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

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Abstract—In this paper, field evidence is presented to support the idea that fluid pressures in excess of lithostatic pressure were operating during the initiation and reactivation of large thrusts and folds in the Wenlock shales of Llangollen, North Wales. It is also argued that as major thrusts are reactivated and as major folds amplify into finite structures they in turn exert an influence on the subsequent migration and concentration of fluids within the deforming sedimentary succession.

INTRODUCTION

Models proposed for the reactivation of faults (e.g. Sibson *et al.*, 1975, 1988) indicate that reshear along a fault occurs in a series of stick–slip movements and that there is an intimate association between fault reactivation and the migration of large quantities of fluid along the fault.

These ideas are broadly compatible with the conclusions drawn from a detailed study of composite veins formed parallel to the bedding planes in the Wenlock slates north of Llangollen, North Wales, which indicate that as the sedimentary succession compacted and was subjected to a tectonic compression the pore fluid pressure increased until it was of sufficient magnitude to cause the formation or reactivation of a bedding plane thrust by hydraulic fracturing. A study of these veins indicates that movement on the thrust drove the fluids from the slip zone and the resulting drop in fluid pressure caused the thrust to lock up temporarily. Continued action of the applied stress caused the fluid pressure to increase again until the conditions for hydraulic fracturing were reestablished and the process was repeated.

It is argued that a similar process will accompany the amplification of large folds in a sedimentary pile. The folds will grow incrementally by a series of stick–slip movements along the bedding plane associated with the build up and release of fluid pressures. The distribution of mean stress within and around a fold has also been determined theoretically (Summers 1979) and it is clear that during the early stages of fold amplification the mean stress gradients draw fluids into the growing fold from the surrounding rock. At some critical point in the fold's amplification the gradient is reversed and further fold growth drives fluids out of the fold.

Thus the combined effect of thrust and fold development considerably influences the migration and concentration of fluids in a sedimentary sequence. It is suggested that the 'pumping' effect of both these structures will in turn help to generate other folds, thrusts and fractures.

The paper begins with a brief discussion of the ideas that have led to the association between high fluid pressures and thrusting and this is followed by a description of field evidence that support this.

THE ASSOCIATION OF THRUSTS AND HIGH FLUID PRESSURES

The recognition of overthrusts, large blocks of rock up to 10 km thick, and with lengths and widths often in excess of 100 km, which had been transported tens of kilometres along sub-horizontal fault planes, presented geologists with the challenge of understanding the mechanism by which these blocks were moved. An early study of this problem was carried out by Smoluchowski (1909) who represented the overthrust block as a simple rectangular prism caused to move over a flat, dry surface by the application of a horizontal push from one end. By selecting appropriate values for the coefficient of sliding friction and rock strength it can be shown that overthrusts with lengths greater than a few tens of kilometres cannot be moved by this mechanism unless the applied stress exceeds the strength of the rock. Although alternative mechanisms were suggested (e.g. Oldham 1921) they were either not widely known or not considered to be acceptable solutions to the overthrust 'paradox', and it was not until 1959 that the mechanical problems associated with the movement of large-scale thrusts were satisfactorily solved by Hubbert & Rubey (1959). These authors argued that the existence of high fluid pressures would reduce the effective normal stress across a potential thrust plane and thus reduce the horizontal compressive stress necessary to move the thrust to below the brittle strength of the rock. This idea represented a major step forward in the understanding of the generation and movement of large overthrusts and, following this work, the association of overthrusting and high fluid pressures became almost axiomatic.

However, the overthrust 'paradox' has recently been reassessed (Price 1989) and this association questioned. The mechanism suggested by Oldham (1921) who argued that an overthrust may not move en masse as is

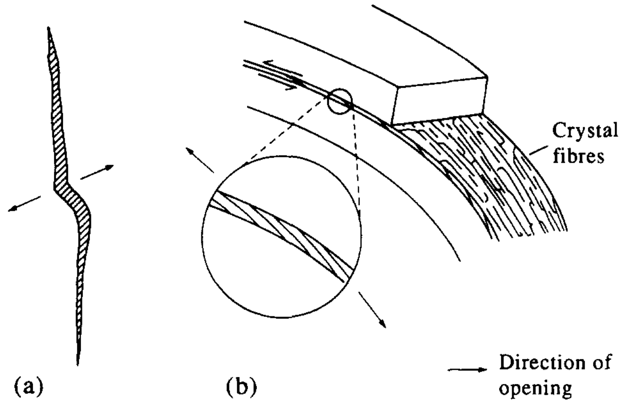

Fig. 1. (a) Vein containing crystal fibres which grew parallel to the direction of opening of a vein. (b) Crystal fibres growing on a bedding plane during either bedding-plane thrusting or flexural-slip folding. A large component of bedding-parallel slip is accompanied by a small component of bedding-plane separation.

assumed in the model proposed by Smoluchowski but a small portion at a time in a caterpillar-like manner, is now looked upon more favourably. This process is analogous to the movement of an edge dislocation through a crystal. The shear stress required to move the dislocation through a crystal (the Peierls–Nabarro stress) is much smaller than the theoretical shear stress necessary to cause slip on the lattice planes. If overthrusts move by a similar mechanism then overthrusts with the dimensions observed in nature could be moved at stresses below the strength of the rocks making up the overthrust without the need for high fluid pressures.

