Deep-water Niger Delta fold and thrust belt modeled as a critical-taper wedge: The influence of elevated basal fluid pressure on structural styles

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ABSTRACT
We use critical-taper wedge mechanics theory to show that the Niger Delta toe-thrust system deforms above a very weak basal detachment induced by high pore-fluid pressure. The Niger Delta exhibits similar rock properties but an anomalously low taper (sum of the bathymetric slope and dip of the basal detachment) compared with most orogenic fold belts. This low taper implies that the Niger Delta has a very weak basal detachment, which we interpret to reflect elevated pore-fluid pressure ($\lambda \approx 0.90$) within the Akata Formation, a prodelta marine shale that contains the basal detachment horizon. The weak basal detachment zone has a significant influence on the structural styles in the deep-water Niger Delta fold belts. The overpressured and, thereby, weak Akata shales ductilely deform within the cores of anticlines and in the hanging walls of toe-thrust structures, leading to the development of shear fault-bend folds and detachment anticlines that form the main structural trap types in the deep-water fold belts. Moreover, the low taper shape leads to the widespread development of backthrust zones, as well as the presence of large, relatively undeformed regions that separate the deep-water fold and thrust belts. This study expands the use of critical-taper wedge mechanics concepts to passive-margin settings, while documenting the influence of elevated basal fluid pressures on the structure and tectonics of the deep-water Niger Delta.

INTRODUCTION
The Niger Delta, located in the Gulf of Guinea, is one of the most prolific petroleum basins in the world (Figure 1). The Delta consists of Tertiary marine and fluvial deposits that overlie oceanic...
crust and fragments of the extended African continental crust. Over the last decade, advances in drilling technology have opened the deep-water Niger Delta to exploration. At the deep-water toe of the delta, a series of large fold and thrust belts (Figure 1) is composed of thrust faults and fault-related folds (e.g., Damuth, 1994; Morley and Guerin, 1996; Wu and Bally, 2000; Corredor et al., 2005). Recent discoveries in this fold and thrust belt include the Agbami, Bonga, Chota, Ngolo, and Nnwa fields, all of which have structural traps formed by contractional folds.

The contractional part of the deep-water Niger Delta is divided into three major zones (Connors et al., 1998; Corredor et al., 2005): the inner fold and thrust belt, the outer fold and thrust belt, and the detachment-fold province (Figure 1). The inner fold and thrust belt is a highly shortened and imbricate fold and thrust belt, whereas the outer fold and thrust belt is a more classic toe-thrust zone with thrust-cored anticlines that are typically separated from one another by several kilometers (Corredor et al., 2005). The detachment fold belt is a transitional zone between the inner and outer fold and thrust belts that is characterized by regions of little or no deformation interspersed with broad detachment anticlines that accommodate relatively small amounts of shortening (Bilotti et al., 2005).

The deformation in the contractional toe of the Niger Delta is driven by updip, gravitational collapse of shelf sediments. Basinward motion of these shelf sediments is accommodated by normal faults that sole to detachments within the prodelta marine strata that lie above the basement (Figure 2). Slip on the detachments is transmitted to the deep water, where it is diverted onto thrust ramps and consumed by contractional folds in deep-water fold and thrust belts (Figures 2, 3). This style of gravitationally driven, linked extensional and contractional fault systems is common in passive-margin deltas (Rowan et al., 2004), including the Gulf of Mexico basin (e.g., Peel et al., 1995). The Niger Delta fold and thrust belts occupy the outboard toe of the delta in

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Figure 1. Map of the offshore Niger Delta showing the location of regional transects (1–10) used in this study, bathymetry, and major offshore structural provinces (modified from Connors et al., 1998; Corredor et al., 2005).
water depths ranging from 1 to 4 km (0.6 to 2.5 mi) below sea level (Figure 1) and create a very gentle (<2°), regional seafloor slope away from the coast.

