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Mylonites in the continental crust and their role as seismic reflectors

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Abstract

Shear zones in the continental crust can accommodate much of the regionally imposed shortening or extension. An analysis of the flow patterns and flow history in active shear zones and of their geometry and orientation contributes to the understanding of large-scale crustal deformation. Information on the flow behaviour in 'fossil' ductile shear zones can be obtained from deformation fabrics in exposed mylonitic fault rocks. Unfortunately, the geometry and orientation of such exposed zones have often been modified by uplift and overprinting, masking the original aspect. However, in situ information on the shape and orientation of active ductile shear zones can be obtained from deep reflection seismograms. Provided the zones have a gentle dip, the unique homogeneous nature of mylonitic fabrics in them can generate high amplitude seismic reflections of large lateral continuity.

Introduction

Regionally imposed strains in the continental crust are largely accommodated by brittle or ductile flow along major shear zones, which transect the crust as thin planar zones of considerable lateral extend (Fig. 1). In the upper crust deformation is usually by brittle fracturing and movement on fault planes or fault zones of negligible width. The faults form complicated and anastomosing systems with predictable geometry and sequence of formation (Boyer & Elliott 1982, Gibbs 1983). Movement on individual fault planes may generate small irregular volumes of gouge, cataclasite or pseudotachylyte (Fig. 1, Sibson 1977). Such fault rock types rarely store any information on the movement sense and direction of faulting in their internal structure; all information of that nature must be obtained from displaced markers along the faults.

At deeper levels in the crust regionally imposed strains can be accommodated within ductile shear zones, commonly 1–100 m wide (Fig. 1). Within these zones deformation is mainly by crystal plastic flow and typical fault rocks produced are mylonites (Sibson 1977, Tullis et al. 1982). Contrary to brittle fault rocks, mylonites carry a wealth of information on the flow pattern and flow history of the shear zone segment in which they were formed. The *geometry* of ductile shear zone systems is less well understood than its brittle counterpart.

In quartzo-feldspatic rocks, the brittle ductile transition for a geothermal gradient of 30° per km will lie at a depth of between 5 and 12 km depending on the locally accommodated strain rate, on the orientation of the bulk kinematic frame of flow and on fluid pressures along the brittle faults (Fig. 1, Sibson 1983). In this transition, brittle faulting and ductile flow seem to alternate spatially and in time

