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Journal of Structural Geology 29 (2007) 273–287

JOURNAL OF STRUCTURAL GEOLOGY

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Origin of striping lineation and transposition of linear structures in shear zones

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Received 29 December 2005; received in revised form 22 August 2006; accepted 28 August 2006
Available online 21 November 2006

Abstract

Striping lineation occurs as fine colour stripes on foliation surfaces of strongly sheared rocks that have a mylonitic colour banding. Although described as intersection lineation, striping lineation in mylonites does not show two different intersecting S-surfaces. Unlike ordinary bedding–cleavage intersection, striping lineation is a typical product of ductile shearing. The colour stripes may have formed at a very early stage of deformation as intersections of a bedding or a colour banding on the foliation surface. At a later stage, the bedding or the colour banding ceased to be reoriented by external rotation. The foliation became the only active S-surface and the deformation of the colour stripes was controlled entirely by the nature of the strain. After the appearance of a layer-trace on the axial plane cleavage in an early stage of deformation, the later history of its changing width and orientation becomes independent of changes in the thickness and orientation of the layer. In strongly sheared rocks, the nature of the original layering is greatly modified. Hence, a colour striping can remain with very small width even when the foliation and bedding have become parallel. The striping lineations in the Phulad Shear Zone in western India and Singhbhum Shear Zone in eastern India are often transposed and retransposed in response to folding, sheath folding and strong stretching. The process is very similar to the development of transposed foliation.

Keywords: Striping lineation; Mylonitic banding; Sheath folds; Transposition; Phulad Shear Zone; Singhbhum Shear Zone

1. Introduction

Mylonites in shear zones generally have a very prominent lineation (e.g. Escher and Watterson, 1974; Bell, 1978; Hobbs et al., 1976; Ghosh and Chatterjee, 1985; Ghosh and Sengupta, 1987, 1990; Sengupta and Ghosh, 1997, 2004; Ghosh et al., 1999, 2003; Piazolo and Passchier, 2002; Alsop and Holdsworth, 1999, 2004; Miller et al., 2006). The shear zone lineation may be marked by strongly elongated grains, fine leaf-shaped micas and streaks of mineral aggregates. In addition, the most penetrative linear structure in many shear zones is manifested by fine parallel linear colour stripes on foliation surfaces. The colour stripes occur only on the foliation surfaces of the mylonites. Instead of using a genetic term for the structure it is preferable to use the descriptive term striping lineation (Ghosh and Chatterjee, 1985; Ghosh and Sengupta, 1987; Ghosh et al., 1999; Sengupta and Ghosh, 1997, 2004).

Examples of striping lineation in this paper have been drawn mostly from two major shear zones of India, the Phulad Shear Zone of Rajasthan in western India and the Singhbhum Shear zone of eastern India, where the structure is ubiquitous and well developed. The two shear zones, situated about 1500 km apart, belong to quite different tectono-stratigraphic settings. Hence, the description and conclusions of this paper regarding striping lineation are not site specific. In both these shear zones, the intermediate strain axis λ_2 is parallel to the sub-horizontal vorticity vector, and the direction of maximum stretching is parallel to the down-dip direction of the mylonitic foliation. The linear structures of both the shear zones have

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doi:10.1016/j.jsg.2006.08.012

often undergone transposition. The Phulad Shear Zone (Golani et al., 1998; Ghosh et al., 1999, 2003; Sengupta and Ghosh, 2004), belonging to the Precambrian Delhi mobile belt (Heron, 1953; Roy and Jakkar, 2002), is a 30 km long, about 20 m wide, ductile shear zone in which the layers of mylonites have alternate calcareous bands and metamorphosed siliciclastic rocks. The mylonitic structure is especially well developed in the very fine grained quartz-rich layers. Although the major part of the rocks is thoroughly mylonitized, there are some remnants of resistant lenses of quartzofeldspathic pegmatities. The Singhbhum Shear Zone in eastern India is a 150 km long arcuate shear zone with a variable width between 1 and 2 km. The mylonites in the Singhbhum Shear Zone (Dunn and Dey, 1942; Naha, 1965; Ghosh and Sengupta, 1987, 1990; Sengupta and Ghosh, 1997) were derived from a variety of Precambrian rocks such as sheared granites, phyllonites and quartz mica schists. Striping lineations similar to those occurring in the Phulad Shear Zone (PSZ) and the Singhbhum Shear Zone (SSZ) have been described from other areas, e.g. Woodroffe thrust of Australia (e.g. Bell, 1978, Fig. 6) and Precambrian Moine metasediments of north Scotland (Alsop and Holdsworth, 1999, Fig. 3d).

The general term intersection lineation has often been used to describe a striping lineation. However, the description of a striping lineation as found in the PSZ or in SSZ as an intersection lineation is not meaningful because these shear zone rocks show only a single set of foliation surfaces. Typical intersection lineations occur in weakly deformed or moderately

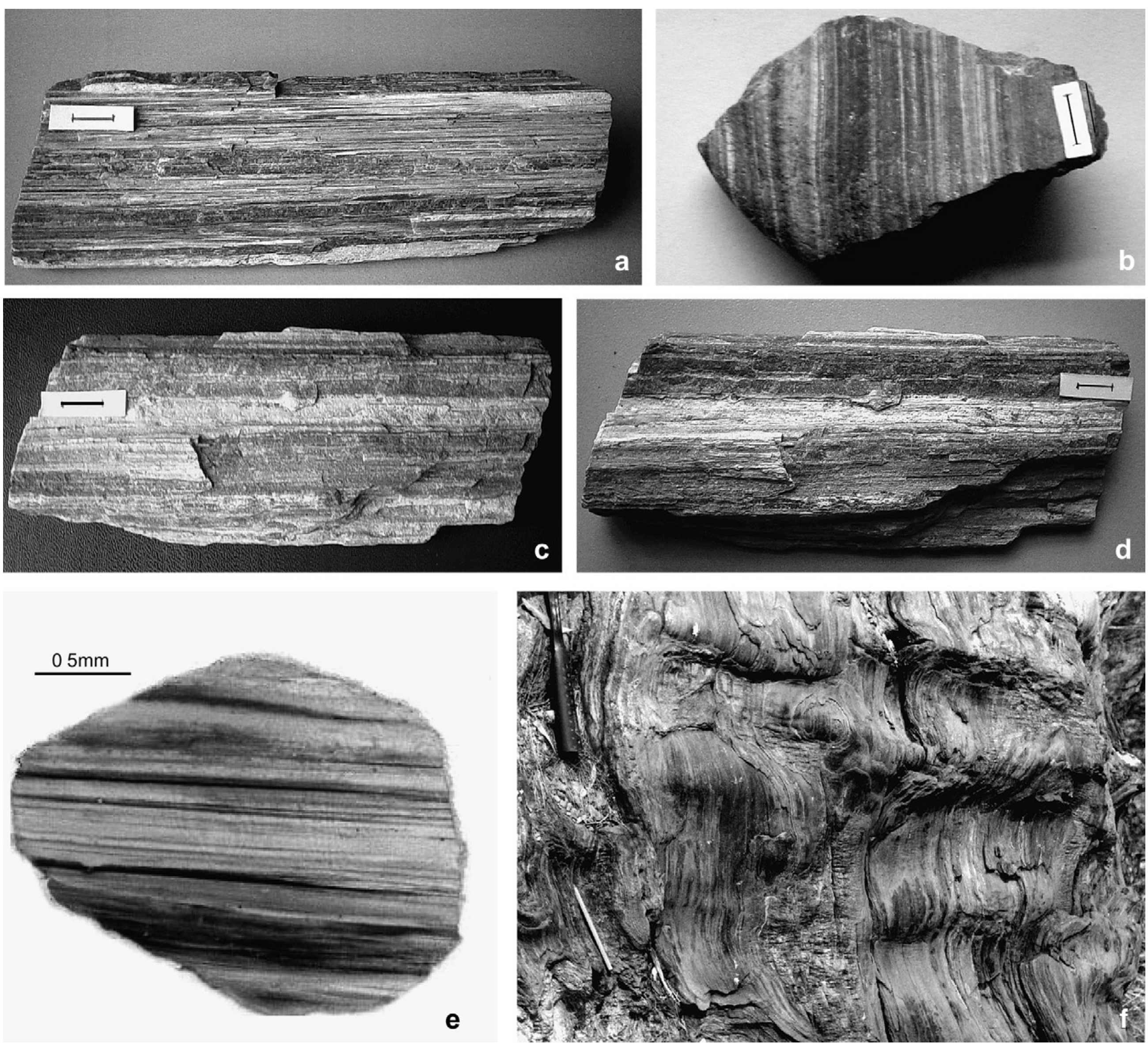

Fig. 1. (a–e) Striping lineation on foliation surfaces of specimens of mylonite from Phulad Shear Zone, Rajasthan, India. The mylonitic rock is composed of alternate calcareous and siliciclastic bands. There is a fine stretching lineation parallel to striping. Scale bar 1 cm. (e) Striping lineation on the foliation surface in the scale of a thin section, directly scanned in plane light. (f) Striping lineation in phyllonite from Singhbhum Shear Zone, eastern India.

