Normal Faults and Their Hanging-Wall Deformation: An Experimental Study

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ABSTRACT

We have used clay models to study the effects of fault shape and displacement distribution on deformation patterns in the hanging wall of a master normal fault. The experimental results show that fault shape influences the style of secondary faulting and folding. Mostly antithetic normal faults form above concave-upward fault bends, whereas mostly synthetic normal faults form above low-angle fault segments and convex-upward fault bends. Beds dip toward the master normal fault above concave-upward fault bends and away from the master normal fault above low-angle fault segments and convex-upward fault bends. Generally, secondary faulting and folding are youngest at fault bends and become progressively older past fault bends.

Hanging-wall deformation patterns differ significantly when a basal plastic sheet imposes a constant-magnitude displacement distribution on the master normal fault. In models without a plastic sheet, numerous secondary normal faults form in the hanging wall of the master normal fault. Most secondary normal faults propagate upward and, consequently, have greater displacement at depth. In models with a plastic sheet, few visible secondary normal faults develop. Most of these faults propagate downward and, consequently, have less displacement at depth. Hanging-wall folding is wider and bedding dips are gentler in models without a plastic sheet than in identical models with a plastic sheet.

The observed particle paths, displacement distributions, bedding dips, and orientations of the principal-strain axes in our physical models with and without a basal plastic sheet are compatible with the assumption that homogeneous, inclined simple shear accommodates the hanging-wall deformation. Not all of our modeling observations, however, are consistent with this assumption. Specifically, the observed variability with depth of the distribution and intensity of deformation is incompatible with homogeneous, inclined simple shear as the hanging-wall deformation mechanism.

INTRODUCTION

For more than 60 yr, geologists have used physical models to simulate normal faults and their hanging-wall deformation (Cloos, 1928; Cloos, 1930; Cloos, 1968; McClay and Ellis, 1987a, b; Ellis and McClay, 1988; McClay, 1989; Islam et al., 1991; McClay and Scott, 1991; McClay et al., 1992; Withjack and Islam, 1993). These experimental studies have guided the structural interpretation of field, well, and seismic data. Additionally, they have provided data for testing and calibrating geometric models of normal faults (Grosehong, 1990; Dula, 1991; White and Yielding, 1991; Kerr and White, 1992; White, 1992; Xiao and Suppe, 1992).

Physical models of normal faults differ in terms of modeling materials (wet clay vs. dry sand) and experimental constraints placed on fault shape, development, and displacement distribution. In physical models by Cloos (1968), the shape and development of the master normal fault and its displacement distribution are unconstrained (Table 1). A master normal fault develops in clay or sand above two diverging, overlapping metal sheets and propagates upward. In physical models by McClay et al. (1992), the shape and development of the master normal fault and its displacement distribution are completely constrained (Table 1). A rigid block and horizontal base act as the footwall of the master normal fault, and sand represents the hanging-wall strata. During modeling, a plastic sheet carries the sand down the sloping surface of the...
footwall block and along the horizontal base. In these models, the rigid footwall block and horizontal base predetermine the shape of the master normal fault. The plastic sheet prevents the fault shape from changing during modeling and imposes a constant-magnitude displacement distribution on the master normal fault.

We have conducted our own physical models of normal faults to study how fault shape and displacement distribution affect hanging-wall deformation (Table 1). In our models, a rigid block and horizontal base act as the footwall of the master normal fault, and a layer of wet, homogeneous clay represents the hanging-wall strata. The sloping surface of the footwall block is either planar or has a single concave-upward or convex-upward bend. Our models differ from those of Cloos (1968) in that the rigid footwall block and horizontal base define the initial shape of the master normal fault. Unlike the models of McClay et al. (1992), the shape of the master normal fault can change during modeling and the displacement distribution on its sloping surface can vary in all but one of our experiments. In that experiment, a mylar sheet beneath the clay layer prevents the master normal fault from changing during the experiment and imposes a constant-magnitude displacement distribution on the master normal fault.

