*Journal of Structural Geology*, Vol. 14, No. 4, pp. 491 to 497, 1992
Printed in Great Britain

0191–8141/92 $05.00+0.00


# The geometrical relationship between the stretching lineation and the movement direction of shear zones

SHOUFA LIN and PAUL F. WILLIAMS

Department of Geology, University of New Brunswick, Fredericton, N.B., Canada E3B 5A3

(*Received 29 May* 1991; *accepted in revised form* 2 *October* 1991)

**Abstract**—The geometrical relationship between foliations and lineations in shear zones is considered quantitatively, assuming that the internal structures of shear zones have monoclinic symmetry. The common practice of directly correlating the pitch (or plunge) of the stretching lineation with the obliquity of the shear direction is challenged. It is the orthogonal projection of the stretching lineation on the shear zone boundary that is parallel to the shear direction. A shear zone is parallel to a plane containing both the pole to the symmetry plane and the strike of the shear zone, and the shear direction is parallel to the intersection of the symmetry plane and the shear zone boundary. The symmetry plane is determined by the stretching lineation and the poles to the *S*-foliation. The implications of this study for the interpretation of shear zones are discussed with reference to an actual example.

## INTRODUCTION

STRETCHING lineations are widely used in the kinematic interpretation of shear zones, and it is a common practice to use the orientation of the stretching lineation to infer the movement direction of the shear zone (e.g. Garnett & Brown 1973, Shackleton & Ries 1984, Choukroune *et al.* 1986, Fueten & Robin 1989, Lin & Williams 1990). If the lineation is horizontal, it is inferred that the movement along the shear zone is strike-slip; if the lineation is oblique, the movement is inferred to be oblique-slip. However, significant errors in interpretation may arise from this practice. For example, in some shear zones in the Canadian Appalachians that are believed to have true strike-slip displacement, the stretching lineation may plunge 10–20°, erroneously suggesting a considerable dip-slip component.

In this paper the geometrical relationship between foliations and lineations in shear zones is considered. It is concluded that it is the orthogonal projection of the stretching lineation on shear surfaces, *not* the stretching lineation itself, that must be correlated with the movement direction. Qualitatively the point is obvious; what is not so obvious is that the magnitude of the potential error is likely to be significant in many natural examples.

The geometrical relationship between the stretching lineation and the movement direction has been previously discussed by Brun & Burg (1982) and Burg *et al.* (1987) with reference to the Ibero-Armorican arc. Assuming the simple shear model, they were able to quantitatively predict the orientation of the *S*-foliation and the stretching lineation for different combinations of the horizontal and vertical movement components. The present study is more general. The only assumption is that the symmetry of the shear zone movement picture is monoclinic, no matter whether the deformation is simple shear or not. With our method, it is not only possible to predict quantitatively the orientation of the *S*-foliation and the stretching lineation for different orientations of the shear zone and the shear direction, but it is also possible to use the orientation of the *S*-foliation, the stretching lineation and the strike of the shear zone to deduce quantitatively the attitude and the movement direction of the shear zone.

## GEOMETRICAL RELATIONSHIP AMONG FOLIATIONS AND LINEATIONS IN SHEAR ZONES

Two principal types of foliation can be developed in shear zones. They are generally called *S*- and *C*-surfaces (Berthé *et al.* 1979). *S*-surfaces are close to the local $\lambda_1\lambda_2$ principal strain plane and the stretching lineation within them is approximately parallel to the $\lambda_1$ direction of the finite strain ellipsoid since the last 'resetting' of the finite strain 'clock' (see discussion by Means 1981, Lister & Snoke 1984). *C*-surfaces are planes or narrow zones of high shear strain parallel to the main shear zone boundary (Berthé *et al.* 1979). Striations of the 'ridge-in-groove' type (Means 1987) may be present on *C*-surfaces and they are parallel to the shear direction (Lin & Williams in press, and references therein). The movement picture of the shear zone is monoclinic in symmetry (Fig. 1). The symmetry plane is perpendicular to the intersection of *S* and *C* and contains the stretching lineation lying in *S* and the shear-direction-parallel striation in *C*. Thus, the shear direction is parallel to the orthogonal projection of the stretching lineation on the *C*-surface (or the shear zone boundary).