deformed rocks in which traces of bedding laminae appear on an intersecting axial plane cleavage. The intersection lineation is not produced by *material* objects (such as strongly stretched and flattened linear mineral aggregates) but is a result of the *geometrical* process of intersection of two S-surfaces. In contrast, a striping lineation is strictly confined to the shear zone, is a product of very high strain, and is composed of linear *material* bodies. They always show microstructures characteristic of very high strain (e.g. Ghosh and Sengupta, 1987; Sengupta and Ghosh, 2004).

The striping lineation of PSZ and SSZ occurs in rocks that have undergone in each of the areas several generations of folds, rotation of fold hinge lines, development of planar sheath folds, nonplanar sheath folds and refolded sheath folds. The details of these geometrical evolutions as well as an analysis of rotation of fold hinge lines and other linear structures have been covered in a number of papers (Ghosh and Sengupta, 1987; Ghosh et al., 1999, 2003; Sengupta and Ghosh, 1997, 2004). Somewhat similar structures have been described from other areas also. Thus, for example, the structures and structural history described by Alsop and Holdsworth (1999, 2004) from the Caledonides of northwestern Scotland show some similarity with the sequence of structural changes in the PSZ and SSZ.

A major objective of this paper is to study the course of evolution of striping lineation through successive stages of progressive ductile shearing. An insight into the problem of origin of striping lineation can be obtained by tracing the

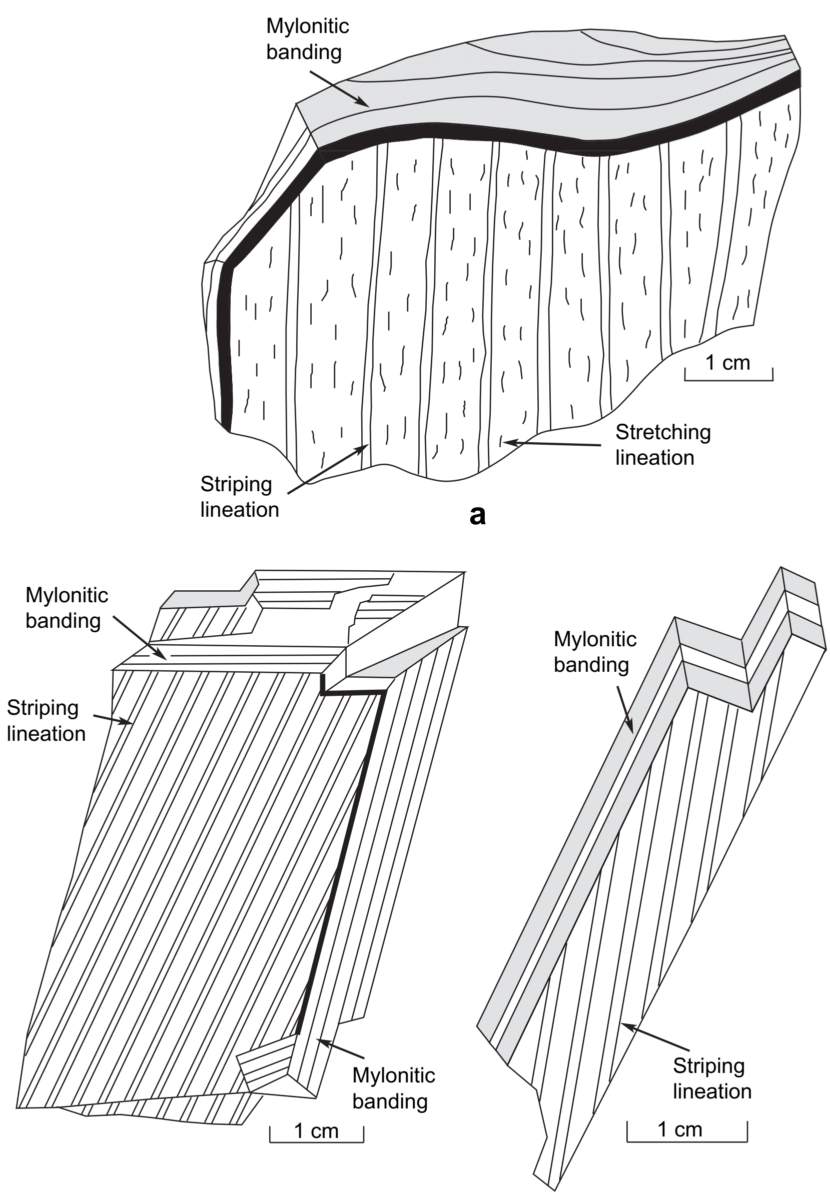

Fig. 2. (a–c) Striping lineation on Phulad mylonites. The specimens do not show any evidence that the lineation was produced by intersection of fine mylonitic banding and the foliation surface on which the striping lineation lies.

successive stages of change from a moderately deformed rock to an intensely deformed rock containing a striping lineation. This aspect has been considered in a later section with reference to the phyllites and schists of the Zawar schist belt (Roy, 1995) of Rajasthan. We have also introduced the concept of transposition of striping lineation. It will be shown that striping lineation is a remarkably persistent structure, which survived through repeated folding, sheath folding, transposition of foliation and lineation.

2. Nature of striping lineation

The following description of striping lineation (Figs. 1–3 and 11, see also Figs. 11–14 showing transposed striping lineation) is based on detailed structures of the mylonites of the Phulad Shear Zone and Singhbhum Shear Zone. The striping lineation may occur at an angle to the stretching lineation (Fig. 3). In most of the mylonites of PSZ and SSZ, however, the stretching lineation is strictly parallel to the striping lineation. The mylonites of these areas have a very fine planar colour banding parallel to a well-developed cleavage. The planar foliation-parallel colour bands range in thickness from the finest to a few millimetres. The colour stripes on the foliation surface are also millimetric in width. In general, the finer the foliation-parallel planar colour banding, the finer are the linear colour stripes. As in the planar colour bands, the colour stripes are also of different orders of widths. Thus, for example, in a relatively coarse scale, the striping may appear as alternate grey and white stripes ranging in width between 3 and 5 mm. Within each of these there are stripes ranging in width between 1 and 2 mm (Fig. 1e). Each of these shows submillimetric stripes of slightly different colour variation. The linear stripes have a remarkable continuity, each stripe continuing in length much more than a hundred times its width.

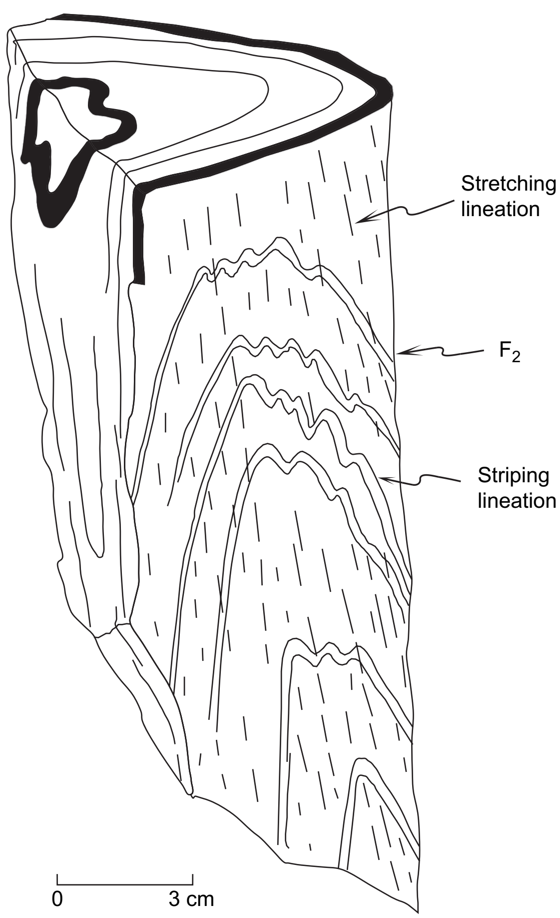

Fig. 3. An isoclinal planar sheath fold F_1 is refolded by F_2. The curved striping lineation (double line), parallel to the curved hinge lines of F_1 also shows smaller subsidiary folds. These are interpreted as two orders of planar sheath folds. Note that the curved F_1 striping lineation is intersected by a more or less straight stretching lineation. Mylonite of alternate calcareous and siliciclastic rock from Phulad Shear Zone.