Table 1. Comparison of Modeling Parameters and Results

<table>
<thead>
<tr>
<th>Modeling Material</th>
<th>Fault Material</th>
<th>Fault Shape Development</th>
<th>Fault Displacement Distribution</th>
<th>Modeling Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet clay</td>
<td>Wet clay</td>
<td>Unconstrained; sloping surface of master normal fault forms during the experiment</td>
<td>Unconstrained along sloping surface; constant magnitude on flat surface</td>
<td>![after Cloos (1968)](after Cloos (1968))</td>
</tr>
<tr>
<td>Dry sand</td>
<td>Dry sand</td>
<td>Completely constrained: 45°-, 30°-, and 0°-dipping segments</td>
<td>Constant magnitude</td>
<td>![after McClay et al. (1992)](after McClay et al. (1992))</td>
</tr>
<tr>
<td>Wet clay</td>
<td>Wet clay</td>
<td>Initially constrained: 45°- and 0°-dipping segments; 30°-, 45°-, and 0°-dipping segments; 45°-, 30°-, and 0°-dipping segments</td>
<td>Unconstrained along sloping surface; constant magnitude on flat surface</td>
<td>![Experiment 1, this paper](Experiment 1, this paper)</td>
</tr>
<tr>
<td>Wet clay</td>
<td>Wet clay</td>
<td>Completely constrained: 45°-, 30°-, and 0°-dipping</td>
<td>Constant magnitude</td>
<td>![Experiment 2, this paper](Experiment 2, this paper)</td>
</tr>
<tr>
<td>Wet clay</td>
<td>Wet clay</td>
<td>Completely constrained: 45°-, 30°-, and 0°-dipping</td>
<td>Constant magnitude</td>
<td>![Experiment 3, this paper](Experiment 3, this paper)</td>
</tr>
<tr>
<td>Wet clay</td>
<td>Wet clay</td>
<td>Completely constrained: 45°-, 30°-, and 0°-dipping</td>
<td>Constant magnitude</td>
<td>![Experiment 4, this paper](Experiment 4, this paper)</td>
</tr>
</tbody>
</table>

* Rigid block  -  Wet Clay  -  Dry sand  -  Metal sheet  -  Plastic sheet.
MODELING PROCEDURE

The experimental apparatus has a horizontal base and three vertical walls (Figure 1). The outer walls are stationary, whereas the middle wall can move toward either outer wall. An aluminum sheet, attached to the moveable wall, covers the base. A 5-cm-high aluminum block overlies the sheet and is attached to a fixed wall. The top surface of the block is square, 25 cm wide and long. The sloping side of the block is planar and dips 45° in experiment 1, has an upper 30°-dipping segment and a lower 45°-dipping segment in experiment 2, and has an upper 45°-dipping segment and a lower 30°-dipping segment in experiments 3 and 4. During the experiments, the middle moveable wall and the attached aluminum sheet move toward the right, away from the aluminum block.

A 7.5-cm-thick layer of clay directly overlies the aluminum block and aluminum sheet in experiments 1, 2, and 3. In experiment 4, a 5-cm-thick layer of clay overlies the mylar sheet. In all experiments, the clay density is 1.6 g/cm³, and its cohesive strength is about 10⁻⁴ MPa (Sims, 1993). The top and sides of the clay layer are free surfaces. Circular markings applied to the top and sides of the clay layer record strain during modeling. During experiments 1, 2, and 3, the moveable wall and the attached aluminum sheet move away from the aluminum block. In response, the clay above the aluminum sheet moves away from the block and down its sloping side. During experiment 4, the moveable wall and the attached aluminum and mylar sheets move away from the aluminum block. The clay, passively carried by the mylar sheet, moves away from the block and down its sloping side. The displacement rate of the moveable wall is 0.004 cm/s in all experiments. We repeat each experiment at least twice to verify the modeling results.