In this article, we show that the Niger Delta toe-thrust system, composed of a sloping sea floor, a basal detachment system, and an internally deforming wedge of sediments, can be successfully modeled as a critical-taper wedge like those found in accretionary wedges at active margins (Davis et al., 1983). The taper of a wedge is the angle between its free surface and basal detachment. The theory of critical-taper wedge mechanics states that once a wedge reaches some critical taper, it grows self-similarly as material is added to or removed from the wedge. Given the strength of the wedge and its basal detachment, the theory defines the critical taper of the wedge. Conversely, we use measurements of the sea floor and the basal detachment to define the wedge shape and subsequently employ measured values of density, fluid pressure, and basal thrust step-up angles to examine the strength of the deforming wedge and its basal detachment. Specifically, we predict the magnitude of fluid overpressure in the basal detachment zone that would be required to produce the observed wedge shape. Finally, we consider the implications of this model for the structural styles and evolution of the Niger Delta fold and thrust belts.

**CRITICAL-TAPER WEDGE MECHANICS**

**Theory**

Critical-taper wedge mechanics theory explains the first-order geometry of fold and thrust belts as a function of the internal strength of the wedge of deforming material and the strength of the basal detachment on which the wedge slides (Davis et al., 1983; Dahlen et al., 1984). For the deformation front to propagate, the basal detachment of the wedge must be weaker than the wedge material. The analogy of a bulldozer pushing a pile of snow or sand is commonly used to illustrate the first-order mechanics of this system (Figure 4). Once the critical taper is reached, the wedge grows self-similarly, and internal deformation of the wedge maintains the taper. The taper of a specific wedge system is determined by the strength of the basal detachment relative to the internal strength of the wedge.

Critical-taper wedge mechanics theory was developed initially to explain accretionary wedges that form at convergent plate boundaries (Davis et al., 1983). In
Figure 3. Regional two-dimensional seismic line through the contractional toe of the Niger Delta, showing the tapered, wedge shape of the deep-water fold and thrust belts modeled in this article. Note that the bathymetric slope is caused by the underlying deformation, and that the basal detachment is subparallel to the top of underlying oceanic basement. Data provided courtesy of Veritas DGC, Ltd.
these tectonic systems, sediments are typically scraped off the subducting slab and incorporated into an internally deforming accretionary wedge; these wedges have a shape generally governed by their internal and basal strength (Chapple, 1978; Davis et al., 1983; Stockmal, 1983). Over the past two decades, critical-taper wedge theory has been successfully applied to study many accretionary wedges and orogenic fold and thrust belts throughout the world (e.g., Zhao et al., 1986; Breen, 1987; Behrmann et al., 1988; Barr and Dahlen, 1989; Dahlen and Barr, 1989; Dahlen, 1990; DeCelles and Mitra, 1995; Braathen et al., 1999; Plesch and Oncken, 1999; Carena et al., 2002). The theory, however, is a general description of any wedge of material deforming by brittle frictional processes. The theory can be used to explain the first-order geometry of fold and thrust belts regardless of their driving mechanisms. Here, we demonstrate that the critical-taper wedge theory can successfully model the gravitationally driven fold belts of the deep-water Niger Delta, extending the application of this theory beyond orogenic systems to passive-margin settings as suggested by Bilotti and Shaw (2001) and Rowan et al. (2004).

Although we will demonstrate that the general wedge theory is applicable to gravitationally driven wedges like the toe of the Niger Delta, it is important to consider differences between these systems and their tectonic counterparts in developing and interpreting wedge models. Foremost of these differences is the manner in which material is added to the wedge. At submarine convergent margins, the primary source of material input to the wedge is from sediments scraped from the subducting sea floor; otherwise, little modification of the overall shape of the wedge is present. In the case of the Niger Delta, material is added to the wedge both at the deformation front, as the basal detachment propagates into the basin, and through active delivery of sediments to the back of the wedge from the Niger River. This additional sedimentary input both modifies the taper of the wedge and provides more drive to the overall gravitational system. This modification of the wedge’s shape is more similar to subaerial wedges, which are subject to erosion that constantly modifies the shape of the wedge.

