The kinematic history of the Singhbhum Shear Zone

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The progressive deformation of the Singhbhum Shear Zone (SSZ) involved the initiation of a mylonitic foliation, its deformation by three generations of reclined folds and superposition of two later groups of folds, i.e., a group of asymmetric folds with subhorizontal or gently plunging axes and a group of gentle and open, transverse and more or less upright folds. The occurrence of sheath folds and U-shaped deformed lineations indicate that the reclined folds were produced by rotation of fold hinges through large angles. The total displacement along the SSZ was compounded of displacements along numerous mesoscopic shear zones. The cleavages in the shear lenses and the mesoscopic shear zones cannot be distinguished as C and S surfaces. They have the same kinematic significance and were produced by ductile deformation, although there were localized discontinuous displacements along both sets of cleavages. A mylonitic foliation had formed before the development of the earliest recognizable folds. Its time of formation and folding could be synchronous, diachronous or partly overlapping in time in the different domains of the SSZ.

1. Introduction

Major ductile shear zones often show several generations of folds, cleavages and lineations with a characteristic geometry and structural history which impart a distinctive character to the rocks and which set them apart from rocks outside the shear zone. The combination of these characters may be regarded as a tectonic style in the sense of Turner and Weiss (1963, p. 79). In the Singhbhum Shear Zone (SSZ) of eastern India the rocks not only show a distinctive tectonic style of the mesoscopic structures but also a characteristic microstructure resulting from progressive mylonitization. The restriction of this combination of characters in a long narrow belt enables us to delineate the SSZ in the map and also gives us a basis of linking a variety of mesoscopic structures with a single tectonic event, the growth of the ductile shear zone.

In spite of the uniformity of the trend of structural evolution, the deformation in the SSZ is heterogeneous, with variation in the intensity of ductile shearing from domain to domain and with diachronous development of structures.

The SSZ does not have a sharp border, and there is no recognizable stratigraphic break either on its northern or it's southern border. The mica schists, quartzites, granites and amphibolites are converted along the shear zone to mylonites and phyllonites; the shear zone is mapped by tracing out this zone of mylonitic rocks. In between the SSZ and the northern fold belt there is a transitional zone with overlapping characters of deformation of the shear zone proper and of the fold belt (Ghosh and Sengupta 1990). The present investigation is restricted to the central part of the SSZ between Mosabani in the East and Turamdih in the West.

The structure of the SSZ and of the folded belt lying to its north have been studied in detail by a number of authors e.g., Dunn and Dey 1942; Naha 1955, 1956 1965; Sarkar and Saha 1962, 1977; Roy 1969; Mukhopadhyay *et al* 1975; Sengupta 1977; Ghosh and Sengupta 1987a, and b, 1990; Mukhopadhyay and Deb 1995.

We dedicate this paper to the memory of Professor Kshitindramohan Naha. We take this opportunity to note that it was Naha who first drew our attention to

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the interesting mesoscopic and microscopic structures and to the kinematic history of the Singhbhum Shear Zone. The structure of the mylonites of the SSZ was also the theme of Naha's (1954) first research publication.

2. Sequence of folding

The most prominent set of mesoscopic structures in the SSZ is a group of northerly plunging nearly reclined folds, a northerly dipping mylonitic foliation and a down-dip mineral lineation (Naha 1965). In many places the reclined folds are deformed by one or two groups of later folds. One of these groups shows open to moderately tight folds with subhorizontal axes nearly parallel to the shear zone trend or with axes pitching up to 40 degrees on the axial planes. The other set of folds is gentle to open, more or less upright or with steep somewhat inclined axial plane and with axis subparallel to the down-dip mineral lineation.

Figure 1. Profile of reclined fold in quartzite mylonite near Ramchandrapahar, south of Tatanagar.

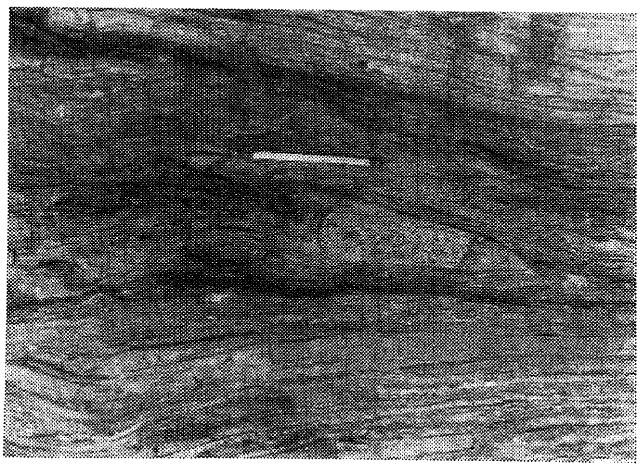

Figure 2. Interference of two generations of reclined folds in strike section.

2.1 *Group of reclined folds*

Among the reclined folds of the SSZ (figures 1, 2) we can distinguish three generations. Even the first generation reclined fold (F_1), the earliest recognizable folds in the SSZ, have developed on a mylonitic foliation. In the phyllosilicate-rich layers the axial planar cleavage of F_1 is essentially a continuous cleavage with relics of a few crenulations of an earlier cleavage preserved near the hinge zones of F_1. In the associated quartz-rich layers, however, we find an earlier cleavage sweeping around the hinge zones of F_1. The F_1 folds are isoclinal, have very large amplitude-wavelength ratios and occur mostly as thin sheet-like bodies (figures 3, 4), with a mineral lineation and occasionally a striping lineation parallel to the hinge lines.

