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Progressive development of structures in a ductile shear zone

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Abstract—In the Singhbhum Shear Zone of eastern India successive generations of folds grew in response to a progressive ductile shearing. During this deformation a mylonitic foliation was initiated and was repeatedly transposed. The majority of fold hinges were formed in an arcuate manner at low angles to the *Y*-axis in an E–W trending subhorizontal position and major segments of the fold hinges were then rotated towards the down-dip northerly plunging *X*-axis. The striping and intersection lineations were rotated in the same manner. The down-dip mylonitic lineation is a composite structure represented by rotated early lineations and newly superimposed stretching lineations. The consistent asymmetry of the folds, the angular relations between *C* and *S* surfaces and the evidence of two-dimensional boudinage indicate that the deformation was non-coaxial, but with a flattening type of strain with $\lambda_1 \gg \lambda_2$. The degree of non-coaxiality varied both in space and time. From the progressive development of mesoscopic structures it is concluded that the 2–3 km wide belt of ductile shear gave rise to successive anastomosing shear zones of mesoscopic scale. When a new set of shear lenses was superimposed on already sheared rocks, the preexisting foliation generally lay at a low angle to the lenses. No new folds developed where the acute angle was sympathetic to the sense of shear displacements. Where the acute angle was counter to the sense of shear, the pre-existing foliation, lying in the instantaneous shortening field, was deformed into a set of asymmetric folds.

INTRODUCTION

THE PROGRESSIVE evolution of mesoscopic shear zone structures has been described in recent years by several authors (Ramsay & Graham 1970, Coward 1976, Berthé *et al.* 1979, Berthé & Brun 1980, Simpson 1983, Choukroune & Gapais 1983). Of particular interest are the studies on the initiation and progressive development of a shear zone foliation from non-foliated rocks, the distinction of *C* and *S* surfaces and the gradual reduction in the angle between them, the development of shear lenses by interconnection of *R*, *P* and *D* shears (Tchalenko 1968, 1970) and the identification of rotated fold axes (Bryant & Reed 1969, Sanderson 1973, Escher & Watterson 1974) or sheath folds (Carreras *et al.* 1977, Quinquis *et al.* 1978, Minnigh 1979, Cobbold & Quinquis 1980, Ramsay 1980). In addition, in many ductile shear zones the structural history involves repeated deformation of relatively early structures and successive development of new structures in a single deformation. In this paper we shall be essentially concerned with this last aspect. Although we shall present evidence from the central part of the Singhbhum Shear Zone (Fig. 1) of Eastern India, the structures there are not unique and an essentially similar course of progressive deformation was noted by us in two other areas, namely, in the Kolar Gold Field of south India (Ghosh & Sengupta 1984, 1985) and in the shear zones of Darjeeling and Sikkim Himalayas.

The Singhbhum Shear Zone (Dunn & Dey 1942) or the Copper Belt Thrust (Sarkar & Saha 1964), the best studied shear zone in India, runs in an arcuate outcrop for more than 150 km and has a variable width of a few kilometres. Along the entire zone mica schists, quartzites, lenses of granite and feldspathised schists have been converted to mylonites. The subsurface structure revealed from mining operations and exploratory drilling shows that a thick zone of mylonite continues undeviated in depth to more than 3 km of dip length. The most characteristic mesoscopic structures in the mylonite belt are reclined or nearly reclined folds and a lineation parallel to the fold axis (Naha 1954, 1965, Roy 1969, Mukhopadhyay *et al.* 1975). The lineation, which appears as a grain elongation, compositional striping on the foliation or as fine grooves and ridges, is roughly parallel to slickenside striations occasionally seen in quartz veins which run parallel to the mylonitic foliation.

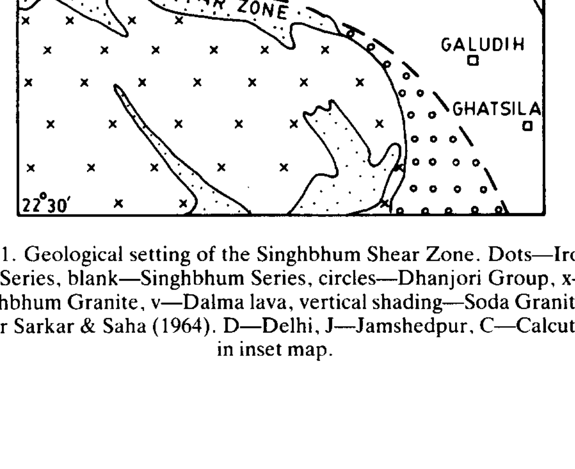

Fig. 1. Geological setting of the Singhbhum Shear Zone. Dots—Iron Ore Series, blank—Singhbhum Series, circles—Dhanjori Group, x—Singhbhum Granite, v—Dalma lava, vertical shading—Soda Granite. After Sarkar & Saha (1964). D—Delhi, J—Jamshedpur, C—Calcutta in inset map.

