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Strains developed in the hangingwalls of thrusts due to their slip/propagation rate: a dislocation model

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Abstract—Fault planes propagate radially from a point source and this failure propagation process is very similar to the movement of a dislocation through a crystal lattice. An elastic strain represented by an extra half plane is necessarily imparted to the lattice at an edge dislocation, and this is equivalent to the ductile bead which accompanies the propagating tip of a thrust fault. This ductile bead migrates with the fault tip, and imparts a characteristic internal strain to the thrust sheet. A two-dimensional model is presented to illustrate the inter-relationship between fault plane slip, fault tip propagation and internal strain. In multilayered sequences, internal strain is usually represented by asymmetric folds verging in the thrust transport direction. A simple technique, the displacement/distance plot utilizes the fact that displacement dies out towards the fault tip. This plot can be used to quantify the relative stretch, measured parallel to the fault movement, which is dependent on the slip/propagation rate, and it may be used to define exactly the position of the fault tip on a cross-section. Examples of fold-thrust structures from Devon (England) and Pembrokeshire (Wales) are used to illustrate the technique.

INTRODUCTION

NUMEROUS examples of folds disrupted by thrusts in their forelimbs (Dahlstrom 1970) have been described from orogenic belts, notably from foreland thrust-fold zones (e.g. Willis 1893, Eby *et al.* 1923, Gallup 1951, Scott *et al.* 1958, Dahlstrom 1970, Thompson 1981, Elliott & Johnson 1980, Hancock *et al.* 1982, Chapman *et al.* in press; see Badgley 1965, pp. 187–254 for other examples). Often it can be seen that individual bed displacement across a thrust decreases in the foreland direction and sometimes becomes zero. Less commonly the displacement amount and thrust plane may die out in both the foreland and hinterland directions from a point of maximum slip at the central part of the observed thrust fault (e.g. Fox 1959). Dahlstrom (1970) noted that in the Rocky Mountain Turner Valley structure (Gallup 1951) diminishing bed displacement upwards on a thrust was compensated by increasing fold shortening above (Fig. 1). He concluded that the thrust was propagating upwards within a growing fold. Eby *et al.* (1923) convincingly explained a diminishing amount of bed displacement in an Appalachian fold-thrust structure, in terms of

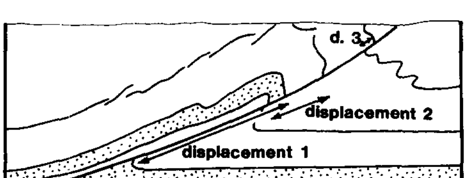

Fig. 1. The Turner Valley structure showing decreasing bed displacement upwards on a major thrust fault (from Dahlstrom 1970 after Gallup 1951).

an overfold growing in front of a propagating thrust. More recently, Thompson (1981) has described blind thrusts from the Canadian Rocky Mountains, noting that strain is taken up in the hangingwalls of blind thrusts by disharmonic folding and this accommodates the thrust displacement.

Whilst studying fold-thrust structures in the Pembrokeshire and South Devon Variscides of Britain, the authors observed a common pattern of variation in the displacement of beds from the hangingwall to footwall of thrusts. It was noted that the hangingwall beds can rarely be matched exactly with the footwall beds because of differences of internal strain above and below thrust faults. Ramps are rarely present although the thrusts obey the rules of thrust geometry (Dahlstrom 1970) and always cut up stratigraphic section. The purpose of this paper, therefore, is to investigate the geometry of fold-thrust structures and explain these geometries in terms of propagating thrusts and accompanying internal strain. It will be shown that a variation in thrust fault propagation rate relative to thrust slip rate can give rise to differing fold-thrust structures. A technique for analysing natural fold-thrust structures will be described using examples from Pembrokeshire and South Devon.

THE PROPAGATION OF THRUST FAULTS: A DISLOCATION MODEL

It has been suggested by Eshelby (1973) that a fault plane which has undergone slip over a limited area can be treated as a Somigliana dislocation. Fault planes propagate radially from a point source, and it has been shown using creepmeters along the trace of the San Andreas fault in Central California that creep is a failure propagation phenomenon (King *et al.* 1973). There are similarities between the kinematics of a creep event on a fault plane and the movement of a dislocation loop through a crystal lattice during intracrystalline slip. The rupture surface on a fault plane is analogous to the slipped region of a crystal lattice. The net slip on the fault is controlled by the magnitude of the creep event and is equivalent to the Burgers Vector of a crystal which is governed by the crystal lattice. In both cases, if the direction of slip is known, the screw, edge and mixed nature of the dislocation can be identified. In order for a dislocation loop to propagate through a crystal lattice, an elastic strain is imparted on the lattice and this strain accompanies the dislocation in its passage along the slip plane. An edge dislocation, at right-angles to the slip direction is often represented by an 'extra half plane' in the crystal lattice. This feature in the fault dislocation model is a zone of elastic or elastic/plastic strain. Any cross-section taken at right angles to the fault plane will show a fault of finite length in a two-dimensional representation. Each end of the fault plane represents a propagating fault tip and in reality this is the intersection of the dislocation loop with the cross-section.

