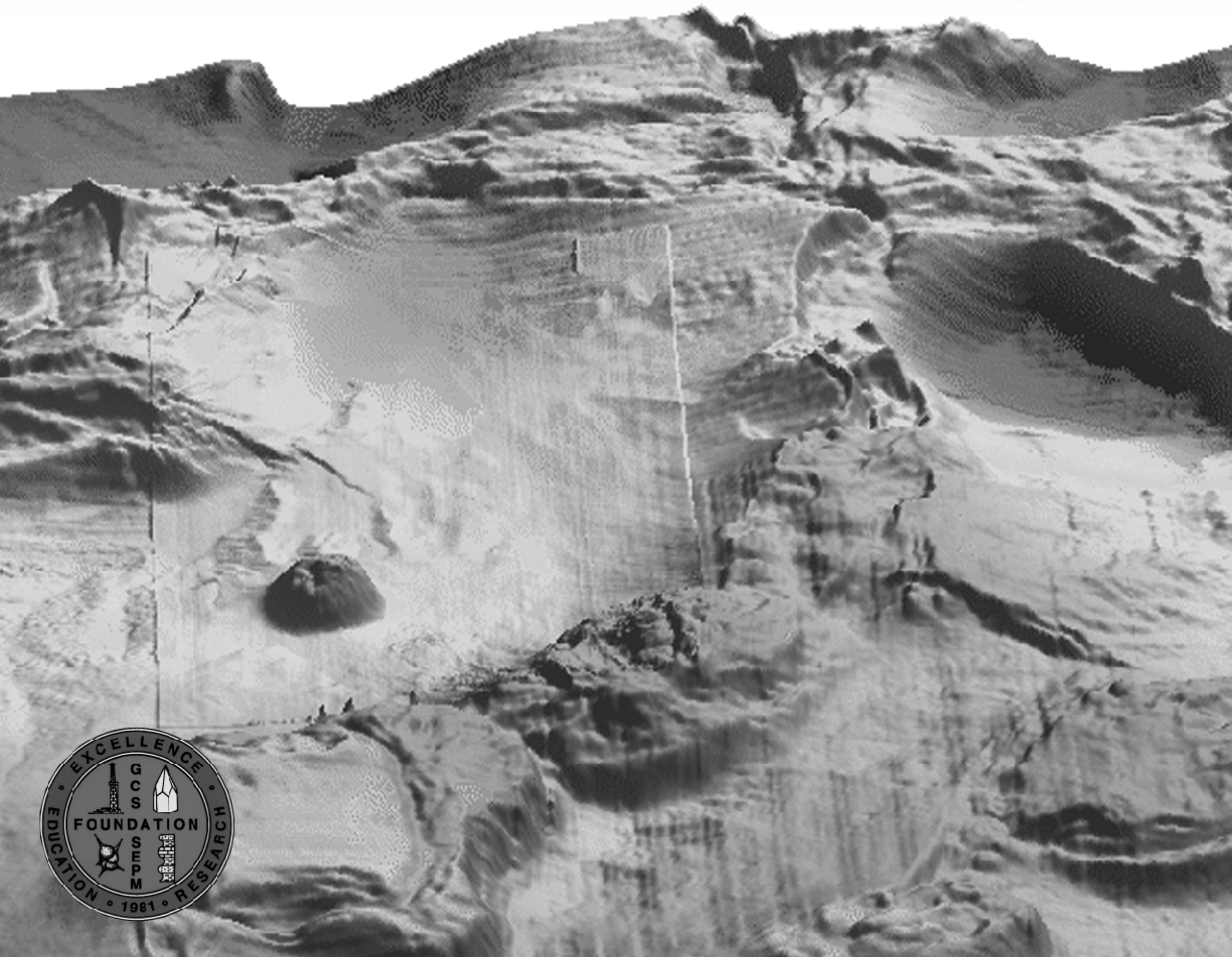
Deep-Water Reservoirs of the World

Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation
20th Annual Bob F. Perkins Research Conference

2000

Edited by
P Weimer • RM Slatt • J Coleman
NC Rosen • H Nelson • AH Bouma
MJ Styzen • DT Lawrence

December 3–6, 2000
Houston, Texas



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Program and Abstracts

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Foreword

The last quarter of the 20th Century has brought a significant increase in the exploration and production of deep-water reservoirs globally. A sizable amount of information from producing fields now exists that can be used to help in the future development of these reservoirs, especially as industry moves into the ultra deep-water.

The purpose of the Bob F. Perkins 20th Annual Research Conference is to address these development issues in deep-water reservoirs. Fifty-nine presentations are planned from companies, universities, and government agencies; presenters represent twelve countries. This year's program consists of four main themes: Gulf of Mexico fields, International fields, the merging of observations from 3-D seismic and sea floor images, and outcrops as analogs for reservoir modeling. Program elements include new fields; fast-track developments; key geoscience and reservoir engineering technologies and their integration; plateau and mature field management; geological modeling and reservoir performance prediction; reservoir description and outcrop analogs; the integration and application of static and dynamic data; the use of outcrops in reservoir modeling and upscaling; and the comparison of 3-D seismic and seafloor images to help develop a dialogue among different deep-water workers.

This conference reflects extensive planning by the convenors during the past four years:

- December 1996: Paul Weimer and Roger Slatt agreed to convene this GCSSEPM research conference. This conference was planned as a significant update to the successful 1994 GCSSEPM Research Conference on deep-water reservoirs. They set out to work on several conferences/sessions whose results would eventually be integrated at this conference.
- October 1998: Paul Weimer and Roger Slatt served as co-convenors (with Peter Dromgoole, Mike Bowman, Andy Leonard) of a one–week EAGE/AAPG research conference in Almeria, Spain. Jim Coleman stated his plans for developing a digital atlas of outcrops that could be used by all companies to help develop reservoir models and for upscaling. Because this theme was already planned as part of the 2000 GCSSEPM meeting, we merged our efforts. The outcrop section is the largest single portion of this year's conference with 21 papers.
- November 1998: Paul Weimer served as co-convenor (with Cesar Cainelli) of two deep-water sessions at the 1998 AAPG International Meeting in Rio de Janeiro.
- April 1999: Hans Nelson, Roger Slatt, and Paul Weimer convened a poster session at AAPG meeting in San Antonio. The theme was comparison of sea floor images with 3-D seismic.
- September 1999: Roger Slatt and Paul Weimer co-convened two deep-water sessions at the AAPG International meeting in Birmingham, England.

We thank all of the authors for their perseverance in writing and editing of their manuscripts, during less than opportune times. The officers of the GCSSEPM and Trustees of the GCSSEPM Foundation have remained incredibly supportive of our efforts during the planning of this conference. We thank the technical program committee for their help and work in soliciting manuscripts and in their review: Trevor Elliott, Tim Garfield, Jory Pacht, Brad Prather, Andy Pulham, Kevin Schofield, Keith Shanley, Gary Steffens, and Mike Sweet.

We thank the following people for their help in reviewing manuscripts under the extremely short deadlines. All of the reviewers helped make this a high-quality scientific conference and refereed publication. To all of them, we extend our sincerest gratitude: Lawrence Amy, Gill Apps, John Armentrout, Gianluca Badalini, Rick Beauboeuf, Gretchen Bolchert, Jim Booth, Wayne Camp, Kurt Campion, Mark Chapin, Tom Cheatham, Mike Clark, Julian Clarke, Chris Clear, George Clemenceau, Steve Cossey, Jennifer Crews, Mike Dean, Mike DeMarco, Bret Dixon, Shirley Dutton, David Jennette, Garry Jones, George Klein, Ven Kolla, Marty Link, Don Lowe, Jeff May, Mike Mayall, Bill McCaffrey, Tom McGilvery, Robert Mitchum. David Mohrig, Bill Morris, Peter Morris, Chris Morton, Robert Morton, Tor Nilsen, Dag Nummedal, Stefan Porebski, Deb Pfeiffer, Sandy Phillips, Carlos Pirmez, Wylie Poag, Henry Posamentier, David Pyles, Richard Redhead, Tony Reynolds, Mikie Smith, Randy Smith, Ryan Sincavage, Mark Sonnenfeld, Bob Spang, Ron Steel, Joe Studlick, Morgan Sullivan, Gabor Tari, Jack Thomas, David Twichell, Peter Varnai, Robert Weimer, Howard White, Charlie Winker, Beth Witton-Barnes, Lesli Wood, and Fred Zelt. A special thanks to Carlos Pirmez and David Pyles for reviewing the largest number of manuscripts (six each). A special bottle of fine Texas wine will be their reward.

We thank the following students at the University of Colorado for their help at critical moments in the editing and assembling of this volume: Gretchen Bolchert, Renato Fonseca, Hector Gonzalez, John Martin, Chris Morton, and David Pyles. Their work at the end of this project made this publication available at the time of the conference.

Finally, we profusely thank Gail Bergan for her Jobian patience in assembling, compiling, and producing this

unprecedented publication. She kept all of the authors and editors in line in regards to what can be accomplished with a digital publication. Her untiring dedication and perseverance were essential for this publication to happen on time.

At the 1994 GCSSEPM Research Conference, Jim Coleman (then at Amoco) aptly summarized the significance of that conference by saying "…at a time when we have to constantly justify our budgets and time in business units, think of how many hundreds of millions of dollars of data were presented for the cost of $300 (registration fee). This was clearly the best possible investment that a company could make." Those words are even more applicable for this conference.

This conference and CD-ROM are a milepost in our industry's collective efforts to improve our understanding of deep-water depositional systems and how they produce petroleum. We hope that the publication will serve as a catalyst for future exploration and production of deep-water depositional systems, especially as industry moves into the ultra deep-water.

Paul Weimer, Roger Slatt, Jim Coleman,
Norman Rosen, Hans Nelson, Arnold Bouma,
Mike Styzen, and David Lawrence

December 2000, Houston, Texas

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Society of Economic Paleontologists and Mineralogists Foundation

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Cover Photo

The theme photo used for this CD ROM appears in two papers in this volume:

Dean *et al.*, *The Present is the Key to the Plio-Pleistocene: Seafloor Analogues at Shell's GB516 Serrano Discovery*, Figure 11;

and

Booth *et al.*, *Sequence Stratigraphic Framework, Depositional Models, and Stacking Patterns of Ponded and Slope Fan Systems in the Auger Basin: Central Gulf of Mexico Slope*, Figure 4. The image originated from NOAA bathymetric data.

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Program

SUNDAY, DECEMBER 3, 2000

4:00 – 6:00 p.m.	Registration—Grand Pavilion Foyer
6:00 – 8:00 p.m.	Welcoming Reception and Poster Preview—Grand Pavilion

MONDAY, DECEMBER 4, 2000

7:00 a.m.	Continuous Registration—Grand Pavilion Foyer
7:45 a.m.	Welcome: Ed Picou, Chairman of the Board of Trustees of the GCSSEPM Foundation
7:50 a.m.	Introduction and Welcome: Paul Weimer, Program Chairman

Session I: Gulf of Mexico Reservoirs

Presiding: David Lawrence, Gary Steffens

9:30 a.m. *Refreshment Break*

Session II: Gulf of Mexico Reservoirs

Presiding: Keith Shanley, Mike Styzen

SESSION III: TUESDAY, DECEMBER 5, 2000

International Reservoirs

Presiding: Tim Garfield, Kevin Schofield

Session IV: Comparing Sea Floor Images with 3-D Seismic

Presiding: Hans Nelson, Jory Pacht

Outcrop Analog Studies for Reservoir Models

Session VI: Outcrop Analog Studies for Reservoir Models

Presiding: Brad Prather, Andy Pulham

POSTERS: Gulf of Mexico

POSTERS: Outcrop Analog Studies for Reservoir Model

POSTERS: Comparing Sea Floor Images with 3-D Seismic

Evaluating the Links Between Turbidite Characteristics and Gross System Architecture: Upscaling Insights from the Turbidite Sheet-System of Peïra Cava, SE France

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Abstract

Understanding how the characteristics of individual turbidites measured along a 1D (vertical) section may relate to reservoir-scale system geometry remains a significant upscaling problem, yet the ability to make this link is fundamentally important when evaluating turbidite reservoirs. Insights into the key relationships are perhaps best gained from well-exposed outcrops in which bed-to-bed correlations can be established. The Peïra Cava outlier of the Tertiary Annot Sandstone contains sheetform turbidites that were deposited in a confined and ponded basin. They are now exposed over a 10 by 6 km area. Bed-to-bed correlations have been established throughout a selected 420 m stratigraphic interval, allowing the 3D geometry of the system to be constrained. We test the significance of bed sand thickness, mud-cap thickness, sand percentage, grain-size, and the presence or absence of erosional structures and cross-stratification for their value as predictors of up-stream and down-stream bed geometry. The results are compared with models currently used to predict the spatial distribution of sediment properties, such as flow-efficiency concepts and the influence of topographic control.

Architecture and Processes in the Late Pleistocene Brazos-Trinity Turbidite System, Gulf of Mexico Continental Slope

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Abstract

High resolution seismic data from shallow analogues can be used to improve our understanding of deeply buried turbidite systems and provide an invaluable aid in resolving what would constitute first-order sub-seismic elements in a conventional seismic survey. This research focuses on the Late Pleistocene Brazos-Trinity turbidite system located on the northern Gulf of Mexico continental slope. The system lies immediately downdip of a lowstand shelf-edge delta and is ponded in four mini-basins linked fill-and-spill style. The sedimentary fill consists of onlap-fill packages in each basin, deposited during the last glacial. The results of this work allow us to: {a) determine the overall architecture of a system where the physiographic context and timing are fairly well constrained; {b) reconstruct a complex basin fill history made up of high frequency forward and backstepping elements; (c) improve our understanding of lithofacies distribution; (d) demonstrate that channel levee systems do not represent the first establishment of bypass to downdip basins and are representative of the last sequence within a glacial cycle; and (e) suggest that high frequency climatically-linked changes in sediment supply may control the deposition of 5th order sequences in deep marine clastic systems.

Architecture of Thick-Bedded Deep-Marine Sandstones of the Vocontian Basin, SE France

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Introduction

Thick-bedded deep-marine (TBDM) sandstones form major hydrocarbon reservoirs throughout the world (North Sea, Gulf of Mexico, etc.). Optimal exploitation of such reservoirs requires detailed insight into the facies architecture and how this influences the reservoir quality, continuity, and connectivity that ultimately will influence the reservoir performance. Outcrop analog studies result in a better understanding of the variation of the facies architecture and can provide conceptual models that will be used for reservoir characterization.

The objective of this study is to provide a sedimentary architecture model of TBDM sandstones of the "Marnes Bleues" Formation (Aptian-Albian), Vocontian basin, southeast France. The study yields data on the distribution of lithofacies and on the geometry and internal heterogeneities of architectural elements.

