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Strain compatibility and shear zones: is there a problem?

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Abstract

In analyzing deformation in rocks, it is important to ensure that the solutions obtained satisfy strain compatibility. This creates a challenge to understanding patterns of strain associated with shear zones, in which measured strain may appear incompatible with the strain in the shear zone walls. Flattening strains are common in natural shear zones with locally straight and parallel boundaries: to satisfy compatibility conditions such strains require volume loss across the shear zone or deviations from plane strain, with or without discontinuities between the shear zone and the wall rock. In the case of shear zones for which there is no evidence of volume loss or discontinuities along the shear zone walls, problems of strain compatibility may be resolved if individual shear zones are linked together in an appropriate fashion. Shear zones commonly occur in anastomosing arrays, and simple configurations of such arrays and the strains associated with them are examined. It is shown that local transpression with strain compatibility can be accounted for in this way. Quite complex local strain patterns can develop in simple arrays.

1. Introduction

There are several reasons to suppose that rock deformation in nature should commonly result in two-dimensional strain patterns. First, many rocks are layered, and the stiff layers may act as planar rigid boundaries to deforming softer layers. Second, in massive rocks, deformation is frequently localized into planar bands of ductile deformation, or shear zones. Third, the boundaries between undeformed and deformed rocks along tectonic fronts are often linear, suggesting that strain variation should be confined to two dimensions. Because of such constraints, it is perhaps natural to analyze rock strain in terms of pure shear and simple shear, the classical 'end-member' types of two-dimensional strain (Ramsay and Graham, 1970; Cobbold, 1977; Ramsay and Huber, 1983; Ramsay and Huber, 1987).

It is important to emphasize the distinction between the finite state of strain—which can be reached by an infinite number of deformation paths, and progressive strain, for which the path is defined. In all that follows, progressive simple shear and progressive pure shear are implied by use of the terms 'simple shear' and 'pure shear'. In the literature, the expressions 'simple shearing' and 'pure shearing' are now commonly used to denote progressive deformation of simple shear and pure shear types, following Means (1990).

A wealth of data on strain and fabric pattern in deformed rocks have accumulated in numerous studies over the past few decades. These show that, despite the common occurrence of bands of localized deformation, the state of natural strain in rock is rarely of 'plane strain' type, that is with strains given by $k = 1$, where $k = (X/Y - 1)/(Y/Z - 1)$ (Ramsay and Huber, 1983, p. 172), and with the convention $X \geq Y \geq Z$, where X, Y and Z are the principal finite stretches. Measured rock strain varies in symmetry from pure flattening to pure constriction (e.g. Hossack, 1968; Hudleston and Schwerdtner, 1997), and in magnitude from undeformed to strains at which markers become unrecognizable—with aspect ratios of up to around 100—the limit at which strain can be measured (Pfiffner and Ramsay, 1982). 'Plane strain' is more the exception than the rule.

If rock deforms as a continuum, the strains that develop must satisfy compatibility conditions, that

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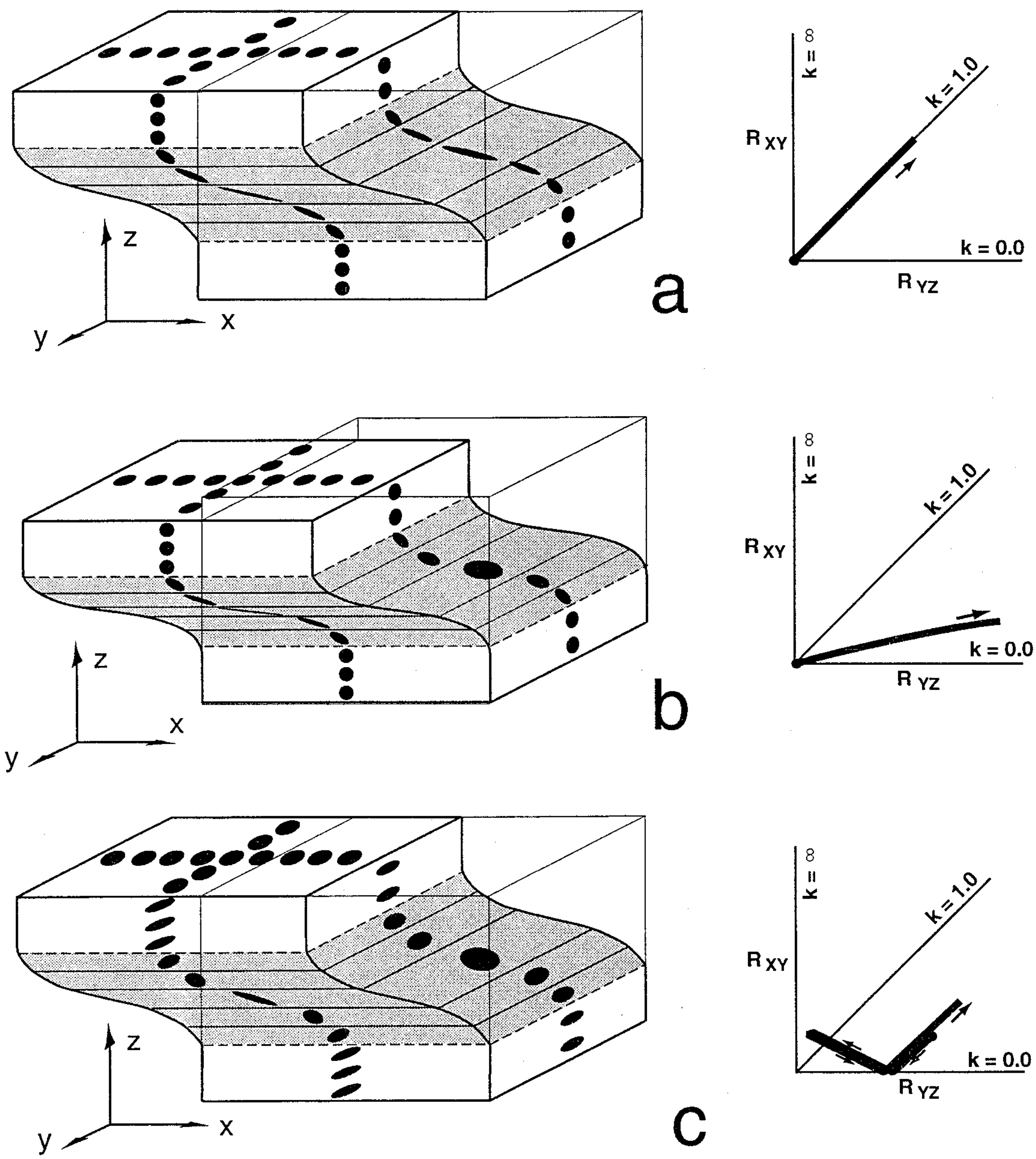