Nevertheless, even though it seems that high fluid pressures may not be an essential prerequisite for thrusting there is no doubt that high fluid pressures will facilitate thrusting and that thrusting and high fluid pressures are frequently found in close association.

For example, the section through the accretionary prism in Taiwan described by Suppe (1985) shows clearly that the thrust trajectories have been guided and constrained by the overpressured horizons. In addition it is known that once formed, these thrusts act as channels along which large volumes of fluid escape from the prism.

FIELD EVIDENCE FOR HIGH FLUID PRESSURES DURING BURIAL, THRUSTING AND FOLDING

It can be argued (see for example Henderson *et al.* 1990) that if the least principal stress is vertical and the pore fluid pressure equals or exceeds the lithostatic pressure the fluid may jack open the bedding planes and locally reduce the effective body weight (the weight of overburden minus the fluid pressure) to zero. In order to find field evidence of this having occurred it is necessary to examine rocks in which any hydraulic fracturing has been preserved as a vein system.

A study of crystal fibres in veins indicates that the fibres grow parallel to the direction of opening (Fig. 1a). If this conclusion is correct then the existence of 'beef' (a fibrous form of calcite) along horizontal bedding planes (Fig. 2a) indicates that the beds overlying the beef were moved vertically away from the underlying beds during the emplacement of the beef. It seems probable that the veins were formed by the jacking open of the beds by high fluid pressure (λ, the ratio of the fluid pressure to the vertical rock pressure, ≥ 1) and the precipitation of the vein from this fluid. The example of 'beef' illustrated in Fig. 2(a) shows that the overburden was lifted vertically by approximately 3 cm. An even more convincing illustration of λ values of 1 or more is given in Fig. 2(b), which shows Keuper Marl cut by numerous sub-horizontal veins of satin spar (a fibrous form of gypsum). Although the orientation (dip) of the veins is quite variable the orientation of the infilling fibres is always vertical. This is exactly what would occur if the fractures were opened by a fluid pressure of sufficient magnitude to overcome the overburden pressure.

The evidence discussed in the previous paragraph and illustrated in Figs. 2(a) & (b) relates to tensile fracture by high fluid pressures. However, it can also be argued that high fluid pressures may play an important role in shear failure, as for example in the initiation of bedding-plane slip either during thrusting or flexural-slip folding and that in addition the formation of both large thrusts and folds causes the migration of fluids through a sedimentary sequence in a series of pulses. It is therefore necessary to consider what field evidence exists for the occurrence of these injections. This evidence takes the form of well-developed vein systems, an excellent example of which can be found in the Wenlock slates north of Llangollen, Wales, on the northern limb of the Llangollen synclinorium.

This structure is part of the Caledonian thrust–fold belt of North Wales. It has a wavelength of about 20 km, an E–W-trending axial trace, plunges gently to the east and has an axial plane dipping steeply to the north. The veins are found parallel to the bedding planes in minor folds (wavelengths of approximately 100 m) which are exposed in the slate quarries of the Horse Shoe Pass (Fig. 3a). The veins are composite, i.e. made up of numerous layers of crystal fibres of either calcite or quartz. The fibres are approximately parallel to bedding and are now folded into micro folds whose axes are approximately normal to the length of the fibres and parallel to the axes of the minor folds (Figs. 3b & c). The crystal fibre multilayers can be traced over the hinges of the minor folds and show no thinning in these regions. The bedding-plane slip with which these fibres are associated therefore pre-dates the folding and probably relates to thrusting.

A similar sequence of thrusting followed by folding can be observed in the shales (now slates) of the Hercynian thrust–fold belt of North Devon. Here, bedding-plane thrusts overlain by composite veins of crystal fibres can be traced around minor folds with wavelengths of approximately 20 m. The composite veins are small-scale multilayers which, like their counterparts in North Wales (Figs. 3b & c), buckle with a wavelength of a few centimetres. These small folds change their sym-

