Prediction of Normal-Fault Geometries—A Sensitivity Analysis

Martha Oliver Withjack and Eric T. Peterson

ABSTRACT

Several workers have developed cross section balancing schemes for extensional structures. Using these geometric models, structural interpreters can predict normal-fault geometries at depth by specifying the shape of a folded bed in the hanging wall of a normal fault, the deformation mechanism that accommodates the folding, the footwall counterpart of the folded hanging-wall bed, and the dip and location of the fault segment between the hanging-wall and footwall beds. We have systematically determined how uncertainties in these input parameters affect the prediction of normal-fault shape and detachment depth. Our sensitivity analysis shows that reasonable uncertainties in the fold shape near the normal fault, the deformation mechanism, the footwall correlation, and the fault dip produce large uncertainties in the predicted fault geometry. Reasonable uncertainties in the fold shape far from the normal fault and the fault location, however, produce only small uncertainties in the predicted fault geometry. Our work suggests that if seismic and well data are lacking or of poor quality, then geometric models cannot provide unique answers to questions about the geometry of a normal fault at depth. Geometric models, however, can provide a range of possible fault geometries.

INTRODUCTION

Exploration and production geoscientists working in extensional provinces, whether the North Sea, Gulf of Suez, or Gulf of Mexico, need information about the geometries of normal faults at depth. Unfortunately, seismic, well, and outcrop data cannot always provide this needed information. Several workers have addressed this problem by developing geometric models that quantitatively relate the shape of a normal fault to the shape of its hanging-wall fold (Verrall, 1981; Suppe, 1983; Coward and Gibbs, 1986; Davison, 1986; White et al., 1986; Wheeler, 1987; Williams and Vann, 1987; Groshong, 1989, 1990; Rowan and Kligfield, 1989; Dula, 1991; White and Yielding, 1991; White, 1992; Kerr and White, 1992; Xiao and Suppe, 1992). The principal assumptions behind these geometric models are that all hanging-wall folding is produced by fault-bend folding, all deformation occurs within the plane of the section, and the footwall remains rigid during deformation. Consequently, these geometric models are not applicable for a normal fault where salt or shale diapirism has significantly modified the geometries of its footwall and hanging-wall beds, or for a normal fault with considerable strike-slip displacement or footwall rotation.

Two types of geometric models exist. Forward models, or fold-prediction models, use the shape of a normal fault to simulate the development of its hanging-wall folds through time. Inverse models, or fault-prediction models, use the shape of a hanging-wall bed to calculate the shape of the underlying normal fault and its detachment depth. Fault-prediction models are especially useful in hydrocarbon exploration and production because they use shallow seismic, well, and outcrop data to predict fault geometries at depth where data commonly are lacking or of poor quality (Figure 1). Users of fault-prediction models must specify the shape of the folded bed in the hanging wall of the normal fault, the deformation mechanism that accommodates the folding, the footwall counterpart of the folded hanging-wall bed, and the dip and location of the fault segment between the hanging-wall and footwall beds (Figure 2a). An error in any of these input parameters produces an error in the predicted shape of a normal fault at depth. For example, case studies have suggested that uncertainty in the hanging-wall deformation mechanism (Rowan and Kligfield, 1989; Dula, 1991; White and Yielding, 1991).

©Copyright 1993. The American Association of Petroleum Geologists. All rights reserved.

*Manuscript received, June 26, 1992; revised manuscript received, December 2, 1992; final acceptance, February 1, 1993.

Mobil Research and Development Corporation, Mobil Place, P.O. Box 650232, Dallas, Texas 75222-0232.

We thank Cynthia Ebinger, Gloria Eisenstadt, Peter Honnings, Stephen Hook, John Lorenz, Tim Reed, and Nigel Uppolt for their careful reviews of the manuscript. We also thank Mobil Research and Development Corporation for permission to publish this work.
the footwall correlation (Rowan and Kligfield, 1989), and the fault dip (Rowan and Kligfield, 1989) can cause considerable uncertainty in the predicted shape of a normal fault.

In this paper, we systematically document the sensitivity of fault-prediction modeling to uncertainties in the input parameters. We show, for specific and general cases, how uncertainties in the deformation mechanism, the fault dip and location, the footwall correlation, and the fold shape affect the prediction of normal-fault shape and detachment depth. Exploration and production geologists working in extensional provinces can use our sensitivity analysis to decide whether fault-prediction modeling can provide solutions to their interpretation problems.