In his study of the motion of thrust faults, Elliott (1976) showed that in plan view, thrusts increase in length as they increase their translation. The maximum translation in the centre of the thrust dies out towards the two propagating ends and this gives rise to Elliott's 'bow and arrow' rule. If the two terminations of the curved thrust are joined by a straight line the slip direction is its perpendicular, and the maximum displacement is midway between these terminations. Elliott also showed that the terminations of such faults were usually marked by folds representing a zone of plastic strain (known as a 'ductile bead') at the propagating fault tip.

Cooper *et al.* (1982) have shown that, in the Henaux Basse Normandie Duplex of Northern France, a zone of ductile layer-parallel shortening advanced in front of the propagating tip of the floor thrust fault. Clay models by Rodgers & Rizer (1981) give some indication of the possible shape and extent of the ductile bead in terms of the shear stress concentration associated with the leading edge of a propagating thrust fault.

A simple flow diagram (Fig. 2) shows in two dimensions the method by which a ductile bead associated with the propagating tip of a thrust fault imparts deformation to a thrust sheet in a single creep event. It is important to note that once the ductile bead and thrust tip have moved through an area of rock, a consistent 'background' strain is imparted to the rock overlying the thrust fault. All further deformation is accommodated by slip on the thrust fault surface with no further ductile strain imposed on the thrust sheet. The propagation of the thrust fault tip and the passage of the ductile bead through an area of rock is analogous to the movement of an edge dislocation represented by an extra half plane through a crystal lattice, the strain in the crystal lattice, however, is recoverable.

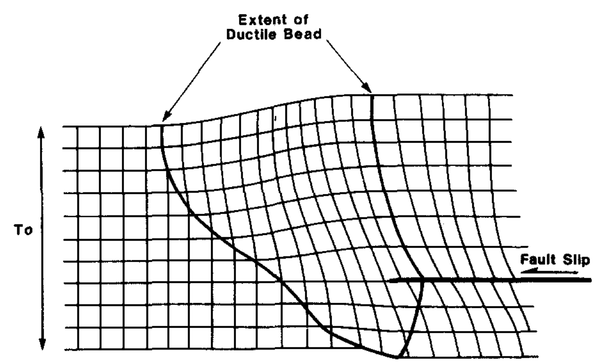

Fig. 2. Possible shape and extent of a ductile bead associated with a propagating fault tip. The original stratigraphic thickness T_0 becomes T_1 after the passage from right to left of the ductile bead and fault tip.

Important components of the thrust-fault dislocation model are thrust-fault plane slip, thrust-fault tip propagation and internal strain of the thrust sheet. All three are interdependent. Let us consider a two-dimensional model cut parallel to the fault slip direction marked with a square grid of unit dimensions. For the purposes of the model, the ductile bead is imagined to be infinitely thin and is situated at the fault tip which propagates right to left through the model, causing deformation in the hangingwall only (Fig. 3a). In this model, the fault propagation increment is fixed at twice the distance of fault slip and therefore, to maintain area, a stretch of 0.5 (a shortening of 50%) is required in the hangingwall parallel to the thrust plane balanced by a stretch of 2 (an extension of 100%) perpendicular to the thrust plane. Conversely, a stretch of 0.5 in the thrust sheet necessitates that the slip/propagation distance ratio is 0.5. This ratio will be controlled by the ratio of the slip/propagation rate in a creep event. At each increment of deformation (Fig. 3a), the deformed length (l_1) measured parallel to the fault in the hangingwall is

$$l_1 = P - S, \quad (1)$$

where P is the total fault length and is equivalent to the

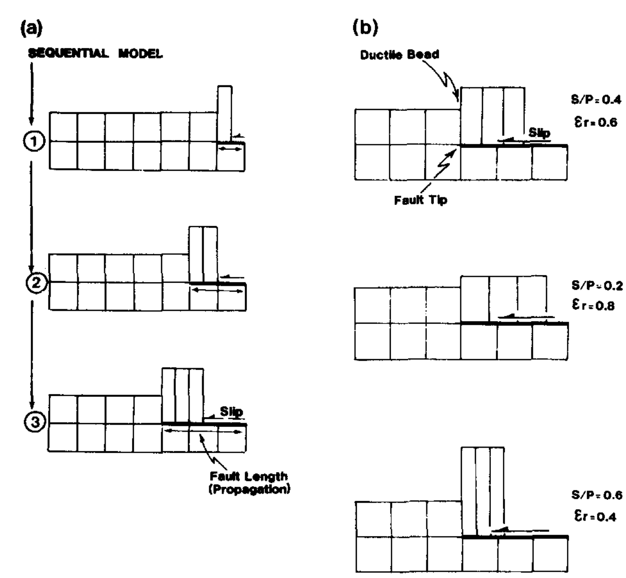

Fig. 3. (a) Two-dimensional model to illustrate the interdependence of slip and internal strain during fault propagation. (b) Examples to illustrate relationship between slip and internal strain for a fixed amount of thrust fault propagation; in each case three units. Area is conserved in all diagrams.

original length in the footwall) (l_o); and S is the total fault slip at the rear of the overthrust mass. Elongation (E) is given by

$$E = \frac{l_1 - l_o}{l_o} = -\frac{S}{P}. \quad (2)$$

The relative stretch (ϵ_r) measured parallel to the fault is dependent on the fault slip/propagation ratio according to the equation

$$\epsilon_r = \frac{l_1}{l_o} = 1 - \frac{S}{P}. \quad (3)$$

Any variation in the ratio of slip/propagation rate and hence slip/propagation distance necessitates a variation in the internal strain of the thrust sheet as shown in Fig. 3(b). The model is easily adapted to a fault propagating in both directions by the addition of a second ductile bead in the footwall (Fig. 4).

