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Journal of Structural Geology 25 (2003) 1551–1560

JOURNAL OF STRUCTURAL GEOLOGY

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Application of geometric models to inverted listric fault systems in sandbox experiments. Paper 1: 2D hanging wall deformation and section restoration

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Received 30 December 2000; recieved in revised form 21 August 2002; accepted 23 September 2002

Abstract

Fault geometry is a primary control on hanging wall deformation. In order to examine their geometrical relationships, a positive inversion analogue experiment was conducted using a rigid fault surface of listric geometry. The hanging wall deformation observed on a representative vertical section was examined with conventional 2D geometric models, and was restored to its pre-inversion phase with two techniques. These results suggest that the deformation can be best approximated by inclined simple shearing (ISS). The ISS model can determine the inclination of the apparent shear plane and the amount of apparent horizontal shortening, which is equivalent to that calculated with the conventional depth-to-detachment method. This estimated apparent shortening was generally smaller than the actual amount of the experiments, probably due to tectonic compaction.

Keywords: Geometric models; Listric fault systems; Sandbox experiments

1. Introduction

Hanging wall deformation above listric fault systems observed in natural structures and analogue models has been analysed for nearly a century, resulting in many models for geometric relationships between the hanging wall structures and the underlying detachment surfaces (Chamberlin, 1910, 1919; Hamblin, 1965; Bally et al., 1966; Dahlstrom, 1969; Verrall, 1981; Boyer and Elliott, 1982; Gibbs, 1983, 1984; Davison, 1986; White et al., 1986; Wheeler, 1987; White, 1987, 1992; Williams and Vann, 1987; Dula, 1991; Withjack and Peterson, 1993 and others). Some of these can be used to produce geometrically balanced geologic cross-sections and are thus referred to as section balancing techniques. The first attempt to apply such geometric techniques to subsurface geology was made by Chamberlin (1910, 1919), who used the depth-to-detachment method to analyse the deformation geometries in the central Appalachians and the Colorado Rockies. Since then, several authors have successfully applied the geometric methods to other fold-and-thrust belts (e.g. Bally et al., 1966; Dahlstrom, 1969; Boyer and Elliott, 1982). Extensional rollover folds have also been examined by these techniques, resulting in significant improvements of the conceptual models of extensional faulting (e.g. Davison, 1986; White et al., 1986; Wheeler, 1987; Williams and Vann, 1987). The generation of a rollover anticline by displacement of a listric normal fault was originally demonstrated by Hamblin (1965) and further developed by Gibbs (1983). They proposed a simple model, which explains a geometrical relation between a fault and its hanging wall, based on conservation of area on a cross-section. The idea of maintaining cross-sectional area above a listric fault can be applied to contractional settings, implying that there should be a predictable relationship between the shape of the master fault and the geometry of an uplifted hanging wall (Fig. 1a–c).

The geometric models and section balancing techniques generally assume that the volume (or area on 2D sections) of the fault hanging wall is conserved during deformation. It is widely known, however, that the volume in natural structures is commonly affected by tectonic stresses (e.g. Geiser and Engelder, 1983; Williams and Chapman, 1983;

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PII: S0191-8141(02)00181-5

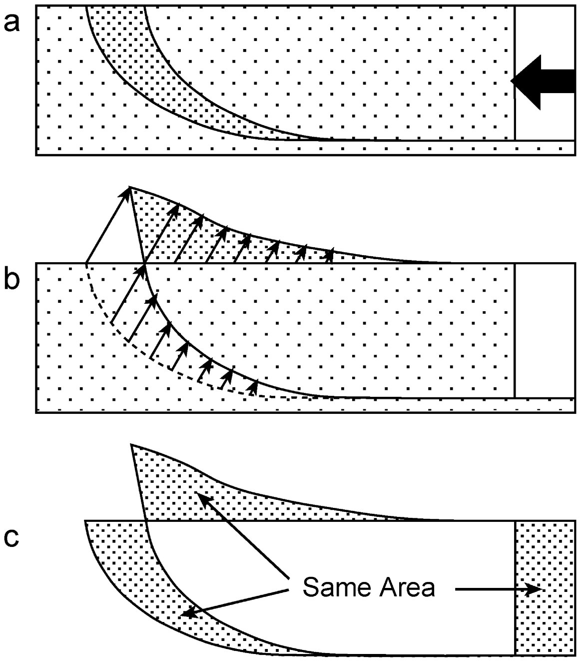


Fig. 1. A model of hanging wall deformation above a listric fault. (a) The hanging wall is displaced horizontally, (b) then uplifted to void the overlap. Thus the resultant deformation of the hanging wall depends on the fault geometry. Note that the areas of the overlap, uplift and shortfall are all equal (c).

Marshak and Engelder, 1985; Evans and Dunne, 1990). In particular, contractional stresses cause a porosity reduction (tectonic compaction), which consumes a part of the total strain in the final deformation geometry. Koyi (2000) showed that this tectonic compaction can also be observed in sandbox experiments of thrust wedges.

