SUBMITTED ABSTRACTS

Sequence Stratigraphy: The Future Defined

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The following is our preliminary list of submitted papers for the conference. We will try and keep it is current as possible. Remember that the submitted abstract is provisional. Abstracts are presented alphabetically by the last name of the principal author.

How close is geological thought to reality? The concept of time as revealed by the Holocene sequence stratigraphy of the Po-Adriatic system, Italy

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Vastness of time is largely beyond human observation, but how aware are most geologists of the concept of time? Time spans of “just” tens to hundreds of thousands of years may become unfamiliar when moving from the modern, observable, and quantifiable depositional processes to the imperceptible series of moments recorded in the rock record. Our experiential concept of time built on the chronologically well-constrained Holocene succession of the Po-Adriatic system demonstrates that highstand deltaic parasequences, tens of meters thick and that locally make up to 95% of the total volume of Holocene deposits, record a relatively short time interval (a few hundreds of years), representing < 10% of the total time involved. Early Holocene transgressive shorelines retreated at a mean rate of ~10 m/y, between 9.2 and 7.7 ky BP, following a stepped trajectory at the centennial scale. At the transition from aggradation to progradation, a laterally extensive prograding deltaic body, up to 30 m thick and > 20 km long downdip, accumulated in less than 2000 years. When dealing with less chronologically constrained, older parasequences of similar size, but assumed to have developed on larger temporal scales, severe distortions can be generated by the traditional idea that any length of time can be averaged into equal parts. In the Holocene succession of the Po Plain, very short periods of sedimentation alternated with long phases of non-deposition, erosion, and/or stratigraphic condensation, recorded at bounding surfaces of individual parasequences. We advocate examining the impact of a highly fragmented sedimentary record on the hierarchical stacking of parasequences and on the formation time scales of ancient alluvial and deltaic depositional systems, by comparing this Holocene stratigraphy against older, middle Pleistocene and Cretaceous strata (Enza River, Italy, and Blackhawk Formation, in the Book Cliffs, respectively).

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

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Deep marine rocks of the Windermere Supergroup record a several kilometer-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 aerially 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, indicate 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.

How Realistic and How Predictive is my Sequence Stratigraphic Interpretation? Stratal Volumes, areas, and Trajectories as a Tool to Test Sequence Stratigraphic Interpretations

Peter M. Burgess (University of Liverpool)
(Extended abstract only)

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 the implied rates of change in accommodation and supply controls are realistic.

Stratal control volumes are sets of points in a three-dimensional volume, in which axes of subsidence, sediment supply, and eustatic rates of change are populated with probabilities derived from analysis of subsidence, supply and eustasy time-series (Fig. 1). These empirical probabilities indicate the likelihood of occurrence of any particular combination of control rates defined by any point in the stratal control volume. 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 allows similar analysis and may be preferable. A stratal control trajectory is a history of supply and accommodation creation rates either interpreted from outcrop or subsurface data or observed in analog and numerical experiments and plotted as a series of linked points forming a trajectory through the stratal control volume (Fig. 1) or area. Stratal control trajectories can form a key test of sequence stratigraphic interpretations. If they pass through areas of the control space having relatively high probabilities, this suggests the implied control rates are more realistic than if the trajectory plots in areas of the space having lower probability.

Much work remains to be done to build a properly representative database of stratal control rates of change and time-series, but 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.

