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INTRODUCTION

Shear criteria in rocks: an introductory review

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INTRODUCTION

OVER the last decade or so, there has been an increasing interest in the use of kinematic indicators, in other words, geological structures (often microstructures) that reveal certain aspects of the deformation history of a rock at a given scale. Amongst these are indicators of the sense or the amount of shear (or slip), in situations where the deformation history has been dominantly one of progressive simple shear (or slip).

In spite of this interest, most papers so far have dealt with specific indicators, or with regional applications. There have been few attempts at summarizing the theoretical basis, the reliability, or the use of kinematic indicators (but see, for example, Simpson & Schmid 1983 for a useful summary of shear criteria).

In May 1986 an international meeting on shear criteria was held at Imperial College, London, after initial plans to hold it at Rennes failed. Many of the contributions to the meeting have found their way into this special issue. In our introductory review we have also tried to incorporate some of the ideas that circulated so freely in the discussion periods of the meeting.

ASPECTS OF KINEMATICS

We first review aspects of the general theory of kinematics that are relevant to the subject of kinematic indicators.

For terminology and definitions, we mainly follow Truesdell & Toupin (1960) because their review is apparently the most complete; but we admit that their terminology is sometimes debatable and often conflicts with current geological usage.

The *deformation* of an element is its entire transformation from the undeformed to the deformed states: it includes a rigid translation, a rigid rotation and a strain. The deformation field is *continuous*, where no material line is disrupted; alternatively, it may exhibit discontinuities of various kinds. Of particular interest are *singular surfaces* of the first order, across which material lines are disrupted. Across *slip surfaces*, material lines are offset tangentially. Thus, most geological faults approximate closely to slip surfaces. The offset is perhaps the best measure of slip at a point.

In a locally continuous deformation field, *shear*, ψ, is the change in angle between two lines. For convenience, it is usual to consider a pair of lines initially at right angles. *Shear strain* is the shear (off-diagonal) component of any symmetric strain tensor. *Simple shear* is a deformation represented by a deformation gradient tensor with unit diagonal components and only one non-vanishing off-diagonal component, which geologists usually label $\gamma = \tan \psi$. Truesdell & Toupin (1960) call γ the *amount of shear*, to distinguish it from a true shear strain as defined above. We find that such a distinction is indeed useful. In simple shear, the *shearing planes* are displaced, without suffering any surface strain, along the *shear direction*; whereas the *plane of shear* is normal to the shearing planes and contains the shearing direction and the long and short axes of the strain ellipsoid.

The *motion* is the time-history of deformation. The *velocity* of a material particle is its instantaneous rate of change of spatial position. The tensor of *velocity gradients* describes the rate of change of deformation and can be written as the sum of two other tensors: the *stretching* (a rate of strain) and the *spin* (a rate of rigid rotation). The *kinematic vorticity number*, W, expresses the relative intensity of spin and stretching and is a fundamental feature of a flow, albeit an instantaneous one. *Simple shearing* is an instantaneous motion for which all the velocity gradients vanish except one, the *amount of shearing*, or rate of simple shear. For simple shearing, $W = 1$; for an irrotational flow (no spin), $W = 0$.

In general, a deformation history is complex and no single quantity suffices to describe it. However it is useful to consider an ideal *flow with steady kinematic vorticity number*, where reference axes are taken parallel to principal directions of stretching. Examples are progressive simple shear ($W = 1$) and coaxial stretch histories ($W = 0$). Where $W \neq 0$ but is steady, strain increments accumulate non-coaxially and in the same sense, as a result of the spin. Thus W is a measure of non-coaxiality in these flows (Means *et al.* 1980). Where $0 < W < 1$, the flow is non-pulsating; where $1 < W < \infty$, the flow is pulsating.

Two other instantaneous measures of non-coaxiality have been suggested by Elliott (1972): (1) the angle between the principal directions of stretching and of finite strain; and (2) the angular velocity, with respect to the principal direction of maximum stretch, of the material line lying instantaneously in this direction.

These measures have the virtue of being history-sensitive and time-dependent.

KINEMATIC INDICATORS: CLASSES AND USES

Different classes of kinematic indicators record different aspects of a motion. Thus we can in theory distinguish between strain indicators of various kinds, vorticity indicators, shear indicators and so on. In practice, for some indicators it is clear what they are indicating; whereas, for others, it is not yet clear.

Strain indicators (for example, grain-shape fabrics) are well known and will not be discussed here.

The best *vorticity indicators* are probably resistant objects, especially round or equant ones, which spin with the enclosing matrix, while suffering little or no strain. Relative rotation between object and matrix is recorded by intrusion trails (for example, in 'snowball' garnets), pressure shadows, or tails (for example, porphyroblasts or boudins). Because they are resistant, such objects have the advantages of being long-lived and producing a continual recording of the vorticity, while not contributing actively to the bulk motion of the matrix.

