STRATIGRAPHIC RESPONSE TO EVOLVING GEOMORPHOLOGY IN A SUBMARINE APRON PERCHED ON THE UPPER NIGER DELTA SLOPE

BRADFORD E. PRATHER
Shell Upstream Americas 200 North Dairy Ashford Road, Rm EPC-A2126, Houston, Texas 77079, U.S.A.
e-mail: bradford.prather@shell.com

CARLOS PIRMEZ
Shell Research & Development, 3737 Bellaire Blvd., Houston, Texas 77001-0481, U.S.A.
present address: Shell Nigeria Exploration and Production Company, Lagos, Nigeria
e-mail: carlos.pirmez@shell.com

ZOLTÁN SYLVESTER
Shell Research & Development, 3737 Bellaire Blvd., Houston, Texas 77001-0481, U.S.A.
e-mail: zoltan.sylvestere@shell.com

AND

DANIEL S. PRATHER
University of Kansas, School of Engineering, 2120 Learned Hall, 1530 W. 15th Street, Lawrence Kansas 66045, U.S.A.
e-mail: danp5150@ku.edu

ABSTRACT: This submarine apron is an analog for the stratigraphic architecture of shallow ponded basins common to stepped, above-grade slopes, where late-stage bypass valleys and channels did not form. Deposition of this apron began within shallow ponded accommodation. Sediment gravity flows entering the basin pass through a leveed channel that incises underlying slope muds. Flows spread, becoming depositional once reaching lower-gradient area within ponded accommodation. Incisions at the distal end of the basin suggest that gravity flows downcut the basin sill as they bypass the basin during filling of ponded accommodation. A channelized apron downlaps the ponded deposits, healing the stepped topographic profile formed after ponded accommodation fills. Collapsing flows exiting the entry-point channel create plunge-pool scours in the proximal part of the apron. Sediment gravity flows exiting the plunge-pool scour accelerate over the steeper face of the apron, eroding bypass channels as healing progresses. Avulsion takes place as the height of the lower apron unit builds, forcing flows to bypass and erode the southwestern flank of the lower apron. Avulsion leads to deposition of an upper apron unit. Throughout deposition of the aprons, flows leave the basin through a gather zone at the exit point of the basin, forming a tributary scour pattern. Acceleration of these flows as they top the basin sill forms a deeply incised submarine valley. Erosion of the sill progresses by headward-migrating knickpoints that truncate apron deposits.

KEY WORDS: submarine apron, stepped slope profile, perched apron, Niger delta slope, above-grade slope, plunge pool, apron gradients

INTRODUCTION

Study of near-seafloor analogues is important because they provide higher resolution of basin-fill stratigraphic architecture than conventional deep-imaged seismic data. Shallow analogs have a variety of uses throughout the life cycle of typical deepwater plays, including: (1) identification of drilling hazards, (2) modeling of slope depositional processes, (3) architecture calibration of seismic facies, and (4) reservoir modeling. Detailed mapping of shallow, well-imaged seismic sequences improves our understanding of models of deepwater depositional processes. Patterns of deposition controlled by slope gradient, entry points, and accommodation are identified most confidently in the near-seafloor setting. Where they reoccur through multiple depositional episodes, near-seafloor features make particularly useful analogs for deeper sequences. Variable acoustic rock properties in most near-seafloor settings, however, require coring for reliable lithologic calibration.

Although typical seismic from near-seafloor analogs have less resolution than outcrops, they provide three-dimensional information typically lacking from outcrops. Near-seafloor seismic is capable of resolving surfaces related to episodes of starvation, bypass, and/or erosion that are related to both reservoir bed length and connectivity. Outcrops show us that units bounded by these surfaces can be too thin to be mapped confidently with conventional seismic. Dimensional data such as channel width, thickness, sinuosity, meander-belt width, and areal extent of slumps from images of shallow analogs can be applied to reservoir models where appropriate.

The objective of this study is to demonstrate how geomorphology of the slope, such as gradient, entry-point position, and accommodation, controls patterns of deposition within a shallow ponded basin located across a “step” on the upper slope offshore Nigeria (Fig. 1). Together with work by Pirmez et al. (2000), Fonnesu (2003), Deptuck et al. (2003); Deptuck et al. (2007), Deptuck et al. (this volume), and Adeogba et al. (2005), this study extends our knowledge about the evolution of stepped slopes, and the deposition of submarine aprons perched on the slope that are unaltered by formation of bypass channels and submarine valleys. We focus this study on the details that characterize the stratigraphic evolution of the intraslope basin located in the southeastern portion of an area designated as Oil Mining License.
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(OML) 134 (Fig. 1) where conventional three-dimensional seismic data that cover an area of 225 km$^2$ (15 km x 15 km) can be integrated with giant piston cores and a sub-bottom profiling survey (Fig. 2).

