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We gratefully acknowledge the support of the sponsors for making this meeting possible.

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Oral Presentation Abstracts

How has Sequence Stratigraphy Delivered on its Promise? Insights from seismic data

Henry Posamentier
Chevron

Sequence stratigraphy embodies an approach to understanding and predicting the succession of depositional systems as well as the occurrence of key bounding surfaces such as unconformities. These concepts were developed largely from stratigraphic observations derived from 2D seismic data. Historically, this involved analyses of stratigraphic architecture coupled with analyses of reflection character. Though the observations were 2D based, the integration of analyses from a grid of 2D sections yielded regional maps of depositional sequences. These depositional sequences were subsequently populated with appropriate lithologies based on geologic first principles. In addition seismic data helped inform lithologic prediction through analyses of seismic character such as amplitude and continuity. Subsequently, these concepts have been applied to a broad range of data, including outcrop, well-logs, core, and biostratigraphy.

With 3D seismic data and the integration of seismic stratigraphy and seismic geomorphology, far more detailed analyses of depositional sequences have been made possible. Discrete depositional elements can be observed. Analysis of 3D seismic-derived stratigraphic successions can afford a far more comprehensive evaluation of temporal and spatial stratigraphic relationships and in certain circumstances can allow for the testing of the predictive potential of sequence stratigraphic concepts. Examples from deep-water settings will be shown as an example of such a test. A typical sequence initiates with relative sea level fall, an event which initially triggers a succession of geologic responses ranging from mass transport deposition to sand-prone turbidites. Later on in the relative sea-level cycle progressively more mud-prone sediments tend to be delivered to the deep-water environment, yielding distinctively different types of geomorphic elements. An evaluation of the predictive capabilities of sequence stratigraphy necessarily involves the integration of local factors into the prediction. Consequently, in deep water, it is essential to also consider such factors as local tectonics, local sediment supply variations, local physiography, climate and vegetative cover from associated watersheds, drainage basin size, and local seismicity. In any case careful application of sequence stratigraphic concepts can lead to robust geologic predictions provided that local factors are integrated into the assessment.

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Four decades with sequence stratigraphy: Musings on a mature method

William Helland-Hansen and Rob Gawthorpe

Department of Earth Science, University of Bergen, Bergen, Norway

Today, more than 30 years after its introduction, sequence stratigraphy is less disputed after many years with confusingly diversified concepts among its various schools of thought. The methodology includes the breakdown of sedimentary successions along laterally extensive surfaces, enabling geologists to obtain an improved understanding of the genesis of the sedimentary record. Although the synchroneity of some of the key sequence stratigraphic surfaces can be questioned, Mitchum's definition from 1977 of a sequence as "a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities" is in our opinion still valid.

With the basis in the above definition, one useful approach to sequence stratigraphy is to define sequence boundaries as surfaces of levels across which Walther's law is violated, whereas sequences are successions of genetically related packages of strata where Walther's law is obeyed. A consequence of the original definition is that cyclicity is not a prerequisite for sequence definition; recent attempts to standardize sequence stratigraphy are in our mind too much inclined to cyclicity, an approach that unwittingly invites a force-fitting to predefined concepts. Systems tracts, contemporaneous linkages of depositional systems, are fundamental units in most sequence stratigraphic schemes. We argue that the position within base-level cycles should not be used as criteria for systems tract definition and a priori assumptions about the succession of systems tracts should be avoided.

In addition to discussing the practical application of Mitchum's definition, we will elaborate on how sequence stratigraphy has developed over four decades and how this branch of stratigraphy relates to other more recent approaches in examination of basin fills, such as trajectory analysis and source-to-sink studies.

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A Simplified Guide For Sequence Stratigraphy: Nomenclature, Definitions and Method

Vitor Abreu[1], Keriann Pederson[1], Jack Neal[2], and Kevin Bohacs[1]

1. ExxonMobil Upstream Research Company
(vitor.abreu@exxonmobil.com)
2. ExxonMobil Exploration Company

All attempts to "codify" Sequence Stratigraphy have failed, from the first effort of the North American Commission on Stratigraphic Nomenclature in the 80's to the more recent endeavor by the International Subcommission on Stratigraphic Classification in Europe. Reasons for not including Sequence Stratigraphy in the stratigraphic code vary. Complaints include: cumbersome nomenclature; conflicting or obscure causing mechanisms; disagreement on basic definitions, primarily in the basic approach to define surfaces and systems tracts; or simply that Sequence Stratigraphy is a "young" science that might need more time to mature. It is interesting to note that Biostratigraphy— just as old as Sequence Stratigraphy— has a very clear set of rules and terminology, or "code," followed by all biostratigraphers. In fact, Biostratigraphy has the same set of challenges as Sequence Stratigraphy: it has a very cumbersome nomenclature classification of fossils; driving mechanisms for rate of evolution of different taxa is subject of debate; there is strong disagreement as how to classify different species and genera; and it is a relatively young science. Perhaps success in the paleontological community is linked to their approach for defining a code. Biostratigraphy is codified as a method, not a science, based on simple criteria that can be directly observed from available data. Implications for interpretation, in terms of causal mechanisms, follow after initial interpretation, and are not part of the code.

The question is then: Why do Sequence Stratigraphers have such difficulty agreeing on basic rules for identifying surfaces and systems tracts based on direct observational criteria? We suggest that the source of this problem lies not mainly in the original definitions, but in the terminology proposed originally for surfaces and systems tracts. Highstand, Transgressive, and Lowstand are inherently ambiguous terms. Two of them (Highstand and Lowstand) imply sea-level positions and one of them (Transgressive) implies a lateral movement of shoreline. We pose that this mixing of terminology is at the heart of the problem, where it appears to be necessary to integrate interpretation of causal mechanisms with direct observations from data in order to "classify" a surface or a systems tract.

This talk emphasizes the original intent of Sequence Stratigraphy: a method to interpret geologic data. As such, a Sequence Stratigraphic code should be based on criteria directly observable from outcrop, core, well-log, and seismic data— independent of causal mechanisms, duration, or magnitude of events. Similar to the biostratigraphers' code, this proposed approach leaves the interpretation of causal mechanisms as a step after the definition of surfaces and systems tracts. In this presentation, rather than proposing a code *per se*, we offer guidelines for interpretation and updated definitions of classical terms, which are slightly modified from the original definitions. Our modifications are intended to emphasize observational criteria, as well as clarify communication of terminology through the use of a set of translation terms taken from literature. We will also present the application of our proposed method to different data sets in order to show the step by step practical application of this method.

Table 1: Surface definitions with translation terms, and primary and secondary recognition criteria. Data for recognition criteria marked with superscript letters: *s=seismic; w=wells; c=core; o=outcrop*.

