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Planar, non-planar and refolded sheath folds in the Phulad Shear Zone, Rajasthan, India

S.K. Ghosh*, S. Hazra, S. Sengupta

Department of Geological Sciences, Jadavpur University, Calcutta 700032, India

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Abstract

Progressive ductile shearing in the Phulad Shear Zone of Rajasthan, India has produced a complex history of folding, with development of planar, non-planar and refolded sheath folds. There are three generations of reclined folds, F_1, F_2 and F_3, with a striping lineation (L_1) parallel to the hinge lines of F_1. The planar sheath folds of F_1 have long subparallel hinge lines at the flanks joining up in hairpin curves at relatively small apices. L_1 swerves harmoniously with the curving of F_1 hinge line. There is a strong down-dip mineral lineation parallel to the striping lineation in most places, but intersecting it at apices of first generation sheath folds. Both the striping and the mineral lineation are deformed in U-patterns over the hinges of reclined F_2 and F_3. Folding of axial surfaces and hinge lines of earlier reclined folds by later folds was accompanied by very large stretching and led to the development of non-planar sheaths. The reclined folds of all the three generations were deformed by a group of subhorizontal folds. Each generation of fold initially grew with the hinge line at a very low angle with the Y-axis of bulk non-coaxial strain and was subsequently rotated towards the down-dip direction of maximum stretching. The patterns of deformed lineations indicate that the stretching along the X-direction was extremely large, much in excess of 6000 percent.

1. Introduction

Sheath folds (e.g. Carreras et al., 1977; Quinquis et al., 1978; Cobbold and Quinquis, 1980; Ramsay, 1980) are strongly non-cylindrical, essentially planar folds (i.e. folds with planar axial surfaces) that develop by extreme accentuation of initially weak hinge line curvatures. In well-grown sheath folds the hinge angle (Williams and Chapman, 1979; Ghosh, 1993, pp. 331–332) is less than 90° (Ramsay and Huber, 1987, p. 638). For sheath folds in ductile shear zones, the growth of the folds and the curving of their hinge lines occur in the course of a single phase of non-coaxial deformation. In major ductile shear zones the early folds are often deformed by late folds (Bell, 1978; Ghosh and Sengupta, 1984, 1987a, b, 1990; Sengupta and Ghosh, 1997). The history of progressive deformation may include development of successive generations of sheath folds, refolding of earlier sheath folds and the development of a hitherto unreported category of structures, non-planar sheath folds.

Non-planar sheath folds in ductile shear zones may develop during superposed folding of early non-sheath folds. When the axial surface of an early fold is unrolled about the axis of a later fold, the earlier fold may appear to have originated as a planar sheath fold. Unlike the folded sheath folds, however, the non-planar sheath folds do not develop by refolding of planar sheath folds, but by refolding of plane cylindrical or subcylindrical segments of early folds. The folding of the axial plane of the early fold and the strong arcuation of its hinge line occur during the growth of the later fold. In the following sections, a planar sheath fold will be considered as a strongly non-cylindrical planar fold, a folded sheath fold will refer to a structure obtained by folding of the axial surface and hinge line of a planar sheath fold, and a non-planar sheath fold will represent a structure whose sheath-like form

* Corresponding author.
E-mail address: subir@jugeo.clib0.ernet.in (S.K. Ghosh)

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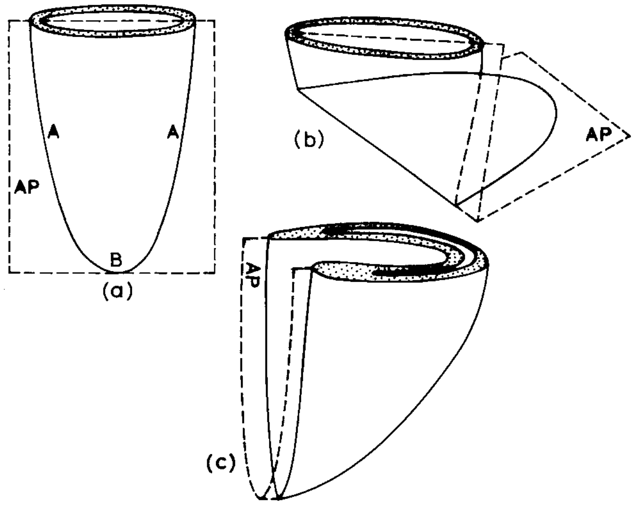

Fig. 1. (a) Planar sheath fold with long arms (A) and a small apex region (B); (b) folded sheath; and (c) non-planar sheath. AP—axial surface.

was produced during refolding of a plane cylindrical or subcylindrical segment of an early fold (Fig. 1).

The history of successive stages of growth of sheath folds and the modification of their forms in later stages of progressive deformation can be traced in terrains where the three-dimensional forms of the folds and their interference patterns are well exposed on a mesoscopic scale. The Phulad Shear Zone in Rajasthan, western India (Fig. 2), is one such terrain where exposed fold hinges, including those of sheath folds, are plentiful, and deformed lineations are ubiquitous.

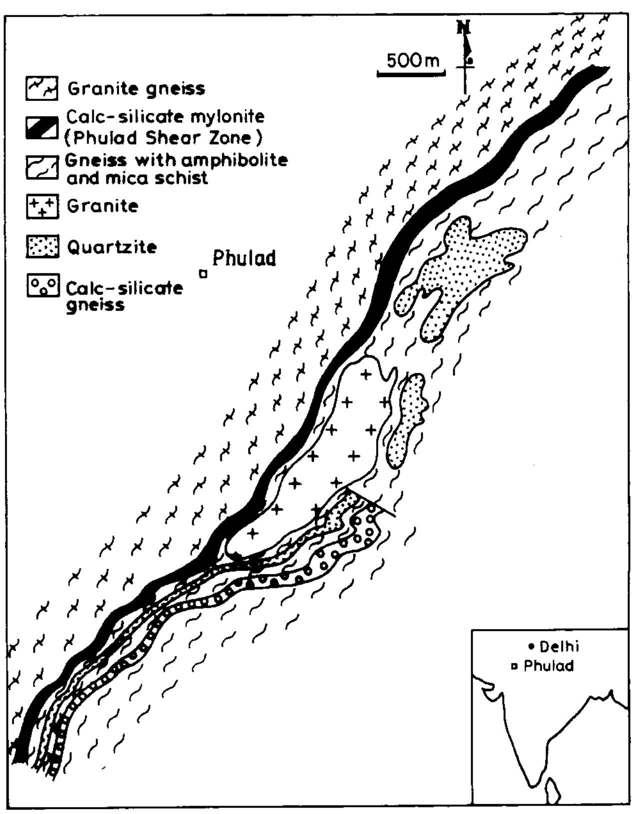

Fig. 2. Geological map of the area around the Phulad Shear Zone in Rajasthan, India.

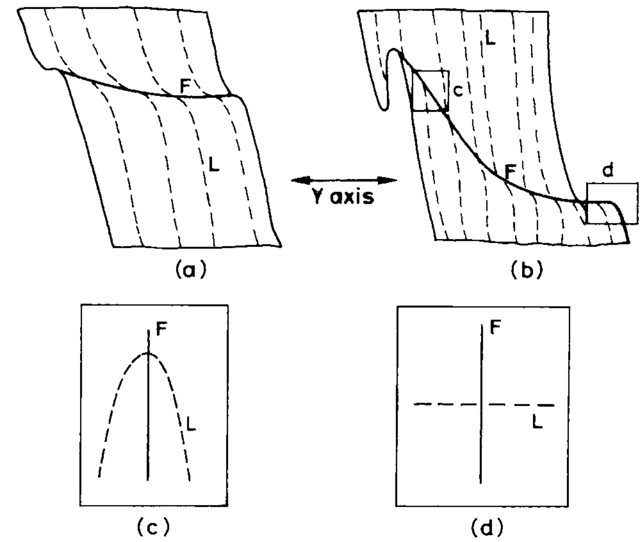

Fig. 3. (a) Initiation of a subhorizontal fold deforming the mylonitic foliation and down-dip mineral lineation. (b) Rotation of fold hinge line. (c) and (d) Patterns of deformed lineation on the unrolled form surface in domains c and d of (b). The general strike of the mylonitic foliation is subparallel to the *Y*-axis of bulk strain.

2. Rotation history of folds from deformed lineation patterns

When an early lineation is deformed by flexure, without significant layer-parallel homogenous strain, the lineation can be straightened out if the fold is unrolled. Such a lineation pattern may be regarded as 'unrollable'. In many places, however, the early lineation cannot be unrolled; it remains curved when the form surface of the fold is unrolled about its axis (e.g. Ramsay, 1960; Hudleston, 1973; Mukhopadhyay and Ghosh, 1980; Ghosh and Chatterjee, 1985). Since the manner in which the angle between the fold axis and lineation varies over a fold is particularly informative, it is necessary that the form surface be exposed at both the hinge and the limbs of a fold. For natural folds on the scale of less than a few tens of centimetres, the lineation pattern can be obtained by placing a transparent polythene sheet over the exposed outer arc of a fold and marking out the orientations of the lineation and the position of the hinge line. The lineation pattern is obtained after straightening out the transparent sheet.

