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The corrugation and bifurcation of fault surfaces by cross-slip

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Abstract—The formation of corrugated and stepped fault surfaces by conservative shear is discussed. It is suggested that fault boundaries which lie parallel to the direction of shear are able to deviate from a plane as a fault spreads, like dislocations that cross-slip in a crystal. It is explained how deviations from planar shear can bifurcate fault surfaces and create en-échelon faults. The residual stresses produced by such deviations are tensions and compressions in the direction of shear.

INTRODUCTION

PLANAR BOUNDARIES of fault surfaces have often been modelled with dislocations (Chinnery 1966, Eshelby 1973, Savage 1980, Williams & Chapman 1983), and an analogy between curved fault boundaries (called tip lines in the case of thrust faults) and dislocations has also been drawn (Boyer & Elliott 1982, Diegel 1986).

In most quantitative models the dislocations are assumed to lie on a plane. The planar loops (Chinnery 1966, Farrell 1984) and pile-ups (Teisseyre 1970, Wojtal & Mitra 1986) that have been used in models are typical of the 'slip-zone' model of plastic shear in crystals (Seeger 1958). In this early model, shear failure starts at a point and is assumed to spread over a plane to form a slip-zone with a simple shape, for example a circle, rectangle or polygon.

A more sophisticated three-dimensional model has been discussed by Boyer & Elliott (1982), who treated the geometry of thrust faults bounded by tip lines (dislocations), on curved surfaces. They describe how these surfaces can divide and rejoin along branch lines. In the majority of cases discussed by Boyer & Elliott (1982) the fault surface is corrugated in a direction parallel to the earth's surface and perpendicular to the thrust direction. Such corrugations are possible because the earth's surface may be displaced vertically by thrust faulting. In dislocation terms the tip lines that are parallel to the corrugations (edge dislocations) can be said to move non-conservatively (i.e. climb is involved) as the fault spreads on a curved surface.

The purpose of this note is to describe how fault surfaces may become corrugated along a line *parallel* to the direction of shear, because of a fundamental property of shear—namely, its propensity to deviate conservatively (i.e. without climb) from a plane as it spreads. In crystals such deviations are common when screw dislocations cross-slip, and lead to a phenomenon called pencil glide.

It is also explained how cross-slip can cause fault surfaces to become bifurcated, as in a possible fault geometry described by Segall & Pollard (1980). Such bifurcations, produced by cross-slip, create en-échelon faults that hinder further shear. Residual stresses are produced which are predominantly tensions and compressions in the direction of shear.

CROSS-SLIP AND THE SPREADING OF SHEAR

Real materials, like rock or dislocated crystals, vary in strength from place to place. As a fault spreads, its boundary must often meet regions that resist shear. The slip front should then follow a path of least resistance as shear continues to spread, like an expanding dislocation loop that meets an obstacle.

Dislocations are able to execute two basic manoeuvres when obstacles are encountered. First, they can bend around the obstacle, leaving a region of stressed but plastically unstrained material. This manoeuvre allows planar slip to percolate through a heterogeneous material (Kocks 1985). When the unsheared region is left behind as an island, it is surrounded by an Orowan loop of dislocation, as shown in Fig. 1.

Orowan loops are observed only in metals where glide is strictly confined to a plane by a low stacking-fault energy. More often, near obstacles, glide deviates from a plane by means of a second basic manoeuvre, cross-slip.

When a dislocation line is parallel to the direction of shear (in screw orientation) it is able in principle to glide in any plane that contains this direction. The transfer of a screw dislocation from one plane to another is called cross-slip. Cross-slip is a conservative process, in the sense that it requires no addition or removal of matter as the dislocation glides. In contrast, when dislocation segments that lie perpendicular to the shear direction (edge dislocations) deviate from a plane, matter must be added or removed to accommodate glide, which is then called non-conservative.