The foliation, i.e. a cleavage marked by parallel alignment of flat leaf-like grains, is strictly parallel to the colour banding. The colour banding in the striped rocks cannot be identified as bedding. Even if there was a bedding in the pre-mylonitic rock, it must have been so greatly modified that it is no longer recognizable. Nevertheless, in its general appearance, the striping lineation is somewhat similar to an intersection lineation, i.e. a lineation produced by intersection of two non-parallel S-surfaces, a colour banding (either a bedding or a metamorphic banding) and a cleavage. An intersection lineation is not ordinarily a striping lineation; it may evolve into a striping lineation under special circumstances, i.e. under very high strain. To study the evolution of a striping lineation we have to address the problem of how the colour stripes occur on a foliation where no other intersecting S-surfaces are discernible. We also need to study the evolution of these structures as quintessential products of extremely large non-coaxial strain in ductile shear zones. Study of successive stages of development of the structure from moderately deformed to intensely deformed terrains is necessary for a proper understanding of the problem. Similar to the case of a striping lineation, a differentiated layering in a metasediment is not necessarily a bedding; it may be a bedding, a modified bedding or may be entirely due to metamorphic differentiation (Hobbs et al., 1976, p. 230). In the PSZ and the SSZ, the foliation-parallel banding is certainly not a bedding. It is itself a product of ductile shearing and metamorphic segregation. It is also likely that the foliation itself has undergone transposition. Successive stages of such changes are difficult to find. After the change to a striping lineation, the structure acquires quite a new character, and to still describe it as an intersection lineation is as irrational as describing a butterfly as a caterpillar.

3. Intersecting S-surfaces in external rotation and in homogeneous strain

During progressive tightening of a fold on a competent bed, the orientation of the limbs changes by external rotation.

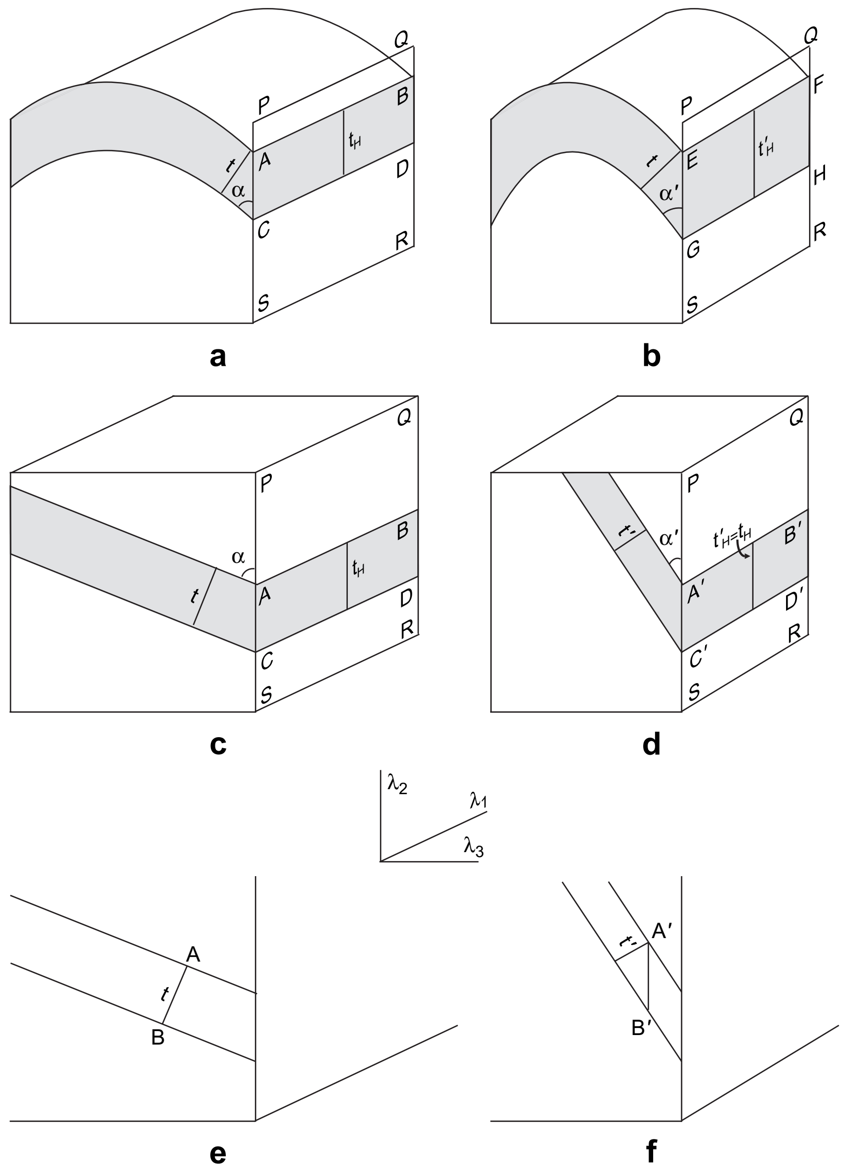

Fig. 4. (a) The orthogonal thickness of a parallel fold is t. The fold limb makes an angle α with a plane parallel to the axial plane cleavage. The width of the layer-trace on this cleavage is t_H. (b) As the fold tightens α decreases (to α') and t'_H (the changed value of t_H) increases. In an isoclinal fold $\alpha' = 0$ and t'_H tends to become infinitely large. (c) A layer with orthogonal thickness t makes an angle α with a plane parallel to the $\lambda_1\lambda_2$ plane. The layer-trace on the $\lambda_1\lambda_2$ plane is parallel to the λ_1 axis and has an initial width t_H. (d) The layer as shown in (c), is passively rotated; α is reduced to α'. The orthogonal thickness t decreases to t'. The width t_H changes to $t'_H = (\sqrt{\lambda_2})t_H$. If $\lambda_2 = 1$, $t_H = t'_H$. (e and f) Distinction between a material line and a geometrically defined line. In (e) AB is a line perpendicular to the layering. AB is equal to the initial orthogonal thickness t; (f) shows the layer after passive rotation. The material line AB has changed to $A'B'$ which is no longer perpendicular to the layering. The geometrically defined perpendicular t' is different from $A'B'$.

Consider a fold limb of thickness t making an angle α with the axial plane of the fold. If the fold tightening is by external rotation, α decreases but the thickness t remains the same. Hence, the width (t_H) of the trace of the bed on the axial plane (Fig. 4a) is

$$t_H = \frac{t}{\sin\alpha} \quad (1)$$

If α decreases to α', t_H increases to t'_H (Fig. 4b). In an isoclinal fold, the angle between the fold limb and the axial plane becomes zero, and the width t'_H tends to become infinitely large.

In contrast, if the rotation of a set of layers occurs by homogeneous strain, the width of the trace of a layer on the axial plane cleavage does not depend on the progressive change in angle between the layer and the cleavage. The width t_H will be determined essentially by the nature of bulk strain. Thus, for example, Fig. 4c and d shows a situation in which the layers are deformed by pure shear, with the direction of maximum stretching (λ_1) along the bedding–cleavage intersection and the intermediate strain axis (λ_2) at a right angle to it on the axial plane cleavage. With progressive deformation, the angle α between the bedding and the cleavage decreases, the thickness (t) decreases, but the width of the layer-trace on the cleavage remains the same (Fig. 4c and d)

$$\tan\alpha' = \frac{\sqrt{\lambda_3}}{\sqrt{\lambda_2}}\tan\alpha \quad (2)$$

$$t'_{\mathrm{H}} = \sqrt{\lambda_2}t_{\mathrm{H}}. \quad (3)$$

The layering and the cleavage may become essentially parallel without the necessity of an unlimited increase in width. Essentially, similar results are obtained for simple shear or more complex types of non-coaxial deformation, with the help of equations similar to those given, for example, by Ghosh (2001, Eqns. 22–24) or somewhat simpler equations of plane noncoaxial deformation (Ramberg, 1975; Ramberg and Ghosh, 1977; Skjernaa, 1980; Ghosh, 1982).

