STRATIGRAPHIC EVOLUTION OF A TORTUOUS CORRIDOR FROM THE STEPPED SLOPE OF ANGOLA

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ABSTRACT: This paper documents the architecture of basin fill and depositional evolution along a stepped, above-grade profile in the Kwanza Basin, Angola Block 21. Detailed mapping of a well-imaged, near-seafloor seismic dataset reveals the influence on preserved depositional architecture of evolving slope gradient, along corridors flanked by pronounced lateral confinement.

Sediment gravity flows entered the upper-slope to mid-slope basin system via an incised valley and interacted with the above-grade stepped topography. Effects of slope topography are most prominent during the early stages of deposition, such that flow contraction occurs over highs and flow expansion occurs in topographic lows. Evidence of sediment bypass, knickpoint migration, and erosion immediately outboard of areas of deposition supports the interpretation of an open stepped slope profile; there is only limited ponded accommodation in the study area.

Initial flows into the system were deposited in both updip and downdip basins, suggesting a weakly confined stepped profile with flow stripping and/or bypass between basins. Ongoing deposition healed the slope profile, with subsequent flows bypassing to downdip basins. Preserved depositional architecture is dominated by distributary channel-lobe complexes that comprise offlapping, shingled lobes deposited downdip of slope breaks, progressively wrapping around the salt topography. Lobes are more numerous, decrease in size, and increase in degree of channelization up through the section. Bypass initially occurred through numerous narrow channel stories that converge to a wider, single through-going system. With time, and sediment progradation, the locus of deposition shifted progressively basinward, away from basal highs. Fan apron stacking patterns are dominantly progradational, but fan packages are retrogradational prior to feeder-channel avulsion. Initial flows from each of the channels produced large-volume, highly channelized lobes. Prior to abandoning the channel system, the flows are smaller and possibly muddier, and deposits are less channelized.

Channel avulsion and local tectonism had a first-order control on the locus of deposition in the area, and caused an incomplete depositional cycle that deviates from predictions according to classic stepped-slope models.

Key words: turbidite, fan, lobe, channel, tortuous corridor, stepped slope, Angola, distributary lobe complex (DLC), accommodation

INTRODUCTION

Accurate characterization of subsurface depositional architecture is an essential prerequisite for successful reservoir appraisal and development, particularly in the challenging and costly environment of deepwater exploration. One approach to better refine our reservoir depositional models is through analysis of high-resolution seismic data from shallow analogues: these data often provide valuable insights that are not possible through analysis of conventional data at the level of deeply buried reservoir horizons. The objective of this study is to use the higher frequencies and hence higher resolution afforded in the shallow stratigraphic section to understand the evolution of a stepped above-grade slope. The results are applicable to more deeply buried reservoirs in analogous intra-slope basins in upper-slope to medial-slope settings.

The approach taken here is to document basinal architecture and apply seismic stratigraphic principles, in order to improve understanding of facies distribution and to reconstruct the depositional evolution of a stepped-slope system from the Lower Congo Basin, offshore Angola. This information can be used to develop predictive models for prospective systems elsewhere, including stepped-slope settings and the perched fill of Gulf of Mexico-type minibasins (Prather et al., 2005).

REGIONAL SETTING

The study area is part of the upper to middle Angolan continental slope between 9° S to 11° S latitude and 12° E to 13° E longitude, in Block 21 of the Kwanza Basin (Fig. 1). It is one of a series of sub-basins developed along the West Africa passive margin that formed in response to early Cretaceous continental breakup of Africa from South America (Karner et al., 1997). As with the adjacent Lower Congo and Benguela basins, subsidence related to early Cretaceous continental breakup preceded the first marine transgression and subsequent deposition of Aptian evaporites. The mobile Aptian evaporites were succeeded by Albian carbonates, and upper Cretaceous through Tertiary clastics, including Upper Cretaceous shales that provide regional source rocks (Anderson et al., 2000; Schoellkopf and Patterson, 2000).

The dataset covers an area of 1875 km², with an in-line spacing of 25 m and a cross-line spacing of 12.5 m, and this study focuses on a high-amplitude package 10 to 520 ms below the seafloor. The near-seafloor dataset has a peak frequency of over 80 Hz, which degrades to 60 Hz at depth.

