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Dilation and linkage of echelon cracks

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Abstract—We investigate arrays of echelon cracks in rock (veins, joints, and dikes) formed by dilation. Individual cracks are interpreted as cross-sections of blade-like cracks at the leading edges of a parent fracture. Two morphological end members are distinguished as having straight or highly curved propagation paths as seen in such cross-sections. Bridges of rock between overlapping straight crack paths bend to accommodate crack dilation. Sigmoidal curvature of the bridges is achieved in a phase of increased dilation as the aspect ratio of bridges increases and their resistance to bending drops. Large bending strains within bridges may lead to cross fractures that link adjacent cracks. Good estimates of the dilation and shear displacement over arrays may be obtained directly from measurements of bridges. In contrast, the sigmoidal form of cracks of the other end member is caused by their curving propagation paths. These cracks may link as one crack tip intersects the adjacent crack wall. Some arrays of sigmoidal echelon cracks are associated with shear zones, but those analyzed here are not.

INTRODUCTION

ARRAYS of echelon cracks in rock occur at length scales of centimeters to kilometers; they grow in a variety of geological environments; and they have been invaded by fluids of various compositions, from magmatic to hydrothermal (e.g. Beach 1977, Delaney & Pollard 1981, Segall & Pollard 1983). The geological structures formed by these crack arrays include veins, joints and dikes. Such cracks are attractive subjects for structural analysis wherein the crack geometry is used to infer the state of deformation (Ramsay & Huber 1983) or the state of stress (Pollard *et al.* 1982, Rickard & Rixon 1983) in the surrounding rock at the time of cracking.

The echelon cracks of some arrays have distinctive sigmoidal shapes in cross-section and have been described as arranged within zones of large shear strain (Shainin 1950, fig. 8, Ramsay & Graham 1970, pp. 801–803, Durney & Ramsay 1973, fig. 15). The states of strain in the host-rock included within arrays (the bridges of this account) have, however, received little or no attention. Close examination of some natural examples (e.g. Ramsay & Graham 1970, fig. 10) seems to show that the strong deformation fabrics implied by the hypothesis of large shear strain are not necessarily developed in arrays of sigmoidal cracks.

Beach (1975, p. 246) distinguished two genetic types of these sigmoidal cracks. Type 1 cracks nucleate and grow within an established shear zone. Thus, the shear zone serves to localize the array, and cracks develop sigmoidal shapes because of their progressive rotation out of the favored propagation direction. Type 2 cracks nucleate in planar arrays by some undisclosed mechanism and then propagate along straight paths into an echelon configuration. This crack array weakens the rock mass so that a shear zone might localize later along the array and distort the cracks into a sigmoidal shape. Beach (1975, p. 263) concluded that type 1 cracks originate as shear fractures and type 2 as tensile fractures. Rickard & Rixon (1983) argued that type 1 cracks are tensile fractures, that is, they develop perpendicular to the least compressive principal stress.

The echelon cracks with which we are concerned do not owe their sigmoidal shape to large shear strain but to dilation. For these cracks dilation is driven by extension of the rock mass and/or fluid pressure acting on the crack walls (Farmin 1941, Pollard *et al.* 1975, Beach 1975, 1977, Price in Fyfe *et al.* 1978). The mechanism of formation of these dilatant echelon cracks has been analyzed recently by Pollard *et al.* (1982): they propagate from the margin of a larger parent crack, twist out of the plane of the parent, and present an echelon geometry in cross section (Lutton 1971, fig. 2, Kulander *et al.* 1979). The parent crack is the structure that serves to localize the echelon array. Both the parent and the echelon cracks are tensile fractures in that they develop perpendicular to the least compressive principal stress. This stress changes orientation spatially or temporally to account for the twist of the echelon cracks (Delaney & Pollard 1981, fig. 29).

