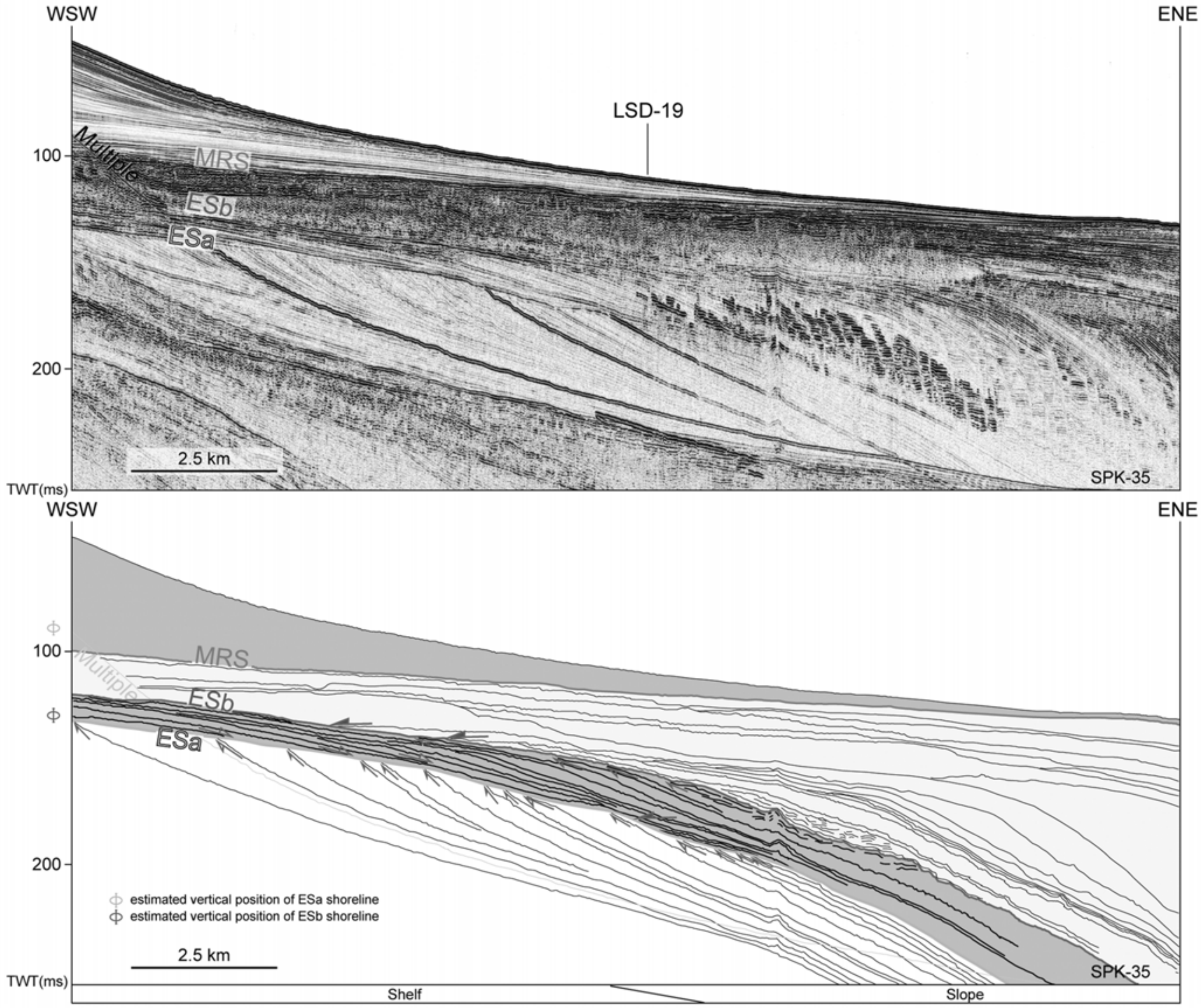

36th Annual GCSSEPM Foundation Perkins-Rosen Research Conference
December 4—5, 2017, Houston, Texas

Sequence Stratigraphy: The Future Defined

Editors: Bruce Hart, Norman C. Rosen, Dorene West, Anthony D'Agostino,
Carlo Messina, Michael Hoffman, and Richard Wild

Program and Abstracts

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Sequence Stratigraphy:
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Perkins-Rosen Research Conference

2017

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Foreword

This year marks the 40th anniversary of the birth of sequence stratigraphy. Although it has older roots, this branch of sedimentary geology really owes its existence to the publication of seminal papers by Peter Vail, Bob Mitchum, John Sangree, and Exxon co-workers in AAPG *Memoir 26—Seismic Stratigraphy: Applications to Hydrocarbon Exploration*. In the subsequent four decades, the methods, concepts, and results of sequence stratigraphic analyses have been accepted, adapted, amended, argued, applied and misapplied in both the petroleum industry and academia.

To mark the birth of this scientific revolution, GCSSEPM Officers and Trustees decided that the 2017 Perkins-Rosen Research Conference should be a look at the field of sequence stratigraphy. Although sequence stratigraphic analyses opened new exploration concepts, aided in the understanding of reservoir compartmentalization, and otherwise helped the hydrocarbon industry, today, and for many potential reasons, sequence stratigraphic concepts seem to be ignored or underemployed in many areas and companies. Do these analyses still add quantifiable value? If so, how? If not, why not? Sequence stratigraphy is probably grossly underexploited as a risk-reduction tool in today's low-price environment.

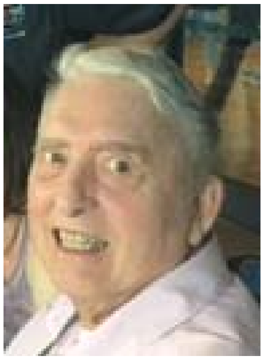
Largely due to its Houston location in the heart of the global petroleum industry, previous incarnations of this meeting have played a key role in the development of sequence stratigraphy and associated disciplines. For example, the 1987 meeting investigated biostratigraphic approaches to sequence analyses, the 1990 meeting examined sequence stratigraphy as exploration tool, shallow-marine and nonmarine sequence stratigraphy and reservoirs were the theme of the 1997 meeting, 2002's meeting looked at sequence stratigraphic models for exploration and development purposes. Other meetings have examined specific depositional systems or geographic regions and, in so doing, applying and testing sequence stratigraphic methods.

This year's Technical Committee solicited and received contributions from a wide spectrum of forward-looking contributors who examine siliciclastic, carbonate, mixed and fine-grained depositional systems in a range of fundamental and applied papers. Like the papers, the presenters themselves represent a diverse suite of interests and backgrounds. Given the breadth of topics and the depth of our presenters, the 36th Annual GCSSEPM Foundation Perkins-Rosen Research Conference will probably become known as a key milestone in the development of sequence stratigraphy.

On behalf of my co-convenors Steve Bachtel and Richard Denne, I thank the technical program committee for their efforts to bring together such an incredible program. Committee members included (in alphabetical order) Jake Covault, Carlo Messina, Hilary Olson, Jory Pacht, Mike Pope, Toni Simo, John Suter, and Richard Wild. Marathon graciously offered their meeting space for this meeting. Gail Bergan prepared this volume and assisted with other aspects of making this meeting happen. Our parent organization, SEPM, now looks after meeting logistics (registration, etc.). GCSSEPM Executive Director Tony D'Agostino was involved in many aspects of the organization to make this meeting possible. Finally, Norm Rosen again demonstrated his selfless commitment to making this meeting happen through his guidance, prodding, editorial work, and other efforts. Thanks Norm.

Bruce Hart, Austin, October 2017

The Little Blue Book that Changed the World (or at least Seismic Interpretation)



Every once in a while, a paper or book is published that has an extraordinary effect on its scientific field. Darwin published on evolution; Einstein on relativity; Wegner on continental drift. In 1977, AAPG published *Memoir 26: Seismic Stratigraphy—Applications to Hydrocarbon Exploration*. This memoir contains many excellent papers on the subject; but like it or not, it is most famous for an eleven-part section under the general heading: **Seismic Stratigraphy and Global Changes of Sea Level**. The way geologists and geophysicists view and interpret seismic data have not been the same since.

The "Exxon Way" was made famous by a group of Exxon workers; probably the most notorious were Peter Vail, Robert Mitchum, Jr., and John Sangree (but they were not the only ones), who vociferously defended their methods and models against all comers. Although there were many contributors, Peter became the godfather of sequence stratigraphy. And I say "vociferously defended" because while there was general agreement on their method of interpreting data, their initial model was (still is?) relatively controversial. (It should be noted that perhaps the best known alternative model was presented by Bill Galloway.) No matter how one felt on the validity of either model, as a result of the ensuing discussion, there began a far greater interest in chronostratigraphic interpretation of how sediments were deposited that continues today. And that, of course, is why we are having this year's conference.

In 1990, we had our first conference on sequence stratigraphy; it was a sellout. We repeated the conference in June of 1991 and it also was a sellout. In 2002, we again discussed how sequence stratigraphy had changed and how it was being used. Fifteen years later, and 40 years after Memoir 26, we are having another conference on sequence stratigraphy. Has the subject or the questions changed since 1977? I suggest you purchase our 1990 CD and compare the differences in what was being written then and what we are discussing now and make up your own mind on how much remains the same and how much has been changed or added.

We are honored and pleased that Peter Vail is attending this conference. His influence on sequence stratigraphy cannot be overemphasized. In 2002, we selected Peter to be an honorary member. Robert Mitchum and John Sangree wrote a few words on his behalf and we repeat them here.

I must add also that another pioneer, Henry Posamentier, is attending the conference and presenting a paper. The presence of these two scientists will add greatly to our conference.

I thank Bruce Hart, Steve Bachtel, and Richard Denne for their hard and excellent work in soliciting the papers and posters for this year's conference.

Norman C. Rosen

Peter R. Vail, GCSSEPM Honorary Member, 2002

The selection of Peter R. Vail as an Honorary Member of the Gulf Coast Section SEPM is a testimony to his pioneering work in sequence stratigraphy and 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 to which we can all aspire.

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 in 1992-93 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
John B. Sangree

Sequence Stratigraphy:
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36th Annual Gulf Coast Section SEPM Foundation
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Program

Sunday, December 3

4:00–6:00 P.M. Registration and refreshments at the Sheraton Suites Houston, 2400 West Loop South.