The geometrical relationship described above can be conveniently represented in hemispherical projection (Fig. 2), where $L_c$ and $L_s$ are the shear direction (parallel to the striation) in *C* and the stretching lineation in *S*, respectively, and B is the intersection of *S* and *C*. $L_c$, $L_s$, $\pi C$ and $\pi S$ all lie on the great circle girdle (SP) which is in fact the symmetry plane for which B is the pole. The variables considered are the dip of *C* parallel to the shear

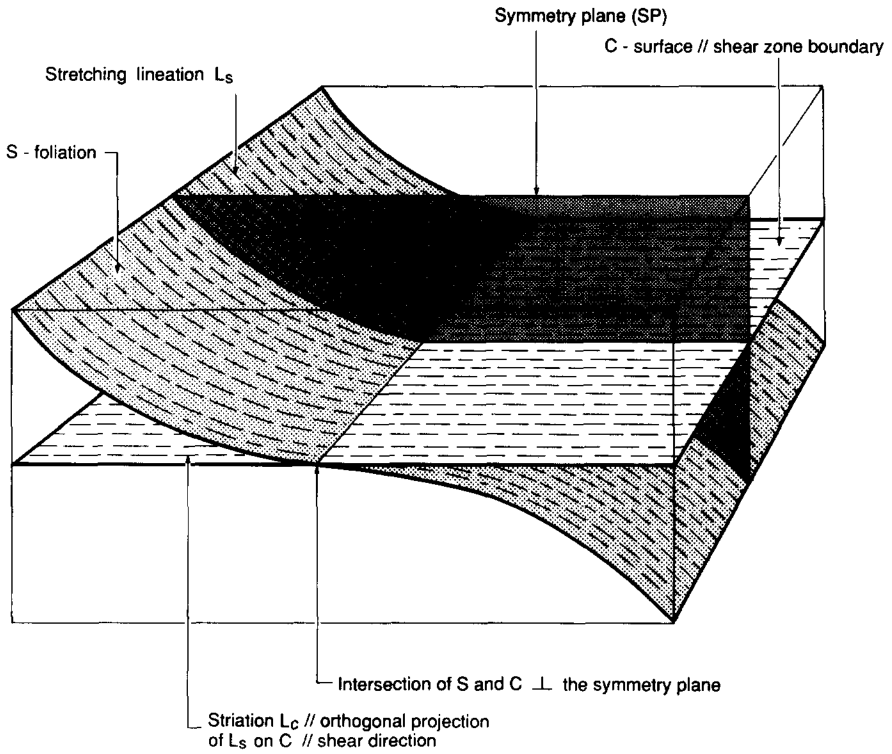


Fig. 1. A block diagram showing the geometrical relationship of the $C$-surface (parallel to the shear zone boundary), the striation on the $C$-surface ($L_c$, parallel to the shear direction), the $S$-surface and the stretching lineation on the $S$-surface ($L_s$).

zone boundary ($\alpha$), the pitch of the shear direction on $C$ ($\beta$), the dip of $S$ ($\gamma$), the pitch of the stretching lineation on $S$ ($\delta$), and the angle between $S$ and $C$ ($\theta$). First, let us assume that the dip of $C$ ($\alpha$), the pitch of the shear direction on $C$ ($\beta$) and the angle between $S$ and $C$ ($\theta$) are known and see how the pitch of the stretching lineation on $S$ ($\delta$) and the dip of $S$ ($\gamma$) vary with them. Later in this paper we will discuss how to use the stretching lineation and the $S$-foliation to determine the attitude of the shear zone and the shear direction.