We will not consider, except in passing remarks, crack arrays supposedly associated with shear zones. In any event, assessment of their status is made difficult through lack of data on deformation fabrics in the host-rock involved in them. Rather, it is the aim of this paper to emphasize the morphology of dilatant echelon cracks in

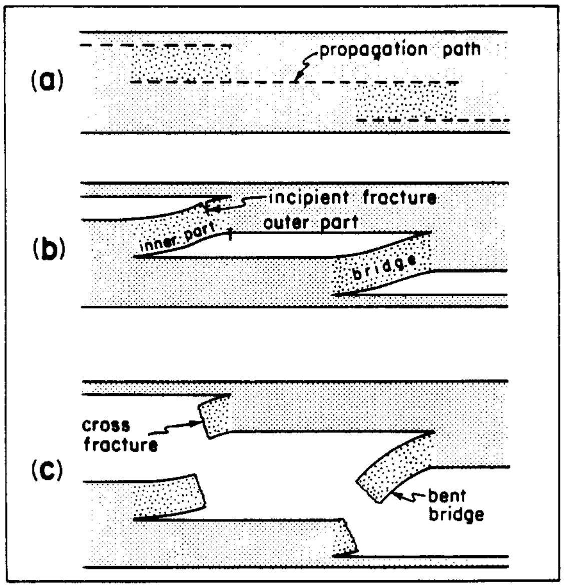

Fig. 1. Schematic illustration of echelon cracks that grow along a straight propagation path. Pattern identifies rock that is part of the bridge separating adjacent cracks. (a) Before cracking: dashed line indicates propagation path. (b) After propagation: some dilation is accommodated by bending of bridges. Crack walls are divided into a curved inner part and a rectilinear outer part. (c) After failure of bridges along cross fractures: crack linkage causes a considerable increase in dilation.

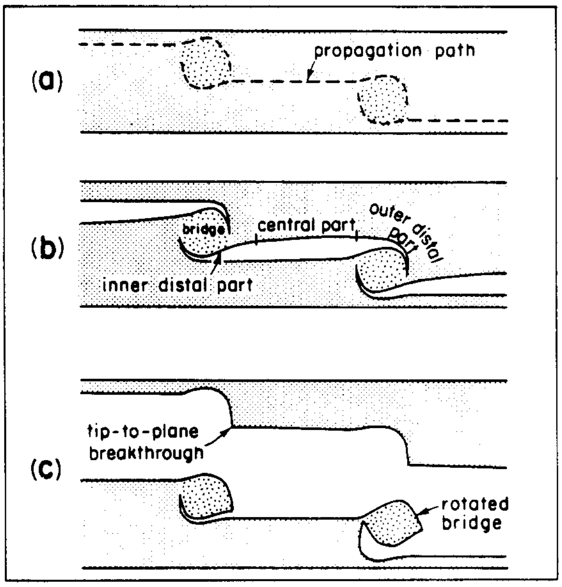

Fig. 2. Schematic illustration of echelon cracks that grow along curved propagation paths. Pattern identifies rock that is part of the bridge separating adjacent cracks. (a) Before cracking: dashed line indicates propagation path. (b) After propagation: some dilation is accommodated by rotation of bridges. Crack walls are divided into two curved distal parts and one rectilinear central part. (c) After linkage by crack-tip to crack-plane intersection: dilation increases considerably.

cross-section as determined by crack propagation path (Figs. 1a and 2a). The volume of rock between the overlapping ends of cracks is bounded by these paths and is of particular interest. The deformation of this rock volume will be characterized and its role in crack dilation and linkage will be analyzed. We will discuss possible inferences regarding the state of deformation and stress associated with these cracks.

MORPHOLOGY OF ECHELON ARRAYS

Arrays of dilatant echelon cracks may be arranged into a morphological spectrum based upon the geometric form of their propagation paths as seen in cross-section. The two end members are distinguished as having straight (Fig. 1a) or highly curved (Fig. 2a) paths. Lesser degrees of curvature identify intermediate members in this spectrum. The curvature is a result of mechanical interaction between adjacent crack tips (Pollard *et al.* 1982). The local stress field induced at one tip alters the field at the adjacent tip such that the next increment of crack growth is not parallel to the preceding increment. The resulting curvature of path is most pronounced if the rock properties and ambient stress are isotropic. A well-developed planar fabric or a bias in the ambient principal stress magnitudes (notably a large compression parallel to the cracks) can negate the mechanical interaction of the crack tips and guide the cracks along straight paths that are parallel to the fabric or to the maximum compressive stress. The quantitative details of these competing effects are under investigation and will be reported in future papers. In this section we describe the two end members, give some geological examples, and offer a qualitative interpretation of their origins.