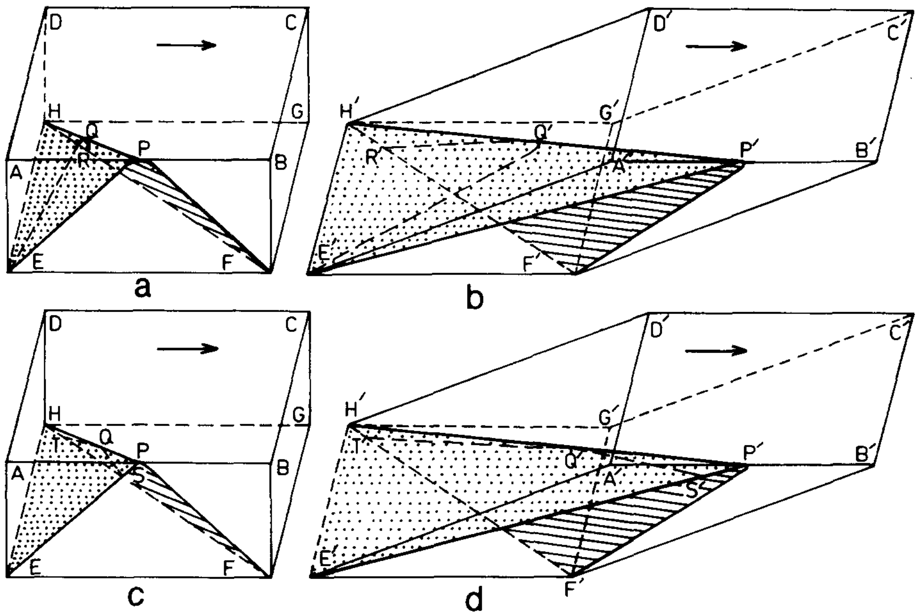

Fig. 2. Deformation of early lineation by flexural-slip followed by homogeneous simple shear. The arrows point in direction of simple shear. (a) Initial flexural-slip fold with PH as hinge line and EQR as deformed lineation at a high angle to the fold axis. ABCD—upper horizontal surface of block, EFGH—lower horizontal surface, ABFE—front vertical surface. (b) Deformation of the fold of (a) by homogeneous simple shear. Points corresponding to (a) shown by primed letters. P′H′—Deformed hinge, E′Q′R′—deformed lineation. The lineation will show a hairpin bend when the fold is unrolled. (c) Initial flexural slip fold with deformed lineation SQT at a low angle to hinge PH. (d) Deformation of the fold of (c) by homogeneous simple shear. S′Q′T′—deformed lineation. The acute angle between the lineation and the hinge opens in the same sense in all parts of the fold.

Strain analyses of deformed pebbles (Mukhopadhyay & Bhattacharya 1969, Sengupta 1977) within the shear zone show that the down-dip lineation is approximately parallel to the direction of maximum stretching and the shear zone schistosity is approximately parallel to the *XY* plane.

A central theme of the paper is that the rotation history of folds can be determined by study of folded lineations and the patterns which emerge when folds are unrolled. The mechanisms of development of the lineation patterns have been described by several authors including Ramsay (1967), Hudleston (1973), Mukhopadhyay & Ghosh (1980) and Ghosh & Chatterjee (1985). In zones of ductile shear, where the fold hinges may have rotated through large angles, the angle between an early lineation and a late fold axis may not remain the same in all parts of the fold. Such lineation patterns are produced by the combined effects of flexure and homogeneous strain. We shall consider here two such lineation patterns. In one of them (type 3b pattern of Ghosh & Chatterjee 1985) the lineation on the unrolled form surface shows an asymmetric hairpin bend with the maximum curvature at a point close to the hinge line. Whether the bulk deformation is coaxial or noncoaxial, this lineation pattern can develop only if the initial angle between the lineation and the fold axis is large. In the other type (2b pattern of Ghosh & Chatterjee 1985) the acute angle between the fold axis and the lineation is variable, with a minimum at the hinge zone, and opens in the same sense in all parts of the fold; if the angle is low we may conclude that the fold hinge was initiated at a low angle to the lineation. Figure 2 illustrates the principle of development of 3b and 2b patterns in a flexural slip fold deformed by homogeneous simple shear. The *type* of lineation pattern would have remained the same if flexural-slip and homogeneous strain had proceeded together, although the lineation pattern in this case would have been somewhat different (Ramsay 1967, 482–483, figs. 8–25, 8–26; Chatterjee 1985). Thus, if a foliation surface with a down-dip lineation is folded, the development of a 3b pattern on a reclined fold would indicate that the fold axis was initiated with a subhorizontal orientation and was rotated through a large angle to assume its present orientation. On the other hand, if the reclined fold has a 2b lineation pattern with low angles between the fold axis and the lineation we can conclude that the fold axis has not undergone significant rotation.

GEOMETRICAL GROUPING OF FOLDS

The axes of mesoscopic folds of the Singhbhum Shear Zone show a large range of pitch on the northerly dipping shear zone foliation. These can be subdivided into the following geometrically distinct groups (Fig. 3): (1) folds with axial surfaces striking parallel to the shear zone but with hinges having a pitch of 60° to 90° on the axial surface, (2) folds with axial surfaces striking parallel to the shear zone but with hinges having a low (0° to 30°) pitch on the axial surface and (3) folds with axial surfaces striking at a high angle to the regional strike of the shear zone and with hinges having a large pitch on the shear zone foliation. The three groups will be desig-

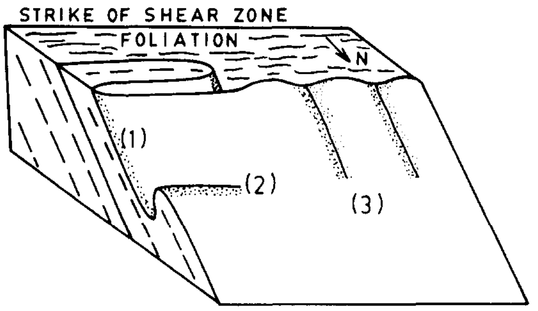

Fig. 3. Three geometrical groups of shear zone folds: (1) reclined folds, (2) subhorizontal folds, (3) upright folds trending at a right angle to the shear zone strike.

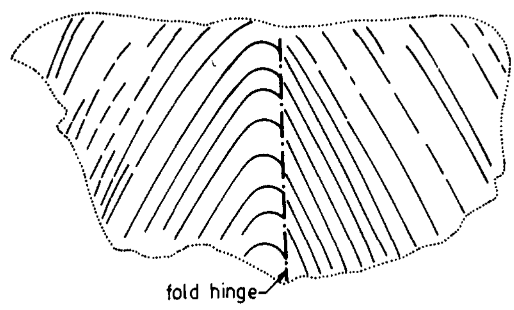

Fig. 5. Lineation pattern of the specimen of Fig. 4(c) when the form surface of the fold is unrolled.

nated in the following discussion as: (1) reclined folds, (2) late subhorizontal folds and (3) late upright folds trending at a right angle to the shear zone strike. Among these, the reclined folds are the most dominant and the late upright folds are very weakly developed.

REPEATED DEVELOPMENT OF RECLINED FOLDS, FOLIATIONS AND LINEATIONS

The Singhbhum Shear Zone very rarely shows isoclinal folds of bedding where the hinge zones are *not* wrapped around by a bedding-parallel foliation. The folds are reclined and a mylonitic foliation is axial planar to them. The mylonitic lineation runs parallel to the fold hinges. These are the earliest generation of structures recognised in the Singhbhum Shear Zone.