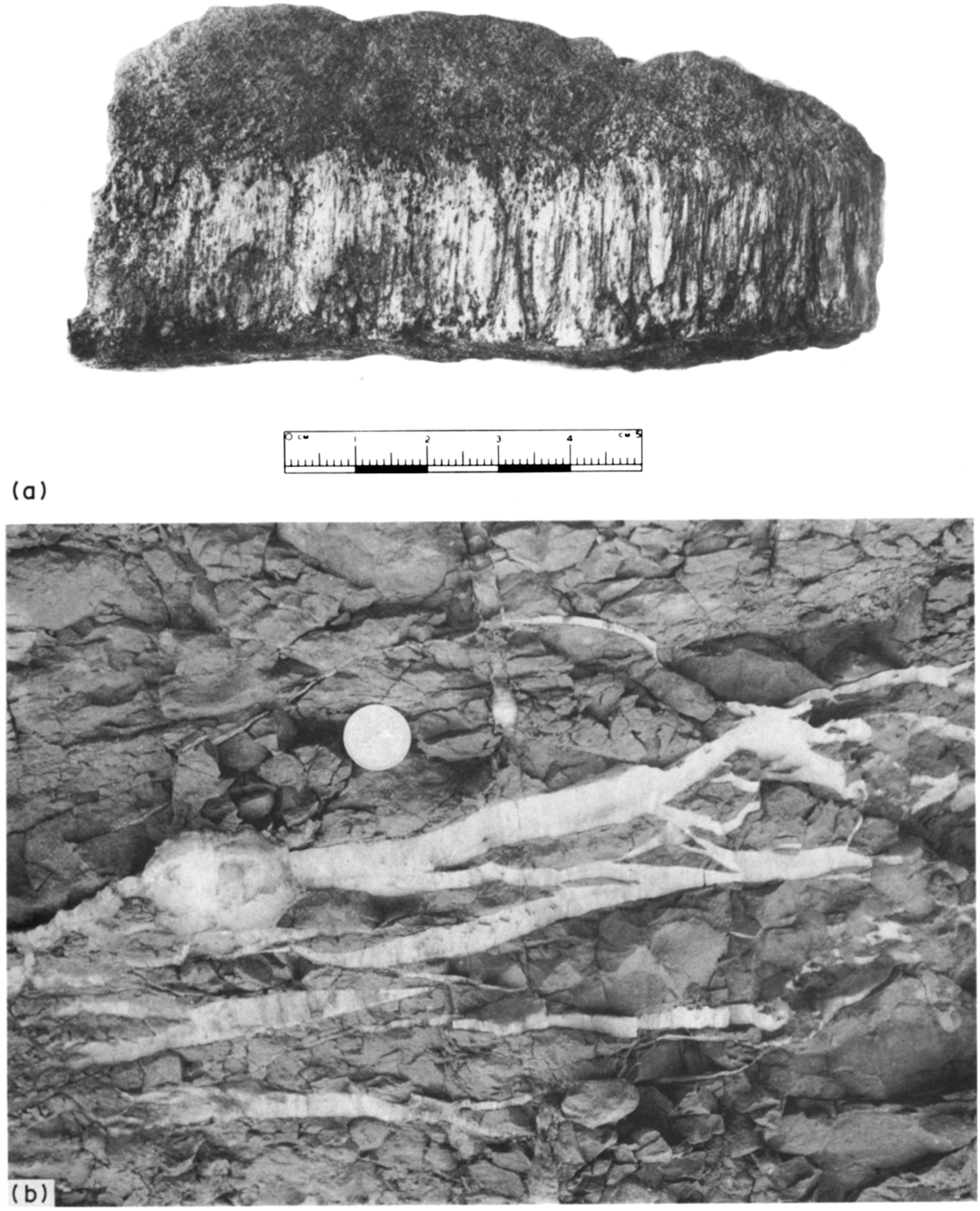

Fig. 2. (a) 'Beef' from the Jurassic rocks of Lulworth Cove, southern England. The crystal fibres form normal to the bedding. (b) Satin spar, a fibrous form of gypsum, infilling sub horizontal fractures in the Keuper marls at Aust Cliff, Bristol Channel, England. Despite the variation in dip of the fractures the crystal fibres are always vertical.