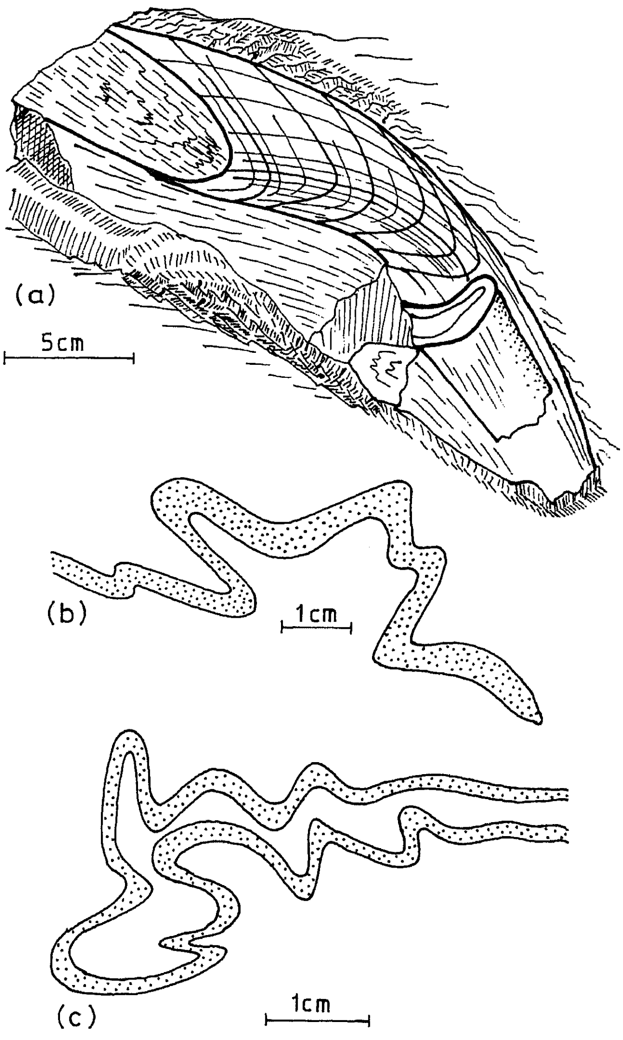

Figure 3. (a) Isoclinal F_1 deformed over the hinge zone of isoclinal F_2. The axial surface of F_2 is deformed by a subhorizontal fold. (b) Sheet-like core of F_1 reclined fold deformed by later reclined folds and transverse folds. (c) Interference of F_1 and F_2 reclined folds and transverse upright folds.

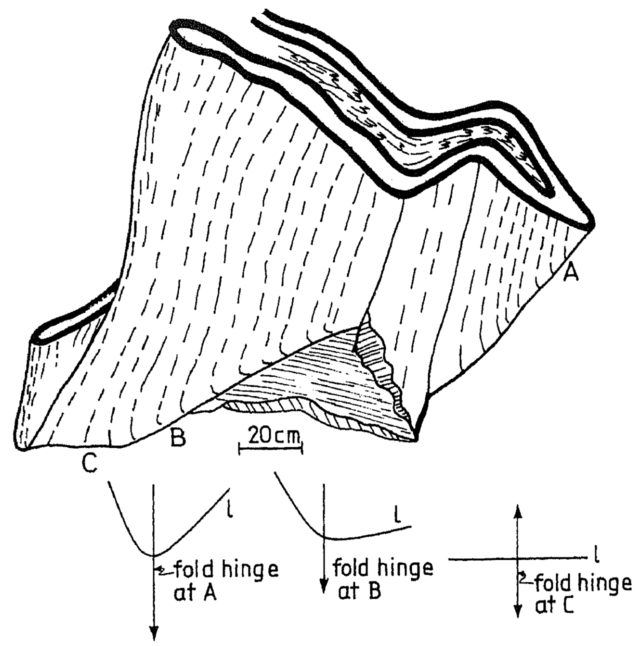

Figure 4. Oriented specimen showing overprinting relations of F_1, F_2 and transverse upright folds. The stretching lineation is parallel to F_1 hinge line (left side) and is deformed to U-pattern over inclined segments of F_2 hinges. The unrolled lineation patterns (l) with reference to the local hinge line (lines with arrows) are shown below.

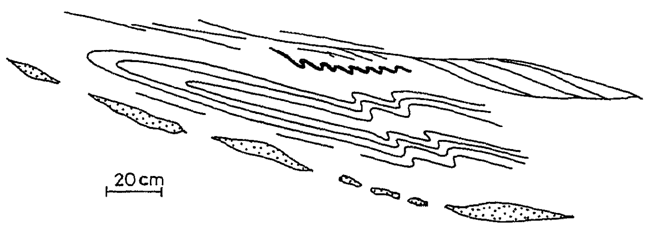

Figure 5. Nearly reclined folds deformed by asymmetric subhorizontal folds on near-dip section. Note that the sense of fold asymmetry as well as the angular relationship of the shear lens both indicate up-dip sense of shear.

Figure 6. Subhorizontal asymmetric folds in quartzite mylonite.

The second generation reclined folds (F_2) are very tight or isoclinal (figures 2, 3). Wherever the hinge zones of these folds are exposed, the mineral lineation and the striping lineation are found to be folded over them, with a distinct angle between the lineation and the hinge lines in most places over the folds (figure 4). The nearly reclined folds of the third generation (F_3) deform the axial surfaces of the earlier folds. The F_3 folds have variable tightness but are mostly close to moderately tight, strongly asymmetrical and with moderate amplitude-wavelength ratios. The shear zone lineation is invariably deformed by these folds.

2.2 *Group of "subhorizontal" folds*

The reclined folds are deformed by a set of folds (figure 5) whose axes have low to moderate pitches on their axial surfaces. The down-dip lineation of the shear zone, deformed by these folds, generally occurs at a large angle to the fold axis in all parts of the folds. Although there is a wide range of tightness of the subhorizontal folds, two different types are easily recognized (Ghosh and Sengupta 1990). One of these types (figure 6) is moderately tight, strongly asymmetric, and has a northerly dip of the axial planes. The sense of asymmetry on vertical down-dip sections is always compatible with a thrusting sense of shear movement. In some places, these folds are very tight or isoclinal and have a prominent axial planar crenulation cleavage. The other type of subhorizontal folds is gentle, has a southerly dip of the axial planes and ranges from symmetric to weakly asymmetric (Ghosh and Sengupta 1990, figure 4).

2.3 *Transverse upright folds*

The reclined folds are also refolded in many places by a set of gentle upright folds transverse to the trend of the shear zone. The axes of these transverse folds are parallel or at a very low angle to the shear zone lineation. The transverse upright folds (figures 3c, 7) are ubiquitous in the SSZ and they often interfere with the gentle subhorizontal folds to give rise to a dome-and-basin structure (figure 8). The transverse upright folds are considered to have developed in the last stage of ductile shearing in the SSZ and not by a later unrelated deformation. This is indicated by their consistent orientation subparallel to the shear zone lineation and also by occurrence of such late lineation-parallel open folds in many other shear zones (e.g., Roberts 1974 from the S W Highlands of Scotland; Coward and Kim 1981 from the Moine Thrust; Jacobson 1983 from the Vincent Thrust, California; Ghosh and Sengupta 1984; Meneilly and Storey 1986 from the South Orkney Islands; and our own observations from the Phulad shear zone of Rajasthan).

