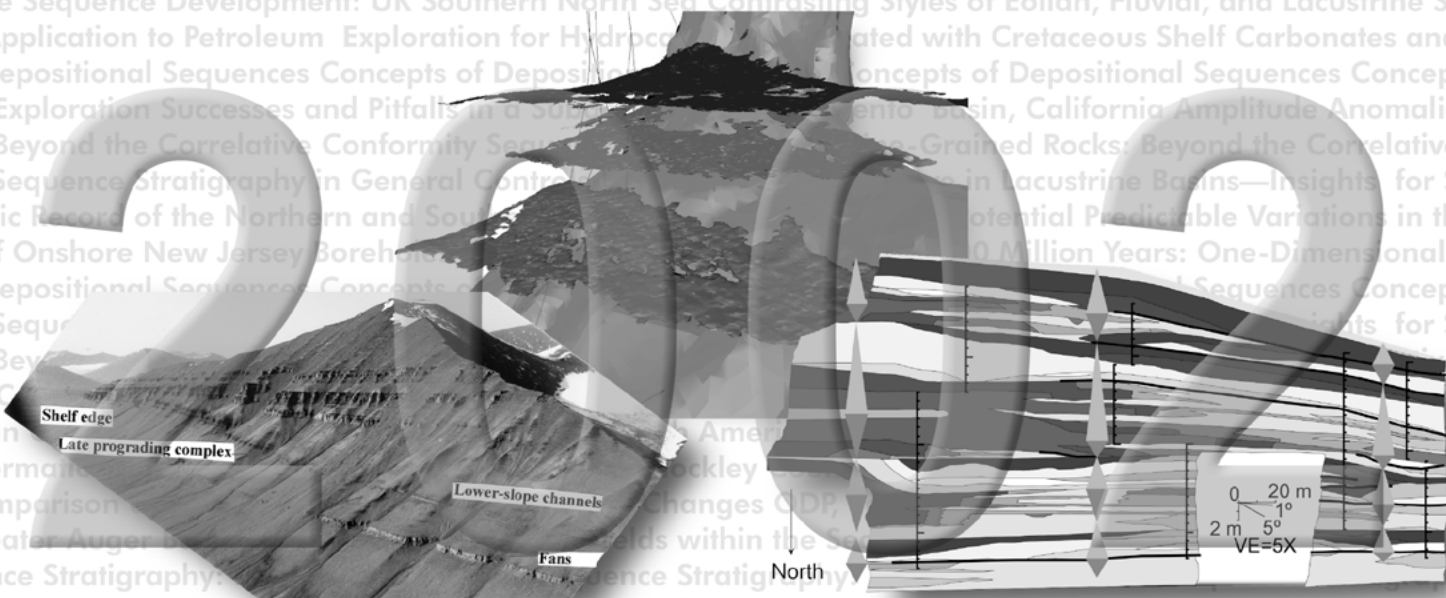
Sequence Stratigraphic Models for Exploration and Production: Evolving Methodology, Emerging Models and Application Histories

22nd Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference

Program and Abstracts



Edited by
John M. Armentrout and
Norman C. Rosen

December 8–11, 2002
Houston, Texas

Print

Sequence Stratigraphic Models for Exploration and Production: Evolving Methodology, Emerging Models and Application Histories

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Dedication

Mention the words "sequence stratigraphy" and the first two words that will occur to you are "Peter Vail." No matter whether you agree or disagree with the "Exxon School," I do not think that anyone could disagree with the statement that Peter Vail has been not only the most influential person in stratigraphy in the past 40 years, but he has also greatly influenced the exploration methodologies in the oil industry.

Dr. Norman C. Rosen,
Executive Director
GCSSEPM Foundation

Upon his retirement from Rice University, a "Vail Fest" conference was held to honor him. We acknowledge that the Foundation helped support the conference and agreed that we would dedicate these Proceedings to him. This was an easy agreement for us as we had decided already that Peter would be elected as a GCSSEPM honorary member. The note that follows is from the GCAGS/GCSSEPM *Transactions* for 2002.

Peter R. Vail: "A Life Dedicated to Stratigraphy"

The spirit of this conference is to honor Peter R. Vail for his original concepts and pioneering work in sequence stratigraphy, and to celebrate his contributions to both industry and academia during his career of over 40 years. The fundamental impact and influence of his ideas on industry and academia have been very significant, and his earnest desire to teach others both as a professor at Rice University and as a peer is a role that we can all aspire to.

Peter R. Vail

Pete's ideas on the unifying paradigm of eustatic cycles are probably as close to an original "breakthrough" concept as most of us are privileged to witness. Pete's worldwide experience with Exxon's research and exploration groups honed the original concept into an immensely practical tool for hydrocarbon exploration, and provided a logical framework in which all geoscientists could build a realistic, predictive stratigraphic framework for their sedimentary rocks, at the seismic or outcrop scale. His lectures, publications, and untiring teaching efforts at Rice have made his methods available to any interpreter or geologist willing to try them.

Peter Vail graduated from Dartmouth College in 1952 with an A.B. degree. He attended Northwestern University from 1952 to 1956 where he received his M.S. and Ph.D. degrees. At Northwestern, he was greatly influenced by Professors Larry Sloss and Bill Krumbein, who were at the height of their work on quantified facies mapping and North American unconformity-bounded cratonic sequences. He began his career with Exxon in 1956 as a research geologist with the Carter Oil Company, an Exxon affiliate in Tulsa, Oklahoma. He and his wife, Carolyn, reared a family of three children, who at first grew faster than his reputation. He relocated to Houston in 1965, at Esso Production Research Company, now ExxonMobil Upstream Research Company, and advanced to a Senior Research Scientist, the highest technical position.

In 1986, Pete was appointed the W. Maurice Ewing Professor of Oceanography at Rice University. Pete continued working toward the refinement and further understanding of sequence stratigraphic techniques, which are fundamental concepts in common usage by many geoscientists today. Pete took a sabbatical leave from 1992 to 1993 with CNRS in Paris, to lead studies of the sequence stratigraphy of European basins and to revise and document the eustatic cycle chart. He retired from Rice in 2001.

Pete's ideas evolved naturally from his first pioneering work on the importance of stratal surfaces in rocks as geologic time lines. He soon recognized the cyclic occurrence of bundles of strata he called sequences in well logs, seismic reflections, and outcrops. When he began seeing that sequence boundaries have the same ages in several basins worldwide, he postulated that global sea level changes are a major control on the stratigraphic record, along with basin tectonics and sediment supply. This realization led to the development of eustatic cycle charts. In 1977, these concepts were published in AAPG Memoir 26. His latest SEPM Special Publication on the sequence stratigraphy of European basins is a tremendous group effort, which led to a major revision of the eustatic cycle chart.

In the natural course of his work, Pete has held many important roles in a variety of industry, government, and academic-based steering committees, and has received the recognition of his peers in the form of many honors both from academic institutions and industry-based societies. He served on a number of important committees, including the U.S. Department of Energy Committee on Research Drilling (1987-88), the U.S. Geodynamics Committee of the National Academy of Sciences, and the American Commission on Stratigraphic Nomenclature. He has been honored by professional societies for his outstanding contributions to geology. A few of his awards include the Virgil Kauffman Gold Medal in 1976 for the Advancement of the Science of Geophysical Exploration by the Society of Exploration Geophysicists, the American Association of Petroleum Geologists President's Award in 1979, and the AAPG's George C. Matson Memorial Award in 1980. In 1983 he was the recipient of the Offshore Technology Conference Individual Distinguished Achievement Award. More recently, he was awarded the Twenhofel Medal by the SEPM (Society for Sedimentary Geology), and Honorary Memberships in the AAPG and SEG. He has been invited by several universities to serve on advisory committees for their Geology Departments, including Princeton and Northwestern. In addition, he was recognized by universities and societies in France, Belgium, Scotland, England, and Australia with various honorary memberships and awards in recognition of his leading-edge research work. Lists of his other honors fill pages!

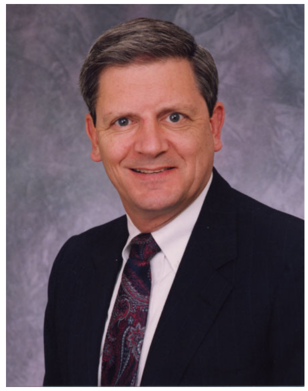
Pete's extensive publications list, combined with the large number of scientific citations that his papers receive each year, indicate the significance of his work and attest to the fact that he is one of the most internationally recognized experts in the field of sequence stratigraphy. Above all, Pete's greatest characteristics are his integrity, his dedication to his family, and his faithfulness to friends, colleagues and students. It is a great honor to have been part of his life.

Robert M. Mitchum and John B. Sangree

Print

Foreword

Sequence stratigraphy as an interpretation methodology is widely applied in petroleum exploration and production. This year's Gulf Coast Section SEPM 22nd Annual Bob F. Perkins Research Conference is entitled "Sequence Stratigraphic Models for Exploration and Production: Evolving Methodology, Emerging Models and Application Histories." The program committee has assembled 48 papers on sequence stratigraphy organized into six categories: Origin and Evolution of the Model, Variations of Sequence Stratigraphic Methodology, Primary Controls on Sequence Architecture, Primary Controls and Case Histories, Applications to Exploration, and Applications to Production. Posters include topics on Case Histories and Sequence Calibration. Depositional environments represented by case studies include alluvial, fluvial, lacustrine, eolian, coastal plain/deltaic, shelf, slope and basin floor.



John M. Armentrout
Committee Co-Chair

In a sense, this year's conference is an update of the 1991, 11th Annual Conference titled "Sequence Stratigraphy as an Exploration Tool: Concepts and Practices." Since that time the concepts and interpretation methodologies have evolved through the infusion of well data, cores, high-resolution biostratigraphy, geochemistry and 3D seismic data. Models for interpretation provide information derived from seismic geometries and attributes ahead of the drill-bit, and for prediction of reservoir type and performance in development projects. The papers presented in this year's program represent a progress report on the evolution of sequence stratigraphic analysis.

Sequence stratigraphic analysis was the "brain child" of Peter Vail and his associates at Esso Production Research. It is with great pleasure that the GCSSEPM dedicates the 2002 program in honor of Peter R. Vail. While the development of seismic sequence stratigraphy, and subsequently sequence stratigraphy, was a collaborative effort of many geoscientists, the initial team members acknowledge that it was Peter Vail's vision of the possible that lead to the documentation of seismic reflections as time-significant horizons and seismic geometries and attribute facies as proxies for specific depositional environments.

This volume results from the combined efforts of the program committee and the more than 100 authors of the papers. All committee members and senior authors helped in the review process. Jory Pacht contributed vision in seeking authors from a wide spectrum of disciplines. Norm Rosen completed the Herculean effort of final editing, and Gail Bergan and staff compiled the CD ROM, overcoming numerous software challenges. Thus, this product reflects the efforts of more than 130 geoscientists. We also want to thank the numerous organizations that employ the contributors and approved publication of the papers. Preparation of manuscripts for publication is an arduous process, and the multitude of partners in most exploration and production projects requires approval for publication from many sources. The authors are commended for their perseverance throughout this process. We all benefit from their efforts.

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The three images used on the cover of this Program appear in papers in the conference proceedings:

Anderson, *Keeping Pace: Continental (Nonmarine) Sequence Stratigraphy in a High Accommodation-Sediment Supply Regime, Hornelen Basin (Devonian), Norway*, Figure 4: **facies architecture map;**

Dean *et al.*, *Multiple Fields within the Sequence Stratigraphic Framework of the Greater Auger Basin, Gulf of Mexico*, Figure 7: **three-dimensional perspective of three reservoirs;**

and

Steel and Olsen, *Clinoforms, Clinoform Trajectories and Deepwater Sands*, Figure 3B: **outcrop photograph of clinoforms.**

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Sequence Stratigraphic Models for Exploration and Production: Evolving Methodology, Emerging Models and Application Histories

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Program and Abstracts

Sunday, December 8

4:00–6:00 p.m. Registration (*Grand Foyer*) and Poster Setup (*Grand Pavilion*)

6:00–8:00 p.m. Welcoming Reception and Poster Preview (*Grand Pavilion)*

Monday, December 9

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7:50 a.m. **Introduction and Welcome: John Armentrout, Program Chair (*Grand Pavilion)***

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Sequence Stratigraphy: Evolution and Effects

Mitchum, R. M.
Consultant
13039 Pebblebrook
Houston, Texas 77079
e-mail: rmm@hic.net

Vail, P. R.
Professor Emeritus
Rice University
Houston, Texas

Sangree, J. B.
Consultant
13724 A La Entrada Calle
Corpus Christi, Texas 78418

Abstract

In many ways, sequence stratigraphy's effect on stratigraphic interpretation is comparable to that of plate tectonics on structural geology. These are markers in the history of geology upon which talented minds can build the next advances. However, concepts that seem self-evident to today's students faced painful periods of ridicule and resistance when first systematized by Peter Vail in the 1960s. The history of this slow acceptance is marked by a gradual evolution of concepts that bring basin tectonics, sea-level fluctuations, and sediment supply into an integrated stratigraphic solution.

One basic idea is the time-significance of stratal surfaces and surfaces of discontinuity, and of the seismic reflections generated by them. Another concept is that cyclic sedimentary sequences form in response to varying rates of eustatic changes, tectonic subsidence, and sedimentary supply. The sequence model is highly variable but astonishingly robust in predicting facies and environments in a wide variety of basin and tectonic settings.

Applications in industry and academia are widespread, especially in predicting deep-marine sands, seals, and source rocks in offshore settings. Other specific applications include sequence stratigraphy of carbonates, estuarine sands, incised valleys, forced regressions, and well-log and outcrop analysis. Development of eustatic cycle charts needs high-quality biostratigraphy for dating and environmental analysis. Advent of 3-D seismic data opens a myriad of uses involving attributes of the seismic signal. No matter how specialized, however, the good interpreter always starts with a rigorously defined chronostratigraphic framework of sequences and systems tracts for proper interpretation.