Water depth increases from approximately 1500 m in the east to over 2000 m in the west. Salt diapirism and associated faulting during Cretaceous and Tertiary times have resulted in a complex seafloor physiography (Fig. 1), comprising discontinuous, salt-cored ridges oriented parallel to the coastline.
Configuration of the Receiving Basin

One of the fundamental controls on deepwater sedimentation is the configuration of the receiving basin (Booth et al., 2003; Prather and Pirmez, 2003; Smith, 2004). Regional bathymetric analysis (Steffens et al., 2003) reveals that the Kwanza Basin comprises both ponded and healed-slope accommodation, with a predominance of the latter. In a broad sense, ponded accommodation is associated with sheet sand deposition, whereas healed-sloped accommodation is associated with alternations of channels, sheets, and mass-transport complexes (Booth et al., 2003). Clearly, accommodation setting is an important control on preserved reservoir character. One of the results of this study is the identification of the type of accommodation in this area and its impact on depositional style.

The study area described here is located in an above-grade setting with a stepped profile (Prather, 2003), where sediment is deposited along a topographically complex “tortuous corridor” (Smith, 2004). In a general sense, above-grade slopes are less confined than slopes with ponded minibasins (Meckel et al., 2002) and are characterized by complex, connected flow paths with varying depositional gradients that induce alternating sections of erosion and deposition (Demyttenaere et al., 2000; O’Byrne et al., 2004; Smith, 2004). Formation of a stepped slope is, in part, dependent on the degree of subsidence relative to sedimentation rates: lower rates of subsidence with average sedimentation rates tend to produce a stepped slope, in contrast to high subsidence rates, which generate minibasin topography (Meckel et al., 2002).

Figure 2 shows a perspective view of the study area and a sample slope profile. Areas of net accumulation (“step flat or floor”) typically have low or negative gradient; these zones are essentially local toe-of-slope settings. Areas of net bypass (“entry or exit ramps”) typically have a higher, positive gradient at the time of deposition (O’Byrne et al., 2004). Figure 2 identifies the three principal depocenters recognized in the study area, labeled Eastern, Southern, and Western Basins respectively. These are zones of low or negative gradient that are connected by higher-gradient ramps (e.g., Central Step in Fig. 2). Three channel complexes are also referred to in the text; the Southern Channel is visible in Figure 2, and the Northern and Eastern Channels are not labeled but are found in the northern and eastern parts of the study area respectively, trending from east to west.

Slope morphology has a fundamental control on deepwater depositional patterns. O’Byrne et al. (2004) proposed a conceptual model for the depositional evolution along a stepped slope profile, which described the depositional and erosional response of turbidity currents to progressive slope buildup and associated accommodation reduction (Fig. 3). In their model, topographic gradient is a key control on depositional patterns: in general, sediment wedges are deposited in low-gradient flats, whereas higher-gradient steps promote erosion and bypass. However, the model also describes higher-gradient flats that undergo erosion and lower-gradient steps that result in levee development. Low-gradient flats eventually grade through sedimentation to the outer lip, such that bypass channels can link with updip-migrating knickpoints, resulting in extensive erosion and/or compartmentalization of reservoirs. Ultimately, topography is partially healed, such that the flats have higher gradients, and erosional fairways predominate, although their geometry and form are influenced by remnant topography. Complete topographic healing promotes consolidation of the channel system into a single, through-going complex that may still be affected by changes in topographic dip. This study aims to supplement the conceptual model with additional information on the range and spatial distribution of depositional facies encountered in this slope setting, and to account for departures from the predicted slope evolution.

Flow behavior, and hence, deposit character, are strongly influenced by abrupt changes in slope gradient. One of the most important changes is in the volume of sediment deposited at the break in slope: deceleration of the flow results in marked thicken-
ing in the deposit toward the slope break (Mulder et al., 1997). Positive topography along the length of the profile can also have an important impact on deposition. If the outer lip of a flat is sufficiently high, it forms an obstacle in the path of the turbidity current that induces rapid flow transformation resulting in deposition updip of an obstacle (Alexander and Morris, 1994). The currents may undergo a hydraulic jump downstream of the obstacle (also at abrupt changes in slope) which induces rapid deposition, and perhaps also an abrupt downstream thickening in the deposit (Kneller and McCaffrey, 1999).

**Fig. 2.—**A) Perspective view of receiving basin (yellow horizon 1 in Part B) illustrates complex salt-related topography of the slope. Labels refer to geographic locations referenced in the text. B) Seismic section (white line in Part A) showing the stepped topography with numerous ramps and flats along the slope. Laterally extensive, continuous reflectors (1–7) define each of the six packages (A–F). Inset shows location of section on depth map of basal (yellow) horizon 1.

