of the rock specimen, collected from the frontal part of the Shumar allochthon, are folded into different orders of folds; the largest order folds are F_1 folds with sharp hinges and the axial surfaces dip gently towards the right-hand side of the photograph. The layers in one set of limbs of the F_1 folds, *viz.* the limb dipping moderately (40–60°) towards the right-hand side

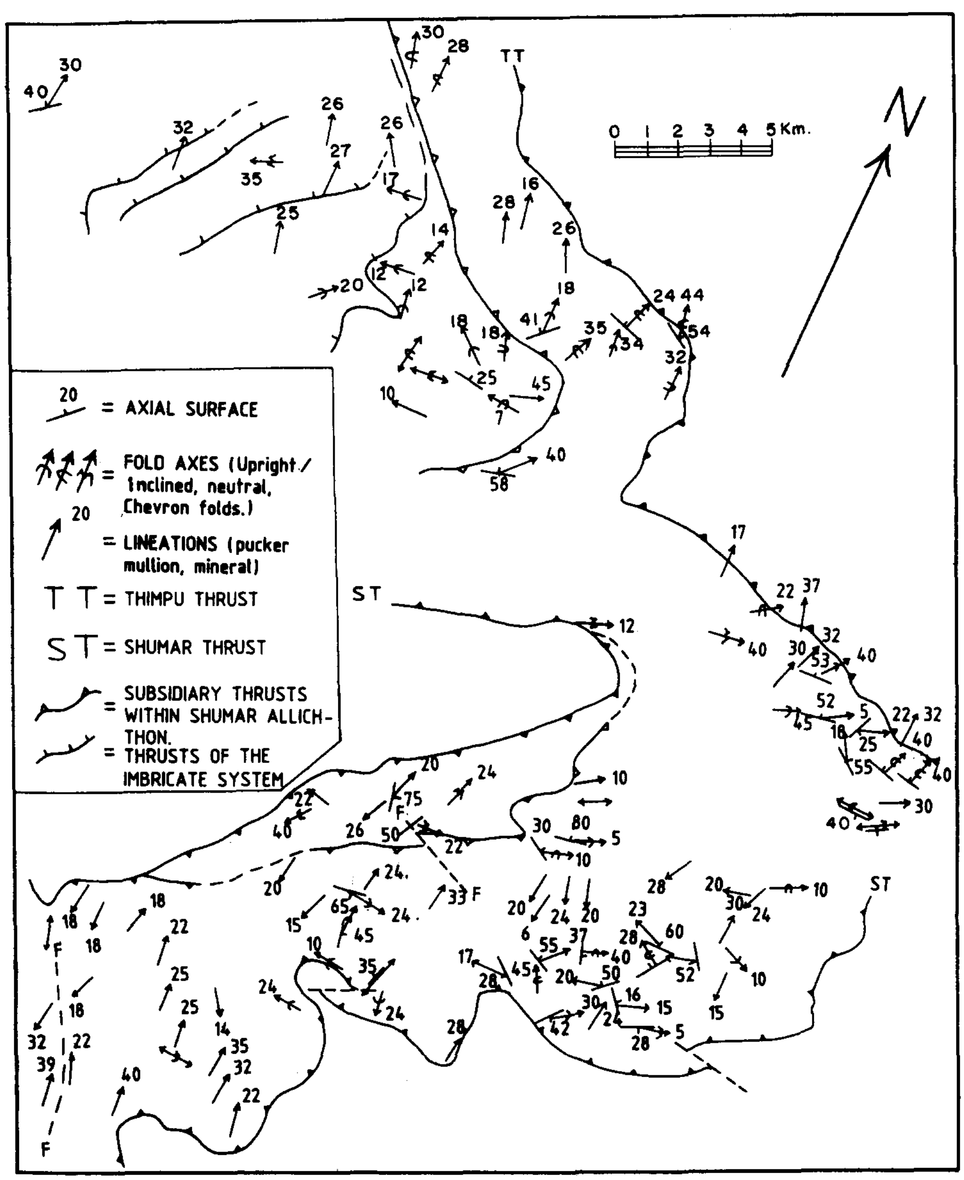

Fig. 6. Linear structures and folds within the Shumar allochthon.