CONSTRUCTION TECHNIQUE

To undertake this sensitivity analysis, we developed a construction technique for fault-prediction modeling. The basic assumption behind our construction technique is that inclined simple shear, at some chosen angle, is the deformation mechanism that accommodates the folding in the hanging walls of curved normal faults (Figure 2b). Our construction technique is similar to the method described by White (1987) and to the methods used in several commercial software packages (e.g., BSEP of Midland Valley Exploration and IOCAGE of IFP). We favor the use of inclined simple shear as the hanging-wall deformation mechanism in our fault-prediction models for several reasons. First, construction techniques with inclined simple shear as the deformation mechanism conserve cross sectional area. Neither the flexural-slip model of Davison (1986) nor the modified-Chevron and dip-line constructions of Williams and Vann (1987) conserve cross sectional area. Second, case studies have shown that inclined simple shear is
a good approximation to the deformation in the hanging walls of curved normal faults (Grosehong 1990; White and Yielding, 1991; Kerr and White, 1992; White, 1992; Xiao and Suppe, 1992).

UNCERTAINTIES IN THE INPUT PARAMETERS

In this section, we show how the uncertainty in each input parameter affects the prediction of normal-fault shape and detachment depth for specific and general cases. In the specific cases, we compare the predicted fault geometry for a standard case with those for several alternate cases. The hanging-wall bed in the standard case has a simple rollover shape (Figure 3). Near the normal fault, the bed dips toward the fault. Dip continuously increases toward the fault. Far from the normal fault, the hanging-wall bed rises to the projected level of its footwall counterpart. The dip of the fault segment between the hanging-wall bed and its footwall counterpart is 60°. The inclined shear direction, measured from the vertical toward the normal fault, is 25°.

Shear Angle

White et al. (1986) defined the shear angle (α) as the acute angle between the vertical and the inclined shear direction (Figure 2b). Recent studies of physical models and seismic examples have shown that the shear angle can range from 0 to 50° (Rowan and Kligfield, 1989; Groshong, 1990; White and Yielding, 1991; Kerr and White, 1992; White, 1992; Xiao and Suppe, 1992). In these case studies, the geometries of the normal faults and their hanging-wall beds were well known, permitting an accurate determination of the shear angle. If seismic data are lacking and fault and fold geometries are not well known, then several tens of degrees of uncertainty in the shear angle can exist.

Uncertainties in the shear angle produce uncertainties in the predicted fault geometries. For example, Figure 3 shows the footwall bed, the corresponding folded hanging-wall bed, and the 60°-dipping segment of the normal fault between the footwall and hanging-wall beds for the standard case. Fault-prediction models use this information, together with the value of the shear angle, to predict the shape of the normal fault at depth. We have computed the complete fault shape for several values of the shear angle. In the standard case with a shear angle of 25°, the predicted normal fault is listric and flattens at a depth of 2.9 km. With α = 10°, the predicted normal fault has steeper dips and a greater detachment depth of 4.0 km. With α = 40°, the predicted normal fault has gentler dips and a shallower detachment depth of 2.1 km. This example shows that the predicted fault shape and detachment depth depend on the assumed shear angle. Specifically, the predicted detachment depth decreases as the assumed shear angle increases. A reasonable uncertainty in the shear angle (15°) can produce a large uncertainty in the predicted fault shape and detachment depth (1 km).

To generalize these observations, we quantified the relationship between the error in the shear angle and the ratio of the true detachment depth to the predicted detachment depth (see Appendix, equation 5). This relationship is independent of the shape of the hanging-wall fold. It depends only on the assumed shear angle and the dip of the fault segment between the hanging-wall and footwall beds. Figure 4 graphically displays this relationship for an assumed shear angle of 25° and a fault dip of 60°. The graph clearly shows that the error in the predicted detachment depth increases significantly as the error in the shear angle increases. If the uncertainty in the assumed shear angle is 10°, then the true detachment depth can range from about 80 to 125% of the predicted detachment depth. If the uncertainty is 20°, then the true detachment depth can range from about 65 to 155% of the predicted detachment depth.

Fault Dip

The dip of the fault segment between the folded hanging-wall bed and its footwall counterpart is another important input parameter of fault-prediction models (Figure 2a). Fault dip is poorly constrained by seismic data if few reflection terminations exist, if reflection terminations fail to align with each other and with surface reflections, or
if the exact velocity function used to convert from two-way traveltimes to depth is unknown. These factors can introduce several tens of degrees of uncertainty in the fault dip (Figure 5).

