Read at the Annual Conference of the Ussher Society, January 1991

A comparison between the displacement geometries of veins and normal faults at Kilve, Somerset

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Peacock, D.C.P. 1991. A comparison between the displacement geometries of veins and normal faults at Kilve, Somerset. *Proceedings of the Ussher Society, 7,* 363-367.

Well-exposed veins and normal faults are examined at Kilve, Somerset. Their geometries result from displacement variations along the lengths of segments, and from the linkage of segments. Veins have similar evolutions and displacement-distance (d-x) characteristics to normal fault segments, with bridges between overstepping veins being analogous to relay ramps between overstepping normal faults. Four evolution stages can be identified from fracture geometries and d-x characteristics. At stage 1, isolated fractures are initiated. Interaction occurs as fractures propagate towards each other, with displacement transferred by relay/bridge structures (stage 2). At stage 3, the relay/bridge starts to break down, and at stage 4 a single irregular fracture is formed by the linkage of segments. A vein array may show all four stages of fracture development. Relay ramps and bridges are responsible for a decrease in total displacement at oversteps, and allow steep d-x gradients at overstepping tips. Relay/bridge development and fracture propagation are intimately related, both influencing the displacement geometry of the overstepping tips. Bridges may be broken at various locations, with the bridge geometry being an important control on the breakage site. Overstepping fracture segments show complex slip/propagation relationships and do not fit the ideal elastic fracture model. Increased interaction between fractures tends to decrease the ratio between the maximum width and the fracture length.

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Introduction

Vein arrays and fault zones result from the displacements along, and the linkage of, component segments. Knowledge of the geometry of the component segments is, therefore, important in understanding the development of fracture zones. Existing models for the displacement geometry of normal faults (eg. Walsh and Watterson 1987) and extension fractures (eg. Pollard and Segall 1987) describe the displacement geometry of isolated fractures, but do not account for the complex displacements seen in fracture arrays. Displacements along interacting normal and strike-slip fault segments have been described by Peacock and Sanderson (1991) and Peacock (1991) respectively. Peacock and Sanderson (1991) describe a normal fault zone at Kilve (Fig. 1), which is exposed for a length of approximately 80m on a gently dipping limestone bed and which has a maximum vertical displacement of about 400mm. It consists of approximately 34 segments which show interaction and linkage effects. The aims of this paper are:

1) to compare the displacement-distance (d-x) characteristics of veins with those of normal faults, and to demonstrate the use of dx methods in the study of veins,
2) to show the analogy between the geometry and development of bridge structures and relay ramps, and
3) to describe the effects of fracture interaction on the ratio of maximum displacement (or width) to fracture length.

The term *overstepping fractures* is used to describe sub-parallel but non-coplanar fractures where the tips are in close proximity (ie. the distance between the tips is smaller than the fracture length) (Biddle and Christie-Blick 1985). *Overstep* is the distance between the tips of two related sub-parallel fractures, measured normal to the fractures. A *bridge* is the area of host rock between two overstepping veins (Fig. 2a), and *a relay ramp* (Larsen 1988) is the area of reoriented rock between two overstepping normal faults (Fig. 2b). Various types of *transfer zone* (including relay ramps) between overstepping normal faults have recently been described by Morley *et al.* (1990).

The veins studied are composed of calcite, and occur in Lower Liassic (Jurassic) limestones and mudrocks, being preferentially developed in the limestones. They are best exposed on limestone bedding planes. Some veins are of diagenetic origin, whilst others are related to extensional faults, and to later contractional and strike-slip faults. The veins studied are essentially mode I fractures, because they tend to be at a low angle to the vein array and tend to have a small overlap in relation to length, so shear is insignificant. These veins are similar to the dyke arrays described by Delaney and Pollard (1981) and Pollard and Segall (1987). Veins with significant shear (Engelder 1987; Rothery 1988) and sigmoidal tension gashes in ductile shear zones (Beach 1975; Craddock and Van Der Pluijm 1988) are not studied.

