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Shear criteria and structural symmetry

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Abstract—During the last decade, it has been shown that most relevant shear criteria within ductile rocks are asymmetric structures (e.g. pressure shadows, shear bands, *C–S* structures, fabrics, tension gashes, folds, veins). The correspondence between coaxial or non-coaxial deformation, and symmetric or asymmetric particle velocity fields, respectively accounts for the use of structural symmetry as an indicator of strain history. The application of this symmetry concept to various field examples emphasizes that: (i) the degree of symmetry of a given structural pattern reflects the bulk strain regime irrespective of the size and the mechanical behaviour of the considered system; and (ii) the strain regime can also be inferred from the order of appearance and dominance of structures which contribute to the total deformation pattern, even where the progressive deformation results in a complex pattern which cannot be directly interpreted.

INTRODUCTION

In the past, the symmetry concept was essentially used to describe geological structures and preferred orientations within deformed rocks, (Turner & Weiss 1963, Sander 1970). More recently, strain concepts have been investigated (e.g. Flinn 1962, Hsu 1966, Ramsay 1967, Jaegar 1969) and geometric effects of displacement and internal distortion discussed in detail. Between these two approaches, very few studies have been made to address the asymmetry of structural patterns in terms of kinematic analysis (see for instance Oertel 1983). However, Brun & Choukroune (1981) have shown that progressive deformation studies can be made on the scale of the entire (bulk) deformed system.

The most commonly used shear criteria in rocks relate to ductile deformation and are deduced from the geometry of local micro-to-mesoscale deformation features; most of them (fabrics, pressure shadows, shear bands, *C–S* structures) are qualitative (Berthé *et al.* 1979a & b, Simpson & Schmid 1983). The consistency of these shear criteria may be used to detect and characterize individual shear zones (Coward 1976, Jegouzo 1980, Gapais & Le Corre 1980, White *et al.* 1986).

However, at a larger scale it appears that such individual shear zones actually belong to an array of comparable structures with various attitudes (Ramsay & Allison 1979, Iglesias & Choukroune 1980, Simpson 1982, Choukroune & Gapais 1983, Gapais *et al.* 1987) (Fig. 1). The estimation of the bulk non-coaxiality suffered by such a system becomes a critical question. For example the Hercynian of Central Brittany, which has been shown to be a dextral shear zone (Gapais & Le Corre 1980), is part of a consistent set of crustal-scale shear zones in western Europe (Fig. 1).

These remarks raise the following major questions.

(1) Can we outline a common geometric characteristic for various shear criteria and, if so, justify this characteristic by kinematic reasoning?

(2) Is this characteristic restricted to ductile deformation or is it applicable to other deformation mechanisms?

(3) Is this characteristic linked to the scale of observation? This question underlines the difficulty of defining what may be called the bulk strain regime suffered by a given area. Can sporadic shear criteria be integrated, or extrapolated, from the small to large scale?

A review of geometric to kinematic aspects of various shear criteria leads us to emphasize that: (i) a non-coaxial deformation imposes the development of asymmetric structures or patterns, whatever the deformation mechanism; (ii) this statement can be applied at all scales; and (iii) in some examples of complex patterns of incompatible structures, their order of appearance is pertinent in determining the strain regime.