The most dominant reclined folds, seen all along the shear zone, are isoclinal (Fig. 4a) and have folded the early mylonitic foliation. A second generation of mylonitic foliation has developed parallel to their axial surfaces. Thus the mylonitic foliation which we see in most places is a transposition structure. While the hinges of these second generation reclined folds are parallel to a set of fine wrinkles and to an intersection lineation marked by a colour striping or by traces of the new cleavage on the form surface, the mineral lineation may or may not be parallel to the reclined fold axis. A close observation of the hinge zones of reclined folds often shows an angle between the first generation mineral lineation and the second generation hinge line. The lineation generally traverses the hinge zone at a high angle, but with a somewhat asymmetric hairpin bend becomes nearly parallel to the fold axis on the limbs of the reclined folds (Fig. 4c). These are the type 3b lineation patterns (Fig. 5) as described by Ghosh & Chatterjee (1985).

Where large segments of fold hinges are exposed they show a considerable variation of pitch; the folds are strongly noncylindrical, but with essentially planar axial surfaces. True sheath folds with hairpin bends of hinge lines are rare and the majority of noncylindrical folds show discontinuous arcs with hinge angles (Williams & Chapman 1979, p. 18) larger than 80° (Fig. 6). The arcuate hinge lines show a high pitch in the major part and sharp swings to zero pitch in comparatively short segments.

Where the fold hinge is subhorizontal, the first generation lineation and the second generation fold axis are approximately at right angles in both the hinge zone and on the limbs. As the hinge swings to a larger pitch the angle between the hinge and the mineral lineation decreases and in the reclined folds they become essentially parallel; however, in the neighbourhood of the hinges of such folds the lineation remains at a high angle to the hinge line (Fig. 6). Such lineation patterns develop where the early lineation and the later fold hinge were *initially* at a high angle to each other. Hence we conclude that the reclined folds were initiated with a subhorizontal orientation of the hinges and were subsequently rotated to become approximately parallel to the down-dip stretching lineation.

The fold packets are often separated by anastomosing zones of intense shear. Within the less deformed lenses (Fig. 7) the second generation axial plane foliation occurs at a low angle to the lens walls and the acute angle points towards an up-dip movement, in agreement with

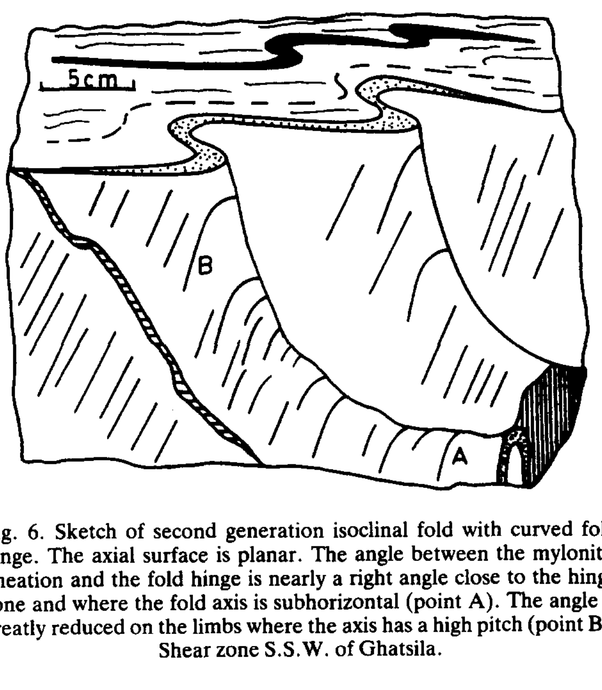

Fig. 6. Sketch of second generation isoclinal fold with curved fold hinge. The axial surface is planar. The angle between the mylonitic lineation and the fold hinge is nearly a right angle close to the hinge zone and where the fold axis is subhorizontal (point A). The angle is greatly reduced on the limbs where the axis has a high pitch (point B). Shear zone S.S.W. of Ghatsila.

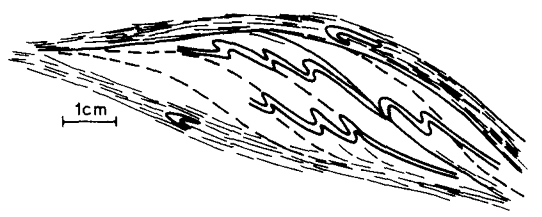

Fig. 7. Lens of less deformed rocks bounded by anastomosing shear zones. The axial plane foliation of the asymmetric second generation folds swerves to become parallel to the foliation of the bounding shear zones. Within the shear zones the folds are almost obliterated. Quartzose mica schists near Surda, S.W. of Ghatsila.

the sense of asymmetry of the folds. The angle between the axial-plane foliation and the lens wall is reduced towards the borders of the lenses. Within the shear zones themselves the first generation foliation (represented by the form surfaces of the folds) is almost obliterated and remains only as a few rootless relict folds. The foliation in these anastomosing shear zones is a well-developed second generation structure with a new mineral lineation plunging down-dip, approximately parallel to the hinges of the second generation reclined folds within the shear lenses.

The third generation folds are fairly common and are mostly seen as moderately tight asymmetrical folds of the quartzite mylonite banding or as coarse crenulations in the phyllonites. The fold hinges show a large variation in pitch even within a single exposure; however, the majority of them have a large pitch on the axial surface and are more or less reclined. Although the folds are noncylindrical, their axial surfaces are essentially planar and are either at a low angle to, or approximately parallel to, the dominant shear zone foliation. Hook-shaped outcrop patterns resulting from interference of second and third generation reclined folds can be recognised in several places. These late reclined folds almost invariably show deformation of the earlier mineral lineation and of the second generation intersection lineation over their fold hinges. On the unrolled form surface the mineral lineation shows an asymmetric U-shaped pattern (Fig. 8a). However, over some of the third generation folds the lineations parallel to the second generation fold hinges may show either a U-shaped pattern or may cross the third generation hinge zone at a low angle (Fig. 8b). In the latter case the lineation is

