PLEISTOCENE SEASCAPE EVOLUTION ABOVE A “SIMPLE” STEPPED SLOPE—WESTERN NIGER DELTA

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ABSTRACT: The morphology of a 1250 km² portion of the middle slope off the western Niger Delta shows that gradients on the Pleistocene slope vary both spatially and at different stratigraphic levels. In the deeper section, three lower-gradient steps are connected by three higher-gradient ramps, generating a stepped-slope morphology. Through time, preferential accumulation of slope aprons, composed of mass-transport deposits, compensationally stacked lobes, and overbank deposits (wedge-shaped outer levees), helped fill slope accommodation, smoothing over the gradient change across ramps and steps, and vice versa. Consequently at the local scale, the stepped slope evolved into a smoother slope that is nearly graded at the modern seafloor. As in other studies, preferential accumulation of sediment on the slope is believed to reflect in part the deceleration of sediment gravity flows (both turbidity currents and debris flows) as they encountered lower-gradient steps.

Down-slope changes in slope morphology also caused variations in the amount, and presumably rate, of erosion along the axes of canyons in the study area—with increased incision depth where knickpoints cut through positive-relief bathymetric structures in an attempt to establish a graded profile. Along the Benin-major Canyon there is an inverse linear relationship between the thickness of deposits that accumulate on the slope adjacent to the canyon and the amount of vertical erosion along its axis. The thickest outer levee deposits coincide with canyon segments that have the shallowest incision, in turn corresponding to slope segments showing a sharp decrease in pre-incision gradient. This implies that the increase in sediment flux to outer levees on some parts of the stepped slope results from a combination of increased overspill from flows passing through shallower canyon reaches, and increased sedimentation caused as mud-dominated flows decelerated on lower-gradient slope segments immediately adjacent to the canyon. Thus there appears to be an intimate relationship between slope morphology, canyon incision depth, and the thickness of overbank deposits adjacent to canyons.

KEY WORDS: 3D seismic geomorphology, stepped slope, slope apron, stratigraphic evolution, overbank deposits, transient fan, Niger Delta, Benin-major Canyon, Benin-minor Canyon

INTRODUCTION

Whether or not sediment gravity flows reach the continental rise depends on the types of obstacles they encounter along the way and their ability to maintain both competence and capacity as they cross such obstacles (Hiscott, 1994; Mulder and Alexander, 2001; Kubo, 2004). The ratio of the size of the obstacle versus the size and composition of the flow is probably very important in this regard (Smith, 2004). Spatial changes in gradient are also important as they cause sediment gravity flows to accelerate or decelerate, and correspondingly erode or deposit sediment (Normark and Piper, 1991; Mulder and Alexander, 2001). For example, down-flow reductions in gradient may promote increased sedimentation by reducing flow velocity, perhaps accompanied by a hydraulic jump (Komar, 1971), with more extreme reductions (> 4°) potentially leading to the formation of plunge pools (Lee et al., 2002). Reversals in gradient, if severe enough, deflect sediment gravity flows (at least the parts traveling nearest to the sea bed), and in instances where there is three-dimensional closure, may trap flows and prevent their passage down the slope (e.g., Prather et al., 1998).

Through time, deposition and erosion tend to grade slope profiles, at least along active sediment-transport corridors, by eroding bathymetric highs and depositing sediment in bathymetric lows. Structural deformation, however, continuously or episodically changes slope morphology, causing disequilibrium (thus generating an ungraded slope). The rate of substrate deformation relative to sediment supply hence influences whether or not a graded slope is possible (Steffens et al., 2003; Prather, 2003) and influences the amount of sediment stored on the slope versus on the continental rise. Sedimentation and erosion are unlikely to establish a graded equilibrium profile in areas where slope deformation rates are very high (e.g., Plio-Pleistocene Gulf of Mexico salt mini-basin province). In contrast, on slowly deforming slopes depositional and erosional processes may dominate the short-term slope evolution, and serve to temporarily establish a smooth concave-upward equilibrium profile profile along at least some reaches of the active sediment-transport corridor. The ability to map seismic horizons at the seafloor and in the shallow subsurface in 3D seismic volumes provides a record of the present-day seafloor morphology as well as past seafloor morphologies that to varying degrees were modified by defor-
formation during burial. Careful study of the history of slope deposition and erosion can help constrain the deformation history, and hence past slope morphology (e.g., Deptuck et al., 2007). This paper documents the seismic stratigraphic evolution before and after initiation of an active sediment-transport corridor on the middle slope off the western Niger Delta (Fig. 1). We demonstrate that the Pleistocene seascape in the study area evolved from a slope with pronounced steps to a smoother seafloor slope that is nearly graded at the local scale. The study interval records the transition from a slope with no canyons, to a slope with deeply incised canyons, to a modern slope with canyons that are largely filled. The fill of these canyons has been studied in detail (see Deptuck et al., 2003a; Deptuck et al., 2007), but until now little focus has been placed on the slope evolution adjacent to the canyons. How did the depositional patterns on the slope adjacent to, and contemporaneous with, the canyons evolve, and do the associated deposits tell us anything about reservoir potential adjacent to canyons in more deeply buried systems?

This paper is focused on the pre-incision, syn-incision, and post-incision deposits that accumulated on the slope adjacent to the Benin-minor and Benin-major canyons, offshore western Niger Delta (Fig. 1). Such deposits record the creation and filling of healed-slope accommodation (*sensu* Prather, 2003) on a slope that deformed in response to thin-skinned gravity-driven tectonics above a relatively slow-moving mobile shale substrate (Cohen and McClay, 1996). We also explore the relationship between slope morphology, gradient, and canyon-channel-levee architecture. Together with work by Fonnesu (2003), Adeogba et al. (2005), and Prather et al. (this volume), this paper extends our knowledge about the evolution of stepped slopes off the western Niger Delta, and the potential for and geometry of reservoir deposits adjacent to canyons in stepped-slope settings.

### Regional Setting

According to the classification of Prather (2003) the western Niger Delta slope is predominantly above grade (i.e., the downslope seafloor profile is elevated above the level of a theoretical concave-upward smoothed graded profile). Regional gradient analysis by Steffens et al. (2003) showed that dip-oriented drainage paths characterize the upper to middle slope of the western Niger Delta, with positive-relief bathymetric obstacles, which may deflect drainage paths, spaced up to 100 km or more. Common on the upper to middle slope are local areas of decreased gradient (“steps”) that typically lack three-dimensional closure. These steps are shown nicely in Figure 13 of Pirmez et al. (2000), forming submarine topography that influences both the path and response of submarine sediment gravity flows. On the lower slope, the drainage paths change to more strike-oriented due to the increasing influence of higher-relief toe thrusts. Both steps and ponds (i.e., three-dimensionally closed intra-slope basins) dominate the region of toe thrusts on the lower slope (Steffens et al., 2003). Some of the steps created by the toe thrusts are connected, resulting in tortuous corridors through which sediment gravity flows are transported (Smith, 2004). In other locations, canyons erode across the crests of growing structures, creating more direct paths that allow sediment gravity flows to bypass tortuous corridors and ponds (e.g., Heiniö and Davies, 2006).

### Study Area

The study area is located on the mid-slope of the western Niger Delta, in water depths between 850 and 1900 m (Figs. 1, 2), about 25 km down-slope from the shelf break and 80 km up-slope...
Fig. 2.—A) Seafloor dip map showing the present-day expression of the Benin-minor and Benin-major canyons. Channel centerlines are traced for the most recently active sinuous channel at Benin-major (dashed line) and the sinuous channel at the base of the Benin-minor Canyon (solid line). Contour interval is 25 m, and darker shades correspond to steeper dips. B) Time-thickness map between horizons 60 and 1 (seafloor), an interval that records the onset of an “active” sediment-transport corridor and the incision of both the Benin-minor and Benin-major canyons. Maximum sediment accumulation took place along the axis of the Benin-major Canyon and above steps 2 and 3 outside the canyon. The deposits outside the canyon are the focus of this paper. Black lines show the profiles oriented perpendicular to the axes of the Benin-minor and Benin-major canyons that were used to acquire valley measurements. Contour interval is 20 ms (or approximately 16 m using 1600 m/s sediment velocities).
from the region of prominent toe thrusts. Average gradients in the study area are \( \text{ca. 1.2}^\circ \), but they can reach \( 6^\circ \) on the flanks of the “Escravos High” in the southeastern corner of the study area (Fig. 2). The slope evolved above pre-existing Miocene and Pliocene structures, associated with gravity-driven extension and compression (Damuth, 1994; Cohen and McClay, 1996).

