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The geometry of listric normal faults and deformation in their hangingwalls

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Abstract—In cross-sections containing listric extensional faults, area balancing techniques for depth to décollement are usually based on either bed length conservation or displacement conservation. Listric fault geometry may be constructed from a hangingwall roll-over profile using the 'Chevron construction'. This construction, based on conservation of heave, necessitates a reduction in fault displacement with decreasing fault dip. A modification of this construction utilizing conservation of fault displacement predicts a listric fault that detaches at a shallower depth. A new construction based on slip lines uses fault-perpendicular displacement segments to generate listric fault shape. Fault propagation strain may be responsible for anomalous hangingwall geometries, and these can be predicted by forward modelling using either a modified Chevron construction or a slip-line construction.

GEOMETRY OF LISTRIC FAULT HANGINGWALLS AND FAULT PROFILES

IT HAS BECOME apparent, recently, that many faults seen in seismic reflection sections have a curved or listric form in profile and are concave upwards (e.g. Bally 1984). Such faults tend to flatten downwards and this results in dominantly horizontal movements above a detachment or décollement. This type of faulting occurs in linked fault systems and minor, antithetic faults downthrow in the opposite sense to more major listric faults (Gibbs 1983). In plan view, many listric normal faults show curvature indicating that their 3-D geometry is spoon shaped. In a theoretical model for listric fault profile shape, Wernicke & Burchfiel (1982) showed that the radius of curvature of faults is approximately twice the décollement depth.

Extensional movement on a listric fault generates a roll-over anticline (Fig. 1), as originally demonstrated by Hamblin (1965). Gibbs (1983) developed this hypothesis, and showed that thinning and layer parallel stretching of bedding in the roll-over was a geometrical necessity for the conservation of cross-sectional areas. Bed thinning and stretching is frequently achieved by families of antithetic faults in the roll-over. An alternative to layer parallel stretching is a component of angular shear, possibly attained through bedding plane slip (Gibbs 1983). Listric faults that are curved in plan will generate roll-over anticlines with curved hinges in plan view (Gibbs 1984). In a similar fashion, complex hangingwall fold structures will be generated by movement over an irregular fault profile (Gibbs 1984).

Using hangingwall fold geometry, it is possible to predict listric fault shape in detail and to calculate depth to décollement. This is commonly done using an existing technique known as the 'Chevron construction' (Verrall 1982, Gibbs 1983) which was introduced to the broad geological community in a JAPEC course run by the Geological Society of London. Recently, a modification to this technique has been presented by White *et al.* (1987). The hangingwall geometries of all other beds may be graphically depicted by using an extension of the Chevron construction when the fault geometry is known in detail. Décollement depth may be estimated using simple area balance techniques (Dahlstrom 1969, Hossack 1979) if total extension is calculable from bed lengths or by the summation of displacements on individual faults (Chapman & Williams 1984).

In this paper, we critically assess the accuracy of existing section construction techniques and present two modified versions of the Chevron construction. These are likely to be more realistic when considered in terms of an extensional faulting model with conservation of displacement along the fault profile, although area conservation is not a feature of these techniques. A fault

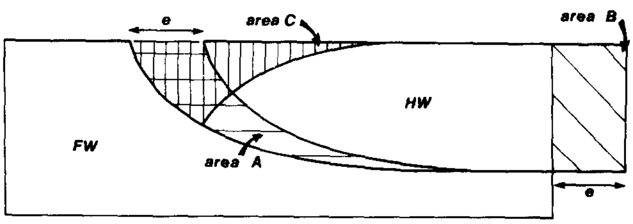

Fig. 1. The generation of a roll-over anticline by movement on a listric normal fault (after Hamblin 1965). Horizontal displacement (*e*) opens up a gap in the section (area A). Rocks of the hangingwall collapse to fill area A, and area C is that between the regional dip and the roll-over anticline. Area A = area B = area C.

slip/propagation model, when applied to listric normal faults renders all existing construction techniques non-viable. This model may be used to explain some of the apparently anomalous structures commonly observed in extensional fault hangingwalls.

DEPTH TO DECOLLEMENT AND FAULT GEOMETRY

Existing techniques assessed here include area balancing and the Chevron construction (Verrall 1982). The Chevron construction is modified to give two new methods for the construction of listric fault profiles. It is worth noting that these techniques give significantly different results for extension and hence décollement depth.