The internal strain, defined here as the stretch ϵ (strained length/initial length), parallel to the thrust-fault is required to accommodate the slip above the propagating fracture. However, the internal strain need not occur on one side of a thrust only (e.g. in the hangingwall as shown in Fig. 3). Shortening in the hangingwall could be balanced by extension in the footwall depending on the overall geometry of the ductile bead. In the general case, to maintain area, both shortening and extension will be present in a quadrantal distribution around a mid-point on a fracture propagating in two directions. Alternate quadrants have shortening and extension analogous to the elastic seismic waves created around an earthquake focus on a fault plane, as illustrated in Fig. 4. Therefore, the stretch above a thrust-fault is not absolute when calculated using strain markers below that thrust fault, but is dependent on the stretch below. The term 'relative stretch' (ϵ_r) is more useful in natural thrusts where deformation often occurs in both the hangingwall and footwall.

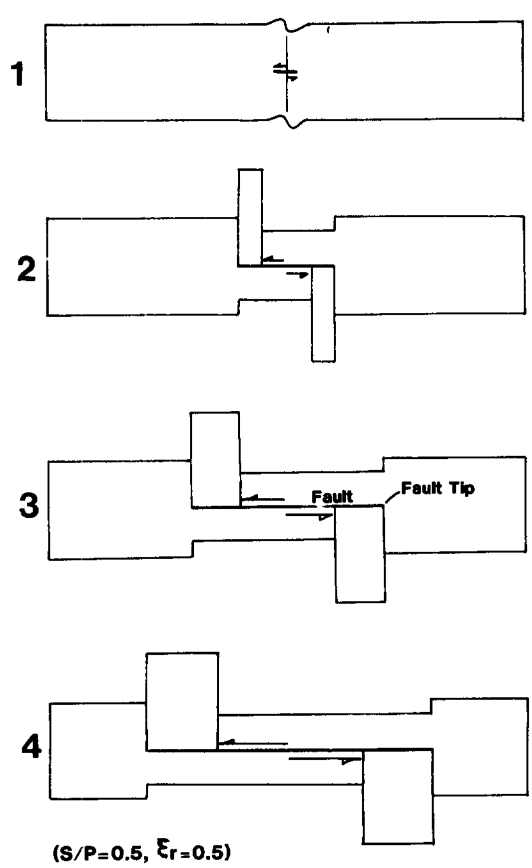

Fig. 4. Sequential development of a fault propagating in two directions requiring extension to balance shortening at each fault tip in order to maintain area in the model.

THE DISPLACEMENT/DISTANCE METHOD

In foreland regions of orogenic belts it is common to see thrust faults which die-out into undeformed regions. With reference to the simple models of Figs. 3 and 4, it can be seen also that the amount of displacement of markers (in this case the vertical lines of the grid) dies out progressively towards the propagating tip of the thrust fault. Thrusts frequently cut up stratigraphic section in their movement direction, obliquely across beds of a layer-cake sedimentary sequence, and internal strain is often accommodated by folding. Such relationships may be used in a simple technique to determine the relative stretch measured in a direction parallel to the movement direction on a thrust plane, and the slip/propagation ratio for that thrust fault.

A displacement vs distance graph is produced (Fig. 5), the technique of its production involving the following steps.

(1) On a cross-section parallel to the thrust slip direction choose an arbitrary reference point (R) on the thrust-fault. Usually, this point is chosen near the propagating tip of the fault if present but this is not essential.

(2) In the hangingwall, measure the distance of a marker bed along the thrust from the reference point.

(3) Measure the total displacement along the thrust-fault, of this marker bed from footwall to hangingwall.

(4) Plot displacement as ordinate and distance as abscissa using the same scale for both axes.

(5) Repeat the procedure for as many marker beds as possible.

(6) Project the slope of the points which may be linear or non-linear down to the abscissa to intersect this axis at T. This predicts the point where all slip dies out on the thrust (distance of T from R).

Because of the geometry of the thrust-fault dislocation model, and the interdependence of slip, propagation and internal strain, the slope of the graph at any point (defined by distance and displacement) is unique to a certain internal strain (relative stretch ϵ_r). The angle of slope of the graph (α) measured anticlockwise from the abscissa is related to internal strain ϵ_r by

