The flexural-slip mechanism: Reply

P. W. Geoff Tanner

Department of Geology and Applied Geology, University of Glasgow, Glasgow G12 8QQ, U.K.

(*Received* 4 *April* 1990; *accepted in revised form* 23 *April* 1990)

INTRODUCTION

I AM pleased to have the opportunity to discuss further the origin of bedding-parallel (B-P) veins from rocks of the Welsh Basin. Such veins are potentially capable of preserving details of the strain history of folded rocks from the time at which the rocks became lithified, to late in the folding process. However, controversy commonly arises over the timing of vein growth especially with respect to folding, as shown by the current debate over the origin of concordant veins in the Meguma Group, Nova Scotia (Henderson *et al.* 1989, Mawer 1989), by this discussion on the origin of the Welsh veins, and by an earlier debate over the origin of B-P veins from NE Wales (Nicholson 1971, Warren *et al.* 1971). Such disputes can only be resolved by establishing clear rules by which the different types of B-P vein may be recognized, and then applying them to individual cases in as rigorous and quantitative a manner as possible.

When I visited Cardigan Bay, Wales, in 1987 my aim was to test whether the criteria which I had established for recognizing flexural-slip veins were of general application. These were listed as items (1)–(7) in the 'Conclusions' of Tanner (1989, p. 653) and I would stress the importance of (i) the geometrical relationship *between* slickenfibres and fold geometry, and (ii) the shear sense *reversal* shown by fibre steps on B-P veins on alternate fold limbs; neither of these crucial features was considered by Fitches *et al.* in their 1986 paper or in the above discussion. Before responding to the detailed points made by these authors it is important to show briefly how these flexural-slip criteria are fulfilled in the Cardigan Bay area.

Examination of a number of well-exposed coastal sections between Aberporth and Borth (Fig. 2a) has shown that the turbidite facies rocks contain fibre veins which occur at regularly-spaced intervals (generally <1 m) throughout the sequence. A good, yet typical, example of this is seen on the coast 1 km WSW of Aberaeron (SN 451 626) where B-P veins occur every 20–70 cm on the limbs of a syncline, and of the succeeding anticline to the south. In all cases where fibre steps are preserved on the veins (over eight examples on each limb of the syncline), the sense of displacement across the veins is consistent with flexural-slip movement (Tanner 1989, fig. 1) (Figs. 1a & b, see facing page), and changes sense within 10 cm or so on either side of the exposed anticlinal hinge. The lineations on the veins are statistically nearly orthogonal to the fold axis (Fig. 2b) and consist of quartz fibres (Figs. 1c & d) which lie at a small angle to the plane of the vein. Some of the fibres contain internal crack–seal inclusion bands which are parallel to the wall-rock contact (Fig. 1e), showing that the fibres have grown by incremental extension almost parallel to the bedding surface. In some veins quartz has recrystallized to a polygonal texture (Fig. 1f), yet in others this effect is minimal (Fig. 1d). Occasional thrusts, which have a flexural-slip displacement sense and are marked by fibre veins, climb up from the movement horizons (cf. Tanner 1989, fig. 22a) and rare, crude duplex development is seen along some of the latter.

All of these features are consistent with a flexural-slip origin for the B-P veins, and similar relationships between the veins and major folds are seen throughout the Cardigan Bay section and particularly at Llanrhystud (SN 535 707) and Constitution Hill, Aberystwyth (SN 583 828). Some B-P veins have a massive, crystalline interior which could have developed by hydraulic jacking during layer-parallel shortening prior to folding, and controlled the subsequent location of the slip surface. I have, however, seen no evidence of early crystal growth orthogonal to the vein margins and it is more likely that these coarsely crystalline, sometimes vuggy, parts of the vein grew in low pressure areas on an irregular slip surface (cf. Durney & Ramsay 1973).

REPLIES TO SPECIFIC POINTS OF THE DISCUSSION

(1) and (2) A major obstacle to discussing the origin of the 'Welsh veins' is that Fitches *et al.* (1986) have used data from B-P veins across a large area (Fig. 2) which vary widely in composition, internal morphology and structural setting, to support their thesis of a 'detachment' origin, when it is clear that the Cardigan Bay veins are dissimilar to those in NE Wales, and the latter possibly fall into two distinct groups (Warren *et al.* 1971). I was guilty of perpetuating this error by discussing the origin of "the bedding-parallel veins from the Welsh Basin" (Tanner 1989, p. 654) instead of stating clearly that my conclusions only related to the veins which I had studied from the Cardigan Bay area.

The occurrence of detachment surfaces in unfolded rocks was not reported from Wales by Fitches *et al.* (1986) and, referring to the Welsh Basin, they stated that "there are no examples of detachment structures which are obviously unrelated to regional deformation" (*op. cit.* p. 617). The veins illustrated in their figs. 1(a), (c) & (d) are from the cleaved and regionally folded Silurian rocks of NE Wales. They show features characteristic of hydraulic jacking and the main textures are similar to those described previously from the Llangollen area 25 km to the SE by Nettle (1964) and Nicholson (1966). No information on the field occurrence of the Welshpool sample (Fig. 2b) is given either in Fitches *et al.* (1986) or in the above Discussion.