High Resolution Seismic/Sequence Stratigraphic Framework for the Evolution of Pleistocene Intra Slope Basins, Western Gulf of Mexico: Depositional Models and Reservoir Analogs

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Abstract

High resolution 2D seismic, sidescan sonar images, and shallow penetration cores were used to study a portion (approximately 60 km length) of the upper to middle Texas continental slope. Within the study area are four intra-slope basins presently connected to one another via a network of submarine channels. The depositional setting occurs in water depths of 400 to1500 m and is located depositionally down-dip of Pleistocene fluvio-deltaic complexes. These shelf edge systems represent the source of sediment delivered to these intra-slope basins. Three of these basins are filled, while the fourth, most southerly basin is presently underfilled. The filling of these basins occurred very rapidly and with pronounced cyclicity, in perhaps less than 100 Ky during the late Pleistocene. Based on seismic stratigraphy and facies, the fill of these basins is interpreted to exhibit vertical cyclicity reflecting alternating deposition of mass transport complexes (MTC), distributary channel-lobe complexes (DLC), leveed-channel complexes (LCC), and hemipelagic drape complexes (DC). MTCs are low amplitude, chaotic seismic facies units and are interpreted as mud-rich complexes of slumps, slides, and debris flow deposits. The DLCs are sand-rich depositional units characterized by moderate to high reflection amplitude and continuity. The DLCs exhibit onlapping, compensatory and locally erosional internal reflection geometries and fan shaped or distributary map patterns. These complexes were deposited from highly concentrated sediment gravity flows delivered across the basin floor through networks of relatively small distributary channels or as broad sheet-like flow. LCCs form a distinct seismic facies characterized by low amplitude, highly continuous reflection character and "gull-wing" cross-sectional profile. LCCs are considered to form from overbank deposition of low concentration turbidites and contain low to moderate sand percentages. DCs are thin, highly continuous seismic units that represent hemipelagic mudstones deposited during periods of abandonment and sediment starvation. Alternating deposition of MTCs and DLCs dominate the early stages of basin filling. LCCs are not observed within the deeper portions of the basin fills, and are interpreted as elements formed during the latter stages of basin filling episodes. These units represent an integral part of the sediment transport system currently linking the basins. Post-depositional processes have significantly modified these channels and the fill of the basins. Most notable among these processes are headward erosion and mass wasting. This erosional modification occurred in response to flow across local gradient changes along the system as individual basins were filled and subsequently bypassed by sediment gravity flows.

Application of Results from Outcrops of the Deep Water Brushy Canyon Formation, Delaware Basin, as Analogues for the Deep Water Exploration Targets on the Norwegian Shelf

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Abstract

The keys to exploration success are to be able to see different possibilities and to improve the ability to predict. Analogue studies highlight the importance of visualizing geology as seen in outcrop when interpreting subsurface seismic and well data. Outcrops of the deep water Brushy Canyon Formation, Delaware Basin, West Texas, have proven useful as analogues to the deep water exploration targets on the Norwegian shelf.

The Permian Brushy Canyon Formation consists of submarine canyon-fill, slope, and basin-floor deposits. The siltstone-rich slope is dominated by bypass, slope-adjustments, and degradational processes. Through time, slump scars coalesce, confining and directing sediments basinward. The sand-rich basin floor is dominated by constructional processes, complex stacking of sediment bodies, and depositional compensation cycles.

Slope and basin-floor settings are observed in the Tertiary and Cretaceous deep water depositional systems on the Norwegian shelf. The settings and scale of the depositional systems, the distribution of sands, and the geometries of the sand bodies are comparable to the Delaware Basin. Slump-scar confined channel complexes on the slope, multistory channel complexes on the basin floor, and distal pinchout prospects can be defined and directly correlated to field observations.

By integrating field observations with subsurface data, regional 3D seismic interpretation, high-quality well data, and geophysical modeling, the projects have resulted in more reliable interpretations, enhanced prediction of sediment pathways and sand distribution, and finally the development of new prospects on the Norwegian shelf.

Sequence Stratigraphic Framework, Depositional Models, and Stacking Patterns of Ponded and Slope Fan Systems in the Auger Basin: Central Gulf of Mexico Slope

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Abstract

Exploratory and development drilling at Shell's Auger and Macaroni Fields has provided well control in time-equivalent stratigraphy from proximal and distal settings of a contiguous intraslope basin. The oil and gas reservoirs in the basin occur in the Pliocene *Discoaster brouweri–Reticulofenestra pseudoumbilica* interval (3.64 Ma–1.95 Ma) that spans six glacio-eustatic cycles. Higher order cyclicity is demonstrated by the presence of twelve condensed section bounded sequences in the interval, as well as a repetitive vertical facies succession internal to the sequences. The vertical succession consists of basal onlapping facies having good internal continuity overlain by chaotic to transparent facies that has erosional basal contacts and is capped by highly continuous, single-loop reflections. Well data from Auger and Macaroni fields reveals the basal onlap packages to contain high net/gross, thickly-bedded sheet sands and highly amalgamated channel-fill deposits, whereas the overlying chaotic facies contains laterally discontinuous channel-fill and low net/gross overbank deposits. A combination of erosional downcutting by the chaotic zones and stratigraphic pinch outs within onlap packages result in a high degree of proximal to distal seismic facies variation in the basin.

Accommodation in the basin is classified using terminology of Prather *et al.* (1998) into two primary types, slope accommodation and ponded accommodation. Auger Field reservoirs have been deposited as point-sourced submarine fans in the proximal portion of the basin within slope accommodation, whereas reservoirs at Macaroni Field have been deposited in the distal portion of the basin within ponded accommodation. The observed stacking patterns and the proximal to distal facies changes in the basin are attributed to a repetitive fill sequence driven by decreasing accommodation during intervals of turbidite deposition and renewal of accommodation during sequence-bounding intervals of condensed deposition. Two stages of turbidite fill are identified within slope accommodation: (1) an initial 'healing phase' and (2) a subsequent 'bypass phase.' Healing-phase deposition occurs adjacent to seafloor escarpments at the onset of turbidite deposition and is dominated by high net/gross sheet sands and amalgamated channel sands. The bypass phase begins upon establishment of graded slopes and is characterized by channel-fill sands and lower net/gross overbank deposits. Coeval with deposition within slope accommodation, turbidite fill within ponded accommodation also occurs in two stages: (1) an initial 'ponded phase' and (2) a subsequent 'spill phase.' The ponded phase is dominated by high net/gross sheet sands and occurs while deposition is constrained by a basin-bounding bathymetric sill. The spill phase occurs when the basin sill is overtopped and turbidite delivery progresses to the outboard basin. Underlying ponded phase sheet sands are frequently cannibalized by erosional channel systems during the spill phase.

This study establishes that world-class turbidite sheet sands occur not only within ponded accommodation of intraslope basins, but also within slope accommodation. The study also reveals that sheet sands within ponded accommodation may occur stacked at higher frequency than within slope accommodation. The observed proximal-to-distal facies changes in the basin, the vertical stacking patterns, and the spatial distribution and timing of cut and fill events suggest that decreasing accommodation in the basin—not rising eustatic sea level—drives the transition from sheet sand dominated fans to overlying channel and overbank dominated fans.

Late Pleistocene Deep-Water Stratigraphy and Depositional Processes, Offshore Trinidad and Tobago

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Abstract

A 3,000 km^2 3D seismic data set on the slope (600-1500 m water depth) offshore Trinidad provides detailed images of the seafloor and shallow subsurface. This data aids in the interpretation of the stratigraphic architecture and depositional/erosional processes in this frontier deep water basin. Three main elements comprise the deposits imaged: channel complexes, mass-transport complexes, and mud volcanoes.

Channel complex range from nearly straight to highly meandering and from single trunk to distributary and braided/anastomosed patterns. Two main channel systems having seafloor expression are interpreted as the most recent conduits for Orinoco River sediment to the braided fan at the toe of the Barbados accretionary prism. Seismic images help define the genetic evolution of these channels.

Sediment pathways are affected by the presence of large mud volcanoes on the present day slope. These mud volcanoes have an average height of 100 m and an average radius of 2km.

Failure of the continental slope is revealed by several thick, widespread mass-transport complexes (MTCs) in the study area. Seismic images illustrate variations in size, transport direction/distance, and emplacement mechanisms for these MTCs. Syndepositional thrusting and linear basal scours as opposed to internally chaotic deposits are interpreted to indicate slump-dominated versus debris-flow dominated MTCs, respectively. The main depositional elements are organized commonly in sequences beginning with basal MTCs, followed by channel complexes capped by a pelagic abandonment interval. This vertical organization is similar to that observed in other intraslope basin and basin-floor fans and is interpreted to reflect base-level control on the stratal architecture.

Gulf of Mexico Basin Late Tertiary Deep-Water Biostratigraphic Zonation: Relationship to Standard Shelf Foraminiferal and Calcareous Nannofossil Marker Terminology

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Extended Abstract

The science of biostratigraphy has seen its greatest development and usage in Gulf of Mexico Basin oil exploration and production due to certain characteristics of the basin: its interbedded siliciclastic sand and shale sequences, growth faults, and salt tectonics. Although, in recent years, 3-D seismic has reduced the reliance on biostratigraphic data for correlations in routine settings, drilling in the deep waters of the Gulf of Mexico (especially the eastern fold belts) has returned biostratigraphy (using refined deep water zonation) to a prominent position. Reasons for the application of this deep water biostratigraphic zonation include the structural / stratigraphic complexity of the region, proximity of salt sheets to many of the prospects, the poor seismic quality at target depths, sometimes below 8000 m (25,000 ft) subsea, and the absence of standard shelf (neritic) biostratigraphic markers.

Early zonation of the Gulf of Mexico Basin (Tipsword, 1962) has relied primarily on benthic foraminifera characteristic of updip neritic facies to differentiate sand-shale sequences and to aid in correlation across growth faults. Utilization of planktic foraminifera and calcareous nannofossil (nannoplankton) becomes increasingly important as more down-dip exploration occurred. The current focus (1990's) on deep-water exploration has provided biostratigraphy with the unique opportunity to develop new correlative events in settings from which up-dip marker fossils are environmentally excluded. Many standard Gulf of Mexico Basin benthic foraminiferal markers, such as *Angulogerina* 'B,' *Buliminella* '1,' *Textularia* 'X,' and *Cristellaria* 'K,' *etc.*, are restricted to shelf environments and, therefore, are virtually useless in deep-water biostratigraphic zonation (Breard, 1993).

Advances in several areas, including increased understanding of bathyal paleoenvironments, more widespread utilization of local foraminiferal biofacies, improved taxonomic methodology in bathyal calcareous and agglutinated foraminifera and better utilization of calcareous nannofossil abundance events, have contributed to a finer subdivision of the stratigraphic framework of bathyal Neogene sediments in the Gulf of Mexico Basin. The breakup of major oil company micropaleontology staffs, establishment of small industry consulting groups, and subsequent publication of improved down-dip zonations (Breard *et al.*, 1993; Styzen, 1996; Lawless *et al.*, 1997) have also improved understanding of down-dip Neogene stratigraphic sections targeted by current deep-water exploration. The recent publication of the long-awaited Gulf of Mexico Basin Biostratigraphic Index Microfossils volume (Rosen *et al.*, 1999) should contribute to a more unified understanding of the Gulf of Mexico Basin biostratigraphy.

Paleoenvironmental/paleobathymetric models have been proposed for the Gulf of Mexico Basin Miocene, Pliocene, and Pleistocene strata (Breard *et al.*, 1993). These models have recognized a finer subdivision of bathyal paleoenvironments and have identified which key paleoecological indicators species exhibit habitat change through time. Recognition of strictly abyssal (>2000 m / 6000 ft) paleoenvironments remains problematic, based on lack of zonal markers that are restricted to these depths.

Local biofacies are particularly useful in the correlation of bathyal sections in the late Tertiary Gulf of Mexico Basin (Breard *et al*., 1996). Local biofacies include acme zones (increases in faunal/floral abundance), especially among agglutinated (arenaceous) foraminifera, planktic foraminifera, and calcareous nannofossil species (which typically indicate maximum flooding surfaces). Due to the large distances between some deep-water settings and deltaic outflow, some planktic species (both foraminifera and nannofossil) are found to be rare in more proximal settings. Zones of reworking of older species and reoccurring faunas / floras within repeating sedimentary facies have also been useful down-dip correlative tools.

Establishment of a bathyal benthic foraminiferal zonation has provided enhanced correlation points between established planktic extinctions (LAD's) and provides finer resolution in areas where updip and mid-dip species do not occur (Breard *et al.*, 1997). Increased understanding of bathyal foraminiferal taxonomy and accurate establishment of geologic ranges for bathyal foraminifera has provided biostratigraphers with the ability to include these taxa in down-dip stratigraphic correlation schemes (Van Morkhoven *et al.*, 1986).

Outcrop Expression of Confined Channel Complexes

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Abstract

Analog data for many seismically resolved confined-channel complexes comes from outcrop studies that provide insight into the lithofacies distribution and architectural features at the bed, bed set, channel, and channel complex scale. Within the Capistrano Formation (Miocene) near San Clemente, California, is a sand-dominated complex of channel fills that is about 15 m thick and 1.2 km wide and serves as a model for seismically defined, single-cycle reservoirs. In contrast, channel fills exposed in northern California, such as the Bidwell Point (Valanginian) and Gravelly Ridge lenses (Tithonian) of the Stony Creek Formation, are gravel-dominated, 60-200 m thick, and 500 m to 2 km wide and serve as analogs for confined channels defined seismically by multiple cycles.

The Capistrano example is made up of laterally amalgamated channels that exhibit a systematic change in sand fraction, facies preservation, and bed architecture from the margin to axis of each channel fill. The channel-margin facies is low net to gross (<50% sand), non-amalgamated, thin-bedded, and dominated with low-concentration turbidites. In contrast, the channel-axis facies is high net to gross (>90% sand), thick bedded, amalgamated, and dominated with high-concentration sandy turbidites and gravel-rich traction deposits. In the Capistrano case, the channel-margin facies is 200-300 m wide, whereas the channel-axis facies is 600-700 m wide.

The Bidwell Point example consists of two sequences that are marked by incision into slope mudstone followed by deposition of gravel in the channel axes and both low and high-concentration turbidites on the channel margins. The channel-axis facies in both sequences consists of amalgamated channels dominated by granule and pebble conglomerates exhibiting traction features such as clast imbrication and inclined beds. The primary channel margin facies consists of non-amalgamated high- and low-concentration turbidites and local mud-draped erosion surfaces. The lower sequence consists of two stacked channel complexes up to 100 m thick. Locally, muddy debrites mark the base of channel complexes. The lower complex is about 700 m wide and is primarily axial facies, whereas the upper channel complex is about 2 km wide and has an axial facies that is 600 m wide. An abandonment phase consisting of thin-bedded, silt- dominated turbidites marks the top of both lower and upper channel complexes.

The studied section of the Gravelly Ridge lens consists of at least 5 stacked channel complexes separated by mudstone intervals. This set of channel complexes is 500 m to 1.6 km wide, 60-100 m thick, and extend at least 12 km in a down-dip direction; no distinct down-dip fining was detected. Based on outcrop expression and paleocurrent patterns, these deposits are interpreted as filling sinuous channels and primarily are amalgamated granule and pebble conglomerate displaying tractional features.

From a reservoir standpoint, the channel-axis facies in all the studied outcrops has the best potential for lateral and vertical reservoir continuity. The channel-margin facies containing non-amalgamated beds and mud-draped erosion surfaces has low vertical and reduced lateral continuity in reservoir beds.

The Ebro Continental Margin, Western Mediterranean Sea: Interplay Between Canyon-Channel Systems and Mass Wasting Processes

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Abstract

A comprehensive swath bathymetry and high resolution seismic reflection data set of the Ebro progradational margin, in the Western Mediterranean Sea, reveals that its Late Quaternary development results from an interplay between channel-related and mass-wasting processes.