$$\epsilon_r = 1 - \alpha/90. \quad (4)$$

The gradient (μ) relates to relative stretch by

$$\epsilon_r = 1 - \tan^{-1}\mu/90. \quad (5)$$

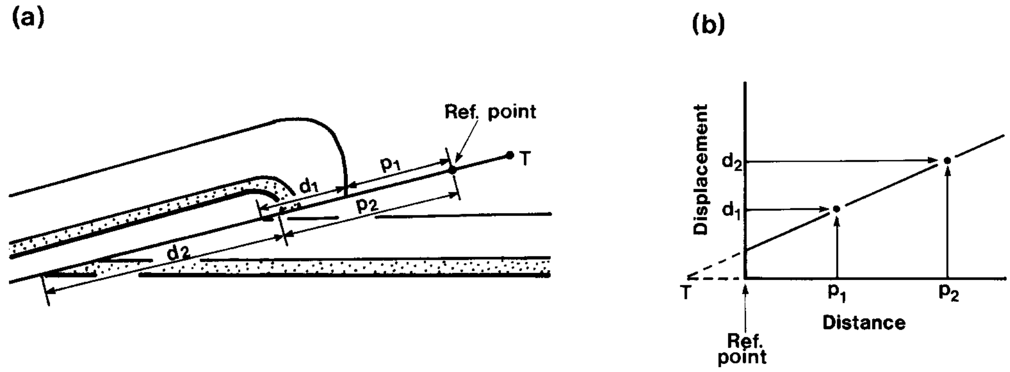

Fig. 5. (a) Schematic fold-thrust structure; p_1 and p_2 are distances of marker beds from an arbitrarily chosen reference point and d_1 and d_2 are displacements of those marker beds from hangingwall to footwall. (b) Displacement–distance plot for (a).

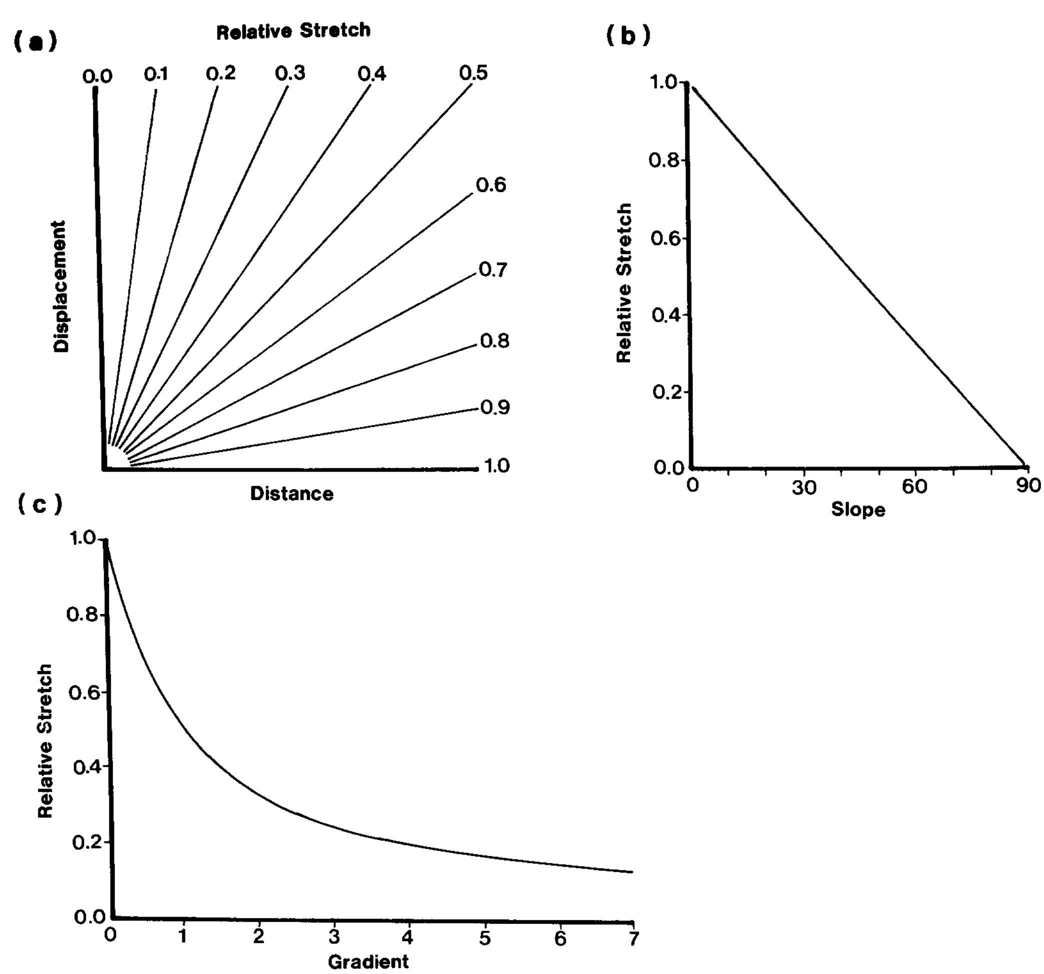

Fig. 6. (a) Relative stretch (hangingwall/footwall) in terms of slopes on the displacement–distance graphs. (b) Angle of slope on displacement–distance graph vs relative stretch. (c) Gradient of line on displacement–distance graph vs relative stretch.

This is shown graphically in Figs. 6(b) and (c) which plot angle of slope (α) and gradient (μ) of the displacement/distance diagram vs relative stretch. Using such graphs it is possible to predict the point at which the thrust slip dies out. Also it may be possible to predict, to some extent, the increasing displacement backwards or downwards along a thrust and this may add further constraints to the construction of geological cross-sections.