**Formulation**

The surface slope ($\alpha$) and the dip of the basal detachment ($\beta$) are the first-order parameters modeled in the critical-taper wedge theory. The sum of $\alpha$ and $\beta$, the wedge taper, is a function of the relative strength of the wedge and the strength of the basal detachment; the weaker the basal detachment and the stronger the wedge material, the narrower the wedge taper. The wedge strength is defined by frictional coefficients and fluid-pressure values for both the internally deforming wedge and its basal detachment. Davis et al. (1983) derived the equation for the wedge taper ($\alpha + \beta$) from a force balance on a wedge at critical taper. An enhancement of the critical-taper equation, with cohesion incorporated, was derived by Dahlen (1990) and is given as

$$
\alpha + \beta \approx \frac{(1 - \rho_w/\rho)\beta + \nu_b(1 - \lambda_b) - S_b/\rho g H}{(1 - \rho_w/\rho) + 2(1 - \lambda)(\sin \phi/1 - \sin \phi) + C/\rho g H}
$$

where $\rho$ is the bulk density of the wedge material; $\rho_w$ is the density of seawater (in the submarine wedge case); $\lambda$ and $\lambda_b$ are the Hubbert-Rubey fluid-pressure ratio...
(Hubbert and Rubey, 1959) for the wedge and the basal detachment; $S_b$ and $C$ are the cohesive strengths of the basal detachment and the wedge material, respectively; $g$ is the gravitational acceleration constant; $H$ is the wedge thickness; and $\mu_b$ is the coefficient of basal sliding friction. The cohesive strength of the wedge ($C$) is more important in the thin toe of the wedge; therefore, the taper also depends on the distance from the toe of the wedge. This is because the ratio of cohesive strength to frictional strength is larger at shallow depths, hence, the $C/gH$ term in the wedge equation.

In the next section, we use this formulation to establish that the Niger Delta fold belts are at critical taper. Subsequently, we examine the strength of the basal detachment in the Niger Delta using internal wedge parameters derived from well data and fault patterns observed in seismic reflection data.

**MODELING THE TOE OF THE NIGER DELTA**

**Measuring the Taper**

The overall shape of the distal toe of the Niger Delta fits the form of a tapered wedge, but to investigate whether it acts mechanically like a critical-taper wedge, we make quantitative measurements of the wedge shape as required by the Dahlen (1990) formulation. We measure the taper of the fold and thrust belt at the toe of the Niger Delta in 10 profiles (Figure 5; locations shown in Figure 1). The sea floor represents the upper free surface of the wedge, and we use a linear approximation of the seafloor slope to measure the angle $\alpha$, the angle below horizontal of the upper surface of the wedge. For the angle $\beta$, we use the observation that the basal detachment of the fold and thrust belt is generally parallel to the underlying basement reflector, as shown in Figure 3. Within the representative 10 profiles, we use a linear fit to the basement reflector to measure the dip of the basal detachment of the wedge, $\beta$.

The measured wedge taper ($\alpha + \beta$) of the Niger Delta toe is $2.5 \pm 0.4^\circ$ (Figure 6). This taper (Figure 7) is lower than all of the accretionary wedges at active margins reported in Davis et al. (1983). This anomalously low taper suggests that either the toe of the Niger Delta is not at critical taper, or it has substantially different mechanical properties compared to most active margins. In the subsequent discussion, we first establish that the deep-water fold belts are at critical taper and then explore the possibility of anomalous mechanical properties for the Niger Delta through critical-taper wedge modeling.

**Is the Toe of the Niger Delta at Critical Taper?**

Critical-taper wedge theory predicts a linear relationship with negative slope between the dip of the basal detachment and the seafloor slope of a contractional
wedge once a wedge has reached its critical taper. An active wedge that has not yet reached critical taper should not exhibit this relationship, nor should it propagate forward (i.e., grow wider). Instead, a subcritical wedge would internally deform until it thickened to its critical taper before it grew wider.