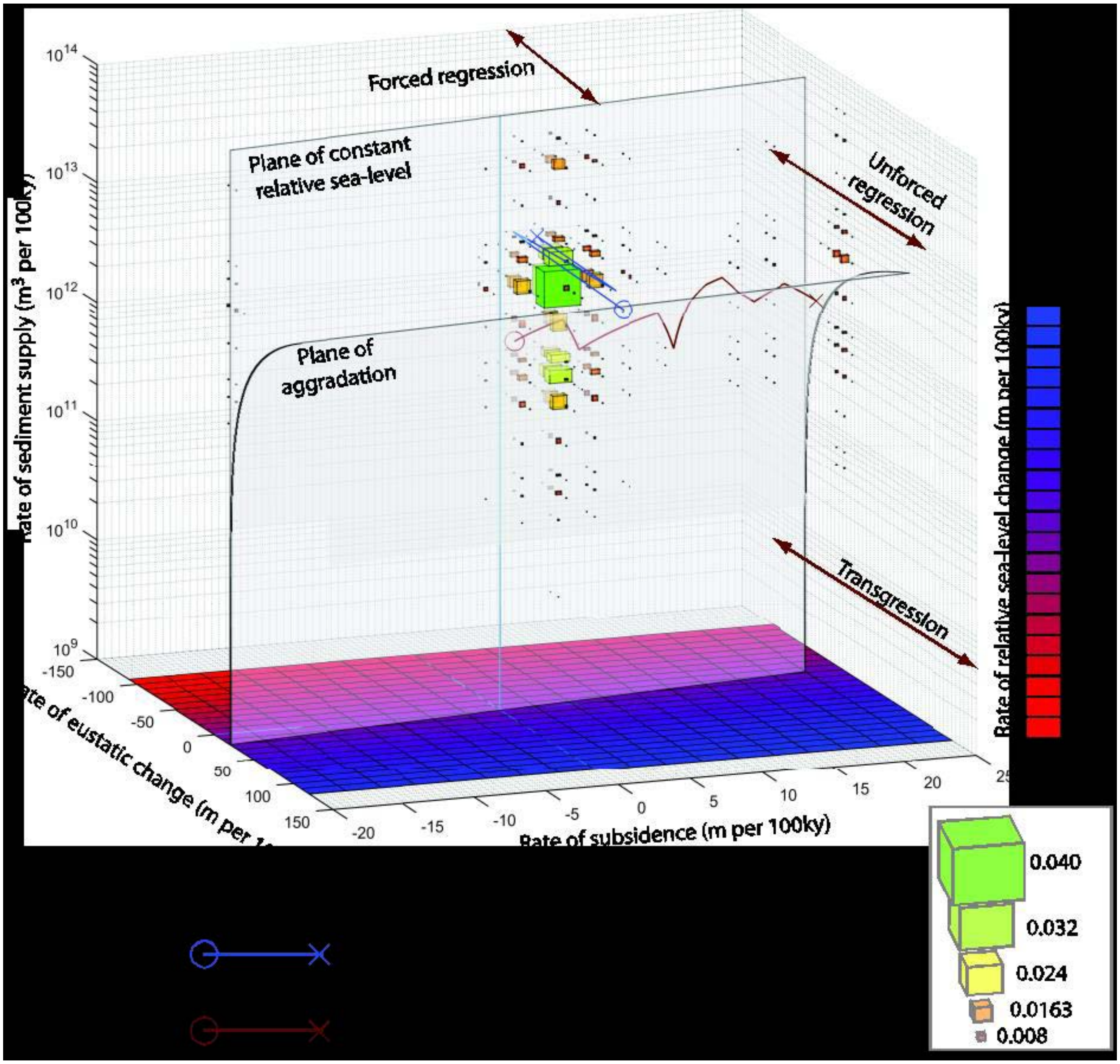

Figure 1. An example stratal control volume and two stratal control trajectories, from Burgess and Steel (in press).

Integrated Carbon Isotope Sequence Stratigraphy for Clastic Successions

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The linkage between cycles of relative sea level observed in sedimentary basins and eustatic or tectonic drivers remains a fundamental problem of broad interest throughout Earth's history. The overarching issue is the lack of independent knowledge of the eustatic and tectonic components of the relative sea level variations and of sediment supply change.

The variations of inorganic carbon isotopic composition in bulk carbonates are considered resistant to diagenesis and burial and have been proposed to provide an indirect proxy of global sea level (e.g., Jenkyns, 1996, Li et al., 2000) through the following mechanism: provided nutrient availability is not a limiting factor, the considerably lower ^{13}C to ^{12}C ratio in organic matter than in dissolved inorganic carbon implies that increased organic productivity on the shelf and its burial during worldwide episodes of transgression would lead to higher ^{13}C to ^{12}C ratio (positive $\delta^{13}C$ excursion: Arthur et al., 1987; Jenkyns, 1996). Conversely, during sea-level lowstands, reduced shelfal productivity and burial, potential oxidation of organic rich shelfal sediments (e.g., Higgins and Schrag, 2006), and enhanced influx of organic matter from the land (Kroopnick, 1985) would all increase the ratio of ^{12}C to ^{13}C (negative $\delta^{13}C$ excursion: Jenkyns, 1996).

Thus far, carbon isotopic studies that have provided records of paleoclimate and oceanographic evolution, and which have proposed a relationship between eustatic changes and carbon isotopic profiles, 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; Weissert, 1989; Jenkyns, 1996; Zachos et al., 2001). A number of studies have also investigated shallower carbonate records but with the drawback of potentially frequent emersions and the possibility of an incomplete record (e.g., 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 of their gradient, making them prone to failure, bypass, and submarine erosion. However, slope systems represent an important proportion of the Earth's surface, remain below sea level during lowstands, are away from mass-transport processes and erosional conduits, 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.

In this work, we test an approach integrating sequence stratigraphy and carbon isotope on bulk carbonate hemipelagic sediments on the clastic turbiditic slope of the Ainsa basin in the southern Pyrenean foreland basin.