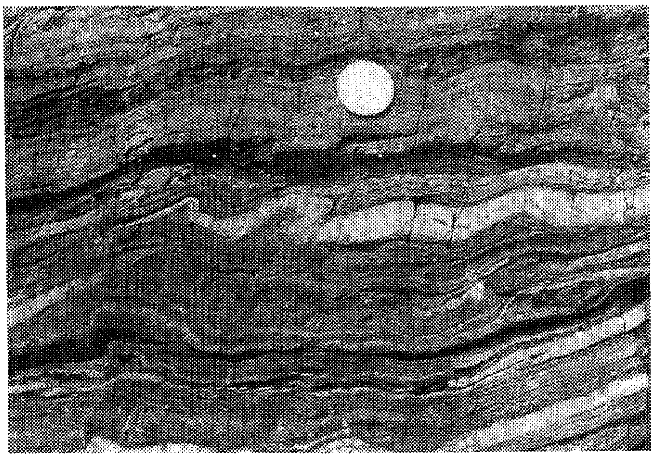

Figure 7. Gentle warps of open transverse folds. Some of the folds are inclined. Vertical section parallel to strike.

Figure 9. Sheath fold in quartzite mylonite. The right-hand part of the sheath fold shows an oval closure.

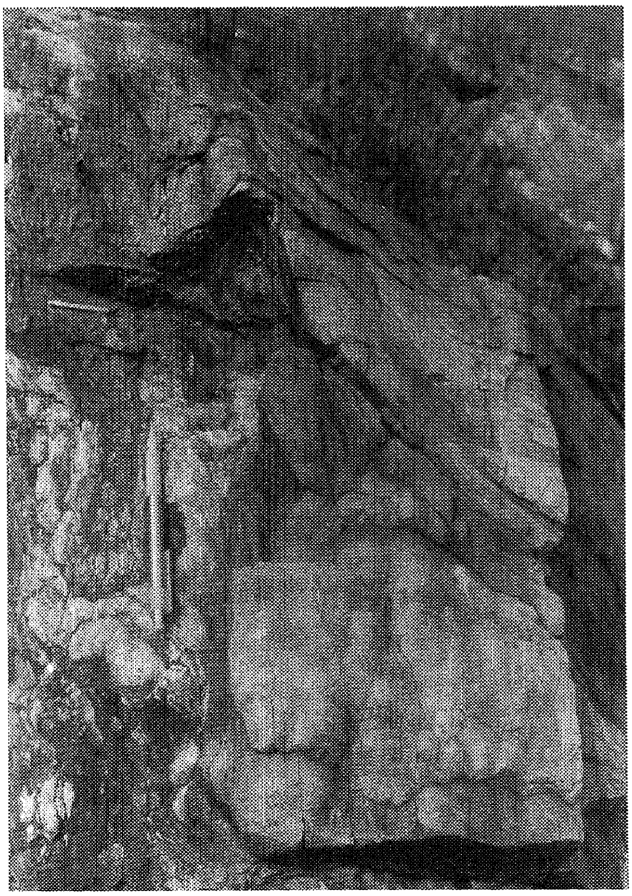

Figure 8. Subhorizontal folds (parallel to pen) interfering with open transverse folds. In the foreground the two sets form the gentle domes and basins.

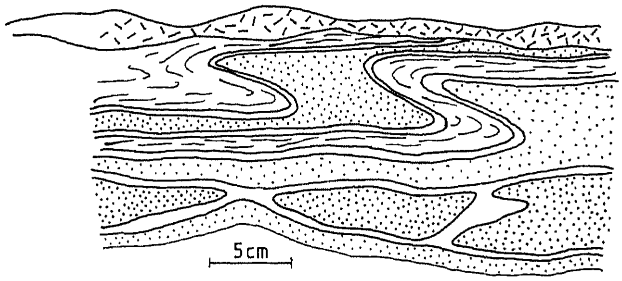

Figure 10. Profile section of sheath folds. Section perpendicular to lineation.

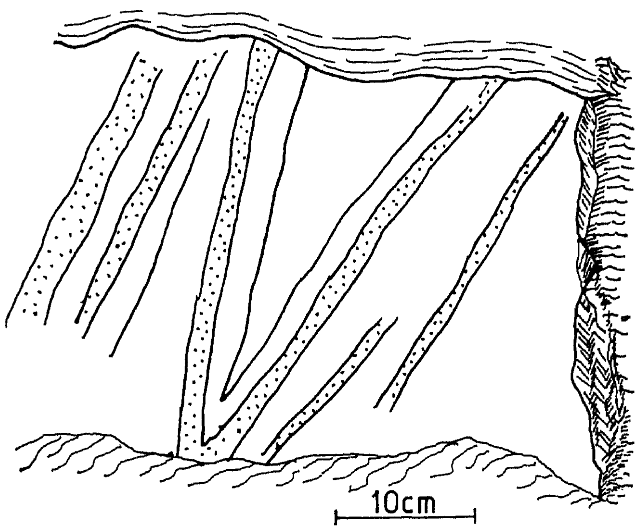

Figure 11. V-shaped striping lineation on planar foliation surface of mylonite.

3. Rotation history of folds from deformed lineation patterns

The majority of the reclined folds of the SSZ attained their present attitude by rotation of fold hinges through large angles (Ghosh and Sengupta 1987a, and b, 1990; Mukhopadhyay and Deb 1995). This is demonstrated not only by the strong hinge line curvatures on the axial surfaces (figures 9 and 10) and by hair pin bends of lineations on planar foliation surfaces (figures 11 and 12), but also by the patterns of deformed lineations (figures 13a, b, d, e) over the hinge zones of folds. The mineral lineation has

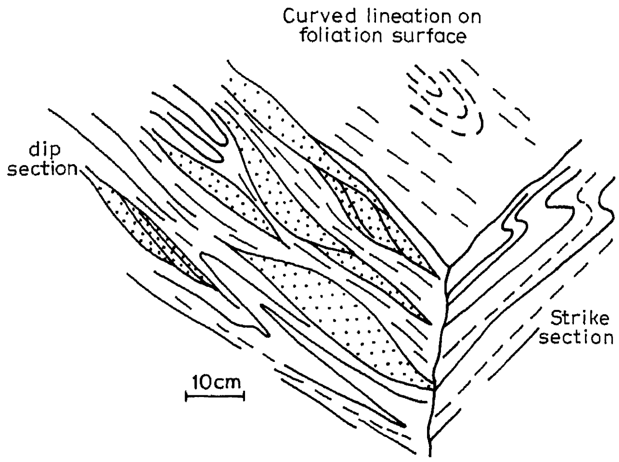

Figure 12. Shear lenses in dip section, profile of reclined fold in strike section and curved lineation on the exposed planar surface of foliation.