The use of displacement-distance methods in the study of veins

The displacement-distance (d-x) method (Williams and Chapman 1983; Chapman and Williams 1984) is here modified to analyse the development of overstepping veins in a similar way in which Peacock and Sanderson (1991) use the d-x method to study the

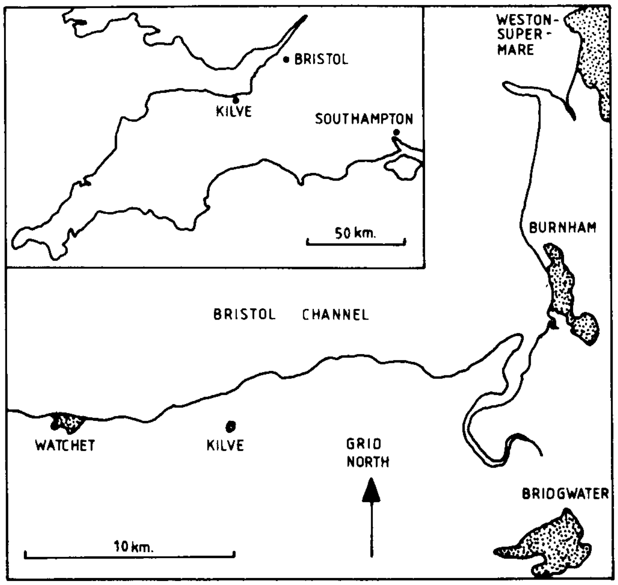

Figure 1. Map showing the location of Kilve. The structures studied are on the coast between Blue Ben (ST123439) and the pill box (ST14884458).

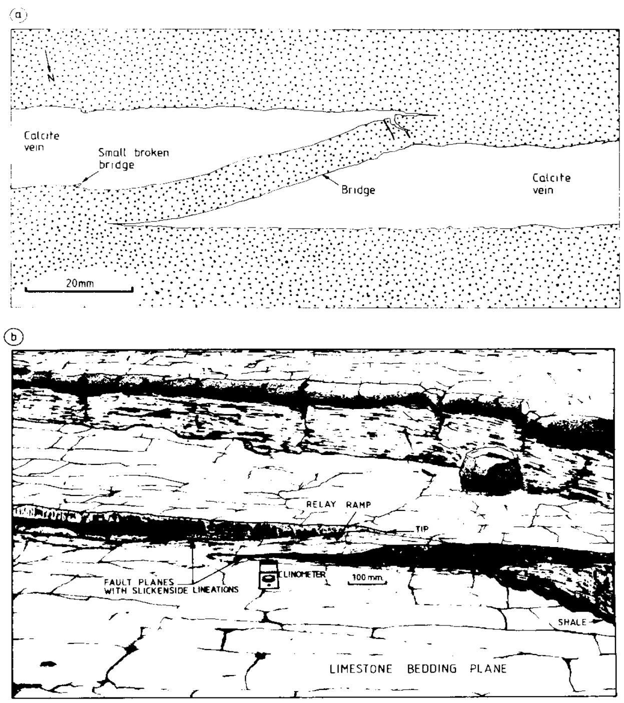

Figure 2. a) Example of two overstepping veins (ST14814458), with displacement transferred between the veins by a bridge. b) Line-drawing of overstepping normal faults (ST13644427), with displacement transferred between the faults by a relay ramp. The faults strike approximately east-west, and are viewed from the south. Relay ramps and bridges are similar because they occur at oversteps, transfer displacement between overstepping fractures, and maintain continuity between the wallrocks.

development of normal fault segments. Distance (x) is measured along the length of a fracture or an array, and displacement (d) can be measured by use of fibres and matching of wallrock structures. However, it is simpler to measure fracture width (w), normal to the x-direction, as actual displacement may involve a shear component and out of plane movement. For the veins discussed in this paper, width is approximately equal to displacement. Photographs of veins were digitised, and the data were analysed and displayed on a spreadsheet. Fig. 3 shows normalised d-x data for 20 veins at Kilve. The scatter of data is explained below by the effects of fracture interaction and linkage.