DATA SOURCES AND INTERPRETATION

Horizon interpretations of the seismic data were done both manually and with auto-trackers from a three-dimensional seismic volume binned with a spacing of 25 m x 12.5 m; this provides for detailed spatial imaging of fine-scale erosional and depositional features. In the case of the OML 134 three-dimensional survey, the 80 Hz frequency content (at -10 dB) provides a vertical resolution of 6 m (1/4 wavelength, assuming a velocity of 1500–1750 m/s). This is about twice the vertical resolution expected from conventional 30 Hz seismic data typical at reservoir levels (Fig. 3). The volume was processed to approximate a zero-phase wavelet. Besides a conventional reflection-coefficient three-dimensional volume, a seismic attribute that combines semblance and amplitude, trace shape of the seabed reflector, and -90° phase-rotated volumes were used for mapping purposes. Higher-frequency content of near-seabed seismic allows for detailed imaging of morphology and smaller-scale geologic features than seismic from conventional exploration depths (Prather 2000; Steffens et al. 2004).

Twenty-three 4-inch diameter piston cores penetrated the uppermost part of the upper apron (Fig. 2). Core recoveries ranged from 1.68 to 18.06 m—recovery depends partially on the composition of sediment at the seabed. Each of the cores penetrated about 1–2 m of hemipelagic drape, and all but four, fan cores 3, 17, 19, and 22, recovered sand below the drape. Muddier sediment tends to have better recoveries than sandy sediment. Some of the shortest recoveries may indicate the presence of sand, but this cannot always be confirmed. Both fan core 1 and 17 provide lithologic information about the slope drape on the flank of the basin.

ACCOMMODATION AND SLOPE MORPHOLOGY

The study area in OML 134 is located on the upper Niger Delta slope west of the present location of the Niger River in 1100–1400 meters of water (Fig. 1). The Niger Delta covers an area of about 75,000 km$^2$ and extends for more than 300 km from its apex to its shoreline (Whiteman 1982; Doust and Omatsola 1990). The Niger Delta continental slope extends westwards for another 150 km from the present-day shelf–slope break. The delta and the slope together comprise a sedimentary wedge that covers 140,000 km$^2$ and reaches about 12 km in thickness (Evamy et al. 1978; Whiteman 1982; Doust and Omatsola 1990).
The large-scale wedge or shelf-margin prism grew by repeated transits of the Niger Delta across its shelf. Mulder and Syvitski (1995) characterize the modern Niger River as a “clean” river, with a water discharge of 6140 m³/s and a sediment load of 1270 kg/s, consisting of grain sizes ranging up to and including gravels. At times when the delta reached the shelf edge, major phases of shelf-margin progradation occurred and deepwater slope and basin-floor deposits accumulated.

Fault-bounded sedimentary depocenters and intervening shale-cored anticlines characterize the modern Niger Delta slope and outer shelf (Cohen and McClay 1996). Lateral shale withdrawal from beneath the advancing deltaic load, combined with compressional uplift and folding of slope strata, drive the tectonics of the area and thus the morphology of the slope (Cohen and McClay 1996). The regional gradient of the present-day Niger Delta slope ranges from 1.0 to 1.2°, but it locally steepens to gradients of 1.7° to 2.2°. Local gradients throughout the margin can be considerably steeper than the regional average. The lowest gradients occur in between deeply rooted shale-cored anticlines that have a curvilinear trend paralleling the coastline (Steffens et al. 2003).

The morphology of the western Niger Delta slope is a prime example of a stepped above-grade slope (Prather, 2003). Above-grade slopes in the classification scheme of Prather (2003) refer to a downslope seafloor profile that is elevated above the level of a theoretical concave-upward smoothed graded profile. Stepped slopes are a class of above-grade slope that exhibits subtle changes in depositional gradient resulting in low-relief stepped or terraced topography. “Steps” are local areas of decreased gradient that lack the three-dimensional closure characteristic of ponds. The part of the continental slope that connects steps is called the “ramp” (Fig. 4).

Healed-slope accommodation dominates stepped slope profiles. Healed-slope accommodation is the space across a step and ramp on the slope below a three-dimensional convex hull fit to the rugose seafloor topography (Prather, 2003; Steffens et al., 2003). Healed-slope accommodation is created by local subsidence and is the space left after filling of ponded accommodation. Although stepped above-grade slopes typically lack the well-developed ponded accommodation such as characterizes the ponded above-grade slope of the Gulf of Mexico, both ponded accommodation and slope accommodation can be present (Prather, 2003).