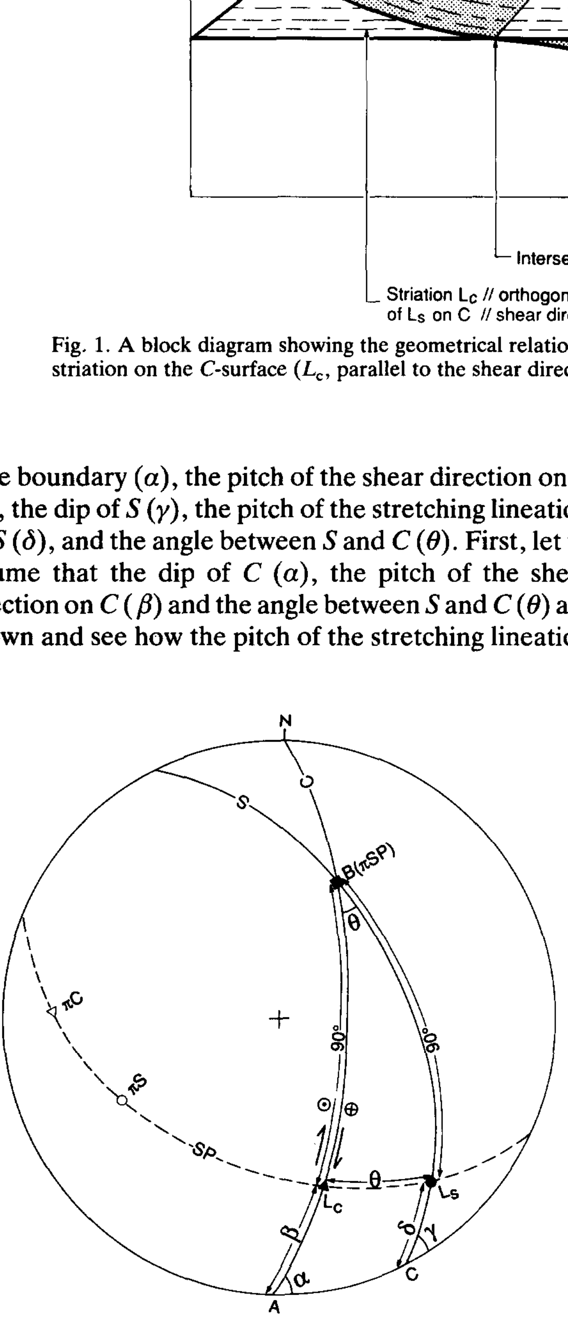


Fig. 2. Equal-area lower-hemisphere projection, showing the geometrical relationship of the $C$-surface (dip = $\alpha$), the striation on the $C$-surface ($L_c$, pitch = $\beta$, parallel to the shear direction), the $S$-surface (dip = $\gamma$) and the stretching lineation on the $S$-surface ($L_s$, pitch = $\delta$). B is the line of intersection between $S$ and $C$ and $\theta$ is the angle between them. Note that $L_c$, $L_s$, the pole-to-$C$ ($\pi C$) and the pole-to-$S$ ($\pi S$) lie on the same girdle (SP, symmetry plane), for which B is the pole.

The first problem can be readily solved by using spherical trigonometry. For spherical triangle ABC (Fig. 2), by application of formula (iv) in Phillips (1971, p. 75) the pitch of the stretching lineation on $S$ is given by:

$$\delta = \tan^{-1}\left(\frac{\cos\dfrac{\alpha-\theta}{2}}{\cos\dfrac{\alpha+\theta}{2}}\tan\frac{90^\circ+\beta}{2}\right) + \tan^{-1}\left(\frac{\sin\dfrac{\alpha-\theta}{2}}{\sin\dfrac{\alpha+\theta}{2}}\tan\frac{90^\circ+\beta}{2}\right) - 90^\circ. \quad (1)$$

By application of formula (iii) in Phillips (1971, p. 75) the dip of $S$ is given by:

$$\gamma = \sin^{-1}\left(\frac{\cos\beta\sin\alpha}{\cos\delta}\right). \quad (2)$$

These relationships are presented in Fig. 3 for $\theta = 15°$, 30° and 45°.

In Fig. 2, from which formulae (1) and (2) and Fig. 3 are derived, the $C$-surface dips east, $L_c$ pitches south and the movement along $C$ has dextral and normal components. Therefore, for $0° < \beta < 90°$ and $90° < \beta < 180°$, $L_c$ pitches south and north, respectively, and the hori-

