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Controls on reservoir distribution, architecture and stratigraphic trapping in slope settings

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Abstract

Submarine sand reservoir distribution and architecture across slope and base-of-slope systems vary as a function of accommodation, sediment flux rates, substrate mobility and sand-mud content. Slopes evolve through time depending on rates of substrata mobility and sediment flux. Above-grade slopes with ponded accommodation are associated with highly mobile substrata and episodic or relatively low sediment flux. Stepped slopes are associated with less mobile substrata and relatively high rates of sediment flux. Graded slopes are associated with less mobile substrata. Sheet sand deposition on above-grade slopes results from ponded basin 'fill-and-spill' processes. Pinchout of ponded sands into slope drapes deposited around ponded basins form lateral seals for the onlap traps common in this setting. Sheet sands are also found in basin floor positions and at the toes of graded (unconfined) slopes associated with stable substrates. The break in slope onto the basin floor provides a key setting for the deposition of both sheet and channel sands. Pinchout of sands or onlap onto the slope form the updip stratigraphic components forming stratigraphic traps with the potential for large hydrocarbon accumulations.

Keywords: Slope types; Reservoir architecture; Slope evolution

1. Introduction

A world-wide comparative analysis of subsurface reservoirs shows that slope topography is an essential element influencing the distribution, quality, and architecture of submarine reservoirs (Fig. 1). Slopes classified on the basis of topography differentiate into (1) above-grade slopes with well-developed ponded accommodation and large amounts of mid- to upper-slope healed-slope accommodation (e.g. Gulf of Mexico), (2) above-grade slopes characterized by stepped profiles that lack well-developed ponded accommodation (e.g. Niger delta slope, Lower Congo, NW Borneo: Fig. 2), and (3) graded slopes (Fig. 3) that lack significant topography (e.g. eastern Gulf of Mexico).

Reading and Richards (1994) sub-divide continental slopes into 12 classes based on grain-size (mud-rich, mud/sand-rich, sand-rich and gravel-rich) and feeder system configuration (point-sourced, line-source and multiple-sourced). Richards, Bowman, and Reading (1998) ascribe predictive value to this classification scheme and describe a '*modus operandi*' for reservoir description and prediction in three stages of investigation: (1) basin screening, (2) fan delineation and (3) fan characterization. Richards and Bowman (1998) further describe a predictive arrangement of architectural elements that form the basic building blocks of each system. All together these papers describe a conceptual framework for the classification of slope types.

Combining Reading and Richards (1994) concepts of sediment supply and concepts for submarine accommodation shows that a majority of the world's recent deepwater discoveries occur in reservoirs from muddy above-grade slopes on passive margins (Fig. 4A and B). This contrasts with the past when the majority of submarine sand discoveries were made in shallower water and/or onshore sand-rich basins associated with graded slopes in a variety of tectonic settings.

The objective of this paper is to describe the distribution of these reservoirs with respect to slope type and accommodation, and characterize significant aspects of their reservoir architecture and stratigraphic trapping as they pertain to hydrocarbon exploration and production.

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Fig. 1. Locations of fields and regions referred to in this paper.

2. Accommodation

The highest concentration of reservoirs along muddy slopes occurs in middle slope and toe-of-slope regions in variety of accommodation, including ponded, healed-slope, and incised submarine valley (compare Figs. 2–4A). Accommodation is the space available for deposition (Vail, 1987). Accommodation on a submarine slope is

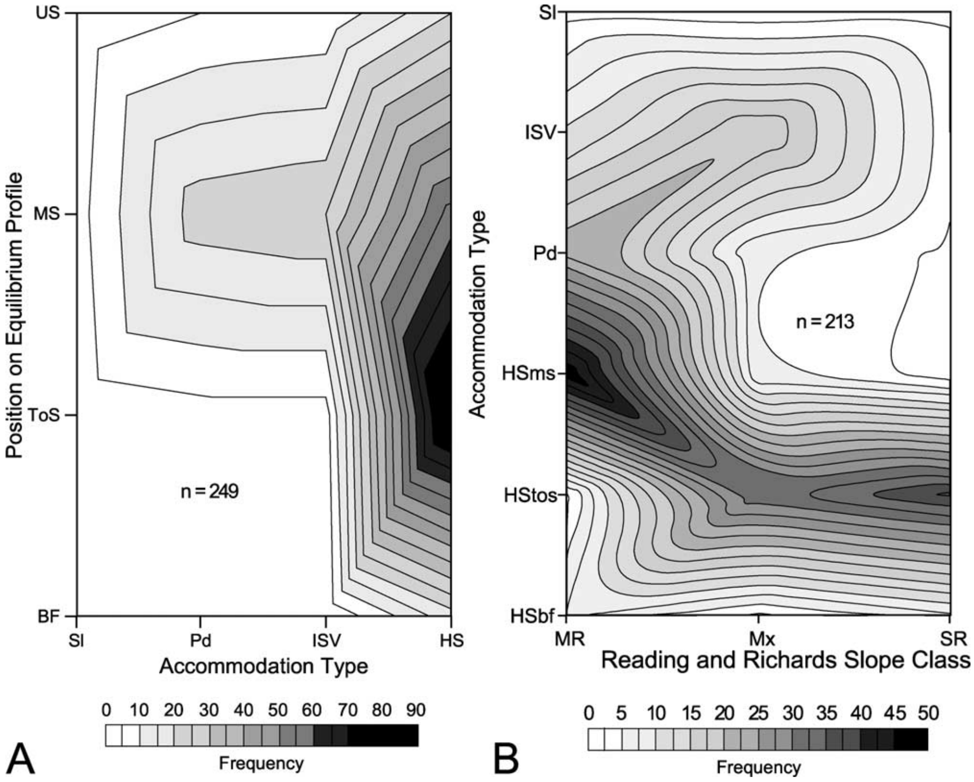

Fig. 2. (A) Chart shows the frequency distribution of reservoirs from various basins with respect to accommodation and position on the equilibrium profile. (B) Chart shows the frequency distribution of reservoirs from various basins with respect to accommodation and Reading and Richards (1994) slope class. Explanation: accommodation: ISV, incised submarine valley, canyon or gorge; Sl, slope, HS, healed-slope; (HSms, healed-slope in a mid-slope position; HStos, healed-slope in a toe-of-slope position; HSbf, healed-slope in a basin floor position); Pd, ponded. Position along Equilibrium Profile: US, upper slope, MS, mid-slope, ToS, Toe-of-Slope, BF, basin floor. Reading and Richards Slope Class: MR, mud-rich, MX, mixed sand and mud, SR, sand-rich.

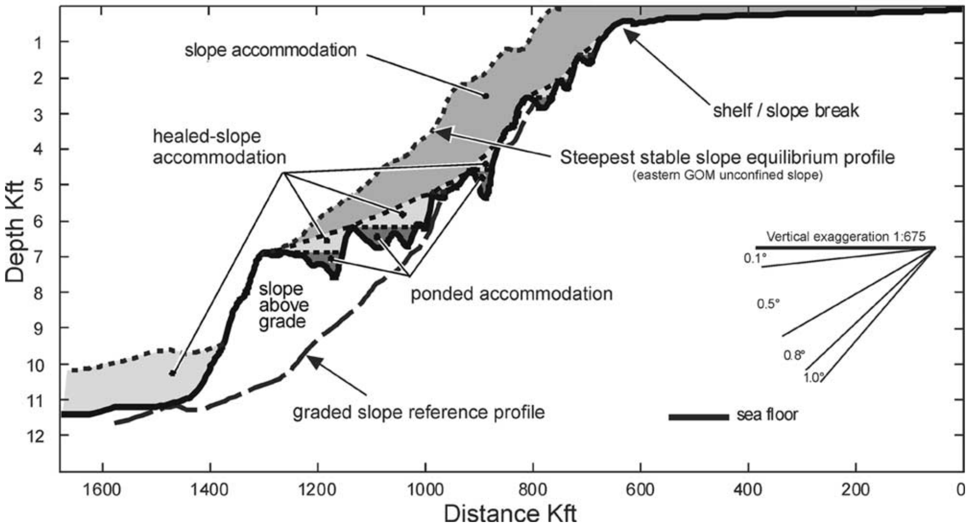

Fig. 3. A seafloor profile shows the distribution of accommodation on an end-member above-grade slope profile with ponded basins from the central GOM (modified from Prather, 2000).

governed by the topography of the depositional surface and its graded, or steady state profile (Section 3). Several types of accommodation exist across most continental slopes: (1) ponded; (2) healed-slope in upper-slope, mid-slope, lower-slope, toe-of-slope, and basin floor positions; (3) slope; and (4) incised submarine valley (Figs. 2 and 3). These accommodation types are descriptive and can have a variety of infilling stratigraphic architectures.

2.1. Ponded accommodation

Ponded accommodation lies within three-dimensionally closed topographic lows (doubly-plunging synclines) on continental slopes (Prather, 2000; Prather, Booth, Steffens, & Craig, 1998; Fig. 2). Ponded accommodation typically forms within intraslope basins as the result of localized withdrawal of mobile substrates, typically salt or shale, but may also be related to structural movements unrelated to withdrawal processes. In areas of salt-based withdrawal, ponded accommodation is usually circular to semi-circular and increases into the distal part of the basin. In areas of shale withdrawal, ponded accommodation commonly takes the form of long, linear to arcuate, doubly-plunging synclines located landward of out-board deep-water thrust belts or within the hanging-walls of faults that cut the seafloor at the time of deposition. 'Fill-and-spill' processes dominate deposition on slopes with ponded intraslope basins eventually forming low gradient stepped-equilibrium profiles (Prather et al., 1998; Satterfield & Behrens, 1990; Winker, 1993; Fig. 2).