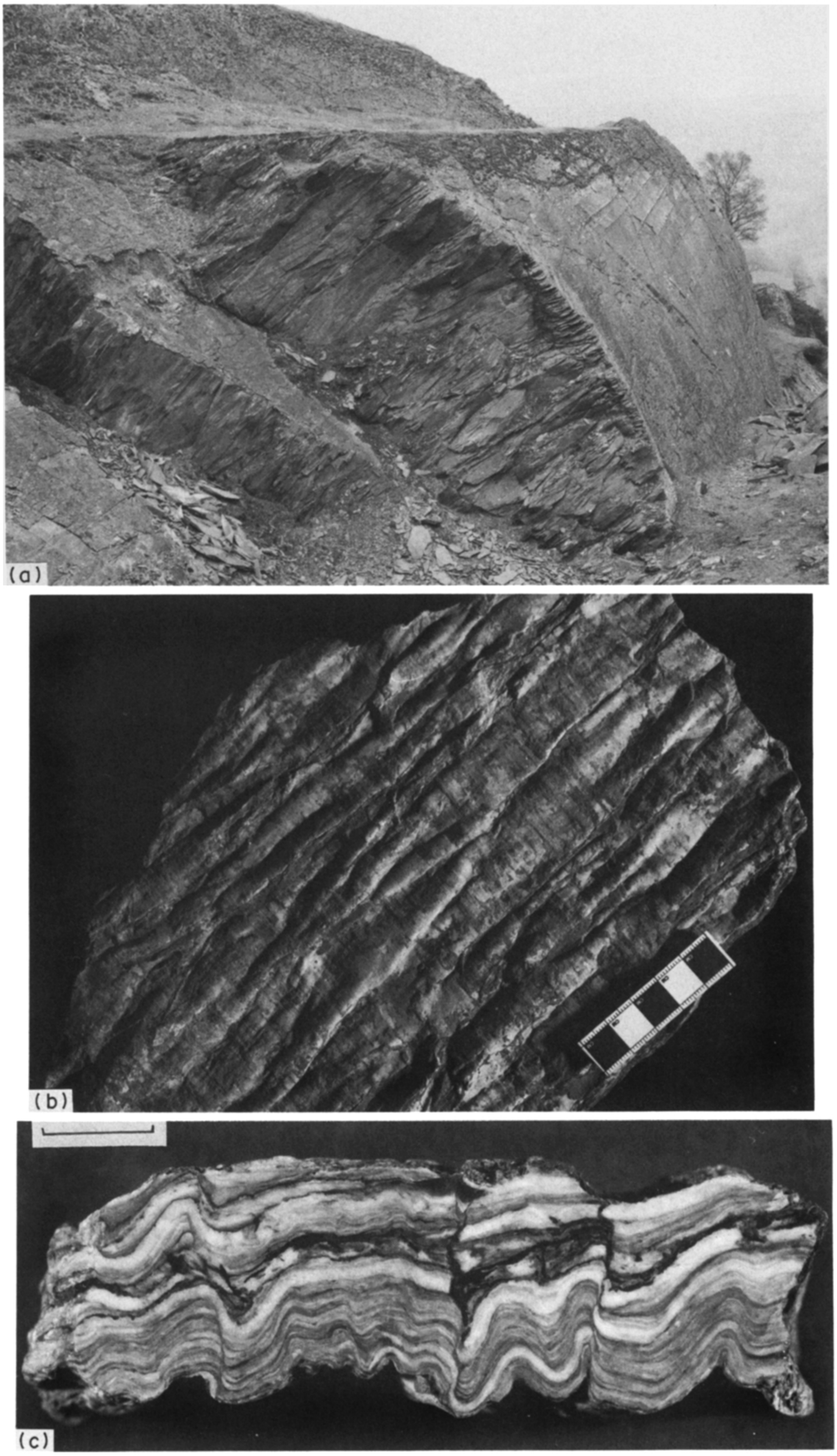

Fig. 3. (a) Minor fold with a wavelength of 25 m in the Pant Glas quarry, north of Llangollen, Wales. (b) Plan view and (c) profile section through minor folds which have formed in a multilayer of crystal fibres found sub-parallel to the bedding planes. Note (in b) that the fold axes are approximately normal to the fibres. Scale bar in (c) is 1 cm.