The study interval lies between the modern seafloor and horizon 90 (discussed later), a stratigraphic interval that ranges from 170 to 350 m thick (Figs. 3–7). Direct age control for this horizon 90 (discussed later), a stratigraphic interval that ranges from deepest to shallowest they are named horizon 90 (yellow marker in previous work), 80, 60 (blue marker in previous work), and 40 (red marker in previous work). The 3D seismic survey covers an area of 1250 km\(^2\) (25 km x 50 km) with a bin spacing of 25 m x 12.5 m and a 4 ms sampling interval. Frequency roll-off is near 65 Hz, resulting in a vertical resolution of approximately 6–7 m (using a velocity of 1500 to 1700 m s\(^{-1}\) for the upper 350 m of strata). The volume was processed to approximate a zero-phase wavelet. A subsequent -90 degree phase rotation was applied to the volume, and hence the seafloor surface corresponds to a zero crossing between an overlying trough and an underlying peak. Horizon interpretations from an amplitude volume were done both manually and with auto-trackers. Along the erosional bases of canyons (Benin-minor and Benin-major; Fig. 3), manual picking was necessary due to the complexity of the surface and the lack of a single seismic reflector. Erosional surfaces were commonly mapped by correlating the terminations of truncated reflections. In such instances every 12.5 m spaced in-line was interpreted. No calibration of seismic facies is available in the study area, but a detailed coring program just 40 km to the south provides some constraints on sediment type (Prather et al., this volume), and analogous deposits have been cored in producing fields at deeper stratigraphic levels (e.g., Chapin et al., 2002).

To better parameterize temporal and spatial changes in slope morphology along sediment-transport corridors in the study area, a series of seismic profiles oriented normal to each canyon centerline was selected at a spacing of 1 km (Fig. 2B). Depths of key seismic horizons both inside of and adjacent to each canyon were measured and used to construct longitudinal depth profiles (valley measurements in Figs. 8A, C, 9A, C). The zero point is located at the easternmost proximal limit of each conduit relative to the study area. These measurements permit comparisons to be made between two adjacent canyons that cross morphologically similar slope segments, but with substantially different dimensions and of slightly different age (at least with respect to the onset of erosion). Average present-day gradients of key seismic markers along the paths of the Benin-major and Benin-minor canyons were calculated in two ways: (1) derived directly from seismic profiles parallel to the canyon axis, averaged over the breadth of what was visually identified as a step or a ramp (Table 1), and (2) calculated from the valley measurements (Figs. 8B, D, 9B, D). The latter were smoothed over a 4 km window to reduce local irregularities, but they represent more detailed gradient measurements (capturing, for example, gradual changes in gradient at the transitions between steps and ramps adjacent to canyons). An average velocity of 1500 m s\(^{-1}\) was used for all gradient calculations (includes water column and up to 350 m of strata). An interval velocity of 1600 m/s was used to calculate all subsurface thickness measurements. For a more detailed description of this approach and associated limitations see Deptuck et al. (2007).

RESULTS

General Changes in Slope Morphology

Five seismic horizons were mapped across the study area; from deepest to shallowest they are named horizon 90 (yellow marker in previous work), 80, 60 (blue marker in previous work), 40 (red marker in previous work), 20, and 10 (green marker in previous work).
Comparisons between horizons 90, 60, and 1 reveal temporal changes in slope morphology that are attributed to a combination of slope deformation and sedimentation. The slope at horizon 90 is characterized by three steps (flatter-lying parts of the slope) linked by three ramps (steeper parts of the slope; Fig. 3C). In Figure 4, steps 2 and 3 have average gradients of 0.4° and 0.5°, respectively, and ramps 1, 2, and 3 have average gradients of 1.3°, 1.4°, and 1.7°, respectively. Step 1 has a gradient less than 0.2°. This step is not shown in Figure 4 due to the absence of 3D seismic coverage on the northern side of the Benin-major Canyon (see Fig. 3B, C). In the western study area Horizon 90 is offset up to 24 m across a series of tightly spaced deep-seated normal faults (Fig. 3C). These faults show increasing offset with depth, indicating that they moved during deposition of strata above horizons 90 and 60.

Horizon 60 is also characterized by three steps connected by three ramps (Fig. 3B). In Figure 4, steps 2 and 3 have average gradients of 0.4° and 0.5°, respectively, and ramps 1, 2, and 3 have average gradients of 1.3°, 1.4°, and 1.7°, respectively. Step 1 has a gradient less than 0.2°. This step is not shown in Figure 4 due to the absence of 3D seismic coverage on the northern side of the Benin-major Canyon (see Fig. 3B, C). In the western study area Horizon 90 is offset up to 24 m across a series of tightly spaced deep-seated normal faults (Fig. 3C). These faults show increasing offset with depth, indicating that they moved during deposition of strata above horizons 90 and 60.

40 (red marker in previous work), and 1 (cyan marker in previous work). Three additional seismic horizons were mapped above horizon 40; these cover smaller areas (horizons 55, 45, and 5; Figs. 4–7).

Fig. 4.—A) Representative dip-oriented seismic profile, and B) line drawing showing the variations in seismic facies and position of key seismic markers discussed in the text. C) Summary of average “step” versus “ramp” gradients on this profile at horizons 90, 60, and 1. Note that steps show an increase in gradient and ramps show a decrease in gradient through time such that the modern seafloor is smoother and shows lower-magnitude changes in gradient. See Figure 3 for line location.
gradients of 0.6° and 0.7°, and ramps 1, 2, and 3 have average gradients of 1.2°, 1.3°, and 1.8°, respectively. Step 1 has an average gradient of 0.6°. Horizon 60 is offset up to 12 m by the normal faults in the westernmost study area.

In contrast to horizons 90 and 60, the slope structure at the modern seafloor (horizon 1) is smoother (Fig. 3A), and except for the Escravos High, only minor changes in the gradient are observed across the study area. Steps 2 and 3 have average seafloor gradients of 1.0° and 0.8°, and ramps 1, 2, and 3 have average gradients of 1.2°, 1.3°, and 1.3°, respectively. The gradient, however, is as low as 0.5° in a small area above the remnants of step 2, west of the Escravos High. Step 1 is no longer present in the study area, and offset across the westernmost faults is no more than 5 m. Hence, the gradient change from ramps to steps at the modern seafloor is smaller compared to both horizons 90 and 60.

Seismic Stratigraphy

A closer look at the seismic stratigraphy between horizons 90 and 1 provides more insight into how the slope evolved. The upper ca. 350 m of strata in the study interval consists predominantly of continuous, relatively parallel intervals of low- to moderate-amplitude draping seismic reflections, alternating with intervals of chaotic and locally developed higher-amplitude reflections (Figs. 4–6). Two canyons, Benin-major and Benin-minor, deeply erode slope strata in the study area, abruptly truncating multiple seismic reflections (e.g., Fig. 3). Horizons 90, 60, 40, and 1 were used to subdivide the stratigraphic section into three intervals: Unit 1 (90 to 60), Unit 2 (60 to 40), and Unit 3 (40 to 1) (Fig. 7).

Unit 1 (Horizon 90 to 60).

Horizon 90 is a zero crossing located 170 to 350 m below the modern seafloor, and defines the base of Unit 1 (Fig. 3A), and except for the Escravos High, only minor changes in the gradient are observed across the study area. Steps 2 and 3 have average seafloor gradients of 1.0° and 0.8°, and ramps 1, 2, and 3 have average gradients of 1.2°, 1.3°, and 1.3°, respectively. The gradient, however, is as low as 0.5° in a small area above the remnants of step 2, west of the Escravos High. Step 1 is no longer present in the study area, and offset across the westernmost faults is no more than 5 m. Hence, the gradient change from ramps to steps at the modern seafloor is smaller compared to both horizons 90 and 60.

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Unit 1 (Horizon 90 to 60).

Horizon 90 is a zero crossing located 170 to 350 m below the modern seafloor, and defines the base of Unit 1 (Fig. 3A). It is overlain by an interval of chaotic low- to moderate-amplitude seismic reflections (Figs. 4–6) that cover an area of 940 km² and extend for an unknown distance beyond the western study limits. These deposits are thickest above steps 2 and 3, where they are up to 100 m and 65 m thick, respectively. They are thinnest above ramps 2 and 3, where they have an average thickness of 35 and 25 m, respectively. As with other chaotic deposits identified in this study and by many other workers (e.g., Piper et al., 1997; Adeogba et al., 2005, Moscardelli et al., 2006), the chaotic interval is interpreted to be a mass-transport deposit. The presence of prominent linear grooves along its base supports this interpretation.