To ensure geometric and kinematic similarity between physical models and actual rock deformation (assuming that inertial forces are negligible and that the density of the modeling material and rock are identical), the strength of the modeling material and the model dimensions must be scaled down by the same factor (Hubbert, 1937). The cohesive strength of rock is about 10⁵ times greater than the cohesive strength of the wet clay in the physical models. The thickness of sedimentary cover is also about 10⁵ times greater than the clay thickness in the physical models. Although the criteria for geometric and kinematic similarity have been satisfied, we emphasize that the physical models are not exact scale models. Rock may deform differently than the clay in the models. For example, rock with preexisting inhomogeneities (e.g., faults, fractures, bedding) may behave very differently than the homogeneous clay in the models.

MODELING PARAMETERS

The constraints on fault shape, development, and displacement distribution differ in the four experiments. The aluminum block initially constrains...
the shape of the master normal fault in experiments 1, 2, and 3. The shape of the master normal fault, however, can change during modeling. For example, an upward-propagating splay fault can cut through the clay layer during the experiments, bypassing the master normal fault and becoming the new master normal fault. In experiment 4, the mylar sheet prevents the shape of the master normal fault from changing during modeling. In experiments 1, 2, and 3, the magnitude of displacement can vary along the sloping surface of the master normal fault. In experiment 4 with the mylar sheet, the magnitude of displacement is constant along the surface of the master normal fault.

MODELING RESULTS

Experiment 1

During the early stages of experiment 1, the master normal fault propagates upward from the top edge of the aluminum block to the top surface of the clay layer. As the experiment progresses, two deformation zones develop (Figures 2b, 3a, b). One zone forms above the 45°-dipping segment of the master normal fault (Figure 3b). The folded clay within this zone dips gently away from the master normal fault. Faulting consists predominantly of steeply dipping synthetic normal faults that propagate upward from the surface of the master normal fault.
fault. This deformation zone becomes inactive during the early stages of the experiment. The second deformation zone extends upward from the fault bend separating the 45°-dipping and flat segments of the master normal fault (i.e., the bottom edge of the aluminum block) (Figure 3a). The deformation zone widens upward and dips steeply toward the master normal fault. The folded clay within the zone dips gently toward the master normal fault. Faulting within the zone consists of synthetic and antithetic normal faults with similar dips relative to bedding. Folding, however, has rotated the faults, decreasing the dip of the synthetic normal faults and increasing the dip of the antithetic normal faults (Figure 3a). Generally, the antithetic normal faults have greater displacements than the synthetic normal faults. Most antithetic normal faults form near the base of the clay layer and propagate upward. Consequently, their displacements decrease upward.

As the experiment progresses, the faulted and folded clay within the second deformation zone moves past the fault bend (Figure 2c). The deformation zone becomes inactive, and a new deformation zone emanating from the fault bend replaces it. Fold and fault patterns within the new zone are similar to those within the old zone, except that antithetic normal faults are more steeply dipping and synthetic normal faults are more gently dipping. Throughout the experiment, deformation zones move past the fault bend and become inactive, and new deformation zones emanating from the fault bend replace them. The location of the active deformation zone, anchored to the fault bend, remains stationary relative to the footwall of the master normal fault during the experiment. After 6 cm of displacement of the moveable wall, the hanging-wall deformation consists of a wide monocline cut by numerous antithetic and synthetic normal faults (Figure 2d). The folded clay has thinned and lengthened. Generally, antithetic normal faults are youngest near the fault bend and oldest far from the fault bend. Most of the synthetic normal faults near the fault bend, however, formed during the early stages of the experiment.

**Experiment 2**

During the early stages of experiment 2, secondary faulting and folding occur within two
upward-widening deformation zones (Figures 4b; 5a, b). As in experiment 1, one deformation zone extends upward from the fault bend separating the 45°-dipping and flat segments of the master normal fault (Figure 5a). A second deformation zone extends upward from the fault bend separating the 30°- and 45°-dipping segments of the master normal fault (Figure 5b). The folded clay within this deformation zone dips away from the master normal fault. Faulting consists of steeply dipping synthetic normal faults and moderately dipping antithetic normal faults. Folding has rotated the faults, increasing the dip of the synthetic normal faults and decreasing the dip of the antithetic normal faults. Generally, the synthetic normal faults have greater displacements than the antithetic normal faults. The synthetic normal faults propagate upward from the fault bend separating the 30°- and 45°-dipping segments. Eventually, one synthetic normal fault propagates through the entire clay layer, bypassing the 30°-dipping segment of the master normal fault (Figure 4c). This through-going synthetic normal fault becomes the new master normal fault.

