An experimental study of the secondary deformation produced by oblique-slip normal faulting

Roy W. Schlische, Martha Oliver Withjack, and Gloria Eisenstadt

ABSTRACT

We have used scaled clay models to define the secondary deformation produced by oblique-slip normal faulting. In the models, the master fault beneath the clay layer dips 45° and strikes at a 45° angle relative to the heave direction (i.e., the horizontal component of the displacement direction). Thus, the master fault has both normal dip-slip and strike-slip components of displacement. The modeling results show the following. (1) The fault patterns produced by oblique-slip normal faulting vary significantly with depth. Secondary faults that strike obliquely to the master-fault trend are more abundant near the top of the clay layer, whereas secondary faults that are subparallel to the master-fault trend are more abundant at depth. (2) A single episode of oblique-slip normal faulting produces two populations of secondary faults that have different trends and ages. Secondary faults that strike obliquely to the master-fault trend are more abundant during the early stages of the experiments, whereas secondary faults that strike subparallel to the master-fault trend are more abundant during the later stages of the experiments. (3) Relay ramps between overlapping secondary synthetic normal faults are wide and temporally persistent in oblique-slip models. The ramps are cut by numerous small-scale normal faults that are subparallel to the ramp-bounding faults. Cross faults are uncommon and begin to develop only during the final stages of the experiments. (4) Both map and cross section data are necessary to distinguish among the deformation patterns produced by strike-slip, oblique-slip, and dip-slip faulting. The map views of oblique-slip models closely resemble those of strike-slip models; in both models, many of the secondary faults strike obliquely to the master-fault trend. These map views, however, differ considerably from those of dip-slip models, in which most of the secondary faults strike subparallel to the master-fault trend. Alternatively, the cross sectional views of oblique-slip models are similar to those of dip-slip

AUTHORS

ROY W. SCHLISCHE ~ Department of Geological Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey, 08854–8066; schlisch@rci.rutgers.edu

Roy W. Schlische is an associate professor of structural geology at Rutgers University. He received his B.A. degree from Rutgers University and his M.A. degree and Ph.D. from Columbia University, where he studied the structural and stratigraphic evolution of Triassic–Jurassic rift basins in eastern North America. His research interests include extensional tectonics, fault-population studies, experimental modeling of geologic structures, and basin inversion.

MARtha Oliver withjack ~ Department of Geological Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey, 08854–8066

Martha Oliver Withjack received her Ph.D. from Brown University in 1978, studying the mechanics of continental rifting. She currently is a professor of structural geology at Rutgers University. Before joining Rutgers, she worked as a research geoscientist at Cities Service, ARCO, and Mobil. Her research interests include extensional, inversion, and salt tectonics; physical and analytical modeling of structures; and structural interpretation of seismic data. She received the Matson Memorial Award in 1999 and is currently first vice chair of the Geological Society of America’s structural geology and tectonics division.

Gloria Eisenstadt ~ Department of Geology, University of Texas at Arlington, Arlington, Texas, 76019–0049

Gloria Eisenstadt is a consultant and adjunct assistant professor at the University of Texas at Arlington. Eisenstadt worked at Mobil Technology Company from 1989 to 2000 as a researcher, international structural consultant, and technical teacher. Eisenstadt received her B.A. and M.A. degrees in geology from Temple University and her Ph.D. from the Johns Hopkins University, where she studied the structural evolution of the Innuitian fold belt in Ellesmere Island, arctic Canada. Her current interests are physical modeling and seismic interpretation of inversion structures.
Oblique-Slip Normal Faulting

models; in both models, a highly faulted extensional forced fold develops. These cross sectional views are dissimilar to those of strike-slip models, which show no appreciable folding and no change of regional level.

INTRODUCTION

The Earth’s crust is riddled with zones of weakness that can be reactivated during subsequent tectonic events. The movement on these reactivated zones of weakness is rarely either pure dip slip or pure strike slip. For example, many Paleozoic contractional structures in eastern North America were reactivated during an episode of northwest-southeast extension associated with Triassic–Jurassic rifting (e.g., Ratcliffe and Burton, 1985; Olsen and Schlische, 1990) (Figure 1). During rifting, northeast-striking Paleozoic reverse faults became normal faults, whereas north-northwest– and east-northeast–striking structures became oblique-slip normal faults, having significant components of right-lateral strike-slip and left-lateral strike-slip, respectively. In particular, the east-northeast–striking, rift-basin boundary faults in the narrow-neck region between the Newark and Gettysburg basins (NN in Figure 1) and in the eastern Fundy basin (MFZ in Figure 1) had a significant left-lateral component of movement during early Mesozoic rifting (e.g., Olsen and Schlische, 1990).

Although oblique slip along reactivated faults is likely to be the rule rather than the exception, few experimental studies have simulated oblique-slip normal faulting. Numerous workers used clay and sand models to study pure dip-slip normal faulting (e.g., Horsfield, 1977; Tsuneishi, 1978; Vendeville, 1987, 1988; Withjack et al., 1990; Withjack and Callaway, 2000; Ackermann et al., 2001) and pure strike-slip faulting (e.g., Cloos, 1928; Riedel, 1929; Wilcox et al., 1973; Naylor et al., 1986). Withjack and Jamison (1986), Tron and Brun (1991), Smith and Durney (1992), McClay and White (1996), and Clifton et al. (2000) used clay and sand models to investigate oblique rifting. In these experiments, deformation occurred in a wide zone above a flat base rather than in a narrow zone above a dipping, oblique-slip normal fault. Richard (1991) and Higgins and Harris (1997) experimentally simulated oblique-slip normal faulting. In their models, either a single layer of sand or two layers composed of sand and silicone putty covered moderately dipping master faults. During the experiments, the master faults were reactivated with both normal dip-slip and strike-slip components of displacement, causing the overlying layers to deform.