Four stages in the development of fractures

The opening displacements of veins are analogous to the shearing displacements of normal fault segments in map view. Displacement is transferred between overstepping veins by bridge structures, which are blocks of wallrock separating overstepping veins. They are analogous to relay ramps between normal faults (Peacock and Sanderson, 1991) because they occur at oversteps, maintain continuity between the wallrocks on either side of the fractures, and transfer displacement between fractures (Fig. 2). Relay ramps and the bridges described here occur normal to the displacement vector. They are different to the oversteps in map views of strikeslip faults (described by Peacock, 1991), which are parallel to the displacement vector (Peacock and Sanderson, 1991 fig. 6). It is possible to identify four stages in the development of overstepping normal faults and veins.

Stage 1: Isolated veins

Stage 1 involves the initial development of non-overlapping, non-interacting fractures. Fig. 4 shows an apparently isolated vein and the corresponding w-x profile, which has a maximum width near the centre of the fracture and width decreasing approximately linearly towards the tips. The profile is similar to the *cumulativeslip* profile of Walsh and Watterson (1987) and the

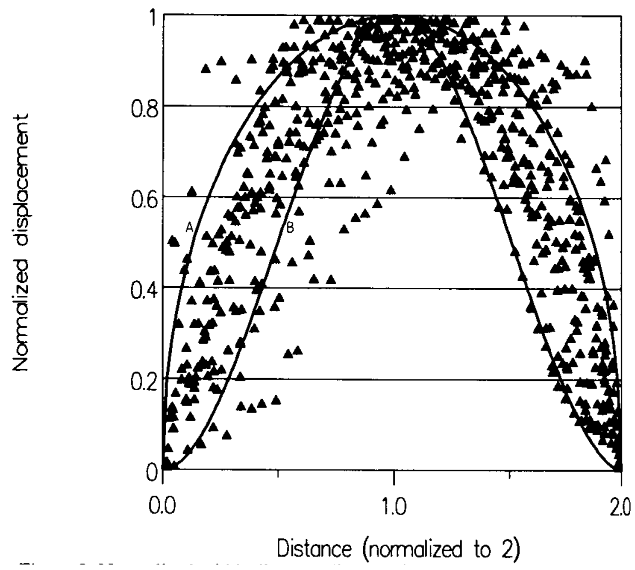

Figure 3. Normalised width-distance diagram for overstepping and linked veins, consisting of 695 data points along 20 veins. To normalise displacement, divide it by the maximum displacement. To normalise distance, measure the distance from the point of maximum displacement, then divide this by distance from the tip to the maximum displacement point. Normalising data allows comparison of different-sized structures. Profiles for the single-event elastic model (profile A) and the Walsh and Watterson (1987) cumulative slip model (profile B) are also shown. The vein data shows a considerable scatter away from the two theoretical profiles.

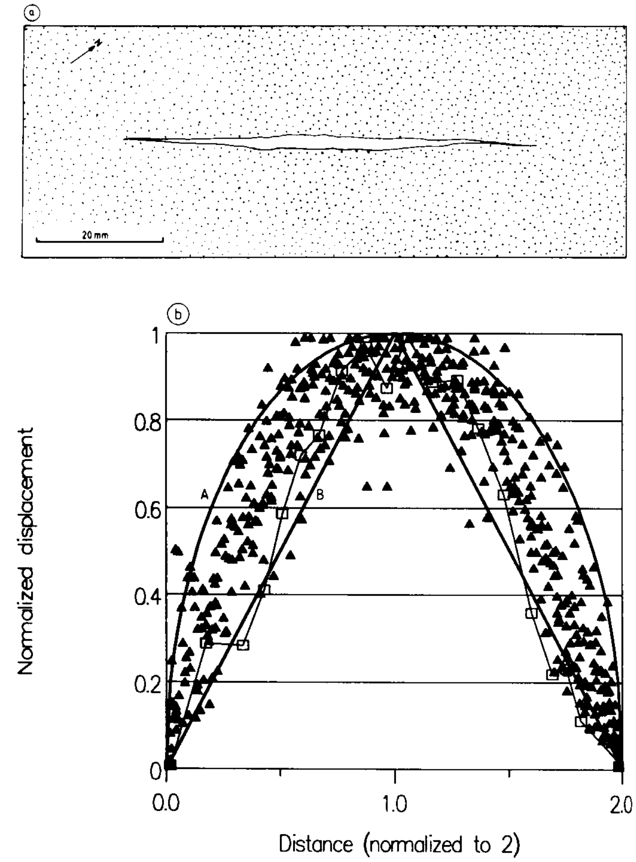

Figure 4. a) Probable isolated, non-tectonic, diagenetic vein from Kilve (ST13914426). The vein is unornamented and the country rock is stippled. b) The normalised width-distance graph for the vein in Fig. 4(a) (open squares), with data for 12 other apparently isolated calcite veins from the Jurassic limestones at Kilve (Somerset) (total number of data points = 545). The ideal elastic fracture (A) and C-type (B) profiles are also shown.