A recurrent theme of the following analysis is the rotational history of folds. In rocks that have undergone a large stretching, the rotation history of the fold hinge lines can be determined from the pattern of deformed lineations over the folds (Ghosh and Chatterjee, 1985; Ghosh and Sengupta, 1987a, b, 1990). Our observations from the Phulad Shear Zone and earlier observations from other areas (Ghosh and Sengupta, 1984, 1987a, b, 1990) show that the shear zone folds initiate as buckle folds but are accompanied by large layer-parallel strains. There is a considerable variation in the initial orientations of the fold hinges, but the majority of them initiate at a low angle to the *Y*-axis of bulk strain. During folding of the mylonitic foliation and of the lineation on it, the fold hinge line rotates towards the direction of maximum stretching. The lineation is reoriented partly by an external rotation and partly by layer-parallel strain. The angle between the hinge line and the lineation changes differently in different parts of the fold (Fig. 3a and b). Consequently, when a cylindrical segment of a plunging fold is unrolled, the lineation remains curved (Fig. 3c). Within the fold segments in which the hinge lines were initially subparallel to the *Y*-axis, however, the rotation of the hinge lines remains negligible and the folded lineation is unrollable (Fig. 3d).

A lineation pattern that is frequently found in ductile shear zones is the U-pattern (type 4 pattern of Ghosh and Chatterjee, 1985). In this pattern the lineation remains more or less at a right angle to the fold axis at the hinge zone but the angle gradually decreases away from it. On the limbs, the lineation may even become parallel to the fold axis. When the form surface of the fold is unrolled, the lineation shows a U-shaped pattern, with the hinge line situated at the turning point of the U (Fig. 3c). The U-pattern develops when, at the initial stage of fold growth, the hinge line is nearly at a right angle (Fig. 3a) to the lineation (Ghosh and Chatterjee, 1985). Similar to the deformed lineation of an earlier stage, an early-formed hinge line may also be deformed to a U-pattern over the rotated fold of a later phase. The occurrence of a lineation deformed in a U-pattern over a cylindrical fold segment gives us crucial information about several aspects of the deformation history. It indicates that the fold hinge line initiated more or less at a right angle to the lineation, that the fold mechanism was by a combination of buckling and layer-parallel strain, and that during the course of folding, both the fold hinge line and the lineation on the fold-limbs rotated through large angles in response to an intense stretching.

3. The Phulad Shear Zone

3.1. General

The Phulad Shear Zone or thrust zone occurs within the Proterozoic Delhi mobile belt of western India. The present study is confined to a 2-km stretch of the shear zone. The ductile shear zone, about 15–20 m wide, and with an average trend of 035, is marked by the presence of a calc-mylonite. The calcareous layers contain thin bands of a metamorphosed siliciclastic rock. The latter shows a fine mylonitic banding of alternate quartz-rich and quartz–feldspar-rich layers. The mylonitic foliation is marked by very fine elongate grains of quartz. The foliation has an average orientation of 035/70E, with the dominant lineation nearly down-dip and with an average pitch of 80° measured from the southwesterly strike (Fig. 4).

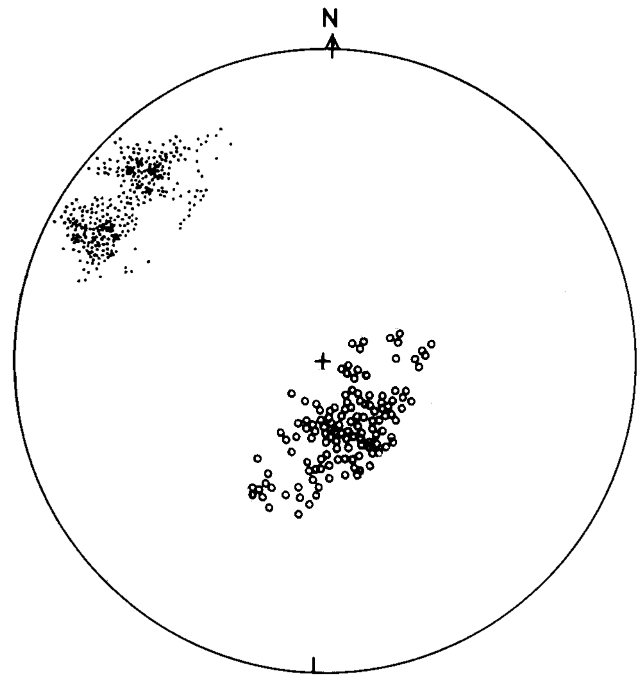

Fig. 4. Equal area projection of lineation (open circle) and foliation poles (dots) of the Phulad Shear Zone. The two overlapping clusters of foliation poles are due to the presence of gentle transverse upright folds in map-scale.

3.2. Sequence of folding

There are several phases of folding in the Phulad Shear Zone. The folds, on the basis of their style, overprinting relationships and orientation, can be subdivided into three broad groups: reclined folds, subhorizontal folds and transverse upright folds. The reclined folds are isoclinal with axial surfaces parallel to the shear zone, the subhorizontal folds are asymmetric, generally varying from open to moderately tight, and the transverse folds are gentle to open, with steep axial surfaces striking more or less at a right angle to the shear zone trend and with axes subparallel to the down-dip mineral lineation.

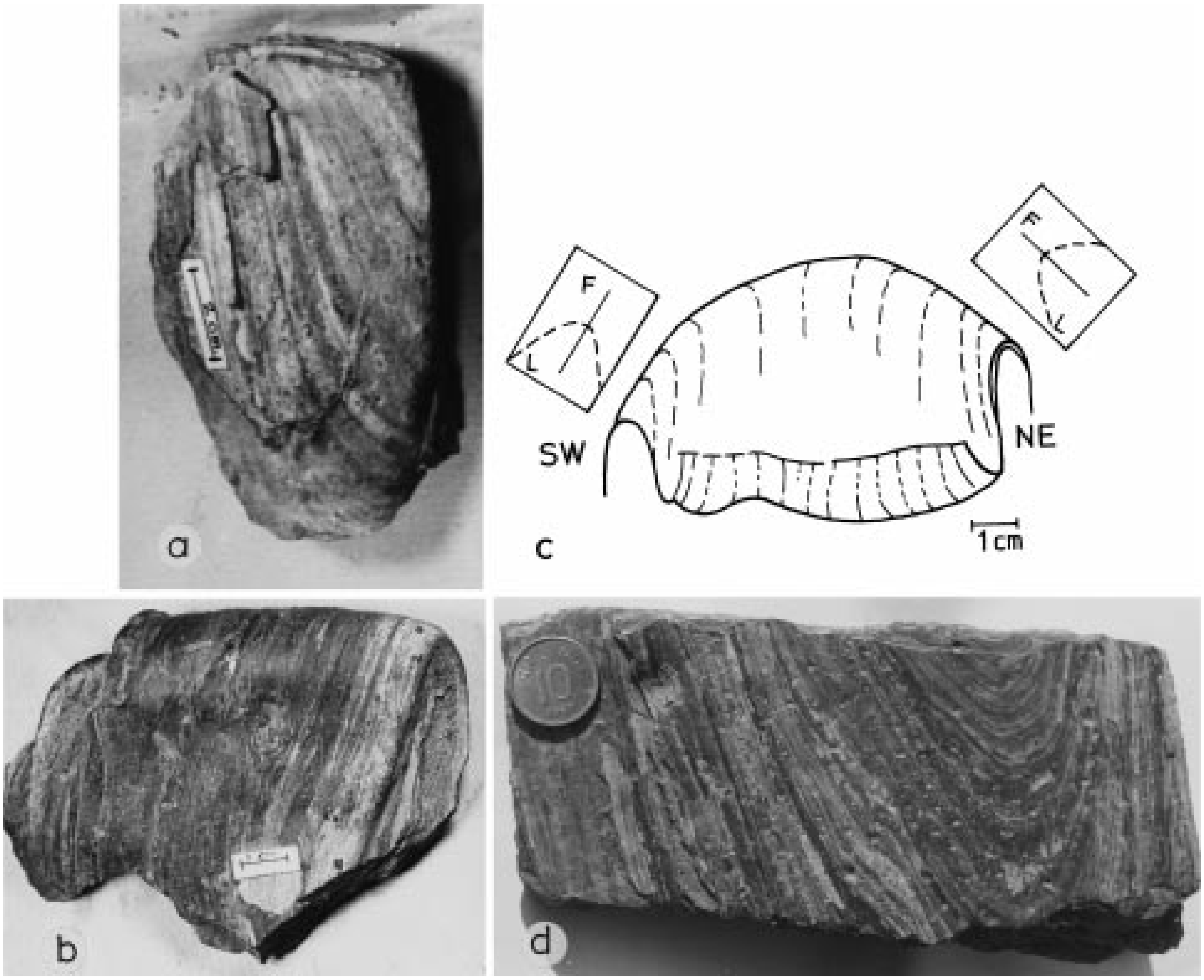

Fig. 5. (a) Oriented specimen of reclined F_2 with striping lineation deformed in a symmetrical U-pattern on the fold hinge. (b) Deformation of L_1 lineation and of the hinge line of an isoclinal F_1 fold (on the right hand side of the specimen) over a subhorizontal fold; oriented specimen. (c) Subhorizontal fold with curved hinge line; the L_1 lineation is at a right angle to the hinge line where the latter is horizontal. Where the hinge line is inclined the lineation shows a U-pattern on the unrolled form surface (insets). The U opens in opposite directions when the plunge of the fold axis is reversed. (d) Curved striping lineation on a planar foliation surface parallel to the axial plane of a sheath fold. Subparallel orientations of F_1 hinge lines along the two arms (as in Fig. 1a) of the sheath fold can be seen at the straight edges at the left and the right hand sides of the specimen. Coin diameter, 1.5 cm.