Ponded accommodation should not be confused with the *Ponded Facies Assemblage* as defined by Prather et al. (1998). The Ponded Facies Assemblage as identified in the Gulf of Mexico consists of multiple, stacked sand-rich convergent-baselapping, chaotic and draping seismic facies (Prather et al., 1998; Fig. 14). The Ponded Facies Assemblage where is overlain by the mud-rich *Bypass Facies Assembalge* that together represent the largest

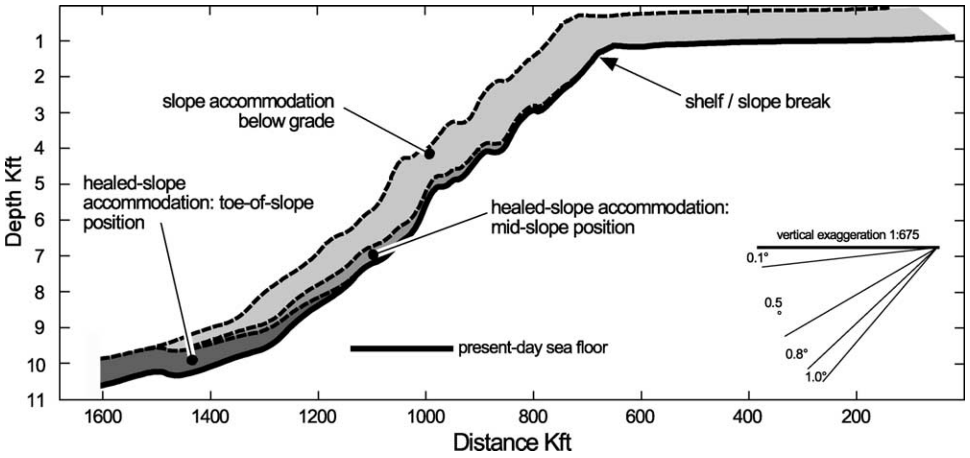

Fig. 4. A seafloor profile across eastern GOM shows the distribution of accommodation on a graded slope profile GOM (modified from Prather, 2000).

startigraphic divisions in the central GOM slope and record deposition over millions of years. Use of the term 'ponded' here attempts to highlight its association with confined styles of deposition over long periods of time within intraslope basins where there is a predominance of convergent-baselapping facies and is not meant to imply that all sediment in the assemblage was deposited solely within ponded accommodation. Booth, Dean, DuVernay, and Styzen (2003) demonstrate that the Ponded Facies Assemblage in the Auger Basin consists of sediments deposited within both ponded and healed-slope accommodation.

2.2. Healed-slope accommodation

Healed-slope accommodation, where it is found across mid-slope regions, is the space above the stepped-equilibrium profile and higher angle equilibrium profiles associated with wedge-shaped slope deposits that taper both landward and seaward (Prather, 2000; Prather et al., 1998; Figs. 2 and 3). It closely corresponds with the space occupied by *perched slope fill* of Beaubouef and Friedmann (2000). As original defined by Prather et al. (1998) and modified in Prather (2000) healed-slope accommodation was conceptual and based on a single 2D transect across the central Gulf of Mexico slope, offshore Louisiana. Healed-slope accommodation now more rigorously defined in 3D by Steffens, Biegert, and Sumner (2003) is the space between the top of ponded accommodation and below a 3D convex hull fit to the rugose seafloor topography. Their analysis shows that healed-slope accommodation is more common and volumetrically greater than ponded accommodation on all slopes studied. The shape of healed-slope accommodation varies from circular and elliptical pods where associated with ponded intraslope basins to more strike-oriented curvilinear elongated ellipsoids on shale-based stepped slope profiles.

On above-grade slope where rates of sediment flux exceed rates of intraslope basin subsidence, a stepped profile can form across a series of filled ponded basins. Sand deposition occurs preferentially near the base of healed-slope accommodation forming upward fining sequences generally associated with cyclic arrangements of sand-rich lobes or sheets and channels (Booth et al., 2003; Prather & Pirmez, 2003). The channels form submarine fans, locally perched on middle to upper parts of slopes where they deflect around topographic highs. Areally extensive mass wasting also occurs as slopes steepen beyond local critical angles during deltaic progradation and/or basinward tilting. The top of healed-slope accommodation forms a base for later unconfined slope progradation.

2.3. Incised submarine valley accommodation

Incised submarine valley or submarine canyon accommodation occurs across many slopes and represents the space created by submarine erosion. Incised submarine valleys are not to be confused with incised valley fills as used in Vail et al.-style sequence stratigraphic terminology (Posamentier, Jervey, & Vail, 1988). Incised valley fills typically contain shallow marine to fluvial deposits. Incised submarine valleys are dip-oriented u-shaped to v-shape erosional features on submarine slopes typically filled with a variety of channel deposits. Significant unconformities form the bases of incised submarine valleys within and between slope systems. Although submarine valleys are typically much larger than channels, size ranges overlap so that scale alone is not diagnostic.

2.4. Slope accommodation

Slope accommodation is the space between the highest stable graded-slope angle and the top of healed-slope accommodation or other older lower-grade depositional profiles (Prather, 2000; Figs. 2 and 3). Stable graded slope angles vary from place to place as a function of pore pressure within muds deposited on the slope. High pore pressure reduces the shear strength of these muds contributing to mass wasting and re-grading of slope deposits that reach some critical angle. Sea-floor escarpments also limit the amount of slope progradation (Ross, 1989). Differentiation of healed-slope from slope accommodation is in practice quite difficult in mid- to upper-slope parts of most slopes. Additionally where identified, it appears to have little associated sand (Fig. 4) and therefore, will not be considered in discussions to follow.

3. Slope types

Type and distribution of accommodation, and the relationship of the depositional surface to an idealized or hypothetical graded profile differentiate above-grade and graded slope types. The hypothetical or idealized graded profile represents the long-term equilibrium between deposition and erosional processes on the continental slope. Relatively smooth, concave-up depth profiles along the courses of submarine channels, where correlated with channel properties such as sinuosity and valley gradient are indicative of slope equilibrium or grade (Pirmez, Beaubouef, Friedmann, & Mohrig, 2000). These profiles grade to submarine baselevel, which is the deepest point, reached by sediment gravity flows in the basin (Pirmez et al., 2000). Local sets of erosional and depositional processes, in what Ross, Halliwell, May, Watts, and Syvitski (1994) refer to as the slope readjustment model, maintain these graded profiles (Ross, 1989; Ross, Watts, & May, 1995; Thorne & Swift, 1991). Channel and slope profiles from regions of the continental margins unaffected or less affected by tectonics, such as the eastern Gulf of Mexico profile as used in Fig. 3, provide a reference for classifying slopes in this paper. Slopes classified on the basis of topography in this way can be differentiated into: (1) above-grade slopes (Fig. 2) with either well-developed enclosed intraslope basins (e.g. GOM), (2) a class of above-grade slope that exhibits subtle changes in depositional gradient resulting in low-relief stepped or terraced topography, lacking well developed ponded basins (e.g. present-day Niger delta and NW Borneo slopes), and (3) graded slopes that lack significant topography (e.g. eastern Gulf of Mexico, Fig. 3).

3.1. Graded slopes

Large amounts of healed-slope accommodation in basin floor and toe-of-slope positions and absence of ponded accommodation distinguish graded-slope systems from above-grade slope systems (Section 2). Because graded-slope systems lack the ponded, and large amounts of healed-slope accommodation in mid-slope regions that distinguish above-grade slopes, stable slope angle and subtle topography become the dominant controls on deposition. As a result, bypass characterizes the upper parts of graded slope profiles, and unconfined deposition dominates the toe-of-slope and basin floor regions. The amount of healed-slope accommodation across both mid- to lower-slope is controlled in part by the volume of basin floor and toe-of-slope deposits, and seafloor topography caused by faulting and submarine slides.

Little sand deposition takes place across mid-slope, probably because slope gradients tend to be too steep. This is especially acute on sandy systems where slopes tend to be both steep and short. Rates of mud deposition across mid-slope play a major role in controlling slope angles. Low angle slopes occur in association with high rates of sediment flux. High rates of sediment flux result in overpressured shales with low shear strength and low stable slope angels. Reservoir distribution therefore reflects a tendency for deposition on lower positions of the equilibrium profile as the sandiness of the slope system increases (Fig. 4B). The majority of submarine reservoirs on graded slopes, as a result, occur at the toes-of-slopes, but only locally across the middle parts of graded slope systems within a combination of slope and healed-slope accommodation, which are the types of space that dominate graded-slope systems.