Concepts of Depositional Sequences

Print

Vail, Peter R.
Professor Emeritus
Rice University
Houston, Texas

Mitchum, Robert M.
Consultant
13039 Pebblebrook
Houston, Texas 77078

Sangree, John B.
Consultant
13729 A La Entrada Calle
Corpus Christi, Texas 78418

Abstract

The depositional sequence was defined in 1977 as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities." This definition has proven singularly robust in any number of sedimentary and tectonic settings.

The depositional sequence model evolves naturally from recognition of stratal surfaces in rocks as geological time lines and from the time-significance of unconformities and their correlative conformities as sequence boundaries. Seismic reflections follow stratal boundaries, and within limits of seismic resolution, represent time lines.

Sequence boundaries have been found to be of the same age in basins worldwide, and it has been postulated that global sea level changes are a major control on the stratigraphic record, along with local basin tectonics and rates of sediment supply. Eustatic cycle charts plot the ages and magnitudes of global eustatic cycles. High-resolution biostratigraphy is essential to dating sequences and determining paleo-environments.

The cyclic sequences bounded by these unconformities have a basic pattern of deposition which results from a relative fall and rise of sea level. This pattern can vary widely from basin to basin, depending on variations in basin tectonics and sediment supply. The accommodation model consists of lowstand, transgressive, and highstand systems tracts formed in response to various stages of the sea-level cycle.

The maximum flooding surface marks the maximum transgression of marine facies on the shelf, and is an important correlation point. It is not a sequence boundary in our model because strata bounded by maximum flooding surfaces would include two disparate units separated by a significant unconformity, which is our sequence boundary.

Several levels of sea level cyclicity may occur in a hierarchy that allows higher frequency cycles to be superposed or stacked into lower frequency cycles. The stacking of parasequences (fourth- or fifth-order cycles) into third-order (sequence) cycles is an example.

Examples of stratigraphic sections from the Paleozoic of the Arabian plate and the northern Gulf of Mexico show applications of sequence stratigraphy to both extremes of the Phanerozoic spectrum. They also contrast characteristics of the best-known models of sedimentary response to cyclic depositional control.

Print

Sequences, Depositional Systems, and Synsedimentary Tectonics, Oligocene Rocks, Corpus Christi Region, South Texas: Revisiting Mature Fields with New Prospecting Tactics

Brown, L. Frank, Jr.
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station Box X
Austin, Texas 78713
e-mail: frank.brown@beg.utexas.edu

Loucks, Robert G.
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station Box X
Austin, Texas 78713
e-mail: bob.loucks@beg.utexas.edu

Treviño, Ramón H.
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station Box X
Austin, Texas 78713
e-mail: ramon.trevino@beg.utexas.edu

Abstract

Subregional 3-D seismic volumes and wireline logs permitted definition of second- to fifth-order (~10 my–10 ky) Frio and Anahuac (Oligocene) sequences, systems tracts, and associated syntectonics. Third- and most fourth-order sequences were correlated within several subregional wireline-log and seismic networks. Vicksburg and Miocene sequences were of secondary interest. Composite sequence logs characterized principal fields. Sequence analysis identified and correlated all key surfaces: type 1 unconformities, maximum-flooding surfaces, and transgressive surfaces bounding systems tracts. Although microfossil occurrences are not necessarily required for sequence analysis, limited data were integrated with the final sequence frameworks, providing secondary verification of assigned ages.

Lithostratigraphic Frio and Anahuac strata comprise six chronostratigraphic, third-order depositional sequences (~32.0–23.6 Ma) and myriad fourth- and fifth-order sequences or parasequence sets. Except for incised valley fills, lowstand tracts comprise off-shelf systems deposited within active, growth-faulted, intraslope subbasins. Maximum Anahuac flooding (~24.57 Ma) provides a regional, dated marker to which latest published ages of sequence surfaces have been calibrated. Maximum flooding surfaces and type 1 unconformities are essentially isochronous, but sand-rich lithofacies are mostly diachronous. Off-shelf and on-shelf deposition are temporally unique. Many previously inferred Frio “stacked barriers” are dip-oriented incised valley-fill facies.

Seaward, lowstand sedimentary wedges and superposed shelves become younger. Entrenched rivers supply sediments via ephemeral deltas for gravity transport to basin floor and slope fans. Eventually, overloaded lowstand depocenters initiate gravity faulting, mobilized mud, and, hence, produce younger faulted, shale-withdrawal subbasins. Diminished faulting permits lowstand deltas to extend shelf edges basinward until the deltaic ramps are anchored at the basinward margin of buried subjacent shale-ridges. These shale buttresses stabilize the upper continental slope and shelf edge. During a later cycle, highstand shorelines prograde basinward over the shallow, lowstand ramps. On-shelf regression eventually stalls by increasing accommodation space near the continental shelf edge, establishing another depocenter and intraslope subbasin.

Gas in lowstand deltaic and distal valley-fill reservoirs is trapped updip against hanging walls of extensional faults overlying shale-cored anticlines. Combination trapping and basin-floor and slope-fan reservoirs are viable targets. Sequence ideas offer new, but deeper prospecting targets.

Sequence Stratigraphy Past, Present and Future, and the Role of 3-D Seismic Data

Posamentier, Henry W.
Anadarko Canada Corporation
425 1st Street SW
Calgary, Alberta T2P 4V4
Canada
e-mail: henry_posamentier@anadarko.com

Abstract

In the twenty-five years since the landmark publication of AAPG Memoir 26 and later, SEPM Special Publication 42, the concepts of sequence stratigraphy have evolved rapidly. This discipline, an outgrowth of seismic stratigraphy, has spread far beyond applications to 2-D seismic data alone. Sequence stratigraphy has seen applications embracing data sets ranging from biostratigraphic to geochemical to physical oceanographic, and from borehole to outcrop, and finally, coming full cycle, to 3-D seismic data. Initially the domain of industry geoscientists, sequence stratigraphy has gained widespread acceptance among geoscientists in all professions, having been recognized as an approach that facilitates integration of a broad range of disciplines.

The evolution of sequence stratigraphic concepts is far from complete. In particular, recent increased availability of high-quality 3-D seismic coverage promises to provide insights that will lead to further fine tuning of sequence concepts. In addition to enhanced 2-D profiles, 3-D seismic data afford exceptional plan views of the subsurface that in the past could only be inferred. These plan view images now comprise a fundamental starting point from which geologic analyses and interpretation can begin. Such images depict paleo-landscapes, which can be analyzed using time-honored principles of geomorphology, leading to the development of the discipline of *seismic geomorphology.* When used in conjunction with seismic stratigraphy, seismic geomorphology can significantly enhance sequence stratigraphic interpretations.

The identification of depositional elements such as channels, valleys, shore faces, shelf ridges, *etc.*, in plan view, can be integrated with seismic stratigraphic analyses of associated seismic profiles to calibrate profile reflection patterns and refine analyses of basin fill histories. Systematic seismic geomorphologic analysis of 3-D seismic volumes can bring to light spatial and temporal relationships of successive depositional systems. Moreover, recognition of these systems and analyses of their succession can help in the identification of possible missing facies tracts. This approach, coupled with direct and indirect recognition of unconformities, comprises an integral aspect of sequence stratigraphic interpretation.

High-Frequency Sequence Stratigraphy from Seismic Sedimentology: A Miocene Gulf Coast Example

Print

Zeng, Hongliu
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station, Box X
Austin, Texas 78713
e-mail: hongliu.zeng@beg.utexas.edu

Hentz, Tucker F.
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin
University Station, Box X
Austin, Texas 78713
e-mail: tucker.hentz@beg.utexas.edu

Abstract

For high-frequency (fourth-order) depositional sequences, seismic-stratigraphic interpretation of vertical seismic sections commonly generates equivocal sequence boundaries and systems tracts because of limited vertical seismic resolution. Extending well-based, high-frequency sequence stratigraphy into a 3-D seismic survey area consequently proves to be a major challenge. We show that critical to such extension is recognition and interpretation of planoform geomorphology of depositional systems. Emphasis should be shifted from interpreting vertical seismic data to developing new tools capable of extracting more horizontal, seismic-sedimentologic information. This case study of the Vermilion Block 50-Tiger Shoal field area, offshore Louisiana, shows that proportional, stratal slicing between Miocene flooding surfaces provides sequential and accurate seismic imagery of depositional systems. This imagery in turn serves as a basis for recognizing and mapping high-frequency systems tracts, sequence boundaries, and sequences in a geologic-time domain. In the Miocene interval, all of the fourth-order sequences or sequence sets from study wells can be seismically mapped at a resolution equivalent to 10 m in thickness, which is necessary for accurate reconstruction of the high-frequency sequence-stratigraphic framework in the region of seismic coverage outside well control.

Using Sequence Hierarchy to Subdivide Miocene Reservoir Systems of the Western Atwater Foldbelt, Ultra Deep Water Gulf of Mexico

Print

Apps, Gillian M.
Moore, Michael G.
Woodall, Mark A.
Delph, Bryan C.
BHPBilliton Petroleum, Americas Inc.
Houston, Texas

Abstract

Recent major discoveries at Mad Dog, Atlantis, and Neptune have opened a major new hydrocarbon province in the Western Atwater Foldbelt of the ultra-deepwater Gulf of Mexico. The hydrocarbons are reservoired in good quality Lower and Middle Miocene turbidite sandstones. There is a clear stratigraphic signature expressed in the ultra-deep water, with the principal reservoir sands strongly partitioned into discrete, high net/gross, laterally extensive bodies, at or close to interpreted sequence boundaries. The upper part of the sequence is dominated by thin-bedded turbidites and mudstones.

Good quality biostratigraphic data allow us to correlate third and fourth order stratigraphic boundaries through all the wells across the region. Seismic data, south of the Sigsbee salt, for these deeper, older reservoirs provides resolution of the third order sequence boundaries. Compensation cycles have been mapped between the third order sequence boundaries, but it is not certain that these directly correspond to the fourth order sequences.

The observed stratigraphic hierarchy starts at second order cyclicity, demonstrated by a systematic change in the distribution of net sand from one third order sequence to the next. The highest resolution sequences that we have been able to map are fifth order. As expected, there is a systematic relationship between the stratigraphic hierarchy and the lateral correlation length of stratigraphic surfaces; ie. condensed sections associated with third order sequences can be correlated over greater lengths than the flood surfaces associated with higher order sequences. Third order sequence boundaries are mapped over a distance of in excess of a hundred miles. Fourth order boundaries have been correlated with confidence over a distance of at least 30 miles, and the fifth order correlation surfaces can only be mapped confidently within a single field, a distance of a few miles.

The nature of the flood surfaces changes with the position in the stratigraphic hierarchy and with the location relative to the sand feeder systems. In the core of the depositional system, we do not observe the foraminiferal marls that are characteristic of significant condensed sections elsewhere in the Gulf of Mexico. Our interpretation is that sediment is being supplied continuously to the basin floor in the form of sediment gravity flows and suspended sediment fall out from turbidity currents. As a result, third order flooding surfaces are characterized by high gamma shales, fourth order flooding surfaces are commonly associated with intervals of thin bedded turbidites; and fifth order flood surfaces have a variety of log signatures, and a ranges of facies association. Away from the focus of sediment input, foraminiferal marls are observed and some are interpreted to represent condensed sections.

The detailed high frequency sequence stratigraphy that has been carried through the three principal discoveries in the Western Atwater Foldbelt has impacted the exploration and development strategy for the area. For example, we have been able to demonstrate the presence of significant paleotopography that affected the lowermost Miocene reservoir distribution. We have proven that the thick sand bodies associated with the third order sequence boundaries are laterally extensive and so have reduced the risk of finding good quality reservoir sands in appraisal wells and nearby exploration wells. We have also demonstrated that not all flood surfaces are created equal and are therefore likely to have different transmissibility properties. This could have a significant impact on fluid flow within the reservoir and therefore medium and long-term field development.

Exploration Play Analysis from a Sequence Stratigraphic Perspective

Snedden, John W.
Sarg, J. F. (Rick)
ExxonMobil Exploration Company
PO Box 4778
Houston, Texas 77210-4778
e-mail: john.w.snedden@exxonmobil.com
e-mail: rick.sarg@exxonmobil.com

Ying, Yudong (Don)
ExxonMobil Upstream Research Company
P.O. Box 2189
Houston, Texas 77252-2189
e-mail: don.ying@exxonmobil.com

Abstract

Examination of exploration drilling histories for many different global basins indicates a counter-intuitive temporal and spatial pattern in the way hydrocarbons are sometimes discovered. Conventional wisdom holds that for any given basin or play, a plot of cumulative discovered hydrocarbon volumes versus time or number of wells drilled generally show a steep curve (rapidly increasing volumes) early in the play history and a later plateau or terrace (slowly increasing volumes). Such a plot is called a creaming curve, as early success in a play is thought to inevitably give way to later failure as the play or basin is drilled-up. It is commonly thought that the "cream of the crop" of any play or basin is found early in the drilling history.

By examining plays or basins with sufficiently long drilling histories and range of reservoir paleoenvironment and trap types, one actually finds two or three "terraces" to the creaming curve. The first string of successes in a given basin generally corresponds to exploitation of the highstand systems tract or sequence set reservoirs developed in updip structural traps. These reservoirs are typically marginal to shallow marine "shelfal" deposits, laterally continuous but lacking internal sealing facies and are seldom self-sourcing. The second or third terrace in the creaming curve usually involves the lowstand reservoir component (systems tract or sequence set), which is often developed in downdip deepwater or slope paleoenvironments. Transgressive (systems tract or sequence set) reservoirs, typically shallow marine shelfal sandstones that are sometimes self-sourced, are variably developed and may or may not occupy the second terrace of the creaming curve. These trends hold true for both second-order (3–10 my) and/or third-order (1–3 my) stratigraphic cycles, depending upon the scale of the basin or play.