Straight propagation paths

These cracks propagate along straight paths (Fig. 1a) and dilate into distinctive shapes in cross section (Fig. 1b). The dilated cracks are usefully described as having two walls, each of which may be divided into two parts. One part, the outer, is approximately rectilinear and bounds the edge of the array. The inner part is curved; it joins one side of the array edge to the other; and it parallels the similarly curving part of the neighboring crack wall. The curving inner walls have rotated relative to the host and to the propagation path. These curved parts bound bridges (called straps by Farmin 1941), curved slabs of rock that separate one crack from its two neighbors in the echelon array (Delaney & Pollard 1981, fig. 4).

Figure 3 is used directly to establish the geometry of crack arrays that display very little curvature of the inner parts of the crack wall. This will be the case if dilation is much less than overlap, that is, $\delta \ll o$. We define

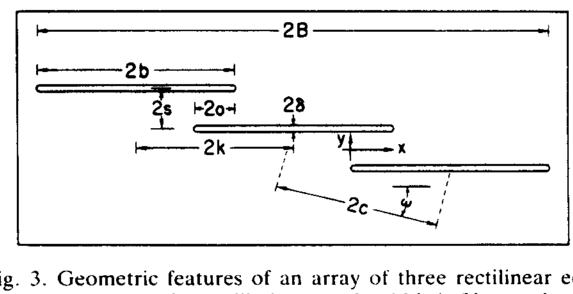

Fig. 3. Geometric features of an array of three rectilinear echelon cracks before significant dilation: crack width is $2b$; overlap is $2o$; separation is $2s$; dilation is 2δ; center spacing measured parallel to cracks is $2k$; center spacing measured parallel to array is $2c$; twist angle is ω; array width is $2B$. Coordinate system x,y has origin on the middle surface between overlapped cracks.

