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Singhbhum Shear Zone: Structural transition and a kinematic model

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Abstract. The northern fold belt away from the Singhbhum Shear Zone displays a set of folds on bedding. The folds are sub-horizontal with E–W to ESE striking steep axial surfaces. In contrast, the folds in the Singhbhum Shear Zone developed on a mylonitic foliation and have a reclined geometry with northerly trending axes. There is a transitional zone between the two, where the bedding and the cleavage have become parallel by isoclinal folding and two sets of reclined folds have developed by deforming the bedding—parallel cleavage. Southward from the northern fold belt the intensity of deformation increases, the folds become tightened and overturned towards the south while the fold hinges are rotated from the sub-horizontal position to a down-dip attitude. Recognition of the transitional zone and the identification of the overlapping character of deformation in the shear zone and the northern belt enable the formulation of a bulk kinematic model for the area as a whole.

Keywords. Shear zone; progressive deformation; rotation of fold hinges; kinematic model; Singhbhum Shear Zone; deformed lineation pattern; refolding;

1. Introduction

The structural evolution of a ductile shear zone cannot usually be studied in isolation from that of the wall rocks. In many shear zones running through massive granites (e.g. Ramsay and Graham 1970; Mitra 1979; Berthé *et al* 1979; Simpson 1983; Gapais *et al* 1987) the wall rocks remain rigid while ductile deformation is localized only in the shear zone. On the other hand we often encounter shear zones running along narrow belts through regionally deformed terrains. The classical description by Albert Heim of the development of a thrust along the middle limb of an overturned fold is a clear example of intense shearing within a volume of rock that is undergoing deformation synchronous with the development of the shear zone itself.

Although the development of a mylonite belt with deforming wall rocks is not uncommon, there are only a few detailed studies about the interrelation of the deformations of the shear zone and its walls, especially in connection with the development of macroscopic shear zones. In many cases it is not clear, for instance, whether the structures within the shear zone and its walls are synchronous, geometrically similar or different, and whether they are gradational or display an abrupt change. The Singhbhum Shear Zone (SSZ) and the folded belt lying to its north (Dunn and Dey 1942) are ideal for such a comparative study since the structures of both these tectonic units have been analysed by a number of workers (Naha 1955, 1965; Sarkar and Saha 1962, 1977; Roy 1969; Mukhopadhyay *et al* 1975; Mukhopadhyay 1984; Ghosh and Sengupta 1987a). A comparative study of the structural histories of the SSZ and the northern belt (Ghosh and Sengupta 1987b) revealed the broadly overlapping character of the progressive deformations of the two regions. Our recent investigations also indicate that there is no abrupt change in the geometry of structures as we pass from the shear zone to the fold belt. To the immediate north of the shear zone there is a transitional zone in which the fold styles and the orientation of the cleavages are similar to those of the shear zone. The structural style of this transitional zone grades southward to that of the shear zone and northward to the characteristic style of the northern fold belt.

The structural history of SSZ is intimately related to the repeated development of folds and the rotation of their axes during progressive deformation. In SSZ the rotation history of folds can be determined not only from the geometrical character of the folds themselves but also from a study of the folded lineation and the patterns which emerge when the folds are unrolled. In the following discussion we shall first describe general principles of the development of different patterns of deformed lineation loci resulting from synchronous buckling and flattening while the fold hinges are being rotated towards the direction of maximum stretching. This will be followed by a description of the sequence of fold generation in SSZ and the rotation history of the folds. The structures of the transitional zone will then be compared with those of the fold belt lying north of it and SSZ lying to its south.

The recognition of the broadly overlapping character of deformations in the shear zone and the northen belt, a correlation of the structural histories of the two domains and the identification of transitional structures have determined a basis for the formulation of a kinematic model for the region as a whole. Evidently, such a kinematic model would be meaningless if the SSZ structures were entirely earlier or later than those of the northern belt. The problems associated with the bulk kinematics of the region have been discussed in the last section.

2. Significance of deformed lineation patterns in SSZ

When an early lineation is deformed by a flexural slip fold the initial angle between the lineation and the fold axis remains the same in all parts of the fold. The lineation can be straightened out when the form surface of the fold is unrolled. If an early lineation occurring on a planar surface is deformed by shear folding, the angle between the lineation and the fold axis varies from place to place; the deformed lineation, however, lies parallel to a plane defined by the shear direction and the initial orientation of the lineation. The deformed SSZ lineations often deviate from either of these ideal patterns. The lineations can neither be unrolled as expected in flexural slip folding nor do they lie in a plane as expected in shear folding. Moreover, the geometry of the folds always indicates that the folds have developed by buckling. These lineation patterns could develop if the process of folding involved both an external rotation or flexure and simultaneous flattening. The development of lineation patterns which connot be unrolled by such a folding process is commonly associated with the rotation of fold hinges during progressive growth of the folds.

The theoretical model of Ghosh and Chatterjee (1985) considers a special situation for the formation of such lineation patterns by simultaneous buckling and flattening. The authors consider the situation in which the axial plane of a fold maintains a constant orientation. Within the axial plane the fold hinge may have an initial orientation that is not necessarily parallel to the X-axis. With progressive tightening of the fold, the hinge remains in the XY-plane but gradually rotates towards the X-axis. Ghosh and Chatterjee have noted that, in such a model, the type of lineation pattern depends largely on the initial angle between the lineation and the fold axis. A convenient method of obtaining the lineation pattern is to place a transparent polythene sheet over the folded surface and to trace out with a marking pen the hinge line and the deformed lineation. When the transparent sheet is flattened the trace of lineation on it may show any one of several typical patterns. The U- or V-shaped pattern develops only when the initial angle between the lineation and the fold axis is almost a right angle. In the theoretical model the progressive deformation was achieved by a succession of incremental deformations. Two types of incremental deformation occur in alternate steps. In one of these, the layer undergoing folding is deformed by a very small homogeneous shortening perpendicular to the axial plane; the homogeneous deformation causes a tightening of the fold, a rotation of the fold axis and a deformation of the lineation lying on the form surface. Because of the diverse orientations of the lineation in different parts of the fold the angle between the lineation and the fold axis changes differently on the limbs and the hinge. In the next step of incremental deformation the folded layer is shortened by a small amount of external rotation. The angle between the fold axis and the lineation does not change in this step. Two such alternating steps make one cycle. The fold was deformed by 200 cycles. Figure 1a shows four stages of deformation for the case in which the fold axis was initially at an angle of 20° with the X-axis while an initial symmetrical fold had a 1° limb dip. The lineation initially made an angle of 85° with the fold axis in all parts of the fold. The deformed lineation loci for the four stages of