Monday, December 4, Marathon Auditorium

7:00 A.M. **Continuous registration (coffee available)**
7:40 A.M. Welcome remarks, Tony D'Agostino (Executive Director, GCSSEPM Foundation)
7:45 A.M. Introduction to the Conference, Bruce Hart (Technical Committee Chairman)

Session 1. Sequence Stratigraphic Methods

Jory Pacht and Tony D'Agostino, Co-Chairs, and Peter Vail, Honorary Chair

Tuesday, December 5

7:00 A.M. **Continuous registration (coffee available)**

Session 3. Sequence Stratigraphy: Clastics (Continued)

John Suter and Jennifer Wadsworth, Co-Chairs

Session 4. Sequence Stratigraphy: Shales

Nick Harris and Thomas Demchuk, Co-Chairs

Session 5. Sequence Stratigraphy: Carbonates

Mike Pope and Laura Zahm, Co-Chairs

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Cover Image

The cover image chosen for this year's conference is from Pellegrini et al.: "Figure 2. Line drawing of sparker profile SPK-35 (along-strike orientation). Reflection terminations highlight the erosional surfaces ESa and ESb. The MRS (maximum regression surface) is atop the late-Pleistocene succession. The estimated vertical position of shoreline during ESa and ESb formation is also reported."

How Realistic and How Predictive is My Sequence Stratigraphic Interpretation? Stratal Control Volumes, Area, and Trajectories as a Tool to Test Sequence Stratigraphic Interpretations

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Abstract

It is important to test if a sequence stratigraphic interpretation is realistic. This is particularly true if predictions of stratal geometries are then made on the basis of the interpretation, because clearly the predictive power depends largely on how realistic the interpretation is. Testing is also a basic element of a falsifiable model; a most basic aspect of the scientific method is that in order to be useful, all models and interpretation should be able to be tested and rejected if they fail that test. So how can we test the realism of otherwise of a sequence stratigraphic interpretation? One approach is to determine if rates of change in accommodation and supply controls implied by the interpretation are realistic.

Analysis of time series of controlling variables such as sediment supply, tectonic subsidence and uplift, and eustasy yields useful information on the range, variability and frequency of occurrence of these rates through time (Burgess and Steel, 2017). Analysing a combination of theoretical tectonic model time series of subsidence and uplift due to lithospheric extension, foreland basin orogenic flexural loading, and dynamic topography related to mantle flow, generates a first attempt at probability of occurrence through time of subsidence and uplift rates (Fig. 1A). A similar approach with a sediment supply history measured from ancient strata in the Gulf of Mexico and scaled to modern river mouth supply rates generates an equivalent probability density function (PDF) for sediment supply rates (Fig. 1B) and, finally, the same approach for eustatic variation from the last 100 My (Miller et al., 2005) generates a probability density function for rates of eustasy (Fig. 1C). These stratal control probability density functions can be used to populate a control volume or a control space which can then be analysed using trajectories defined from interpretation of outcrop of subsurface strata.

Stratal control volumes are sets of points in a three-dimensional volume, in which the axes of subsidence, sediment supply, and eustatic rates of change are populated with the probabilities derived from analysis of subsidence, supply and eustasy time-series (Fig. 2). These empirical probabilities indicate the likelihood of occurrence of any particular combination of control rates, defined by any point in the stratal control volume. A stratal control trajectory is a history of supply and accommodation creation rates, interpreted from outcrop or subsurface data, or observed in analogue and numerical experiments, and plotted as a series of linked points forming a trajectory through the stratal control volume (Fig. 2) or area. Stratal control trajectories can form a key test of sequence stratigraphic interpretations. If they pass through areas of the control space with relatively high probabilities, this suggests the implied control rates are more realistic than if the trajectory plots in areas of the space with lower probability (Fig. 3). For outcrop and subsurface analysis, using a two-dimensional stratal control area in which eustasy and subsidence are combined on a relative sea-level axis (Fig. 4) allows similar analysis to the 3D example, and may be preferable.

Much work remains to be done to build a properly representative database of stratal control rates of change and time-series but hopefully these new methods of plotting control rate probabilities in stratal control volumes and areas could encourage this effort. Analysis of stratal control trajectories in stratal control volumes and areas could be an important way to test sequence stratigraphic interpretations and models and better understand the nature and extent of their predictive power. Analysis of stratal control volumes, areas

and trajectories constructed from outcrop, subsurface analysis, and experimental model analysis may also develop significant new understanding through comparison and integration of examples from these different methods of analysis.

Development of Predictive Stratigraphy—Sequences, Source-to-Sink, and Back to Seismic

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Abstract

Predictive stratigraphy developed in the 1950s and 60s through the breakthrough work of Larry Sloss and Harry Wheeler. The major change from previous work was an understanding of time stratigraphy and major breaks in stratigraphic sequences. With the advent of new technology, such as high-resolution logging, coring, seismic, and remote sensing, succeeding decades were dominated by drastic progress of new methods and geological understanding, namely facies analysis and seismic and sequence stratigraphy. Offshore exploration required predictive methods to be developed because wells in these basins had very high costs in contrast to onshore basins and were technically very challenging to drill, so that offshore basins and plays were best investigated using "remote" methods.

Seismic and sequence stratigraphy are extremely powerful techniques for understanding the fill of sedimentary basins but have been incorporated to a lesser degree in onshore sediment source areas. A common theme for breakthroughs in geology has been the development of new technology. Many new concepts have developed in the wake of new geophysical methods.

Remote sensing technology using satellites came into the public domain in the 1990s after the large military campaigns during the 1980s. This was a quantum leap in the ability to retrieve quantitative geomorphic and topographic data efficiently from onshore regions. While classic geomorphological techniques had been in use for decades, they were largely analog and constrained to analysis of topographic maps. Digital onshore data allowed for breakthrough analysis of onshore geomorphology, drainage, bedrock, and water and sediment flux to offshore basins.

The ability to combine the quantitative onshore data with offshore data (such as seismic) allowed for a new predictive methodology to develop based on semi-quantitative and integrated analysis of entire, linked onshore and offshore systems. The technique, termed source-to-sink, built on studies from the early 1980s regarding sediment flux to modern offshore basins. The early techniques, however, did not consider stratigraphy and had little predictive power. Various source-to-sink methods developed, both experimental computer-based modeling, and geomorphic-based, but initial methods were not tuned to be used in exploration due to using data and methods not suited and aligned to conventional exploration data. A simpler more morphological approach thus developed that allowed for predictive analysis based on onshore remote sensing data and conventional offshore seismic. Source-to-sink analysis complements sequence stratigraphy rather than replacing it. Detailed analysis of basin fill sequences based on seismic and well data requires sequence stratigraphic analysis, but this analysis is augmented by a wider view including the onshore sediment-generating area. A new development with source-to-sink analysis was the ability to use the methodology on outcrop data. This required the ability to measure, calculate, and/or interpret critical data from the outcrop sequences, such as slope lengths.

Extensive offshore exploration in some basins has allowed for almost basin-wide coverage of 3D seismic data. Merging these data sets lifts predictive stratigraphy and source-to-sink to a new level. It is now possible to visualize entire source-to-sink systems, also including antecedent onshore drainage systems as well as their offshore complementary sequences. Increased efficiency and precision in subsurface and seismic interpretation allow for incisive perspectives on quantitative aspects of these source-to-sink systems. Thus, new understanding of complete systems will likely develop as a response to these extremely extensive seismic data sets where "everything" can be seen.

Accommodation Succession (δA/δS) Sequence Stratigraphy: Observational Method, Utility and Insights into Sequence Boundary Formation

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Abstract

Sequence stratigraphy is a method to systematically place key stratal observations into a chronostratigraphic framework for more accurate predictions away from control points. The depositional sequence is its basic unit, defined 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 surfaces" (Abreu et al., 2014 modified from Mitchum et. al., 1977a), which forms as a result of transgressions and regressions. Sequence stratigraphy is first and foremost a method that guides observations in the stratigraphic record across an array of depositional settings, stratal attributes, and data sets, explicitly recognizing that the stratigraphic record is comprised of both rocks and surfaces in various forms. These observations are then summarized in models that generalize details to facilitate prediction away from data control points. For completeness, sometimes the models are interpreted in terms of mechanisms (e.g., eustasy, climate, etc.) that may help explain observations and enhance prediction. The accommodation succession method of sequence stratigraphy (Neal and Abreu, 2009) assumes that these building blocks form in response to varying rates of coastal accommodation increase and decrease (δA) relative to the rate of sediment flux (δS).

The accommodation succession (δA/δS) method can be summarized in five steps:

1. Define lithofacies and vertical lithofacies successions to identify vertical stacking trends and stratal terminations
2. Use vertical stacking patterns, stratal terminal patterns, and shoreline trajectory to define surfaces: Sequence Boundary, Maximum Regressive Surface (Transgressive Surface), and Maximum Transgressive Surface (Maximum Flooding Surface);
3. Use surfaces and stratal geometries together with stacking patterns to identify systems tracts;
4. Use surfaces and systems tracts to define depositional sequences;
5. Use sequence stacking to define sequence sets and stratigraphic hierarchy for play element prediction.

A complete depositional sequence (Fig. 1) can be described using 3 types of stratal termination, 3 types of vertical/lateral shoreline trajectories, and 3 key bounding surfaces. Stratal terminations occur where sedimentary layers end onto an underlying surface (baselap) or under an overlying surface (toplap) (Mitchum et al., 1977b). The ability to differentiate the significance of stratal terminations can tell a great deal about the accommodation/sediment supply history of a margin.

Stratal terminations indicate missing or condensed time in the rock record and represent the evolving depositional substrate. Coastal onlap (horizontal coastal strata terminating onto an inclined exposure surface) is important to distinguish from subaqueous relative onlap or downlap (inclined strata onto a less dipping surface) in that coastal onlap represents the updip extent of strata within a depositional sequence. The aggradation of horizontal clinoform topset beds requires that coastal onlap occurs updip (Fig. 1) even if progradation continues downdip due to excess sediment supply relative to accommodation creation rate. Downlap onto horizontal clinoform topset beds is also an indicator of increased accommodation, discussed further below. Top-discordant stratal terminations, toplap, and truncation occur along with sedimentary bypass and erosion (Mitchum et al., 1977b). Truncation can occur due to fluvial incision on a regional exposure surface or angular erosion of horizontally deposited beds that are tectonically deformed. Stratal terminations point to key surfaces and key sur-

faces mark changes in the observed vertical/lateral stratal stacking.