Source to Sink Processes in the Indus River System

Peter Clift (Louisiana State University)

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.

Regional Sequence Biostratigraphy in the Neogene of the GOM

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Global models of Neogene third-order sequence stratigraphy predict regionally recognizable sequence boundaries and flooding surfaces. Past sequence biostratigraphy in the Gulf of Mexico has focused on the transgressive episodes, and a robust Neogene biostratigraphy has evolved for the basin. Upper Pliocene “Dtam” or middle Miocene “CatMex” are terms and horizon names familiar to Gulf of Mexico geoscientists. They are assumed to be coeval surfaces, correlative regionally, and typically tied to seismic data. They are rarely presented in their sequence stratigraphic context such as lowstand or highstand. Sequence biostratigraphy has, for a large part, ignored the sequence boundary and the depositional sequence as a whole. Each sequence has a distinct sequence assemblage of fossil events such as extinctions and acmes.

Analysis of biostratigraphic data, well logs, and well reports allows for the interpretation of the sequence boundary surfaces in wells that penetrate these globally correlated sequences. Sequence boundary surfaces are interpreted from log character and are age-constrained by the sequence assemblages above and below. Those surfaces, interpreted in the well, can then be tied to seismic data and tested for other key aspects of a sequence boundary, such as downlap. This approach results in an interpreted surface fundamental to the depositional history of each third order lowstand. Depositional episodes such as a turbidite-channel fill or basin-floor fan are of a higher order within each sequence.

Third order sequences, with one exception (Bur5/Langhian), provide a finer scale of resolution beyond stage level and they are characterized by more than a single species event. Because multiple fossil events are utilized, this method is a robust way to identify stratigraphic sequences in the Gulf of Mexico. The sequence boundaries provide the genetic depositional component to the interpretation of each sequence that had been absent using the traditional approach which has focused on transgressive events. Other data can be placed into this framework to improve confidence in correlation and resulting maps and models of depositional systems. Increased stratigraphic resolution leads to better choices for field and reservoir analogs and more realistic prediction of geologic and reservoir factors. Because the fossil data and the sequence data are built on the same fundamental data sets there will always be a link between historical data and maps to anything newly interpreted and mapped.

Sequence biostratigraphy in unconventional resource plays: Do we need a different paradigm?

Richard A. Denne (Texas Christian University)

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.

The Sequence Stratigraphy Revolution, its Setbacks and Challenges

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The sequence stratigraphy revolution affected both stratigraphy and sedimentology. For stratigraphy, the novel idea was subdividing the strata along unconformities and their correlative conformities that as a consequence expanded chronostratigraphy from one lithostratigraphic unit to a succession of lithologies. This expansion enabled placing time lines across facies belts from the shoreline to the deep basin. With this introduction of time into genetically related strata, the sequence stratigraphic concept had major implications for sedimentology. Walther's law had documented how facies relate to each other vertically and laterally but the sequence stratigraphic concept unraveled the dynamics of how facies belts moved as they adjusted to changing relative sea levels. It explained how these changes partitioned the facies into groups or system tracts. The result of all these qualities made sequence stratigraphy the only stratigraphic method having predictable capability.

One of the first challenges for the sequence stratigraphic concept was to prove the chronostratigraphic significance of sequence boundaries. The notion that seismic reflections were, with a few exceptions, time lines was for many geophysicists an unjustified and unproven assumption. Drilling and coring the facies along transects of prograding sequences in both siliciclastic and carbonate environments by the Ocean Drilling Program (ODP) provided robust data sets that documented the chronostratigraphic significance of seismic reflections. It was implemented in all seismic interpretation programs and used in the work flow of seismic analysis.

Sequence stratigraphy was first developed and applied on seismic data where seismic reflection patterns defined the sequence boundaries. Populating the geometrical pattern of these seismic sequences with lithologic facies helped predict lithologies in the subsurface and increased the exploration success of many deep-water plays. Calibrating the seismic sequences with robust lithologic content, however, prompted the application of the sequence stratigraphic concept to outcrops where facies could be assessed in sections. Although outcrops provided the vertical succession, the modern marine environments added information of the lateral arrangements of the facies along the depositional profile.

Applying the sequence stratigraphic concept to log and outcrop data resulted in the recognition of sub-seismic, high-frequency sequences that are also called parasequences, cycles, and genetic units. It added increased understanding on the dynamics with the sedimentary systems and the revision of many sedimentary models. All these studies that include rates of accommodation space creation, sedimentation, and subsidence established the parameters for modeling sedimentary systems. In addition, the recognition of facies partitioning on the high-frequency level has dramatically improved success in reservoir modeling.