EXAMPLES OF FOLD-THRUST STRUCTURES AND THE USE OF THE DISPLACEMENT DISTANCE GRAPH

Example 1. Hope's Nose, Torquay, Devon (grid ref. SX94716327) (Fig. 7)

This classic example of a fold-thrust structure is developed in Middle Devonian, thinly-bedded limestones and slates. The thrust is bedding-parallel in the southeast in the hangingwall and then cuts up-section across the beds to the northwest where it must again become bedding-parallel, although this relationship is obscured. In the footwall it is bedding-parallel in the northwest and to the south the thrust cuts obliquely across the beds and must become bedding-parallel beyond the cliff. The thrust is horizontal, planar and a ramp is not exposed in the outcrop. A minor thrust splays off the main thrust footwall in the south. Ignoring the minor thrust and folding in the footwall, visual inspection of this structure indicates a relative stretch of around 0.5, as the same stratigraphic thickness in the hangingwall occupies about 50% of that in the footwall when measured parallel to the thrust plane. This is simply a consequence of the geometry of the fold which is overturned in the hangingwall giving a high angle between thrust and bedding, and gently dipping in the footwall, giving a low angle between thrust and bedding.

A displacement–distance graph quantifies this and gives an average relative stretch of 0.5 for the main thrust. Extrapolation of the line down to the abscissa makes it possible to predict the point at which the main displacement dies out (T). From a consideration of the beds below the thrust it is possible to predict that the beds above must be parallel to the thrust before the displacement dies out.

A relative stretch of 0.5 indicates a fairly large slip/propagation ratio for this thrust ($S/P = 0.5$), implying a fairly slow propagation rate relative to slip rate. This necessitates a large amount of internal strain accompanying the propagating thrust which has been taken up mainly in the hangingwall by a growing asymmetric fold.

It may be noted that, on the restored section (Fig. 7c) a ramp connecting two flats is present and this is a consequence of unfolding the beds. However, the thrust

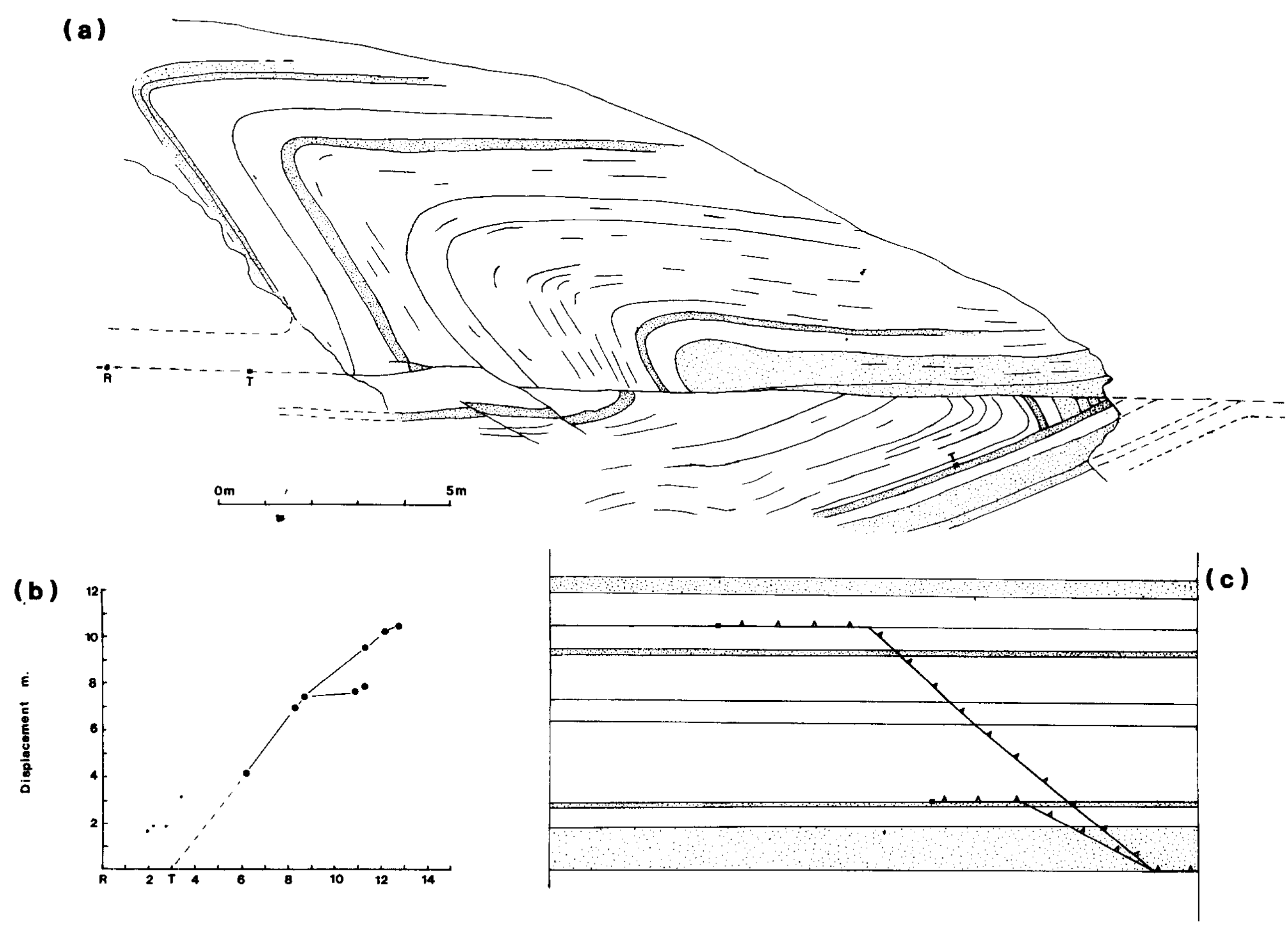

Fig. 7. (a) Fold-thrust structure, Hope's Nose, Torquay, Devon. (b) Associated displacement–distance plot. (c) Restored section showing the existence of an apparent ramp-flat geometry.