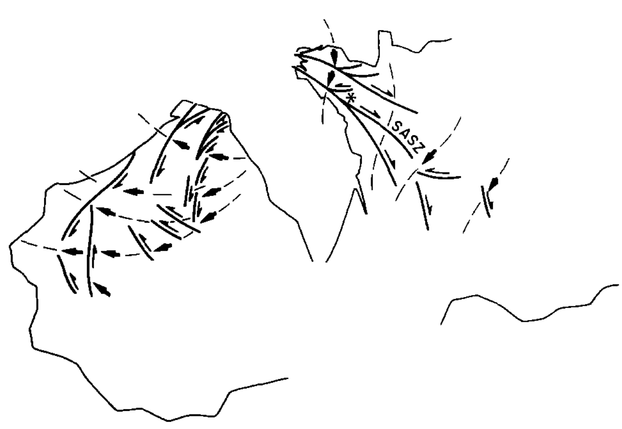

Fig. 1. Schematic representation of ductile shear zones affecting the Hercynian crust of present day France and Spain at about 310 Ma. Thick arrows indicate local shortening trajectories. Large shear zones, such as the South Armorican S.Z. (S.A.S.Z.) constitute domains in which local shear criteria are consistent both in sense and orientation. Star indicates location of local shear criteria shown on Figs. 3(b), 4 and 5. Displacements at the boundaries of the system cannot be simply deduced from the overall geometry.

GEOMETRY OF LOCAL SHEAR CRITERIA

Three main types of features which are used as strain history indicators can be distinguished.

(1) *Slip systems* (Fig. 2a & b). This type of criterion refers to shear surfaces in the deformed material. In particular these are intracrystalline slip systems (lattice fabrics) (Fig. 2b) (Lister & Hobbs 1980, Bouchez *et al.* 1983, Oertel 1983, Etchecopar 1977, 1984), shear bands/zones (Fig. 2a) (Berthé *et al.* 1979b, Platt & Vissers 1980, Choukroune & Gapais 1983) and discontinuities/faults (Tchalenko 1970, Tapponnier & Molnar 1976). All these structures are direct indicators of local motion (Cobbold & Gapais 1987).

(2) *Recorders of incremental strain and rotations* (Fig. 2c–f). These structures are preserved stages of progressive deformation within the deformed material: in particular, fibres in shadow zones or gashes (Fig. 2c & d) (Choukroune 1971, Durney & Ramsay 1973, Casey *et al.* 1983) and fabrics attached to rotated objects (Fig. 2e & f) (Powell & Treagus 1970, Rosenfeld 1970, Passchier & Simpson 1986, Van den Driessche 1986, Van den Driessche & Brun 1987).

(3) *Finite strain markers* (Fig. 2g & h). This group refers to orientations or attitudes of deformed objects (e.g. veins, layering, pebbles, etc.) with respect to principal finite strain axes. In particular, the orientation of non-passive elliptical objects in the deformed state not