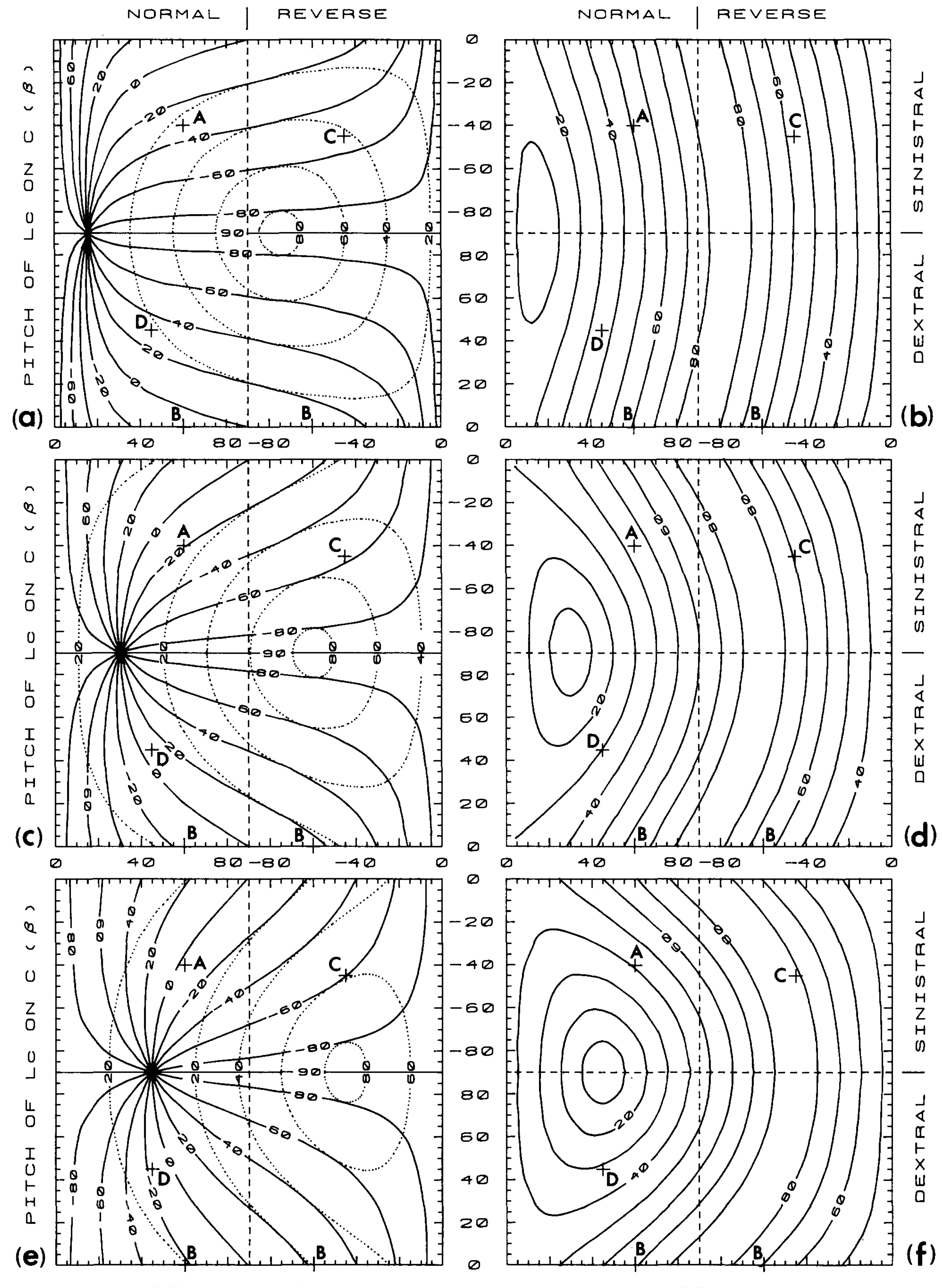


Fig. 3. (a), (c) & (e) show the pitch (solid line) and the plunge (dashed line) of the stretching lineation on *S*-surfaces and (b), (d) & (f) show the dip of the *S*-surface, with respect to the dip of the *C*-surface and the pitch of striation (shear direction) on *C*. The angles between *S* and *C* are 15° for (a) & (b), 30° for (c) & (d) and 45° for (e) & (f). Points A, B, C and D are examples discussed in the text. See text for further explanation.

zontal components of movement are dextral and sinistral, respectively; for $0° < \alpha < 90°$ and $90° < \alpha < 180°$, $C$-surfaces dip east and west, respectively, and the vertical components of movement are normal and reverse, respectively. Conventionally, values of dip and pitch are $\leq 90°$. Therefore, in Fig. 3 and in the following discussion, easterly dips where $\alpha > 90°$ are expressed as westerly dips with dip $= (180° - \alpha)$, and southerly pitches where $\beta > 90°$ are expressed as northerly pitches with pitch $= (180° - \beta)$. A minus sign for $\beta$ and $\alpha$ is used to indicate that $L_c$ pitches north and the horizontal component of movement is sinistral, and the $C$-surface dips west and the vertical component of movement is reverse, respectively. However, it should be noted that to use formulae (1) and (2), $\alpha$ and $\beta$ values between 0° and 180° should be used. In Fig. 3 each diagram can be divided into four quadrants according to whether the vertical component of movement is normal or reverse and whether the horizontal component is dextral or sinistral. In Fig. 3, for $0° < \delta < 90°$ and $-90° < \delta < 0°$, $L_s$ pitches south and north, respectively. The dip of $S$ ($\gamma$) and the plunge of $L_s$ in Fig. 3 are absolute values. It should be noted that until we deal with natural shear zone data, only the relative orientations of $C$, $S$, $L_c$ and $L_s$ are important. The geographical orientation in Fig. 2 and as described above is arbitrary. Therefore, no matter what the strike is, any shear zone can be correlated with a point in Fig. 3 with certain values of $\alpha$ and $\beta$, plus or minus depending on whether the vertical component of movement is normal ($\alpha > 0°$, $\alpha$ = dip of $C$) or reverse ($\alpha < 0°$, $\alpha$ = −dip of $C$) and whether the horizontal component is dextral ($\beta > 0°$, $\beta$ = pitch of the shear direction) or sinistral ($\beta < 0°$, $\beta$ = −pitch of the shear direction). For example, if the movement along a shear zone dipping 60° is *sinistral normal* with a movement direction pitching 40°, the values of $\alpha$ and $\beta$ representing the shear zone are 60° and −40°, respectively. If the angle between $S$ and $C$ is 30°, it can be read from Figs. 3(c) & (d) (point A) that the stretching lineation pitches *ca* −19° (plunges *ca* 13°) on an $S$-foliation dipping *ca* 45°. The same result can be calculated from formulae (1) and (2) using $\alpha = 60°$ and $\beta = (180° - 40°)$.