We have computed the complete fault shape for three different fault dips (Figure 6). In the standard case with a 60°-dipping fault segment (case 5), the predicted normal fault is listric and flattens at a depth of 2.9 km. With a 50°-dipping fault segment (case 1), the predicted normal fault has gentler dips and a shallower detachment depth of 2.4 km. With a 70°-dipping fault segment (case 2), the predicted normal fault has steeper dips and a greater detachment depth of 3.5 km. This example shows that the predicted detachment depth increases as the assumed fault dip increases. Also, a reasonable uncertainty in the fault dip (10°) can produce a large uncertainty in the predicted fault shape and detachment depth (500 m).

To generalize these observations, we quantified the relationship between the error in the fault dip and the ratio of the true detachment depth to the predicted detachment depth (see Appendix, equation 7). This relationship depends on the assumed fault dip, the shear angle, and the fold shape. Figure 7 graphically shows this relationship for an assumed fault dip of 60°, a shear angle of 25°, flat-lying hanging-wall beds near the fault, and an average fold width of three times the fault throw. The error in the predicted detachment depth increases as the error in the fault dip increases. If the uncertainty in the assumed fault dip is 5°, then the true detachment depth can range from about 90 to 115% of the predicted detachment depth. If the uncertainty is 10°, then the true detachment depth can range from about 75 to 130% of the predicted detachment depth.

Figure 5—(a) Hypothetical seismic section showing well-constrained fault dip and location. Multiple reflection terminations align with each other and with the fault-surface reflection. (b) Hypothetical seismic section showing poorly constrained fault dip and location. Few reflection terminations exist. They fail to align with each other and with the fault-surface reflection. (c) Time-migrated seismic section from Grass Valley, Nevada, showing west-dipping normal fault (after Zoback and Anderson, 1983). The dip and location of the normal fault are poorly constrained by seismic data because reflection terminations fail to align with each other and with possible fault-surface reflections. F is the fault location at the earth's surface.

Fault Location

The location of the fault segment between the folded hanging-wall bed and its footwall counterpart is another input parameter of fault-prediction models (Figure 2a). If few reflection terminations exist or if reflection terminations fail to align with each other and with fault-surface reflections, then fault locations are poorly constrained by seismic data (Figure 5). If well and outcrop data are also lacking, then several hundred meters of uncertainty in the fault location can exist.

Reasonable uncertainties in the fault location pro-
Figure 6—Fault-prediction models for several fault dips. Bold black lines are input parameters: the footwall bed, the upper segment of the normal fault, and the folded hanging-wall bed. S is the standard case with the upper segment of the normal fault dipping 60°. Alternate cases 1 and 2 have the upper fault segment dipping 50° and 70°, respectively. In all cases, the shear angle is 25°. Thin black lines are predicted fault shapes.

Figure 7—Graph showing the relationship between the error in the assumed fault dip and the ratio of true detachment depth to predicted detachment depth. The assumed dip of the upper segment of the normal fault is 60°, and the shear angle is 25°. Labels on the curves give the true fault dips.

Figure 8—Fault-prediction models for several fault locations. Bold black lines are input parameters: the footwall bed, the 60°-dipping upper segment of the normal fault, and the folded hanging-wall bed. S is the standard case. Alternate cases 1 and 2 have the upper fault segment moved 100 m toward the footwall and hanging wall, respectively. In all cases, the shear angle is 25°. Thin black lines are predicted fault shapes.

Footwall Correlation

The correlation of a footwall bed with the folded hanging-wall bed is an important input parameter of fault-prediction models (Figure 2a). Footwall correlations are poorly constrained by seismic data if few distinctive reflection packages exist or if hanging-wall and footwall reflection packages differ (Figure 10). Facies changes and thickness variations associat-
Figure 9—Graph showing the relationship between the error in the assumed fault location (relative to fault throw) and the ratio of true detachment depth to predicted detachment depth. The fault dip is 60°, the hanging-wall bed is flat-lying near the fault, and the average fold width is three times the fault throw.

...ed with growth and compaction commonly produce significant differences in hanging-wall and footwall stratigraphies and, consequently, reflection packages. Without well or outcrop data to provide additional constraints, several hundred meters of uncertainty in the footwall correlation can exist. Footwall erosion introduces additional uncertainty. If footwall erosion has occurred, then hanging-wall beds may no longer have footwall counterparts.