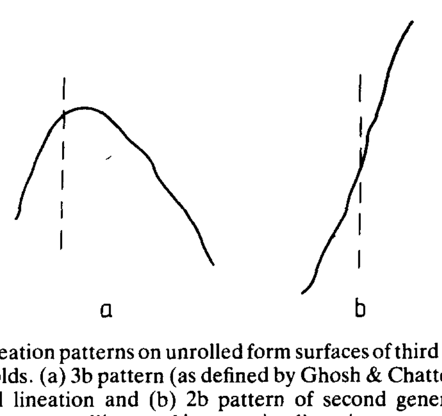

Fig. 8. Lineation patterns on unrolled form surfaces of third generation reclined folds. (a) 3b pattern (as defined by Ghosh & Chatterjee 1985) of mineral lineation and (b) 2b pattern of second generation fold mullions and intersection lineation.

either unrollable or shows a gentle curvature on the unrolled form surface (type 2b pattern of Ghosh & Chatterjee 1985). Such patterns could have developed if the initial angle between the second and the third generation fold hinges was not too large. These relations suggest that the third generation folds were initiated when some of the second generation folds had undergone only a partial rotation. In other words, in some places the second generation fold hinges had acquired only a low to moderate pitch when the third generation folds were initiated with a subhorizontal attitude. With progressive deformation certain segments of both fold hinges rotated to an almost reclined position.

The crenulation cleavage associated with the third generation folds varies in intensity and is either parallel to the alignment of some of the anastomosing shear zones or makes a low angle with them in their intervening less deformed lenses. Where the cleavage is well-developed it contains a new down-dip lineation.

LATE SUBHORIZONTAL FOLDS

Late subhorizontal folds, which deform the mineral lineation and hinges of all the reclined folds, occur throughout the entire length of the central part of the Singhbhum Shear Zone and are mostly concentrated towards its frontal or northern part. The best and the most well-known exposures are located in the quartzite mylonites south of Jamshedpur. These are generally described as folded mylonites, although as we have seen, excepting the rarely preserved first generation reclined folds, all the other reclined folds had also developed in mylonitised rocks.

Wherever long segments of the late fold hinges are exposed, they are arcuate, discontinuous and at a low angle to one another, with a generalised subhorizontal orientation. This arcuate form is present even when the folds are quite open (Fig. 9a). Although such open folds are nonplanar and noncylindrical, with increasing tightness and asymmetry their axial surfaces make lower angles with the enveloping surfaces. Thus, fairly tight noncylindrical folds have essentially planar axial surfaces. Where the fold axis is horizontal the deformed lineation is usually normal to the fold axis (Fig. 9c). Where the fold axis has a moderate pitch on the axial surface the lineation may be unrollable in some cases (Fig. 10f), but usually the angle between the lineation and the fold axis varies in different parts of the fold (Figs. 9b and 10a–e).

The broadly orthogonal relationship between the early lineations and the generalised orientation of the late folds, the localised development of an axial-planar foliation and of a lineation on it approximately parallel to the dominant shear zone lineation, and the sense of asymmetry of the folds consistent with an up-dip movement of structurally higher layers, indicate that this group of folds, though later than all the reclined folds, must have grown in the course of a progressive deformation associated with the development of the ductile shear