## IMPLICATIONS FOR THE STUDY OF SHEAR ZONES

The geometrical relationship described above by formulae (1) and (2) has significant implications for the interpretation of shear zones. It can be seen clearly from Fig. 3 that the situation in which the pitch of the stretching lineation on $S$ ($\delta$) is equal to the pitch of the shear direction on $C$ ($\beta$) is a special case; this occurs only when the symmetry plane is vertical or horizontal. In general, there is a considerable difference between $\delta$ and $\beta$. Therefore, the common practice of using the stretching lineation to directly infer the shear direction cannot be justified.

*Examples*

(1) A consistently shallowly plunging stretching lineation on a steeply dipping foliation in a shear zone is commonly interpreted as indicating strike-slip motion *with a minor vertical component*. The analysis above shows that this may not necessarily be true. From Fig. 3 it can be seen that even in pure strike-slip shear zones ($\beta = 0°$), the pitch of the stretching lineation on $S$ ($\delta$) can vary with the dip of the shear zone ($\alpha$). Only where the shear zone is vertical ($\alpha = 90°$), is the stretching lineation truly horizontal ($\delta = 0°$), in which case the foliation ($S$) is vertical ($\gamma = 90°$) too. Otherwise, the stretching lineation cannot be horizontal. For example, the stretching lineation formed in a *true strike-slip* shear zone dipping 60° ($\alpha = \pm 60°$, $\beta = 0°$) would pitch ±16° ($\delta$, plunge 14°) on $S$ dipping 64° ($\gamma$), if the angle between $S$ and $C$ ($\theta$) is 30° (point B in Figs. 3c & d; see Figs. 3 and 4a for other values of $\theta$).

(2) Steeply plunging stretching lineations on steeply dipping foliations in shear zones are usually interpreted as indicating dominant dip-slip movement *with only a minor horizontal component*. However, this also may not necessarily be true as is clear in Fig. 3. For example, *sinistral reverse* movement along a shear zone dipping 45° with movement direction pitching 45° (plunging 30°) ($\alpha = -45°$, $\beta = -45°$) would form a stretching lineation pitching −58° ($\delta$, plunging 52°) on a foliation dipping 69° ($\gamma$), if the angle between $S$ and $C$ is 30° ($\theta$) (point C in Figs. 3c & d; see Figs. 3 and 4b for other values of $\theta$).

(3) If the movement along a shear zone dipping 45° with a movement direction pitching 45° (plunging 30°) is *dextral normal* ($\alpha = 45°$, $\beta = 45°$), the stretching lineation formed would pitch +9° ($\delta$, plunge 5°) on a foliation dipping 30° ($\gamma$), if the angle between $S$ and $C$ is 30° ($\theta$) (point D in Figs. 3c & d; see Figs. 3 and 4c for other values of $\theta$).

*Variation in the orientation of the stretching lineation and S-foliation in a shear zone*

The deformation in shear zones is heterogeneous. The angle between $S$ and $C$ gets smaller with increasing deformation until a steady state condition is reached (Means 1981, Lister & Snoke 1984, Mawer & Williams 1991). Similarly, the attitude of the stretching lineation changes (Fig. 4).

