Journal of Structural Geology, Vol. 13, No. 6, pp. 635 to 641, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00

Vein morphology, host rock deformation and the origin of the fabrics of echelon mineral veins

R. NICHOLSON

Department of Geology, The University, Manchester M13 9PL, U.K.

(*Received* 11 *May* 1989; *accepted in revised form* 31 *December* 1990)

Abstract—A system of sigmoidal echelon veins from a sample of sandstone from the Upper Carboniferous Culm sequence of southwest England is described. Veins are separated from one another by strips of sandstone, and divided internally by thin seams with crack–seal fabrics. The latter extend as thin veins into the sandstone host rock without change of fabric. Seams appear to be merely parts of crack–seal veins formed in a first phase of deposition in only minutely opened fractures. This phase ended as rates of fracture opening greatly increased. To allow for this widespread opening host rock between dilatating fractures (sandstone strips and seams) had to be deformed. This deformation was limited, however, to rotation, bending and fracture. Shear displacement was a function of dilatation, not zone-parallel ductile shear strain. The textures of the quartz and carbonate aggregates filling the sigmoidal veins show that second-phase crystallization took place into cavities opening more rapidly than growth was able to fill them. Growth for the greater part took place from fibres in seams and not off vein walls of the sandstone host rock. Coarsest aggregates fill the arcs of folds in seams, where rates of vein opening might be expected to have been highest and the scope for competitive cavity growth greatest.

INTRODUCTION

IT IS necessary when attempting to understand the development of the morphologies and fabrics of echelon veins to establish the relative timing of fracture propagation and opening. As vein fabrics are the object of study, it is desirable that any criteria employed for the purpose be independent of fabric. Two published models may be used to show both the significance of this relationship for vein formation and how it determines the strain at the same time imposed on the host rock.

In Model 1 fracture propagation and opening take place together from the start. The echelon fractures concerned propagate and dilatate together, linked during development by ductile shear strain (bulk simple shear) in the host rock between them (Ramsay & Huber 1983, p. 24). No net increase in area occurs where fractures propagate at 45° to zone limits (but see Ramsay & Huber 1987, p. 629 for details of more complex versions involving net gain or loss of area when this angle is not 45°).

No shear strain is developed in the host rock between growing fractures in Model 2. Dilatation of the primary fractures begins only after their propagation has ceased. Up to this point the strips of host rock or bridges that lie between echelon fractures are undeformed. Now they are bent and rotated to allow fracture opening. As this happens the system gains in area. For bending to be possible, however, fractures must first overlap sufficiently to give bridges the aspect ratio (Nicholson & Pollard 1985) in cross-section required to allow it. Such a constraint on bridge morphology has no place in the first model.

The advantages to be gained by independently establishing the relationship between fracture propagation and opening by actually examining the host rock of vein sets (or arrays) have often gone unregarded (e.g. Durney & Ramsay 1973. Cox & Etheridge 1983, Cox 1987, Rye & Bradbury 1988). Vein fabric interpretation has had to depend primarily on data from fabrics themselves, sometimes supplemented by data derived from vein morphology. The latter, however, are insufficient on their own to offer the basis of an independent assessment of the relationship between fracture propagation and opening. Only examination of the host rock can provide that.

Failure to examine the host rock has a further disadvantage. The same analysis that can reveal the relationship between fracture propagation and opening can also help the assessment of differences in rates of fracture opening from vein to vein and within individual veins. The latter data are important because the relationship of rate of opening to contemporary rate of mineral growth does much to control fabric character (Grigor'ev 1965, p. 199). In the case of this second relationship, we may also recognize two limiting cases (Grigor'ev 1965, p. 199). In the first, rates of opening are much the greater and fabrics representative of growth into cavities develop (Dickson 1983). The second, in which rates of opening are less than those of growth (Grigor'ev 1965, p. 198), is characterized by crack–seal fabrics (Ramsay 1980). Of course, if veins and host rock are deformed together after vein formation, then the task of distinguishing how much deformation was vein-related may well be difficult. Such a complication does not arise here.