**TERMINOLOGY**

Terminology in this paper (Fig. 4) is used primarily to describe the observed stratatal architecture, and no interpretation of the hierarchy in terms of erosional or depositional events is intended, except where explicitly indicated. Depositional architectures of channels and lobes follow that proposed by O’Byrne et al. (2007). The channel deposits in this study are bounded by valleys, which are the erosional and/or depositional conduits within which channel complexes reside. Each channel complex comprises...
Fig. 3.—Conceptual model for depositional evolution along a stepped-slope profile (modified from O’Byrne et al., 2004). Predicted slope evolution describes depositional and erosional response of turbidity currents to progressive slope buildup and associated accommodation reduction.

Fig. 4.—A) Lobe-story stacking patterns using terminology introduced by O’Byrne (2007). Lobe stories (LS) stack to form lobe story sets (LSS), which stack to form lobe complexes (LC). B) Channel-story stacking patterns within high-aggradation systems (modified from O’Byrne, 2007). Channel stories (CS) stack to form channel story sets (CSS), which stack to form channel complexes (CC). OB refers to overbank deposits and IL refers to inner lobes.

CHARACTERISTICS OF BASIN FILL AND FEEDER CHANNELS

The high-amplitude basin-fill succession is entirely encased in low-amplitude, highly continuous slope deposits, as illustrated in the representative section in Figure 2. The reflection character and continuity of the latter imply that the encasing units are widespread hemipelagic or pelagic deposits; these units correspond to the Miocene–Pliocene Quifangondo Formation (Fig. 2).

The basin fill is subdivided into six packages with distinct seismic characteristics (packages A–F in Fig. 2), which are bounded by seven horizons (1–7), four of which are found throughout the area of interest.

Package A

Package A is distributed throughout the study area (Fig. 5A). The package has moderate- to high-amplitude reflectors, with moderate continuity that converge onto the basin margins, and it has an internal shingled geometry. The unit is associated updip with high-amplitude discontinuous seismic facies contained within a valley.

The isochore map of package A (Fig. 5A) and the distribution of the valley facies with a sinuous pattern in the southeast of the area reveals that the unit was fed by the Southern Channel; other sediment entry points may have existed to the south, beyond the available dataset.

The thickest deposits are found close to basin entry points, as illustrated by the depositional thickening updip of the deepest basin contours shown in Figure 5A. The interval thins at locations that are present-day structurally high positions. Together, these observations provide insight into the slope morphology during deposition of package A. The thin strata probably corresponded to intrabasinal highs associated with bypass and reduced deposition,
Fig. 5.—A–F) Isochores of each package as a drape over basin topography. Basins are associated with flow expansion and deposition. White dashed lines are basin depth contours.
and the thick strata were relative lows along the depositional profile. Although the present-day structural configuration of the basin may not be exactly representative of the basin configuration at the time of deposition, the correspondence of depositional thinning with highs in present-day topography implies that the overall structure observed today was similar at the time of deposition. If this is the case, then the depositional thicks in the Western Basin are offset updip from the structurally deepest parts of the basin (Fig. 5A), which is perhaps the simplest explanation for the observed depositional patterns. An alternative hypothesis is that the depositional lobes are thickest adjacent to the feeder channel and thin into the basin. However, localized thinning across present-day highs implies that structural relief had an important impact on deposition beyond proximity to the feeder channel.

The mode of deposition is revealed in amplitude maps of the region (Fig. 6). A confined feeder-channel network across the Central Step expands at the entry to the Western Basin to form a distributary-channel network that feeds depositional lobes.

**Fig. 6.** A) Perspective view of basin topography facing west across central step and Western Basin, draped with amplitude extraction of 30 ms above base of package A. B) Interpretation illustrating expansion of a confined feeder-channel system at the entry of Western Basin into a distributary-channel network. Dark blue lines represent early stage of the feeder-channels; turquoise lines represent later-stage feeder-channel evolution. The erosion front shifts updip through time, cutting back into the central-step deposits. The dashed pink lines represent a zone of intense channelization that shifts progressively downdip as the depositional system shifts downdip.
Expansion and contraction of the system occurs in areas of low and high confinement respectively, and semblance data indicate that increased channelization occurs at topographically high points along the sediment transport route (Fig. 7C).

**Step Evolution During Deposition of Package A.**

Fig. 7A is a NW–SE-oriented profile across the basin that highlights the complex topography of the receiving basin. The Central Step is the first zone of low gradient encountered by the Southern Channel in the study area.

The interpreted paleo-step morphology, controlled by a mobile salt substrate, formed a flat between the two partially overlapping diapirs (A in Fig. 7A). The southern end of the flat has a lip defined by an intrabasinal high (C in Fig. 7A), which acted as a partial backstop, trapping flows or parts of flows in the step accommodation space updip (Fig. 7A). Sediments deposited on the step during package A time are highlighted in blue.