In most places horizon 90 coincides with a translational bedding-plane detachment at the base of the chaotic deposits, largely
Fig. 6.—**A)** Representative strike-oriented seismic profile across step 3 and **B)** corresponding line drawing. Profile crosses the Benin-minor and Benin-major canyons, which truncate higher-amplitude seismic reflections above horizon 60, interpreted as stacked sand-prone submarine lobes deposited above step 3 prior to incision. See Figure 5 for legend and Figure 3 for line location.

Fig. 7.—Schematic Wheeler diagram showing the stratigraphic framework defined in this study. Vertical axis is relative time. Bold dashed lines represent unconformities either at the base of mass-transport deposits (MTDs) or at the base of channels and canyons. Bold continuous lines show the relative stratigraphic position of key seismic horizons defined in this study. White areas correspond either to condensed intervals or represent parts of the stratigraphic column removed by erosion. The blue highlighted surface is a highly diachronous composite surface of erosion correlated along horizon 60 and mapped along the base of erosional features that truncate it. Figure locations relative to the stratigraphic framework are identified in blue.
The anomaly on 14 August 2019 of Benin-major Canyon incision.
section (Unit 2b; 55 to 40) that appears to coincide with the onset predate development of the Benin-major Canyon, and an upper be separated into a lower section (Unit 2a; 60 to 55) interpreted to ite surface and the deposits above it (Fig. 7). At step 2, Unit 2 can sodes that help to unravel the evolution of the horizon 60 compos-
tiation of multiple higher-order depositional and erosional epi-
where it varies from 50 to 100 m thick.
consistently thick along the axis of the Benin-minor Canyon, where it is up to 115 m thick above step 2, 65 m thick above step 3, and 50 m thick above ramp 3. Unit 2 is also Canyon, where it is less than 20 m thick) and absent along the axis of the
of about 40 km long, has a maximum width of about 6 km, and covers an area
ramp 1 to step 2. The apex of the anomaly is located at the transition from
shingled reflections. Locally, the detachment surface is irregular and rises upward into shallower coherent strata, preserving small outliers of undisturbed strata above horizon 90 (e.g., northern part of Fig. 6). To the south and east, the chaotic deposits are separated from adjacent coheren strata by a stepped failure scarp 50 to 60 m high, trending SW–NE along the western flank of the Escravos High (Fig. 5).
The top of the chaotic deposits roughly coincides with horizon 80, the first widespread continuous reflection above horizon 90. Horizon 80 is located near the base of a 75–90-m-thick interval of low- to moderate-amplitude continuous and concordant reflections that is identical in character to the strata below the mass-transport deposit. The coherent strata drape the underlying incoherent deposits (e.g., Fig. 6), and they show only minor thickness variations across the study area (e.g., thinning above the Escravos High).

**Unit 2 (Horizon 60 to 40).—**

Horizon 60 is a zero crossing located above the interval of concordant reflections described previously. It defines the base of Unit 2 and records an abrupt change to more complicated seismic facies compared to underlying strata. Horizon 60 was correlated along the base of erosional features that truncate it, like the Benin-major and Benin-minor canyons (Deptuck et al., 2003a; Deptuck et al., 2007), several failure scarps, and grooves developed along the base of a mass-transport deposit (Fig. 10B). The marker therefore represents a highly diachronous compos-
tion surface and the deposits above it (Fig. 7). At step 2, Unit 2 can be separated into a lower section (Unit 2a; 60 to 55) interpreted to predate development of the Benin-major Canyon, and an upper section (Unit 2b; 55 to 40) that appears to coincide with the onset of Benin-major Canyon incision.

**Table 1.—Average gradients (in degrees) of the 60, 40, and 1 markers adjacent to the Benin-minor and Benin-major canyons.**

<table>
<thead>
<tr>
<th>Marker</th>
<th>Ramp 1</th>
<th>Step 2</th>
<th>Ramp 2</th>
<th>Step 3</th>
<th>Ramp 3</th>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>1.09</td>
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<td>0.91</td>
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<td></td>
<td></td>
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<tr>
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<td>0.98</td>
<td>0.73</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>0.6</td>
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<td>0.80</td>
<td>0.27</td>
<td>1.87</td>
</tr>
</tbody>
</table>

**Fig. 8.—** A) Depth profile of key seismic markers along the axis of the Benin-minor Canyon. B) Down-canyon variations in gradient of horizons 60, 40, and 1 along the canyon axis. C) Depth profile of key seismic markers adjacent to the path of the Benin-minor Canyon. D) Down-canyon variations in gradient on the slope adjacent to the Benin-minor Canyon. Note that in Parts A and C the canyon incision profile is convex upward, with a prominent knickpoint present at the 12–13 km measurement. This indicates that erosion at the base of the canyon failed to erase the topography that existed on the seafloor before incision, and as a result the Benin-minor Canyon did not establish a graded profile. In Parts B and D darker shades show areas where the gradient decreased through time (generally corresponding to steps) and lighter shades show areas where the gradient increased through time (generally corresponding to ramps). All measurements were made using a series of profiles spaced every 1 km perpendicular to the trend of the canyon (see Fig. 2).

- shaped amplitude anomaly is present above step 2 (Figs. 10B, 11A). The apex of the anomaly is located at the transition from ramp 1 to step 2. The anomaly broadens to the west. Detailed mapping of these deposits pushes the limits of seismic resolution, but in cross section the anomaly appears to consist of at least two laterally offset high-amplitude shingled reflections (Figs. 5, 12A, B). The northern reflection is approximately 19 km long, has a maximum width of about 6 km, and covers an area of about 40 km². The younger southern reflection is about 14 km
FIG. 9.—A) Depth profile of key seismic markers adjacent to the right side of the Benin-major Canyon, and the canyon incision profile along its axis. B) Down-canyon variations in gradient of horizons 60, 40, and 1 along the slope adjacent to the right side of the canyon. C) Depth profile of key seismic markers on the left side of the Benin-major Canyon, and the canyon incision profile along its axis. D) Down-canyon variations in gradient on the slope adjacent to the Benin-major Canyon. Note that in Parts A and C the canyon incision profile is concave upward, indicating that it likely established a graded or quasi-graded profile that erased the pre-incision topography (ramps and steps at horizon 60) along its path. In Parts B and D darker shades show areas of the slope where the gradient increased through time (generally corresponding to steps) and lighter shades show areas where the gradient decreased through time (generally corresponding to ramps). All measurements were made using a series of profiles spaced every 1 km perpendicular to the trend of the canyon (see Fig. 2).

long, has a maximum width > 8 km, and covers an area of 55 km$^2$. It is more continuous than the underlying reflection.

Several narrow (< 50 m wide, southwest-oriented linear scours 2–4 km long characterize the western fringe of the amplitude anomaly approaching the exit ramp of step 2. They form subtle linear amplitude lows on amplitude extractions (Fig. 11A). In addition, three shallow (30 to 70 m deep) and narrow (140 to 300 m wide) sinuous channels, identified herein as channels A, B, and C, erode the high-amplitude reflections above step 2 (Fig. 12C). These channels join the deeper and wider (> 100 m deep and > 600 m wide) Benin-minor Canyon to the west, near the transition to ramp 2 (where the slope is steeper). Channels A, B, and C are flanked by low-amplitude wedge-shaped deposits that sharply overlie the fan-shaped amplitude anomaly above step 2. They are interpreted as outer levees formed from the overbanking of turbulent flows as they crossed step 2. The levees are particularly well developed adjacent to the youngest incised channel C, where they are up to 30 m thick at the crest (Fig. 5). Like the high-amplitude reflections, the levees thin down-slope as they approach ramp 2 (Fig. 4).

The higher-amplitude reflections above horizons 60 terminate abruptly along the path of the deeply eroded Benin-major Canyon (Fig. 11A). Another amplitude anomaly is found south of the canyon. It is 12.3 km long and < 1.7 km wide, and it covers an area of 18 km$^2$. In cross section it corresponds to a single reflection that is truncated by the Benin-major Canyon to the north and west, and a failure scarp associated with a younger slope failure to the south and east (along the “failure corridor” described in Deptuck et al. (2003a). Hence the southernmost high-amplitude reflection above step 2 now forms an erosional remnant that is entirely compartmentalized from similar deposits elsewhere above step 2. Correlations across the Benin-major Canyon indicate that these deposits are younger than the high-amplitude reflections to the north. Subtle remnants of sinuous channels also erode it from above, but their relationship to channels A, B, and C to the north cannot be determined.