Although few reservoirs are penetrated in the basin floor in most slopes systems (Fig. 4A and B) recent drilling suggests that this part of graded slope systems can be quite sandy even in systems that are overall muddy (e.g. Niger delta slope or GOM). The paucity of reservoirs penetrated in muddy toe-of-slope and basin floor settings at the time of this study (ca. 1998) probably reflects more a sampling bias introduced by water-depth and drilling-depth limitations in the various muddy systems along continental slopes currently undergoing exploration. These limitation include both (1) lack of deep drilling in many relative shallow-water (<1000 m) continental slopes to sufficient depths to penetrate the underlying unconfined basin-floor fan systems, and/or (2) lack of drilling for unconfined basin-floor fans in present-day abyssal plains outboard of muddy slopes. Lobate distributary sheet sands, levee/overbank and leveed channels representing classical submarine fan systems are expected reservoirs types in this setting (Droz & Bellaiche, 1985; Galloway, 1998; Mutti & Ricci Lucchi, 1975; Normark, 1970; Normark, Piper, & Hess, 1979; Walker, 1978, 1985). The presence of areally extensive dip-elongate pod- and sheet-like reservoirs (HARP's) penetrated in the Amazon fan during ODP Leg 155 (Flood, Manley, Kowsmann, Appi, & Peirmez, 1991) suggest additional reservoir types may exist in muddy basin-floor settings. The lack of extensive sand on graded slope sourced with sand-rich flows probably reflects the inefficiency of high-concentration turbidite flows in carrying sands beyond the toe-of-slope and well out onto the basin floor. Under these conditions sandy submarine aprons preferentially occupy healed-slope accommodation at the toes-of-slopes (Fig. 4B).

3.1.1. Unconfined or bypass slopes

Although reservoirs in mid- to upper-slope positions of graded slopes are relatively less common than other settings, they do represent significant targets in the eastern unconfined slope the Gulf of Mexico. SE Tahoe, Mensa, Ram/Powell, and Tahoe fields (Kendrick, 2000) typify reservoirs from this setting. These reservoirs are highly discontinuous regionally, as the sands are deposited very near the equilibrium profile and are therefore susceptible to erosion and dissection by younger gravity flows and submarine slides. The combination of erosion and lap-out of sands across the slope produces erosional remnants that later become stratigraphic truncation traps (Fig. 5). Reservoir sand deposition occurs on portions of the slope that are locally below the regionally graded profile in either incised submarine valleys or slide scars. These localized depressions on the slope tend to capture gravity flows moving across the slope. Sand deposition above the graded profile across open unconfined slopes occurs only in association with leveed-channels as either thin-bedded levees or channel-fills confined between levees (Fig. 5). These leveed-channels complexes form across lower gradient portions or steps on the slope equilibrium profile.

Reservoirs in this setting tend to be one seismic wavelet thick or less; have shoestring plan geometries, where associated with channel fills confined between levees; and ribbon and pod plan geometries where associated with levees and incised submarine valleys or slide scars. Perched oil–water contacts observed in the Ram/Powell N sand suggest that reservoirs in these settings may not have uniform hydrocarbon sweep, suggesting complex subseismic architectures consisting both shale baffles and barriers (Kendrick, 2000).

The tendency for lower slope gradients across the eastern Gulf of Mexico, due to high rates of mud deposition, may explain in part why mid-slope

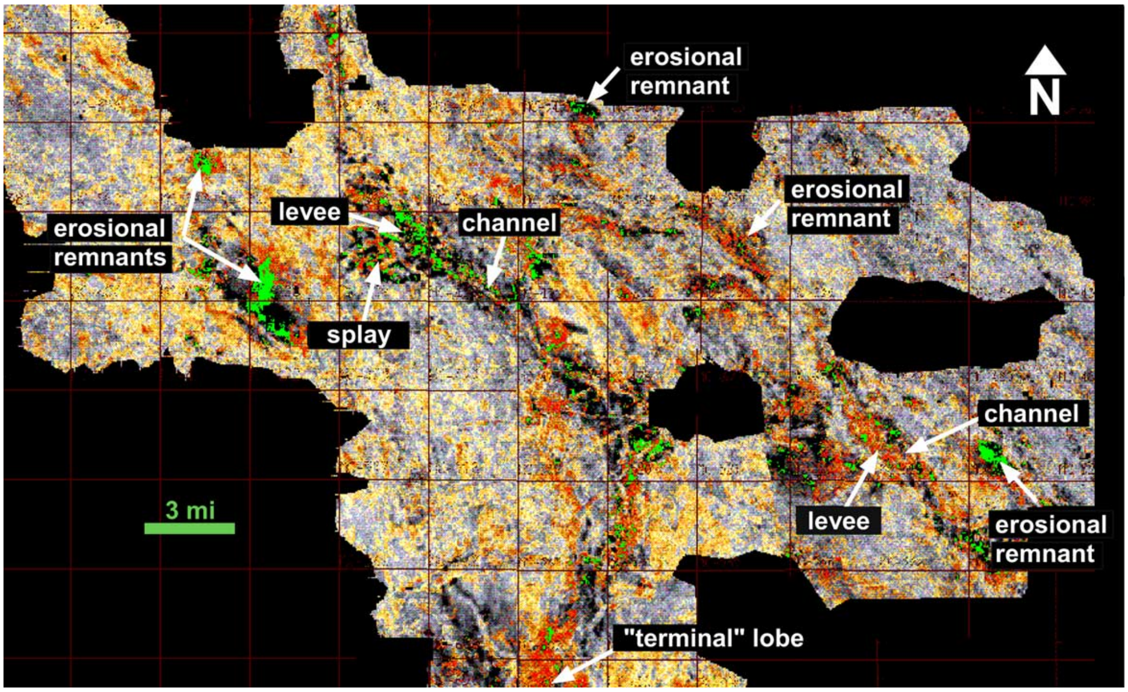

Fig. 5. Horizon slice through the unconfined eastern Gulf of Mexico mid-slope.

leveed-channel reservoirs are so common here and not in other unconfined slope systems. The thin discontinuous ribbon, pod and shoestring nature of these reservoirs suggests economically viable developments in these settings may prove challenging. The complex external, seismically mappable scale and subsiesmic scale architectures require the use of three-dimensional seismic data for mapping reservoir distribution and inferring subsiesmic reservoir architecture required for static reservoir model construction.

3.1.2. *Toe-of-slope*

Reservoirs in toe-of-slope settings are very common even on muddy slopes. Fields such as Marlim and Albacora East (Campos basin, Brazil, Carminatti & Scarton, 1991; Peres, 1993), Schiehallion, and Foinaven, (west of

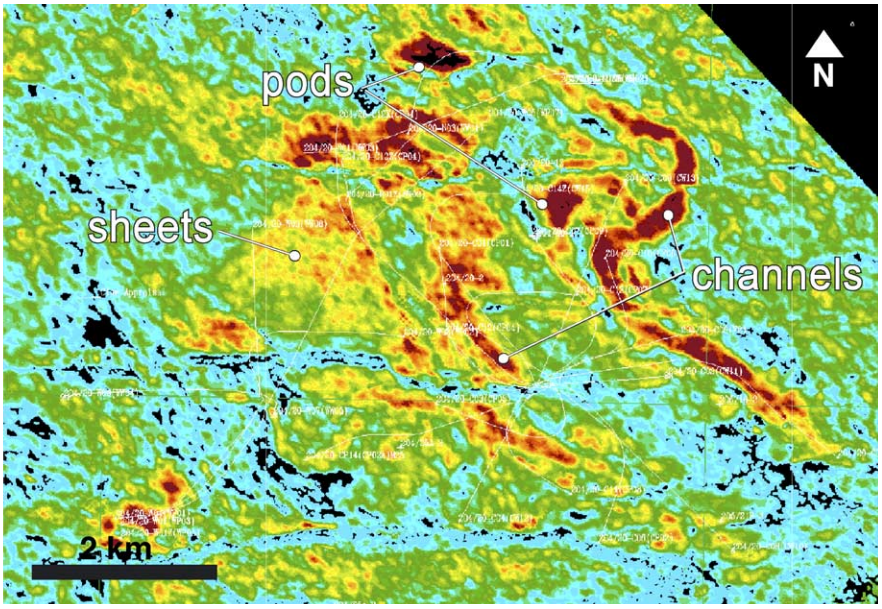

Fig. 6. Gated amplitude extraction from three-dimensional seismic data over Schiehallion field, West of Shetlands, UK, showing plan geometry of reservoir components.

Shetlands, UK, Straccia & Prather, 1999), and Mejillones (Carupano basin, offshore Venezuela, Straccia & Prather, 1999) typify reservoirs from this setting. Deposition in the toe-of-slope occurs as the result of many down-slope processes widely described in the geological literature. Gravity flows sourced by high-flux muddy deltas or collapse of progradational delta fronts that build beyond some critical slope angle collect at the toe-of-slope. In these sand-rich, mud-lean settings sands can bypass the upper- and mid-slope regions, forming sandy submarine fans or aprons, because there is insufficient mud in the system to rapidly prograde the slope. These sand-rich slopes tend to occur in tectonically active areas, and have sand-rich sediment sources (e.g. Paleogene North Sea, West of Shetlands, and California). Toe-of-slope fans in muddy slopes are expected to have similar facies associations and sand distribution patterns as well as large-scale leveed-channel complexes more akin to modern big-river fans like those of the Mississippi (Feeley, Buffler, & Bryant, 1985; O'Byrne, Halder, Berman, Klecker, & Martinez, 1999; Weimer, 1990), Indus (Deptuck, Steffens, Barton, & Pirmez, 2003; Droz & Bellaiche, 1991; McHargue, 1991; Kenyon, Amir, & Cramp, 1995; Naini & Kolla, 1982), Amazon (Damuth, Flood, Kowsman, Belderson, & Gorini, 1988; Flood et al., 1991; Pirmez & Flood, 1995) and Bengal (Hubscher, Speiβ, Breitzke, & Weber, 1997; Weber, Wiedicke, & Kudrass, 1997) systems.