The goal of this article is to supplement this previous work by using scaled, single-layer clay models. Our specific objectives are to (1) better define the range of secondary fault and fold patterns produced by oblique-slip normal faulting, (2) determine how the magnitude of the displacement on the master fault and the thickness of the sedimentary cover influence the secondary fault and fold patterns in map view, and (3) develop criteria to distinguish the de-
formation patterns produced by oblique-slip normal faulting from those produced by dip-slip normal faulting and strike-slip faulting. The following sections describe the experimental procedure; review our modeling results and compare them with those from previous studies; describe the implications of our modeling results for hydrocarbon exploration and production; and discuss how the models compare with actual examples of oblique-slip normal faults from the eastern Fundy basin of Nova Scotia, Canada, and the Carnarvon basin on the northwest shelf of Australia.

**EXPERIMENTAL PROCEDURE**

The modeling apparatus (Figure 2a) has three configurations: dip slip, strike slip, and oblique slip. In the dip-slip configuration, the apparatus has a fixed footwall block and a mobile hanging-wall block (Figure 2b). The top surfaces of the blocks are initially level, together forming a flat, $32 \times 61$ cm surface. The master fault between the blocks dips $45^\circ$, and its strike is perpendicular to the heave direction, which we define as the horizontal component of the displacement direction (following Bates and Jackson, 1987, p. 286).

Consequently, as the hanging-wall block slides down the surface of the master fault during the experiment, the master fault undergoes pure normal dip-slip displacement. In the strike-slip configuration, the apparatus consists of a fixed plate and a juxtaposed mobile plate (Figure 2b). Together, the plates form a level surface ($61 \times 61$ cm). The strike of the master fault between the plates is parallel to the displacement direction of the moving plate. Consequently, the master fault undergoes pure left-lateral, strike-slip displacement during the experiment. In the oblique-slip configuration, the apparatus has a fixed footwall block and a mobile hanging-wall block. The top surfaces of the blocks are initially level, together forming a flat, $61 \times 61$ cm surface. The master fault dips $45^\circ$ and strikes at a $45^\circ$ angle relative to the heave direction. During the experiments, the hanging-wall block slides down the surface of the master fault and undergoes equal amounts of normal dip-slip and left-lateral, strike-slip displacement.

In our experiments, a layer of wet clay simulates the sedimentary cover above the master fault. In several models, the clay layer is subdivided into colored sublayers. These sublayers are mechanically identical and are used as marker horizons to identify faults and
folds in cross sectional view. The wet clay is composed predominantly of kaolinite and water (~40% by weight). Its density is about 1600 kg m$^{-3}$. The clay has a low cohesion (~50 Pa) and a coefficient of internal friction of about 0.5 (Fugro-McClelland, Inc., 1992, personal communication; Sims, 1993; S. Dixon, 1996, personal communication). Distributed cataclasis, as defined by Rutter (1986), is the primary deformation style in the wet clay when strains are small. With increasing strain, however, deformation becomes localized, discrete faults develop, and cataclastic faulting is the primary deformation style (Withjack and Callaway, 2000). We preferred wet clay, rather than dry sand, as the modeling medium because (1) both faults and folds form in the wet clay; (2) more faults develop, propagate, and link in wet clay than in dry sand; and (3) fault zones are narrower and better defined in wet clay than in dry sand (e.g., Withjack and Callaway, 2000).

Tables 1 and 2 provide specific information about the experiments. We repeated most of the experiments to verify the reproducibility of the modeling results. In the experiments, the horizontal displacement rate of the moving wall and, thus, the rate of heave on the master fault is 4 cm hr$^{-1}$. In most experiments, the clay layer is initially 4 cm thick. In experiment III, however, the clay is initially 2 cm thick. During the experiments, we photographed the upper surface of the clay layer at regular increments of displacement on the master fault (using multiple lighting directions) to document the surface deformation through time. We used a low-angle light source to emphasize the fault scarps (Figure 3a). During experiments V and VII, we filled in the subsiding hanging wall with clay at regular increments of the displacement on the master fault (using multiple lighting directions) to document the surface deformation through time. We used a low-angle light source to emphasize the fault scarps (Figure 3a).

During experiments V and VII, we filled in the subsiding hanging wall with clay at regular increments of the displacement on the master fault. These growth layers initially had a horizontal upper surface. After models IV, V, VI, and VII had dried, we cut them into 1–2 cm–wide strips. These strips were photographed, and some strips were sectioned vertically and horizontally to document the final deformation state in detail.
Table 1. Description of Models Used for Map Views

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Experimental Configuration</th>
<th>Maximum Heave (cm)</th>
<th>Maximum Throw (cm)</th>
<th>Initial Overburden Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Dip slip</td>
<td>2.8</td>
<td>2.8</td>
<td>~4</td>
</tr>
<tr>
<td>II</td>
<td>Oblique slip</td>
<td>2.8</td>
<td>1.9</td>
<td>~4</td>
</tr>
<tr>
<td>II A, II B</td>
<td>Oblique slip</td>
<td>3.8</td>
<td>2.7</td>
<td>~4</td>
</tr>
<tr>
<td>III</td>
<td>Oblique slip</td>
<td>2.8</td>
<td>1.9</td>
<td>~2</td>
</tr>
<tr>
<td>IV</td>
<td>Strike slip</td>
<td>2.8</td>
<td>0</td>
<td>~4</td>
</tr>
</tbody>
</table>