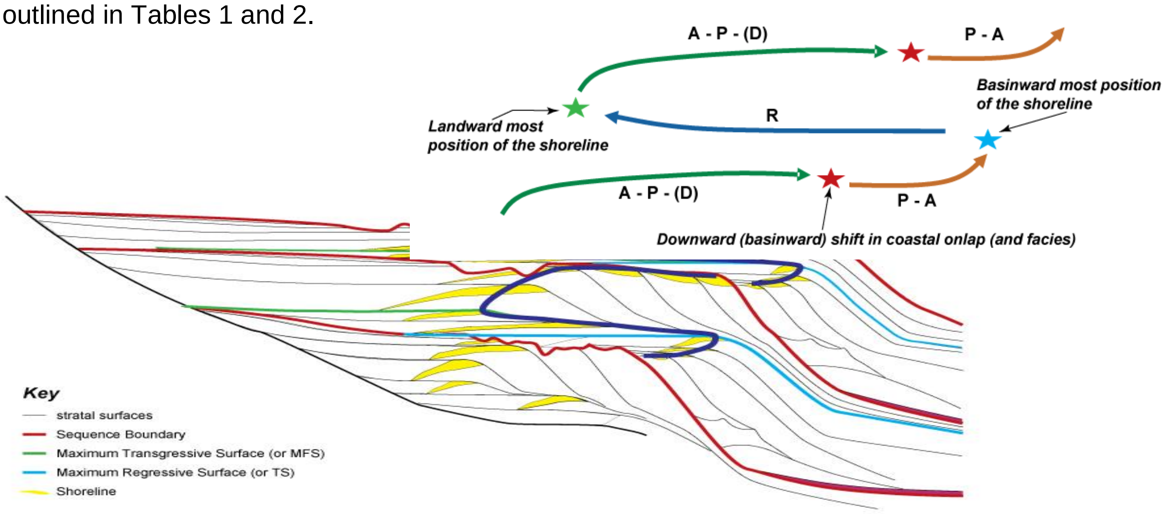
Surface	Translation Terms	Primary Recognition Criteria	Secondary Recognition Criteria (based on limited available data)
Maximum Flooding Surface *MFS*	Maximum Transgressive Surface *MTS*	Atop maximum landward position of the shoreline	Downlaps[s]. Turn around in stacking pattern from retrogradation to aggradation or progradation[w,c,o].
Transgressive Surface *TS*	Maximum Regressive Surface* *MRS*	Atop maximum basinward position of the shoreline	Surface beneath first backstep (landward step) of shelf-slope break[s]. Turn around in stacking pattern from progradation or aggradation to retrogradation[w,c,o].
Sequence Boundary *SB*	Sequence Boundary *SB*	Beneath abrupt basinward shift in shoreline	Surface beneath first increase in accommodation after progradation or degradation[s]. Break in shoreline trajectory 'S'[s]. Truncation and/or toplap below, onlap above[s]. Abrupt occurrence of proximal facies over distal facies[w,c,o].

**sensu* Embry, 2002

Table 2: Systems Tracts definitions with stacking patterns and recognition criteria.

Systems Tract	Observable Stacking Pattern	Bounding Surfaces	Accommodation/Sediment Supply Trend
Highstand Systems Tract *HST*	Aggradation to Progradation to (possible) Degradation *A-P-(D)*	Above: ***SB*** Below: ***MFS (MTS)***	Decreasing, at increasing rate
Transgressive Systems Tract *TST*	Retrogradation *R*	Above: ***MFS (MTS)*** Below: ***TS (MRS)***	Rapidly increasing, to a maximum
Lowstand Systems Tract *LST*	Progradation to Aggradation *P-A*	Above: ***TS (MRS)*** Below: ***SB***	Increasing, at increasing rate

Fig. 1: Accommodation succession showing definition of surfaces and systems tracts using definitions outlined in Tables 1 and 2.



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Sequence stratigraphy by accommodation succession method, stratigraphic hierarchy and stratigraphic signatures

Jack E. Neal, Vitor Abreu

1. ExxonMobil Exploration Company (jack.e.neal@exxonmobil.com)
2. ExxonMobil Upstream Research Company

Sequence stratigraphy is a method to systematically place key stratal observations into a 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 conformities” (Mitchum et. al., 1977), which forms as a result of transgressions and regressions. A depositional sequence and its internal architecture (Fig.1) are preserved in the rock record due to changes in the rate of accommodation (space) and sedimentation (fill). Despite the simplicity of its objective and core concepts, sequence stratigraphy has always suffered from a jargon problem and attempts to mix physical observations (geometry) with causal mechanism interpretations (position on a sea-level curve or eustasy). We propose a “back-to-basics” approach to sequence stratigraphy that focuses on observations of stratal geometries, stratal terminations and vertical stacking patterns resulting from repeated successions of accommodation creation and sediment fill. The repeating motif in a depositional succession starting with negative accommodation on the shelf (unconformity = sequence boundary), to maximum accommodation and then to negative again consists of progradational to aggradation (PA or lowstand ST) stacking, followed by retrogradation (R or transgressive ST), and then aggradation to progradation to degradation (APD or highstand ST) stacking. These stacking patterns are bounded by key surfaces that are recognized by stratal terminations and vertical facies successions (Fig.2). Resulting stratigraphic frameworks are based on the physical relations of strata, independent of time duration and not tied to a position on a sea level curve but with an awareness of hierarchal stacking. Such an approach is useful when working across multiple data resolution scales and vintages to more accurately characterize the stratigraphy and improve our predictive power. As better data is collected and resolution improves, units once thought to be relatively conformable can be demonstrated to contain internal unconformities, which leads to a new set of predictions and opportunity. A stratigraphic framework built on objective physical stratigraphy recognition criteria from the accommodation succession methodology provides flexibility, longevity, and eases communication.

Of course there is more to sequence stratigraphy than just nearshore siliciclastic environments. Carbonate systems responds to transgression and regression differently than siliciclastic ones but the same method focused on physical stratigraphy, accommodation and fill changes applies – only its expression may differ. In deep marine environments, sediment supply and bathymetric gradient are major controls. Likewise, continental settings feel accommodation and sediment supply variations through changes in climate and tectonics. Without a tie of correlative surfaces into the nearshore environment, sequence stratigraphy is still possible but the stacking pattern equivalents are inferred and bounding surfaces more difficult to identify. Chronostratigraphic frameworks can improve the correlation. In the absence of high resolution chronostratigraphic data, certain periods of geologic time have a “stratigraphic signature”. Use of a consistent method focused on physical stratigraphic properties, independent of sea level and time duration interpretation will improve sequence stratigraphic communication and predictability.

Fig. 1: Shoreline stacking patterns relative to rates of accommodation and sedimentation