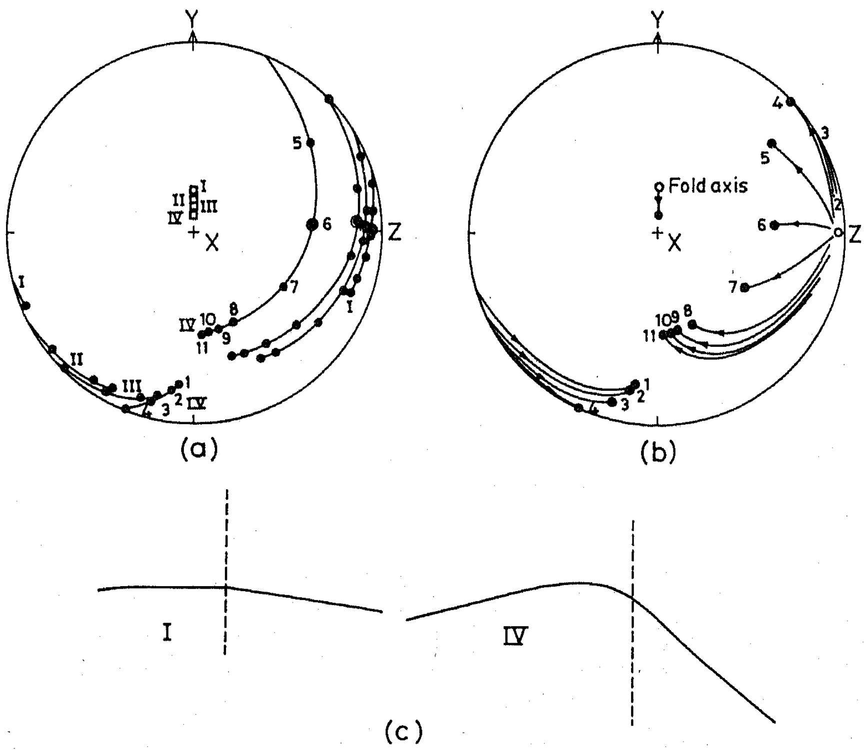

Figure 1. (**a**) Equal area projection of deformed lineation loci corresponding to 10, 50, 100 and 200 cycles of combined buckling and flattening increments. X, Y, Z are the bulk strain axes. Squares—fold axes; dots—lineations; encircled dots—lineations at hinge. Lineations 1 and 11 are at the two points of inflection of a fold, (**b**) Paths of lineations with progressive deformation for the case considered in (**a**). (**c**) Lineation patterns on the unrolled form surfaces for I (cycle 10) and IV (cycle 200). Dashed line—fold hinge.

progressive deformation, for 10, 50, 100 and 200 cycles are shown in figure 1b. The corresponding lineation patterns on the unrolled form surface for the first and the fourth stages are shown in figure 1c. The angle between the fold axis and the lineation remains large, at or near the fold hinge; the angle is much smaller in the limbs of the folds.

According to Ghosh and Sengupta (1987a) this lineation pattern may also develop in non-coaxial deformation in which the initial angle between the lineation and the fold axis is large. The frequent occurrence of this lineation pattern in SSZ leads to the following conclusions. (i) The initial angle between the lineation and the fold axis was close to a right angle. Since the mineral lineation in SSZ was always initiated with a large pitch on the mylonitic foliation, the initial fold axis must have been subhorizontal or gently plunging. The mineral lineation in SSZ is approximately parallel to the direction of maximum stretching. The fold axis was thus initially at a low angle to the Y-axis of bulk strain. (ii) During progressive shearing the fold axis rotated towards the down-dip X-axis and the fold became nearly reclined. (iii) Near the fold hinge the lineation continued to make a high angle to the fold axis but on the fold limbs the lineation rotated to become nearly parallel to the axis.

3. Refolding in SSZ

The mylonites of SSZ show different generations of mesoscopic folds. The most prominent among these are the *reclined folds*. There are three generations of reclined folds in SSZ (Ghosh and Sengupta 1987a, b). The *first generation reclined folds*, the earliest folds in SSZ, have developed on a mylonitic foliation. We had earlier reported that the first generation folds had developed on a bedding. However, later microscopic studies revealed that the lithologic layering on which the folds had developed is parallel to a mylonitic foliation. Even if this layering is derived from bedding laminae its orginal character has been modified by intense deformation. The first generation folds are strictly isoclinal, with extremely large amplitude-wavelength ratios and often with an axial planar foliation which itself is mylonitic. The hinges and axial surfaces of these folds have been deformed by two successive generations of reclined folds. Simultaneous overprinting of all the three sets of reclined folds has been observed at a few places (figure 2); however, overprinting (figure 3C) of two of the three generations of reclined folds is observed in many outcrops especially near Pathargora, Surda ridge, Bhatin ridge, the low ridge east of Ramchandra Pahar and along the northern border of the shear zone north of Ramchandra Pahar. A new generation of mylonitic foliation has also developed parallel to the axial surfaces of the *second generation reclined folds*. A crenulation cleavage has sporadically developed during the *third generation reclined folding*.

The axial surfaces of reclined folds of all the three generations have been deformed by two sets of later folds, i.e. *subhorizontal folds* and *upright transverse folds*. The subhorizontal folds are fairly common throughout SSZ. Most of these are strongly asymmetrical, moderately tight and have north-dipping axial planes. There is also a somewhat later set of subhorizontal folds; these are open or gentle folds with south-dipping axial planes (figure 4). The upright transverse folds are mostly open with axes subparallel to the mylonitic lineation. In almost all cases they interfere with the open subhorizontal folds and give rise to a dome-and-basin structure in the

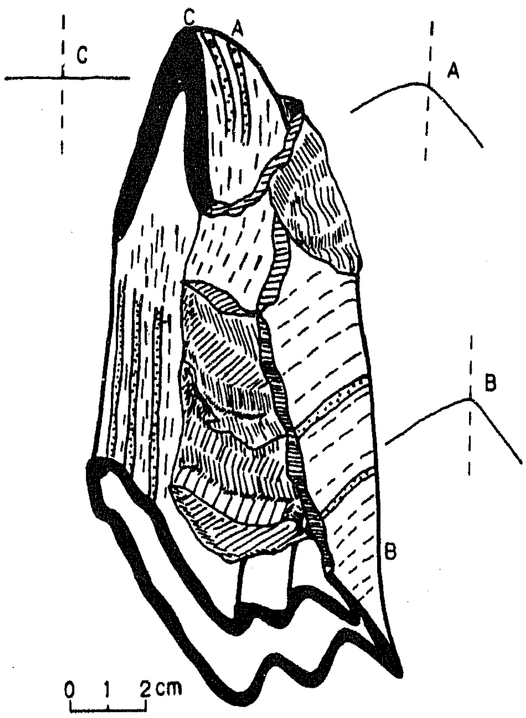

Figure 2. Three generations of reclined folds in a hand specimen of banded granite mylonite from the Pathargora quarry. The hinge of the earliest fold is seen on the left margin. The hinge of the second generation fold curves from sub-horizontal to a steep attitude and occurs at the right and at the top margin. The hinges of third generation folds are seen towards the bottom. Dashed line—mineral lineation, dotted segment—striping on foliation surface. The lineation-patterns obtained by unrolling the form surface around the local hinge segments at points A, B and C are also shown.

mesoscopic scale. The time-relation between the upright transverse folds and the subhorizontal folds is not clearly established from the interference patterns. However, both sets of folds are undoubtedly later than the reclined folds.

4. Rotation of fold hinges

The reclined folds of SSZ are strongly non-cylindrical even when they maintain approximately planar axial surfaces. The exposed hinge lines usually occur in short discontinuous arcs and sometimes as clearly defined sheath folds with hinge lines deformed into hair pin bends within more or less planar axial surfaces (figure 3d). The arcuate hinge lines have short subhorizontal segments and large segments with a high pitch on the axial surfaces. A few excellent three-dimensional exposures of sheath folds occur in the low quartzite ridge east of Ramchandra Pahar.