Fig. 1. (a) A 'classical' ductile shear zone, shaded, with deformation accommodated solely by heterogeneous simple shearing on the *xy*-plane and parallel to *x*. Strain intensity increases toward the center of the zone, as indicated by the black strain ellipses. On the right, a schematic Flinn plot of the strain path for the simple shearing shown on the left. $R_{xy} = X/Y$, $R_{yz} = Y/Z$. (b) Heterogeneous simple shearing, as in (a), with the addition of volume loss, also increasing in intensity toward the center of the shear zone. (c) Heterogeneous simple shearing as in (a) superimposed on a homogeneous strain, as indicated by the strain ellipses in the walls to the shear zone. Note that the strain path does not originate at the origin of the Flinn plot, nor does it follow a simple path away from the origin.

is, there must be no discontinuities in displacement and no gaps or overlaps of material (see, for example Borg, 1963, p. 119, for the mathematical relationships of compatibility; and Ramsay and Graham, 1970 or Ramsay and Huber, 1983, p. 33, for their development in a geological context). Even in a rock containing shear discontinuities, certain compatibility conditions must be satisfied. In nature, zones of high strain are frequently juxtaposed against zones of low strain or no strain. This is readily understood and poses no problem of strain compatibility if the strain pattern can be developed by heterogeneous simple shearing (Fig. 1a). The strain that results will be of plane strain type if volume is constant and the walls to the shear zone are undeformed (Fig. 1a). Heterogeneous volume change across the shear zone may accompany simple shearing, without violating compatibility,

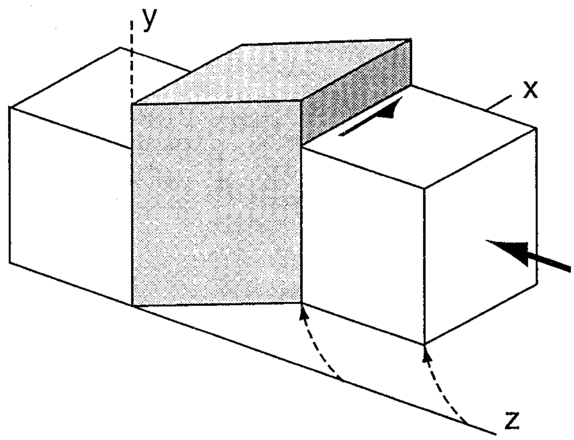

Fig. 2. Transpression, as modeled by Sanderson and Marchini (1984). Simple shear occurs in the *yx*-plane, parallel to *x*, and pure shear in the *yz*-plane, with shortening parallel to *z* and extension parallel to *y*.

leading to flattening strains if volume decreases, and constrictional strains if volume increases (Fig. 1b; Ramsay and Graham, 1970). Addition of a homogeneous strain to the wall rock and shear zone will also maintain strain compatibility. In this case, strain magnitude, symmetry, and orientation in the shear zone will depend on the nature and orientation of the wall rock strain upon which the simple shear is superimposed or which is superimposed on the simple shear (Fig. 1c).