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**Fig. 7.—**A) Seismic section along thalweg of the Southern Channel, and across the Western Basin (see inset for location). Pale blue shade highlights sediment A trapped behind backstop C, and pink shade highlights erosion (B) updip of the backstop. Inset shows location of section on map. B) Isochore of sheetlike sands trapped behind backstop, draped over semblance data. The map shows thinning at the downdip side of the step, interpreted as erosion by flows at the toe of the step; the isochore pattern is indicative of a series of channels that eat away at the sediments at the toe of the step. Other thin areas in the isochore correspond to eroding channels, which cut across the step. C) Semblance slice (20 ms below horizon 2) highlights a single channel bypassing the central step following infilling of central-step accommodation.
Depositional and channel patterns changed as the slope topography was progressively filled. Initially, channels expanded outward from the updp feeder channel, depositing sheetlike deposits that are trapped behind the backstop (A in Fig. 7A, B). The toe of the step is bisected by an erosion front, which implies that bypassing flows eroded the top of the high as they proceeded to the Western Basin (B in Fig. 7A, B). During the early stages of step evolution, few channels linked from the feeder channel across the center of the step, although channels appear to bypass the step adjacent to the northwest diapir. In the upper part of the package (20 ms below top of package A), a single channel cuts across the center of the step (Fig. 7C).

From these observations, the depositional evolution of the step can be inferred. During the earliest stage of step evolution, flows entered the Central Step area via the Southern Channel. The flow expanded in response to the rapid decrease in confinement, forming a distributary network at the mouth of the canyon. Flows moving down slope were partially trapped behind a structural high, where flow stripping of the finer components occurred; there is little evidence for fully trapped flows on the step. Acceleration down the ramp caused erosion and formation of a knickpoint front that propagates updp. The erosion front eventually connected with the feeder channel to form a single bypass channel across the step. In addition, a number of flows bypassed the step entirely, forming a dense network of channels adjacent to the central diapir.

Lobe Evolution during Deposition of Package A.—

Perspective views of the Western Basin illustrate the depositional style in the area. Figure 6A shows a confined feeder-channel network that feeds large, dispersive lobe complexes, which were deposited in low-gradient, low-confinement areas beyond the Central Step. Package A comprises at least five wedge-shaped units that have a distributary character in plan view. They are interpreted as offlapping lobe complexes deposited as the locus of deposition switched through time. The size of each lobe complex was strongly dependent on the underlying topography. Internally, each of the units comprised lobe story sets that successively propagate basinward through extension of the channel network. In turn, each lobe story set is made up of smaller-scale lobe stories that are deposited at the termini of distributary channels (Fig. 6A).

Along higher-gradient sections, the distributary complex is characterized by highly discontinuous, high-amplitude reflectors (Fig. 7A), which appear as a dense network of channels in amplitude slices (Fig. 6A). Downdip, the distributary packages are less channelized and individual lobe stories can be identified (Fig. 6A); this change in character reflects a decrease in lateral confinement of the flows and slope gradient of the underlying topography. In the southwest, lobe story sets tend to be smaller and have discontinuous reflectors at intrabasinal highs; erosion of the southwestern high implies that flows escaped over the high and eroded the underlying deposits during deposition of the lobe story sets.

Higher up in the sequence, lobe story sets were deposited farther into the basin and were connected to high-amplitude channels that bypassed earlier deposits. As the lobes prograded into the basin, the feeder-channel system also extended basinward. Some of the earlier deposits were cannibalized, and lobes were deposited deeper and farther in the basin. Small channels linked up with the feeder channel to completely bypass the system.

Figure 6B summarizes the key observations described in the previous paragraphs. The dark blue lines represent the earliest feeder-channel system and the associated lobe complexes. The fans progressively shifted away from the structurally high region next to the central diapir, into the deepest part of the Western Basin, where they wrap around and abut against salt highs. Progradation of the depositional system into the basin is accompanied by intense channelization updp of the lobes. Knickpoints retreat updp as depositional progradation occurs deeper into the basin.

Feeder-Channel System.—

Package A was fed by the Southern Channel, which is an incised, moderately sinuous channel complex that cuts a path from the southeast to feed sediment to the Southern, Eastern, and Western Basins (Fig. 8A). Prior to deposition of package B, the erosional valley was infilled with moderately discontinuous high-amplitude deposits and no significant overbank deposition (Fig. 8B).