3.2.1. Group of reclined folds

The reclined folds, the most dominant of the Phulad Shear Zone, are earlier than the other two groups of folds. There are at least three generations of reclined folds, F_1, F_2 and F_3. Since all of them are isoclinal, their limbs and axial surfaces are parallel in most domains and they can be distinguished only by their overprinting relations and from their geometric relations with the striping lineation. The striping lineation (L_1) is an intersection lineation (e.g. Bell, 1978; Gregg, 1980). It is parallel to the axes of F_1 folds. A down-dip mineral lineation, marked by strongly elongated grains of quartz and flakes of mica, is parallel to the striping lineation of reclined F_1. The mineral lineation, which is also a stretching lineation, may, however, occur at an angle to the striping lineation where the latter bends at the apex regions of F_1 sheath folds. The geometrical relations among striping lineations, mineral lineations and F_1 hinge lines in the Phulad Shear Zone are very similar to those described by Bell (1978, p. 290, fig. 6) from the Woodroffe Thrust. The extremely attenuated reclined folds, with a hinge-parallel striping lineation (L_1), are the earliest reclined folds (F_1) of the Phulad Shear Zone. L_1 is always folded over the hinge zones of all the later reclined and subhorizontal folds.

The post-F_1 reclined folds can be distinguished either from the overprinting relation with the first generation folds or from the occurrence of folded L_1 lineation over their hinges. The L_1 lineation is deformed to a U-pattern over the hinges of post-F_1 reclined folds (Fig. 5a). The second and the third generation reclined folds cannot be distinguished from each other unless the two sets of folds occur together, with one set overprinting the other. Where interfering F_2 and F_3 folds appear together in subhorizontal outcrop faces, they may produce hook-shaped type 3 interference patterns (Ramsay, 1967; Ramsay and Huber, 1987), since both these folds are nearly reclined and nearly coaxial in the major part of the structure. However, where fairly long segments of hinge lines of both F_2 and F_3 are exposed, the hinge line of the earlier fold is clearly folded by that of the later fold. Direct observation of the three-dimensional forms of the folds is therefore essential for a complete geometrical reconstruction of the fold interference. Since the folds are very tight to isoclinal, the exposed form surface over both the hinge zone and the adjoining limbs of a fold cannot usually be observed in an outcrop; however, it was easy to obtain three-dimensional forms because samples could often be detached along the form surfaces of the folds. A major part of the geometrical analysis of the interfering folds in the Phulad area was carried out using a large number of oriented hand specimens with exposed fold hinges.

3.2.2. Group of subhorizontal folds

The reclined folds of all the three generations have been deformed by a group of 'subhorizontal' folds. These folds are strongly asymmetrical, with steep easterly dipping axial planes striking nearly parallel to the shear zone trend. Although the folds of this group have been described as 'subhorizontal', the pitch of the fold axis on the axial plane ranges between 0 and 20°. The hinge lines of the subhorizontal group of folds are rarely straight. Wherever long segments of hinge lines of the folds of this group are exposed, they are found to be gently curved but lying on more or less planar axial surfaces.

The L_1 lineation, the mineral lineation, and the hinge lines of the reclined folds are deformed by the subhorizontal folds (Fig. 5b). Where the hinge lines are more or less horizontal, the lineations remain at a right angle to the fold axis in all parts of the fold. The lineation can be straightened out by unrolling the form surface of the fold. Where the hinge line is not at a right angle to the regional down-dip orientation of the shear zone lineation, the angle between the lineation and the fold axis is different in different parts of the fold. Their orthogonal relation is still maintained at the hinge, but the angle decreases at the limbs. If the fold is unrolled about the inclined segment of the fold axis, the lineation shows a gently curved U-pattern, with the turning point of U located on the hinge itself. The curvature of the unrolled lineation pattern becomes stronger with increasing pitch of the fold axis. The sense of curvature depends on the sense of pitch of the fold axis on the axial plane. Thus, for example, if an antiformal fold-hinge has a northerly pitch, the concave side of the curved lineation (on the unrolled form surface) is towards a northerly direction. If the fold hinge has a southerly pitch, it is towards a southerly direction (Fig. 5c). Reverse relations are found over synformal hinges. These patterns were consistently seen, without a single exception, for all the plunging segments of folds of the group of 'subhorizontal' folds, even when the pitch is only a few degrees. This indicates that the mechanism of folding was by a combination of simultaneous buckling and flattening (Ghosh and Chatterjee, 1985). It further indicates that a fold hinge that did not initiate perpendicular to the down-dip lineation, rotated towards the direction of maximum stretching, i.e. the down-dip direction of the shear zone; there was a component of hinge-parallel extension from the initial stage of rotation of fold-hinge lines. This is the reason for the development of a 'non-unrollable' pattern of L_1. If we face westward, the sense of rotation of the hinge line is clockwise for northerly pitching hinge lines and anticlockwise for southerly pitching hinge lines.

The occurrence of non-unrollable L_1, even on gently pitching folds, implies that most folds of the 'subhorizontal' group initiated with a very low pitch. Since the direction of maximum stretching coincided approximately with the down-dip direction of the shear zone, the Y-axis of strain is approximately parallel to the local trend of the shear zone. The pitch of a linear structure on the foliation surface therefore approximately measures its angle with the Y-axis. There is a wide range of variation in the tightness of the subhorizontal folds. The folds may be open, tight or isoclinal, and interlimb angles of 30–60° are fairly common. The subhorizontal folds are consistently asymmetrical; the sense of asymmetry is always in accordance with a thrusting sense of movement.

3.2.3. Transverse upright folds

These are gentle to open mesoscopic and macroscopic folds, with axes essentially parallel to the regional down-dip stretching lineation and with subvertical axial planes roughly perpendicular to the shear zone trend. These transverse folds are the latest generation of folds in the Phulad Shear Zone.

4. The earliest planar sheath folds

The down-dip mineral lineation generally maintains an overall uniform orientation. However, on horizontal surfaces, closed outcrops of strictly isoclinal folds are very common. These represent the earliest sheath folds that have undergone an extreme stretching along

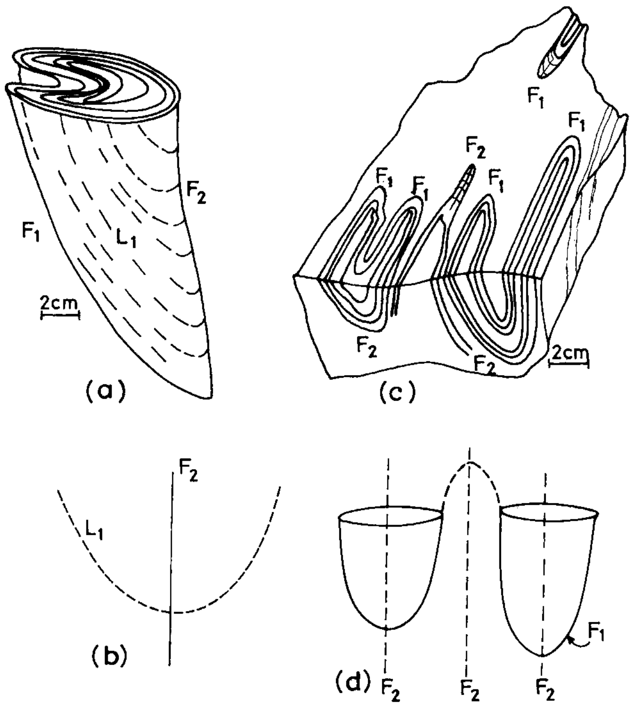

Fig. 6. (a) Sketch of a non-planar sheath fold from oriented hand specimen. Over the essentially straight hinge line of the reclined F_2 fold, the F_1 hinge line is at a right angle to the F_2 axis. On the limbs of F_2, both L_1 and the F_1 hinge lines gradually curve to become nearly parallel to the F_2 axis. The F_2 hinge line and the curved form of the F_1 hinge line (or of hinge-parallel L_1) were traced on a transparent polythene sheet placed over the F_2 fold. (b) The tracing of the F_1 hinge line (and of L_1) of the specimen of (a) on the unrolled form surface of F_2 shows a symmetrical U-pattern, with the turning point of U situated on the hinge line of F_2. (c) Outcrop of non-planar sheath folds on two faces of an oriented specimen. In the short exposed segments, F_1 and F_2 hinge lines are subparallel. (d) Reconstructed form of F_1 obtained by unrolling the axial surfaces of F_2. The situation of the F_2 hinge lines at the turning points of the curved U-shaped F_1 hinge line indicates that the sheath-like structure of F_1 was produced during refolding of F_1 by F_2.

the down-dip direction of the axial planes. Strongly curved hinge lines of sheath folds, with planar axial surfaces, are exposed in many places. These sheath folds have essentially parallel hinge lines on either side of relatively small strongly curved apices. In some places, surfaces parallel to axial planes of these planar sheath folds show a striping lineation, strongly curved in accordance with the curved hinge lines of the sheath folds (Fig. 5d).