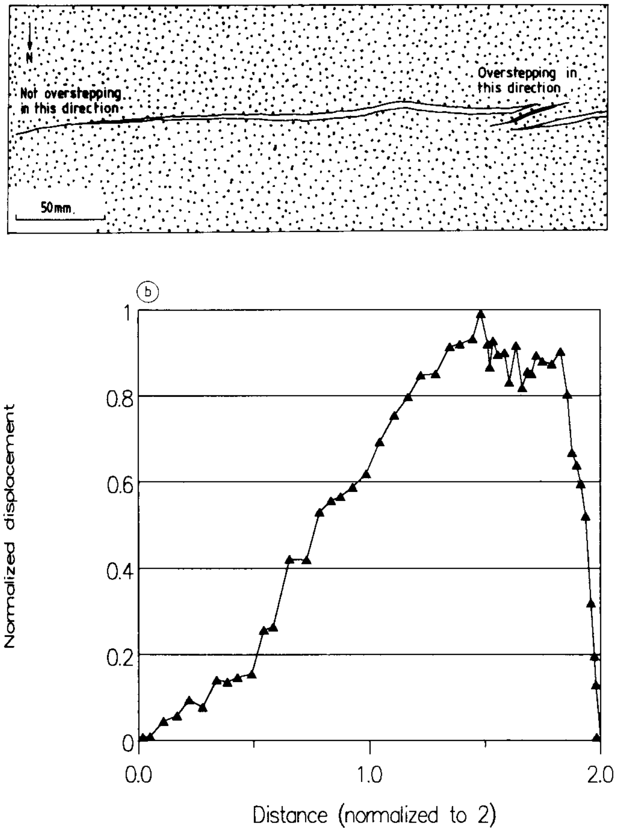

Figure 5. a) Vein segment from (Kilve ST136442), overstepping in one direction (stage 2) but not overstepping in the other direction (stage 1). The veins are unornamented and the country rock is stippled. b) The normalised width-distance profile for the vein in Fig. 5(a).

C-type profile of Muraoka and Kamata (1983) (see Peacock 1991). Fig. 4 also shows data for 12 other apparently isolated veins. The w-x profiles are usually intermediate between the ideal elastic model (Pollard and Segall 1987) and the C-type profile. In the ideal elastic model, a crack in an elastic material has an elliptical form (profile A, Fig. 3). Walsh and Watterson (1987) suggest that fault displacements result from a number of slip events. Their cumulative-slip model (profile B, Fig. 3) assumes that a propagating isolated planar fault accumulates slip increments according to the elastic model, the amount of incremental slip being proportional to fault length. These models may also apply to isolated veins. Engelder (1987) describes vein recracking, which indicates multiple displacement events. It is possible that vein length has been underestimated; if the thin tips do extend further than was measured, the profiles would be closer to the Walsh and Watterson (1987) cumulativeslip model.

Stage 2: Overstepping and interacting veins, and the effects of bridges.