Area balance

Area balance techniques are in common use for the calculation of décollement depth (Dahlstrom 1969) or shortening (Hossack 1979) in thrust fault terrains. The principles are identical, when applied to regions of extensional faulting (e.g. Bosworth 1985), and isovolumetric, plane strain conditions are assumed. The technique relies on the fact that the area removed from the cross-section (area X in Fig. 2a & b) is the same as that of a rectangle ABCD at the right-hand end of the section (area y in Fig. 2a & b). The area of the rectangle ABCD, area Y, is the product of the total extension (e) and the décollement depth (s),

$$\text{area } X = \text{area } Y = es. \quad (1)$$

An estimate of total extension may be equivalent to the maximum displacement of the fault (d) (Chapman & Williams 1984) in which case the hangingwall in the roll-over suffers layer parallel extension and thinning to conserve area (Fig. 2b). Alternatively, total extension may be calculated using bed length techniques (Hossack 1979), in which case, displacement (d) will not be conserved along the fault profile (Fig. 2a). Using either of the above extension estimates, décollement depth is calculated by:

$$s = \text{area } X/e. \quad (2)$$

These estimates of décollement depth are likely to be unreliable using either total displacement or bed length extension calculations. Realistically, the area ABCD at the right of the section (Fig. 2a & b) will not be a rectangle, but will have undergone some degree of angular shear due to bed parallel slip (Gibbs 1984). This may be analysed by assuming no bed length change and conservation of displacement along the fault profile (Fig. 2c). Original bed length is calculated by summing the footwall (L_f) and hangingwall (L_h) bed lengths

$$L_o = L_f + L_h. \quad (3)$$

As both displacement and bed length are conserved,

$$CD = d \quad (4)$$

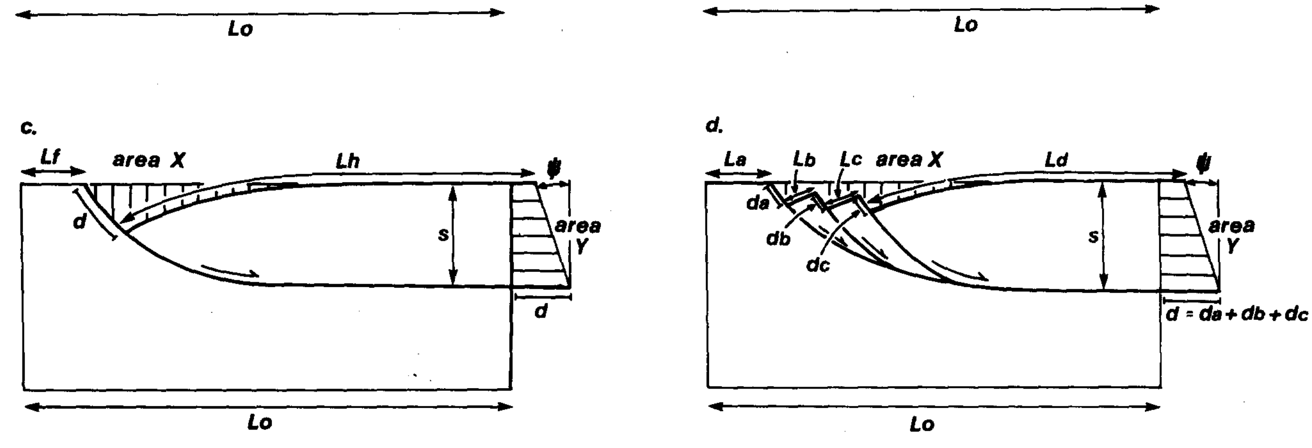

Fig. 2. Calculation of depth to décollement (s) by area balance methods. Area X = area Y. (a) Area balance using extension estimate based on bed lengths $L_f + L_h = L_o$. (b) Area balance using conservation of displacement $e = d$. (c) Area balance using both bed length and displacement conservation. This necessitates angular shear (ψ) at the right-hand end of the section. (d) Area balance using both bed length and displacement conservation within a linked extentional fault system.