The Ebro continental margin is mainly fed by the terrigenous input of the Ebro River. The continental slope and rise, extending down to 1,300-1,800 m, has been built by multiple turbidite systems, which include channel-levee complexes and base-of-slope non-channelized deposits. Our data set shows a variety of processes controlling the distribution of different sediment types. These processes include channel abandonment, incision of inner channel courses, formation of hanging valleys, retrogressive erosion, avulsion, channel wall sliding, and channel spillover. Recurrent slides wipe out the upper sediment cover of large segments of the margin and lead to extensive mass transport deposits at the base of the slope. The youngest of these deposits, AMS ^{14}C dated at 10,000 years BP, is the BIG'95 debris flow covering 2,000 km^2 and thicknesses locally exceed 40 m. The data show that landslide deposits can conceal large channel portions such as the upper course of the mid-ocean type Valencia Channel, which downstream drains several of the Ebro canyon-channel systems. The modeling of the three-dimensional channel geometry illustrates the potential infill of these channels and thus the sediment volumes transferred downslope by mass transport processes.

Recurrent slope failures in the Ebro margin represent catastrophic events that interrupt the "normal" development of canyon-channel systems and channel-levee complexes. Slope failures rejuvenate the slope both by destroying upper canyon-channel courses and filling pre-existing channel lower courses. Combined with canyon-channel erosional-depositional processes they create pathways for new canyon-channel systems to form thus modifying depocentre locations.

Characterization of an Active-Margin, Fan-Shaped Turbidite Reservoir Complex, Miocene Stevens Sandstone, San Joaquin Basin, California

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Abstract

Yowlumne is a giant oil field in the San Joaquin basin, California that has produced over 100 MMBO from a low-permeability (10-100 md), fan-shaped turbidite complex with left- and basinward-stepping geometries deposited in an active-margin basin. The Yowlumne and other “deep water,” upper Miocene sandstones in the San Joaquin basin make up a clastic facies of the Monterey Shale called the “Stevens” sandstone, which has contributed more than 15% of 12 BBO produced here since 1864.

The Yowlumne reservoir is a prograding turbidite complex of seven lobes deposited on the basin margin during Miocene orogeny. Although the fan is lens-shaped, it does not significantly incise underlying strata. Apparently, deposition resulted from confinement of prograding lobes, about 2 km wide by 4 km long, between a faulted paleohigh on the west (left) side of the fan, and another high, associated with overbank deposition and possibly differential compaction, on the east (right) side. Basinward-stepping compartments in the reservoir represent deposition during decreasing accommodation, and high sediment flux, whereas left-stepping compartments reflect the influence of Coriolis forces.

More abundant shale-bearing levee facies characterize the east (right) margin of the fan, whereas sand-rich lobe facies characterize the west. Therefore, reservoir quality decreases from the fan axis eastward towards the fan margin. Cost-effective exploitation of bypassed oil trapped against the thinning margin is facilitated by 3D-computer modeling to effectively locate highly deviated to horizontal wells, and design completions that maximize productivity from the layered, low permeability turbidite reservoir that characterizes the distal fan margin.

Outcrop Analogues for Deep-Water Channel and Levee Genetic Units from the Grès d'Annot Turbidite System, SE France

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Abstract

Large-scale exposures of the Grès d'Annot in southeast France provide excellent opportunities to study detailed architecture of sand-rich turbidite systems deposited in a relatively confined basin. The deposits are dominated by laterally extensive sheet-like sandstone packets which have, in general, quite distinctive bed thickness characteristics and sandstone-to-shale proportions. In addition to these sheet-like packets, field studies in the Grand Coyer, Trois Evêchés, and Col de la Cayolle outcrop areas have identified a common type of turbidite channel succession. The channels occur at a variety of scales, with channel dimensions ranging from 900 m to 4000 m wide and 14 m to 110 m deep, and are characterized by a relatively high aspect ratio. The channel fills are sand-rich, moderately to highly amalgamated, but the sandstones show largely planar bedding architecture. The relatively low relief of the channels and their sheet-like fill makes them difficult to distinguish in areas without good lateral continuity of exposure, and it is possible that their importance within the fill of the Grès d'Annot basin has previously been underestimated. Likewise, it is possible that the occurrence of analogous channel-levee complexes may be underestimated in subsurface reservoirs that are otherwise dominated by sheet-like turbidite sands.

Several channel exposures allow detailed examination of channel margin architecture, and clearly demonstrate several periods of reactivated channel activity. Typically, the margins show the most complex sedimentary architecture.

Laterally away from the channel margin, and/or stratigraphically above or below the channel-fill, thin-bedded sandstones and shales form distinctive packets. Within these packets, the thin-bedded sandstones are relatively coarse-grained, cross-laminated, and planar-laminated, and beds are commonly discontinuous over relatively short distances. Cross bedding is common in the thicker beds, and trace fossils, including *Ophiomorpha* and *Thalassinoides,* are abundant. Sandstones containing wood fragments and lignite are commonly found. Megascours and small-scale channel-fill sandstone bodies are also present in these intervals. This combination of features, and their association with the channels, suggest that the thin-bedded packets represent the levees to sandier channelized deposits. The levees formed by the aggradation of sand and mud which were deposited from flows, or parts of flows, that spilled from the channels. This facies association has been used to interpret other levee deposits elsewhere in the Grès d'Annot, where channels are not exposed. It is not, however, possible to interpret all thin-bedded packets in the Grès d'Annot succession as levee facies; for this interpretation to be valid, the packets must include some or all of the distinctive features described above.

3-D Geological Modeling and Horizontal Drilling Bring More Oil Out of the 68-Year-Old Wilmington Oil Field of Southern California

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Abstract

The giant Wilmington oil field of Los Angeles County California, on production since 1932, has produced over 2.5 billion barrels of oil from Pliocene and Miocene age basin turbidite sands. The seven productive zones were subdivided into 52 subzones through detailed reservoir characterization to better define the actual hydrologic units. The asymmetrical anticline is highly faulted and development proceeded from west to east through each of the ten fault blocks. In the western fault blocks water cuts exceed 96% and the reservoirs are near the economic limit. Several new technologies have been applied to specific areas to improve the production efficiencies and thus prolong the field life.

Tertiary and secondary recovery techniques utilizing steam have proven successful in the heavy oil reservoirs but potential subsidence has limited its application. Case history 1 involves detailed reservoir characterization and optimization of a steam flood in the Tar Zone, Fault Block II. Lessons learned were successfully applied in the Tar Zone, Fault Block V (4000 meters to the East). Case history 2 focuses on 3-D reservoir property and geological modeling to define and exploit bypassed oil. Case history 3 describes how this technology is brought deeper into the formation to capture bypassed oil with a tight radius horizontal well.

Production Results from Levee-Overbank Turbidite Sands at Ram/Powell Field, Deepwater Gulf of Mexico

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Abstract

The Ram/Powell Field is located in the northeastern Gulf of Mexico in 3200 feet of water. BPAmoco has a 31% WI in the field, which is currently producing from several stratigraphically trapped reservoirs. These reservoirs occur within the channel-levee facies of a submarine fan system in a mid to lower slope setting.

The L gas-condensate reservoir is trapped entirely within thin-bedded levee-overbank facies sands. The proximal and distal levee-overbank facies can be distinguished by net sand percentage and bedding architecture. These sands have porosities of 15-32% and permeabilities of 20-1000 mD; however, the presence of interbedded mudstones within a complex bedding architecture reduces apparent reservoir connectivity and was expected to decrease well rate and recovery.

The L reservoir is completed with a single 2500 foot near-horizontal well located in the proximal levee facies. The well peaked at a rate of 8.8 MBOPD and 108 MMCFD. Well data indicates that lateral and vertical connectivity is better than predicted from log and core data and that there is pressure communication across the entire 4000 acre reservoir. Three-dimensional connectivity is thought to be enhanced by small sand filled overbank channels which cut into obliquely dipping thin-bedded levee sands.

Reassessment of the Cerro Toro (Chile) Sandstones in View of Channel-Levee-Overbank Reservoir Continuity Issues

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Abstract

Outcrops of the Cretaceous Cerro Toro sandstones within Parque Nacional Torres del Paine (southern Chile) have been described in a submarine channel-levee-overbank context; the adjacent, thin, levee-overbank beds genetically are associated with the main channel bodies, which are present as post-erosional fill. Examination of key outcrops indicates that a more complex association exists between the thick- to massively bedded channel-fill sandstones and the laterally adjacent thin-bedded sandstones.

The Cerro Toro sandstones are composed of three primary rock types: (1) gravely sandstone containing clasts ranging from coarse sandstone to small boulders; (2) fine- to medium- (at times coarse-) grained quartzo-feldspathic sandstones and siltstones in sheet sandstones possessing few or no sedimentary structures, probably deposited in lobe or distal overbank facies; and (3) fine- to medium-grained quartzo-feldspathic sandstones and siltstones in sheet sandstones, possessing abundant sedimentary structures, indicative of the levee-overbank facies.

The gravely sandstones occupy multi-storied, channel-fill positions and rest on erosional surfaces cut into sandstones, siltstones, and/or shales. The gravels rest only in erosional contact with the lobe sandstones and not the overbank sandstones. No thick- to massively bedded gravely sandstones have been found to be genetically related to the overbank sandstones.

A reservoir model based on the Cerro Toro sandstones of the Torres del Paine area would be composed of a laterally extensive, thin-bedded lobe sheet sand having a high degree of lateral continuity and punctuated by channel-fill sandstones having a highly variable internal lithologic and potential fluid flow character.

The Inter-Relationships of Scales of Heterogeneity in Subsurface, Deep Water E&P Projects—Lessons Learned from the Mount Messenger Formation (Miocene), Taranaki Basin, New Zealand

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Sea cliff exposures, conventional and high resolution seismic profiles, conventional oil and gas field boreholes, and shallow behind-outcrop core holes along the west coast of the Taranaki Basin, North Island, New Zealand, afford an excellent opportunity to examine the inter-relationships of scales of heterogeneity within slope channel-levee-overbank and toe-of-slope deep water sediments. Here, the Taranaki sea cliffs, are up to 240 m high and exhibit over 25 km of nearly continuous exposure. Across the spectrum from seismic profile to microscopic and instrumental analysis, detectable features that affect reservoir heterogeneity range across at least 13 orders of magnitude from greater than 10^4 m to 10^{-9} m.

Using the exposures along the Taranaki Coast, it is possible to assess the extent and detectability of the various scales of lithologic heterogeneity and to estimate their effects on analogous intervals in the subsurface. Bed/bed-set heterogeneity ratios (calculated as vertical distance divided by horizontal distance of a given parameter), as detected by the tools mentioned above, cluster in two domains. Because of their limited radius of investigation, borehole logs have ratios between 10^0 and 10^{-1}, whereas outcrop, seismic, and log profiles, which are based on a horizontal arrangement of data, generally show ratios between 10^{-1} to 10^{-3}. Because of their design limitations and strengths, each of the tools sees a different scale of lithologic or bedform heterogeneity.

Data sets such as that available from the Taranaki cliffs section are invaluable for constraining estimates of reservoir heterogeneity in subsurface models.

Producibility of Deepwater Reservoirs in the North Sea and Gulf of Mexico

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Abstract

A goal of field development is to place high rate, productive wells in "sweet spots" or areas where pay is thickest. However, thick pay does not necessarily mean high flow rates. Producibility (normalized flow rate) of a reservoir should be used in conjunction with pay thickness to locate "sweet spots." This study uses data from over 159 completions in deep-water clastic reservoirs from 11 Gulf of Mexico and North Sea fields. The data have been analyzed to determine which geological and engineering factors might contribute to a higher normalized flow rate or Specific Productivity Index (SPI), here defined as BOPD/psi of drawdown/per foot perforated. SPI has been compared to tubing size, permeability, viscosity, architectural element, net-to-gross, and log shape. The highest SPI's in the North Sea are from reservoirs having net/gross >90%, although 60% is a critical cut-off in the Gulf of Mexico. There is a good correlation between average reservoir permeability and maximum SPI in unconsolidated Gulf of Mexico reservoirs. In addition, good correlation is observed between average permeability and minimum SPI in more consolidated North Sea reservoirs. The highest SPI's also are found in completions with 4.5" tubing. A simple classification of log shape has been used in the study to determine the range of uncertainty of SPI for each reservoir type. Reservoirs having blocky log shapes have the highest SPI's, and reservoirs having funnel or bell log shapes have lower but similar ranges of uncertainty in SPI's. Hilterman (1998) has shown that acoustic impedance varies with log shape in the Gulf of Mexico, indicating that some aspects of producibility may be mappable from seismic data.

The Present is the Key to the Plio-Pleistocene: Seafloor Analogues at Shell's GB 516 Serrano Discovery

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Abstract

Prospect Serrano is located approximately 220 miles southwest of New Orleans and 6 miles southeast of the Auger TLP in Garden Banks Block 516. The Shell GB 516 #1 well, drilled in 1996, has encountered 86 net feet of Pleistocene age (*P. lacunosa*) gas pay at the main objective horizon. The objective horizon occurs in the largely channelized bypass seismic facies assemblage (*e.g.,* Prather *et al.*, 1998), and is mapped regionally as a highly continuous draping seismic event. In offset penetrations the objective horizon is sand lean and generally associated with pyroclastic sediments. Mapping of 3D seismic data and comparisons to the present day seafloor, however, suggest a sand-prone depositional setting at the Serrano prospect. Loop level attributes and interval isochores indicate that several depositional systems were active at Serrano. In addition, present day seafloor bathymetry reveals the presence of a backstop setting within low-relief ponded accommodation space (*e.g.,* Prather *et al.*, 1998). Furthermore, images of the present day seafloor support the interpretation of multiple sediment entry points and offer clues to depositional and erosional relationships preserved in the subsurface. The seafloor analogue is instrumental to understanding the distribution of sheet sands, depositional and erosional bypass channel systems, debris flows, and large-scale erosional gorge systems at the Serrano prospect. The seafloor is a present-day analogue of Pleistocene depositional processes in the Gulf of Mexico and is a valuable tool in reservoir prediction.

Some of the terminology used in this paper is common within Shell, but less well known in the oil industry in general. The following table defines some of this terminology.

Brunei Deep Water Exploration: From Sea Floor Images and Shallow Seismic Analogues to Depositional Models in a Slope Turbidite Setting

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Abstract

The present-day slope in the licensed part of the deepwater acreage in Brunei (NW Borneo) has been modified into a stepped slope profile by mobile shale ridges, and is characterized by the dominance of "slope accommodation space." Canyon systems, which cut across the shale ridges, are partially in-filled with channel-levee complexes that display various degrees of channel sinuosity. The presence of high amplitude reflection packages at the base of the channel-levee complexes indicates the existence of subtle ponding within the canyon systems prior to infill by channel-levee systems.

A generic model for stepped slopes having a slow-moving substrate is described based on the structural, erosional, and depositional elements that are observed on images of the present-day sea floor and the shallow seismic data on the Brunei slope. Turbidite deposition on these slopes is dominated by shale prone "bypass facies assemblages," but prospective reservoirs may be present in the form of channel-levee deposits and fan lobes. The fan lobes are deposited in subtle "ponded accommodation space" and at local breaks on the slope induced by mobile shale ridges.