5. Non-planar sheaths of F_1 over reclined F_2 folds

A typical example of a non-planar sheath fold is shown by the oriented hand specimen of Fig. 6(a). The specimen shows an interference of two generations of isoclinal folds, F_1 and F_2. In a section perpendicular to the F_2 hinge line the deformed foliation surfaces show a tightly compressed crescentic outcrop produced by the interference of the two generations of folds. A combined striping and mineral lineation parallel to the F_1 hinge line is deformed to a U-pattern over the essentially straight hinge line of the reclined F_2 fold (Fig. 6b). The coincidence of the turning point of the F_1 hinge line with the F_2 hinge zone implies that the U-pattern developed in the course of refolding of F_1 by F_2. Evidently, if the axial surface of the F_1 fold is unrolled about the axis of F_2, the F_1 fold will have the appearance of a planar sheath fold. The non-planar sheath fold was produced when the cylindrical segment of an F_1 fold was refolded by F_2 in the course of rotation of the F_2 hinge line towards the down-dip stretching direction. This is a commonly developed pattern of deformed L_1 over cylindrical segments of reclined F_2 and F_3 folds (Fig. 6c and d).

Non-planar sheath folds of F_1 over F_2 are very common throughout the Phulad Shear Zone. In many places where such non-planar sheaths are present, there are alternate thickened and thinned zones as we move along or across the F_2 hinge line. This apparent pinching and swelling is because of the combination of mirror-image repetition of strongly asymmetrical F_1 folds on either side of the F_2 axial surface and development of a U-pattern of the deformed F_1 hinge lines (Fig. 7a).

Crescent, mushroom-shaped and mirror image forms, as described by Ramsay (1967, pp. 525–530; Thiessen and Means, 1980; Thiessen, 1986), are the characteristic outcrop patterns of a type 2 interference. Where non-planar sheath folds are present, such characteristic outcrop patterns are commonly found on the transverse profiles of the F_2 folds. This is an uncommon situation for most terrains where superposed folding is not associated with extreme stretching. If the F_1 fold hinge line is refolded by flexure, simply by an external rotation around the F_2 axis, the hinge line of the F_1 fold can either be parallel (Fig. 8a) to the profile plane of F_2 (when F_1 and F_2 are at right angles), or the F_1 hinge line will meet the profile plane (Fig. 8b) once only (if F_1 and F_2 are oblique). The characteristic crescent or mushroom-shaped outcrop cannot develop in either of these cases on the profile surface of F_2. In ductile shear zones, such outcrops on the F_2 profile occur because of the strong U-shaped bending of the F_1 hinge line over the F_2 fold, so that a single fold hinge can meet the transverse section of F_2 at two points (Fig. 8c). Whether a crescent or a mushroom-shaped or a mirror-image outcrop will form in this situation will depend upon the position of the profile plane with reference to the geometry of F_1 folds. The crescent outcrops will appear on the profile plane only when both limbs of an F_1 fold intersect the axial surface trace of F_2 on its profile (Fig. 7b). Otherwise, a

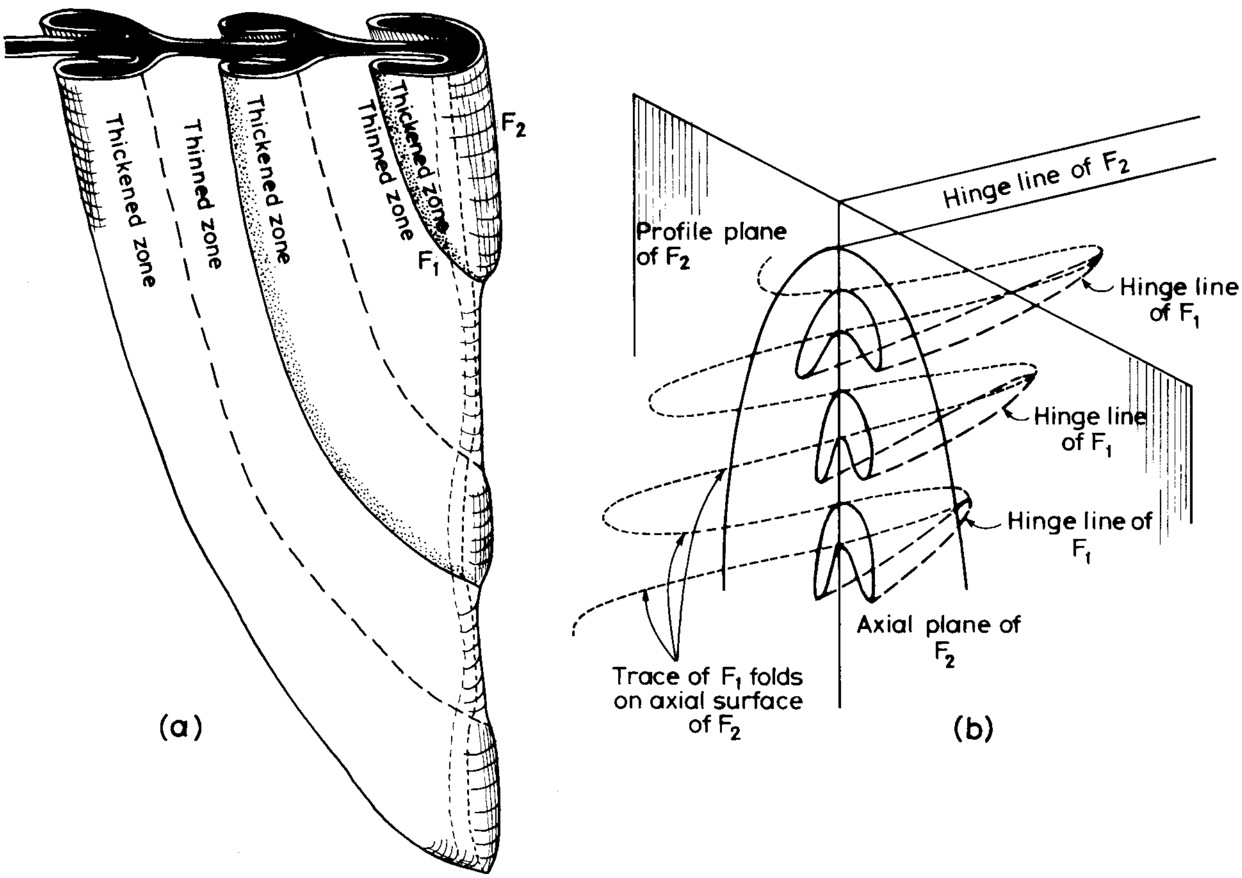

Fig. 7. (a) Non-planar sheath folds of F_1 over F_2. The strong asymmetry of the F_1 folds has given rise to alternate thickened and thinned zones along the F_2 hinge line. An isoclinal *S*- or a *Z*-fold with its long–short–long limbs shows a repetition of the three limbs on either side of an F_2 fold. A thickened zone is produced by coalescence of these six limbs. The thickened zones alternate with comparatively thinner zones where only the long limb of an *S*- or a *Z*-fold is repeated by F_2. (b). Geometrical relations among structural elements of non-planar sheath folds.

mushroom-shaped or mirror image outcrop will appear on the profile plane (Fig. 7a).

Non-planar sheath folds can be most easily recognized where, as in this area, the U-patterns of early fold hinge lines are fully exposed over the later folds in the mesoscopic scale. In the Phulad area, the existence of non-planar sheath folds of F_1 over F_2 is also established by the frequent occurrence of the U-pattern of L_1 lineation over reclined F_2 folds (Fig. 5a), and by the occurrence of tightly compressed crescentic outcrops of F_1–F_2 interference, with subparallel hinge lines of both sets of folds.

6. Non-planar sheaths of F_1 over planar sheaths of F_2

Sheath folds have developed in successive stages of progressive ductile shearing in the Phulad Shear Zone. Fig. 9(a) is a typical example, which shows the oriented specimen of a second generation planar sheath fold with a flattened oval outcrop and steeply plunging F_2 hinge lines on either side. One of the F_2 hinge lines (left hand side of Fig. 9b) refolds an F_1 hinge line in a U-pattern. The lineation is parallel to this curved hinge line. Over the short exposed segment of the F_2 fold hinge, the F_1 hinge line and the hinge-parallel L_1 lineation are at a right angle to the F_2 hinge line. The angle decreases away from the F_2 hinge. If the axial surface of F_1 is unrolled over a short segment of the F_2 hinge, L_1 and the F_1 hinge line occur in a U-pattern, with the turning point of U located on the hinge of F_2. Thus, the non-planar sheath fold of F_1 was produced during the development of the planar sheath fold of F_2. Similar structures were observed in different parts of the Phulad Shear Zone. Indeed, wherever the hinge lines of post-F_1 sheath folds are wholly or partially exposed, they deform the L_1 lineation in a U-pattern (Fig. 9c and d).

7. Refolding of sheath folds

7.1. Early sheath folds deformed by later ones

As mentioned earlier, there are at least three generations of reclined folds in the Phulad Shear Zone.

