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Application of geometric models to inverted listric fault systems in sandbox experiments. Paper 2: insights for possible along strike migration of material during 3D hanging wall deformation

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Abstract

Fault geometry is a primary control on hanging wall deformation. In this study, a series of positive inversion analogue experiments was conducted using rigid fault surfaces of true 3D geometry, with consistent listric geometry along the transport direction. The deformed geometry of the top horizon of the syn-extension sequence on vertical serial sections was examined with a conventional 2D geometric restoration technique to calculate the inclined antithetic shear angle that best approximates the actual fault shape, and to estimate the amount of apparent horizontal shortening during contraction. The apparent shear inclination and the estimated apparent shortening show a systematic change along strike, corresponding to the plan geometry of the master detachment surface. At the hanging wall above embayments in the fault geometry, the uplift is highest, the apparent shear inclination is gentlest and the apparent horizontal shortening is greatest. In contrast, the apparent shear inclination is steepest and the estimated shortening is smallest above salients in the master detachment geometry, where the uplift is lowest. These changes suggest that the hanging wall displacement had an along-strike component during deformation; the hanging wall material moves from the regions above salients to those above embayments in the detachment surface during contraction. Average of the estimated apparent shortening was smaller than the actual amount of the experiments, probably due to tectonic compaction. This study shows that the geometry of the master detachment in plan view has the primary control on the lateral variation of the hanging wall deformation. The data presented in this paper help understand 3D geometric relations between the hanging wall deformation and the underlying detachment surfaces.

Keywords: Geometric models; Listric fault systems; Sandbox experiments

1. Introduction

The previous study (Yamada and McClay, 2003a) examined hanging wall deformation on a cross-section seen in an analogue experiment with a series of geometric models. The results illustrated that hanging wall deformation above inverted listric fault can be best approximated by the inclined simple shearing. Since the top horizon of the syn-extension sequence was horizontal at the beginning of contraction, the apparent shear inclination and the apparent shortening can be calculated from the deformed geometry of the horizon.

In this paper, the inclined simple shear (ISS) method is applied to sandbox experiments carried out with 3D listric fault surfaces. The apparent shear angle which closely approximates to the actual geometry of the master detachment fault is then calculated for serial sections produced from 3D experimental models. The variation in the shear inclination, and the apparent shortening calculated from the shear inclination, as seen in the 3D models are also discussed. Finally, conceptual models are presented for displaying the along-strike displacement above 3D fault geometries.

2. Analogue experiments of positive inversion structures

Analogue experiments above various listric fault geometries were analysed to investigate the hanging wall deformation (see Yamada (1999) and Yamada and McClay (2003b) for details), and those analysed in this paper had

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two listric fault geometries. The vertical profiles of these faults were exactly the same; a simple concave upward listric, whereas those in plan view were different; sigmoidal (Model I; Fig. 1) and double concave shape (Model II; Fig. 2). The listric profile is exactly the same as that of the experiment presented in Yamada and McClay (2003a). Rigid footwall blocks were employed so that the geometries of these master faults remained fixed throughout the deformation history (Figs. 1a and 2a).

The model kinematics were exactly the same as that of Yamada and McClay (2003a); 10 cm of extension followed by 10 cm of contraction. The displacement was generated by pulling or pushing the footwall blocks at a constant displacement rate of 4.16×10^{-3} cm s^{-1}. The experimental material was dry homogeneous cohesionless sand.

On the free surfaces of Models I and II during extension, normal faults associated with crestal collapse graben systems were observed (Figs. 1b and 2b). The graben faults were initiated almost simultaneously in the hanging wall, and the grabens were broadly parallel to the plan geometry of the master fault. In addition, thrust faults were also observed above the salient or the cusp in the master fault geometry. During contraction, the master fault was reactivated as a thrust and the hanging wall was uplifted to form inversion anticlines. Backthrusts were also initiated at the tip of the former graben faults and propagated upwards and downwards. The axis of the inversion anticline and the backthrust systems were again sub-parallel to the plan geometry of the master fault (Figs. 1b and 2b). The thrust faulting was initiated at the regions where the former graben was oblique to the direction of contraction (Yamada, 1999; Yamada and McClay, 2003b). Yamada (1999) expanded the 2D theory of preferential reactivation by Sibson (1985) to 3D and found that the thrust faulting agrees with the 3D theory. The amount of subsidence during extension and that of uplift during contraction showed variations along strike of the master fault in both models. Each model was sliced into 60 vertical sections (Figs. 1c and 2c) and analysed with fault geometric methods.