Two deeper subsurface seismic examples are presented where the shallow observations and the model have been used to interpret the most likely depositional setting in the absence of well control. A third example shows how the increased understanding of the slope processes has helped to interpret the complex depositional setting of the Merpati and Meragi gas and condensate discoveries.

Seismic facies analysis calibrated with the sparse well data indicate that despite close similarities with the bypass and slope facies assemblages in the Gulf of Mexico, the Brunei facies assemblages contain less net sand, reflecting the mud-dominated sediment provenance and the limited amount of available accommodation space.

Reservoir-Scale Characteristics of Fine-Grained Sheet Sandstones, Tanqua Karoo Subbasin, South Africa

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Abstract

Outcrop exposures of the Permian Skoorsteenberg Formation, in the Tanqua Karoo subbasin, South Africa, show a succession of five laterally continuous submarine-fan systems. Thick basin shales (> 25 m) bound each fan. We concentrated on Fan 4, over 60 m thick, which exhibits seemingly laterally continuous sheet sandstones that can be subdivided into six distinct depositional packages. The reservoir-scale (cm-scale) attributes of the basal package, a thickening-upward succession, include excellent overall lateral and vertical connectivity and continuity.

Abundant sole marks, rip-up clasts, shallow bedding-plane scours, and parallel laminations/ ripple cross-laminations, in association with vertical stacking patterns and the absence of channels, suggest deposition from unconfined turbidity flows in a proximal to intermediate depositional lobe (sheet sandstone) setting. The reservoir-scale observations reveal that: (1) apparently tabular, plane-parallel, laterally continuous sandstones in fact vary in thickness and thin gradually to rapidly; (2) the system is dominated by amalgamated, very fine-grained, structureless (massive) sandstones; (3) lateral continuity of sandstone beds exceeds 2 km; (4) dip-oriented shale bed lengths average less than 600 m whereas strike-oriented shales are more laterally continuous (>1 km); (5) basin-floor topography strongly influenced the distribution of sediment; (6) lateral switching of relatively narrow sandstone bodies (one to tens of km) comprise the depositional lobe; (7) good reservoir connectivity exists for a theoretical well spacing of 2 km; and (8) correlation of gamma-ray logs on a kilometer scale is achievable, with thick-bedded sandstones (>20 cm) and/or amalgamated beds of equal thickness showing the best correlation.

Depositional Architecture of a Sand-Rich, Channelized Turbidite System: The Upper Carboniferous Ross Sandstone Formation, Western Ireland

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Abstract

The Ross Sandstone Formation is a 380m thick sand-rich turbidite system deposited in an intracratonic basin during a period of *ca*. 500,000 years. In overall terms, the system has a net aggradational/progradational trend, but this trend has been interrupted repeatedly by glacially-forced fluctuations in sea level that produced a series of condensed sections and interpreted sequence boundaries. Sheet-like turbidites, turbidite channels, megaflute surfaces, mudstone-filled gullies, and slides/slumps are recognised in the turbidite system. Channels dominate the mid to upper parts of the system and show considerable variability. The most widely developed type is a sandstone-dominated channel which comprises two sectors: (1) a locally developed channel axis defined by a master basal erosion surface; and (2) laterally extensive channel wings that overlie megaflute erosion surfaces that flank the channel axis. Channel axes are dominated by massive, highly amalgamated turbidites whereas the equivalent channel wings comprise turbidites having varying degrees of amalgamation and a pronounced thickening upwards trend above the megaflute erosion surface. This trend records the late expansion phase of the channel that followed initial aggradational filling of the channel axis. The ratio of channel axis to channel wing is around 1:10 minimum, resulting in a dominance of sheet-like, channel wing bedsets bounded by megaflute erosion surfaces. Vertically stacked channel wings can be correlated using megaflute erosion surfaces that are laterally extensive and link with axial erosion surfaces.

Sinuous, meandering turbidite channels characterized by lateral accretion surfaces also are recognized. The prime example is 7.5 m deep, 130 m wide, and migrated laterally to produce a meander belt 380m wide, giving a channel width to meander belt ratio of 1:3. Most of the channels in this turbidite system are single-story, but a sandstone-dominated, compound channel is recognized towards the top of the succession. Permeability barriers and baffles in the turbidite system comprise a hierarchical series in terms of lateral extent and potential effectiveness.

High Resolution Morpho-Sedimentary Characteristics of the Distal Orinoco Turbidite System

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Abstract

The distal Orinoco turbidite system (from 4,200 to 5,000 m water depth) has been surveyed with state-of-art, high-resolution acoustic techniques, such as the SIMRAD EM12 multibeam and the SIMRAD TOPAS ultra high-resolution parametric echo sounders. New results indicate that the distal part of this turbidite system shows at least two active systems of sediment transfer, towards the north and towards the east. Both sediment transfer systems depict a large sedimentary complex on which channels with variable sinuosity, degree of incision, and width/relief ratio, braided channels, and distal depositional lobes coexist even in short distances. Such complexity is the result of different patterns of sediment transport of the gravity flows within the turbidite system and of different styles of sedimentation. In addition, the complexity of the east-trending distributary system is accentuated by the probable activity of unchannelized turbidity currents whose interaction with the topography generates a sediment wave field on the right-hand inner margin of this system. The east-trending distributary system connects with the Vidal mid-ocean channel, earlier through a channel that now is filled, and at the present time through a bypass zone of unchannelized debris flows.

Production Characteristics of Sheet and Channelized Turbidite Reservoirs, Garden Banks 191, Gulf of Mexico, U.S.A.

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Abstract

Garden Banks 191 is about 160 miles (257 km) from Lafayette, Louisiana, in 700 feet (214 m) of water. Block 191 has produced over 230 BCF dry gas from Pleistocene reservoirs since 1993. We will address the production characteristics of turbidite sheet (4500' Sand) and channel (8500' Sand) sand reservoirs. Understanding the distribution of shale breaks within both reservoir types is critical because the shales compartmentalize gas production and control water encroachment through the reservoirs.

The 4500' Sand reservoir is about 1000 ft (305 m) thick and is composed of interbedded sands and shales typical of amalgamated and layered sheet sands. The sand is subdivided into four production members (designated 1-4) by shale breaks that extend across the reservoir interval. The reservoir has exhibited a good water drive. Water encroachment occurs individually within each member.

The 8500' Sand is an approximately 900 ft (274 m) thick "fining-upward" channel succession that was deposited in a slope mini-basin formed by salt withdrawal. Shale breaks in this stacked channel succession do not extend across the reservoir, but they do control water encroachment in individual wells. The sand is informally divided into five members based on shale breaks and perched water contacts. Members 3, 4 and 5 are connected, based on RFT pressures. The 8500' Sand has produced from a combination pressure depletion/limited water drive mechanism resulting in excellent recoveries.

The Interaction of Shelf Accommodation, Sediment Supply and Sea Level in Controlling the Facies, Architecture and Sequence Stacking Patterns of the Tay and Forties/Sele Basin-Floor Fans, Central North Sea

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Abstract

A unique perspective of sand-rich, basin-floor fan deposition was gained through an integrated study of the Paleogene deepwater reservoirs in the UK Central North Sea. The data set included contiguous 3D seismic (8400 km^2), 2D seismic (11,100 km), well logs (350 wells), high-resolution palynology (180 wells), and core (30 wells). The study provided new insight into downfan changes in reservoir facies and architecture and a framework to understand fan evolution through both low- and high-frequency depositional cycles.

The Paleogene in this part of the basin is subdivided into four low-frequency (1-3 MY) composite sequences. Major basin floor fan cycles include the Maureen Formation, the Andrew-Lista units, the Forties-Sele-Balder units, and the Tay-Chestnut units. These low-order successions exhibit large-scale compensational stacking behavior and, in contrast to classical fan models, maintain channel-form patterns to their distal pinchouts. Sheet geometries are surprisingly rare. Sandstone body geometries, coupled with core-based lithofacies suggest that both turbidity currents and semi-cohesive sandy debris flows were active during reservoir deposition.

Each of the major sand-rich fan units (*e.g.*, Forties, Tay) is composed of higher frequency depositional sequences that display important changes in lithofacies and architecture through time. The early sequences are heterolithic consisting of variable proportions of mud-rich debrites and sandstones that are commonly thin and arranged into broadly channelized bodies (high aspect ratios). The later sequences are much sandier. The sandstone bodies show slightly sinuous to linear channel-form patterns (lower aspect ratios). Although less laterally extensive, the youngest sequences have high quality reser-

voirs that locally have strongly mounded cross-sectional geometries.

The vertical change in reservoir character reflects a progressive change in the composition and relative volume of the sediment gravity flows being triggered at the shelf edge and then delivered into the basin. Following initial phases of muddy debris flows and sandy turbidity currents, sediment gravity flows became progressively sandier and confined in discrete channels. Latest-stage sequences are locally dominated by sandy debrites. This pattern records the evolution of the lowstand shelf-margin system as it became progressively sandier and increasingly prone to large, sand-rich failures that maintained a semi-cohesive rheology as they flowed onto the basin floor. Superimposed on this changing sediment composition is a progressive decrease in sediment volume as more sediment is trapped on the shelf in response to the low-order rise in sea level.

This integrated seismic, lithofacies, and stratigraphic analysis leads to an improved regional (play) to local (field-scale) stratigraphic correlation and reservoir mapping methodology. This analysis also addresses variations in reservoir quality, channel geometry, and lateral and down-fan facies changes.

The Annot Sandstone Outcrops (French Alps): Architecture Description as Input for Quantification and 3D Reservoir Modeling

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Abstract

The Eocene-Oligocene Annot Sandstone of South East France is a sand-rich turbiditic system, up to 1000 m thick, which was deposited in several parallel and tectonically controlled sub-basins. For reservoir characterization purposes, three kilometer-scale outcrop areas were studied in detail, resulting in bed-scale, 2D and 3D architecture descriptions.

The western Annot-Chalufy confined sub-basin, probably fed from a fan-delta located near Saint Antonin, shows a downstream evolution from very coarse-grained erosive channels (developing lateral terrace deposits) to tabular channelized or depositional lobes separated by thick heterolithic levels acting as major permeability barriers.

The eastern Sanguinière narrow sub-basin was probably fed by multiple braided deltas at the border of the Alpine mountain chain to the east. In a ramp setting, coarsening then fining-upward sequences register the increase then decrease in flow energy of coarse-grained amalgamated channelized turbidites that evolve downstream into erosional channels, then finer-grained slope depositional channels and elongated sand tongues.

In this framework, the geometrical and geostatistical characteristics of the constitutive architectural elements have been quantified. 3D geocellular reservoir models of the outcrops have been reconstructed and used for synthetic seismic modeling.

Turbidite Reservoir Architecture in the Northern Gulf of Mexico Deepwater: Insights from the Development of Auger, Tahoe, and Ram/Powell Fields

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Abstract

The development and early production of several fields is making available new geological, fluid, and pressure data with which to validate, or modify, existing models of reservoir architecture. This paper summarizes the observations and insights from several developed turbidite reservoirs. The reservoirs represent examples from each of several major reservoir architecture types, including layered/amalgamated sheet sands (Auger field); channel-levee deposits (Tahoe Field); and amalgamated channel complexes (Ram/Powell field).

Previous authors (McGee et al., 1994) have described the “S” sand at the Auger field as a layered- and amalgamated- sheet sand deposited within a structurally confined salt minibasin. Production performance reveals that the pressure of the reservoir has declined more slowly than expected, indicating aquifer support from sheet sands that extend across the entire minibasin. Sequential production logs of a downdip well indicate that the reservoir is not watering out in a uniform, bottom-to-top pattern, however. The occurrence of water-bearing zones above oil-bearing ones indicates the presence of effective internal seals within the reservoir that, like the sands, are laterally extensive.

Thin-bedded reservoirs, such as those that produce gas at prospect Tahoe, are interpreted as the overbank portion of channel-levee complexes. The thin-bed reservoirs comprise millimeter to centimeter thick sand beds separated by mudstones of similar thickness. Early concern about the lateral extent of such thin-bedded sands led to pre-development production testing (Shew et al., 1993), which indicated that the beds were laterally continuous over areas exceeding several hundred acres. Pressure profiles in newly drilled wells, however, exhibit stratigraphically varying pressure depletion. Sands in the upper levee facies appear to be laterally continuous, even across the channel. Sands in the lower portion of the reservoir, however, are much less connected. Channel-levee architecture appears to evolve from localized to extensive overbank sedimentation. The thicker beds, which occur at the base of the levee facies, do not appear to be the more continuous.

Most problematic, from a development perspective, are channel-fill reservoirs, such as the Miocene “N” sand at Ram/Powell. The reservoir appears to comprise multiple, partially stacked, laterally migrating sand units deposited within a pre-existing erosional scour; they exhibit large thickness differences, even over short distances. Paradoxically, all wells indicate some degree of pressure communication, but the occurrence of numerous perched water levels implies the existence of multiple, internal reservoir compartments. Partial amalgamation of the two sand members allows fluid communication to occur, but the lateral heterogeneity in sand thickness creates structurally low closures in which water is trapped.

Our observations illustrate a spectrum of turbidite reservoir architectures and their influence on production performance. The elements important to reservoir characterization are often below the limits of seismic resolution. It is valuable therefore to integrate the diverse information that comes from development and production activities in order to develop the reservoir architecture models that will facilitate future planning and decision making.

The Relationship Between Channelized Deep-Water Reservoir Architecture and Recovery from Petroleum Reservoirs

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Introduction

In a typical reservoir modeling workflow, the stratigrapher defines the architecture of the petroleum reservoir and provides constraints and insights on its permeability distribution. A geologic model-builder or geo-statistician then constructs a 3-D geologic model that simplifies by necessity the fine scale heterogeneity perceived by the stratigrapher. Subsequently, a reservoir engineer performs flow simulations. Commonly, little feedback is provided to the stratigrapher about flow simulation results. As a result, stratigraphers usually do not have a clear idea how their interpretations influence the flow simulation. The situation is further confounded because geologic models are typically upscaled, such that models that are flow simulated only vaguely resemble the original geologic models, which are themselves simplifications of the stratigraphers' original concept about the reservoir. Certainly, when stratigraphers see the flow simulation results of a model, they can't help but wonder what the results would have been had they changed their interpretation slightly, or greatly. We have had the opportunity to study multiple feedback loops, numbering in the hundreds, between definition of reservoir and permeability architecture, model building, and flow simulation for both conceptual and field-based models for channelized and sheet-like reservoirs. Some results of our investigations are presented here for channelized deep-water reservoirs.

Exploring Deepwater Technical Challenges in the Gulf of Mexico

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Abstract

The Gulf of Mexico has been a center of deepwater exploration and development activity since the early 1980s. Technological developments have been key to the strong reserve and production growth levels experienced today.

This presentation explores the status of today's deepwater activities and assesses the subsurface concepts and development technologies needed to successfully explore and develop deepwater reservoirs.