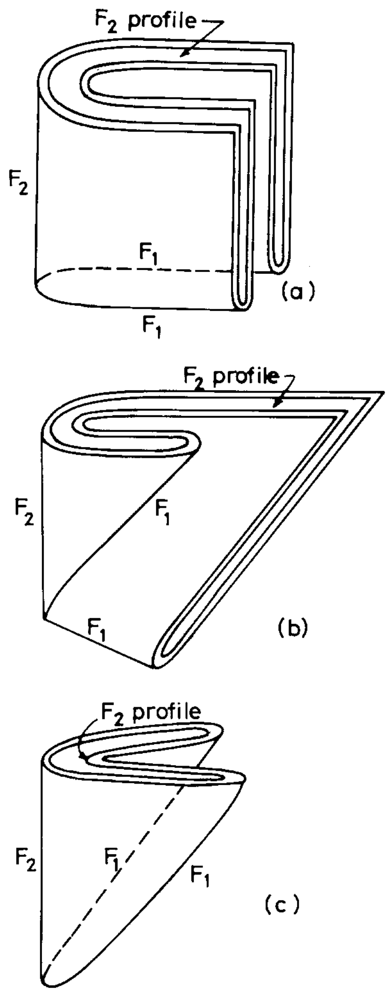

Fig. 8. Different forms of Type 2 fold interference. (a) F_1 and F_2 hinge lines are at a right angles in every part of the fold. (b) F_1 and F_2 hinge lines are oblique but maintain a constant angle. Crescent outcrops as in (c) can appear on the profile plane of F_2 only if the hinge line of F_1 is deformed to a U-pattern. If the deformation of the F_1 hinge line takes place simply by flexure folding or an external rotation around F_2 axis as in (a) and (b), a crescent outcrop cannot appear on the F_2 profile plane.

Many of them represent the steeply pitching long arms of planar sheath folds (as in Fig. 9c). Figs. 9(e) and 11(b), of an oriented specimen, show the complete three-dimensional form of two basinal sheath folds with a domal sheath fold in-between. The horizontal section shows the oval outcrops of the synformal sheath folds. The exposed form surface shows the bent hinge lines of the apical regions of the sheath folds. On one limb of a sheath fold (front of Fig. 9e), the L_1 lineation has a strongly curved pattern. The lineation is deformed over the hinge line of the sheath fold. It crosses the hinge line at a low angle and does not make a U-pattern as in the previously described non-planar sheath folds. On the other face of the specimen the lineation is nearly straight. The occurrence of the strongly curved pattern of L_1 on the limb of the sheath fold and the folding of L_1 over the hinge indicate that the planar sheath folds formed during the growth of either F_2 or F_3 and that the later sheath folds have refolded the earlier folds of F_1. Similar refold structures of F_1 sheath folds by F_2 or F_3 or by both can be seen in many places

7.2. Complexly folded L_1

The complex geometric relations among successive generations of folds and their effect on the deformation of lineations are very clearly seen in the oriented specimen of Fig. 10. The specimen shows the overprinting relations of three generations of folds, F_1, F_2 and F_3. The profiles of all the three generations of folds are exposed in different parts of the specimen. The hinge lines of the folds are also exposed in certain domains. Since all three generations of folds are isoclinal, their limbs and axial surfaces are parallel in most places. The folding of the axial surface of an early fold can be seen only on the hinge zone of a later fold. The F_1 fold is exposed at the hinge zone of an F_3 fold (Fig. 10a). A fine striping lineation is parallel to the F_1 hinge line, a short segment of which is exposed and deformed over F_3. The F_3 fold also deforms the axial surface of the F_2 (Fig. 10b) fold. The hinge line of F_2 is at a low angle (or, in places, subparallel) to the F_3 hinge line. F_1/F_2 interference is seen only at a short segment, where the axial surface of F_1 is folded by F_2 (Fig. 10a). The orientation of L_1 is different in different domains. L_1 is parallel to the F_1 hinge line. On one limb of F_2 the L_1 lineation curves in a hairpin bend on an essentially planar surface (Fig. 10b and d). In the neighbourhood of the F_2 hinge line the lineation becomes subparallel to it. However, on the other limb of F_2, the lineation curves gradually, and in the major part, swings to make a high angle to the F_2 hinge line (Fig. 10d). Over the hinge zone of F_3, L_1 makes variable angles with the F_3 axis. The lineation cannot be straightened out by unrolling the form surface around short segments of the F_3 hinge. As shown by Fig. 10, on the same limb of the F_3 fold, the lineation shows an abrupt change in orientation on two close-spaced surfaces that belong to the two limbs of F_2.

To describe the orientation of L_1 at different places, we have designated the two limbs of F_1 as F_{1A} and F_{1B}, the two limbs of F_2 as F_{2C} and F_{2D}, and the limbs of F_3 as F_{3E} and F_{3F} (Fig. 10c). For the specimen shown in Fig. 10(a) and (b), small segments of the form surfaces can be unrolled around short cylindrical segments of the fold hinge lines. The lineation pattern of one such domain is drawn in Fig. 10(d). Since the axial surfaces of each of these folds, F_1, F_2 and F_3 can be traced in the specimen, it is possible to decide which particular limb of a fold is exposed on a small planar domain of an exposed foliation surface. Thus,

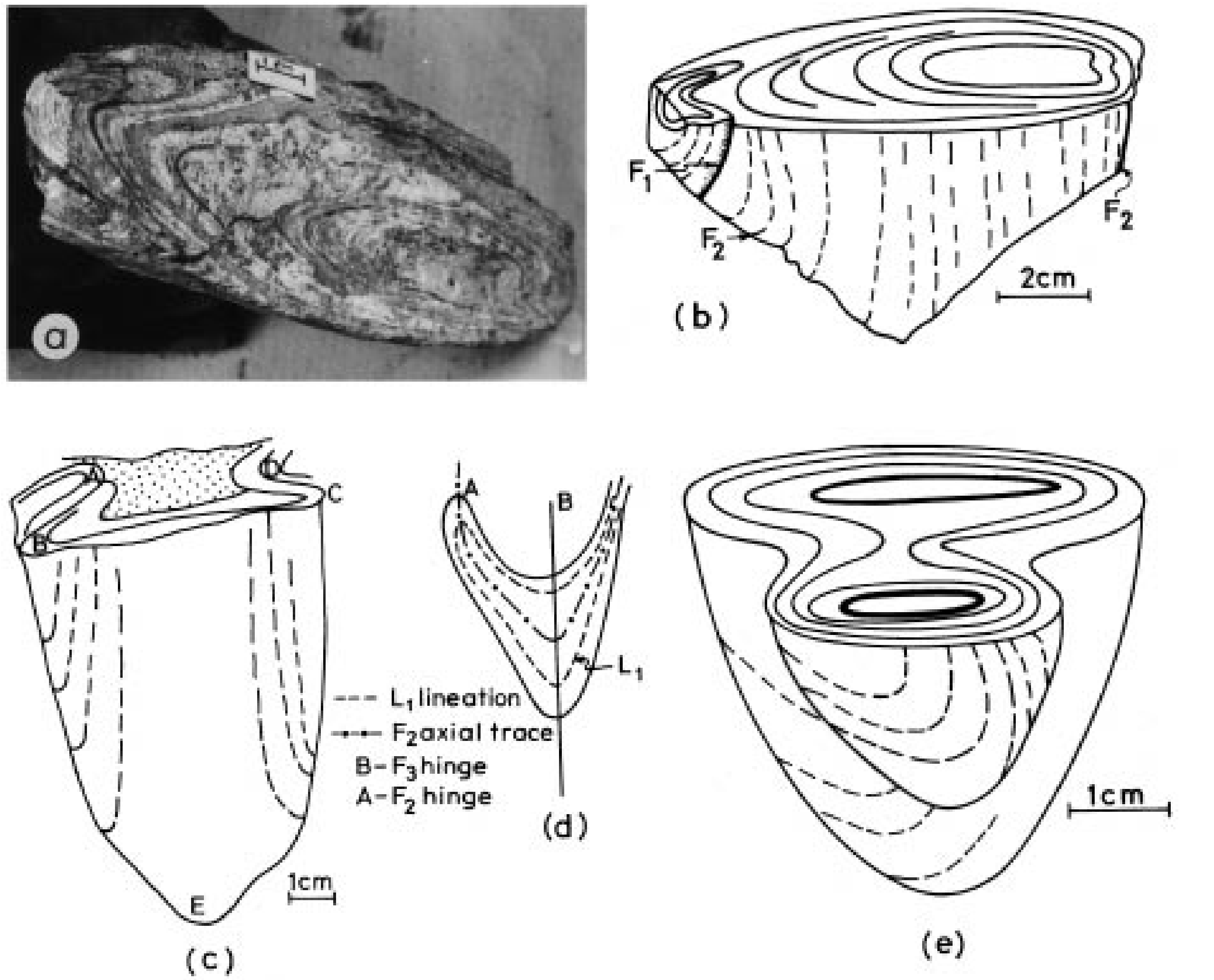

Fig. 9. (a) Subhorizontal surface of oriented hand specimen showing oval outcrop of F_2 sheath fold (central and right hand side of figure) and a crescentic outcrop of a non-planar sheath fold on the left hand side. (b) Side-view sketch of oriented hand specimen shown in (a). (c) Planar sheath fold of F_3. At the apex E, L_1 and the subhorizontal segment of the F_3 hinge line are at a right angle. On either side, L_1 is deformed to a U-pattern over the steep segments of F_3. In the major part of the specimen, L_1, F_2 and F_3 are subparallel. An F_2 hinge (at point A) is exposed on the back side of the specimen. The F_2 hinge line is itself deformed to a U-pattern over the F_3 hinge line. (d) Pattern of L_1 over the unrolled form surface in the neighbourhood of B at the left side of the specimen of (c). Note that L_1 is deformed to a U-pattern over both the F_3 and the F_2 hinges. (e) Post-F_1 planar sheath folds. The U-pattern of deformed L_1 is refolded over the curved hinge lines of the F_2 folds. This is an example of an early sheath fold deformed by a later sheath fold. See Fig. 11(b) for plan view of specimen.

for example, the surface with the curved lineations, on the right hand side of Fig. 10(d), belongs to the common limb of F_{1B}, F_{2D} and F_{3E}. A single limb of F_3 may contain both limbs of F_1 and both limbs of F_2. Different planar segments of these limbs are exposed in different places. Since the lineation is parallel to the F_1 axis, it is evidently parallel on its two limbs of a cylindrical fold-segment. For all later folds, however, the orientations of L_1 on two adjacent limbs of an isoclinal fold are different, unless L_1 is at a right angle to a subhorizontal segment of a fold hinge line, or L_1 on both limbs have been reoriented by a very large stretching towards the down-dip direction.