Reservoir plan geometries at the toe-of-slope include amalgamations of mostly sheets, pods and ribbons with a few shoestrings elements (Fig. 6). These plan geometries suggest environments of deposition typically associated with submarine fans ranging from predominately submarine valley fills, fan lobes, fan channels and a few channel-levee complexes.

Significant hydrocarbon accumulations exist in toe-of-slope settings, most notably in the Campos basin, offshore Brazil. The multi-billion barrel Marlim field is the largest of them. The break in slope onto the basin floor provides a key setting for the deposition of laterally continuous turbidite sands. Pinchout of reservoir sands or onlap onto the front of the slope form the updip stratigraphic components to these turbidite stratigraphic traps. Leakage of hydrocarbons via feeder systems connected to turbidite sands at the toe-of-slopes probably represents the main trap risk in this setting. Disruption of these thief zones resulting from faulting, slumping, and massive fluid escape promotes stratigraphic trapping (Straccia & Prather, 1999, 2000). Lateral and downdip trapping elements include sand pinchouts and truncation against localized salt or shale diapirs, monoclinal dip and faulting.

3.2. Above-grade slope

Presence of ponded accommodation and/or large amounts of mid- to upper-slope healed-slope accommodation distinguish above-grade slope systems (Fig. 2) from graded-slope systems (Fig. 3). Movement of mobile substrates, either salt or shale, forming outboard structural highs, stepped bathymetric profiles and intraslope basins characterize above-grade slopes. The amount of healed-slope accommodation across both mid- to upper-slope is ultimately controlled by the height of an outboard high such as the Sigsbee salt nappe in the GOM or the ultra-deepwater salt-cored ridges such as those of the lower Congo slope.

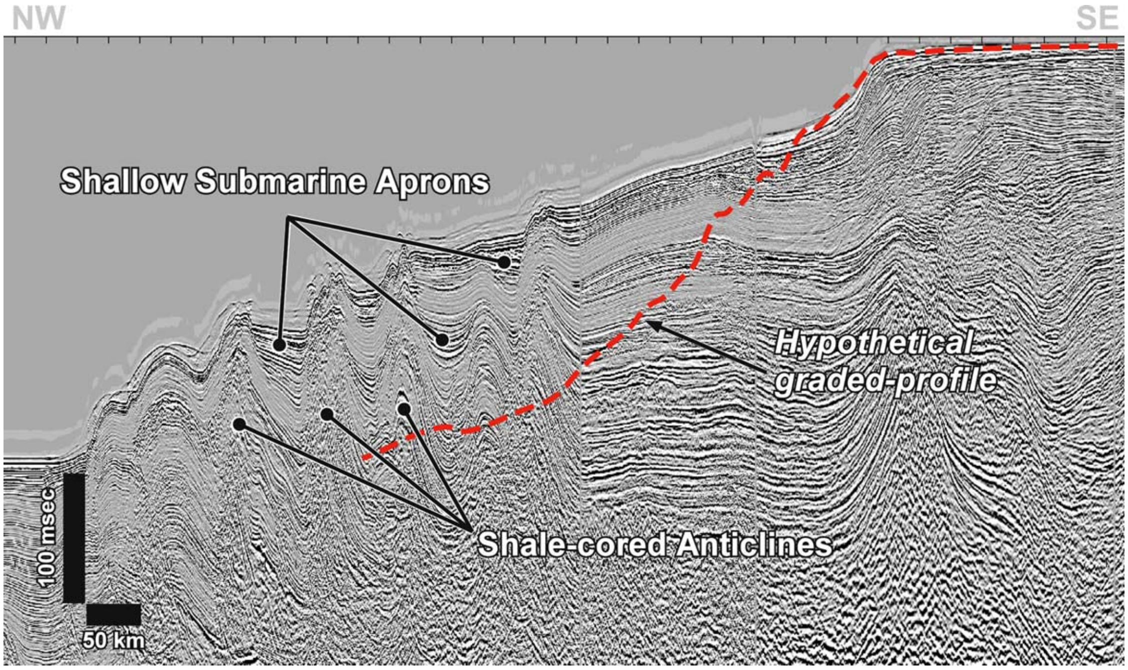

Fig. 7. Seismic section showing a typical shale-based above-grade slope with shale-cored anticlines and shallow ponded basins. The reference graded profile comes from the unconfined slope from the eastern Gulf of Mexico.

In areas of salt-based withdrawal, salt movement along the seaward edge of either allochthonous or autochthonous salt bodies controls the height of the outboard high. The height of the outboard high in shale-based slopes is controlled by the height of shale-cored, out-board thrust belts (e.g. Tarakan, Mahakam, Baram and Niger slopes).

The presence of ponded-basin accommodation is sensitive to relative intraslope basin subsidence and sediment flux rates (Prather, 2000). Slope systems with high rates of intraslope basin subsidence are typically associated with highly mobile salt substrata. Some salt-based slopes, where the rates of sediment flux are high relative to rates of intraslope basin subsidence, however, tend to evolve into stepped above-grade slopes more akin to shale-based slopes (e.g. Lower Congo slope).

Intraslope basins in salt-based withdrawal slopes, such as the Gulf of Mexico evolve from earlier ponded basins to 'perched' bypass slope deposits (Booth, DuVernay, Pfeiffer, & Styzen, 2000; Booth, Prather, & Steffens, 2002; Prather et al., 1998). Shale-based slopes commonly evolve from early, unconfined, graded-slopes into stepped above-grade slopes with minor shallow intraslope basins and submarine aprons (Fig. 7). Delay in formation of above-grade condition in shale-based slopes reflects slow response to sediment loading as sufficient overpressures build to the point where the shales become mobile or late stage tectonic movements. The steps are typically related to syndepositional tectonics feature such as shale-walls, toe thrusts, normal faults, or wrench-folds. Movement of these structural elements produce the steeper and flatter intervals associated with stepped profiles (Fig. 7).

The resulting topography of above-grade slopes dominates deposition. Much sand deposition takes place across the upper and especially mid-slope portion of above-grade slopes. These sands occur in nearly equal numbers in both ponded and healed-slope accommodation with fewer sands in slope and incised submarine valley accommodation (Booth et al., 2002; Prather et al., 1998). Submarine sands are also found along stepped or terraced slopes, but these reservoirs are more poorly understood and have only been extensively drilled as of late. These sands are associated with incised slope canyons and gorges containing highly sinuous sandy channel complexes, and are especially common across portions of the Lower Congo slope system (Fig. 8).

3.2.1. Intraslope basins

Reservoirs from intraslope basins are common in the Plio-Pleistocene of central mid-slope Gulf of Mexico, where they are primary exploration targets. The central Gulf of Mexico mid-slope region is the archetype above-grade slope system with ponded intraslope basins. Here highly reflective convergent-baselapping facies represent the seismic manifestation of fill-and-spill depositional processes (Booth et al., 2000, 2002; Prather et al., 1998). Few slope systems in the world have as well developed highly reflective convergent-baselapping facies as in the Gulf of Mexico. Although, some thin highly reflective convergent-baselapping facies characteristic of shallow ponded accommodation are present in the slopes of the Lower Congo basin, Baram and Niger slopes.

Reservoirs from intraslope basins tend to occur in two settings: (1) as ponded sheet-sands and (2) as slope wedges consisting of mixed sheets and channels (Booth et al., 2002). Troika, Macaroni, and parts of Mars (Meckel, 2002) fields typify ponded sheet sand reservoirs. There is much ponded sand in the Gulf of Mexico, however, traps more commonly occur in healed-slope wedges than ponded sheet-sands because healed-slope wedges tend to be in structurally higher parts of intraslope basins and lie directly below top sealing condensed sections (Booth et al., 2002). Auger, parts of Mars, Princess, Mensa, Llano, Glider, and Baldpate fields typify reservoirs from the healed-slope setting. The presence of ponded accommodation is sensitive to relative intraslope basin subsidence and sediment flux rates (Prather, 2000).

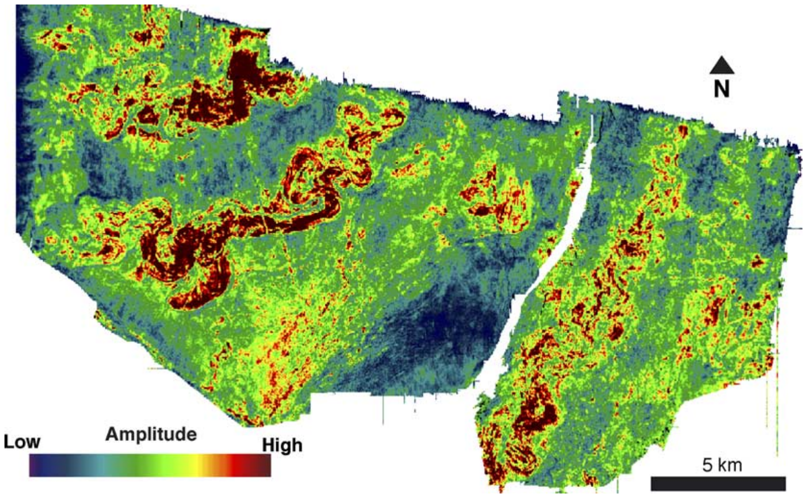

Fig. 8. Gated amplitude extraction from lower Congo slope showing highly sinuous amalgamated channels within incised slope canyons (Sikkema & Wojcik, 2001).