The geometrical relation between the down-dip mineral lineation and the axes of the nearly reclined folds (figure 2, figure 3a, b) is rather complex. Although there is a general belief that the axes of the reclined folds are parallel to the down-dip mineral lineation of the mylonites, this is not strictly true. Just as the earliest mylonitic foliation has been deformed by the earliest reclined folds, similarly the earliest mylonitic lineation has been folded over the hinge zones of all sets of reclined folds. The geometrical relation between the mineral lineation and the hinge lines of reclined

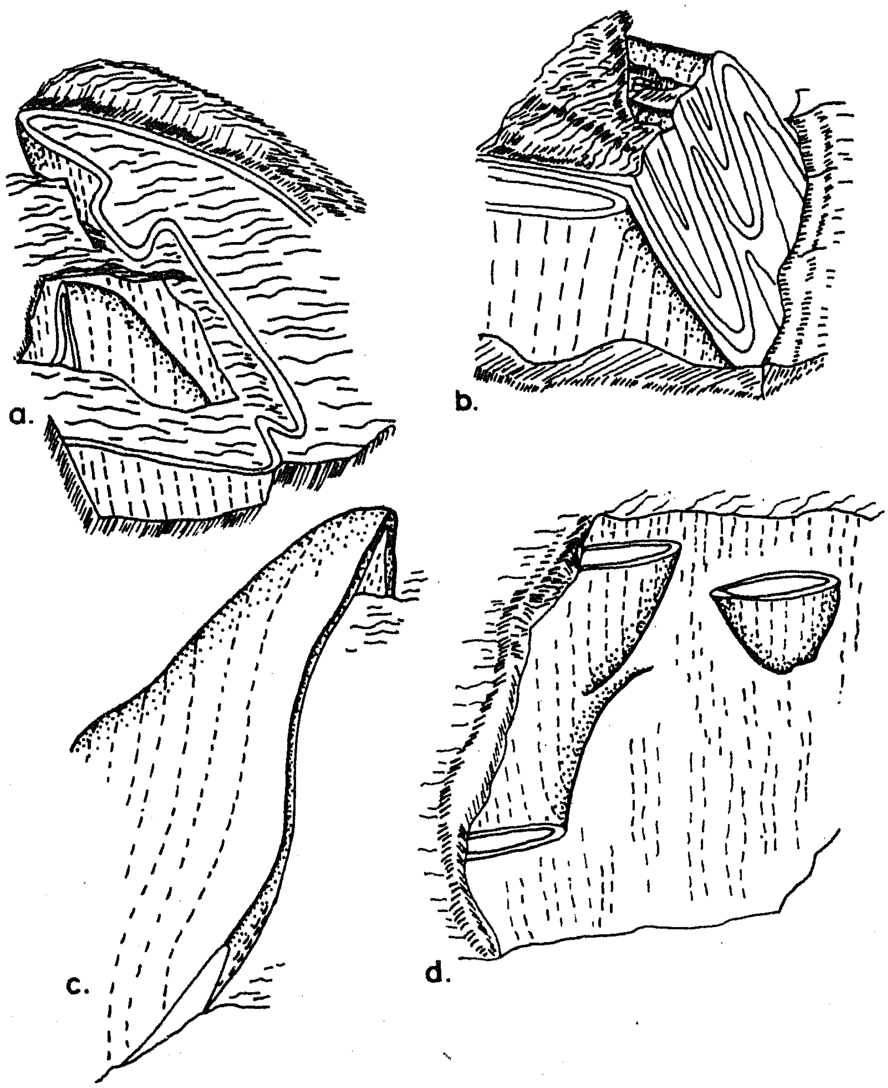

Figure 3. (**a**) Folding of mineral lineation (dashed line) over arcuate hinge line in quartz-mica schist. Ramchandra Pahar. (**b**) Reclined fold and subhorizontal folds in Bhatin ridge. Note the angle between lineation and the hinge of the reclined fold. (**c**) Hinge of first generation isoclinal fold deformed by second generation fold. Pathargora. (**d**) Arcuate hinge lines and sheath folds in Ramchandra Pahar. Dashed lines—mineral lineation.

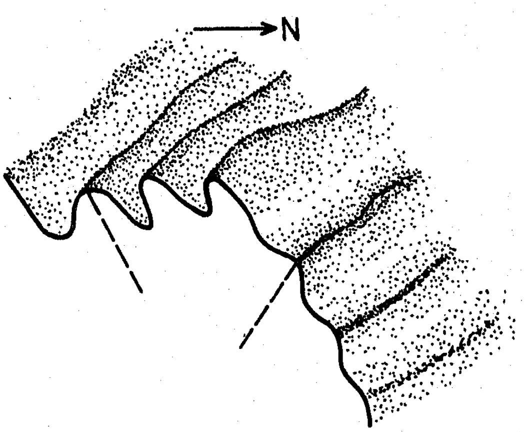

Figure 4. Two types of sub-horizontal folds in SSZ. The tighter has north-dipping axial planes and the open and gentle folds have axial planes dipping towards S.

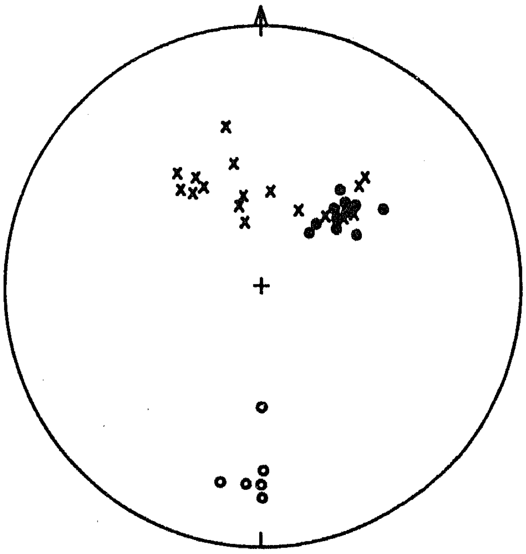

Figure 5. Equal area projection of axes of nearly reclined folds (X), mineral lineation (dot) and poles to axial planes (circles) from an outcrop at Bhatin ridge.

folds is most clearly observed on the second generation reclined folds which are the most dominant and the most commonly observed mesoscopic folds of SSZ. Thus, figure 3b, the sketch of an outcrop in the Bhatin ridge, shows that both the mineral lineation and the fold hinges have large pitches on the limb of the isoclinal fold. However, the fold axis plunges 50° towards 320° while the lineation on the limb plunges 42° towards 60°. The lineation has more or less the same attitude on both the limbs of the fold and it curves over the fold hinge with a hair-pin bend. On the unrolled form surface the lineation gives a V-shaped pattern. A detailed study of the neighbouring outcrops shows that the mineral lineation is consistently folded over the hinges of the reclined folds. The attitudes of the lineation over the fold limbs show a small range of variation. This range is much smaller than that of the attitudes of the fold axis. In certain places the fold axis and the lineation have become sub-parallel (figure 5). A similar relationship is found in several parts of SSZ and is most spectacularly seen in oriented hand specimens in which the hinge lines swing from subhorizontal to a nearly down-dip orientation. On the more or less planar limbs of the folds the lineation maintains a fairly uniform orientation. Over the subhorizontal segments of the folds, the lineation and the fold axis are nearly at a right angle; the lineation is therefore unrollable over such segments. In other segments of the folds the lineation cannot be straightened out by unrolling the form surface around the local orientation of the fold axis; on the unrolled form surface the lineation shows a V- or U-shaped pattern. The angle between the lineation and the fold axis decreases as the fold hinge swerves to a larger pitch.