It is my aim to provide an example of the usefulness of examining host rock as well as vein fabrics. I employ for the purpose a sample of well-cemented sandstone from the Crackington Formation of north Cornwall, containing a number of echelon veins. The formation itself is part of the thick Culm sequence of turbiditic sandstones and shales of Upper Carboniferous age, well-exposed in the sea cliffs of southwest England (Freshney *et al.*

1972). Serial sections show that veins are blade-like in three dimensions. I shall confine most of my observations to a plane perpendicular to the lengths of these blades (Fig. 1a), the profile plane of this account, and to veins V1A and V1B in particular. (The two veins are labelled in this way because they merge within a short distance perpendicular to the profile.) The profile plane is parallel to bedding and shows the traces of fore-set laminae (Fig. 1a). The sigmoidal dark areas in Fig. 1(a) are veins. The about-circular dark areas, however, are merely bubbles in the acetate film from which the positive print of Fig. 1(a) was made.

VEIN FABRICS

Introduction

The aggregates of coarse quartz filling veins V1A and V1B share two distinctive characteristics. First, the coarse aggregate filling each is divided by a very thin seam-like surface, running through the vein. Second, in both cases the crystals making up these aggregates are arranged systematically with respect to these surfaces. Where the latter are curved, crystals are radially arranged, but where these surfaces are planar, crystals lie parallel to one another. I begin with a description of these surfaces, or seams as I term them here, because I regard them as the oldest elements of the vein system.

The character of seams

The seams, which appear as lines running along veins in cross-section (Figs. 1 and 2), are traces of surfaces which in three dimensions extend through the blade-like veins. Seams are disposed in rounded, fold-like waves where veins are thickest, becoming straight where veins grow thinner (Fig. 1a). Seams may also be broken. However, whether curved or planar, broken or unbroken, seams are composed of 0.10 mm-long quartz fibres (Fig. 1c) oriented at right angles to seam length. Seams have several features that suggest they formed through crack–seal processes (Ramsay 1980, but see Hulin 1929, as well as Grigor'ev 1965, p. 199 for earlier proposals of a similar nature). For example, fibres have zig-zag boundaries with one another, bands of inclusions run down fibre lengths and there are trails of inclusions parallel to seam length, passing from fibre to fibre (Fig. 1c here, Ramsay & Huber 1987, p. 576).

In spite of being largely included now within the coarse-grained aggregates of the veins there are several reasons to doubt that seams actually formed there. Firstly, at vein margins seams often extend a little from the coarse-grained vein-fill to form thin planar veins in the sandstone country rock (Figs. 1a and 2b & c). Secondly, fabrics remain unchanged whether seams lie within the sandstone or within the veins. Thirdly, where seams lie in the sandstone their fibres clearly overgrow sedimentary grains whose crystallographic orientations they share. It appears probable, therefore, that seams formed in the host rock sandstone, and were incorporated at some later stage in the major veins. The independence of the seams of these major veins evidently is limited, however, as in no case does a seam penetrate far into the host rock between the major veins, i.e. seams are confined to the zones of fractures from which the major veins formed.

The coarse vein-fill

As noted in the introduction to this section, the relatively large and elongate quartz crystals that fill the major veins such as V1A and V1B (Fig. 1b) are broadly arranged at right angles to seams. These crystals, which are predominantly length slow, have a radial arrangement where seams are curved. Where seams straighten, however, such radial fabrics grade into others composed of parallel quartz crystals also elongate perpendicular to seams. In both types of fabric a proportion of the large quartz crystals can be seen in thin section to be optically continuous with quartz fibres within seams, as if growing from them. The rest appear to be isolated crystals. It appears probable, however, that even the latter grow off fibres, but from sites off-section (Dickson 1983).

In both radial and parallel fabrics some of the constituent quartz crystals rapidly widen away from seams, occluding others that do not. This coarsening appears to have arisen through the successful growth into cavities of crystals oriented with their greatest growth vectors at right angles to the substrate (Dickson 1983). This vigour of growth off seams is not matched, however, by growth off sandstone walls. There are obvious relationships here both between the way quartz crystals are arranged and the shape of the surfaces from which they grow, and between the scale of growth and the nature of the substrate. Carbonate-filled vugs occur within the concave arcs of curving seams (Figs. 1a and 2a & b). They are absent where seams are straight.