This analysis fits well with the definition of an exploration play provided by Magoon and Sanchez (1995): a fully developed play is the simple volume difference between the petroleum system capability and the current discovered hydrocarbon volumes (commercial or not). Where the difference is large, either the petroleum system has significant leakage problems (*e.g.*, Barents Sea Mesozoic play) or the lowstand systems tract or sequence set has not been fully exploited.

Examples supporting these ideas are drawn from several global basins (Gulf of Mexico Miocene, Norway Upper Jurassic, Mahakam Delta, and Texas Wilcox). Case studies demonstrate how critical elements of exploration risk shift from trap and seal in highstand plays to reservoir and source in lowstand components of these plays.

The Many Faces of Erosion: Theory Meets Data in Sequence Stratigraphic Analysis

Galloway, William E.
Jackson School of Geosciences
Department of Geological Sciences
The University of Texas at Austin
Austin, Texas 78712
e-mail: Galloway@mail.utexas.edu

Sylvia, Dennis A.
Jackson School of Geosciences
The University of Texas Institute for Geophysics
4412 Spicewood Springs Rd.
Austin, Texas 78759
e-mail: Dsylvia@ig.utexas.edu

Abstract

Sequence stratigraphic application has emphasized the recognition and use of subaerial (fluvial entrenchment) or shallow marine/shoreface (regressive ravinement) surfaces as critical boundaries for defining sequences. These surfaces are variously objectively or conceptually associated with times of onset, maximum rate, and/or lowest position of relative sea level fall. However, well-dated Quaternary analogues demonstrate that the fluvial entrenchment surface is neither inherently synchronous nor regional, and that lowstand facies associations and their bounding surfaces are highly dependent upon the vagaries of paleogeography and sediment supply. Furthermore, some basin fills display stratigraphy in which demonstrable subaerial or ravinement surfaces correlative to fall events are poorly preserved or entirely lacking, but in which sequences can be defined by use of various combinations of transgressive ravinement, marine deflation, and marine starvation surfaces. These surfaces may not and need not correspond to a relative fall (or rise) of sea level. Selection of stratigraphic surfaces as sequence boundaries and interpretation of *sequence* systems tract compositions and relationships both require understanding of the overall *depositional* systems tract and of the full array of regime variables: sediment supply, sediment composition, base level change, and energy regime. Functional, reproducible, and chronostratigraphic "… genetically related successions of strata bounded by unconformities or their correlative conformities…" can be defined, correlated, mapped, dated, and interpreted through the use of a variety of regional stratigraphic surfaces of non-deposition and erosion.

Genetic Stratigraphy, Stratigraphic Architecture, and Reservoir Stacking Patterns of the Upper Miocene—Lower Pliocene Greater Mars–Ursa Intraslope Basin, Mississippi Canyon, Gulf of Mexico

Meckel, Lawrence D., III
Ugueto, Gustavo A.
Lynch, H. David
Cumming, Earl W.
Hewett, Ben M.
Bocage, Eric J.
Shell Exploration & Production Company
701 Poydras Street
New Orleans, Louisiana 70139

Winker, Charlie D.
Shell Technology EP
Bellaire Technology Center
PO Box 481
Houston, Texas 77001

O'Neill, Brian J.
Shell Deepwater Services
701 Poydras Street
New Orleans, Louisiana 70139

Abstract

The late Miocene–early Pliocene sediments of the northern greater Mars-Ursa intraslope basin in the Gulf of Mexico record high-resolution (ca. 0.5 Ma) cyclic deposition of couplets of deep water fan lobes (sheet sands) and channelized or amalgamated systems bounded by local to regional condensed sections. Internally, the sheet sand and channelized systems are separated by a transitional surface of bypass, avulsion, and/or erosion. These fourth-order cycles are the building blocks that make up third-order seismic facies assemblages, which in turn record the progressive fill and spill sedimentary dynamics in salt-withdrawal minibasins.

Third-order sequences in the greater Mars-Ursa intraslope basin reflect regional variations in accommodation and sediment supply. The rate of deposition of an older (10.0–7.0 Ma) third-order assemblage is significantly greater than that of a younger (7.0–4.2 Ma) assemblage. The older assemblage has a greater abundance of thick, laterally extensive sheet sands and a higher composite net-to-gross ratio than the younger assemblage, which contains more amalgamated and bypass channels and associated over bank facies, and has a lower composite net-to-gross.

Fourth-order cycles display compensational stacking patterns in which the overlying channel system is best developed where the sheet sand system is thin or not present. The fourth-order stratigraphy of the basin is controlled by high frequency variations in accommodation and sediment supply. Eustatic changes affect the supply of sediment from the shelf to the slope, but they are not a primary control in the formation of fourth-order deepwater sequences.

Condensed sections that bound the fourth-order cycles are deep marine (pelagic) mudstones that drape topography. They occur in association with faunal abundance and diversity peaks and often correspond to abrupt changes in incremental overpressure. Because they represent periods of minimum relative sedimentation rates and maximum relative rates of accommodation creation, basin margins have their highest relief at the ends of these periods. Several of the condensed sections are interpreted to correlate to maximum flooding events on the shelf.

Thick, high net-to-gross fan lobes that occur above the condensed sections have been deposited as sedimentation rates in the basin increased. They fill paleo-topographic lows and onlap abruptly against high-relief basin margins. Deep water faunal abundances in these sections are at relative minima due to the influx of sediment, and in some instances, the sands have a biofacies signature indicative of reworking. However, a lack of corresponding increases in

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either terrigenous content or reworked Cretaceous material suggests a local source for these reworked sands.

Subtle transitional surfaces separating the sheets and channels are identified by the onset of apparent paleo-bathymetric deepening at the bases of faunal abundance and diversity peaks. Typically, these surfaces document intra-basinal avulsion or erosion and sediment bypass, caused by infill of available accommodation by sheet sands.

The channelized systems or amalgamated channel/sheet systems that overlie transitional surfaces are associated with decreasing rates of sedimentation and low rates of creation of accommodation. Thin, laterally restricted amalgamated channels and sheet deposits may accumulate in the limited accommodation. If present, erosional channels and bypass scours are filled by sand.

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Allostratigraphy Versus Sequence Stratigraphy

Bhattacharya, Janok P.
Geosciences, University of Texas at Dallas
P.O. Box 830688, FO21
Richardson, Texas 75083-0688
e-mail: janokb@utdallas.edu

Abstract

Allostratigraphy is the only means available for formally naming stratigraphic units defined on the basis of observed bounding discontinuities. Sequence stratigraphy represents a powerful way of interpreting allostratigraphic units in the context of cyclic changes in accommodation and accumulation. Lack of consistency in definition and usage of sequence terms, however, shows that it is premature as a means of formal naming. Sequence stratigraphic terms are inconsistent in that they may convey either positional or temporal concepts. For example, many sequence stratigraphers' reveal their temporal bias by referring to *early* and *late* subdivision within “systems tracts,” despite claims that "systems tracts" are defined purely physically. Sequence stratigraphic terminology also emphasizes that units are genetically related by a particular process. For example, sequence boundaries are defined as unconformities, and their correlative conformities, that show evidence of subaerial exposure. Marine discontinuities, although highly useful for allostratigraphic correlations, do not satisfy this strict definition of a sequence boundary. In addition, there are significant practical problems in defining a sequence boundary where it is expressed wholly as a correlative conformity. This potentially limits the ability to define sequences in areas where evidence for an unconformity may be cryptic or absent. The bias towards subaerial exposure has resulted in confusion in the interpretation of tectonically produced marine erosion surfaces in the Cretaceous Seaway of North America. Marine erosion may remove evidence of prior subaerial exposure, which must then be inferred rather than observed. Allostratigraphy is inherently more practical in that it emphasizes mappable, observable discontinuities, rather than inferred exposure surfaces. Until the terminological confusion in sequence stratigraphy has been mopped-up, it must remain a highly valuable tool for interpretation but a less valuable tool for formally naming rock units.

Transgressive-Regressive (T-R) Sequence Stratigraphy

Embry, Ashton F.
Geological Survey of Canada
Calgary, Alberta, Canada, T2L 2A7
e-mail: aembry@nrcan.gc.ca

Abstract

A sequence, as originally defined by Sloss and colleagues, was a stratigraphic unit bounded by subaerial unconformities. Such a stratigraphic unit proved to be of limited value because, in most instances, sequences could be recognized only on the margins of a basin where subaerial unconformities were present. Vail and colleagues greatly expanded the utility of sequences for basin analysis when they redefined the term as a unit bounded by unconformities or correlative conformities. The addition of correlative conformities allowed a sequence to potentially be recognized over an entire basin.

This revised definition has led to the formulation of four different types of sequences, each having a different set of bounding surfaces. Vail and colleagues have defined two types: a type 1 depositional sequence and a type 2 depositional sequence. A type 1 depositional sequence utilizes a subaerial unconformity as the unconformable portion of the boundary and a time line equivalent to the start of base level fall for the correlative conformity. Because the subaerial unconformity migrates basinward during base level fall, much of it is therefore included within such a sequence rather than being on the boundary. Also it is impossible to objectively recognize a time line that corresponds to the start of base level fall. For these reasons a type 1 depositional sequence has little practical value.

A type 2 depositional sequence also uses the subaerial unconformity as the unconformable portion of the boundary but uses a time line equivalent to the end, rather than the start, of base level fall for the correlative conformity. This resolves the problem of including a portion of the unconformity inside the sequence. However, it is essentially impossible to objectively recognize a time line that corresponds with the end of base level fall (start of base level rise) and thus this type of sequence also has no practical value. Galloway proposed the use of maximum flooding surfaces as sequence boundaries and named such a unit a genetic stratigraphic sequence. This alleviated the problem of major subjectivity in boundary recognition because maximum flooding surfaces can be determined by objective scientific analysis. However, this sequence type founders on the problem that the subaerial unconformity occurs within the sequence and thus it lacks genetic coherency on the basin margins.

To overcome these major deficiencies in sequence definition, Embry and Johannessen have defined a fourth type of sequence that they term a **T-R** sequence. This sequence uses the subaerial unconformity as the unconformable portion of the boundary and the maximum regressive surface as the correlative conformity. This methodology keeps the subaerial unconformity on the boundary and also provides for a correlative conformity that can be objectively determined. It thus avoids the fatal flaws of previously defined types. A **T-R** sequence can be divided into a transgressive systems tract below and a regressive systems tract above by using the maximum flooding surface as a mutual boundary. **T-R** sequence stratigraphy, unlike the other proposed methodologies, has maximum practical utility with a minimum of stultifying jargon.

Transgressive-Regressive Cycles: Application to Petroleum Exploration for Hydrocarbons Associated with Cretaceous Shelf Carbonates and Coastal and Fluvial-Deltaic Siliciclastics, Northeastern Gulf of Mexico

Mancini, Ernest A.
Puckett, T. Markham
Center for Sedimentary Basin Studies
Department of Geological Sciences
Box 870338
The University of Alabama
Tuscaloosa, Alabama 35487-0338
e-mail: emancini@wgs.geo.ua.edu
e-mail: mpuckett@wgs.geo.ua.edu

Abstract

Stratigraphic analysis of sedimentary basins is critical for correlation in a basin, for reconstructing the geohistory of a basin, and for developing a successful petroleum exploration strategy for a basin. In studying only the shelfal areas of basins that are characterized by carbonate or mixed carbonate and siliciclastic deposition and in which stratal patterns are driven by low-frequency, tectonic-eustatic events, a stratigraphic analysis based on the cyclicity recorded in the strata (transgressive-regressive cycles) has utility for correlation, for geohistory interpretation, and in formulating petroleum exploration strategies. This is the case for the Cretaceous section in basins of the northeastern Gulf of Mexico.

In utilizing the concept of transgressive-regressive (T-R) cycles, eight T-R cycles are recognized in Cretaceous (upper Valanginian to lower upper Maastrichtian) strata of the northern Gulf of Mexico. The cycles consist of a transgressive (aggrading and backstepping) phase and a regressive (infilling) phase. These T-R cycles are useful for intrabasin correlation of Cretaceous strata in the Mississippi interior salt basin and for interbasin correlation of Cretaceous strata in the Mississippi interior salt basin and the East Texas salt basin. Six regional Cretaceous unconformities and associated hiatuses (late Valanginian, middle Cenomanian, late Turonian to middle Coniacian, middle Campanian, late Campanian to early Maastrichtian, and late Maastrichtian) and nine regional transgressive events (early Aptian, early Albian, middle Albian, early Cenomanian, late Cenomanian to early Turonian, late Santonian, early middle Campanian, early late Campanian, and early Maastrichtian) have been identified as major events in the geohistory of these basins.

Hydrocarbon production from Cretaceous reservoirs in the northeastern Gulf of Mexico can be categorized as to the phase of T-R cycles. Sandstone reservoirs associated with the early transgressive aggrading phase have accounted for 42% of the 7.437 TCF of natural gas produced from Cretaceous reservoirs in this region. Sandstone reservoirs associated with the late transgressive backstepping and regressive infilling phases have accounted for 63% of the 2 BBO produced from Cretaceous reservoirs in this region. These findings indicate that the primary natural gas exploration target in the northeastern Gulf of Mexico should be Cretaceous sandstone reservoirs of the transgressive aggrading phase of T-R cycles and that the principal oil exploration target in this region should be Cretaceous sandstone reservoirs of the transgressive backstepping and regressive infilling phases of T-R cycles. These exploration targets are associated with structural traps related to salt movement.