The aim of this and a subsequent paper (Yamada and McClay, 2003a) is to evaluate the hanging wall deformation above listric faults with geometric models. This paper focuses on 2D deformation above a listric fault, and begins with a review on a series of existing geometric models that help to determine master fault geometry from a known geometry of deformed horizons in the hanging wall. Two common restoration techniques are also introduced. Then the geometric models are applied to section geometry of a positive inversion structure (Williams et al., 1989) produced by a sandbox experiment. Using the inclined simple shear method, the apparent shear angle that closely approximates to the actual geometry of the master detachment fault is then calculated. After a discussion on a geometric relationship between structural features with a comparison between the restoration results, the effects of tectonic compaction observed in the experiment are presented. A subsequent paper will apply these results to a series of cross-sections from sandbox experiments using 3D listric master fault geometries, and discusses possible along-strike migrations of the hanging wall (Yamada and McClay, 2003a).

2. Geometric models

A number of geometric models have been proposed and discussed by several authors (e.g. Williams and Vann, 1987; Dula, 1991; Withjack and Peterson, 1993) and are well established. Fig. 2 illustrates how fault geometry can be reconstructed from a deformed horizon with five existing methods commonly used for analysis of the hanging wall deformation above a listric extensional fault. In this section, these methods and their limitations are briefly described.

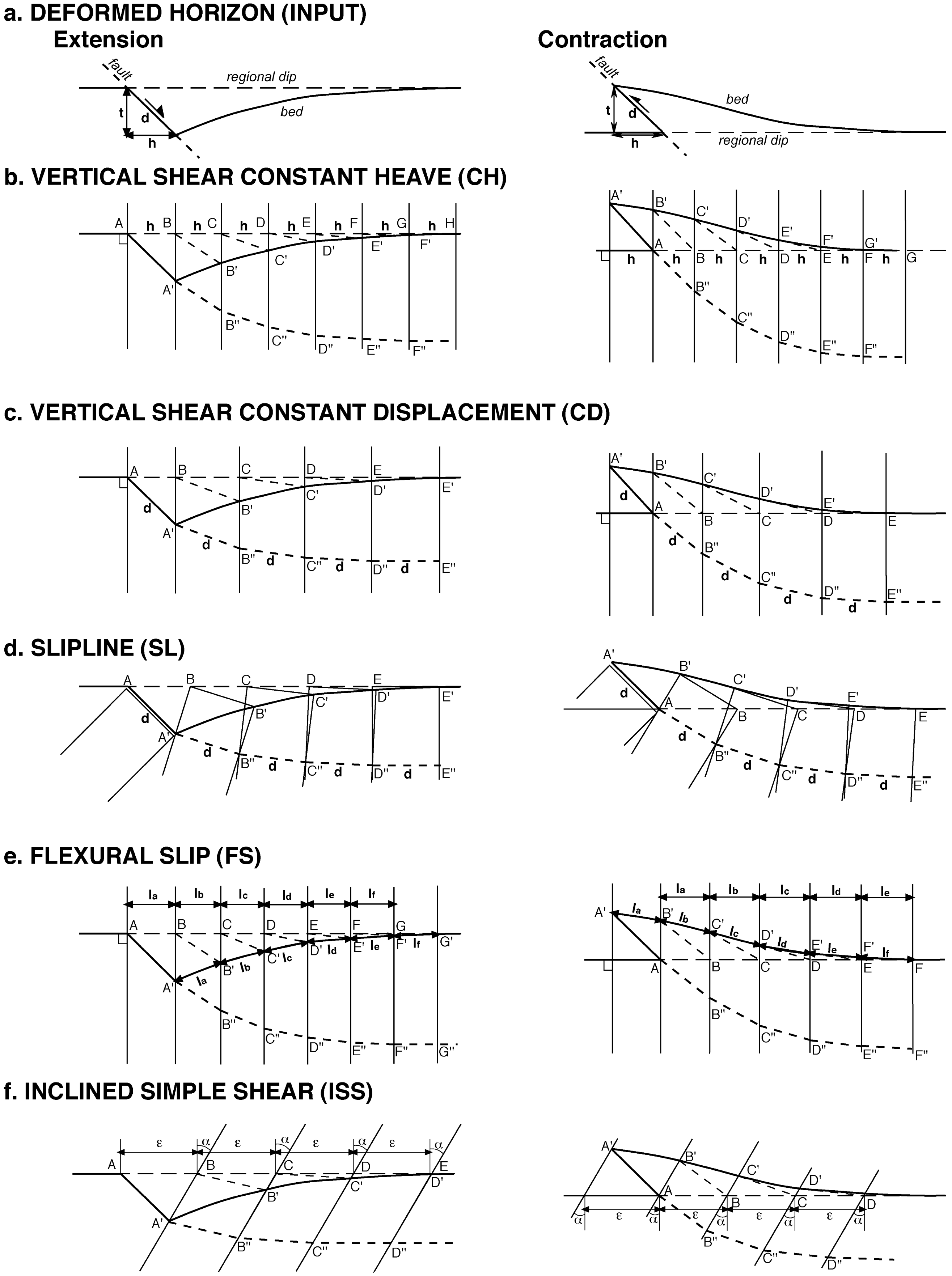
2.1. Vertical shear method with constant heave (CH method); Fig. 2b

The vertical shear method with constant heave (CH method; Verrall, 1981; Gibbs, 1983, 1984), also known as the Chevron construction, assumes that the horizontal component of the fault displacement (*d*, see Fig. 2a), the fault heave (*h*), stays constant during deformation. From the initial undeformed position, the hanging wall is supposed to translate a distance horizontally, and then collapse along vertical slip planes to fill the void between the footwall and hanging wall. Therefore, the vertical simple shear is the fundamental assumption of this method for the hanging wall deformation and formation of the rollover anticline. This helps to make the bed thickness along the vertical shear planes stay constant, and the hanging wall folds are area-balanced. In contrast, the orthogonal thickness of the strata is variable and the bed length increases.