Lessons Learned from the Management of Basin Floor Submarine Fan Reservoirs in the UKCS

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Introduction

This paper reviews approaches and lessons learned from the exploitation of reserves from moderate to high net:gross submarine fan systems from the UK sectors of the North Sea and the Atlantic Margin. Examples are given from the Forties, Magnus, Andrew and Schiehallion fields (Fig. 1). We show how contrasting reservoir management approaches and experiences can be related to architectural elements of the different fan systems. The submarine fans range in age from Jurassic to Palaeocene and the development schemes from platform drilled 'conventional' wells to geosteered horizontal wells tied back to floating production systems.

The Forties, Andrew and Schiehallion fields have reservoirs of Palaeocene age (Forties and Andrew Formations, respectively). The main reservoir in the Magnus Field is Late Jurassic in age (Magnus Sandstone Member). Slope apron systems (*e.g.,* Brae Fields) are excluded from this discussion.

Characterization of Lateral Heterogeneities in an Exceptionally Exposed Turbidite Sand Body, Grès d'Annot (Eocene-Oligocene), SE France

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Abstract

The Trois Evêchés outcrop of the Grès d'Annot (Annot Sandstones: Eocene-Oligocene, SE France) represents one of the world's best exposed examples of a confined sandy turbidite system and has exceptional exposures of 'channelised lobe' or 'amalgamated sheet' sand-bodies. The sand bodies have simple tabular external geometries (lobe/sheet-like) but show complex internal organisation characterised by a combination of scouring, bypass and aggradational features (channel-like). We have targeted the best exposed, most laterally continuous sand body (termed the FB unit) for very detailed studies at a scale appropriate to reservoir modeling. The result is a west northwest-east southeast panel 35 m thick, 1700 m long parallel to palaeocurrent direction ('downdip'), within which all zones are characterised in terms of key properties (grain-size, sorting, cementation, and primary and secondary structures) and all key surfaces are absolutely correlated (*i.e.*, directly physically traced). This unique database allows quantification of lateral facies relationships and deterministic definition of both architectural components and stratal hierarchy. The FB body is a thick, tabular, high-net:gross unit having a simple tabular external geometry but a complex internal structure. Key observations are that: (1) the system shows considerable lateral variability; (2) the well-defined base of the FB sand body is a different genetic surface in different places; (3) a few beds and surfaces are laterally persistent but, because of erosion, many are not traceable for more than 100-200 m; (4) packages within the sand body are erosive based and vary laterally in thickness, having an element of compensation between successive packages; (5) the erosive-based packages show a back-stepping arrangement of successive points of deepest erosion (*i.e.*, migrating towards the east-southeast, up-palaeocurrent). The FB sand body appears relatively uniform at a distance but in detail contains numerous heterogeneities at variable scales which would have a considerable impact on fluid flow through an apparently homogeneous sandstone.

Remobilization and Injection in Deepwater Depositional Systems: Implications for Reservoir Architecture and Prediction

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Abstract

Several productive Paleogene deepwater sandstone reservoirs in the North Sea show evidence of having undergone post-depositional remobilization and clastic injection, which can result in major disruption of the primary reservoir distribution (*e.g.*, Alba, Forth/Harding, Balder, and Gryphon fields). Case studies of deepwater sandstones from UK Quadrants 9, 15, 16 and 21 are presented to illustrate the wide spectrum of remobilization features, which range from centimeters (*e.g.*, core-scale) to hundreds of meters (*e.g.*, seismic-scale). Most common are clastic injection structures such as dikes and sills. Sills of massive sand, over 20 m thick, have been identified. Intrusions associated with the propagation of syn- to early post-depositional, dewatering-related polygonal fault systems in adjacent deepwater mudrocks are also common. The scale of the clastic intrusion and remobilization has significant impact on reservoir architecture and production performance, including changes in (a) original depositional geometries; (b) reservoir properties; (c) connectivity, (d) top reservoir surface structure, (e) reservoir volumetrics, and (f) recovery/performance predictions.

There are several prerequisites for sandstone intrusions to form: the source sediment must be uncemented, and the 'parent' sand body must be sealed such that an overpressure with a steep hydraulic gradient can be generated. The seal on the overpressured sand body must then be breached for the sand to fluidize and inject. The stress state within the basin, burial depth, fluid pressure and the nature of the sedimentary host rock all contribute to the final style, geometry and scale of intrusion. At shallow depths, within a few meters of the surface, small irregular intrusions are generated, more commonly forming sills, whereas at greater depth larger and more continuous dikes and sills form clastic intrusion networks. Field examples from the Ordovician in Ireland, and Panoche Hills in California are used to illustrate the control of burial depth/stress on intrusion scale.

Earthquake induced liquefaction, tectonics stresses and build-up of excess *in-situ* pore pressure are the most commonly cited explanations for the occurrence of clastic intrusions. However, our work suggests that the large-scale, 'catastrophic' sandstone intrusions within the North Sea Paleogene, which remobilized hundreds of cubic meters of sediment, probably require the presence of fluids migrating from deeper within the basin (*e.g.*, gas charge) to drive the injection. Deepwater sand bodies within the North Sea that appear most susceptible to remobilization

occur in mud-dominated successions and include (1) narrow, elongate channel or gully-filled sands (*i.e.*, non-leveed channel systems), and (2) isolated sand-rich mounds (*e.g.*, 'ponded' sand bodies and terminal fan lobes). Sand bodies located above rift-related basin-forming faults, which periodically appear to have acted as vertical fluid escape pathways, were especially susceptible to remobilization. Sand remobilization may influence reservoir distribution in other mud-dominated, deepwater depositional systems.

Upper Carboniferous Deep Water Sediments, Western Ireland: Analogues for Passive Margin Turbidite Plays

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Abstract

The Upper Carboniferous Shannon Basin of western Ireland is an extensional basin with a 930 m thick, sandstone-bearing, deep water succession comparable to several passive margin basins around the world. A range of possible play types can be illustrated, deposited either in a sand-rich basin floor setting, or in a more mud-rich slope-basin floor transitional setting.

The sandstones mainly belong to the 380 m thick basin floor succession of the Ross Formation. This formation is a sand-rich submarine fan system which was axially supplied, and which sidelapped the basin margins. Several reservoir-type sandstones occur, including randomly organized tabular bed packages, channel sandstones, and sandier-upward packages capped by giant flutes.

In contrast, the overlying, 550 m thick Gull Island Formation is a mud-rich turbidite system and can be divided into two parts. (1) The lower 420 m represent interfingering between axially-transported, sidelapping basin floor turbidites and muddy slump and slide deposits from the lateral, probably degrading northern basin slope. This part is composed of three laterally variable facies associations: turbidite sandstones which thin and disappear upwards, slump and slide sheets, and thin hemipelagic draping mudstones and shales. The main reservoir type sandstones occur in this part of the Gull Island Formation and include mud diapir-bounded channel sequences, regular channel-fill sequences, growth-fault controlled packages, thickening sandier-upward inter-channel packages, and tabular-lenticular packages. (2) The upper 130 m, together with the overlying frontal deltaic deposits of the Tullig Cyclothem, represent the prograding, northern basin slope which advanced laterally across the basin floor deposits, and contains deep-water reservoir type sandstones of only one type: slope channel-fill sandstones.

The stratigraphy and sedimentology of the Ross and Gull Island formations form an important analogue for turbidite systems in other passive margin basins such as the North Sea Basin, the eastern North Atlantic margin, the West African margin, and in some ways with the Cenozoic Gulf of Mexico Basin. The observed change in the Shannon Basin from sidelapping sandstone-rich to sandstone-poor basin floor systems to a downlapping mudstone-rich slope system is important to understand for prediction in these prolific basins.

Bounding Surfaces, Lithologic Variability, and Sandstone Connectivity Within Submarine-Canyon Outcrops, Eocene of San Diego, California

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Abstract

Beach cliffs north of San Diego, California, provide superb three-dimensional exposures of an exhumed Eocene submarine-canyon complex. Photomosaics aid in analyzing bounding surfaces and lithologic patterns.

An irregular sequence boundary defines the canyon floor. Two stratigraphic sequences comprise the canyon fill; two sequences lie beneath. The canyon base unconformably separates lagoonal and tidal deposits of the underlying Delmar and Torrey sequences from bathyal units of the Ardath Sequence. A second submarine sequence boundary occurs within the canyon succession, eroding into the top of the Ardath Sequence and dividing it from the overlying Scripps Sequence. A fifth (shallow-marine) sequence, which is not described here, truncates the Scripps Sequence to the north and inland. Pleistocene wave-cut terraces plane off the Eocene interval at the top of the cliffs. Internally the canyon complex displays multiple cross-cutting channels on a multitude of scales and with widely diverse lithofacies. Individual channels range from subtly scoured and only a few meters deep to over 1 km wide and up to 100 m deep.

The lowermost canyon fill (Ardath Sequence) comprises amalgamated, pebbly and diffusely laminated sandstones, which fine upward to convolute-bedded fine-grained sandstones, which then grade into laminated to bioturbated silty mudstones. The mudstones fill channels that exhibit a sinuous morphology. Multiple erosional episodes scoured each channel; channel fill predominantly occurred during abandonment. Subsequent flows evacuated a multitude of cross-cutting successions. Coarser grained units often punctuate the mudstone channels. Some contain interbedded $T_{(b)c\text{-}e}$ turbidites. Others display a mantle of mudstone along their base overlain by a massive sandstone plug

Large slump blocks define the base of the Scripps Sequence. They line the sequence boundary and represent canyon rejuvenation. The overlying section displays laterally interconnected coarse-grained channels 100’s of meters wide but less than 30 m thick, arranged in a braided architecture. Complete successions in these channels contain basal conglomerates overlain by pebbly sandstones that grade upward to interbedded sandstone and siltstone, and finally mudstone.

Lithologic predictability within ancient submarine canyons is problematic. Variable channel fills in this Eocene system produce complex vertical and lateral patterns. However, the canyon succession exhibits overall large-scale fining-upward trends above each sequence boundary, yielding a general facies model.

The Architecture of Turbidite Slope Channels

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Abstract

Large-area 3D seismic surveys over Tertiary deepwater basins have started to show remarkable details of the geometry and facies of turbidite slope channels. The slope systems, which are presented here, are characterised by subtle to complex structural topography created by salt or shale diapirism or faults. In the upper part of the slope, the channels are often relatively narrow (<1 km), have fairly straight leveed margins, and may or may not contain a moderate-high sinuosity channel axis. Downslope the channels become broader (1-3 km), highly sinuous (sinuosity >2), have erosional bases and local levee and crevasse-splay development. In this part of the slope the channels typically show a vertical sequence which consists of an erosional base, a coarse-grained lag (by-pass phase), slumps and/or debris flows (locally derived or more distant transport?), high N:G sandy fill of stacked channels which may be straight or sinuous, and finally a lower N:G sequence having highly sinuous channels and levees. The relative proportion of each of these facies can vary significantly.

Moderate to high sinuosity is a characteristic of many of the channels. However, a range of sinuosity styles are present and these include: (i) Sinuosity controlled by local sea-floor topography - usually faults; (ii) sinuous channels which show no lateral shift of the channel; (iii) sinuous channels which show successive lateral shifts in the channel axis; and (iv) channels, usually on a smaller scale (tens to 200 m wide) which may show inclined reflectors dipping in the direction of channel migration. It is this latter form of sinuosity which produces features very similar to fluvial systems. It is possible that the range of sinuosity styles reflects a variety in control from local basin floor topography to flow process. The facies seen in cores indicates that turbidity current and debris flow process are dominant in all cases.

In our experience, ponded systems, that is basins in which the channel systems terminate on the slope as a result of slope topography, are not common. Indeed the appearance of ‘ponding’ can be a function of the extent of the 3-D data set; in areas of smaller data coverage, it is often easy to interpret channel systems terminating in intra-slope basins. However with increasing coverage of 3-D data the channels can usually be seen to have continuous but very convoluted courses which takes them through and beyond complex slope topography. At sharp bends in channels, it is common to observe sheet-like seismic facies (although generally thin), extending away from the channel margins.

Topographic constraints within the slope topography may locally fix the course of the channel system for some time, while down slope of the constriction the channels take different, usually compensatory off-setting courses through time.

Associated with the channels are more ‘sheet-like’ single seismic cycle facies. The genesis of these features is less clear and they appear to have multiple origins. Some are clearly levees and splays of the larger channels but many others are single channels varying from straight to highly sinuous and have mud- to sand-filled axes. These types of channels appear to be the ‘building blocks’ which amalgamate to form the sandy stacked channel component within the larger erosional channel fills.

These Tertiary channel systems have very similar geometries to those observed in many modern fans, such as the Amazon and the Zaire, and pose many questions regarding the nature of the currents which transported and deposited the sediments.

Using Outcrop Analogs to Improve 3D Heterogeneity Modeling of Brazilian Sand-Rich Turbidite Reservoirs

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Abstract

The Carapeba field reservoirs, located in Campos Basin, offshore southeastern Brazil, consist of sand-rich deep-water deposits formed by amalgamated turbiditic channels, whose properties were modeled using subsurface and outcrop-analog information. Outcrop analogs have been found in the Eocene Annot Sandstone, of southern France. The main geological inputs to the reservoir modeling process include: (1) recognition of main intra-reservoir stratigraphic units, (2) determination of facies continuity and connectivity, and (3) determination of shale (permeability barrier) continuity. The recognition, both in the outcrops and at the subsurface, of two hierarchical levels of intra-reservoir stratigraphic units, which are interpreted to represent the products of 4th- and 5th-order sea-level cycles, and are possible to correlate at typical offshore interwell distances, is particularly relevant to reduce flow-unit scale stratigraphic uncertainty. Facies continuity has been estimated using outcrop data calibrated to cores, well-logs, and production data. Outcrop facies continuity is used to guide facies extrapolation in the subsurface 3D model, resulting in more realistic permeability structures. Shale continuity, which is a major factor controlling fluid movement within the reservoir, is mainly resultant, in these high-energy sand-rich turbidite systems, of the frequency and intensity of erosional processes. Most shales show continuity of several hundred meters or more, with erosive "windows" appearing locally. In these areas, permeable vertical pathways connect adjacent units. Nevertheless, overlapping of semi-continuous beds causes a general tendency of lowering effective vertical permeability. The final subsurface 3D model, showing reduced effective vertical permeability and moderate horizontal anisotropy, is quite different from what is conventionally expected for sand-rich turbidite reservoirs.

Reservoir Architecture of Deepwater Sandstones: Examples from the Skoorsteenberg Formation, Tanqua Karoo Sub-Basin, South Africa

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Abstract

Outcrops of the Permian-age Skoorsteenberg Formation contain six major deep-marine systems. These systems vary from 20 to 60 m (66 to 197 ft) in thickness, are exposed up to 40 km (25 mi) in length and are vertically compartmentalized by basinal mudstones of varying thicknesses. Channel-fill deposits associated with levee-overbank systems occur as laterally stacked channel thalweg complexes (<200 m or 656 ft wide, 5 m or 16 ft thick), aggradational channels (over 1000 m or 3280 ft wide, 25 m or 82 ft thick), or erosional channels (500 m or 1640 ft wide and 18 m or 59 ft thick) that later have been back-filled by channel aggradation. They are composed of amalgamated Ta beds with few internal mudstone breaks and relatively high kv/kh ratios. Channel fills are in limited hydraulic communication with sandy levee-overbank deposits due to scour and interfingering. Packages of sandy levee-overbank deposits, about 10 m (33 ft) thick, extend well over 1500 m (4920 ft) away from channel axes. Such packages may exceed 90% net sand but have low kv/kh ratios. Associated crevasse channels, are about 430 m (1410 ft) wide and 26 m (85 ft) thick with a complex fill architecture. Vertically stacked fan lobes (sheet) attain 60 m (197 ft) in thickness, are commonly off-stacked and show an upward increase in degree of amalgamation. Distal lobe (sheet) thins too less than 13 m (43 ft) and is less well amalgamated. Dominant mudstone types within lobe (sheets) include laterally continuous 1 to 2 meter (3.3 to 6.6 foot) thick Tcde intervals between major tabular bodies and thin, discontinuous mudstone drapes within amalgamated tabular bodies.