Keeping Pace: Continental (Nonmarine) Sequence Stratigraphy in a High Accommodation-Sediment Supply Regime, Hornelen Basin (Devonian), Norway

Print

Anderson, Donna S.
Department of Geology and Geological Engineering
Colorado School of Mines
Golden, Colorado 80401
e-mail: dsanders@mines.edu

Abstract

Cyclic alluvial fan, braid plain, and lake deposits in a study area in the north-central Hornelen basin of west-central Norway yield insights into the formation of sequence boundaries and condensed surfaces in a high accommodation-sediment supply setting. Examination of facies architecture at two critical stratigraphic positions (times) within three large-scale cycles (sequences), the time of maximum basinward progradation of the orthogonally sourced alluvial fan and braid plain facies tracts and the time of maximum flooding across the basin, shows little erosion and sediment starvation, respectively. Hence, two key stratigraphic surfaces, sequence boundaries and condensed sections, do not form. In addition, the systems-tract configuration, while readily recognizable, becomes modified by the lack of regional erosion during sequence-boundary formation: a volumetrically displaced lowstand systems tract does not form. In this basin, high sediment supply keeps pace with high tectonic subsidence, creating an aggradational yet cyclic stratigraphic architecture.

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Bounding-Surface Hierarchies and Related Sources of Heterogeneity in Seemingly Uniform Fluvial Sandstone Sheets

Holbrook, John
Department of Geosciences
Southeast Missouri State University
Cape Girardeau, Missouri 63701
e-mail: jholbrook@semovm.semo.edu

Oboh-Ikuenobe, Francisca E.
Department of Geology and Geophysics
University of Missouri, Rolla
Rolla, Missouri 65409

Abstract

Fluvial sandstone sheets may appear uniform initially, but detailed examination tends to reveal sharp lithologic contrasts across bounding surfaces. The mid-Cretaceous Muddy Sandstone of southeast Colorado, USA contains two sandstone sheets and provides examples of such potential permeability barriers. Sediment bodies bound and respective bounding surfaces are, in order of ascending rank: bar and dune deposits (1^{st}- to 3^{rd}-order), nested channel fills (4^{th}-order), channel fills (5^{th}-order), channel belts (6^{th}-order), nested valley-fills (7^{th}-order), valley-fills (8^{th}-order), and sequences (9^{th}-order). Bar and dune through channel-belt deposits commonly have permeability barriers because the episodes of waning flow common to their deposition tend to cause draping of surfaces and filling of scours locally with finer grained deposits. Channel-fills through sequences tend to have permeability barriers related to juxtaposition of permeable and non-permeable lithofacies during successive incision-and-fill events. Fluvial sandstone sheets can have reduced permeability in paleodip orientation that operates on the scale of individual wells because of draping of down-dip-oriented bar- and dune-accretion surfaces. A dip-oriented grain, reducing permeability in the strike direction, may arise on the scale of fields, because of permeability barriers formed at nested channel through higher-order valley and sequence boundaries.

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Predictable Variations in the Marine Stratigraphic Record of the Northern and Southern Hemispheres and Reservoir Potential

Perlmutter, Martin A.
ChevronTexaco
ILT/ERTC
4800 Fournace Place, Ste. W502
Bellaire, Texas 77401
e-mail: MPerlmutter@chevrontexaco.com

Plotnick, Roy E.
Department of Earth and Environmental Sciences
University of Illinois at Chicago
845 W. Taylor St.
Chicago, Illinois .60607
e-mail: Plotnick@uic.edu

Abstract

Variation in the phase relationships of precession-scale sediment yield cycles and glacioeustatic cycles may cause systematic differences in the marine stratigraphy of the Northern and Southern Hemispheres. These differences should be evident in the variations in lithology, and bed thickness and distribution and therefore could impact the interpretation of reservoir potential.

At precession-scale (~20 kyr), Northern and Southern Hemisphere insolation cycles are 180° out of phase. Consequently, similar climatic successions in opposite hemisphere, and associated sediment yield cycles can be 180° out of phase, as well. Prior to the Plio-Pleistocene, the common glacial condition was a unipolar icecap. Under this condition, precession-scale eustasy will tend to track the insolation cycle of the glaciated hemisphere. The result is that similar climatic successions in opposite hemispheres will have yield cycles with distinctly different phase relationships to glacioeustasy. Such differences should not exist in an ice-free world.

By taking these variations into account, stratigraphic interpretations will improve, reducing uncertainty associated with exploration analyses. Further, by determining which regions will be prone to maximum sediment yield at lowstands, the regions that are prone to the development of sand rich submarine fans could be high graded. This approach may also lead to a more complete understanding of the paleoclimate record by being able to determine whether a particular interpreted sea level shift occurred as a result of glaciation, or a more local forcing agent.

Print

Depositional Topography: Key Element of Stratigraphic Interpretation and Panacea for Log Correlation; Part 1: Concepts and Transitional Icehouse-Greenhouse Systems

Tinker, Scott W.
Kerans, Charles
Bureau of Economic Geology
The University of Texas at Austin

Abstract

In any modern or ancient carbonate setting, one depositional environment eventually transitions into another, and facies change. Topography is a primary driver of lateral facies change. In a given shelf or ramp profile, carbonate facies tend to be more continuous along strike and more apt to change along dip. If topographic dip is steep, facies change in shorter distances than if topographic dip is gradual. Because facies (1) dictate original petrophysical properties and strongly influence diagenetic alteration, (2) strongly influence petrophysical properties and associated wireline log and seismic responses, and most importantly (3) change within a time-bound package of rock, it is highly unlikely that the correlation of similar wireline log signatures or the tracing of a continuous seismic reflector for great distances will result in an accurate chronostratigraphic interpretation.

Although these concepts are widely understood and accepted today, and in spite of ever-improved seismic imaging technologies, accomplishing the feat of building realistic depositional topography into subsurface stratigraphic interpretation remains a difficult task. Even though sequence stratigraphy has revolutionized both exploration and exploitation in the oil industry by showing that chronostratigraphy improves the ability to predict the 3D distribution of reservoir, source, and seal strata, stratigraphers continue to hedge bets towards flat correlation by correlating similar log signatures and carrying continuous seismic reflectors.

The only way to avoid this tendency toward the horizontal is to impose a facies-driven model of depositional topography onto the stratigraphic interpretation. An accurate assessment of depositional topography requires a sedimentologic analysis of core and outcrop analog data to determine reasonable water-depth ranges for component facies, and the definition of a hierarchy of stratigraphic cyclicity to determine longer term water-depth variation represented by component facies. Concepts of depositional topography are applied differently for each high-frequency cycle (cycle) as follows:

1. Constructional cycle—Individual cycles should illustrate depositional topography that represents the water depth of the included facies (*i.e.*, if a cycle contains a range of facies from tidal flat through 100-ft-water-depth outer ramp facies, then the bounding surfaces should illustrate that topography). Because of the relatively short time duration represented by an individual cycle, each cycle should allow reconstruction of paleo-bathymetry once compaction/subsidence are removed.
2. Draped cycle—High-frequency cycles that drape preexisting topography will not necessarily show a simple facies to predicted water-depth correlation.
3. Conformable high-frequency sequence (HFS) boundaries—are a composite stratigraphic record of short-term and long-term eustasy, subsidence, sedimentation rate, and compaction, and therefore may not show a direct relationship to facies that are found directly below them but will nonetheless control depositional topography of the facies in the overlying sequence.
4. Disconformable (erosional) HFS boundaries—are not candidates for reconstruction of depositional topography of the underlying facies, but like conformable HFS boundaries, they will control depositional topography of the facies in the overlying sequence.

Permian-age outcrops and subsurface datasets from West Texas and New Mexico, representing transitional icehouse-greenhouse systems, provide an excellent starting point to illustrate the importance of depositional topography on stratigraphic interpretation. Eustatic amplitude in transitional icehouse-greenhouse systems was neither too great nor too small, but just right to record a relatively complete stratigraphic signal along the depositional profile. Examples include ramp to steep-rimmed profiles.

Depositional Topography: Key Element of Stratigraphic Interpretation and Panacea for Log Correlation Part 2: Concepts and Transitional Icehouse-Greenhouse Systems

Print

Kerans, Charles
Tinker, Scott W.
Bureau of Economic Geology
The University of Texas at Austin

Abstract

In any modern or ancient carbonate setting, one depositional environment eventually transitions into another, and facies change. Topography is a primary driver of lateral facies change. In a given shelf or ramp profile, carbonate facies tend to be more continuous along strike and more apt to change along dip. If topographic dip is steep, facies change in shorter distances than if topographic dip is gradual. Because facies (1) dictate original petrophysical properties and strongly influence diagenetic alteration, (2) strongly influence petrophysical properties and associated wireline log and seismic responses, and most importantly (3) change within a time-bound package of rock, it is highly unlikely that the correlation of similar wireline log signatures or the tracing of a continuous seismic reflector for great distances will result in an accurate chronostratigraphic interpretation.

Although these concepts are widely understood and accepted today, and in spite of ever-improved seismic imaging technologies, accomplishing the feat of building realistic depositional topography into subsurface stratigraphic interpretation remains a difficult task. Even though sequence stratigraphy has revolutionized both exploration and exploitation in the oil industry by showing that chronostratigraphy improves the ability to predict the 3D distribution of reservoir, source, and seal strata, stratigraphers continue to hedge bets towards flat correlation by correlating similar log signatures and carrying continuous seismic reflectors.

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Paleoclimate and the Origin of Middle Pennsylvanian Cyclothems (Fourth-Order Sequences) of North America

Cecil, C. Blaine
Dulong, Frank T.
U.S. Geological Survey
Reston, Virginia 20192
e-mail: bcecil@usgs.gov
e-mail: fdulong@usgs.gov

West, Ronald R.
Department of Geology
Kansas State University
Manhattan, Kansas 66506
e-mail: rrwest@ksu.edu

Edgar, N. Terence
U.S. Geological Survey
St. Petersburg, Florida 33710
e-mail: tedgar@usgs.gov

Abstract

Transcontinental correlations of a Middle Pennsylvanian fourth-order sequence provided evidence for the relative importance of allocyclic controls on the formation of Pennsylvanian cyclothems. These correlations (and related studies) further indicated that eustasy was the primary control on accommodation space in most basins, whereas tectonic subsidence provided additional accommodation space in a few basins. Temporal and spatial variations in climate, however, were the primary controls on physical and chemical sedimentology. The climate model developed herein suggested that repetitive changes in rainfall patterns and surface winds at low latitudes were coincident with the glacial and interglacial intervals. During glacial intervals, a large permanent high pressure cell was associated with a southern hemisphere ice cap and a nearly stationary polar front. The ice cap minimized annual (summer to winter) thermal variation in the atmosphere (sensible heating) over the southern hemisphere land mass. As a result, permanent high pressure over the ice cap confined the intertropical convergence zone (ITCZ) to low latitudes, and a low pressure rainy belt (doldrums) developed in the equatorial region of Pangea during lowstands. During interglacials, the doldrums belt (low pressure belt) degenerated and was replaced by seasonal swings in the ITCZ, in response to seasonal sensible heating of the atmosphere over both northern and southern hemisphere land masses. As a result, the climate in low latitudes changed from relatively wet conditions during glacial intervals to drier and more seasonal conditions during interglacial periods.

Paleoclimates in the eastern United States during glacial intervals are indicated by the following: (1) intense chemical weathering of paleosols, (2) low fluvial sediment supply, (3) peat formation (now coal) during lowstands in response to a permanent low-pressure rainy belt and wet conditions, (4) deposition of black shale in basin centers during the early stages of transgression in response to low wind speeds and poor wind-driven circulation in epeiric seas prior to significant deterioration of the doldrums belt, and (5) transport, deposition, and preservation of eolian sediments (in basin margins) following a period of weathering of lowstand exposure surfaces (western United States). Paleoclimates during interglacial intervals are indicated by an influx of fluvial sediments as the doldrums belt disappeared (eastern United States), and deposition of marine limestone west of the Appalachian basin in response to increased wind speeds and wind-driven circulation in epeiric seas coincident with highstands and maximum north-south swings of the ITCZ. All climatic factors (annual rainfall, seasonality of annual rainfall, wind speed, and wind direction) have controlled sedimentation in cratonic depositional environments as sea level rose and fell. Although tectonics and eustasy control accommodation space, paleoclimate cycles (coincident with eustasy) control the lithostratigraphy of upper Middle Pennsylvanian cyclothems at any given paleo-latitude in the tropical regions of Pangea. Furthermore, the present study negates “deep water” models for the origin of Middle Pennsylvanian black shale and autocyclic models (delta plain, back barrier, or fluvial depositional environments) for peat formation as precursors to Pennsylvanian commercial coal deposits.

Stratigraphic Architecture and Fundamental Sedimentology of Two Late Pleistocene Deltas: Gulf of Mexico and Indonesia

Print

Roberts, Harry H.
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana 70803

Sydow, John
Exploration Business Unit
P.O. Box 714
Port of Spain, Trinidad

Fillon, Richard
Earth Studies Associate
3730 Rue Nichole
New Orleans, Louisiana 70131

Kohl, Barry
Department of Geology
Tulane University
New Orleans, Louisiana 70118

Abstract

The Mobile River shelf-edge delta, built on the outer Mississippi-Alabama shelf, prograded to the shelf-slope break as sea level approached the latest Pleistocene glacial maximum. At the same time, the Mahakam River built a complex shelf-edge delta on the eastern shelf of Borneo (Indonesia). Both late Pleistocene deltas were constructed during falling-to-lowstand relative sea-level conditions. The former was fed by the temperate Mobile River, the latter by the equatorial Mahakam River. Four coreholes provided detailed calibration of high resolution seismic data for stratigraphic control within the Mobile River delta while one long corehole and numerous piston and vibracores provided similar seismic calibration for stratigraphic control in the Mahakam delta. Systems tracts and key bounding surfaces were related to global eustacy in both settings over ca. 125 ka.