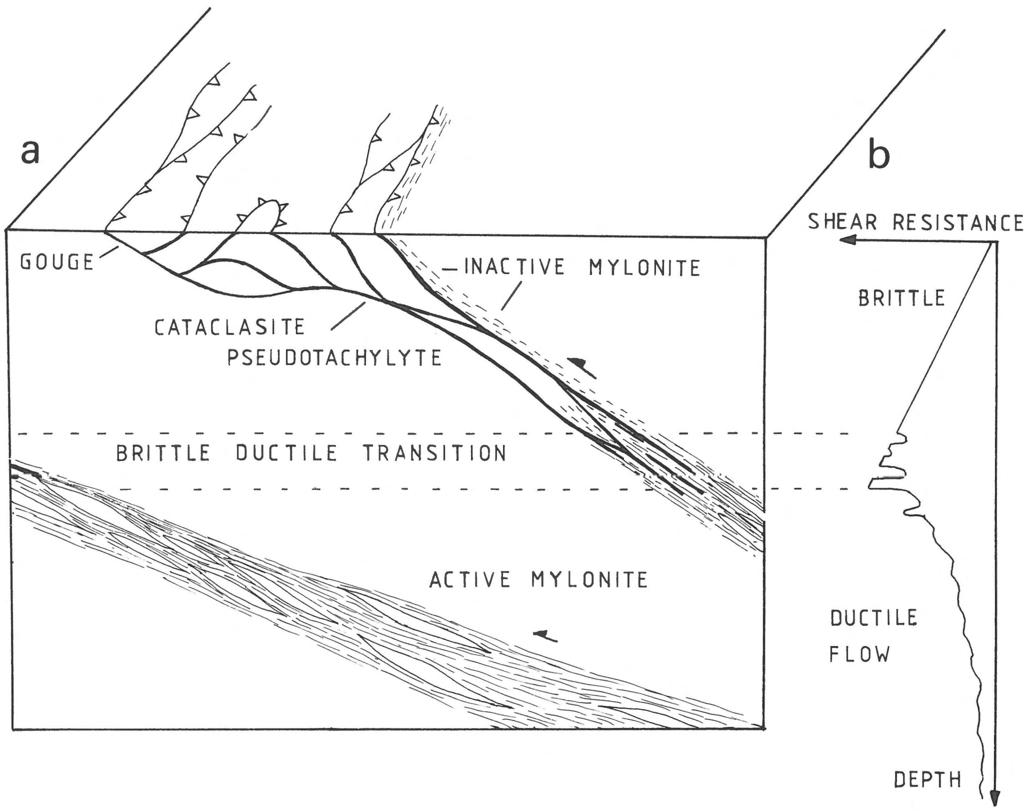

Fig. 1. a) Schematic representation of fault rock distribution and geometry along a natural constrictional shear zone; b) plot of shear resistance against depth after Sibson (1977, 1983).

(Sibson 1980). This leads to the formation of ductilely deformed pseudotachylyte (Passchier 1982) or cataclasite (Stel 1984) and veins of brittle fault rocks transecting mylonite (Passchier 1982).

Ductile shear zones can accommodate a large part of the regionally imposed strain by non-coaxial flow. The limits within which variations to this flow pattern occur are in many cases constricted enough to form mylonites with a relatively uniform final deformation fabric (Fig. 2 and below). The country rock between shear zones, however will tend to deform much more inhomogeneously: movement on shear zones with an anastomosing geometry (Fig. 2) may cause large changes in the nature and orientation of the local flow pattern with time, causing several overprinting sets of foliations or phases of folding which only give information on local flow history. Consequently, mylonites in ductile shear zones are expected to carry more and more easily interpretable information on the regional pattern of crustal deformation than the country rock. In fact, knowledge of the large scale geometry of the ductile shear zone pattern in a certain part of the continental crust and of the flow history in the zones would allow the reconstruction of a 'deformation skeleton', comparable to a fault zone system in the upper crust, which carries most of the information needed to reconstruct the regional deformation pattern. First attempts at such reconstructions have been made in most major orogens (e.g. Blundell 1984, Soper & Barber 1982). They first of all require a sound understanding of mylonites and the way in which they are formed.

Mylonites

In accordance with definitions by Bell & Etheridge (1973) and White et al. (1980) mylonites can be described as strongly deformed rocks which have