During the later stages of experiment 2, deformation patterns are similar to those in experiment 1. The folded and faulted clay moves past the fault bend separating the 45°-dipping and flat segments of the master normal fault. Deformation zones become inactive, and new deformation zones emanating from the fault bend replace them (Figure 4c, d). After 6 cm of displacement of the moveable wall.
Withjack et al. 7

1 cm

Wall, the hanging-wall deformation consists of a wide monocline cut by numerous antithetic and synthetic normal faults. As in experiment 1, antithetic faults are generally youngest near the footwall block and oldest far from the footwall block. Most of the synthetic normal faults near the footwall block, however, formed during the early stages of the experiment.

**Experiment 3**

During the early stages of experiment 3, the master normal fault propagates upward from the top edge of the aluminum block to the clay surface. As the experiment progresses, secondary faulting and folding occur within two upward-widening deformation zones (Figure 6b). One deformation zone extends upward from the fault bend separating the 30°-dipping and flat segments of the master normal fault. A second deformation zone forms above the sloping footwall of the master normal fault (Figure 7). The folded clay within this zone dips gently away from the master normal fault. Antithetic normal faults propagate upward from the fault bend separating the 45°- and 30°-dipping

Figure 5—Close-up photographs of experiment 2 after 2 cm of displacement of the moveable wall. Locations are shown in Figure 4b. (a) Deformation zone extending upward from the fault bend separating the 45°-dipping and flat segments of the master normal fault. (b) Deformation zone extending upward from the fault bend separating the 30°- and 45°-dipping segments of the master normal fault.
segments of the master normal fault, and synthetic normal faults propagate upward from the 30°-dipping segment of the master normal fault. Some synthetic normal faults cut the antithetic normal faults.

As the experiment progresses, the folded and faulted clay within each deformation zone moves past the corresponding fault bend. The original deformation zones become inactive, and new deformation zones emanating from the same fault bends replace them (Figure 6c). This process continues throughout the experiment. The synthetic normal faults associated with the 30°-dipping segment of the master normal fault remain active until they move past the fault bend separating the 30°-dipping and flat segments of the master normal fault. As they move past this fault bend, they are faulted and rotated to gentler dips (Figure 6d). After 6 cm of displacement of the moveable wall, the hanging-wall deformation consists of a wide monocline cut by numerous antithetic and synthetic normal faults (Figure 6d). As in experiments 1 and 2, antithetic faults are generally youngest near fault bends and oldest far from fault bends. Many of the synthetic normal faults near the fault bend separating the 30°-dipping and flat segments of the master normal fault, however, developed during the early stages of the experiment.

**Experiment 4**

During the early stages of experiment 4 with the mylar sheet, folding occurs in two steeply dipping
deformation zones (Figure 8b). The first zone extends upward from the fault bend separating the 30°-dipping and flat segments of the master normal fault. The second zone extends upward from the fault bend separating the 45°- and 30°-dipping segments of the master normal fault. The folded clay within both zones dips toward the master normal fault. Unlike experiments 1, 2, and 3, little visible faulting accompanies the folding in experiment 4. The few visible faults have small normal displacements. They commonly form at the top surface of the clay layer and propagate downward. Consequently, their displacement decreases with depth.

As in experiment 3, deformation zones move past fault bends and become inactive, and new deformation zones emanating from the same fault bends replace them (Figure 8c). This process continues throughout the experiment. After 6 cm of displacement of the moveable wall, the hanging-wall deformation consists of a wide monocline, generally unaffected by visible faulting (Figure 8d).

**Displacement Distribution**

Figure 9 shows the displacement distribution on the master normal fault for the four experiments after 6 cm of displacement of the moveable wall. In experiments 1, 2, and 3, the displacement magnitude varies along the sloping surface of the master normal fault. Points originally near the top of the footwall block move about 4 cm along the surface of the master normal fault; points originally near the middle of the footwall block move about 5 cm; and points originally near the bottom of the footwall block move about 6 cm along the surface of the master normal fault. In experiment 4 with the mylar sheet, the displacement magnitude is constant, 6 cm, along the entire surface of the master normal fault.