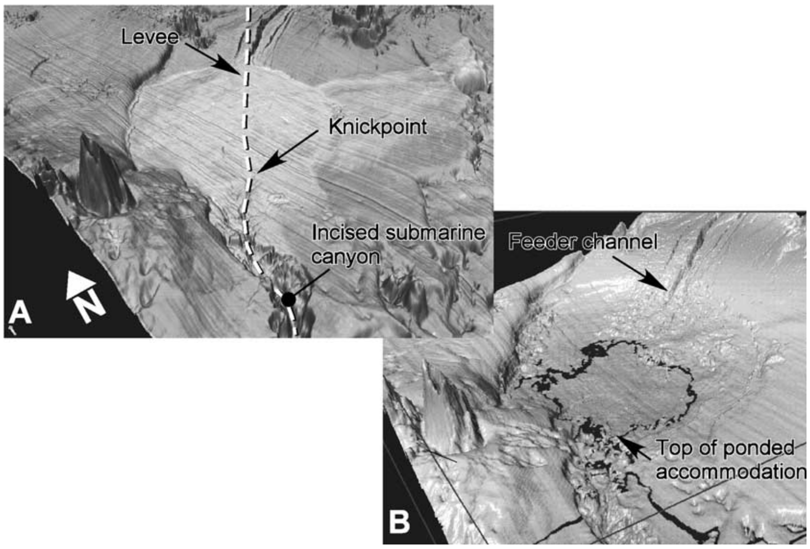

Fig. 9. Image of the top (A) and base (B) of the upper slope confined fan from offshore Nigeria showing seafloor features on the top of the fan and the amount ponded accommodation, entry channel system and an incised submarine canyon at the exit of the basin. Dashed line indicated location of section shown in Fig. 12.

Slope systems with high rates of intraslope basin subsidence are typically associated with salt withdrawal.

The idealized sequence within typical intraslope basins begins with deposition of coeval submarine fans consisting of distributary channels and lobes at the base of the local slope break below the basin entry point and more sheet-like deposits down slope in ponded accommodation (Fig. 9; Booth et al., 2003). Depending on the composition of the flows entering the basin, these fans form either nearly horizontal sheets or wedges (Booth et al., 2003; Smith, 2003). Healing of the slope with deposition of slope wedges occurs locally in the proximal part of some intraslope basins as deposition of ponded fans continues distally (Beaubouef & Friedmann, 2000; Booth et al., 2000). Bypass, erosion and formation of a topographic 'knick' at the spill-point begins as the ponded accommodation fills in the distal part of the basin and gravity flows spill down-slope as the sill separating the up-slope basin from the down-slope basin is topped (Fig. 10), similar to the process described by Pirmez (2000), Beaubouef and Friedmann (2000) and

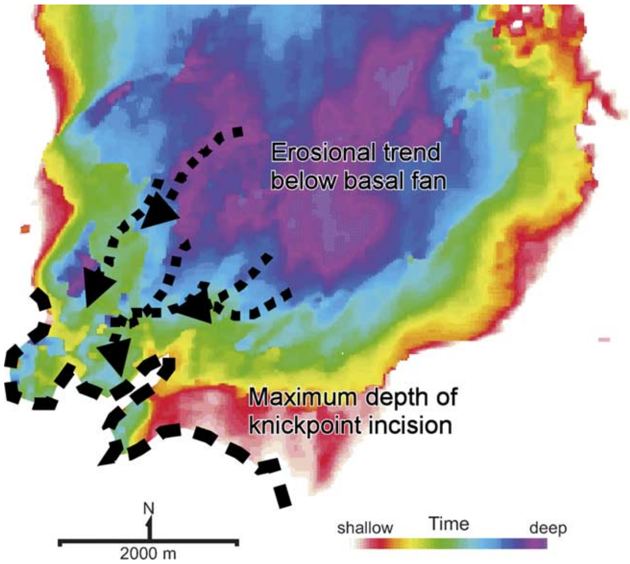

Fig. 10. Structure map at the base of the upper slope confined fan (Fig. 9) shows dip-oriented channels formed from bypass of flows across the ponded fan at the base of fill sequence.

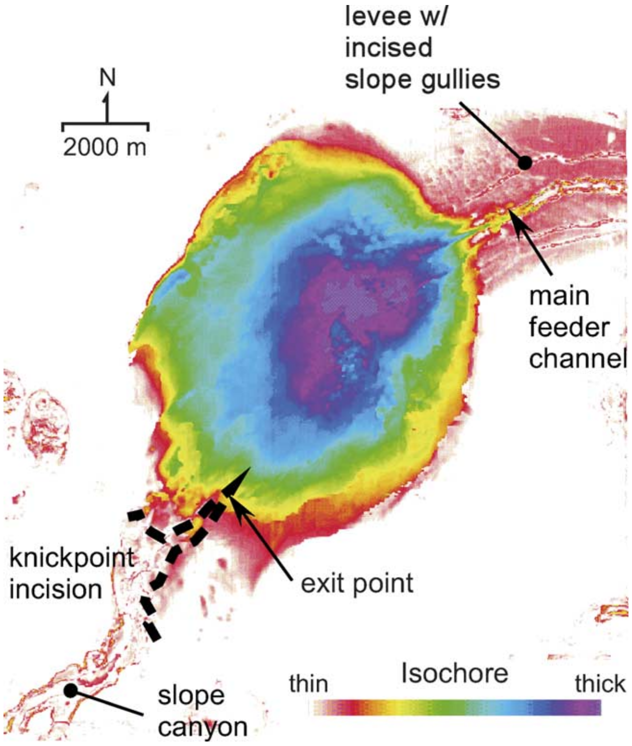

Fig. 11. Isochore map of upper slope confined fan (Fig. 9) showing leveed feeder channel and smaller slope gullies flanking feeder channel. Note the incision beneath knickpoint at exit of the basin.

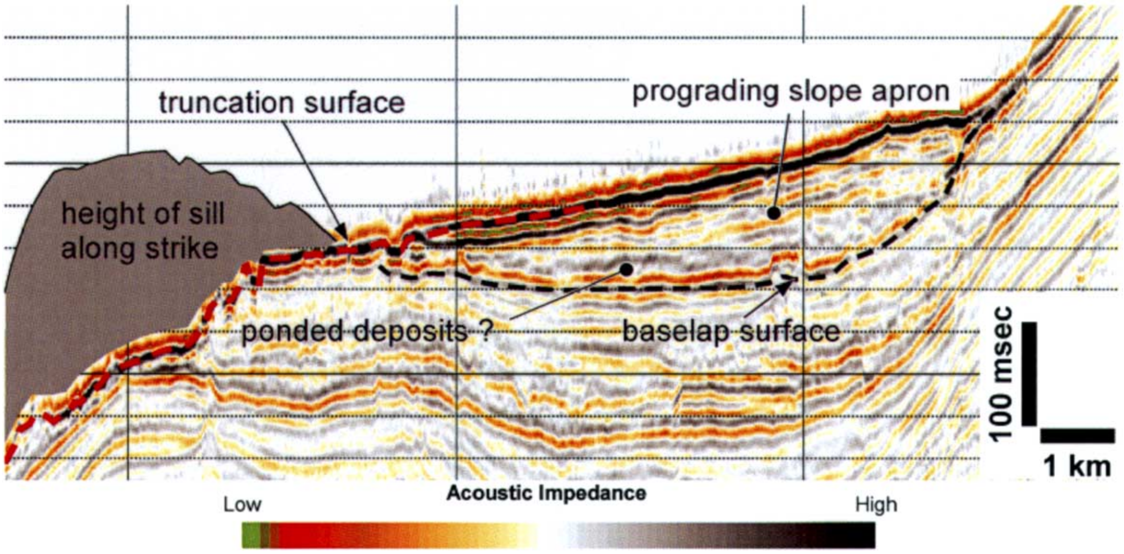

Fig. 12. A prograding slope apron overlies the ponded fan at the base of the fill sequence.

Booth (2003). Progradation of a submarine fan follows within healed-slope accommodation. Truncation of the prograding fan follows as knickpoints migrate across the fan up-slope from the distal part of the fan at the basin spill point (Figs. 11 and 12). Where these knickpoints migrate across the entire basin, the feeder channels connect directly to the basin spill-point. Connection of these features can promote coarse-grained sediment bypass in upper parts of the slope wedge as flows are directed to the next outboard basin. Muddy gravity flows and/or hemipelagic deposits drape the basins after the slope grades to the new equilibrium profile, or there is a decrease in sediment influx resulting from either a rise in eustatic sea level or slope-system avulsion (Booth et al., 2000, 2002; Prather et al., 1998).

High sand:shale ratios in highly reflective convergent-baselapping facies result from high density turbidite deposition and/or large-scale flow-stripping processes associated with areas of (1) abrupt reduction in seafloor gradient or (2) reversals of slope. Areas of abrupt reduction in seafloor gradient at the entry points of ponded intraslope basins produce conditions conducive to formation of hydraulic jumps (Haughton, 1994). Deceleration and spreading of sediment gravity flows beyond the hydraulic jump results in fall-out of a significant amount of entrained coarse sediment from turbulent suspension. Large-scale flow-stripping processes occur as finer-grained sediment that remains in suspension are then transported further downslope as the upper portions of turbidite flows overtop basin sills. Sand deposition also occurs in response to the collapse of gravity flows upon encountering slope reversals associated with downdip salt highs or counter-regional faults similar to the process described by Haughton (1994) and Kleverlaan (1994) from ponded basins in Spain and confined Tertiary turbidite basins in the Alpine regions of southeastern France (Sinclair & Tomasso, 2002).