The coarse quartz aggregates that fill the veins are typically asymmetrical. This asymmetry is determined in two ways. First, where seams are straight they always lie much nearer one vein wall than the other (Fig. 1a), rather than centrally. Second, where seams are curved, the outer arcs of hinges lie so near sandstone vein walls that very little growth was possible between the two. In this case, of course, the coarse fabrics filling inner arcs are directed first to one side of the vein and then to the other, rather than consistently in one direction.

DEFORMATION OF THE SANDSTONE HOST ROCK

The effects on the host rock sandstone of fracture opening are concentrated in the parallel-sided, sandstone bridges between veins. As seen in a single profile plane these bridges (Figs. 1a and 2b & c) may be bent but unfractured (as in the case of those in V4), both bent and cut through by cross-fractures (see B1), or pulled apart so that the broken ends project into the compound vein so formed (as those in V3 demonstrate). Little or no

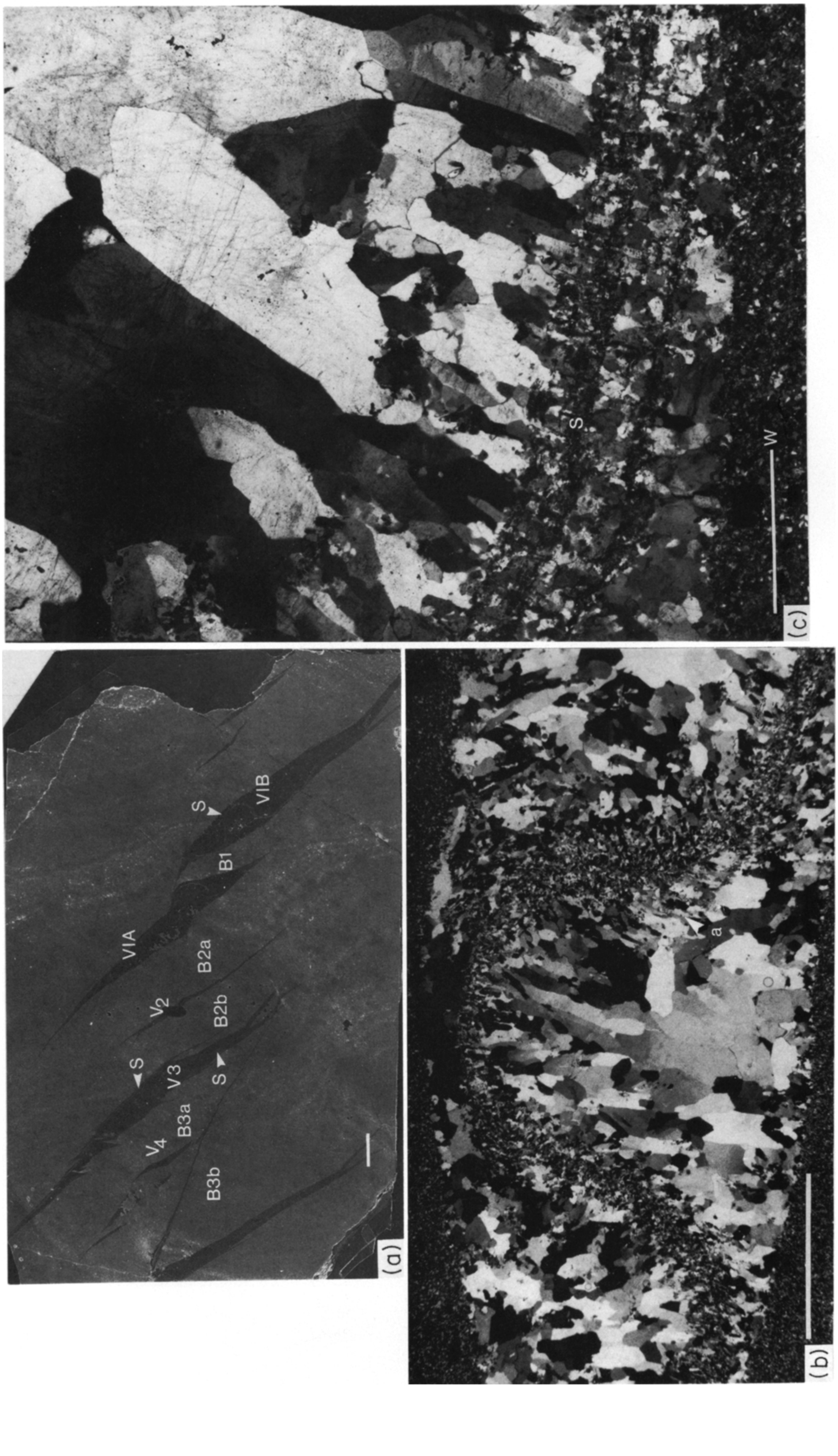

Fig. 1. (a) Peel print of a profile plane of the system of veins described here. Note the line-like seams that run through several of the veins. Scale bar: 10 mm. In this and following figures, bridges are distinguished by the letter B; veins by the letter V; seams by the letter S. (b) Photomicrograph of a profile through vein V1A showing a curving seam and the fabric of coarse, radial quartz crystals that fills inner arcs. Note that in region *a* fibres in seams are longer than elsewhere and curve from a radial attitude into a near-tangential one at a high angle to the sandstone wall of the vein. Scale bar: 1 mm. (c) Photomicrograph of a profile of vein V1A showing a seam just as it leaves the sandstone of the vein outer wall (W) and curves into the vein interior. Scale bar: 1 mm. Note patterns of inclusions in quartz fibres of seams and comparative lack of quartz growth off the sandstone walls.