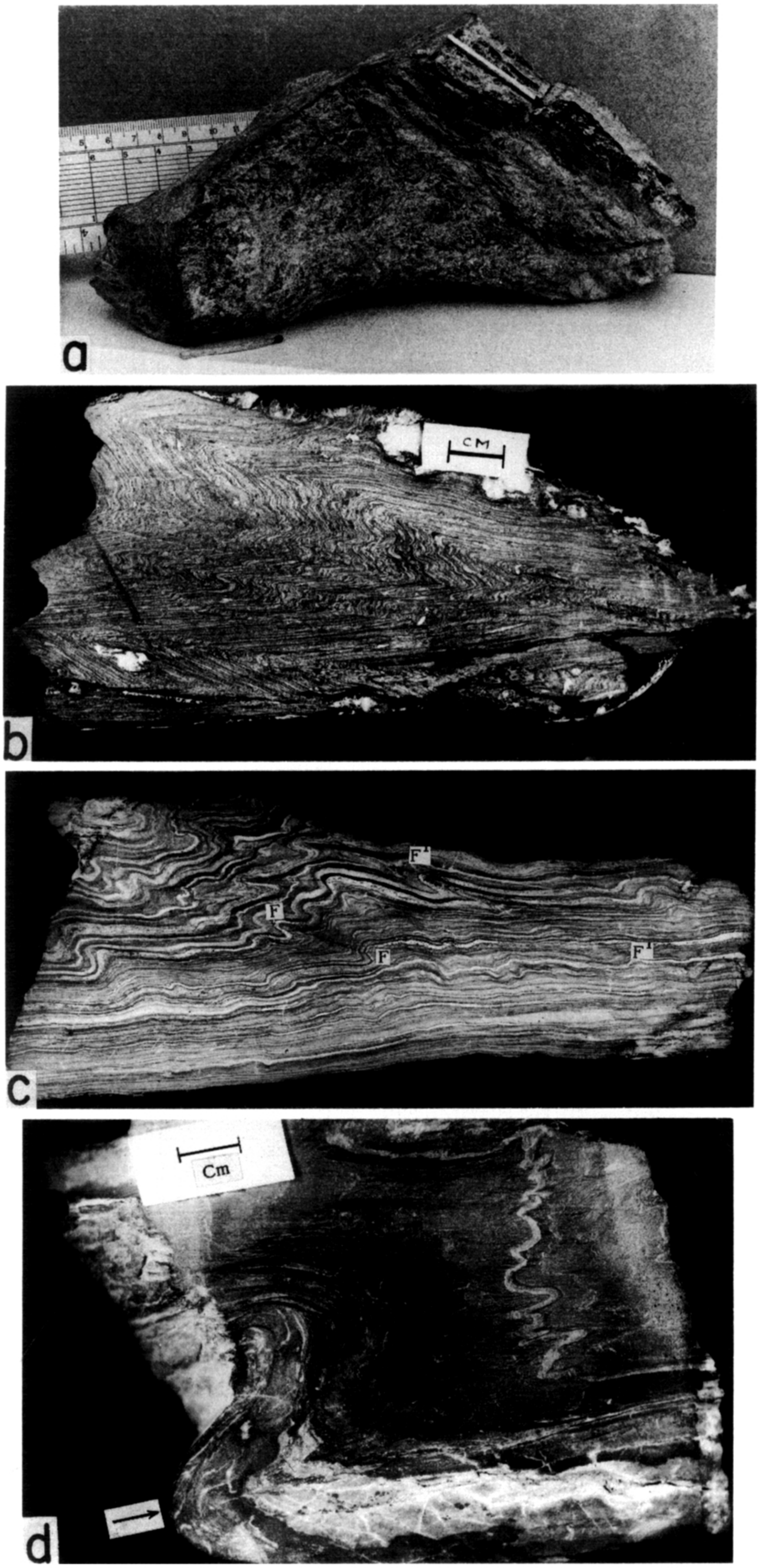

Fig. 7. (a) Plane non-cylindrical F_1 folds within the Shumar allochthon. The matchsticks are parallel to the fold hinge. (b)–(d) Photographs of profile planes of the pre-existing folds affected by forelimb folding. The forelimb folds are developed only on one set of limbs of the larger order pre-existing folds (for description see text).

of the photograph, are thickened and affected by forelimb folding. The layers in the other set of limbs (broadly parallel to the lower and upper boundaries of the photograph) are comparatively thinner and straight, and represent the backlimb. The hinges of the forelimb folds are oblique (at 35° angle) to the F_1 fold axes and they do not ride over the F_1 fold hinges, suggesting that the F_1 folds are earlier and pre-existed the shearing movement producing the forelimb folds. Disharmonic, asymmetric and polyclinal folds indicate that the forelimb folds are buckle folds.