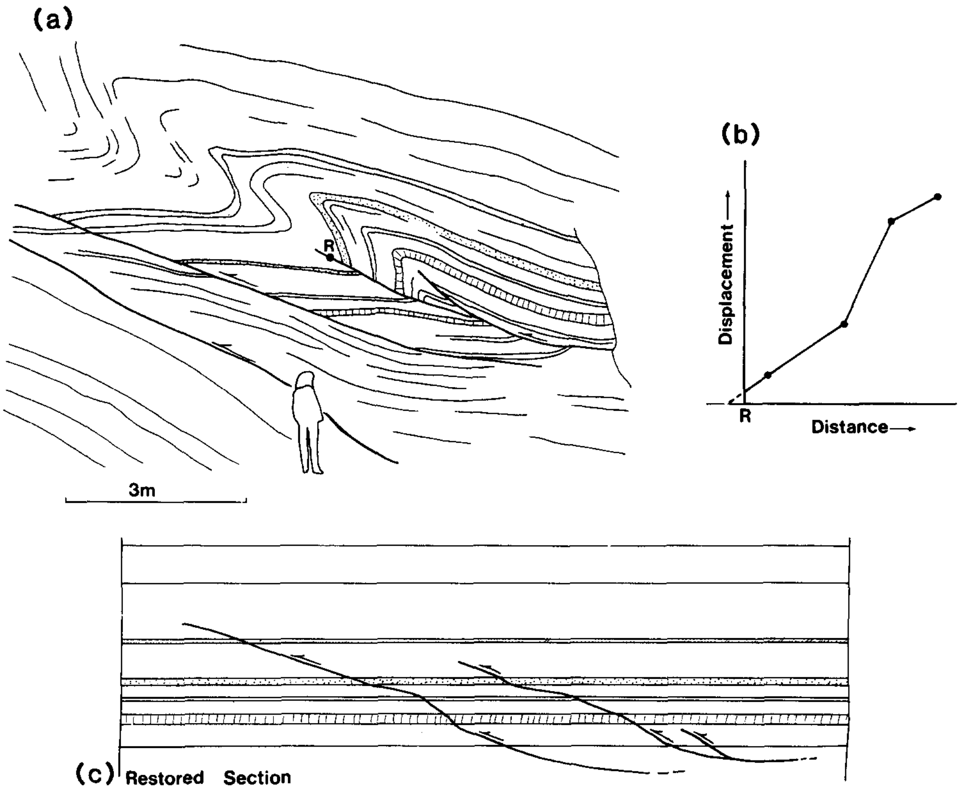

Fig. 8. (a) Fold-thrust structure, Broadhaven, Pembrokeshire (thrust fault labelled R goes blind into large asymmetric fold indicating extent of ductile bead). (b) Displacement–distance plot. (c) Restored section indicating ramp-flat geometry.

never had a ramp-flat geometry or a staircase trajectory; it propagated as a planar surface through a growing fold. The presence of ramps on restored sections does not necessarily imply the existence of real ramps, and their importance may have been overestimated in the past.

Example 2. Broad Haven, Pembrokeshire (grid ref. SM 18602143) (*Fig.* 8)

This fold-thrust structure is developed in sandstones and shales of the Coal Measures (Hancock *et al.* 1982) and is similar to the Hope's Nose structure except that the thrust and bed displacement is seen to die out in a foreland (northerly) direction. The overfolded fore-limb above the thrust and the gentle right-way up limb below give rise to a similar relative stretch as that of the Hope's Nose structure. This is determined from the displacement–distance graph, at an average of around 0.5. The overfold extends for a considerable distance in front of the propagating thrust tip, and this indicates the extent and shape of the ductile bead.

Example 3. Broad Haven, Pembrokeshire (grid ref. SM 18602144) (*Fig.* 9)

This example, also in Coal Measure sandstone and shale (Hancock *et al.* 1982), is a complex fold-thrust structure, and on a restored section it is possible to number the thrusts in order of their development. The main feature is an overturned fold in which the thrust cuts through the middle of, rather than the base of the fore-limb. Thus steep beds approximately perpendicular to the thrust occur both above and below the main thrust plane (No. 4 on the restored section). This gives rise to a lower relative stretch ($\epsilon_r = 0.89$) than in the preceding examples and a relatively fast thrust propagation is implied. The relative stretch is generally 0.89 but it starts off higher at 0.74 possibly due to a change in relative slip/propagation ratio.