**Fold Shapes**

The hanging-wall folds in experiments 1, 2, and 3 have similarities and differences (Figure 10a, b, c). During the early stages of the three experiments, the folds are synclinal. Near the master normal fault, the folded clay dips away from the fault. Far from the master normal fault, the folded clay dips 15 to 20° toward the fault. The folds become monoclinal during the later stages of the experiments. The hanging-wall folds are narrower in experiments 1 and 2 than in experiment 3.

The hanging-wall folds in experiments 3 and 4 differ considerably, even though the master normal faults are identical in the two models (Figure 10c, d). The hanging-wall fold in experiment 4 is never synclinal, even during the early stages of the experiment. The clay near the master normal fault is either flat-lying or dips toward the fault. Also, the fold is much narrower and the folded clay dips more steeply (25–30°) in experiment 4 than in experiment 3 (15–20°).

**Particle Paths and Inclined Shear Angles**

Figure 11 shows particle paths for the four experiments in both a footwall and hanging-wall reference frame. In the footwall reference frame, points in the hanging wall have paths that parallel the surface of the master normal fault. In the hanging-wall reference frame, points in the hanging wall near the master normal fault have sloping paths. In experiments 1, 2, and 3 without the mylar sheet, the sloping paths dip between 50 and 60°. In experiment 4 with the mylar sheet, the sloping paths dip between 70 and 75°.

Several authors have proposed that homogeneous, inclined simple shear accommodates the deformation in the hanging walls of normal faults (e.g., White et al., 1986; Dula, 1991; White and Yielding, 1991; Kerr and White, 1992; White, 1992; Xiao and Suppe, 1992; Withjack and...
Peterson, 1993). White et al. (1986) define the inclined shear angle as the acute angle between the vertical and the inclined shear direction. If the particle paths in the hanging-wall reference frame parallel the inclined shear direction, then the inclined shear angle in our physical models is 30 to 40° in experiments 1, 2, and 3 and 15 to 20° in experiment 4 (Figure 11).

**Strain Distributions**

Figure 12 shows the strain state in the four experiments after 6 cm of displacement of the moveable wall. In experiments 1, 2, and 3, the maximum extension direction is subparallel to bedding. The magnitude of the maximum extension is greater near the base of the clay layer (about 60 to 70%) than near the top (about 20 to 30%). Similarly, the magnitude of the maximum shortening is greater near the base of the clay layer (about -25 to -35%) than near the top (about -10 to -20%).

The strain state differs significantly in experiment 4. In the deformed clay, the maximum extension direction is about 15° counterclockwise from bedding. The magnitude of the maximum extension is relatively constant throughout the deformed clay, about 30% near the base of the clay layer and 20% near the top. The magnitude of the maximum shortening is also relatively constant throughout the deformed clay, about -20% near the base of the clay layer and -10% near the top.
SUMMARY OF MODELING RESULTS

The physical models show that deformation patterns in the hanging wall of a master normal fault depend on fault shape (Table 1). In experiments without a mylar sheet, secondary faulting and folding occur: (1) above low-angle fault segments, and (2) in upward-widening zones that emanate from fault bends. Above low-angle fault segments, upward-propagating synthetic normal faults form, and folded beds dip away from the master normal fault. At concave-upward fault bends, most secondary faults are antithetic normal faults with displacements that decrease upward. Folded beds dip toward the master normal fault. At convex-upward fault bends, most secondary faults are synthetic normal faults. The synthetic faults propagate upward and, eventually, bypass the master normal fault. Folded beds dip away from the master normal fault. When deformation zones move past fault bends, they become inactive, and new deformation zones emanating from the same fault bends replace them. The locations of the active deformation zones, anchored to fault bends, remain stationary relative to the footwall of the master normal fault. Generally, secondary faulting and folding are youngest at fault bends and become progressively older past fault bends.

