INTRODUCTION

The study of near-seafloor deepwater landscapes and the processes that form them (Normark, 1970; Piper, 1970; Coleman and Bouma, 1984) are as important to the understanding of deeply buried marine depositional systems as the study of modern fluvial environments is to our understanding of ancient terrestrial depositional systems. In fact, these near-seafloor studies follow in the great tradition established by earlier clastic sedimentologists (e.g., Fisk, 1947; Lowman, 1947; Shepard et al., 1960; Shepard, 1964; Bernard and LeBlanc, 1965; Le Blanc, 1975) in using modern systems to understand ancient environments.

The acquisition of exploration 3D seismic surveys over the last few decades represents a significant advancement in data quality and density that can be used to push forward our community’s general understanding of slope and base-of-slope systems. High-frequency content near the seabed in 3D seismic volumes allows the display of seafloor geomorphology with a spatial resolution comparable to most deepwater multibeam bathymetric tools (Mosher et al. 2006).

Although near-seafloor depositional systems are imaged at a lower resolution than outcrops, they provide 3D information typically lacking from surface exposures. Near-seafloor seismic data allows the recognition of surfaces related to episodes of starvation, bypass, and/or erosion that control both reservoir bed-length and connectivity.

The ability to correlate similar surfaces below the seafloor allows the study of geomorphology through time. Interpretation of this buried seafloor topography serves as the foundation for a newly proposed discipline termed seismic geomorphology (Posamentier et al., 2007).Dimensional data collected during analysis of shallow 3D seismic volumes can include submarine channel width, depth, and sinuosity, meanderbelt width, and the areal extent of slumps and other depositional bodies. These dimensional data, as well as geometric and kinematic information that constrains the spatial arrangement of stratigraphic bodies, can be applied to improve models of the continental-slope and deep-water reservoirs.

Posamentier et al. (2007) defined seismic geomorphology as the application of analytical techniques traditionally used in the study of landforms to the analysis of ancient, buried geomorphological surfaces as imaged by 3D seismic data. Seismic geomorphology, when used in conjunction with seismic stratigraphy, represents an approach that enhances the extraction of stratigraphic information from 3D seismic data. With examples from a broad range of geological settings, Davies et al. (2007) compile state-of-the-art techniques and principles most relevant to this evolving discipline. This is therefore an opportune time to examine improvements in the understanding of slope and toe-of-slope depositional systems afforded by 3D seismic volumes and other geomorphological tools like multibeam bathymetry. This special publication builds on this earlier work and demonstrates how the application of seismic geomorphology principles to seafloor and near-surface seafloor case studies can be used to develop depositional models that can be used, in turn, to predict reservoir distribution and architecture in continental-slope and base-of-slope environments.

The seafloor and near-seafloor are ideal locations for these geomorphic studies since patterns of deposition controlled by slope gradient, entry-point location, and accommodation style are most confidently identified there, especially those sites where drilling provides reliable lithologic calibration and age dating. Depositional and erosional topographies preserved in the near-seafloor are particularly useful localities for testing developing models of submarine sedimentation and analogs for studies of more deeply buried sequences.
In response to these emerging ideas an SEPM research conference was convened in December 2009 in order to bring together researchers interested in the application of the principles of seismic geomorphology in developing depositional models for continental-slope and base-of-slope systems through the use of seafloor and near-surface seafloor seismic data. The conference was a natural follow up of the 2005 GSL-SEPM conference on “Seismic Geomorphology; Applications to Hydrocarbon Exploration and Production”, but with a focus on one of the most critical depositional settings for the oil and gas industry. Twenty-three papers were presented at this two-day conference, 18 of which are included in this SEPM Special Publication.