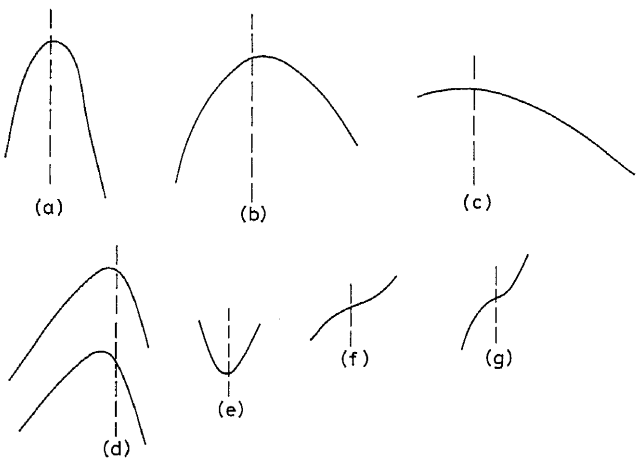

Figure 13. Deformed lineation patterns on the unrolled form surfaces of folds. Dashed line – fold hinge line. Continuous line – lineation a,b,d, and e are from reclined folds. *c* is from a moderately inclined segment of a 'subhorizontal' fold. *f* and *g* are from gently inclined segments of 'subhorizontal' folds.

developed parallel to the local direction of maximum stretching although its final orientation has often been modified by later folding. The fine striping lineation is an intersection lineation. It is essentially parallel to the hinges of the earliest reclined folds F_1 (figure 4). With some exception, the striping lineation is oblique to the hinges of all later reclined folds.

The lineations deformed by the folds may show different patterns. In a flexural slip fold the lineation on the unrolled form surface is a straight line. In a shear fold the deformed lineation cannot be unrolled or straightened out, and the folded lineation on the outcrop lies on a plane. When a fold is formed by simultaneous buckling and flattening, the lineation does not necessarily lie on a plane, and the lineation pattern on the unrolled form surface is generally curved. Depending on the initial orientation of the lineation and the relative amounts of buckling and flattening, we may have different types of lineation patterns (Ghosh and Chatterjee 1985). Although several of these patterns (figure 13) are found in the SSZ, we are mostly concerned in the present context with a V- or U-shaped pattern of the deformed lineation on the unrolled form surfaces, the closure of U-being situated at or close to the hinge line of the fold. This lineation pattern, as shown by Ghosh and Chatterjee (1985), develops only when the initial angle between the lineation and the fold axis is close to 90 degrees. The lineation makes a high angle with the fold axis at the hinge zone of the fold, whereas towards the limbs the angle is gradually reduced (figure 13a, b, d, e).

The observation of the orientations of the lineations on the fold hinges is not only crucial for the determination of the rotation history of folds but is also essential to confirm that the folds had developed by a process of simultaneous buckling and flattening. If, for the U-shaped patterns, only the lineation data from the fold limbs are considered, it may appear that the deformed lineation lies on a plane. However, when the data from the hinge zone are included it is generally found that the deformed lineation is not coplanar. Both these features, i.e., the non-coplanar and non-unrollable nature, characterize the U-shaped lineation pattern as a product of a deformation by buckling and flattening concomitant with rotation of the hinge line through a large angle.

In the SSZ the U-pattern of lineation (type 4 and type 3b of Ghosh and Chatterjee 1985) is seen in many places over the exposed form surfaces of second and third generation reclined folds. The F_2 axes generally make a low angle with the down-dip stretching lineation. In certain places, the lineation on the limbs of isoclinal F_2 folds has become essentially parallel to the F_2 axis. The lineation at the F_2 hinge zone, however, makes a distinctly high angle with the hinge line. Over the unrolled form surfaces of the nearly reclined F_3 folds, the lineation also shows a U-pattern. The lineation almost always occurs at a distinct angle with the F_3 axes at the fold limbs. Thus, the hinge lines of both the second and third generation reclined folds have rotated towards the stretching direction to a great extent but they have not rotated enough to become essentially parallel to the direction of maximum stretching. In contrast, the hinge lines of the first generation reclined folds have rotated to a very large extent, so that major segments of the hinge lines have become essentially parallel to the direction of maximum stretching in the shear zone. A stretching lineation has freshly formed during this process. The deformed early lineation has either been rotated to parallelism or has been replaced by the newly formed lineation.

Sharp hair-pin bends of a prominent striping lineation can be seen in several places on more or less planar foliation surfaces (figures 11 and 12). Since the

Figure 14. Very tight, strongly asymmetrical 'subhorizontal folds' with curved hinge lines in quartz-mica schist. The down-dip lineation is visible on the long limbs of the asymmetrical folds.

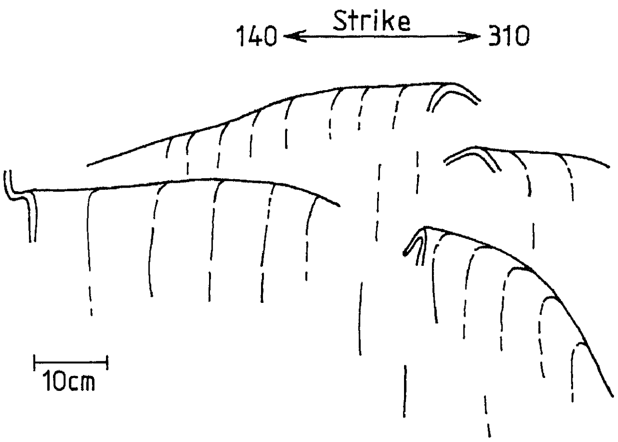

Figure 15. Diversely oriented fold hinges on the mylonitic foliation. The folds show complete gradation from subhorizontal to nearly reclined. Note that the lineation is unrollable only where the fold axis is horizontal. Where it is inclined the lineation shows U-patterns.

prominent striping lineation of the SSZ has formed parallel to the hinge lines of the F_1 folds, the hair-pin bend on a planar foliation surface must have formed because of the sheath folding of F_1. Sheath folding of F_1 is also indicated by the occurrence of extremely flattened oval outcrops (figure 10) with subparallel hinge lines at either extremities. Sheath folds on F_2 and F_3 occur in many places in the SSZ (Ghosh and Sengupta 1987a and b, 1990). Figure 9 shows the exposed hinge of an isoclinal F_2-fold with a tightly appressed V-shaped pattern on a more or less planar axial surface. The hinge line on one flank of the sheath fold is subparallel to the general orientation of the mineral lineation. The hinge line on the other flank makes a distinct angle with the lineation. Evidently, depending on the initial orientation, one segment of the initial F_2 hinge line has rotated to become subparallel to the X-direction while the other segment still makes an angle with it.