2.2. Vertical shear method with constant displacement (CD method); Fig. 2c

In the CH method, as the fault flattens towards horizontal at depth, the displacement is reduced by the reduction of the throw (*t*, see Fig. 2a) and the conservation of the heave. Therefore any listric fault shows a reduction of displacement down-dip. The vertical shear method with constant displacement (CD method; Williams and Vann, 1987), also called modified Chevron construction, was developed to overcome this problem. The CD method assumes that each increment of displacement measured along the fault surface, is conserved and the hanging wall is deformed by simple vertical shear.

Fig. 2. Geometric models used in this paper. (a) Input parameters to construct fault trajectories. (b) Vertical shear with constant heave (CH) method. (c) Vertical shear with constant displacement (CD) method. (d) Slipline (SL) method. (e) Flexural slip (FS) method. (f) Inclined simple shear (ISS) method. See text for details.



a. DEFORMED HORIZON (INPUT)

Extension

Contraction

b. VERTICAL SHEAR CONSTANT HEAVE (CH)

c. VERTICAL SHEAR CONSTANT DISPLACEMENT (CD)

d. SLIPLINE (SL)

e. FLEXURAL SLIP (FS)

f. INCLINED SIMPLE SHEAR (ISS)

2.3. Slipline (SL) method; Fig. 2d

Both the CH and the CD methods require displacement paths to be parallel in any given vertical column in the hanging wall. However, material in the hanging wall may move along the sliplines or trajectories parallel to the fault profile, which is the fundamental assumption of the slipline (SL) method (Williams and Vann, 1987). In this SL method, the hanging wall deformation is determined with displacement segments perpendicular to the master fault, rather than vertical heave segments.

2.4. Flexural slip (FS) method; Fig. 2e

Conservation of bed length is one of the strong constraints when balanced cross-sections are constructed. Davison (1986) proposed a construction method with the constant bed length concept and the vertical simple shear as the deformation mechanism. This combination assumes that the deformation of hanging wall is accomplished by flexural slip folding through bedding plane slip, and is called the flexural slip (FS) method (e.g. Bulnes and McClay, 1999). In the FS method, the displacement of a listric extensional fault is reduced down-dip by the reduction of both the throw and the heave. In the case of contraction, fault displacement toward down-dip is defined by the effects of the reducing throw and the increasing heave (Fig. 2e).

2.5. Inclined simple shear (ISS) method; Fig. 2f

Examples of natural deformation often include numerous antithetic and synthetic faults within the hanging wall, suggesting that shear faulting is a common deformation mechanism (Dula, 1991). It is thus assumed that simple shear is more likely to occur on inclined planes. The planes are believed to be parallel to the synthetic or antithetic faults, such that developed in the roll-over folding above extensional listric faults (e.g. Coward, 1992). However, an investigation by White (1992) argued that planar simple shear may not be clearly apparent since it only represents the bulk or average deformation.

In the construction methods based on this inclined simple shear concept (White et al., 1986; White, 1987; Dula, 1991), the hanging wall is translated parallel to the regional dip and then sheared at an angle parallel to the shear plane. To construct the master fault geometry from a roll-over geometry, the shear angle as well as the heave must be estimated. As the assumption of this method, the inclined simple shear allows bed thicknesses along the shear plane to remain fixed, and the hanging wall will be area-balanced.

2.6. Limitations

Each geometric model is based on a single geometrical relation between the deformed hanging wall and the underlying master fault. The deformation is therefore simplified as a bulk deformation above a fixed master fault. The CH and ISS methods approximate the deformation of simple shearing, whereas others may be more complicated combinations of simple deformation mechanisms. Differential compaction and heterogeneity in the strata may affect the final deformation geometry, but are excluded from the analysis presented in this paper.

Selection of the horizons from which the master fault geometry is extrapolated may also cause errors or inaccurate results in estimating the cross-sectional shape of the master fault, if the horizons are widely spaced or their number is too small (e.g. single horizon). To overcome this problem, White (1992) recommended using a large number of hanging wall beds in the growth sequence. This paper employed five horizons in the syn-contractional growth to reconstruct fault trajectories using the methods illustrated above.

As the techniques are relatively simple, complexity in the hanging wall geometry generated by minor faults, which are commonly seen in both natural and experimental examples, generally introduce significant complications in the master fault geometries. Two approaches can be used to solve this problem. One is to use a simple low pass filter to remove short wavelength wiggles from the resultant trajectory (e.g. White, 1992). The other is to remove minor faults from the section by using section balancing techniques and making the geometry of each horizon smooth. This method maintains the overall hanging wall geometry unchanged. This paper has taken the latter approach because of its simplicity.