Steffens et al. (2003) conclude that ponded accommodation is rare to nonexistent across the modern Niger Delta middle and upper slope, where healed-slope accommodation dominates and the overall morphology is that of a stepped above-grade slope. Anastomosing dip-oriented drainage corridors extend for 100 km westward across the upper and middle parts of this stepped slope (Steffens et al., 2003). This is particularly evident in the lower slope, where drainage pathways become more strike-oriented as higher-relief toe thrusts increasingly influence the direction of sediment transport. The little ponded accommodation found on the Niger delta slope occurs in the lower slope (Steffens et al., 2003). Where the steps connect through the toe thrusts, tortuous corridors result in which sediment gravity flows pass (Smith, 2004). In this way deposits in these corridors record a complex tectonosedimentary history, with numerous active structures and throughgoing submarine valleys and channels that maintained a stepped above-grade slope profile (cf. Prather 2003) throughout the Neogene (Heiniö and Davies 2007).

The study area consists of a series of perched submarine aprons. Submarine aprons in our scheme include fan aprons (O’Byrne et al., 1999), ponded-basin deposits, and healed-slope deposits (Prather et al., 1998; Prather et al., this volume). Perched submarine aprons include perched slope fills (Beaubouef and Friedmann, 2000), healed-slope aprons (Booth et al., 2002), and transient fans (Adeogba et al., 2005). Submarine aprons are associated with convergent-baselapping seismic facies (cf. Prather et al., 1998). Slope aprons consist of outer levees associated with
bypass canyons and channels, channel story elements, mass-transport deposits, and turbidite-lobe story elements (Barton, this volume; Hay, this volume; Deptuck et al., this volume; Prather et al., this volume). Direct age control for the interval of interest is not available, but jump correlations to interpretations from Cohen and McClay (1996) suggest that the dsp horizon (Fig. 5) is approximately of Pliocene–Pleistocene age and the base apron reflector is of Pleistocene age.

These apron systems have been the subject of several studies in recent years (Iunio et al., 1998; Friedmann et al., 1999; Pirmez et al., 2000; Prather and Pirmez, 2003). The aprons occupy healed-slope accommodation created across steps on the slope profile as shale-cored structural features rose during slope evolution (Fig. 5). The steps link across ramps at present via submarine valleys and channels (Fig. 1; Pirmez et al., 2000).

Pirmez et al. (2000) believe that the distinct rim and onlapping geometry in the subsurface below the steps suggest they were closed intraslope basins in the past (Fig. 5). The most downdip perched submarine apron in the OML 134 area passes updip into lower-gradient unconfined slope deposits that bury earlier perched submarine aprons (Fig. 5). Apparently, recent rates of sedimentation exceeded local rates of subsidence, resulting in a present-day bathymetry characterized by only subtle breaks in slope above the basin rims (Pirmez et al., 2000). Earlier depositional and erosional events also affected the local topography and influence subsequent deposition (Friedmann et al., 1999).

Depositional processes and morphology, causing both ponding of sediment and diversion of flows, are most strongly influenced by counter-regional structures associated with shale-cored anticlines at depth.

The near-seafloor submarine apron that is the focus of this study occupies a topographic low formed between localized uplifts of mobile shale within the underlying slope (Fig. 5). Evidence of movement of underlying shale is expressed in the near-seafloor geology as a mud volcano, ridges, and linked faults (Fig. 1). An intraslope basin forms in the hanging wall of the northwest-striking fault across the crest of the buried shale ridge. A series of down-to-the-north faults forms the north flank of the shale ridge. An east-striking shale-cored ridge bounds the intraslope basin to the south, as does the regional Niger Delta slope to the east. A structural saddle with steeply plunging southwestern flanks forms where a domal structure and the east-striking shale-cored ridge meet (Fig. 6A). Intersection of the east-striking shale ridge and the north-striking continental slope forms another structural saddle in the southeastern part of the study area. The combination of these structural elements forms a doubly plunging syncline with a shallow westward-plunging syncline extension below the position of the seafloor submarine apron that is the subject of this study.

Submarine aprons and unconfined slope deposits occupy the two synclines at depths below the near-seafloor apron. Channelscale and valley-scale scours evident on the dsp horizon (see Fig. 5) and the isochore map (Fig. 6B) suggest deposition of these earlier submarine aprons from submarine gravity flows entering the slope from the southeast (Fig. 6A). Thickened stratigraphy into the synclines (Fig. 6B) suggests that deposition of these units likely healed-over some of the topography created within the syncline. Either some amount of accommodation remained underfilled and/or additional uplift of surrounding shale-cored structural elements created the accommodation occupied by the seabed apron. Underfilled accommodation in the syncline combined with continued subsidence has resulted in formation of a nearly circular topographic low with ~ 25 m of ponded relief (Fig. 7A).