Unit 2b (horizons 55 to 40 above step 2).—Horizon 55 defines the top reflection of the low-amplitude wedge-shaped levees that flank the smaller channels above step 2. The marker merges with horizon 60 at the edge of ramp 2 (Fig. 4). A thin interval (< 25 m thick) of high-amplitude chaotic seismic facies, interpreted as a mass-transport deposit, overlies horizon 55 north and south of Benin-major (Fig. 5). These chaotic deposits are truncated along the axis of the Benin-major Canyon, which cuts obliquely...
across step 2, and are overlain by low-amplitude continuous reflections that converge away from the canyon axis (below horizon 45). These convergent strata define wedge-shaped deposits that are best preserved along the right-hand side of the system (facing down flow) above step 2, where they are up to 45 m thick, thinning away from the canyon axis to < 10 m thick over distances of ca. 3 km. These deposits also thin towards the western edge of step 2, and they are absent above the steeper ramp 2 (Fig. 4). Like the wedge-shaped deposits flanking the narrower channels above step 2, they are interpreted as the eroded remnants of outer levees that flank the larger Benin-major incision (Fig. 5).
Fig. 11.—A) Shaded relief map showing step 2 at horizon 60 draped by RMS amplitude extracted from a 30 ms window above the marker. Lighting is from the east (azimuth of 90 degrees) at an elevation dip of 60 degrees. B) Line drawing based on multiple dissemblance horizon slices through the 25 m interval directly above horizon 60. Note the complex history of channel development above the high-amplitude anomaly.
FIG. 12.—A) Seismic profile (location shown in Figure 11B) across step 2 showing the lower interval of high-amplitude reflections above horizon 60, overlain by lower-amplitude intervals dominated by overbank deposits associated with the Benin-minor and Benin-major systems. B) Seismic profile (location shown in Figure 11B) showing the shingled stacking pattern of high-amplitude reflections above the proximal parts of step 2. C) Dissemblance horizon slice 8 ms above a smoothed horizon 60, showing crosscutting relationships of channels A, B, and C. The northernmost channel A formed first, followed by the southernmost channel B, and finally the most recent channel C between the first two. Of the three channels, Channels A and C are the most erosional and are interpreted to have evolved as knickpoints that extended up-slope from the wider, more deeply entrenched Benin-minor Canyon as headward erosion cut across step 2. See Figure 15 and the text for a summary of how the deposits above step 2 evolved.

The overlying horizon 45 to 40 interval, in contrast, consists of one or two continuous, parallel seismic reflections that drape underlying strata (Figs. 4, 5). The interval is typically 22 to 26 m thick but increases to 45 m thick in the easternmost part of the survey (approaching the shelf break). Where the interval can be correlated into the fill of the Benin-major Canyon it forms an expanded section > 80 m thick. The 45 to 40 interval therefore corresponds to a period of condensed sedimentation across most of the study area except along the axis of the Benin-major Canyon, where sedimentation rates were more than three times higher.

Unit 3 (Horizon 40 to 1).—

Horizon 40 forms a prominent surface that can be correlated throughout the study area, except along the axis of the Benin-major Canyon. It defines the base of Unit 3, which is thickest above steps 2 and 3. Deposits immediately above horizon 40 consist of complex wedge-shaped accumulations that thin away from the Benin-major Canyon axis. They commonly consist of discontinuous low- to moderate-amplitude seismic reflections that locally form large-scale climbing bedforms (sediment waves) that migrated up-slope, normal or oblique to the canyon axis (e.g., Figure 8C of Deptuck et al., 2003a). The 40 to 1 interval (Unit 3) was correlated into the fill of the Benin-major Canyon, where equivalent strata form an expanded section up to 210 m thick. The canyon fill is composed of stacked submarine channel forms flanked by a complex arrangement of inner-levee deposits (Fig. 5; described in detail in Deptuck et al., 2007).

To the north, horizon 40 can also be correlated through the fill of the Benin-minor Canyon, and Unit 3 forms an expanded section 36 to 68 m thick along the canyon axis (Fig. 6). The fill consists predominantly of low- to moderate-amplitude continuous seismic reflections with local erosion along horizon 40. Hence, preferential deposition along remnant negative relief of the Benin-minor Canyon took place at the same time that the Benin-major Canyon filled (but produced a much different seismic character; Fig. 6).

Horizon 5 defines the upper boundary of the Benin-major system, but it can be mapped only where the overlying interval is sufficiently thick (i.e., in the eastern part of the study area; Fig. 5). Horizon 5 is locally overlain by a final interval of chaotic deposits up to 42 m thick that define a “lobate” mass-transport deposit 16 km long by 5 km wide south of the Benin-major Canyon (Figure 17B of Deptuck et al., 2007). This mass-transport deposit has an erosional base characterized by NE to SW oriented linear grooves. It is confined to the north by the outer-levee crest on the left-hand side of the Benin-major Canyon (facing down flow) and to the south by the Escravos High. The mass-transport deposit also fills the youngest sinuous channel of the Benin-major system, where little channel relief exists on the present-day seafloor in the northeastern study area (Fig. 2A). These deposits correspond to the chaotic fill of channel forms 3 or 5 described in Deptuck et al. (2007).

The mass-transport deposit is draped by a thin veneer (17 to 32 m thick) of low- to moderate-amplitude highly continuous seismic reflections that extend to the modern seafloor. Although these deposits show a relatively small range in thickness, they
tend to thin above steeper parts of the slope and thicken above flatter areas (Fig. 5; Figure 17A of Deptuck et al., 2007). These draping deposits are thickest in the eastern part of the study area, nearest the shelf break (similar to the 45 to 40 interval), and they thin below seismic resolution to the west, where both canyons still have a pronounced negative relief.

**Canyons**

Along with temporal changes in the overall stepped morphology, the slope evolved from a period when no canyons were present (horizon 90), to a period when the Benin-minor and eventually the Benin-major canyons were deeply incised (just above horizon 60), to a period when these canyons were partially to completely filled (horizon 1) (Fig. 3). The erosional profiles of the Benin-minor and Benin-major canyons provide additional constraints on the slope morphology and its evolution above horizon 60 (Figs. 8, 9, 14).

**Benin-Minor Canyon.**

The Benin-minor Canyon was traced for 37 km and consists of a relatively straight but heavily scalloped incision that is up to 1.4 km wide and 154 m deep, and it locally erodes as deep as horizon 90 (Figs. 2A, 3B, C, 13B). It also truncates the higher-amplitude reflections above horizon 60 at steps 2 and 3. The canyon is floored by a single narrow (50 to 90 m wide), highly sinuous to meandering thalweg channel. The small size of this channel approaches the horizontal and vertical limits of seismic resolution, but nonetheless it was mapped with a high degree of confidence (Fig. 13B). Some sinuous high-amplitude channel segments are terraced 16 to 40 m above the deepest incision. The channel thalweg (excluding terraced cutoff loops) has an along-channel length of 58 km within a canyon 37 km long, yielding an average sinuosity of 1.57, with an average along-channel gradient of 0.7°. The highest sinuosity is 2.4, where eight tightly spaced meander bends developed between the 1600 and 1675 m

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**Fig. 13.**—Close-up plan-view images of horizon 60. **A** Prominent scalloped erosional surface at the base (thalweg) of the Benin-major Canyon, with elevated amplitudes above step 3 outside the canyon. In contrast to the Benin-minor Canyon, the erosional floor of the Benin-major Canyon shows multiple sinuous channel segments recording a complex history of incision. **B** Narrow, highly sinuous channel at the erosional base (thalweg) of the deeply incised Benin-minor Canyon. Aside from high-amplitude reflections at the very base of Benin-minor, the fill is characterized by low-amplitude draping reflections. Both (A) and (B) are draped by the RMS amplitude extracted from a 30 ms window above the marker, and lighting is from the east (azimuth of 90 degrees) at an elevation dip of 60 degrees. **C** Time-structure map showing deeply entrenched meander bends of the Benin-minor Canyon. Highest channel sinuosity is located above step 3. See Figure 10 for location.
isobaths (above step 3; Fig. 13C). Canyon margins are steep (19° to 26°), and canyon-margin scallops scale directly with the bend amplitude and radius of curvature of the thalweg channel and its terraced segments. On seismic cross sections, the higher-amplitude basal channel deposits (Unit 2) pass abruptly upwards into an interval of moderate- to low-amplitude seismic reflections that drape the lower fill and onlap the canyon walls (upper part of Unit 2 to Unit 3).