These 3D experiments are a part of an intensive 3D analogue modelling programme and were conducted with a similar procedure including the use of dry sand (Yamada, 1999). Since the material has been considered to be appropriate to model the brittle behaviour of the upper crust, the results have been successfully applied to many natural geologic structures in the world (e.g. McClay, 1996; Yamada, 1999). This suggests that the deformation styles seen in the experiments may be analogous to those of the natural geologic structures.

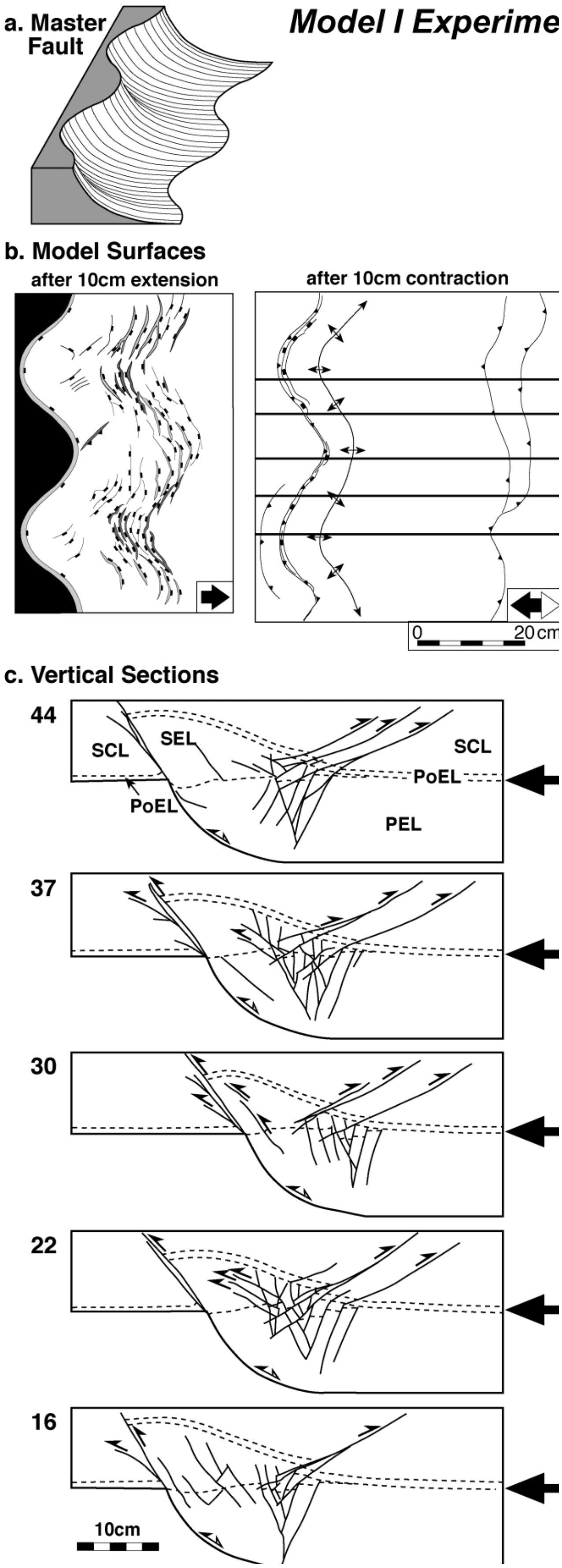
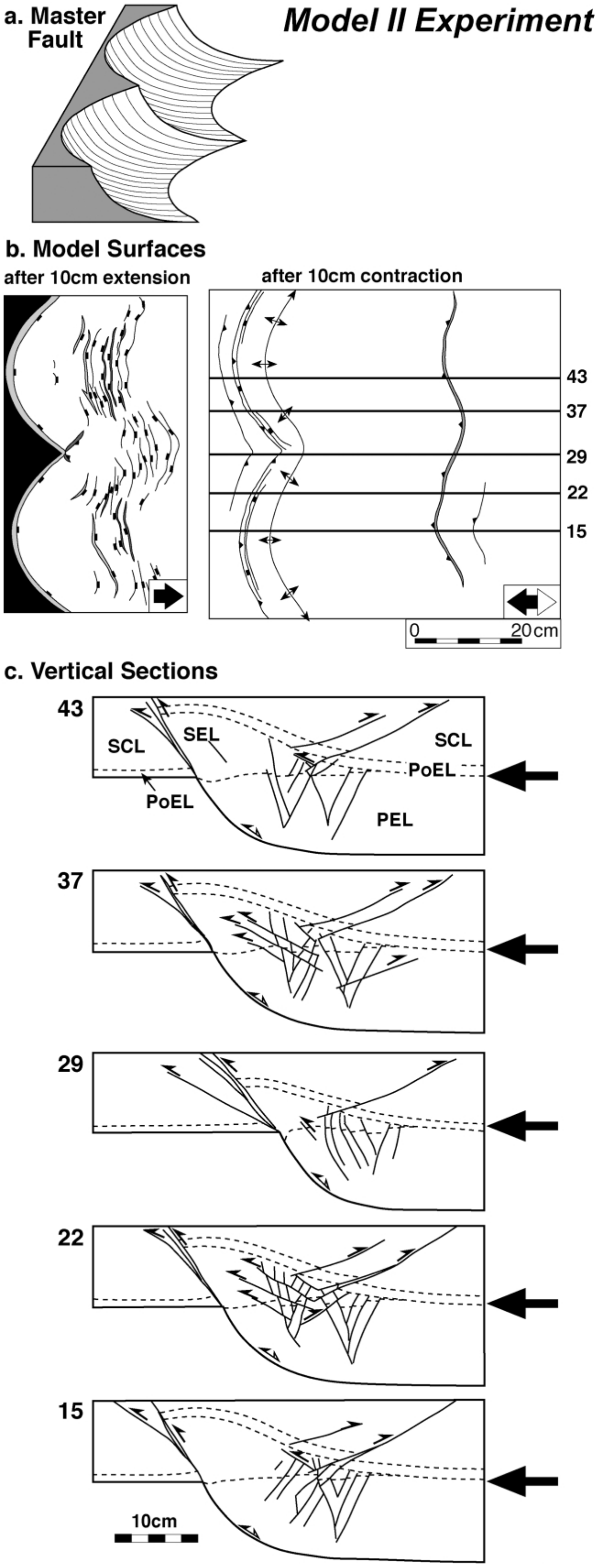


Fig. 1. Model I experiment. (a) Master fault geometry; a concave listric fault, which is sigmoidal in plan view. (b) Structural geometry on the model surface at the final stages of extension and subsequent contraction. (c) A series of vertical sections after contraction. PEL; pre-extension layers, SEL; syn-extension layers, PoEL; post-extension layers, SCL; syn-contraction layers.