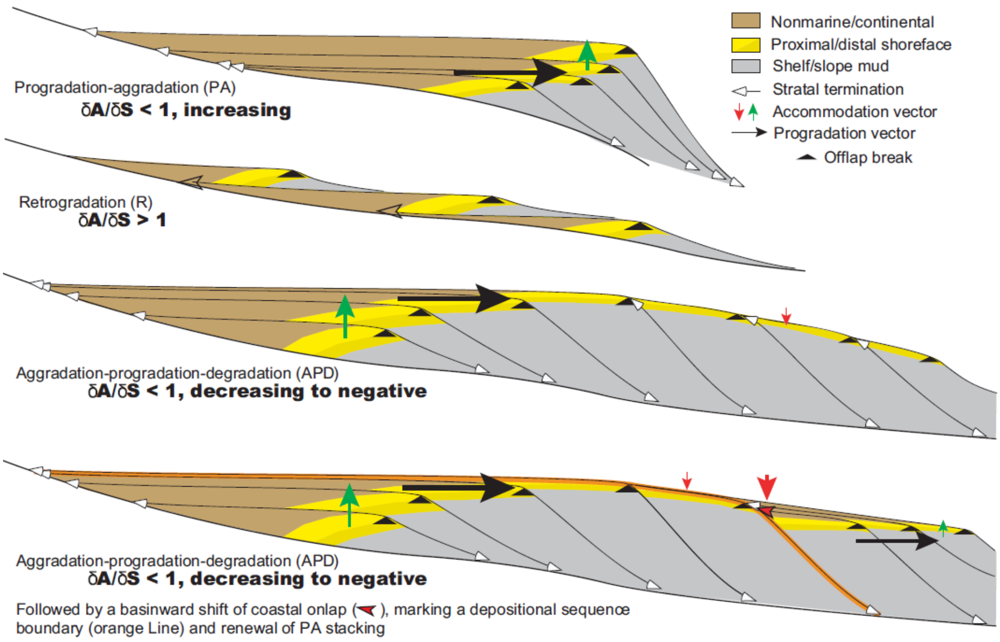
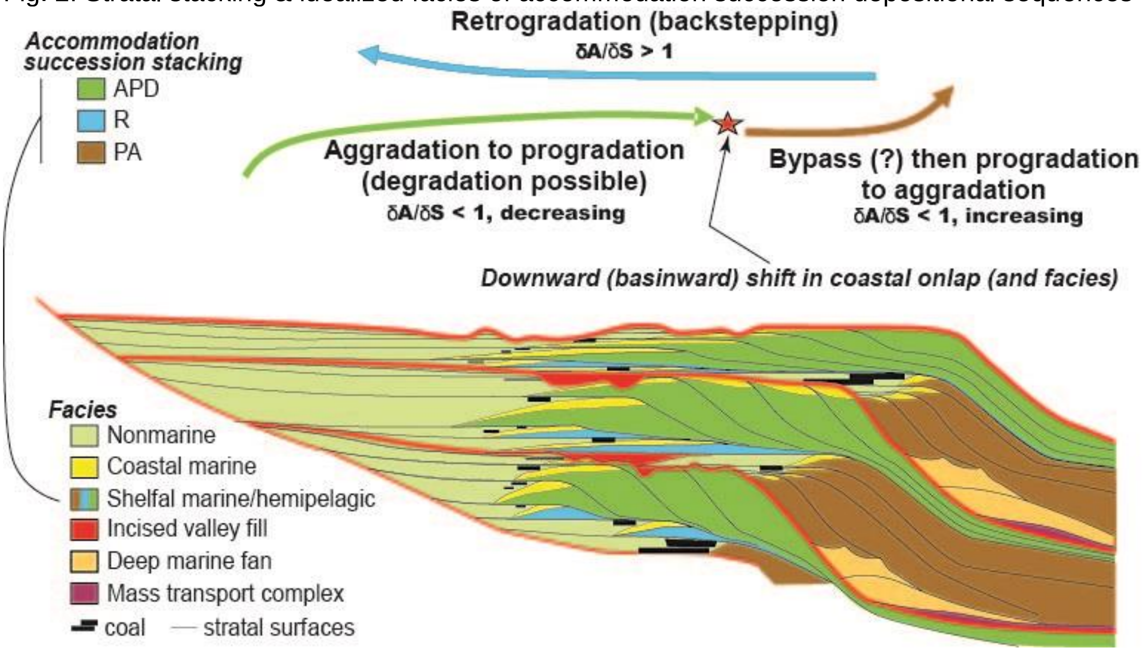


Fig. 2: Strata stacking & idealized facies of accommodation succession depositional sequences



NOTES

Modelling spatial and temporal variation of productivity, anoxia and TOC associated with sea-level changes.

C.J. Bjerrum[1], M. A. Azhar[1], M. Lenniger[1], S. A. Rosing[1]

Nordic Center for Earth Evolution, and Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark.(cjb@ign.ku.dk)

A fundamental assumption of many sequence stratigraphic interpretations is that the zones of maximum gamma radiation and/or organic matter enrichment in marine sediments are indicative of the maximum flooding zone (~MFS). This assumption, for good reasons often is correct. However, the oceanographic/sedimentological processes underpinning the spectral gamma signal or total organic matter (TOC) content have received little quantitative evaluation from first principles. A thorough process understanding becomes ever more pressing when trying to predict the spatial TOC distribution during shale gas exploration.

Here, we present modelling result on the spatial and temporal TOC distribution using a high resolution three dimensional ocean model coupled to a sequence architecture model. Our ocean model includes a new ecosystem and water column chemistry module capable of handling marine organic carbon cycling under oxic as well as anoxic and sulfidic conditions. First, we address the spatial productivity and water column chemistry related to changing shelf geometry during changing relative sea level. Second, we model the TOC distribution using the spatially and temporally varying flux of organic matter to the seafloor as a function of changing sea level.
Importantly, we find that we can reproduce the TOC distribution in modern upwelling systems only when the ocean model has a resolution permitting ocean eddies (ie. ~5 km). In the model shelf eutrophic conditions and anoxia naturally develops in upwelling systems, and variably in other systems, when the shelf geometry becomes sufficiently wide, all else being equal. The productivity is spatially variable depending on water depth and oceanographic fronts. This variability, together with changes in sedimentations rate, influence the spatial distribution of TOC. A two hump structure in dip section is generated as observed in modern shelf sediments.

By coupling the ocean model results to our nutrients and TOC enabled sequence architecture model we find, as expected, that the MFS is diachronus. In general, based on 100.000 different basin configurations, the TOC or gamma enrichment of offshore fine grained sediments occur during the early relative sea-level rise in the distal setting and late in the rise in more proximal settings. The timing depends on sediment delivery, subsidence, shoreface-coastal geometry, rate of sea-level rise, and wave energy. In some configurations the TOC enrichments even occur during sea-level fall. In conclusion the sequence stratigraphic concept of MFS is supported in general in our new oceanographic-sequence architecture model framework with significant deviations in some sedimentation-basin configurations. Our successful modelling of modern upwelling systems seems promising toward source rock prediction in new ventures.

NOTES

Is there a stable reference frame for eustasy?

Gurnis, M.

Seismological Laboratory, California Institute of Technology, Pasadena, CA, United States (e-mail: gurnis@gps.caltech.edu)

Studies of sea level change over periods of tens to hundreds of millions of years often implicitly assume that there is a stable reference frame for eustatic change. We will critically evaluate this assumption and show that the topography induced by mantle convection, dynamic topography, likely precludes any such reference frame. However, this does not imply that there isn't eustatic change. We will argue that the coupled dynamics of plate tectonics and mantle flow has had an important influence on sea level fluctuations and that it's effects have been recorded in the sedimentary record on continents including passive margins. We explore these possibilities empirically and theoretically, highlight pitfalls and uncertainties, describe approaches that integrate plate tectonics and mantle dynamics, and discuss possibilities for future research directions.

Since the emergence of plate tectonics, a simple connection between mid-oceanic ridge volume and 'sea level' has been made. Although there is general agreement between the inundation since the Late Cretaceous inferred from remaining marine sediments on continental platforms and that inferred from volume of ocean basins in plate tectonic reconstructions, the model fails to conserve mass. This failure is considered along with the physics of dynamic topography from flow in a viscously dominated fluid. A more expansive theoretical view of sea level in principle predicts the vertical motions of continents since the Late Cretaceous that are discrepant from the overall trend, i.e. epeirogenic motions versus eustasy.

The vertical motions inferred from the rock record is intimately tied to local sea level and therefore the record should be interpreted in terms: (a) evolving mantle convection and subduction (and by consequence evolving topography and the geoid); (b) plate motions with respect to this changing mantle (since the rock record is carried by the plates); (c) the volume of ocean water; and (d) the carrying capacity of the oceans which is a function of sea floor ages, dynamic topography, and the changing surface area of continents. We have embodied these ideas in a workflow linking a paleogeographic system with spherical mantle convection with stretching passive margins that are referred to as 4-D dynamic earth models. Both forward and inverse models of mantle convection matching present day seismic tomography and the geoid have been used.