Large-scale flow-stripping processes (Piper & Normark, 1983) can occur in these settings as clays and silts, suspended due to local turbulence, are carried by the momentum of the flow over the salt high or fault scarp and out of the basin, similar to processes observed in flume studies (Alexander & Morris, 1994; Edwards, Leeder, Best, & Pantin, 1994; Kneller & McCaffrey, 1995). The efficiency of this process in depositing sand depends on the height of flow entering the basin relative to the height of the outboard basin sill. Where sill height is high relative to flow height the majority of the flow, both sand and mud, will be ponded in the basin. Where the intraslope basin is shallow flow-stripping can be more efficient in depositing sand because suspended muds will more easily of top the sill. Convergent-baselapping seismic facies, the most sand-prone seismic facies in the Gulf of Mexico, consists of on average of 70% mud (Prather et al., 1998) suggesting high sill heights relative to flow heights. Booth et al. (2003) demonstrates this relationship at the scale of individual reservoirs in Auger basin.

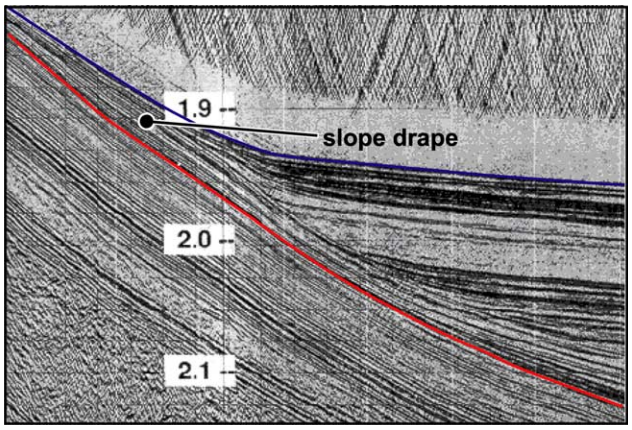

Fig. 13. Slope drapes on the flank of a near-seafloor ponded basin from the GOM. Note the continuation of onlapping events up the basin flank.

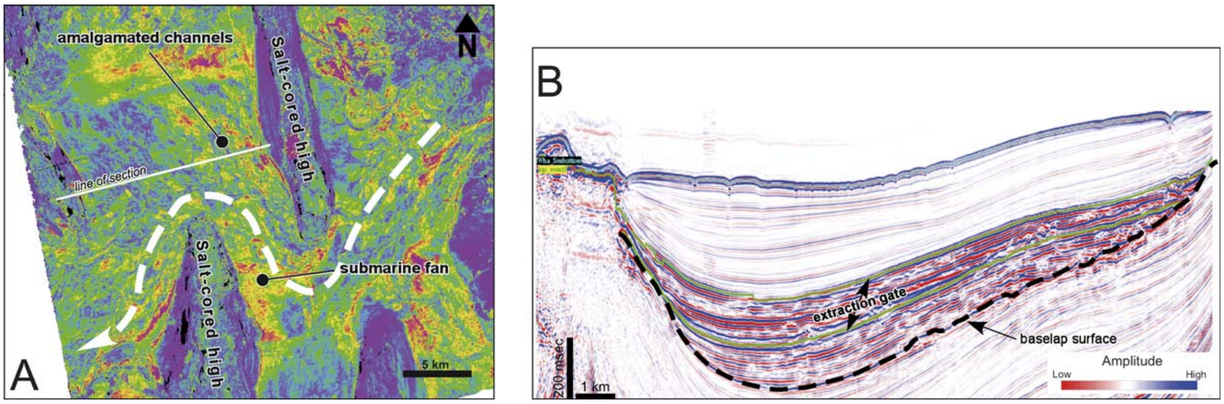

Fig. 14. Horizon slice through the near-seafloor sediment prism from west Africa (A). Tortuous corridors is indicated with dashed line. Amplitudes extracted across as shown in B. Seismic section shows external convergence, internal baselap and high reflectivity through a sediment prism from west Africa (B). Note amplitude map (A) comes from extraction gate as indicated.

Pinchout of ponded sands into slope drapes deposited around ponded basins form lateral seals for the onlap traps common in this setting (Fig. 13). Slope drapes are fine grained, thin-bedded units that drape the depositional profile external to higher net-to-gross submarine sands. Drapes form from a combination of hemipelagic/pelagic suspension fall-out as well as fall-out from the fine-grained suspended portion of turbid flows (Kneller & McCaffrey, 1999). Since silts and fine sand are carried in the fine-grained portion of turbid flows and since turbid flows have the potential to run-up on topographic highs (Kneller & McCaffrey, 1999), these silts and sands can be carried up and over topographic highs draping them with silt and sand laminae forming waste and thief zones for stratigraphic traps found in this setting. A similar process carries fine-grained sediment out of channels into levee and overbank positions.

3.2.2. Stepped-profiles

Two-dimensional sections across stepped above-grade slopes with complex slope topographies locally have convergent thinning and convergent baselap seismic facies (Figs. 7 and 14B) that appear similar to sections through the intraslope basin province of Plio-Pleistocene Gulf of Mexico slope. However, three-dimensional seismic data in these areas show that apparent sub-basins are in fact connected in the third dimension (Figs. 14A and 15). This type of sediment-receiving depression on a topographically complex slopes are termed a ‘connected tortuous corridor’ by Smith (2003) to distinguish them from ponded intraslope basins like those from the Gulf of Mexico. Although seismic evidence for reservoirs in this setting is common, few are penetrated to date. Probably most the representative of them comes from the Carapeda field, Campos basin, Brazil (Smith, 2002, personal communication). Reservoirs in Carapeda field are confined to a NNW-SSE to WNW-ESE oriented troughs on the slope resulting from subsidence along listric faults (Moraes, Becker, Monteiro, & Netto, 2000). The Carapeda reservoirs are laterally continuous, high net-to-gross sheet and channel complexes with elements that show thinning-upward patterns related to evolution from confined to unconfined deposition (Moraes et al., 2000).

An excellent example of reservoir architecture in this setting comes from the near-seafloor of offshore Angola. The lower Congo slope is a salt-based above-grade slope. Intraslope basin structure and fill architecture varies along strike, from north-south trending elongate salt-withdrawal troughs and more equi-dimensional intraslope basins in the north to more strike oriented troughs in the south. The near seafloor geology in southern regions of the basin show map-view patterns within the troughs, highly suggestive of complexes of amalgamated channels. Depositional patterns suggest the channels deflect around linear salt-cored structure highs (Fig. 14A) producing localized fans on the inboard sides of salt ridges. Map-view patterns also show abrupt changes in channel trends with deflections and convergence within gaps toward and between the salt ridges, and distributary patterns emanating from gaps into the more unconfined troughs basinward.

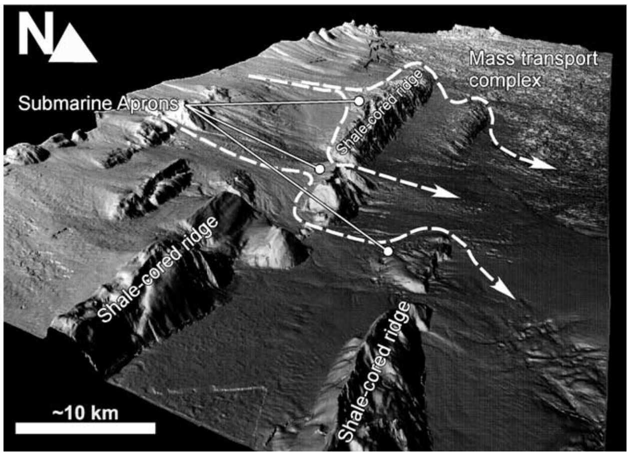

Fig. 15. Sediment prisms located on the landward sides of shale-cored ridges from northwest Borneo (courtesy of Petroleum Geo-Services). Tortuous corridors are indicated with dashed lines.

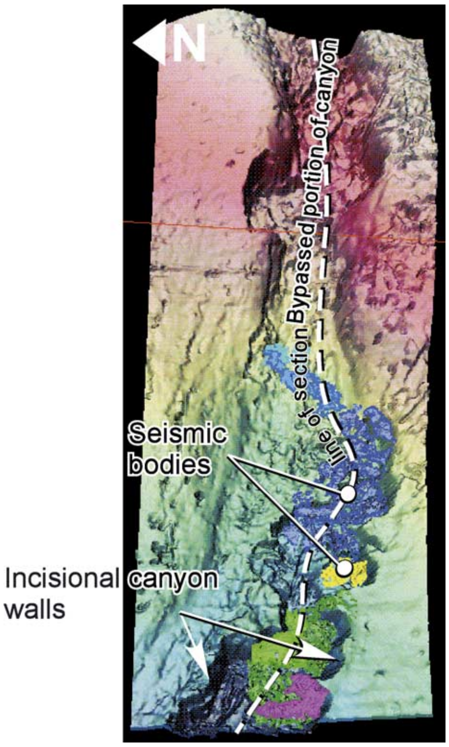

Fig. 16. Perspective view of the canyon fill shows the distribution of seismic bodies within the incised portion of canyon. Dashed line indicates location of section shown in Fig. 17.