A body of work on localized deformation has examined the effect of adding a component of pure shearing in the zone acting simultaneously with simple shearing (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Simpson and De Paor, 1993; Tikoff and Fossen, 1993). Transpression is a deformation of this type (Fig. 2), with shortening across the zone and extension parallel with the walls of the zone and perpendicular to the movement direction of the simple shear. Transtension involves pure shear with principal stretches of the opposite sign. Homogeneous deformation and vertical extension or shortening in the shear zone results in displacement discontinuity along the walls of the zone (Fig. 2).

There are patterns of strain in nature (e.g. Mawer, 1983; Simpson, 1983; Srivastava et al., 1995) that are clearly associated with shear zones, but that are not readily explained in terms of the 'ideal' band model of shear zones. In these examples, there are inconsistencies among strain data and the geochemical data that bear on volume loss. In one way or another, this is probably because strain deviates from the two-dimensional pattern which is the basis of most strain analysis of shear zones. In this paper, I discuss such problems and consider approaches to attempt to resolve them.

2. Shear zones

Since the classic paper of Ramsay and Graham (1970) there has been much work done on ductile shear zones. With no volume change, heterogeneous simple shearing across a shear zone leads to plane strain of variable magnitude (Ramsay and Graham, 1970; Fig. 1a). As noted above, if volume change (decrease) accompanies simple shearing, strain symmetry changes to become flattening within the shear zone (Fig. 1b). If deformation is steady-state, with rate of volume loss and rate of shearing constant, the deformation path will be of the kind shown in Fig. 1(b), following a smooth trajectory from the origin of the plot, with monotonically increasing values of R_{xy} and R_{yz}. By contrast, if simple shearing without volume loss is superimposed on a pre-existing strain fabric, the deformation path on a Flinn diagram will not follow such a path from the origin (Fig. 1c). Depending on the initial state of strain, the path may initially be toward the origin of the plot (implying that the simple shear is 'undoing' the effects of the pre-existing strain), take a negative slope and run from pure constriction to pure flattening, or vice versa. Eventually, at sufficiently large strains, the path will parallel the plane strain line and move away from the plot origin (Fig. 1c). This is the kind of strain history inferred for fabrics and folds in ice (Hudleston, 1983) and is equivalent to the superposition of tectonic strain on compactional strain in slates (Graham, 1978; Ramsay and Huber, 1983, p. 174). In none of these situations is there a problem of strain compatibility, even though in all cases there may be close juxtaposition of strains of widely varying symmetry. In each case, a section cut perpendicular to the shear direction and shear plane will show variation in axial ratio of the strain, but no change in dimension of the strain ellipse (or of particles that may reflect the strain) parallel to the shear zone. All the variation is in the *xz*-plane.

It should be noted that if an individual shear zone terminates in undeformed rock, in order to satisfy strain compatibility, strains at the ends of the zone must deviate from simple shear, and must involve a combination of flattening and constrictional strains (Coward, 1976; Ramsay, 1980, fig. 17). The same situation exists for accommodating displacement by strain at the terminations of a fault.

Work over the past 10 years or so has suggested that transpression is widely developed along tectonic boundaries (e.g. Ratliff et al., 1986; Hutton, 1987; Hudleston et al., 1988; Fossen and Tikoff, 1993; Tikoff and Fossen, 1993; Teyssier et al., 1995). In a vertical zone of transpression, simple shearing within the zone is accompanied by shortening perpendicular to the zone and a corresponding vertical extension (Sanderson and Marchini, 1984; Fig. 2). Strains within

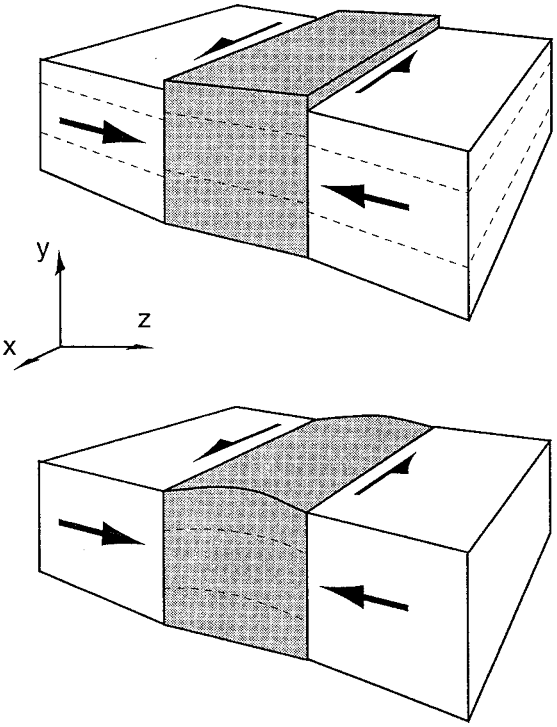

Fig. 3. Transpression, showing how the discontinuities along the margins of the zone can be avoided, according to Robin and Cruden (1994).

a zone of transpression are of flattening type. Maximum stretch is either vertical when pure shear dominates, or horizontal, when simple shear dominates. Sanderson and Marchini (1984) demonstrated that there may be a switch from horizontal to vertical in the direction of maximum finite stretch during steady state progressive deformation. For the switch to happen, the value of the kinematic vorticity number, W_k, must exceed 0.81; the value of shear strain at which the switch occurs increases as W_k increases (Fossen and Tikoff, 1993, fig. 8).