The angles between the deformed linear structures in different domains were progressively reduced in response to the large stretching along the down-dip direction of the shear zone. Because of the extreme stretching, hinge lines at long steeply pitching flanks of first generation sheath folds have become subparallel in most places. A common pattern of L_1 in the non-planar sheath folds is the parallelism of L_1 or of F_1 hinge lines with the F_2 axis on both limbs of the reclined F_2 folds. The curved form of L_1 and its angular relation with F_2 is preserved only in the neighbourhood of tightly compressed F_2 hinge zones. Repeated refolding of curved patterns of L_1 has produced complex lineation patterns. One consequence of repeated isoclinal folding is that subparallel foliation surfaces,

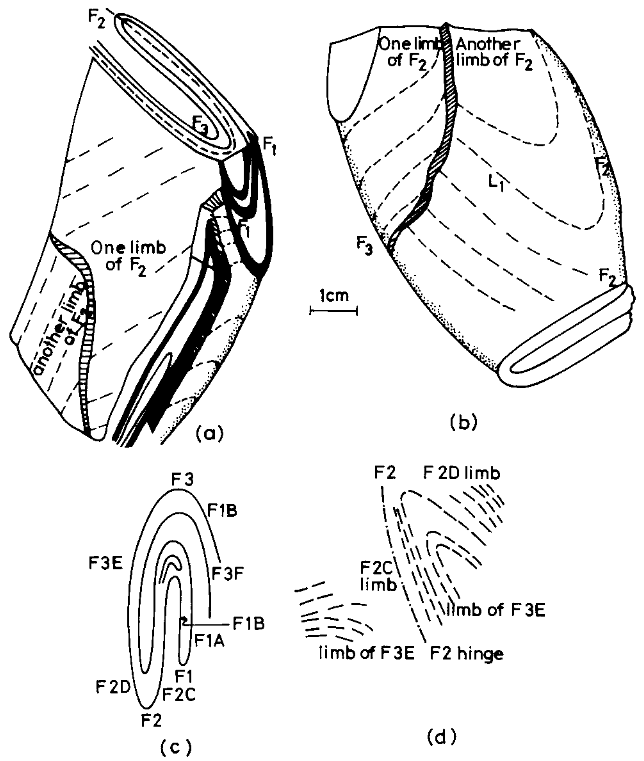

Fig. 10. (a) Interference of three sets of isoclinal folds F_1, F_2 and F_3 in a single hand specimen; (a) and (b) are the two faces of the same specimen. In (b) note the occurrence of strongly curved L_1 on one limb of F_2. Since the folds are very tightly appressed, foliation surfaces a few millimetres apart may represent different fold limbs and consequently different orientations of the lineations. (c) Schematic diagram showing refolding of different limbs of F_1 and F_2 by F_3 of the specimen of (a) and (b). Since all the folds are strictly isoclinal, the limbs of all the folds are parallel in most places. (d) Pattern of L_1 over a segment of the form surface of the F_2 folds.

even a few millimetres apart, may have different orientations of L_1 (Fig. 11c). Indeed, even where the fold hinges are not exposed, the very presence of abruptly changing orientation of L_1 on parallel surfaces imply that, in-between them, there is the axial surface of a fold (cf. Ghosh, 1993, p. 375).

Similar reorientation of lineations and hinge lines has also occurred during re-folding of earlier sheath folds. Thus, for example, Figs. 11(a) and 12(a) show an oriented specimen of a reclined fold. The striping lineation on one planar limb (front face of Fig. 12a) shows V-shaped curves representing F_1 sheath folds. The Vs become tighter as one approaches the F_2 hinge. At the hinge zone itself the lineation makes a low angle with the F_2 axis. Fig. 12(b) shows the lineation pattern on both the limbs after the form surface is unrolled about the F_2 axis.

A still more advanced stage of reorientation can be seen in the oriented specimen of Fig. 11(d) in which the striping lineation has, in the major part, a uniform orientation parallel to the general down-dip direction of stretching in the shear zone. However, along a narrow zone on one limb of the fold, the striping lineation has a folded pattern on the planar limb. The lineation is folded by the F_2 hinge. Towards either side of the narrow zone the lineation sharply swings to become parallel to the down-dip direction. On the other limb of the fold, the V-shaped form is replaced by a uniform hinge-parallel orientation of the striping lineation.

8. Stretching associated with U-pattern of lineation

The U-pattern of lineation is very frequently seen over reclined folds of the Phulad Shear Zone (e.g. Fig. 6a and b). At the apices of planar sheath folds, the hinge lines are mostly subhorizontal. L_1 is at a right angle to the hinge line at the apices of the planar sheath folds of F_2. L_1 is unrollable at a short segment of the apex. The U-pattern of lineation develops only along the two arms of planar sheath folds (e.g. Fig. 9c) where the hinge lines are rotated. From these consistent relations we conclude that, during progressive ductile shearing, each generation of folds (except for the last generation of transverse upright folds) initiated with hinge lines nearly at a right angle to the direction of stretching (X) and close to the orientation of the subhorizontal Y-axis of bulk strain. Accordingly, the following model assumes that the fold axis initiated at a very small angle with the Y-axis and that the initial angle between L_1 and F_2 (or F_3) was more or less a right angle.

There are two types of U-pattern of lineation on unrolled form surfaces of folds. In one of these, the point of maximum curvature of the lineation on the unrolled form surface is located at or very close to the hinge line of the fold (Type 4 pattern of Ghosh and Chatterjee, 1985). In the other, the point of maximum curvature occurs distinctly on one side of the hinge line (Type 3b pattern of Ghosh and Chatterjee, 1985). Both these types are common in the Phulad Shear Zone. For both these types, the lineation swerves to make a low angle to the fold axis on the limbs of the folds. In many places, the lineation on the fold limbs has become essentially parallel to the fold axis. The following analyses will show that an extremely large amount of stretching is required for the development of a U-pattern with such low angles between the fold axis and the lineations on fold limbs.

We shall consider here a simple model of passive deformation of an isoclinal fold with an early lineation initially at a right angle to the fold axis in every part of the fold. We shall consider only plane strain without volume change for both simple shear and general shear (combined pure shear and simple shear). We have taken coordinate axes x, y and z, with x as the