The predicted shape of a normal fault depends on the assumed footwall correlation. We calculated the complete fault shape for four different footwall correlations (Figure 11). In the standard case (case S), the hanging-wall bed rises to the projected level of the footwall bed. At depth, the predicted normal fault flattens at 2.9 km. With a footwall correlation 100 m lower than the standard case (case 1), the hanging-wall bed rises above the projected level of its footwall counterpart. At depth, the predicted normal fault dips gently, about 5°, toward the footwall. With a footwall correlation 100 m higher than the standard case (case 2), the hanging-wall bed always lies below the projected level of its footwall counterpart. At depth, the predicted normal fault dips gently, about 5°, toward the hanging wall. With a footwall correlation 500 m higher than the standard case (case 3), the predicted normal fault at depth dips about 20° toward the hanging wall. This example shows that the predicted fault shape and detachment dip depend on the assumed footwall correlation. Specifically, detachment dip is greater if the assumed footwall correlation is higher. Also, an uncertainty of only 100 m in the assumed footwall correlation can produce a large uncertainty in the predicted geometry of a normal fault at depth.

We quantified the relationship between the error in the footwall correlation and the fault dip at depth (see Appendix, equation 11). Assuming that the projected level of the footwall bed is horizontal, this relationship depends on the shear angle, the dip of the fault segment between the hanging-wall and footwall beds, the fault throw, and the far-field fault throw (i.e., the elevation difference between the hanging-wall and footwall beds).
Figure 11—Fault-prediction models for several footwall correlations. Bold black lines are input parameters: the footwall bed, the 60°-dipping upper segment of the normal fault, and the folded hanging-wall bed. S is the standard case. Alternate cases 1, 2, and 3 have the footwall correlations moved 100 m down, 100 m up, and 500 m up, respectively. In all cases, the shear angle is 25°. Thin black lines are predicted fault shapes.

Figure 12—Graph showing the relationship between the error in the assumed footwall correlation (relative to fault throw) and the true detachment dip. The fault dip is 60°, the projected level of the footwall bed is horizontal, and no elevation difference exists between the hanging-wall bed and the projected level of the footwall bed far from the fault. Negative dips indicate that the detachment dips toward the footwall. Positive dips indicate that the detachment dips toward the hanging wall.

Fold Shape

The shape of the fault-bend fold in the hanging wall of a normal fault is another important input parameter of fault-prediction models (Figure 2a). Fold shapes can be distorted on seismic data if lateral velocity variations produce pull-ups and push-downs. Also, several geologic processes including compaction, forced folding, and diapirism can alter the shape of the fault-bend fold in the hanging wall of a normal fault. Fault-prediction models, based on the assumption that all hanging-wall folding is fault-bend folding, will be inaccurate if other folding processes have occurred.

Figure 13a shows a hanging-wall bed with three different fold shapes. In the standard case (case S), the folded bed has the shape of a typical rollover fold. In alternate case 1, we modified the standard fold shape by adding a "bump" far from the normal fault. An unrecognized velocity pull-up could produce such a bump. In alternate case 2, we modified the standard fold shape by adding a flexure near the normal fault. Forced folding could create a similar flexure (Withjack et al., 1990). Figure 13b shows alternate case 3 in which we altered the standard fold shape by compacting the hanging-wall strata using the exponential-decay formula, \( \phi = 0.5e^{-0.5z} \), where \( \phi \) is porosity and \( z \) is depth in kilometers.

We used fault-prediction models to calculate the fault shape for these four cases with the assumption that the hanging-wall folding is produced only by fault-bend folding. The models predict that the normal fault in the standard case flattens at a depth of 2.9 km. In alternate case 1, the predicted normal fault has a slightly shallower detachment depth of 2.7 km. In alternate cases 2 and 3, the predicted normal faults are steeper and have much greater detachment depths of 3.6 and 3.4 km, respectively. These examples show that erroneous assumptions about the shape of the fault-bend fold distant from the normal fault have little effect on the predicted fault shape and detachment depth. Erroneous assumptions about the shape of the fault-bend fold near the normal fault, however, have significant effects on the predicted fault geometry. Compaction, if not incorporated into the fault-prediction model, also introduces significant uncertainty in the predicted fault geometry. White and Yielding (1991) provide
data, can use this sensitivity analysis to decide whether fault-prediction models can provide solutions to their interpretation problems in extensional basins. The following example shows how our sensitivity analysis applies to seismic data from offshore Norway.