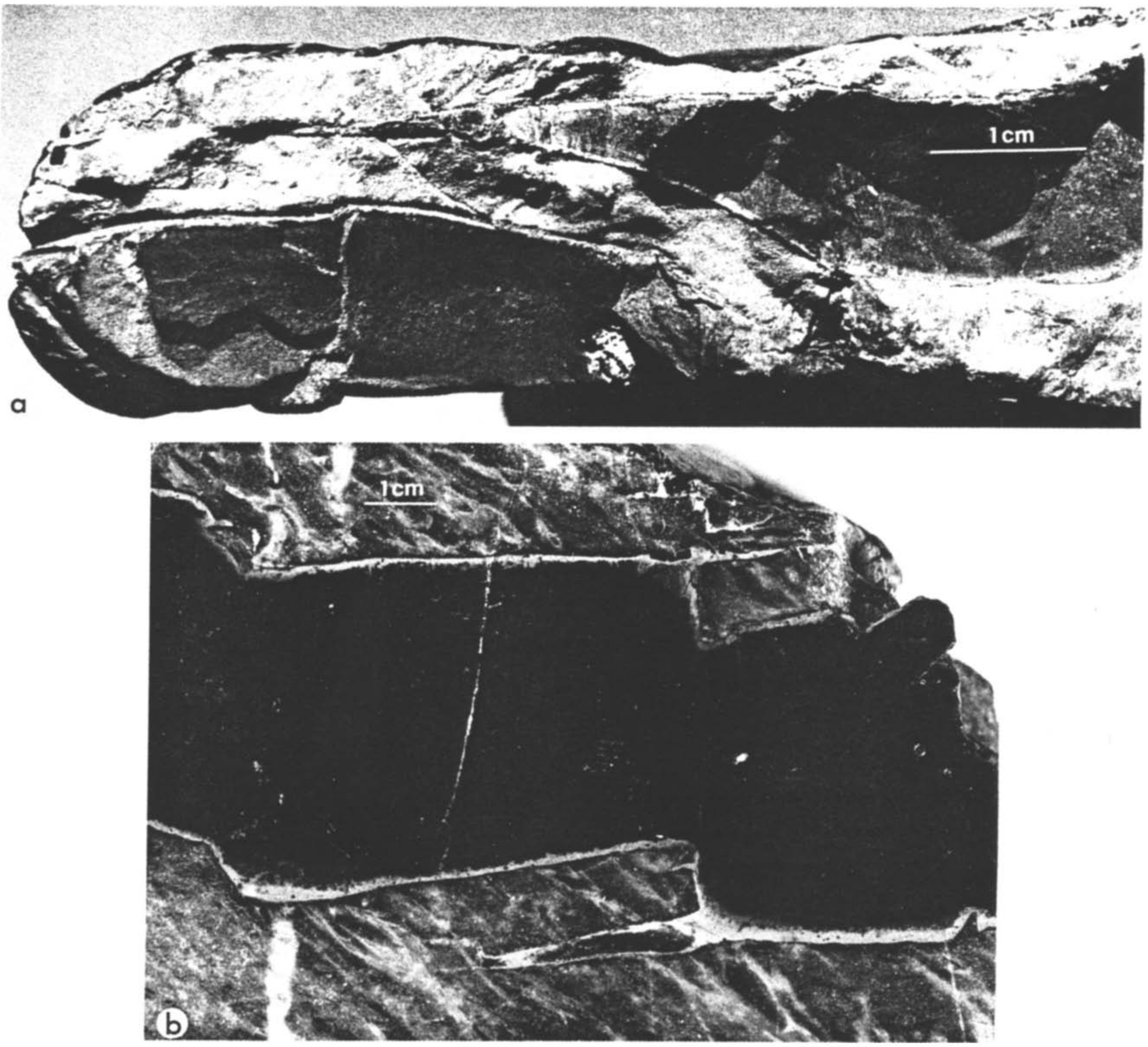

Fig. 4. Basaltic dike segments in carbonates of Durness Formation specimens from the shore of Loch Slapin, Isle of Skye, Scotland. (a) Two echelon segments with straight outer parts and curved inner parts of the crack wall. The bridge between them is almost cut by a cross-fracture. (b) A basaltic dike with matching steps in its wall, each with a projecting off-shoot at its outer corner.

dilation, δ, as the opening displacement at the crack center. Even if curvature of the inner parts is great, we suggest that outer rectilinear parts have retained, approximately, their geometric relation to the host-rock. It is the outer parts that should be used to determine the propagation path and the twist angle, ω, of the echelon cracks relative to the array and to the parent crack. In earlier accounts the average inclination of sigmoidal quartz-filled cracks has been used (Roering 1968, p. 109), or the center-line of the biconvex lens used to model them (Hancock 1972, fig. 1).

Where outer parts of walls are straight, the curvature of the inner parts arises primarily by bending of the bridge as cracks dilate (Farmin 1941). The rock slabs that become the bridges between cracks were rectangular before they began to bend (Fig. 1a). After bending (Fig. 1b) longitudinal strains, ϵ_x, are proportional to distance from the middle surface of the bridge, $y = 0$, and inversely proportional to the radius of curvature, ρ, such that

$$\epsilon_x = y/\rho \tag{1}$$

(Fig. 3) (Johnson 1970, p. 55). Near the top and bottom surface of the bridge ϵ_x may be large. However, the middle surface should behave much as the neutral surface of a bending plate or beam. Thus both crack width, b, and center spacing, k, may be measured by incorporating the arc length of the middle surface. The antisymmetric distribution of longitudinal strain defined by equation (1) results in extension on one side and an equal contraction on the other side of the middle surface. This should produce a negligible strain across the bridge so crack separation, s, may be measured perpendicular to the middle surface.