Given these considerations, we propose that the toe of the Niger Delta has indeed reached critical taper based on two main observations:

1. The wedge has grown appreciably wider by means of the basal detachment propagating into the basin. The fold and thrust belt shown in Figure 3 is more than 40 km (25 mi) wide, and the entire contractional toe is on the order of 100 km (62 mi) wide (Figure 5). A noncritical wedge first builds taper by internal deformation and then propagates basinward after reaching critical taper. A pronounced widening of a contractional wedge is an indication that it has reached critical taper and has continued to grow.

2. The regionally consistent taper of the wedge as shown by the negative slope of a graph of $\alpha$ versus $\beta$ indicates a consistent taper of about $2.5 \pm 0.4^\circ$ over a range of values for $\alpha$ and $\beta$ (Figure 6). Critical-taper wedge shape measured in 10 transects across the deep-water Niger Delta fold and thrust belts. The transect number is labeled on each point. The overall negative slope of the points is consistent with a critically tapered wedge with taper ($\alpha + \beta$) between 2.3 and 2.9°. Transect locations are shown in Figure 1.

![Figure 6. Plot of wedge shape measured in 10 transects across the deep-water Niger Delta fold and thrust belts.](image)

![Figure 7. Comparison in range of bathymetric slope and decollement (basal detachment) dip for the Niger Delta versus active submarine fold and thrust belts at convergent margins (modified from Davis et al., 1983). The Niger Delta has much lower taper ($\alpha + \beta$) than most other measured fold and thrust belts. Those with similar tapers (Makran and the toe of the Barbados accretionary wedge) are known to have high basal fluid pressures (Davis et al., 1983), implying the same condition for the Niger Delta. $\lambda = \lambda_b$, line assumes $\mu_b = 0.85$ and $\mu = 1.03$.](image)
wedge theory predicts that the properties of the wedge and basal detachment prescribe a wedge geometry that is as consistent as the regional material strength properties. Conversely, if the wedge was dominated by sedimentary processes, such as the angle of repose, we would not expect a consistent relationship between the basal detachment geometry and the seafloor slope.

Based on these considerations, we conclude that the toe of the Niger Delta is a contractional wedge at critical taper, and we now explore which properties of the wedge give it its uniquely low taper. To model the Niger Delta as a critical-taper wedge, we need to provide constraints on the main parameters of the formulation of Dahlen (1990). The following sections discuss the constraints on these parameters for the toe of the Niger Delta.

**Wedge Strength Parameters**

**Internal Coefficient of Friction**

We can constrain the internal coefficient of friction ($\mu$) using the geometry of the wedge as well as basic rock mechanics. Because a critical-taper wedge is on the verge of failure throughout the wedge, two planes are oriented at angles $\pm (\pi/4 - \phi/2)$, measured with respect to the maximum principal compression vector, $\sigma_1$, on which the failure criterion is satisfied (Jaeger and Cook, 1979) (Figure 8). We use this relationship and measurements of the angle that thrusts step up from the basal detachment, $\delta_b$, to estimate the angle of internal friction, $\phi$. We use the relationship from Dahlen et al. (1984, equation 27):

$$\delta_b = \pi/4 - \phi/2 - \psi_b$$  \hspace{1cm} (2)

where $\mu = \tan \phi$ and $\psi_b$ is the angle between the maximum principal compression ($\sigma_1$) and the basal detachment (Figure 8).

From 49 measurements of the dips of thrust faults from the fold and thrust belts of the Niger Delta (Corredor et al., 2005), we derive the histogram of values for $\delta_b$ presented in Figure 8. The bimodal graph has peaks at about 22 and 32°. The corresponding values for $\mu = \tan \phi$ (for $\psi_b = 2^\circ$) are $\mu = 0.90$ and $\mu = 0.40$, respectively. The value for $\mu$ (0.40) corresponding to $\delta_b = 32^\circ$ falls outside of the range of empirically derived rock strength values $0.6 \leq \mu \leq 1.0$, known as Byerlee’s Law (Byerlee, 1978). Therefore, we suggest that $\delta_b = 32^\circ$ does not represent a fundamental step-up angle in the area but instead reflects a typical value for imbricated faults (Suppe, 1983; Shaw et al., 1999) or perhaps faults that propagated as kink bands (Dahlen et al., 1984). In contrast, the value for $\mu$ (0.90) corresponding to $\delta_b = 22^\circ$ is consistent with Byerlee’s Law. This suggests that $\delta_b = 22^\circ$ represents the fundamental ramp step-up angle, and we employ the corresponding frictional value ($\mu = 0.90$) in our subsequent modeling.
Internal Fluid Pressure