and

$$AB = L_l - L_o, \quad (5)$$

where L_l is the measured deformed section length. Assuming plane strain conditions, the area at the right-hand end of the section ABCD (area Y) is equal to the area removed from the section (area X). Depth to décollement (s) using this technique is calculated by:

$$s = \text{area } X \Big/ \left[\frac{d + (L_l - L_o)}{2}\right]. \quad (6)$$

Shear strain (γ) represented by angular shear (ψ) at the right-hand end of the section (Fig. 2c) is given by:

$$\gamma = \tan \psi = (DC - AB)/s \quad (7)$$

or

$$\gamma = \frac{d - (L_l - L_o)}{s}. \quad (8)$$

Chapman & Williams (1984) and Bosworth (1985) have suggested that in linked extensional fault systems, displacement on subsidiary splays is cumulative on the main detachment surface (Fig. 2d). In a simple geometry, this produces a large angular shear (ψ) for a relatively small surface extension. Individual bed lengths (L_a, L_b, L_c, etc.) may be summed to give initial bed length (L_o) and similarly, displacements (d_a, d_b, d_c) on individual splay faults may be summed to give total displacement (d). Initial bed length (L_o) and displacement (d) may now be used in equation (6) to calculate depth to detachment (Fig. 2d).

PREDICTIONS OF FAULT GEOMETRY USING ROLL-OVER PROFILE

Chevron construction

The Chevron construction (Verrall 1982) is used to construct listric fault shape from a roll-over profile. Heave is the primary consideration in this construction because it is assumed that when a listric normal fault develops, the horizontal component is the only consistent factor in movement of the fault hangingwall. Both throw and displacement vary with changing fault angle. Heave is obtained by measuring the horizontal displacement of a marker bed across the fault (Fig. 3b). A vertical grid is laid out across the section with horizontal spacing of heave (h) increments (Fig. 3a). The regional dip of the marker bed is projected from footwall to hangingwall. Point A in the fault footwall is displaced to point A′ in the hangingwall by displacement d, which may be resolved into a horizontal component of heave (h) and a vertical component of throw (t). The fault dips at α degrees (Fig. 3b),

$$h = d \cos \alpha \quad (9)$$

$$t = d \sin \alpha \quad (10)$$

$$t = h \tan \alpha. \quad (11)$$

In a listric fault, if heave (h) is considered to be conserved, then throw (t) will vary with the angle of dip of the fault according to equation (11).

This is represented in graphical form using the Chevron construction. Point A′ reached its present position via components of heave (h) and throw (t), where throw is dependent on fault angle [equation (5)]. Point B′ reached its present position by components of constant heave (h) and a throw which depends upon fault angle. The diagonal BB′ represents the resultant vector of heave and throw in this segment, and it is parallel to the displacement direction along the fault. Therefore BB′ is parallel to the fault profile in this segment which may be constructed by drawing a line through A′ parallel to BB′. This procedure may be continued for all the other heave segments of the roll-over profile, and the fault geometry is completed (Fig. 3a)

This construction may not reasonably reflect the displacement pattern of the fault. As the fault flattens towards horizontal, both displacement (d) and throw (t) are reduced according to equations (9) and (11) if heave (h) is conserved. The amount of displacement decreases and tends towards the amount of heave with reduced fault dip until at the limit $\alpha = 0°$ and $d = h$. Therefore, with conservation of heave, any extensional fault of listric geometry shows a reduction of displacement down-dip. Modifications of this construction involve the conservation of displacement along the fault, with both throw and heave varying along the fault profile.

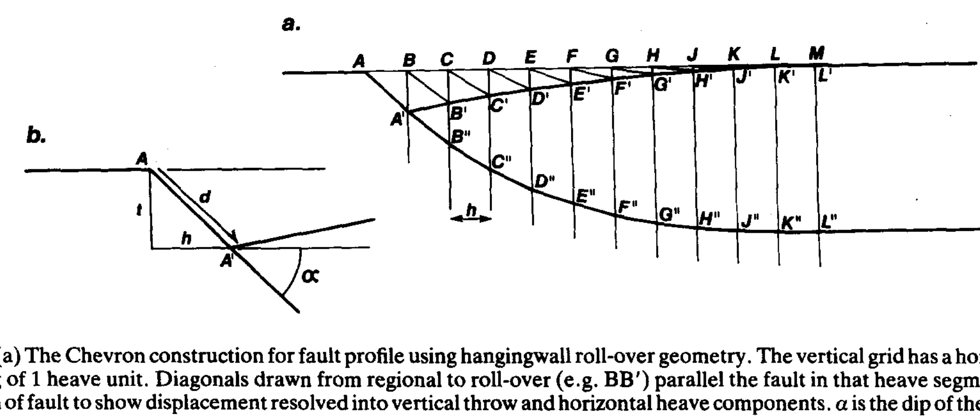

Fig. 3. (a) The Chevron construction for fault profile using hangingwall roll-over geometry. The vertical grid has a horizontal spacing of 1 heave unit. Diagonals drawn from regional to roll-over (e.g. BB′) parallel the fault in that heave segment. (b) Detail of fault to show displacement resolved into vertical throw and horizontal heave components. α is the dip of the fault.