Details of regional vertical motions provide guidance on how the rock record can be connected to models. As time permits, we describe case studies from North America, South America, Australia, New Zealand, and Indonesia using different combinations of present day residual topography maps, isopachs, paleoshorelines, tectonic subsidence curves, and rock uplift inferred from low temperature thermochronology that are integrated with global or regional 4-D dynamic earth models. Several different kinds of signals over length scales of <100 km to >2,000 km and with amplitudes >100 m can be identified. Both long-wavelength tilting as well as the spatial migration of sediment depocenters are evident. In some global models, self-consistency between the buoyancy of subducted material and the paleo-ages of the oceanic crust overcomes mass conservation issues in earlier concepts of sea level change. We find that a common component to sea level change, mostly driven by the age distribution of the sea floor, is preferred, although for many continents the dynamic

topography signal may dominate. Although there is no stable reference frame, this common component to global sea level change implies there still is a eustatic component. Future approaches to developing sea level curves over the last one hundred million years (or earlier) will need to allow for both a global uniform component and regional variations.

NOTES

The influence of large-scale tectonics, mantle flow and climatic change on sediment accumulation

John J Armitage [1], Miguel Andrés Martinez [1], Jason P. Morgan [1], Marta Perez-Gussinye [1], Robert A. Duller [2]

1. Department of Earth Science, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK
(john.armitage@rhul.ac.uk)
2. Department of Earth, Ocean and Ecological Sciences, School of Environmental Sciences,
University of Liverpool, 4 Brownlow Street, Liverpool L69 3GP, UK

Change in the rate of sediment accumulation at passive margins and within the continental interior have been linked to extension of the lithosphere, mantle flow and climatic change. For example, upper mantle flow has been invoked as the cause of Neogene uplift of the interior Rocky Mountains and Colorado Plateau, warping and tilting sediment transport slopes that link to the widespread deposition of gravel units within the Great Plains. These geomorphic and sedimentologic features however can also be generated by an increase in run-off, since erosion will promote change in elevation due to isostatic compensation, and the loading of the lithosphere by the deposition of sediment. Is their a diagnostic difference between signals of change in uplift and climate which allows us to differentiate between the processes responsible for change? We will present a general length dependent diffusive sediment transport law to model both erosion and deposition, which includes the concentrative effects of river systems. The simplicity of the approach means that we can collapse sediment transport to one dimension, and couple erosion and deposition with plate flexure and the visco-elastic flow of the upper mantle.

From the coupled surface processes - flexure model, we will show that for a landscape that is gently tilted, a change in run-off has a minor effect on transport gradient, as sediment transport and associated flexural response maintain topography at a similar elevation. However, there can be a significant change in depositional style when the degree of tilt is altered by, for example, a local change in upper mantle density. An increase in buoyancy within the upper mantle, which increases slopes, leads to a transient reduction in grain-sizes deposited at a fixed location. A reduction in tilt has the opposite effect, the older deposits are eroded and the erosion-deposition transition rapidly moves down-system.

The same model of surface processes is also coupled to a visco-elastic solver for deformation of the lithosphere. This model is put under extensional stress, and we explore the effect of erosion and deposition as the model continent rifts. Regions of unconformity and increased sediment accumulation at the young margins are found to naturally occur without additional climatic forcing. Sediment delivery to the margin changes due to local change in topography as faults form and the surface uplifts. This complicates linking sedimentary sequences to large-scale change in extension or climate.

Based on the results of our coupled model, we suggest that widespread conglomerate units within the continental interior, such as the Ogallala Formation in Nebraska, USA, are a consequence of a reduction in slope as the dynamic support for regions of high topography reduces. Climatic change however has a much weaker influence on long-term sediment accumulation.

NOTES

The Relationship between Sequence Stratigraphy and Dynamic Topography

Mark Hoggard

Bullard Laboratories
Madingley Rise
Madingley Road
Cambridge
CB3 0EZ

The evolving pattern of convective circulation within the Earth's mantle generates and maintains dynamic topography which is some fraction of observed topography. Spatial variations of dynamic topography are easy to measure within the oceanic realm since the subsidence history of oceanic lithosphere as a function of age is well known. A group of us have used inventories of seismic reflection and wide-angle profiles to determine dynamic topography of the oldest oceanic lithosphere which abuts passive continental margins. Our results show that oceanic lithosphere has dynamic topographic anomalies of +/- 1 km with wavelengths of 500-1000 km. These significant anomalies usually intersect coastal shelves and so we expect that the development of these anomalies has affected sequence stratigraphic architecture in important ways. A series of examples will be used to illustrate how sequence stratigraphy can be profoundly influenced by changing patterns of dynamic topography. First, along the West African margin a set of dynamic topographic domes intersect the shelf. Onshore, the Neogene growth of these domes is recorded by emergent marine terraces and by drainage patterns. Offshore, an Oligo-Miocene switch from aggradation to progradation together with a series of younger disconformities have modified stratigraphic architectures along the shelf. Secondly, along the Northwest Shelf of Australia there is excellent evidence for about 700 metres of dynamic drawdown of the oldest oceanic floor which abuts this shelf. Regional mapping and backstripping of clinoformal geometries within a Miocene carbonate reef complex shows that there is a dramatic switch from progradation to aggradation which cannot be attributed to glacio-eustatic sea-level variations. Instead, this switch appears to reflect growth of dynamic drawdown within the mantle. Finally, the Icelandic plume is a large convective upwelling which has controlled vertical motions along fringing North Atlantic continental margins over the last 60 million years. There is independent evidence that the temperature of this plume fluctuates as a function of time. These fluctuations are recorded within the sequence stratigraphic architecture of fringing margins where a series of ephemeral terrestrial landscapes have been mapped. In this way, transient activity of the Earth's convecting mantle is stratigraphically recorded. Thus the sequence stratigraphic architecture of continental margins appears to be an important repository of details about convective circulation which are otherwise difficult to obtain.

NOTES

Building a better eustatic model: comments on Palaeozoic sea level change

David C. Ray, Andrew Davies, Roger B. Davies and Michael D. Simmons

Neftex, 97 Jubilee Avenue, Milton Park, Abingdon, OX14 4RW, United Kingdom; David.Ray@neftex.com

The establishment of a eustatic model of sea level (SL) change requires a global dataset rooted in a detailed knowledge of regional stratigraphy and built around key reference sections containing detailed age and relative SL information. An understanding of events affecting the biosphere, atmosphere and hydrosphere is also critical in the calibration of SL change between multiple palaeo-continents. The utilisation of such a global dataset is presented here and provides a clearer understanding of eustatic SL change and associated events during the Palaeozoic.

By an evaluation of over 220 key sections from 40 countries, augmented by primary fieldwork, we have identified 19 second and 64 third order sequence stratigraphic cycles in the Palaeozoic Era. In establishing our record of SL change only sections that are biostratigraphically well constrained, show an unambiguous sedimentological expression of relative SL change and are associated with tectonically stable regions have been used. Furthermore, attention has been given to sections exhibiting isotope excursions, biotic events, glaciogenic sediments and palaeo-water-depth indicators.

The long-term SL trend shows a broad rise through the Cambrian to Late Ordovician, with second order SL lows during Series 3, Furongian and Middle Ordovician times. Following the Late Ordovician SL high, pronounced SL fluctuations are observed until the middle Silurian and appear coincident with the Early Palaeozoic Icehouse. After which SL broadly falls until the Early Devonian. The remainder of the Devonian is represented by three drawn-out episodes of transgression (second order) separated by pronounced regressions. Carboniferous to middle Permian times are associated with the Late Palaeozoic Icehouse and exhibit some of the most notable SL changes of the Palaeozoic. With the exception of a Visean SL low, second order SL lows occur near each of the Epoch boundaries during Carboniferous and Permian times.