Stage 2 involves the interaction of overstepping segments, with displacement transferred by bridge structures. Propagation is hindered by interaction with adjacent fractures (Pollard et al. 1982), so high w-x gradients develop at overstepping tips, leading to the development of w-x profiles which plot above the C-type profile. Fig. 5 shows a vein which is overstepping in only one direction. In the non-overstepping direction it shows a C-type profile, but in the overstepping direction the profile plots above the C-type profile. Displacement is transferred onto the adjacent vein by a bridge, and as interaction increases, plastic strain becomes increasingly localised at the bridge. As with the d-x profiles of fault segments (Peacock 1990; Peacock and Sanderson, 1991; Peacock, 1991), it is possible to model w-x profiles of veins as two straight line portions, with steep gradients at overstepping tips, ie. the profile rises above the C-type profile because of bridge rotation. This model is, however, only a first order approximation of reality because bridges often undergo bending during development. Bridge development has a strong effect on fracture displacement and propagation (or fracture displacement and propagation controls bridge development). Bridges can induce shear, and bridge bending can cause the veins to be sigmoidal. Nicholson and Pollard (1985, fig. 7) show that some sigmoidal fractures are mode I, twisting as they propagate away from a parent fracture, with the stress system changing to account for the twist.

Stage 3: Linkage of veins

Stage 3 involves the bridge starting to break down as it is cut by a connecting fracture (or fractures), which links the overstepping segments. Connecting fractures can develop at various locations (Fig. 6). Nicholson and Pollard (1985) show that a bridge has outer arc extension and inner arc compression, with cross fractures usually initiating on the extensional convex surface of the bridge. Such bridges may be modelled in a similar way to beams in engineering (eg. Beer and Johnston 1977; Meriam 1980). In some cases (eg. Fig. 6e) (Beach 1975, fig. 8), renewed vein propagation occurs in preference to further bridge rotation or bridge fracturing. Fig. 6(f) shows veins with bridges being broken by connecting fractures. It would appear that dilation and rotation have been controlled by the longer thicker bridges (between segments A and B, and between C and D). This would have caused tensile stresses in the smaller thinner bridges (in segment A), which have broken near their centres. The bridge between segments B and C has broken at one of its ends.

As described above, where displacement is predominantly extensional, bridges can be broken by cross-cutting veins. Where shear is important, three other methods of bridge breakage occur. Firstly, Gamond (1983, 1987) shows that initial extension fractures can be linked by shear fractures, which cut bridges to produce pull-aparts which have both extension and shear displacement. The second method is for the extension fractures to be cut by a single planar throughgoing fault. The third method is by ductile shearing; Beach (1975) describes sigmoidal vein arrays that underwent shear after dilation.

Stage 4: Formation of a single, irregular fracture

Stage 4 involves segment linkage to produce a single irregular fracture with remnant bridges often preserved as wallrock irregularities (Fig. 7) or as inclusions within the vein. These fractures have irregular w-x profiles, with width minima at linkage points, often causing w-x profiles to plot partially below the C-type profile. Like other fractures, the overall profile is strongly influenced by adjacent overstepping fractures. For instance, segment A in Fig. 6(f) has a w-x profile which plots above the C-type profile because of interaction with segment B.

Vein arrays

Vein arrays can show the four stages of development, from approximately isolated fractures (stage 1) at the ends of the array, to an irregular single fracture (stage 4) at the centre of the array. Fig. 8 shows a w-x profile along the length of an array which consists mostly of stage 2 oversteps. The profile is C-type, which is asymmetric because the array is overstepping onto another array to the west. The profile is irregular because displacement minima occur at oversteps as a result of bridge rotation. The three-dimensional geometry of vein arrays is described by Pollard *et al.* (1982), who show that a parent fracture breaks down at its periphery into en echelon arrays, which may be idealised as helicoidal surfaces. The implication of this geometry and of the stages of fracture development described above, is that a parent tensile fracture is surrounded by thinner segments at progressively earlier stages of development outwards.

Length/width ratios for veins

Peacock and Sanderson (1991) and Peacock (1991) demonstrate that interaction between overstepping faults hinders their propagation. Displacement increases proportionally faster than length, with high displacement gradients developing at the tips of over