Application of the δA/δS method in coastal siliciclastic systems is a straightforward way to build observation-based frameworks that enable interpretation debate from objective criteria. Knowledge of sea level changes is not required to make rigorous, logical, and predictive interpretations. One area where this is particularly critical is sequence boundary recognition and formation mechanisms. A sequence boundary is a surface that separates "relatively conformable, genetically related successions" from one another. It is the surface that initiates the predictive model of sequence stratigraphy, so its recognition carries great significance. Key to the statement above are the words "relatively conformable," highlighting the fact that depositional sequence recognition is dependent on data resolution but not sea level and that autogenic (facies) surfaces must be distinguished from more regional allogenic (sequence) ones. The examples discussed in this talk highlight the physical stratigraphic recognition criteria for a sequence boundary, which requires sufficient data resolution and regional perspective to identify and differs from the eustasy-focused branch of sequence stratigraphy (Abreu et al., 2014). Applying the δA/δS method across a range of data resolutions always in siliciclastic systems results in sequence boundary placement where shoreline stacking changes from degradation to progradation-aggradation regardless of inferred sea level. Critically, outside the mouth of the incised valley (Fig. 2), this surface is marked by an abrupt basinward shift in depositional facies and the onset of coastal onlap as coastal deposition renews atop the previously exposed unconformity surface (Sydow and Roberts, 1994), hence satisfying the original definition of a sequence boundary from Mitchum et al. (1977a).

Use of the δA/δS method can generate more varied but also more predictive hierarchal stratigraphic frameworks, influenced by inherited depositional profile and external controls on accommodation and sediment supply (Fig. 3). Systems tracts are characterized by their key bounding surfaces and stacking patterns, regardless of position on the shelf, on a ramp, or in the basin, provided the depositional setting is coastal and not deep marine. The recognition of significant stratal terminations points to key surfaces that bound packages having characteristic stacking patterns. Packages of characteristic stacking patterns predict what the succeeding stacking patterns, facies and facies association should be. Use of the δA/δS method can make stratigraphic interpretations objective, repeatable, and independent of confusing sea-level terminology.

The δA/δS method of sequence stratigraphy is a return to observation-based approach to constructing frameworks based on stratal terminations, key surfaces, and stacking patterns of stratal units that define systems tracts and depositional sequences. Analogously, at a larger scale within a hierarchal framework, observations of stacking trends of depositional sequences define sequence sets and composite sequences. Sequence stratigraphy is a powerful tool to construct an ordered stratigraphic framework that leads to testable predictions away from control points. When a robust framework is in place, mechanisms that control the character of that framework can be hypothesized. Mechanisms (e.g., eustasy, climate, etc.) and time duration (order by any definition) are not parts of sequence stratigraphy interpretations by the δA/δS method but the method produces frameworks that can be used to more reliably interpret causal mechanisms.

Carbonate Sequences as Complex Systems: Geochemically Influenced Sediment Supply Issues

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Abstract

Outcrop, core, log, and seismic data from carbonate sequences ranging in age from Proterozoic through Pleistocene have led to the understanding that the carbonate stratigraphic record is best understood as a complex system: i.e., any system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is nonlinear (not derivable from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures.” (www.informatics.indiana.edu/rocha/publications/complex/csm.html).

Stratigraphers typically work with a limited set of regime variables (sea level, subsidence, sediment supply, climate) in order to predict patterns of accumulation from seismic scale down to grain-size and pore networks, but typically wind up short. Deviations from what would be predicted using the already complex multivariate parameters above are the norm not the exception. Clearly a broader spectrum of inputs, short-lived and long-term, periodic, and chaotic is at play and demand consideration. Here I focus on three examples of geochemically influenced sediment supply patterns that fundamentally alter sequence architecture but that are not easily predicted from standard consideration of the A/S equation.

Permian mixed siliciclastic-carbonate sequences of the Permian Basin have served as a testing ground for carbonate sequence stratigraphy since the pioneering publications by Exxon in the mid 80s. RCRL began research in these outcrops in 1987 starting with San Andres ramps, Grayburg mixed siliciclastic-carbonate shelves, and more recently complexly faulted Capitan reef-rimmed profiles. A framework has been developed in the outcrop that captures much of the system and serves as an important guide for deciphering the Delaware and Midland basin patterns as well as the Northwest Shelf/Central Basin Platform record. Though A/S is a good high-level predictor of sequence development, facies substitution and evolution across ramp/rim transitions requires an understanding of basin geochemistry and slope stability at a range of scales. Ignoring these controls hampers prediction of such fundamental attributes as depositional profiles, reservoir facies distributions, and of reef morphology and evolution.

Greenhouse (Cretaceous/Jurassic) carbonate sequences of the Gulf of Mexico illustrate another challenge to standard A/S-driven patterns. Order-of-magnitude perturbations in carbonate factory rates are seen during oceanic anoxic events with their attendant decrease in oxygenation and potential ocean acidification. These drastic impacts on the carbonate factory cause shifts in accumulation patterns that are not simply linked to base-level. Because geochemical forcing varies significantly within a basin and between basins as driven by oceanographic effects, eustatic signals typically do not produce regionally mappable and predictable sequence frameworks.

In young highly constrained carbonate sequences of the mid-late Pleistocene the impact appears even more dramatic, as two to four times increases in depositional rates can be shown to occur within a 2-4 ky time scale. Such “explosions” of ooid facies as shown in the Caribbean are likely analogous to the “overshoots” tied to oceanic anoxic events like the Toarcian. Currently our more widely applied sequence models do not predict these complex system responses. These deviations should excite and challenge researchers dedicated to unraveling carbonate sequence stratigraphy. Rather than becoming passé or irrelevant, carbonate sequence stratigraphy is an essential first step in constraining known parameters, allowing focus to shift to critical but less well understood signals.

The Importance of Unconformities in Sequence Stratigraphy

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Introduction

Subdividing sedimentary successions by unconformities and their correlative conformities has revolutionized stratigraphy as it divided the strata into chronostratigraphic units containing genetically related facies successions rather than time-transgressive lithostratigraphic units. This makes sequence stratigraphy the only stratigraphic method having predictable capability for ages and facies. The age prediction is a consequence of the chronostratigraphic nature of sequence boundaries and seismic reflection horizons that allows one to populate a seismic grid with age information from one point of observation, such as a well or a section in outcrop well (Vail et al., 1977a). As a result, ages can faithfully be carried throughout the basin for the prediction of ages.

The prediction of facies is rooted in the recognition of genetically related strata and the shifts of the facies with changing sea level (Vail et al., 1977b; Posamentier et al. 1988; Sarg, 1988). As such, it captured the dynamics of the sedimentary system within the context of changing sea level. The concomitant facies that form during sea level fall and rise partition into lowstand, transgressive, and highstand systems tracts. This recognition of facies partitioning expands Walther's law from the prediction of lateral and vertical facies relationships to how facies belts move during changing relative sea levels. In addition, placing the facies within the geometries seen on seismic data helps in estimating the size of facies belts in the subsurface.

Because so much of the predictive capability for facies in sequence stratigraphy is related to the dynamics of the sedimentary system in regards to sea level change, only unconformities that are formed by a falling sea level were originally considered and defined as sequence boundaries. Yet, in carbonates, major unconformities form during rapid sea level rise when platforms drown (Schlager, 1999). Likewise, major unconformities form in drift sequences when ocean currents shift (Eberli et al., 2010; Lüdmann et al., 2013). The drift unconformities mark the turning points in current controlled sedimentary systems (Fig. 1). It remains to be shown how closely related these drift unconformities are to major sea level changes; however, because atmospheric circulation changes that are largely driven by climate changes are also responsible for sea-level changes, a causal and timely connection is likely to exist.

Admittedly, falling sea level is the main producer of unconformities on continental shelves but unconformities that separate genetically related successions are formed by various processes other than sea-level lowering. Drowning unconformities across submerged carbonate platforms fulfill the criteria of sequence boundaries; they are chronostratigraphic horizons that separate older from younger strata (Schlager, 1999). Also, in carbonates a change of the ecologic system can produce an unconformity when carbonate production is shifted to another level (Pomar, 2001). These latter unconformities are rather rare. In contrast, unconformities in deep-water drift deposits are wide spread and occur throughout Earth's history. Drift unconformities do not contain any evidence of subaerial exposure but otherwise also qualify as sequence boundaries. A sequence stratigraphic analysis of drift successions will separate the strata in genetically related sequences within a chronostratigraphic context.

Enhancing Sequence Stratigraphic Concepts Through the Integration of Seismic Stratigraphy and Seismic Geomorphology with Process Sedimentology—Positive Feedback Loops that Result in Improved Stratigraphic and Lithologic Predictions

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Abstract

Seismic stratigraphic and seismic geomorphologic observations can yield comprehensive sequence stratigraphic interpretations. When these interpretations incorporate process sedimentological inferences, more robust interpretations are produced. In practice, each informs the other, creating a strong positive feedback loop that results in a more comprehensive interpretation. Moreover, considerations of process sedimentology can lead to extension of interpretations both up-system and down-system of study areas. The end result will be enhanced regional lithologic prediction. Two examples are used to illustrate this work flow: deep-water channels and deep-water terminal fans. In the former, the architecture of channel fills implies an early erosional phase associated with relatively large flows, which commonly characterize early lowstand periods. This early erosional phase, having little to no preserved deposits due to repeated cannibalization, creates the "container" that will ultimately provide the accommodation for sedimentation. Subsequently, this sedimentation occurs during late lowstand, which is characterized by relatively smaller, less energetic flows that result in a net depositional phase. Considerations of process sedimentology shed light both on the genesis of deposits within the channel as well as what has occurred up-system where associated flows originated. In the case of deep-water terminal fans, the succession of depositional systems as documented by seismic stratigraphic and seismic geomorphologic data is interpreted through the lens of process sedimentology, resulting in enhanced understanding of the depositional sequence that is preserved and enhanced lithologic predictability. In this case as well, this integrated work flow results in predictions relevant to both up-system and down-system deposits.

How Close is Geological Thought to Reality? The Concept of Time as Revealed by the Sequence Stratigraphy of the Late Quaternary Record

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Abstract

The vastness of time is largely beyond human observation, but how aware are most geologists of the concept of time? Time spans of just a few thousands of years may become unfamiliar when moving from the modern, observable, and quantifiable, sedimentary processes acting on decadal to centennial time scales to the intricate series of depositional events discontinuously preserved in the rock record. Our experiential concept of geologic time built on the sequence stratigraphy of chronologically well-constrained, late Quaternary successions delineates a virtually unexplored hierarchy of hiatal surfaces (and condensed intervals) on 10^2 to 10^5-year time scales; i.e., below the chronologic resolution of most dating techniques commonly used to interpret the ancient stratigraphic record.

In continental-margin settings, the fourth-order, Late Pleistocene-Holocene depositional sequence is punctuated by sedimentary hiatuses, and highly episodic deposition appears to be the rule rather than the exception. Systems-tract and parasequence boundaries record long periods of non-deposition, erosion, and/or stratigraphic condensation, and as little as 20% of elapsed time is represented by preserved lithofacies assemblages. In the Po River basin, a significant stratigraphic break having a cumulative duration of up to 80 ky has been produced by the prolonged, stepped phase of eustatic fall and subsequent lowstand between about 120 ky and 20 ky BP. Fluvial channel-belt sand bodies developed during relatively short time periods (~10–15 ky). Early Holocene isolated transgressive sand bodies extend for tens of kilometers along dip, spanning intervals of time of just a few centuries. In coastal-plain successions in this system, up to 50% of geologic time is in the interval just below parasequence boundaries, during formation of relatively condensed peat-bearing intervals. Finally, progradational sets of highstand deltaic parasequences, up to 30-m thick, can make up to 95% of the total volume of Holocene deposits, but embrace just 10% of elapsed time.