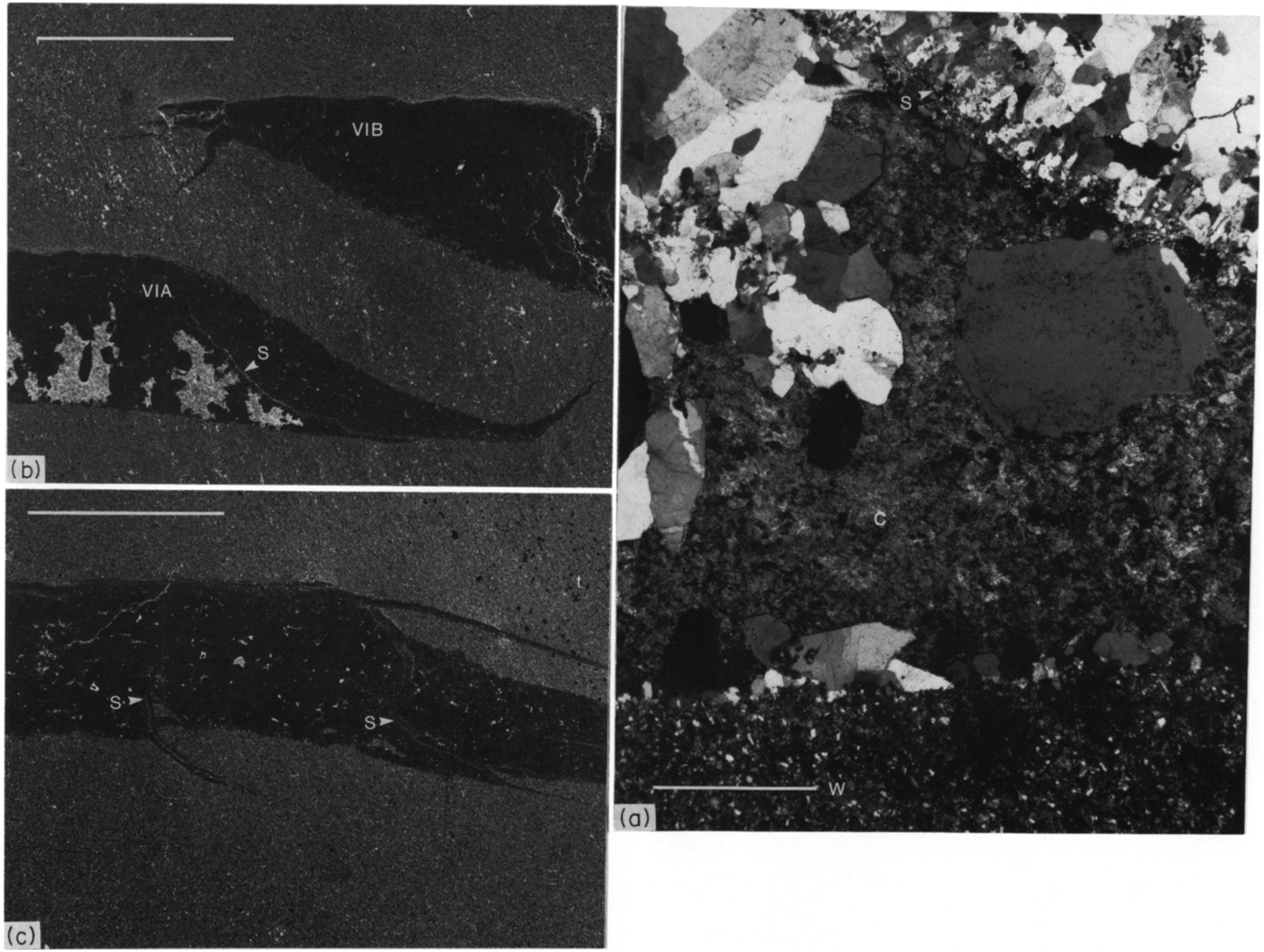

Fig. 2. (a) Photomicrograph of a profile of vein V1A showing a carbonate-filled druze (C) between the outer, sandstone wall (W) of the vein and the curving **length of seam within it. Scale bar: 1 mm. (b) Peel print of part of a profile** of the vein system showing the zone of overlap between veins V1A and V1B and the **sandstone bridge between them. Note how the seam in V1B** enters the vein from the sandstone country rock (lower edge, towards the tip of the vein). (c) Peel print showing part of vein V3 in profile. The ends of lengths of seam included