For example (2) above, if the angle between $S$ and $C$ varies with decreasing deformation from 0° to 45°, the dip of the $S$-surface will vary from 45° to 82° and the pitch (plunge) of the stretching lineation on $S$ from 45° (30°) to 60° (59°) (Fig. 4b). However, it is generally only in narrow restricted zones in the shear zones that rocks are sufficiently deformed for $S$ and $C$ to be almost parallel and the stretching lineation to be close to the shear direction. In some cases even these very narrow zones are lacking because of the development of a steady-state foliation. For these reasons and because of the potential of limited outcrop, if $C$-surfaces were not developed, what we would see in the field would mainly be a steep $S$-

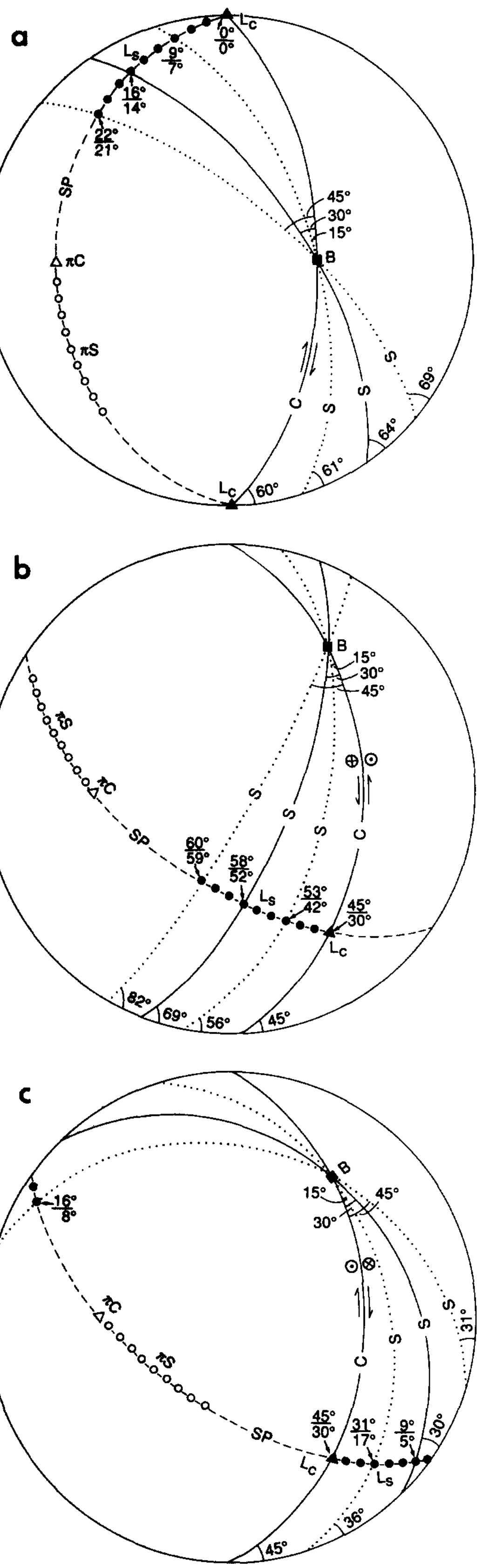


Fig. 4. Equal-area lower-hemisphere projections for examples discussed in the text. (a) Example 1, horizontal movement along a shear zone dipping 60°. (b) Example 2, sinistral reverse movement along a shear zone dipping 45° with movement direction pitching 45°. (c) Example 3, dextral normal movement along a shear zone dipping 45° with movement direction pitching 45°. Variation in the dip of $S$ and the pitch (the higher number) and the plunge (the lower number) of $L_s$ with variation in the angle between $S$ and $C$ from 0° to 45° is also shown. See text for discussion.

foliation with a steep lineation. The shear zone in example (2) would then probably be interpreted as steep with dominantly dip-slip movement.

### *Using stretching lineation and* S*-foliation to determine the attitude and the movement direction of a shear zone*

From the discussion above, it is clear that there can be a large error if the pitch (or plunge) of the stretching lineation is correlated directly with the obliquity of the movement direction. However, this does not mean that the stretching lineation cannot be used to determine the shear direction. As described above, the shear zone boundary is parallel to the *C*-surface and the shear direction is parallel to the orthogonal projection of the stretching lineation on the *C*-surface. Therefore, the key is to determine the attitude of the shear zone or *C*-surface when the latter cannot be measured directly in the field.

This problem can be solved if the strike of the shear zone can be determined, which is usually possible by mapping, because the pole (B) to the great circle girdle (SP, symmetry plane) defined by the stretching lineation ($L_s$) and poles to $S$ is the intersection of $S$ and $C$ (Fig. 2). The surface defined by the strike of the shear zone and B is parallel to the shear zone boundary or *C*-surface. The intersection of this surface and the great circle (SP) is the direction of shear, and the *S–C* relationship indicates the sense of shear (Fig. 2). Because the stretching lineation and the poles to $S$ are always 90° apart, if they form good statistical maxima the circle (SP) can be defined with confidence. This is especially true when there is a systematic spatial variation of $S$ and $L_s$ due to the heterogeneity of deformation in the shear zone as described above, because the great circle (SP) is confirmed by the spread of data which should lie in the same plane (Fig. 4).