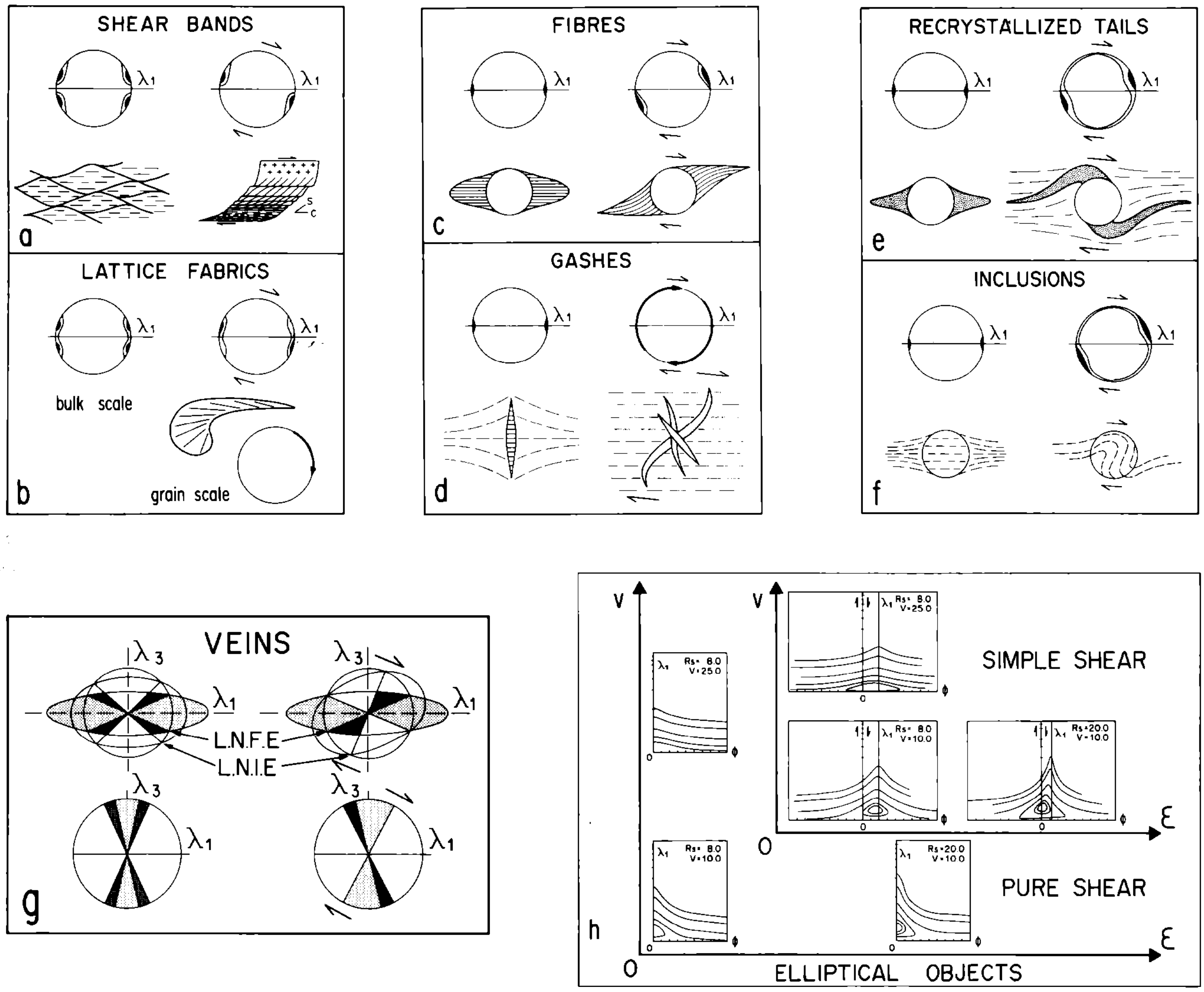

Fig. 2. Strain regime deduced from shear criteria. (a) and (b) Distribution of expressed active slip systems, (c)–(f) structures or patterns used as incremental strain recorders, and (g)–(h) data related to the distribution of finite strain markers. The left- and right-hand sides of each sketch refer to coaxial and non-coaxial histories, respectively. (a) Preferred orientation of shear directions measured on ductile shear bands. (b) Preferred orientation of intracrystalline slip directions. (c) Preferred orientation of fibres within shadow zone around rigid object. (d) Preferred orientation of poles to tension gashes. (e) Preferred orientation of recrystallized tail axis. (f) Preferred orientation of inclusion within synkinematic crystal. (g) Schematic representation of domains of stretching (dotted) and shortening (white) at a given stage of pure shearing (left) and simple shearing (right) for both finite and incremental plane strain. Dark field, overlaps between shortening domain of the finite strain ellipse and stretching domain of the incremental strain ellipse; poles to both extended and shortened veins may occur in this orientation. L.N.F.E., line of no finite extension; L.N.I.E., line of no incremental extension (after Hutton 1982). (h) R_f/ϕ diagrams computed for various finite strains (R_s) and various viscosity contrasts (V) between elliptical markers and matrix. Only half of the symmetric diagrams for pure shear are represented. In all cases (a–h) *asymmetric distributions of the considered criteria with respect to the principal strain axis characterize the non-coaxial history of the deformation.*

only depends on their initial orientation, initial aspect ratio and viscosity contrast with respect to the matrix, but also on the strain regime (Fig. 2h) (Cobbold & Gapais 1983). Similarly the attitude of deformed veins in a ductile matrix depends on their initial and final orientations with respect to the bulk strain ellipsoid, and also on the strain regime (Fig. 2g) (Hutton 1982).