In crystals, cross-slip may be restricted for two reasons. First, glide occurs only on crystallographic planes that intersect at large angles (70.5° in face-centred

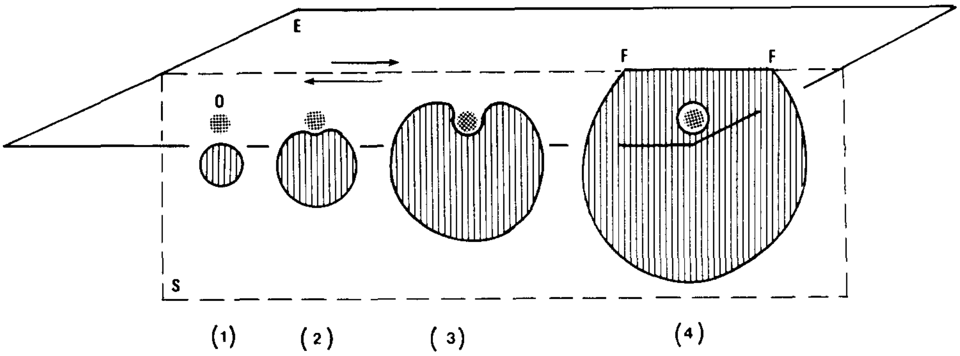

Fig. 1. Stages (1–4) in the spread of shear (hatched region) over a vertically dipping strike–slip fault plane (S). Shear percolates past a region (O) that resists shear. In (4) this region is surrounded by an 'Orowan loop', and a fault FF has outcropped on the earth's surface, E.

cubic crystals; 90° in body-centred cubic crystals or those with the rocksalt structure). Conditions are often such that there is insufficient applied stress to drive slip on steeply inclined planes. Only brief deviations from a plane are then possible, driven by internal stresses. The second restriction on cross-slip in crystals is due to the shape of dislocations. In face centred cubic metals, dislocations are ribbons flattened on the glide plane. This restricts cross-slip.

Fault displacements are large enough for the microscopic crystallinity of the rock to be ignored, and with it, the above restrictions. It is therefore suggested that in rock, segments of a slip front which are parallel to the direction of shear are able to deviate easily and continuously from a plane to avoid regions that are hard to shear, as shown in Fig. 2.

In metals, frequent cross-slip can corrugate the glide plane, and stepped or wavy slip traces are produced on the surface (Fig. 3). It is suggested that the geological analogue of dislocation cross-slip (which we shall also call cross-slip) corrugates and striates fault surfaces in a direction parallel to the shear, in a similar manner, and that this occurs on all scales.

The fact that dislocations are able to cross-slip only where they are in screw orientation, parallel to the direction of shear, has important consequences. It produces steps on the corrugations, that can hinder further shear. Consider the situation where only part of a dislocation (or slip front) is held up by an obstacle. This situation must be common because obstacles are finite. The slip front then follows a path of least resistance by a combination of percolation and cross-slip (Fig. 4). That part of the slip front not in screw orientation continues to spread on the original surface of shear. It cannot cross-slip. The screw segment cross-slips to avoid the obstacle. The result is that the slip surface becomes bifurcated, and a cusp develops in the slip front.

Beyond a bifurcation in the slip surface, shear can continue to spread on two surfaces. However, it is known from dislocation theory (Hirth & Lothe 1982) that the internal stresses around the spreading slip fronts hinder their crossing behind the cusp (A, Fig. 4), and that they can trap each other along a line roughly at right angles to the direction of shear. In crystals this sessile configuration is often observed. It is called a dislocation dipole. The details of dipole formation by cross-slip were first described by Johnston & Gilman (1960). On faults the analogues of dislocation dipoles should be common. They should consist of fault boundaries on neighbouring planes, trapped along a line perpendicular to the direction of shear, like the dipoles observed by Fourie & Murphy (1962).

On strike–slip faults the places where 'dipoles' reach the surface will mark the ends of en-échelon fault segments (Fig. 4). Each en-échelon segment of such a fault may be an outcrop of a single multiply-connected fault surface, as in a model sketched by Segall & Pollard (1980).