Package B deposits have an areal distribution similar to that of package A, with the addition of deposits in a small basin in the extreme east of the study area (Fig. 5B). Also similarly to package A, the depositional thick in the Western Basin is updp of the deepest part of the present-day configuration of the basin. Package B comprises laterally continuous, high-amplitude baselapping deposits in the Western Basin and adjacent to the Southern Channel, and discontinuous, high-amplitude reflectors in the Central Step between the basins. The initial deposits appear to be ponded in the Western Basin. The plan-view and sectional morphologies of package B are shown in Figure 9. The amplitude slice highlights the fan deposits fed by a distributary-channel network. Also highlighted are higher-amplitude areas across intrabasinal highs that correspond to increased channelization and dissection. The sectional view (Fig. 9C) highlights the high-amplitude, high-continuity nature of the sheets in the Western Basin; the distributary network shown in Figure 9B is characterized by subtle undulations in the sheetlike reflectors. Also highlighted in Figure 9C are a series of truncated horizons. These are interpreted as three knickpoint fronts that propagated updp, possibly from the intrabasinal highs at the toe of the Western Basin.

The Western Basin sediments were fed from the southern entry point. Flow expansion occurred at the entry to the Western Basin, via numerous small channels emanating from a central channel that appear as faint striations on amplitude slices (Fig. 9) and undulations in the highly continuous reflectors. The fan extends radially into the Western Basin, with rugose terminations to the north; in cross section, these appear as short, discontinuous reflectors that are interpreted as channels extending from the toe of the fan.

Both packages B and C are truncated to the south, and there is an angular discontinuity between these units and the overlying horizon at the base of package D. Truncation is greatest in the south of the Eastern Basin; the units become conformable in the north. Tilting of units adjacent to the southeastern salt high caused partial erosion of packages B and C.

Feeder-Channel System.—

The Southern Channel fed Package B (Fig. 8B), but in contrast to Package A, the channel complex is aggradational during package B time, with deposition inside and outside of the channel valley (Fig. 8B). A channel complex that is narrower and straighter
than observed during deposition of Package A bypasses these deposits. The complex splits into three channel networks that transect the Western Basin fan (Fig. 9).

**Package C**

Package C is found exclusively in the Western and Eastern Basins separated by thin deposits at the Central Ramp (Fig. 5C). Thin deposits in the Western Basin coincide with depositional thicks in both packages A and B. This observation implies that either (1) structural activity caused inversion of this zone from a topographic low to a high, or (2) deposition of packages A and B has caused subsequent compensational stacking. In this case, package B infills at the break in slope at the entry to the Western Basin, such that the slope gradient is increased. Thick deposits on either side of this location, and slight truncation of package C deposits, imply that depositional topography of package B causes focusing of package C deposition into downdip basins.

The seismic character of package C is similar to that of package A: high-amplitude reflectors with moderate continuity converge onto basin margins and have an internally shingled geometry. The presence of high-amplitude, discontinuous reflectors contained within a valley in the Eastern Basin indicates that sediment was fed through the Eastern Channel system. Analogous to Package A, the Western Basin contains distributary-lobe deposits that extend from the Central Step to the basin exits (Fig. 10).

**Lobe Evolution during Deposition of Package C.**

Package C comprises multiple lobe story sets that radiate outwards from the channel mouth at the entry point to the Western Basin (Fig. 10). Lobe story sets were deposited in the

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**Fig. 8.** A) Semblance slice 8 ms above minimum-curvature map of channel base. Inset shows location of map. B) Cross-sectional profile through channel, as indicated in Part A. Channel infills erosional valley prior to package B deposition. Channel is aggradational during deposition of package B.
FIG. 9.—A) Uninterpreted and B) interpreted amplitude slice (28 ms above base of package B), draped over basin topography to illustrate plan-view amplitude characteristics of Package B. Deposits with sheet-like characteristics in the updip basin and western basin are bisected by a through-going channel system. C) Seismic section illustrates wedge-shaped geometry with tapered edges of package B, and intense channelization across highs.