Valley measurements were made relative to both the left and the right sides of the system (facing down-slope), but the differences in measurements are negligible. The erosional floor of the Benin-minor Canyon has a convex-upward geometry with an abrupt increase in gradient across the seaward edge of step 2, defining a knickpoint at the 12–13 km valley measurement (Fig. 8A, C). The knickpoint coincides with an abrupt change in the depth and width of the Benin-minor system, with the three shallow and narrow channels (flanked by wedge-shaped outer levees) located up-slope, and the wider and deeper solitary trunk of the Benin-minor Canyon located down-slope (Fig. 14A, C). The Benin-minor Canyon has a relatively consistent width above step 2 (350–400 m), but the width increases and becomes more sporadic above ramp 2, varying between 532 and 1358 m (Fig. 14C). On step 3 and ramp 3 its width is less variable, ranging from 622 to 1062 m. The width-to-depth ratio of Benin-minor varies from greater than 16:1 above step 2 to less than 6:1 above step 3 and ramp 3.
The depth of thalweg entrenchment below horizon 60 varies along the length of the canyon (Fig. 14A). Incision depth generally increases to the west, but local maximums develop at 18 km (92 m deep) and 32 km (154 m deep). These maximums coincide with the down-slope transition from steps to ramps, which formed convex-upward positive relief structures on the pre-incision slope (Fig. 4). The depth of incision decreases abruptly west of the 32 km measurement.

**Benin-Major Canyon.**

The Benin-major Canyon was traced for 54 km and consists of a relatively straight and heavily scoured incision that is much wider than Benin-minor and is floored by multiple cross-cutting sinuous to meandering erosional channels (compare Figs. 13A and 13B). Thalweg channels vary in width from 130 to > 450 m, much wider than the channel that floors the Benin-minor Canyon. Its margins are steep (13° to more than 26°) and truncate a combination of parallel-bedded and chaotic seismic facies. Folded slope reflections below the canyon are sharply truncated. Like Benin-minor, Benin-major also truncates the higher-amplitude reflections above horizon 60 at steps 2 (Fig. 11) and 3 (Fig. 13A).

Valley measurements were made relative to both the left and the right sides of the system (facing down slope), which are treated separately because of the width of the system. In contrast to Benin-minor, the erosional base of the Benin-major Canyon has a subtle concave-upward erosional profile (Fig. 9A, C), with a few subtle perturbations inferred to reflect slope deformation that took place after canyon incision (Deptuck et al., 2007). The Benin-major Canyon varies from 2.67 to 5.11 km wide, and is up to 330 m deep, eroding through horizon 90 along much of its length (Fig. 3C). The most sporadic variations in width occur above ramp 2 and step 3, where the largest arcuate scallops are observed along its margins (Fig. 14F). The overall width-to-depth ratio is larger than Benin-minor, varying from 26:1 above step 2, where the basal incision is shallow, to 11:1 above ramp 3, where the basal incision is deep.

In general, the depth of incision below horizon 60 is shallowest in the up-dip parts of the survey (about 95 m deep) and deepest in the distal parts of the survey (up to 330 m deep). Like Benin-minor, local increases of incision depth are observed near the 30 km and 45 km measurements, where the canyon crossed the same convex-upward bathymetric highs on the pre-incision seafloor (Fig. 14D). The depth of incision decreases abruptly west of the 48 km measurement.

**INTERPRETATION—STRATIGRAPHIC EVOLUTION OF A STEPPED SLOPE**

**Background Slope Sedimentation with Periods of Slope Instability**

Unit 1 (horizon 90 to 60), and to some extent the strata below it, record a period dominated by highly continuous, concordant and largely isochronous strata. Such deposits probably accumulated in a more passive manner, predominantly through suspension fallout of pelagic and hemipelagic sediments during a period of relative slope stability in the study area. This period of passive sedimentation was interrupted by the deposition of a mass-transport deposit when mud-prone coherent strata above horizon 90 failed. The failure probably originated from the Escravos High, where a prominent scarp is observed (Fig. 5) or elsewhere on the slope up-dip from the study area. Variation in the thickness distribution of the resulting mass-transport deposit indicates that the slope had a stepped morphology at the time of failure. Failed material preferentially accumulated above local areas of reduced gradient, and as such the mass-transport deposit helped smooth over pre-existing gradient changes (Fig. 4). Normal background sedimentation resumed after the period of slope instability (above horizon 80), draping the mass-transport deposit and any remaining irregularities on the slope. While sediment accumulated passively between horizons 80 and 60, slope deformation probably continued as deeper-seated folds evolved, producing a pronounced stepped-slope morphology by the time Unit 2 was deposited (discussed below).

**Onset of an Active Turbidity-Current Corridor**

In contrast to the upper parts of Unit 1, horizon 60 defines an abrupt change to more complex seismic facies indicative of more active sedimentation dominated by turbulent submarine sediment gravity flows. The sediment thickness distribution of Unit 2 varies widely, with preferential deposition taking place on steps 2 and 3 (Figs. 2B, 8A, C, 9A, C). It was during deposition of Unit 2 that the Benin-minor and eventually the Benin-major canyons were incised and partially filled. Crosscutting and onlap relationships of erosional and depositional features in the expanded stratigraphic interval above step 2 help further constrain the stratigraphic evolution of the slope and incision history of the canyon (Fig. 15).

Near the base of Unit 2a, the high-amplitude reflections above step 2 resemble the single seismic loop “lobes” documented on the Niger Delta slope by Fonnes (2003). Although no direct calibration of lithology is available in the study area, multiple cores from similar seismic facies about 40 km to the south encountered sand-rich turbidites located above a lower-gradient step on the middle slope (Prather et al., this volume). Well penetrations and coring through single-loop high-amplitude seismic reflections at deeper stratigraphic levels near this location (in Miocene strata now buried by 2 km of strata) indicate that such reflections are produced by unconsolidated sand bodies up to 15 m thick encased in mudstone (Bonga oil field; Chapin et al., 2002). These sand bodies produce a “blocky” gamma-ray response and are dissected by younger mud-filled channels (similar to the channels that dissect the high-amplitude reflections above step 2). Finally, a core through similar seismic facies in late Quaternary strata in the eastern Gulf of Mexico encountered an 8-m-thick interval dominated by turbidite sands that were also deposited above a subtle break in the slope (see Sylvester et al., this volume).

Like these calibrated examples, the high-amplitude seismic reflections above horizon 60 are interpreted to be sand-prone turbidites deposited in submarine lobes or amalgamated sheet sands down-slope from where ramp 1 transitions to step 2 (Figs. 11, 12, 16). Here the gradient decreased by about 0.8° relative to the path of the Benin-minor Canyon and 1.0° along the path of the Benin-major Canyon (Table 1). Similar deposits are also found above step 3 (Figs. 6, 13A, B), where there is a more subtle reduction in gradient from 1.1° (ramp 2) to 0.9° (step 3) adjacent to Benin-minor, and 1.0° to 0.4° adjacent to Benin-major (average of left and right side; Table 1).

We interpret the amplitude anomaly above step 2 to be composed of three or more stacked submarine lobes that probably form the sandiest component of the slope apron. Sand-prone slope deposits that accumulate down-dip from important breaks in slope, and that show evidence of channel incision and bypassing of flows, were termed “transient fans” by Adeogba et al. (2005). This term can equally be used to describe the stacked
Erosion across step and outer levee deposition

Knickpoint erosion followed by deep incision of the Benin-major Canyon down to equilibrium profile

Channel avulsions, lobe switching, and hanging valleys

Southern shift in sediment-transport corridor

Lobe deposited above step 2

Linear scours

Knickpoint erosion

MTD

2 km

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Fig. 15 (facing page).—Conceptual diagram illustrating the relative timing of the slope-apron deposits. A) The northernmost highly elevated area, corresponding to the proto-Benin-Minor Canyon, had been incised by the time of submarine apron deposition. B) The proto-Benin-Minor Canyon was filled by channel A deposition, which bypassed the Benin-Minor system. Erosional scours in the Benin-Minor system are interpreted to have been filled by the proto-Benin-Minor system and, at this time, the Benin-Minor system was incised by the Benin-Major system. C) A final channel avulsion at the entry point of the Benin-Minor system led to the deposition of lobe 3 above step 2. A final channel avulsion at the entry point of the Benin-Minor system led to the deposition of lobe 3 above step 2 (Fig. 15D). Combined with a second smaller transient fan located 12 km down-slope (above step 2; Figs. 6, 13A), this avulsion appears to have helped to deepen the Benin-Minor system, a precursor to the Benin-Major system and associated deposits. The abrupt change in fill pattern in the Benin-minor Canyon, from high-amplitude sinuous reflections above its erosional floor to lower-amplitude onlapping to draping reflections, probably marks an abrupt change in the types of flows transiting the canyon, and this change is interpreted to coincide with the southward shift in sediment transport and the eventual incision of the Benin-major system. This shift took place before the Benin-minor system could establish a graded slope profile, and while it still had prominent negative relief. Smaller-scale leveed channel(s), similar to channels A, B, and C, may have been present above step 2 along this new corridor, but such deposits had little preservation potential along the path of the deeply incised Benin-major Canyon (hence the configuration illustrated in Fig. 15D is partly speculative).

