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The flexural-slip mechanism: Discussion

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INTRODUCTION

We welcome the recent contribution by Geoff Tanner on this important mechanism of folding (Tanner 1989), and his drawing attention to the bedding-parallel veins we described from the Welsh Basin (Fitches *et al.* 1986). Tanner argues that such veins originated during flexural-slip folding, in contrast to our interpretation that they mostly arose during pre-folding hydraulic detachment at depth.

Although the present discussion is restricted to the examples from the Welsh Basin, the problem of the timing and mechanics of bedding-parallel vein generation is clearly a general issue (e.g. see Henderson *et al.* 1989, Mawer 1989). We acknowledge that some of the veins may be syn-folding in origin, but our observations, illustrated and discussed in detail in our original article, have forced us away from this interpretation for most of the Welsh veins. We now focus on nine particular points for discussion.

DISCUSSION

(1) The bedding-parallel veins occur in rocks that are not folded. Completed undeformed rocks are uncommon in Wales because of the widespread tectonism, but they occur in flat-lying and virtually undeformed strata, and can be seen persisting for tens of metres—as much as the exposures allow—without any sign of folding. Although some of the observations that follow could conceivably be explained by invoking special geometries of flexural-slip, they are inapplicable to rocks that are not folded.

(2) Some of the veins have complex but regular internal textures that cannot be explained by the flexural-slip past local "surface asperities" invoked by Tanner. For example, a single vein can comprise numerous alternating and laterally continuous ribbons of calcite, quartz and opaque material (Fig. 1a), with crystals oriented perpendicular to the vein wall (Fig. 1b) and crack–seal textures parallel to the vein walls. The arrangement is wholly in accord with the bedding-normal dilation that hydraulic jacking would cause.

(3) Many of the veins are cleaved and have been buckled by minor folds during the regional deformation (Figs. 1c & d). While a hinge migration process may explain some instances of a vein passing round a fold hinge, our examples were series of folds on the scale of less than 1 m, which allowed close examination of particular veins as they continued throughout an entire fold train. There are numerous instances of striated and cleaved veins passing from fold limbs over successive hinges without any change of character or of the intensity of development that would result from hinge migration.

(4) Tanner gives no explanation for the suite of structures associated with the bedding-parallel veins, such as tension-gash arrays, breccia zones and bedding-normal veins, all of which we demonstrated (Fitches *et al.* 1986) to be an integral part of the detachment process.

(5) The striations make variable angles with the fold hinges. Tanner outlines possible relationships between the fold hinge and the movement horizon during flexural-slip which are plausible in principle, but which depend heavily on the folding being non-cylindrical. Although this is a well-known feature in west Wales, the examples we described of bedding-parallel veins de-

formed by cylindrical coaxial folds require the veins to be genetically independent of the folds.

(6) Striations on successive laminations within a vein differ in orientation. Even allowing for special non-cylindrical geometries, it is difficult to explain by a folding mechanism the numerous extensive planar sheets of perfectly linear striations that abruptly change to another consistent orientation on the adjacent lamina.

(7) Tanner alleges a problem for our model in explaining how sands and muds can sustain brittle fracture and allow fibre-growth. Even if that were the scenario we suggested there would be no difficulty. However, nowhere in our article did we invoke unlithified material and nowhere did we report fibre-growth. We showed that diagenesis *preceded* detachment and stated that "no maximum depth can be inferred". We did not say that the detachment was syn-depositional: we made it clear that movements such as slumping are substantially earlier than detachment. The detachment processes are viewed as being integral parts of basin subsidence, but that is not to equate them with sedimentation.

(8) Tanner's discussion of fibre-growth seems of little relevance, at least to his Cardigan Bay study area, because bedding-parallel fibres are not a normal feature there. The lineations on the vast majority, if not all, of the veins are surface striations.

(9) Tanner's "most telling observation" in favour of a flexural-slip origin for the veins is that the same features occur in rock sequences of different age deposited in *different sedimentary environments* (Tanner 1989, p.652, his italics). However, the rocks of the three areas he describes are all turbidites of similar lithologies and bedding characteristics. It is these factors that are relevant in the present context. The logic that these features were important in inducing flexural-slip in all three areas holds equally for their potential role in influencing processes such as dewatering, diagenesis, overpressuring and initiation of detachment horizons. The fact that unlike the Lower Palaeozoic Welsh Basin rocks the North Devon veins are Carboniferous, or that the South Georgia Basin closed in mid-Cretaceous times seems much less relevant to understanding the deformation than the similar mechanical characteristics of the three rock successions.

CONCLUSION

Because of the awkwardness of explaining the above observations by flexural-slip, especially when they are taken together, we were led to an interpretation involving gravitational detachment at depth on very slight but varying slopes, prompted by overpressuring and hydraulic jacking, and largely *succeeded* by folding and cleavage. This model explains all the observations in a much simpler way than having to invoke the host of elaborate special cases that the flexural-slip interpretation requires.