Shear indicators include slip surfaces of various kinds, crystallographic slip systems, shear zones and shear bands. Such structures can of course occur individually, at a given local scale, in which case they cannot have a more regional significance. More commonly, however, they occur as sets of parallel surfaces throughout a given domain. At the domainal scale, they may share a common slip or shear direction, forming a slip system (or shear system). They then contribute a component of progressive simple shear to the deformation history of the domain. Thus they are not only shear indicators, but a *mechanism* of progressive simple shear. In some instances, their contribution may account for practically all of the deformation history in a given domain.

There are some geological situations (for example, fault gouges) where the deformation history at some local scale is *known* to be nearly a progressive simple shear, but where the sense or amount of shear are unknown. Shear sense indicators have been frequently described; but indicators of the amount of shear (or slip) seem to be less common or have received less attention, so far.

REASONS WHY SHEAR ZONES AND FAULTS ARE COMMON

Two phenomena, one mechanical and one kinematic, appear to be sufficient (and may even be necessary) to account for the frequent geological occurrence of shear zones and faults. The mechanical reason is deformation softening. By this we mean that further deformation becomes easier in those material positions where it has most accumulated, producing a runaway instability. For convenience, we distinguish *penetrative softening*, in areas of continuous deformation from *slip softening*, on slip surfaces. To measure how much deformation has accumulated, we may use strain intensity or perhaps an amount of shear in areas of continuous deformation; the offset of material lines, across slip surfaces.

Deformation softening thus defined cannot explain why deformation is concentrated in the form of shear zones or faults. There is an additional kinematic reason: material continuity. If an ideal band of large strain is in *coherent* contact with adjacent areas of no strain and if there are no volume changes, the deformation in the band is a simple shear with reference to axes parallel and normal to the band (Ramsay & Graham 1970). Furthermore, if the band persists materially as strain intensifies, the local deformation history is a progressive simple shear (Cobbold 1977a). This can occur under uniform shear stress, as a result of penetrative softening (e.g. Bowden 1970, Poirier 1980). Indeed softening has been proved to be necessary, under rather general conditions, for an ideal band (Cobbold 1977b). In the limit where a shear band has vanishing thickness, it becomes a slip surface and the condition of coherence between band and matrix is irrelevant; whereas the condition of no volume loss implies a continuity of normal displacements across the slip surface.

In both numerical experiments (Priour 1985) and experiments on real materials, conditions of strong penetrative softening and of no volume change invariably result in the formation of shear bands (or shear zones). Similarly, slip softening is known to occur in granular materials, as a result of dilatancy (Mandl *et al.* 1977).

SLIP SYSTEM DISTRIBUTIONS AND REGIONAL KINEMATICS

Although some deformed regions contain only a single set of parallel faults or shear bands, forming a single slip system, other regions contain two or more sets, with differing orientations. If each slip system contributes a component of progressive simple shear, the regional deformation history is a combination of these simple shears. In general, this combination is not itself a progressive simple shear. For example, with conjugate sets that are equally active, the regional history may be one of bulk coaxial stretching (pure strain); whereas, if one set dominates over the other, the history may be one of non-pulsating flow, with kinematic vorticity number between 0 and 1. The exact nature of the regional kinematics depends upon how the slip systems are distributed, as well as on their relative activities. For the slip systems to function independently, they cannot in general cross-cut one another (Oertel 1965) although there is one important exception, that of lattice slip systems. A domainal distribution avoids problems of interference between different slip systems and this may be one reason why domainal distributions are relatively common (Cobbold & Gapais 1987).

If a given distribution of slip systems results in a velocity field with a certain bulk kinematic vorticity number, it is reasonable to ask if the opposite is true. Is the history of boundary displacements an important factor in governing the distributions and relative activities of various slip systems? Experiments with granular materials (e.g. Hoeppener *et al.* 1969) seem to suggest that the answer is yes, and that this is an important subject for future research.

Meanwhile, it is clearly prudent to determine shear criteria at a local scale, then to approach the regional kinematics by sampling at close intervals, so as to be able to detect variations and integrate them accordingly.

CONTENTS OF THE SPECIAL ISSUE

The Special Issue is in five sections.

The first section deals with regional aspects, including a general paper on symmetry and bulk motion, and others describing the use of kinematic indicators at various crustal levels. Of special interest are deep and shallow levels, where indicators have seldom been described until now.

The second section deals with the particular problem of determining the sense of slip or shear on individual fault surfaces, or within narrow zones of fault gouge. Both natural and experimental criteria are described and most of these are new.

The remaining three sections describe specific kinds of kinematic indicators: patterns of faults or shear zones, pressure shadows and porphyroblasts, and petrofabrics. Of these three kinds, the first have seldom been used before, and the latter sections contain new mathematical and computer models, as well as new experimental data of special interest.

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SHEAR CRITERIA IN ROCKS

Section I:

Regional studies at various crustal levels