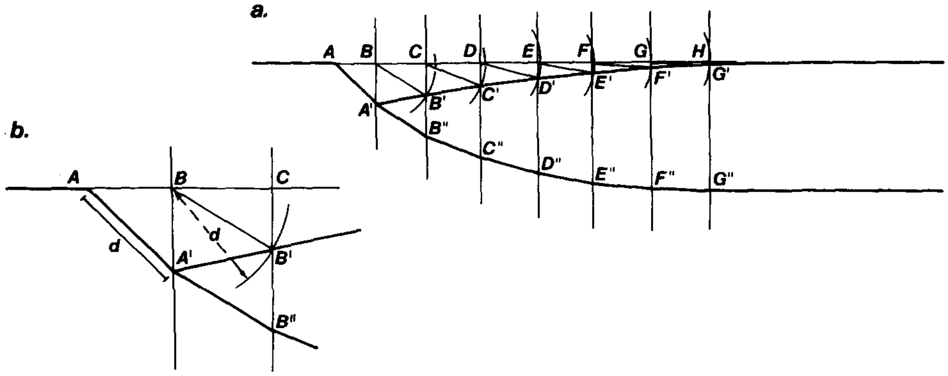

Fig. 4. (a) Modified Chevron construction for fault profile using hangingwall roll-over geometry. (b) Detail of construction technique. Vertical line through A′ defines B at regional intersection. Arc of radius d intersects roll-over at B′. Fault drawn parallel to BB′ through A′.

Modified Chevron construction

In the proposed modified Chevron construction, displacement along the fault is conserved, and both heave and throw vary continuously with fault dip angle according to equations (9) and (10). Displacement (d) is measured as the displacement in the section plane of a marker bed (AA′ on Fig. 4a & b). A vertical line is constructed through A′ and the regional dip of the marker bed is projected from footwall to hangingwall. A line of equivalent length to the displacement (d) (AA′ Fig. 4b) is drawn from point B to touch the roll-over profile defining point B′. This is most easily obtained by constructing an arc of radius d centred at B which intersects the roll-over profile at B′. A vertical line is drawn through B′ and the line BB′ is parallel to the displacement vector for this segment of the fault. The fault segment is drawn through A′ and parallel to BB′. The procedure is repeated for all other fault segments, using a constant displacement value (Fig. 4a).

As the fault flattens towards horizontal, heave (h) is increased and throw (t) is reduced according to equations (9) and (11), when displacement is conserved. The amount of heave increases and tends towards the displacement amount with reduced fault dip until at the limit $\alpha = 0$ and $h = d$.

Slip-line construction

Both the Chevron and modified Chevron constructions depend on variations in heave or displacement along the fault profile. Displacement affects all material in vertical heave segments to deform the fault hangingwall. Is it realistic to treat fault displacement in terms of vertical segments? It may be more sensible to consider that material in a fault hangingwall moves along a series of slip lines or trajectories parallel to the fault profile (Fig. 5a). If displacement is conserved along the slip lines, stretching of marker beds is a necessity, as it is with both Chevron and modified Chevron constructions. In any vertical segment, particle trajectories reduce in dip angle, with depth, remaining parallel to the fault profile. Therefore, in an individual heave segment, the particle path from regional to roll-over profile assumed in a Chevron construction is not the same as the slip-line trajectory (Fig. 5b).