**Normal Faults from the Haltenbanken Area, Offshore Norway**

Several episodes of normal faulting affected the Haltenbanken area of offshore Norway from the late Paleozoic to the Eocene (Bukovics and Ziegler, 1985). Many of the normal faults that formed during these extensional episodes were deep-seated structures, involving the basement. Others, however, were detached structures, flattening within Triassic salt (Withjack et al., 1989).

Figure 14a is a line drawing of a proprietary seismic line from the Haltenbanken area (Withjack et al., 1989). The seismic data show that a normal fault offsets the base Cretaceous unconformity and the underlying Triassic/Jurassic coals. It is listric, dipping about 60° at the level of the base Cretaceous unconformity and 45° at the level of the Triassic/Jurassic coals. The fault throw is about 600 m at the levels of the base Cretaceous unconformity and the Triassic/Jurassic coals. The hanging-wall strata dip gently toward the normal fault. Two anticlinal normal faults offset the hanging-wall strata. Several questions exist about the geometry of the master normal fault at depth. Is the normal-fault basement involved? Does it flatten at depth? If so, does it flatten within the Triassic salt?

We have used fault-prediction models to address these questions. In the standard case, we have assumed that the inclined shear angle is 25° and that the fault dip at the base Cretaceous unconformity is 60°. We have also assumed that the footwall correlation shown in Figure 14a is correct for the base Cretaceous unconformity. Using the fold shape at the base Cretaceous unconformity, fault-prediction models indicate that the detachment depth of the normal fault is 3.5 km below the base Cretaceous unconformity (Figure 14b). Triassic salt, a reasonable detachment material, probably exists at this depth.

Figure 14b shows the sensitivity of the predicted fault shape and detachment depth to errors in the shear angle. For our assumed shear angle of 25°, the fault flattens at 3.5 km below the base Cretaceous unconformity. If the true shear angle is 15°, then the true detachment depth is only 2.8 km below the base Cretaceous unconformity. If the true shear angle is 35°, then the true detachment depth is 4.4 km below the base Cretaceous unconformity. Figure 14c shows the sensitivity of the predicted fault shape and detachment depth to errors in the dip of the fault segment at the base Cretaceous unconformity. For our assumed fault dip of 60°, the fault flat-

**DISCUSSION AND APPLICATIONS**

Our sensitivity analysis shows that reasonable uncertainties in the assumed shear angle, fault dip, footwall correlation, and fold shape near the fault significantly affect the prediction of fault shape and detachment depth (Table 1). Reasonable uncertainties in the fault location and the fold shape distant from the fault, however, have little effect on the prediction of fault shape and detachment depth (Table 1). Structural interpreters, after evaluating the quality of their input data, can use this sensitivity analysis to decide whether fault-prediction models can provide solutions to their interpretation problems in extensional basins. The following example shows how our sensitivity analysis applies to seismic data from offshore Norway.
Table 1. Influence of Input Parameters on Predictive Capabilities of Geometric Models

<table>
<thead>
<tr>
<th>Reasonable Uncertainties</th>
<th>Reasonable Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce Large Uncertainties In</td>
<td>Produce Small Uncertainties In</td>
</tr>
<tr>
<td>Predicted Fault Shape</td>
<td>Predicted Fault Shape</td>
</tr>
</tbody>
</table>