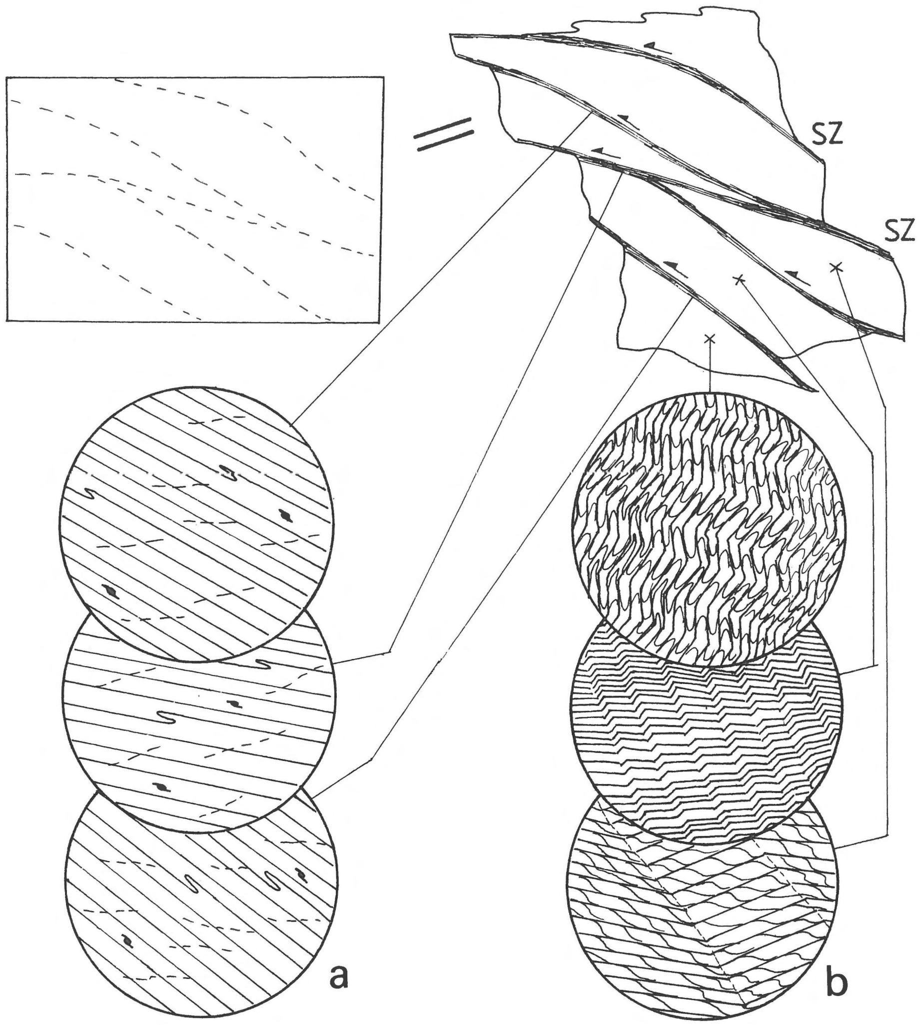

Fig. 2. Effects of crustal shortening by localization of flow along ductile shear zones (SZ). Fabric patterns in mylonite from the shear zones (a) show much less lateral variation than those in the country rock (b) with a more complex variation in flow type and orientation.

been generated from a less deformed parent rock dominantly by non-coaxial crystal plastic flow. Mylonites occur in plate-shaped bodies of limited thickness and significant lateral extend called mylonite zones, often with an anastomosing internal structure around lenses of less intensely deformed rock (Fig. 3a). In these zones, which are interpreted as exhumed, 'fossil' ductile shear zones (Ramsay 1980, Tullis et al. 1982) finite strain values of mylonitic deformation are significantly higher than synchronously produced strain values in the country rock. Lapworth (1885) originally defined a mylonite as a dominantly brittle fault rock and Higgins (1971) continued this use, but their interpretation of mylonitic microstructures has proven to be in error (Bell & Etheridge 1973). Brittle deformation structures do occur in mylonites but faulting only happens on a very small scale, e.g. in isolated rigid crystals and accommodates a neglectable part of the total strain. The matrix of mylonites, which accommmodates most of the deformation, invariably deforms by ductile flow. Mylonites have the following characteristic fabric elements (Fig. 3):

(1) a shape fabric consisting of planar ('compositional layering' – S_o) and linear ('stretching lineation' – L) elements subparallel or at a small angle to mylonite zone boundaries (Fig. 3b). This fabric element is usually defined by alternating disc or rod-shaped domains of different mineral content, e.g. quartz- and feldspar-rich domains. Characteristic is the planar and straight nature of the shape fabric over large sectors of most mylonite zones, quite unlike the always sligthly irregular orientation of foliations and lineations in other naturally deformed rocks (Fig. 3b, c);

(2) a preferred orientation of minerals which have been subjected to crystal plastic deformation processes;

(3) flow folds of two basic types: a) sheath folds, either dome-and-basin shaped or tube shaped, flattened parallel to the foliation envelope in the mylonite and with large sectors of the folded surface subparallel to the local stretching lineation (Fig. 3c). Some small sectors in the 'nose' of the folded surface lie at a high angle or normal to the lineation; (b) oblique folds of strongly cylindrical nature with the entire folded surface parallel to the local stretching lineation (Fig. 3c, Passchier in prep.);

(4) a monoclinic symmetry of many fabric elements with a two-fold symmetry axis in the plane of the shape fabric and normal to the stretching lineation (Fig. 3d).

Monoclinic fabric elements

Examples of common monoclinic fabric elements in mylonites are (numbers refer to Figure 3d):

(a) systematic obliqueness of shape fabric elements and crystallographic preferred orientation patterns of constituent minerals in a mylonite with the boundaries of the zone (Fig. 3b: Simpson & Schmid 1983, Ramsay & Graham 1970);

(b) systematic obliqueness of planar fabric elements in the zone which developed synchronously, such as the obliqueness of elongated newly recrystallized quartz grains (7, Means 1981, Lister & Snoke 1984) or a mica preferred orientation S_m (4) with respect to the mylonitic shape fabric S_o.