Intervals of older fluvial and shallow-marine strata having sizes and architectures similar to the Po River system, which are chronologically constrained at much lower resolutions, tend to be interpreted to have developed on larger temporal scales. In these cases, severe distortions can be generated by the over-generalized assumption that sediment packages between regional unconformities represent *relatively continuous successions of strata*. This assumption will result in a bias towards estimates of sedimentation rates, event frequencies or durations, and sediment fluxes that can be incorrect by orders of magnitude. In addition, stratal successions bounded by surfaces of chronostrati-

graphic significance may not be as closely genetically related as commonly supposed. Appreciating the highly fragmented nature of the sedimentary record can fundamentally change the interpretation of hierarchical stacking of parasequences and the time scales of formation of ancient alluvial and deltaic depositional systems. We illustrate the impact of this appreciation by comparing the late Quaternary Po Plain basin stratigraphy against older strata of the Eocene Escanilla Formation and Cretaceous Blackhawk Formation strata.

It is generally accepted that geologic time can be largely unrepresented by rocks, although this concept has been poorly clarified and only roughly estimated. In this paper, we extend the uniformitarian principle that "the present is the key to the past" to encompass a broader vision in which, at least for certain periods in the Earth's history, "the recent past is the key to the deep past."

Eustatic Driver and Stratigraphic Response in an Ancient Continent Margin Turbidite System, Neoproterozoic Windermere Supergroup, Western Canada

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Abstract

Deep marine rocks of the Windermere Supergroup record a several km-thick sedimentary pile that accumulated along the passive continental margin of Neoproterozoic Laurentia (ancestral North America). The succession comprises mostly siliciclastic sedimentary rocks intercalated with carbonate and mixed carbonate-siliciclastic intervals that range up to a few 100 m in thickness. Observations along a several 100 km-long depositional transect that stretches from upper slope canyons to deep basin-floor deposits shows a number of systematic changes that appear to be principally controlled by changes of eustasy. Significantly, these changes are only recognized in the slope part of the transect.

Slope deposits form a ~2 km-thick succession dominated by thin-bedded turbidites that locally are intercalated with up to >100 m-thick by several km-wide erosional and leveed channel complexes. Channels exhibit two end member kinds of fill: aggradational and laterally accreting. Aggradationally filled channels are flanked by well developed sandy levees compared to mud-rich levees in the case of laterally accreting channels. Unlike aggradationally filled channels and laterally accreting channels are associated with the input of carbonate sediment, typically in the form of carbonate-cemented sandstone and mudstone clasts. Additionally, evidence of mass wasting, evidenced by thickly developed and areally extensive debrites, slump, and slide deposits, become an important component in the stratigraphy. Fragments within these strata, namely stromatolite and oolite fragments, in addition to abundant carbonate-cemented sandstone and mudstone clasts, indicates the resedimentation of debris sourced from an upslope shallow-water carbonate platform under late transgressive, highstand and possibly also early falling stage conditions. Specifically, the rise of eustasy is interpreted to have not only initiated the development of a carbonate platform, and thereby the input of carbonate sediment, but more importantly changed the make-up of the siliciclastic sediment supply, principally in terms of its grain size and grain-size distribution.

Integrated Carbon Isotope Sequence Stratigraphy for Clastic Successions

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Introduction

The linkage between cycles of relative sea level observed in sedimentary basins and their eustatic or tectonic drivers remains a fundamental problem of broad interest. The overarching issue is the lack of independent knowledge of the eustatic and tectonic components of the cyclic changes of sediment supply and relative sea level.

Variation of inorganic carbon isotopes in bulk carbonates have been proposed to provide an indirect proxy of global sea level (Jenkyns, 1996; Li et al., 2000) because they are considered resistant to diagenesis and other changes due to burial. The proxy model assumes that provided nutrient availability is not a limiting factor, as increased organic productivity on the shelf and its burial during global transgressions would result in a higher 13C/12C ratio expressed as a positive excursion (positive d13C excursion, (Jenkyns, 1996) due to the considerably lower 13C/12C ratio in organic matter compared to inorganic carbon. Conversely, during global sea level lowstands, reduced shelfal productivity and burial, combined with potential oxidation of organic-rich sediments (Higgins and Schrag, 2006) and enhanced influx of organic matter from the land to the slope and basin, would all decrease the 13C/12C ratio expressed as a negative excursion (Jenkyns, 1996).

Thus far, carbon isotopic studies have classically targeted pelagic sections within predominantly fine-grained carbonate rich lithologies and preferably away from the clastic influx from active continental margins (Woodruff and Savin, 1985, Arthur et al., 1987, Jenkyns, 1996, Zachos et al., 2001). A number of studies have also investigated shallower carbonate records but with the drawback of potentially frequent emergence and the possibility of an incomplete record (Buonocunto et al., 2002, Embry et al. 2010). Only a few studies have addressed predominantly clastic settings and explored the relationship between sequence stratigraphic patterns and carbon isotopes (Li et al., 2000, Castelltort et al., in review). However, the distal carbonate pelagic record has limited physical relationship with the thick clastic stratigraphic sequences preserved on continental margins that have constituted an important base of observation for building sequence stratigraphic concepts and applications.

On the contrary, slope systems, at the transition between shallow shelves and deep-sea environments have generally been overlooked as recorders of past environmental signals because their gradient makes them prone to failure, bypass, and submarine erosion. Bypass zones, canyons, slope failures, and associated mass-transport complexes are localized features. Their impact on the slope record can be recognized and accounted for. However, slope systems represent an important proportion of the Earth's surface, remain below sea level during lowstands, and are dominated by hemipelagic processes (Stow and Mayall, 2000), providing a potentially continuous record of environmental changes of both the marine and continental influences.

The Stratigraphic Interpretation of Subaerial and Submarine Valleys

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Abstract

Understanding the origin and geometry of large-scale erosional surfaces in fluvial and channelized submarine depositional settings is critical for interpreting reservoir architecture and connectivity, as these surfaces strongly influence reservoir heterogeneity. We use simple and fast-running forward stratigraphic models to investigate the geometry and the relative age of complex erosional surfaces that form in both the subaerial and submarine domain.

Because low-sinuosity systems tend to have relatively simple incisional and aggradational geometries, we focus on high-sinuosity systems. Fluvial deposits are commonly preserved on terraces that form during incision, and the basal erosional surface is highly time transgressive. Terraces can form without any external influence as a result of cessation of incision at channel cutoff locations. Similar processes and geometries can be observed in systems containing incising submarine channels. However, extensive deposition of fine-grained sediment in the overbank area of submarine channels tends to result in draping and long-term preservation of terrace geometries.

This is in contrast with fluvial systems, as the incisional terrace morphology can be quickly buried after valley filling initiates. Once incision ceases and aggradation begins, erosional surfaces become less continuous and form an intricate network inside the larger and longitudinally more continuous valley surface. Depending on the rate of aggradation and local rate of lateral migration, the internal erosional surfaces can be similar in vertical extent to a single channel depth, or to multiple channel depths and one channel bend in plan view. Phases of low aggradation cause these scallop-shaped surfaces to connect in the downslope direction and form an extensive erosional surface, without any significant re-incision. As relatively fine-grained deposits (e.g., shale drapes, slides, and debris-flow deposits) are primarily distributed along geomorphic surfaces, differentiating time-transgressive erosional surfaces from geomorphic ones results in a better prediction of reservoir compartmentalization and fluid flow. Understanding the origin and geometry of valleys and their deposits informs the controls on the sequence stratigraphy of basin margins. That is, most erosional surfaces are time transgressive and some of them reflect the autogenic dynamics of valley formation, rather than external forcing.

Autogenic and Allogenic Controls on Deep-Water Sand Delivery: Insights from Numerical Stratigraphic Forward Modeling

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Abstract

Allogenic and autogenic processes interact to regulate sediment distribution in sedimentary basins. Depositional systems can respond in a complex manner to these processes, complicating interpretation of the controls on the stratigraphic record. Here we used published and constant eustatic curves in a stratigraphic forward model to examine the effects of sea-level variation on deep-water sand delivery on a passive continental margin. We found that: (1) models with constant sea level and those with eustatic fluctuations deliver similar volumes of sand to deep water; (2) both large and small eustatic variations result in similar magnitudes of fluctuations in deep-water sand delivery; and (3) deep-water sand delivery signals show similar periodicities for all models. These results suggest that the characteristics of the imposed eustatic curve may not have a significant impact on the total volume of sand delivered to deep water. We propose that the equilibrium state of the shelf-edge delta, where no net deposition or erosion occurs, could explain the similarity in deep-water sand volumes. We posit that such a state could be induced by the progradation of an initial shelf-edge delta that creates a slope which maximizes the efficiency of sediment delivery across the shelf. Because our models show that autogenic and allogenic processes can result in similar deep-water sand volumes, we conclude that other characteristics of sediment-routing systems, such as sediment supply, must exert strong controls on deep-water sand volume.

Primary External and Internal Controls on Wilcox Submarine Fan Deposition during the Late Paleocene to Early Eocene of Deep-Water Gulf of Mexico: Implications on Sequence Stratigraphic Concepts

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Abstract

Wilcox deposition from late Paleocene to early Eocene in age (60–52 Ma) recorded one of the largest and most laterally extensive periods of sand deposition within the Gulf of Mexico. The receiving basin extends seaward over 300 miles from its equivalent shelf margin and along strike approximately 450 miles, attaining thicknesses greater than 3000 feet. Based on previous research by Blum and others utilizing detrital zircons to reconstruct Cretaceous to Paleogene drainage systems, a rerouting of sediment flux occurred in going from Cretaceous to the Paleocene Wilcox, during which time the sediment drainage systems incorporate nearly the entire continental United States ranging from the Appalachians to the east and the Sierra Nevada's to the west. Massive amounts of sediment were transported through large river systems seaward into coastal fluvial-deltaic systems. These extensive deltaic systems provided the staging area for deposition into the "deeper-water" environments through a sediment pathway system differing in gradient and paleotopography than the younger Miocene to Plio-Pleistocene systems that industry commonly uses for comparison with respect to sediment distribution and architecture. Fluctuations in climate during the mid-Paleocene–early Eocene resulted in erratic high rates of erosion experienced in hinterland sediment sources and contributed to an unusually high sediment flux into the Gulf of Mexico Basin. Unique to the Wilcox submarine fan deposition is that it occurred during an ice-cap free world when greenhouse conditions dominated and was not the characteristic "low stand fan" we associate within our sequence stratigraphic concepts.