Sequence architectures differ significantly, an important consequence of different depositional settings. The northeastern Gulf of Mexico is relatively stable, also with low wave energy, but dominated by siliciclastic sedimentation. Falling-to-lowstand progradation of the Mobile River's Lagniappe delta has occurred in numerous overlapping and spatially offset lobes incised by a complex channel network. Clinoforms downlap the outer shelf shale directly overlying an isotope stage 5 interglacial condensed section. By contrast, the tropical Mahakam shelf is tectonically active, has low wave energy, strong oceanic currents, upwelling, and a mixed siliciclastic–carbonate depositional system. Falling-to-lowstand clinoforms of this delta downlap a highly irregular surface of isolated and fused carbonate bioherms built above a transgressive surface that formed during the preceding sea level rise. Both the Mahakam and Mobile River depocenters are multilobate and clearly built by autocyclic switching of depositional sites. The eastern lobes of the Mobile River delta show evidence of wave reworking while the western flank is fluvially dominated. Both the Mahakam and Mobile deltas are composed of sand-rich clinoforms and channel deposits that possess excellent reservoir properties.

Sea-Level Estimates for the Latest 100 Million Years: One-Dimensional Backstripping of Onshore New Jersey Boreholes

Print

Kominz, Michelle A.
Van Sickel, William A.
Western Michigan University
Department of Geosciences
Kalamazoo Michigan

Miller, Kenneth G.
Browning, James V.
Rutgers, the State University of New Jersey
Department of Geological Sciences
Piscataway, New Jersey

Abstract

Backstripping analysis of the Bass River and Ancora boreholes from the New Jersey Coastal Plain (Ocean Drilling Project Leg 174AX) provided new Late Cretaceous sea-level estimates and tested previously published Cenozoic sea-level estimates. Amplitudes calculated from all New Jersey boreholes were based on new porosity-depth relationships estimated from New Jersey Coastal Plain electric logs. In most cases, amplitudes and duration of sea level were comparable when sequences were represented at multiple borehole sites, suggesting that the resultant curves were an approximation of regional sea level. Sea-level amplitudes as great as 50 m were required by third-order Cretaceous sequences. Most amplitudes were probably closer to 20 to 40 m. Third-order (0.5–3 m.y.) sea-level changes of Paleocene and younger sequences were generally less than 30 m and were superimposed on a long-term (= 100 m.y. duration) sea-level fall from a maximum early Eocene value of approximately 100 to 140 m.

Print

ODP, Sequences, and Global Sea-Level Change: Comparison of Icehouse vs. Greenhouse Eustatic Changes

Miller, Kenneth G.
Browning, James V.
Wright, James D.
Mountain, Gregory S.
Hernández, John C.
Olsson, Richard K.
Feigenson, Mark D.
Department of Geological Sciences
Rutgers University
Piscataway, New Jersey 08854

Kominz, Michelle A.
Van Sickel, William A.
Western Michigan University
Kalamazoo, Michigan 49008-5150

Sugarman, Peter J.
New Jersey Geological Survey
PO Box 427
Trenton, New Jersey 08625

Abstract

Understanding eustatic (global sea-level) changes and their effects on the geological record is an important but difficult task because eustatic effects are complexly intertwined with basin subsidence and changes in sediment supply. Led by Peter Vail, researchers at EPR reconstructed a eustatic history by applying sequence stratigraphy to a global array of proprietary seismic profiles, industry wells, and outcrops. This EPR eustatic record has been controversial owing to methodological concerns and reliance on largely unpublished data. The Ocean Drilling Program (ODP) has focussed on drilling the New Jersey, Bahamas, and Australian margins for sea-level studies and has accomplished the following:

1. Validated a transect approach of drilling passive continental margins and carbonate platforms (onshore, shelf, slope);
2. Tested and validated the assumption that the primary cause of impedance contrasts producing seismic reflections on continental margins are stratal surfaces including unconformities;
3. Proved that the ages of sequence boundaries on margins can be determined to better than ±0.5 m.y. and provided a chronology of eustatic lowering for the past 100 m.y.;
4. Achieved orbital-scale (perhaps suborbital) stratigraphic resolution on continental slopes and carbonate platforms;
5. Showed that siliciclastic and carbonate margins yield correlatable and in some cases comparable records of sea-level change;
6. Evaluated the sedimentary response of both tropical and cool-water carbonate platforms to eustatic changes;
7. Begun to constrain the amplitude and cause of eustatic change for both the Iceahouse World of the past 42 m.y. and the Greenhouse World of 250-42 Ma, as outlined below.

Sequence Stratigraphy in Fine-Grained Rocks: Beyond the Correlative Conformity

Bohacs, Kevin M.
ExxonMobil Upstream Research Company
3120 Buffalo Speedway
Houston, Texas 77098
e-mail: Kevin.M.Bohacs@exxonmobil.com

Neal, Jack E.
Grabowski, George J., Jr.
ExxonMobil Exploration Company
233 Benmar Street
Houston, Texas 77060-2598

Abstract

Mudrocks provide the source and seal of hydrocarbons and are key elements in reservoir models as baffles and barriers. Sequence stratigraphy provides an excellent framework within which one can integrate the many scales of physical, chemical, and biological observations necessary to understand these rocks across the spectrum of depositional settings. Although flooding surfaces and depositional-sequence boundaries may be subtly expressed in mudrocks, they can be recognized through distinct changes observed in core, outcrop, well-logs, and on seismic data. Beyond the chronostratigraphic utility of the correlative conformity, abundant paleoenvironmental information is recorded in fine-grained strata—depositional sequences do not just fade away into obscurity in distal reaches, but have objective attributes that allow extension of stratigraphic frameworks and play-element predictions over very large areas.

Flooding surfaces fundamentally record a critical increase in accommodation relative to sediment supply, commonly recorded in mudrocks by laterally extensive accumulations of authigenic and pelagic components, along with evidence of sediment starvation and low bottom-energy levels. Even in mudrocks, some may record minor erosion, reworking, and lag formation due to low sediment supply, but all are marked by a significant decrease in advected clastic input—contrasting with sequence boundaries.

Depositional sequence boundaries record a critical decrease in accommodation relative to sediment supply, commonly accompanied by an increase in depositional energy or a significant change in sediment supply, or both, over hundreds to thousands of square kilometers in both fine- and coarse-grained lithologies. This is recorded even in fine-grained lithofacies by regional erosional truncation associated with subsequent onlap, exposure, reworked fossils, decreased continuity at lamina to bedset scale, along with increased accumulations of advected clastics and fossils or secular changes in biogenic lithology. All of these attributes (except subaerial exposure) are observed in physically correlative distal reaches of unconformities across their correlative conformities.

Interactions of sediment supply and accommodation with pre-existing topography control the expression of depositional sequences. Marine environments tend to have the most widespread, gradually varying facies tracts, whereas paralic facies tracts tend to be most localized and abruptly changing. Lacustrine sequences vary according to lake-basin type and range from very similar to shallow-marine siliciclastic sequences to very dissimilar.

Sequence Stratigraphy and Eustatic Sea Level

Kominz, Michelle A.
Department of Geosciences
Western Michigan University
Kalamazoo, Michigan
United States
e-mail: michelle.kominz@wmich.edu

Pekar, Stephen F.
Lamont-Doherty Earth Observatory
Palisades, New York 10964
United States

Abstract

A number of the basic assumptions are made regarding the relationship between sequence stratigraphy, sequence architecture, water depth and sea-level change. Testing of these relationships is made particularly problematic as a result of the recent and prevalent assertion that it is impossible to obtain eustatic magnitudes from sequence stratigraphic data. While much qualitative data has been amassed to define and corroborate the sequence model, we consider the implications of rigorous quantitative estimates of eustasy, derived directly from sequence data.

Two-dimensional backstripping of strata in a sequence stratigraphic framework coupled with quantitative benthic foraminiferal biofacies analyses has yielded quantitative estimates of the geometry and water depths of ancient, prograding sequences at a sub-sequence level (Kominz and Pekar, 2001). The data set is from Oligocene strata beneath the New Jersey Coastal Plain. Borehole data, largely from Ocean Drilling Project Sites 150X and 174AX, provided excellent recovery for quantitative estimates of age, lithology, compaction, and benthic biofacies (Miller *et al.*, 1994, 1996, 1997, and 1998).

Results indicate that in most cases sequence boundaries are associated with a downward shift in sea level as suggested by most sequence models. Maximum flooding surfaces generally occur at or near the maximum value of sea-level rise. Finally, there is no consistent relationship between clinoform breaks and water depth.

Clinoforms, Clinoform Trajectories and Deepwater Sands

Steel, Ron
University of Wyoming
Laramie, Wyoming 82071
e-mail: rsteel@uwyo.edu

Olsen, Torben
Statoil
Stavanger, Norway

Abstract

Sedimentary prisms build out from the margins of most types of sedimentary basin where there is significant differential subsidence. Clinoforms are the large-scale (hundreds of meters), time-line expressions of discrete phases of aggradation and accretion within these prisms. The sigmoidal clinoforms are surfaces of dynamic equilibrium that are created and maintained by sediment aggradation to form topsets and then sediment by-pass through the topsets onto the accreting deepwater slope and beyond (Swift and Thorne, 1991). It is argued, on this basis, that the topset surface of such large-scale clinoforms is referred to as a morphological ‘shelf’ and that the upper rollover of the clinoform is referred to as the ‘shelf-slope break.’ Such features form at the supply margins of many types of basin where there is a water depth of at least several hundred meters and are not restricted to continental margins.

The geometry and internal architecture of individual clinoforms, or groups/sets of clinoforms, can be used to predict how sediment budgets have been partitioned between the shelf and deepwater areas beyond the shelf break. The architecture of individual clinoforms (time scale of several 100ky), mainly the degree of shelf-edge incision and the degree of slope disruption, can indicate whether or not significant volumes of sand have been delivered beyond the shelf margin. Another method of prediction makes use of the ‘trajectory’ of the shelf margin on time scales of 1Ma or more; *i.e.*, how the break-of-slope of successive clinoforms stack with respect to each other. High-angle trajectories generally imply preferential sediment storage on the shelf and coastal plain, whereas low-angle or falling trajectories involve erosion and sediment by-pass to the deepwater slope and basin floor. These concepts are illustrated from well-exposed clinoforms and clinoform sets within a shelf margin that has migrated and accreted some 30 km during an interval of some 6 Ma, in the Central Basin of Spitsbergen.

Print

Allocyclic and Autocyclic Processes as Primary Controls on the Stratal Architecture and Sedimentological Expression of Depositional Systems from the Bolivian Sub-Andean Foreland Basin

Wagner, John B.
Nexen Petroleum U.S.A
Dallas, Texas

Bhattacharya, Janok
Department of Geosciences, University of Texas at Dallas
Richardson, Texas

Soegaard, Kristian
Norsk Hydro
Stavanger, Norway

Moiola, Richard J.
Dallas, Texas

Coleman, James M.
Coastal Studies Institute-LSU
Baton Rouge, Louisiana

Abstract

The Madre de Dios Basin of Bolivia represents two distinct phases of tectonic development that illustrate the linked stratigraphic responses to a changing basin style. The first phase associated with the Paleozoic is characterized as an intracratonic setting. The second, which began during the late Mesozoic and persists today, is the development of the Sub-Andean Foreland Basin. Hydrocarbons occur primarily within stratigraphic traps, potential reservoirs and seals are Paleozoic to Late Mesozoic in age.

Paleozoic depositional environments identified from core indicate major changes in climatic conditions have occurred and include fluvial/deltaic, eolian dune, coastal sabkha, and shallow marine carbonate facies. A Late Devonian marine source rock with total organic carbon (TOC) content of up to 18% also occurs within the basin. Cretaceous age sediments contain an incised valley system of 10 to 15 kilometers in width and 300 meters in depth. Valley fill facies represent low sinuosity, braided fluvial systems grading upwards into estuarine muds. Terracing of the valley margin formed in response to multiple cut and fill episodes (baselevel fluctuations) of valley formation. Recurrent movements of basement involved fault blocks related to migration of the advancing forebulge, controlled the location and magnitude of valley incision and drainage incisement patterns.

Large-scale variations in depositional environments, duration of geologic time (450 to 60 MY) represented by the stratigraphic section within a changing tectonic style, provides the Madre de Dios Basin as an example of the process to response interplay between tectonics, eustasy, climate and sediment supply.

Print

Influence of Paleotopography, Eustasy and Tectonic Subsidence: Upper Jurassic Smackover Formation, Vocation Field, Manila Sub-Basin (Eastern Gulf Coastal Plain)

Llinás, Juan Carlos
Department of Geological Sciences
The University of Alabama
Box 870338
Tuscaloosa, Alabama 35487
e-mail: llina001@bama.ua.edu

Abstract

The sequence of deposition of the Upper Jurassic Smackover Formation in updip marginal positions, north of the regional peripheral fault trend in the eastern Gulf Coastal Plain is the result of the combined effects of many variables including paleotopography, eustasy, tectonic subsidence, and carbonate productivity, which have been highly influenced by environmental conditions. Tectonic subsidence is identified as a critical mechanism for the generation of the accommodation space required for the accumulation of thick Smackover sections measured in wells located in areas associated with basement paleohighs that were elevated during the time of Smackover deposition.

This study focuses on Vocation Field located in southwestern Alabama, in the eastern margin of the Manila subbasin, along the western flank of the Conecuh ridge. The structure in Vocation Field is a Paleozoic basement high associated with the Triassic/Jurassic rifting event. The reservoir in the field is the Upper Jurassic Smackover Formation, which overlies siliciclastic deposits of the Norphlet Formation in the margins of the structure and onlaps crystalline basement rocks in updip positions. Based on core and thin section descriptions, four subenvironments have been interpreted for Smackover deposits: microbial reef complex, shallow lagoon, shoal complex, and sabkha-tidal flat. These subenvironments define an overall aggradational to progradational shallowing-upward marine cycle developed in an evaporate-carbonate setting. The reef and shoal complexes are the main and potential petroleum reservoirs. Significant boundstone accumulations have been deposited on the northeastern side of the basement structure due to restricted environmental conditions that favored the establishment and growth of the microbial reefs in that area.

Smackover deposition in Vocation Field was initiated as a result of a rapid relative sea level rise (transgressive event) that partially submerged the basement paleohigh and led to the development of microbial reef buildups on the northeastern flank of the structure during the “catch–up” phase of the carbonate system. Changes in the depositional environment and a decrease in the rate of relative sea level rise initiated the “keep-up” phase characterized by the aggradation and finally progradation of shallow subtidal and peritidal sediments of the upper part of the Smackover Formation.