Table 2. Description of Models Used for Cross Section Views

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Experimental Configuration</th>
<th>Maximum Heave (cm)</th>
<th>Maximum Throw (cm)</th>
<th>Initial Overburden Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Dip slip with growth beds</td>
<td>2.0</td>
<td>2.0</td>
<td>~4</td>
</tr>
<tr>
<td>VI</td>
<td>Oblique slip</td>
<td>2.8</td>
<td>1.9</td>
<td>~4</td>
</tr>
<tr>
<td>VII</td>
<td>Oblique slip with growth beds</td>
<td>2.9</td>
<td>2.0</td>
<td>~4</td>
</tr>
<tr>
<td>IV</td>
<td>Strike slip</td>
<td>2.8</td>
<td>0</td>
<td>~4</td>
</tr>
</tbody>
</table>

For the experiments to be valid, the models must be geometrically, kinematically, and dynamically similar to their geological counterparts (e.g., Hubbert, 1937). The scaling factor between the models and geologic prototype is $10^4 / 10^5$ (Appendix). Thus, a 4 cm–thick layer of wet clay in the models corresponds to a 0.4–4 km–thick sedimentary package in nature. Also, 1 cm of displacement on the master fault in the models corresponds to 0.1–1 km of fault displacement in nature. We emphasize that the experimental models are not exact scale models of natural systems. Rock may deform differently than the clay in the models. For example, rock that has preexisting heterogeneities (e.g., fractures, bedding) may behave very differently than the relatively homogeneous clay in the models.

MAP-VIEW DEFORMATION

We used photographs of the clay surface to define the map-view deformation. In the photographs, faults appear either very bright or very dark, depending on their dip direction relative to the light source (Figure 3a). The fault maps in Figures 4 and 5 represent the faults as polygons bounded by the footwall and hanging-wall cutoffs of the top of the clay layer. The width of the polygon is approximately equal to the heave on the faults. For ease of comparison, we oriented all of the fault maps so that the master fault trends left to right, defined as an azimuth of 090°. Also, we divided the secondary faults in the dip-slip and oblique-slip experiments into those that dip in the same direction as the master fault (synthetic faults) and those that dip in the opposite direction from the master fault (antithetic faults). Finally, we divided each of the secondary faults into segments of uniform trend. The graphs in Figures 4 and 5 show the summed length of these fault segments vs. the trend of the fault segments (binned in 5° intervals).

Experiment I: Dip-Slip Master Fault

During the early stages of experiment I, an extensional forced fold develops in the clay above the master fault. Soon after, synthetic and antithetic secondary normal faults form in a wide zone above the master normal fault (Figure 4a). The strike of most of the secondary normal faults is subparallel to the master-fault trend (Figure 4b). Initially, the secondary normal faults are isolated features with maximum displacements near the center of their fault traces and diminishing displacements toward their tips. They grow predominantly by tip propagation. As the experiment progresses, however, many of the propagating secondary normal faults overlap each other, and narrow relay ramps develop between them. Cross faults (e.g., CF in Figure 4a) soon breach the narrow relay ramps,
forming throughgoing fault zones during the early stages of experiment I. These throughgoing fault zones are subparallel to the master-fault trend and have normal dip-slip displacement. Fault linkage and the development of throughgoing faults continue throughout the duration of experiment I (Figure 5a, b). The throughgoing fault zones in experiment I exhibit little along-strike variation in displacement, although minor
Figure 4. Comparison of fault-trace maps for (a) dip-slip model, (c) thick oblique-slip model (4 cm–thick clay layer), (e) thin oblique-slip model (2 cm–thick clay layer), and (g) strike-slip model shown at 1.5 cm of heave on the master fault. CF denotes cross faults, and L shows faults that will link in Figure 5a. Light gray areas in (a), (c), and (e) denote the region between the footwall and hanging-wall cutoffs at the base of the clay layer; synthetic faults are black, antithetic faults are dark gray. Dashed lines in (g) are surficial markers, initially straight, on the clay surface. Graphs (b, d, f, h) show the summed length of fault segments vs. the trend of fault segments binned in 5° intervals. MF is the master-fault trend, D is the trend of the displacement direction, and DN is the displacement-normal trend.
Figure 5. Comparison of fault trace maps for (a) dip-slip model, (c) thick oblique-slip model, (e) thin oblique-slip model, and (g) strike-slip model shown at 2.75 cm of heave on the master fault. CF denotes cross faults; L denotes complex fault that formed by linkage. Light gray areas in (a), (c), and (e) denote the region between the footwall and hanging-wall cutoffs at the base of the clay layer; synthetic faults are black, antithetic faults are dark gray. Dashed lines in (g) are surficial markers, initially straight, on the clay surface. Graphs (b, d, f, h) show the summed length of fault segments vs. the trend of fault segments binned in 5° intervals. MF is the master-fault trend, D is the trend of the displacement direction, and DN is the displacement-normal trend.
displacement minima mark areas where fault segments had linked.

**Experiment II: Oblique-Slip Master Fault**

Experiment II is similar to experiment I, except that the master fault has oblique-slip displacement rather than dip-slip displacement. In both experiments, an extensional forced fold develops in the clay above the master fault, and secondary normal faults form in a wide zone above the master normal fault (Figures 4c, 5c). Unlike experiment I, however, the strike of most of the secondary normal faults in experiment II is oblique to the strike of the master fault (Figures 4d, 5d).