in the latter (not readily visible in a peel print) project as veins into the sandstone host rock.

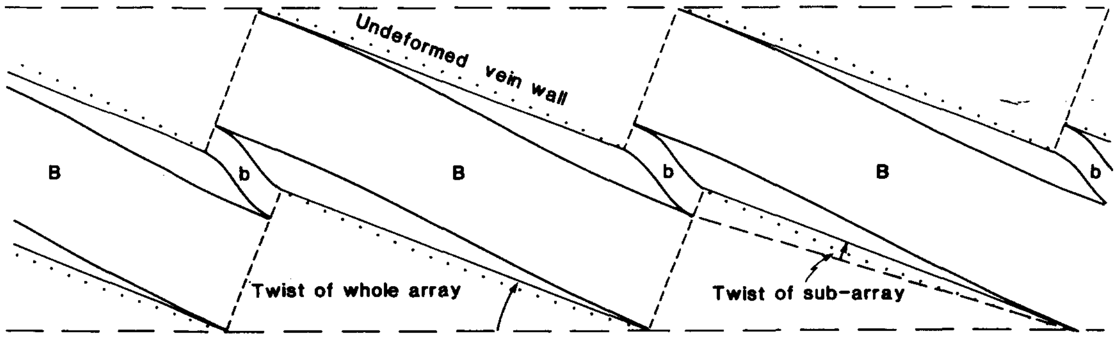

Fig. 3. Sketch showing in idealized form the appearance in profile of a vein system made up entirely of pairs of veins such as V1A and V1B. The undeformed lengths of vein wall are distinguished from deformed lengths. Note how shorter bridges (b) have been rotated through larger angles than the longer bridges (B). Compare with Fig. 1(a).

ductile strain is present in any of the bridges and an obvious increase in area has taken place as veins formed.