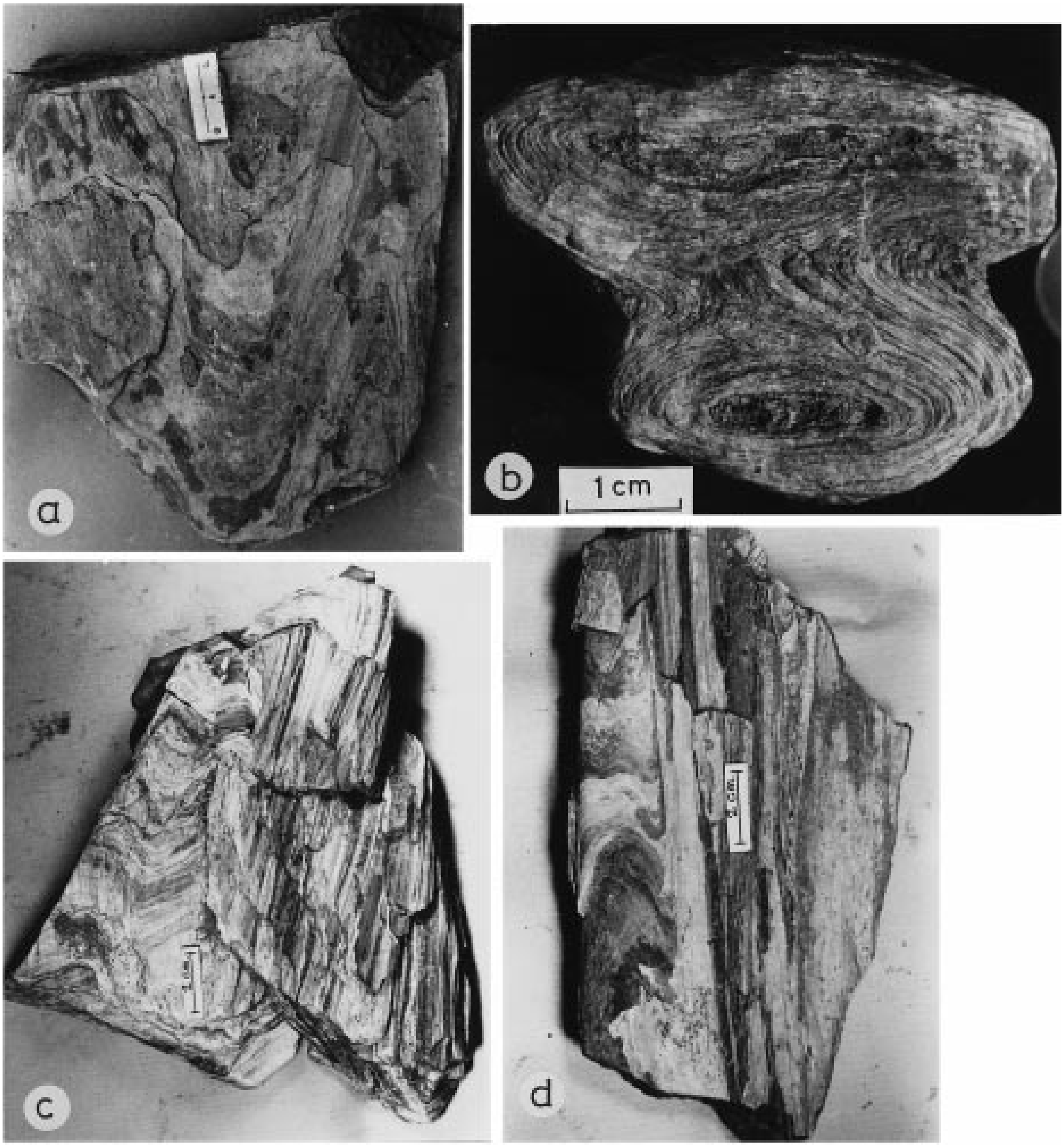

Fig. 11. (a) Strongly curved striping lineation (representing an F_1 sheath fold) occurring on the planar limb of an F_2 fold, the hinge line of which is at the right edge of the specimen. The sketch of the specimen and the lineation pattern on the unrolled form surface are shown in Fig. 12(a) and (b). (b) Closed outcrops of sheath folds on the horizontal surface of the oriented specimen shown in Fig. 9(e). (c) Post-F_1 reclined fold with striping lineations at a high angle to each other on two parallel limbs. On the right hand side, the lineation on one limb of the fold is down-dip. On the other limb, on the left hand side of the figure, the striping lineation shows a folded pattern. (d) Reorientation of strongly curved striping lineation on planar limbs of an F_2 reclined fold. The lineation is deformed by the F_2 hinge. The hinge line is at the left edge of the specimen. In the major part of the specimen (right side of the figure), the lineation on the planar limb shows an isoclinally folded pattern; consequently, the reoriented lineation has become subparallel to the F_2 hinge line. Elsewhere, that is on the left hand side, the folded lineation is less tight.

direction of simple shear and the y-axis parallel to the intermediate axis of strain (direction of no strain). For combined pure shear and simple shear (Ramberg, 1975), x is the direction of maximum elongation and z is the direction of maximum shortening for the pure shear component (Fig. 12c). The limbs and axial planes of isoclinal folds are taken to be parallel to the y-axis and are inclined at an angle of 40° with the x–y plane. The fold axis (F) is at an angle of 5° with the y-axis and the lineation (L) is at 90° with F (Fig. 12d).

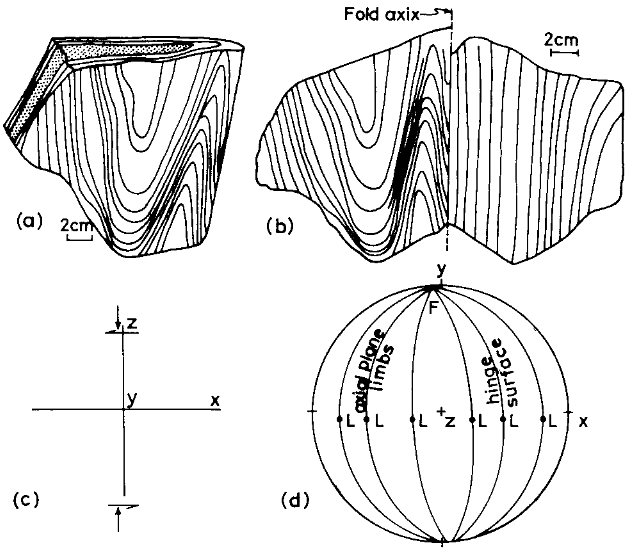

Fig. 12. (a) Reclined F_2 fold of the same specimen as shown in Fig. 11(a). (b) The pattern of deformed lineation when the form surface of the F_2 fold of (a) is unrolled. (c) Orientations of x, y, z coordinate axes for combined pure shear and simple shear. (d) Equal area projection showing orientations of axial plane, limbs, hinge surface, lineations (L) and fold axis (F) for the theoretical model.

The hinge zone of the fold is considered to be composed of a bundle of S-planes parallel to the fold axis, with consecutive S-planes at intervals of 5°, and with the S-plane at the hinge at a right angle to the limbs of the isoclinal fold. The relevant mathematical equations for the deformation of S-planes and lineations are given in the Appendix.

The numerical calculations show that, although U-patterns of lineations can develop in both simple shear and general shear (provided the initial angle between F and L was close to 90°), a symmetrical U-pattern does not develop in bulk simple shear. On the unrolled form surface of the fold, the point of maximum curvature of the deformed lineation occurs distinctly on one side of the hinge line (Fig. 13a). This asymmetry of the U-pattern clearly results from hinge migration. Hinge migration also takes place in combined pure shear and simple shear, since in non-coaxial deformation the material S-surface of the initial hinge no longer remains perpendicular to the deformed axial plane. Nevertheless, the numerical calculations show that a U-pattern of lineations, with the turning point of the U at or very close to the hinge, can develop when the bulk deformation is by combined pure shear and simple shear (Fig. 13).

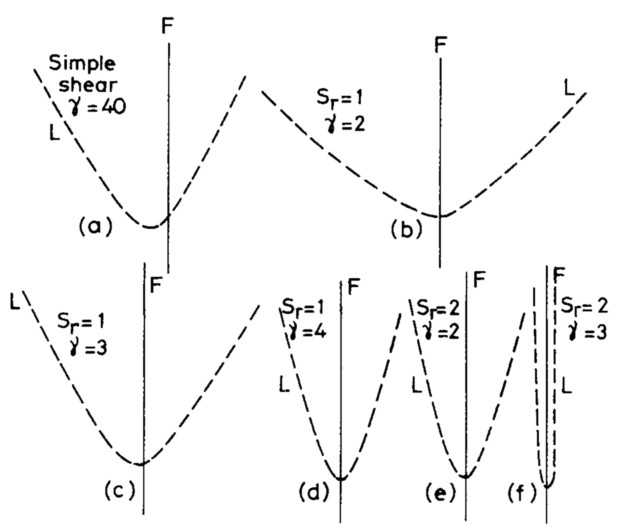

Fig. 13. Patterns of deformed lineations on unrolled foliation surfaces as obtained from the theoretical model.

The numerical calculations further show that in both types of bulk deformation, an unusually large stretching is required for obtaining even moderately low angles between L and F or between the arms of the U-shaped pattern of lineation on the unrolled form surface. Thus, for example, for $S_r = 1.0$ and $\gamma = 2$ (S_r is the ratio of pure shear and simple shear) corresponding to an extension of more than 700% ($X = 8.2$), the angle between L and F at the fold limbs is as large as 55° (Fig. 13b). For the same value of S_r, but with $\gamma = 3$, corresponding to an extension of 2150% ($X = 22.5$), $L \wedge F = 28°$ (Fig. 13c). For $\gamma = 4$, ($X = 61$, or an extension of 6000%), $L \wedge F = 11°$ (Fig. 13d). A very low value of $L \wedge F = 4°$ is indeed obtained when γ increases to 5, but stretching in this case is enormous, an extension of 16 500% ($X = 166$). Similar results are obtained for $S_r = 2$. Thus, $L \wedge F = 13°$ for $\gamma = 2$ (Fig. 13e) corresponding to an extension of more than 5500% ($X = 56.3$), and $L \wedge F = 1°8'$ for $\gamma = 3$ (Fig. 13f) corresponding to an extension of 41 500% ($X = 416$).

These numerical calculations suggest that for a low value of $L \wedge F$ (< 10°), as is so often seen on the limbs of an isoclinal F_2 or F_3, the stretching in the down-dip direction must have been a minimum of 6000%. Since the lineation on the arms of a U-pattern has often become nearly parallel to the fold axis, it is likely that the total extension in the down-dip direction of the shear zone is very much in excess of 6000%.

9. Summary and conclusions

Progressive ductile shearing in the Phulad Shear Zone has produced a complex history of folding, with development of planar, non-planar and refolded sheath folds. Sheath folds have developed in successive stages. In some places the earlier sheath folds are deformed by later ones. The more or less cylindrical segments of the isoclinal F_1 reclined folds, with a prominent hinge-parallel striping lineation (L_1), may also occur along the lateral arms of planar sheath folds. At the relatively small apices of the sheath folds L_1 swerves harmoniously with the hairpin curve of the F_1 hinge line. The down-dip mineral lineation is a stretching lineation, which is parallel to the striping lineation in most places but intersects the striping lineation where the latter is bent at apices of first generation sheath folds. Both the striping and the mineral lineations are deformed in U-patterns over the hinges of later reclined folds (F_2 and F_3) and over the steeply pitching straight hinge lines at the lateral arms of planar sheath folds of F_2 or F_3. The folding of axial surfaces of subcylindrical segments of F_2 by F_3, or of F_1 by either F_2 or F_3, was often associated with rotation of the earlier hinge lines by homogeneous strain, leading to the development of non-planar sheath folds, with the hinge lines of the earlier fold deformed to a U-pattern over the hinge of the later fold. The theoretical model indicates that the U-pattern of lineation, with a low angle between the arms of the U, is produced only when the initial angle between L_1 and F_2 is close to 90° and the stretching is extremely large.