In both experiments I and II, the secondary normal faults are initially isolated features with maximum displacements near the center of their fault traces and diminishing displacements toward their tips. Fault linkage and the development of throughgoing faults, however, are delayed in experiment II compared to experiment I. During the later stages of experiment II, some of the secondary normal faults begin to link, resulting in complex fault traces (L in Figure 5c). Generally, the synthetic secondary faults grow longer and have more displacement than their antithetic counterparts. Well-developed relay ramps form between large, overlapping (en echelon) synthetic faults (Figures 3b, 5c). The relay ramps are cut by minor, mostly antithetic faults subparallel to the synthetic faults that bound the ramps. The relay ramps are never fully breached during experiment II. Cross faults begin to develop and cut the relay ramps only during the final stages of the experiment (Figure 5c; also see Figure 3b for an oblique-slip experiment with larger displacement on the master fault).

**Experiment III: Oblique-Slip Master Fault (Thin Cover)**

Experiment III (Figures 4e, 5e) is identical with experiment II, except that the clay layer is 2 cm thick rather than 4 cm thick (Table 1). In both experiments II and III, an extensional forced fold develops in the clay above the master fault, and secondary normal faults form in a wide zone located above the master fault. In both experiments, the strike of most of the secondary faults is oblique to the strike of the master fault (Figures 4f, 5f). In experiment III, however, the secondary normal faults form and link together much sooner than those in experiment II. In fact, the linkage of secondary faults forms a through-going oblique-slip fault zone subparallel to the underlying master fault during the early stages of experiment III (Figure 4e). The surface trace of this throughgoing fault zone is complex, consisting of both oblique-fault segments and linking-fault segments oriented subparallel to the master-fault trend. The hanging wall of the throughgoing fault zone contains numerous synthetic faults that are oblique to the master-fault trend. Antithetic faults are much less common in the thin model than in the thick model. Also, the deformed zone is narrower in the thin model than in the thick model.

**Experiment IV: Strike-Slip Master Fault**

As in the oblique-slip and dip-slip experiments, the secondary faults in the strike-slip experiment develop in a zone located above the master fault (Figures 4g, 5g). The deformed zone, however, is much narrower in the strike-slip model than in the oblique-slip and dip-slip models. The strike of most of the early formed secondary faults in the strike-slip model is oblique to the master-fault trend (Figure 4h), similar to the strike of the early formed secondary faults in the oblique-slip experiments (Figure 4d, f). Unlike the oblique-slip experiments, however, the early formed secondary faults in the strike-slip experiment have predominantly left-lateral displacement rather than normal displacement. The fault pattern observed in experiment IV is similar to the R1 Riedel shears produced in previous experimental models of strike-slip fault systems (e.g., Cloos, 1928; Riedel, 1929; Tchalenko, 1970; Wilcox et al., 1973; Naylor et al., 1986). During the final stages of experiment IV, faults subparallel to the master-fault trend develop, cutting the clay surface and linking the early formed strike-slip faults (Figure 5g, h). An incipient throughgoing strike-slip fault zone develops during the final stages of experiment IV.

**Summary of Map-View Deformation**

Comparisons of the fault-trace maps (Figures 4, 5) show the following. (1) A zone of folding and/or faulting forms in the clay above the master fault in all experiments. The deformation zone is wider in the dip-slip and oblique-slip experiments than in the strike-slip experiment. (2) Relay ramps develop between overlapping normal faults in the dip-slip and oblique-slip experiments. In the dip-slip experiments, the relay ramps are narrow and breached by cross faults. (3) Throughgoing fault zones, subparallel to the
master-fault trend, develop in the dip-slip and strike-slip experiments but not in the oblique-slip experiment with the thick clay layer (experiment II). Apparently, the oblique orientation of the widely spaced secondary faults in experiment II prevented the secondary faults from readily propagating along strike to link with each other. Given enough displacement on the master fault, however, the ramps between overlapping faults in the oblique-slip experiment would likely become breached by cross faults and a throughgoing oblique-slip fault system would develop. A throughgoing oblique-slip fault subparallel to the master-fault trend did develop in the oblique-slip experiment with the thin clay layer (experiment III).

(4) The type and orientation of secondary faults in the experimental models depend on the type and orientation of the master fault relative to the heave direction. Most secondary faults in the dip-slip experiment have normal displacements and are subparallel to the master-fault trend. Most secondary faults in the thick oblique-slip experiment have normal displacements and are oblique to the master-fault trend. In the strike-slip model, the secondary faults have strike-slip displacements and are both parallel and oblique to the master-fault trend. The orientation (but not the slip) of the faults that form during the early stages of the oblique-slip experiment closely resembles those that form during the early stages of the strike-slip experiment. Therefore, the modeling results indicate that map-view fault patterns are insufficient to distinguish oblique-slip faulting from strike-slip faulting. Map-view fault patterns, however, are sufficient to distinguish dip-slip faulting from oblique-slip and strike-slip faulting.

DEFORMATION IN CROSS SECTIONAL VIEW

We used vertical sections from the dried, layered models to define the deformation in cross sectional view (Figure 6). All sections were decompacted to their approximate original thicknesses before drying. The dip-slip and oblique-slip cross sections have approximately the same throw (~2.0 cm; Table 2), whereas the strike-slip and oblique-slip sections have approximately the same heave (~2.8 cm; Table 2). Dip-slip cross sections are perpendicular to the master-fault trend and parallel to the heave direction; strike-slip cross sections are perpendicular to both the master-fault trend and the displacement direction; and oblique-slip cross sections are either perpendicular to the master-fault trend or parallel to the heave direction.