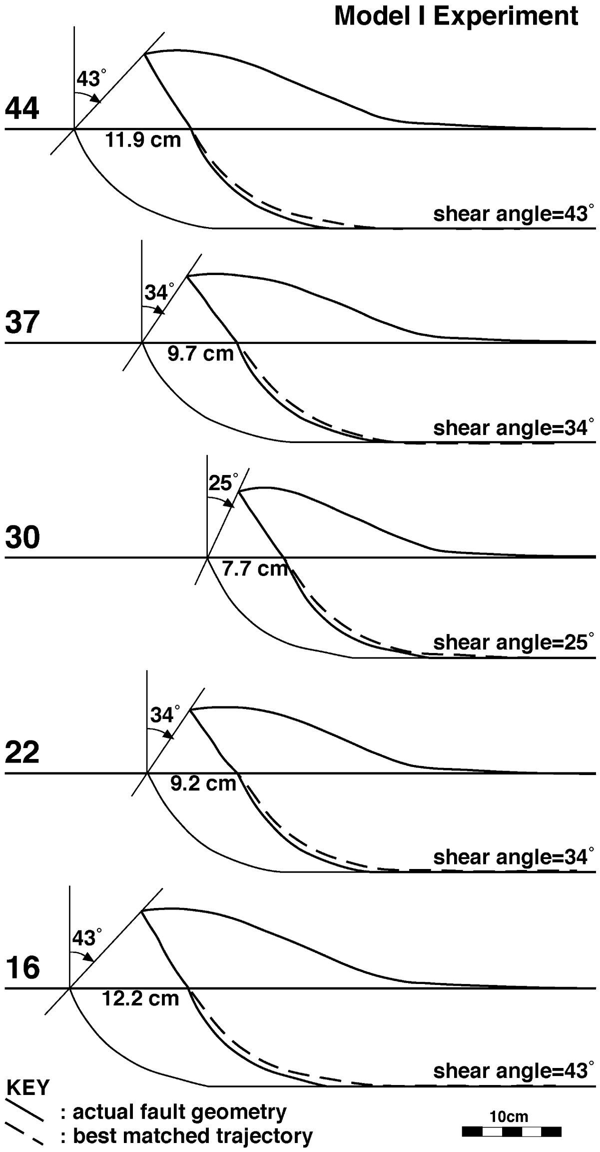


Fig. 3. Fault trajectories and amounts of shortening estimated from the base horizon of the syn-contraction sequence on the five representative sections from the Model I experiment.

3. Results of geometric analysis

The series of vertical sections from Model I (Fig. 1c) and Model II (Fig. 2c) were analysed with the ISS method, and the shear inclination and the apparent shortening were calculated. Fig. 3 displays the fault trajectories (dashed lines), which produced the geometries most similar to the actual fault (bold lines), together with the estimated shear angles for the representative five sections from Model I.

Fig. 2. Model II experiment. (a) Master fault geometry; a concave listric fault, which is double-concave in plan view. (b) Structural geometry on the model surface at the final stages of extension and subsequent contraction. (c) A series of vertical sections after contraction. See the caption of Fig. 1 for the key.

Fig. 4 displays the along-strike variations of the shear inclination and the apparent shortening calculated from the 50 serial sections from Model I.

Clearly, these results illustrate that the shear inclination and the apparent shortening have been affected by the plan geometry of the underlying master fault. Take section 30 (see Fig. 1) for example, it has the minimum value of a shear angle of 25° (Fig. 3). This is smaller than the shear angle of 32° estimated from the 2D section of Yamada and McClay (2003a), which has the same vertical profile as that of Model I. The apparent shortening on the section is only 7.7 cm (Fig. 3), which is the minimum value in Model I. In contrast, the shear angle and the apparent shortening is greatest (43° and 12 cm, respectively) above the embayments in the master fault, as shown in sections 16 and 44. This apparent shortening (12 cm) exceeds the actual shortening (10 cm) given to the experiment.

The vertical sections from the Model II experiment were also examined by the ISS method and the results (Figs. 5 and 6) present similar features to those of Model I (Figs. 3 and 4). That is, the sections above the embayments in the master fault show the greatest inclination in the shear angle (e.g. 40.8° in section 15), and section 29 produced at the cusp of the two concaves in the master fault displays that the trajectory predicts a very small inclination of the shear angle (12.9°).

The apparent shortening also shows similar variations to those of the Model I experiment. The sections above the embayments in the master fault suggest longer apparent shortening (e.g. 10.9 cm in section 15) than the actual shortening (Fig. 5). On the other hand, section 29 illustrates that the apparent shortening is 5.7 cm. As described earlier, the actual shortening given to the models is always equal (10 cm). The apparent shortening is, however, generally smaller (Fig. 6).