Within the deep-water Gulf of Mexico, the Wilcox interval is commonly greater than 3000 feet in stratigraphic thickness. The chronostratigraphic framework is typically subdivided into four depositional sequences referred to as Wilcox 1–4. The Wilcox 4 is the oldest and serves as a proxy for early paleotopography of the basin as the architecture observed during the onset of Wilcox 4 deposition appears to be influenced by a resetting of the paleotopography in response to the Cretaceous Chicxulub meteorite impact on the Yucatan Peninsula. The deep-water Wilcox chronostratigraphic model integrates foraminifera, calcareous nannofossils, chemostratigraphy, palynology, and siliceous microfossils, specifically radiolarians, to aid in age determination as well as duration of sequences.

Wilcox 2–4 sequences span approximately 60–54 Ma and are underlain by the Midway Shale to Cretaceous age sediments and continue upward through the end of the Paleocene to Eocene Thermal Maximum (PETM). The PETM separates the Lower Wilcox (Wilcox 2–4) from Upper Wilcox (Wilcox 1) and is a major global warming event that occurred around 55 Ma and lasted approximately 200,000 years, with observed changes in sediment style and architecture across this boundary, and is considered by many to be a proxy for today's climate change. Lower Wilcox intervals (2–4) commonly exhibit high net to gross and laterally extensive, weakly confined channelized distributive lobe architecture. Upper Wilcox 1 unit tends to be more variable across the basin possibly due to (1) sporadic sediment flux from the river systems and associated ephemeral nature of these deposits in response to the effects of high CO_2 levels and extremely warm climate, (2) basin gradients approaching regional equilibrium establishing more bypass of sediments further out into the basin, and (3) sediment flux variability due to changing drainage basin inputs from the updip large riverine systems.

Sequence Stratigraphy and Sea Level. A Marine Quaternary Perspective

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Abstract

Sequence stratigraphy arose as a paradigm in stratigraphy following the introduction of the seismic method and its integration with genetic concepts linking seismic attributes to sedimentary dynamics. In its early shape, the sequence stratigraphy model was essentially rooted on the assumption that sea level cycles, in the form of basin-scale events, controlled the origin of depositional sequences. This founding assumption was vital for any revised version of sequence stratigraphy willing to maintain the status of "paradigm" and required evidence for "sequential" arrangement of progradational–aggradational–retrogradational patterns primarily governed by relative sea level.

Marine Quaternary stratigraphy provides plain evidence of such basin-scale sea-level control, albeit resulting in sequence shape and overall architecture substantially different from those of the basic sequence stratigraphy model. These differences have been settled by conceiving Quaternary sequences as atypical cases, commonly estranged from the debate on model refining. A reversal of this approach may be insightful, since Quaternary successions can be referred to sea-level curves of known periodicity and amplitude, in contrast with the older stratigraphy from which the basic model was derived.

Quaternary sequences indicate that the predominance of sea level (over other environmental factors) in shaping sequences depends on the duration of the full cycle and composing phases, scaled to its amplitude. Therefore, different sequence architectures may not represent fundamentally different models but rather a different balance between the main parameters of cycle duration, sea-level amplitude, and sedimentation rates. Changes in this balance may shift between end-member scenarios, ranging from greatly sea level-dominated (as in the Quaternary) to supply-dominated (as in large delta environments of pre-Quaternary greenhouse periods). This interpretative key allows us to explore different contexts all within a comprehensive model in which the control of sea level can vary significantly yet still coherently with the prediction potential of the model.

Sequence Stratigraphy of the Bakken and Three Forks Formations, Williston Basin, USA

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Abstract

The Williston Basin Bakken petroleum system is a giant continuous hydrocarbon accumulation. The petroleum system consists of source beds in the upper and lower Bakken shales and reservoirs in the middle and upper Three Forks, the Pronghorn member of the Bakken, and the middle Bakken. The petroleum system is characterized generally by low-porosity and permeability reservoirs, organic-rich source rocks, and regional hydrocarbon charge. The USGS (2013) mean technologically recoverable resource estimates for the Bakken Petroleum System is 7.375 billion barrels oil, 6.7 TCF gas, and 527 million barrels of natural gas liquids (Gaswirth et al., 2013).

In the western US, relative sea level changes may be a combination of glaciation in the southern hemisphere, regional flexural tectonics related to the Antler orogeny, epeirogenic uplift, and/or localized structural movement (Cole et al., 2015). The controls are not fully or clearly differentiated in the rock record.

The Three Forks is a silty dolostone throughout much of its stratigraphic interval. The Three Forks ranges in thickness from less than 25 ft to over 250 ft in the mapped area. Thickness patterns are controlled by paleostructural features such as the Poplar dome and the Nesson, Antelope, and Cedar Creek anticlines. Thinning and/or truncation occurs over the crest of the highs and thickening of strata occurs on the flanks of the highs.

The Three Forks unconformably (?) overlies the Birdbear in the Williston Basin and in turn is unconformably overlain by the Bakken Formation. The Three Forks consists of one overall deepening upward third-order sequence consisting of continental sabkha dolostones and anhydrites at the base changing to supratidal dolostones in the middle part to intertidal dolostones and mudstones in the upper part. The unit is subdivided into six shallowing upward parasequences by various authors. For mapping purposes, a three subdivision scheme has been adopted for this paper (i.e., upper, middle, lower). Most of the development activity in the Three Forks targets the upper Three Forks.

The Bakken Formation in the Williston Basin consists of four members: a basal member (dolostone, limestone, and siltstone) recently named the Pronghorn; a lower organic-rich black shale; a middle member (silty dolostone or limestone to sandstone lithology); and an upper organic-rich shale member. The Bakken Formation ranges in thickness from a wedge edge to over 140 ft with the thickest area in the Bakken located in northwest North Dakota, east of the Nesson anticline.

The Bakken appears to be composed of one complete third order sequence and part of a second third order sequence. The basal Pronghorn to middle part of the Middle Bakken represents one complete sequence (lowstand to transgressive to highstand system tracts). The Pronghorn to Lower Bakken Shale represent lowstand to transgressive system tracts. The lower Middle Bakken (facies A-C) represents a highstand system tract (falling stage system tract in upper part). The upper Middle Bakken (facies D-F) through the Upper Bakken Shale represents part of another third order sequence (lowstand to transgressive system tract). The Middle Bakken has an oolitic, bioclastic, sandy middle facies (facies D) which represents a lowstand deposit. This is overlain by the upper Middle Bakken (facies E-F) and the Upper Bakken Shale which is a transgressive system tract. Part of the overlying Lodgepole represents the highstand part of the second sequence.

Sharp downlap surfaces are noted at the base of the Middle Bakken and the base of the Lodgepole. The downlap surfaces represent the transition from transgressive system tracts to highstand system tracts. Maximum flooding surfaces are found in the middle

and upper portions of the upper and lower Bakken shales.

Source to Sink Processes in the Indus River System

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Abstract

The Indus River drains the Western Himalayas and is supplying sediment to the second largest submarine fan in the world in the Arabian Sea. Sediment flux represents erosion in the mountains, driven by tectonic and climatic processes, yet these are buffered over several time scales, spanning millions of years in the foreland basin and shorter time scales due to storage in terraces and on floodplains. Further recycling and buffering of the erosional signal is possible because of interactions with the dunes of the Thar Desert, whose volume exceeds the size of the Holocene Delta along the eastern edge of the drainage basin.

Volume calculations suggest significant storage and recycling of sediment on time scales of around 10–20 ka both in the valleys of the Karakoram and on the flood plains adjacent to the mountain front. Although much of the sediment is generated by glacial processes, the transport of that material appears to be controlled by the strength of the monsoon precipitation. Sediments that are delivered to the ocean are transported relatively quickly into the submarine canyon but with only limited buffering at least in the landward portions. Rising and high stand sea level conditions do not cut off sediment supply to the canyon. The composition of material in the thalweg and terraces indicate lag times of no more than around 8000 years and probably much less between the river mouth and the canyon, especially in the early Holocene. Sediment supply modulated by the monsoon appears to dominate over sea level in controlling delivery to the deep ocean. On longer time scales (~2 Ma) sediments recovered on the submarine fan by IODP have most similarity with the interglacial composition of the Indus River rather than the glacial, as defined by zircon U-Pb ages. This again implies that monsoon precipitation dominates in controlling sediment flux to the deep sea.

The Late Pleistocene Po River Lowstand Wedge in a High-Resolution Source-to-Sink Sequence Stratigraphic Framework

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Abstract

Even in a system whose stratal record is well expressed, it can be challenging to confidently differentiate sequence boundaries from other erosional surfaces because of lateral changes in stratal patterns due to variations in accommodation and sediment-supply rates and routes. Identifying a sequence boundary, as originally defined by Mitchum et al. (1977), is based on objective geometric relations. The original and standard criteria for defining a sequence boundary include not only the recognition and interpretation of stratal terminations but also an assessment of the spatial distribution of such terminations. Key geometric relations, however, are not always apparent on every single seismic line and are commonly inferred solely from vertical sections from boreholes. Hence it is essential to correlate and map the three-dimensional distribution and character of potential sequence boundaries (and any other sequence-stratigraphic surfaces) for a more confident interpretation. Variations in observed geometric relations are a function of profile location and orientation with respect to sediment-entry points and shelf-edge, as well as to spatial changes in rates of change in accommodation relative to the rates of sediment supply (e.g., Madof et al., 2016).

We illustrate this interpretation process using our work in the Adriatic continental margin taking advantage of the preserved and well-expressed strata and surfaces of the late Pleistocene succession. In addition, in the study area, independent evidence of accommodation changes (eustasy and subsidence), sediment-supply (rates and routes), and robust geochronological control are available (Pellegrini et al., 2017). On the Adriatic margin, the late Pleistocene stratigraphy consists of a succession of regressive depositional sequences bounded by shelf-wide erosional surfaces, each recording approximately 100-ky glacio-eustatic cycles (Trincardi and Correggiari, 2000; Ridente and Trincardi, 2005). The most recent depositional sequence shows at its top different erosional surfaces developed during higher frequency changes in accommodation and sediment supply. Following the classic definition of sequence boundary by Mitchum et al. (1977), we are able to differentiate the sequence boundary from other erosional surfaces by their different types and extents of onlap on the slope and different basinal deposits. We compare and contrast the character of these surfaces in three dimensions, taking into account the importance of along-strike variations in supply regime along a continental margin, and show how this aids interpretation of causal mechanisms and the consequences for predictions of rock properties.