The physical models also show that experimental constraints on displacement distribution strongly influence the modeling results (Table 1). In experiments 1, 2, and 3 without a mylar sheet, the displacement magnitude varies along the surface of the master normal fault in experiments 1, 2, and 3 (circles) and is constant, 6 cm, in experiment 4 (crosses).
Figure 11—Particle paths in the footwall reference frame (left) and hanging-wall reference frame (right) for (a) experiment 1, (b) experiment 2, (c) experiment 3, and (d) experiment 4. In experiments 1, 2, and 3, the displacement of the moveable wall is 8 cm; in experiment 4, it is 6 cm. Open and black circles are original and final locations of points, respectively. In the footwall reference frame, the vertical gray lines are the original positions of the moveable wall. In the hanging-wall reference frame, the gray dashed lines show the original positions of the aluminum block.

normal fault. The hanging-wall fold is monoclinal during the early and late stages of the experiment. The fold is narrower and bedding dips are steeper than those in experiments 1, 2, and 3. Few visible secondary normal faults develop during experiment 4. Many of these normal faults propagate downward and, consequently, have less displacement at depth. The inclined shear angle is 15 to 20°, and the direction of maximum extension dips more steeply than bedding.

COMPARISON WITH OTHER EXPERIMENTAL MODELS

Physical models by Cloos (1968) differ from experiments 1, 2, and 3 in that the shape of the master normal fault is not predetermined (Table 1). In Cloos’ models, a layer of wet clay or dry sand covers two overlapping metal sheets. As the sheets diverge, a normal fault develops near the base of the clay or sand layer and propagates upward. The resultant sloping segment of the master normal fault is planar and steeply dipping. In the clay model, a rollover fold and numerous antithetic and synthetic normal faults form in the hanging wall of the master normal fault. In the sand model, hanging-wall deformation consists mostly of steeply dipping antithetic normal faults. Although deformation patterns in Cloos’ clay and sand models resemble those in experiments 1, 2, and 3, some differences exist (Table 1). Few secondary normal faults form near the planar, high-angle segment of the master normal fault in Cloos’ models. In experiments
1, 2, and 3, numerous antithetic and synthetic normal faults develop near fault bends and above low-angle fault segments of the master normal fault. A sand model by McClay et al. (1992) resembles experiment 4 (Table 1). A rigid block and horizontal base act as the footwall of the master normal fault, and a layer of dry, homogeneous sand represents the hanging-wall strata. The rigid block has an upper 45°-dipping segment and a lower 30°-dipping segment. During modeling, a plastic sheet carries the sand down the sloping surface of the footwall block and along the horizontal base. In response, a rollover fold develops in the hanging wall of the master normal fault. Downward-steepening synthetic and antithetic normal faults form near the top of the sand layer far from the master normal fault, producing a crestal collapse graben. The displacement on most secondary normal faults decreases with depth. Hanging-wall deformation patterns in the sand model by McClay et al. resemble those in experiment 4. The hanging-wall folds have similar shapes. Also, most secondary normal faults form near the top of the models and propagate downward. The secondary faults in the sand model by McClay et al., however, have much greater displacements than those in experiment 4.

Comparisons of models without a plastic sheet [i.e., experiments 1, 2, and 3 and Cloos’ (1968) models] with those with a plastic sheet [i.e., experiment 4 and the model of McClay et al. (1992)] confirm our conclusion that constraints on displacement distribution profoundly affect experimental results. In clay and sand models without a plastic sheet, numerous secondary synthetic and antithetic normal faults develop near fault bends. Most secondary antithetic normal faults propagate upward. Consequently, their displacement decreases upward. In clay and sand models with a plastic sheet, secondary faults are much less numerous. Most secondary faults form near the top surface of the model and propagate downward. Consequently, their displacement increases upward.