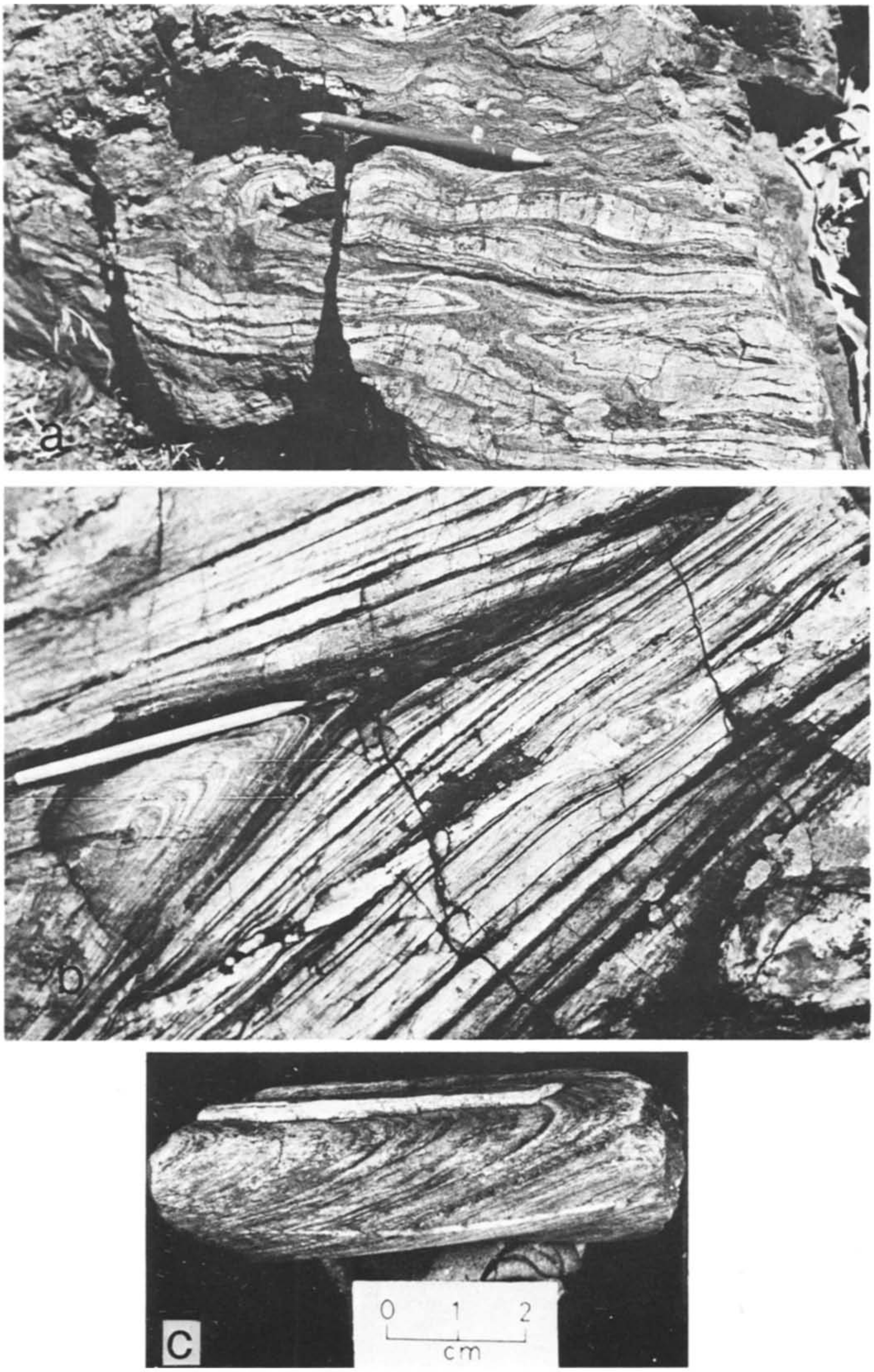

Fig. 4. (a) Reclined isoclinal folds of second generation from Ramchandra Pahar, south of Jamshedpur. The axial surfaces are deformed by nearly coaxial open upright folds. The photograph is a down-plunge view, looking N. (b) Transverse profile of a late subhorizontal fold with a quartz vein emplaced parallel to its axial surface. The vein quartz itself is mylonitised and is subjected to pinching-and-swelling. (c) Specimen of second generation isoclinal fold with deformed first generation lineation. This is a composite lineation with mineral elongation parallel to colour striping. The traces of second generation axial planar cleavage on the form surface are faintly visible at the hinge zone. The pattern of first generation lineation on the unrolled form surface is shown in Fig. 5.

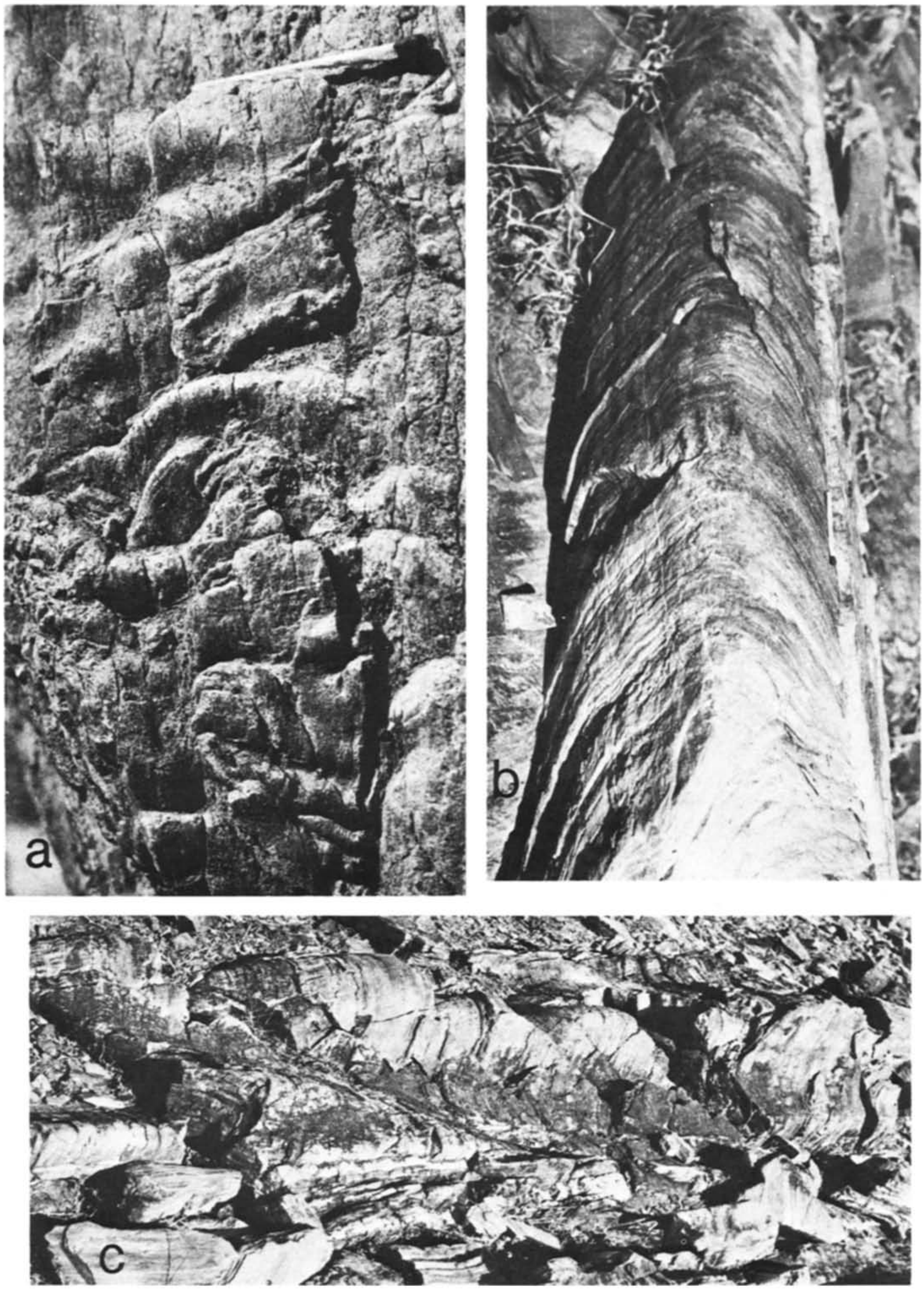

Fig. 9. (a) Late subhorizontal open folds in quartzite mylonite near Ramchandra Pahar, south of Jamshedpur. Note the discontinuous arcuate hinges. The matchstick is parallel to strike. The mylonitic lineation is down-dip. (b) Moderately plunging late fold with deformed lineation. When the fold is unrolled the lineation shows a slightly asymmetric U-shaped curve. South of Jamshedpur. (c) Subhorizontal fold in quartzite mylonite with lineation at a right angle to fold axis in all parts of the fold. Nandup, S. of Jamshedpur. Length of photograph represents 1.6 m.