Sequence Biostratigraphy in Unconventional Resource Plays: Do We Need a Different Paradigm?

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Abstract

Much of industry's perceptions and applications of biostratigraphy in relation to sequence stratigraphy were developed in expanded, siliciclastic-dominated, continental margin deposits. A nearly universal paradigm is that high concentrations of microfossils, especially planktic forms, are indicative of condensed sections, and more specifically, maximum flooding surfaces (MFS). Thus, planktic abundance curves are often used to identify MFS's in systems tracts interpretations, for correlations, and to identify potential reservoir seals. Although this is a proven technique on continental margins, it is not necessarily applicable to the study of condensed, organic-rich mud rocks deposited within epeiric seas that are often the target of unconventional resource plays.

There are several assumptions about microfossil abundance curves that are implicit when using them to recognize MFS's: (1) abundances within samples are reflective of the original microfossil assemblage; (2) high abundances directly correlate to a decrease in clastic input and are not due to other processes; and (3) the microfossils are *in situ*. The accuracy of a microfossil count is dependent on fossil preservation, recovery, and the selection of representative samples. Diagenetic processes, thermal maturity, redox conditions, and compaction can negatively impact fossil preservation, whereas fossil recovery is often poor in brittle mud rocks and carbonates. Examination of thin-sections has found that microfossil occurrences are often concentrated in discrete laminations or lag deposits, making it difficult to accurately estimate average abundances from thin-sections or core plugs. High microfossil abundances are often related to low sedimentation rates, but they may also be a product of plankton productivity and winnowing by bottom-water currents. Likewise, turbidity currents and other downslope transport processes may produce high concentrations of reworked and/or transported microfossils. It is recommended that sequence biostratigraphy in organic-rich mud rocks should focus on identifying hiatal surfaces, depositional environments, estimating rock accumulation rates, and correlating to updip locations where sequence stratigraphic surfaces are more readily identified.

Shale Sequence Stratigraphy: Erle Kauffman Got it Mostly Right 40 Years Ago

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Abstract

The Shale Revolution caught sedimentary geologists by surprise. Unlike deltas, submarine fans, carbonate ramps or other types of depositional systems, there were no ready-made shale facies models that could be used to help guide the exploration and development of source-rock reservoirs (Haynesville, Barnett, Eagle Ford, etc.). More than 15 years after the initial Barnett Shale boom, the sedimentary geology community still lacks widely applied shale facies models that integrate sedimentology, lithology, organic geochemistry and other aspects of shales in ways that can be used to understand and predict the distribution of properties of economic importance. Because depositional systems are the fundamental building blocks of systems tracts, sequence stratigraphic analyses of fine-grained systems (important as source rocks, reservoirs, seals, intra-formational seals, etc. in the petroleum industry) is problematic.

Cenomanian-Turonian rocks of the Cretaceous Western Interior Seaway (KWIS) constitute an ideal data set for generating facies and sequence models that link proximal siliciclastic sediments to distal pelagic deposits in an epicontinental basin. Cores, outcrops, and wireline logs from many parts of the basin allow lateral facies relationships and stacking patterns to be precisely defined. Forty years ago, Erle Kauffman (Kauffman, 1977) identified the Greenhorn Cyclothem as a transgressive-regressive succession that represents approximately 6 million years. Erle's data-based "model of sedimentation patterns within one Cretaceous marine cycle" depicted lateral facies transitions and a Waltherian stacking pattern for the Cretaceous Western Interior Seaway in the Utah/Colorado/Kansas portion of the basin.

I present a process-based facies model (Hart, 2016; Fig. 1) that links shoreline sandstones to basin-center pelagic carbonates, and update Kauffman's cyclothem concept to show how stratigraphic stacking patterns differ between distal and proximal areas (Hart, 2015; Fig. 2). The model integrates process sedimentology, lithology/inorganic geochemistry, and organic geochemistry. Proximal (western) portions of the basin have sandstone-shale successions that are familiar to most clastic sequence stratigraphers. However, distal (central) portions of the basin have pelagic carbonate-rich deposits that generate counterintuitive stacking patterns in these areas, in which "clean" rocks (deposited during peak transgression) represent the most distal deposits.

In the Cretaceous Western Interior Seaway, the character of the facies transitions varies latitudinally from Canada (Second White Specks) to south Texas (Eagle Ford). Deviations from the idealized model, developed for the Utah/Colorado/Kansas area, are useful for deciphering the impact of different forcing mechanisms (e.g., subsidence, siliciclastic sediment supply) on shale sequence development.

In the same way that no one facies or sequence stratigraphic model is applicable to all "sandstones" or "limestones," no single model is applicable to all shale-dominated settings. The model presented here needs companions that can be used to understand and predict properties (lithology/geochemistry/etc.) on shelf-margin upwelling systems, continental slope deposits, and other muddy depositional settings.

The Use of Chemostratigraphy to Refine Ambiguous Sequence Stratigraphic Correlations in Marine Shales: An Example from the Woodford Shale, Oklahoma

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Abstract

Identifying distinct facies shifts within mudrocks has made it difficult to build sequence stratigraphic frameworks within fine-grained lithologies. Three cores from Lincoln, Pottawatomie, and Pontotoc counties and two outcrops at the Hunton anticline quarry in Murray County cover proximal and distal regions of the Arkoma basin within southern Oklahoma. Chemostratigraphic and gamma-ray profiles supplemented with lithologic descriptions can be used to build sequence stratigraphic interpretations within mudrock systems.

Detrital sediment input is associated with Ti, Zr, Al, and K. The degree of basin restriction correlates with Mo and V concentrations, barring certain mineralogical affinities. Silicon is found in biogenic quartz, detrital quartz, feldspars, and clays. However, evaluating Si as a ratio between Si/Al, in conjunction with the Ti and Zr concentrations, the Si/Al ratio provides a rough approximation for the amount of biogenic quartz present within a sample. At several horizons in the Woodford, the Si/Al value spikes, and the Ti and Zr values drop; these spikes are interpreted as planktonic blooms.

Stratigraphic successions with ambiguous gamma-ray profiles correlations can be correlated accurately by utilizing surfaces that are recognized within chemostratigraphic profiles. Within the Arkoma basin, the chemostratigraphic profile of the Woodford Shale is interpreted within a sequence-stratigraphic framework using the following general criteria. Progradational packages record increasing concentrations of Ti, Zr, Al, and K. Retrogradational packages record a declining trend in these elements, indicating the transgressive systems tract. Lowstand system tracts and highstand system tracts can be distinguished by the degree of bottom-water restriction. Low base level correlates to a greater degree of basin restriction.

Depositional Cycles and Sequences in an Organic-Rich Lake Basin: Eocene Green River Formation, Lake Uinta, Colorado and Utah

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Abstract

Green River Formation lacustrine deposits in the eastern portion of Lake Uinta formed in two sub-basins (the Piceance basin and the Uinta basin) and represent mixed siliciclastic-carbonate and organic-rich lake deposits deposited during the Eocene climate optimum. The formation is comprised of organic-rich and organic-poor mudstone, siliciclastics, and carbonates, formed in a shallow to deep (tens of meters), stratified lake environment. Integrated sequence stratigraphic analysis using gamma logs, Fisher Assay plots, core, and outcrop has resulted in a predictive framework for organic-rich oil shale distribution, reservoir characterization, and hydrocarbon systems analysis.

Lacustrine strata are characterized by three types of (meter to decimeter) depositional cycles: (1) Type 1 cycles formed in a littoral/sublittoral zones and comprise progradational siliciclastic-rich deposits that pass upward into progradational to aggradational carbonate shoal and microbial carbonate and are capped by mud- to silt-sized sublittoral deposits. In the profundal zone, two types of depositional cycles occur: (2) Type 2 cycles start with lean oil shale, pass upwards into siliciclastic turbidites, and are overlain by rich oil shale deposits. (3) Type 3 cycles initiate with evaporites and mixed lean and rich oil shale that is overlain by rich oil shale. Stacked depositional cycles form depositional sequences meters to tens of meters thick. Eleven upward-deepening depositional sequences have been described and are divided into periods of low, rising, and high lake that are separated by sequence boundaries, transgressive surfaces, and main flooding surfaces, respectively.

The development of depositional cycles and sequences in these lacustrine basins appear to be strongly affected by climate changes and respective inflow; i.e., during times of low inflow (low lake level) siliciclastic and nutrient input into the lake decreased. In contrast, the highest input of siliciclastics and nutrients occurred during increased and high inflow (rising and high lake level). Low lake level is marked by thin marginal deposits and lean oil shale and at times, evaporite deposition in profundal areas. Increased runoff is marked along basin margins by sharp-based sandstones and carbonates. In the profundal area, rich oil shale overlay lean oil shale.

Seismic-Scale Geometries and Sequence-Stratigraphic Architecture of Early Cretaceous Syn-Post Rift Lacustrine Carbonate Systems, Pre-Salt Section, South Atlantic Margins

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Abstract

Regional and detailed seismic stratigraphic analyses of Early Cretaceous (Aptian) pre-salt carbonate sections in the offshore South Atlantic reveal the complex stratigraphic architecture of lacustrine carbonate systems that developed during late- and post-rift tectonic phases. The lateral and vertical distribution of calibrated seismic facies within this framework highlights the stratigraphic evolution of the pre-salt carbonate system.

Despite the simple, largely abiotic and microbial components, lacustrine carbonates formed complex geometries that closely resemble those observed from marine systems, suggesting that a downward tapering carbonate production profile must have occurred. The complexity of the stratigraphic architecture in the pre-salt system reflects lateral variations in subsidence patterns combined with the interference of the basement rugosity, paleo-wind directions, and basinal filling patterns. Well-imaged clinoforms several hundred meters high attest to both the existence of significant lake-bottom topography and the at least occasional occurrence of deep water at time of deposition of the carbonate units, although rapid variations in base level are predicted. The shape of clinoforms varies from linear or tangential, have an average dip angle of 8–12° (depositional slopes) but can be up to 18–20° dip (bypass slopes), to erosional (>30° dip), reflecting differences in antecedent topography, and from tabular to climbing, reflecting varying rates of sediment accumulation in the basin. Closely spaced basement highs formed the nuclei for coalescing systems in the post-rift phase when subsidence rates where greatly subdued; margins abutting deep basins developed aggradational and retrogradational stacking patterns having erosional collapse scars and gravity flow deposits at the basin margin. Platform margin path and vertical and lateral architecture of clinoform packages through time reveal distinct sequence boundaries that can be correlated in detail only locally, demonstrating the large impact of syndepositional tectonics and possibly the recurrent isolation of smaller lakes during lowstands.