Figure 3 shows in idealized form a similar arrangement of veins. In both this model and my sample (Fig. 1a) longer bridges have been rotated through lesser angles on dilatation than shorter bridges. This is because in spite of differences of length, the two types of bridge have had to adjust to the same amount of opening (a point already made by Nicholson & Ejiofor 1987, for another vein system of the same type).

Folds in bridges have an approximately class 1B morphology; inner arcs are more tightly curved than outer ones (Ramsay & Huber 1987, p. 348). For such folds to be produced the pairs of fractures defining each bridge must have formed before folding began, and must have been opened together. Thus B1 was deformed as V1A and V1B were opened. Then as V1A and V2 share the curved bridge B2, V1A must at the same time have begun to open with V2. A comparable link can be established between V2 and V3, and so on, until it appears probable that the fractures visible in the profile plane were all opened together.

In this context, we might enquire whether sandstone bridges have the aspect ratios the formation of these half-wave folds appears to require (Nicholson & Pollard 1985). The data recorded in Table 1 seem to provide evidence that they do. By what means, however, was the development of these favourable shapes assured?

I suggest a solution is best sought through developments in three dimensions. Serial sections show that the profile plane of my sample is not one of symmetry, as it is in Model 1 (Ramsay & Huber 1987, p. 625). The pattern of fractures seen in the profile plane instead, as in Model 2, is determined by the entry of the dilatating fluid from one side only. In particular, it is the earlier development of dilatation on the 'upstream' side of the profile that appears to control the pattern of fractures in the plane in question, and therefore of bridge morphology in it (Nicholson & Ejiofor 1987). The fact that a pair of echelon veins seen in the profile plane is separated by a curving bridge itself implies that in three dimensions the two are connected with one another. The bridge they share must already be broken, although the rupture has not reached the plane under observation.

Table 1. Bridge aspect ratios

B1	4
B2a	3.75
B2b	4.7

THE INCORPORATION OF LENGTHS OF SEAM INTO THE MAJOR VEINS

I have already concluded that seams were part of the host rock at the time when the echelon fractures from which major veins formed began to open: that is seams are older than the major veins, and older therefore than the coarsely crystalline material that fills them. Seams divide major veins into subareas that may be described as sub-veins. Here seams function like the stouter sandstone strips between major veins. Seams, in other words, also act as bridges. To open the fractures from which the major veins formed required that both seams and the stouter sandstone bridges be deformed. The materials making up the two types of bridge thus were incorporated into the vein system at the same time. Accepting this argument implies, of course, accepting in turn that each major vein formed not from one fracture but from several fractures that together might be termed a sub-array.

RECONSTRUCTION OF THE FRACTURE PATTERN PRESENT AS SIGNIFICANT DILATATION BEGAN

The lengths of fracture wall that remain undeflected (i.e. those parts not defining bridges) face the mass of host rock outside the vein set or array (Figs. 3 and 4). These lengths preserve both original length and orientation. We also know that even where they are folded the parallel-sided bridges, whether composed of the sandstone host rock or consisting of lengths of seam, are little strained. To close the major cavities within which the main phase crystallization occurred it is enough merely to push both types of bridge back against unde-

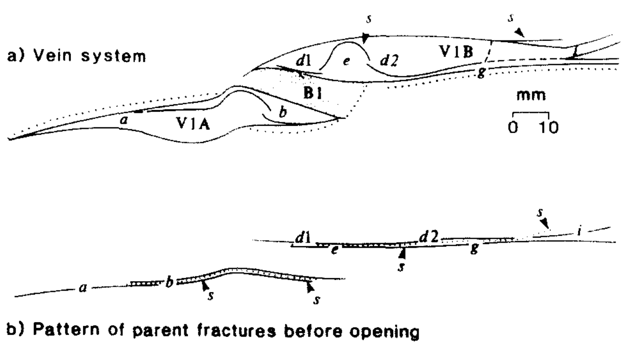

Fig. 4. The upper sketch shows significant features of a profile through veins V1A and V1B. The undeformed parts of vein walls are marked by parallel rows of coarse dots. Note the zig-zag limits of the zone of veins. The lower sketch shows the pattern of fractures inferred to exist as opening was about to begin. Seams are labelled with the letter S in both sketches. In the upper, however, seams are shown as continuous lines but in the lower by a row of fine dots. The cavities separated by seams are distinguished in each sketch by the letters a, b, d, e, g and i.