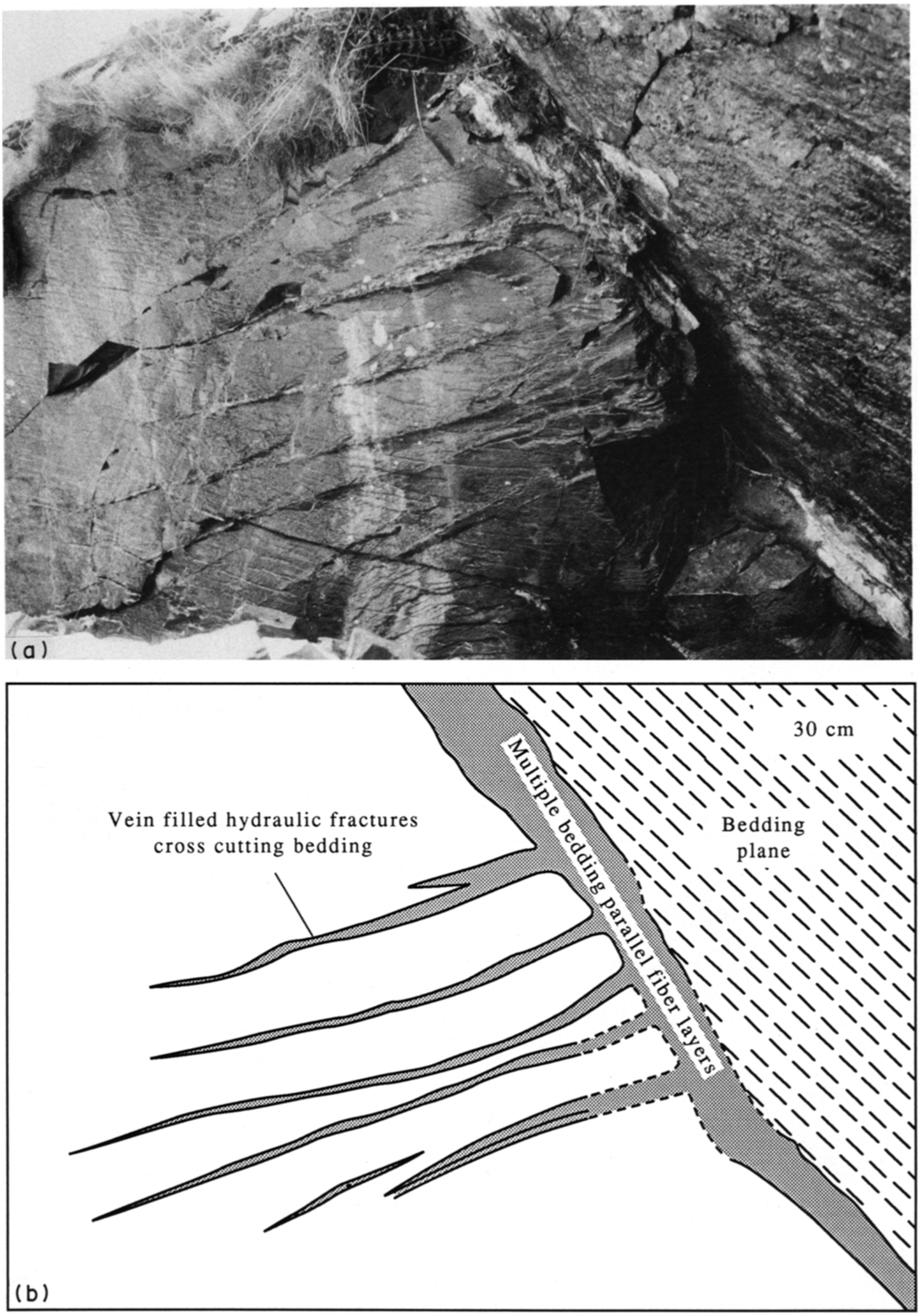

Fig. 5. (a) Veins cutting across the bedding. These veins fill hydraulic fractures initiated by high fluid pressures acting along the bedding planes on which the composite veins of crystal fibres occur. Note that the cross-cutting veins thin and die out when traced away from the composite veins. (b) Line drawing of (a). Width of diagram = 2 m.

metry when traced over the hinge of one of the larger folds (Fig. 4) indicating clearly that they were generated during the post-thrust folding.

It was noted earlier that the crystal fibres of the individual layers making up the composite veins are approximately parallel to bedding. Most fibres are in fact inclined at a few degrees to bedding. The implication of them being at a low angle to bedding rather than parallel to it is that, as well as indicating that a considerable amount of bedding-plane slip took place during thrusting, they also indicate that a small component of opening normal to bedding occurred (Fig. 1b).

In both the Hercynian and Caledonian thrust–fold belts mentioned above the individual layers of fibres making up the composite veins are often separated from each other by a thin slice of country rock (Fig. 3c). It seems likely that each layer of fibres is associated with a single episode of hydraulic fracturing and an increment of shear movement during which the crystal fibres grow. The dissipation of the fluid pressure during bedding-plane slip eventually inhibits further slip and the newly formed fibres effectively 'seal' the bedding plane at the site where the hydraulic fracturing occurred. Subsequent increments of movement therefore occur along new hydraulic fractures which form parallel to bedding in the country rock (a finely laminated pelitic rock)