The intersection of an externally rotated layer and the axial plane of a fold, as shown in Fig. 4a and b, is a geometrically defined line. The distinction between a material line and a geometrically defined line can be easily visualized from Fig. 4e and f. In Fig. 4e, the orthogonal thickness of a layer t is equal to the line segment AB. After deformation of the layer, the deformed material line $A'B'$ is no longer perpendicular to the layering. The geometrically defined perpendicular t' (Fig. 4f) is different from the material line $A'B'$. Thus, for example, in Fig. 4a, the trace of the fold limb on the axial plane (PQRS) is bordered by the lines AB and CD. After external rotation, the orthogonal thickness of the bed has remained the same but the width of the trace of the bed has increased. These lines of intersection are geometrically defined. The material lines (i.e. lines joining material points) AB and CD are not the same as the lines EF and GH (Fig. 4b). On the other hand, in the model of homogeneous strain, a layer-trace on the surface of the axial plane cleavage (PQRS) is a material entity (Fig. 4c and d). The material lines AB and CD of Fig. 4c have been transformed to the material lines $A'B'$ and $C'D'$ after homogeneous deformation (Fig. 4d). For this reason, once the trace of a layer occurs at some stage of deformation on the axial plane cleavage, it can never vanish even when the two surfaces have become essentially parallel. Indeed, after a layer-trace appears on the axial planar cleavage, the subsequent history of its changing width and orientation becomes independent of changes in the thickness and orientation of the layer. This can be clearly seen in the simple analogue experiment described in the next section.

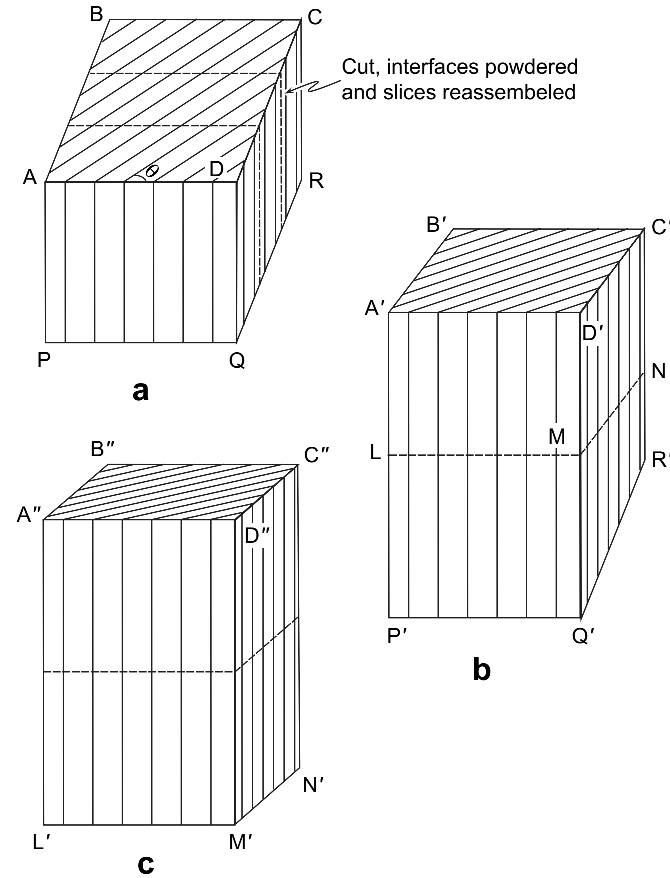

Fig. 5. Method of preparation of model. (a) At the initial stage, the model was rolled on the surface ADQP, with stretching along DQ or AP. The initial angle between the layering and the ADQP surface is θ. The model was cut into three blocks (along the dashed lines). The cut surfaces were liberally sprinkled with talc powder and reassembled. (b) The model after the first stage of rolling. The model was elongated along $D'Q'$and shortened along $D'C'$. The angle θ was reduced. The model was cut into two pieces along the surface LMN. (c) One half of this model was further rolled and the process was repeated till θ was reduced to a very small value.

4. Experiments to simulate the origins of striping lineation

A few simple experiments (Figs. 5 and 6) were conducted with modelling clay multilayers to simulate the development of striping lineations. A multilayer was prepared by placing alternate layers of modeling clay of two colours. The multilayer was trimmed in the manner represented in Fig. 5a. The layer-traces on the face ABCD made an angle (θ) of 30° with the edges AD and BC. The layer-traces on the faces ADQP and CDQR are parallel to the long edges AP, DQ and CR. Such a block of multilayer was then cut up into three slices parallel to the face ADQP. The intervening faces were liberally sprinkled with talc powder, and the slices were assembled once again. The model was then rolled on the face ADQP parallel to the layer-traces along AP. After a certain stage of deformation (say 50%), the model was cut into two pieces across the length (Figs. 5b and 6a). One of the pieces was taken apart along the previously cut powdered surfaces to expose the stripes (Fig. 6e). The dimensions of the model and the width of the stripes were measured. The remaining part of the model was further rolled (Figs. 5c and 6b). This deformed model was again cut up into two

Fig. 6. (a–d) ABCD face of the deformed model after 50%, 65%, 78% and 125% of strain. (e–h) The corresponding ADPQ faces at different stages of deformation. Initial θ was 30°. Scale bar 1 cm. Note that from initial to final stage of deformations, θ is greatly reduced but the average width of the stripes has not changed much.

pieces. One of the two pieces was taken apart along the two previously cut and powdered surfaces (Fig. 6f), and the widths of the stripes were measured. This process was repeated two or three more times till the model was rolled into a thin sheet (Fig. 6d), and the angle between the layering and the powdered surfaces was greatly reduced. Fig. 6e–h shows some of the powdered surfaces of the model that were exposed after deformation. The colour stripes are the traces of colour bands on the powdered surfaces.

The results of one the experiments are represented graphically in Fig. 7, the lower curve of which shows the changes in the widths of the stripes with progressive deformation. The

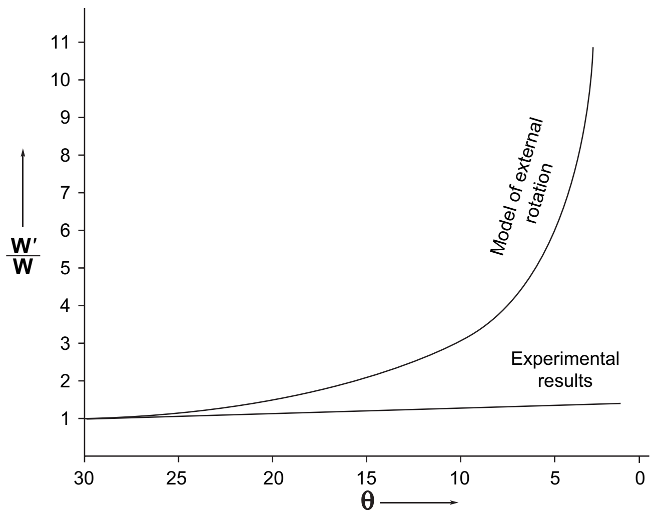

Fig. 7. Plot of actual experimental results and results expected when geometrically defined S-surfaces intersect. The upper curve is for the model in which the layering undergoes only external rotation with progressive deformation. Consequently, the width of stripes on the foliation increases rapidly with decrease in θ. In the experiments (lower curve), the deformation is essentially by homogeneous strain. There is a slight increase in the width of the stripes because of small extension along Y direction. W and W' are initial and deformed width of stripes; θ is the angle between foliation and initial layering.

initial angle θ (30°) is progressively reduced. The graph shows the ratio W'/W (where W' is the width of the deformed stripes, and W is the initial width) increases very slightly with progressive deformation. This is essentially a result of a slight increase in the width of the model in the Y direction, i.e. along the axis of rolling. This slight change in width is in sharp contrast with the graph showing the change in W'/W for the theoretical model (upper curve of Fig. 7) in which the layering changes its orientation by external rotation alone. As expected, for the latter graph, the ratio W'/W rapidly increases to a very large value as the angle θ decreases to a very small value. The experiments show that unless the layering is reoriented in an active manner by external rotation, the width and orientation of the layer-traces on a foliation surface would change in accordance with the nature of the bulk strain and will not depend on the orientation of the layering.