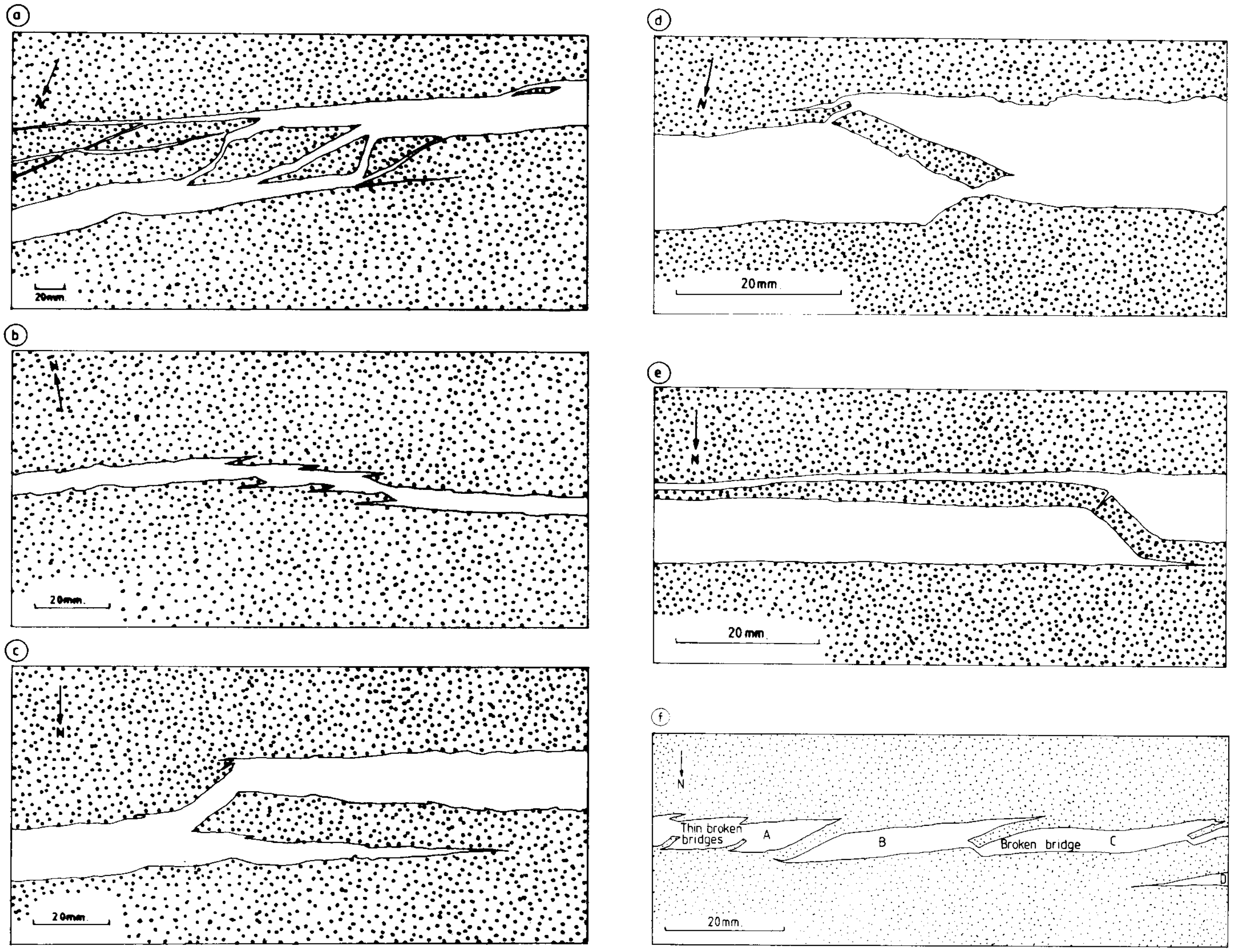

Figure 6. Examples of locations of bridge breakage. The veins are exposed on bedding planes, except Fig. 6(e), which is a vertical section through a bed. The limestone host-rocks are stippled and the calcite veins are unornamented. a) The bridge has been fractured at several locations, and so has been brecciated (ST14944458). b) Fracturing has occurred at the centres of the bridges (ST14884460). c) A fracture has developed at one end of the bridge (ST14804458). d) Both ends of the bridge have been broken, forming a rectangular inclusion of wallrock within the vein (ST14794453). e) The bridge has become locked, so further displacement has been accommodated by renewed propagation of one of the vein segments (ST14794453). f) Part of a vein array, with different thickness bridges showing different behaviour (ST14794453). The thickest bridges have not been fractured, the medium thickness bridges are starting to fracture at one end, whilst the thinnest bridges have been broken near their centres.