3. Restoration of cross-sections

There are two main reasons for restoring cross-sections. First, restoration with geometric models helps to evaluate whether the section is geometrically reasonable or not. This is particularly relevant to balanced cross-sections, which need to be restored to their undeformed state by a reasonable kinematic pathway (Mitra and Namson, 1993). Second, the section restoration provides information on the progressive development of structural deformation. This information is vital for the petroleum exploration industry because hydrocarbon migration and the distribution of reservoirs is closely related to the structural development. This section summarises two techniques that are applied to an experimental model section.

3.1. Line length restoration

Line length restoration is the simplest and most commonly used method for restoring sections (Bally et al., 1966; Price and Mountjoy, 1970; Mitra and Namson, 1993). This method assumes that all line lengths and thicknesses are consistent during deformation. The restoration is completed by plotting the measured bed lengths of deformed strata as straight segments from a fixed reference line called a ‘pin line’. The pin line is established in an area of no interbed slip; such as an undeformed area in the foreland or an axial plane of a major fold (Woodward et al., 1985; Mitra and Namson, 1993).

3.2. Restoration by inclined simple shear method

The geometric models described above also constrain restoration of cross-sections. As discussed later, the inclined simple shear (ISS) method best approximates the hanging wall deformation of the experiment, and was used to restore the model section.

Restoration of contractional deformations above a listric fault is achieved by the procedure presented in Fig. 3. First, the hanging wall is displaced horizontally with the amount of apparent shortening, then the deformed hanging wall is restored to its undeformed state by being displaced along the inclined shear plane defined by the trajectory technique. The amount of displacement along each shear plane is defined by the distance along the plane between the regional and the deformed geometry of the target horizon in the hanging wall.

4. Analogue experiment of positive inversion structures

A series of analogue experiments were carried out to investigate the hanging wall deformation above listric fault geometries (see Yamada (1999) and Yamada and McClay (2003b) for details). Rigid footwall blocks were employed so that the geometry of the master fault remained fixed throughout the deformation history. The experiment analysed in this paper employed a footwall block, which had a simple upward concave listric geometry in profile and also a gentle concave curvature in the plan view (Fig. 4).

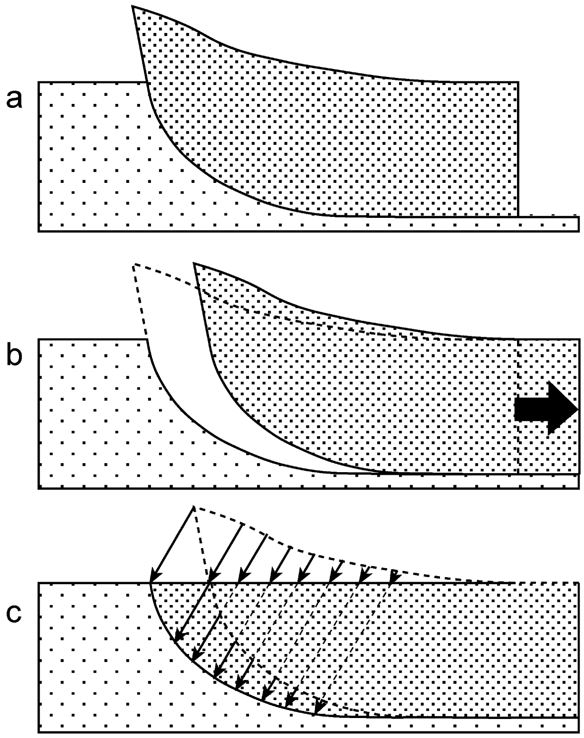


Fig. 3. Restoration procedure with the ISS method. (a) Original geometry. (b) The hanging wall is translated horizontally. (c) The hanging wall is sheared to fill the void. Note that this is the reverse process of deformation model in Fig. 1.

In the experiment, the hanging wall composed of dry quartz sand was uniformly extended by 10 cm by pulling the footwall block at a constant displacement rate of