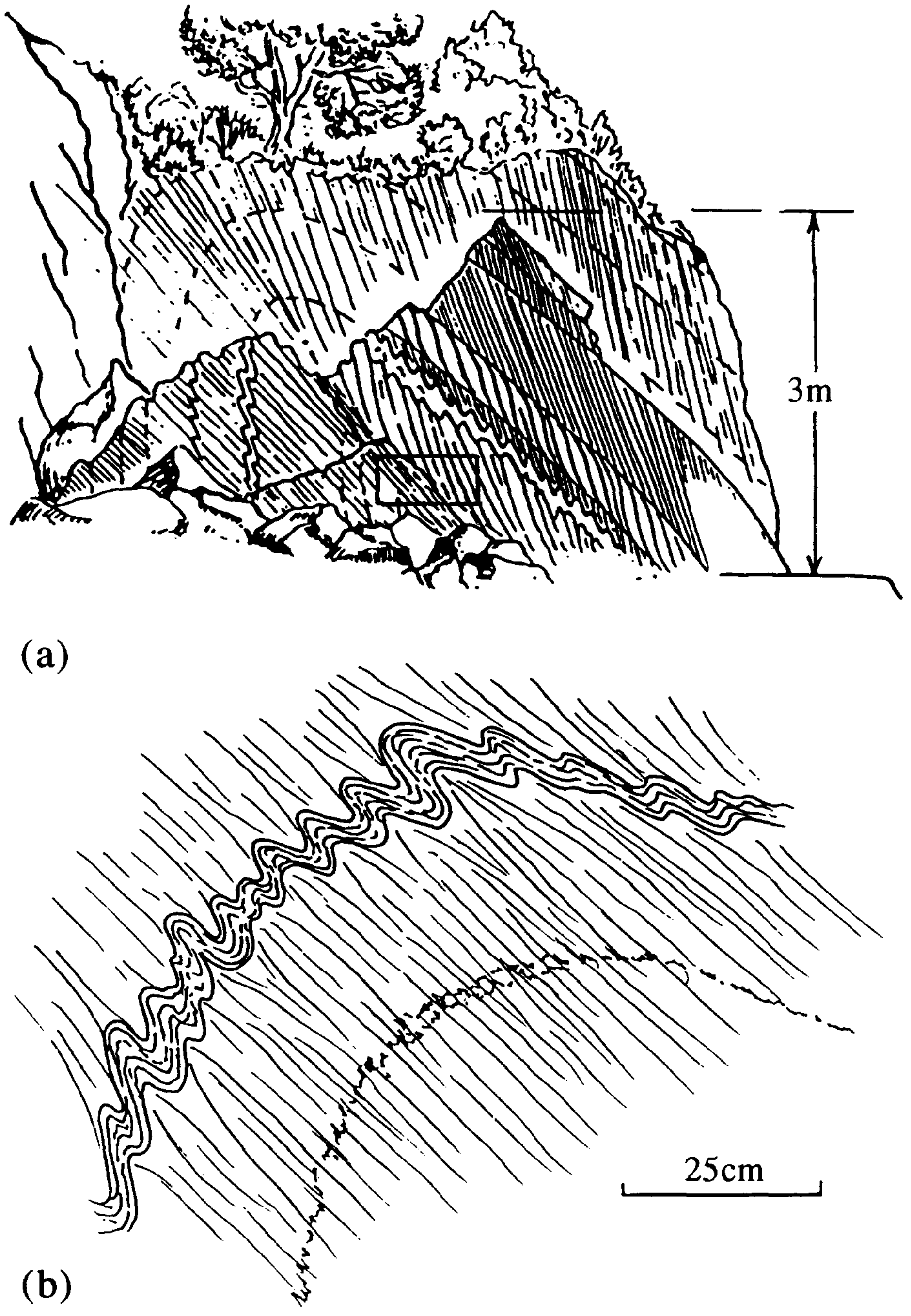

Fig. 4. (a) Fold in the Devonian metasediments of Combe Martin, Devon (after Wilson 1961, reproduced with permission). (b) detail of (a) showing a composite vein of crystal-fibre horizons folded around the fold. The change in symmetry of the minor folds in the composite vein when traced over the hinge of the larger fold indicates that the vein predates the large fold.

immediately adjacent to the existing layer of fibres leaving a thin film of rock between the old and new slip plane. Thus as a result of this process of slip–seal, a considerable thickness of fibres is built up, each layer sandwiched between slivers of country rock (Fig. 3c).

Further evidence of high fluid pressures having existed along the bedding planes is provided by the quartz and calcite veins which emanate from the crystal fibre horizons and which cut across bedding (Fig. 5). These veins thin as they are traced away from the fibre horizons and probably represent infilled hydraulic fractures formed by the (transient) high fluid pressures that existed along the slip planes.

It is difficult to determine the rate at which hydraulic fracturing and fluid migration occurred during the formation of the individual fibre horizons which make up the composite veins. A study of thin sections of the fibres show that they formed by 'continuous growth' rather than by the process of 'crack–seal', indicating that the crystal growth kept pace with fracture opening. Although it is not yet possible to quantify the rates at which these processes occur it is clear that hydraulic fracturing need not occur rapidly. Indeed, movement along the thrusts may have occurred aseismically.

The insight into the hydrodynamics of rock deformation provided by these vein systems can be extrapolated to deformation that occurs at shallower depths in the crust where conditions are not appropriate for the formation of veins. Thus although high fluid pressures undoubtedly play an important role in both dewatering and deformation in the upper levels of the crust, many hydraulic fractures will close and 'heal' after fluids have been injected along them, leaving no trace.

THE MIGRATION OF FLUIDS DURING THRUSTING AND FOLDING

Although Hubbert & Rubey's (1959) work on high fluid pressures provided a great insight into the role that fluid pressure may play in thrust initiation, it says nothing about the migration of fluids during thrusting.

The migration of fluids along major faults during and immediately after reshear has been discussed by Sibson *et al.* (1975) who introduced the idea of seismic pumping. This concept sprang from observations of hydrothermal vein deposits found in the upper, brittle regions of ancient fault zones. The textures of these deposits usually indicate that mineralisation took place episodically and it was suggested that the episodic injection of hydrothermal fluids could be accounted for by the dilatancy–fluid diffusion model for energy release in shallow earthquakes proposed by Scholz *et al.* (1973). In later papers, Sibson *et al.* (1988) and Sibson (1990), proposed two other mechanisms, the suction-pump and fault-valve mechanisms which also predict periodic variations in fluid pressure along faults associated with fault reactivation.

In contrast, the migration of fluids in association with the development of folds has received comparatively little attention. It is however possible to determine the stress gradients within and around a fold from the equations that govern the buckling behaviour of anisotropic bodies such as accretionary prisms and other sedimentary sequences. They show that there is a difference between the mean stress inside and outside a fold and that this difference (i.e. the stress gradient) changes as the fold amplifies. For a box fold the gradient is initially such that fluids are drawn into the fold from the surrounding region. However, beyond a certain amplification the gradient is reversed and fluids are driven out of the fold. This process can be inferred from the geometric changes that accompany the amplification of a kink-band in a layered material where the layers maintain a constant thickness during the deformation (Figs. 6a–c). Initially there is an increase in volume within the