The vertical extension in transpression creates a problem of compatibility; there is a discontinuity in displacement and strain at the edge of the zone (Fig. 2). To deal with this problem, Robin and Cruden (1994) presented an analytical model for deformation in a zone of transpression which represents the deformation as being continuous (and inhomogeneous), thus removing the discontinuity in displacement at the edges of the zone (Fig. 3). They demonstrated how strain rate varies across such a zone, and infer how foliation and lineation, produced by finite deformation, would vary in such a zone. Dutton (1997) has extended this approach to consider finite states of deformation.

If deformation in a shear zone is by transpression, with the pattern of foliation or variation in strain being sigmoidal, as commonly seen in nature, the situation will be as illustrated in Fig. 4(a). Zones of increasing intensity of shear strain and shortening are also zones of increasing lateral extension. This could be accommodated by slip on multiple faults, as shown, or involve more complex three-dimensional strains of the kind modeled by Robin and Cruden (1994; Fig. 3). In any case, there has to be substantial involvement of the surrounding rock in some manner to accommodate the lateral extension in the zone.

The pure shear component in a shear zone may involve shortening perpendicular to the zone (as in transpression), but involve extension in the direction of shear rather than perpendicular to it (Fossen and Tikoff, 1993, fig. 1, 1997). Like transpression, this also involves displacement discontinuities at the edges of the shear zone (Fig. 4b). This may be geologically most realistic in the case of nappes or thrust sheets, for which the lower boundary of the zone is the thrust, and the upper boundary the Earth's surface (Fossen and Tikoff, 1997). It should be noted that in this case the strain remains plane, with $k = 1$.

The 'pure shearing' component in a shear zone could involve extension in both the x- and z-directions (Tikoff and Fossen, 1993), with discontinuities in both vertical and horizontal directions of Fig. 2, or in all horizontal directions in Fig. 4. Are there circumstances in which this occurs in nature?

A switching in orientations of the principal stretches occurs in other situations. In the case of a spreading nappe or ice sheet, there will be a horizontal stretch perpendicular to the flow direction associated with the spreading (Hudleston, 1983; Merle, 1986, 1989). The X-direction of strain is in the direction of flow near the base of the sheet where shear strains are highest, but will be perpendicular to the flow and horizontal higher up, as shear strain decreases. Neither of these situations presents a problem of strain compatibility.

Flattening strains are very common in ductile shear zones. In many cases, there is evidence for volume loss accompanying the simple shear, in which case there need be no problem of strain compatibility (e.g. Schwerdtner, 1982; O'Hara, 1988, 1990; Newman and Mitra, 1993). In other cases, geochemical analysis indicates little or no volume change associated with the deformation (Simpson, 1983, although see Mohanty and Ramsay, 1994; Srivastava et al., 1995). If volume change is disallowed, there must either be discontinuities at the edges of the shear zones as in Figs. 2 and 4—allowing, in some way, material in the zone to be 'extruded'—or some other pattern of strain distribution involving the rock surrounding the shear zone, that satisfies strain compatibility. There is little evidence for the former in these natural examples; the latter possibility is explored in the next section.