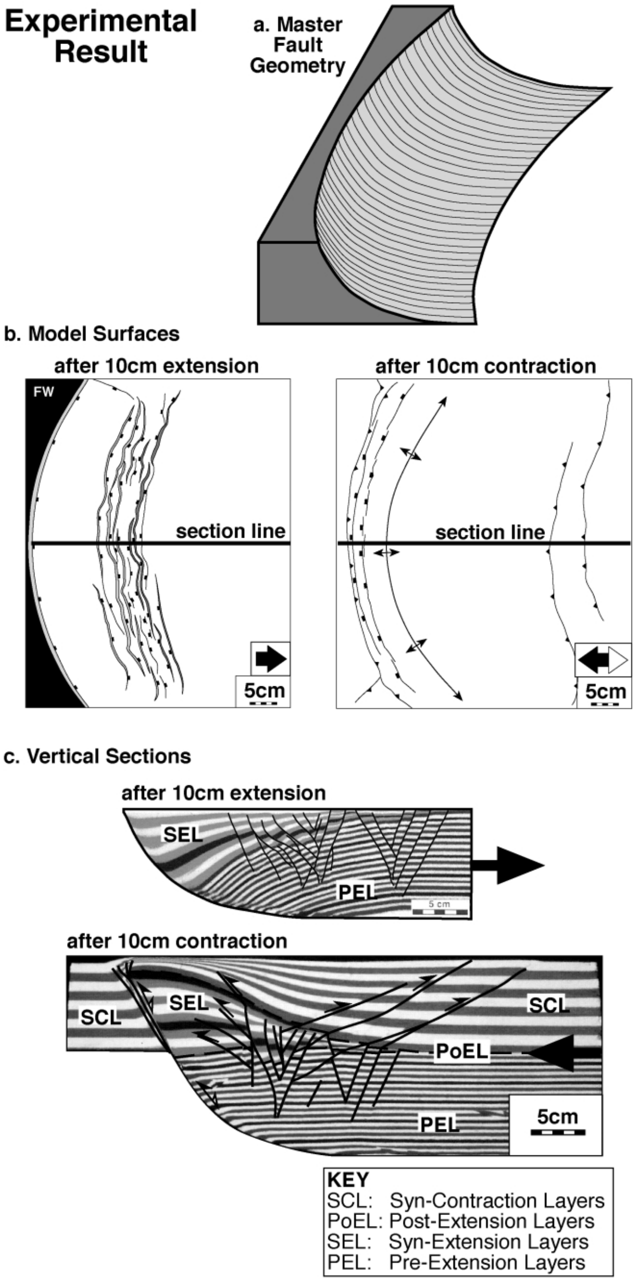


Fig. 4. Experimental result. (a) Master fault geometry; a concave listric fault which is gentle concave in plan view. (b) Structural geometry on the model surface at the final stages of extension and subsequent contraction. (c) Vertical sections after extension and subsequent contraction.

4.16×10^{-3} cm s^{-1}. A post-extension layer was added. Then the hanging wall was uniformly contracted by 10 cm, by pushing the footwall block back in the exactly opposite direction at the same rate as that of extension. The accommodation space generated by extension was infilled after every 10 mm increment of extension with the same modelling material as the pre-kinematic sequences. During contraction, uplifted structures were also preserved by sedimentation of the sand, which was poured on the upper free surface after every 10 mm of contraction. The models were then solidified and sliced into serial vertical sections in 10 mm thickness along the displacement direction of the footwall.

During extension, the experiment produced normal faults associated with a characteristic crestal collapse graben system, which is broadly parallel to the plan geometry of the master fault (Fig. 4b). The faulting occurred almost simultaneously in the hanging wall and showed little variation along strike. During inversion, the master fault was reactivated as a thrust and the hanging wall was uplifted to form an inversion anticline. At the tip of the former graben faults, backthrusts were initiated and propagated upwards and downwards. The axis of the anticline and the backthrusts observed on the top free surface were again sub-parallel to the plan geometry of the master fault (Fig. 4b). The section analysed was produced at the centre of this experiment, where the section line was generally perpendicular to the structures. Little variation was observed on the serial sections, and no structure was observed related to the gentle 3D shape of the master fault. The deformation thus can be approximated as 2D on the section (Fig. 4c).

The experimental result presented in this paper and those of 2D inversion analogue models using a similar procedure have successfully been applied to natural inversion structures (e.g. Buchanan and Buchanan, 1995; Yamada, 1999). This is because the experimental material (dry sand) is appropriate to model the brittle behaviour of the upper crust.

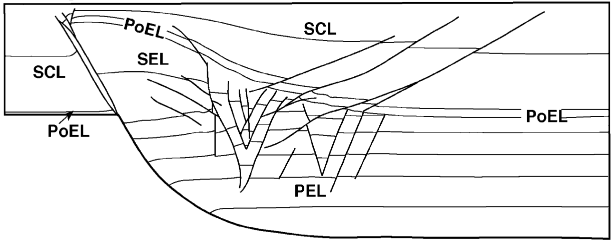
5. Results of geometric analysis and section restoration

5.1. Geometric analysis

Constructing a series of fault trajectories helps in deducing the most suitable shape of the master fault. Prior to the construction, minor thrust faults were removed from the section (Fig. 5). Since the line length was kept constant during the removal of the thrust faults and the procedure started from the master fault toward the hanging wall side, the right end of the section could not be kept as a straight line indicating a various shortening on each horizon by the thrust faults (Fig. 5b).

Fig. 6 displays the fault geometries predicted from the hanging wall deformation with the CH, FS, CD and SL methods. With the trajectories by the former three methods drawn from the five horizons in the syn-contraction sequence, the detachment horizons are estimated to be significantly deeper than the actual fault geometry. Although the SL method predicts the approximate depth of the detachment horizon, the model geometry flattens more gradually than the actual fault. Thus the assumptions on which these four techniques are based are not acceptable for reconstructing the fault shape of the sandbox model.

a. original section



b. thrust-removed section

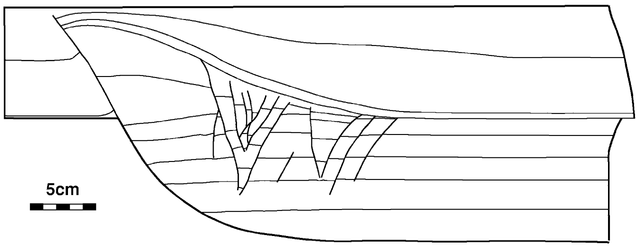


Fig. 5. (a) A line drawing of the vertical section from the experiment. (b) A line drawing of the section from which minor thrusts have been removed. Note that the line-length is kept constant during the removal.