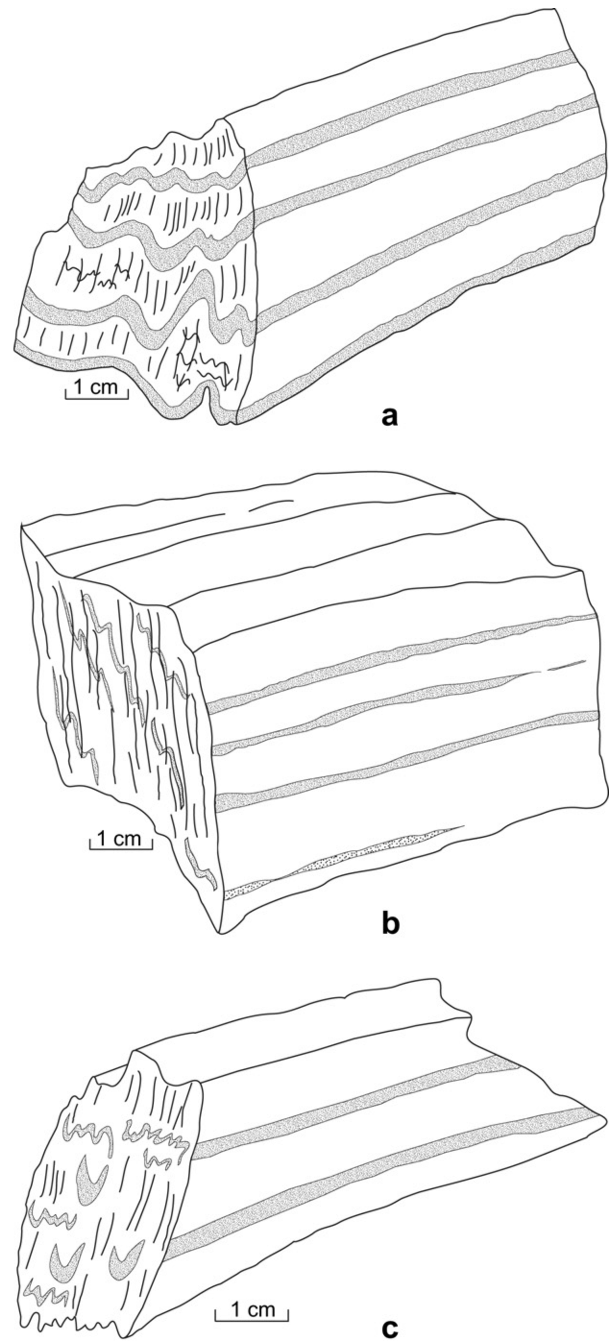

Fig. 8. Sketches of specimens of phyllites and schists from the Zawar schist belt. Figures (a–c) show different stages of progressive shearing and progressive destruction of bedding laminae. See text for details.

5. Origin of striping lineation

In both the PSZ and SSZ, the intensity of deformation is so large that we can only see a fine foliation-parallel mylonitic banding and linear colour stripes often with a parallel stretching lineation on the foliation surface. Some insight into the problem of origin of striping lineation may be obtained when successive stages of progressive deformation can be traced in phyllites and schists which initially showed bedding laminae in a mesoscopic scale at an angle to the axial plane cleavage. Such changes through different intensities of shearing can be seen, for example, in the Zawar schist belt (Roy, 1995) of Rajasthan, western India (Fig. 8). Here the dominant cleavage in most of the rocks is a second generation cleavage, axial planar to folds of bedding laminae. The earlier cleavage is parallel to the bedding. In the least sheared rocks (Fig. 8a), traces of bedding appear as colour stripes on the dominant axial plane cleavage. As the rocks are traced to more and more sheared domains, the bedding laminae become isoclinally folded and transposed. A striping lineation on the dominant cleavage can also be seen in these rocks. In the sheared

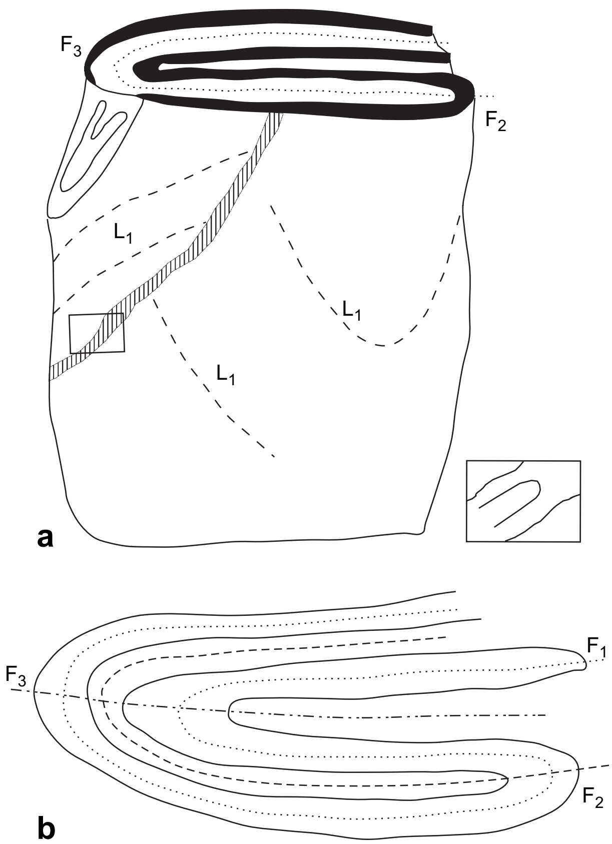

Fig. 9. (a) Hand specimen from Phulad Shear Zone showing interference of F_1, F_2 and F_3. On the front face of the specimen L_1 has very different orientations on two surfaces a few millimetres apart. Inset shows the remnant of an isoclinal fold. (b) Schematic diagram showing three sets of folds with their respective axial surfaces.

varieties, the bedding can be recognized as remnants of a few fold hinges (Fig. 8b and c), and a rough colour banding appears sporadically in some places parallel to the newly transposed cleavage. Colour stripes parallel to the fold axis are still recognizable on the cleavage surface. The rock is still not a mylonite. It is likely that on a more advanced stage of shearing, the structure would evolve into a typical striping lineation similar to that of the PSZ and SSZ.

The sequence of changes described above implies that the striping lineation in mylonites such as in the PSZ and the SSZ developed during intense shearing of rocks. At some stage of deformation, the cleavage became the most active plane, and the colour bands were deformed in a passive manner. At a very advanced stage of deformation when the rocks had attained the character of a mylonite, a new set of colour bands was produced (by tectonic–metamorphic processes) parallel to the cleavage, but the traces of the earlier bands remained as vestiges on the cleavage surface and were strongly modified by intense shearing to produce a striping lineation. The later stage of evolution of striping lineation does not preserve any geometrical feature that indicates its origin by intersection. This is a consequence of the fact that, once produced, the colour stripes on the cleavage surface behave as passive markers; they are further modified only by the nature of the bulk strain, and not by the changes in orientation and thickness of the layering as expected in an active rotation of the layers.

The structures in the PSZ and the SSZ developed in the course of very large deformation. The principles of rotation of planar and linear structures in simple shear or in more complex types of three dimensional noncoaxial deformation are well known (e.g. Ramberg and Ghosh, 1977 for complex pure shear and simple shear; see also Skjernaa, 1980 for progressive simple shear). It is difficult to measure the magnitude of total finite strain in zones of very high strain, as in the PSZ and the SSZ. There are several reasons for this. Within the shear zones, all the objects have been so stretched and distorted that it is impossible to find suitable strain gauges. Secondly, an intractable problem is that the deformation did not take place in one casting. There were folding and refolding and repeated transposition of cleavages. Quartz veins have been syntectonically introduced in the SSZ at different stages of deformation. In the PSZ, syntectonic pegmatites have been emplaced in different stages of mylonitization. The microstructures of these rocks show that the mylonitic foliation did not initiate all throughout a shear zone at one go. In different places within each of the shear zones, it was synchronous or diachronous or partly overlapping in time. It has also undergone transposition in different stages in different domains. As Williams (1985) pointed out in case of folds, ''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''.