It should be pointed out that the traces of the axial planar cleavages at the hinge zones of folds sometimes form an intersection lineation parallel to the fold axis. This lineation should be carefully distinguished from the mineral lineation. Over some of the reclined folds the mineral lineation makes a distinct angle with the fold axis at the limbs of the folds. At the hinge zone the mineral lineation may become obscure and is often replaced by a hinge-parallel intersection lineation.

The strongly arcuate forms of the hinge lines, the occurrence of sheath folds and

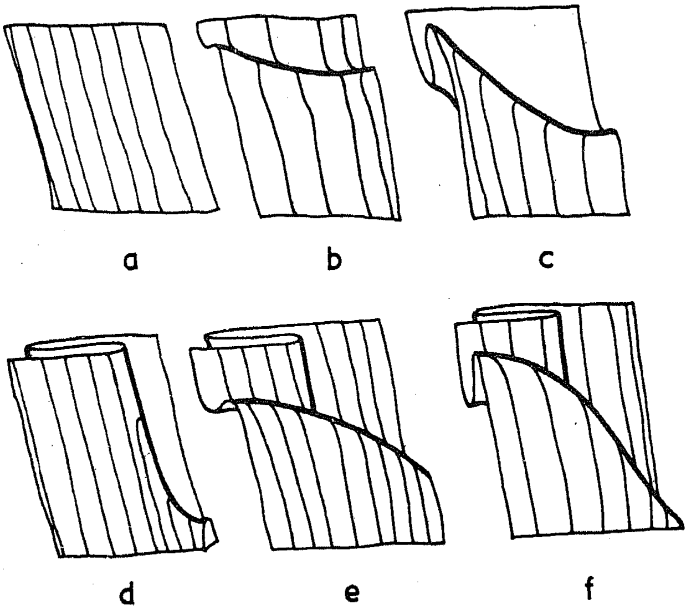

Figure 6. Schematic diagram showing repeated development of subhorizontal folds and rotation of their hinges towards the direction of maximum stretching. The initial down-dip mineral lineation of (**a**) is folded over subhorizontal axis (**b**). (**c**) shows farther rotation of fold hinge. In (**d**) the hinge line has become subparallel to the lineation in most segments. (**e**) and (**f**) show refolding of a first generation reclined fold and rotation of the newly formed hinge.

the patterns of deformed lineations indicate that the hinges of the mesoscopic folds were initially oriented with a subhorizontal attitude and had low initial pitches on their axial surfaces (figure 6b). With progressive deformation major segments of the fold hinges rotated towards the down-dip stretching direction (figure 6c, d) while new subhorizontal folds started to grow by deforming the earlier axial surfaces (figure 6e). With continued deformation the newly formed hinges also rotated to acquire a nearly reclined geometry. Only major segments of the earliest fold hinges and some second generation hinge segments become subparallel to the general orientation of the mineral lineation; elsewhere the hinges of the nearly reclined folds remained at an angle to it. The group of present-day sub-horizontal folds must have developed towards a late stage of the same progressive deformation. Their hinges have low pitches on the axial surfaces because they have rotated to a relatively small extent.

5. Progressive development of subsidiary shear zones, foliations and lineations

Although SSZ shows along its entire length a broad uniformity of character, with a north dipping mylonitic foliation and a down-dip mineral lineation, a detailed examination shows that the deformation within the shear zone is extremely heterogeneous. SSZ is composed of numerous subsidiary shear zones. This anastomosing network of shear zones (figure 7) which can be traced from the microscopic scale to the scale of a few decimetres, are zones of intense shear along which the earliest mylonitic foliation has been destroyed and a new foliation has formed. A new mylonitic lineation has developed on these surfaces. The shear lenses or domains between the shear zones

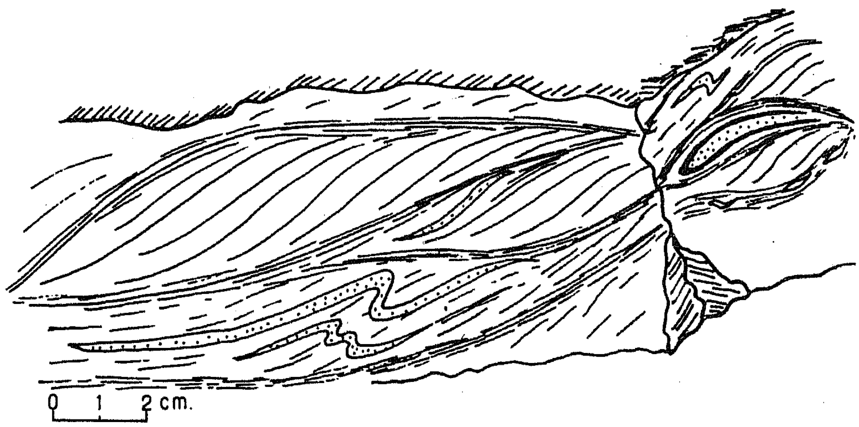

Figure 7. Anastomosing network of subsidiary shear zones in mylonitic micacenous quartzite in Ramchandra Pahar. Dotted bands—sheared quartz veins.

are less deformed and preserve the earlier mylonitic foliation which itself is often crenulated and shows various stages of overprinting by a new foliation. The subsidiary shear zones have formed repeatedly, one set superimposed on the other (Ghosh and Sengupta 1987a), and in the course of progressive deformation any small domain has sometimes been a part of a shear lens and sometimes a part of a subsidiary shear zone.

In view of the ubiquitous occurrence of subsidiary shear zones and their continual development during progressive deformation, it is reasonable to conclude that during the initial stage of growth of SSZ intense ductile shearing was localized along an anastomosing network of subsidiary shear zones while the volume of rocks lying between them had still remained nonmylonitic. With continued deformation the volume of such unreconstituted rocks was progressively reduced till a mylonitic foliation was imprinted on all the rocks of SSZ. Fresh subsidiary shear zones were superimposed on the mylonitic rocks. Even with such a prolonged history of repeated mylonitization SSZ still retains in certain places unreconstituted lenses of unfoliated granite in the microscopic scale and in the scale of a few centimetres. The foliated matrix of such rocks may show folds of different generations. Thus, the initial mylonitic foliation could not have developed at the same time all over SSZ. While in some domains the initial mylonitic foliation was being impressed on unreconstituted rocks, elsewhere the same foliation was being deformed into first generation or later folds. By similar arguments, the folds of one generation did not all develop at the same time all over SSZ. At any one point the growth of the first mylonitic foliation and the growth of different generations of folds on it were events which took place in a proper sequence. However, a first generation fold (i.e. a reclined fold which first deformed the initial mylonitic foliation) in one place could have been initiated earlier than, synchronous with or later than a second generation fold at some other point.