Impact of Salt Tectonics on Mesozoic Carbonate Platform Development: Insights from Outcrop Analogues (High-Atlas, Morocco)

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Abstract

Carbonate platforms affected by salt tectonics form important hydrocarbon reservoirs. In an effort to gain new insights of the impact of diapirism on carbonate systems we have undertaken an integrated structural and sedimentological study of Jurassic carbonate platforms of the Moroccan High-Atlas basin. In this natural laboratory, the scale of outcrop exposure is similar in area to a large offshore seismic data set, and field observations provide high details on the geometries and facies distributions around diapiric structures.

The Atlas intracontinental basin initiated during the Triassic, contemporaneously with Atlantic rifting. The Triassic synrift sequence includes thick shales and evaporite deposits accumulated in multiple tectonic sub-basins. A thick (>5000m) Jurassic sequence was deposited during an overall post-rift stage in a west-southwest/east-northeast shallow-marine basin open towards the NeoTethys. Since the Sinemurian, sedimentation was mainly carbonates. However, geodynamic events linked with the evolution of the Atlantic margin produced several phases of clastic influx leading to the development of mixed systems (Toarcian and Bathonian).

During the Early Pliensbachian, an extensional tectonic event triggered synsedimentary diapiric movements which locally lasted until the Cretaceous. These movements were responsible for the development of narrow diapiric ridges of large extent (>100km), controlled by normal west-southwest/east-northeast relay faults. These ridges were separating several kilometers-wide elongated mini-basins, which subsidence was induced by salt/shale withdrawal.

Regionally, diapiric movements have been discontinuous in time and space, leading to significant thickness variations within the different stratigraphic units. However, diapirism has not had any major influence on the nature and distribution of sedimentary systems at the basin scale. The impact of diapirs remains essentially localized in the immediate vicinity of these structures (km-scale), where they affected both stratigraphic geometries and facies distribution. This impact appears to be very different in oolitic and mixed ramp systems in which subtle differentiation of depositional profiles controlled progressive facies variations, or in bioconstructed carbonate systems in which diapiric movements had a major role on the location and morphology of platform margins and associated "micro-rim-basins." In return, the geometry of the diapirs has been clearly influenced by the lithology of surrounding rocks.

Contrasting the Stratigraphic Architecture of Carbonate Shelves and Slopes across a Foreland Basin: Permian of the Delaware Basin

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Abstract

The Permian strata on the shelves around the Delaware Basin represent more than 1000 meters of carbonates and mixed carbonate/siliciclastic deposits. These strata host vast amount of hydrocarbon, and their stratigraphic architecture is very well understood based on numerous studies form the outcrop in the northern and western part of the basin and a wealth of subsurface data in and around the basin. The stratigraphic evolution of the early to middle Permian mixed carbonate-siliciclastic system is the combined result of a waning tectonic activity and a transition from an icehouse to greenhouse climatic-eustatic signal. Comparing two classic outcrop localities between the south (Glass Mountains) and the north (Guadalupe Mountains) of the basin shows some striking difference in the overall stratigraphic architecture of the Woflcampian, Leonardian, and Guadalupian strata.

The Woflcampian and Leonardian in the Glass Mountains is about 75% the thickness of the similar interval in the north and has an overall retrograding architecture compared to an overall prograding motif in the north. In the Glass Mountains, the Leonardian slope (Bone Spring Fm. equivalent) is dominated by silt and coarse-grained gravity flow deposits (turbidites and megabreccia) compared to the huge volume of muddy dilute carbonate turbidites in the Bone Spring Formation of the Guadalupe Mountains. The thinner and mostly retrograding architecture of the Leonardian in the south compared to the northern margins indicates a larger accommodation space versus sediment supply ratio. This difference may be due to either an increased subsidence due to waning tectonic activity or a reduced sediment production and accumulation compared to the north, or a combination of the two. A potential explanation for a reduced sediment production rate might be the large amount of siliciclastics mixed into the carbonate system in the south due to the proximity of the orogenic front compared to a larger mostly purely carbonate Leonardian shelf in the north that produced huge amount of carbonate mud that is exported to the slope and allows for the shelf margin to prograde by more effectively infilling the basin topography.

The Guadalupian interval and especially the section from the Vidrio Formation to the end of the Capitan Formation is much more prograding (17 km of basinward step for 500m of thickness) compared to the similar interval in the Guadalupe Mountains (6 km of basinward step from Goat Seep Formation to end Tansill Formation for 300m of thickness). That equates to a P/A ratio of 34 in the Glass Mountains compared to 20 in the Guadalupe Mountains. We hypothesize that the strong influx of sand on the slope and in the basin allowed the Guadalupian reef in the south to build outward in a similar fashion that the mud exported in the basin during the Bone Spring time promoted the progradation of the northern Leonardian shelf in the Guadalupe Mountains.

These two overall architecture differences between the south and northern part of the basin point toward a strong control of the overall sediment production rate and accumulation of sediment on the slope combined with antecedent topography and subsidence rate on the stratigraphic architecture of those carbonate shelves experiencing the same eustatic and climatic signal.

Meter-Scale Vertical and Lateral Facies Variability in a Sequence Stratigraphic Framework: Example from Shallow-Marine Carbonates of the Middle Jurassic Izhara Formation (United Arab Emirates)

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Abstract

A sedimentary bed is classically defined as a distinct layer of sedimentary rock that has a relatively uniform composition. Several outcrop-based studies have shown that facies within individual beds can vary laterally on a scale of around 100 m. As facies transitions are important criterions used as a proxy for the depositional environment and often to infer sequence stratigraphic trends in subsurface studies where data is limited to one-dimensional wells, this observed facies heterogeneity has implications for both paleoenvironmental studies and sequence stratigraphy. In this study, we investigate whether sedimentary and facies heterogeneities known to occur at the hundred meters scale are also present at the meter to tens of meters scale in a well-preserved facies mosaic deposited on a carbonate ramp (Wadi Naqab, Izhara Formation, Lower Bajocian, northern UAE), where a robust, outcrop-based sequence stratigraphic framework exists.

A bed set was logged and mapped across a 120 m long curving cliff face; combined with thin section analysis, the data allowed the reconstruction and quantification of facies heterogeneity at this location. Results reveal a large amount of lateral facies transitions at the meter scale. Lithofacies types have a probability of less than 70% of being laterally continuous over 12 to 18 meters, representing the highest amount of lateral facies heterogeneity so far reported in an ancient example. The case study reveals intra-bed facies transitioning attributed to spatially heterogeneous biogenic carbonate production as well as to syndepositional homogenizing and sieving processes occurring within shallow-marine depositional environments in ancient as well as in modern analogous systems. A series of continuous hardgrounds, previously interpreted as flooding and exposure surfaces, provide an independent sequence stratigraphic framework that demonstrate that the existence of small-scale lateral facies heterogeneities complicates interpretation of the vertical stacking pattern of facies. This confirms that the best practice is to limit sequence stratigraphic interpretations based on facies trends to larger stacking patterns (>10 meters). Meter-scale vertical patterns in carbonates often do not represent a proxy for base level changes, as illustrated in our study; therefore, fine-scaled, high-resolution sequence stratigraphy or lateral correlations are not attainable in carbonate sequences based on lithostratigraphy.

Upper Cambrian Transgressions—A Driver for Microbial Reef Development across the Southwest Great American Carbonate Bank: Case Study from Central Texas

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Abstract

Upper Cambrian microbial reefs established themselves on an extensive shallow shelf portion of Laurentia, also referred to as the Great American Carbonate Bank. Four dominant regressions and three transgressions synchronously occurred across Laurentia, based on measured sections, regional correlation, and biostratigraphy. The youngest transgression in Central Texas, corresponding to the Point Peak Member of the Wilberns Formation, is evident in several outcrops within a 2500 Km^2 area that has been the focus of study by the Rice/Trinity Industry Microbial Research Consortium.

The Point Peak Member is divided into lower and upper portions by a regional time marker bed—the *Plectrotrophia* zone (*Plectrotrophia bridgei* and species of *Billingsella*). Microbial accumulations of the Lower Point Peak crop out along the Llano River and Mill Creek and consist of a series of 50cm-thick biostromes and some individual buildups one meter or less in height, intercalated with heterolithic facies, glauconitic siltstones, and oolitic, skeletal, and interclastic carbonate grainstone. These interrelated facies are interpreted to represent shallow subtidal to intertidal depositional environments. Farther offshore, equivalent thicker microbial buildups (up to 30 m thick) have been recorded in the literature, indicating the wide extent of subtidal microbial facies across the up to 50 km wide shelf.

Above the *Plectrotrophia* zone, spectacular outcrops of Upper Point Peak reveal large microbial reefs (10-14 m high and tens of meters in diameter). These reefs are exposed in 2D and 3D, along the James and Llano rivers, and Mill Creek, providing unique opportunities to quantify their distribution and heterogeneity and to better place them into a sequence stratigraphy framework. Meter-thick skeletal and oolitic grainstone inter-reef beds, contemporaneous to the buildup growth evolution, are intercalated with a series of siliciclastic-rich silty beds onlapping the different buildup growth phases. These large reefs are equivalent in depositional setting to the offshore large buildups below the *Plectrotrophia* zone.

The microbial buildups both below and above the *Plectrotrophia* zone are interpreted as a response to sea level rises, whereas siliciclastic-rich beds, in particular the thick bed onlapping the final phase of buildup growth, are most likely a result of sea level falls. The belt of thicker buildups in the Upper Point Peak is located farther landward relative to that of the Lower Point Peak, indicating that these "higher-frequency" sea-level changes were occurring within an overall transgression.

Effects of Sea Level and Upwelling on Development of a Miocene Shallow-Water Tropical Carbonate Ramp System, Ponce, Puerto Rico

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Abstract

Middle-late Miocene (ca. 13-10 Ma) Ponce Limestone exposures in southern Puerto Rico provide an opportunity to evaluate development of a tropical carbonate ramp system during a time of known regional upwelling in the Caribbean. Three sequences (DS1, DS2, and DS3) developed in response to relative sea-level fluctuations. Each sequence is characterized by basal heterozoan-larger benthic foraminifera (LBF) facies that grades upward to a photozoan facies composed of corals tolerant of cool and turbid water at the top. DS1 transgressive deposits include *Kuphus (?incrassatus)*, *Amphistegina-Archaias* packstone interbedded with *Amphistegina* packstone, and *Archaias angulatus* and gastropod-rich packstone. Maximum flooding is indicated by a Globigerinid planktonic foraminiferal facies. Upper DS1 strata consist of *Montastraea imperatoris*, *Goniopora imperatoris*, and several species of *Porites* coral rud-floatstone and framestone, which were deposited during highstand and sea-level fall. DS1 is capped by a surface of subaerial exposure (SB1).