Two important ratios may be calculated using the measurements described above. The first is the bridge aspect ratio, R_a, defined as

$$R_a = (b - k)/s, \quad b > k. \tag{2}$$

The condition $b > k$ assures that neighboring crack tips have overlapped to create a bridge. The second ratio is the relative lengths of the rectilinear and curved parts of crack walls, or the crack-tip overlap ratio, R_0. This is defined as

$$R_o = (b - k)/k, \quad b > 0. \tag{3}$$

The condition $b > 0$ assures that the cracks have some finite length. Negative values of R_o signify that cracks underlap their neighbors.

A natural example of an echelon array in which cracks followed straight paths is illustrated in Fig. 4. The aspect ratio for bridges and the overlap ratio for cracks varies considerably among natural arrays. These geometric variations lead to cross-sectional forms of cracks that might not, at first glance, be classified in the same family. For example, compare the dike segments of Fig. 4 with those mapped by Delaney & Pollard (1981, plate 1) and with the veins pictured by Beach (1977, fig. 5A). Upon reflection it is clear that all of these arrays share the fundamental geometric elements described above. We

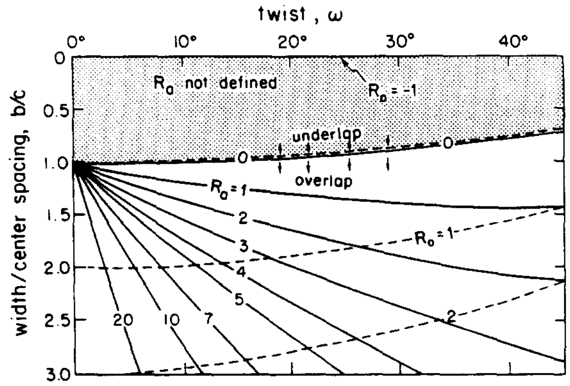

Fig. 5. Graph of crack width normalized by center spacing, b/c plotted vs twist angle, ω. Solid curves are for constant bridge aspect ratio, R_a. Dashed curves are for constant crack overlap ratio, R_o. See equations (2)–(4) and accompanying text for details.

suggest that these arrays shared a common mechanical origin that depended upon growth along nearly straight propagation paths accompanied by crack dilation.

The bridge aspect ratio, R_a, and crack-tip overlap ratio, R_o, for cracks with rectilinear outer walls may be used as parameters to plot curves on a graph of twist, ω, vs the ratio b/c (Fig. 5), where b/c is a measure of crack width to center spacing. Curves of constant aspect ratio converge on 0° of twist and $b/c = 1$; curves of constant overlap ratio converge on 90° twist and $b/c = 0$. These curves are congruent for $R_a = 0 = R_o$ and define the boundary between cracks that underlap and those that overlap. This is also the limit beyond which R_a is not defined. Beach (1975, p. 255) plotted the ratio overlap to crack length, $(b - k)/b$, against twist for quartz-filled veins from SW England, showing how overlap increases with twist.

Given values of aspect ratio are associated with greater overlap ratios as greater angles of twist are considered (Fig. 5). The relationship is

$$R_o = R_a \tan \omega. \tag{4}$$

A greater overlap ratio indicates an increase in the extent to which the dilation of one crack opposes that of its neighbors. Similarly for a given overlap ratio, smaller aspect ratios are associated with greater twist angles (Fig. 5). A smaller bridge aspect ratio indicates a greater resistance to the bending of bridges. These relations express constraints involved in the observation that few echelon cracks of this kind have angles of twist greater than about 45°. They may be summarized by describing arrays of higher twist angle as 'stiffer' with respect to dilation where this stiffness is a direct result of the smaller aspect ratio of bridges.