**Shear Angle**

- $\alpha = 40^\circ$
- $\alpha = 25^\circ$
- $\alpha = 10^\circ$

**Fault Dip**

**Footwall Correlation**

**Fold Shape Near Fault**

**Fault Location**

**Fold Shape Distant From Fault**
Figure 14—(a) Interpreted line drawing of time-migrated seismic section from the Haltenbanken area, offshore Norway (displayed with no vertical exaggeration assuming a velocity of 3000 m/s) (after Withjack et al., 1989). [1] is the base Cretaceous unconformity, [2] is the Triassic/Jurassic coal, and [3] is the top of the Triassic salt. The thickness of the salt is unknown. (b) Fault-prediction models for different shear angles. The assumed fault dip at the base Cretaceous unconformity is 60°, and the fold shape is that of the base Cretaceous unconformity. With shear angles of 35°, 25°, and 15°, the predicted detachment depths are 2.8, 3.5, and 4.4 km, respectively, below the base Cretaceous unconformity. (c) Fault-prediction models for different fault dips. The assumed shear angle is 25°, and the fold shape is that of the base Cretaceous unconformity. With fault dips of 55°, 60°, and 65°, the predicted detachment depths are 3.1, 3.5, and 3.8 km, respectively, below the base Cretaceous unconformity. (d) Fault-prediction models for different footwall correlations. The assumed shear angle is 25°, the fault dip at the base Cretaceous unconformity is 60°, and the fold shape is that of the base Cretaceous unconformity. With a footwall correlation 150 m higher than the one used in the previous examples, the predicted detachment (gray line) is no longer flat, but dips 10° to the southeast.

tens at 3.5 km below the base Cretaceous unconformity. If the true fault dip is 55°, then the true detachment depth is 3.1 km below the base Cretaceous unconformity. If the true fault dip is 65°, then the true detachment depth is 3.8 km below the base Cretaceous unconformity. Figure 14d shows the sensitivity of the predicted fault shape to errors in the footwall correlation. With the footwall correlation in Figure 14a, the normal fault flattens at depth. If the assumed footwall correlation is 150 m too low (i.e., the true correlation is 150 m higher), then the normal fault actually dips 10° at depth.

This example from offshore Norway shows that, unless the footwall correlation is well known, we cannot use fault-prediction modeling to determine whether the normal fault is deep-seated or whether it detaches within the Triassic salt. If the footwall correlation is well known, then we can use fault-prediction modeling to define a range of possible fault shapes and detachment depths. With the footwall correlation shown in Figure 14a and for reasonable values of the shear angle and the fault dip, the fault-prediction models suggest that the normal fault from offshore Norway flattens between about 3 and 4.5
km below the base Cretaceous unconformity. Triassic salt, a reasonable detachment material, probably exists within this depth interval.

CONCLUSIONS

We have determined how typical uncertainties in the input parameters affect the prediction of normal-fault shape and detachment depth. We conducted this sensitivity analysis by using fault-prediction models and by quantitatively relating the uncertainty of the input parameters to the uncertainty of detachment depth and dip. Our sensitivity analysis shows that typical uncertainties in the shear angle, fault dip, footwall correlation, and fold shape near the fault significantly affect the prediction of fault shape and detachment depth (Table 1). Typical uncertainties in the fault location and the fold shape distant from the fault, however, have little effect on the prediction of fault shape and detachment depth (Table 1).

Our sensitivity analysis suggests that, if seismic and well data are lacking or of poor quality, then geometric models cannot provide unique answers to questions about the geometry of a normal fault at depth. Structural interpreters, however, can use fault-prediction modeling to define a range of possible fault shapes and detachment depths and, then, using principles of mechanical stratigraphy, decide the most likely shape and detachment depth. For example, any known salt or shale layers within the defined range of detachment depths would be likely detachment horizons. Structural interpreters can also enhance the capabilities of fault-prediction modeling by applying the technique to several hanging wall beds (White and Yielding, 1991; Kerr and White, 1992, White, 1992).

Our sensitivity analysis also has general implications for the balancing of extensional cross sections. All of the fault-prediction models in this paper are balanced cross sections. Although they closely resemble each other at shallow levels, they have significantly different structural geometries at depth. Consequently, balancing cannot uniquely constrain deep-seated structural geometries in extensional provinces. Balanced cross sections with significantly different structural geometries at depth can honor the same seismic, well, and outcrop data.

APPENDIX

In this Appendix, we derive equations that quantify the sensitivity of fault prediction modeling. Each of the sensitivity equations relates the uncertainty of the predicted detachment depth or dip to the uncertainty of an input parameter. The basic assumption behind the sensitivity equations is preservation of cross sectional area during deformation.

\[ D = \frac{A}{E}, \]  

where \( D \) is the detachment depth, \( A \) is the area bounded by the projected level of the footwall bed, the upper segment of the normal fault, and the folded hanging wall bed; and \( E \) is the extension.