Not all revisions to the original concept have been advantageous to sequence stratigraphy and some have proved to be setbacks. For example, the expansion of the definition of the sequence boundary as "a surface…along which there is evidence of subaerial exposure truncation (and in some cases correlative submarine erosion)"… added an unwarranted genetic element to the formation of a sequence boundary. Although it helped separating unconformable reflection terminations within sequences, such as downlap surfaces from sequence boundaries, it also reduced the scope of sequence stratigraphy. Admittedly, change in sea level is the main producer of unconformities but unconformities that separate genetically related successions are formed by various processes not only sea-level lowering. For example, drowning unconformities in carbonates fulfill the criteria of sequence boundaries; they are chronostratigraphic horizon that separate older from younger strata. Another example is an unconformity in carbonate that is caused by changes of the ecologic system. Likewise, unconformities in the deep-water drift deposits do not contain any evidence of subaerial exposure but otherwise qualify as sequence boundaries. Changing current patterns that may or may not be related to a shift in climate and the concomitant sea level change produces these unconformities.

The underlying problem for the exclusion of certain unconformities in sequence stratigraphy is the quest for a single process – sea level - for the formation of sequences. This assumption is also responsible for the early attempts to produce a global onlap chart that can be applied on different margins for age determination. Extracting the sea level signal from depositional sequences is still a focus of several studies in sequence stratigraphy, the ultimate goal of which is "standardization of sequence stratigraphy." This standard will not encompass the entire sequence stratigraphic record. Reducing sequence stratigraphy to only transgressive and regressive packages is another example of a setback as the methodology can only be applied to shelf succession. To a certain extent, subdividing the strata in geobodies is a new way of doing lithostratigraphy, although geobodies are useful for modeling; however, geobody modeling is a static approach that does not have a predictive capability of the dynamic sequence stratigraphy.

The precise dating of Cenozoic sequence boundaries in various ocean basins by ODP provides strong evidence of the global synchrony of the unconformities that separate the so-called third-order sequences. Documenting that these unconformities are related to glacio-eustasy is an ongoing challenge. Although stable isotope records across these sequence boundaries indicate a long-term build-up of ice sheets, the reason for such prolonged glaciations is still elusive. The problem is that insulation differences from orbital constellation changes that cause the glaciations in the Neogene are of higher frequency than the globally recognized third-order sequences and interference patterns of orbital forces do not coincide with the frequency of third-order sequences.

Another challenge is to establish the cause of suborbital sea level changes and their impact on high-resolution sequence stratigraphy. Orbital forcing has been considered the forming high-frequency sequences with precession being the highest frequency for sea level changes. Recent studies, however, have documented that shallow-water carbonates record meter-scale oscillations that occur in sea-level highstands even within precession cycles, indicating that carbonates are sensitive recorders of meter-scale sea level changes that occur over a few thousand years.

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

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Allogenic and autogenic processes interact to regulate sediment distribution in sedimentary basins. Depositional systems can respond in a complex manner to these processes, complicating the interpretation of the controls on the stratigraphic record. In this paper, we used a stratigraphic forward model and published and constant eustatic curves to examine the effects of sea-level variation on deep-water sand delivery for a passive continental margin. We found that: (1) models using constant sea level and those using eustatic fluctuations deliver similar volumes of sand to deep water; and (2) both large and small eustatic variations result in fluctuations in deep-water sand delivery of similar magnitudes. 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 could explain the similarity in deep-water sand delivery rates. Because our models show that autogenic and allogenic processes can result in similar deep-water sand volumes, we conclude that other characteristics of depositional systems, such as sediment supply, may also exert strong controls on deep-water sand volume.

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

Bruce Hart (Statoil, Austin)

Until the shale-gas revolution of the early 2000s, “distal” shale depositional systems were ignored by most stratigraphers. Unlike sandstone or carbonate systems (“deltas,” “submarine fans,” “reefs,” etc.) the sedimentary geology community has lacked process-based facies models for linking process to product in these rocks. Without this scale of understanding, it is not possible to develop meaningful sequence stratigraphic models.

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 carbonates. Cores, outcrops and wireline logs from many parts of the basin allow lateral facies relationships and stacking patterns to be precisely defined. In 1977, Erle Kauffman 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.

In this paper I present a process-based facies model 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. 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 counter-intuitive 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.

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

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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 ice-house 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 Fm. of the Guadalupe Mountains. The thinner and mostly retrograding architecture of the Leonardian in the south compared to the northern margins indicate a larger accommodation space versus sediment supply ratio. This difference may be due to either a 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 Fm. to the end of the Capitan Fm. 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 Fm. to end Tansill Fm. 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 Fm. 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.