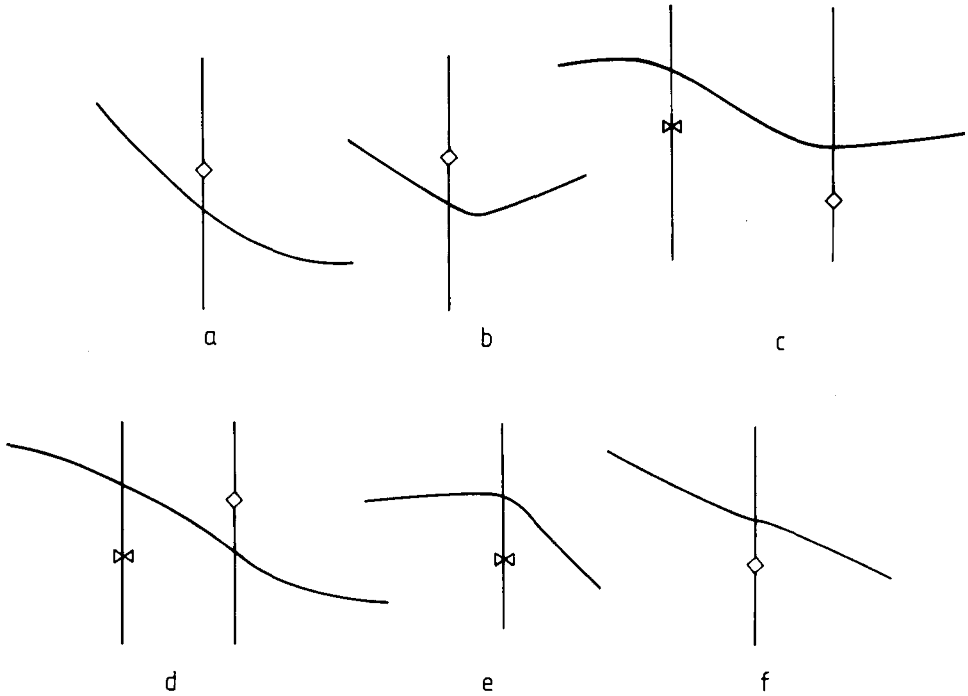

Fig. 10. Patterns of deformed lineations on unrolled form surfaces of late subhorizontal folds.

zone. These late folds are the least rotated among the shear zone folds; hence it is reasonable to assume that their geometry is similar to the initial geometry of the reclined folds prior to rotation.

LATE UPRIGHT FOLDS TRENDING PERPENDICULAR TO SHEAR ZONE TREND

These locally developed open folds range in size from fine crenulations to warps on the map-scale. They refold the reclined folds and the inclined subhorizontal folds (Fig. 4a). The hinges of the folds are either parallel to, or are at a low angle to, the reclined fold hinges and the mylonitic lineation. The open character of the folds, the low angle between the lineations and the fold hinges and absence of strongly curved lineation patterns on the unrolled form surfaces indicate that the hinges of these folds, although they are approximately coaxial with the reclined folds, did not undergo any significant rotation but were initiated in their present orientation. The genetic relationship of these folds to the shear zone structures is not clear, since the folds have grown later than the last stages of mylonitization.

STRUCTURAL EVOLUTION IN PROGRESSIVE DEFORMATION

Although the mesoscopic structures of the central segment of the Singhbhum Shear Zone show a broad homogeneity and a uniformity of the structural history throughout its length and width, in detail the deformation is characteristically heterogeneous, with anastomosing shear zones sweeping around lenses of less deformed rocks. The asymmetrical folds, which grew during the development of a shear lens, may belong to any one of the three generations of reclined folds or may even belong to the group of subhorizontal folds. That the intensity of deformation in the Singhbhum Shear Zone is variable in both space and the time is clearly shown by development of thin subparallel shear zones in the quartzite mylonites south of Jamshedpur. The development of these shear zones was broadly contemporaneous with the growth of late subhorizontal folds. The shear zones, a few millimetres to a few centimetres thick, run roughly parallel to the axial surfaces of strongly asymmetrical late subhorizontal folds and are separated by slabs or lenses of folded quartzite mylonite a few centimetres to a few decimetres thick. The anastomosing shear zones have thus formed repeatedly in different stages of development of the Singhbhum Shear Zone.

The shear zone folds are disharmonic and show type 1B or 1C fold morphology in competent units; hence they were initiated as buckling folds. The initial orientation of a newly formed hinge within a shear lens would depend on the orientation of the pre-existing foliation with respect to the incremental shortening field. Thus a certain amount of dispersion of the orientation of the initial fold axes is expected. The occurrence of deformed mineral lineations, with low angles between the lineation and the axis of some of the third generation reclined folds, suggests that the hinges of some of these folds were initiated at high angles to the Y-axis of bulk strain. Thus a comparatively small number of reclined folds might not have undergone significant rotations of their hinges. However, the evidence adduced in the foregoing section leads us to conclude that the majority of transport-parallel folds rotated through large angles to assume their present reclined attitude. The geometry of the least rotated late subhorizontal folds suggests that the majority of reclined folds were initiated as non-plane folds with discontinuous arcuate hinge lines, which had an overall trend approximately parallel to the Y-axis but with characteristic local deviations. The angle between the Y-axis and the local hinge line was generally less than 30°. With progressive shearing movement, the geometry of the folds was modified so that (1) the folds were tightened, (2) their asymmetry increased, (3) the curvature of the axial surfaces decreased, (4) the hinge lines rotated towards X, (5) the early lineation on the fold limbs rotated towards X, (6) a new axial-planar cleavage developed and (7) a new stretching lineation was superimposed on it. In the final stage the axial surfaces became essentially planar, at a low angle to the enveloping surface, while the early stretching lineation, the fold hinge which deformed the lineation and the superimposed new lineation came to lie at a low angle to one another.

The following arguments indicate that the successive development of the structures took place in the course of a single progressive deformation.

(1) Although some reclined folds occur in the fold-belt north of the Singhbhum Shear Zone (Ghosh & Sengupta, in press), they are rather rare and the dominant folds of the northern wall-rocks are E–W trending with gentle culminations and depressions. In contrast the dominant folds in the shear zone itself are reclined and northerly trending. Hence it is justified to conclude that the three generations of reclined folds of similar style and orientation, which are concentrated in a narrow zone of mylonitic rocks, grew in response to a progressive shearing movement.

(2) The repeated development of a down-dip stretching lineation on successive axial plane foliations leads us to the same conclusion.