(c) obliqueness of S_m or S_o with a shear band cleavage, i.e. a cophase younger foliation element (White 1979). There are two types: wavy, anastomosing extensional crenulation cleavage (ecc) in micaceous mylonites, which are oblique to the zone boundaries and to the older foliation (3, Platt & Vissers 1980, White 1979), or planar, distinct C-planes (1) which parallel shear zone boundaries but lie oblique to the older foliation (Berthe et al. 1979, Lister & Snoke 1984).

(d) crystallographic preferred orientation patterns of constituent minerals, e.g. quartz (8): Lister & Williams 1979) and calcite (Behrmann 1983).

(e) lozenge shaped single crystals of mica (10: Eisbacher 1970, Lister & Snoke 1984) and feldspar (6; Passchier in prep.).

(f) fragmented rigid grains with antithetic slip between the fragments due to extension in a ductile matrix (5: Simpson & Schmid 1983).

(g) pressure shadows and other symmetrically distributed concentrations of a certain mineral around rigid inclusions (9: Simpson & Schmid 1983).

(h) rigid porphyroclasts and their dynamically recrystallized mantle, which form systems with two distinct types of internal symmetry (Passchier & Simpson in press): delta-type, with bended tails (11) or sigma-type with wedge-shaped straight tails (12).

(i) stepped stretching tails of material (S_o) which have been generated on relatively rigid objects in the mylonite (10, 11, 12: Lister & Snoke 1984).

(j) constrictional (microfolding) or extensional (crack-seal) structures between microshear zones or microfaults with on-stepping (15) or off-stepping (16) geometry (Knipe & Wintch 1985).

(k) synkinematic porphyroblasts with a monoclinic inclusion trail such as snowball garnets (2: Schoneveld 1977). (1) obliqueness of the long axis of oblong rigid objects relative to the mylonitic shape fabric (13).

(m) symmetry of sheath folds in sections through the 'nose' of the structure (Fig. 3c, d14: Passchier 1983).