Scale-Dependence of the Sequence Stratigraphic Framework in Carbonates: Impact of Facies Heterogeneities in Case Studies from Outcrops in the Middle East

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The original concepts of sequence stratigraphy were defined at the regional to field scale using seismic data, but the initial success of the model soon prompted its application to multiple scales using outcrop and core data. The question we want to address here is whether a scale dependency exists in sequence stratigraphy, and how the interpretation of parasequences and system tracts can be biased by the scale of observation.

To answer this question, we present our own carbonate outcrop data from the Middle East at a range of observational scales, as well as additional examples from the literature. Facies and diagenetic heterogeneities were captured in Arab Formation analogues from the UAE and Oman at regional (30-40 km), field-scale (>1 km), production scale (100’s m), and small-scale (<100 m). At the regional scale, sequence stratigraphic concepts can be applied coupled with biostratigraphic and chemostratigraphic constraints, and broad EODs remain continuous even though individual facies associations are not. At the field scale, bedding is uniform but significant lateral heterogeneity associated with facies changes exists within individual beds. This heterogeneity is also apparent at the <100 m scale where facies vary laterally over <10 m. We compare this with data from the Lower Cretaceous in Oman, where similar heterogeneities exist, and conclude that within the high-energy shoal environment, facies are characterized by a mosaic pattern. The high lateral facies heterogeneity results from paleotopographic infilling in different hydrodynamic conditions; as a result, small sections measured at different locations laterally will yield a range of relative sea-level trends including shoaling, deepening, or aggrading upward trends.

This observation stresses that caution needs to be taken when applying sequence stratigraphy using a small window of observation, as facies patterns can be poor indicators for the larger scale sequence stratigraphic framework.

Wilcox Submarine Fan Deposition during the Paleocene to Eocene of deep-water Gulf of Mexico: Greenhouse Conditions and Importance of Source to Sink Concepts

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Wilcox deposition from late Paleocene to early Eocene (60-52 Ma) recorded one of the largest and most laterally extensive periods of sand deposition within the Gulf of Mexico. The receiving basin was located nearly 300 miles from its equivalent shelf margin, extended laterally approximately 450 miles, and gross thickness was greater than 3000 feet. Based on previous research utilizing detrital zircons to reconstruct mid-Cretaceous to Paleogene drainage systems, Wilcox sediment drainage system incorporated a large portion the entire continental United States ranging from the Appalachian to the Sierra Nevada Mountains. Massive amounts of sediment were transported through intervening large fluvial-deltaic systems into the deep water in response to re-routed drainage patterns to the Gulf of Mexico during the late Paleocene to early Eocene. Periodic climate warming from 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 was that it occurred during an ice-cap free world where greenhouse conditions dominated and was not the characteristic "lowstand fan" we associate within our sequence stratigraphic concepts.

The deep-water Wilcox interval ranges approximately 2000 to 5000 feet in stratigraphic thickness. The chronostratigraphic framework is typically subdivided into four depositional sequences referred to as Wilcox 1-4, Wilcox 4 being the oldest sequence and a proxy for the early paleotopograhy of the basin. The deep-water Wilcox chronostratigraphic model integrates foraminifera, calcareous nannofossils, palynology, and siliceous microfossils, specifically radiolarians, to aid in age determination as well as duration. Wilcox 2-4 sequences span approximately 60-54 Ma and commonly are underlain by the Midway Shale to Cretaceous age sediments and continue through the end of the Paleocene-Eocene Thermal Maximum (PETM).

Characteristically, Wilcox reservoirs within the Wilcox 2-4 intervals exhibit high net to gross, blocky, laterally extensive unconfined distributary channel-lobe architecture. Conversely, Wilcox 1 tends to be a more mud-rich system made up of weakly confined channelized deposits not consistently observed in deep-water Wilcox wells possibly due to (1) a decrease in sediment supply from the shelf, (2) basin gradients approaching regional equilibrium, (3) reduction in accommodation space from rapid infilling of prior Wilcox sediment deposition, and (4) the ephemeral nature of these sediments in response to the effects of high CO_2 levels and extremely warm climate on sediment flux. This Paleocene-Eocene boundary (PETM) separates Wilcox 2-4 sequences from the Wilcox 1 sequence which spanned approximately 54-52 Ma in the early Eocene. Our observations indicate the Wilcox 1 sequence marked a significant change in depositional architecture from an environment of more sustained higher energy sand dominated submarine fans to one of sporadic higher energy alternating with longer period of lower energy mud rich system.

Carbonate Sequences as Complex Systems: Geochemically Influenced Sediment Supply Issues

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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, both short-lived and long-term, periodic and chaotic, are 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 hampered 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 if 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.

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

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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.