Configuration of the Entry Channel

Three channels cross the seafloor in the study area; Pirmez et al. (2000) designate them X, Y, and Y’, respectively (Fig. 1). These channels link the upper slope to a shelf margin sourced from relatively small, updip incised coastal river systems unlike the large incised valleys associated with the Opuama or Afam valleys, located on eastern and western Niger deltas respectively. The X channel originates below a shelf-margin delta and incised valley in the northeast corner of the OML 134 three-dimensional seismic survey (Pirmez et al., 2000). Here the X channel cuts older chaotic, transparent deposits derived from adjacent shelf-margin deltas deposited within the uppermost intraslope basin on the shelf (Pirmez et al., 2000). The X channel varies in width, depth of incision, character of fill, and sinuosity...
depending on local gradient, degree of confinement, and character of the substrate. Where the X channel crosses faults and shale diapirs, local gradient and the depositional patterns change. It disappears below the entry point of the intraslope basin, located in the southwestern corner of the OML 134 three-dimensional survey at about the 62 km mark (Fig. 4; Pirmez et al., 2000). The channel re-emerges downslope of a knickpoint at the distal end of the intraslope basin, where it joins with a large submarine valley (the Y channel of Pirmez et al., 2000) that cuts through several shale-cored ridges as it trends westward, downslope of the study area, eventually feeding a large submarine apron located at the present base of slope (Fig. 1).

At least six smaller channels or slope gullies flank the X channel (Fig. 8). Together with the X channel they form a distributary-channel pattern emanating from a point along the X channel several kilometers updip of the apex of the submarine apron. Hanging U-shaped incisions associated with these gullies along the walls of the X channel suggest that the gullies existed prior to formation of the X channel but were abandoned as the X channel cut down through the slope to its present depth. Levees flank the X channel in its lower reaches, draping the slope gullies and extending downdip onto the top of the submarine apron (Fig. 8). The submarine apron deposits backfill each of these channels, indicating that except for the X channel the slope gullies predate the latest phase of deposition on the apron. Extension of the levees onto the upper surface of the apron indicates that the levees are coeval with the latest phases of apron deposition.

The slope gullies and the X channel incise the top of the hemipelagics where they enter the intraslope basin, modifying the morphology of the topographic surface at the base of the submarine apron (Fig. 9). These channels are deflected around topography as they cut down to the bottom of the basin, suggesting that the rugose topography near the entry point existed while the basin was unfilled. The X channel extends farthest downdip, ending at the top of ponded accommodation (Fig. 9). The other channels end at various positions on the basin entry slope as they fed younger parts of the apron (Fig. 9).

A broad downdip-oriented tributary drainage pattern is evident near the exit point of the basin (Fig. 10). Since this area is buried by submarine apron deposits and is updip of knickpoint erosion created during later bypass of the basin, it evidently developed early in the history of the basin fill, probably by erosive flows bypassing the area of ponded accommodation. The upper reaches of these tributary scours end at the downdip limit of ponded accommodation.

**APRON ARCHITECTURE**

The OML 134 submarine apron represents the last and farthest downdip of the intraslope basin fill sequences along the X channel in OML 134 (Fig. 4). The apron occupies the intraslope basin located in the southwest corner of the three-dimensional survey below where the X channel disappears into the apron and updip of where it reemerges from the apron before linking with the Y channel (Fig. 1). The submarine apron in OML 134 consists of at least three units—a thin low-relief ponded apron (?) and two perched aprons which downlap the underlying unit and prograde across the intraslope basin floor (Fig. 11). The blue horizon separates the perched apron into lower and upper units (Fig. 11). Discontinuous, highly reflective seismic facies characterizes the lower apron, whereas more continuous highly reflective seismic facies characterizes the upper apron (Fig. 11, 12). This is also the deepest seismic event that connects the basin entry point directly to the basin exit point (Fig. 11).

The submarine apron that occupies the OML 134 intraslope basin is generally circular in planform (Fig. 13B), reflecting the infilling of nearly circular ponded and healed-slope accommodation (Fig. 13A, C, E). Although we are not able to isolate and
Fig. 7.— Measurement of A) depth and slope gradients of the B) upper apron, C) lower apron, and D) base surfaces along the central apron transect. Red triangles indicate locations of slope breaks. Line of section is shown in Fig. 2.
independently map a seismic event associated with a ponded submarine apron, the presence of demonstrable ponded accommodation of about ~ 25 m (Fig. 11, 13A) and a corresponding single baselapping seismic event that onlaps the intraslope floor below the spill point (Fig. 11) suggests the existence of a low-relief ponded apron (sensu Prather et al., this volume).