The hinges of the 'subhorizontal' folds have also been rotated. Those 'subhorizontal' folds, which are tight, show a much larger variation of pitch of the hinge line (figure 14) on the axial surface than the more open folds. The hinge angles (Williams and Chapman 1979) of the tight folds may be as large as 30 to 45 degrees. Thus, although this group of folds is classified as 'subhorizontal', their hinge lines often have local inclined segments. Indeed, some of the very tight members of this group have fairly large pitches and are transitional to the nearly reclined F_3 folds (figure 15).

4. Mesoscopic shear zones and shear lenses

Mesoscopic shear zones (figures 16–20) ranging in thickness from less than a millimetre to a few tens of centimetres are narrow zones of intense shear which anastomose through less deformed rocks. The wavy adjoining shear zones may meet each other and enclose a lozenge-shaped body of less deformed rocks. These lozenge-shaped bodies or shear lenses have their long axes subparallel to the mineral lineation. Most of the shear lenses are asymmetrical, the asymmetry being more pronounced along XZ sections than along YZ sections. In certain instances the shear zones undulate, do not meet each other but terminate in zones of folding (figure 17b, c).

Some of the shear zones have developed within weakly deformed massive rocks. Within the major part of SSZ, however, an anastomosing network of subsidiary shear zones occur within rocks that are already mylonitized (figure 17). A detailed study of drill cores and of sections cut through large hand specimens reveal that mesoscopic shear zones are ubiquitous. The drill cores show shear lenses (figure 18) in the scale of a few centimetres stacked upon one another through at least tens of metres of continuous vertical sections. Larger shear lenses in the scale of a

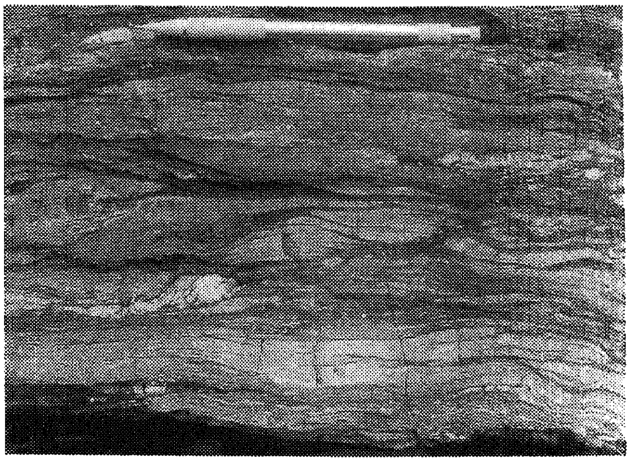

Figure 16. Shear lenses in quartzite mylonite in dip-section.

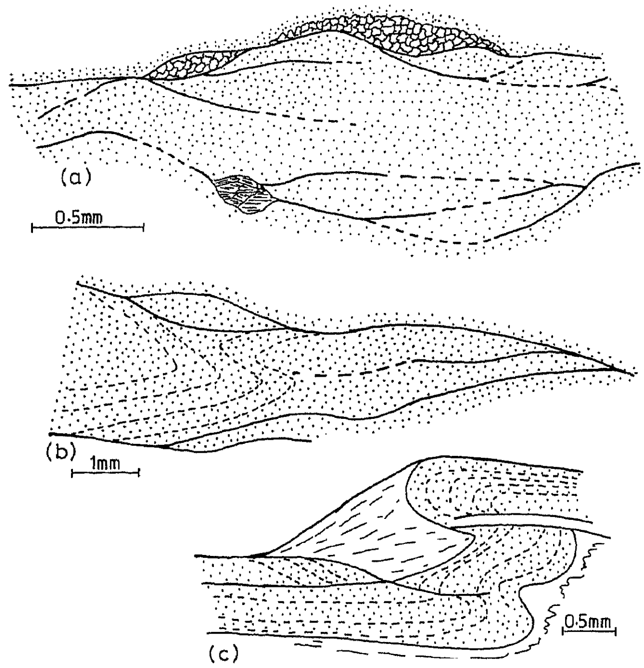

Figure 17. Microscopic shear zones in quartzite mylonite. The very fine recrystallized texture has been shown only in one part of (a).

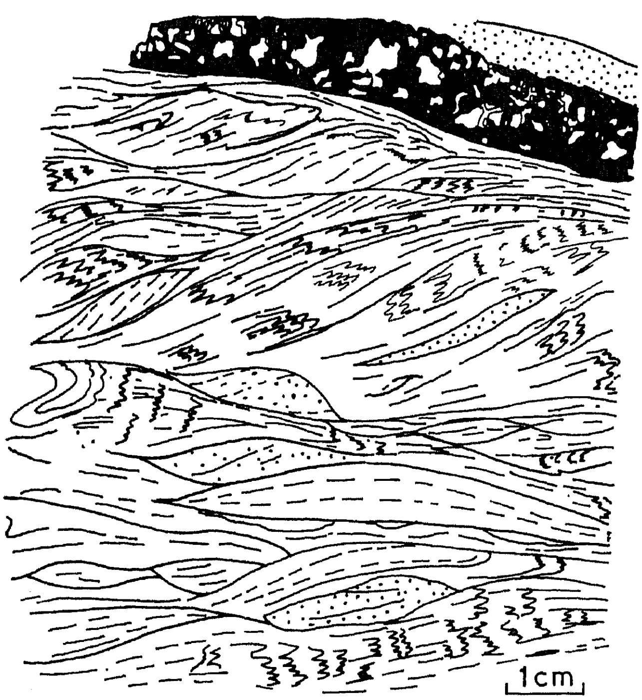

Figure 18. Stacks of shear lenses in core section of granite mylonite perpendicular to the lineation. The upper dark band shows fragments of apatite in a chloritic groundmass.

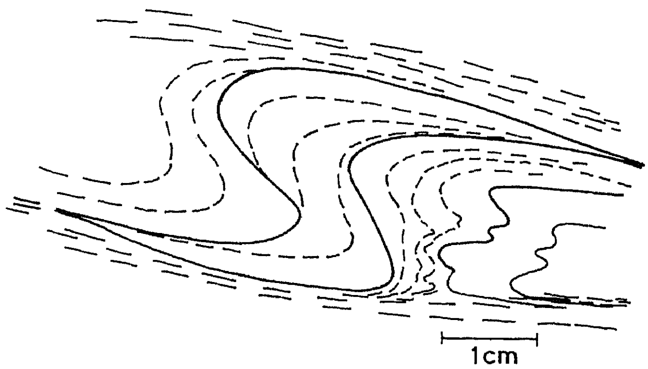

Figure 19. Shear lenses deformed to reclined folds.