Experiment V: Dip Slip

The cross sections from the dip-slip experiment consist of an extensional forced fold dissected by numerous secondary faults (Figure 6a). Surface observations indicate that the extensional forced folding occurs before and during the development of the secondary faults. All of the secondary faults have normal separation. Surface observations show that the secondary faults at the model surface have normal displacement. Antithetic normal faults are more common in the upper part of the cross sections. Many of the antithetic faults are blind, dying out both upward and downward. The surface of many of the antithetic faults in the footwall region is curved, steepening with depth. These antithetic faults are probably related to bending associated with the extensional forced folding. The upper, gently dipping parts of these fault surfaces were initially more steeply dipping but were rotated to shallower dips by the subsequent forced folding. Synthetic normal faults are more common in the lower part of the cross sections. Most of the synthetic faults splay off the master fault and die out upward. The synthetic faults are probably related to aborted attempts of the master fault to propagate upward through the folded and attenuated clay layer. The secondary faults with the greatest displacement are the synthetic faults that emanate from the footwall cutoff of the base of the clay on the master fault. Synthetic faults preferentially propagate into the growth layers.

Experiments VI and VII: Oblique Slip

The cross sections from the oblique-slip experiments closely resemble those from the dip-slip experiment. The cross sections from experiments VI and VII consist of a highly faulted extensional forced fold in the clay above the master fault (Figure 6b). All of the secondary faults in the cross sections have normal separation. Surface observations show that the secondary faults at the model surface have mostly normal displacement. Some of the deeper secondary normal faults in the cross sections from experiments VI and VII, however, may have oblique-slip displacement. Antithetic faults are more common in the upper part of the cross sections. Many of the antithetic faults are blind, dying out both upward and downward. As in the dip-slip cross sections, the surfaces of many of the antithetic faults in the
footwall region are curved, steepening with depth as a result of the forced folding. Synthetic faults are more common in the lower part of the cross sections. Most of the synthetic faults splay off the master fault and die out upward. The secondary faults that have the greatest displacement are the synthetic faults emanating...
from the footwall cutoff of the base of the clay layer on the master fault. More synthetic faults than anti-
thetic faults propagate into the growth layers.

**Experiment IV: Strike Slip**

The cross sections from the strike-slip experiment (Figure 6c) show that a narrow, steeply dipping fault zone is present in the clay layer directly above the master fault. The secondary faults are high-angle splays off the master fault and have very small reverse or normal separations (most likely a result of the lateral juxtaposition of small irregularities in the clay sublayers). Surface observations indicate that the secondary faults at the model surface have predominantly left-lateral, strike-
slip displacement. Cross sectional geometries change along strike. For example, the attitude of the deforma-
tion zone in adjacent cross sections 13T and 12B changes from right-dipping to left-dipping (Figure 6c). No appreciable folding occurs in any of the cross sections.

**Summary of Deformation in Cross Sectional View**

The oblique-slip and dip-slip models are similar in cross sectional view. Cross sections in both models con-
sist of a highly faulted extensional forced fold in which the regional level steps down from the footwall block to the hanging-wall block. Thus, the modeling results suggest that cross sectional data alone are insufficient to distinguish between dip-slip and oblique-slip faulting. The deformation patterns in the strike-slip cross sections differ significantly from those in the oblique-
slip and dip-slip cross sections. No appreciable folding, no change in regional level, and no significant normal separation occur on any of the secondary faults in the strike-slip cross sections. Therefore, the modeling results suggest that cross sectional data alone are suffi-
cient to distinguish strike-slip faulting from dip-slip and oblique-slip faulting.

**CHANGE IN FAULT GEOMETRY WITH DEPTH**

Selected pieces of experiment VI, an oblique-slip model, were vertically and horizontally sectioned to determine the geometries of the secondary structures at depth. The spacing between the vertical sections is approximately 1 mm. For each vertical slice, we de-

1. The unambiguous recognition of oblique-slip nor-
mal faulting requires observations from both map and cross sectional views. In map view, the fault patterns in the oblique-slip models resemble those in the strike-slip models (Figures 4, 5). In both cases, two fault trends develop in the cover se-
quence. One fault trend is oblique to the trend of the underlying master fault, and one fault trend is subparallel to the trend of the underlying master fault. In cross sectional view, the fault patterns in the oblique-slip models resemble those in the dip-
slip models (Figure 6). In both cases, the regional level of the cover sequence drops across the master fault. A combination of extensional forced folding and faulting accommodates the drop in regional level.

2. The presence of two fault populations that have different trends and ages need not indicate two distinct episodes of regional extension. A single episode of oblique-slip normal faulting can produce such fault populations. In the oblique-slip models, two populations of secondary faults develop in the cover sequence (Figures 4, 5). One population consists of early formed faults whose strike is oblique to the trend of the underlying master fault. The second population consists of later formed throughgoing faults whose strike is subparallel to the trend of the master fault. The faults of the second population generally cut the faults of the first population.
Figure 8. Horizontal sections through part of experiment VI (oblique-slip normal faulting). (a) Photograph of vertical side of sectioned piece showing the locations of the two map levels (b and c). The inset diagrams show the average trend of small faults (thin black line) relative to the trend of the master fault (thick gray line). The white arrow gives the heave direction.

3. The secondary structures associated with oblique-slip normal faulting are likely to vary with depth. In the upper part of the oblique-slip models with the thick clay layer (experiments II and VI), secondary structures include en echelon horsts, grabens, and tilted fault blocks (Figures 3b, 7b). The strike of these secondary structures is oblique to the trend of the master fault, and many of the horst blocks and footwall highs have three-way closure. In the lower part of these oblique-slip models, throughgoing oblique-slip normal faults are the primary structures (Figure 7c). These faults link with the master fault, and their strike is subparallel to that of the master fault. Fewer structures with three-way closure exist in the lower part of the oblique-slip models.