An examination of the patterns associated with all the above features reveals an important characteristic: *the patterns are asymmetric with respect to bulk strain where the deformation is non-coaxial.*

Can we justify this fact by kinematic reasoning? A given structure will result from a given field of particle paths; it is recognized that the symmetry of the particle velocity field is at least orthorhombic when the deformation is coaxial (Ramberg 1975, fig. 15, Hoeppener *et al.* 1983). Moreover, at each stage of progressive coaxial deformation, the elements of symmetry of the finite strain must coincide with those of the velocity field. This is not the case when the deformation is non-coaxial and this explains why non-coaxial deformation generates asymmetric structures.

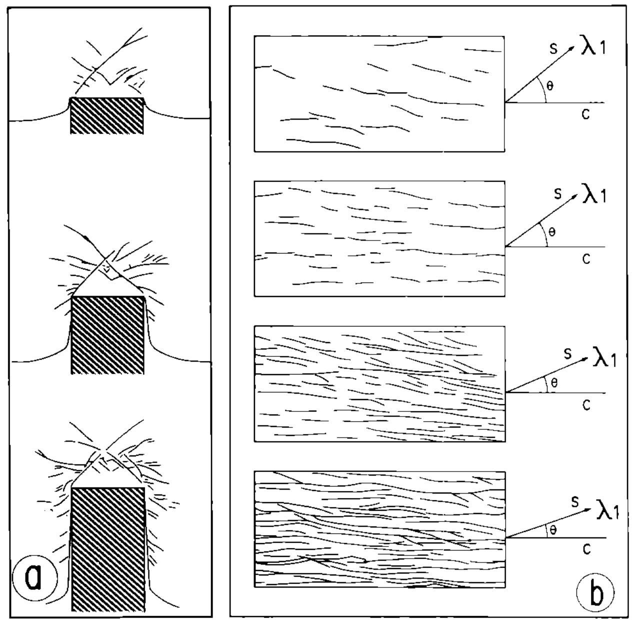

Fig. 3. Examples of progressive evolution of shear zone patterns during (a) a coaxial strain history (experiment from Tapponnier *et al.* 1982) and (b) a non-coaxial history (South Armorican shear zone, see location on Fig. 1). At each stage the overall degree of symmetry remains unchanged despite the continuous addition of new shear zones. A progressive coaxial deformation (a) results in successive symmetric fault patterns. In (b), the shear zone patterns (*C* structures) are always asymmetric with respect to the $\lambda_1\lambda_2$ finite strain plane (*S*) and correspond to a progressive non-coaxial deformation (on the figure, *S* planes are only represented by their average attitudes with respect to *C* planes).

DEVELOPMENT OF STRUCTURAL PATTERNS DURING PROGRESSIVE COAXIAL AND NON-COAXIAL DEFORMATION

The concept of a strain regime results from determining the deformation history from strain recorders and shear criteria. If one given type of structure can be observed at different stages of its development and/or if the order of appearance of superimposed structures can be determined within a complex interference pattern, the regime can be estimated. Sheath folds (Quinquis *et al.* 1978) or conjugate curviplanar folds (Berthé & Brun 1980) are such examples from domains of ductile shearing deformation.

We consider below three examples which illustrate the development of discontinuities during progressive deformation.

(1) This is an analogue experiment where the different stages of deformation can be directly observed (Fig. 3a) (Tapponnier *et al.* 1982). A rigid punch imposes a bulk coaxial deformation on a Plasticine block. The final result of this deformation is a symmetric network of wrench discontinuities with respect to the rigid punch. The observation of stages of development of these discontinuities shows that the structures added are symmetric with respect to the punch: the coaxial deformation creates symmetric 'incremental' structural patterns and the final pattern shows the same degree of symmetry.