Mudstones are the most important heterogeneity controlling fluid flow in this type of reservoir. Deterministic mapping of mudstone-bounded flow units would be most readily applied to lobe (sheet) deposits. Small-scale mudstones must be treated as stochastic elements in a numerical description.

Sedimentologic and Geometric Criteria for Comparing Modern and Ancient Sandy Turbidite Elements

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Abstract

Deep water depositional systems are formed by a combination of turbidite elements, which can be recognized from modern and ancient settings using outcrop observations, seismic-reflection data, or well-log and core data. Elements of turbidite systems can be compared to derive general sedimentologic parameters only if physical scales, geometry, time frame for deposition, and linked turbidite elements are reasonably similar. If these parameters are not considered, turbidite-channel elements, a common reservoir target, can easily be confused with other "channel-like" elements. In some deposits, one or more of the elements are represented by several distinct sub-elements, *e.g.*, a succession of both lensoid and wedge-shaped lobe deposits can comprise the lobe-element area. The different lobe sub-elements develop in response to shifts in position of the channel mouth and changes in the sediment supply. An understanding of the dimensions, facies, and stratigraphic development of these modern and ancient turbidite elements can provide criteria for distinguishing turbidite elements. In addition, an improvement in our understanding of the geometric and sedimentologic characteristics of specific turbidite systems can eventually lead to better predictive depositional models.

Sequence Stratigraphy of the Alaminos Fan (Upper Miocene-Pleistocene), Northwestern Deep Gulf of Mexico

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Abstract

The Alaminos Fan (uppermost Miocene to lower Pleistocene) is a moderate sized, mud-dominated submarine fan in the northwestern deep Gulf of Mexico. Located in the southern portion of the Alaminos protraction area, the fan is bounded to the north by the salt tongues of the Sigsbee Escarpment; the fan overlies and extends southeast of the northern portion of the Perdido fold belt. Interpretation of 1500 km of 2D multifold seismic data has defined five depositional sequences, four of which consist of thin shallow distributary channel-fills, thicker aggradational levee/overbank, and areas of mass transport complex (MTC) and/or localized slides. Distributary and channel-fill deposits are characterized by high amplitude and subparallel reflections having poor to good continuity. Levee/overbank deposits are characterized by low-moderate amplitude, parallel to subparallel reflections with good continuity. MTC's and/or slides are characterized by a series of hummocky to chaotic reflections with variable amplitude and poor continuity.

Channels in the two oldest sequences have come from the lower slope east of the modern Alaminos Submarine Canyon. Channels in the two youngest sequences came from the Alaminos Submarine Canyon, and extend across the "Baha" fold of the Perdido Foldbelt, to the unconfined setting to the southeast. All channels have a low to relatively high degree of sinuosity, from 0 to 5.5 km lateral migration, and widths of up to 1.5 km. MTC's and/or localized slides exhibit varying degrees of geometry as well. Two sequences have elongated MTC's, mimicked by overlying channels, and one MTC that is areally widespread. Localized slides exhibit varying degrees of width and length but are not as areally extensive as the MTC's.

Typical vertical succession of an Alaminos fan sequence begins with an erosional base, which is overlain by an MTC. This, in turn, is overlain by a relatively thin zone of distributary channels (high amplitude reflections) that is areally widespread (up to16 km wide). This zone evolves upward into one main aggradational channel that has low to high sinuosity, shows lateral migration, and bifurcates downfan. Lastly, a condensed section drapes the sequence, and may be eroded by an overlying fan sequence.

Sediment age is unknown, but is tentatively interpreted as being sourced from Texas deltas and the Mississippi Delta during the latest Miocene to early Pleistocene (about 6.6 to 1.9 Ma).

Reservoir Architecture of a Fine-Grained Turbidite System: Lower Triassic Montney Formation, Western Canada Sedimentary Basin

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Abstract

The Lower Triassic Montney Formation of west-central Alberta has been widely recognized as the first and only documented turbidite reservoir in the Western Canada Sedimentary Basin. First discovered and exploited in 1993, this play has yielded over 1.5 TCF of gas, plus liquids, and continues to be an active and expanding exploration play. Extensive well and core control provides the basis for constructing a sequence stratigraphic framework and reservoir architecture of these fine-grained sandstone turbidites. Within the lowstand systems tract of the mid-Montney, turbidite channel, lobe/sheet-sand and levee-overbank facies associations are recognized. Reservoir quality and heterogeneity of these facies are predominately a product of hydrodynamic processes of deposition. Subregional syn- or post-depositional extensional tectonism is recognized as playing a significant role in the distribution, over-thickening and orientation of turbidite reservoir facies.

A distinct ramp-”edge” or break-in-slope trends north-northwest/south-southeast and defines the updip depositional limit of turbidite facies. The ramp-edge orientation is fault controlled and marks the onset of rapid and abrupt thickening of lowstand facies associations. Due to the updip headward retreat of turbidite channels, the ramp-edge is highly modified by mass-wasting processes. Turbidite channels coalesce down-dip towards the base of slope and then grade into turbidite lobes basinward. Turbidite channels are associated with significant lateral discontinuity along depositional strike due to cross-cutting and have greater continuity along dispositional dip. Turbidite channel facies associations can be amalgamated to thicknesses of up to 30 m, due to synsedimentary tectonism within localized grabens or half-grabens. The distribution of levee overbank or channel-margin facies associations constrains the width of turbidite channels to a few hundred meters. In addition to inferring proximity, a levee-overbank facies association can be used to infer the direction of the associated turbidite channel through dipmeter log patterns. Turbidite lobes have a broad aerial extent, up to 10 km^2 in size, occur at the down-dip depositional limit of turbidite facies deposition and thin and grade basinward to shaly siltstone.

Variation of Modern Turbidite Systems Along the Subduction Zone Margin of Cascadia Basin and Implications for Turbidite Reservoir Beds

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Abstract

Cascadia Basin contains a variety of turbidite systems located from Vancouver Island, Canada to Cape Mendocino California, USA. These systems have been studied with multibeam bathymetry, sidescan sonar, high-resolution seismic profiles, and piston cores. On the Washington margin, multiple canyon sources funnel turbidites into Cascadia Channel, a single high-relief deep-sea channel, that extends across Cascadia Basin and cuts through Blanco Fracture Zone. Astoria Canyon feeds Astoria Fan, a submarine fan with channel splays and depositional lobes which fill the subduction zone trench off Oregon. Both of these large turbidite systems (1000 km length) prograde mainly southward parallel to the margin in northern Cascadia Basin. In south Cascadia Basin, small turbidite systems (5-50 km) prograde perpendicular to the margin. Rogue Canyon feeds a small (<5 km) base-of-slope apron. Trinidad and Eel canyons feed into plunge pools and sediment wave fields that extend tens of km radially out from the canyon mouth. A channel-levee complex drains the Eel sediment waves and feeds into a sand-rich lobe. Mendicino Channel, a connecting channel-levee complex without distal lobes, traverses the base of Mendocino Escarpment at the triple junction. Turbidite systems from the Rogue River north contain 13 correlative post-Mazama turbidite events based on the first occurrence of Mazama Ash (MA) at about 7530 calendar yr BP. Another 12,300 calendar yr datum, at approximately the Pleistocene/Holocene boundary (H/P), is found throughout Cascadia Basin. Based on these datums, turbidite events appear to be triggered by seismic events on average every 600 years in northern Cascadia Basin and progressively more often toward the Mendocino Triple Junction (i.e in Trinidad pool every 492 yr, in Eel lobe every 246 yr and in Mendocino Channel every 40-65 yr)

The correlation of turbidite events can be used to compare bedding continuity within systems and between different systems to provide important implications for turbidite reservoir characteristics. The progressive loss of post MA turbidites down the proximal 150 km of Astoria Channel suggests that during this time, downfan continuity in turbidite beds is less in fan channels compared to Cascadia Channel where all 13 post-MA beds are continuous throughout the deep-sea channel. In contrast, both deep-sea and fan channels exhibit cut and fill in proximal

regions, sediment bypassing and down channel dropout of beds during the Pleistocene. As a result, high sand:shale ratios (1:1 to 3:1) are found in distal fan lobes during the Pleistocene whereas low ratios are found during the Holocene. Good lateral bedding continuity is found throughout the Rogue apron that is undisrupted by channels. Turbidite events are twice as common in plunge pools compared to the downstream sediment waves, which suggests a loss of bedding continuity in sediment waves that is analogous to that in channel levees. However, in the case of the Eel system, when the pool and waves are drained by a channel-levee complex, the highest frequency of turbidite beds and sand:shale ratios (1.8:1) are found in the distal lobe. Sand:Shale ratios and frequency of events suggest that during the Pleistocene, sediment erosion and bypassing took place in the pools compared to the infilling of the Holocene. The greatest Holocene infilling rate takes place in Mendocino Channel where turbidite events occur every few decades and sand:shale ratios are 2.5:1.

Baldpate Field Exploration History, Garden Banks 260, Gulf of Mexico

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Abstract

Baldpate Field (GB 260) is located in the offshore Gulf of Mexico approximately 195 miles (122 km) southwest of New Orleans, Louisiana, in 1650 feet (503m) of water. The prospect was identified on 2-D seismic as a pair of stacked amplitude anomalies which were regionally tied to Shell's Auger discovery, and in 1991 Amerada Hess and partner Oryx Energy (now Kerr-McGee) drilled the Baldpate discovery well. Proved and probable reserves of 128 MMBOE are present in four Plio-Pleistocene turbidite reservoirs covering portions of Garden Banks 259, 260, 216, and the south half of 215.

Delineation drilling based on time-migrated 3-D seismic data demonstrated significant lateral mis-positioning of the reservoirs. Detailed evaluation showed that seismic velocities were too fast as a result of severe local anisotropy, resulting in over-migration of the reservoir anomalies. Using proprietary in-house processing capabilities, the velocity field was dynamically updated during the development phase, and a post-stack depth migration was generated which was calibrated to the well control. This migration was used to successfully complete the development drilling.

Baldpate Field reservoirs range from Pliocene turbidite sheet sands (Big sand, Twin sands) to early Pleistocene amalgamated channel and sheet sands (BL-3 sands). The primary reservoirs in the field are the turbidite sheet sands that are characterized by high porosity and permeability and exhibit excellent lateral continuity. These reservoirs contain under-saturated volatile fluid; a significant compositional gradient is trapped on the southwest flank of a sub-horizontal salt feature.

Understanding of the Baldpate reservoir geometries through integration of conventional core analysis, DST results, petrophysics, and reservoir simulation modeling has led to better development planning, resulting in significant cost savings due to a reduced well count and subsequently smaller production facilities.

Amerada Hess, operator of the field and 50% partner Kerr-McGee chose a compliant tower to develop Baldpate field. Production began in September 1998, at a peak rate of 59,000 BOPD and 234 MMCFGPD. Cumulative production through July, 2000 was 26.5 MMBO and 97.6 BCF.

Mensa, Mississippi Canyon Block 731 Field, Gulf of Mexico – An Integrated Field Study

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Abstract

Shell Offshore Inc.'s Mississippi Canyon Block 731 Field (Mensa) is a large turbidite reservoir in 5300-ft (1615 m) water depth containing estimated in-place reserves of over 1.3 TCF of dry gas. The field is currently producing over 240 MMCFGD out of three wells, connected to a subsea manifold located 5 mi (8 km) away. The gas and associated condensate (1.75 bbls/mmcf) is carried through a 63 mi (101 km) flowline to Shell's West Delta 143 platform for processing. There are limited opportunities to intervene in such a system, and any additional work in the field (e.g. recompletions/workovers) is very costly. An understanding of the reservoir geology is critical to optimize the development and minimize the need for future intervention work.

The vast majority of the gas reserves is in the Late Miocene "I" sand, an amalgamated sheet sand deposited as a fan in a relatively unconfined basinal setting. Salt withdrawal on the south end of the basin provided accommodation space (Table 1), and the fan is proximal to a sediment entry point on the northwest edge of the field. Based on 3-D seismic and two well penetrations (the discovery and appraisal wells), the "I" reservoir was originally modeled as a very homogeneous sand connected to a large aquifer to the south that provided the field's drive mechanism. However, when production from the first well commenced, initial pressure measurements did not support this model, and reservoir simulations using these data suggested that the "I" sand was primarily a depletion-drive reservoir with little or no aquifer support. This had serious negative implications for the estimated recoverable reserves and the development strategy; the 63 mi (101 km) flowline and glycol-based hydrate inhibition system requires maintaining a reservoir pressure above 3200 PSI over the lifetime of the field with the support of a large, well-connected aquifer.

The Mensa subsurface team re-mapped the field using a high-frequency seismic dataset that had not been previously available. The team re-evaluated both the geologic model for the "I" sand and other new but smaller gas reservoirs encountered in the last production well to be drilled in the field (MC-687 A-2). The results suggested that the original geologic model for the "I" sand was overly simplistic. The reservoir is now viewed to be an amalgamated sheet sand complex, with at least two distinct sand lobes seen seismically and in well logs, one cutting down into the other, and with the possibility for there being at least a partial permeability barrier between them. Some of the new reservoirs seen in the A-2 well appear to be juxtaposed with the "I" sand across a series of faults within the field, providing additional reserves that could be at least partially drained by the three producing wells. An erosional bypass (Table 1) channel partially bisects the "I" sand aquifer and may help to limit the amount of pressure support that the aquifer can provide. The aquifer itself may be composed of several sand lobes that may not fully communicate with each other, although there is no current evidence seismically and there are no wet "I" sand penetrations. The presence of partial permeability barriers in the "I" sand, either from a post-depositional bypass channel or internal baffles, could give an early pressure history that would suggest a depletion drive. Over time, however, the team expects that these internal barriers, if present, will break down as the pressure differential across them increases (this has been Shell's experience elsewhere, e.g. Shell's South Timbalier 292 Field), and the reservoir will then behave more like an aquifer-driven system. Recent pressure data appear to confirm this and no change in the development is planned at this time.

3D Reservoir-Scale Study of Eocene Confined Submarine Fans, South-Central Spanish Pyrenees

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Abstract

The Ainsa deep water (drilling) project was designed as an integrated outcrop-subsurface study of sand-rich submarine fans, in order to use the data for quantitative reservoir-scale characterisation, leading to improved reservoir performance prediction and simulation. Due to confidentiality agreements, this poster only considers the outcrop data.

The deep water middle Eocene (early middle Lutetian) Ainsa clastic systems are interpreted as cross-sections through the proximal parts of topographically and structurally confined, coarse-grained sand-rich, lower slope and axial basin-floor submarine fans within the South Pyrenean foreland basin (Fig. 1). Three discrete fan systems are identified, and named the Ainsa I, II, and III fans (Fig. 2). Palynological and sedimentological data support the concept that all three fans (Ainsa I, II, and III) are a response to changing relative base level in the sediment source area.