FIG. 10.—A) Uninterpreted and B) interpreted amplitude slice (55 ms above horizon three) illustrating distributary lobes wrapping around basin topography. Larger lobes infill greater accommodation space in the Western Basin; smaller lobes infill confined topography in the southwest of the study area.
Western Basin, and wrapped around the southern diapir, abut-
ting the opposite diapir to the west. Close to the top of the
package, small, highly channelized-flow deposits of low ampli-
itude were in the south of the area; remnant highs of previous
flows are preserved as zones of high amplitude in the data.
Assuming that the higher-amplitude fans are sandy, the de-
creased amplitudes of the later flows imply that they were
(possibly) muddier. These lobes infill topographic lows on the
surface of underlying lobe story sets. The larger bifurcation
angles and the recurrent widening and narrowing of the system
is related to underlying structural highs; the systems narrow
above fault highs, and the channels bifurcate downdip of highs.
Internally, the lobe story sets comprise at least three deposi-
tional elements: channels, lobe stories, and erosional remnants.
The channels range in character from braids to wider, straighter,
individual channels. Associated with the channels are erosional
remnants between channel elements, and depositional lobe sto-
ries at the channel termini and sides. The erosional remnants are
polygonal in shape (generally diamond-shaped, with the small-
est angle pointing upstream), and are generally of higher amplit-
itude than the channels.

**Feeder-Channel System.**

Package C was fed through the Eastern Channel System (Figs.
5C, 11). During this period, the channel flowed directly into the
Eastern Basin, and is highly sinuous with a tight loop along its
course (Fig. 11A, B), coinciding with an increase in basinal gradi-
ent. The valley is steep-sided, and there is no evidence for
overbank deposition at this time (Eastern Early Channel in Fig.
11C). The valley cuts across the current location of the diapir,
which implies that there was less structural relief at the time of
deposition, such that the flows cut across the area unhindered.

**Package D**

Package D deposits form a wedge-shaped complex that is
located exclusively in the southeast of the area, in the Eastern and

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**Fig. 11.**—A) Semblance slice close to the base of the eastern early channel, which feeds the distributary-lob complex of package C. Inset shows location of slice. B) Semblance slice at 8 ms above the base of the eastern early channel highlighting the tight loop along the channel course. C) Seismic section (red line in Fig. 9B) illustrating the incised nature of the eastern early channel. Package C infills the incised channel.
Southern Basin (Fig. 5C), with thicker isochores in a corridor between the basins, and in the feeder system. Moderate to high-amplitude shingled reflectors that are convergent to basin margins correspond to distributary-lobe complexes, and high-amplitude discontinuous reflectors contained within a valley are interpreted as confined-channel deposits. Figure 12 is an RMS amplitude extraction of package D, which highlights units with different seismic characteristics within the fan complex. Unit X comprises a distributary-lobe complex, which terminates at a high zone between two salt highs. Unit Y consists of a lower-amplitude distributary-channel complex with more sheetlike character down-dip, which is connected to an updip narrow channel belt, with high-amplitude deposits on the flanks interpreted as overbank deposits. Unit Z is a sheetlike fan in the Southern Basin (Fig. 12) that is connected to an updip channel.

The fan-scale evolution of package D can be understood in terms of changing topography as a result of progressive infilling of the depositional profile. In the initial stage, the Eastern Basin was a topographic low; sediment gravity flows entering the area from the east experienced flow expansion associated with rapid deceleration, inducing high sedimentation rates. Lobe complex X was deposited at this time, at the break in slope at the channel mouth. Sediments prograded outward to the next intrabasinal high. Although most deposition was in updip regions at this time, it is likely that finer-grained components of the flow passed over the topographic high. As topography was progressively filled, lobe complexes Y and Z built outward, bypassing the earlier deposits via incised-channel systems.

**Feeder-Channel System.**

Package D was fed through the Eastern Channel system, as a wider system than during deposition of package C (Fig. 11C). Sediments backfilled the entry point, and the channel complex eventually bypassed the Eastern Basin to flow northward (Fig. 13). The channel complex is highly sinuous with poorly preserved overbank deposits. The extreme width of the system implies that the system is either a relatively unconfined stack of channel complexes (and therefore not a confined-valley system), or is a low-relief channel system transitioning into a downdip unconfined-channel system. The data presented here do not allow differentiation of the two hypotheses. The Northern Channel cuts across the path of the Eastern Channel (Fig. 13A, B).

**Package E**

In contrast to the previous units, package E is found exclusively in the northern portion of the area (Fig. 5E), where it forms a wedge that thins to the south. The seismic character of the unit comprises low-amplitude, discontinuous reflectors, and the unit has a slightly erosional base in parts (Fig. 14B). Package E is interpreted as a mass-transport complex, comprising a chaotic volume of slumps and/or slides. It is unlikely to have been derived locally, inasmuch as it covers a very extensive area of over 300 km², and there is no evidence for large-scale slump scars in the vicinity.