The Hubbert and Rubey (1959) fluid-pressure ratio is the ratio of fluid pressure to the lithostatic pressure. This value is from Hubbert and Rubey’s formulation of effective stress that sought to explain how large thrust sheets could be translated long distances with little internal deformation from friction on the underlying fault. Through critical-taper wedge theory, Davis et al. (1983) showed that high fluid pressures were not necessary to explain the large-scale geometry of fold and thrust belts; critical-taper wedge theory explains the first-order geometry of fold and thrust belts without calling on significant overpressure. However, the fluid pressure is still an important component of the effective strength of the wedge material.

For the Niger Delta, we obtain regional values for the Hubbert-Rubey fluid-pressure ratio, \( \lambda \), generalized for the submarine case from formation pressures measured in deep-water wells:

\[
\lambda = \frac{(P_f - \rho_w g D)}{\rho g h}
\]

where \( D \) is the water depth, \( h \) is the depth of the measurement below the sea floor (Dahlen et al., 1984), and \( \rho \) is an estimate of the bulk rock density derived from many well-density logs. This formulation removes the effect of the overlying water because the hydrostatic and lithostatic pressure curves are identical in the water column. Figure 9 shows the distribution of \( \lambda \) values for 13 wells in the deep-water Niger Delta. The average value is \( \lambda = 0.54 \), and we use this value in subsequent models. For comparison, lambda for hydrostatic fluid pressure, \( \lambda_h \), is approximately 0.43, indicating that the Niger Delta section is, in general, slightly overpressured.

Cohesive Strength

The cohesive strength of the wedge material can be an important property for thin wedges and near the tip of high-taper wedges. In the toe of the Niger Delta, the relative significance of the cohesive strength of the rocks in the wedge, \( C \), is small because the wedge tip is at the distal end of the basal detachment, which is typically about 3 km (1.8 mi) below the sea floor (Figure 5). At depth, the effect of the increasing frictional strength of the material overwhelms the effect of the relatively small cohesive strength. Because the result is relatively insensitive to the cohesive strength of the material, we can safely estimate the cohesive strength of the wedge from rock-mechanics experiments (Hoshino et al., 1972) to be 10 ± 5 MPa for our deep-water sediments.

Basal Strength Parameters

The basal detachment of the toe of the Niger Delta lies within the Akata Formation, a thick marine shale that is thought to contain the source section for some...
of the major oil fields of the deep-water Niger Delta. A few wells have approached this section, but we know of no penetrations of the deeper parts of the formation where the basal detachment of the fold and thrust belt resides. The mechanical properties of the basal detachment cannot be measured directly and must be inferred from rock-mechanics experiments or derived from the critical-taper modeling.

Three parameters in the generalized wedge equation of Dahlen (1990) address the strength of the basal detachment of the wedge: the basal friction, the basal cohesive strength, and the basal fluid-pressure ratio. In this analysis, we assume that the basal coefficient of friction is similar to that derived for the wedge material, $\mu_b = 0.91$, which is consistent with Byerlee’s Law (Byerlee, 1978). In addition, because the basal detachment is a regionally continuous surface that is actively sliding, we assert that it is working as a frictional fault with low or no cohesive strength. We assume in our modeling that the basal cohesion is equal to zero.