Incision of the Benin-Minor Canyon

Incision of the Benin-minor Canyon was initiated during or shortly after deposition of the transient fans between horizons 60 and 55. This interpretation is based on the abrupt along-canyon truncation of transient fans across step 2 and the presence of lower-amplitude channel-flanking wedge-shaped outer levees above the stacked lobes (Fig. 5). Variations in canyon incision depth confirm that the slope had a stepped morphology at the time of canyon incision (Fig. 14A). The smaller channels above step 2 (channels A, B, and C; Fig. 12C) appear to record at least three unsuccessful attempts to regrade the slope and remove the sharp increase in gradient at the transition to ramp 2 (Fig. 8A, C). This transition was characterized by progressive headward erosion of associated deposits. However, the erosional profile of the Benin-minor system indicates that it never established a smooth, concave-upward graded slope profile. Instead, the increase in gradient at the exit ramp formed a persistent knickpoint that is still present today where channels A, B, and C join the main trunk of the canyon (Fig. 8A, C).

The switch from channel A to B to C is interpreted to have taken place through channel avulsions located near the base of ramp 1 (see Fig. 15A–C and its caption for a more detailed account). Each avulsion resulted in a subtle shift in the sediment-transport path that led to repeated cycles of deposition from early unconfined flows above step 2, followed by headward erosion and deepening of a leveed knickpoint channel that progressively increased flow confinement and bypass of the coarse fraction across step 2 (Fig. 17). A final channel avulsion at the base of ramp 1 led to the deposition of lobe 3 above step 2 (Fig. 15D). Combined with a second smaller transient fan located 12 km down-slope (above step 2; Figs. 6, 13A), this avulsion appears to have helped to define the early development of a new sediment-transport corridor south of the Benin-minor system, a precursor to the Benin-Minor system and associated deposits. The abrupt change in fill pattern in the Benin-minor Canyon, from high-amplitude sinuous reflections above its erosional floor to lower-amplitude onlapping to draping reflections, probably marks an abrupt change in the types of flows transiting the canyon, and this change is interpreted to coincide with the southward shift in sediment transport and the eventual incision of the Benin-major system. This shift took place before the Benin-minor system could establish a graded slope profile, and while it still had prominent negative relief. Smaller-scale leveed channel(s), similar to channels A, B, and C, may have been present above step 2 along this new corridor, but such deposits had little preservation potential along the path of the deeply incised Benin-major Canyon (hence the configuration illustrated in Fig. 15D is partly speculative).

Incision of the Benin-Major Canyon

The horizon 55 to 45 interval (Unit 2b) corresponds to a time of mass wasting, vertical incision of the Benin-Major Canyon, and deposition of outer levees. A thin interval of chaotic seismic facies, interpreted as a mass-transport deposit, overlies horizon 55 (Fig. 5). These deposits accumulated above the levees of channel C and fill the proximal reaches of the Benin-minor Canyon (above step 2; Fig. 5). They were also correlated south of the Benin-major system where they lie above a bedding-plane detachment within a broad failure corridor. This corridor formed south of the incipient Benin-major Canyon, and is bordered by two side scarps that bracket a broad failure plane or detachment surface, with multiple linear grooves oriented in the direction of sediment transport (Figs. 15E, 16). A retrogressive failure scarp adjacent to the Escravos High is roughly time-equivalent to the failure corridor (Fig. 16). Deptuck et al. (2003a) interpreted the period of mass wasting as the precursor to vertical incision of the Benin-Major Canyon. This interpretation is corroborated by the presence of wedge-shaped outer levees preserved adjacent to the Benin-Major system on the underlying mass transport deposit (Fig. 5). We interpret outer-levee deposition to have started during early incision and ended...
when the incision was deep enough to prevent overspill from the upper parts of most sediment gravity flows. Continued incision and widening of the canyon heavily eroded the early outer-levee crests and locally removed them entirely (Deptuck et al., 2007). As in Benin-minor, variations in incision depth of the Benin-major Canyon confirm that the slope still had a stepped morphology at the time of incision (Fig. 14D). In contrast to Benin-minor, however, the linear to subtly concave-upward erosional profile at the base of the Benin-major Canyon (Fig. 9A, C) implies that the canyon removed the gradient changes associated with the stepped pre-incision slope and a smooth graded slope profile was temporarily established along its axis.

**Fill of the Benin-Major Canyon**

The upper part of Unit 2b and Unit 3 (horizons 45 and 1) correspond to the active filling of the Benin-major Canyon and a pronounced change in the style of deposits in the upper fill of the Benin-minor Canyon (discussed previously). An early phase of inner-levee deposition between horizons 45 and 40 in the Benin-major Canyon is time-equivalent to the accumulation of a thin isochronous interval outside the canyon (Fig. 5). The condensed deposits outside the canyon are interpreted to be composed of hemipelagic sediment that accumulated passively while most flows were contained within the margins of the deeply incised Benin-major Canyon. Consequently, sedimentation rates above the canyon floor were much higher than on the adjacent slope.

The overlying 40 to 5 interval adjacent to the Benin-major Canyon corresponds to a second phase of outer-levee deposition associated with the channel deposits and equivalent inner levees that aggraded above the canyon floor and largely filled the canyon. These overbank deposits are time-equivalent to the post-channel-form 33 deposits described in detail by Deptuck et al. (2007). Hence, sedimentation rates outside the canyon increased after the Benin-major Canyon was filled sufficiently to allow flows once again to overspill the canyon margins. Like the wedge-shaped deposits between horizons 55 and 45, these overbank deposits are thickest on step 2 (Fig. 18), particularly adjacent to the outer bends of sharp meander loops of the most recent sinuous channel (where they are up to 100 m thick at the crest). The presence of sediment waves indicates that late-stage overspilled flows behaved somewhat differently than overspilled...
flows between horizons 60 and 45, which accumulated while the canyons were vertically entrenched. This difference may reflect the poor preservation potential of the early outer levees compared to the younger ones, but otherwise this disparity is poorly understood.

Pronounced channel straightening and reincision in the middle to upper fill of the Benin-major Canyon (upper part of Unit 3, with incision corresponding to channel forms 20 and 10 of Deptuck et al., 2007; Fig. 6) probably indicate that at least two periods of rejuvenated slope deformation took place in the western study area as the canyon filled. Periodic amplification of an underlying fold in this area probably also deformed the seafloor adjacent to the canyon, an idea corroborated by the presence of small offsets in horizons 60 and 40 across normal faults in the western study area (Figs. 3, 4). These observations indicate that along with depositional and erosional processes, the slope morphology continued to change in response to deformation.

The overlying horizon 5 to 1 interval corresponds to a period of mass wasting and plugging of the remaining relief of the proximal parts of the Benin-major Canyon in the eastern part of the study area. During this time, the system is interpreted to have been abandoned and draped by pelagic and hemipelagic deposits that thicken toward the shelf break. The seaward tapering of such deposits is probably associated with decreasing hemipelagic sedimentation rates with increasing distance from shelf-edge depositional systems. Finally, high-amplitude reflections at the seafloor record the deposition of a younger transient fan above a step located south of the Benin-major Canyon (Figs. 6, 10A). This fan is probably associated with flows that travelled around the southern side of the Escravos High, and indicates that the depositional system to the south was active as the proximal reaches of the Benin-major system were plugged and abandoned.