Equilibrium Profile and Baselevel in Submarine Channels: Examples from Late Pleistocene Systems and Implications for the Architecture of Deepwater Reservoirs

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Abstract

Modern submarine channels in a variety of tectonic settings display relatively smooth longitudinal thalweg depth profiles despite the topographic irregularity of the adjacent seafloor. The erosional and depositional action of turbidity currents over periods of thousands of years leads to the development of a depth profile tending to an equilibrium condition, i.e., with a local slope such that the prevailing sediment discharge is carried through the channel with minimum aggradation or degradation. Where sedimentary processes are the dominant shaping mechanism, the equilibrium channel tends to assume a concave-up thalweg profile, as illustrated by the modern Amazon and Rhône Fan channels. Where the rates of tectonic deformation are comparable to the sediment flux, the thalweg profile smoothes irregularities but reflects, in part, the motion of active structures, as illustrated by intra-slope channels in the Gulf of Mexico and offshore Nigeria.

Disruption of the equilibrium profile occurs when the rates of tectonic deformation (e.g., faults and/or folds) exceed the sediment flux or when there is a systematic change in the sediment flux compared with the prevailing flow conditions. Channel avulsion and down-to-basin normal faults are a common expression of equilibrium disruption, with introduction of a steeper segment along the thalweg profile. Three-dimensional seismic and sidescan sonar images illustrate in detail the various processes of equilibrium disruption and stages associated with equilibrium re-establishment. These include thalweg down cutting and meander cut-offs updip of knickpoints, development of distributary channels and sheets as aggradation progresses downdip, and channel damming and redirection associated with up-to-basin normal faults and folds. The mechanics of equilibrium profiles in submarine channels is key to understanding the type and spatial distribution of reservoir elements in deepwater systems.

Deep Water Depositional Systems—Ultra-Deep Makassar Strait, Indonesia

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Abstract

The ultra deep environment in the Makassar Strait, offshore eastern Kalimantan, Indonesia is characterized by abundant turbidite, debrite, and sediment wave deposits. Key depositional elements imaged by 3-D seismic data include leveed channels, distributary channels/frontal splays, overbank wedges (levees), overbank splays/sediment waves, bottom-current sediment waves, debris flow sheets and debris flow lobes. These elements are systematically deposited within the context of a deep-water depositional sequence in the following order: 1) debris flow sheets/lobes at the base, 2) distributary channels or frontal splays, 3) single, prominent leveed channels, capped by 4) less widespread debris flow sheets or lobes.

Leveed channels of inferred Miocene to Pleistocene age are common in the stratigraphic record of the ultra-deep (i.e., greater than 2000 m water depth) Makassar Strait. These channels are characterized by moderate to high sinuosity and range in width from less than 250 m up to one km, and are associated with overbank wedges approximately one order of magnitude wider. Overbank wedges are characterized by abundant sediment waves. These sediment waves commonly are best developed on outer bends of channel meanders. Sea-floor irregularities have a marked impact on channel pattern as well as stratigraphic architecture. One prominent channel is characterized by a dramatic increase in sinuosity and decrease in channel width just down-system from a toe-thrust ridge across which it flows.

Leveed channels commonly feed as well as overlie distributary channel complexes. Distributary channel complexes can attain widths of greater than 10 km and thicknesses exceeding 80 m. Frontal splays appear to be channelized throughout, nearly to their distal extremities.

Debris flow deposits, in the form of sheets, lobes, and channel fill, are common in the study area. Amalgamated debris flow sheets reach thicknesses up to 150 m and widths greater than 20 km. The base of debris flow sheets are characterized by scour and exhibit deep (up to 30 m) and long (greater than 20 km) parallel grooves that diverge basinward.

Hierarchy of Deep-Water Architectural Elements With Reference to Seismic Resolution: Implications for Reservoir Prediction and Modeling

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Abstract

Seismic acquisition and processing imposes a spatial filter on the resolution of subsurface stratigraphy. In deep water settings, we recognize four orders of seismic and several orders of sub-seismic stratigraphy. Individual deep water sandstone bodies are usually resolvable on conventional 6-60 Hz seismic data as an amalgam of seismic loops or wavelets (fourth-order seismic). Upon closer inspection, units within many of these sandstone bodies display an internal architecture resulting from depositional topography and various small-scale erosional processes. Internal (first- and second-order sub-seismic) reservoir architecture is locally seen on seismic data as changes in waveform morphology and develops from episodes of starvation, bypass, and/or erosion. These processes produce surfaces that may pass from the tops to the bases of reservoir units. The surfaces influence bed-length and connectivity, especially where draped by mudstone. Classical depositional models usually focus on external reservoir architecture, thereby failing to fully explain reservoir compartmentalization as a control on hydrocarbon recovery.

A High Frequency Sequence Stratigraphic Framework for Shallow through Deep-Water Deposits of the Lewis Shale and Fox Hills Sandstone, Great Divide and Washakie Basins, Wyoming

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Abstract

A detailed study of outcrops, cores, and well logs in the Upper Cretaceous Lewis Shale and Fox Hills Sandstone of south-central Wyoming indicates that the formations were deposited in a transitional shelf-slope-basin setting during a time of rapid relative changes in sea level and sediment supply. The relative changes in sea level and sediment supply affected the location and style of sand and mud deposition. Sequence analysis from outcrops, cores, and in well log correlations was used to interpret a high frequency sequence stratigraphic framework along a regional, 65 km (40 mi.) long, depositional dip-oriented cross section.

High frequency lowstand, transgressive, and highstand systems tracts are interpreted in the sequence stratigraphic framework. Lowstand systems tracts can be divided into the basin floor fan, slope fan, and prograding complex. The basin floor fans comprise continuous thick-bedded sandstones and thin-bedded mudstones that bi-directionally downlap the basin floor in the well log cross section. Slope fans comprise channelized, discontinuous sandstones, thin-bedded continuous sandstones, and continuous mudstones that downlap the basin floor fan and onlap the slope in the well log cross section. Prograding complexes comprise thin-bedded, continuous sandstones and mudstones that downlap the slope fan and basin floor fan and onlap the upper slope and shelf in the well log cross section. All the lowstand systems tract deposits are good candidates for reservoirs and stratigraphic traps when deposited beyond the shelf-slope break.

Transgressive systems tracts comprise highly continuous, organic rich shales when deposited below storm wave base and continuous interbedded sandstones and mudstones when deposited above storm wave base. They onlap the coastline and downlap the basin floor in the well log cross section. They are potential source rocks and seals.

Highstand systems tracts comprise continuous, thick-bedded sandstones and thin-bedded mudstones when deposited above storm wave base and continuous thin-bedded sandstones and mudstones when deposited below storm wave base. They onlap above the coastline and downlap on the shelf and upper slope in the well log cross section.

Development strategies in Lewis fields should integrate a regional perspective with time-based correlations, which allows for the interpretation of the different types of lowstand systems tract deposits, their associated depositional environments, net-to-gross, lateral continuity, and vertical connectivity.

The Lewis Shale and Fox Hills Sandstone can be used as an outcrop and subsurface stratigraphic analog to mud-rich turbidite reservoirs, most notably some Gulf of Mexico and offshore South Africa turbidite reservoirs.

West Seno Field Discovery, Makassar Straits, East Kalimantan, Indonesia

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Abstract

In August 1998 Unocal Indonesia drilled the discovery well for the West Seno Field located in the Kutei Basin offshore East Kalimantan, Indonesia. Following an accelerated delineation program, a Plan of Development was submitted and approved in September, 1999, which served to commercialize the Makassar Straits Production Sharing Contract (PSC) area.

In the West Seno area, hydrocarbon accumulations occur where upper and middle Miocene sandstones are fault and stratigraphically trapped in an updip position. The lateral continuity of seismic reflectors, biostratigraphic analysis, and well log data in the West Seno area suggest the sand-prone intervals display significant lateral distribution. These sandstones are interpreted to be amalgamated, turbidite channel sands associated with interbedded, levee-overbank sand/shale sequences deposited in a mid-slope position. Porosity in the reservoir sandstones ranges from 22 to 32 % and permeability ranges from 150 to 1500 mD. Productive sandstones are characterized by resistivity readings ranging from 4 to 20 ohms. Core data show that low-resistive pay intervals, with 4 to 5 ohms resistivity, are characterized by reservoir bed thickness ranging from millimeter to centimeter scale, interbedded with shale and carbonaceous laminae of similar bed thickness.

Geochemical analyses of the Miocene oils and gases demonstrate they are most likely derived from predominantly terrestrial plant organic material. The hydrocarbons found in West Seno are interpreted to have migrated vertically along faults from the source area to the upper Miocene reservoirs. The oils are all good quality crude having an API gravity range between 35 to 46 degrees.

Data gained from conventional cores, special petrophysical logging tools, and drill stem tests were used to construct a petrophysical model to calculate reservoir properties used in the quantification of the West Seno Field reserves.

The West Seno Field is a "fast tracked" project; only 14 months from time of first discovery through to Plan of Development approval. This will be the first deepwater development for Indonesia and for Unocal; expected first production will commence in 2002.

Reservoir Architecture in the Mars Field, Deepwater Gulf of Mexico, USA: The Implications of Production, Seismic, Core and Well-Log Data

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Abstract

The Mars Field was discovered in 1989 in 2,900 ft of water 56 miles south-southeast of the mouth of the Mississippi River. Production commenced in 1996 and since that time the field has produced via natural depletion over 100 million barrels. Today (December, 1999) the field produces from 16 wells completed in ten reservoir intervals at a rate of around 180,000 barrels of oil equivalent a day. All the reservoir sands have been deposited in deep water, in an intraslope basin. The need to understand pressure data collected during production and the requirement to predict two-phase flow and evaluation of a waterflood scheme has prompted review of the architecture of major reservoir intervals. The largest of these reservoirs, the 100m thick Yellow interval, is discussed here.

Appraisal mapping revealed two key geometries: (i) a sheet sand, the Lower Yellow, which was described in two parts, a lower "amalgamated sheet" and an upper "layered sheet" and (ii) an overlying channel complex, the Upper Yellow. Although initially in pressure equilibrium, it was thought that an intervening shale would compartmentalise these intervals into two distinct reservoirs during production.

The present study has refined the appraisal view to reveal eight first order architectural elements, AE1 to AE8, defined and mapped on seismic data. These architectural elements have been divided into second order, sub-seismic elements using wireline log and core data, and characterised in terms of facies proportions, facies successions, reservoir properties, and likely inter-well architecture.

Key findings are that (i) small areas of contact between first order architectural elements have allowed significant pressure communication throughout the Yellow Reservoir; (ii) pressure data do not indicate low vertical permeability in interbedded sand and shale successions previously described as a layered sheet, and an alternative inter-well view of a low net-to-gross channelised sheet is suggested; (iii) aquifer influx has not been observed, suggesting that the original field-wide OWC is perched and that the true OWC is deeper; and (iv) the bulk of the reservoir drive energy is due to time varying compaction.

The “Above Magenta” Reservoir at Ursa Field: A Process-Response Model to Explain a Classic Wireline Log Signature

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Abstract

In many deep water slope and basin settings, the gamma ray (GR) log profile of a blocky, low gamma unit capped by a “fining upward” trend of increasing GR response back to the shale baseline is commonly interpreted as the signature of a leveed channel system. The “Above Magenta,” the smallest and shallowest of the three principal reservoirs at Ursa Field (located in the Gulf of Mexico some 130 miles southeast of New Orleans), is a classic example of this profile.

The interval has been cored in the Mississippi Canyon (MC) Block 809-1 well. It is characterized by five lithofacies, ranging from clean, structureless fine sands through very fine to fine, laminated sands; carbonaceous very fine sand; finely interbedded very fine sands and mudstones; and structureless gray mudstones. The sand-dominated lithofacies are associated with stacked “blocky” GR responses at the base, representative of at least three sand bodies, each with a different, but internally-consistent sedimentological character. These are in turn overlain by an upward-increasing GR motif, associated with the heterolithic facies.

Within the leveed channel model, these log and core facies are interpreted as a channel fill or lag, overlain by a fining-upward levee. Recent descriptions of the process dynamics of leveed submarine channels (Peakall *et al.*, 2000) suggest that this interpretation is mechanically difficult to justify, as even highly sinuous leveed submarine channels rarely migrate far enough laterally to deposit a full levee profile over a channel fill.

We propose an alternative model for explaining the vertical profile of the “Above Magenta” sand. The model provides a more reasonable explanation for the observed wireline log, core, and seismic character of the sands which are not well accounted for by the leveed channel model. More importantly, it offers a predictive description of the geometry of the reservoir sands, which suggests different connectivity and lateral extent than would be expected from the channel model.

The model proposes that the “Above Magenta” sands are representative of lobate bedforms akin to “HARP” facies (*sensu* Damuth, 1998) associated with deposition precipitated in the region of the basin-edge by the interaction of gravity currents and the local slope. Different lithofacies in the sands are ascribed to deposition from differing gravity flow regimes associated with deposition from variously through-going or deflected flows.

We predict that in the most active depocenter, in the region immediately adjacent to the “Venus” salt, thickly amalgamated lobate sands will occur, forming a series of laterally-offsetting sheets. These will be separated by thinner intervals of more distal facies, representing periods of relative inactivity when the active depocenter migrated to adjacent lows. Thinner bedded, lower net-to-gross facies will predominate away from the salt-defined edge of the basin to the east and south, where flows are unimpeded and pass through the basin with only minor deposition.

Our model explains the seismically observed increase in thickness towards the “Venus” salt, and the apparent cessation of thick sand deposition to the south. It implies a different geometry for the sands than the channel-fill model. The overlying low net-to-gross package may represent the levee deposits of a channel system which develop in the center of the basin subsequent to the phase of deposition described above, or a period of unconfined flow and relatively slow deposition as the deposystem evolves from sand-rich to sand-poor through the depositional cycle.

Preliminary Discussion of Net/Gross Distribution in Gulf of Mexico Deep Water Reservoirs

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Abstract

In recent years, exploration and development portfolios have increasingly shifted towards deep water reservoir systems, the majority of which are physically located in present-day deep water settings. Because of their deep water setting, decisions regarding substantial capital expenditure are often required on the basis of 3D seismic coverage and extremely limited well data. The drilling of multiple appraisal wells to delimit accurately reservoirs often results in unacceptable erosion of financial value. These operational and financial constraints make early probabilistic assessments of project value increasingly important in decision analysis.

A critical component of the analysis of project value is an understanding of the distribution of reservoir parameters including reservoir net/gross. Cumulative probability distributions of reservoir net/gross, based on well penetrations, have been calibrated to a suite of deep water seismic facies in an attempt to quantify variations in reservoir quality and to supplement seismic attribute analyses. This approach of calibrating distinctive seismic facies provides a useful tool for risk assessment in both early phases of exploration as well as development planning. We recognize 10 seismic facies comprising 6 major facies classes in deep water deposits in the Gulf of Mexico. These seismic facies represent discrete elements that share similar, observable (on seismic data) geometric characteristics. Similar to rock-based facies, these seismic facies elements form the building blocks of larger facies assemblages or associations.