Healed-slope accommodation makes up the remaining ~ 150 m of sediment thickness (maximum) in the basin. Maximum thickness of the basin fill is offset from the deepest point of the basin towards the entry point. The basin fill thins to the southeast towards the basin exit point. Thinning results in part from downlap towards the basin rim and in part from erosional truncation beneath a knickpoint at the seafloor that cuts progressively downward into the large submarine valley that represents the downdip extension of the X channel (Fig. 11). The exit point of the basin corresponds to the structural saddle located in the southwestern corner of the study area (compare Fig. 6 and Fig. 13A). Such erosional truncation of the downdip portion of the basin fill is a typical characteristic of perched aprons.

An isochore thickening of strata symmetrically distributed around the X channel (Fig. 14B) and “gull-wing” cross sections suggest the presence of levees near the basin entry point. Three curvilinear thins that run parallel to the levees suggest that the levees are incised by small slope gullies. The gullies overtop the levees at a break in slope a few kilometers updip of the apron entry point where the channel crosses a fault (Fig. 8).

The seafloor, which is the top of upper apron in OML 134, has a prominent knickpoint that connects downlap to a submarine valley (Fig. 13E). This submarine valley merges with a larger valley to the east (termed the Y channel by Pirmez et al (2000) that cuts across the entire slope, connecting the shelf-slope break to a well-defined submarine apron at the toe of slope (Fig. 1). Slope profiles, both down the feeder channel axis and through the aprons at several levels, show gradually flattening gradients (Fig. 7D). The gradient change between the feeder channel and the baselap surfaces takes place within ponded accommodation and represents a break in slope that is perched well above the ultimate toe of slope outboard of the deep-water fold belt of the Niger delta slope. Over time, as the OML 134 step healed by deposition of the apron, this perched break in slope progressively steps back into the feeder channel (Fig. 7B, C). The downdip limit of the perched apron corresponds to the downlap edge of the apron on top of any ponded apron deposits. Length of the slope across the step increases from 5 km to 12 km during progradation of the apron. These line lengths are always less than the distance across the step, except for the last phase of deposition, when the apron prograded to the basin exit point.

**Lower Apron**

The surface of the lower apron has an asymmetrical radial-fan shape with its apex slightly off of center to the north relative to the basin entry point (Fig. 13C). The gradient across the proximal part of the lower apron is lower than the gradient across the same region in the upper apron (Fig. 7). Thinning, multiple knickpoints, and irregular topography suggest that the asymmetry of the apron is related to a broad area of erosion on its southern flank. The depocenter for the lower apron is also offset updip of the

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**Fig. 8.**—Perspective view of the entry channel showing the locations of splays and associated channels or gullies that incise levees lateral to the entry-point channel.
Fig. 9.—Close-up view of the entry-point configuration below the submarine apron, which has been stripped away for viewing the hemipelagics at the bottom of the basin. Note that the X channel ends at the top of ponded accommodation whereas the downdip termini of slope gullies, indicated by red triangles, occur at higher levels.

Fig. 10.—Perspective into the intraslope-basin exit point towards the southwest. This perspective shows the top of the conformable succession that underlies the basin fill (interpreted as unconfined slope deposits). It shows linear erosional patterns converging into the basin exit point and the incision from the late-stage submarine valley that emanates from the basin exit point and cuts into the mapped horizon. The black band marks the top of ponded accommodation.
underlying ponded accommodation, suggesting that the bulk of the deposition did not occur within the pond (Fig. 14A). Stratal slices through a “seismic texture” volume shows that the lower apron consists of complexes of small distributary channels and lobes (Fig. 15A). Channels emanating from the basin entry point fan out laterally across the prograding apron toward the basin exit point and are confined to the thickest part of the lower apron (Fig. 15A).

Thickening apron deposits, immediately down-dip of the basin entry point, reflect the location of multiple erosional features (Fig. 11). Only the shallowest of these erosional features can be mapped outside of the proximal part of the lower apron, because deeper erosional cuts are only partially preserved. The latest of these erosional features modifies the top of the lower apron surface where the entry channel merges with the proximal apron, forming a dip-elongated scour (Fig. 16). Channels exit the scour area and shallow as they extend down the apron, before they link up with a knickpoint that leads to the basin exit point. The scour is possibly analogous to the “plunge pools” reported from the continental slope off California and from outcrops of the Grès d’Annot, SE France (Lee et al., 2004).