In Fig. 7(c), the layers in the left-hand side of the photograph, representing one limb of an open, low-amplitude antiform, is affected by forelimb folding. The forelimb folds are polyclinal, disharmonic and the folded layers are thicker compared to the layers in the other limb (the backlimb) in the right-hand side of the photograph. The amplitude of the open antiform gradually decreases in the lower part of the specimen (Fig. 7c) and no trace of folding is present in the bottommost part. This feature suggests slip along a basal décollement surface parallel to the layering (bedding). Only the layers above the décollement surface have been folded. Parallelism of the axes of the forelimb folds and the larger open antiformal fold indicates that both the sets of folds are product of the same deformation episode. Hence the larger fold in this example is not F_1 fold, and probably represents a syn-thrusting fold. This is further supported by the fact that the open, low-amplitude style of this larger fold is different from the tight to isoclinal, high amplitude style of the F_1 folds. Two thrust faults (rather ductile shear zones FF and F′F′ in Fig. 7c) provide evidences in support of simple shear origin of these forelimb folds. The shear zones make a 30° angle with the décollement surface and are almost orthogonal to the limb affected by forelimb folding. These shear zones cannot be explained by the pure shear model of forelimb folding and suggest that either: (1) the forelimb folds and the shear zones were produced in a single episode of simple shear deformation, or (2) they are unrelated. The former possibility is further supported by the fact that the movement direction along the shear zones is consistent with the shear sense (counterclockwise in the plane of the photograph) indicated by the forelimb folds.

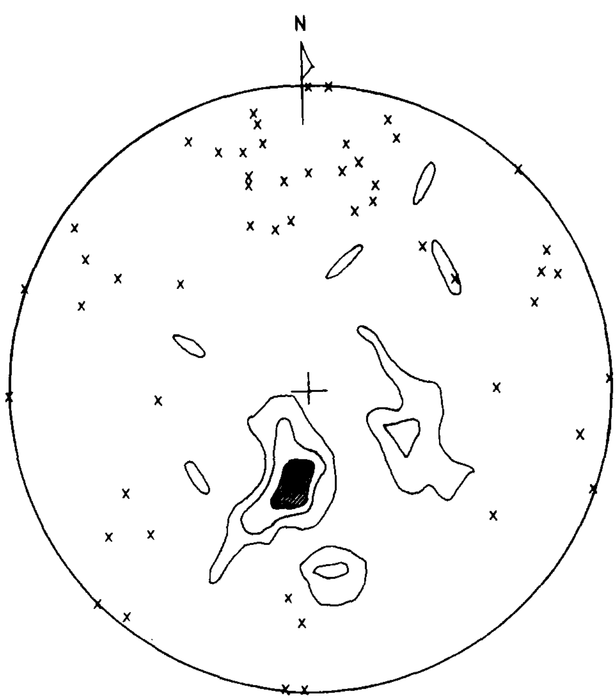

Fig. 8. Orientation pattern of the axes and axial surfaces of the F_1 folds within the Shumar allochthon. ×: fold axes. Contours: poles of axial surfaces 4.5, 9 and 13.5% per 1% area.

In Fig. 7(d), the layers are of varying thickness and competence. The backlimbs are parallel to the upper and lower boundaries of the photograph. The forelimb folds are prominently developed in a thin light-coloured band in the right-hand side of the photograph. A half-wavelength forelimb fold has also affected the thick and competent quartzite band (shown by arrow). The axes of the forelimb folds in this specimen make a 40° angle with the axes of the larger (F_1) folds.