An analysis of the magnitude of strain in the PSZ was made by Ghosh et al. (1999, p. 1726) with the help of development of U-patterns of lineation. It was concluded that the total extension in the down-dip direction of the shear zone must have been very much in excess of 6000%. At such extremely large strain, earlier premylonitic structures are unlikely to be preserved. The magnitude of deformation is in conformity with our general conclusions that all linear structures are passively rotated to parallelism in the direction of maximum strain.

6. Transposition of lineation

A well-developed schistosity is a remarkably persistent structure. In most intensely deformed schistose terrains of superposed deformations, the earlier schistosity is isoclinally folded and a new schistosity is produced by reorientation of the earlier schistosity leading to the development of a transposition structure (e.g. Weiss, 1949; King and Rast, 1956; Rickard, 1961; Naha, 1965; Hobbs et al., 1976; Williams, 1976; Powell, 1979; Price and Cosgrove, 1990; Ham and Bell, 2004). What we mean by the new schistosity in such a case is the schistosity along the limbs of the folds, the hinge zones occupying negligibly small domains. In certain areas such transposed schistosity has been retransposed (Fig. 9). The earliest foliation has not been destroyed but has undergone repeated isoclinal folding. If the deformation is very intense, as in ductile shear zones,

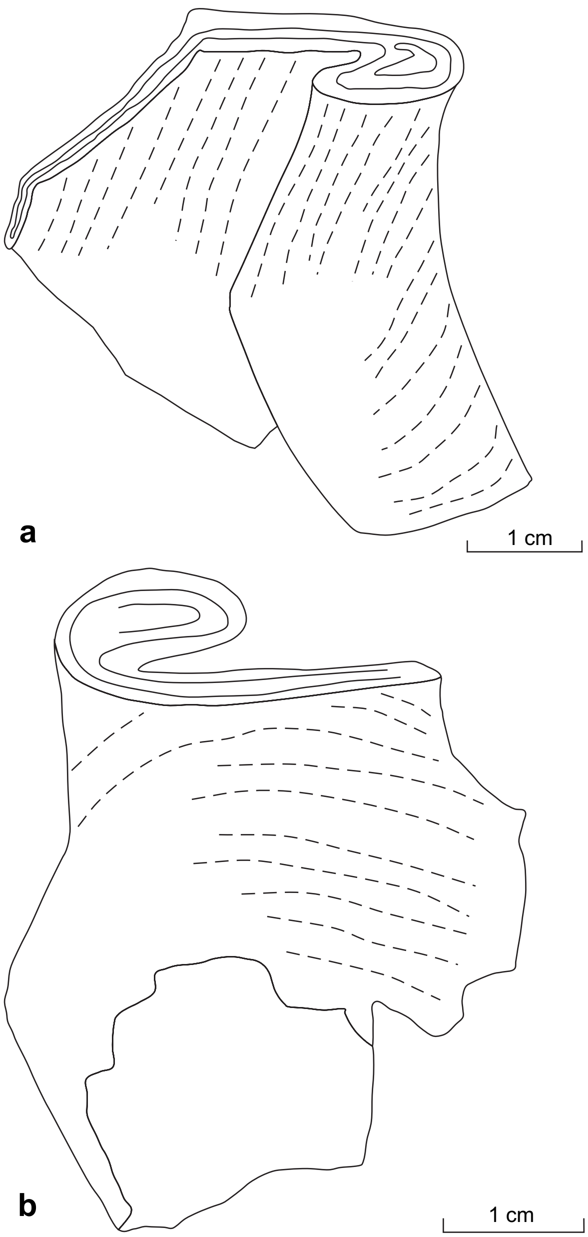

Fig. 10. (a and b) Opposite faces of a finely layered sheet of folded mylonite of PSZ. The lineation has very different orientations and is almost at right angles on the opposite faces. The different attitudes on two faces are because the faces are separated by the axial surface of an isoclinal fold.

the hinge zones of the folded schistosity may be sheared out. The origin of the structure by transposition cannot be detected in such cases, unless remnants of apices of isoclinal folds are preserved in some places.

The striping lineation in a strongly sheared rock is also a remarkably persistent structure. It survives through prolonged and repeated phases of progressive folding and ductile shearing. If the foliation on which the lineation lies is isoclinally folded by buckling or flexure with the fold axis at an acute angle to the lineation, the lineation will show different orientations on the two limbs (Fig. 10a and b). If the hinge zones are destroyed or lie outside the domain of observation, we may have an apparently complex situation of differently oriented lineations on closely spaced parallel surfaces (Figs. 9a and 11). In all such cases, a careful search will reveal the presence of a fold axial surface between the two foliation surfaces. Whatever be the reason for different orientations of the lineation in different domains, an extremely large deformation, as in a major ductile shear zone, will tend to reduce the angle between the lineations. In many cases, the lineations that were initially divergent became essentially parallel. When the initial divergence resulted from folding of the foliation, the final parallelism was very similar to the process of transposition, in the sense that an earlier lineation has been folded and become parallel.

Transposition occurred in different ways (Figs. 12–15). Thus, in some places in the Phulad shear zone, isoclinal folding of down-dip F_1 striping lineation by sub-horizontal later folds caused the reoriented striping lineation on the two limbs of the fold to become virtually parallel (Figs. 12a, b and 14a). Indeed, where the F_2 hinges are very much attenuated and large expanses of limbs are exposed, the lineations in successive surfaces appear as subparallel without leaving any clue that the closely spaced parallel surfaces on which the lineations lie are indeed on two limbs of a fold with reorientation of surfaces through 180°. The striping lineation is often deformed by successive stages of later folding. The deformed striping lineation may occur at an angle with each other at different limbs of folds (Figs. 9–11). With

Fig. 11. Differently oriented striping lineation in different surfaces. The difference in orientation is mainly due to the presence of isoclinal folds. Match stick is 4 cm long.