Even if the attitude of the shear zone boundary (or *C*-surface) cannot be determined with confidence, it is still useful to estimate a *C*-surface attitude by estimating the angle between $S$ and $C$ according to the intensity of deformation and determining the relative sense of movement using shear sense indicators (Fig. 2), so that the potential problem involved in the stretching lineation interpretation can be assessed.

### *Application to the Cadillac tectonic zone*

As an example, this technique is tentatively applied to the $D_1$ deformation along the Cadillac tectonic zone (CTZ) as reported by Robert (1989). CTZ is a segment of the Kirkland Lake–Larder Lake–Cadillac break of the Abitibi greenstone belt, Canada.

According to Robert (1989), the CTZ strikes approximately east–west. The $D_1$ deformation is characterized by a steep, mostly N-dipping $S_1$ foliation containing a steep E-plunging stretching lineation ($L_1$) (fig. 5 in Robert 1989, compiled as Fig. 5 here). Intrafolial folds ($F_1$), ranging from non-cylindrical, subhorizontal folds to subvertical sheath folds, indicate dip-slip movement.

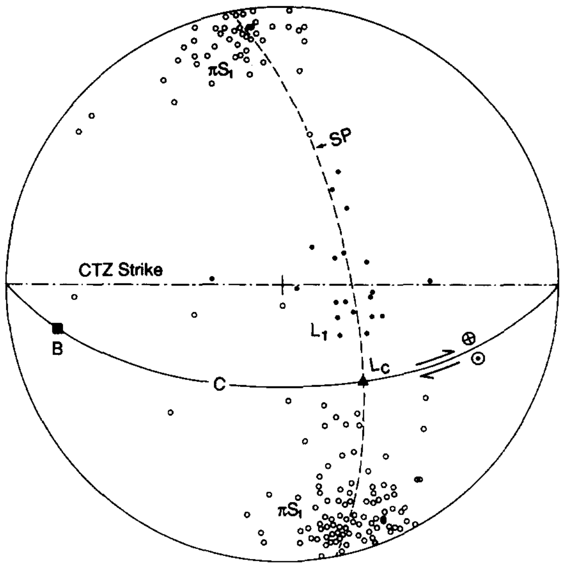


Fig. 5. A possible alternative interpretation of the $D_1$ structural data of the Cadillac tectonic zone (CTZ). The data for poles to $S_1$ and $L_1$ are compiled from zone 2, area A and area B in fig. 5 of Robert (1989) using the known CTZ strike as the reference line. Zone 4 is not included because $F_2$ folding obscures the pattern in that domain. Using the geometrical relationship established in the present study, the data are reinterpreted as the result of dextral reverse movement along a shear zone ($C$) dipping 60°S. The movement direction ($L_c$) pitches 66° on $C$ (plunges 52°). B is the pole to the great circle girdle (SP) defined by $L_1$ and the poles to $S_1$ and lies in the shear surface ($C$). The circle ($C$) defined by the CTZ strike and B is parallel to the shear zone boundary, and the intersection ($L_c$) between $C$ and SP is parallel to the shear direction. The $S$–$C$ relationship indicates the sense of shear.

However, other evidence, mainly the obliquity in the strike of $S_1$ to the strike of the CTZ, suggests dextral transcurrent shearing. The shear zone is interpreted as dipping steeply north. The $D_1$ deformation is interpreted as transpressional with dextral transcurrent shearing and zone-normal shortening. The steeply plunging stretching lineation is attributed to the subvertical elongation accompanying the zone-normal shortening (see Robert 1989 for detailed description).