Curved propagation paths

These cracks propagate along curved paths (Fig. 2a) and dilate into distinctive shapes in cross-section (Fig. 2b). The dilated cracks at this end of the morphological spectrum may be described as having two walls, each of which may be divided into three parts. The central part is approximately rectilinear, but the outer and inner distal parts may be quite curved. Indeed, in extreme cases the curvature changes sign such that adjacent crack paths first diverge weakly and then converge strongly (Pollard *et al.* 1982). Two converging paths partially encircle and may nearly isolate a bridge of rock from its surroundings. We suggest that the central rectilinear part and the outer curved part of a crack wall nearly retain their geometric relation to the host rock. The inner curved part and the bridge itself may undergo considerable rotation as one crack tip approaches or breaks through the neighboring crack wall (Fig. 2c).

Curvature of the distal parts of crack walls does not arise by bending of the host rock. It is simply the curved path followed by the propagating tip of the crack. In contrast with bridges formed by straight propagation paths, these bridges do not have a rectangular shape, nor do they undergo significant bending strains. Indeed, as the adjacent crack tips isolate the bridge from the host rock, elastic strains that may have existed there before crack propagation are relieved. The curvature of the crack path may produce cracks with a sigmoidal shape in cross-section that is similar to the shape attributed to large strain within shear zones (Ramsay & Graham 1970). We reiterate the finding of Pollard *et al.* (1982) that the curved paths shown on Fig. 2 are caused by the local stresses of crack interaction and do not imply more than slight shear strain along the length of the array.

Several natural examples of echelon cracks with curved paths are illustrated in Pollard *et al.* (1982, figs. 13 and 14), and Escher *et al.* (1976, fig. 4) describe some very convincing examples of sheet intrusions with these rounded bridges. It is clear that the relative lengths of the rectilinear and curved parts of natural crack walls may vary. Also the magnitude of the curvature may vary from the doubly curved extreme, to singly curved, to nearly straight. We suggest that these cracks shared a mechanical origin that depended upon growth along curved propagation paths. These paths are traced by the outer walls of the cracks.

DILATION OF ECHELON ARRAYS

It has been argued above that where outer walls of cracks are straight the curvature of inner walls arose through bending of the rock bridge during crack dilation. We will demonstrate here how dilation increases as the cracks propagate laterally along a straight path, overlap one another, and bending becomes pronounced.

Consider a crack in an elastic solid that is subject to a driving pressure, $\Delta p = P - S_3$. Driving pressure is the difference between internal fluid pressure, P, and remote least compressive stress, S_3. Any positive difference ($P > S_3$) produces some dilation. The elastic shear modulus is μ and Poisson's ratio is ν. Dilation, δ, is measured as the normal displacement component at the middle of the crack. The dilation of a single isolated crack of width $2b$ is given by

$$\delta = \Delta p(1 - \nu)b/\mu \quad (5)$$

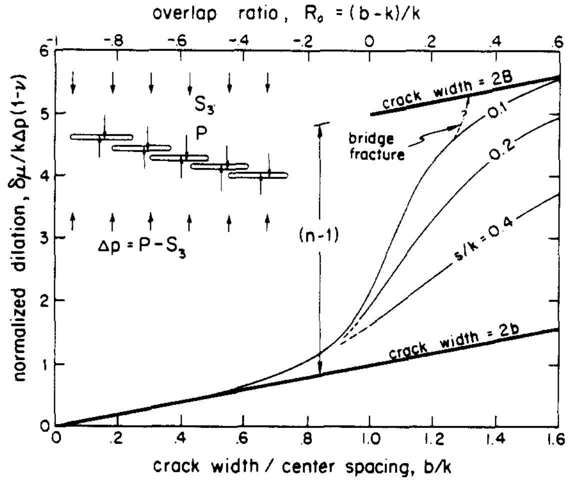

Fig. 6. Graph of normalized crack dilation plotted vs the ratio crack width to center spacing. Heavy solid curves are values of dilation for a single crack of width $2b$ (equation 5) and for a single crack of width $2B$ (equation 6). Light lines are for an array of 5 cracks with different separations. See text for details.

Pollard *et al.* (1983, equation 5). From this relation we note that dilation of the single crack increases linearly with crack width.