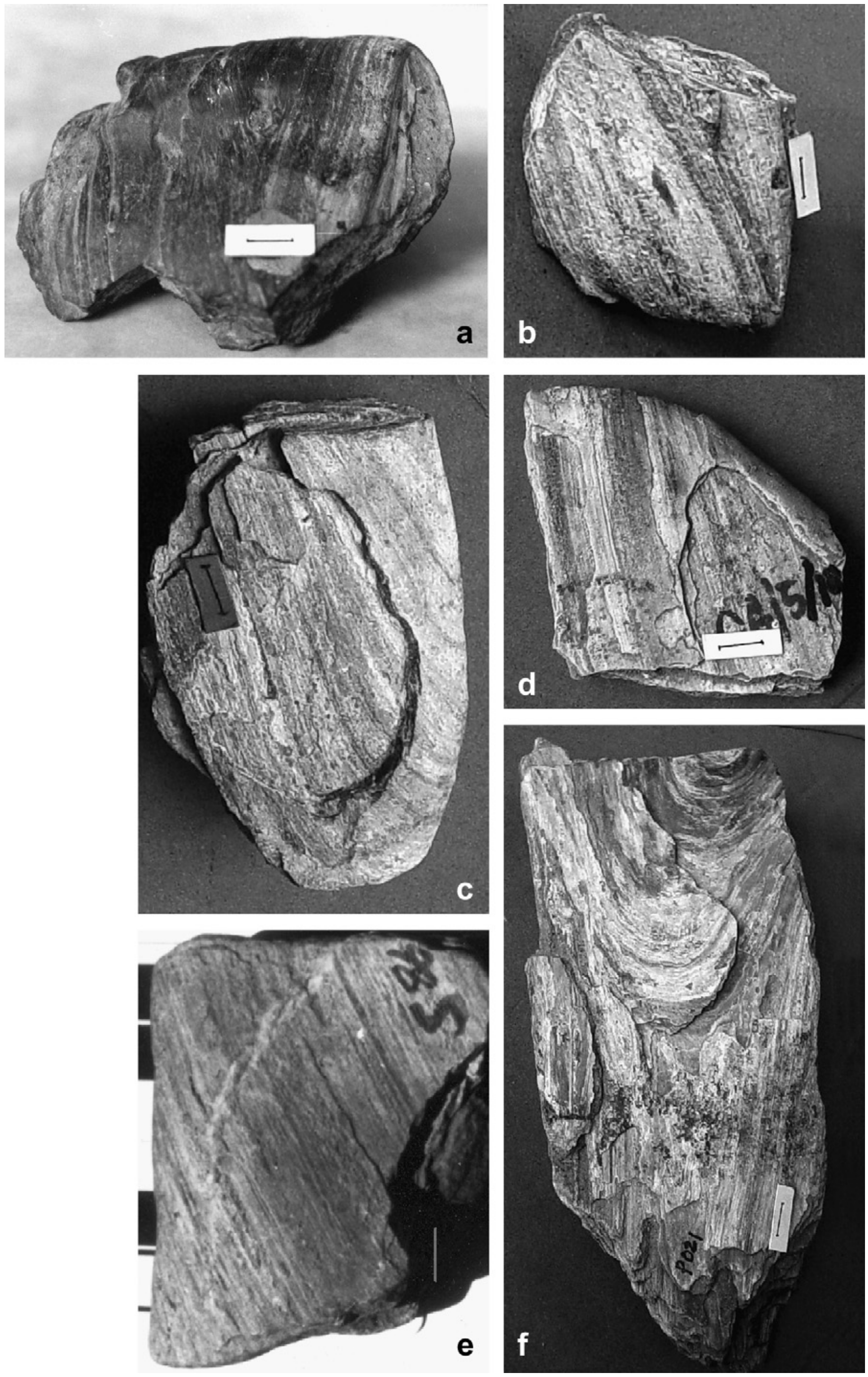

Fig. 12. Specimens of (a–d, f are from PSZ and e is from SSZ) mylonites showing transposed striping lineation. The stretching lineation is parallel to the striping lineation in all cases except in (f) where the stretching lineation intersects the curved striping lineation. Scale bar 1 cm. (a) The upper edge of the specimen is the hinge of a sub-horizontal fold. The profile of an isoclinally folded hinge can be seen at the right hand side. On the unrolled surface, the lineation becomes straight as in Fig. 15a. (b) Specimen of an isoclinal reclined fold deformed by isoclinal sub-horizontal fold. The folded striping lineations in different parts of the specimen are nearly parallel. (c) A reclined isoclinal fold. The profile can be seen at the top of the specimen and the hinge line is seen at the right side. The striping lineation is at low angle to the hinge on both limbs of the fold in the major part; it is at a right angle to the hinge line at the hinge zone. The lineation is effectively transposed in major part of the specimen. On the unrolled form surface the deformed lineation shows a U-pattern similar to Fig. 15b. (d) Front limb of a tightly appressed isoclinal fold. The upper edge of the specimen is the hinge line of the fold with the other limb on the reverse side. The profile of the fold is at the right and left side of the specimen. The striping lineation is parallel on both limbs although the foliation and lineation are folded. Note that the lineation remains parallel in spite of the curving of the hinge line. See sketch of the specimen in Fig. 14b. (e) Specimen of a reclined fold of quartzite mylonite from SSZ. The vertical edge on the left side is an F_2 hinge line. The striping lineation is deformed by the F_2 to a U-pattern. If the fold is unfolded, the L_1 striping shows the form similar to Fig. 15b. (f) Transposition of striping lineation on the axial plane foliation. That the parallel lineation seen in the lower part is a result of transposition of a deformed lineation is indicated by the occurrence of apices of the folded form in some domains as in the upper part of the specimen.

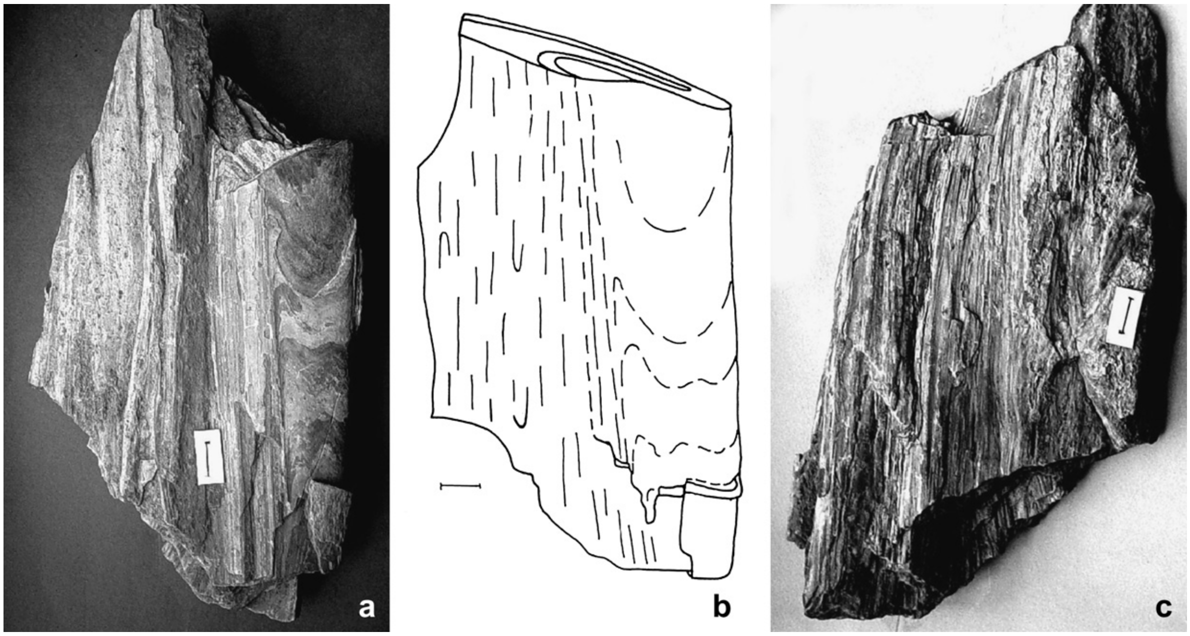

Fig. 13. Specimen of folded mylonite from Phulad Shear Zone. (a) The right hand edge of the specimen is the hinge of an isoclinal F_2 fold. The front face of the specimen shows curving of the striping lineation. As we move away from the hinge towards the left, the lineation is transposed. (b) Sketch of the specimen shown in (a). Note the presence of relict isoclinally curved segments of the folded lineation on the left hand side. (c) Back side of the specimen shown in (a). On this surface, the striping lineation is effectively transposed with some rare relicts of folded segments.

progressive ductile shearing, the angles between the divergent domains of lineation are greatly reduced and the striping lineation becomes essentially parallel in all domains. This may also be regarded as one form of transposition.

A similar type of transposition can also be seen where the F_1 striping lineation and the F_2 axis are at very high angle at the F_2 hinges but become nearly parallel at the limbs (Figs. 12c–e and 14b). In such cases, the striping lineation forms a U-shaped pattern on the unrolled form surface of F_2 (Fig. 15b). Because of extreme stretching, the reoriented striping lineation as well as the F_2 hinge lines, rotated towards the direction of maximum stretching (see Ghosh, 1993, Fig. 16.8, p. 377). At a very advanced stage of deformation, the hinge lines of the later folds and the early striping lineation on the limbs have all become parallel.

The striping lineation is usually parallel to early fold hinge lines. Where the hinge line is curved as in a planar sheath fold (Ghosh et al., 1999), the striping lineation shows a similar hair pin bend on the limbs parallel to the axial surfaces of the isoclinal folds (Figs. 3, 12f, 13 and 14c, d). In the PSZ and SSZ, the maximum stretching is in a down-dip direction along vertices of the sheath folds. With progressive stretching, the two arms of the bent lineation on the two flanks of the sheath fold become virtually parallel. Its initially curved form is then showed by only very small domains of the apices. In many sheath folds in the Phulad shear zone, the two flanking limbs of the sheath fold are essentially parallel and the foliation surface shows a single stretching lineation. The origin of that lineation by transposition is indicated in some instances by remnants of the apices (Figs. 13, 14c, d, and 15c, d).

The manner in which transposition has taken place cannot always be identified in extremely sheared rocks. However, evidence of transposition is often found in such rocks where the occurrence of subparallel lineation on planar foliation surfaces is either associated with domains of hairpin bends or contains relict apices of strongly curved lineations.