From Cambrian to Devonian times SL change varies in magnitude from a few tens of meters to a little over one hundred meters, with the largest changes broadly coeval with glacial-interglacial intervals. More substantial SL changes are reported from the Carboniferous and early Permian. In addition episodes of regionally developed sea floor anoxia, biotic change and carbon isotopic excursions also appear closely linked to second and third order SL change and are most widely evident during Middle Ordovician to Early Mississippian times.

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High amplitude Cretaceous sea level fluctuations registered in the carbonate systems of the Eastern Arabian Plate

Frans van Buchem, Emmanuel Dujoncquoy, Florian Maurer, and Niels Rameil

Maersk Oil, Esplanaden 50, 1263 Copenhagen K, Denmark (frans.vanbuchem@maerskoil.com)

Exceptional outcrop and subsurface datasets available for the carbonate dominated Lower and Middle Cretaceous succession of the Eastern Arabian Plate allow to document and age date a number of high amplitude sea level fluctuations that controlled plate-wide sedimentation patterns. Even though locally tectonic factors have modified the sedimentary expression, the overriding eustatic control is clearly recognisable and can be correlated with similar events on other tectonic plates. The case is made for the need of systematically constructed transects across tectonic plates (margins) in order to improve the existing global eustatic reference curves.
Our documentation consists of three parts. Firstly, the lower part of the Lower Cretaceous (Upper Berriasian to Late Valanginian) of Oman is represented by a regional 3D seismic survey showing a carbonate platform (Habshan and Salil formations) prograding over a distance of about 150 km. The clinoforms document the variation of sea level fluctuations during this interval, with medium-scale sea level fluctuations in the order of 50 to 100m in the Berriasian, a maximum sea level fall in the order of 100-150 m in the Early Valanginian, and smaller fluctuations (20 to 50m) in the Late Valanginian. Secondly, a plate-wide dataset including seismic, logs, core, outcrops, and detailed biostratigraphy and C-isotope stratigraphy, documents the relative sea level fluctuations recorded in the Barremian and Aptian/Early Albian (Kharaib and Shu'aiba Formations). This interval is well known for the occurrence of the Early Aptian global transgression, which in large areas is marked by the accumulation of organic matter, such as in the Bab Basin (Oman, UAE, Iran). In addition, evidence has also been found for a long lasting (5 My), eustatic lowstand that covered most of the Late Aptian. The associated sea level fall is estimated to be in the order of 50m. Finally, the Cenomanian and Turonian interval (Natih, Mishrif and Sarvak Formations) is also characterised by a number of significant sea level fluctuations (20 to 40m in amplitude) that are expressed at the scale of the plate.

The construction of similarly complete and well documented transects along the margins of the NeoTethys Ocean would be an important step towards establishing a better insight in the nature (rate and amplitude) of global sealevel fluctuations and their effect on Cretaceous sedimentation patterns.

NOTES

William Smith Lecture: The Sequence Stratigraphy Revolution

Ron Steel
University of Texas at Austin, USA & Aberdeen University, UK

As co-discoverer of the Spitsbergen shelf-margin outcrop transect, the first outcrops to detail the Exxon slug diagram, I have no doubt that there was substance and foresight to Exxon's early claim of a fundamental and repetitive motif seen on global seismic data, that was to become the new key to stratigraphy. The motif was a basinward-accreting then retrograding stratal 'sequence' that takes many shapes and dimensions; it varies from the simplest T-R platform cycle to the larger scale and more complex clinoform shapes that include deepwater deposits. A key aspect now known is that the sequence develops across the shelf and beyond the shelf edge during a time interval of a few 100Ky, far shorter than that earlier envisaged by Exxon. Because the basic shelf-margin clinothem has open marine, tramline-like topsets and implies cross-shelf transgression as well as regression, the boundaries of the sequence are fairly well defined and likely to be an allogenic response to unsteadiness in the combined supply and accommodation drivers. However, there is huge variability (and major correlation problems) inside the sequence, and currently great progress is being made on autogenic responses at these shorter time scales (100s to 1000s of years).

The Sequence revolution has thus brought significant value to stratigraphy in terms of (1) highlighting the dynamic character of the new stratigraphy; (2) providing guidelines and a methodology for deciphering stratigraphy in new regions, i.e., emphasizing the need to identify the basic regressive and transgressive components of the shelf-transiting system, and if the basin water is deeper than 150-200m, an additional deepwater component exists or should be predicted. At the main topographic break of slope (shelf edge), correlation is no longer layercake, but must be downslope; and (3) it provides the framework for a source-to-sink understanding of stratigraphy, and thereby enables a deciphering of sediment-budget, grain size, reservoir & source rock and other partitioning from alluvial plain to deepwater environments. The budget volume partitioning is beginning to bring surprises. A component of this source-to-sink understanding is the predictive power that Exxon sought.

Sequence stratigraphy has been much less successful in providing an understanding of the sequence-controlling variables, partly because it was initially tied strongly to sea-level change, and stratal patterns were given sea-level terms. Ironically, just as a great number of stratigraphers (including myself) appeared to reach consensus on terminology in 2009, Exxon stratigraphers recanted and suggested that it may have been a mistake to link stratal pattern and sea-level condition. Release from this constraint is now allowing great progress in integrating outcrop, subsurface and experimental studies in dynamic stratigraphy. On well-supplied margins, deepwater fans are now commonly reported at sea-level highstands, the non-uniqueness of stratigraphic changes and key surfaces is being emphasized, and autogenic responses in experimental stratigraphy are being seen on longer time scales. These approaches are no longer 'threatening' to sequence stratigraphy, but strengthen it.

NOTES

The Autostratigraphic View of Non-uniqueness

Tetsuji Muto

Graduate School of Fisheries Science and Environmental Studies, Nagasaki University
1-14 Bunkyomachi, Nagasaki, 852-8521 Japan (tmuto@nagasaki-u.ac.jp)

A principal theorem in geology that dates back to Huttonian theory of the late 18th century suggests that given steady external forcing by constant sediment supply (rate Qs) and constant relative sea level rise (rate Rslr), a deltaic depositional system grows to achieve an equilibrium configuration and produces a particular sediment-stacking pattern. This mode of stratigraphic response is referred to as *equilibrium response*, by which steady external forcing results in steady stratigraphic pattern of deposition. Most existing models of genetic stratigraphy including sequence stratigraphy rely, explicitly or implicitly, on the assumption that equilibrium response holds true in general, and consequently are apt to favor the interpretation that any large-scale facies break or change in the stratigraphic pattern within a deltaic succession reflects unsteady external forcing such as temporal changes in Rslr or Qs. With this conventional view of stratigraphic responses, it would be difficult to imagine that the same (i.e. non-unique) stratigraphic configuration can be produced through different modes of response of the depositional system.

Autostratigraphy suggests that equilibrium response is not the only response to steady forcing, nor even necessarily the expected response. Steady dynamic external forcing generally results in unsteady stratigraphic response, and steady stratigraphic configuration can result from unsteady dynamic external forcing (Fig. 1). These are referred to as *non-equilibrium responses*, which arise from downstream transformation of the sediment- supply signal from constant to variable due to systematic deposition and erosion along the path of transport. Unfortunately, stratigraphic interpretation of equilibrium response can often be flawed due to a failure to appropri- ately consider non-equilibrium response. The insufficient awareness of non- uniqueness is partly due to ignorance of non-equilibrium responses.