SHELF-TO-SLOPE TRANSITION

Papers in the first section of this volume focus on the delivery of sediment to the shelf edge and its inferred link to the evolution of the upper continental slope. Case studies range from low-latitude settings where sediment is delivered to deepwater either through direct or indirect linkage to river discharge and associated development of shelf-edge deltas, to high-latitude settings where sediment is delivered to the shelf edge during the advance and retreat of shelf-crossing glaciers and associated periods of glacial meltwater discharge. Straub et al. describe how networks of submarine channels on the present-day continental slope offshore Brunel Darussalam (NW Borneo) were constructed from turbidity currents initiated at the shelf edge as sheet-flows prior to transitioning a short distance down slope into weakly confined flows through the construction of aggradational channels. They contrast the aggradational submarine channel network to terrestrial settings where tributary networks are net erosional features. They observe an anti-correlation between channel relief and deposit thickness that suggests that the degree to which currents are confined within channels exerts a first-order control on local deposition rates. They also find that over 80% of the deposit volume associated with the aggradational network is within the immediate channel-margin deposits or levees.

Sylvester et al. describe the seismic stratigraphy and morphology of a linked delta and turbidite system on a nearly graded slope using a well-imaged and largely undeformed mid-Pleistocene shelf-edge delta to submarine slope channels system in the north-eastern Gulf of Mexico. They demonstrate through detailed seismic mapping and the use of sparsely distributed cores and boreholes (1) the linkage between the history of delta-lobe switching and the evolution of gullies and channels on the upper slope and (2) that spatial changes in the erosional – bypass – depositional character of slope gullies, channels and other associated topographic elements are connected to and likely caused by subtle irregularities in an otherwise smooth slope with a concave-up equilibrium profile. They also document the formation of falling-stage to lowstand mud belts that onlap forced-regression progradational packages on the upper slope, complicating traditional sequence stratigraphic interpretations.

Piper et al. use seafloor geomorphological data from multibeam bathymetry and 3D seismic surveys, coupled with high-resolution seismic profiles and piston cores, to evaluate the main processes that influence submarine fan development seaward of shelf ice streams and helped grade the slope across much of the eastern Canadian margin. Based on a series of case studies, they demonstrate that the variability in seafloor geomorphology out in front of ice streams can be explained by the relative dominance of deposits from glaciogenic debris flows, channel-levee complexes, and blocky mass-transport deposits. They describe the roles that slope gradient, the magnitude and duration of discharge from sub-glacial meltwater events, depth of the shelf break, and latitude play in influencing slope geomorphology.

SLOPE

The first set of papers in the second section of this volume focus on erosional and depositional processes and products that lead to the development of submarine aprons and the valleys and channels that connect aprons along slope sediment-transport pathways. Submarine aprons develop in response to changing slope morphology, so the papers in this section are arranged according to the degree of topographic confinement from three dimensionally confined, ponded intraslope basins in the Gulf of Mexico, to highly tortuous pathways around linear salt-cored folds off Angola, to subtle stepped surfaces offshore Nigeria. A second set of papers in this section focus on the conduits that route sediment transport across slopes. These papers illustrate the transition from submarine apron deposition to local slope bypass as submarine channels develop. The final paper describes the architecture of a channel–levee system in a tectonically active submarine setting.

Aprons

Based on the last phase of drilling and coring, combined with detailed seismic mapping, Prather et al. provide an overview of the regional geology and local stratigraphic framework of the Brazos–Trinity slope system in the central Gulf of Mexico that includes newly released data from Shell proprietary cores and well logs from Basin II and IODP cores and well logs from Basin IV, as well as results from detailed seismic mapping. The chain of intraslope basins within this system has become the type locality for understanding the stratigraphic evolution and filling of ponded accommodation, and the subsequent filling of healed-slope accommodation. A companion paper by Pirmez et al. builds on the stratigraphic framework presented by Prather et al. They develop a chronostratigraphic framework for the Brazos–Trinity depositional system with millennial-scale resolution, afforded by the ultra-high sediment accumulation rates in this system. They demonstrate that most basin infill occurred within a short time interval spanning just ~ 12 ky and that during this time coeval sedimentation took place in multiple basins within the system. They also document sediment partitioning that resulted in the trapping of sand in updip basins while mud was preferentially deposited in down-dip basins. Finally, they conclude that the stratigraphic architecture is largely driven by autogenic processes associated with variable sediment flux resulting from the shifting positions of shelf-margin deltas.