The slip-line construction uses displacement (d) as the primary measure, and the hangingwall deformation is considered in terms of fault perpendicular displacement segments rather than vertical heave segments. Displacement is measured using a displaced marker across the fault (AA′ on Fig. 6b) and this defines the width of the rectangular displacement segment. This construction technique is facilitated by the use of a paper or card template cut to the size of the displacement segment. The regional dip of a marker is projected from footwall to hangingwall. There is a unique position where the left side of the rectangular displacement segment passes through A′ and the ends of displacement segment of length (d) touch both the regional and roll-over profile. The two points where length d touches regional and roll-over profile are labelled B and B′ and this line represents a slip-line parallel to the displacement vector for the second displacement segment (Fig. 6a). The fault segment is constructed from point A′ parallel to BB′ defining point B″. The third fault segment is constructed by finding points C and C′ on the regional and roll-over profile with the left side of the rectangular displacement segment passing through B″. This process is continued for the whole roll-over profile to construct the full fault geometry (Fig. 6a).

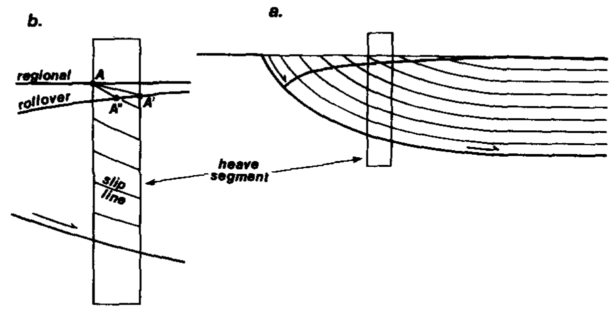

Fig. 5. (a) Displacement trajectories or slip-lines on a listric normal fault. (b) Detail of a heave segment: AA′ is the assumed particle movement path in the Chevron construction, AA″ is that in a slip-line treatment.

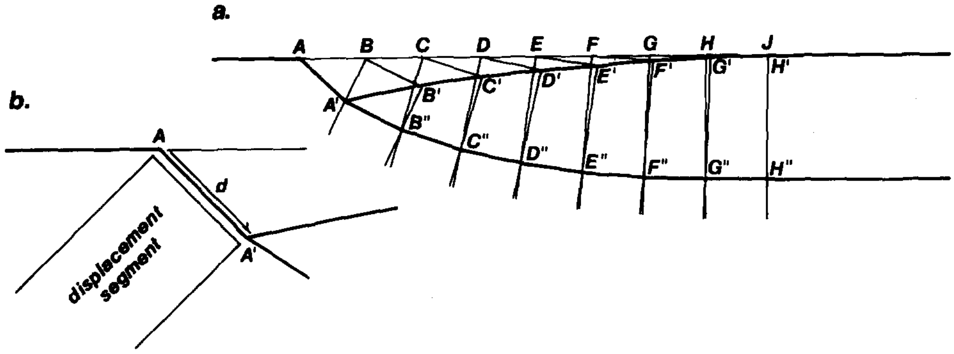

Fig. 6. (a) Slip-line construction for fault profile using hangingwall roll-over geometry, displacement segment dimensions are conserved (e.g. BB' = CC' = d). (b) Detail of rectangular displacement segment (AA' = d).

CROSS-SECTION RESTORATION

It is possible to use the Chevron-derived techniques to restore cross-sections (either extensional, contractional or mixed mode sections) to their pre-faulting geometries. All points in fault hangingwalls move according to the principle of the chosen construction technique. A marker bed restored to its pre-faulting geometry should display a consistent dip across the section and this defines its cross-section regional dip. A restoration based on one marker bed across a section should ensure that all other beds become perfectly restored. This technique can be used as a check for balance in completed cross-sections.

Graphical techniques for section restoration give reproducible results but are time consuming. It is a relatively simple matter to produce computer programs that perform fault shape prediction and section restoration based on the Chevron-derived methods. Such programs have been written at Cardiff in both FORTRAN and BASIC and are available.

A FAULT SLIP/PROPAGATION MODEL

Using the same initial hangingwall geometry, fault shapes and décollement depths differ according to the construction method used (Fig. 7). Both area balance involving bed length techniques and the Chevron construction require the unrealistic geometry that fault displacement reduces from a maximum at the surface to a minimum at depth along the décollement. This implies that the fault initiated at the surface and propagated

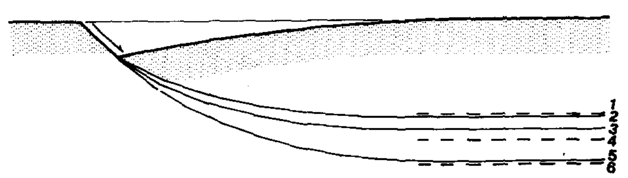

Fig. 7. Fault profiles and depths to décollement using six different techniques on the same roll-over geometry. 1. Area balance, with displacement conservation only; 2. slip-line construction; 3. modified Chevron construction; 4. area balance with displacement and bed length conservation; 5. Chevron construction; and 6. area balance with bed length conservation only.

downwards. This kinematic scheme would impart a contractional strain to the hangingwall (see Williams & Chapman 1983, Farrell 1984).