The resultant geometries of fault prediction by the ISS method are shown in Fig. 7 for a series of antithetic shear angles. The shear inclination for each section was determined to minimise the difference between the depth of the actual and predicted detachment horizons. Again, the trajectories are drawn for five horizons in the syn-contraction sequence. The fault prediction with a shear angle of 32° is nearly coincident with the actual master fault

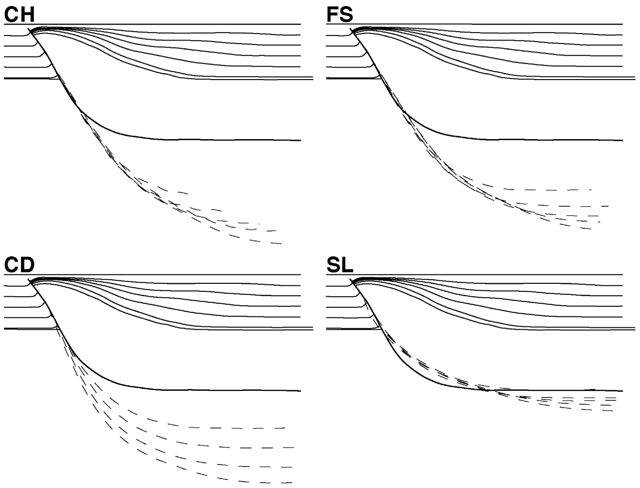


Fig. 6. Master fault geometries estimated from the deformed horizons in the syn-contraction sequence of Fig. 5b with four fault trajectory methods.

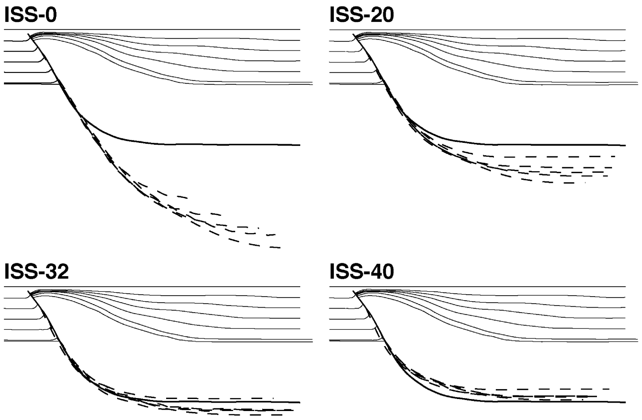


Fig. 7. Master fault geometries estimated from the deformed horizons in the syn-contraction sequence of Fig. 5b with the inclined simple shear (ISS) method with various shear angles. The trajectories with 32° show a coincidental agreement with the actual master fault geometry. The shear angles are all antithetic (0° refers vertical shear).

geometry and almost identical to the detachment horizon (Fig. 7). Since the ISS method approximates the deformation as simple shearing, the trajectory result suggests that the bulk hanging wall deformation above the concave listric fault can be best approximated by antithetic simple shearing inclined 32°.

With the shear inclination obtained by the above procedure, an apparent shortening can be calculated. In Fig. 8, point X′ was originally at O and displaced along the fault surface. The ISS method, however, approximates this displacement path being a product of two paths: a displacement parallel to the regional horizon (OX) and another parallel to the shear plane (XX′). The point X can be determined by drawing a line from the point X′ with the inclination obtained by the above analysis. Therefore the line OX can be determined and this length refers to the apparent shortening, i.e. an amount of shortening calculated from the final deformation geometry of the horizon.

When this procedure is applied to the top horizon of the syn-extension sequence, the result shows how much shortening the section has obtained during contraction. Therefore the shear inclination 32° suggests that the section had an apparent shortening of 8.9 cm during contraction (Fig. 8). As described earlier, the displacement given to the experiment was 10 cm, this apparent shortening is thus significantly smaller. Since the deformation on this section can be approximated as plane strain, the difference (1.1 cm) must be consumed by internal deformation of the sand pack. Actually during the experimental runs, the first 1 cm of contraction produced almost no deformation (Yamada, 1999). This observation, together with the calculation presented here, suggests that the first 1 cm of contraction may be consumed by re-orientation and packing of sand grains. This can be regarded as an effect of tectonic compaction.

The basic principle of the ISS method assumes that areas on sections will be conserved during deformation. This refers to that the apparent shortening and therefore the shear inclination are both determined to conserve the areas. In Fig. 8, the area of the hanging wall uplift (HU) is 89 cm^2, which accords with the CS area defined by the depth-to-detachment (10 cm) and the calculated shortening (8.9 cm). This relationship is exactly the same as that of the depth-to-detachment method by Chamberlin (1910, 1919). In addition, these areas of HU and CS are identical to the overlapped ones (OV in Fig. 8) of the footwall and the hanging wall caused by the displacement along the fault segment parallel to the regional (Fig. 8).