(2) The second example is the progressive development of shear bands (*C* bands) within syntectonic granites along the South Armorican shear zone (Fig. 3b) (Berthé *et al.* 1979b). In this case we assume that stages of increasing strain actually observed across the shear zone also illustrate an evolution in time. The increasing deformation is marked by an increasing number of *C* discontinuities (nucleation), an increasing length of these bands (propagation), and a decreasing value of the *C–S* angle. Discontinuities with constant orientation add up during progressive shearing, while the *S* plane ($\lambda_1\lambda_2$) is rotating. At every stage, the pattern remains asymmetric with respect to the *S* plane, except at the stage where *C* and *S* are parallel; but at this stage the oblique *C′* discontinuities become important (Berthé *et al.* 1979a, b) and maintain the asymmetry of the whole deformed system.

This evolution can be compared with the brittle model experiment by Riedel (1929), in which an incremental asymmetry of the evolving discontinuities is also observed (see also Freund 1974, Gamond 1983).

(3) The third example, also from the South Armorican shear zone, concerns the orientation patterns of small-scale brittle-type discontinuities linked to the shearing history within sedimentary rocks. The observed total pattern (Fig. 4b) does not show any preferred orientation of discontinuities. Moreover, discontinuities with an incompatible attitude (opposite sense of shear) occur in the same orientation domain (Fig. 4b). This kind of final pattern can be analysed only if: (i) different sets of compatible discontinuities can be separated; and (ii) field data allow the order of appearance and activation of the distinguishable sets to be determined. This microtectonic technique, classically applied to superimposed structures, in this example reveals the consistent rotation of the finite principal strain axes during the deformation history (Fig. 4c–e) (Choukroune *et al.* 1983). As it is known that the regional structure is simple