Mylonitic foliations and lineations have repeatedly formed in SSZ. A new foliation has either developed as an axial planar crenulation cleavage or, as in the subsidiary shear zones, by complete transposition and obliteration of the earlier cleavage. By repeated isoclinal folding the rotated earlier cleavages on fold limbs and the newly formed axial plane cleavages have become subparallel while, because of the extreme stretching down the dip of SSZ, the rotated early lineations and the newly formed stretching lineations on the axial plane cleavages have become nearly parallel in most places. The "down-dip lineation" of SSZ can thus belong to any one of the following categories: (i) rotated mineral lineation, (ii) rotated intersection lineation represented by a colour striping parallel to the hinge lines of first generation reclined folds, (iii) newly formed mineral lineation and (iv) newly formed intersection lineation parallel to hinge lines of second or third generation reclined folds. (i) (ii) and (iii) are essentially parallel to one another and often make an angle with (iv).

6. Structures of the northern belt

The structure of the main part of the northern fold belt, N and WNW from Ghatsila, is fairly simple in comparison with the structure of SSZ. In the major part of the fold belt between Ghatshila and Tatanagar the dominant folds are E or ESE trending with subhorizontal or gently plunging axes (Naha 1955, 1965). The folds have developed on bedding surfaces and there is a sub-vertical axial planar cleavage. This is the earliest cleavage in the northern fold belt. Away from SSZ these folds are moderately tight and non-isoclinal. The bedding laminae and the penecontemporaneous deformation structures are well-preserved in these rocks. Towards the southern part of this belt, from the neighbourhood of Ghatsila southward, the axial planar cleavage in the mica schists contains a prominent mineral lineation at a high angle to the bedding-cleavage intersection. The mineral lineation is sub-parallel to a pressure shadow lineation. Thus, the mineral lineation in the northern belt is essentially parallel to the maximum stretching which is directed upward and nearly at a right angle to the subhorizontal fold axis.

As we approach SSZ from this part of the northern belt this simple geometry is gradually modified (figure 8). South of Ghatsila the axis of the large scale syncline plunging at a low angle towards ESE suddenly steepens and plunges in the opposite direction, thereby giving rise to a canoe-shaped structure (Naha 1965). Further south and ESE, the folds on bedding become subvertical. The hinges of the large scale folds must have been sharply bent in this region (Naha 1965). From this location up to a point about a kilometre north of SSZ the bedding is still preserved and the penecontemporaneous structures, though strongly deformed, are still recognizable. However, along this zone, a few kilometres in width and running parallel to SSZ, the bedding and cleavage have become essentially parallel by isoclinal folding. The cleavage in this zone strikes SE to ESE and dips steeply northward. It has a well-developed down-dip mineral lineation often parallel to a prominent colour striping on the cleavage surface. Two generations of coaxial isoclinal reclined folds have been recognized in the hillock near the village of Tentuldanga.

Farther south, i.e. in a zone about a kilometre wide and immediately to the north of SSZ, the intensity of deformation is so large that the bedding laminae have either been obliterated or are greatly modified by transposition. The cleavage of the mica schists is occasionally deformed to isoclinal reclined folds with an axial planar crenulation cleavage. The structural transition from this zone to SSZ can be very well traced along the Gara nala near Rakha Mines and across the low ridge east of Sundarnagar and north-east of Ramchandra Pahar. In both these localities the north-dipping foliation, the down-dip lineation and the reclined folds can be traced from the mylonitic rocks of the shear zone to the mica schists and quartz mica schists immediately outside the shear zone.

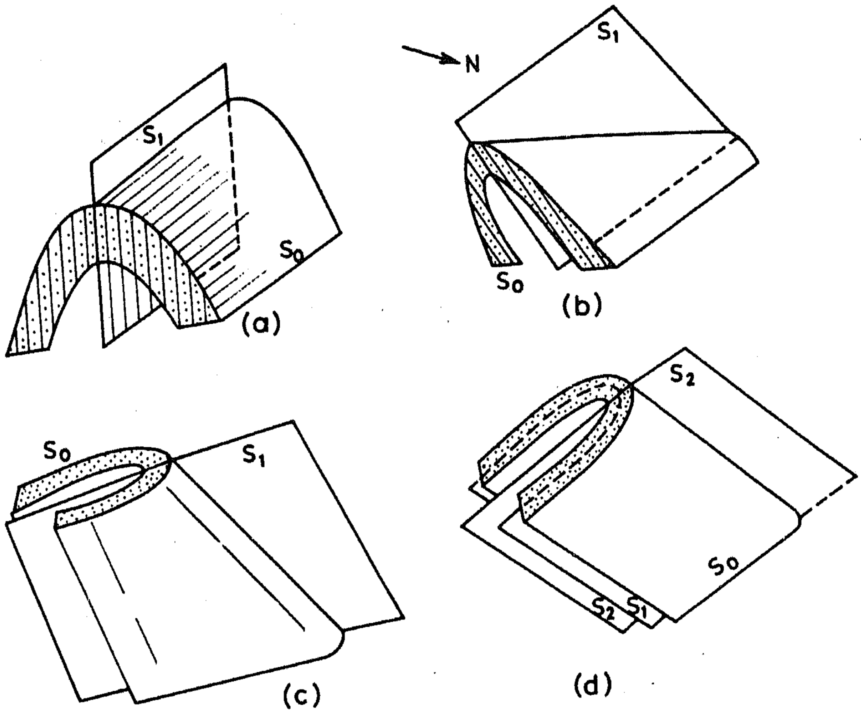

Figure 8. Schematic diagram showing characteristic structures in northern fold belt and the transitional zone. (**a**) Easterly trending subhorizontal folds on bedding (S_0) with subvertical axial planar cleavage (S_1) in northern fold belt. (**b**) shows tightening of fold and increase of pitch on axial surface south of Ghatsila. (**c**) shows nearly reclined folds in the transitional zone. S_0 and S_1 have become parallel in most places by isoclinal folding. In (**d**) a new generation of reclined folds has developed on S_1 and an axial planar crenulation cleavage (S_2) has developed in the transitional zone.

Thus, many of the SSZ structures are transitional to those of the northern fold belt. The foregoing description shows that the mineral lineation of the northern belt occurs nearly at a right angle to the axes of the sub-horizontal folds of the Ghatsila region. The rocks of this region show a single axial planar cleavage. The development of the mineral lineation must have taken place during the growth of the subhorizontal folds on bedding and the subvertical axial planar cleavage. Since this down-dip mineral lineation can be traced continuously to the down-dip lineation of SSZ it is justified to conclude that ductile shearing in SSZ and the growth of the subhorizontal folds of the northern belt were broadly contemporaneous events. Our studies further indicate that there is a gradual increase in the tightening of the folds and an increase in the intensity of deformation within the northern fold belt as we move southward towards SSZ. Moreover, the upright folds of the northern belt become more and more overturned towards the south as we approach the shear zone from the north.

The structures in the transitional zone show the following changes in the style of folding as we move towards the northern border of SSZ.

(i) There is an increase in the tightness of the folds.
(ii) The E–W to ESE striking, steep axial planes of the northern belt are tilted at moderate angles towards north.
(iii) The pitch on the axial plane of the axis of folds on bedding increases rapidly in a zone just south of Ghatsila. Farther southward the dominant folds of the northern

belt, mostly seen on bedding-parallel cleavage, become nearly reclined and maintain the same style as in the Singhbhum Shear Zone.