Significantly, the seismic facies characteristics of this amalgamated channel and sheet complex shows external convergence, internal baselap and high reflectivity, easily confused with truly ponded basins similar to those seen in the Gulf of Mexico (Fig. 14B).

3.2.3. Slope canyons

Many of the recent discoveries in west Africa have reservoirs within incised submarine canyons, valleys and gorges. Numerous recent discoveries from offshore Angola, Nigeria and Equatorial Guinea (Andrea, Bloch, & Webb, 2000; Barrett, Ruiter, Schirmer, & Kapela, 1998; Kolla, Bourges, Urruty, & Safa, 2001; Mayall & Stewart, 2001; McHargue, 2001) typify reservoirs from this setting. These reservoirs consist of variably amalgamated sinuous shoestring, pod and ribbon shaped sand bodies. Formation of slope canyon systems can occur on graded, above-grade ponded and above-grade stepped slopes, but those that occur on above-grade stepped slopes are significantly more common.

An excellent example of a typical broadly confined canyon-fill comes from the near-seafloor of west Africa (Fig. 16). Here high frequency seismic displays the details of morphology and geologic features. This example is situated on a stepped or terraced above-grade slope that lacks intraslope basins with ponded accommodation, as are many recent turbidite discoveries principally on the continental slope of west Africa (Fig. 17). The near-seafloor canyon shows a complex fill history within a broadly confined, upper slope submarine canyon (Fig. 18). The sequence of depositional events above seismic horizon 7.3 begins with (1) incision of an older canyon fill by down-cutting submarine channels forming a board canyon floor (Fig. 16), (2) deposition of highly-amalgamated, high sinuosity channel elements within a chaotic seismic facies confined within the resulting incised submarine valley accommodation (Fig. 19A and B), (3) deposition of a less tightly confined

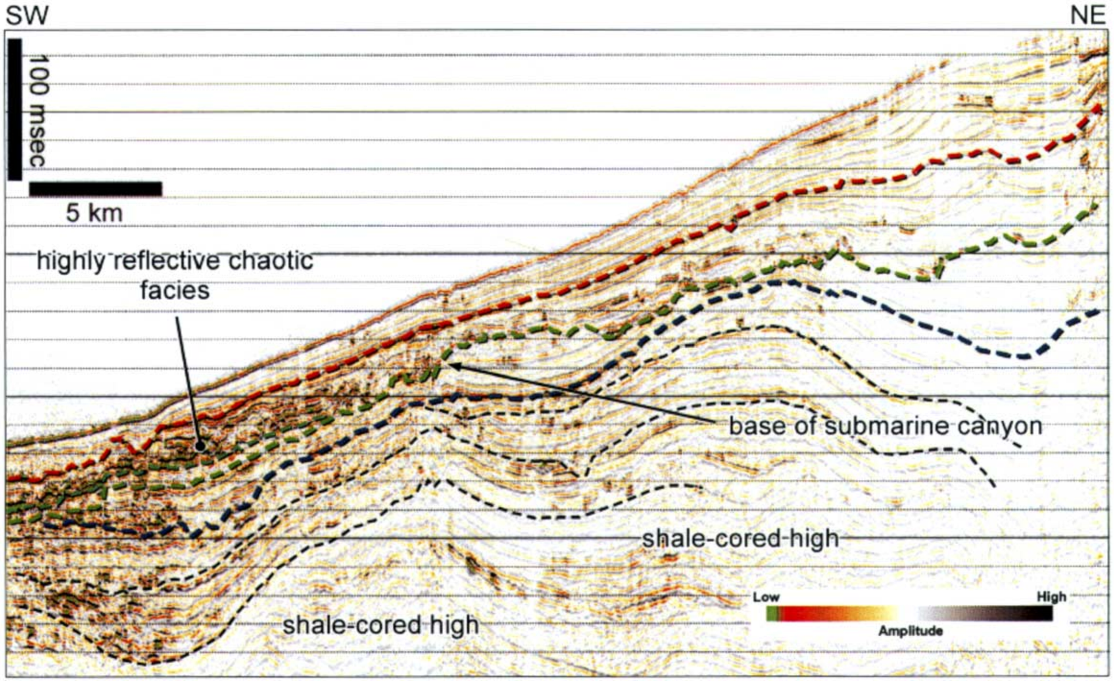

Fig. 17. Seismic section down slope within canyon from upper slope of Niger delta slope showing erosion at the base of a canyon fill and seismic facies types.

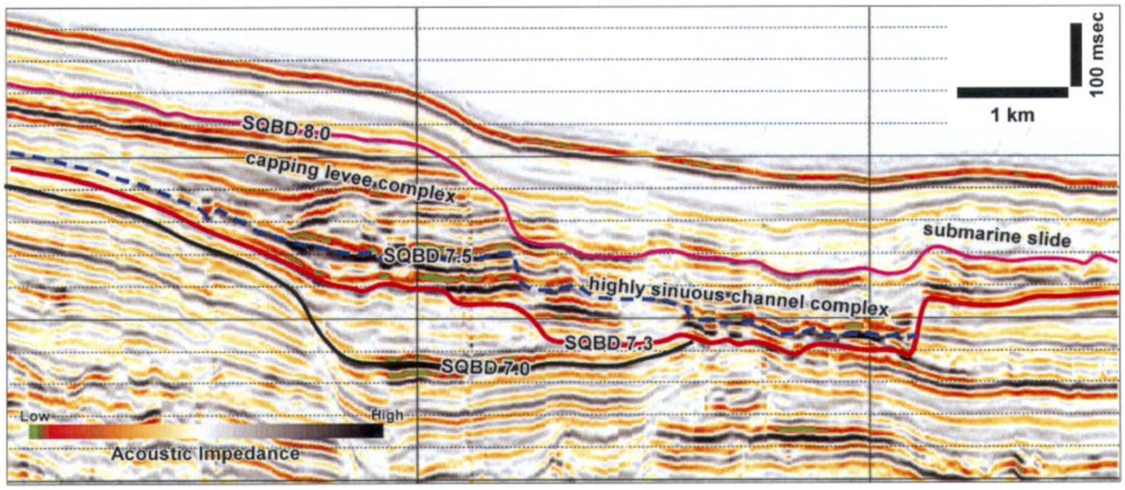

Fig. 18. Seismic section across canyon fill showing interpretations of reflection configurations. Note removal of right-hand levee resulted from erosion associated with a submarine slide.

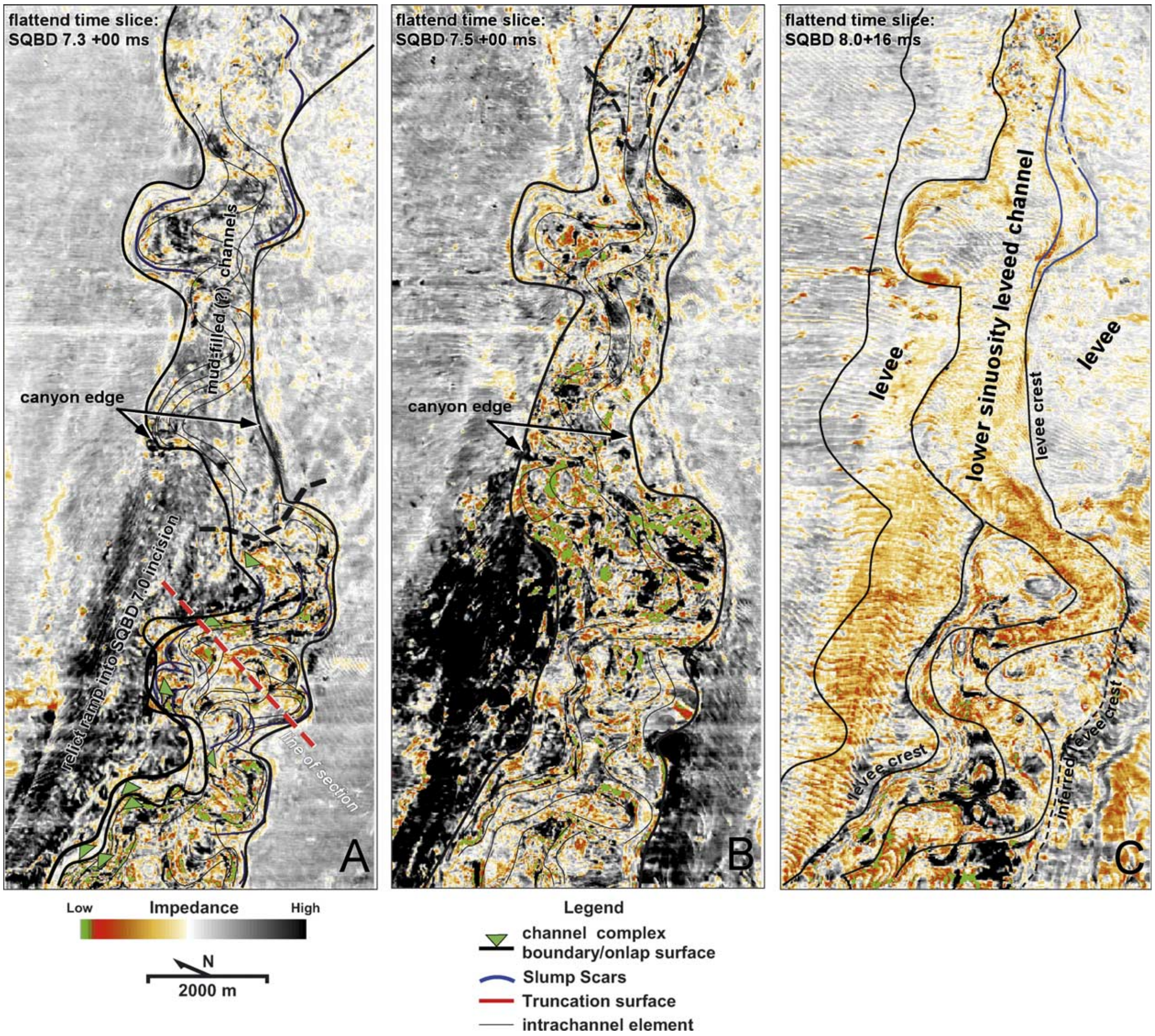

Fig. 19. Horizon slices from near the base of the canyon shows chaotic seismic facies within near the base of incised submarine canyon (A). The canyon is filled with highly sinuous amalgamated channel (?) elements that progressively backstep during filling (B). Dashed line indicates location section shown in Fig. 18.