The application of the technique described here to the CTZ suggests an alternative interpretation. In the CTZ, $L_1$ and the poles to $S_1$ clearly define a great circle girdle (SP). Because the strike of the CTZ is known (fig. 5 in Robert 1989), the attitude of the shear zone boundary and the shear direction can be determined (Fig. 5). The result shows that the CTZ dips *ca* 60°S. The movement along the CTZ was essentially reverse with a weak dextral horizontal component. The movement direction pitches *ca* 66° on the shear surface (i.e. plunges 52°). This interpretation can explain the data as described (Robert 1989), including the subvertical $S_1$, the steeply E-plunging $L_1$, the evidence for dip-slip movement and the evidence for dextral transcurrent movement. The interpreted sense of shear is consistent with the northward vergence of the $F_1$ fold observed in a particularly well exposed area (Robert 1989, p. 2667). It can also explain why, near the northern edge of the CTZ, the younging direction faces south, while near the southern edge, it faces north (Robert 1989, p. 2664); this is consistent with 'drag' associated with reverse movement. This interpretation is supported by recent mapping in the Kirkland Lake area by Cruden (1990), who found that "kinematic indicators within $S_1$ (rotated asymmetric pebbles, $S$–$C$ fabrics and extensional crenulation cleavage) together with the orientation of $L_1$ suggest that $D_1$ is related to dominantly south-over-north shearing with a minor dextral horizontal component". Because we are not familiar with the regional geology around the CTZ, we present this alternative interpretation only as a tentative suggestion and note that Cruden (1991, written communication) has modified his ideas and now believes that the transpression model of Robert (1989) cannot be ruled out.

## SUMMARY AND DISCUSSION

Stretching lineations are very useful in determining the movement direction in shear zones. However, caution is needed; significant errors can result from directly correlating the stretching lineation with the movement direction, especially when the movement is oblique along a moderately dipping shear zone. The true movement direction is parallel to the striation on $C$-surfaces where present or to the orthogonal projection of the stretching lineation on the shear zone boundary (or $C$-surface). The attitude of the shear zone boundary ($C$-surface), if not directly measurable in the field, can be determined if the strike of the shear zone can be estimated by mapping or if the angle between $S$ and $C$ can be estimated and the sense of shear can be determined.

The result of this study may help in the interpretation of many apparently contradictory structures in shear zones, especially plunges of the stretching lineation which seem inconsistent with the obliquity of the movement direction and the systematic change of the attitude of the foliation and lineation across a shear zone, as exemplified above and further discussed below.

There are many shear zones in which the plunge of what appears to be a stretching lineation is strongly inclined to the interpreted movement direction (e.g. Lister & Price 1978, Bleeker & Williams in preparation) and we believe this to be an important problem in the understanding of shear zones. The ideas presented here may explain some of the discrepancies but we do not believe that they are the complete answer to the problem. In many shear zones the stretching lineation plunges down-dip even though the movement appears to have been transcurrent—e.g. sheath folds in the Thompson Nickel Belt plunge down-dip (Fueten & Robin 1989) in what appears to have been a transcurrent movement zone (Bleeker 1991). Elsewhere, the stretching lineation, in passing through the shear zone, may vary in pitch by as much as 90° (e.g. Garnett & Brown 1973, Caron & Williams 1988, Goodwin *et al.* 1991). Such situations cannot be explained by the ideas presented here, but the ideas are still relevant since the complete geometry should still be determined before further analysis is attempted. For example, if the bulk symmetry of the internal structures of a shear zone is not monoclinic as discussed in this paper, it suggests that the structural processes involved may be more complex. In this case, if the shear zone can be divided into domains of monoclinic symmetry, further interpretation may be much easier. This last point will be explored in another paper.

The discrepancies between the orientation of the stretching lineation and the movement direction discussed in this paper are relatively small but they are nevertheless potentially significant. They are important for example, in situations where accurate prediction is required such as in mining. They are also important where major faults may be mistakenly interpreted as having a significant dip-slip component which may result in erroneous tectonic reconstructions. For instance, consider further the example given above of a truly transcurrent fault dipping *ca* 60° with a stretching lineation plunging *ca* 15° and assume that it is of regional extent. Movement on such a fault could be hundreds of kilometres. However, if the stretching lineation were correlated with the movement direction, there would be *ca* 2.6 km dip-slip for every 10 km strike-slip, and if there is no metamorphic change across the fault, we would conclude, perhaps erroneously, that the movement could be no more than 10–20 km. Faults with such geometry are known in the Canadian Appalachians.

In summary, we wish to stress that it is probable that the strain in shear zones is commonly more complex than assumed in our analysis which considers only shear zones with monoclinic symmetry. Therefore, we do not suggest this study is an answer to all shear zone lineation problems. However, we do suggest that the geometrical relationship established in this paper be taken into consideration in any shear zone interpretation that involves the use of the lineation to determine the movement direction.

*Acknowledgements*—We are grateful to Dr Laurel Goodwin for helpful discussion and comments and to Angel Gomez for assistance with figure preparation. Special thanks go to Dr Sandy Cruden for his information and comments on the CTZ, and to Professor Peter Hudleston and two Journal referees for their helpful review. P. F. Williams gratefully acknowledges the support by NSERC operating grant OGP0007419. The paper forms part of S. Lin's Ph.D. thesis at the University of New Brunswick.

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