In this paper we present preliminary net/gross distributions for two common seismic facies – "Facies C - Sheets" and "Facies B - Concave-erosional." Each of these facies can be subdivided into two sub-facies, C1/C2 and B1/B2. Examination of the distributions of these data suggest that minimum estimates of net/gross (P10 value; *i.e.*; 90% of all data have a net/gross in excess of P10) range from approximately 25% (C2) to 55% (C1), most likely estimates of net/gross (P50 value; *i.e.*, 50% of all data have a net/gross in excess of P50) range from approximately 72% (C1) to 86% (B1), and maximum estimates of net/gross (P90 value; *i.e.*, 10% of all data have a net/gross in excess of P90) range from approximately 92% (C2 and B2) to 97% (C1). These values vary somewhat from other data sources, notably Deepstar (1996) and Prather *et al.* (1998). Possible reasons for the variations from these datasets are discussed in this paper.

3D Visualization of Turbidite Systems, Lower Congo Basin, Offshore Angola

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Abstract

This paper describes the architecture of deep marine turbiditic systems in the lower Congo basin, offshore Angola, as seen on the 3D seismic. Thanks to the relatively shallow burial depth and the excellent resolution of the 3D seismic data, detailed interpretation of the turbidites is possible, even in those areas where well information is scarce. Both large-scale distributary systems and reservoir-scale internal architecture can be visualised and interpreted in terms of hydrocarbon reservoir potential. The paper presents several examples from different settings in the lower Congo basin. The emphasis lies on channelized turbiditic systems, which are described in their large -cale tectonic and sedimentary framework.

Characterization of Slope and Basin Facies Tracts, Jackfork Group, Arkansas, with Applications to Deepwater (Turbidite) Reservoir Management

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Abstract

Characterization of 15 stratigraphic sections of the Pennsylvanian Jackfork Group deepwater (turbidite) deposits of Arkansas have provided a set of criteria to distinguish an *updip slope facies tract* from a *downdip basinal facies tract*. The updip facies tract is characterized by lenticular sandstone packages with internal thick-bedded, lenticular to sheet sandstones, associated muddy debrites, and other 'disturbed' strata. Characteristic features at a smaller scale include (a) irregular upper and lower slumped/scoured surfaces of beds, (b) stretched, distorted, and contorted shales, (c) a wide variety of lithofacies, including muddy debrites and pseudo-conglomerates or breccias, (d) common shale rip-up clasts in sandstones, (e) non-systematic vertical stacking of diverse facies, and (f) overall fining- and thinning-upward stratification pattern. Lenticular, channel-fill sandstones generally comprise >50% of the sandstone strata.

By contrast, the downdip basinal facies tract is characterized by evenly- bedded sheet sandstones, as well as thinner channel-fill sandstones in variable proportions. Characteristic features at a smaller scale include (a) flat-based, thick amalgamated and layered sheet sandstones with fewer erosional bases and slumped/scoured tops, (b) relatively good lateral continuity, (c) compensation style deposition, (d) relatively fewer muddy debrites, (e) laminated shales and mudstones, and (f) relatively ordered vertical stacking of strata.

Sandstone packages within the downdip basinal facies tract thin at rates on the order of 0.40%. Individual sandstone beds thin at appreciably lower rates of <0.1%. Thus, sheet sandstone beds can be continuous for thousands of feet and packages of beds can be continuous for miles.

Many of the sedimentologic and stratigraphic criteria for distinguishing these updip and downdip facies tracts can be identified in core or borehole-image logs from subsurface reservoirs, in order to better understand reservoir characteristics and architecture.

The architectural differences between updip and downdip facies tracts indicate that in analog reservoirs, different development and management scenarios should be employed to maximize production. Owing to lateral and vertical discontinuities and internal complexities in the updip facies tract, wells should be more closely spaced in order to maximize primary or secondary recovery. In the more continuous downdip facies tract, wells can be drilled at larger, more economical spacing and hydrocarbons can be produced more easily in both primary and secondary recovery modes.

Deltas vs. Rivers on the Shelf Edge: Their Relative Contributions to the Growth of Shelf-Margins and Basin-Floor Fans (Barremian and Eocene, Spitsbergen)

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Abstract

A series of seismic-scale (10 km x 1 km) shelf-sandstone-tongue outcrops of Barremian and Eocene age in Spitsbergen's Central Basin have been used to examine the relationship between shelf-edge regime and the accumulation of sands on deepwater slope or basin-floor areas. The setting is a small foreland basin where shelf-slope-basin floor clinoforms indicate water depths of up to 400 meters, slope lengths up to 5 km., slope gradients up to 3 degrees, and basin-floor fans extending away from the slope up to 10 km.

The datasets show that shelf edges dominated by intact deltas have a relatively undisturbed morphologic profile and produce broad shelf-margin progradation, but little or no basin-floor sand accumulation. Basin-floor fans, on the other hand, tend to occur when the time-equivalent outer shelf was dominated by rivers, the shelf edge shows collapse/ block-rotation/ growth faulting, and the slope contains canyons that focus sediment by-pass to the basin floor.

Shelf edges that were dominated by a fluvial sediment supply tend to evolve to a system dominated by shelf-margin deltas, as relative sea level rises on the shelf. This evolution is accompanied by a change in how sandy sediment volumes are partitioned between basin floor and slope. Initial focussed degradation of the shelf edge/slope, accompanied by aggradation of sandy basin-floor fans and late development of channel-levee systems on the lower slope, changes to sandy slope accretion by turbidites that pinch-out before they reach the base of the slope. This cycle is completed by shaly slope aggradation. Most cycles of relative fall and rise of sea level in the Central Basin lack the initial "fluvial/basin-floor fan" phase, and simply start with the "shelf-edge delta/slope accretion" phase. The identification of the rarer cycle (that lacking the basin-floor fans), and the distinction between the two types of cycle is critical for the prediction of deepwater, sandy fans.

Architectural Analysis of Deep-Water Outcrops: Implications for Exploration and Development of the Diana Sub-Basin, Western Gulf of Mexico

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Abstract

Outcrops span a critical gap in both scale and resolution between seismic and well-bore data and can provide the geometric properties required for interpreting reservoir architecture at sub-seismic or flow unit scale. The Lower Permian Skoorsteenberg Formation in Tanqua Karoo basin, South Africa, and the Lower Carboniferous Ross Formation in the Clare basin, western Ireland, both contain sand-rich turbidites deposited in a channelized to unchannelized basin-floor fan setting. Based on detailed characterization, these outcrops can be divided into (i) proximal, (ii) transition from proximal to medial, and (iii) medial fan settings. The most proximal settings are characterized by narrow, erosionally confined, channelized sandbodies. Very broad, compensationally stacked channel complexes dominate the transition from proximal to medial fan settings. The medial fan setting is comprised of extremely broad channels to sheets. Based on seismic, well-log and core data, the Skoorsteenberg and Ross formations have sediment compositions and architectures very similar to many deep water petroleum reservoirs, such as the Diana field in the western Gulf of Mexico. Therefore, net-to-gross, dimensional and architectural data from these outcrops can be used to help assess future exploration prospects and newly discovered fields. Furthermore, the integration of seismic, well-log, core, outcrop data, and forward seismic modeling in fields with similar reservoir characteristics can provide the framework to maximize the architectural controls on petroleum production, development and management.

Late-Stage Development of the Bryant Canyon Turbidite Pathway on the Louisiana Continental Slope

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Abstract

GLORIA sidescan imagery, multibeam bathymetry, seismic profiles, and piston cores (3-5 m penetration) reveal the near-surface geology of the Bryant Canyon turbidite pathway on the continental margin of Louisiana. This pathway extends from the continental shelf edge, across the continental slope, to a deep-sea fan on the continental rise. The pathway is narrow (<2 km) where it crosses shallow salt deposits. Turbidites have been sampled from these narrow segments, and radiocarbon dates indicate that some of them accumulated as recently as 10,150 yr B.P. The pathway broadens however, where it crosses mini-basins whose floors are covered largely by muddy mass-transport deposits and coarse silt turbidites. Mass-transport deposits in the upper 4.7 m of cores from the floors of mini-basins accumulated 18,140-3,400 yr. BP. Seismic profiles show that the mass-transport deposits in some of the mini-basins are as much as 225 milliseconds thick and that turbidites in the basin floor are buried by these deposits. Salt movement has had a major impact on this pathway, and its thalweg no longer has a continuous down-slope gradient. Some mini-basin floors along the pathway are now more than 500 m deeper than their basin's spill point.

We propose a 6-stage conceptual model to explain our observations for the evolution of a mini-basin along this turbidite pathway. In this model, an active channel feeds sand to a mini-basin (Stabe B). Once the mini-basin is filled, the sand deposit is entrenched by a bypass channel (Stage C). When the turbidite system shuts off, salt migration oversteepens the mini-basin walls (Stage D) which collapse and create a layer of mass-transport deposits on the mini-basin floor (Stage E). The depositional succession is capped by a layer of highstand hemipelagic drape (Stage F). The Bryant Canyon turbidite pathway provides a recent example of a large turbidite pathway in the Gulf of Mexico that crosses an area of active salt tectonics thus providing a conceptual model for older systems in similar settings. In Bryant Canyon, thick turbidite sands presumably are found in mini-basins however, they are sealed by thick, fine-grained, mass-transport deposits which terminate mini-basin turbidite deposition cycles. The importance of mass-transport deposits in basins along this turbidite pathway is in startling contrast to the Trinity-Brazos pathway whose shallow subsurface expression is virtually free of mass-transport deposits and has undergone minimal deformation by salt movement.

The Quaternary Congo Deep-Sea Fan: Preliminary Results on Reservoir Complexity in Turbiditic Systems Using 2D High Resolution Seismic and Multibeam Data

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Abstract

The Congo deep-sea fan was surveyed recently by a unique set of data that includes as of today more than 30 piston cores and 25,000 km of 2D high resolution seismic acquisition. During the different cruises, the following tools were used simultaneously: an EM12 dual Simrad swath bathymetric and sonar system, a 3.5 kHz mud penetrator, an oceanographic seismic system (6 traces), and a multichannel seismic streamer (96 traces) with G.I. air gun source. The data set covers an area in excess of 200,000 km² from the canyon head to the most recent depositional lobes 700 km downslope. In this four year project co-sponsored by ELF and IFREMER, the prime objective was to gain comprehension of the construction and the lateral evolution of the recent fan. As a result, we were able to build a chronostratigraphic and architectural model at the fan scale.

The Congo Canyon geometry has been enhanced and has confirmed the lack of any tributaries downdip from the continental shelf. Furthermore, no real large scale slumped blocks have observed at the base of the steep submarine canyon slopes. Therefore, widening of the canyon seems to have occurred through progressive sliding and creeping of the bordering Congolese and Angola platform into the canyon valley.

The recent Congo fan growth results from the stacking and overlapping of at least 3 main stratigraphic units. Each unit is composed of numerous channel-levee complexes laterally switching path through time by avulsion. Previous interpretation of "distributaries" at the toe of the Congo submarine canyon is invalidated as this surveys shows that they are in fact abandoned channel-levee complexes. It has also been confirmed that in this particular mud-rich submarine fan setting, only one channel is active at a time. The present day "active" fan channel as well as the canyon are eroding into previously deposited sediments.

In the levees, individual sub-kilometer scale morphological features have been mapped, and sedimentary and/or structural processes responsible for such geometries have been reviewed.

The present day depositional lobe is more than 700 km away from the Congo River mouth. It occupies an area of around 300 km² and shows clustered lobes, 20 km long, prograding down slope.

It is now clear that multibeam coverage of the lower part of the canyon, over complex lobe, and channel avulsion zones shows strong similarities with seismic attribute maps of West Africa's structurally controlled turbiditic channel complexes.

Sedimentary Dynamics of the Salt-Dominated Continental Slope, Gulf of Mexico: Integration of Observations from the Seafloor, Near-Surface, and Deep Subsurface

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Abstract

Intraslope mini-basins in more proximal (updip) settings are characterized by the bypass facies assemblage (BFA), in which sedimentation is dominated by MTCs (including debris flows), channels, and overbank sedimentation. More distal settings are characterized by the ponded facies assemblage (PFA), in which sedimentation is dominated by sand-enriched turbidity currents. Nevertheless, ponding of turbidites can occur in the BFA and bypass can occur in the PFA. As the Mississippi River has shifted during the late Pleistocene and throughout the late Cenozoic, it has repeatedly supplied sufficient sediment to fill intraslope mini-basins and cause bypass to the abyssal plain, even across the broadest parts of the continental slope. In late Pleistocene Mississippi deposystems, discrete phases of ponding (with shelf-margin deltas feeding intraslope fans) and bypass (with canyons feeding abyssal plain fans) can be recognized. In the late Brazos-Trinity deposystem, only the ponding phase developed. In ancestral Mississippi deposystems of the Miocene and Pliocene, bypass to the abyssal plain may have occurred across mini-basins dominated by PFA, without the formation of large canyons.

Within a mini-basin, deposition proximal to a sediment entry point may be dominated by sand-rich fan lobes, by mud-rich MTCs, or by channel and overbank deposits. Sand-rich fan lobes, and thus the best reservoirs, should be more characteristic of the most distal mini-basins within a corridor, while MTCs should be characteristic of the most proximal mini-basins. The distal end of a mini-basin may be dominated by complete ponding of turbidity currents, by partial ponding and partial bypass over a low sill, or by bypass through a channel incised into the sill.

Outcrop and Subsurface Criteria for Differentiation of Sheet and Channel-Fill Strata: Example from the Cretaceous Lewis Shale, Wyoming

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Abstract

The Dad Sandstone Member of the Lewis Shale (Maastrichtian), south central Wyoming, provides a unique opportunity to model the lateral continuity of deep-water turbidite and debrite sandstone reservoirs at an inter-well scale in outcrop. Outcrops located within the Sierra Madre Uplift area on the eastern rim of the Washakie Basin have been correlated confidently to subsurface data, allowing rock-based continuity and geometry models generated in outcrop to be carried into and applied in the subsurface.

Outcrop study identified four lithofacies types distinguishable by either specific lithic attributes or geometry. These four lithofacies types include:

Laterally continuous turbidite sheet sandstones exhibiting successions of Bouma T_a to T_b intervals, flat, non-scoured bases with underlying fine-grained deposits, and evidence of rapid dewatering including convolute bedding, dish and vertical dewatering structures.

Laterally discontinuous turbidite and debrite channel-fill sandstones exhibiting characteristics of a high-energy, erosive, confined environment including scour-based beds and an abundance of concentrated rip-up clasts.

Thin turbidite sandstones of variable lateral continuity, interbedded with laminated siltstone and mudstone.

Fine-grained laminated sandstone, mudstone, siltstone, and shale which are proximity indicators to the other three facies types.

An excellent correlation has been established between these deposits in outcrop and STAR™ borehole images of correlative sandstone bodies in the subsurface in the Barrel Springs 7-22 well located 11.2 km (7 mi) west of the outcrop. Qualitative comparison of outcrop and borehole image features, coupled with quantitative analysis of data, including modified Fischer plots, provides diagnostic criteria for characterizing potential sandstone reservoirs intersected in the borehole. These criteria may be used elsewhere to differentiate deep-water facies in outcrop and subsurface data.