The B-P veins from NE Wales carry a strong lineation which is generally orthogonal to the later fold axes (Nicholson 1971) and an alternative scenario to the detachment hypothesis is that the veins began to grow as a result of hydraulic jacking during *layer-parallel shortening* prior to folding; continued to develop and be modified by (?)episodic jacking and flexural slip during folding; and finally became inactive and were buckled during the final stages of the regional deformation.

With regard to the question of flat-lying sequences, flexural-slip can be transmitted through rock sequences regardless of their orientation and, as the following cartoons show, a horizontal attitude does not preclude flexural-slip movement (Fig. 3), even in rocks on the foreland to an orogenic belt.

(3) The diagnostic relationships between B-P veins and folds are only clearly seen in three-dimensional exposures of hinge zones where details of the direction and sense of slip on each movement horizon can be seen. These relationships are summarized in fig. 22 of Tanner (1989). The most common situation, where a movement horizon on one limb cuts across the hinge zone of the fold and continues as a thrust on the other limb (*op. cit.* fig. 22c), is clearly shown by several folds in the Llanrhystud section, and the relationship shown in fig. 22(b) is described above from Aberaeron.

The particular small folds quoted by Fitches *et al.* as evidence that the movement horizons and their lineations are folded (Fitches *et al.* 1986, figs. 7b & c) I find to be small buckle folds with gently inclined axial surfaces, which formed as a result of a *late* phase of deformation superimposed on the main folds and their associated slaty cleavage. This deformation caused layer-parallel shortening of already inactive movement horizons. Similar folds are seen at several other localities including Aberaeron: they are not relevant to a discussion on the origin of the B-P veins. I have not seen a *cleavage* affecting any of the laminated quartz–carbonate B-P veins.

(4) To the contrary, Fitches *et al.* (1986) have only demonstrated that this family of structures is related kinematically; I contend that the causal mechanism is flexural-slip folding, not syn-sedimentary detachment. Flexural slip involves frictional contact between two surfaces and features normally found on fault planes such as brecciation, 'polishing' and quartz fibre growth also occur on movement horizons, depending upon such factors as fluid pressure, strain rate, surface roughness, etc. Quartz veins orthogonal to, and terminating against, movement horizons are common (see Tanner 1989, p. 651 and fig. 24) and result from bed-parallel extension of the rock packets between the slip surfaces. As noted by Strong (1974), in Fitches *et al.* (1986) and in Tanner (1989, p. 651), the incremental extension directions in both the bedding-normal veins and the B-P veins are commonly parallel. En échelon vein arrays have been long recognized to result from simple shear within beds on the limbs of folds. They are also seen adjacent to B-P veins on a microscopic scale and indicate the shear sense required by flexural slip.

(5) Few data were given by Fitches *et al.* (1986) to substantiate the final statement. They refer to their fig. 7(c), which shows late buckles (referred to in (3) above) formed after the main folding, and to fig. 3(d) which merely shows a vein surface with various fibre orientations. At Aberaeron (Fig. 2b) the pole to the best-fit plane containing the slickenfibres is within 5° of parallelism with the fold axis and it is this systematic and reproducible relationship between the geometry of the slickenfibres and that of the folds which has not been explained by Fitches *et al.*

(6) At Aberaeron only 5–10% of the movement horizons show two or more slickenfibre lineations in the field, but the percentage is greater in situations where the folds are strongly non-cylindrical such as at Llanrhystud. Discordant sets of fibres on successive surfaces are most commonly seen in thick B-P veins which bifurcate and become cross-cutting in the hinge zones of folds, and preserve evidence of a long and complex movement history. Aberrant slickenfibres making a low angle with the fold axis are most common on movement horizons within the hinge zones of folds and probably document the complex adjustments required to overcome space problems in this part of the the structure.

(7) I thank the authors for clarifying these points.

(8) This point is simply a matter of observation and is easily resolved. Fitches *et al.* (1986, p. 619) ascribe the "striation lineation" seen on the B-P veins to mechanical damage caused by one mineral species scratching another during movement on the detachment surface. Mechanical scratches and grooves on the vein surfaces are in fact very rare but are sometimes seen where a B-P vein has been ground and polished during late movement.

On the overwhelming majority of B-P veins the fine striations are caused by aligned quartz fibres (Fig. 1) which are usually 0.1–1.0 mm across and many cm long. The larger-scale ridges and grooves on the vein surfaces are commonly due to slickolites which have their cones aligned parallel to the quartz fibres, and have partially pressure-solved the fibre sheets. On some movement horizons the fibre sheet has been removed by erosion and only the *cast* of the vein surface remains; this can be misleading but careful observation shows that the vein is often seen still preserved at the same level in an adjoining rock face(s).