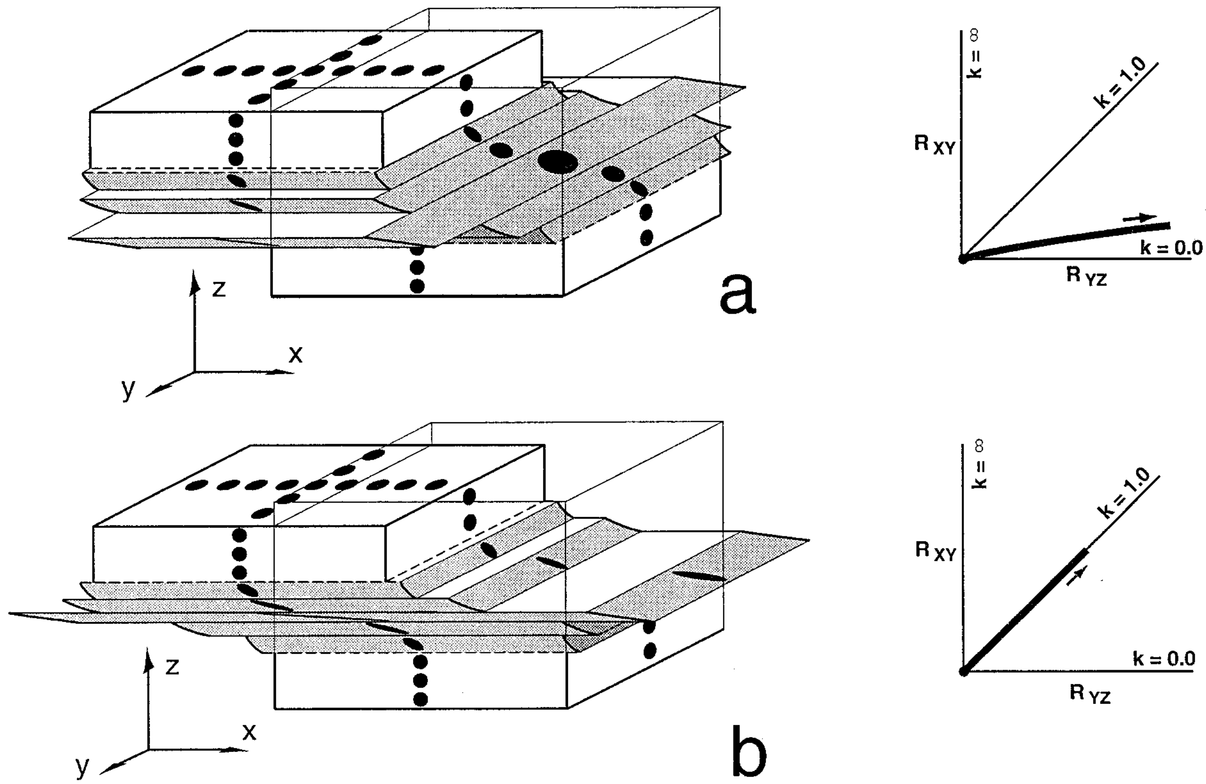

Fig. 4. (a) Transpression in a shear zone with sigmoidal fabric. A shear zone similar to that shown in Fig. 1, with shortening in the *z*-direction, as in Fig. 1(b), accommodated by extension in *y*, rather than by volume loss. Deformation is homogeneous in each slice, leading to discontinuities in the shear plane in the *y*-direction. The strain path is similar to that for Fig. 1(b). (b) Similar to (a), but with extension in *x* rather than *y*. The strain path follows the plane strain line on the Flinn plot.

3. Arrays of shear zones

Isolated, straight, parallel-sided shear zones may be the exception in nature. Domains of localized shear are often arranged in a three-dimensional network (e.g. Ramsay and Allison, 1979; Bell, 1981; Choukroune and Gapais, 1983). Shear zones in these networks may be systematically arranged, and the strain of the bulk rock different from that in the shear zones. Detailed mapping shows that the pattern of shear zone arrays may be irregular (Fig. 5; Coward, 1976; Ramsay and Allison, 1979), although conjugate sets with some systematic relationship to the bulk principal strain directions have been reported in a number of different tectonic situations (Gapais et al., 1987).

It is instructive to examine simple patterns of shear zone arrays and to consider the strain that may be associated with them. I follow the approach taken by Bell (1981) in examining patterns of foliation in rock and relating these to strain. Observations suggest that arrays of shear zones may isolate lozenge-shaped zones of weakly deformed or undeformed rock. A simple and regular pattern of zones of undeformed rock is depicted in Fig. 6(a). For simplicity and for the purpose of demonstration, these are lozenge shaped in the *yz*-plane and parallel-sided in the *x*-direction, thus defining a set of rigid prisms. Under bulk simple shear, with the shear plane parallel to *xy*, and shear in the *x*-direction, the prisms are displaced parallel to the prism axes. Deformation everywhere within the region between the prisms is effectively simple shear, with constant shear direction, but with local variation in strain magnitude and orientation of shear plane. Sets of material planes parallel to *xy* and *xz* remain orthogonal throughout the deformation. The shear 'plane' in the lozenge necks is parallel to *xy*, the bulk shear plane. The shear plane in the lozenge sides is parallel to the lozenge sides. Obviously, the magnitude of the shear within the shear zones will be greater than that of the bulk shear, by a factor that is the ratio of thickness of lozenge plus shear zone to thickness of the shear zone. In the example illustrated, this factor will be about 3 in the necks of the lozenges and 4 in the parallel-sided shear zones. Strain measured anywhere in this system will be plane, with $k = 1$.

One way of developing flattening strains in the shear zones, while maintaining constant volume, is to allow for bulk stretching in *y* and shortening in *z*. This is illustrated in Fig. 6(c). The bulk strain in the *yz*-plane is arbitrarily taken as 2:1. The positions of the centers

Fig. 5. A natural pattern of shear zones, indicated by foliation traces in an outcrop of Archean mafic dike, Scotland (after Coward, 1976). The shear directions in individual shear zones are not indicated; they presumably are neither parallel nor perpendicular to the plane of the map.