(3) The rocks of the Singhbhum Shear Zone were profusely invaded by quartz veins (Fig. 4b) which were emplaced along successive foliations or parallel to axial surfaces of the three generations of reclined folds and of the late subhorizontal folds (Ghosh & Sengupta 1987). The quartz veins themselves are mylonitised. The mylonitic foliation and lineation within them are roughly parallel to the dominant shear zone foliation and lineation respectively. This links the three generations of reclined folds and the late subhorizontal folds with an essentially continuous process of ductile shearing.

GENERAL CHARACTER OF DEFORMATION

As mentioned above the majority of reclined fold hinges were initiated at high angles to the down-dip stretching lineation and major segments of them were rotated towards the direction of stretching. The subhorizontal segments of such folds are the least rotated segments. In all such segments the folds are strongly asymmetrical and the sense of asymmetry is in agreement with a thrusting movement. The acute angles between the C- and S-surfaces of the shear lenses also

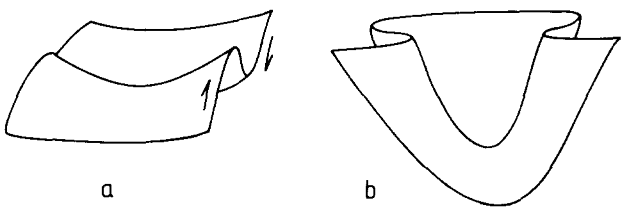

Fig. 11. Asymmetry of rotated folds. Where the fold is subhorizontal the asymmetry is consistent with a thrusting movement. After rotation the asymmetry is retained but depending on the sense of rotation the fold may show apparent dextral or apparent sinistral shear.

indicate the same sense of movement. Thus the deformation within the ductile shear zone must have been distinctly noncoaxial. It is worth noting that the asymmetrical shapes of the folds are retained after rotation to a reclined position; the sense of asymmetry of such rotated folds would be unrelated to the sense of thrusting movement. Indeed, depending on whether the rotation of a fold hinge is clockwise or anticlockwise, the sense of asymmetry may indicate either an apparent dextral or an apparent sinistral shear (Fig. 11).

The repeated development of two dimensional pinch-and-swell and boudinage (Ghosh & Sengupta, in press) of quartz veins of successive generations shows that the deformation clearly deviated from the plane-strain model of progressive simple shear. Here the Y-axis or the axis of rotation was also a direction of elongation, although the stretching along X was much larger than along Y. The evidence of two-dimensional boudinage is consistent with the earlier results of strain analysis from deformed pebbles by Sengupta (1977), who showed that in the major part of the central segment of Singhbhum Shear Zone the Y-axis was a direction of elongation. While the deformed pebbles can give only the total or cumulative strain, the development of two-dimensional boudinage on synkinematic quartz veins of successive generations indicates that the incremental strains were consistently of a flattening type with $\lambda_2 > 1$.

INITIATION OF SHEAR ZONE FOLDS

As pointed out by Platt (1983) and by Ghosh & Sengupta (1984), when shear zone folds develop repeatedly in a progressive deformation on successive generations of axial plane foliations, the major problem is to explain the *initiation* of the folds. The geometry clearly indicates that the reclined folds of all three generations and the late subhorizontal folds were initiated as buckling folds. The problem is to explain how a foliation, approximately parallel to the XY plane of a particular stage, along with the stretching lineation lying on it, could be folded at a later stage in the course of an essentially continuous deformation. The shortening of a stretching fabric is explained neither by a progressive simple shear deformation nor by deformations involving combined pure and simple shears which give rise to nonpulsating stain ellipsoids (Ramberg 1975). Moreover, if we assume that the orientation of a parallel set of shear zone walls and the sense of their shear displacements remain constant, then any conceivable manner of variation in time of the ratio of the rates of pure strain to simple shear cannot bring a stretched linear element into the shortening field. We consider below some of the alternative mechanisms.

Some earlier studies of drag folds (Ramberg 1963, 1964, Ghosh 1966) indicated that buckling folds were not formed by a layer-parallel shearing movement; the drag merely rotated the axial planes of folds which had already formed by a layer-parallel compression. However as yet no experimental studies on drag folding have been made with anisotropic materials and with sheets whose mechanical property varies along the plane of layering. No doubt folds could have been generated by local disturbances in the flow field around rigid or less deformed units such as porphyroclasts, pebbles or boudins (Bell 1978, Cobbold & Quinquis 1980). This cannot be a general explanation since, as Platt (1983) points out, the majority of shear zone folds do not show such an association with localised islands of undeformed rocks. Yet, with their boudinage and pinch-and-swell on mesoscopic and microscopic scales, transposed layering and strong spatial variation in the anisotropic character, the shear zone rocks are mechanically heterogeneous in a pervasive manner. In an earlier publication (Ghosh & Sengupta 1984) we considered the possibility that in such mechanically heterogeneous foliated rocks, the translatory movement of sheets of rocks past one another will be facilitated in certain segments and inhibited in others. This will give rise to zones of layer-parallel shortening where the foliation can be folded. Moreover, since the variation in mechanical property is present both along and across the direction of shear, the folds will be characteristically discontinuous and noncylindrical. This process can be considered as sufficiently general to explain the more or less regular development of shear zone folds, provided the totality of small local disturbances creates a mechanical instability within a much larger volume in which the foliated rocks can undergo buckle folding. According to Lister & Williams (1983), a variation in strength properties in layers translating past one another may cause a perturbation in the flow field and generate a local spin or body rotation; propagation of the disturbances in the flow field will alter the flow character over a much larger volume of rock. A somewhat similar mechanism was also proposed by Platt (1983), who considered infinitesimal variations in the rate of shear strain along the foliation. A small increase in the rate will cause a forward rotation of the S-surface and the resulting fold will amplify with progressive deformation.