4. Long-lived, well-developed relay ramps are more likely to form in the sedimentary cover above an oblique-slip normal fault than a dip-slip normal fault. In the models of oblique-slip normal faulting with the thick clay layer, relay ramps are wide and persist throughout the duration of the experiment. In identical models of dip-slip normal faulting (where the heave and fault dip are identical), relay ramps are narrow and become breached by cross faults during the early stages of the experiment (Figures 4, 5). Previous studies have shown that relay ramps can have a profound impact on the petro-
leum system. They are preferred sites of sediment transport from eroded footwall highs into hanging-wall basins (e.g., Gawthorpe and Hurst, 1993; Peacock and Sanderson, 1994; Childs et al., 1995) (Figure 9), and they are potential pathways for hydrocarbon migration from hanging-wall kitchens into footwall structural traps.

5. The small-scale faulting affecting relay ramps can vary considerably. In the models of oblique-slip normal faulting with the thick clay layer, relay ramps are cut by numerous small-scale normal faults that are subparallel to the ramp-bounding faults (Figure 5c). Cross faults are uncommon and begin to develop only during the final stages of the experiment when the displacement on the master fault is large (incipient ramp-breaching fault in Figure 3b). In identical models of dip-slip normal faulting, relay ramps are cut by some small-scale normal faults that are oblique to the ramp-bounding faults. These cross faults are abundant and developed throughout the duration of the experiment (Figures 4a, 5a). This latter fault pattern resembles the fault pattern conventionally assumed for relay ramps (e.g., Peacock and Sanderson, 1994). The small-scale faults that cut or breach relay ramps can retard or enhance fluid migration.

**Previous Modeling Studies and Deformational Styles Associated with Oblique Deformation**

Richard (1991) and Higgins and Harris (1997) also experimentally studied the secondary deformation associated with oblique-slip normal faulting (in which the strike of the fault is at an approximately 45° angle to the heave direction) (Figure 10). In their models, the cover sequence above the master fault was composed of either a layer of dry sand or a layer of dry sand over a layer of silicone putty. Dry sand deforms primarily by cataclastic faulting, whereas silicone putty deforms by viscous flow. Direct comparisons of these models with our models are difficult because boundary conditions (e.g., displacement on the master fault, thickness of the cover sequence) and modeling materials were substantially different. Nevertheless, comparisons suggest that three distinct deformation styles can develop in the cover sequence above an oblique-slip normal fault: partitioned, focused, and distributed (Figure 11).

In the pure sand model of Richard (1991) (Figure 10a), deformation in the cover sequence is partitioned. A steeply dipping, synthetic normal fault accommodates most of the dip-slip component of displacement on the master fault, whereas a high-angle strike-slip fault zone accommodates most of the strike-slip component of displacement. In map view, all faults are subparallel to the master fault. In cross sectional view, all faults link directly with the master fault. During the later stages of our thin clay model (experiment III; Figure 5e), and in the deeper parts of our other clay models (experiment VI; Figures 7c, 8c), most deformation in the cover sequence is focused on a throughgoing oblique-slip normal fault. In map view, these faults are subparallel to the master fault. In cross sectional view, they link directly with the master fault. Finally, in the sand/putty models of Richard (1991) (Figure 10b), during the early stages of our thin clay model (experiment III; Figure 4e), and in the shallow parts of our other clay models (experiments II and VI; Figures 5c,
Oblique-Slip Normal Faulting

Figure 10. Results from Richard’s (1991) study of oblique-slip normal faulting in which the master fault dips 45° and strikes 45° relative to the heave direction. (a) Fault-trace maps and cross sections from experiment with sand over rigid blocks. The thickness of the sand is 8 cm. (b) Fault-trace maps and cross sections from experiment with sand over putty over rigid blocks. The thickness of the sand is approximately 6 cm, and the thickness of the putty is approximately 2 cm.

In this section, we show that our models reproduce many of the key features observed in a known geologic example (Minas subbasin, Canada) of oblique-slip normal faulting. We then show that the modeling results can be used to infer oblique-slip normal faulting for another geologic example (Dampier subbasin, Australia).

Minas Subbasin of the Fundy Basin
Numerous rift basins developed in eastern North America during the Late Triassic–Early Jurassic (Figure 1). One of the largest of these rift basins, the Fundy basin of New Brunswick and Nova Scotia, Canada, has three structural elements: the northeast-trending Chignecto and Fundy subbasins and the east-northeast–trending Minas subbasin (Olsen and Schlische, 1990; Withjack et al., 1995) (Figure 12a). The trends of the subbasins reflect the trends of the Paleozoic contractional fabric. Northwest-southeast extension during the early Mesozoic (e.g., Schlische and Ackermann, 1995) reactivated northeast-trending Paleozoic reverse faults along the northwest margins of the Chignecto and Fundy subbasins as normal faults. Simultaneously, east-northeast–trending Paleozoic structures along the northern margin of the Minas subbasin (i.e., the Cobequid-Chedabucto fault system) became faults with both normal dip-slip and left-lateral strike-slip components of displacement. Thus, the northern boundary of the Minas subbasin was an oblique-slip normal fault zone during Late Triassic–Early Jurassic rifting. Little subsidence and deposition occurred after Paleozoic shortening and before Mesozoic extension. Thus, it is likely that the sedimentary cover above the reactivated Paleozoic structures was thin to absent.

Field mapping in the Minas subbasin shows that rift-related faults have two trends (Figure 12b). East-northeast–striking faults form throughgoing fault zones with combined normal dip-slip and left-lateral strike-slip displacement. They are subparallel to the trend of the Minas subbasin and to the reactivated Paleozoic fabric. Northeast-striking faults have normal displace-
Deformation & Attributes | Simplified Map Pattern | Simplified Cross Section
---|---|---
**Partitioned (sand models)**
- Normal and strike-slip faulting parallel to master fault

**Focused oblique-slip normal faulting (sand & thin clay models)**
- Oblique-slip normal fault parallel to master fault
- Some secondary normal faults oblique to master fault in clay models
- Moderate folding in clay models

**Distributed (sand/putty & thick clay models)**
- Secondary normal faults oblique to master fault
- Block rotation and reverse faulting in sand/putty models
- Significant folding in clay models

**Figure 11.** Simplified map patterns and cross sectional geometries observed experimentally in the cover sequence above an oblique-slip normal fault. The three end-member types of deformation are partitioned, focused oblique-slip normal faulting, and distributed.