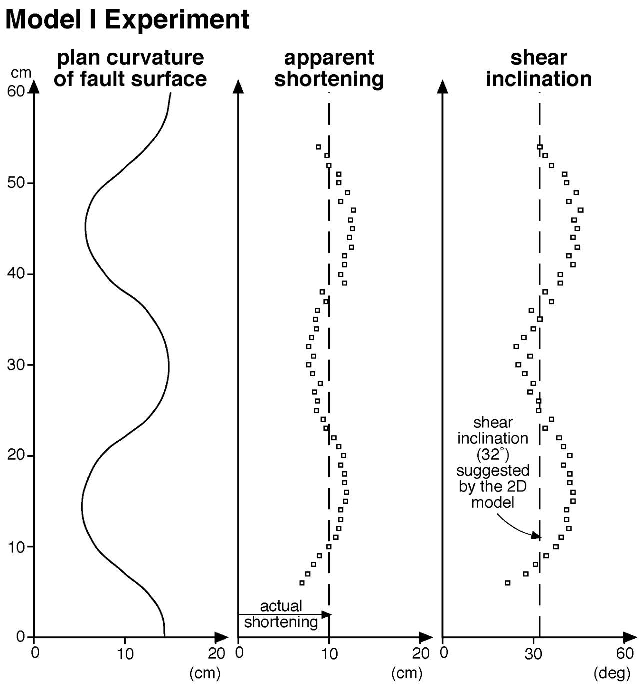


Fig. 4. Lateral variations in the shear angle and the shortening amount estimated from the base horizon of the syn-contraction sequence of the Model I experiment. See text for details.

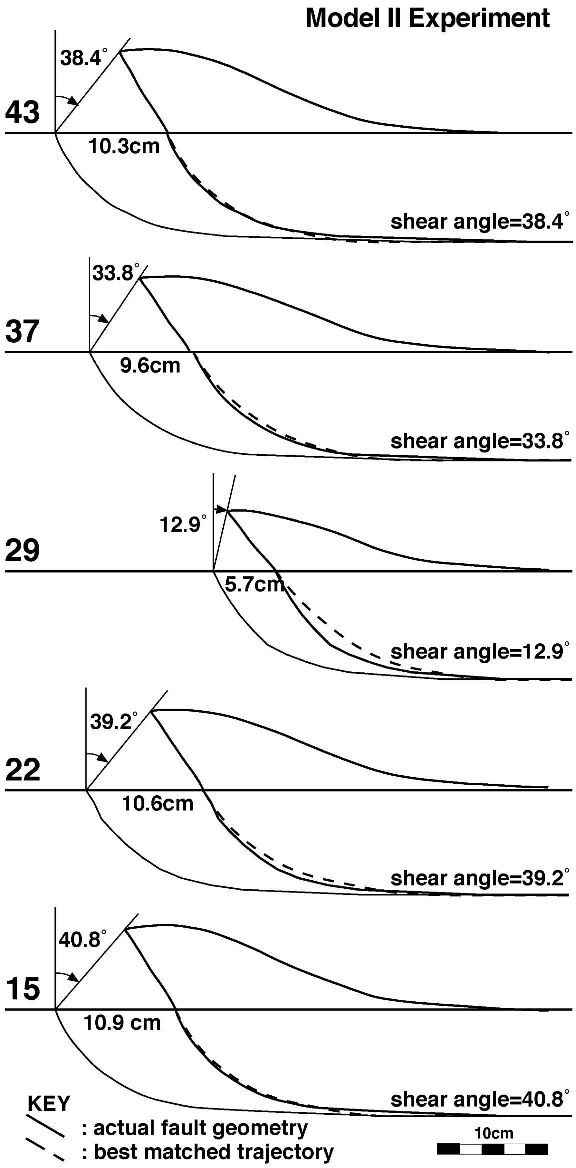


Fig. 5. Fault trajectories and amounts of shortening estimated from the base horizon of the syn-contraction sequence on the five representative sections from the Model II experiment.