According to the depositional model, the microbial boundstones are equivalent to the peloidal wackestones and laminated carbonate mudstones of the middle Smackover accumulated in downdip areas having greater water depths.

Print

Controls on Sequence Architecture in Lacustrine Basins—Insights for Sequence Stratigraphy in General

Bohacs, Kevin M.
ExxonMobil Upstream Research Company
3120 Buffalo Speedway
Houston, Texas 77098
e-mail: Kevin.M.Bohacs@exxonmobil.com

Neal, Jack E.
Grabowski, George J., Jr.
ExxonMobil Exploration Company
233 Benmar Street
Houston, Texas 77060-2598

Reynolds, David J.
ExxonMobil Upstream Research Company
3120 Buffalo Speedway
Houston, Texas 77098

Carroll, Alan R.
Department of Geology and Geophysics
University of Wisconsin-Madison
1215 W. Dayton Avenue
Madison, Wisconsin 53706

Abstract

The sequence-stratigraphic approach of evaluating a hierarchy of rock packages bounded by various surfaces works very well in lake strata. The expression of depositional sequences, however, varies as a function of lake depositional system, just as shallow marine-carbonate sequences look different from shallow-marine-siliciclastic sequences. Contrasts among lake and marine systems make it inappropriate to directly apply one unmodified marine sequence-stratigraphic model to all lake systems. Indeed, one lacustrine model is not applicable to all lake-basin types.

Contrasts of sequence expression among lake-basin types arise from several key attributes: Lake level and sediment supply are commonly linked closely in lake systems (most marine models assume no linkage); lake shorelines commonly move basinward by a combination of progradation and desiccation. In addition, the character of a lake is fundamentally controlled by the relative rates of potential accommodation change and supply of sediment+water, giving rise to three distinct lake-basin types: overfilled, balanced-filled, and underfilled.

These differences strongly influence the occurrence, distribution, and character of hydrocarbon source, reservoir, and seal lithologies. Sequence boundaries vary from nonexistent or minimally developed, through extensive erosion and incised-valley formation, to large basinward shifts and widespread exposure. Flooding surfaces are enhanced as they are commonly coincident with decreased sediment supply.

Lowstands vary from aggradational stacks of basin-floor turbidite parasequences to basin-center evaporites surrounded by extensive desiccation surfaces. Transgressive systems tracts vary from thin and shale prone to thick and coarse-clastic prone. Highstand systems tracts range from obliquely progradational clastic shoreline parasequences to aggradational carbonate shoreline parasequences.

Successful exploration and production in lake basins requires attention to these variations.

Print

Contrasting Styles of Eolian, Fluvial, and Lacustrine Sequence Development: UK Southern North Sea

Sweet, Michael L.
ExxonMobil Upstream Research Company
P. O. Box 2189
Houston, Texas 77252
e-mail: mike.l.sweet@exxonmobil.com

Abstract

A sequence stratigraphic framework for the Permian, non-marine rocks of the southern North Sea was constructed by recognizing and correlating lacustrine transgressive surfaces and maximum flooding surfaces and eolian and fluvial sequence boundaries. These surfaces and the stacking patterns of the rocks they bound were found to have markedly different expressions in lacustrine-dominated areas towards the basin center as compared to the fluvially dominated systems at the basin margin.

In the more distal reaches of this depositional system the elevation of the water table exerts the main control on the development of surfaces and facies architecture. Here, during lake lowstands, laterally extensive eolian sequence boundaries record deflation down to the water table and the growth of eolian dune fields. These eolian deposits have excellent reservoir quality. Laterally extensive, lacustrine transgressive surfaces overlain by poor reservoir quality sabkha and lacustrine deposits record a shift to a wetter climate and rising lake levels. Fields in this part of the depositional system are characterized by sheet-like reservoir architecture with good lateral, but poor vertical connectivity.

In contrast, sequences nearer the tectonically active, western margin of the basin were marked by locally deep fluvial incision (up to 70 m). It was during the onset of lake transgression when gradients were steep and fluvial discharge was increasing that extensive fluvial incision occurred. Incised valleys were filled with a complex mosaic of eolian, fluvial and lacustrine facies. Lateral facies variability is high, which reduces lateral connectivity and predictability. These fluvial systems experienced diminishing competence during falling lake level. Eolian erosion of older sabkha and fluvial deposits and eolian deposition characterized lake lowstands.

Extracting Stratigraphic Information from 3D: Exploiting the Seismic Data

Liro, Louis M.
Cline, Kimberly
Veritas DGC Inc.
10300 Town Park
Houston, Texas 77072 USA

Abstract

Whereas seismic stratigraphy has its roots in the identification and delineation of depositional packages and their bounding unconformities on seismic data, sequence stratigraphy is primarily concerned with well log patterns and outcrop geometry to evaluate sub-sequence packages. In this paper, we discuss the identification of depositional packages and stratigraphic elements from seismic volumes, utilizing not just vertical sections of conventional amplitude data but alternative slice views, animations, and visualization techniques.

Cyclic Attributes on Seismic Data and Sequence Stratigraphy—New Criteria for Exploration, New Interpretation Styles

Radovich, Barbara J.
Integrated Geophysics Corporation
710 N. Post Oak Blvd., Suite 300
Houston, Texas 77024
e-mail: barbara@igcworld.com

Abstract

The application of sequence stratigraphy on seismic data has long centered about the process of interpretation of seismic reflection geometries of onlap and downlap and the tying of well data to seismic. But in many basins, and especially in deepwater areas, well data may be rare or nonexistent. Tying shelf sequences to basin sequences is often impossible because of long distances, gaps in seismic data and complex structures. The concept of aggradation cycles within sequence architectures offers new criteria for exploration and new ways to interpret the seismic data on 2D and 3D datasets with modern visualization tools. Manipulation of seismic voxels and attributes become tools to study stratigraphy. The focus of seismic interpretation shifts from finding reflection geometries to finding cyclic vertical stacking patterns even if geometries are absent or subtle. This framework can give insight into the sediment delivery system of margins and to the aggradation of sediments in deep water in areas of sparse or no geologic control. These criteria have been applied for almost a decade to the offshore Nigeria exploration areas and key discoveries have been made using these techniques. Other areas of application include Gulf of Mexico, the Northwest Shelf of Australia, offshore Brunei, and Bangladesh.

The key criterion that guides the interpreter in these settings is the repetitive cyclicity of seismic reflection attributes and seismic facies patterns. The most useful cyclic attribute are changes in seismic instantaneous amplitude and frequency. Vertical stacking patterns of seismic attributes can be utilized in much the way that well log curve stacking patterns are used to guide sequence stratigraphy analysis. Cyclic seismic facies patterns often change upwards from laterally continuous reflections to subtle mounded patterns or chaotic patterns. The attribute cycles and succession of seismic facies most often correlate to the 3^{rd}-order sequence and the different depositional energy and styles that predominate as sea level falls then rises. The key parameters that change through this cycle are bed thickness, lithology, facies assemblages, and depositional styles such as sheet-forms or sinuous channel-forms. In deep water settings, these cycles are often a very prominent feature of the seismic data. Full analysis of the seismic data from these areas typically reveals the framework on three scales; the mega-architecture basin scale of 2^{nd}-order sea level change and tectonic subsidence, the 3^{rd}-order "building block" sequence scale of many sea level falls and rises, and the parasequence scale suitable for well prediction and reserve calculation. The repetitive nature of the cycles implies a time of balance for important parameters like sedimentation rate, subsidence, sea level, and the development of a matured, efficient sediment delivery system. These patterns also imply a high potential of recycled sediments stored in an intermediate position ready to be delivered efficiently to the basin at each lowstand of sea level. Thus, the more repetitive the cycles, the better the potential for good quality reservoir sands occurring in the deepwater facies.

Print

Oligocene/Miocene Depositional System, Volta Fan Fold Belt, Ghana

Nibbelink, K. A.
Huggard, J. D.
Devon Energy Corporation
333 Clay Street, 10th Floor
Houston, Texas 77002

Abstract

Inversion structures of the Volta Fan Fold Belt, Ghana developed during the Upper Cretaceous in response to right lateral strike slip movement along a restraining bend in the Romanche fault zone across the Keta Arch. The depositional architecture of the Oligocene to Miocene deep water sandstone reservoirs was controlled by topography created by the inversion structures and subsequent erosion during the Upper Oligocene, 30 my lowstand of sea level. Erosion at the 30 my sequence boundary cut 15 to 20 canyons across the shelf. These canyons were cut 200 to 500 meters deep, 1 to 2 km wide and provided a critical part of the sediment delivery system from the Volta River, across the shelf to the deep water.

Amplitude patterns from 3-D seismic define the deepwater sequences that systematically fill the topographic relief created by the Upper Cretaceous structural and Oligocene erosional events. Upper Oligocene to Lower Miocene sedimentation consists of 1) base of shelf fans at the mouth of the shelf canyons, 2) ponded fans behind the inversion structures, and 3) basin floor fans in front of these structures. Middle Miocene fan systems are deposited in a back stepping succession with the larger fans on the flanks of the Keta Arch. During the Upper Miocene, a major progradation of the shelf occurs and the deep water topography is filled, which allows fan sedimentation across the entire arch. These Oligocene to Miocene deep water sandstones as well as the deeper Upper Cretaceous sandstones should provide excellent reservoirs for the developing hydrocarbon system in the Volta Fan Fold Belt.

Print

Sequence Stratigraphic Framework for Oil- and Gas-Prospective Brookian Turbidites, National Petroleum Reserve in Alaska (NPRA)

Houseknecht, David W.
U.S. Geological Survey
12201 Sunrise Valley Drive, MS 956
Reston, Virginia 20192
e-mail: dhouse@usgs.gov

Schenk, Christopher J.
U.S. Geological Survey
Denver, Colorado

Abstract

Integrated field and subsurface studies of the Albian Torok and Nanushuk formations (coeval clinoform and topset couplet) have produced a sequence stratigraphic framework for identifying fairways most likely to contain stratigraphic traps in Brookian turbidites in NPRA. Stratigraphic traps in the Torok involve lowstand, sand-rich turbidite facies sealed by condensed mudstones deposited during transgression. The lowstand deposits commonly downlap onto, and interfinger basinward with, oil-prone source rocks of the gamma-ray zone (GRZ), an Aptian-Albian condensed section.

Optimum reservoirs occur in amalgamated turbidites deposited in channels incised into mudstones of the mid-lower slope or in channel-levee systems on submarine fans; the former may grade downslope into the latter within a single stratigraphic trap. Reservoir potential also may occur in backstepping fan lobes deposited during earliest transgression.

At least 15 Albian shelf margins displaying lowstand sequence boundaries have been mapped in NPRA using public domain, 2-D seismic data. Shelf margins are generally oriented north-south in northern NPRA and swing eastward to parallel the Brooks Range in southern NPRA. Sediment dispersal patterns and accommodation may influence the size and distribution of potential stratigraphic traps in turbidite facies along these shelf margins. For example, deposition in distal parts of the sediment dispersal system combined with low accommodation may favor the occurrence of point-sourced, isolated lenses of turbidite facies in northern NPRA. In contrast, deposition in proximal parts of the sediment dispersal system combined with high accommodation may favor the occurrence of line-sourced, laterally coalescing aprons of turbidite facies in southern NPRA.

Print

Sequence and Seismic Stratigraphy of the Bossier Formation (Tithonian; Uppermost Jurassic), Western East Texas Basin

Klein, George D.
SED-STRAT Geoscience Consultants, Inc.
14019 SW Frwy.; Suite 301, PMB 335
Sugar Land, Texas, 77478-3563
e-mail: gdkgeo@concentric.net

Chaivre, Kenneth R.
Phillips Petroleum Co.
North American Production
6330 West Loop South
Bellaire, Texas, 77401
e-mail: krchaiv@ppco.com

Abstract

Sequence and seismic stratigraphic analysis of well logs and 2-D seismic lines from Freestone, Anderson, Leon, Houston, Madison, Robertson and Limestone Counties, Texas, demonstrates that the Bossier Formation of the western East Texas basin can be subdivided into two recognizable sequences separated by a major sequence boundary (SB-2). Similarly, the Bossier Formation is also bracketed by a basal (SB-1) and upper (SB-3) sequence boundary separating it from the Gilmer (Cotton Valley) Lime of the Haynesville Formation below, and the Cotton Valley Sand above, respectively.

In seismic sections, the SB-2 boundary in the middle of the Bossier Formation was identified by tracing mounded basal reflectors and sigmoid basal reflectors representing basin floor and slope fans. This boundary was correlated onto the shelf below deltaic sands. In well log sections, basin floor fan log shapes were traced laterally into slope fan and stacked delta log patterns to identify SB-2. These basin floor and slope fans immediately above the SB-2 boundary represent a lowstand systems tract, whereas the lower Bossier (below the SB-2 Sequence Boundary) represents a transgressive systems tract and the upper Bossier (above the SB-2 boundary) represents a prograding complex.

Burial history analysis suggests that the lower Bossier accumulated during a time of rapid mechanical subsidence when the East Texas basin was underfilled. A drop in sea level associated with the SB-2 boundary represents a major climate shift from tropical to cooler conditions, favoring rapid influx of sands from the ancestral Mississippi, Ouachita, and Red River systems. These sands developed inner shelf prograding deltaic packages, outer shelf and incised valley fill stacked deltas, and basin submarine fan systems. The stacked deltas and basin fan sand systems all represent prospective gas plays.