ANALYSIS AND DISCUSSION OF MODELING RESULTS

We have calculated displacement magnitudes, bedding dips, and strain states associated with movement past a single fault bend assuming that finite, homogeneous, inclined simple shear accommodates the hanging-wall deformation (Appendix). Our analysis predicts that the displacement magnitude on a sloping fault segment should differ from that on an adjacent flat segment, unless the value of the inclined shear angle is half of the value of the dip of the sloping fault segment. Consequently, in models with a basal mylar sheet and a constant displacement magnitude, the value of the inclined shear angle should be half of the value of the dip of the sloping fault segment. This prediction matches observations from the physical models (Table 2). For example, in experiment 4 with the basal mylar sheet, the displacement magnitude on the 30°-dipping fault segment equals that on the adjacent flat segment. Particle paths indicate that the inclined shear angle is about 15°, half of the value of the dip of the sloping fault segment. Our analysis also predicts that the direction of maximum extension depends on the inclined shear angle. In experiment 3 with an inclined shear angle of 40°, the direction of maximum extension should be subparallel to bedding. In
experiment 4, with an inclined shear angle of 15°, the direction of maximum extension should be about 15° counterclockwise from bedding. These predictions also match observations from the physical models (Table 2). In experiment 3, the direction of maximum extension is subparallel to bedding. In experiment 4, the direction of maximum extension is about 15° counterclockwise from bedding.

Generally, our analysis shows that the observed particle paths, displacement distributions, bedding dips, and principal strain orientations in the physical models are compatible with the assumption that finite, homogeneous, inclined simple shear accommodates the hanging-wall deformation. Not all modeling results, however, are consistent with this assumption. If finite, homogeneous, inclined simple shear accommodates the hanging-wall deformation, then the magnitudes of the principal strains should be constant throughout the deformed clay. Also, the two boundaries of each deformation zone should parallel each other and the inclined shear direction. In the physical models, especially experiments 1, 2, and 3, strain magnitudes significantly decrease from the base to the top of the deformed clay, and the boundaries of the deformation zones diverge upward. This observed variability with depth is incompatible with finite, homogeneous, inclined simple shear as the hanging-wall deformation mechanism.

Our experimental results support many of the conclusions of the geometric forward modeling by Xiao and Suppe (1992). For example, both the physical and geometric models predict that hanging-wall folding occurs in zones that emanate from fault bends and that folding ceases when hanging-wall rocks move past fault bends. As discussed by White and Yielding (1991) and Xiao and Suppe (1992), geometric models provide little information about the small-scale deformation mechanisms that accommodate the hanging-wall folding. Our
experimental study complements the geometric study by Xiao and Suppe (1992) by providing this important information. For example, the physical models show that antithetic normal faults develop near concave-upward fault bends and synthetic normal faults develop near convex-upward fault bends. These results support the assertion of Xiao and Suppe (1992) that antithetic simple shear is associated with concave-upward fault bends and synthetic simple shear is associated convex-upward fault bends. Our experimental results also suggest that the basic premise of most geometric models (i.e., homogeneous, inclined simple shear accommodates the hanging-wall deformation) has limitations. For example, contrary to the geometric models of Xiao and Suppe (1992), the physical models indicate that the width of the deformed zones and the intensity of deformation can vary significantly with depth, even in strata deposited before faulting.

APPLICATION

The Corsair (Brazos Ridge) fault of offshore Texas is a gently dipping, northeast-trending normal fault that detaches at depth, probably within the Louann Salt (Christiansen, 1983; Worrall and Snelson, 1989). The growth fault developed during Miocene to Holocene time. Locally, its displacement exceeds 15 km. The shape of the Corsair fault varies along strike. At some locations, the fault surface has a single concave-upward bend between 2 and 3 km depth (Figure 13a). At these sites, numerous antithetic normal faults cut the hanging-wall strata. Antithetic faults that intersect the surface of the Corsair fault at the fault bend are recently active. Antithetic faults that intersect the fault surface below the fault bend are inactive and become progressively older below the fault bend. At other locations, the Corsair fault has a concave-upward bend and a convex-upward bend at about 3 km depth (Figure 13b). At these sites, numerous antithetic and synthetic normal faults cut the hanging-wall strata. Many synthetic faults splay from the surface of the Corsair fault near the convex-upward fault bend and are recently active. Antithetic faults that intersect the fault surface near the fault bends are also active, whereas antithetic faults that intersect the surface of the Corsair fault below both fault bends are inactive.