Amalgams of flute-shaped scours each approximately 500 m across coalesce across on the southeastern flank of the lower apron, forming a scour field. Seismic reflectors are truncated below the surface, suggesting that the scour field forms an erosional surface produced from the amalgamation of these smaller-scale flutes. Several of the most prominent scours connect up-dip through channels to the basin entry point. Grades across the eroded apron flank are steeper than gradients perpendicular to the main apron axes of either the lower or the upper aprons (Fig. 7). The position of the scour field suggests that it formed as flows entering the apex area of the lower apron were diverted to the southwest out of the plunge-pool scour located at the apex of the lower apron. Bonnel et al. (2005) interpret scour fields on the Rhone Fan as either relics of buried channel topography or products of flow stripping from a bend in the channel, combined with a break-in-slope feature on the surface of the Rhone Fan. In a similar way the lower-apron scour field appears to be either a precursory to, or coeval with, avulsion across the top of the lower apron. In either case this led to a shift in the locus of upper apron deposition, off the main lower-apron depositional axis.

Upper Apron

The surface of the upper apron has a symmetrical, radial fan shape with its apex centered down-dip of the of the entry-point channel (Fig. 13E). However, there is a lateral (eastwards) shift in thickening in the upper apron compared to the lower apron (Fig. 13F). The upper apron depocenter corresponds to the location of the broad, eroded area at the top of the lower apron. Isochrome and trace shape patterns suggest the presence of distributary lobes within the upper apron. The lobes emanate from the basin entry point, switch laterally in a compensating fashion as they prograde downslope across the top of the lower apron, and then switch to the southeast (Fig. 15B). Sediment waves, levees, and scour flutes are also present at the seafloor and represent depositional environments in the uppermost part of the upper apron (Fig. 9). This surficial expression suggests that the levee and the sediment waves probably formed towards the end of upper-apron deposition, possibly coeval with deposition of the southernmost lobes (Fig. 15B). The scour is ~ 200 m wide and connects to the entry point through a broad (1.8 km wide), shallow trough on the top of the apron just inside the outer levee (Fig. 13E).

The sediment waves are deflected around and over the low-relief levee, modifying their shape just down dip of the entry point (Fig. 8). These bedforms appear to have steep lee sides, with a total amplitude of approximately 1.5 m or less and an average wavelength of ~ 62 m across a slope ranging from 1.0° to 0.5° (Fig. 17). The sediment waves disappear approximately 10 km down-dip of the entry-point channel. Comparison with measurements of bedforms compiled by Wynn et al. (2002) suggests that they may be sandy. Their relatively high acoustic impedance, and location extending from the channel floor into the proximal apron apex just down-dip of the basin entry point, further suggests that they are sandy. Some simple calculations, assuming these features to represent antidunes and using the methodology of Prave and Duke (1990), suggests a flow thickness of about one-twelfth of the wavelength, or about 5 m, assuming a densimetric Froude number of 1. This thickness should correspond to the height of the velocity maximum of the turbidity currents, which occurs at approximately one-quarter of the total flow height. So total flow thickness would be of the order of 20 m, well within the observed relief of the modern feeder channel up-dip (Fig. 4). Furthermore, assuming a typical flow density of 1050 kg/m³ (about 3% concentration by volume), we estimate a flow velocity of the order of 3 m/s, which is sufficient to carry granules and pebbles in the bedload.
Fig. 13.—A) Perspective rendering of the base of the submarine apron; note the closed contour that marks the top of shallow (~ 30 m) ponded accommodation. B) Total isochore of the combined lower and upper aprons shows circular plan form, leved channel feeding the apron and exit-point valley. C) Perspective view of lower apron. D) Isochore map of the lower apron. E) Perspective view of upper apron. F) Upper apron isochore. Depth and thickness units are two-way travel time (ms).
Fig. 14—A) Time isochore map of the lower apron (color-fill contours) and time structure map of basin bottom surface (gray contours). B) Time isochore map of the upper apron (color-fill contours) and time structure map of the lower apron top (gray contours).

Fig. 15—A) Distributary channel and lobe complexes within the lower apron. Colors represent a seismic attribute computed from a combination of amplitude and semblance. Horizon slice is extracted a few milliseconds below the blue horizon (see Fig. 12 for mapping horizons); gray contours are from the time isochore map of the same interval (Fig. 14A). B) Trace-shape map of seabed reflector showing compensating lobes, levees, and exit-point submarine valley. Note the close correspondence of the trace shape and the thickness of the upper apron (gray contour representation of Fig. 14B).
Although seabed cores in the proximal apron were short and recovered no sand, cores downdip of the sediment waves show that sands in the granule and pebble size range are present in this area (Fig. 18).