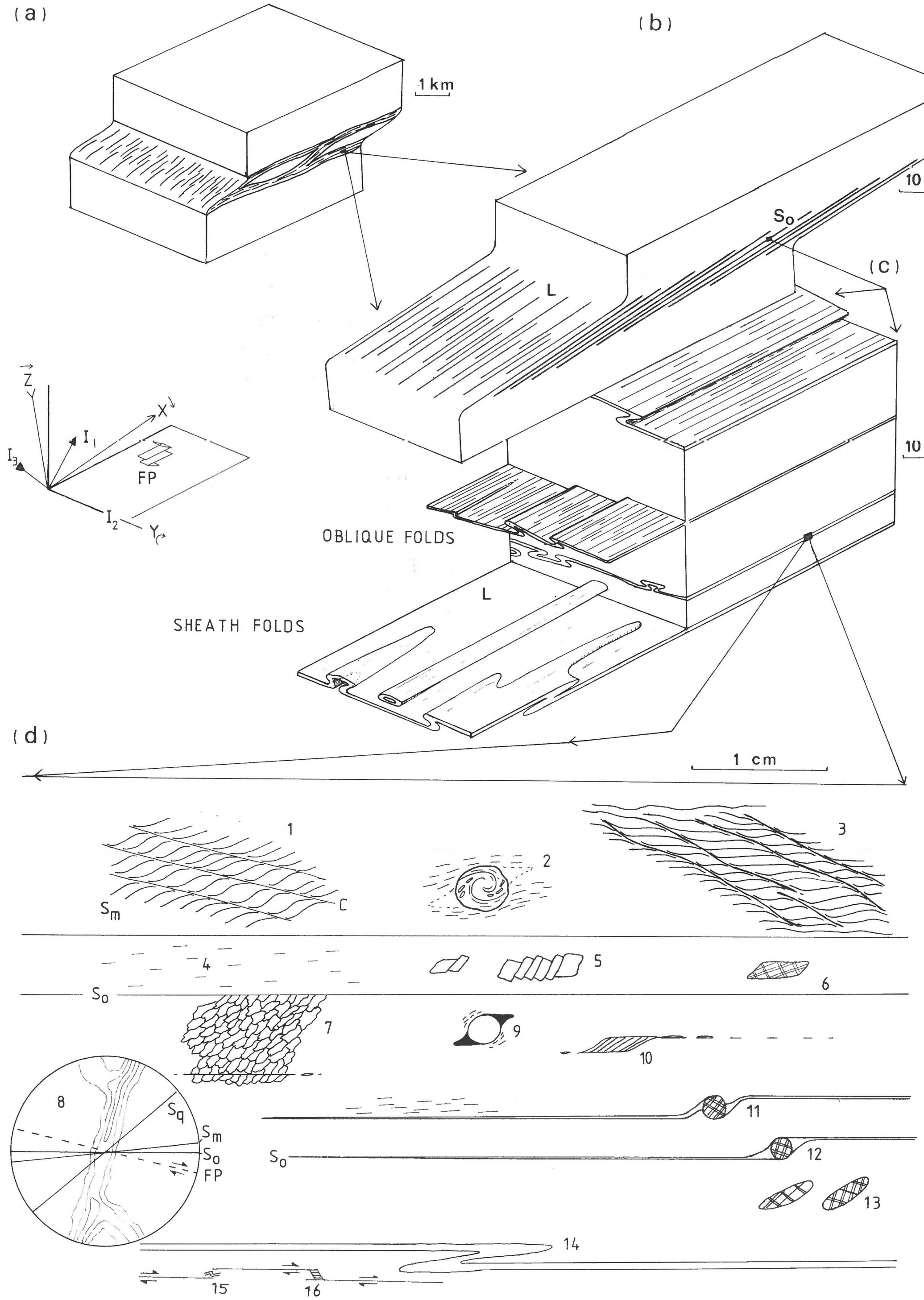

Fig. 3. a) ductile shear zone with anastomosing internal structure; b) shear zone branch from (a) showing compositional layering (S_o) oblique to shear zone margin; c) fragment from (b) with two types of flow folding; d) schematic summary of common monoclinic fabric elements (1–16) in mylonites on sections parallel to the stretching lineation (L) and normal to the compositional layering (S_o): explanation see text. S_m – mica preferred orientation. S_q shape fabric of recrystallized quartz grains. FP – flow plane of simple shear.

Flow in shear zones

Mylonitic fabrics with monoclinic elements are often assumed to form by irrotational simply shear flow. In fact, there is often evidence for synchronous ductile deformation of shear zone wall rocks and significant deviations from such simple flow in the zone (Law et al. 1984, Passchier 1986). Non-coaxiality of flow can be described by a kinematic vorticity number W (Fig. 4: Means et al. 1980), defined here for plane strain as

$$W = \cos \alpha$$

where α is the angle between the apophyses of flow, two unique planes in plane strain flow along which particle paths are straight lines (Fig. 4: Ramberg 1975, Lister & Williams 1983). The fact that monoclinic fabric elements occur in a mylonite does not mean that flow was a simple shear ($W = 1$; Fig. 4c), but only that flow was non-coaxial ($W \neq 0$; Fig. 4b,c). Data on the magnitude of W and its time-dependance during flow in a shear zone are difficult to obtain from most mylonitic fabrics, but where this can be done flow in the 'fossil' shear zone is completely defined (Passchier 1986). Additionally, some theoretical constraints can be placed on the possible flow regimes in natural shear zones.