(iv) The single axial plane cleavage of the northern belt becomes modified as we move southward toward SSZ. In the transitional zone the most dominant isoclinal folds are on cleavage surfaces and the most dominant cleavage is a crenulation cleavage parallel to the axial surfaces of the reclined isoclinal folds. In the neighbourhood of SSZ the crenulation cleavage north of it is parallel to the mylonitic foliation of the shear zone itself.

(v) Lastly, there is a similarity in the history of superposed folding in SSZ and the transitional zone of the northern belt. As mentioned earlier, three generations of reclined folds can be recognized in SSZ. Although there are reclined folds all throughout the transitional zone the overprinting relation of two generations of reclined folds can be seen only in the Tentuldanga outcrops. The strongly asymmetrical late sub-horizontal folds, with north dipping axial planes, which have deformed the axial surfaces of the reclined folds, have also affected the rocks of the transitional zone. The intensity of development of these folds decreases northward from the shear zone. In the folded belt north of the shear zone these late subhorizontal folds appear sporadically as open subhorizontal warps and crenulations. The north-dipping crenulation cleavage axial planar to these late sub-horizontal folds occur both within the shear zone itself and in the zone immediately north of it. This cleavage can be traced to the transitional zone farther north also. However, here the tightness of the folds has decreased and the cleavage has become very steep.

The modification of the fold geometry from the nothern belt to the transitional zone is shown schematically in figure 8. The figure depicts the sub-horizontal or gently plunging upright folds on bedding (S_0) with an axial planar cleavage (S_1). Figures 8(b, c) illustrate the situation south of Ghatsila where the earliest folds on bedding have been tightened and the fold hinges have been rotated to acquire a large pitch on S_1. In the major part of the zone, except in the fold hinges, the bedding (S_0) and the cleavage (S_1) are parallel. In the transitional zone south of this, parallel surfaces of S_0 and S_1 are deformed to reclined folds, sometimes, as in the Tentuldang outcrop, with two generations of coaxial isoclinal folds. The first generation folds on bedding have been obliterated in this zone.

7. A kinematic model of SSZ and its wall rocks

The kinematic picture within a shear zone is closely interlinked with problems concerning the kinematics of its wall-rocks. We shall first clarify the general nature of this problem the different aspects of which have been discussed by Ramsay and Graham (1970), Sanderson (1979, 1982), Rattey and Sanderson (1982), Ramsay and Huber (1987) and Gapais *et al* (1987). Consider a tabular zone which is undergoing ductile deformation by either homogeneous or heterogeneous simple shear. In such a situation the wall rocks may either remain rigid or be deformed by simple shear. In either case a surface of discontinuity may or may not develop along a contact between the shear zone and its wall. Next consider the situation in which the deformation in the shear zone is not by simple shear and a material line element within the shear zone and parallel to its boundary is lengthened (or shortened) during progressive deformation. Under this situation the elements of a wall cannot remain rigid and at the same time in continuity with the elements within the shear zone. For rigid or unstrained walls it is likely that a discontinuity or a discrete fault develops between the shear zone and the wall. However, here we may have a rather unrealistic situation in which a large volume of material has to be squeezed out from the shear zone, a phenomenon described by Ramsay and Huber (1987, p. 611) as "cream cake effect". In any case, a deviation from the simple shear model must be associated either with discontinuity or with deformation of the wall rocks with or without the development of a discontinuity. If a discontinuity does develop, the slip along it, as Ramsay and Huber have shown, will vary along the surface of discontinuity. In the absence of a discontinuity the shear strain should vary along the shear zone.

It was evident from the description in the foregoing sections that the northern wall rocks of SSZ were deformed at the same time in which the rocks of the shear zone were deformed by intense ductile shearing. There is a wide zone of structural transition between the northern fold belt and the SSZ proper. The large scale structural geometry of the northern belt suggests that there was a N–S or NNE–SSW subhorizontal compression and a moderate amount of subvertical extension which gave rise to steep E to ESE striking axial plane cleavages. In the transitional zone farther south the intensity of deformation increased southward, the deformation became more and more rotational (non-coaxial) and the down-dip extension on the cleavage surfaces became larger. The folds in the transitional zone continued to be initiated subhorizontally but the fold hinges gradually rotated towards the down-dip stretching direction. In the absence of such a strong stretching the folds of the northern belt remained subhorizontal or gently plunging.

There is not only a similarity between the rotation histories of the folds of SSZ and the transitional zone, both these zones also show a similar history of refolding in the course of progressive deformation. Such a history of progressive folding and refolding during shearing movement is not unique for this area. A similar history has been recorded by Bell (1978) from the Woodroffe thrust zone. Indeed, Bell's description of the sheared rocks is very similar to what we have found in SSZ and in the transitional belt. We suggest that the progressive refolding in SSZ and the transitional zone and its absence in the fold belt farther north is closely associated with a rapid southward increase in both the intensity and the non-coaxiality of deformation.

In the area under consideration between Mosabani in the east and Tatanagar in the west, the deformed conglomerates of SSZ indicate a flattening type of deformation with an extremely large stretch along the λ_1-direction parallel to the down-dip mineral lineation and a moderate-to-weak stretch along the subhorizontal λ_2-direction (Mukhopadhyay and Bhattacharya 1969; Sengupta 1977). A similar flattening type of deformation is also indicated by the two-dimensional boudinage of synkinematically emplaced quartz veins concordant with the mylonitic foliation (Ghosh and Sengupta 1987b). The mesoscopic subsidiary shear zones in SSZ show a curved pattern both in the $\lambda_1\lambda_3$ and $\lambda_2\lambda_3$ planes. The shear lenses surrounded by these zones are asymmetric in the $\lambda_1\lambda_3$ plane. The lenses are also greatly flattened and are much longer along λ_1-than along the λ_2-axis. As Gapais *et al* (1987) have pointed out, this three-dimensional geometry of the subsidiary shear zones indicates non-coaxial deformation in a flattening field.

A kinematic model of SSZ and its wall rocks must take into account (i) the E–W striking steep XY-planes in the northern fold belt, with a moderate amount of vertical stretching and the gradual tilting of the XY-planes to low-to-moderate northward dips in the shear zone and its neighbourhood, (ii) the increase in tightness of folds and an overall increase in the intensity of deformation as we approach the shear zone from the north, (iii) the evidence of extreme stretching in the shear zone in an approximately down-dip direction in the $\lambda_1\lambda_3$ section, (iv) the non-coaxial character of deformation in the shear zone and in the transitional zone and (v) the moderate amount of extension of the shear zone rocks in the λ_2-direction and a thinning of the mesoscopic shear lenses normal to the bordering subsidiary shear zones. We should also take note of the fact that there is no lithologic or structural discontinuity between SSZ and its northern wall rocks. The structural history of the southern side of the shear zone is less well-known. However, from the observations of Dunn and Dey (1942) it appears that there is a discontinuity in the form of a thrust fault between SSZ and the southern wall rocks. In a very thin zone close to SSZ the southern wall rocks have undergone a deformation during the development of the shear zone itself. In all likelihood, beyond this zone, the southern wall rocks behaved more or less as a rigid block during the development of SSZ.

The kinematic model which best fits these observations involves a N–S directed bulk subhorizontal shortening. Over this regional strain was simultaneously superposed a strong shearing movement along a moderate-to-low dipping zone bounded on the far side by a thrust fault the footwall of which remained more or less rigid. Although there was an overall crustal thickening for the region as a whole, the shear zone itself was slightly thinned, with an extremely large up-dip stretching at a low angle to the shear zone boundary and with a small-to-moderate stretching along the shear zone strike.