...ment and are nearly perpendicular to the northwest-southeast regional extension direction. They form predominantly in the hanging walls of the throughgoing east-northeast–striking fault zones and locally link with them. The observed fault pattern along the northern margin of the Minas subbasin is very similar to the one that developed in the thin oblique-slip model (experiment III, Figure 12c). Most deformation is localized on east-northeast–striking, throughgoing, oblique-slip normal faults; northeast-striking normal faults, however, accommodate some of the deformation. Using the classification in Figure 11, the style of deformation along the northern margin of the Minas subbasin is focused.

**Northwest Shelf of Australia**
The northern Carnarvon basin is located on the northwest shelf of Australia (Figure 13a, b). Its main tectonic components include the Exmouth Plateau and several elongate structural lows (e.g., the Exmouth, Barrow, and Dampier subbasins) and highs (e.g., the Brigadier and Rankin platforms) (Vincent and Tilbury, 1988; Stagg and Colwell, 1994; Romine et al., 1997). The northeast-trending Exmouth, Barrow, and Dampier subbasins developed during an episode of Early Jurassic–Early Cretaceous rifting. Northeast-trending regional folds (synclines, monoclines) developed during rifting within and along the boundaries of the subbasins (Figure 13a, b). For example, seismic data show that the western boundary of the Dampier subbasin is a northeast-trending monocline cut by numerous secondary normal faults (e.g., Veenstra, 1985; Newman, 1994; Jablonski, 1997) (Figure 13c, d). Units in the thick Paleozoic–Triassic cover sequence consistently drop down from the northwest to the southeast, suggesting the presence of a southeast-dipping, northeast-striking master fault at depth. The normal faults that were active during rifting have two distinct trends: northeast, subparallel to the trend of the Dampier subbasin, and north-northeast. In the Dampier subbasin, seismic data suggest that the faults with the north-northeast trend are slightly older than those with the northeast trend (Newman, 1994). Newman (1994) proposed that the presence of these two fault sets that have different trends and ages reflected two distinct episodes of deformation in the Dampier subbasin: west-northwest–east-southeast extension during the Early–Middle Jurassic followed...
by northwest-southeast extension during the Late Jurassic–Early Cretaceous.

We propose an alternate explanation for the observed deformation patterns in the Dampier subbasin: distributed deformation (see Figure 11) associated with oblique-slip normal faulting during a single episode of west-northwest–east-southeast regional extension. With this explanation, rifting during the Early Jurassic–Early Cretaceous reactivated a southeast-dipping, northeast-striking, preexisting zone of weakness in the basement beneath the northwestern edge of the Dampier subbasin. In response to west-northwest–east-southeast regional extension, the zone of weakness became an oblique-slip fault zone with components of both normal and left-lateral strike-slip displacement. Initially, an extensional forced fold developed in the thick Paleozoic–Triassic cover sequence above the oblique-slip normal fault, forming the Dampier monocline. Soon after, north-northeast–striking secondary normal faults developed in the Paleozoic–Triassic strata above the footwall of the master fault. These secondary normal faults, oblique to the masterfault trend, formed a series of relay ramps and en echelon horsts and grabens. As the displacement on the master fault increased, the northeast-striking, oblique-slip normal fault eventually propagated upward, cutting the early formed north-northeast–striking secondary normal faults.

Oil fields in the Rankin trend (e.g., Newman, 1994) are primarily associated with en echelon horst blocks that provide three-way closure (Figure 14a). Similar en echelon horst blocks are also well developed at shallow structural levels in our experimental models of oblique-slip faulting (Figure 14b).

**SUMMARY AND CONCLUSIONS**

We have used clay models to define the secondary fault and fold patterns produced by oblique-slip normal faulting. Our modeling results, together with the results of previous modeling studies with sand and putty as the modeling media, suggest the following.

1. Three deformation styles can develop in the sedimentary cover above an oblique-slip normal fault: partitioned, focused, and distributed. With partitioned deformation, normal faulting accommodates
Figure 13. (a) Simplified geologic map of the northwest shelf of Australia showing the fault pattern on the Exmouth Plateau and the distribution of subbasins and regional folds. Box shows area detailed in (b). Based on Vincent and Tilbury (1988), Stagg and Colwell (1994), and Romine et al. (1997). (b) Structure map for Dampier subbasin. Faults active during rifting have two distinct trends: northeast, subparallel to the trend of the Dampier subbasin, and north-northeast. Faults with the north-northeast trend are slightly older than those with the northeast trend. The thick line gives the location of the composite seismic line in (c). Based on Vincent and Tilbury (1988), Stagg and Colwell (1994), and Romine et al. (1997). (c) Interpretation of regional composite seismic profile across the Dampier subbasin showing an inferred offset of top basement and secondary faults and folds in the Jurassic and Cretaceous sedimentary cover. Box shows area detailed in (d). Based on Jablonski (1997). (d) Part of composite seismic profile restored to top of Upper Cretaceous. (e) Comparable cross section from oblique-slip model (experiment VI).
Oblique-Slip Normal Faulting

Figure 14. Comparison of structural geometries from (a) northwestern boundary of Dampier subbasin and (b) model of oblique-slip normal faulting. Map from Dampier subbasin modified from Newman (1994). Note that the north arrow points toward the lower right. Horsts in the Rankin trend and horsts in the model are en echelon and have three-way closure.