**Fig. 17.—Schematic showing the transition from A) early periods of deposition of sandy lobes caused by the loss of competence and/or capacity from turbidity currents upon encountering a sharp (about 1° in the study area) decrease in gradient at the transition from a ramp to a step, to B) later periods of sand bypass once a channel is established through knickpoint erosion and entrenchment (focused near the seaward lip of the step) combined with outer-levee aggradation (above the step). These processes provide confinement for the lower, potentially sandier parts of flows.**

The upper fill of the Benin-minor Canyon (Unit 3) appears to have been deposited while the Benin-major Canyon formed the main conduit. The increased thickness of Unit 3 along the axis of the Benin-minor Canyon (Fig. 6) indicates that it continued to funnel sediment gravity flows despite the southern shift in sediment transport through the Benin-major system. Subtle linear to curvilinear scour-like features at horizon 40 and at the modern seafloor attest to its recent activity, but the geomorphology of these erosional features is clearly much different from the geomorphology of channels at the base of the Benin-minor Canyon (~ 50-m-wide channel with vertically entrenched meander loops) and in time-equivalent intervals within the Benin-major Canyon. The change from high-amplitude reflections above its erosional base to predominantly low-amplitude onlapping reflections in its upper fill suggests that an abrupt change took place in the style of flows passing through the Benin-minor Canyon.

Direct correlation of the Unit 3 fill of the Benin-minor Canyon on ramp 2 to the thick outer-levee deposits adjacent to the Benin-major Canyon on step 2 suggests that sediment funneled through the Benin-minor Canyon above horizon 40 was sourced from the upper, finer-grained parts of flows that overspilled the Benin-major Canyon margins. The increased thickness of overbank deposits in the heads of channels A and C supports this interpretation (Fig. 18). In addition, the overbank deposits in this area are dominated by sediment waves (Figure 8C of Deptuck et al., 2003a) with roughly north–south-oriented crests, consistent with flows that escaped (or were “stripped”) from sharp channel bends within the Benin-major Canyon and traveled northwards or southwestwards towards the main trunk of the Benin-minor Canyon (Fig. 18). The low-amplitude character of post-40 deposits in Benin-minor, therefore, is interpreted to reflect the preferential accumulation of fine-grained lithologies associated with the passage of muddy flows derived from the upper parts of flow-stripped turbidity currents passing through the Benin-major Canyon.

**Towards a Graded Profile—Changes in Slope Morphology Along Sediment-Transport Corridors**

The transition from a stepped slope at horizons 90 and 60 to a smoother, more graded slope at the modern seafloor suggests that in recent times (during the latter part of the Pleistocene) erosion and sedimentation largely outpaced structural deformation in the study area. The mechanism by which a smooth, concave-upward graded slope is achieved depends on where you are on the slope relative to slope depositional systems. Outside active sediment-transport corridors, for example, slope deformation may continue unchecked by erosional and depositional processes. With the exception of failures generated on the flanks of oversteepened structures (as may have been the case for the mass-transport deposits above horizon 90), few mechanisms exist for regrading the slope in such settings. Along active sediment-transport corridors, however, the slope may establish a graded profile through erosion or deposition from sediment gravity flows (Pirimetz et al., 2000; Smith, 2004; Adeogba et al., 2005).

Given enough time and enough flows, erosion along the base of a canyon may achieve a graded profile on an otherwise
Fig. 18.—A) Dip map of horizon 5 (top surface of the Benin-major system) draped by time-thickness map of the upper outer levees (between horizons 40 and 5). Maximum thickness (red) corresponds to a time-thickness of about 100 ms two-way travel time. Thickest outer levee deposits are found above steps 2 and 3, which also correspond to areas with the longest-wavelength sediment waves. Red arrows show the flow trajectory along the Benin Channel axis, whereas orange and purple arrows show the interpreted flow trajectory higher up in a flow, based on the crest orientation of inner- and outer-levee sediment waves, respectively. B) Perspective-view shaded relief map and C) plan-view dip azimuth map showing the development of short-wavelength outer-levee sediment waves outboard a sharp meander bend near the seaward edge of step 2.
“bumpy” slope if the rate of incision is faster than the rate of substrate deformation (i.e., fold growth). The Benin-major Canyon, for example, likely achieved a graded or quasi-graded profile along its erosional base, at least temporarily, through vertical incision and the removal of obstacles along its path (Fig. 19). The relatively subtle step to ramp morphology at horizon 60 was therefore erased along the canyon axis, and younger canyon-fill deposits aggraded roughly parallel to the smoother “graded” canyon floor. The stratigraphic response of younger canyon fill, therefore, was largely independent of the morphology of the pre-incision slope, except where continued deformation forced the otherwise aggradational canyon-filling channel deposits to adjust their sinuosity or incision depth accordingly (Deptuck et al., 2007).

In contrast to vertical incision, the slope adjacent to erosional conduits evolved towards a graded profile through sedimentation (Fig. 19). Here, buildup of the local slope via deposition of slope aprons helped erase gradient changes (see Figs. 8, 9), and this happened contemporaneously while the Benin-minor canyon and eventually the Benin-major canyon were incised and filled. Deposition of transient fans above steps was probably caused by a loss of competence (and hence deposition of the coarser fraction), and perhaps flow capacity (in which case a broader spectrum of grain sizes would fall out of suspension) (Hiscott, 1994; Mulder and Alexander, 2001) as turbidity currents decelerated (see also Adeogba et al., 2005; Sylvester et al., this volume). The absence of high-amplitude reflections on steeper ramps (Fig. 16) probably indicates that flow competence and capacity stabilized or increased once flows reaccelerated across steeper parts of the slope. Evidence for erosional linear scour possibly supporting the exit ramp of step 2 supports this interpretation. Such erosion, combined with aggradation of outer levees, eventually led to flow confinement, which allowed the basal, coarser fraction of flows to bypass the step (Figs. 15A, B, 17) (Badalini et al., 2000).

Comparisons of horizons 60, 40, and 1 indicate that in general the slope adjacent to canyons evolved through time such that gradients increased above steps and decreased above ramps. This led to a smoother slope profile characterized by lower-magnitude gradient changes at the present-day seafloor (Fig. 8B, D). The areal extent of steps correspondingly decreased through time. The net result was a progressive decrease in the impact of the stepped-slope morphology on successive submarine sediment gravity flows, and presumably an increased tendency towards sediment bypass as breaks in slope were erased both along canyon axes and on the adjacent slope (Prather et al., 1998; Booth et al., 2003; Smith, 2004; O’Byrne et al., 2004; Adeogba et al., 2005). Because there are indications that the

![Fig. 19.—A) Schematic showing a stepped pre-incision slope with alternating higher-gradient ramps and lower-gradient steps. Given enough time and enough flows, erosion along the base of a canyon may achieve a graded profile (dashed line) on an otherwise “bumpy” slope if the rate of incision is faster than the rate of substrate deformation. A hypothetical graded profile develops along a canyon axis during incision, but a corresponding “depositional” graded profile may also develop contemporaneously outside the canyon during slope apron buildup that smooths over gradient changes. The difference between the two reflects, in part, the dominant behavior of flows traveling along the canyon axis and on the adjacent slope (see Kneller, 2003). On slowly deforming slopes like in the study area, where depositional and erosional processes dominate short-term slope evolution along active sediment-transport corridors, the broad-scale architecture of canyon–channel–levee systems depends strongly on location relative to the pre-incision slope morphology. Thicker overbank deposits and lower incision depths, B) may develop at the down-flow transition from steeper ramps to shallow steps. Conversely, thinner overbank deposits and deeper incision depths, C) may develop at the down-flow transition from steps to ramps that form convex-upward “bumps” on the pre-incision slope. These positive-relief features are preferentially eroded during early incision. In areas where the hypothetical canyon-thalweg graded profile is elevated above the pre-incision slope, D) the resulting deposits may be dominated by aggradational channel–levee systems that experience common avulsions and compensational stacking.](https://pubs.geoscienceworld.org/books/chapter-pdf/4259938/9781565763043_ch10.pdf)
slope continued to deform after horizon 40 (discussed previously and in Deptuck et al., 2007), however, the measured gradient changes presented in Figures 4, 8, and 9 should be considered maximum values. It is possible that the amount of gradient change from step 3 to ramp 3 in the western study area, for example, was more subtle during the incision of the Benin-minor Canyon (above horizon 60). Later fold amplification and normal faulting probably modified this buried surface, but the magnitude of this effect is difficult to determine. Nonetheless, a more pronounced stepped slope morphology probably existed while Units 2 and 3 were deposited than is observed on the present-day seafloor. Likewise, changes in slope morphology above horizon 60 are believed to reflect erosional and depositional processes that, with the exception of the westernmost study area, outpaced the rates of slope deformation.