Using 3D seismic data coupled with giant piston cores from the upper Niger Delta slope, Prather et al. show that slope gradient, entry-point location, and accommodation type control patterns of deposition within what was initially a shallow ponded basin. They use detailed mapping to show that the topography of an early phase of sediment bypass and erosion was followed by filling of shallow ponded accommodation, which in turn preceded the progradation of submarine aprons across a stepped slope. The intraslope basin described by Prather et al. is an analogue for shallow ponded basins common on stepped, above-grade slopes that have not undergone extensive late-stage dissection by canyons and channels.

Hay documents the architecture and evolution of basin-fill deposits from a stepped, above-grade system in the Kwanza Basin, offshore Angola. Unlike the previous papers in this section, very little three-dimensional confinement exists in this slope system. Instead, Hay describes how distributary lobes and amal-
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Gamut and magnetic analysis of topographic gradient along depositional corridors flanked by pronounced lateral confinement from adjacent salt structures. Results from the study can be used for prediction of stratigraphic architecture in partially confined intraslope basins with a complex stepped-slope topography.

Barton shows that stepped-slope fill consists of an initial perched apron overlain by a distributive network of channel–levee complexes. Elements that constitute the fan are from oldest to youngest: (1) a system of prograding lobes, (2) a complex of offset stacked channels, and (3) a sinuous, deeply incised bypass channel. Fan evolution reflects the adjustment and response of sediment gravity flows to an evolving slope gradient. Initially, lobes are deposited as flows entering the basin encounter an abrupt decrease in slope, decelerate, and lose confinement. Eventually, as the break in slope is smoothed over, the apron becomes a site of erosion and bypass as down-dip basins become linked by a common graded profile. Barton also provides outcrop examples interpreted to represent some of the key seismic stratigraphic architectures observed from this shallow-analogue case study.

Deptuck et al. couple detailed geomorphic and gradient measurements along sediment transport pathways on the western Niger Delta slope with loop-scale seismic stratigraphy and geomorphology to better understand the spatial and temporal evolution of a relatively simple stepped slope. They show that the subtle stepped profile along sediment transport pathways evolves toward a smoother nearly graded state in two ways: first, through variations in the amount and rate of vertical incision and eventually aggradation along canyon axes, and second through contemporaneous variation in the amount and rate of sediment build-up on the slope immediately adjacent to canyons. Preferential accumulation of slope aprons, composed of mass-transport deposits, compensationally stacked lobes, and overbank deposits, decreased the gradient of ramps and increased the gradient of steps through time. They also describe the intimate relationship that exists between canyon incision depth, the thickness of overbank deposits adjacent to canyons, and slope morphology, showing that the thickest outer levee deposits coincide with canyon segments that have the shallowest incision, in turn corresponding to slope segments showing a sharp decrease in pre-incision gradient.

Valleys

Using 3D seismic and well data coupled with channel measurements, Bohn et al. document the transition from ponding within to bypass across the Auger intraslope in the Gulf of Mexico. They observe that bypass is recorded by increasing gradients along four channels within a channel complex. Healed-slope accommodation is filled as these channels aggrade at the sediment entry point. In the proximal reaches, the channels are flanked by thick levee deposits and show minimal incision. Down-dip, the levee deposit thickness decreases and incision depth increases where underlying ponded deposits increasingly become compartmentalized. Each channel aggrades to a single gradient; once this gradient is achieved, the channel appears to avulse to an area of greater accommodation.