This fold structure may have developed in advance of a propagating thrust in an elongate ductile bead; the thrust then cut through at a fairly fast rate (compared with examples 1 and 2). Internal shortening parallel to the main thrust was taken up by thinning of the beds in the hangingwall, already sub-perpendicular to the thrust as a result of the initial folding. It is also possible that thrust 3, a back thrust, formed contemporaneously with thrust 4 as an additional way of accommodating the required shortening in the hangingwall.

Thrust No. 2, which may have formed before thrust No. 4 shows slight overturning of the beds in the hangingwall and no overturning in the footwall. It is therefore intermediate in character between the overall geometry of the main fold-thrust structure of this example (3), and examples 1 and 2. Predictably, it has an intermediate relative stretch value of 0.71.

DISCUSSION

Using the displacement–distance graph it is possible to categorize fold-thrust structures according to relative stretch. A relative stretch of around 0.5 is the highest strain recorded by the authors in these and other fold-

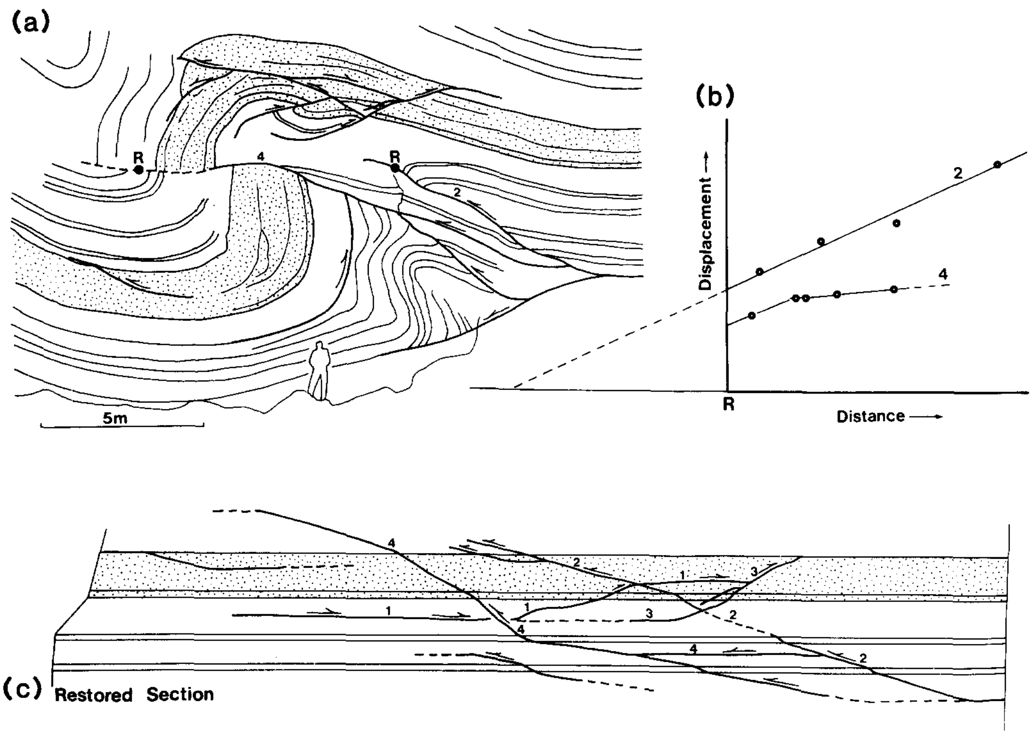

Fig. 9. (a) Fold-thrust structure, Broadhaven, Pembrokeshire. (b) Displacement–distance plots. (c) Restored section with thrusts numbered in order of development.

thrust structures, and this appears to be the maximum value in other published examples. The observed geometries of natural fold-thrust structures are widely variable and this variability is often a direct result of differing thrust-fault slip to thrust-fault propagation rates. Examples of overfolds in the hangingwall (e.g. the Hope's Nose structure) are formed within a ductile bead at the leading edge of a propagating thrust, due to a relatively fast slip rate on a relatively slowly propagating thrust. However, structurally necessary folds above ramps are a direct result of the staircase trajectory of a thrust. Similarly, certain thrusts are a direct result of folding as accommodation structures in fold cores.

The response to an overall shortening of an anisotropic, multilayered sequence of lithologies may be folding without thrusts (in which case there is effectively a thrust-fault propagation rate of 0). At a certain stage due to stress concentrations and rock competency contrasts, a fracture may nucleate and start to propagate radially; in two dimensions, forwards and backwards relative to the slip direction. The folding will continue but will be modified as the ductile bead sweeps in front of the fracture.

Such a sequence of events has been well demonstrated in experiments performed by Dubey & Behzadi (1981). A multilayered plasticene sequence undergoing shortening starts to fold and then fractures nucleate and propagate causing the already formed folds to undergo thinning and overturning to accommodate the fault slip (Fig. 10). Some fold-thrust structures may develop in association with thrusts that extend to a common floor thrust, but from a consideration of Dubey & Behzadi's (1981) work it is seen that this is not a necessity.

The sub-horizontal Hope's Nose thrust may extend backwards and downwards to a floor thrust or it could eventually die out into a backwards-propagating fault with an overfold in its southern footwall. Such structures must have formed in a similar way to those in Dubey & Behzadi's (1981) experiments, with no connection to a floor thrust of the classical duplex model (Boyer & Elliott 1982).