In a critical review of models of strain variation in nappes and thrust sheets Sanderson (1982) analysed the patterns expected in (i) simple shear zones (ii) thrust sheets with thrust-parallel shortening and (iii) thrust sheets with thrust-parallel lengthening. The observations from SSZ and the northern fold belt fit none of these cases. In the present area the extensional shearing (Gapais *et al* 1987) within the shear zone must somehow be compatible with a bulk horizontal shortening for the region as a whole. It must also be remembered that, as a first approximation, most theoretical models of deformation of the shear zone and its wall-rocks involve plane strain, whereas deformation of SSZ is associated with some stretching along the λ_2-axis.

The pattern of strain variation from SSZ to the northern fold belt must be rather complex. A kinematic model for the region as a whole is therefore expected to have complex problems of strain compatibility across the belt. It is also difficult to visualize the details of the kinematic picture (say, the variation in the boundary-parallel shear and boundary-parallel stretching, the relative importance of stretching in the λ_2-direction or the variation in orientation of the XY-plane across the belt) which inevitably follow from a choice of any particular model of bulk deformation for the region as a whole. To get a deeper insight into the kinematic aspects of this complex problem the following experiment was performed. The experiment does not involve an enquiry about the mechanism of formation of the shear zone itself. Its objective is mainly to check whether the pattern of strain variation arising from the prescribed movements at the model-boundary is consistent with the field observations in SSZ, the transitional zone and the northern fold belt.

The model of bulk kinematics which best fits the field observations involves a subhorizontal shortening across a large terrain of deformable rocks which terminate against the boundary of a more or less rigid block. A thrust fault develops along the contact of the two blocks while the rocks immediately above the fault are subjected to intense ductile shear. In accordance with the model proposed by Ramsay (1980) and Ramsay and Huber (1987, figure 26.30 A) we have assumed that the shear zone steepens at depth. This assumption is perhaps also consistent with the extensive synkinematic mineralization localised along SSZ. For access to the sources of mineralizing fluids the shear zone must reach a deeper level rather than form a ramp-and-flat geometry. For an experimental simulation of this situation we prepared a model (figures 9 and 10) consisting of three parts, viz. a rigid block (A) with a

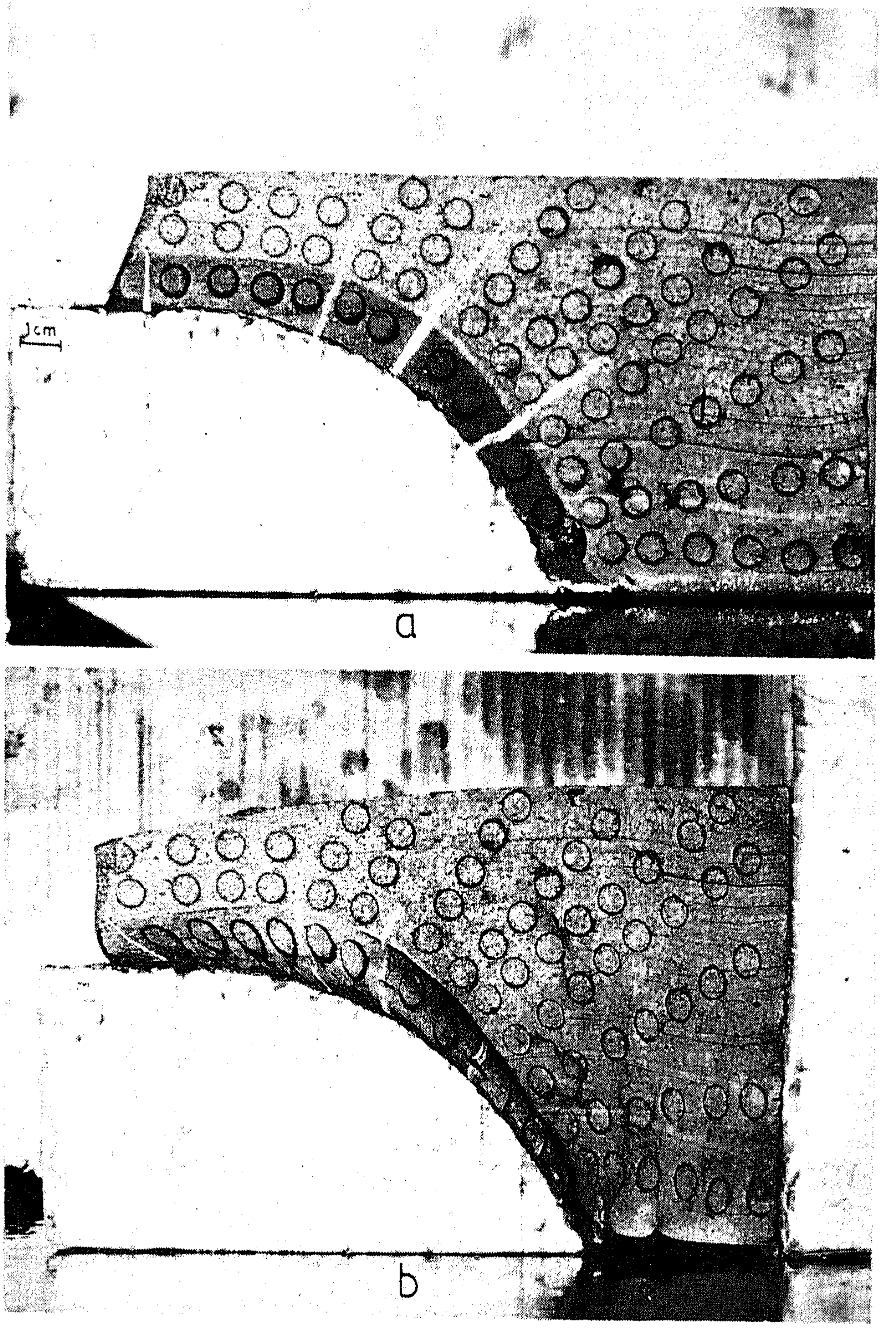

Figure 9. (**a**) Side view of the undeformed model with rigid block (white) on left, a layer of painter's putty (dark gray) and a somewhat stiffer block (light gray) of modelling clay mixed with oil. (**b**) Model after a longitudinal shortening. Note that the painted lines (white) are no longer orthogonal to the layer of putty. There is a strong shear strain immediately above the rigid block.