**Package F**

Package F is at the top of the basin-fill sequence, and is characterized by moderate-amplitude reflectors with high continuity (Fig. 14). The unit is found in the northern portion of the area (Fig. 5F), and extends only a short distance beyond the southern edge of the MTC of package E (compare Figs. 5E and 5F). In the Western Basin, the package is thickest in the east, adjacent to the central diapir, and is thinnest over an intrabasinal high (Fig. 5F). Narrow channels mark an intrabasinal high (Fig. 14A).

**Feeder-Channel System.**

It is unclear which feeder system fed Package F, but it was likely fed by an early-stage Northern Channel system which later incised through packages E and F. Following deposition of package F, the channel system completely bypassed the area (Fig. 15). The Northern Channel flowed from east to west in the northern portion of the area (Fig. 15) and was highly sinuous. The system expands to the west, where it reaches its maximum width. The continuous, low-amplitude character of the channel fill (Fig. 13B) implies that the fill is mud-prone, and there is no evidence for levee development; these observations imply that sediment bypassed this part of the slope. The channel is interpreted as a bypass-channel complex, the youngest in the area of interest.

**DISCUSSION**

The characteristics of basin fill and slope channels can be used to interpret relative temporal relationships in the absence of direct dating of deposits. In this section, a basin-fill model is described (Fig. 16) and an evolutionary sequence is proposed (Fig. 17).

**Basin-Fill Model**

Basin fill comprises two couplets of distributary channels feeding lobe story sets ("distributary-lobe complexes" of packages A and C in Figs. 16A and 16C and sheetlike packages B and...
Deposition in the basin was dominated by distributary-lobe complexes that were influenced by slope topography: deposition occurred at breaks in slope where flow expansion occurs, resulting in depocenters that were positioned updip of basin lows and adjacent to the break in slope. Similarities include a distributive channel network and sheetlike elements arranged in fan patterns. There is an architectural down-fan decrease in channel elements in tandem with increasing sheetlike elements as inferred from seismic facies, and deposition fans out in a radial fashion from entry points. These observations are consistent with a model of decreasing flow velocity and turbulence and lower concentrations and sedimentation rates with distance from channel mouths (Beaubouef et al., 2003). Fans shifted away from structural highs and wrap around high topography. Progressive reduction in accommodation and progradation of the depositional front caused cannibalization of earlier deposits, such that many of the structural highs and updip regions in the basin are composed of stacked channels and intervening erosional remnants. Overall, there is an increase in the number of smaller lobe elements and the amount of channelization up through the sequence.

Although distributary-lobe complexes dominated deposition in the basin (packages A and C in Fig. 17), these units are separated by sheetlike units (package B and parts of package D in Fig. 17), which have very different characteristics. The distributary-channel complexes have extensive channel systems with significant facies changes across and along the fan. In contrast, the sheetlike packages have few channels and comparatively uniform seismic-amplitude characteristics. Updip deposition and
aggradational channel fill with overbank deposition are characteristics of sheet packages B and D that are not observed in packages A and C. Deposition of sheetlike units in packages B and D was followed by relocation of feeder channels. In this example, lobe complexes are progradational in nature. However, on a larger scale, fan couplets A-B and C-D show retrogradational stacking patterns, interpreted here as due to a waning feeder-channel system.

The final stage of basin filling involved complete bypass via large channel complexes. Package D is bypassed by an aggradational, sinuous channel system (Eastern Channel), but complete bypass of the area occurred via the Northern Channel system, which was infilled with low-amplitude muds.

The basin is characterized by a set of connected sub-basins without significant sills or three-dimensional closure, which implies that there is little or no ponded accommodation within the available dataset. Each depositional package shows evidence for sediment bypass as gravity flows passed from one basin to the next, with the possible exception of the earliest fill of package B into the Western Basin. This is typical of healed-slope deposits (Meckel et al., 2002; Prather, 2000; Prather and Pirmez, 2003), and is an important characteristic of stepped-slope basin. Where substrate subsidence rate is not fast enough relative to sedimentation rate to form sediment-trapping sills (Meckel et al., 2002). Although some basin fills have character similar to that of ponded basin fills in minibasin settings (convergent, continuous, baselapping facies), contemporaneous bypass of these zones indicate that these deposits were not truly ponded. The healed deposits were superseded by complete bypass of the system.