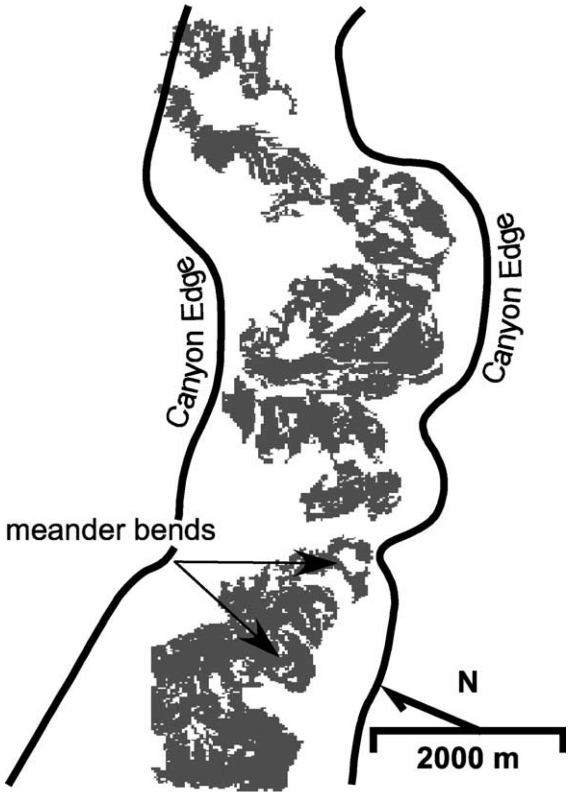

Fig. 20. Detail of seismic bodies extracted from three-dimensional data volume over the canyon fill showing sinuous sweeping patterns suggestive of lateral migrating channels.

complex of highly-amalgamated channels ending with, (4) a sinuous leveed-channel (Fig. 19C). The pod and ribbon plan geometries result from erosion of individual channel elements into one another. A submarine slide subsequently removes most of the southern levee at the end of this depositional episode (Figs. 18 and 19C).

The chaotic seismic facies of loosely-amalgamated highly reflective, shoestring and pod-like bodies characterize the highly amalgamated, high sinuosity channel complex in the middle part of the canyon fill (Fig. 18). A more continuous, moderately reflective seismic facies characterizes the capping, lower-sinuosity leveed channel (Fig. 18). In this case there seems to be little evidence of sand within the channel confined between these levees based on the lack of reflectivity at the bottom of the canyon floor (horizon 8.0, Fig. 17).

Seismic bodies isolated from within the canyon fill have distinctive sinuous shapes and sweeping plan geometries suggestive of migrating channels (Fig. 20). These patterns are similar to patterns observed in other submarine canyon fills as well as fluvial systems (Roberts & Compani, 1996; Kolla et al., 2001; Peakall, McCaffrey, & Kneller, 2000). Plan view maps also show that these seismic bodies have complex edges which might not be easily resolved by conventional seismic. These edges could represent dead-ends not easily swept during development and production. Static reservoir modelling of canyon fills is therefore problematic for most deep-water operators where connectivity, tortuousity, and sweep efficiency associated with these reservoirs can affect estimates of recoverable reserves, well number and well placement. This is why the highly discontinuous external and internal (subseismic) architectures associated with these reservoir types present development challenges not encountered with sheet sand reservoirs that characterize the predominant reservoir type of above-grade slopes with ponded accommodation.

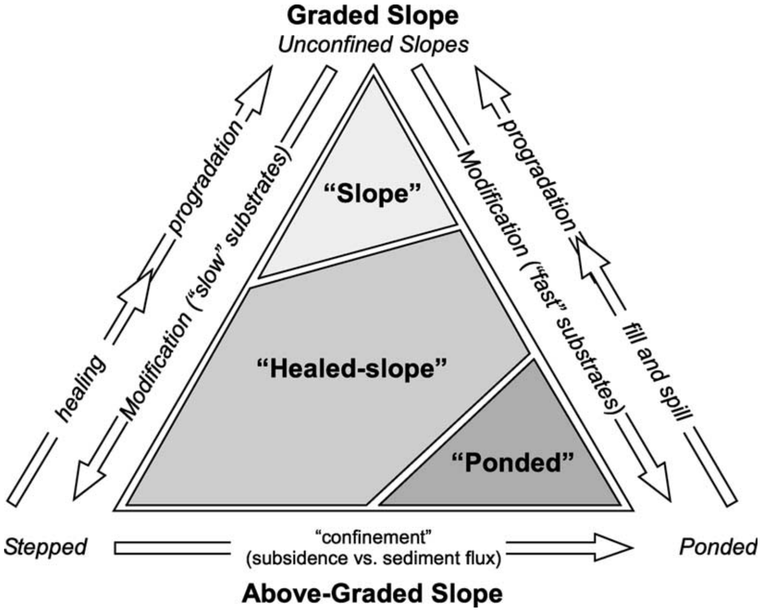

Fig. 21. Ternary diagram (modified from Meckel, Ibrahim, & Pelechaty, 2000; Booth et al., 2002) showing slope type end-members and key processes controlling graded to above-grade slope transitions.

4. Discussion

The three types of slopes described here: (1) above-grade with ponded basins (2) stepped or terraced and (3) graded represent end-members in a continuum based on the degree of substrata mobility and sediment flux (Fig. 21). Slopes that lack mobile substrata tend to be graded. The dominant processes controlling sand distribution on graded slopes are bypass and erosion. Sediments bypassing higher gradient upper- and mid-slope regions of graded slopes supply aggradational turbidite sequences in onlapping wedges at the toe-of-slope and deep basin. As the onlapping fan-apron grows, the basin depth shallows providing a platform over which the slope progrades. (Ross et al., 1994). Where there is insufficient aggradation of fan-apron deposits at the toe-of-slope progradation of the slope is slow. Under conditions of slow progradation, sands such as those on the upper- and middle parts of the eastern Gulf of Mexico graded slope (Fig. 5), remain at or near the equilibrium profile, where they are subjected to erosion by subsequent gravity flow processes reducing their preservation potential.

Slopes with highly mobile substrata tend to form above-grade slopes. Above-graded slopes tend to evolve from early, unconfined, graded slopes into above-grade slopes. Forward models show that optimal combinations of sediment supply relative to uplift of mobile substrates and down building of intraslope basins is critical to the creation of above-grade slopes with ponded basins (Prather, 2000). These models suggest that episodes of high sediment flux must be followed by episode of little sediment flux in order to form ponded accommodation, the key feature distinguishing ponded and stepped above-grade slopes. Above-grade slopes with stepped profiles therefore characterize regions where sediment accumulation rates exceed rates of intraslope basin subsidence. Steffens et al. (2003) demonstrate that salt-based above-grade slopes have significantly more volume of ponded accommodation (25% across the central GOM mid-slope) than lower mobility salt-based stepped profiles such as the Lower Congo Slope and shale-based stepped profiles such as where the amount of ponded accommodation is generally less than 2%.

Without ponded accommodation, the sand content of the entire slope system can drop, because there is less accommodation to capture sandy gravity flow deposits (Prather, 2000). Sand deposition tends to occur within incised submarine canyons as we have observed on typical stepped above-grade slopes. This suggests that above-grade slope systems, without episodic sediment fluxes, are less likely to have the thick ponded basin successions, than slope systems with highly variable sediment fluxes like the GOM (Prather, 2000).

5. Conclusions

1. The highest concentration of reservoirs along muddy slopes occurs across mid-slope and toe-of-slope regions in a variety of accommodation types including ponded, healed-slope, and incised submarine valley
2. Turbidite reservoir architecture across slope environments also varies as a function of accommodation. Sheet sands tend to be found in ponded accommodation and channel sands tend to be found in incised submarine valleys.
3. Sand deposition occurs preferentially near the base of healed-slope accommodation where it is generally associated with cyclic arrangements of sand-rich sheet overlain by channels in an overall upward fining sequence.
4. Many of the recent turbidite discoveries associated with stepped or terraced above-grade slopes occur as belts of highly sinuous ribbon and shoestring channel sands.
5. Slopes evolve through time depending on rates of substrata mobility and sediment flux. Above-grade slopes with ponded accommodation are associated with highly mobile substrata and episodic sediment flux. Stepped slopes are associated with less mobile substrata and relatively fast rates of sediment flux. Graded slopes are associated with immobile substrata.

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