The fold-thrust structures analysed in this paper did not form at ramps as is often assumed. A thrust cutting through a growing fold will cut up section and on a restored section will have a ramp-flat geometry, although in reality the thrust fault was always perfectly planar. Some groups of fold-thrust structures probably formed as collapsing footwall ramps (Elliott & Johnson 1980) with the thrusts extending down to a common floor thrust; the Pembrokeshire structures may be of this type. However, the folds did not form as a result of the presence of the ramp as is often suggested, but probably grew in front of each thrust as it propagated upwards from the floor thrust into a growing fold. The fold shape is continuously modified during further thrusting and this may explain restored cross-sections with apparently very steep ramps. Because of the progressive nature of the development of fold-thrust structures, it is not possible to carry out a two-stage balance (first restore the folding, then the thrusting) to achieve a true restored section. The restored sections presented here, therefore, do not retain true angular relationships between thrusts and stratigraphy.

CONCLUSIONS

(1) A fault plane propagates radially from a point

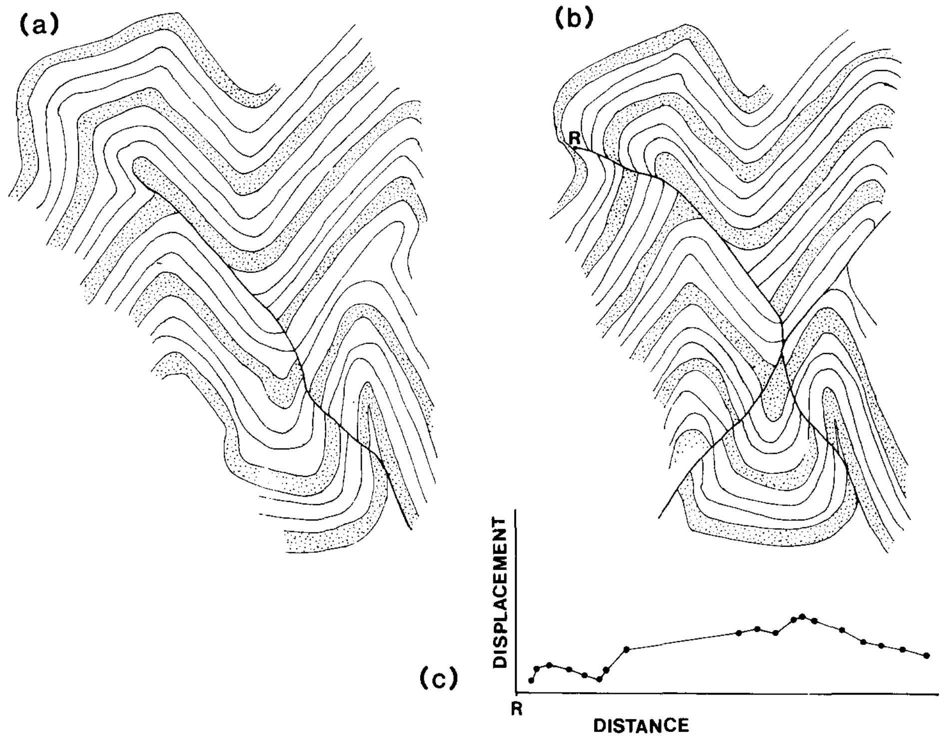

Fig. 10. (a) and (b) Sequential development of folds and growth of faults in plasticene models (after Dubey & Behzadi 1981). (c) Displacement–distance plot for the fault marked R. The change in slope marks the initial nucleation point of the fault; the positive and negative slopes representing forwards and backwards fault propagation.

source and there are similarities between the kinematics of a fault creep event and the movement of a dislocation through a crystal lattice. The elastic strain of the crystal lattice is broadly equivalent to the ductile bead associated with the propagating fault tip. Ductile beads associated with thrust faults have been recorded explicitly by Elliott (1976) and implicitly by Cooper *et al.* (1982) in field examples, and by Rodgers & Rizer (1981) in clay models.

(2) The ductile bead propagates with the thrust fault and imparts an internal strain to the thrust sheet. Internal strain is dependent on fault propagation rate relative to slip rate. In order to conserve area in simple models, shortening on one side of a propagating fault should be balanced by extension on the opposite side of the fault. Where a fault propagates forwards and backwards relative to the slip direction, shortening and extension should have a quadrantal distribution about the fault nucleation point.

(3) The interrelationship between slip/propagation rate and internal strain of thrust sheets (relative stretch measured parallel to the fault) can be studied using displacement–distance graphs. Also, using these graphs, it should be possible to predict the point at which thrust fault slip dies out. This may enable a prediction of unexposed fold-thrust structures and may place additional constraints on geological cross-sections.

(4) The different types of fold-thrust structures reflect different ratios of slip/propagation rate and are, to some extent, dependent on the geometry of the ductile beads at the leading edge of propagating thrusts. Overturned folds are not likely to have formed because of ramps as structurally necessary folds.

(5) Ramps are less common than is commonly suggested, and in restored sections, they do not necessarily imply a staircase trajectory. It is not necessary for all thrusts to extend down to a floor thrust as they may die out in the hinterland direction after nucleation and propagation both forwards and backwards relative to the slip direction.

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