Shear Angle

We quantified the relationship between the error in the assumed shear angle (\( \Delta \alpha \)), the predicted detachment depth (\( D \)), and the true detachment depth (\( D_j \)) (Figure 16). The extension (\( E \)) is

\[ E = T \left( \cot \beta + \tan \alpha \right), \]  

where \( T \) is fault throw, \( \beta \) is the dip of the upper segment of the normal fault, and \( \alpha \) is the shear angle. Combining equations 1 and 2, the predicted detachment depth is

\[ D = \frac{A}{T \left( \cot \beta + \tan \alpha \right)}. \]  

Similarly, the true detachment depth is

\[ D_j = \frac{A}{E_j \left( \cot \beta + \tan \left( \alpha + \Delta \alpha \right) \right)} \]  

where \( E_j \) is the extension associated with the true shear angle, \( \alpha_j = \alpha + \Delta \alpha \). Combining equations 3 and 4 yields the sensitivity equation,

\[ \frac{D_j}{D} = \frac{\cot \beta + \tan \alpha}{\cot \beta + \tan \left( \alpha + \Delta \alpha \right)}. \]
Figure 16—Schematic cross section of a fault-bend fold showing variables used to define the relationship between $\Delta \alpha$, the error in the assumed shear angle; $D$, the predicted detachment depth associated with the assumed shear angle, $\alpha$; and $D_1$, the true detachment depth associated with the true shear angle, $\alpha_t = \alpha + \Delta \alpha$. $E$ and $E_t$ are the extensions associated with the assumed and true shear angles, respectively. $T$ is the fault throw. $\beta$ is the dip of the upper segment of the normal fault. Gray lines are variables associated with the assumed shear angle. Black lines are variables associated with the true shear angle. The dashed line is the projected level of the footwall bed. The thin gray line is the predicted fault shape. The thin black line is the true fault shape.

The ratio of the true detachment depth to the predicted detachment depth depends on the dip of the upper segment of the normal fault, the assumed shear angle, and the error in the assumed shear angle. It is independent of the fold shape.

Fault Dip

We quantified the relationship between the error in the assumed fault dip ($\Delta \beta$), the predicted detachment depth ($D_1$), and the true detachment depth ($D$). The predicted detachment depth is given by equation 3. The true detachment depth is

$$D_t = \frac{A + \Delta A}{E_t} = \frac{A + \Delta A}{T_t [\cot(\beta + \Delta \beta) + \tan \alpha]},$$

where $\Delta A$ is the small area bounded by the true and assumed upper segments of the normal fault and the folded bed, $E_t$ is the amount of extension associated with the true fault dip ($\beta_t = \beta + \Delta \beta$), and $T_t$ is the throw associated with the true fault dip (Figure 17). Combining equations 3 and 6 yields the sensitivity equation,

$$\frac{D_t}{D} = \left[ 1 - \frac{1}{2w} \left( \frac{\sin \Delta \beta}{\sin \beta \sin(\beta + \Delta \beta)} \right) \right] \left[ \frac{\cot \beta + \tan \alpha}{\cot(\beta + \Delta \beta) + \tan \alpha} \right],$$

where $f = \sin \Delta \beta \sin \alpha / \sin(\beta + \Delta \beta) \sin(\beta + \alpha)$, $w$ is the average fold width relative to fault throw ($A/2$, and $\delta$ is the dip of the hanging-wall bed near the fault (Figure 17). The ratio of the true detachment depth to the predicted detachment depth depends on the assumed fault dip, the error in the assumed fault dip, the shear angle, the dip of the hanging-wall bed near the fault, and the average fold width relative to fault throw.

Fault Location

We quantified the relationship between the error in the assumed fault location relative to fault throw ($\Delta \gamma / T$), the predicted
Figure 18—Schematic cross section of a fault-bend fold showing variables used to define the relationship between $\Delta l$, the error in the assumed fault location $D$, the predicted detachment depth associated with the assumed fault location; and $D_1$, the true detachment depth associated with the true fault location. $\Delta A$ is the small area bounded by the true and assumed upper segments of the normal fault, the projected level of the footwall bed, and the folded bed. Other variables are the same as in Figures 16 and 17. Gray lines are variables associated with the assumed fault location. Black lines are variables associated with the true fault location. The dashed line is the projected level of the footwall bed. The thin gray line is the predicted fault shape at depth. The thin black line is the true fault shape.