For several mechanically interacting cracks the increase in dilation with crack width is non-linear. To solve the elastic problem for an array of interacting cracks we follow the boundary element methods employed by Pollard *et al.* (1982) and compute the dilation for the central crack of a five-member array. To generalize our results dilation is normalized by $\delta k/b$ from equation (5) and all lengths are normalized by center spacing, k. Dilation is plotted vs crack width in Fig. 6. The lower heavy line in Fig. 6 represents the linear increase in dilation experienced by a single crack of width $2b$. The upper heavy line is dilation for a single crack of width $2B$, where

$$B = (n - 1)k + b \quad (6)$$

is the half-width of the entire array and $n = 5$ is the number of echelon cracks. The three curves on Fig. 6 represent the dilation of arrays with different separations.

For all separations the cracks behave as mechanically isolated for $b/k < 0.5$; that is, dilation follows the heavy curve for a single crack of width $2b$. As b/k increases to 1.0, dilation somewhat exceeds that for an isolated crack for all separations. As crack ends overlap, $b/k > 1.0$, cracks with very small separations, $s/k < 0.1$, experience a very rapid increase in dilation, and approach the dilation of a single crack of width $2B$ for $b/k > 1.5$. For these cases the bridges of rock have a large aspect ratio, $R_a > 5$, and therefore bend so easily that they provide little resistance to dilation. Cracks with greater separations experience a less rapid increase in dilation and for $s/k > 1.0$ the behavior remains similar to the isolated crack of width $2b$. For these greater separations the bridges offer greater resistance to bending, so dilations are less.

The transition from isolated behavior (lower heavy curve) to combined behavior (upper heavy curve) involves an increase of $(n - 1)$ in crack dilation. For small separations, $s/k = 0.1$, this transition occurs smoothly over a range of crack widths, from $0.5 < b/k < 1.5$, that corresponds to a range of bridge aspect ratios up to $R_a = 5$. Only in the upper part of this range does pronounced bending of rock bridges occur.

There is no guarantee that the transition depicted in Fig. 6 will proceed to completion. Competition among adjacent overlapping cracks for the available propagation energy inhibits lateral growth (Pollard *et al.* 1982) and accounts for the large number of bridges, frozen in place at low aspect ratios, that are preserved in outcrop. Other cracks follow curved propagation paths that preclude large bridge aspect ratios (Fig. 2). Finally, fracture of bridges or coalescence of curving cracks may provide a direct fluid connection between cracks that thereby jump immediately to a combined behavior (e.g. dashed line, Fig. 6).

CRACK LINKAGE

We identify two mechanisms for crack linkage; one operates if crack paths are straight and the other if paths are curved. For straight cracks it is the bent bridges that fail as cross-fractures form and one echelon crack connects with the next (Figs. 1b & c). In this way paired steps are formed in the margins of continuous cracks, each step with an off-shoot projecting from its outer corner (Fig. 4b) (Farmin 1941, fig. 2, Beach 1977, fig. 10). These projections, sometimes called horns or flanges, are the lateral edges of the echelon cracks. The connecting fractures cut across bridges and are not continuous with the tips of primary cracks. In contrast, for curved cracks it is the primary tip that simply propagates into the side of the adjacent crack to form the linkage (Fig. 2b & c) (Swain *et al.* 1974, fig. 3c, Escher *et al.* 1976, fig. 4). When linkage is complete for all cracks, regardless of mechanism, the array will behave as a single crack of half-width B given by equation (6). Dilation in this case is approximated by equation (5) with B substituted for b.

As bridges begin to bend, the significant strains are longitudinal extension along the convex surfaces and contraction along the concave surfaces. According to equation (1), these strains are linearly distributed across the bridge from zero at the middle to maxima at the two surfaces. They also vary along the bridge from zero at the midsection (inflection) to maxima at either end. The normal stress acting parallel to the bridge induced by bending should be proportional to these strains (Johnson 1970, p. 56). Cross fractures should initiate in the region of greatest tension near bridge ends on the convex surfaces (Fig. 4).