The sediment waves described here are similar to cyclic steps found in bedrock rivers (e.g., Wohl, 2000) and created in flume experiments with cohesive and erodible beds (Sawai 1977; Koyama and Ikeda 1998). Cyclic steps occur in net-erosional (Parker and Izumi, 2000) or net-depositional (Sun and Parker 2005) flows. Fildani et al. (2006) suggested that the steps in the distributary channel on the Monterey Fan are analogous to the former, whereas fields of sediment waves found throughout the fan are analogous to the latter. Lamb et al. (2008) hypothesize that steps in a the linear depression in a distributary channel on the Eel River submarine canyon are cyclic-step bedforms created by turbidity currents.

**DISCUSSION**

Our preferred interpretation for the stratigraphic evolution of this shallow-ponded intraslope basin is built on the assumption that there are ponded deposits onlapping the intraslope basin floor in OML 134 and that these are overlain by a submarine apron that downlaps the top of ponded deposits (Fig. 11). In this scenario deposition began following subsidence of the intraslope basin and creation of ponded accommodation. The presence of older apron units above the dsp horizon suggests that subsidence occurred relatively early and the basin was at least partially filled. Thickening of unconfined slope units above this older apron unit suggests that any residual topography that remained after deposition of the older aprons was filled, possibly forming a local graded to stepped-slope profile. Reformation of ponded accommodation at the base of the younger apron

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Fig. 16.—Perspective-view detail of the top of the lower apron showing entry-point scours, scour field, and channels exiting the scoured area.

Fig. 17.—A) Seismic profile and B) topography measurements across the field of sediment waves at the apron entry point (see Fig. 8 for location).
An alternative interpretation for the stratigraphic evolution of this shallow intraslope basin is built on the assumption that a single ponded apron does not cover the entire intraslope-basin floor, but rather there are multiple ponded aprons, resolved by seismic as the toesets of the prograding clinoforms, that characterize the apron (Fig. 19). Under this scenario deposition begins as an apron progrades into ponded accommodation of ~ 30 m depth. The apron clinoform builds angle until bypass begins on its proximal part. Denser parts of sediment gravity flows bypass the upper part of the clinoform and pond in front of the apron and behind the downdip basin sill. Progradation continues until the apron grades to the basin sill. The rest of the depositional history is the same as in the preferred scenario. We expect that this scenario is less likely, inasmuch as we observed that the gradient of clinoforms within the apron remains constant (Fig. 7). If the toes of the clinoforms were healed over during progradation, we expect that the intra-apron clinoforms would shallow upwards.
PONDING AND EARLY-STAGE BYPASS PHASE

Introduction of sediment gravity flows into the ponded slope basin occurred through the leveed slope channels that incise underlying slope mud at the proximal end of the basin. The sediment gravity flows became depositional and spread upon entering ponded accommodation. If there was any ponded accommodation, this phase of deposition would produce a low-relief ponded apron in the basin. If the alternative scenario was the case and no ponded accommodation existed in the basin, then deposition of a perched submarine apron would occur. In either case incisions between the rim of the basin and the basin exit point (Fig. 10) suggest an episode of early sediment bypass as sediment gravity flows downcut the basin sill after available accommodation was filled (Fig. 20A). Early bypass produced truncation at the exit point similar to that seen in the shallow ponded Brazos–Trinity Basin II (Prather et al., this volume).

Healing Phase

Filling of the pond was followed by progradation of two apron sequences. The aprons downlap the ponded deposits, healing some of the topography of the step (Fig. 20B, C). Sedi-

Fig. 19.—Alternative interpretation for the stratigraphic architecture of the OML 134 perched submarine apron (modified from Prather, 2003).

Fig. 20.—Stratigraphic evolution of the OML 134 intraslope basin.
ment gravity flows entered a newly created step after filling of ponded accommodation. The flows formed a broad apron with continuous to discontinuous seismic facies associated with a proximal distributary-channel complex and a distal tributary network of channels and lobes that converges toward the exit point of the basin. Lateral deposition away from the channels at the head of the apron is partly responsible for the overall up-dip shift in depocenter during deposition. Convergence of the flows forced by increased lateral confinement formed a gather zone of tributary erosional features observed at the basin exit point (Figs. 20B, C).