Clark and Cartwright use conventional 3D seismic methods to investigate the interaction between depositional systems and the growth history on a fold located on the lower Niger Delta slope. In particular they document the history of compensational stacking of channel–levee systems and mass-transport deposits as sediment distribution pathways were altered during fold growth. In turn, they describe how the response of depositional systems can be used to constrain the structural history during fold amplification.

Tripsanas et al. document a buried Quaternary channel–levee system from 3-D seismic-reflection data on the lower continental slope of the NW Niger Delta. This study describes how turbidity currents that transition through a hydraulic jump and develop a turbulent bore, may locally prevent deposition and enhanced erosion. As flows thin and spread down-dip of the region of erosion, sand deposition may take place. Tripsanas et al. also show that their interpretations are consistent with flume studies, where flows are able to surmount and transfer their suspended material over an obstruction where relief is less than half the height of the sediment gravity flow.

Minisini et al. use a large 3D seismic volume combined with three industry wells to study Pleistocene forereef deposits in the Adriatic Sea. They focus on the morphology of a sinuous submarine channel system supplied by sediment from the paleo–Po River that drained the Alps with secondary sediment sources from rivers draining the Apennine Mountains. They also describe the role of bottom currents on channel development along a collisional margin.

BASE OF SLOPE TO ABYSSAL PLAIN

The five papers in the final section investigate sedimentary systems from the lower continental slope to deep abyssal plain. All of them explore interrelations between seafloor gradient and flow processes and resulting deposits beyond the toe-of-slope.

Babonneau et al. use seafloor imagery (multibeam bathymetry and sidescan sonar) and shallow sediment cores to describe the morphology and internal architecture of the recently discovered Kramis Fan, offshore Algeria. This fan covers an area of 1200 km$^2$ at the base of the Algerian continental slope, at water depths of 2000–2550 m. Sediment delivery to the fan is via two submarine canyons that converge to form a confined channel, pinned between the base of slope and a well-developed right-hand levee (called the Kramis Ridge). Mapping of large-scale bedforms, such as sediment waves and erosional scours, has revealed that the spatial distribution of erosion and deposition across the ridge is controlled by ridge height and proximity to the two canyon sources.

Jiang et al. apply high-resolution, near-seafloor 3D seismic data to the study of the two youngest Pleistocene sequences on the Alaminos Fan in the Gulf of Mexico. The older sequence comprises mass-transport deposits, channels, and lobes, whereas the younger sequence consists of a single channel that decreases in width and increases in sinuosity upwards. Vertical and lateral changes in depositional style across both systems are linked to variations in seafloor topography, gradient, flow volume, and mud content.

Campbell and Deptuck utilize 3D seismic data to demonstrate the importance of inherited topography on a succession of alternating gravity-flow- and bottom-current-dominated deposits along the continental slope and rise off western Nova Scotia. Miocene mass wasting and channel incision produced a topographically complex lower slope and rise on which a Late Miocene and Pliocene contourite sediment drift and base-of-slope terrace was constructed. Sediment waves associated with cross-slope sediment transport display variations in morphology and evolution that can be directly linked to the underlying topography that developed during periods dominated by down-slope-sediment transport. The morphology of the bottom-current-influenced seafloor, in turn, controlled the trajectory and response of erosional and depositional features associated with the return to down-slope oriented sediment gravity flows later in
the Plioocene. Hence, Campbell and Deptuck document the complex feedback that exists between cross-slope and down-slope erosional and depositional processes in deepwater settings.

Using a combination of multibeam bathymetry, a high resolution 3D seismic volume and shallow piston cores, Kolla et al. present some unprecedented images of very large, highly sinuous channel–levee systems on the Benga! Fan. This superb example illustrates the potential complexity of some channelized reservoirs. The authors attempt to unravel the intricate but highly complex stratigraphic relationships between inner levees, the deposits from laterally migrating or vertically aggrading channels, and the outer levees that ultimately flank the system. This paper is sure to pique the interest of those interested in the origin and hierarchy of erosional surfaces in such systems.