(9) The point that I was making was that it seemed surprising to me that in such diverse back-arc and

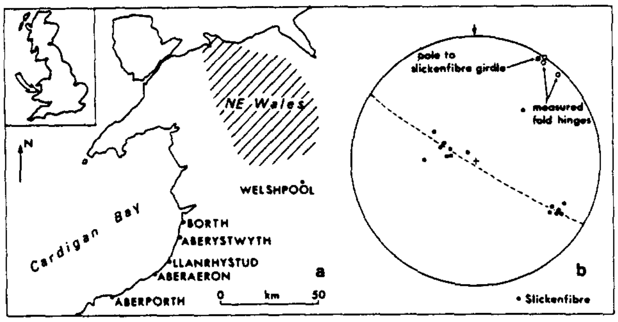

Fig. 2. (a) Localities referred to in the text. (b) Equal-area, lower-hemisphere projection of slickenfibre orientations from movement horizons on the limbs of a syncline at Aberaeron (SN 451 626).

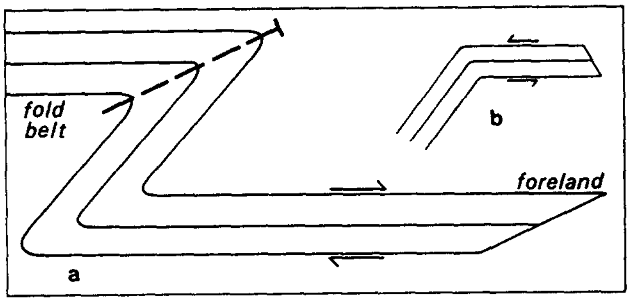

Fig. 3. (a) & (b) Simple models which show that flexural slip can be transmitted through packets of horizontal strata, (a) could be on a km scale and depict the transmission of B-P shear to horizontal strata on the foreland of an orogenic belt.

foreland basin environments, detachment horizons formed during basin subsidence should develop at a density of 1000–2000 per km of sediment thickness throughout each sedimentary sequence regardless of tectonic setting. If the process is truly universal, why have these detachment surfaces not been reported from undeformed sediments or modern sedimentary basins?

The model of a multitude of lithified slabs, separated by crack–seal B-P veins, sliding about in a complex manner and driven by gravitational forces is not one that I can easily subscribe to, but if it *were* true, and all of the B-P veins in the Cardigan Bay area, for example, were of detachment origin as proposed by Fitches *et al.*, how did the folds form? I began work on the flexural-slip mechanism by looking for the, then enigmatic, flexural-slip surfaces: in the field they can be shown to equate with those called "detachment surfaces" by Fitches *et al.*, and there are no other bedding-parallel surfaces on which flexural slip could have taken place.

CONCLUSIONS

(a) There are *at least* two different types of B-P vein in rocks of the Welsh Basin and they should be analysed and interpreted separately.

(b) B-P veins from NE Wales show clear evidence of having formed as a result of hydraulic jacking (probably during layer-parallel shortening) followed by flexural-slip, but too few quantitative field data have been published on which to base a detailed interpretation of these particular veins.

(c) B-P veins from the Cardigan Bay area have a morphology, geometry and relationship to individual folds which is entirely consistent with their having grown during flexural-slip. I have not seen any field evidence from this area to support the 'detachment' hypothesis of Fitches *et al.* (1986) which requires both hydraulic jacking *and* movement on the B-P surfaces prior to folding.

CONSOLIDATED REFERENCES

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

Fitches, W. R., Cave, R., Craig, J. & Maltman, A. J. 1986. Early veins as evidence of detachment in the Lower Palaeozoic rocks of the Welsh Basin. *J. Struct. Geol.* **8**, 607–620.

Fyfe, W. S., Price, N. J. & Thompson, A. B. 1978. *Fluids in the Earth's Crust.* Elsevier, Amsterdam.

Henderson, J. R., Wright, T. O. & Henderson, M. N. 1989. Mechanics of formation of gold-bearing quartz veins, Nova Scotia, Canada—Comment. *Tectonophysics* **166**, 351–352.

Mawer, C. K. 1989. The late-syntectonic gold-bearing quartz veins of Nova Scotia—Reply. *Tectonophysics* **166**, 352–354.

Nettle, J. T. 1964. Fabric analysis of a deformed vein. *Geol. Mag.* **101**, 220–227.

Nicholson, R. 1966. The problem of origin, deformation and recrystallization of calcite–quartz bodies. *Geol. J.* **5**, 117–126.

Nicholson, R. 1971. Tectonic ripples and associated minor structures in the Silurian rocks of Denbighshire (discussion). *Geol. Mag.* **108**, 447–449.

Sibson, R. H. In press. Conditions for fault-valve behaviour. In: Deformation mechanisms, rheology and tectonics (edited by Knipe, R. J.) *Spec. Publs. geol. Soc. Lond.*

Tanner, P. W. G. 1989. The flexural-slip mechanism. *J. Struct. Geol.* **11**, 635–655.

Warren, P. T., Harrison, R. K., Wilson, H. E., Smith, E. G. & Nutt, M. J. C. 1971. Tectonic ripples and associated minor structures in the Silurian rocks of Denbighshire (reply to discussion). *Geol. Mag.* **108**, 449–450.