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

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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 occurred during subaerial exposure (surface 1 to 6), which 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 fresh water-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 wet climate, major amounts of calcite cementation reduced porosity, forming an upper and a lower cemented zone. Cements in the upper cemented zone are non-luminescent, whereas those in the lower cemented zone exhibit zonations. In the upper cemented zone, isotopic data from calcite cements show two meteoric calcite lines with mean $\delta^{18}O$ at -5.1 ‰ and -5.8 ‰ VPDB, whereas no clear meteoric calcite line is defined in the lower cemented zone having a mean of -6.7‰ VPDB. $\delta^{13}C$ 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 positions of two different paleo-water tables that formed during a relative fall in sea-level and erosional down cutting during the Plio-Pleistocene. The upper cemented zone pre-dated the lower cemented zone on the basis of known relative sea-level history. Each texture (boundstone, grainstone, packstone, 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.

Development of Predictive Stratigraphy – Sequences, Source-to-Sink, and Back to seismic

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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 and coring and 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 is the ability to use the methodology on outcrop data. This requires 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.

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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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^{o} (depositional slopes) but can be up to 18-20^{o} dip (bypass slopes), to erosional (>30^{o} 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 were 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.

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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(Extended abstract only)

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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(Extended abstract only)

The long-lived Yangtze platform 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 and 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 later terminated 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.

Accommodation succession (δA/δS) sequence stratigraphy: observational method, utility and insights into sequence boundary formation

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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.

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

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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.

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

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As part of a source-to-sink project on the Po Plain – Adriatic system, we focus on the late-Pleistocene Po River lowstand wedge (attaining a thickness of 350 m in only 17,000 years), in order to determine the factors that control the stacking of composing clinothems and their facies distributions, using a grid of high-resolution multichannel seismic profiles tied to a distal continuous recovery borehole. The Po River lowstand wedge, encompassing the last glacial maximum (LGM), is characterized by component clinothems exhibiting a physical dimension (each clinothem is up to 100 m thick and indicates a progradation of the shelf-edge of up to 10 km), commonly attributed to much longer time scales. Clinothems stacking patterns reflect both global (eustasy), and regional (climate-driven supply fluctuations), controls. In particular, three clinothem types are differentiated based on topset geometry, shelf-edge, and onlap-point trajectory, internal seismic facies, and bottomset deposits: Type A has moderate topset aggradation, ascending shelf-edge trajectory, and bottomset mass-transport complexes; Type B has eroded topsets, descending shelf-edge trajectory, and bottomset distributary channel-lobe complexes; and Type C has maximal topset aggradation, ascending shelf-edge trajectory, and concordant bottomsets.

During the interval of overall enhanced sediment accumulation into the basin related to the last glacial maximum chronozone, the distinctive types of clinothems record short-term supply fluctuations. In particular, micropaleontological analysis and sediment accumulation rates suggest that Type B clinothems having bottomset distributary channel-lobe complexes are associated with phases of increased fresh-water and sediment supply in the basin. Clinothems individually span a range of 0.4-4.7 k.y. indicating that: (1) the response time of the Po River lowstand wedge to high-frequency variations in accommodation and sediment supply is as short as centuries; (2) even millennial-scale stratal units can record substantial influence of allogenic controls; (3) sandy deposits at the slope base can be compartmentalized even in a short-duration lowstand systems tract; and (4) clinothems display either in sub-rounded or elongated depocenters denoting a varying influence of marine processes in controlling along-shore sediment dispersal.

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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Modern sequence stratigraphic concepts originated with the analysis of stratigraphic architecture as imaged on 2D seismic data. Subsequently sequence stratigraphy came to embrace multiple disciplines involving the integration of multiple data types. The general concepts, rather than comprising a classical "model" were best applied as a set of rules, and in that way the model was applicable in virtually all settings. Variations on the general theme are countless as no two geologic settings are identical. The integration of process sedimentology with sequence stratigraphic analyses has the potential of further adding precision and accuracy to sequence stratigraphic analyses while also improving understanding of how sediments are deposited.

The integration of sequence stratigraphy and process sedimentology is illustrated in analysis of deep-water lowstand deposits. Understanding the effects of relative sea level changes, a principal driver for sequence stratigraphic effects on sedimentary process, can significantly enhance lithologic prediction in both time and space. Relative sea-level changes can have a profound effect on sedimentary process and associated depositional products. At the onset of relative sea-level fall, the effects can be observed from the shallow shelf to ultra-deepwater depths. On the shelf, lowered relative sea-level results in lowered wave base and consequently a modification in what constitutes equilibrium there. The balance between deposition and erosion will be reset. Erosion will likely occur, while at the same time lowered relative sea level will induce forced regression and shore-face progradation with possible associated incised valley incision. At the same time, lowered relative sea level can have significant effects on the slope and deep water, well below storm wave base. Lowered relative sea level has the potential to influence and modify oceanic currents and consequently depositional elements. In addition, temperature and pressure conditions of the section immediately below the mud line can be affected, which, in turn, can affect the stability of shallow hydrate accumulations. Abrupt dissociation of hydrates can drastically affect the stability of slope substrates and initiate mass flows.