Finally, Wynn et al. use an extensive dataset of shallow sediment cores to investigate the lateral evolution of individual flow deposits across distances of several hundred kilometers. The largest flows can travel for more than 1000 km across slopes of < 0.1°, and yet are extremely sensitive to remarkably subtle gradient changes. For example, one of the largest flows underwent multiple flow transformations as it crossed Agadir Basin, e.g., the transition from gravel lag and cut-and-fill scour to a thick linked turbidite–debris bed occurred in response to a decrease in slope from 0.05° to < 0.01°. The absolute value of slope change is insignificant, but, more importantly, in relative terms this represents a five-fold change in slope. Such variations clearly exert a major control on flow behavior and generate significant complexity in deep-water reservoirs, but they would not be detectable in outcrop or subsurface sequences.

**FUTURE CHALLENGES IN SUBMARINE GEOLOGY**

The papers assembled for this volume demonstrate the utility of seafloor-to-shallow-subsurface data sets in studying the development of submarine landscapes and their affiliated sedimentary deposits. These contributions highlight the importance of distance from the shelf edge, and local slope and curvature (i.e., spatial change in surface slope) on patterns of both sedimentation and erosion. Many of the papers also highlight the influence of pre-existing seafloor relief in confining the specific transport pathways of sediment gravity flows, thereby affecting subsequent evolution of the seafloor. These studies that connect the kinematics of deep-sea topography to the geometry of accumulating sediment bodies are leading to improved models for construction of both the continental slope and deep-water hydrocarbon reservoirs. Unfortunately these remotely sensed data sets do not provide enough information to accurately reconstruct the processes active in a particular deep-water system. An important conclusion drawn from this research conference and associated papers is the need for greater amounts of well-bore data to complement the analyses of acoustic data sets (i.e., seismic and multi-beam bathymetric surveys). Well data and shallow cores provide the only direct measurements of rock composition (grain size, mineralogy, and pore fluids), as well as the only unambiguous assessments of geologic time through the use of chronostratigraphic, biostratigraphic, and tectonostratigraphic tools. A handful of papers in this collection document significantly revised interpretations for both the timing and styles of depositional processes based on the availability of rock data from drilled wells.

The scientific community should continue to push for increased calibration of deep marine depositional environments, so that future studies of the type found in this collection of papers can more fruitfully be used to determine sediment flux, deposition rates, and lithology needed to calibrate and guide the development of numerical models that simulate bed- to basin-scale depositional processes. Such models will ultimately help unravel the link between evolving submarine topography and stratigraphy. The understanding of depositional processes that comes from studying deepwater analogue systems remains the best way to take knowledge from one basin or system and apply it confidently to another for prediction and characterization of reservoirs for exploration and production of hydrocarbons.

Joint research conferences bringing field geologists together with marine geologists should be undertaken, because near-seafloor case studies used in combination with outcrop studies have the potential to provide unique constraints for static models needed by the oil and gas industry to facilitate field appraisal and development planning. These static models are particularly important to the oil and gas industry inasmuch as they are used to facilitate oil and gas field appraisal and development planning. More accurate and consistent application of detailed bed-scale geometric analogues to subsurface reservoirs aids the production geologist and reservoir engineer in understanding the extent to which reservoir performance can be impacted by the details of reservoirs in nature and the limited detail commonly represented in conventional static models. Comparison of stratigraphic patterns from the near-seafloor to those observed in outcrops can provide additional insights into how isolated outcrops may relate to one another at basin scale. Improved understanding of depositional and erosional processes is essential in this endeavor, and is the key to predictive understanding of deepwater reservoirs. Ultimately it is the knowledge of processes that is transferable from one basin or system to another and continued calibration of 3D seismic images from well-imaged shallow analogues will go a long way towards improving our understanding of seafloor evolution and the prediction and characterization of reservoirs for the exploration and production of hydrocarbons.

**REFERENCES**