With the values as described above (summarized in Table 1), we can directly compute a value for a range of basal fluid pressures from the critical-taper wedge equation. Figure 10 shows the predicted wedge taper for values of $\lambda_b$ compared to the measured taper values from the toe of the Niger Delta. Critical-taper wedge theory predicts Hubbert-Rubey fluid-pressure ratios of $0.89 < \lambda_b < 0.92$ for the range of measured transects and our preferred values for each parameter. The total range of predicted fluid pressures using the low- and high-pressure end members of each parameter is $0.82 < \lambda_b < 1.01$. Figure 11 shows the sensitivity of the wedge model to more typical values of $\lambda_b$ using the wedge formulation of Dahlen et al. (1984). These models show that for reasonable values of wedge strength and basal strength, the wedge geometry is very sensitive to the basal fluid pressure. Based on the observed wedge shape, we are readily able to distinguish the effects of basal fluid pressure and conclude that the low taper of the contractional toe of the Niger Delta is the result of strongly elevated fluid pressure at the basal detachment.

Elevated basal fluid pressures have also been invoked to explain the anomalously low taper of some orogenic fold and thrust belts, including the Barbados accretionary wedge (Figure 7) (e.g., Behrmann et al., 1988). We suggest that the elevated basal fluid pressure is the dominant cause of low-taper fold and thrust belts, regardless of whether they are orogenic or gravitationally driven. In the case of the Niger Delta, the elevated basal fluid pressure is also consistent with the anomalously low compressional wave speeds ($\leq 2500$ m/sec; $\leq 8202$ ft/sec) in the Akata Formation, as well as the general structural styles manifest in this shale tectonic province (Wu and Bally, 2000; Rowan et al., 2004; Corredor et al., 2005). In the next section, we examine how the elevated basal fluid pressure and the corresponding weak basal detachment in the Niger Delta influence the regional structural architecture of the deep-water fold belts, as well as the structural styles expressed by individual toe-thrust structures.

### Properties of Low-Taper Wedges with Elevated Basal Fluid Pressures

Elevated basal fluid pressure in the Niger Delta has had a substantial influence on the architecture and deformational history of its deep-water fold belts. The elevated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Method of Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface slope $\alpha$</td>
<td>$0.7–1.3^\circ$</td>
<td>Measured from 10 regional transects of seismic-derived seafloor map (see Figure 5)</td>
</tr>
<tr>
<td>Detachment dip $\beta$</td>
<td>$1.2–2.2^\circ$</td>
<td>Measured from 10 regional transects of seismic-derived basement map (see Figure 5 and text for justification)</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>2400 kg/m$^3$</td>
<td>Deep-water well-density logs (approximate)</td>
</tr>
<tr>
<td>Fluid-pressure ratio $\lambda$</td>
<td>$0.54 \pm 0.15$</td>
<td>Pressure data from 13 deep-water wells (see Figure 9)</td>
</tr>
<tr>
<td>Basal step-up angle $\delta_b$</td>
<td>$22^\circ$</td>
<td>Measured from seismic data (lower peak of graph in Figure 8)</td>
</tr>
<tr>
<td>Internal coefficient of friction $\mu$</td>
<td>$0.91 \pm 0.06$</td>
<td>Calculated from basal step-up angle</td>
</tr>
<tr>
<td>Basal coefficient of friction $\mu_b$</td>
<td>$0.91 \pm 0.3$</td>
<td>Similar to wedge material strength and Byerlee’s Law (Byerlee, 1978)</td>
</tr>
<tr>
<td>Wedge cohesion $C$</td>
<td>$5–15$ MPa</td>
<td>Hoshino et al. (1972); see discussion</td>
</tr>
<tr>
<td>Basal cohesion $S_b$</td>
<td>$0–5$ MPa</td>
<td>Hoshino et al. (1972); see discussion</td>
</tr>
</tbody>
</table>
Figure 10. Plots of seafloor slope ($\alpha$) versus detachment dip ($\beta$) for 10 transects across the toe of the Niger Delta, with curves of constant basal fluid pressure ($\lambda_b$). The plots display model results for the high (A), middle (B), and low (C) fluid-pressure end members of the model parameters. The observed wedge taper values are consistent with Hubbert-Rubey basal fluid-pressure ratios ($\lambda_b$) between 0.82 and 1.01, which are greatly elevated above the observed fluid pressures in the wedge (see Figure 9).
fluid pressure presumably localized the basal detachment in the Akata Formation and controlled the overall shape of the thrust belts as expressed by its narrow taper. Furthermore, the low strength of the Akata Formation and the weakness of the basal detachment have dictated the structural styles expressed in the fold belt. Individual toe-thrust structures involve large components of shear within their hanging walls, forming shear fault-bend folds (Suppe et al., 2004) as documented by Corredor et al. (2005). Moreover, detachment folds formed by ductile thickening of the Akata Formation are common in the deep-water Niger Delta, reflecting distributed deformation in the weak Akata Formation as it slides above a basal detachment (Bilotti et al., 2005).