The modified Chevron construction, the slip-line construction and area balance dependent on displacement conservation rely on the fact that displacement is equal along each segment of the fault profile. This too is an unrealistic assumption as fault displacements have been shown to decrease from the point of fault initiation towards the propagating fault tip (Muraoka & Kamata 1983, Williams & Chapman 1983, Farrell 1984).

In its simplest form the fault slip/propagation model (Williams & Chapman 1983) involves a fracture initiating at a point source and growing radially by means of a spreading dislocation or fault tip. The dislocation loop encloses an area which has undergone slip. When considered in a cross-section parallel to the slip direction, the fault shows decreasing slip from the point of initiation towards the fault tips which, in such a section, are equivalent to edge dislocations (Fig. 8). When the fault slip direction is in the opposite sense to the direction of fault propagation, extensional strain results and when both slip and propagation have the same sense, contractional strain is developed. Fault propagation strain has been quantified as relative stretch (ε_r) by Williams & Chapman (1983).

$$\varepsilon_r = 1 - \dot{S}/\dot{P}, \qquad (12)$$

where $\dot{S}$ is the rate of fault slip measured in terms of displacement and $\dot{P}$ is the rate of fault propagation or fault length. Williams & Chapman (1983) demonstrated that in thrust fault terrains, displacement (fault slip) reaches a maximum of one half of the fault length (fault propagation), but lower values are more common ($\dot{S}/\dot{P} = 0.5$ maximum). Muraoka & Kamata (1983) studied displacement distributions in planar faults cutting Quaternary lacustrine sediments in Japan. Frequently, both faults tips were exposed in vertical sections; $\dot{S}/\dot{P}$ values of 0.01 were the norm, with a maximum of $\dot{S}/\dot{P} = 0.05$ being recorded. The fault slip/propagation model may now be applied to shallow angle planar faults and listric normal faults of fixed geometry. By means of the modified Chevron and slip-line constructions, resultant hangingwall profiles may be constructed.

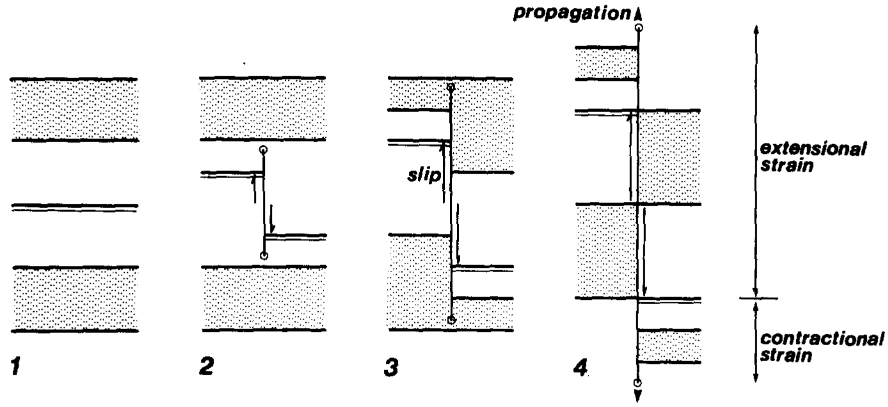

Fig. 8. Fault slip/propagation model for the generation of a planar, vertical fault. Extensional strain where slip is in the opposite sense to propagation, and contractional strain where slip and propagation have the same sense.

A planar fault dipping at 30° has a maximum displacement at its centre, with displacement dying to zero at the fault tips. The upper fault tip is above the marker bed, and the fault $\dot{S}/\dot{P}$ ratio is fixed at 0.4. In both the modified Chevron (Fig. 9a) and the slip-line construction (Fig. 9b) a broad hangingwall syncline and an apparent roll-over anticline is generated due to variations of internal strain in the hangingwall.