As healing progressed, the bypassing portion of gravity flows accelerated over the steep lee face of the basin sill, developing a deeply incised submarine valley (Fig. 20). Erosion of the sill occurred by headward-migrating knickpoints in the gather zone, truncating the distal parts of the apron (Fig. 20). At OML 134 these knickpoints do not migrate across the apron, so the submarine valley does not connect directly to the basin entry point as observed in many other aprons (O’Byrne et al., 2004; Barton, this volume; Bohn et al., this volume; Deptuck et al., this volume; Prather et al., this volume). The reason for this incomplete connection in OML 134 is not fully understood, but it is likely related to early apron abandonment, and shutdown of turbidity current input into the system.

Transition upward from the channelized aprons with their discontinuous seismic facies to more continuous seismic facies associated with compensating sandy (?) apron lobes took place across the blue horizon (Fig. 20D). The blue horizon marks the first time in the basin-fill history that a depositional surface connects the entry point to the exit point without the intervening step created at the run-out edge of the prograding apron (Fig. 7). Depositional profiles of the aprons evolve through time, from an initial shallow pond of 25 m depth to a progressively lengthening depositional surface on top of the overlying perched aprons (Fig. 7). Lengthening occurs by coeval progradation of the distal edge and backstepping of a break of slope into the basin entry point. Measurement of gradients on the slope updip of the intraslope basin (i.e., a ramp) and across the top of the perched apron shows no significant changes throughout the fill history of the basin (Fig. 7).

Late-Stage Bypass and/or Abandonment Phase

The change from a perched apron characterized by aggradational distributary channels and lobes with multiple plunge-pool scours at the entry point, to an apron characterized by laterally shifting distributary lobes, levees, and sediment waves, suggests a change in the character of sediment gravity flows entering the basin. A channel to lobe transition in the lower apron within the area of the step, (Fig. 15) and an upper unit consisting of small sandy (?) lobes also within the area of the step (Fig. 8), demonstrates that flows entering the step throughout apron deposition were small enough to have sand runout distances less than the slope length across the step. Decrease in the size of lobes and a change from sandy (?) lobes to a muddy lobe in the upper part of the apron further suggests a decrease in the size of sediment gravity flows entering the basin and possible abandonment of the feeder channel. If the sediment flows are decreasing, then the absence of a throughgoing bypass channel or submarine valley suggests that the lobes and levees are parts of an abandonment facies assemblage.

The association of a well-developed knickpoint with laterally shifting distributary lobes, levees, and sediment waves in the upper apron suggests that this assemblage of seismic facies may be indicative of bypass conditions and could serve as a model for the stratigraphic architecture of perched aprons either prior to

FIG. 21.—Frequency distribution of types of slope reservoirs (from a proprietary Shell database; Prather et al., 2009).
distributary channel-lobe complexes, (4) late-stage sediment bypass through a single knickpoint connected to a submarine valley, and/or (5) abandonment. The upper apron provides a unique example of a thin abandonment or bypass facies assemblage of small lobes without the leveed, bypass channel or valley commonly observed on the tops of other perched aprons such as observed in Basin II of the Brazos–Trinity system (Winker, 1996; Beaubouef and Friedmann, 2000; Prather et al., this volume) and Benin Major (Deptuck et al., this volume).

At conventional exploration and production depths and seismic frequencies the entire intraslope basin fill would be considered part of a convergent base-lapping seismic facies (sensu Prather et al., 1998). Convergent base-lapping seismic facies are often assumed to be indicative of depositional ponding and the presence of areally extensive “sheet” sand reservoirs. The OML 134 example suggests that this expectation is not always well founded. In the case of OML 134 the thickest reservoirs, up to about 100 meters thick in this case, probably occur close to the intraslope basin entry and are located neither in the center of the basin nor at the basin exit point or backstop position. Expected reservoir architecture in the perched apron is dominated by distributive channel systems, and there is little evidence of “sheet” sands. OML 134 also provides an example of vertical facies change from distributary channel complexes to a “bypass facies assemblage” consisting of sandy distributary lobes, sediment waves, and levees that cap the perched apron as depositional equilibrium is reached (after the apron progrades to the basin exit point). OML 134 can be used to develop reservoir-architecture scenarios used for construction of static models for a class of hydrocarbon-bearing perched-apron reservoirs that show little evidence of knickpoint migration and incision. The exit point of the OML 134 apron may also offer some useful information for understanding discontinuous and compartmentalized reservoirs such as in the Macaroni field (Booth et al., 2003), located at the exit point of the Auger intraslope basin in the Gulf of Mexico. The OML 134 analog shows that sands at exit-point position have the potential of occupying isolated channels associated with early bypass of the step followed by further stratigraphic isolation due to erosion from the overlying knickpoint (Fig. 10).

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REFERENCES