Shear zones result from strain softening and consequent concentration of flow wherever mechanisms exist which allow a local retardation of strain hardening relative to the surrounding material (Poirier 1980). After an initial, possibly complicated growth stage, the number of stable flow types in shear zones is limited, provided the following boundary conditions are imposed (These conditions are derived from the interpretation of common mylonitic fabric elements as described above); (1) flow compatibility is maintained between the shear zone and the country rock; (2) flow in the

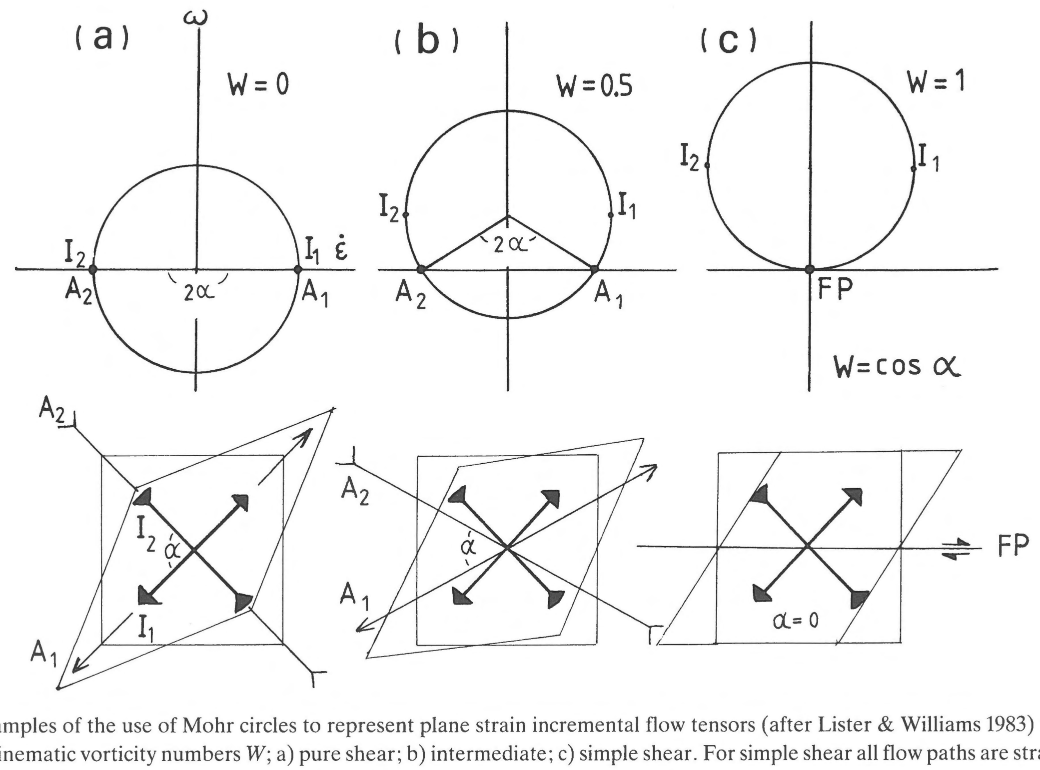

Fig. 4. Examples of the use of Mohr circles to represent plane strain incremental flow tensors (after Lister & Williams 1983) for three different kinematic vorticity numbers W; a) pure shear; b) intermediate; c) simple shear. For simple shear all flow paths are straight and define a flow plane (FP). In real space, incremental flow is along hyperboloid curves except for two straight particle paths (apophyses: A) and leads to finite strain types illustrated by outlines of undeformed and deformed squares. For time-independent flow at constant W the apophyses are fixed with respect to incremental stretching axes (I). The coordinate axes of the Mohr circles represent angular velocity (ς) and stretching rate ($\dot{\varepsilon}$) of material lines.

zone is essentially non-coaxial (Fig. 4) with incremental stretching rates significantly exceeding those in the country rock; (3) volume change rate is significantly less than incremental stretching rate in the zone; (4) flow approaches plane strain and is essentially two-dimensional within the X-Z plane. Flow types are considered in a reference frame fixed to shear zone boundaries. Figure 5 shows four types of flow regime pairs for shear zone and wall rock which are stable in time for the conditions stated, provided that apophyses of flow coincide continuously with the same material points. Other types of pairs cannot be time-independent; they would lead to rapid reorientation of the kinematic frame of flow with respect to shear zone boundaries and eventually to one of the basic flow pair types or to a type which violates the boundary conditions. Actual flow in natural shear zones is likely to occur by an alternation of these basic types, laterally in the zone and in time. It is clear that a time independent simple shear (Fig. 4c, 5a) with the flow plane parallel to shear zone boundaries is just one of the possibilities. Monoclinic fabric elements and a mylonitic planar and linear shape fabric can be produced by any of the basic flow-pair types or by an overprinting sequence of these types. In all cases the shape fabric rotates during its development towards the extensional apophysis of flow (Fig. 4: Ramberg 1975), indicated by the right intersection point of the shear zone Mohr circle of incremental flow with the stretching axis (Fig. 5).