1. The dip-slip component of displacement on the master fault, whereas strike-slip faulting accommodates the strike-slip component of displacement. With focused deformation, throughgoing, oblique-slip normal faults accommodate the deformation. With distributed deformation, extensional forced folding and secondary normal faulting, oblique to the master-fault trend, accommodate the deformation.

2. Partitioned and focused deformation are more likely to occur if the cover sequence is thin, the relative depth within the cover sequence is large, the displacement on the master fault is large, and/or the cover sequence deforms primarily by cataclastic faulting. Alternatively, distributed deformation is more likely to occur if the cover sequence is thick, the relative depth within the cover sequence is small, the displacement on the master fault is small, and/or parts of the cover sequence deform by distributed cataclasis or viscous flow.

3. Focused deformation is the primary deformation style during the later stages of the thin clay models of oblique-slip normal faulting and at the deep levels of the models with the thick clay layer. Focused deformation in the clay models is characterized by a series of throughgoing oblique-slip normal faults. These faults are subparallel to the master fault in map view and link with the master fault at depth. Some minor secondary normal faults also develop and are oblique to the master-fault trend.

4. Distributed deformation is the primary deformation style in the cover sequence during the early stages of our clay models of oblique-slip normal faulting. During the later stages of the experiments, distributed deformation occurs only at the shallow levels of the models with the thick clay layer. Distributed deformation in the clay models is characterized by an extensional forced fold above the master fault. Numerous secondary normal faults, both antithetic and synthetic to the master fault, cut the cover sequence above the footwall of the master fault. In map view, most of the secondary faults are oblique to the master-fault trend. In cross sectional view, some of the secondary normal faults die out at depth, whereas others link with the master fault at depth.

5. Both map and cross section data are needed to distinguish oblique-slip deformation from dip-slip and strike-slip deformation. In map view, the fault patterns in the oblique-slip clay models resemble those in the strike-slip models. In both cases, two fault trends develop in the cover sequence. One fault trend is oblique to the trend of the master fault, and one fault trend is subparallel to the trend of the master fault. In cross sectional view, the fault pat-
terns in the oblique-slip clay models resemble those in the dip-slip models. In both cases, the cover sequence deforms by a combination of extensional forced folding and faulting.

6. A single episode of oblique-slip normal faulting can produce two fault populations that have different trends and ages. In the oblique-slip clay models, two populations of secondary faults develop in the cover sequence. One population consists of early formed faults whose strike is oblique to the trend of the underlying master fault. The second population consists of later formed throughgoing faults whose strike is subparallel to the trend of the master fault. The faults of the second population generally cut the faults of the first population.

7. Long-lived, well-developed relay ramps are more likely to form in the sedimentary cover above an oblique-slip normal fault than a dip-slip normal fault. In the thick clay models of oblique-slip normal faulting, relay ramps are wide and persist throughout the duration of the experiment. The relay ramps are cut by numerous small-scale normal faults that are subparallel to the ramp-bounding faults. Cross faults are uncommon and begin to develop only during the final stages of the experiment. In identical models of dip-slip normal faulting, relay ramps are narrow. Cross faults are abundant and develop throughout the duration of the experiment.

8. The deformation patterns in our experiments closely resemble those observed in the Minas sub-basin of the Fundy rift and the Dampier subbasin on the northwest shelf of Australia. These similarities suggest that the modeling results can apply to many oblique-slip normal faults and can provide guidelines for interpreting field, well, or seismic data in extensional provinces.

**APPENDIX**

The strength of most upper crustal rocks increases with depth, obeying a Mohr-Coulomb criterion of failure (e.g., Byerlee, 1978). According to this criterion,

\[ \tau = c + \mu \sigma_n \]

where \( \tau \) and \( \sigma_n \) are, respectively, the shear and normal stresses on a potential fault surface, \( c \) is the cohesion, and \( \mu \) is the coefficient of internal friction. This empirical criterion of failure describes the initiation of new faults rather than the frictional reactivation of existing faults. For most sedimentary rocks, \( \mu \) ranges from about 0.55 to 0.85 (e.g., Handin, 1966; Byerlee, 1978). For intact sedimentary rocks, \( c \) is about 10–20 MPa (Handin, 1966), whereas for highly fractured sedimentary rocks, \( c \) is significantly less (e.g., Byerlee, 1978; Brace and Kohlstedt, 1980). To insure dynamic similarity between the models and natural prototypes, two conditions must be satisfied. First, the modeling materials and the rocks in nature must have similar coefficients of internal friction (e.g., Nalpas and Brun, 1993; Weijermars et al., 1993). This condition is satisfied using wet clay as the modeling material. Second,

\[ c^* = \rho^* g^* l^* \]

where \( c^* \), \( \rho^* \), \( g^* \), and \( l^* \) are model to natural prototype ratios for cohesion, density, gravity, and length, respectively (e.g., Hubbert, 1937; Weijermars et al., 1993; Vendeville et al., 1995). In our models, the values of \( \rho^* \) and \( g^* \) are about 0.7 and 1, respectively, and \( l^* \) is \( 10^{-4} - 10^{-5} \) (i.e., 1 cm in the models equaled 100–1000 m in nature). Thus, to insure dynamic similarity between the models and natural prototypes, the cohesion of rock must be about \( 10^2 - 10^5 \) greater than that of the modeling material. This condition is satisfied using wet clay as the modeling material.

**REFERENCES CITED**


Jablonski, D., 1997, Recent advances in the sequence stratigraphy of the Triassic to Lower Cretaceous succession in the northern