Within major ductile shear zones the total shear displacement is accomplished by separate displacements along numerous small shear zones, which develop heterogeneously throughout the belt and are superimposed on one another. In such a situation the foliation need not remain in the extension field nor parallel to the planes of shear. Thus, the 2–3 km wide belt of Singhbhum Shear Zone is composed of smaller anastomosing shear zones of the mesoscopic scale. The anastomosing shear zones could have formed according to the model proposed by Ramsay (1980) by the joining of curving tips of two approaching shear zones or in a manner analogous to the merging of principal displacement (D) shears and thrust (P) shears (Tchalenko 1968, 1970). During the initial stage of development of a shear lens the newly formed foliation and lineation within it would remain at an acute angle to the bounding shear zones. The acute angles are in the same sense as the shear displacements. With progressive deformation this angle is reduced. Finally, with increase in thickness of the bounding shear zones the remnant pods lose their separate identity. A similar course of development was recorded by Simpson (1983) from the sheared granite gneiss of the Maggia Nappe in Switzerland. In the Singhbhum Shear Zone such shear lenses have developed repeatedly at different stages of progressive deformation. When a new set of shear lenses is superimposed on the already sheared rocks, the pre-existing foliation and lineation within the lenses will not necessarily be parallel to their walls; in general they will make a low angle with the lenses and the acute angle will not necessarily be in agreement with the sense of shear displacement. No new folds will develop when the acute angle is sympathetic with the sense of displacement; but when counter to the sense of shear, the pre-existing foliation will lie in the instantaneous shortening field and become deformed into a set of asymmetric folds (Fig. 12). Because of the mechanical heterogeneity of the rocks and the heterogeneous character of displacements within the lozenge-shaped pods, the fold hinges are likely to be initiated in an arcuate manner.

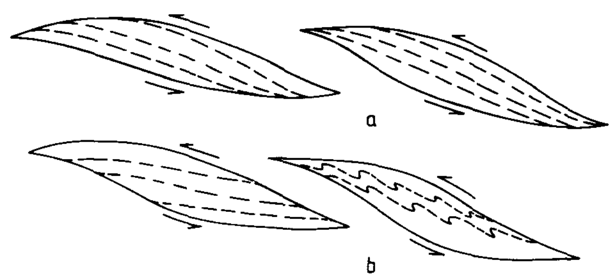

Fig. 12. Newly formed shear lens superimposed on already sheared rocks. (a) No new folds develop when acute angle between pre-existing foliation and shear zone border is sympathetic to sense of shear. (b) New folds are initiated when acute angle is counter to sense of shear.

Although both the above mentioned proposals are viable for the origin of shear zone folds we realise that they are tentative solutions and that the problem of initiation of shear zone folds requires a much more thorough analysis. As mentioned above and in Ghosh & Sengupta (1984, pp. 707–708, 1985), shear zone folds show all the morphological characters of buckling folds, and regarding the first proposal, viz. the initiation of folds by a foliation-parallel shear, the theoretical analyses have yet to demonstrate the presence of a wavelength choosing mechanism.

CONCLUSIONS

(1) In the Singhbhum Shear Zone successive generations of folds grew in response to a progressive shearing movement. The majority of reclined folds initially grew with arcuate hinges with an overall trend subparallel to the shear zone strike and to the Y-axis of strain. With progressive deformation large segments of the hinges were rotated towards the down-dip direction of stretching (cf. Sanderson 1973). After the last phase of mylonitisation, a set of open upright folds were initiated with hinges subparallel to the stretching lineation.

(2) The mylonitic foliation was repeatedly transposed in the course of an essentially continuous deformation. The down-dip stretching lineation consists of both rotated earlier lineations and superimposed new ones. The patterns of deformed stretching lineations and intersection lineations over the fold hinges not only enable us to distinguish successive episodes of deformation, but also indicate whether rotated hinges were initially at a high or a low angle to the lineation.

(3) The lineation patterns indicate that the present coaxiality of successive generations of folds, plunging down the dip of the shear zone, was brought about in different ways: (a) most commonly, by refolding of a fully rotated reclined fold, around a subhorizontal axis, and subsequent rotation of the later hinge towards the down-dip direction (Fig. 13a), (b) by initiation of a third generation hinge after a second generation one was partially rotated to a low or moderate pitch, and by subsequent rotation of both hinges towards the down-dip direction (Fig. 13b), and (c) by initiation of a new hinge (late upright folds and some of the third generation folds) subparallel to, or at a low angle to, the already rotated reclined fold hinges (Fig. 13c).

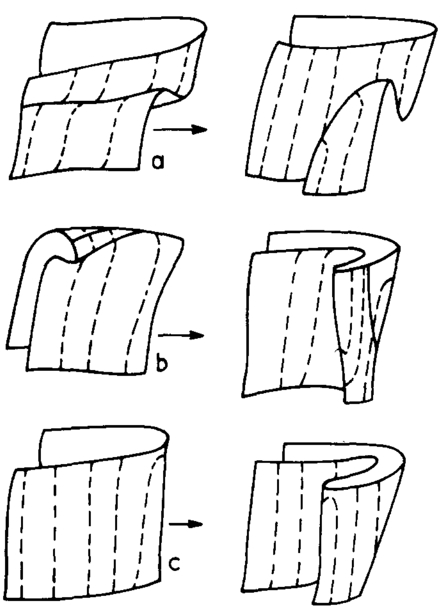

Fig. 13. Three different sequences in development of broadly coaxial folds: (a) by refolding of reclined fold around a subhorizontal axis and subsequent rotation of later hinge towards down-dip direction, (b) by refolding on subhorizontal axis of an earlier fold with low to moderate pitch of fold axis and by subsequent rotation of both hinges towards the down-dip direction of the axial surfaces and (c) by refolding of a reclined fold on a new down-dip hinge. Note the different patterns of deformed mineral lineation (dashed lines) and intersection lineation (continuous line) on the later fold.

(4) The deformation in the shear zone is characterised by both a larger magnitude of strain and a higher degree of noncoaxiality with reference to the deformations outside the shear zone. In the Singhbhum Shear Zone the noncoaxial deformation significantly deviated from the plane-strain model and, during the major period, the Y-axis was a direction of elongation, with $\lambda_1 \gg \lambda_2$.

(5) Mesoscopic shear lenses wrapped by anastomosing shear zones repeatedly developed at different stages of progressive deformation.

(6) The shear zone folds were generated by buckling. We have considered two likely mechanisms for the fold initiation: (a) Shear zone folds could have been initiated due to the unequal ease of gliding in mechanically heterogeneous foliated rocks. (b) The folds may develop when a new set of shear lenses is superimposed on already sheared rocks. The pre-existing foliation will generally lie at a low angle to the lens walls. No new folds develop where the acute angle points to the direction of shear; but where it is opposite to the direction of shear, the pre-existing foliation is progressively shortened to give rise to a series of asymmetric buckling folds.

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