7. Summary and conclusions

Striping lineation occurs as fine colour stripes on the foliation surfaces of mylonitic rocks. This has sometimes been interpreted as intersection lineation. However, neither hand specimens nor thin sections show any evidence that the stripes on the foliation surface occur as an intersection of a mylonitic colour band and a foliation surface. The mylonitic colour bands are invariably parallel to the foliation surfaces. Hence, it is appropriate to describe the structure by the morphological term striping lineation instead of the genetic term intersection lineation. Striping lineations are quintessential products of extremely large deformation. Where successive stages of progressive shearing leading to the development of mylonites can be traced, it appears that initially the colour stripes were intersections of a bedding or a colour banding on an axial plane cleavage. At some stage of progressive deformation, the cleavage or the foliation became the most active plane and the colour

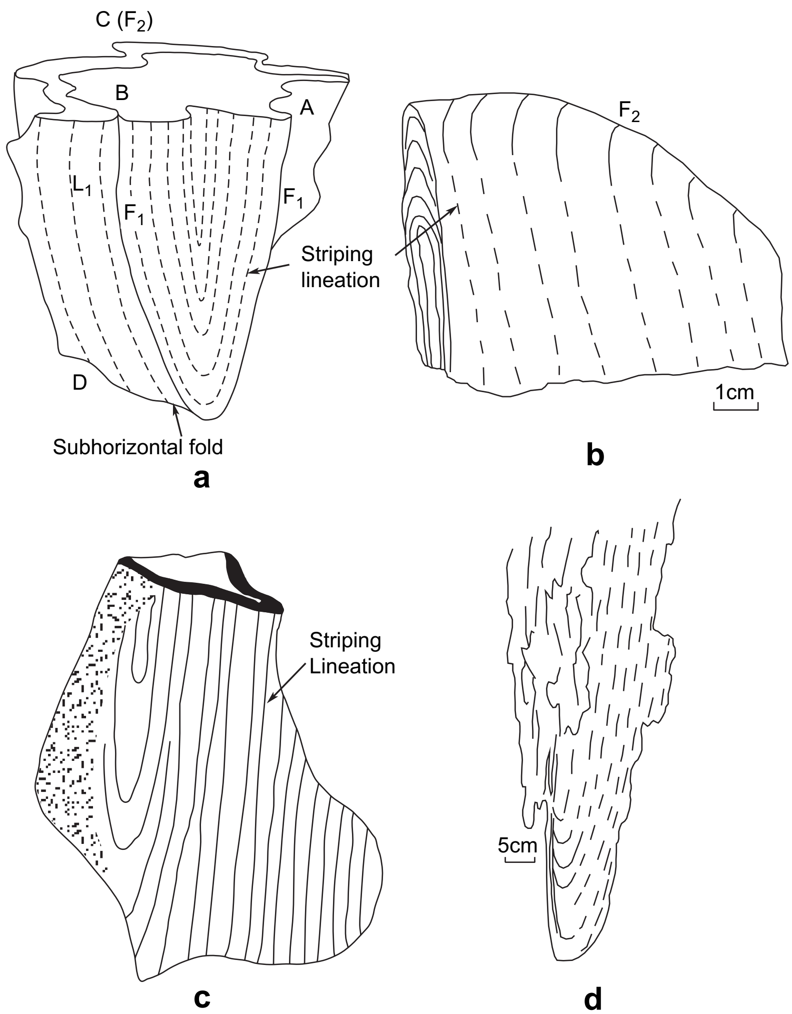

Fig. 14. Transposition of lineations from mylonites of Phulad Shear Zone. (a) L_1 striping lineation transposed by later sub-horizontal folding. A and B belong to a single curved F_1 hinge line, C is the hinge of an F_2 fold. (b) An isoclinal fold with hinge line curved from horizontal to plunging. Sketch of specimen shown in Fig. 12d. (c) Isoclinally curved striping lineation on the limb of a fold. Because of extreme stretching, a gently curved lineation on a planar limb may be deformed to a hairpin bend. (d) Transposed lineation on a planar surface of a mylonite. The lineation is parallel in most places; transposition is indicated by the remnants of apices of form at the lower part of the specimen.

stripes were deformed as passive lines. In an actively rotated set of colour bands, the width of the stripes on the foliation surface would tend to be infinitely large when the foliation and the colour bands would essentially become parallel at large strains. During the development of the striping lineation in ductile shear zones, the current mylonitic banding and the foliation surface are strictly parallel although the colour stripes on the foliation surface have generally small (millimetric) width. This is because the reorientation of the layers at some stage of deformation takes place by homogeneous strain. In such a situation, the width of the stripes on the foliation surface does not depend on the angle between the layer and the cleavage. It depends essentially on the nature of bulk strain. The striping lineation behaves as a material line and not as intersection of two geometrically defined surfaces. That a striping lineation in mylonites in an advanced stage of ductile shearing is a true material linear structure and not a geometrically defined intersection of two S-surfaces is spectacularly shown where the striping lineation is folded and refolded and gives rise to a transposed linear structure. Although the term ‘‘transposition’’ is commonly used for foliation surfaces only, the essential features of transposition lie in the folding of a structure and its reorientation so that the structure is effectively parallel in most places. Transposition of a striping lineation can occur in different ways, e.g. by planar sheath folding, by extreme stretching associated with folding, by development of U-patterns of lineation, rotation of fold hinges in ductile shear zones and by the general mechanism of drastic reduction of angles of divergent lineations in consequence of extreme stretching. Just as in transposed foliation, transposed lineation may also be recognized by remnants of isolated apices of folded lineations.

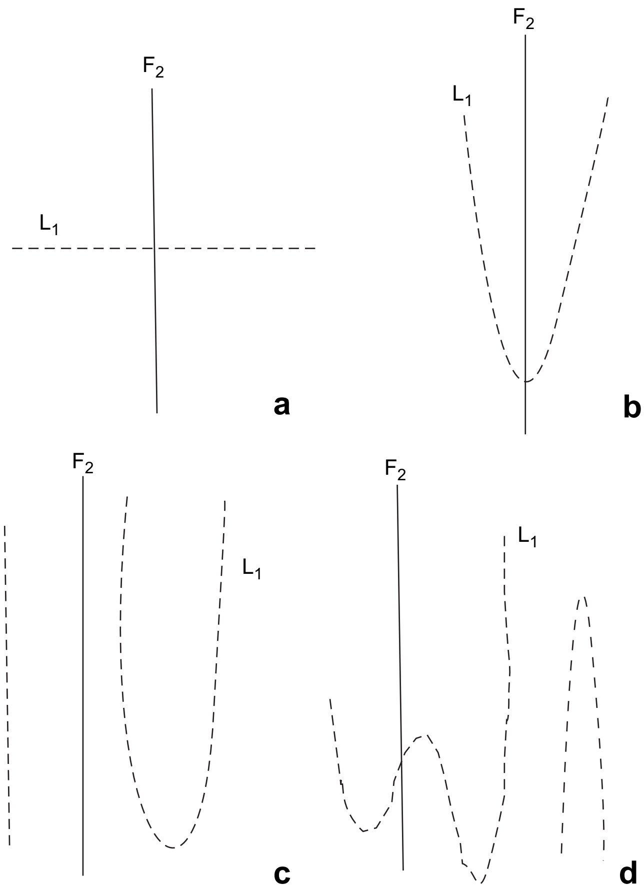

Fig. 15. Transposition of striping lineation may take place in different ways. Here we show the lineation patterns on the unrolled surfaces of folds. The F_2 folds are isoclinal in all cases. (a) Similar to the situation in Fig. 13a where the lineation is parallel on the two limbs of the fold and becomes straightened out when the fold is unrolled. (b) A typical U-pattern of lineation on the unrolled surface of a fold similar to that shown in Fig. 12c and e. (c and d) Transposition of striping lineation by occurrence of hair pin bend on the surface of a limb. The lineation is essentially parallel in the major part of the specimen, thereby causing an effective transposition.

Acknowledgement

This work was made possible by financial support of the Council of Scientific and Industrial Research, India. We thank D. Khan for his help in drafting the line drawings. We are grateful to Robert Holdsworth, Ian Alsop and an anonymous reviewer for their critical comments and suggestions.

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