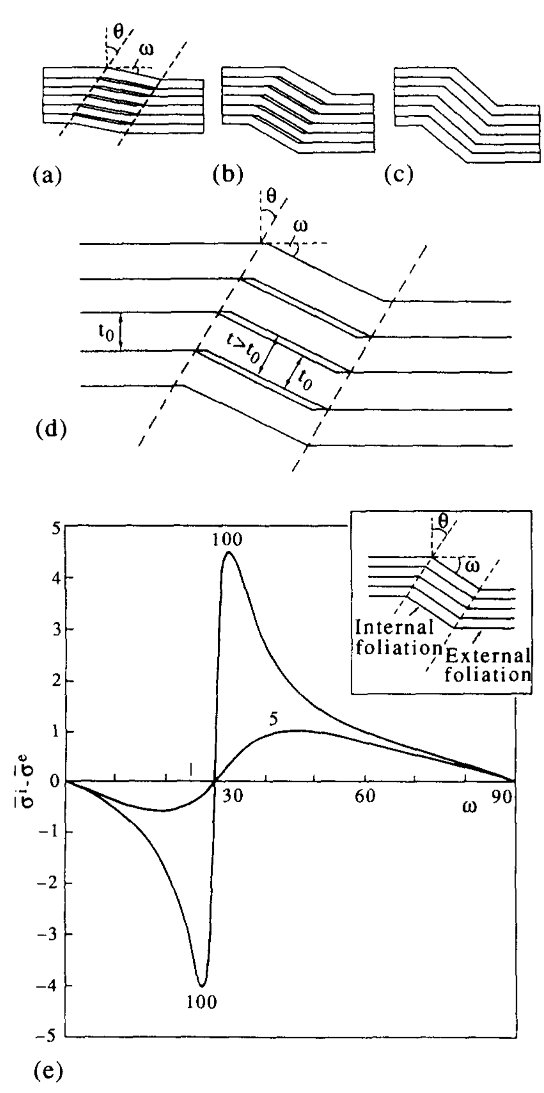

Fig. 6. (a)–(d) Volume changes that accompany the amplification of a kink-band. During the early stages the volume increases and fluids are drawn into the fold (stages a–b). However, as the structure amplifies beyond the stage, where $\omega = \theta$ (b), the volume decreases and fluids are expelled. (d) detail of (b) showing the dilation within the kink-band. t_0 = thickness of layering. (e) The graphical expression of equation (1) showing the relationship between the difference in mean stress inside ($\bar{\sigma}_i$) and outside ($\bar{\sigma}_e$) the kink-band and the orientation (ω) of the foliation within the kink-band. Graphs for materials with anisotropies (N/Q) of 5 and 100 are shown (e after Summers 1979, reproduced with permission).

kink-band. This continues until the layering inside the kink-band is normal to the kink-band boundary, i.e. $\omega = \theta$ (Fig. 6b), when it reaches a maximum. Up to this point fluids will be drawn into the fold from the surrounding, unfolded region. As the kink-band amplifies beyond this point the volume of the kink-band is reduced and fluids will be expelled from the fold. When $\omega = 2\theta$ (Fig. 6c), the volume of the kink-band is the same as it was before the fold was initiated. Any further amplification would require the layering inside the kink-band to thin and if there is no mechanism by which this thinning can be achieved, the fold locks up.

The magnitude of the stress gradient between a fold and its surroundings has been quantified by Summers (1979) who shows that the difference in mean stress inside ($\bar{\sigma}_i$) and outside ($\bar{\sigma}_e$) a fold is given by

$$\bar{\sigma}_i - \bar{\sigma}_e = \tau_e^m \left[\frac{(N/Q - 1)\{\cos 2\theta - c\,2(2\omega - \theta)\}}{(N/Q + 1) - (N/Q - 1)\cos 4(\theta - \omega)}\right], \qquad (1)$$

where θ and ω are as defined as in Fig. 6(d), N and Q are measures of the resistance to compression and shear, respectively, in the direction of the applied principal stress and τ_e^m is the maximum shear stress in the layering adjacent to (i.e. outside) the fold. The variation in mean stress gradient as the fold amplifies can be clearly seen by expressing equation (1) graphically (Fig. 6e). As the fold begins to amplify, there is an increase in the stress difference which would tend to draw fluids *into* the fold. The stress difference rises sharply until the layering inside the kink-band is normal to the kink-band boundary ($\omega = \theta$). The gradient then drops dramatically and reverses so that a large gradient is established which will tend to drive fluids *out of* the fold as it continues to amplify.

During the buckling of a complex multilayer, that is a multilayer made up of a variety of different rock types and layer thicknesses, the individual layers will attempt to develop their own characteristic wavelengths. However, the multilayer will impose its own characteristic wavelength onto these layers and, as they accommodate themselves to the multilayer wavelength, they often develop second-order structures known as accommodation structures (Ramsay 1974, Price & Cosgrove 1990, pp. 319–321). These structures, which form predominantly in the hinge region of the fold, may be either ductile or brittle (Figs. 7a–d). In addition to accommodation structures, the high stresses generated in the inner and outer arcs of the hinge region often lead to localized brittle failure. These fractures, combined with the brittle accommodation structures shown in Figs. 7(b)–(d), can dramatically increase the permeability of the hinge regions which become channels of relatively easy fluid migration. Thus, during the expulsion of fluids from the fold during the late stages of its amplification in response to the stress gradients illustrated in Fig. 6(e), the fluids are likely to be expelled along these zones of high, fracture-induced, permeability.