During the course of a sea-level lowstand episode, sedimentological processes at the shelf edge can vary predictably and can have a profound influence on the style of depositional products down-system. At the outset of a period of falling relative sea level, even when river mouths are well inboard of the shelf edge, slope instability associated with hydrate dissociation can occur.

Mass failure can be the result of this instability and herald the onset of lowstand deposition. As relative sea level continues to fall, slope failure becomes more common as rivers get closer to delivering sediment loads to the shelf edge and turbidites begin to dominate. Once relative sea-level lowstand is achieved and sea level then starts to rise, shelf fluvial down cutting ceases and sediment load partitioning results in less sand and less volume of sediment delivered to river mouths. Consequent mass failures leading to turbidity currents tend to be progressively smaller and more mud rich. In response to increased mud content, levee construction will be favored and longer trunk channels and smaller fans will form. In detail, after each major failure event, subsequent re-equilibrating failures should occur, resulting in slope and basin-floor channel filling by subsequently smaller mass flow events, which subsequently can be described as channel fill stages.

Consequently, relative sea-level changes influence sedimentological processes, and changing sedimentological processes, in turn, can have profound influence over depositional products. This feedback loop between sedimentological process and sequence stratigraphic response thus operates in both directions.

Depositional Facies Patterns Across the Modern Great Bahama Bank: Guidelines for Sequence Stratigraphic Correlations in Ancient Systems

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Recent studies of Holocene sediments across the top of Great Bahama Bank have focused on platform-wide mapping of sediment distribution (Harris et. al., 2015), a comparison between key ooid sand bodies (Harris, 2010; Harris et. al., 2011), and an analysis of the variable filling of accommodation space (Purkis and Harris, 2016). Collectively, these quantitative-based studies are aimed to provide new insight into the variability of depositional facies that challenge subsurface correlations, development of rock- and log-based geologic models, and the building of reservoir models. The added insight into depositional facies patterns also leads to new "guidelines" for the sequence stratigraphic correlation of ancient carbonate platforms from the 1D, 2D, or 3D perspective during the analysis of an outcrop or a cored reservoir. Missing from these analyses, however, has been a scrutiny of the physical controls over modern platform-top deposition, which, coupled with the enhanced mapping may provide even more robust quantitative comparative sedimentology and stratigraphy guidelines for interpretation of the ancient.

There remains a relatively poor understanding of the hydrodynamics atop isolated carbonate platforms, including the Great Bahama Bank. As such, a generally accepted premise is that platform-top currents are wind and/or tidally driven; hence, there is limited appreciation of how platform-top facies patterns and depositional cycles may or may not be influenced by ocean circulation surrounding a platform. To explore these fundamental controls, we develop a hydrodynamic model for the Great Bahama Bank and a nearby smaller platform, the Cay Sal Bank, and surrounding waters. The model, run for 12 months at time increments of one minute, is forced by the northward Florida Current, tides, winds, and atmospheric pressure. Platform-top bathymetry for the Great Bahama Bank and Cay Sal Bank are constrained by high-resolution digital terrain models.

The hydrodynamic modeling suggests episodic, but meaningful, excursions of the Florida Current onto the tops of both platforms. Following the lead of Boss and Neumann (1993), on the basis of the model, the Great Bahama Bank and Cay Sal Bank can be partitioned into zones of mean annual hydrodynamic energy. Areas of vigorous tidal exchange in the model correspond to localities where high-energy ooid shoal systems have developed along the Great Bahama Bank platform margin. The portion of the Great Bahama Bank west of Andros Island routinely experiences flow linked to the activity of the Florida Current. A connection between platform-top hydrodynamics and the formation/suppression of whitings is evidenced in this area, which suggests a relationship between the production/deposition of platform-top lime muds and off-platform circulation patterns.

The modeling, along with the supportive facies studies, emphasize how surrounding ocean circulation patterns have the potential to exert control on shallow water hydrodynamics and therefore influence the type and distribution of sediments accumulating on the platform top, their thickness and lateral heterogeneity – including the distribution of extensive hiatal surfaces (sites of non-deposition). A broader understanding of platform-top currents and their diverse controls can aid interpretation of the rock record, including identification of locations on a platform which have the potential to host the most complete depositional cycles and therefore a key to the sequence stratigraphic reconstruction of the system

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

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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 syn-rift 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 Neo-Tethys. From the Sinemurian, sedimentation consisted mainly of 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 syn-sedimentary 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-southeast relay faults. These ridges were separating several kilometers-wide elongated mini-basins, which subsidence was induced by salt/shale withdrawal.