of the lozenges in Fig. 6(c) were calculated according to the imposed bulk pure shear. The geometry of the space between the lozenges and hence strain (approximately) of the rock occupying this space was then determined by the new positions of the lozenges. The local deformation now varies in strain symmetry as well as in strain magnitude. In the necks of the lozenges, the combination of simple shear parallel to x with shortening along z and extension along y results in a flattening strain ($k<1$). This is kinematically equivalent to transpression. The strain at the center of the neck will be given by the appropriate equation for homogeneous transpression (Sanderson and Marchini, 1984, eq. 1; Fossen and Tikoff, 1993, eq. 24). As noted by Fossen and Tikoff, the orientation of the X-direction will depend on the relative magnitudes of the pure shear and simple shear components: it will either be in the direction of bulk shear (in the zx-plane and approaching x as strain magnitude increases) or, as in the example illustrated here, parallel to y and perpendicular to the direction of bulk shear. In the parallel-sided zones between the lozenges, the combined effect of simple shear parallel to x and shear in the yz-plane parallel to the lozenge sides will itself be very close to simple shear. This is because, with the particular combination of initial distribution of lozenge centers and the angle the sides of the lozenges make with the y-direction, the gap between lozenges in the initial state is almost the same as the gap between them in the final state. The deformation in the yz-plane is thus close to simple shear. The net effect of two simple shears in the same plane but in different directions is the same as a third simple shear. The X-direction in the lozenge side-shear zones will depend on the relative magnitude of the two simple shear components, but it will not trend in the x-direction of the reference frame. The region between the center of the lozenge necks and the lozenge sides is one of rapid variation between the two end members. Strain compatibility is, however, maintained.

The exact nature of the strain in the shear zones along the lozenge sides will depend on the orientation of the sides to the principal directions of bulk strain, the initial positions of the lozenges centers, and the magnitudes of bulk strain. If the aspect ratio of the lozenges in Fig. 6 is increased, there will be net shortening across the lozenge-side shear zones, leading to transpression here in addition to at the lozenge necks. The degree of transpression will differ in the two locations.

Although the distance between adjacent lozenge sides does not change much during the deformation, it is not truly constant. It actually decreases slightly and then increases again in the example shown. This implies deviation from simple shearing in the lozenge sides, involving modest transpression followed by transtension. The amount of initial shortening (and subsequent extension) across the shear zone in the example given in Fig. 6 is slight, no more than about 5%.

The strain at different positions in the shear zone array is schematically shown in Fig. 6(c), with representation on a Flinn plot in Fig. 6(d), and the pattern of foliation that might develop shown in Fig. 6(e).

The situation illustrated in Fig. 6 is one way of producing local strains of transpressive type without vio-

