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

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I AM obliged to Tanner for the interesting comments he has made in his discussion. While much of what he writes concerns wider issues than those tackled in the two papers to which he refers principally (Nicholson & Ejiofor 1987, Nicholson 1991), I am grateful for the opportunity provided to discuss them, as well as the narrower issues that derive directly from the two accounts.

Tanner is, of course, correct when he writes that the data employed by Nicholson & Ejiofor (1987) were obtained from beach cobbles. The same is true of data employed by Nicholson (1991). Collection in this fashion had the advantage of allowing us to obtain numerous samples within which occurred the characteristic of interest to us; viz. the transition from a single vein to an array of echelon veins. Our aim was to investigate the relationships in three dimensions of vein morphology, vein-fill and the enclosing host rock in material drawn from a rock sequence much used as a source of data on echelon veins.

In his opening remarks Tanner states that our samples provided examples of the single, simple (parental) fractures at whose margins arrays of echelon veins arise. However, in none of the many examples examined did it appear that the single vein was anything but itself compound, i.e. formed through linkage of echelon fractures such as still made up the less dilatated leading edge of the vein system.

An echelon arrangement of veins in the Crackington Formation is not limited, moreover, to sandstone bed margins, as Tanner describes, as echelon veins often extend through the whole thickness of a bed. In other words, often it is the perpendicular veins of cross-sections through beds that at the same time are the echelon veins seen on bed-parallel surfaces. This seems to be the view of Price & Cosgrove (1990, fig. 16.5) for this area. It is also my observation that many of these bed-normal veins at Crackington have themselves formed through fracture linkage.

Tanner finds that sigmoidal veins are uncommon at Crackington. Perhaps, however, he does not apply the term to echelon veins in which the overlap ratio is low (i.e. where bent bridge walls are short compared with undeflected, still-straight vein walls, Nicholson & Pollard 1985). In that case Tanner follows Beach (1975, fig. 8), who describes as non-sigmoidal a pair of overlapping, long, mostly straight-walled veins, separated from one another nevertheless by a short bridge with unmistakably 'S'-shaped margins.

Even where sigmoidal echelon veins do occur at Crackington, Tanner suggests that the curvature of veins (and bridges) did not develop while fractures opened and mineral deposition took place, but by modification of essentially straight veins through later-imposed, array-parallel, shear strain. Where vein-fill and bridges are appropriately deformed this conclusion may be compelling. However, the process does not seem to me to be apt as a general explanation for the sigmoidal veins I have examined at Crackington. In any event I should expect primary and secondary curvature to give rise to different combinations of veins and bridge morphology. Where curvature is primary, an alternation of class 1b fold form for bridges and class 3 for the intervening veins is to be expected. Where curvature is secondary, however, and veins necessarily much nearer parallel-sided before folding, no such systematic morphological contrast is likely to develop. Moreover, as implied also by the hypothesis that sigmoidal veins develop in zones of ductile shear strain (Ramsay & Huber 1983, p. 24), one might expect where curvature is secondary to find isolated sigmoidal veins comparable with that shown in diagrammatic form by Scholz (1990, fig. 3.16) in a zone of ductile strain. In contrast it is integral to the hypothesis that sigmoidal shape arises on dilatation that echelon veins always develop in groups and never on their own.

Tanner accepts that where dilatation is responsible for veins, two consecutive stages in development may be recognized, dominated, respectively, by fracture growth and fracture opening. He adopts a similar approach in a second context. Now, however, opening is not seen as directly following the stage of fracture growth but as relatively delayed. The evidence that persuades Tanner that this is so is the existence in opened single, simple (parental) fractures of parallel mineral fibres consistently arranged at angles other than 90° to vein walls. Two questions immediately arise.

The first is whether such fibres need track the opening direction, and the second whether the fractures involved are truly simple in the sense implied by Tanner. I leave aside the first question as beyond the scope of this reply. I turn, therefore, to the second which is concerned with the matter of how we might obtain evidence independent of fibre patterns on which to decide the direction of vein opening. One obvious way is to examine the fit of vein walls. This I also leave aside. Three other responses to this second question may be made, and are discussed below.

The first of them is that, as suggested above, lengthy, truly simple, single fractures do not seem to be common at Crackington. Many fractures that at first sight appear to be simple, prove on close examination to have the stepped margins, etc., indicative of formation through crack linkage. (This indeed seems to be the case for at least two such veins shown by Tanner, in his fig. 1a.) In that case, opening is not perpendicular to straight vein walls. For as long as bridges remain unbroken, a degree of rotation during opening is necessarily involved.

My second response is to suggest that even if veins show no sign that they themselves formed through fracture linkage, that need not imply they dilatated on their own. Instead, and again as Tanner suggests, such veins may well have formed part of some larger system of fractures. Once more, we might expect opening to be oblique to even undeflected vein walls.

Thirdly, as Tanner makes clear in his penultimate paragraph, vein formation at Crackington is merely part of a complex structural development in which various phenomena develop contemporaneously. One way of making the connections obvious in a system involving extensional veins largely perpendicular to bedding, is to term the broad process one of boudinage. The objection might be made that while boudin-like in cross-section the presence on bedding surfaces of arrays of echelon veins, rather than the long, single, simple fractures that should separate boudins, precludes the use of the term. As boudins are often identified on appearances in cross-sections without reference to the third dimension, the objection seems to me unsustainable. It may even be that given the apparent commonness of compound fractures rather than simple ones, many boudins separated by mineral-filled veins and seen only in cross-section, in fact are separated in the third dimension by arrays of echelon fractures, or by single fractures formed through fracture linkage. As a probable example the boudins reported from the External French Alps by Beach & Jack (1982) may be cited. Not only do they appear to have been identified on the evidence of cross-sections alone but the veins separating boudins (Beach & Jack 1982, figs. 3, 4 and 9) typically seem to be compound in the sense employed here, as are many such veins at Crackington.

It seems appropriate to end with a reference to one structure well-developed at Crackington but not included in Tanner's analysis. This is the widely developed axial plane, spaced cleavage of the sandstones. The omission provides a contrast with earlier explanations of arrays of sigmoidal veins (e.g. Beach 1975, Ramsay & Huber 1983, p. 24) in which the slow development of such a cleavage is regarded as providing, little by little, the material needed to fill developing fractures. Acceptance of such a source was, in its turn, one reason for supposing that vein formation itself is a drawn-out affair, in which fracture growth and mineral deposition take place at the same time instead of consecutively, as implied by the dilatational hypothesis. However, even though a direct link between vein mineralization and pressure solution of the adjacent wallrock for these Crackington veins is ruled out, a comprehensive account of the boudinage and folding, of which vein formation at Crackington is a part, will have to allow also for the development of this axial planar, spaced cleavage.

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