Print

Continental Shelf Sand Ridges: Genesis, Stratigraphy and Petroleum Significance

Nummedal, Dag
Institute for Energy Research, Department of Geology and Geophysics
University of Wyoming
Laramie, Wyoming 82071-4068

Suter, John R.
ConocoPhillips
P.O. Box 2189
Houston, Texas 77252-2197

Abstract

The debate about the origin of sand ridges on modern continental shelves that took place in the 70s and early 80s is now repeating itself with respect to ancient 'isolated shallow marine' sand bodies. A review of the multiple interpretations of one such controversial sand body, the Upper Cretaceous Shannon Sandstone of Wyoming, conducted by Suter and Clifton in 1999, concludes: "we cannot, as a result of our analysis, unequivocally disprove any of the interpretations proposed for the Shannon, and we suspect that a collective inability to do so [...] is the fuel on which this controversy runs."

A 'paradigm shift' is needed in shelf sand ridge studies at this time, and it is this: shelf sand ridges are composite features. The debate needs to move beyond arguing about the implications of seemingly contradictory implications of the sedimentary structures, to one where the sedimentology is constrained by precise stratigraphic architecture. Numerous studies of modern ridge fields demonstrate that they commonly are separated from their substrate by a ravinement surface, or by a marine erosion surface formed in swales between migrating ridges. It is also clear that that many shelf sand ridges contains cores, or 'precursors' of shoreline deposits, the preservation of which is a function of the amount of migration of the ridge after its initial formation at the shoreline.

Shelf sand ridges are potentially major hydrocarbon reservoirs. The cumulative oil production from the Tocito Sandstone fields in the San Juan basin is about 160 MMBO; that from Shannon strata in the Powder River basin is even greater. Hartzog Draw, which is dominantly a Shannon field, has an estimated 400 MMBO in place. Several Middle and Upper Miocene oil fields on the northwest Java shelf also are producing from reservoirs interpreted as shelf sand ridges.

Controversy about outcropping shelf sand ridges will probably continue for some time, because only small parts of the commonly composite ridges are available for examination.

Print

Amplitude Anomalies in a Sequence Stratigraphic Framework: Exploration Successes and Pitfalls in a Subgorge Play, Sacramento Basin, California

May, Jeffrey A.
EOG Resources, Inc. (formerly at DDD Energy, Inc.)
600 17th Street, Suite 1100N
Denver, Colorado 80120

Przywara, Mark S.
DDD Energy, Inc.
50 Briar Hollow Lane, 7th Floor West
Houston, Texas 77027

Mazza, Thomas A.
Deceased (formerly at DDD Energy, Inc.)

Clark, Ruble
Yuma Exploration & Production Co. (formerly at DDD Energy, Inc.)
1177 West Loop South, Suite 1825
Houston, Texas 77027

Dlouhy, John
Hettenhausen, Roger
OXY U.S.A., Inc.
P.O. Box 1002
Tupman, California 93276-1002

Abstract

The Sacramento Basin is part of the Great Valley, a prolific hydrocarbon province that is the remnant of a Late Mesozoic-Early Cenozoic forearc basin in California. A series of buried submarine canyons extend seaward from the eastern margin of the forearc. These “gorges” have formed during multiple episodes of relative sea-level fall during the Tertiary, truncating Late Cretaceous through Eocene marine and nonmarine sandstones. Mudstones dominate the canyon fill, creating lateral and top seals for numerous gas reservoirs.

The late Paleocene Meganos Gorge crosses a proprietary three-dimensional (3-D) seismic survey where DDD Energy and OXY U.S.A. jointly have drilled numerous gas discoveries. Five discoveries occur in fluvial-deltaic sandstones of the Maestrichtian Mokelumne River Formation from traps beneath the Meganos Gorge, a configuration with which we have had 100% success. The key to this success is understanding the associated amplitude anomalies within their sequence stratigraphic and lithologic context.

Initially, we (1) identified all amplitude anomalies, (2) mapped the base Meganos Gorge sequence boundary, and (3) mapped regional flooding surfaces within the highstand Mokelumne River section, paying particular attention to truncations beneath the sequence boundary. Two gas fields in the area are analogs for subcrop production from the Mokelumne River: McDonald Island Field (now used for gas storage), which has an estimated ultimate recovery (EUR) of ~184 billion cubic feet (bcf) of gas, and King Island Field, which has a EUR of ~11 bcf.

We next conducted amplitude-versus-offset (AVO) analyses for all lithologies that yield anomalously high amplitude signatures. We built a database for lignites, low-velocity mudstones, carbonate-cemented sandstones, and conglomerates, in addition to gas-charged sandstones. Finally, we risked our subgorge prospects based on AVO response, structural position relative to the canyon-base sequence boundary, and juxtaposition of lithologies across the sequence boundary. The analytical steps used here can be applied to the continued discovery of subcrop reservoirs associated with other gorges in the Sacramento Basin, as well as the search for hydrocarbons trapped beneath submarine canyons in deep-water basins worldwide.

Print

Regional Facies Relationships and Sequence Stratigraphy of a Super-Giant Reservoir (Arab-D Member), Saudi Arabia

Handford, C. Robertson
Strata-Search, LLC
10744 Chestnut Ridge Road
Austin, Texas 78726
e-mail: handford@strata-search.com

Cantrell, Dave L.
Geological Research and Development Center
Saudi Aramco
Dhahran 31311, Saudi Arabia

Keith, Thomas H.
Southern Fields Characterization Department
Saudi Aramco
Dhahran 31311, Saudi Arabia

Abstract

The Late Jurassic (Kimmeridgian) Arab-D member consists of complex facies associations and clinoform units that make up the intrashelf Arabian basin and associated platform. A ramp borders the Arabian basin and extended >300 km from Abu Safah and Berri fields (offshore) in the north to the interior of Saudi Arabia. This basin encloses the largest field in the world (Ghawar) as well as several other supergiant fields (Qatif, Abqaiq and Khurais) fields, all of which produce from the Arab-D member.

From bottom to top, the Arab-D member consists of predominantly mud/intraclast-, organic-, and grain-dominated facies associations, which generally record an overall shallowing upward history and a long-term base-level fall. However, we recognize numerous high-frequency sequences on the basis of facies stacking patterns and regional correlations. Lime mudstones, which are common in the lower Arab-D, represent a sub-wave base (~100 ft), outer ramp setting. Interbedded intraclastic and oncolitic rudstones represent storm-dominated tidal channel and algal bank environments. Thick, amalgamated rudstones record base-level fall and storm-wave erosion of the firmground substrates. The upper Arab-D reservoir mainly consists of open-marine low-relief biohermal and biostromal limestones succeeded by skeletal/peloidal and oolitic grainstones. Coral-stromatoroid facies have accumulated as sheets and local buildups (10-20 ft of relief) during a major base-level rise that culminated with a bank margin centered in Abqaiq and northern Ghawar fields.

These organic-rich facies were laid down as backstepping, northward thickening buildups. Subsequent base-level fall led to the deposition of several seaward stepping (southward), skeletal, peloid, and ooid grain shoal complexes, which have shingled or clinoform geometry. The youngest clinoforms stepped southward as base level fell and were followed by lowstand to transgressive, onlapping anhydrite units that formed in a subqueous to desiccated salina, which extended across the remnant Arabian basin and provide a regional seal.

Facies and Sequence Stratigraphy of the Abo Formation in the Kingdom Field Area, Terry and Hockley Counties, West Texas

Print

D'Agostino, Anthony E.
PGS Reservoir Consultants Inc.
16010 Barkers Point Lane, Suite 550
Houston, Texas 77079
e-mail: tony.dagostino@pgs.com

Party, J. Michael
Wagner & Brown, Ltd.
P.O. Box 1714
Midland, Texas 79702
e-mail: mparty@wbltd.com

Abstract

Study of conventional cores, well logs, and seismic data in the Kingdom Field and other parts of the Abo shelf complex trend in eastern New Mexico and west Texas has led to new concepts about the style of deposition and techniques for stratigraphic subdivision of the Leonardian Abo Formation. The implications of paleogeographic restoration of the Abo shelf, combined with detailed description and interpretation of conventional cores from nine wells in Kingdom Field has resulted in the identification of four important depositional facies that have significant control on reservoir character. The facies are; **Supratidal/Terrestrial** (up-dip and top seal), **Intertidal** (reservoir grainstones), **Platform Interior** (reservoir barrier), and **Shelf-edge** (secondary reservoir). A fifth facies, **Karst Breccia**, is also defined. This study reveals that the most productive facies in Kingdom Field (and along the trend) is the intertidal facies (peloid grainstones) not the shelf-edge facies (boundstone reef). High-resolution stratigraphic analysis combining Fischer plots, well-log cross-sections, and 3D seismic data shows that at least three third-order sequence boundaries, associated with exposure of the shelf and significant karsting, are intraformational in nature.

Sequence Stratigraphic Framework in a Humid Alluvial Fan Complex, Quiriquire Oil Field, Venezuela

Print

Kong, Fanchen
Repsol YPF / Maxus Energy Corporation
1330 Lake Robbins Dr. #300
The Woodlands, Texas 77380
e-mail: fkongd@repsol-ypf.com

Jalfin, Guillermo

Lukito, Pujianto
Repsol YPF
Paseo de La Castellana 280
4ª Planta
28046 Madrid, Spain

Sarkawi, Ichsan
Repsol YPF / Maxus Energy Corporation
1330 Lake Robbins Dr. #300
The Woodlands, Texas 77380

Abstract

The giant Quiriquire Shallow oil field is located in the southeastern foothills of the Serrania del Interior in northeastern Venezuela. The main reservoir interval, the Quiriquire Formation, consists of conglomerates and sandstones deposited during 2.4-0.9 Ma in a humid alluvial fan complex inter-fingered with axial fluvial systems. Sequence stratigraphic concepts are applied to interpret 3D seismic volume to establish an accurate tectono-stratigraphic depositional model for facies prediction. Sequence boundary recognition criteria are explored for humid alluvial fans.

Five regionally extensive erosional unconformities are recognized as sequence boundaries. Maximum fluvial flooding surfaces and correlatives are recognizable as continuous high amplitude reflectors with overlying wide troughs. Each sequence may have rising base level, high base level, and falling base level systems tracts. At least five levels of cyclicity are interpreted. The three higher levels are controlled by intermittent tectonic events of hill uplift and basin subsidence from southeast contraction in a clockwise wrench-fault setting. Episodic growth strata, stratal truncations, and linear shale diapirs are associated with these tectonic events. Smaller cycles appear associated with sediment supply and climatic changes or autocyclic processes.

Analyses of seismic reflection facies, trace shape facies, and various attributes reveal a general basinward decrease of conglomerates and sandstones and an increase of shales. Alluvial-fluvial evolution shows a general northward fluvial onlapping trend and two major alluvial fan progradations, in which conglomerates and conglomeratic sandstones prograde farther basinward. Analyzing and imaging alluvial and fluvial internal architectural complexity and vertical/lateral alluvial-fluvial boundaries plays a critical role in our detailed reservoir correlation and characterization.

Print

Application of Sequence Stratigraphy in Production Geology and 3-D Reservoir Modeling

Howell, John
STRAT Group
Department of Earth Sciences
University of Liverpool
4 Brownlow Street
Liverpool L69 3GP, U.K.

Present address:
Geologisk Institutt
Universitetet i Bergen
Allegaten 4, N-5007
Bergen, Norway
e-mail: john.howell@geol.uib.no

Flint, Stephen
STRAT Group
Department of Earth Sciences
University of Liverpool
4 Brownlow Street
Liverpool L69 3GP, U.K.

Abstract

Sequence stratigraphy provides a deterministic framework for understanding facies and ultimately reservoir architecture. It provides a framework for building reservoir models based upon logical, testable geological principles. This framework allows prediction of connectivity of flow units, distribution of major permeability barriers and systematic changes in sand body architecture. Zonation of reservoir models into genetically related packages of strata (such as parasequences or systems tracts) allows zones to be populated with predictable facies trends. These facies then form the basis for the distribution of petrophysical parameters within the reservoir. Sequence stratigraphy also provides a reality check for stochastic models.

Print

Examples of Fluvial Stratigraphy in the Wilcox Group, Louisiana as Revealed by High-Resolution 3D Seismic Data

Phelps, Jeanne S. F.
Pennant Exploration, L.L.C.
1520 Eighth St.
New Orleans, Louisiana 70115
e-mail: pgeoserv@bellsouth.net

Jee, Jonathan L., Ph.D., P.G.
850 Wilkinson Trace, No. 183
Bowling Green, Kentucky 42103

Fogarty, Michael A.
Pennant Exploration, L.L.C.
1520 Eighth St.
New Orleans, Louisiana 70115

Phelps, R. David
Phelps Geoscience Services
5803 Canal Blvd.
New Orleans, Louisiana 70124

Abstract

Historically, both 2D and 3D seismic data have proven of limited value in petroleum exploration in the Wilcox Group (Paleocene-Eocene) of central Louisiana. Modern, conventionally processed 3D seismic data are useful for general sequence stratigraphic interpretation (*e.g.*, delineation of sequence boundaries) but do not have the vertical and horizontal resolution required to image the details of fluvial-deltaic stratigraphic features used to identify subtle hydrocarbon traps. Our processing of existing 3D seismic data, using propriety software algorithms, sufficiently enhanced the seismic data resolution to make it an effective tool for petroleum exploration in fluvial-deltaic strata.

The processed seismic data have been calibrated with geological information and synthesized with previous stratigraphic interpretations of the Wilcox Group in the region. The high-resolution seismic data make recognizable subtle hydrocarbon trapping situations that result from sand pinchouts and differential compaction. When integrated with the subsurface data, it is possible to create a more detailed stratigraphic framework for use in a hydrocarbon exploration program.