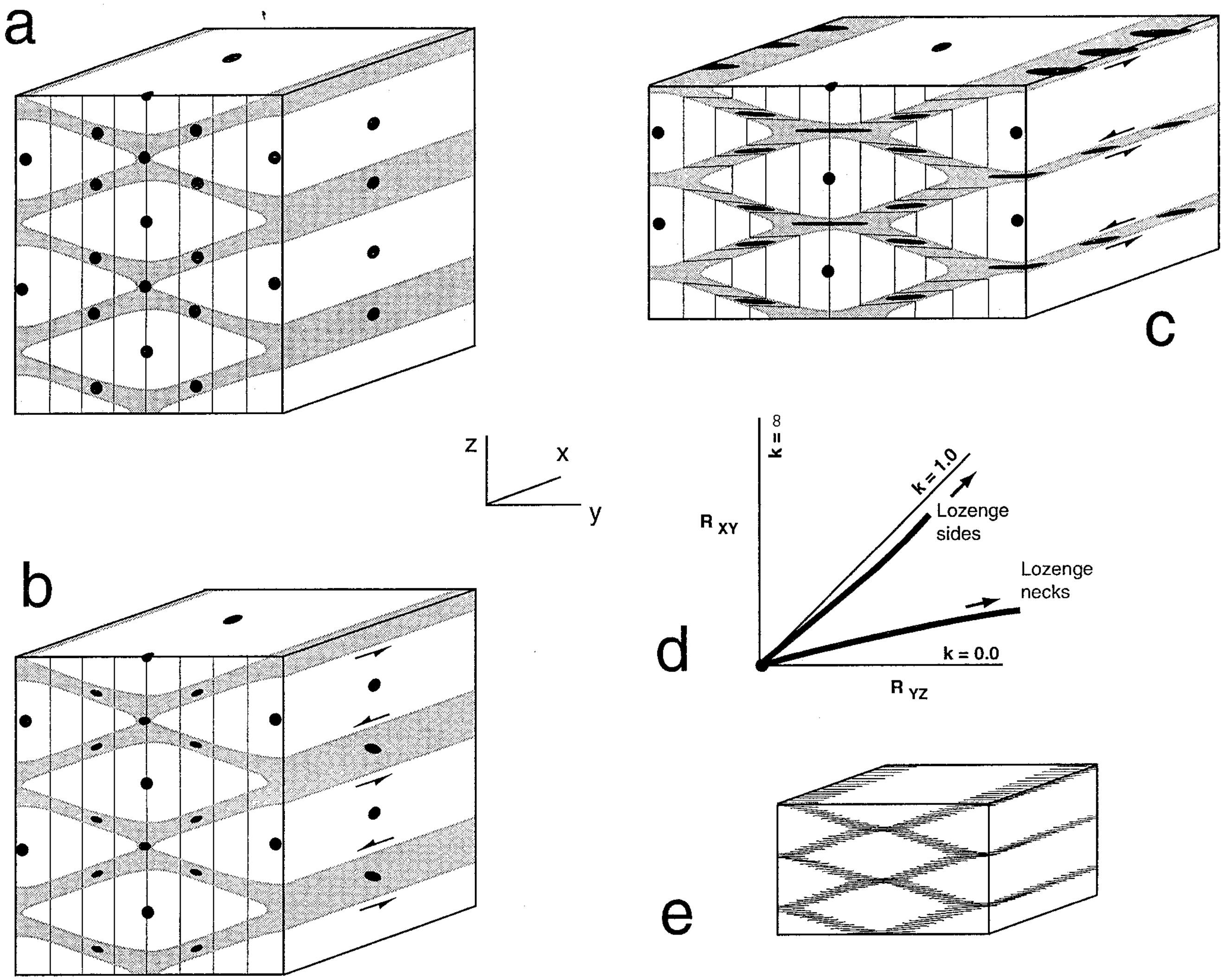

Fig. 6. Network of shear zones defining prismatic lozenges of undeformed rock. (a) Undeformed state, with vertical lines as markers on the front face of the block. (b) The block after bulk simple shear parallel to x (note that the shape of the block on the xz face does not indicate the shear strain). (c) The block in (a) after a bulk strain of $R_{yz} = 2$, and a simple shear on the shear zones in the x-direction, as seen on the xz face (again the shape of the block does not indicate the shear strain in x). (d) Flinn plot to represent deformation paths in (c). More complex paths than the two shown will exist for regions near the necks of the lozenges. (e) Foliation pattern that could be associated with the strain in (c).

lating compatibility requirements. The problem has in effect been displaced to a larger scale—the bulk strain is also one of transpression, with potentially the same problem at the margin of the zone as in Fig. 2. However, a bulk strain of the type represented by transpression and with the attitude shown in Fig. 6 would be consistent with a spreading nappe, in which case the base of the nappe would be a discontinuity between the deforming region and adjacent rock. In this case the upper boundary is not an issue.

If the strain in the yz-plane is the only deformation affecting the rock, that is if we omit the simple shear parallel to x, the local strain (not illustrated) will vary from coaxial pure shear in the lozenge necks (with $R_{yz} \approx 40$), to quasi-simple shear between the straight edges of the lozenges (with shear strain, $\gamma \approx 4$, and $R_{yz} \approx 18$). Because this is close to plane strain, deformation states everywhere will lie near the plane strain line, $k = 1$, on the Flinn plot.

To produce a dominant pattern of flattening strains in shear zones, without volume loss, requires a net extension in the y-direction (for transpressive mode). Fig. 7 illustrates a situation in which there is adjustment of the positions of the same original pattern of lozenges as shown in Fig. 6(a), but no bulk strain in the yz-plane. This pattern was produced by systematic displacements of the centers of the lozenges in the yz-plane, by small arbitrary amounts, in opposite senses for neighboring lozenges, resulting in no bulk strain. With bulk simple shearing on the yx-plane, shear in the x-direction, and all deformation accommodated between the lozenge prisms, this produces alternating