A second example involves a listric normal fault of fixed geometry that flattens with depth into a horizontal décollement. In this case, the fault is considered to have propagated from depth towards the surface (from right to left in Fig. 10a & b). Displacement increases downwards and the rate of increase is fixed by $\dot{S}/\dot{P} = 0.4$. Both the modified Chevron (Fig. 10a) and the slip-line constructions (Fig. 10b) show a broad roll-over geometry in the hangingwall with a minor 'drag-type' syncline near the fault contact. The synclinal geometry results from significant layer-parallel extension in the marker bed as a consequence of fault displacement reducing upwards. This is contrary to the theory that hangingwall synclines must be generated by movement over upward flattening faults.

DISCUSSION

In this contribution, we have attempted to show that the Chevron construction and techniques of area balancing may not be universally applicable in extensional faulting terrains. Conservation of heave is the prime consideration in the Chevron construction, but conservation of displacement may be more realistic in some cases. In a similar way, the treatment of hangingwall deformation in terms of heave segments may not be as sensible as a fault-parallel, slip-line analysis using displacement-normal segments. The construction techniques presented here give rise to different fault geometries from the same hangingwall data.

Clearly, complications in hangingwall geometry may be due to an irregular fault profile. However, it is likely that fault displacement will not be constant along the whole listric fault profile, but will increase downwards if a fault slip/propagation model is applied. Fault propagation strain may have a profound effect upon hangingwall geometry, and this may explain the existence of 'drag-type' synclines first illustrated by Hamblin (1965) from the Grand Canyon of U.S.A. and seen on numerous seismic sections (e.g. Bally 1984). Displacement gradients on faults necessitate area changes within a cross-section which in reality is finite strain in the rock mass. Finite strain in extensional sections may take the form of sediment compaction and/or distributed normal faulting.

This article is not an attempt to describe the most universally applicable construction in extensional fault terrains. Rather, it is designed to pinpoint some of the many pitfalls in using only one construction technique

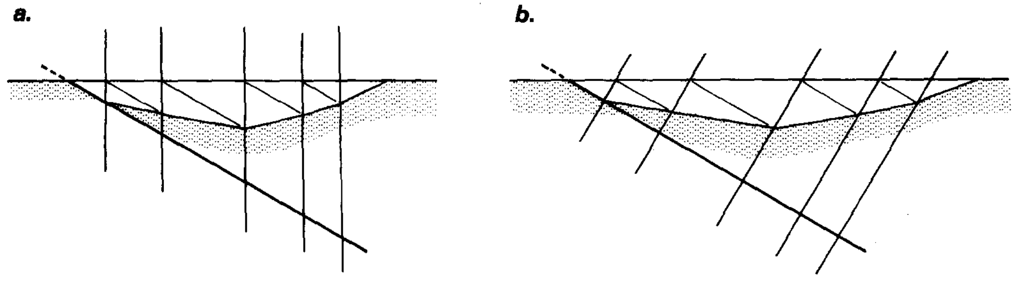

Fig. 9. Hangingwall deformation in a planar normal fault with 30° dip. Displacement reduces towards the fault tips. (a) Modified Chevron construction, (b) slip-line construction.

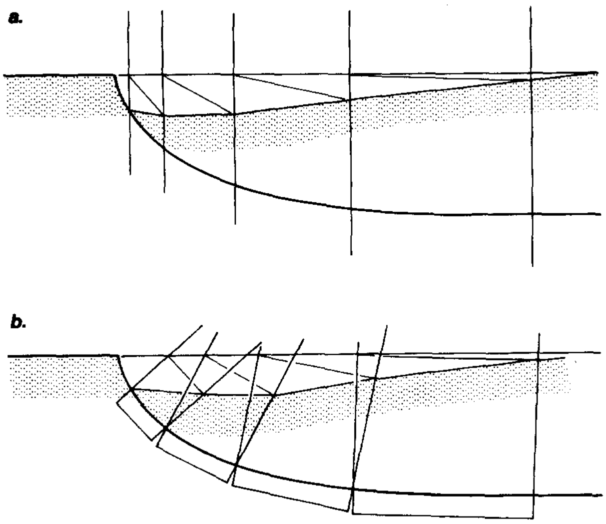

Fig. 10. Hangingwall deformation in a listric normal fault with displacement increasing with depth. (a) Modified Chevron construction, (b) slip-line construction.

heavily dependent upon heave or displacement conservation in sections. If fault propagation strain is significant in determining the hangingwall geometry in an area, then fault profile geometry is practically non-soluble by existing techniques without knowledge of displacement variations.

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