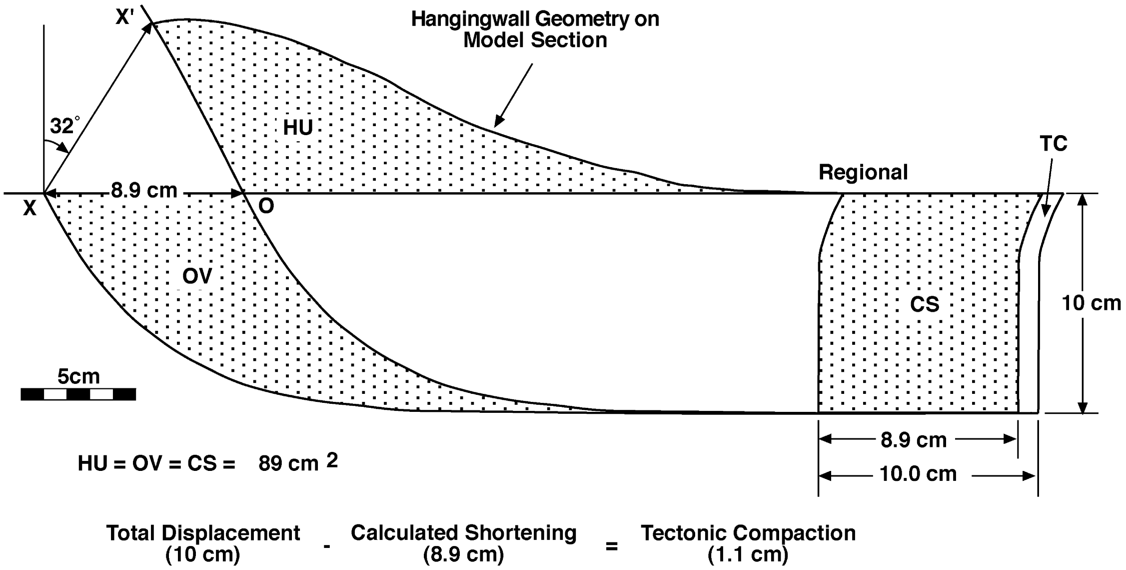


Fig. 8. The relationship between the shear inclination and the apparent hanging wall shortening based on the ISS method. The areas of HU, OV and CS are all equal (cf. Fig. 1c). The horizon analysed is the top of the syn-extension sequence of the experiment (see Fig. 5b).

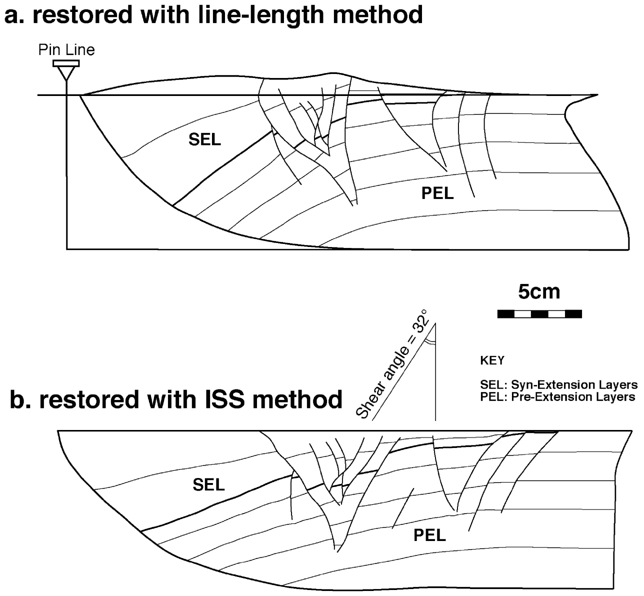


Fig. 9. Restoration of the Fig. 5b section to the pre-inversion stage by two methods; (a) the line length method, (b) the ISS method with a shear angle of 32°.

5.2. Section restoration

Fig. 9a shows the line-length restoration result with a pin line set in the footwall. The listric master fault geometry was preserved during the restoration. By following the assumptions of this method, with the lengths and thicknesses constant, the geometry restored to the pre-inversion stage shows that the section was not restored appropriately. Nevertheless, the restored section provides useful information on the structural geometry. First, the sheared geometry of the crestal collapse graben in Fig. 9a refers to that the horizons in the syn-extension layers and the uppermost one in the pre-extension layers shortened in length under subsequent contraction. By examining the deformation geometry of the restored section, it can be understood that this shortening mostly occurred around the major crestal collapse graben and at the area in between the graben and the master thrust. Second, the restored hanging wall geometry demonstrates a significant increase in thickness of the syn- and pre-extension sequences during contraction. This thickening effect occurred mainly at the area of the crestal collapse graben. These shortened lengths and the thickened layers at or around the major crestal graben system suggest that the hanging wall was deformed in this particular area. As a result, this method does not restore the section properly, because neither the length nor thickness were apparently conserved during contraction.