Figure 20. Core section of a mylonite. The section (perpendicular to the lineation.) shows interference of two generations of reclined folds and transverse upright folds.

few decimetres can also be recognized in the outcrops. There are shear lenses of different orders; the size of the smallest lenses depends upon the type of rock, especially upon the fineness of the mylonitic banding. The size is smaller in thinly banded rocks than in coarsely banded mylonites. The shear lenses in the thick quartzite mylonites are distinctly larger than those found in quartz-mica schists and chlorite-rich phyllonites. The ubiquitous presence of the shear lenses leads us to conclude that the total thickness of the SSZ is made up of packets of shear lenses of different scales.

The mesoscopic shear zones bordering the shear lenses have formed at different stages. The earliest recognizable mesoscopic shear zones enclose lenticular bodies of isoclinally folded mylonitic rocks. The profiles of the isoclinal reclined folds within the shear

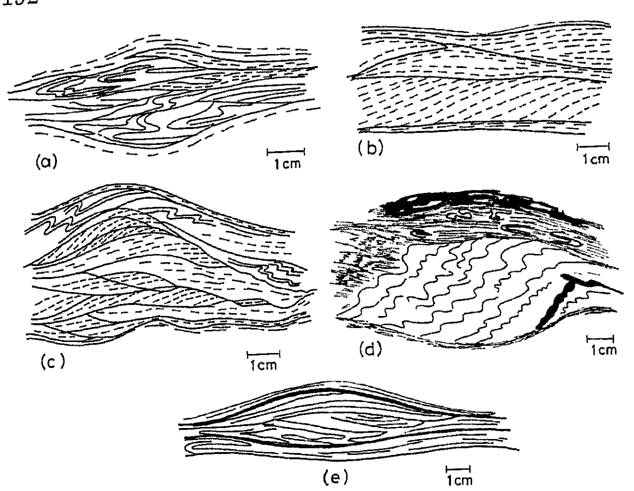

Figure 21. Shear lenses and shear zones in polished sections of mylonite. Note that many of the lenses are greatly flattened, with a low angle between shear zone and shear lens cleavages and fold axial planes.

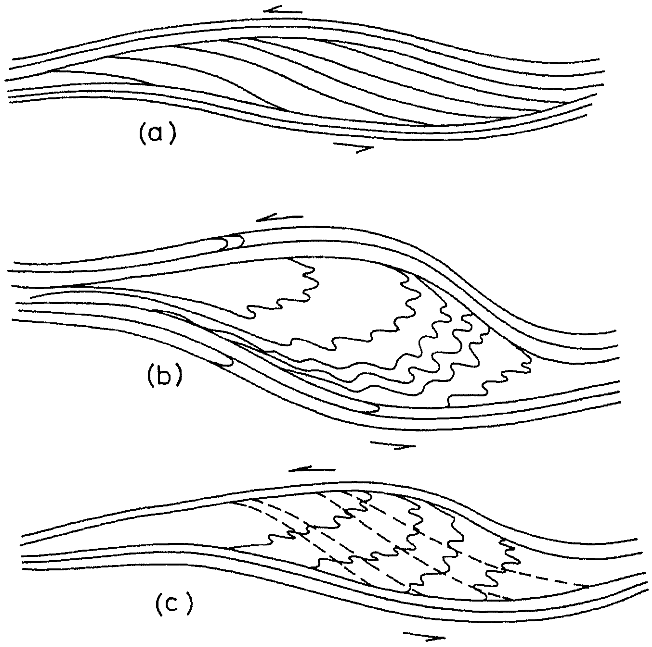

Figure 22. (a) Shear lens cleavage at acute angle to shear zone boundary. (b) and (c) Schematic representation of successive stages of development of a shear lens cleavage by crenulation of an earlier cleavage.

lenses are visible mostly in sections at a high angle to the mineral lineation. In these sections the axial planes of the isoclinal folds are subparallel or are at a very low angle to the boundaries of the lenses.

In sections parallel to the lineation the S-surfaces within the lenses generally make an angle of less than 30 degrees with the bounding shear zones. The later shear lenses often include folded earlier shear lenses (figures 19 and 20). The folds are either F_2 or F_3 reclined folds. Mesoscopic shear zones can also be seen to surround lenticular bodies containing sets of strongly asymmetrical subhorizontal folds, the sigmoidally curved axial surfaces of which make a perceptible angle with the shear zones but become subparallel to them at the shear zone borders.

In the mesoscopic shear zones the cleavage is parallel to the shear zone boundaries. Within the shear lenses the cleavage occurs at an acute angle to the lens borders. This angle decreases outward to become subparallel to the shear zones near their borders (figures 21 and 22a). In sections parallel to the lineation the acute angle between the synchronously developed cleavages inside and outside a shear zone invariably indicates the up-dip sense of shear.

The cleavage within a mesoscopic shear zone is essentially a continuous cleavage, with rare relics of an isoclinally folded earlier S-surface. The shear zone cleavage is therefore formed by transposition of an earlier cleavage. In the domains outside the shear zones there may or may not be a new cleavage contemporaneous with the shear zone cleavage. The shear lenses often contain a crenulated earlier cleavage. In such cases the acute angle between the lens boundary and the axial planes of the crenulations points towards the sense of shear. Depending on the intensity of deformation there may be incipient cleavage-development parallel to the axial surfaces of these crenulations (figures 21d and 22c). In some places the axial planar crenulation cleavage is very well developed. In the extreme case the earlier cleavage is almost entirely replaced by a new cleavage. This newly formed cleavage in the shear lenses is of the same generation as the shear zone cleavage, and the acute angle between them points towards the sense of shear.

The synchronous cleavages in the shear zones and in the shear lenses have the same kinematic significance. The angular difference between them is a result of a much larger intensity of ductile shearing within the shear zones than in the shear lenses. Because of the large intensity of shearing the cleavage in the shear zones has become parallel to their boundaries. With progressive deformation the shear lenses themselves have been elongated and the acute angle between the shear lens cleavage and the shear zone boundary has greatly decreased. Indeed, in many of the early-formed shear lenses the cleavage makes an angle of only a few degrees with the shear zones. It is likely that with progressive deformation the thickness of the shear zones increases at the expense of the thickness of the shear lenses, the cleavages in the shear lenses and the bounding shear zones become virtually parallel and consequently the difference between the two domains is lost.

As mentioned above the weakly deformed shea lenses may contain a cleavage earlier than the shea zone cleavage. This cleavage may or may not b crenulated. Where it is not crenulated, its acute angl with the shear zone boundary is in agreement with th sense of ductile shearing in the SSZ (figure 22a). O the other hand, wherever this earlier cleavage is crenulated the acute angle between its enveloping surface and the shear zone boundary is opposite to the sense of shear (figure 22b and c). This observation strengthens our earlier suggestion (Ghosh and Sengupta 1987a) that the development of a mylonitic foliation and its folding in a progressive deformation is closely associated with repeated formation of shear lenses, one set superimposed on another. When a new set of shear lens is superimposed in such a manner that its acute angle with the pre-existing foliation is opposite to the sense of shear, the foliation lies along a direction of instantaneous shortening and gives rise to a set of asymmetrical folds.