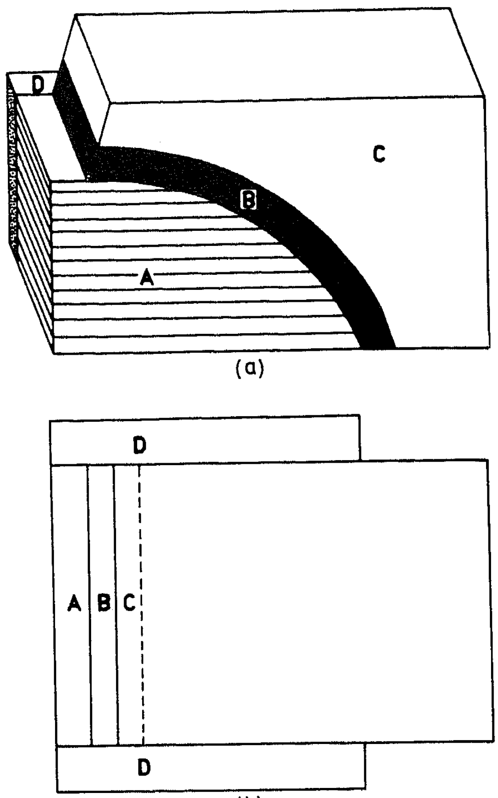

Figure 10. (a) Block diagram of model shown in figure 9. The rigid slab D has been removed from the front face. (b) Plan view of the same model. Before deformation the front and back faces of the block A are flush with those of the units B and C. After deformation B and C slightly extend in the λ_2-direction. These sidewise extended segments then lie on the D blocks.

smoothly curved upper surface sloping from horizontal at the top to a dip of 63° at the bottom, a thin layer of putty (B) placed above the curved surface of the rigid block and a block of modelling clay (C) which rests on the putty layer and has a horizontal upper surface. The modelling clay was considerably softened by mixing it with oil; however, it was significantly more competent than the putty layer. The model was prepared in such a way that the three units A, B and C stuck firmly along the interfaces. Two rigid blocks (D) were stuck on either side of the block A so that the curved upper surface of these combined blocks projected sidewise beyond the width of B and C. These projections were provided to serve as a floor on which any sidewise extension of the deformable material could be accommodated. After deformation the D blocks could be easily detached to reveal the extent of sidewise extension.

The model was shortened by a horizontal compression along its length. A vertical face of the model after its deformation and after removal of the D blocks is shown in figure 9b. The main features of the pattern of deformation are summarized below.

(i) There is a large variation in the intensity of deformation on the $\lambda_1\lambda_3$-plane of the model. The stretch is largest at the base of the B-layer and decreases as we move away from it. There is a sharp decrease in stretch as we pass from the B-layer to the C-block.

(ii) On the $\lambda_1\lambda_3$ plane there is a large boundary-parallel shear strain concentrated in the B-layer. The shear strain is largest at the bottom of the B-layer, decreases towards its top and sharply falls off in the C-block. Along any one surface in the B-layer at some fixed distance from a boundary the shear strain increases with a decrease in the dip of the layer.

(iii) There is a thinning of the B-layer along the major part of its length. The thinning is maximum at the bottom and decreases to zero as the layer becomes horizontal. In the horizontal segment the deformation is essentially by simple shear.

(iv) There is a stretching in the λ_2-direction in the B-layer and in the C-block immediately above it. This sidewise stretching is maximum where the B-layer has the maximum dip. The stretching decreases as the dip decreases and becomes negligible at a dip of about 10°. The sidewise stretching also decreases as we move away from the B-layer.

(v) The strain is much smaller in the C-block than in the underlying layer. Away from the B-layer, the X-axis in the C-block is nearly vertical. The X-axis becomes tilted as we come closer to the B-layer.

(vi) In the initial stage of deformation there was no discontinuity between the small elements of the rigid block A and the adjoining elements of the B-layer. A discontinuity developed only at a later stage of deformation. The amplitude of discontinuity increases in the direction of shear.

The broad pattern of strain variation in the deformed model is remarkably similar to what we find in SSZ and its wall-rocks. The kinematics of that part of the B-layer which lies nearest to the rigid block is similar to that of SSZ. The other part of the B-layer which is in contact with the C-block behaves similar to the transitional zone. Lastly, the strain variation in the C-block is similar to that of the northern fold belt.

The experiment shows that there is no internal inconsistency in the bulk kinematic model proposed by us. It shows, among other things, that it is physically possible to have an extensional shearing along a moderately low dipping shear zone within a larger domain of crustal thickening. It should be noted that there is in the experimental model an extensional shearing in the $\lambda_1\lambda_3$-plane and a stretching in the λ_2 direction even where the experimental shear zone dips as low as 20°. It is clear from the experiment that in a shear zone which curves in the $\lambda_1\lambda_3$ plane, the nature of deformation changes along the direction of shear. For the particular case considered by us the deformation in the major part of the shear zone was by a combination of simple shear and flattening; the relative importance of these two types of deformation varied along the shear zone, with the simple shear gaining in importance as the dip of the shear zone decreased at the upper levels.

8. Summary and conclusions

The northern fold belt shows a series of sub-horizontal folds on bedding with steep E to ESE striking axial plane cleavages. The reclined folds in the Singhbhum Shear Zone on the other hand are northerly plunging and have developed on a mylonitic foliation. There is between these two units a transitional zone through which the folds on bedding become progressively tightened and overturned towards south. At the same time the deformation becomes more and more non-coaxial while the stretching in the down-dip direction progressively increases. In response to the strong non-coaxial

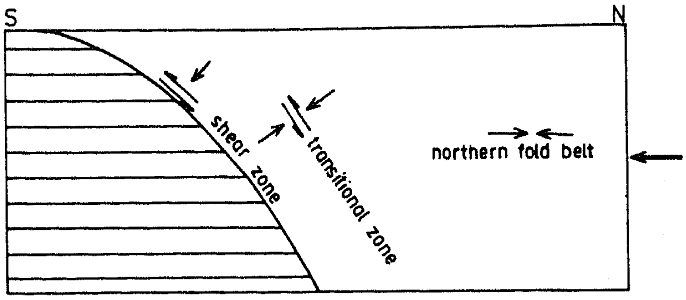

Figure 11. Schematic diagram of the bulk kinematic model for SSZ and the northern belt (see text for details).

movement the subhorizontal fold hinges, which were initiated at low angles to the Y-axis of bulk strain, rotated towards the down-dip X-direction. The sharp increase in the non-coaxial character of deformation in the transitional zone was also associated with folding and refolding of the bedding-parallel cleavage on the limbs of the isoclinal folds. These folds with initial subhorizontal axes were rotated to become reclined. In the shear zone and its vicinity the bedding is mostly obliterated. In the shear zone there is an extremely large stretching in the λ_1-direction and a weak stretching in the λ_2-direction. A late generation of subhorizontal folds, produced during the same progresive deformation, deforms the earlier sets of reclined folds in both the shear zone and in the transitional zone. The structures in the northern belt and those in SSZ were produced during the same progressive deformation, although the nature of deformation changed from the northern belt through the transitional zone, to SSZ. The sub-horizontal folds in the northern belt which were initiated early, did not rotate towards the X-direction because the stretching along the X-axis was small in this belt throughout the entire course of deformation. On the contrary, the late sub-horizontal folds on the transoposed and crenulation cleavages in the shear zone and the transitional zone remained subhorizontal and were rotated to a small extent because they had formed towards the terminal phase of an extremely large deformation.

The bulk kinematic model (figure 11) which best fits these observations involves a N–S to NNE–SSW subhorizontal compression over which was superimposed, in the southern part, a strong shearing movement which resulted in the formation of a discontinuity or thrust along the southern border of the shear zone. South of it, except in a narrow zone, the rocks mostly remained rigid during the development of SSZ. It is likely that the shear zone steepens at depth. It is because of the presence of a rigid and downward steepening boundary of the southern wall-rocks that the southward-directed regional shortening of the rocks caused, in the neighbourhood of the rigid wall, a strong wall-parallel shearing movement along with a strong wall-parallel stretching in the down-dip direction and a smaller stretching along the strike direction.

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