Regionally, diapiric movements were discontinuous in time and space, leading to significant thickness variations within the different stratigraphic units. However, diapirism did not have any major influence on the nature and distribution of sedimentary systems at the basin scale. The impact of diapirs remained 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 bio-constructed 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 was clearly influenced by the lithology of surrounding rocks.

Sequence stratigraphy and sea level. A marine Quaternary perspective

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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 is vital for any revised version of sequence stratigraphy willing to maintain the status of "paradigm" and requires 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.

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

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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 (10's m), 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.

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

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The Williston Basin Bakken petroleum system is a giant continuous accumulation. The petroleum system consists of source beds in the upper and lower Bakken shales and reservoirs in the middle, and upper Three Forks, Pronghorn member of the Bakken, and the middle Bakken. The petroleum system is characterized by low-porosity and permeability reservoirs, organic-rich source rocks, and regional hydrocarbon charge. 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.

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, Nesson, Antelope, Cedar Creek, and Bottineau 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 can be subdivided into three units (up to six by some authors). Most of the development activity in the Three Forks targets the upper Three Forks.

The Three Forks consists of at least five system tracts: a lowstand system tract consisting of the lower continental to supratidal sediments (overlies marine Birdbear carbonates and evaporites); overlain by a transgressive system tract of subtidal dolostone; overlain by a highstand systems tract of the middle Three Forks consisting mainly of peritidal sediments; in turn overlain by a transgressive system tract representing subtidal dolostones; which in turn is overlain by highstand systems tract of the upper Three Forks consisting of peritidal dolostones. A major unconformity separates the Three Forks from the Bakken Formations, probably representing tectonic movement from the Acadian/Antler orogenies. The unconformity is complex in that it probably represents both a lowstand surface of erosion and a transgressive surface of erosion.

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

The Bakken in the U.S. Williston Basin consists of five system tracts: the Pronghorn member represents a lowstand to transgressive system tract (proximal and distal members); a lower transgressive system tract consisting of the lower Bakken Shale; a highstand systems tract consisting of the lower Middle Member; a falling stage to lowstand systems tract consisting of the oolitic, bioclastic, sandy Middle Member; overlain by a transgressive system tract consisting of the upper Middle Bakken and the upper Bakken Shale. The upper Bakken Shale is overlain sharply by the Lodgepole Formation which represents a highstand systems tract.

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.

Relative sea level changes occur in the Bakken and Three Forks intervals related to both tectonics and glaciation. These changes result in the numerous system tracts identified in this study.

The stratigraphic interpretation of subaerial and submarine valleys

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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, where 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.

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

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(Extended Abstract Only)

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 value drops, these spikes are interpreted as planktonic blooms.

Stratigraphic successions having ambiguous gamma-ray (GR) profiles correlations can be correlated accurately by utilizing surfaces that are recognized within chemostratigraphic profiles. Within the Arkoma Basin, Oklahoma, 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 (TST). Lowstands Systems Tracts (LST) and Highstands Systems Tracts (HST) can be distinguished by the degree of bottom-water restriction. Low base level correlates to a greater degree of basin restriction.

Genetic Versus Depositional Sequences for Deltaic Paleo-Orinoco Outcrops

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One of the fundamental aspects related to sequence stratigraphy is the usage of depositional or genetic parasequences, and the eventual classification can be dictated by the nature of outcrop exposures or available subsurface data. Deltaic paleo-Orinoco successions have traditionally been represented as genetic successions based on bounding mudstones, as much of the current understanding has been driven by wireline log and biostratigraphic data. 3D seismic was largely unavailable and underutilized. This approach was largely used to define the stratigraphy across the Southern basin of Trinidad including the Pliocene Morne L'Enfer, Forest, and Mayaro formations. Detailed outcrop studies together with the increasing use of seismic data sets are highlighting the presence and characteristics of sequence boundaries. It is best defined in the Morne L'Enfer Formation where at least three progradational parasequences show increasing evidence for successively shallower paleoenvironments before being truncated by a well-defined sequence boundary. Progradational to aggradational stacking patterns below the sequence boundary change to retrogradational above the boundary, and there is a parallel change from sheet to ribbon sand geometries respectively. Biogenic sedimentary structures are particularly useful in highlighting the shallowing paleobathymetries as they increase in abundance to the unconformity, and disappear following. The variable paleoenvironments, sand geometries, and stacking patterns above and below the sequence boundary are more significant to hydrocarbon reservoir descriptions than that of the maximum flooding surfaces. Additional work using 3D seismic data is needed to define further the extents and significance of paleo-Orinoco depositional packages.