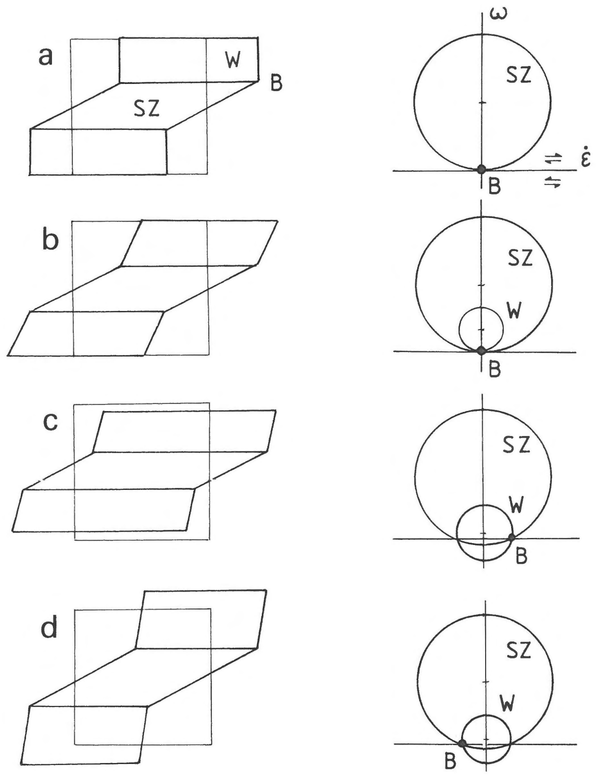

Fig. 5. Four basic types of volume-constant time-independent plane strain flow in a shear zone (SZ) and its wall rock (W), illustrated in real space for a certain finite strain, and in Mohr-space for incremental flow. Shear zone boundaries (B) coincide with the flow plane (FP) of simple shear (a,b) or with one of the apophyses of flow in both the shear zone and the wall rock (c, d).

Flow inhomogeneity

Inhomogeneities of flow in shear zones produce many of the characteristic monoclinic fabric elements of mylonites. Shear band cleavages probably form due to a breakdown of homogeneous flow in the zone, e.g. due to strain hardening. Mylonites with a shear band cleavage parallel to shear zone boundaries (C-planes) can form by strongly heterogeneous simple shear in a shear zone with rigid wall rocks (Fig. 5a). This is impossible for most types of extensional crenulation cleavage which indicate a significant stretching component of flow parallel to shear zone boundaries: they may form during late stages of flow in a shear zone when hardening of the zone induces renewed ductile flow in the wall rock. Since most mylonites contain such late extensional crenulation cleavages, the last stage of flow in the shear zones may have been as in Figure 5c. Considerations of this type provide some data on the time behaviour of flow in ancient shear zones.

Tight to isoclinal folding of the shape fabric in mylonites probably occurs by small inhomogeneities of flow which cause deviant orientations of small sectors of layering which become amplified into isoclinal folds by continuing flow. Local deviations in stretching rate or orientation of the kinematic frame within the XZ plane of the flow can produce dome-and-basin shaped folds which develop into sheath folds with progressive deformation (Platt 1983, Cobbold & Quinquis 1980). Deviations of flow from plane strain in the Y direction probably produces cylindrical oblique folds (Passchier in prep).