5. Synkinematic quartz veins

Synkinematic quartz veins, emplaced at different stages of ductile shearing, constitute a significantly large volume of rocks in many places of the SSZ. The early formed veins, folded and refolded, are thoroughly mylonitized, and are subparallel to the mylonitic banding. The later veins show varying degrees of ductile shearing. The veins often show boudinage and pinch- and swell structures, indicating thereby that the quartz veins with their coarse grain size have behaved as competent units with respect to different types of mylonitic host rocks. Quartz veins with folded boudins and pinch- and swells are very common in most parts of the SSZ. Quartz veins have also been emplaced parallel to axial planes of subhorizontal folds. Some of these veins show an incipient mylonitic foliation. Thick lenticular pods of late veins have retained the coarse grained texture in most parts, although the grains show strong undulatory extinctions, and are dissected by an anastomosing network of thin shear zones along which there has been a drastic grain refinement and initiation of a mylonitic foliation. Within these relatively late quartz veins, this is the first imprint of a mylonitic foliation; this foliation must be later than the folded and refolded mylonitic foliation of the host rock.

6. Resistant remnants

The SSZ occasionally shows resistant remnants of different materials. These remnant pods are massive, unfoliated, nonmylonitic, and lenticular in shape and occur within an intensely mylonitized host with a prominent foliation sweeping around them. The foliation in the host rock is deformed to isoclinal folds the axial surfaces of which sweep around the resistant remnants. The remnant materials may be pods of massive vein quartz, very rarely an unreconstituted granite (figure 23) and in certain localities, very large crystals and crystal aggregates of apatite or tourmaline (figures 24 and 25).

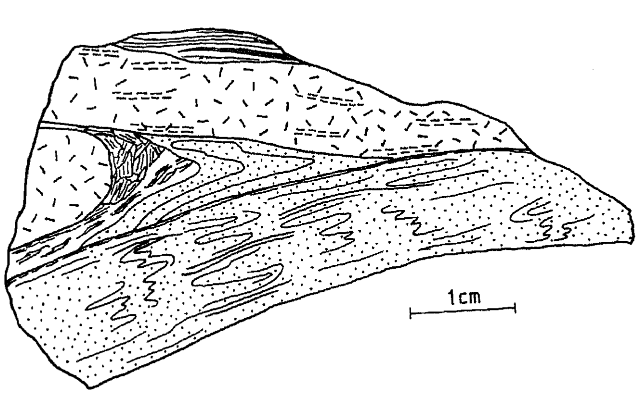

Figure 23. Resistant remnants of granite (unoriented dash) within intensely deformed very fine grained granite mylonite. Drawn from large thin section.

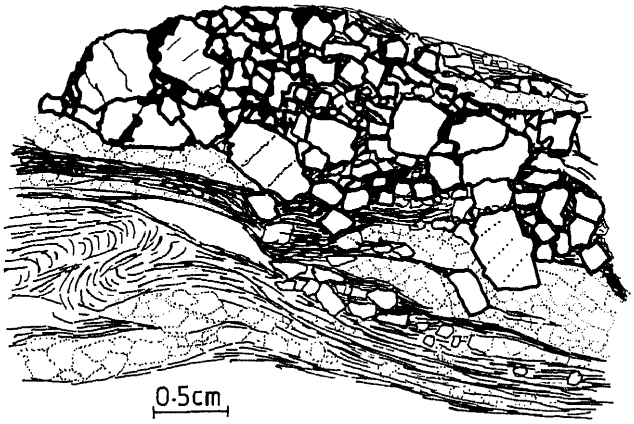

Figure 24. Large fragments of apatite separated by chlorite-quartz aggregate occurring within very fine grained mylonitic host.

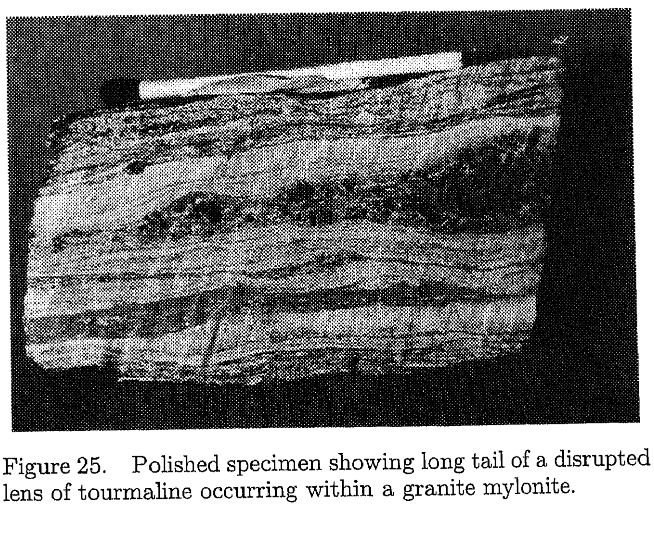

Figure 25. Polished specimen showing long tail of a disrupted lens of tourmaline occurring within a granite mylonite.

Along a thin peripheral rim, the lenticular fragments of granite and vein quartz have developed a foliation parallel to the bordering shear zone foliation. The larger lenses measuring a few centimetres in length, have sometimes been subdivided into two or more smaller lenses by thin sigmoidally curved shear zones along which a new cleavage has developed. Many of the lenses have very long tails, the length of which is many times larger than the lens itself. The tails, much longer in XZ-sections than along YZ-sections, may contain a few smaller pieces of the unreconstituted material but have developed in most parts a mylonitic foliation and a fine banding in the microscopic scale. Thus, for example, figure 23 shows resistant remnants of a coarse grained granitic rock within a mylonitized groundmass with isoclinally folded foliation.

Unlike the deformed veins of quartz or the resistant remnants of granitic rocks, the shearing of the large crystals of apatite (figure 24) or tourmaline (figure 25) does not produce, in the intermediate stages, a mortar structure with rims of a recrystallized fine grained material. In the initial stage of deformation the coarse crystals of apatite are traversed by thin irregular veins of chlorite. In addition, the large grains are dissected by subparallel tension fractures filled with quartz and subordinate chlorites. The tension fractures are oriented perpendicular to the mylonitic lineation of the host rock. Quartz, in these tension fractures do not have a fibrous appearance. However, the chlorite flakes are often roughly perpendicular to the vein walls. At a more advance stage of disruption the very coarse aggregates of apatite are subdivided into a number of large roundish grains separated by randomly oriented medium sized flakes of chlorite and subordinate quartz. As we move from the central part towards the borders and towards the tails of the lenses, the remnant grains of apatite become smaller in size while the intervening chlorite clots become weakly foliated and tend to swerve around the roundish resistant grains. At the border of the lenticular aggregates and along their tapering tails, apatite occurs as fine grains disseminated through a strongly foliated mass of well-crystallized chlorite flakes with lenticular bodies of fine grained recrystallized quartz.