DISCUSSION

As already made abundantly clear, echelon arrays may constitute fringes on the margins of continuous joints (Hodgson 1961, Bankwitz 1966) or fingers on the margins of igneous sheet intrusions (Pollard *et al.* 1975, Delaney & Pollard 1981). Apart from Farmin (1941), published references to the three-dimensional shape of dilatant echelon veins are difficult to find, but we expect them to be of a similar form to joints and dikes. Wilson & Cosgrove (1982, fig. 3.1b) include a diagram showing blade-like bodies of which the sigmoidal veins are cross-sections. Only in Hancock (1972, p. 274) have we found any reference to change of vein morphology in the third dimension. Following Lutton (1971, fig. 2), we suggest that the different frames of Figs. 1 and 2 can represent either simultaneous developments in successively more proximal sections, or the successive appearances of one cross-section as it passes from a stage of smaller to greater dilation.

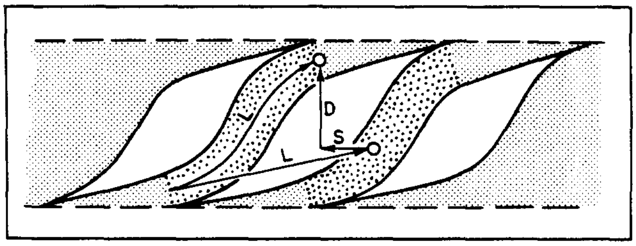

Fig. 7. Schematic illustration of technique for measuring displacement components D and S for the ends of bridges separating echelon cracks. The arc length along the middle surface of the bridge, L, is set off parallel to the outer rectilinear wall of the crack.

For cross-sections that are very close to the parent crack, the orientation of echelon cracks may not reflect the remote principal stress orientations (Pollard *et al.* 1982). In this 'breakdown zone' the local and remote directions of least compressive stress are not necessarily parallel. At greater distances from the parent crack, where echelon cracks are consistently oriented, these cracks may provide a good stress-direction indicator. In this case the central rectilinear part of the crack wall, regardless of whether the more distal part is straight or curved, should be nearly perpendicular to the remote least compressive stress.

We emphasize that the method just suggested for inferring a stress orientation from crack geometry is only qualitative. The theoretical analyses and laboratory experiments necessary to quantify such a method have not been completed. However, two things are clear from the work to date: (1) the local state of stress near echelon cracks is not spatially homogeneous and (2) this local stress state varies in time as the echelon cracks propagate laterally. We suggest that these two statements are applicable to all echelon arrays, regardless of their mechanism of formation. However, the methods used to infer stress orientation from echelon cracks in conjugate shear zones (see summary by Rickard & Rixon 1983) all assume a homogeneous and time-invariant state of stress in the zone. These methods must be viewed with some skepticism until proper analyses have been completed.

As the stretching of the middle surface of bridges of dilated arrays is believed to be slight, their present length is effectively their initial length. This length, set off parallel to the outer rectilinear wall of the sigmoidal crack, fixes the point from which the end of the bridge began its course of displacement (Fig. 7). The displacement of this point has a component normal to the array margin, D, and one parallel to the margin, S. These components are measures of the dilation and shear across the array. This shear component of displacement, of course, is different from the shear displacement obtained by assuming that such crack geometries are a response to simple shear (Ramsay & Graham 1970, pp. 801–802).

Arrays of echelon cracks with small separation undergo a dramatic increase in dilation as crack ends overlap and thin rectangular bridges begin bending. We have shown that dilation, even in the absence of cross fractures, may approach that of a single crack of width equal to the entire array, approximately an n-fold increase. When cross fractures form or curved crack tips break through to the neighboring crack, this linkage assures a great increase in dilation. Besides the accommodation of a much greater displacement, a most profound implication of this transition is the consequent change in rate of fluid transport through the array of cracks. The volumetric flow rate of a viscous fluid through a narrow slot is proportional to the cube of the slot opening (Bird *et al.* 1960, p. 62). For a constant fluid viscosity and a constant fluid pressure drop perpendicular to the cross section of the cracks, we would expect an increase by a factor of about n^3 in volumetric flow rate as adjacent cracks overlap and link.

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