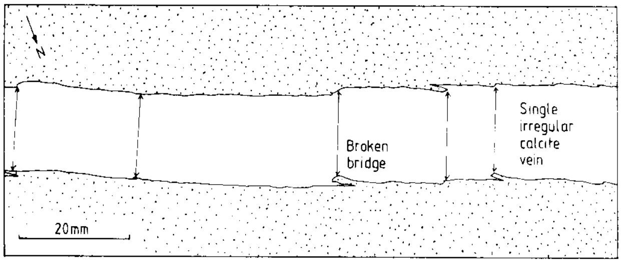

Figure 7. Stage 4 vein from Kilve, formed by the linkage of vein segments (ST136442). The remnant bridges cause irregularities in the vein walls, and width minima. It may be possible to match bridges across the vein.

stepping fault segments. This produces lower ratios of length/ maximum displacement than shown by isolated faults. Similarly, the model presented here for vein development implies that the length/maximum width ratio decreases as interaction between veins increases, because the w-x gradient increases at overstepping tips. Because of the asymmetry of many veins, it is useful to measure the distance (r) between the point of maximum displacement and a tip. For example, the vein in Fig. 5 shows r/ maximum width ratios of 54 and 18 for its non-overstepping and

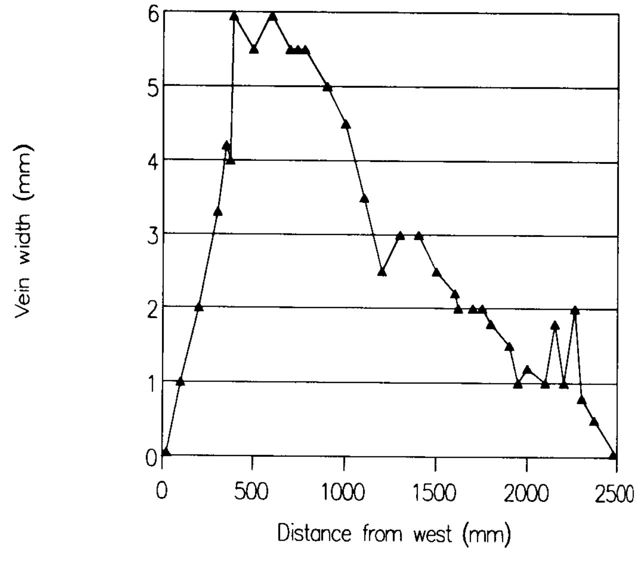

Figure 8. Width-distance profile of a vein array from Kilve (ST13154401). The asymmetry appears to be caused by the array overstepping to the west.

overstepping ends, respectively. It should be noted that the veins studied probably show edge and profile effects; the section may not be normal to the plane of the fracture, and may not pass through the actual point of maximum width.

Conclusions

This study of the displacement geometry of veins indicates the following:

1) Veins have very similar displacement characteristics to normal faults in map view. Bridges between overstepping veins are analogous to relay structures between normal faults; both structures transfer displacement and maintain continuity between the wallrocks.

2) Four stages can be identified in the development of vein segments. Isolated (stage 1) veins show width-distance (w-x) profiles between the ideal elastic model and the C-type profile. When fractures start to interact (stage 2), displacement is transferred by means of bridges. The w-x profiles of each segment may be idealised as two straight line portions, with a steeper gradient at the overstepping tips, so the w-x profile is elevated above the C-type profile. Very long segments with small overlaps can plot well above the elastic fracture profile. When linkage occurs (stages 3 and 4), an irregular fracture is produced, with width minima at linkage points caused by bridge rotation and plastic strain of the wallrocks; the w-x profiles of such veins plot partially below the C-type profile. Bridges can be broken at various locations, with the displacement often being controlled by the longer, thicker bridges in an array.

3) Length/maximum width ratios of veins are largely controlled by interaction with adjacent veins; the ratio decreases as interaction increases because propagation is hindered although the veins continue to dilate.

Acknowledgements. I am grateful to D.J. Sanderson, who supervised the Natural Environment Research Council funded studentship, and to P.L. Hancock for his helpful review. R.R. Jackson is thanked for his help. The diagrams were produced with the help of P. Durnford.

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