A similar series of textures has also developed by the progressive disruption of the very coarse tourmaline crystals or crystal aggregates and their progressive incorporation within the mylonitic groundmass. The mylonitic foliation of the host rock sweeps asymmetrically around the rotated grains of tourmaline in some places. At the initial stage of disruption the large lenticular remnants of tourmaline are dissected by subparallel tension fractures filled with quartz and a few flakes of chlorite, the chlorite flakes being perpendicular to the vein walls and subparallel to the elongation direction of the tourmaline bearing lenses. At a more advance stage of disruption the tourmaline lens is subdivided into a number of large grains while the intervening areas are filled by coarse and medium sized quartz and subordinate chlorite. The texture of this quartz-chlorite aggregate is much coarser than that of the extremely fine grained foliated groundmass of the granite mylonite. With progressive deformation the remnant tourmaline grains become further disrupted and smaller in size, the intervening quartz-chlorite masses become sheared and foliated, and the tail of the lenticular aggregate becomes extremely elongated (figure 25). The final product is a fine-grained mylonitized tourmaline-bearing band of quartz-chlorite schist parallel to the foliation of the host rock of granite mylonite.

The development of shear zones and the initiation of a first generation cleavage, along narrow domains within the unreconstituted pods, must be a relatively late feature, since outside these pods the mylonitic foliation of the host material is strongly folded or refolded.

7. Problem of time-correlation

The features described above indicate that the mylonitic foliation did not initiate at the same time in all the domains. The mylonitic foliation which develops inside the resistant materials is the *first generation cleavage within these domains*, whereas the cleavage, which occurs in the groundmass, is a transposed mylonitic foliation, which is itself deformed into isoclinal folds. The occurrence of such features suggests that the pre-mylonitic rock, whether schistose or massive, became mylonitized along a number of anastomosing shear zones and left undeformed or weakly deformed remnants in between them. With progressive deformation the mylonitic foliation was impressed on a larger volume of rocks while folding and refolding of the same foliation were taking place elsewhere. In other words, the time of formation of an initial shear zone foliation (say, Sm) must have varied from domain to domain, and the initiation of the cleavage at one point could be contemporaneous with the development of folds on the cleavage at some neighbouring point. At each domain the initiation of the mylonitic foliation (Sm), the growth of the first generation folds (F_1) on it and the formation of its axial planar cleavage (S_1) were sequential; for the SSZ as a whole, however, it is likely that the events overlapped in time.

It is evident from the foregoing discussion that a time-correlation of specific structures from subarea to subarea are somewhat pointless in the SSZ. Such a time-correlation is all the more difficult to make between different generations of structures of the SSZ and those of the deformed rocks lying to the north of it.

Since the mylonitic foliation of the same generation (say, Sm) could be diachronous in different domains, the folds of any particular generation also might not have started to grow at the same time all over the SSZ. It is more likely that the folds were initiated at varying times, were tightened at different rates and began to be refolded by the next generation of folds not all at once. This implies that: (**1**) the folds of different generations are sequential in one place, (**2**) the folds of different generations and in different places may be synchronous or diachronous or partly overlapping in time, and (**3**) the folds of the same generation in different places may or may not be synchronous. This is not a new conclusion and is inherent in the definition of a fold generation (Hobbs *et al* 1976). As Williams (1985) points out, "just as a man may be older than his uncle, so an F_2 fold may be older than an F_1 fold elsewhere in the same area".

8. Conclusions

(1) A mylonitic foliation in the SSZ developed before the earliest recognizable folds.

(2) The shear zone folds initiated at different stages. At each stage the fold hinges developed with gentle to moderate pitches on their axial surfaces. The hinge lines were then rotated towards the down-dip stretching direction. The axes of the earliest reclined folds F_1 have become essentially parallel to the lineation. The hinge lines of the second and third generation reclined folds (F_2 and F_3) have also been rotated through large angles but in most cases their hinge lines are at an angle to the down-dip stretching lineation. The reclined folds are deformed by a group of subhorizontal folds. A group of transverse upright folds with steep axial planes parallel to the down-dip lineation developed towards a late stage of shearing. Gentle domes and basins have formed by their interference with gentle or open subhorizontal folds.

(3) The shear zone lineation is deformed over F_2 and F_3. The U-shaped pattern of lineation on the unrolled form surfaces of folds indicate that the folds were produced by combined buckling and flattening.

(4) The displacement along the SSZ is mostly compounded of numerous closely spaced subsidiary shear zones in the mesoscopic scale. Compared to the shear lenses enclosed by them, the bounding shear zones are domains of strain concentration.

(5) The mesoscopic shear zones have repeatedly developed, one set superimposed on another. Excepting a few resistant remnants, all the rocks of the SSZ, either within the mesoscopic shear lenses or in the bordering shear zones, have been mylonitized. Hence, almost every small domain of SSZ have, at one time or other, been a part of a shear zone domain and at other times a part of a shear lens.

(6) In the mesoscopic shear zones the earlier cleavage is transposed to a new cleavage. In the less deformed shear lenses the earlier cleavage may or may not be retained. Depending upon its initial orientation the earlier cleavage in the lenses may be passively rotated or crenulated. With progressive deformation a new axial planar cleavage developed in the crenulated domains and their acute angle with the bounding shear zones points towards the sense of shear.

(7) The cleavage surfaces in the domains of the mesoscopic shear zones and the shear lenses cannot be strictly regarded as C and S surfaces. As defined by Berthe *et al* (1979), the C surfaces are domains of discontinuous relative movement. Offset of overturned limbs of folded quartz veins along cleavage surfaces can be occasionally seen in the SSZ; nevertheless, in most parts, both the shear lenses and the shear zones are domains of ductile deformation and the cleavages of the two domains have identical kinematic significance. In other words, in the terminology of Berthe *et al* (1979) the cleavages in the mesoscopic shear zones and shear lenses are both S-surfaces.

(8) The initial mylonitic foliation did not develop synchronously in all the domains in the SSZ. The folds of a particular generation also did not initiate at the same time everywhere. Although at each domain the folds of the different generations are sequential, the folds of the same generation in different domains may be synchronous, diachronous or partly overlapping in time.

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