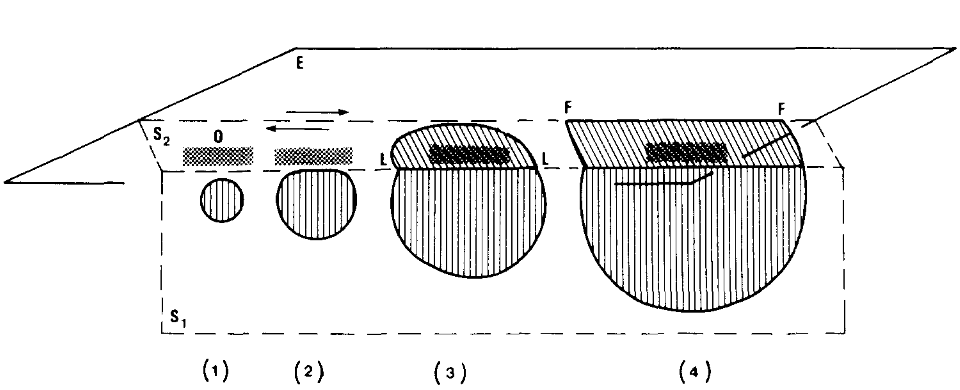

Fig. 2. As Fig. 1, but shear avoids an obstacle O by transferring from plane S_1 to a second plane S_2 parallel to the shear direction. The transfer by cross-slip occurs along a line LL parallel to the direction of shear.

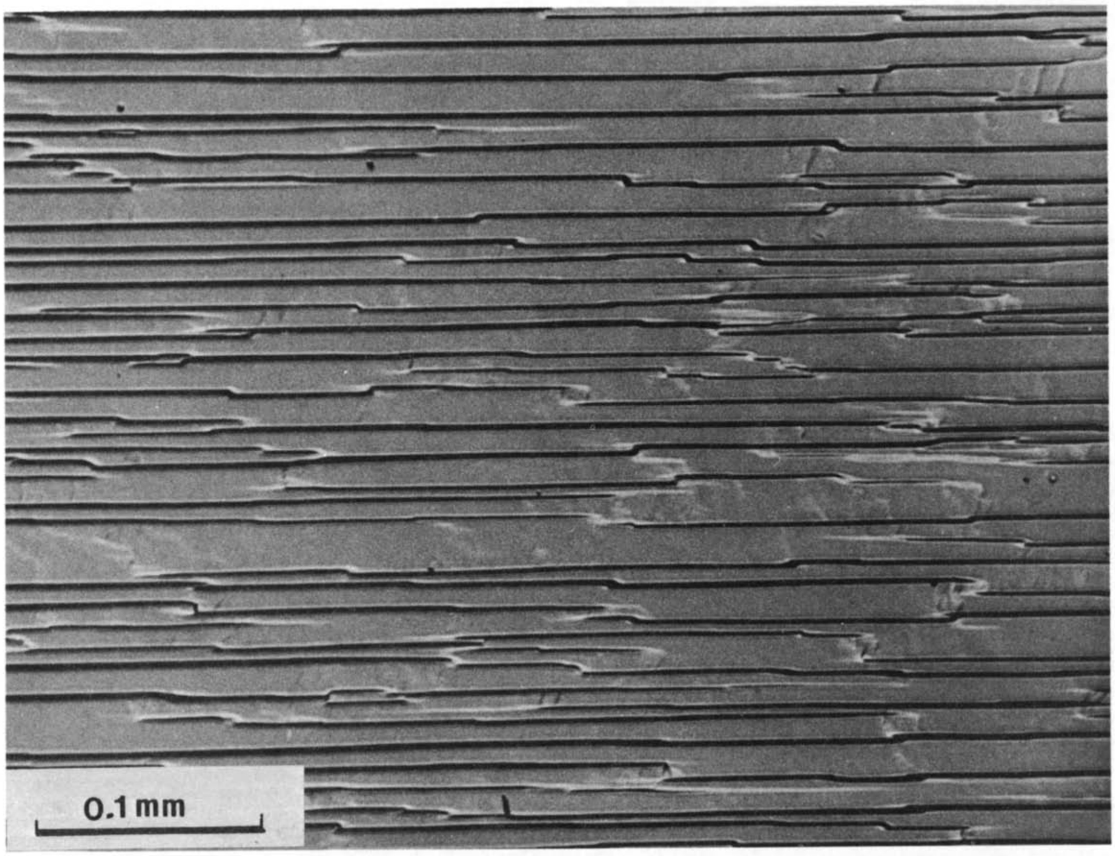

Fig. 3. Stepped slip traces produced by cross-slip on the surface of a plastically deformed aluminium single crystal. The direction of shear in this case is inclined at 50° to the crystal surface, so that the corrugations running parallel to the direction of shear are visible. This pattern is typical of slip in crystals.