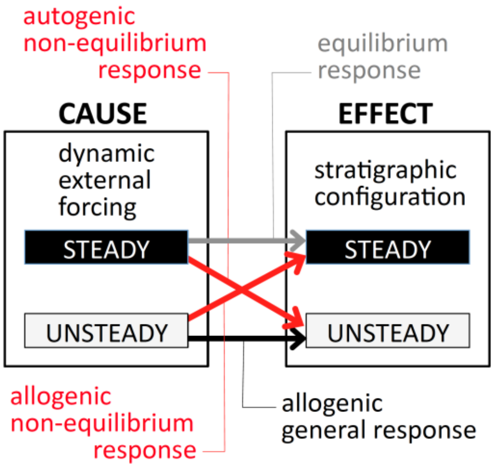


Figure 1. The autostratigraphic rationale for non-uniqueness in terms of strati- graphic responses of a depositional system to dynamic external forcing.

The intrinsic non-uniqueness of stratigraphic products would be typically illustrated with shoreline autoretreat in river deltas evolving under relative sea level rise. Increasing Rslr and/or decreasing Qs can produce a regressive-transgressive succession that is allogenic but looks closely similar to an autoretreat-autobreak succession, though the effect of allogenesis is unknown until the effect of autogenesis is subtracted from the succession. This example represents a case that a particular, unsteady stratigraphic configuration arises from different histories of the forcing.

Another possible scenario for non-uniqueness is that a particular, steady stratigraphic configuration arises from different histories of forcing. An illustrative example for this is alluvial grade that is attained in a moving-boundary system. As has recently been clarified by experimental studies, an alluvial river emptying into sea can become graded through equilibrium response to steady sea level forcing (autogenic grade) and also through non-equilibrium response to unsteady sea level forcing (allogenic grade), both dependent on basin slope conditions.

No-uniqueness can be realized even within the same mode of stratigraphic response but with different basin floor configurations. Figure 2 shows river deltas built in tank experiments where deltas prograded over bathymetry that varies in the transverse direction. Each delta prograded while maintaining an arcuate shoreline displaying approximate axial symmetry, implying that the differential bathymetry exerted no critical influence on the overall shoreline configuration. In fact, basement bathymetry intensely affected the local residence time and avulsion frequency of active feeder channels. The point here is that the non-unique shoreline configuration arose from significantly different behaviors of feeder channels.

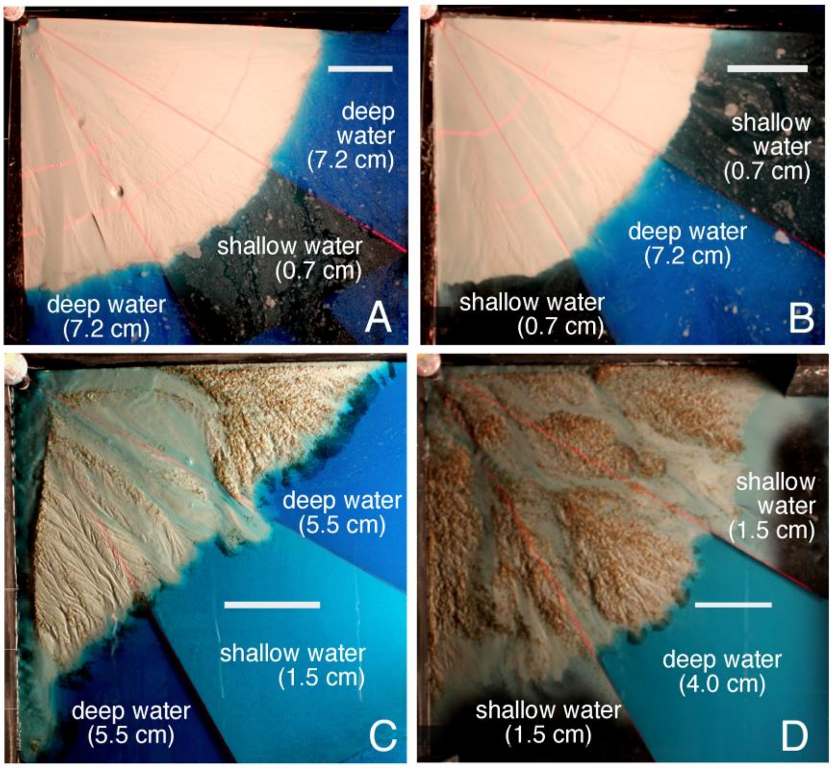


Figure 2. River deltas produced in tank experiments: A and B with single grain-size sediment, C and D with bimodal grain-size sediment. A differential basement was created by placing a several-cm high, wedge-shaped platform on the basement, so that the water depth of the basin floor changed abruptly in the direction transverse to the delta's progradation. Scale bar is 20 cm long.

NOTES

Sequence stratigraphy and lithostratigraphy, the devil is in the details

Joep E.A. Storms, Andrea Forzoni, Helena van der Vegt, Liang Li

Dept. Geoscience and Engineering, Delft University of Technology
j.e.a.storms@tudelft.nl

Sequence stratigraphy is an extremely useful tool to describe depositional units in a chronological framework. The recognition of general stratigraphic contacts (unconformities and their correlative conformities) and linked contemporaneous depositional systems reflecting the accommodation/sedimentation regime during base level change has had a major impact on the field of sedimentary geology.

The emphasis on stratal architecture, geometries and surfaces in sequence stratigraphy has increased the understanding (and to some degree the predictability) of a depositional sequence. Yet, the numerous examples from sequence stratigraphy being applied to field data show that this unifying theory needs to be customised for each specific setting as each basin and each setting is unique.

As sequence stratigraphy builds on a basic building block, the parasequence, it is essential to understanding its formation in response to external forcings. First, we need to better understand lithostratigraphy within a parasequence, and second how do changes in parasequence formation affect the bigger scale (system tract and sequence). So far, little attention has been paid to bridge the scales from lithostratigraphy at the parasequence scale to the systems tract scale in an attempt to understand how variability in lithostratigraphy translates into changes of systems tract .

For example, studies addressing the formation of continental shelves using numerical simulation models generally confirm the sequence stratigraphic concepts and focus on base level changes. Numerical models, however, can also be used to study in more detail the formation of individual parasequences at the lithostratigraphy scale and how they stack into systems tracts given a base level change and a sediment supply signal.

We make use of a simple process-response model (BarSim) to simulate a regressive systems tract consisting of shallow-marine deposits. Using BarSim provides the opportunity to test hypotheses regarding changes in both sediment supply rates and sediment grain size distribution during the formation of the regressive systems tract which forms a continental shelf. As the model simulates the dispersal systems of sand, silt and clay, we can classify the lithostratigraphy in terms of three granulometric facies: amalgamated sand (AS), interstratified sand and mud (ISM) and laminated mud (LM). This lithostratigraphic classification can be directly compared to field observations from outcrops or to well data. The distribution of the granulometric facies in the regressive systems tract shows a wide variability, depending on the provided mean grain size over time and it also affects the overall geometry of the regressive systems tract. In conclusion, the future of sequence stratigraphy could benefit from a better understanding of the observed lithostratigraphic heterogeneity at the parasequence scale as this heterogeneity will translate in geometric variability of parasequences and any other higher order units within the sequence stratigraphic framework.