Print

Sequence Stratigraphic Framework for Prediction of Shallow Water Flow in the Greater Mars-Ursa Area, Mississippi Canyon Area, Gulf of Mexico Continental Slope

Winker, Charles D.
Shipp, R. Craig
Shell International EP
P.O. Box 481
Houston, Texas 77001

Abstract

Shallow water flows (SWF) occur when a well is drilled underbalanced into near-surface, overpressured sands. SWF has been one of the most problematic aspects of deep-water drilling operations in the Gulf of Mexico, causing premature abandonment of many wells and expensive delays in many others; total costs to the industry have been estimated at hundreds of million dollars. In recent years, engineering solutions have been largely successful in preventing or managing SWF; nevertheless, it is still vital to predict both the depth of occurrence and degree of overpressure in near-surface sands. Seismic signatures of these sands range from ambiguous to invisible, and pressure prediction methods from seismic moveout velocities are inconsistent. Therefore, the most practical prediction methods are based on geologic and engineering data from previous wells and boreholes (>50 surface locations in southwestern Mississippi Canyon alone), including LWD logs, direct and indirect overpressure indicators, and drilling summaries. To make lateral predictions from these well data, a local sequence stratigraphic framework has been established, which utilizes overlapping conventional and high-resolution 3D seismic surveys tied to a regional framework based on 2D and 3D seismic data.

Occurrences of near-surface sands and their potential for overpressure on the Gulf of Mexico continental slope are intimately related to late Pleistocene sequence stratigraphy of the Mississippi delta and fan. This is best illustrated in the Greater Mars-Ursa Area (GMUA) and vicinity, site of the industry's greatest SWF-related losses. The base of the main trouble zone in the GMUA is defined by a subregional sequence boundary (SB) (~*Globorotalia flexuosa*, P1), typically marked by a "soft shale" and in many minibasins (but not in GMUA)) by an onlap surface. Interpretation of the post-SB stratigraphy is complicated by numerous mass-transport complexes (MTCs) of diverse origin and by abundant gas-related amplitude anomalies.

Overlying the P1 SB is a basin-floor fan (BFF) system, informally known as the MC Blue Unit, ponded on the slope by subtle antecedent topography. This BFF is apparently contemporaneous with the last lowstand delta complex of the Mississippi (Stage 2 and possibly 4); the equivalent unit has not been identified on the Mississippi fan. The BFF is characterized by abundant, but highly discontinuous sands, typically in vertically separate pressure compartments. On high-resolution data, the seismic character consists of both layered, subparallel, high-amplitude facies containing small channels and chaotic, high-amplitude facies produced by local MTCs; at least four MTCs within the BFF have been identified at the Ursa field alone.

The BFF, composed of the MC Blue Unit, is overlain by a slope fan (SF) complex comprising a succession of four canyon-channel-levee systems (named Ursa, Southwest Pass, Old Timbalier, Young Timbalier), numerous mud-rich MTCs, and hemipelagic mud. Some of these canyon systems can be traced from incised valleys of the Mississippi River on the continental shelf to fan channels on the Mississippi fan. Channel sands (massive to thick-bedded) and levee sands (thin-bedded) of the Ursa Canyon and Southwest Pass Canyon (SWPC) have been penetrated in several locations. The SF-BFF boundary is obscured over much of GMUA, partly by channel incision, but more importantly by paired, channel-margin slides, which are most extensively developed subjacent to SWPC. The SWPC channel-margin slides comprise a 2-5 mile wide belt of rotated slide blocks dipping away from the channel axis. The P1 SB typically serves as the detachment surface for the SWPC slide complex; this detachment level is several hundred feet deeper than the channel thalweg. The geometry of these slide complexes clearly indicates that they were triggered by channel incision. Similar slide complexes occur on the Mississippi fan, where they have previously been misinterpreted as MTCs predating their corresponding fan channels.

Print

Multiple Fields within the Sequence Stratigraphic Framework of the Greater Auger Basin, Gulf of Mexico

Dean, Michael C.
Shell Exploration and Production Company
P.O. Box 61933
New Orleans, Louisiana 70161

Booth, James R.
Brunei Shell Petroleum Company
Seria, KB3534
Brunei Darussalam

Mitchell, Bruce T.
Shell Exploration and Production Company
Houston, Texas 77001-0576

Abstract

The greater Auger basin lies approximately 220 miles south southwest of New Orleans, Louisiana in the deep water Gulf of Mexico. Multiple exploration and development wells from five Shell producing fields in the greater Auger basin have provided sequence stratigraphic information from several different basin settings and different seismic facies (*e.g.*, Prather *et al.*, 1998). Two of these, the proximal Auger Field and the distal Macaroni Field have been used by Booth *et al.* (2000) to classify the overall seismic–stratigraphic framework of the basin. Additional drilling has provided information from three other fields to tie into this framework. Shell's producing fields in the greater Auger basin are Auger, Cardamom, Macaroni, Oregano, and Serrano. Though these fields lie within the same basin-scale sequence stratigraphic framework, their depositional settings vary considerably. Presently, the Auger salt dome, East Auger fault, and North Auger fault partition the greater Auger bbasin into two sub-basins. At the time of deposition of many of the producing reservoirs, these structural features have manifested themselves in the form of the northwest-southeast trending Auger ridge. Macaroni, Oregano, and Auger fields lie south of these structural features, in the Auger basin proper and are primarily oil-bearing. Serrano and Cardamom lie northeast of these features in the Andros basin and are primarily gas bearing. The greater Auger basin is an excellent case study for variations in the deposition and preservation of reservoir quality sands in multiple basin settings. Although the mechanisms differ in different settings, productive sands can be found in proximal, distal, and lateral settings within the basin. In each setting, however, deposition is controlled both by sediment source and accommodation space. The reservoirs at Oregano Field are healed slope deposits most similar to those at Auger Field; Serrano reservoirs are locally ponded deposits similar to those at Macaroni Field; and Cardamom reservoirs appear to represent both healed slope and ponded deposits.

A Simple Methodology for Carbonate Sequence Stratigraphic and Seismic Stratigraphic Interpretation: Examples from the Lower Cretaceous Section in Offshore Alabama and Mississippi

Print

Badali`, Marcello
Department of Geological Sciences
University of Alabama
Box 870338
Tuscaloosa, Alabama 35487
e-mail: mbadali@wgs.geo.ua.edu

Abstract

Carbonate sequence stratigraphic analysis requires a different approach than siliciclastic sequence stratigraphic interpretation. This paper provides a simple methodology for recognizing and mapping third-order depositional sequences using a widely spaced dataset, integrating core data, well log information, and seismic data. The investigation of the Lower Cretaceous carbonate section in offshore Alabama and Mississippi is used as an example. A carbonate rimmed shelf margin, characterized by periodic siliciclastic sediment input, and the correlative slope, represent the Early Cretaceous geologic setting in this area.

This study incorporates various kinds of data at different scales. Approximately 3,500 kilometers of 2D multichannel seismic reflection data are interpreted and integrated with gamma ray, lithologic well-log descriptions, well-log lithostratigraphic picks from more than 50 wells, and 527 meters of core from wells in the study area and surrounding areas. Seven check-shot surveys have been used to integrate the seismic and well log data, and software for PC is used to integrate and interpret the various data sets.

The interpretation includes several steps. The seismic attributes are first characterized, and then the seismic data are interpreted without the support of the well-log and core data. Once the main seismic sequence boundaries and systems tracts are recognized, they are projected onto the well-log records. The core data are correlated with the well-log signatures. The final interpretation includes the integration of seismic, well-log, and core data in order to improve the preliminary interpretation and to perform a sequence stratigraphic and seismic stratigraphic analysis.

Squinting Through Leaded Glass: A Public Domain View of the Alpine Play in the National Petroleum Reserve in Alaska (NPRA)

Houseknecht, David W.
U.S. Geological Survey
12201 Sunrise Valley Drive, MS 956
Reston, Virginia 20192
e-mail: dhouse@usgs.gov

Abstract

The 1994 discovery of the Alpine oil field (>400 MMBO recoverable), a subsequent Federal lease sale in northeast NPRA, and the 2001 announcement of discoveries of commercial quantities of hydrocarbons in Alpine-type traps within NPRA have reinvigorated exploration interest in a formerly moribund part of the Alaska North Slope. Limited data available in the public domain suggest that key ingredients of Alpine-type accumulations include a high gravity oil charge apparently sourced from a condensed section in the Lower Jurassic and stratigraphic traps in the Upper Jurassic comprising a transgressive assemblage of lenticular, fine-grained, well winnowed shoreface sands deposited in erosional incisions and sealed by condensed mudstone.

Regional mapping of Jurassic depositional sequences using public domain, 2-D seismic and well data indicates excellent potential for extending the Alpine play westward in the NPRA. Although the Upper Jurassic play extends across the entire NPRA, the greatest potential may exist in eastern NPRA where a Lower Jurassic condensed section is present basinward (south) of a well defined shelf margin. Upper Jurassic depositional sequences offlap that shelf margin and include thick clinoforms that downlap onto the Lower Jurassic condensed section. Those clinoforms either toplap progradational shoreface sands or are truncated by sequence bounding unconformities or ravinements capped by transgressive systems tracts that locally contain Alpine-type stratigraphic traps. From the Colville delta, this prospective depocenter trends southwestward for more than 100 miles. However, play depths increase southwestward, thereby increasing the chances of reduced reservoir quality and increased proportions of thermogenic gas.

Elsewhere in NPRA the apparent absence of both the Lower Jurassic basinal condensed section and clear migration pathways within Upper Jurassic strata may indicate increased charge risk and lower resource potential.

Niger Delta Pleistocene Leveed-Channel Fans: Models for Offshore Reservoirs

Print

Mitchum, Robert M.
Consultant
13039 Pebblebrook
Houston, Texas 77079
e-mail: rmm@hic.net

Wach, Grant D.
ChevronTexaco
Houston, Texas
Current address: Dalhousie University
Department of Earth Sciences
Halifax, Nova Scotia, B3J 3E5

Abstract

The youngest Pleistocene leveed-channel fans of the Niger delta, offshore Nigeria, are defined by sea-bottom images and shallow reflection patterns in 2-D and 3-D seismic surveys. They make excellent analogues for interpreting older fans in the delta depocenter.

Niger delta structural trends control Pleistocene shelf, slope and basin depositional environments. The shelf margin is cut by canyons and gullies that are lowstand sediment paths to the basin. Upper slope areas, underlain by diapir and inner toe thrust structural trends, are zones of channel erosion and bypass. Lower slope areas, between the inner and outer thrust trends, contain leveed channels in local sags. They exhibit channel erosion and bypass in areas of active thrusts and tear faults.

The basin plain outboard of the outer thrust trend has major deposition of large leveed channel complexes. The central reentrant in the outer thrust trend is a major depocenter of leveed channels fed through a larger canyon. The area to the far northwest contains well-developed fans in the low area between the delta and the continental margin to the north.

A 3-D grid at the mouth of the large central canyon shows details of leveed channels deposited from the canyon. The first large sinuous channel was crevassed and abandoned by a smaller, straighter distributary near the canyon mouth. Slumping and mass transport are important elements, and are intimately involved in and adjacent to the channel systems.

The locations of fan complexes that comprise the deep-water depocenters appear directly related to the updip delta morphology and progradation of the fluvio-deltaic system.

Print

The Sequence Stratigraphy of the East China Sea: Where are the Incised Valleys?

Warren, Jeffrey D.
Department of Geological Sciences
University of North Carolina at Chapel Hill
Mitchell Hall, CB #3315
Chapel Hill, NC 27599-3315
e-mail: seismic@unc.edu

Bartek, Louis R., III
Department of Geological Sciences
University of North Carolina at Chapel Hill
Mitchell Hall, CB #3315
Chapel Hill, NC 27599-3315
e-mail: Bartek@email.unc.edu

Abstract

The lowstand systems tract from the last glacial maximum (*i.e.*, oxygen isotope stage 2; c. 14-24 ka) preserved on the East China Sea continental margin is the only lowstand systems tract during the Holocene and late Pleistocene (500 ka to present) that exhibits major incision. Evidence of these incised valleys is found in both present-day bathymetry and in seismic and chirp data. Older lowstand systems tracts, however, lack major incisive features on the inner and mid shelf and exhibit laterally and vertically extensive (up to 300 km and 60 m, respectively) packages of chaotic seismic reflections attributed to frequent fluvial avulsion. Incision in these older lowstand systems tracts, where it does occur, is primarily restricted to the outer shelf, however, it is not associated with knickpoint migration from the shelf-slope break, which remained submerged during even the lowest lowstands.

Oil Exploration Under the Catastrophist Paradigm

Wilson, James R.
Holbrook, Mark
Jones, Jim
Centre for Future Technologies, Inc.
722 S. Maurine
Idaho Falls, Idaho 83401
e-mail: wilson@srv.net

Abstract

The uniformitarian paradigm, a key assumption in the interpretation of the stratigraphic record, directs most of the oil exploration, making the history of discoveries a circular argument for this paradigm. However, a plot of giant oil field discoveries shows interesting, nonrandom patterns that are inexplicable under current theory. The catastrophist paradigm explains these patterns and yields interesting insights for discovering future oil deposits.

Ninety percent of the giant oil fields (proven oil>500 million bbl or gas>3 Tcf) and ninety percent of the Large Igneous Provinces (LIPs) are distributed along two great circles on the Earth. These great circles also intersect the original sites of the craters of the three largest meteorites to ever impact the Earth, suggesting that these patterns or groupings were caused by these meteorites.

Print

Ages of Maximum Flooding Surfaces and Revisions of Sequence Boundaries and Their Ages, Cenozoic to Triassic

Wornardt, Walter W. Jr.
MICRO-STRAT INC.
5755 Bonhomme, Suite 406
Houston, Texas 77036
713-977-2120
e-mail: msiw3@Micro-Strat.com
Web Site: www.Micro-Strat.com

Abstract

The key to recognizing the third and fourth order depositional sequences is the maximum flooding surface. An age designation of this surface is extremely important in seismic sequence stratigraphic analysis. Therefore, the purpose of this paper is to recognize and date the Cenozoic, Cretaceous, and Jurassic maximum flooding surfaces in Ma and to assign a specific numerical age and letter designation to each of these maximum flooding surfaces from the Jurassic to Recent. These numerical age designations are proposed as a standard of reference for these maximum flooding surfaces worldwide.

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