4. Discussion; variety of shear plane inclination and horizontal shortening

The hanging wall deformation of the experiments presented in this paper is mainly controlled by a 2D mechanism that explains the structural geometry on the vertical sections produced parallel to the tectonic transport direction. This is supported by the fact that the structural

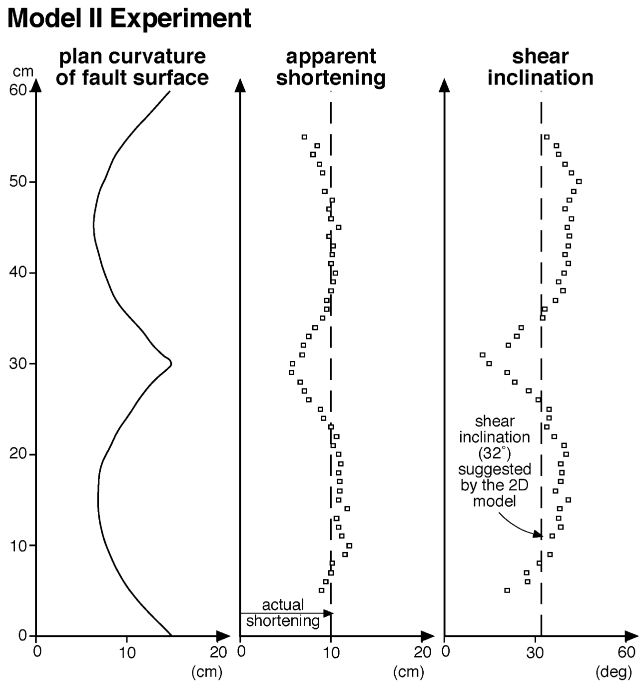


Fig. 6. Lateral variations in the shear angle and the shortening amount estimated from the base horizon of the syn-contraction sequence of the Model II experiment. See text for details.

geometries observed on the serial vertical sections from the 3D experiments are almost identical (e.g. Figs. 1c and 2c). In addition, the structural features on horizontal sections show their directions are generally parallel to the plan geometry of the master fault surface (Yamada, 1999). Thus it is presumed that the mechanism defining the 2D deformation geometry also controls most of the hanging wall deformation above the master fault of a 3D geometry. This may be related to the kinematics of the experiments; the footwall blocks are pulled and pushed back along one defined line without rotation.

Detachment faults having a 3D geometry produce lateral variations in the hanging wall deformation (Yamada, 1999). Accordingly, the results of the fault trajectory suggest that the inclination of shear planes may not be consistent within one 3D experimental model. Since the amount of shortening can be calculated from the shear angle, this variation of the shear angle observed on the model sections can be expressed as the difference in the amount of shortening that the sections acquired. This calculated apparent shortening refers to the horizontal displacement required to generate the hanging wall deformation on the section, if the section geometry of the underlying master detachment fault had been kept unchanged during deformation. As shown in Figs. 4 and 6, this apparent shortening amount exhibits a systematic change along-strike whose curvature shows similarities to the plan geometry of the underlying master fault. Thus the lateral variation of the apparent shortening calculated from the section geometry of the hanging wall deformation may be defined by the geometry of the underlying detachment.

The variation in the estimated apparent shortening suggests a non-planar deformation of the hanging wall during contraction. That is, if materials in the hanging wall moved away from a model section during deformation, the apparent shortening will be reduced. In contrast, if the hanging wall gains volume by a lateral motion of the materials, the apparent shortening will be increased. Thus the change in the amount of apparent shortening, i.e. the change in the inclination of the shear angle, is presumably brought about by the material moving from the regions above the salient to the regions above the embayments in the master fault.