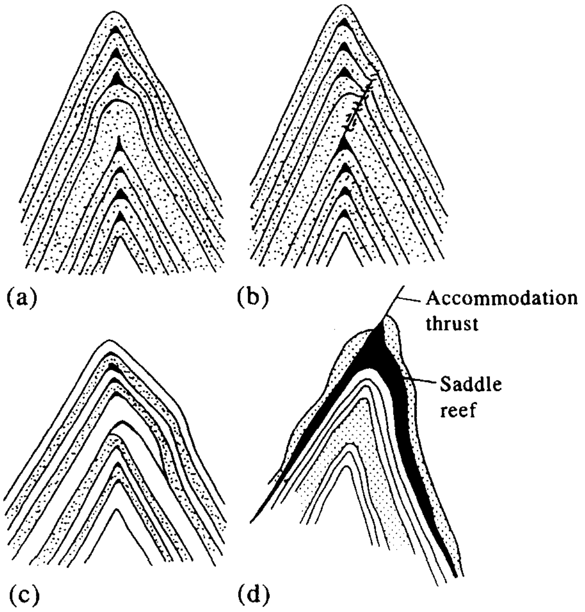

Fig. 7. (a)–(d) Various accommodation structures that develop during multilayer buckling as layers with anomalous thicknesses adjust to fit into the overall wavelength and amplitude of the multilayer buckles. These may considerably increase the permeability of the hinge region of the fold (a & b after Ramsay 1974, c after Price & Cosgrove 1990, p. 320 and d after Herman 1923—reproduced with permission).

DISCUSSION

The composite crystal veins discussed earlier provide evidence to indicate that in some situations bedding plane-parallel thrusts may be initiated or reactivated by high fluid pressures which jack the beds apart by hydrofracture as they slide past each other.

It is suggested that once the hydraulic fracture has occurred, the resulting lens of fluid will be driven along the bedding plane in a manner analogous to an edge dislocation being driven along a lattice plane in a crystal subjected to a shear stress. As the fluid lens is driven away from the site of initial hydraulic fracturing, bedding-plane slip ceases at this locality and the system locks up. Reshear will occur only when the deformation processes have re-established the fluid pressure necessary to regenerate hydraulic fracture. Thus movement of the thrust will occur in a stick–slip manner.

The movement of tectonically driven fluids along a fracture system in a deforming accretionary complex has been considered by Vrolijk (1987). On the basis of a fluid inclusion study he was able to demonstrate that there was a 20–45% drop in fluid pressure during the growth of quartz in syntectonic extensional veins. He argues that this pressure drop is probably the result of the relatively rapid expulsion of fluids along an interconnected fracture network.

It has been argued by Price & Cosgrove (1990, pp. 367–384) that like thrusts, large folds are likely to be initiated at local sites of hydraulic fracture that form parallel to bedding in areas of relatively low bedding-plane cohesion. At these locations a lens of fluid will form along the bedding plane which jacks the beds apart, reducing the effective stress across the bedding plane to zero.

As these folds amplify by the process of flexural-slip, bedding-plane slip and fluid flow will occur. Multiple layers of crystal fibres found on bedding planes on the limbs of such fold indicate that the slip occurred in a series of pulses associated with the build up and dissipation of fluid pressures. During flexural-slip folding bedding-plane slip is greatest at the inflection point and decreases to zero at the hinge. It is suggested that the process of bedding-plane slip which accompanies flexural-slip folding is directly analogous to slip on thrusts discussed above, i.e. bedding-plane slip occurs in a series of pulses (stick–slip) and during each pulse fluid is ejected from the area of local slip towards the hinges. Bedding-plane slip during folding could thus produce a local migration of fluids within the fold from the limbs to the hinge regions.

It follows that during folding there will be a local migration of fluids within the fold from the limbs to the hinges associated with episodes of bedding-plane slip, together with a migration of fluid in and out of the fold associated with the stress gradients defined by equation (1) and illustrated in Fig. 6(e).

If the concept of stick–slip movement along the bedding planes during flexural-slip folding is valid (and the multiple crystal fibre horizons found on folded bedding planes and formed during the folding indicate that it is) then the implication is that the folds amplify in a series of pulses rather than in a smooth and gradual manner. Immediately after an increment of amplification a stress gradient would be established and fluid would migrate either into or out of the fold depending on the limb dip, ω (Fig. 6e). The gradients and associated migration would gradually decay until the next increment of fold amplification reestablished a stress gradient and the process was repeated. It is not difficult to envisage the formation of several cross-cutting generations of hydraulic fractures and veins as these pulses of fluid flow into and out of the fold.

CONCLUSION

The evidence from the study of composite calcite veins formed parallel to bedding during the thrusting of the Wenlock shales north of Llangollen, North Wales, indicates that movement occurred in a series of pulses and was associated with high fluid pressures ($\lambda \geqslant 1$).

Composite horizons of slickensides found on the limbs of large box-folds indicates that the bedding-plane slip that occurs during their formation also occurred in a similar, stick–slip manner. In addition the stress distribution within and around an amplifying box-fold shows that initially fluids will be drawn into the structure but at some critical stage in its amplification will begin to be expelled.

Thus in a deforming sedimentary succession both folding and thrusting can be expected to cause episodic variations in pore pressure and stress. The expulsion of fluids along thrusts and out of folds as they lock up may help to generate new structures in the adjacent relatively undeformed parts of the succession.

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