This early set of folds was deformed by a group of plane folds whose hinge lines are either subhorizontal or are weakly curved. L_1 can be unrolled or straightened out over the subhorizontal segments of their hinge lines. However, over even the gently plunging segments of their hinge lines, L_1 cannot be straightened out by unrolling the form surface; it invariably shows an open U-pattern. This indicates that even at a relatively late stage of ductile shearing in the Phulad Shear Zone, rotation of fold hinges in response to stretching in the down-dip direction was an active process.

Isoclinal folding has repeatedly transposed the banding parallel to the mylonitic foliation in the Phulad Shear Zone. In a similar way, because of the extreme stretching, the L_1 lineation and the hinge lines of isoclinal folds, deformed by planar, non-planar and refolded sheath folds, have become subparallel in many places. The geometry of the sheath folds and of the U-patterns of lineation on the unrolled form surfaces of the reclined folds clearly indicate a very large magnitude of rotation of the fold hinge lines and of the lineation. Numerical calculations indicate that a minimum value of stretching of 6000% along the down-dip X direction of the shear zone is required to explain the reorientation of the linear structures by homogenous strain. In view of the history of repeated sheath folding and the very large degrees of rotation of linear structures in the Phulad Shear Zone, it is likely that the actual value of total stretching was much in excess of 6000%. The geometry of the U-pattern of lineation is consistent with a bulk deformation of general shear with shortening across the shear zone along with shearing parallel to the zone boundaries.

Acknowledgements

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Appendix

A.1. Deformation of isoclinal folds and lineations

In simple shear, a point (x, y, z) moves to the point (x', y', z') according to the equations

$$x' = x + \gamma z,$$

$$y' = y,$$

$$z' = z.$$

If a lineation (L_1) with direction cosines l_1, l_2, l_3 is deformed by simple shear, its direction ratios will be

$$a' = (l_1/l_3) + \gamma, \quad b' = (l_2/l_3) \quad \text{and} \quad c' = 1.$$

The direction cosines are then calculated:

$$l_1' = a'/\delta, \quad l_2' = b'/\delta \quad \text{and} \quad l_3' = c'/\delta,$$

where $\delta = [(a')^2 + (b')^2 + (c')^2]^{1/2}$.

The length of the long axis of the strain ellipsoid is

$$X = \sqrt{(\gamma/2)^2 + 1} + (\gamma/2),$$

(Jaeger, 1964), and its orientation (θ') is $\tan 2\theta' = 2/\gamma$.

If the initial fold axis has direction cosines f_1, f_2, f_3, its direction cosines after deformation can be determined in a similar manner as in the case of lineation.

Similarly, for combined pure shear and simple shear (Ramberg, 1975) as in Fig. 12(c), with S_r as the ratio of the rates of pure shear and simple shear (Ghosh and Ramberg, 1976; Ghosh, 1993, p. 166), we have

$$x' = \exp(\gamma S_r)x + (1/S_r)[\sinh(\gamma S_r)]z,$$

$$y' = y,$$

$$z' = [\exp(-\gamma S_r)]z.$$

S_r can also be expressed in terms of the kinematical vorticity number W_k (Ghosh, 1993, p. 205):

$$S_r = \frac{\sqrt{1 - W_k^2}}{2W_k},$$

$$W_k = \frac{1}{\sqrt{1+4S_r^2}}.$$

The direction ratios of a linear structure after deformation will be:

$$a' = [\exp(2\gamma S_r)]\frac{l_1}{l_3} + \frac{1}{S_r}\frac{\sinh(\gamma S_r)}{\exp(-\gamma S_r)},$$

$$b' = [\exp(\gamma S_r)]\frac{l_2}{l_3},$$

$$c' = 1,$$

from which the direction cosines (l_1', l_2', l_3') can be calculated.

The angle (ψ) between the fold axis and the lineation can then be determined from the relation

$$\cos\psi = l_1'f_1' + l_2'f_2' + l_3'f_3'.$$

If there is no volume change, for plane strain, $XZ = 1$. The semi-axes X and Z of the strain ellipsoid (Jaeger, 1964, p. 28) can be obtained from the equation:

$$X^2 + Z^2 = \exp(2\gamma S_r) + \frac{1}{S_r^2}\sinh^2(\gamma S_r) + \exp(-2\gamma S_r),$$

and since $XZ = 1$,

$$X = \frac{1}{2}\left[\sqrt{(4+AB)} + \sqrt{AB}\right]$$

where $A = \sinh^2(\gamma S_r)$, and $B = 4 + 1/S_r^2$.

We have considered an isoclinal fold with axial plane and limbs parallel to the y coordinate axis and inclined at an angle of 40° with the x–z plane (Fig. 12d). The fold axis (say F_2) is at an angle of 5° with the y-axis. The lineation (L_1) on each S-surface is at an angle of 90° with F_2. In addition to the two parallel limbs and the hinge surface at a right angle to them, we have taken a bundle of consecutive S-surfaces at intervals of 5° and intersecting along the fold axis. The numerical calculations were carried out both for simple shear and for combined pure and simple shears, with different values of S_r. For each case, the successive stages of deformation were obtained by increasing the value of γ. The orientation of the deformed S-surface for each stage was obtained by stereographic projection of the great circle passing through the lineation and the fold axis. The lineation pattern on the unrolled form surfaces was then drawn from the angle between the lineation and the fold axis on each S-surface. Some of these patterns are shown in Fig. 13. The lineation pattern obtained in this manner only gives the angle between L and F at different dip angles of the form surface. Since we have not considered the arc-length of the fold, we do not obtain the curvature of the lineation on the unrolled form surface. Nevertheless, as we started with an isoclinal fold and as the total deformation was extremely large, the hinge zone of the fold must have been very small, compared to the lengths of the nearly straight limbs. Hence the distinctly curved segment of the lineation pattern must also be a very small portion of the total pattern of L on the unrolled form surface of a complete fold.

References

Bell, T.H., 1978. Progressive deformation and reorientation of fold axes in a ductile mylonite zone: the Woodroffe thrust. Tectonophysics 44, 285–320.

Carreras, J., Estrada, A., White, S., 1977. The effect of folding on the *c*-axis fabric of a quartz mylonite. Tectonophysics 39, 3–24.

Cobbold, P.R., Quinquis, H., 1980. Development of sheath folds in shear regimes. Journal of Structural Geology 2, 119–126.

Ghosh, S.K., 1993. Structural Geology: Fundamentals and Modern Developments. Pergamon Press, Oxford.

Ghosh, S.K., Chatterjee, A., 1985. Patterns of deformed early lineations over late folds formed by buckling and flattening. Journal of Structural Geology 7, 651–666.

Ghosh, S.K., Ramberg, H., 1976. Reorientation of inclusions by combination of pure shear and simple shear. Tectonophysics 34, 1–70.

Ghosh, S.K., Sengupta, S., 1984. Successive development of plane noncylindrical folds in a progressive deformation. Journal of Structural Geology 6, 703–709.

Ghosh, S.K., Sengupta, S., 1987a. Progressive evolution of structures in a ductile shear zone. Journal of Structural Geology 9, 277–288.

Ghosh, S.K., Sengupta, S., 1987b. Structural history of the Singbhum Shear Zone in relation to the northern belt. In: Saha, A.K. (Ed.), Geological Evolution of Peninsular India: Petrological and Structural Aspects. Hindustan Publishing Corporation, pp. 31–44.

Ghosh, S.K., Sengupta, S., 1990. Singbhum Shear Zone: Structural transition and a kinematic model. Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences) 99, 229–247.

Gregg, W.J., 1980. The texture of cross-micas in rocks affected by schistosity-parallel displacements. Journal of Structural Geology 2, 333–340.

Hudleston, P.J., 1973. The analysis and interpretation of minor folds developed in the Moine rocks of Monar, Scotland. Tectonophysics 17, 89–132.

Jaeger, J.C., 1964. Elasticity, Fracture and Flow. Methuen, London.

Mukhopadhyay, D., Ghosh, K.P., 1980. Deformation of early lineation in the Aravalli rocks around Fathepur, Udaipur District, southern Rajasthan, India. Indian Journal of Earth Sciences 7, 64–75.

Quinquis, H., Audren, C., Brun, J.P., Cobbold, P.R., 1978. Intense progressive shear in Ile de Groix blueschists and compatibility with subduction or obduction. Nature 273, 43–45.

Ramberg, H., 1975. Particle paths, displacements and progressive strain applicable to rocks. Tectonophysics 28, 1–37.

Ramsay, J.G., 1960. The deformation of early linear structures in areas of repeated folding. Journal of Geology 68, 75–93.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York.

Ramsay, J.G., 1980. Shear zone geometry: a review. Journal of Structural Geology 2, 83–99.

Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology. 2, Folds and Fractures. Academic Press, London.

Sengupta, S., Ghosh, S.K., 1997. Kinematic history of the Singbhum shear zone. Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences) 106, 185–196.
Thiessen, R., 1986. Two-dimensional refold interference patterns. Journal of Structural Geology 8, 563–573.
Thiessen, R., Means, W.D., 1980. Classification of fold interference patterns: a reexamination. Journal of Structural Geology 2, 311–316.
Williams, G.D., Chapman, T.J., 1979. The geometrical classification of non-cylindrical folds. Journal of Structural Geology 1, 181–185.