DS2 transgressive deposits consist of *Amphistegina*-coralline red algae packstone-grainstone that grade upward to coralgal-*Amphistegina* packstone deposited during highstand and sea-level fall. DS2 is capped by a surface of subaerial exposure (SB2).

A rapid sea-level rise for DS3 is interpreted due to the apparent lack of transgressive deposits.

Preserved strata consist of prograding coralgal clinoforms developed during highstand. SB1 (~13-12 Ma) and SB2 (~11-10 Ma) may correlate with unconformities in other Caribbean areas, which could indicate regional tectonic or eustatic control on sequence development. The dominance of heterozoans and larger benthic foraminifera tolerant of mesotrophic and temperate water conditions and the presence only of those photozoan corals tolerant to turbidity and cooler water are consistent with a system affected by upwelling. The presence of photozoan corals only in the highstand and regressive portions of sequences suggests highest upwelling intensity and/or transport of upwelled water and nutrients to shallowest water ramp environments during transgressions. Our results have direct implications for other similar age-equivalent systems developed in the Caribbean, including those forming important reservoirs, and other tropical systems in the rock record affected by adverse photic zone conditions.

Stratigraphic Sweet Spots—Exploration Insights from a Eustatic Model

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Abstract

The successful application of sequence stratigraphy in the petroleum industry is linked to its capability to predict stratigraphic architecture accurately. This includes the distribution and nature of petroleum system elements (reservoir, source rock, and seal) away from subsurface control points. These predictions generally address the intermediate, or third-order sequence scale, and related systems tracts. An up-scaled view can help determine the long-term temporal and large-scale spatial stratigraphic patterns link to eustasy and related or coinciding global events. The ultimate objective of such an endeavor is to identify and predict stratigraphic sweet spots (i.e., those moments in time when all factors align to create effective petroleum habitats). The existence of such sweet spots is demonstrated by the uneven distribution of petroleum resources throughout geological time.

A two-stepped approach is advocated to identify stratigraphic sweet spots. First, the character of the sea-level curve is documented, paying particular attention to amplitude and frequency. Secondly, its relationship to other global events and the resulting stratigraphic patterns are illustrated. Two examples are presented — the hydrocarbon-rich Lower Cretaceous Aptian and Valanginian stages. In both cases, well documented, high-amplitude sea-level fluctuations occur, but they are characterized by very different petroleum habitats. Factors responsible for this difference are the rate of sea-level fluctuations, the coincidence with an Oceanic Anoxic Event (OAE), and the plate tectonic configuration.

Erosion and Ponding of Thunder Horse Deep-Water Turbidites by Mass Transport Complexes in Mississippi Canyon Based on Image Log Sedimentology

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Abstract

Stacked mass transport deposits interbedded with turbidite sandstone reservoirs were characterized in detail from image logs at Thunder Horse, a conventional asset located in the Boarshead mini-basin, lower Mississippi Canyon, Gulf of Mexico. Image logs visualize the borehole wall, allowing bedding boundary information and some sedimentary fabric to be identified. From bedding boundaries, dip azimuths and magnitudes can be calculated, and depositional processes can be inferred from patterns in the dips. Dips in the primary sandstone reservoirs show little variation (< 20°) in structural tilt, indicating continuous deposition by high density turbidity currents prior to major structural deformation and are thus the best proxy for regional structural dip. In contrast, dips in 80% of all mudrocks in this canyon show widely varying dip magnitude and azimuth over small and large scales and are interpreted as having been deposited by slumps, slides, and folds, building up to form mass transport complexes. Only very rarely do we observe mudrock dips that are conformable to the regional dip and strike.

Unconformable bedding contacts at the tops of the sandstone reservoirs in northern Thunder Horse suggest scouring and erosion by overlying mass transport deposits, whereas basal sandstone contacts are in conformance with structural dip, suggesting amalgamation. On seismic data, albeit low-resolution due to the overhanging salt canopy, the mass transport complexes appear to build up into a gradual mound.

Core was acquired in the upper 60 m of the mass transport complex, revealing convoluted and folded bedding capped by highly bioturbated marl, which is thought to represent a *Glossifungites* hiatal surface resulting from the mass transport complexes building up a topographic high, forcing subsequent debris and turbidite flows to travel around rather than over that location. The topographic high ponded the overlying reservoir behind it, preferentially thickening the sandstone reservoir behind the mound. Thus, mass transport complexes were found to both erode and augment sandstone reservoirs. Biostratigraphic dating of the two reservoirs brackets their deposition as occurring in <400,000 years during the Serravalian, Middle Miocene, probably as a result of the Harang shelf failure.

As a case study this type of integrated, high resolution data (core, image logs, seismic) has wide applicability to other deepwater, subsalt reservoirs, as improved structural and depositional interpretations inform reservoir performance and impact future well plans. Further, recognition of mass transport complexes as agents of reservoir compartmentalization and sandstone ponding allow for more accurate reserve estimation.

Diagenesis and Sequence Stratigraphic Framework—A Case Study in Upper Miocene Carbonates, La Molata, Southeastern Spain

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Abstract

Upper Miocene carbonates in La Molata, southeast Spain, consist of eight depositional sequences, capped by subaerial exposure surfaces 1 to 7. Known stratigraphy, mineralogy, climate, and duration of exposure provide superb opportunity for studying diagenesis and sequence framework. This integrated study shows that only minor diagenetic alteration has occurred during subaerial exposure (surface 1 to 6) that was short-lived (<533 k.y.) and in an arid climate, or the carbonate sediments were composed primarily of calcite.

Dolomitization occurred during the initial stages of sea-level fall associated with surface 7, by ascending freshwater-mesohaline mixing. This resulted in dissolution to create 10-20% porosity. During this long-lived period of subaerial exposure (greater than 5.3 m.y.) in a wet climate, major amounts of calcite cementation reduced porosity, forming an upper and a lower cemented zone. Cements in the upper zone are nonluminescent, whereas those in the lower zone exhibit luminescent zonation. In the upper zone, isotopic data from calcite cements show two meteoric calcite lines having a mean of d^{18}O at -5.1 ‰ and -5.8 ‰ VPDB. No clear meteoric calcite lines are defined in the lower cemented zone, which has a mean of -6.7‰ VPDB. d^{13}C. Values in both cement zones are predominantly negative, ranging from -10 to +2 ‰ VPDB, suggestive of carbon from soil gas or decayed organics. Tm ice in primary fluid inclusions shows a mode of 0.0 °C in both zones, indicating calcite cementation from fresh water.

These two zones define the position of two different paleo-water tables that formed during a relative fall in sea-level and erosional downcutting during the Plio-Pleistocene. The upper cemented zone pre-dates the lower cemented zone on the basis of known relative sea-level history. Each texture (boundstone, grainstone, packstone, and wackestone) produces a different relationship between percent calcite cement and porosity/permeability. Distribution of cements may be predictable on the basis of known sea-level history, and the effect of the cementation can be incorporated into subsurface geomodels by defining surfaces of rock boundaries that separate cemented zones from uncemented zones and applying texture-specific relationships among cementation, porosity and permeability.

Controls on Seismic-Scale Geometries and Sequence-Stratigraphic Architecture of Mixed Carbonate-Siliciclastic Systems: Example from the Triassic Nanpanjang Basin, South China

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Abstract

Comparative analysis of platform evolution recorded along multiple 2D platform-to-basin transects of the Triassic Yangtze carbonate shelf and several isolated platforms in the Triassic Nanpanjiang basin, south China, indicates that laterally variable tectonic subsidence, rate of basinal clastic deposition at the toe of slope, antecedent topography, and changes of carbonate factory type controlled the evolution, large-scale sequence stratigraphic architecture, and geometry of the platform margin and slope. Lateral and temporal changes in these parameters, and their various combinations during the Middle and early Late Triassic, were responsible for the remarkable vertical and along-strike variability in the observed platform architecture and slope profile.

Timing and rates of subsidence largely controlled along-strike variability, timing of drowning, back-step geometries, and pinnacle development. Antecedent topography and timing of clastic basin fill dictated differences in platform-margin stability and geometries such as slope angle, relief above basin floor, development of collapse scars, and progradation at basin margins. Changes in slope profile through the Early and Middle Triassic reflect changes in carbonate-factory type and evolving seawater chemistry following the end-Permian extinction. Eustasy, in contrast, had very little influence on platform morphology and large-scale architecture.

Process-based depositional models derived from the Nanpanjiang basin of south China present an important analog for understanding, quantifying, and predicting facies distribution and architectural styles at the basin scale in other systems, particularly in areas of active tectonism and temporal variations in oceanic conditions, such as, for example, the prolific Tertiary carbonates reservoir province of southeast Asia.

Tectonic Control on Late-Stage Sequence-Stratigraphic Architecture and Drowning of the Triassic Yangtze Platform, Nanpanjang Basin, South China

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Abstract

The long-lived Yangtze platform (YP) drowned abruptly and was buried by pelagic facies and siliciclastic turbidites in western Guizhou Province during the Late Triassic (Carnian). The uppermost carbonate platform facies are peritidal cyclic limestone and dolostone containing a restricted biota and having fenestral laminate caps. Equivalent margin facies consist of intraclastic, grapestone, oolitic grainstone, and lenses of coral-*Tubiphytes* algal boundstone indicating high-energy shoals and patch reefs.

The drowning horizon is a laterally variable sharp surface or gradational shift to dark, nodular-bedded, pelagic lime mudstone to wackestone. The contact lacks hardgrounds, phosphatized, or glauconitic surfaces that would indicate drowning by excess nutrient flux. Uppermost platform carbonates have a tropical photozoan biota and lack siliciclastic content, indicating neither climate cooling nor clastic flux played a role in drowning. Rare bioturbation and benthic biota in the lower part of the drowning interval indicate dysaerobic conditions with an upward shift to anoxic conditions.

Syndepositional faults had a significant impact on the evolution of the western sector of the Yangtze platform and controlled three local accommodation cycles. Faults developed during the last accommodation cycle tip out at the drowning horizon and include a flower structure upon which a pinnacle reef developed as the rest of the platform drowned. Lateral variability in the drowning horizon and thickness of the post-drowning pelagic facies point to differential tectonic subsidence causing sinking of the platform into deep water along faults.

Magnetic susceptibility and paleomagnetic reversal correlation demonstrates that the western sector of the platform drowned while shallow marine mixed carbonate-siliciclastic sedimentation continued in the eastern sector to be terminated later in shallow water by increasing rates of clastic flux. Starved black shale horizons in the basin indicate persistent water stratification and bottom water anoxia; elevated trace metal concentrations indicate dysaerobic to anoxic conditions and enhanced preservation of organic matter. Tectonic subsidence likely submerged the western sector into deep, toxic waters of the stratified basin causing the killing of benthic marine carbonate production.

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