The deep-water Niger Delta also exhibits other, perhaps more enigmatic, structural characteristics that we also attribute to its fluid overpressure. Specifically, the widespread occurrence of backthrusts and the physical separation of the inner and outer fold belts can be attributed to the weak basal detachment and correspondingly low wedge taper based on the critical-taper concept, as discussed below.
In thrust wedges with very low taper, the maximum principal compressive stress ($\sigma_1$) is necessarily subhorizontal and very nearly parallel to the basal detachment ($\psi_b \approx 0$) as well as the sea floor. When this is the case, as it is in the Niger Delta, only a very small component of $\sigma_1$ acts on the basal detachment. This configuration yields no mechanical preference for developing fore- or backthrusts. This relationship is quantified by $\psi_b$, the angle between $\sigma_1$ and the basal detachment (Figure 8), which is also a measure of the difference between the dips of fore- and backthrusts. Regionally, in the Niger Delta, we estimate $\psi_b$ to be $1^\circ$–$5^\circ$. As expected, the basal step-up angle of the backthrusts ranges from $15^\circ$ to $25^\circ$ (excluding thrusts that seem to be folded or imbricated), similar to the range of primary step-up angles for forethrusts shown in Figure 8. Furthermore, once the faults are formed, the low bathymetric slope means little difference exists between the overburden shoreward or offshore from a given fault, making forethrusts and backthrusts equally mechanically efficient at accommodating shortening. In contrast, wedges with large tapers and steep surface slopes have backthrusts that dip much more steeply than forethrusts (Figure 12). This makes the forethrusts much more efficient at accommodating shortening, and therefore, most of the thrust displacement in wedges with large tapers occurs on forethrusts. The lack of preference for forethrusts over backthrusts in many parts of the Niger Delta results from its low taper and weak basal detachment (Figures 12, 13). Backthrusts are most common in the lowest taper zones in the outer fold and thrust belt, as expected based on the critical-taper wedge theory.

Another consequence of a low-taper wedge is that sedimentary deposits can readily enable the wedge to reach critical taper, even in the absence of deformation. The seismic line in Figure 14 shows such a case. The part of the outer fold and thrust belt shown in the seismic image is separated from the inner fold and thrust belt by more than 35 km (21 mi) of essentially flat-lying seismic reflectors. This relatively undeformed zone, however, has the necessary critical taper and is sliding stably without requiring internal deformation. Close inspection of the shallow strata reveals that the taper of the wedge in this area is generated by a young wedge of sediments coming from the continental shelf. This illustrates how normal sedimentary input to a part of the wedge can achieve the necessary taper, which has the effect of retarding deformation in the underlying part of the wedge. This phenomenon is presumably most

**Figure 12.** Schematic models illustrating the effects of taper angle on the tendencies for fore- and backthrusting in a deforming wedge. In high and moderate taper wedges (left), forethrusts typically dip at a lower angle than backthrusts and, thus, are more effective at accommodating shortening. In extremely low taper wedges (right), fore- and backthrusts should have essentially the same dip values and are equally effective at accommodating shortening. Areas of the Niger Delta where backthrusts are prevalent (Figure 14) are generally associated with regions of very low taper, consistent with this theory.
Figure 13. Seismic reflection profile across the toe of the Niger Delta in a region dominated by backthrusts. Data provided courtesy of Veritas DGC, Ltd.
Figure 14. Seismic reflection profile through the northern part of the Niger Delta fold and thrust belt, showing a large (30 km [18 mi] wide) undeformed zone lying to the east of a series of toe-thrust structures. The critical taper of this undeformed zone is provided by a lobe of sediments that thin toward the deep water, making it unnecessary for this zone to internally deform to maintain taper. The inferred weakness of the basal detachment caused by elevated fluid overpressure also facilitates sliding of this undeformed zone without internal deformation. Data provided courtesy of Veritas DGC, Ltd.
apparent in low-taper, passive-margin wedges such as the Niger Delta because sedimentary deposits alone could not likely achieve critical taper in wedges with higher surface slopes.