formed walls (Fig. 3) (Nicholson & Pollard 1985). As the latter are close to being straight, the fracture traces defined in this way are near-straight also.

Only host rock deformed during fracture opening can properly be included within the vein system of our sample. The limits of the system in profile, therefore, are not lines drawn joining the tips of fracture traces, as is the case for Model 1. Instead, as in Model 2, the limits have a stepped form and consist of lengths of undeflected vein wall joined by lines drawn across the ends of bridges (Figs. 3 and 4).

FOLDING OF BRIDGES

Bridges are deformed primarily because of a reduction in the distance between their ends. This occurs as the echelon fractures on either side of each are opened and change shape (Figs. 3 and 4). The sigmoidal shapes of the sandstone bridges between major echelon veins (e.g. B1) directly reflect the combination of dilatation and shear displacement imposed. The lengths of seam in V1A and V1B, however, are disposed in rounded fold arcs and not sigmoidal ones (Fig. 4). In the first instance this appears to be because seams have much greater aspect ratios than the thicker, sandstone bridges.

A second factor also appears to contribute to the development of the rounded fold arcs in seams. We have seen that the textures developed in the coarse quartz aggregates of the major veins have a cavity-filling character. Crystal growth off the lengths of seam incorporated in the major veins appears for the greater part to have occurred after bridge deformation. Before crystallization began newly bent seams lay within relatively wide, fluid-filled cavities. Until main-stage crystallization fixed them in place seams were only weakly confined. Such an interpretation of the circumstances of folding is consistent with the way in which the outer arcs of folds in the fragile seams are pressed close against vein sandstone walls. It also accounts for the way in which the broken ends of seams could be separated from one another, as well as the vein walls, before being engulfed by cavity-filling crystal growth (Fig. 1a).

There are indications that crack–seal growth did not cease abruptly, but that at first it was able to keep up with increased opening. In positions flanking the hinges of folds individual fibres in seams grow distinctly longer than is usual (e.g. V1A, Fig. 1a), and curve from a radial attitude with respect to seams, into a tangential one. In this way they advance at high angles towards the neighbouring sandstone walls, although they now fail to reach them. We may surmise that in the main phase of opening rates very soon were too high for crack–seal processes to compete. As opening continued fibres were plucked off walls, further proof that the folding of the seams was an integral part of fracture opening.

SYNTHESIS

Both the character of the deformation associated with vein formation, and the morphology of the veins themselves, indicate that fracture propagation and fracture opening in the profile plane of my sample did not take place together but followed one another. Shear displacement over the vein system was a consequence of dilatation and not of zone-parallel ductile shear strain. Three stages of development are recognizable in the profile plane. The first stage was one of the growth of a complex set of echelon, extension fractures. The reason for their arrangement are outside the remit of this account. In the second stage, the propagation of these fractures in the profile ceased and fractures were opened together. Mineral deposition had begun. Concerted opening implies that veins are connected with one another in three dimensions. That this is so can be checked by cutting serial sections, as I have done here. In a third stage bridges were forced into failure, shorter ones first (e.g. B3 but not B1), and individual veins linked with one another within the profile plane.

The second stage was more complex than this summary of vein development in the profile plane allows, as opening and mineral precipitation may be divided into two phases. In the first the opening involved was minute, leading only to the formation of crack–seal seams. These crack–seal veins appear, nevertheless, to be integral parts of the vein system, confined as they are to the zones of fractures from which the main veins formed. Seams may be thought of as developing in fractures ahead of the wave of major dilatation that accompanies the wholesale intrusion of fluid along the lengths of the blade-like veins. When the morphology of the controlling sandstone bridges of a given profile was appropriate significant dilatation could be extended to it, employing the fractures available at that moment. At this point the second phase of precipitation began. Rates of opening evidently were soon too high, however, for crack–seal growth to keep pace and it was replaced by cavity-filling crystallization. The development of the coarsest cavity-filling growth in the inner arcs of folded seams where veins were thickest is consistent with the view that rates of opening were highest there.