The material movement along the strike in the hanging wall is supported by the thickness of the syn-contraction sedimentary sequence in the experiments (Yamada, 1999). Since the sequence is growth strata, a change in its thickness refers to a deformation event in the hanging wall. The syn-contraction sequence above the inversion anticline is thin above the embayment in the master fault geometry (e.g. sections 16 and 44 in Fig. 1c), and is thick above the salient (e.g. section 30 in Fig. 1c). This shows that the uplift at the embayments is greater than that at the salients in the master fault, suggesting that the hanging wall is displaced from the regions above the salients to the embayment regions.

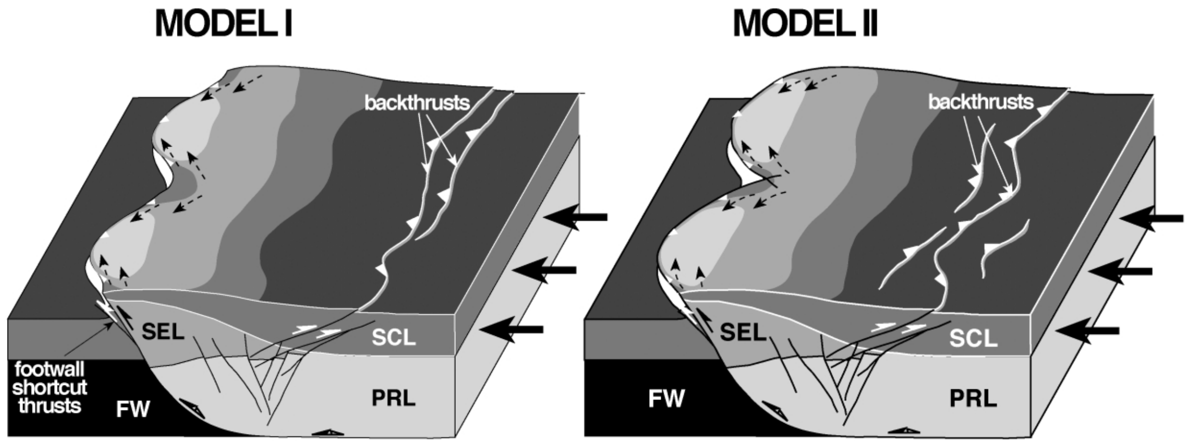


Fig. 7. Synoptic models of the hanging wall deformation of the Model I and II experiments (from Yamada, 1999).

Many may assume that such variation in the hanging wall uplift relates with an along-strike variation in the syn-tectonic sedimentation during extension. However, experimental analyses by Yamada (1999) showed that the subsidence in the hanging wall during extension is at a maximum above the embayments in the master fault geometry. These regions are of porous sediments, because of the thick sedimentation during extension; thus it can be predicted that the contractional deformation would be more consumed at embayments. The analysis of this paper resulted in the opposite conclusion to this prediction. This suggests that the out-of-plane deformation of the hanging wall during contraction is much more significant than the effect of the syn-tectonic sedimentation during extension. In order to examine this sedimentation effect, more experiments with porosity variations are necessary.

Fig. 7 shows synoptic models of the Model I and II experiments constructed from the experimental results (from Yamada, 1999), which illustrates the characteristics of structural deformation during the contraction stages. This lateral displacement of the hanging wall may be an effect similar to that proposed by Apotria et al. (1992), who described lateral displacements where the underlying thrust fault surface has a bend in plan view.

5. Conclusions

The results of the geometric analysis presented in this paper illustrate that the shear angle estimated with the ISS method shows a lateral variation in each 3D experimental model. This implies that the materials of the hanging wall move laterally, from regions above a salient geometry in the detachment surface to those above an embayment, during contractional deformation. Therefore, non-plane strain may happen above the fault surfaces of truly 3D structures. As plane strain is one of the major limitations of the 2D geometric methods, the mechanism of 3D hanging wall deformation cannot be modelled accurately by the conventional 2D geometric models. However, this study shows that, by examining the deformation geometry on serially produced sections and by comparing the results, it is possible to analyse 3D hanging wall deformation with the conventional 2D geometric models.

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