In-situ shear zones

Nearly all our knowledge about natural shear zones and their role in the accommodation of crustal deformation is derived from mylonite zones in uplifted segments of orogenic belts. Data on the flow regime and its time behaviour in these 'fossil' shear zones, derived from mylonitic fabric elements as discussed above can put some constraint on the possible patterns of regional structural evolution. A 'deformation skeleton' can only be reconstructed if additional data exist on the geometry of the ancient shear zone system. Presently exposed mylonite zones have been brought to the surface by uplift and erosion, e.g. where they occur in the hanging wall of thrust fault systems (Fig. 1) by transport along the zone, or in the footwall of extensional fault systems by passive uplift or subsequent thrusting (Passchier 1984). Mylonite zones have necessarily been deactivated during their ascent through the brittle-ductile transition and the brittle upper sector of the crust, and their geometry is usually severely damaged by large scale refolding and other late events which are unrelated to the major flow period in the zone. Moreover, the outcrop surface of mylonite zones is often small and only allows two dimensional observation. These factors impair the use of presently exposed mylonite zones in the reconstruction of 'deformation skeletons of large scale crustal deformation, although data on the kinematic behaviour of the mylonite may be well preserved. Direct observations of natural shear zones 'in-situ' can solve part of this problem; such observations have now become available by seismic reflection methods.

Gently dipping reflectors of vast lateral extend which can be followed from brittle fault zones at the surface to depths below the local brittle-ductile transition have been recognized at several sites. The most spectacular published examples are the COCORP profiles of the Wind River Thrust (Smithson et al. 1979, Bloxsom Lynn et al. 1983) and the southern Appalachian Thrust (Cook et al. 1979); the MOIST profile of Caledonian thrusts in northern Scotland (Smythe et al. 1982, Blundell 1984) and the ECORS section through the Variscan thrust belt of northern France and Belgium (Cazes et al. 1985, Meissner et al. 1981). Strong reflections in these sections are most probably derived from shear zones which extend through most of the continental crust. Seismic reflections from shear zones at depth could be explained by a lithologic contrast over the zone, by high fluid pressures along the zone (Jones & Nur 1982), or by specific properties of deformed rocks in the shear zone (Jones & Nur 1984). Lithologic contrast across a major shear zone will tend to vary strongly along most zones since variations in composition in most presently exposed crustal segments occurs on a 100 m–1000 m scale. The resulting reflections should vary strongly in amplitude and cannot produce the unbroken strong reflectors seen on most of the sections. High fluid pressures can be generated by dewatering of crustal slabs descending due to movement on the shear zone or CO_2 production by breakdown of carbonates. Such high fluid pressures are unlikely to exist for prolonged periods of time even at very low permeability of the rock (Jones & Nur 1984); pressure decay will take place by diffusion into the country rock and retrograde reactions in the zone (Etheridge & Vernon 1983). For these reasons, strong reflections from deep sections of shear zones which have been inactive for several tens of millions of years must reflect intrinsic properties of deformed rocks in the zone.

In shear zones, mylonitic rocks will be formed below a certain depth which depends on the local geothermal gradient, lithology and strain rate. Jones & Nur (1982, 1984), Fountain et al. (1984) and Hurich et al. (1985) have shown that mylonitic rocks with high mica content and banded internal structure with a hectometric period can act as strong seismic reflectors in the continental crust. This results from the fact that seismically anisotropic minerals such as micas develop a strong preferred orientation in mylonites, which can be relatively constant in orientation over large sectors of the shearzone. Mylonites which have been deformed under greenschist facies conditions are commonly enriched in white mica by breakdown of feldspars and alluminium silicates, provided a sufficient influx of water is possible and potassium can be removed from the system (Etheridge & Vernon 1983, Passchier 1985, Wintsch & Knipe 1983). These micas, and possibly also quartz provide the velocity anisotropy which is responsible for the reflective activity of mylonite zones (Etheridge & Vernon 1983, Jones & Nur 1984). In the deeper crust, where influx of water may be of lesser importance, mica enrichment will be insignificant, but crystal plastic flow of feldspars, hornblende and pyroxenes beside quartz and micas may generate a mineral-preferred orientation and compositional layering which can produce seismic anisotropies. The unique property which causes shear zones to act as good reflectors is not so much the mineral-preferred orientation, which probably occurs in many structures in the deep crust, but the large lateral extend over which similar and similarly oriented mylonitic fabrics have developed. Mylonitic shear zones at depth are likely to produce spectacular reflectors over large parts of the continental crust, provided the zones are dipping gently. This means that under favourable conditions the deeper structure of thrust and normal fault belts can be studied in situ (e.g. Blundell 1984). In combination with the data on kinematics and evolution of ductile shear zones obtained from mylonite zones this will provide important new insight in the large-scale geometry of lithospheric deformation.

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