In common with perched fill deposits from the Gulf of Mexico (Beaubouef et al., 2003, Beaubouef and Friedmann, 2000, Prather et al., 2005), distributive channel complexes with both channel-form and sheetlike depositional elements dominate deposition, and depocenters are located updip of basin centers. These similarities imply that the study area will make a suitable analogue for “healed-slope” deposits elsewhere. Assuming that high amplitudes reflect sandy deposits, the abundance of possibly sandy distributary-lobe complexes suggests that the greatest proportion of reservoir sands will have a complex distribution: the fan complexes in these units are highly channelized, with a complex,
Fig. 16.—Basin-fill sequence, described in detail in the text.
Character and Evolution of Feeder Channels

The channel complexes described in this study range from erosional channel complexes (Southern Channel during deposition of package A, eastern early channel, Northern Channel) to low-relief, leveed-channel complexes (Southern Channel during deposition of package B, Eastern Channel following deposition of packages C and D). The valley-confined channel complexes are generally characterized by confinement within an erosional cut with channel story stacking as indicated by multiple high-amplitude, discontinuous reflectors. The Northern Channel is the only valley-confined channel complex that has low-amplitude, continuous reflector infill interpreted as muddy. This system was completely bypassed by sand, and the canyon was infilled by suspension fines, if the assumption of low amplitudes indicating finer deposits is correct. The overbank-confined channels have well defined overbank deposits and axial deposition. In general, the valley-confined channel complexes have lower sinuosity than overbank-confined channel complexes. The change from valley-confined to overbank-confined occurs abruptly: in the case of package A and B, it occurs at a single seismic horizon. The change may be due to a change in flow parameters, in that the aggradational channel of package B is associated with a decrease in flow volume as inferred from the deposition of relatively small-volume sheet sands. Slope gradient change may also have played a part, inasmuch as both the southern and eastern aggradation occurs after the downdip basins were substantially filled.

It is unclear from the available data what caused the shift in location of the feeder-channel complex through time. The most clear stratigraphic relationship is exhibited by the shift of the Eastern Channel to the Northern Channel. The Eastern Channel was cut off by the mass-transport complex of package E, and the Northern Channel cuts through packages E and F, which implies that rerouting of the channel system farther to the north was promoted by deposition of the large MTC. The location shift of the feeder channel during deposition of packages A–D is not clear, however, and was most likely controlled by updip topography changes that cause progressive northward shift in the system.

Departures from Predictive Models of Stratigraphic Architecture within Stepped Slope Systems

Idealized stepped-slope models effectively “freeze” variability of substrate and feeder system in order to describe a complete vertical succession. The basin-fill model here illustrates some of the variability that can occur due to changes in the (1) substrate, (2) feeder system, and (3) updip controls. For instance, structural growth caused erosional removal of package C, and confinement of package D in updip basins. Channel avulsion following deposition of packages B and D occurred before complete bypass of the system occurred, and waning of the channel system prior to avulsion is recorded in sheet-sand deposition prior to avulsion. Deposition of the mass-transport complex of package E precedes a complete change in the locus of deposition to the north of the area.

CONCLUSIONS

Local gradient controls location, size, and degree of cannibalization of depositional lobes.

- Deposition was dominated by offlapping, distributary channel–lobe systems that progressively shifted away from, and swung around, depositional highs.
- Bypass initially occurred via a wide channel network that eventually converged onto a single through-going channel. Bypass fronts at intrabasinal highs propagated updip with time, whereas the channelization front extended downdip.
- Lobes increase in number, decrease in size, and increase in channelization up through the section. Bypass channelization at intrabasinal highs and basinal exit points may have a significant impact on reservoir continuity.
• Within depositional packages, fan elements are predominantly progradational, but on a larger scale, depositional couplets have a retrogradational stacking pattern (i.e., the stratigraphically younger package is located in updip basins only), which probably reflects the influence of decreasing flow size prior to channel abandonment.

Depositional patterns strongly influenced by channel evolution.

• Earliest stages of channel evolution are characterized by large flows forming shingled distributary deposits. Prior to channel abandonment, the flows are smaller, and perhaps muddier, which gives rise to smaller lobes and more homogeneous amplitude characteristics.

• Channel avulsion has a first-order control on the locus of deposition. As a corollary to this, the classic stepped-slope depositional cycle from accommodation infill through to a graded profile with an erosional fairway may not occur in all parts of the basin, in that avulsion may take place before it is realized.

• Two of the three channel feeder systems have two-stage evolution: the first stage involved infilling of an erosional canyon, and the second stage involved development of low-relief levee systems.

• Channel feeder systems are controlled by (unknown) updip factors (east of the study area).

This example is applicable to weakly confined stepped-slope systems. It highlights some of the variability that is found in stepped-slope systems in a synkinematic setting, which results in stepped-slope systems in a synkinematic setting, which results in systems. It highlights some of the variability that is found in

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