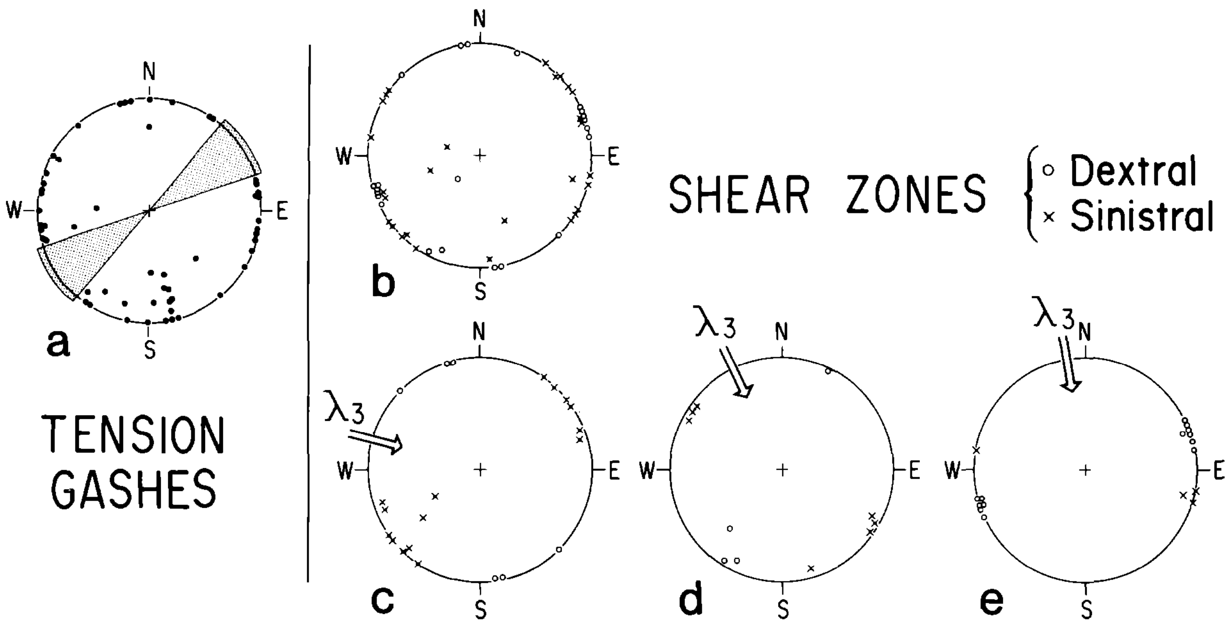

Fig. 4. Natural example of the model presented in Fig. 5 (South Armorican Shear Zone, see location on Fig. 1): the distribution of incompatible superimposed structures (b) can be split into three successive stages, leading to infer (c–e) the dextral rotation of λ_3 during the Hercynian shearing of central Brittany (the estimated effect of reorientation has been removed) (from Choukroune *et al.* 1983). The asymmetric diagram for orientation of gashes (a), measured on one outcrop, is similar to that theoretically expected and shown on Fig. 2(d).

and of one phase, we can propose a model in which conjugate sets of discontinuities are due to successive coaxial deformations, each of them being characterized by different finite strain directions (Fig. 5).

One can note that the successive position of finite shortening (λ_3) cannot be interpreted simply as incremental steps because of the theoretically constant orientation of incremental λ_3 during the simple shearing. We have here superimposed structures which are compatible with a rotational deformation and consistent with the regional context of dextral shearing.

These three examples show that the symmetry concept used to determine the strain regime can be applied to discontinuity patterns as well as to ductile features. This symmetry concept is verified at each stage of the development of the observed structures. Moreover, the history of appearance of compatible structures reflects the bulk regime suffered by a finite deformed system.

BULK STRAIN REGIME FROM SYMMETRY OF CRUSTAL STRUCTURES

In deformation theory, the strain regime refers to the deformation history at a point (Means 1976) and is basically linked to relative attitudes of finite and incremental strain ellipsoids during progressive deformation. In fact, this strict definition forbids any scale enlargement of the strain regime concept even at the scale of any local shear criteria. Nevertheless, we infer that the symmetry concept developed previously allows us to discuss the nature of the displacements at the boundary of a given system whatever its size; these displacements constrain and determine what can be defined as the bulk strain regime at a particular scale.

Figure 6 illustrates well-known examples of crustal structures associated with: (i) either brittle or ductile deformation; (ii) various deformation processes within the crust; and (iii) various kinds of instabilities (faults, folds, shear zones, diapirs) of different origins (with and without gravitational effects).

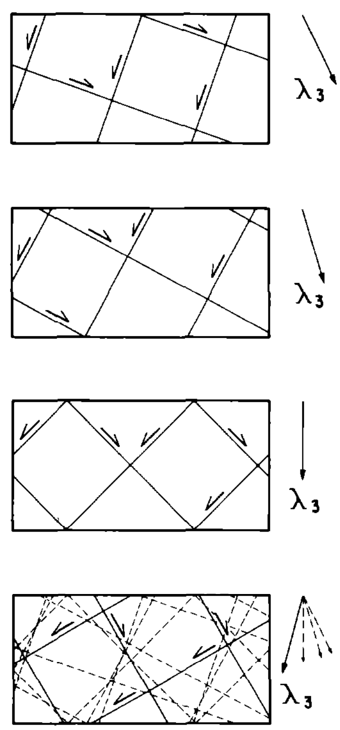

Fig. 5. Theoretical model in which sets of conjugate shear zones symmetric with respect to λ_3 are superimposed during progressive deformation with rotating λ_3. This yields a complex finite pattern of incompatible structure (reorientation of shear zones is not taken into account).