The thrust-removed section of the experiment (Fig. 5b) was also restored to the pre-inversion stage with the inclined simple shear method (Fig. 9b). The shear plane inclination of 32° and the horizontal displacement of 8.9 cm were applied. In comparison with the section obtained before inversion (Fig. 4c), the restored section displays similar geometries of extension structures. The restored master fault is also close to its listric geometry. These observations support that the hanging wall deformation can be approximated as inclined (32°) simple shearing.

6. Discussion; 2D hanging wall deformation

These experiments are conducted such that both the detachment profile and the resulting hanging wall geometry are known. Therefore the comparison of the geometric models and the analogue model constrains the major deformation mechanism by which the hanging wall geometries are formed.

The deformation mechanism of natural hanging wall structures will be complex and is a combination of simple mechanisms, such as pure or simple shear, bedding plane slip, and differential compaction. The combination depends on the physical property of the rock and the deformation environment. However, the final result of finite deformation can be approximated by a single mechanism when that mechanism predominates. Alternatively, one can envision that a deformation mechanism accomplishes all deformation in the hanging wall. In such regions, the techniques of the 2D geometric models can be applied successfully for deformation analysis.

The pre-existing structures formed before inversion can be the most important control of structural deformation formed under subsequent stress fields (Buchanan, 1991; Yamada, 1999). In addition, sedimentation during extension may also affect the deformation under subsequent stress fields, because the sedimentary load variation due to the sedimentation causes along-strike variation in the overburden pressure on the main thrust surface. In the experiment, the final geometry of inversion structures may include these effects, thus the results show general features seen in many inverted structures.

The results of the analyses based on the geometric models show that many features of the hanging wall deformation during contraction can be well explained by the inclined simple shear (ISS) mechanism. This may be influenced by the physical property of the modelling material. The hanging wall of the experiments consists of homogeneous dry sands, thus no anisotropy exists in the experimental models during deformation. The granular nature of the material does not necessarily cause a flexural slip at each bedding plane, but simple shear along a vertical or inclined plane would be preferable as the sand pack behaves as a single homogeneous body. Simple shear has also been used to explain the structural deformation in homogeneous wet clay models (e.g. Dula, 1991; Xiao and Suppe, 1992). It is thus presumed that simple shear is a common deformation mechanism of fault hanging walls where the lithology is not highly anisotropic.

The shear plane estimated for the experimental model showed an antithetic inclination. White et al. (1986) argued that the contractional deformation by an antithetic shear commonly produces a series of pervasive backthrusting in the hanging wall, whereas a synthetic shear deformation is frequently accompanied by a series of imbricate thrusting. This agrees with the fact that in the experiments the backthrust systems are developed more frequently than the imbricate thrust systems during contraction (Yamada, 1999). Comparing this conclusion with an argument by White (1992) that synthetic shearing is unrealistic in extensional settings, antithetic shearing may be the common deformation mechanism of fault hanging walls.

An effect of tectonic compaction consumed part of the displacement given to the experiments, and the amount of shortening calculated from the 2D deformation geometry was smaller than that actually given to the experiments (e.g. 8.9 cm in Fig. 8). This may be related to the physical status of the experimental material. The experimental models conducted for this research employed dry sand as the deforming material. If the sand was reasonably well-compacted, the volume should increase during deformation (Boerner and Sclater, 1992). However, the sand was loosely packed (not tapped) when the models were constructed. According to Allen (1970), the intergranular porosity of natural quartz sands (270 μm in diameter) was 44% in a loosely packed condition, similar to that of the experiments. The porosity then decreased to 36% when the sand was densely packed by tapping a container of the sand (Allen, 1970). This porosity reduction is caused by a change in the grain orientation. Thus if a tectonic inversion acted as a trigger to re-orient the sand grains, the porosity reduction of some percentage could also happen in the experimental models.

7. Conclusions

The hanging wall deformation above the inverted listric master fault of the sandbox experiment can be approximated by the antithetic simple shearing inclined 32°. This can also be supported by section restoration. Since the experiment can be considered to satisfy the similarity conditions, this inclined simple shearing may be a common mechanism of hanging wall deformation where there is no strong anisotropy in the hanging wall. The apparent shortening estimated with the geometric technique is smaller than the actual amount of contraction applied to the experiment. This suggests an effect of tectonic compaction produced by re-orientation of sand grains.

Acknowledgements

This work is based on YY's PhD research at Royal Holloway University of London, and further developed at JAPEX Research Centre. The analogue modelling was supported by the Fault Dynamics Project, sponsored by ARCO British Ltd, PETROBRAS UK Ltd, BP Exploration, Conoco (UK) Ltd, Mobil North Sea Ltd, and Sun Oil Britain. JNOC and JAPEX are thanked for their financial support during YY's stay at Royal Holloway (1994–1996). The earlier version of the manuscript was greatly improved after constructive comments by Takashi Tsuji at JAPEX. Rasoul Sorkhabi and Fumio Akiba carefully reviewed the manuscript. Journal reviews by Fabrizio Storti and Steve Wojtal are also acknowledged for their constructive criticism.

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