The fault patterns in the hanging wall of the Corsair fault resemble those in our physical models. At concave-upward fault bends, most secondary faults are antithetic normal faults. At convex-upward fault bends, most secondary faults are synthetic normal faults. Secondary antithetic and synthetic normal faults that intersect the fault surface at fault bends are active today. Antithetic normal faults that intersect the fault surface below concave-upward fault bends are inactive and become progressively older below the fault bends.

CONCLUSIONS

We have used clay models to study how the shape of a master normal fault and its displacement distribution affect the hanging-wall deformation. The modeling results show that the hanging-wall deformation depends on both fault shape and displacement distribution.

(1) Fault shape controls the style of secondary faulting and folding. In models without a basal mylar sheet, mostly antithetic normal faults form near concave-upward fault bends, whereas mostly synthetic normal faults form near convex-upward fault bends and above low-angle fault segments. Beds generally dip toward the master normal fault near concave-upward fault bends and away from the master normal fault near convex-upward fault bends and above low-angle fault segments. When deformation zones move past fault bends, they become inactive and new deformation zones emanating from the same fault bends replace them. Consequently, most secondary faults and folds are youngest at fault bends and become progressively older beyond fault bends.

(2) Displacement distribution also affects the patterns of hanging-wall deformation. In models without a mylar sheet, the displacement magnitude varies along the surface of the master normal fault. Numerous secondary normal faults form in the hanging wall. Most secondary normal faults propagate upward and, consequently, have greater displacement at depth. The inclined shear angle is 30 to 40°, and the direction of maximum extension is subparallel to bedding. In models with a mylar sheet, the displacement magnitude is constant along the surface of the master normal fault. Few visible secondary normal faults form in the hanging wall. Most of these faults propagate downward and, consequently, have less displacement at depth. The inclined shear angle is 15 to 20°, and the direction of maximum extension dips more steeply than bedding. Hanging-wall folds are wider and bedding dips are gentler in models without a mylar sheet than in identical models with a mylar sheet.

The particle paths, displacement distributions, bedding dips, and orientations of the principal-strain axes in our physical models with and without a basal mylar sheet are compatible with the assumption that finite, homogeneous, inclined
simple shear accommodates the hanging-wall deformation. The observed variability with depth of the distribution and intensity of deformation, however, is not compatible with this assumption. Thus, our experimental results suggest that geometric models of normal faults based on the assumption that finite, homogeneous, inclined simple shear accommodates the hanging-wall deformation may not accurately represent the changes in deformation patterns with depth.
APPENDIX

If finite, homogeneous, inclined simple shear accommodates the hanging-wall deformation associated with movement past a single fault bend, then the displacement magnitude for points on the sloping segment of the master normal fault that do not move past the fault bend is

\[ d = D \cos \alpha / \cos(\gamma - \alpha) \]

where \( D \) is the displacement magnitude of points on the flat segment, \( \alpha \) is the inclined shear angle, and \( \gamma \) is the dip of the sloping segment (Table 2). For points on the sloping segment that move past the fault bend,

\[ D \cos \alpha / \cos(\gamma - \alpha) < d < D . \]

Based on Jaeger (1969), bedding dip is

\[ \delta = \tan^{-1}(c + \tan \alpha) - \alpha \]

where \( c = \sin \gamma / \cos \alpha \) and \( \cos(\gamma - \alpha) \) and counterclockwise is positive. The magnitudes of the principal strains are

\[ \varepsilon_1 = [(4 + c^2)^{1/2} - c] / 2 - 1 \quad \text{and} \quad \varepsilon_2 = [(4 + c^2)^{1/2} - c] / 2 - 1 \]

where extension is positive. The axes of the principal strains trend \( \psi \) and \( \psi + 90^\circ \) relative to the horizontal where \( \psi = [\tan^{-1}(\gamma - 2\alpha) - \alpha] / 2 \) and counterclockwise is positive.

REFERENCES CITED


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