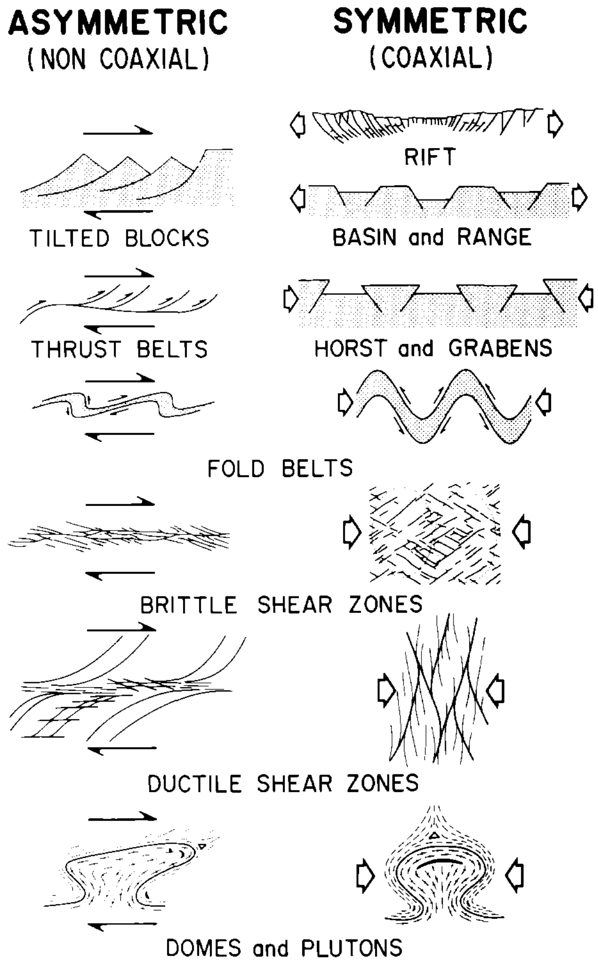

Fig. 6. Bulk strain regime and symmetry of deformed crustal domains. Patterns of brittle shear zones refer to experiment of Tchalenko (1970) and Hoeppener *et al.* (1969). Patterns of domes and plutons after Brun (1983).

It outlines the following major features.

(1) A direct relationship between a coaxial strain regime and a symmetric structural pattern at the scale of the considered crustal structure can be inferred. In contrast, asymmetric patterns must be interpreted more carefully: on the one hand, certain initial orientations of pre-existing markers can produce asymmetric patterns (e.g. folded surfaces) during a coaxial history; on the other hand, a bulk coaxial history is generally partitioned into local non coaxial histories (e.g. tilted blocks on each side of a symmetric rift; Fig. 6). Nevertheless a non-coaxial history always yields an asymmetric pattern provided that the size of the system, in which all criteria are consistent, has been well chosen.

(2) If the assessment of structural symmetry is necessary to infer the bulk strain regime, the determination of boundary displacements is further required to take into account both mechanical factors (such as boundary conditions) and the geological context; this point is well illustrated by comparing the case of tilted blocks with that of thrust belts (Fig. 6). Both show similar overall asymmetry and bulk shear sense, but individual faults have opposite shear sense although their orientations are the same with respect to the system boundary: ignoring the general context (thinning or thickening) can give a wrong answer.

CONCLUSIONS

To establish the bulk strain regime of a crustal structure, we need simply to consider the degree of symmetry of the structural pattern. Our approach has been basically kinematic, ignoring the mechanical behaviour of the deformed system. However, the quantitative relationships that may exist between the degree of non-coaxiality and the degree of asymmetry must be debated (Passchier 1986). Useful approaches could perhaps involve statistical studies of geometric features (e.g. orientations, length, spacing and population density of structures) and of their correlations with the amount of bulk shear strain. This generally requires each particular geometry to be considered together with boundary conditions and deformation mechanisms; but for some well constrained situations where mechanical conditions are extreme, kinematic factors become most important and structural asymmetry, such as fold asymmetry (Hoeppener *et al.* 1973) or asymmetry of slip-system preferred orientations (Oertel 1983, Cobbold & Gapais 1987), can be sufficient to determine the bulk degree of non-coaxiality.

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