A subsequent decrease in the supply of sediment gravity flows to the corridor, perhaps in response to a shift in shelf depositional systems or a rise in eustatic sea level, would probably mark a return to normal background slope sedimentation (as was likely the case between horizons 80 to 60). In this hypothetical scenario, slope deformation may once again outpace the depositional and erosional processes needed to achieve (or maintain) a graded profile. This would bring the system full cycle and preclude the slope for accumulation of slope aprons once an active sediment transport corridor is re-established. If any predictable cyclicity exists in such systems, it must be governed by the processes that deform the slope (and the rate of substrate deformation) and the processes that initiate sediment gravity flows (and the corresponding frequency and style of flows).

**Relationship between Slope-Apron Thickness and Canyon Incision Depth**

A cross-plot of slope-apron thickness and the incision depth of the Benin-major Canyon shows a strong inverse linear relationship ($R^2$ of 0.84; Fig. 20). Where the canyon is most deeply incised, adjacent slope aprons are thinnest or absent; where canyon incision is shallowest, adjacent slope aprons are thickest. Depth of incision does not appear to be related to the pre-incision gradient ($R^2$ of 0.003). Instead, the depth of incision is governed by the difference between the pre-incision topography and a theoretical graded equilibrium profile along the canyon path (Fig. 19; see also Pirmez et al., 2000; Kneller, 2003). The similarity in the pattern of variations in incision depth indicates that both the Benin-minor and Benin-major canyons encountered similar changes in pre-existing topography along their paths. Local incision maxima are found at the down-slope transition from lower-gradient steps to higher-gradient ramps, forming convex-upward bathymetric structures on the pre-incision slope, and these correspond to locations with the lowest amount of deposition outside the canyon (Figs. 14, 19C). Conversely, areas with low incision depth correspond to the down-slope transition from ramps to steps, and these areas are concave upward and experience the greatest amount of slope accumulation adjacent to the canyon (Fig. 19B).

Aside from the accumulation of transient fans (which account for less than 20% of the total apron thickness above horizon 60), this relationship appears to be largely due to the increased thickness of overbank deposits adjacent to canyon or channel reaches with the shallowest incision (Deptuck et al., 2003b). This is probably because a turbidity current is most likely to exceed the height of canyon margins in reaches with the shallowest incision. Both the Benin-minor and Benin-major canyons show wide variations in incision depth (Figs. 14A, D), and so the upper parts of turbidity currents passing through them during both incision and their subsequent fill would be prone to overspill some canyon reaches while being contained in others. In addition to local increases in sediment flux from overspill flows in shallow canyon reaches, the stepped-slope topography remaining outside the graded to quasi-graded path of the canyon (or the sinuous channel within the canyon) probably also impacts flow behavior. Once a flow escapes confinement, it too may thicken at or just down-slope from important reductions in gradient, contributing to the preferential accumulation of sediment on some parts of the slope. Adjacent to both Benin-minor and Benin-major, overbank deposits are thickest above step 2 where the gradients were lowest and the incision depth is shallowest.

Although local increases in incision depth are not directly dependent on gradient, the initiation of erosion is, with local acceleration of sediment gravity flows taking place where gradients increase. Flow acceleration is needed to initiate knickpoints that eventually erode across positive bathymetric structures to produce local incision maxima (Pirmez et al., 2000; Smith, 2004). For this reason, down-flow variations in the rate of incision are also important because canyon reaches with the highest incision rates probably have the shortest period of time to accumulate overbank deposits before incision depth exceeds the average flow thickness.

For Benin-major, accumulation of initial outer levees (those that develop contemporaneously with incision) presumably continued until they aggraded to the level of the thickest flows (at the down-flow transition from ramps to steps) or until vertical incision overdeepened the conduit and prevented flows from overspilling (at the down-flow transition from steps to ramps). The condensed section between horizons 45 and 40 may record a period when most flows were confined within the Benin-major Canyon. After the confinement depth was reached, the muddier upper parts of flows either accumulated as inner levees within the canyon or the fines were transported seaward. This continued until aggradation on the floor of the canyon allowed flows once again to overspill the canyon margins. As with the lower outer levees, the upper outer levees thicken above steps 2 and 3 (Fig. 18). The distinct increase in wavelength of outer-levee sediment waves may record increases in flow thickness above steps 2 and 3 (Normark et al., 1980), consistent with flows that decelerated above lower-gradient parts of the slope.
slope adjacent to the canyon path. Thus, there appears to be an intimate but complex relationship between slope morphology, canyon incision depth, and the thickness and character of overbank deposits adjacent to canyons.

CONCLUSIONS

(1) Temporal and spatial changes in slope morphology.—The ability to map seismic horizons at the seafloor and in the shallow subsurface in 3D seismic volumes provides a record of the present-day seafloor morphology as well as past seafloor morphologies that to varying degrees were modified by deformation during burial. Careful study of the history of slope deposition and erosion can help constrain the deformation history, and hence past slope morphology. Evidence from (1) canyon incision depths, (2) spatial and temporal variations in sediment thickness, and (3) the geomorphology of various seafloor features indicates that the slope in the study area evolved from having a pronounced stepped morphology at horizons 90 and 60 to having a smoother morphology, with lower-magnitude ramp-to-step (and vice versa) gradient changes at the modern seafloor (locally forming a nearly graded profile). The study area also evolved from having no canyons (horizons 90 to 60), to prominently incised canyons (horizons 60 to 40), to canyons that are locally filled and have no remaining relief (modern seafloor).

(2) The role of down-slope sediment transport.—Deposits between horizon 90 and 60 are dominated by concordant, largely isochronous strata that record a period of normal background sedimentation at a time when, with the exception of one slope failure, slope deformation went largely unchecked by depositional or erosional processes. During the period of slope instability, failed material was transported down the slope and preferentially accumulated above pre-existing lower-gradient steps, helping to smooth over seafloor gradient changes. Likewise, the onset of an active turbidity-current corridor above horizon 60 records a period when slope aprons were deposited and canyons were eroded. Development of these features temporarily outpaced deformation rates, allowing a smoother seafloor profile to develop along canyon axes and the immediately adjacent slope.

(3) Slope aprons and reservoir potential adjacent to canyons.—Preferential accumulation of slope aprons helped reduce the difference in gradient from ramps to steps by about 1° across the study area. Detailed mapping indicates that slope aprons are composed primarily of (1) overbank deposits adjacent to canyons or channels, (2) mass-transport deposits, and (3) stacked potentially sand-prone lobes. Observations from this study are therefore consistent with other studies of stepped slopes, and they indicate that the slope adjacent to canyons may have reservoir potential, particularly in the lower parts of aprons where sandy lobes are most likely to accumulate during the passage of early flows (at the onset of, or just prior to, canyon erosion). Hence, on stepped slopes the presence of deeply incised canyons does not necessarily indicate pure slope bypass. Once a canyon is established, however, it is generally more difficult to deposit coarser material outside the canyon, and mud-prone overbank sediments appear to form the dominant deposits within aprons.

(4) Coexistence of erosional and depositional “graded” profiles.—In settings with relatively slowly-moving substrates, the slope along an active sediment-transport corridor appears to evolve toward a more graded profile in two ways: (1) through vertical incision and removal of gradient changes along canyon axes (with younger canyon-floor deposits aggregating roughly parallel to the basal incision surface, plus or minus later deformation that modifies the erosional graded profile; see Deptuck et al., 2007); and (2) through preferential accumulation of slope aprons in areas of reduced gradient adjacent to (and at least in part contemporaneous with) canyons.

(5) Apron thickness versus canyon incision depth.—There is an inverse linear relationship between apron thickness and the depth of incision along contemporaneous canyons (i.e., where the canyon is most deeply incised, slope aprons are thinnest, and vice versa). This relationship appears to be largely due to the increased thickness of overbank deposits adjacent to canyon or channel reaches with the shallowest incision. These reaches coincide with areas where flows (1) are most likely to overtop their banks, and once they escape canyon confinement, (2) are most likely to decelerate upon encountering local reductions in gradient on the adjacent slope. All outer levee deposits are thickest at or just down-slope from important reductions in gradient, hence the thickness of overbank deposits adjacent to a canyon may help constrain paleo-slope morphology in more deeply buried systems. Reaches with the thickest overbank deposits may also correspond to areas where sand-prone lobes are most likely to accumulate prior to canyon incision, and hence identification of locally thick overbank deposits, or canyon reaches with locally shallow incision, may help to identify potential reservoir intervals adjacent to canyons on paleo-stepped slopes.

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