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The interplay between fluids, folds and thrusts during the deformation of a sedimentary succession: Reply

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In his discussion Dr Nicholson raises three points regarding my article (Cosgrove 1993) in which the tectonic and hydrodynamic implications of the bedding-parallel composite vein systems in the Wenlock slates of the Horse Shoe pass area north of Llangollen, North Wales are considered.

The author is grateful to Dr Nicholson for drawing his attention to previous work carried out on these veins (Nettle 1964, Nicholson 1966, 1978, and Warren *et al.* 1970) and for providing an opportunity to discuss the origin of these interesting structures further. The works referenced above are primarily concerned with the petrographic analysis of the veins, and the discussion of the textures and minor structures imposed on them during the folding and metamorphism of the Wenlock shales to slates. Although they do not comment on the hydrodynamic implications of the veins, these papers do discuss the timing of vein formation. The various ideas can be summarized as follows.

Nettle (1964) argued that the veins occurred early in the deformation and that the associated slickensides represent the effect of bedding-plane slip during the folding of the Wenlock shales. Although he suggested that the small-scale folding of the veins accompanied this bedding-plane slip, he concluded that these folds formed after the slaty cleavage. This conclusion seems puzzling in view of the fact that the majority of bedding-plane slip during folding is thought to precede the formation of cleavage, which is considered to form relatively late in the folding history during the locking-up and post-buckle flattening stage. Nicholson (1966), following a model proposed by Hancock (1965), who described similar bedding-parallel calcite–quartz veneers in folds in Pembrokeshire, South Wales, implied that the veins formed during the development of the folds in the Wenlock shales and that the slickensides are the result of bedding-plane slip during flexural slip. He concluded that the small-scale folding of the veins occurred later in the folding event during the formation of the cleavage.

The present author suggested (Cosgrove 1993) that the veins predated the folding of the Wenlock beds and were formed in association with pre-fold thrusting. Evidence cited to support this idea was the fact that where the veins can be traced over the present fold hinges, they show no sign of thinning, an observation incompatible with the idea that they formed during folding by the process of flexural slip. He argued that the small-scale folding of the veins probably coincided with the regional folding, and drew attention to the folding of similar composite veins from the Hercynian fold-thrust belt at Combe Martin, where the symmetry of the folds in the veins reverses when traced over the hinge of a fold in the country rock (Cosgrove 1993 fig. 4). However, if as suggested, these vein systems are the result of pre-fold thrusting, there is the possibility that some small-scale folding of the composite veins could have formed during thrusting. In this regard it is interesting to note that Warren *et al.* (1970), who in the course of the Geological Survey mapping of the 1″ Sheet 107 (Denbigh) encountered folded composite veins in eleven widely scattered localities over about 400 square kilometres, observed that the vast majority of the folds in the veins are north facing, even in those localities that lie on the northern limbs of anticlines, where bedding-plane slip contemporaneous with folding would have produced structures with the opposite asymmetry.

Dr Nicholson, in the accompanying discussion, points out that the veins are at present not fibrous and by implication cannot be used to support the hydrodynamic model proposed by Cosgrove (1993). However, as the following discussion indicates, evidence does exist which indicates that the veins were originally fibrous.

Associated with the composite layers of calcite veins, are well-preserved linear features which indicate that slip occurred along the bedding. There has been considerable work over the last two decades on the types of movement indicators that can develop on a plane along which movement occurred. Most relevant to the present discussion is the formation of crystal fibres which frequently form in association with, or in place of, slickensides. The process by which these sheets of fibres are formed is described and illustrated by Ramsay & Huber (1983 figs. 13.32 and 13.37), who argue that the fibres grow from small dilational jogs along the movement plane. One of the features of these sheets of fibres, particularly when they form in relatively weak rocks such as shale, is that the impression of the fibres becomes imprinted on the wall rock producing characteristic linear ridges.

It can be argued that the ribbing, which is often well preserved at the vein–country rock interface, and on the slivers of country rock which sometimes separate the individual calcite veins making up the composite layers (Cosgrove 1983 fig. 3b, Nicholson, accompanying discussion), represents the imprint of such crystal fibres.

Since the formation of the veins the rocks have been folded and metamorphosed to form slate and, in addition, considerable quartz veining has occurred in the hinge region of some of the second-order folds around which the vein sheets have been folded. In view of the ease with which calcite recrystallizes, it is interesting to consider how much of the original texture of the calcite veins would have survived this deformation.

Inevitably, previous workers have disagreed regarding the amount of recrystallization which had occurred. Nettle (1964) considered the calcite to be totally recrystallized, whereas Nicholson (1966), whilst acknowledging that one of the interesting features of the calcite–quartz bodies is the presence in them of considerable post-kinematic recrystallization, concluded that overall relatively little recrystallization occurred.

Clearly because of the contention regarding the amount of recrystallization that has occurred in the calcite veins, it is difficult to use this example to demonstrate unequivocally the viability of the hydrodynamic model of thrusting and folding proposed by Cosgrove (1993). What is needed is a similar composite vein system, more resistant to recrystallization, in which is preserved crystallographic evidence for numerous events of bedding-parallel shear coupled with dilation of the bedding plane.

Fortunately, such a vein system has recently been described by Jessell *et al.* (1994) who discuss and analyse the kinematic implications of laminated bedding-parallel veins hosted in a turbiditic sandstone shale sequence, which consists of stacked, millimetre thick, sub-parallel sheets of quartz separated by micaceous layers, wall rock slivers and pressure-solution seams. The system seems very similar to the vein system from North Wales discussed earlier in this article, except that the calcite veins are replaced by quartz.

The bedding-parallel veins described by Jessell *et al.* (1994) have two morphological forms which they term Type 1 and 2. Type 1 are thin (commonly 5–10 cm) laminated veins which have complex microstructures dominated by phyllosilicate inclusion surfaces, which they argue are related to oblique openings along bedding, with varying rates of opening relative to shear displacement along the bedding surfaces. The authors conclude from the field and microstructural data that the inclusion surfaces track the opening direction during vein formation, and that the vein-opening sense criteria suggest cyclic pore fluid pressure fluctuations, which predate the amplification and propagation of the host chevron folds. This model of multiple episodes of synchronous bedding-plane dilation and shear during vein formation is compatible with the model proposed by Cosgrove for the formation of the composite veins in North Wales.

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