The residual stresses that develop along dipoles which trail from cusps in a bifurcated slip surface are predominantly tensions and compressions in the direction of shear. The dipoles are essentially releasing and restraining 'steps' in the fault surface, like the dilational and antidilational jogs discussed by Sibson (1986). The stresses can be calculated from dislocation theory, if the two slip fronts are modelled as overlapping groups of dislocations of opposite sign (de Lange *et al.* 1980). Such stresses have been found in crystals sheared on a single glide system (Willke 1972).

DISCUSSION

The main conclusions of this paper are (i) that because cross-slip is an intrinsic feature of shear in a solid, it should corrugate fault surfaces, and (ii) that fault surfaces may, on a range of scales, be interconnected and bifurcated, like glide surfaces in crystals.

At present it is difficult to establish whether fault surfaces on a large scale are bifurcated and interconnected as suggested in the present article. The surfaces of interest are generally buried and inaccessible, and apart from the well-known existence of en-échelon faulting, fault mapping is not useful in this context. The seismological evidence (e.g. Bakun *et al.* 1980) suggests that the details of fault geometry that can be mapped on the surface extend to depths of 5–8 km, so that if bifurcations exist below en-échelon arrays, they may be deeply buried.

On a smaller scale there is some evidence for the features that cross-slip produces. On slickensides (Hobbs *et al.* 1976) and exposed sections of fault surfaces (Etchecopar *et al.* 1981) corrugations and steps are prominent. Many of these features must be produced by the dragging and scouring of fault gouge, but some may have been produced by cross-slip. It has been noted that in some cases the length of the striations exceeds the fault displacement (Hobbs *et al.* 1976). This is expected in the present model, because the length of corrugations produced by cross-slip depends on the length of the slip front that cross-slips coherently, and not on the fault displacement.

The internally stressed dipoles or steps produced by cross-slip should run roughly at right angles to the direction of shear, like dipoles in crystals. Their internal stresses may weaken rock, so that the steps could form surfaces of easy parting, like those that are observed on slickensides (Hobbs *et al.* 1976) and deformed rock (Paterson 1958).

Sibson (1986) has suggested that dilational and antidilational jogs in strike–slip faults may exert major controls on the starting and stopping of earthquake ruptures. These jogs are geometrically identical to the dipoles produced by cross-slip, as described here, and

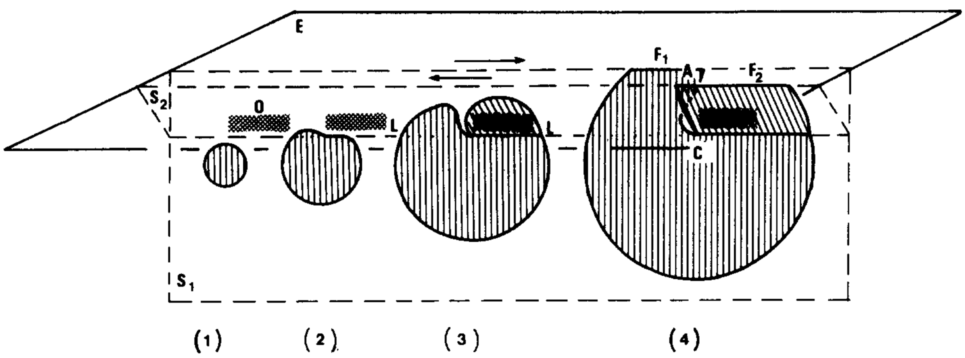

Fig. 4. As Figs. 1 and 2, but the obstacle O is avoided by a combination of percolation and cross-slip along LL. A cusp forms at C (4) and there is an outcrop of two en-échelon faults (F_1 and F_2). Along AC there is a dipole, or step, in the bifurcated slip surface. In rock a dipole should be less regular than in a crystal, because movement of the slip front in rock will be irreversible whereas in a crystal line tension can straighten a dislocation.

cross-slip may therefore provide a mechanism for the origin of such asperities on fault surfaces.

Perhaps the most important deduction to be made from this model of fault spreading is that the predominant stresses along a fault zone which consists of many en-échelon strike–slip faults are likely to be tensions and compressions along the strike direction.

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