CONCLUSIONS

The fabrics of sigmoidal veins should be investigated together with the deformation imposed on the host rock during vein formation. This is because the host rock can provide evidence independent of fabric of the relationship of fracture propagation to fracture opening. In vein systems in which more than one phase of mineral deposition has taken place the host rock in which each developed obviously must include earlier-formed vein material, and not merely the wider country rock itself. Where deformation is limited to bending and rupture of the strips of host rocks (bridges) between echelon veins, significant opening cannot have begun before the echelon, parent fractures were established. Shear displacement developed over such a system of fractures takes place as the latter are dilatated by intruding fluid. The connection of fractures in three dimensions is implied by appearances in cross-section where the curving bridges between veins are essentially free of ductile strain. It is demonstrated where bridges are broken and where they are not can be confirmed by the examination of serial sections.

Knowledge of the relationship of fracture propagation to opening in the profile plane also provides a context independent of fabric in which the relationship of rates of fracture opening to rates of mineral growth may be investigated. Where curving bridges have undergone little or no ductile strain, opening must have begun at the same time over the length of each sigmoidal vein. Thus rates of opening must have been highest where the increments of opening were greatest, that is at the centres of the veins. Competition amongst growing crystals is here able to develop furthest and mineral aggregates become coarsest. On the other hand, rates of growth dominate over those of opening where increments of opening are very small. Here veins develop crack–seal fabrics, host rock deformation remains minimal and veins stay essentially parallel-sided.

Acknowledgements—I am much obliged to Peter Hudleston for advice in the preparation of this account.

REFERENCES

Cox, S. F. 1987. Antitaxial crack–seal vein microstructure and their relationship to displacement paths. *J. Struct. Geol.* **9**, 779–787.

Cox, S. F. & Etheridge, M. A. 1983. Crack–seal fibre growth mechanisms and their significance in the development of oriented layer silicate microstructures. *Tectonophysics* **92**, 147–170.

Dickson, J. A. D. 1983. Graphical modelling of crystal aggregates and its relevance to cement diagnosis. *Phil. Trans. R. Soc. Lond.* **A309**, 465–502.

Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic growth. In: *Gravity and Tectonics* (edited by De Jong, K. A. & Scholten, R.). Wiley, New York, 67–96.

Freshney, E. C., McKeown, M. C. & Williams, M. 1972. Geology of the coast between Tintagel and Bude. *Mem. geol. Surv. U.K.* H.M.S.O., London.

Grigor'ev, D. P. 1965. *Ontogeny of Minerals*. Israeli Program for Scientific Translations, Jerusalem.

Hulin, C. D. 1929. Structural control of ore deposition. *Econ. Geol.* **24**, 15–49.

Nicholson, R. & Ejiofor, I. B. 1987. The three-dimensional morphology of arrays of echelon and sigmoidal mineral-filled fractures: data from North Cornwall. *J. geol. Soc. Lond.* **144**, 79–83.

Nicholson, R. & Pollard, D. D. 1985. Dilation and linkage of echelon cracks. *J. Struct. Geol.* **7**, 583–590.

Ramsay, J. G. 1980. The crack–seal mechanism of rock deformation. *Nature* **284**, 135–139.

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology: Volume* 1, *Strain Analysis*. Academic Press, London.

Ramsay, J. G. & Huber, M. I. 1987. *The Techniques of Modern Structural Geology: Volume* 2, *Folds and Fractures*. Academic Press, London.

Rye, D. M. & Bradbury, H. J. 1988. Fluid flow in the crust: An example from a Pyrenean thrust ramp. *Am. J. Sci.* **288**, 197–235.