TECTONIC SIGNIFICANCE OF THE FORELIMB FOLDS

In the last few years many examples of sheath folds in shear zones have been published. But sheath folds do not automatically indicate proximity to shear zones (Ramsay & Huber 1987, p. 619). In the present context, the association of forelimb folds with the sheath folds is significant. The hinges of the F_1 folds within the Shumar allochthon are bent producing sheath folds, and the limbs of the F_1 folds have been affected by forelimb folding. These two types of superposed deformations imprinted on the F_1 folds cannot be explained by a single phase of compression (non-rotational strain). Compression at high angles to the F_1 axial surfaces, or parallel to the F_1 fold axes, may produce sheath folds, but cannot generate the forelimb folds. On the other hand, a single phase of superposed shear movement (shear direction at moderate to high angles to the F_1 fold axes as is indicated by the wide spread of F_1 fold axes in Fig. 8) may generate the forelimb folds on the F_1 fold limbs, and simultaneously bend the F_1 fold hinges producing the sheath folds. Close spatial association of the forelimb folds and the sheath folds within the Shumar allochthon thus indicates simple shear strain generated within the thrust sheet.

Morphological features (described earlier) of the forelimb folds within the Shumar allochthon indicate that they are buckle folds. It emerges from the following discussion that this buckling is genetically related to simple shear deformation within the Shumar allochthon. The mechanism of formation of these forelimb folds is comparable to that of the buckle folds generated in simple shear experiments by Ghosh (1966). It has been pointed out by Ramsay & Huber (1987, pp. 377 and 525) that during thrusting, upper parts of the allochthon may be displaced more than the lower part, so that the thrust sheet undergoes shear deformation. This shearing will lead to shortening and buckle folding of the layers disposed obliquely to the stratigraphically upward cutting thrust surface (Ramsay & Huber 1987, fig. 23.33). The forelimb folds are also generated in the same way by the shear strain within an advancing thrust sheet. The present study however, recognizes the differences in the response of the two limbs of the pre- or syn-thrusting folds to the bulk shear strain. It has been shown that due to variation in their orientation, only one set of limbs may be folded and shortened, while the other set of the limbs may be stretched.

Deformation of folds in domains of bulk simple shear has been studied by many workers in theoretical models and experiments. Such studies revealed that in progressive simple shear: (1) these folds become strongly asymmetric and isoclinal; (2) the axial surfaces rotate towards the shear plane; and (3) the hinges, initially oblique to the shear direction, become curved producing sheath folds (Quinquis *et al.* 1978, Cobbold & Quinquis 1980) in extreme cases. The present study reveals that superposed forelimb folds may also occur in shear zones. Analysis of the sheath folds and the forelimb folds observed within the Shumar thrust sheet in the Lesser Himalayan zone of eastern Bhutan has helped to establish simple shear deformation within the thrust sheet. Sense of rotational strain has also been determined with the help of forelimb folds.

The problem of rootless folds

The forelimbs in the course of shearing will undergo rotation and eventually become perpendicular to the shear plane (Fig. 9). This is a critical stage, because if the deformation continues beyond this stage, the forelimb will no longer be shortened. It will then be oriented in the stretching sector of the instantaneous strain ellipsoid and the earlier formed forelimb folds will be boudinaged and disrupted. These disrupted folds will occur as rootless folds in the thrust sheet (Fig. 9). Moreover, the hinges of these mesoscopic scale rootless folds, in the course of progressive shearing, will be rotated towards the shear direction (Sanderson 1973, Escher & Watterson 1974, Rhodes & Gayer 1977, Williams 1977). Such rootless folds with their axes parallel to the thrust direction are common within the Shumar thrust sheet.

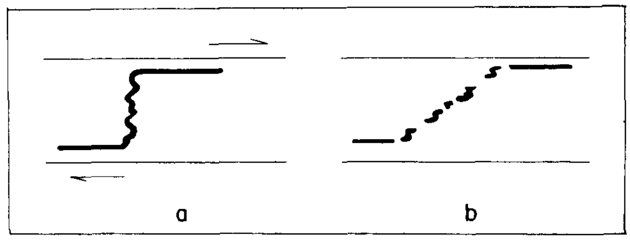

Fig. 9. Forelimb folding continues till the forelimbs attain a critical orientation (a) when the forelimb is perpendicular to the shear plane. If the deformation continues beyond the critical stage, the forelimb folds are disrupted and boudinaged (b) and occur as rootless folds within the shear zone.

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