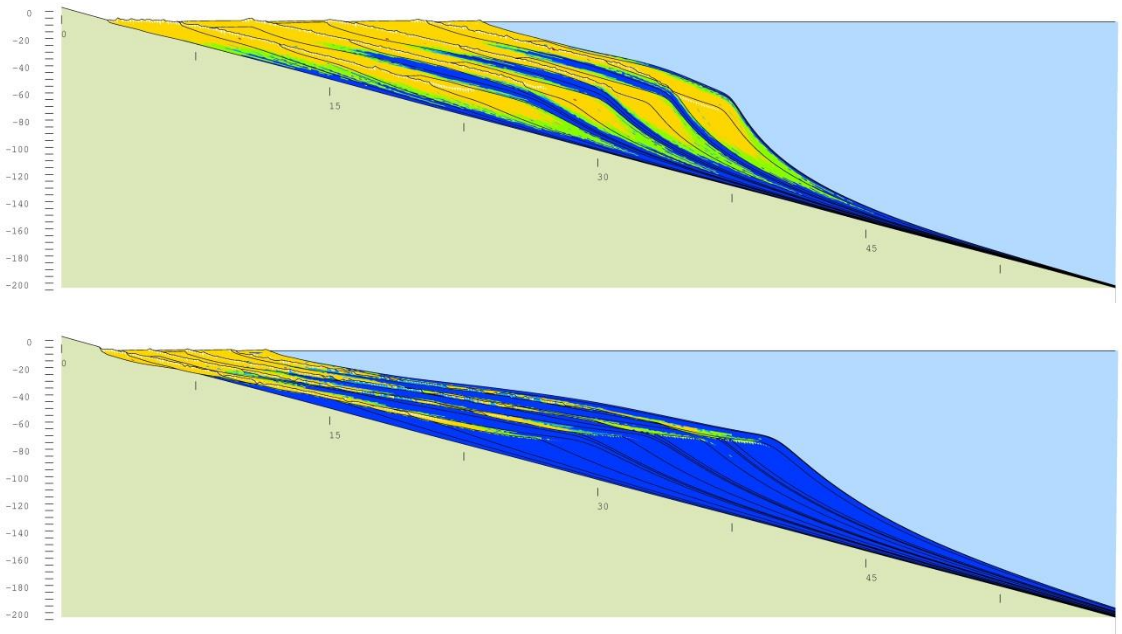


Figure: two examples of regressive systems tracts building a continental shelf with a similar base level and sediment supply signal in a similar basin setting for a sand-rich (top) and a clay rich (bottom) setting. Horizontal scale in kilometers, the vertical scale is in meters, dark blue represents Laminated Mud facies (LM), green represents interstratified sand and mud facies (ISM), and yellow represents amalgamated sand (AS)

NOTES

Re-interpretation of sequence stratigraphic architectures as the product of autogenic behaviours and variations in sediment flux: Upper Cretaceous Blackhawk Formation, Book Cliffs, Utah, U.S.A.

Gary J. Hampson

Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK. (g.j.hampson@imperial.ac.uk)

Numerical and physical experiments have repeatedly generated insights that contradict the sequence stratigraphic model that is near-universally used to interpret ancient strata. Two such insights are considered here:

- Stratigraphic architectures at a range of spatial scales may be generated by the internal dynamics of the erosion-transport-depositional system under constant external forcing. We need to recognise such autogenically driven architectures in ancient strata, in order to robustly interpret allogenic controls.

- Experimentalists have developed methods to characterise the role of sediment supply in controlling stratigraphic architecture. We often pay lip service to the role of sediment supply in generating ancient stratigraphic architectures, but it is rarely addressed meaningfully.

The Upper Cretaceous Blackhawk Formation. Castlegate Sandstone and related strata exposed in the Book Cliffs of east-central Utah are widely used as an archtype for the sequence stratigraphy of marginal-marine and shallow-marine strata. Stratigraphic architectures in these strata are classically interpreted to reflect forcing by relative sea level, but key aspects can instead be attributed to autogenic behaviours or variations in sediment flux.

- Blackhawk Formation coastal plain deposits exhibit only weak stratigraphic organisation related to relative sea-level change. Instead, the architectures, dimensions and distributions of major channelised fluvial sandbodies were controlled principally by avulsion history and local variations in sediment flux and transport capacity. These variations are likely expressed by subtle architectures that record shifts in the location of sediment point sources and variations in local wave climate within wave-dominated deltaic parasequences. At larger spatial and temporal scales, parasequences in the lower Blackhawk Formation are stacked to form concave-landward, net-regressive shoreline trajectories that may record autogenic behaviour (autoretreat) of the erosion-transport-depositional system. Parasequence stacking in the upper Blackhawk Formation forms concave-seaward, net-regressive shoreline trajectories that reflect decreasing tectonic subsidence rate and/or increasing sediment flux.

- Relative variations in sediment supply can be characterised using a mass-balance framework that captures the rate of upstream-to-downstream loss of sediment (mass) and the spatial distribution of tectonic subsidence. Comparison of the downsystem mass-balance characteristics of eight stratigraphic intervals (each equivalent to a parasequence set) suggests that there were depositional gains and losses of shallow-marine shale in the middle-to-upper Blackhawk Formation, which can be attributed to longshore sediment transport. These results are consistent with three-dimensionally complex stratal architectures in the Mancos Shale. The upstream-unconformable base of the Castlegate Sandstone is marked by a pronounced increase in the sand-to gravel-grade mass fraction of the fluvially supplied depositional volume, which can be attributed to hinterland unroofing and/or cannibalization of wedge-top basins that lead to import of coarse-grained sediment into the Castlegate fluvial system.

In summary, recent experimental work has provided concepts and tools that enable interpretation of stratigraphic architectures in the context of the integrated erosion-transport-depositional system, rather than relative sea-level forcing. The challenge for sedimentologists and stratigraphers interpreting outcrop and subsurface datasets (including the author) is to integrate effectively these concepts and tools into their working methods, in order to improve understanding and prediction of stratigraphic architectures and associated hydrocarbon-play elements.

NOTES

Delta growth and river valleys: The influence of high-frequency climate and sea level changes on the South Adriatic shelf (Mediterranean Sea).

Maselli, V.[1*], Trincardi, F.[1], Asioli, A.[2], Ceregato, A[3], Rizzetto, F.[3], Taviani, M.[1,4]

[1], Istituto di Scienze Marine, ISMAR-CNR, Via Gobetti 101, 40129, Bologna, Italy.
[2], Istituto di Geoscienze e Georisorse, IGG-CNR, Via Gradenigo 6, 35131, Padova, Italy.
[3], Istituto di Scienze Marine, ISMAR-CNR, Arsenale, Tesa 104, Castello 2737/F, 30122, Venice, Italy.
[4], Woods Hole Oceanographic Institution, WHOI, 86 Water St., Woods Hole, MA 02543, USA.
**Speaker: Vittorio Maselli, e-mail: vittorio.maselli@bo.ismar.cnr.it*

The Manfredonia Incised Valley formed during the last glacial sea level lowstand, when most of the southern Adriatic shelf was sub-aerially exposed (Fig. 1). Until the Oldest Dryas, the valley fed a major shelf-phase delta that remained confined on the outer shelf by alongshore circulation. During a substantial part of the post-glacial sea level rise the valley remained underfilled, acting as an area of increased accomodation space compared to the surrounding shelf. A sea level jump occurring around 8.2 kyr cal BP resulted in a final drowning of the incision, leading to the formation of a sheltered and confined marine embayment under the influence of fresh waters. This mini-basin was rapidly filled by coarse-grained bayhead deltas prograding from both the northern and southern sides of the valley, and then leveled off by marine fine-grained deposits. It is remarkable that in these sheltered conditions, delta formation occurred in few centuries, between ca. 8 and 7.2 kyr cal BP, an interval that is almost synchronously with the formation of Sapropel S1b and may imply enhanced runoff from the mainland (Fig. 2). During this interval a major climatic reorganization in the Mediterranean region led to a dramatic change in the hydrological cycle, with increased precipitations and fresh water discharge from rivers that favoured water stagnation and accumulation of organic-rich layers in the deep basins.