**CAUSES OF ELEVATED BASAL FLUID PRESSURE**

Several possible causes exist for the elevated fluid pressure that controls the shape of the Niger Delta thrust wedge, including rapid burial, tectonic forces, and increased fluid volume caused by hydrocarbon maturation. Disequilibrium compaction in shales is common in sedimentary basins (e.g., Osborne and Swarbrick, 1997) because permeability declines abruptly with burial of shales, preventing fluid expulsion and mechanical compaction. However, once mechanical compaction stops, subsequent burial causes the pore-fluid pressure to rise only as fast as the lithostatic gradient (Osborne and Swarbrick, 1997). To produce fluid pressure as high as we predict in the critical-taper wedge model ($\lambda = 0.90$), fluid retention would need to begin at about 500 m (1640 ft) below mud line. Permeability in mudstones at 500-m (1640-ft) depth is generally too great to cause fluid retention; to produce fluid pressure in these relatively permeable rocks, sedimentation would have to strongly outpace fluid expulsion. Predicted sedimentation rates to produce fluid retention at 500-m (1640-ft) depth are in excess of 3000 m/m.y. (10,000 ft/m.y.) (Mann and MacKenzie, 1990), certainly unreasonable rates to sustain at the toe of the Niger Delta. Although it is likely that some fraction of the total basal overpressure in the Akata Formation is caused by disequilibrium compaction, this process alone is probably not capable of elevating fluid pressure to the level we infer.

Horizontal tectonic forces can also elevate fluid pressure (Osborne and Swarbrick, 1997). Because we see very young or active thrusts in the Niger Delta wedge (Corredor et al., 2005), the maximum principal compressive stress is subhorizontal today, and some fraction of the overpressure we model may be caused by horizontal stress. In this case, the upper limit of overpressure is the minimum principal stress (Swarbrick et al., 2002), which is vertical (i.e., the lithostatic stress) in the case of fold and thrust belts. With sufficient horizontal differential stress, it is possible to elevate fluid pressure to the values we model with critical-taper wedge mechanics. Because we lack data on the magnitude of the maximum compressive stress, we are unable to quantify this effect.

Finally, Frost (1996) proposed that the maturation of the source facies of the Akata Formation produced a sufficient change in fluid pressure to start structural growth of the toe-thrust belt. The change in volume caused by the generation of oil from type II kerogen could be as large as 25% (Meissner, 1978; Swarbrick et al., 2002). If hydrocarbon maturation is in fact linked to the elevated basal fluid pressures we model, there may be both a temporal and spatial relationship between the shape of the Niger Delta thrust wedge and the maturity state of the Akata source rocks.

**CONCLUSIONS**

We have shown that the contractional toe of the Niger Delta acts as a critical-taper wedge similar to the fold and thrust belts found at active margins. The toe of the Niger Delta is unique in that it has a very low taper that results from a very weak basal detachment. By using measured properties of the wedge material and making reasonable assumptions about the properties of the basal detachment strength, we calculate that the basal detachment in the Akata Formation is strongly overpressured, with a Hubbert-Rubey fluid-pressure ratio $\lambda_b \approx 0.90$. That is, 90% of the weight of the outer Niger Delta is supported by pore fluids in the Akata Formation. This result explains the widespread occurrence of detachment folds, shear fault-bend folds, backthrusts, and the large, relatively undeformed regions that separate fold belts in parts of the Niger Delta. The elevated fluid pressure that we model is likely caused by the combined effects of disequilibrium compaction, tectonic stresses, and perhaps, increased fluid volume caused by hydrocarbon maturation.

**REFERENCES CITED**


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