Tanner acknowledges that "pre-tectonic quartz veins" do exist in the rocks, at least in South Georgia, and he allows for "episodic hydraulic fracture" as a vein-generating mechanism. Theory predicts that hydraulic detachment should arise in sedimentary piles (e.g. Fyfe *et al.* 1978, Sibson in press) and our observations on the bedding-parallel veins indicate that it did indeed take place, at least in the Welsh Basin.

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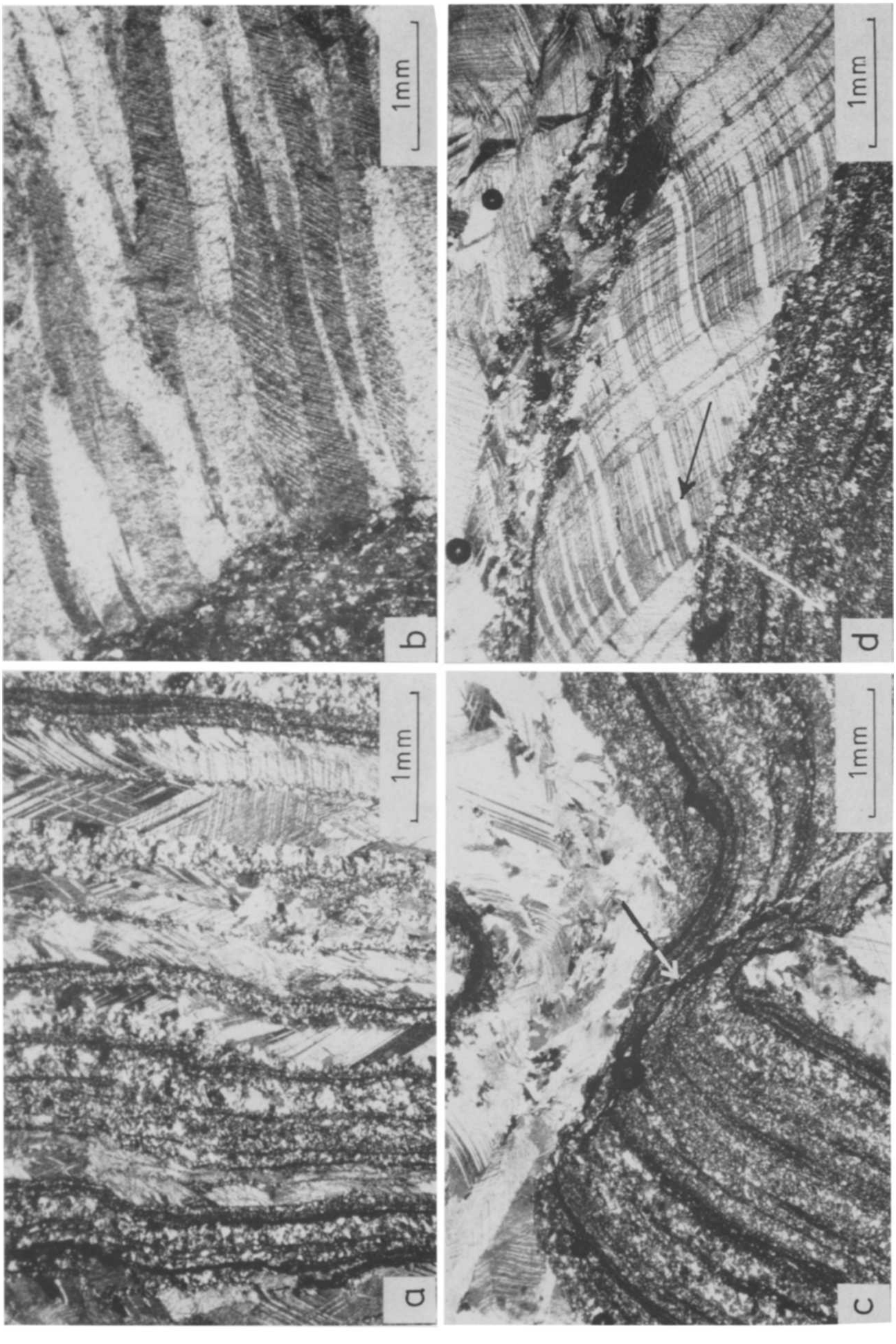
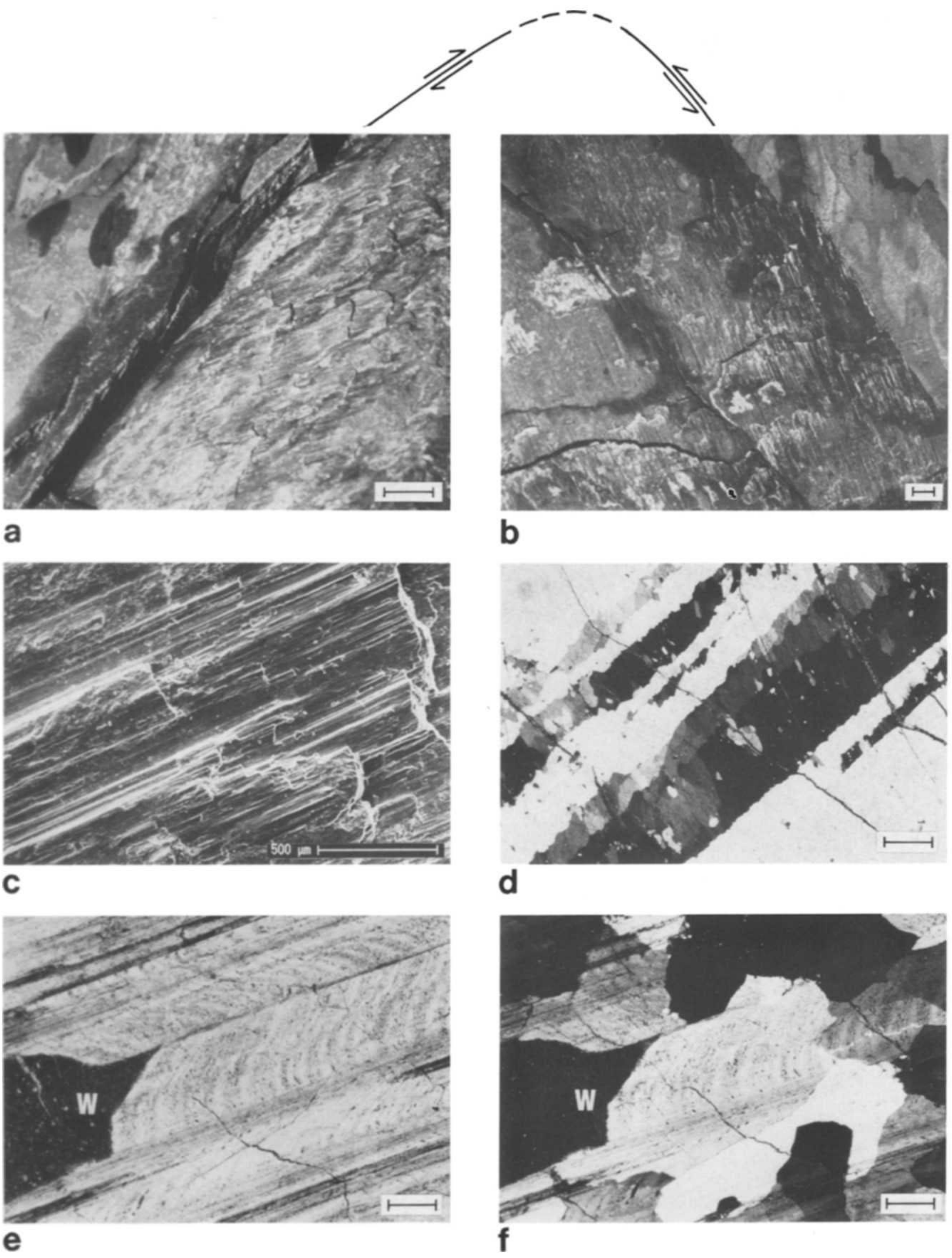
Fig. 1. Photomicrographs of vein details. (a) Composite fabric of the veins. Note the numerous alternations of layers of calcite, quartz and opaque material, of various grain sizes. The hydraulic detachment model explains these observations by fluctuating physico-chemical environments during episodic hydraulic jacking. Gorsedd-Bran, Clwyd (SH 966605). (b) Fibre-growth normal to vein margins. Calcite fibres are oriented perpendicular to the vein wall, seen to the lower left. The fibre orientation is consistent with the hydraulic jacking model, but not with parallel wall slippage due to flexural slip. Welshpool, Powys (SJ 194135). (c) Pre-folding age of the veins. Part of a single vein with multiple layers of fine quartz and opaque material flanked by layers of coarse calcite. The whole vein is folded, and transected by pressure solution seams (an example visible here is arrowed). Locality as (a). (d) Pre-folding age of the veins. Part of a folded vein, showing multiple layers and calcite twin lamellae displaced (example arrowed) when the vein was folded. Locality as (a).



(Fig. 1 of Fitches *et al.*)



(Fig. 1 of Tanner)

Fig. 1. (a) & (b) Movement horizons (B-P veins) with fibre steps which indicate a reversal of slip movement across the anticlinal hinge at Aberaeron. Scale bar = 1 cm. (c) Electron photomicrograph showing the external morphology of quartz fibres on a B-P vein from Aberaeron. (d) Photomicrograph (CN) of quartz fibres from the specimen in (c), sectioned parallel to the plane of the vein. (e) Photomicrograph (PPL) showing that quartz fibres sectioned in the plane of a B-P vein from Llanrhystud (SN 535 707) preserve inclusion bands and have grown by crack–seal accretion from the country-rock (W) contact. (f) Photomicrograph of (e) under CN to show that the originally fibrous quartz has been recrystallized to form an equigranular mosaic. Scale bars in (c)–(f) are 500 μm long.