 detachment depth ($D$), and the true detachment depth ($D_1$) (Figure 18). The predicted detachment depth is given by equation 5. The true detachment depth is

$$D_1 = \frac{A + \Delta A}{E_1} = \frac{A + \Delta A}{T_1 \cot \beta + \tan \alpha},$$

where $\Delta A$ is the small area bounded by the true and assumed upper segments of the normal fault, the projected level of the footwall bed, and the folded bed; $E_1$ is the amount of extension associated with the true fault location; and $T_1$ is the throw associated with the true fault location (Figure 18). Combining equations 3 and 8, and eliminating a second-order term, yields

$$\frac{D_1}{D} = \frac{1 + \frac{1}{w} \frac{\Delta l}{T}}{1 + \frac{\Delta l}{T} \frac{\sin \beta \sin \delta}{\sin (\beta + \delta)},}$$

where $w$ is the average fold width relative to fault throw ($A/T$), and $\delta$ is the dip of the hanging-wall bed near the fault. The ratio of the true detachment depth to the predicted detachment depth depends on the error in the assumed fault location relative to fault throw, the fault dip, the dip of the hanging-wall bed near the fault, and the average fold width relative to fault throw. For realistic values of these parameters, the ratio of the true detachment depth to the predicted detachment depth is very close to one.

Figure 19—Schematic cross section of a fault-bend fold showing variables used in equation 10 to determine the predicted detachment dip ($\gamma$) associated with the assumed footwall correlation. The fault throw ($T$) is the elevation difference between the hanging-wall and footwall beds measured near the fault. The far-field fault throw ($\tau$) is the elevation difference between the hanging-wall bed and the projected level of the footwall bed measured far from the fault. $E$ is the extension associated with the assumed footwall correlation. $\alpha$ is the shear angle, and $\beta$ is the dip of the upper segment of the normal fault. The dashed line is the projected level of the footwall bed. The thin black line is the predicted fault shape at depth.

Figure 20—Schematic cross section showing variables used in equation 11 to determine the true detachment dip ($\gamma$). $E_1$ is the extension associated with the true footwall correlation, and $\Delta T$ is the elevation difference between the assumed and true footwall correlations. Other variables are the same as in Figure 19. The gray dashed line is the projected level of the footwall bed for the true footwall correlation. The black dashed line is the projected level of the footwall bed for the true footwall correlation. The thin black line is the true fault shape at depth.
Footwall Correlation

Assuming that the projected level of the footwall bed is horizontal, the predicted detachment dip ($\gamma$) is given by

$$\cot \gamma = \frac{T}{\tau} \left( \cot \beta + \tan \alpha \right) - \tan \alpha,$$  \hspace{1cm} (10)

where the fault throw ($T$) is the elevation difference between the hanging-wall and footwall beds measured near the fault, the footwall fault throw ($\gamma$) is the elevation difference between the hanging-wall and the projected level of the footwall bed measured far from the fault, $\beta$ is the dip of the upper segment of the normal fault, and $\alpha$ is the shear angle (Figure 19). If the true footwall correlation is $\Delta T$ higher than the assumed footwall correlation, then the true fault throw is $T + \Delta T$ and the true footwall fault throw is $\tau + \Delta T$ (Figure 20). The true detachment dip ($\gamma_T$) is

$$\cot \gamma_T = \frac{T + \Delta T}{\tau + \Delta T} \left( \cot \beta + \tan \alpha \right) - \tan \alpha.$$  \hspace{1cm} (11)

REFERENCES CITED


Verrall, P., 1981, Structural interpretation with application to North Sea problems: Joint Association for Petroleum Exploration Courses Course Notes 3.


ABOUT THE AUTHORS

Martha Oliver Withjack

Martha Oliver Withjack received her Ph.D. from Brown University in 1978, focusing on the mechanics of continental rifting. Before joining Mobil Research and Development Corporation in 1988, she worked as a research geologist at Cities Service Oil and Gas Company and ARCO Oil and Gas Company. Her research interests include extensional tectonics, physical and analytical modeling of structures, and structural interpretation of seismic data. She was an AAPG Distinguished Lecturer (1984–1985) and a recipient of the J. C. "Cam" Sprout Memorial Award (1986), and is a fellow of the Geological Society of America.

Eric T. Peterson

Eric T. Peterson is a research geophysicist at Mobil Research and Development Corporation in Dallas, Texas. He received his B.S. in geophysics from California Institute of Technology in 1980 and his Ph.D. in geophysics from Stanford University in 1985. At Mobil, he has developed computer programs to model structural geometries and thermal histories of sedimentary basins as tools for hydrocarbon exploration. He is currently in the Basin Analysis Group.