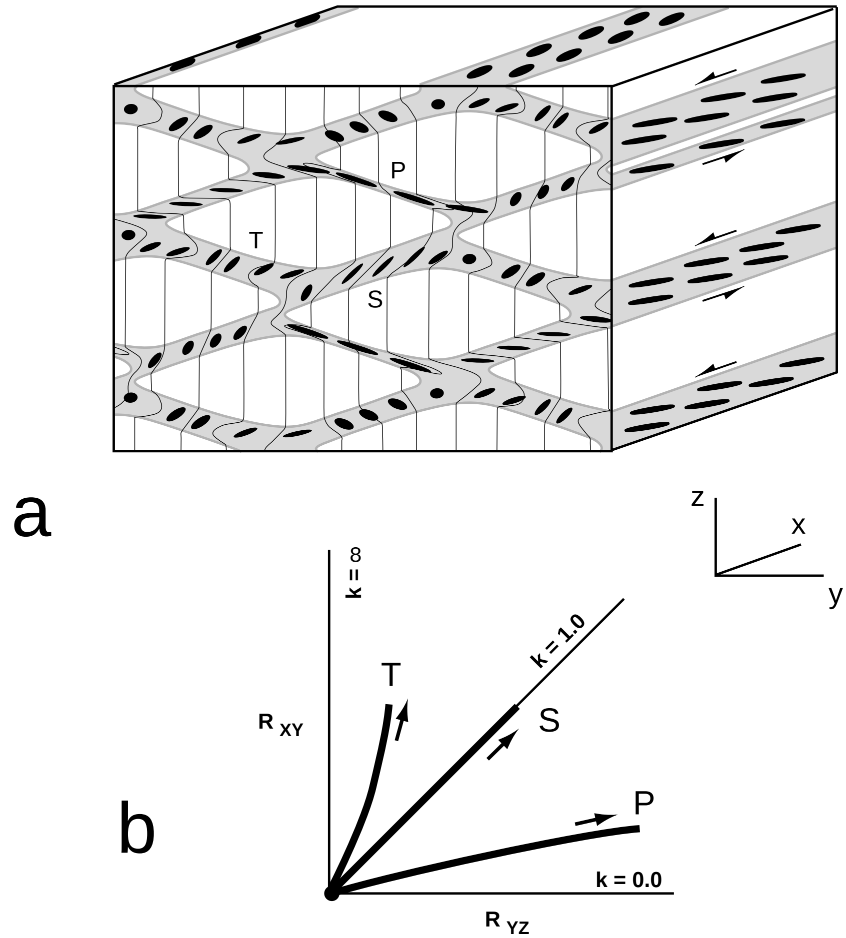

Fig. 7. Network of shear zones as in Fig. 6(b), but with no bulk strain in the *yz*-plane. Starting configuration as in Fig. 6(a). Along individual lozenge boundaries occur transpression, '*P*', transtension, '*T*', and simple shearing, '*S*'. Simple shearing as in Fig. 6 in the *x*-direction. (b) Deformation paths on the Flinn plot highly variable, corresponding to different positions around the lozenges. Most paths will be close to simple shearing. Note that the shape of the block in (a) does not imply shortening in *z* or extension in *y*.

local zones of transtension and transpression between the sides of the lozenges (shown schematically in Fig. 7b). In the example shown, there are three types of boundary; transpression, *P*, transtension, *T*, and quasi-simple shear, *S*. Of course, there is no reason why this particular pattern of displacement among lozenges should develop, but it is quite possible that inhomogeneities in the rock or irregularities in the lozenge shapes in the *x*-direction, cause some 'jostling' of the lozenges in the *yz*-plane to occur. Such behavior in nature would not be as regular as in Fig. 7; here, strain in the transpressive zones is flattening, and strain in the transtensive zones is constrictional. Strain is more intense in the transpressional boundaries than in the transtensional ones, so the visual impression is that flattening is more prevalent than constriction. Is there any evidence in nature for the kind of fabric or strain pattern shown in Fig. 7?

4. Discussion

4.1. Role of discontinuities

Displacements can occur on fractures at all scales in rocks, and whether or not a particular fracture is considered a discontinuity depends on the scale one is dealing with. At one limit is particulate flow, as in a sand, in which all deformation is accommodated by slip on grain boundaries. On the scale of the rock mass, shear zones may be considered as equivalent to slip systems in metals (Cobbold and Gapais, 1986; Gapais and Cobbold, 1987). In the discussion above, I have considered ways to account for strain patterns within a rock mass containing zones of localized shear, without introducing discontinuities. If the bulk strain in such a rock mass is of flattening type, and if the zone in which this strain is developed is planar, then the problem of shear zone boundaries occurs on the larger scale. This is the situation normally encountered in transpression along tectonic boundaries (Figs. 2 and 3). On this scale, the presence of faults allows transpression or transtension to develop with an abrupt change in strain and displacement at the edge of the deformation zone.

Discontinuities on the intra-shear zone scale may produce complicating effects of their own. Lister and Williams (1979), for example, showed how deformation can be accommodated by coaxial pure shear in a zone of simple shear. Slip on discontinuities allows the vorticity of the bulk deformation to be that of simple shear, while allowing coaxial strain in rotating microlithons.

There can be strain discontinuities across coherent interfaces, as Treagus (1988) has shown. This can occur, for example, when there is a viscosity contrast across the interface. This does not present a problem of compatibility. It is in fact likely that the development of shear zones in originally homogeneous and isotropic rock itself creates variations in viscosity associated with deformation-induced changes in grain-size and fabric.

4.2. Three-dimensional relationships

Everything discussed above involves prismatic lozenges. In reality, shear zones generally anastomose in three dimensions, defining polyhedral lozenges of less deformed or undeformed rock, which vary in size and shape. Gapais et al. (1987) argue that shear zones will form conjugate arrays with individual zones lying parallel to directions of no finite stretch in the bulk strain of the rock. If this is the case, shear in all such zones away from their terminations, regardless of the bulk strain, should be close to simple shear, if no volume change is involved. For large strains, material planes of no finite stretch must have experienced shortening and subsequent extension during progressive deformation, (see Ramsay and Huber, 1983, p. 294), complicating strain history in the shear zones, which cannot therefore experience true simple shear.

More realistic models of shear zone arrays would be truly three-dimensional. It seems that certain features of the simple two-dimensional models discussed here, will be found also in three-dimensional configurations. Local conditions of strain (strain magnitude, symmetry, vorticity, and orientation) in individual shear zones may vary greatly with position within the array and differ significantly from the bulk strain experienced by the rock. Local deformation may be of transpressive type, without producing problems of strain compatibility—there will, however, be large local strain variations. In general, the behavior of the shear zone walls is critical to the behavior of the material within the shear zones. Further studies of strain in natural arrays of shear zones, and further modeling of shear zone deformation in three dimensions, are required to better understand how strain on the scale of individual shear bands relates to deformation of the rock mass.

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