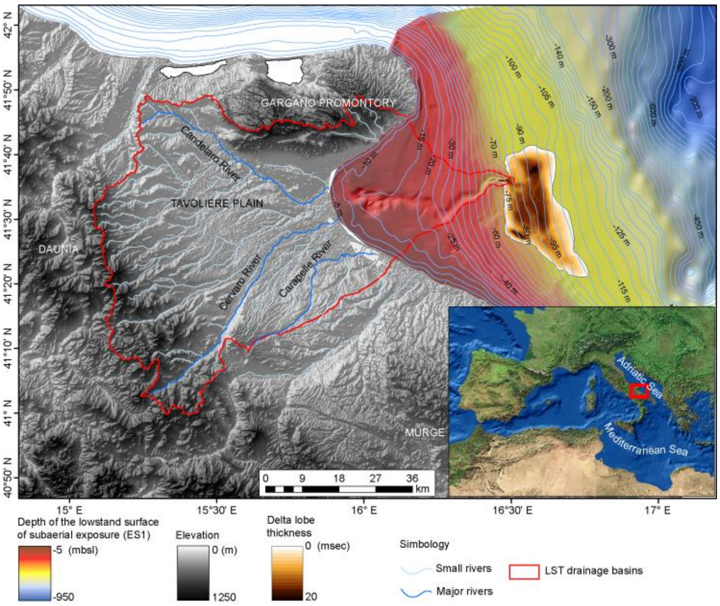


Figure 1. Digital Elevation Model of the study area. The red line represents the maximum extent of the catchment area of the Manfredonia Incised Valley at the Last Glacial Maximum. Offshore is shown the depth of the reconstructed lowstand surface of subaerial exposure and the thickness of the lowstand delta (brown).

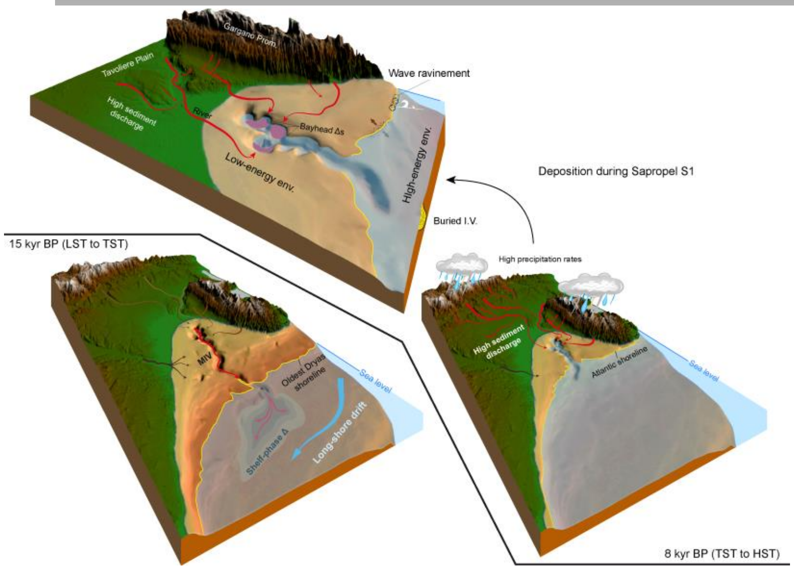
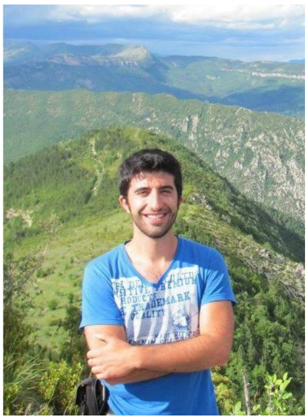


Figure 2. Paleogeographic reconstruction of the Apulian shelf from the Last Glacial maximum to 8 kyr BP. At LGM the South Adriatic shelf was almost subaerial exposed, with a major incised valley feeding a 10 m thick shelf-phase delta that was drowned during the Meltwater Pulse 1A. Around 8 kyr BP the valley was further drowned, favoring the formation of a sheltered (low-energy) embayment, tens of kilometers far from the open marine shoreline. The major change in the precipitation pattern that occurred in the Mediterranean region at this time was reflected by increased fresh-water and sediment discharge from southern Apennine rivers that favoured the formation of multiple and coalescing bayhead deltas that filled the valley from its northern and southern sides.

NOTES

Vertical and lateral heterogeneities in shallow marine reservoir analogues: the Panther Tongue (para)sequence, Utah



Andrea Forzoni (1), Joep Storms (1), Gary Hampson (2)

(1) Delft University of Technology, Delft, the Netherlands
(2) Imperial College, London, United Kingdom
a.forzoni@tudelft.nl

Understanding the architecture and heterogeneities in sedimentary basins is crucial for untangling the causative controls on stratigraphy and for predicting subsurface characteristics. Along-strike differences in sediment supply, subsidence, and wave action result in different facies distributions, preservation potential and expression of sequence stratigraphic surfaces in shallow-marine deposits. Consequently, the record of sea level change markedly varies along-strike within the same deltaic system. The Panther Tongue, Wasatch Plateau, Utah, is an excellent example to investigate the lateral and vertical heterogeneities in shallow-marine reservoirs, because of the continuous exposures subparallel to the regional depositional strike of deltaic shorelines.

Based on detailed outcrop studies in the northern Wasatch Plateau, Utah, the Panther Tongue is commonly considered as a typical analogue for fluvial-dominated river delta systems and reservoirs and is interpreted to record forced regression. However, it also represents the northern continuation of the Ksp040 parasequence in the southern Wasatch Plateau, which records normal regression of a wave-dominated shoreline. This apparent contradiction suggests that the architecture of the Panther Tongue as a coastal system and the heterogeneities on the spatial scale of the whole Wasatch Plateau are still poorly understood, and that the signal of sea-level changes is strongly modified along-strike.

We investigated the 3D architecture of the Panther Tongue delta-shoreface system by correlating stratigraphic, petrological and wireline data, in order to understand the connection between the different parts of the coastal system, to describe its vertical and lateral heterogeneities, and to better understand its evolution. We measured new stratigraphic logs along the Wasatch Plateau and analysed rock samples of the distal shoreface and offshore deposits with XRF (X-Ray fluorescence), thin sections and CT-scans. Then we correlated our data with stratigraphic and wireline logs from previous work.

Our results indicate that the Panther Tongue delta system represents the upper one of three, vertically stacked, prograding units within the stratigraphic boundaries of the ksp040 ‘parasequence’, representing episodes of shoreline regression in a general trend of normal regression. Phases of forced regression likely occurred within the first and in the third stage of delta development in the northern Wasatch Plateau. River-dominated deltaic successions, formed by deposition in distributary channels and mouth bars, fill in the depression incised in wave-dominated successions, resulting in a complex architecture and marked lateral heterogeneities. Based on our observations the Panther Tongue in the Wasatch Plateau records deposition in a mixed river- and wave-influenced river delta, analogous to the modern Ebro Delta, Spain.

We show that characterizing the facies distribution and thickness, and the expression of flooding surfaces and bedsets boundaries is vital for interpreting the along-strike variability and the controlling mechanisms in stratigraphic architectures. Finally, the increasing importance of wave action from the north to the south of the Panther Tongue coastal system reminds us that the classification of deltas in wave- vs tides- vs river- dominated is scale dependent and that lateral heterogeneity in a coastal system should be taken into account when building reservoir models.

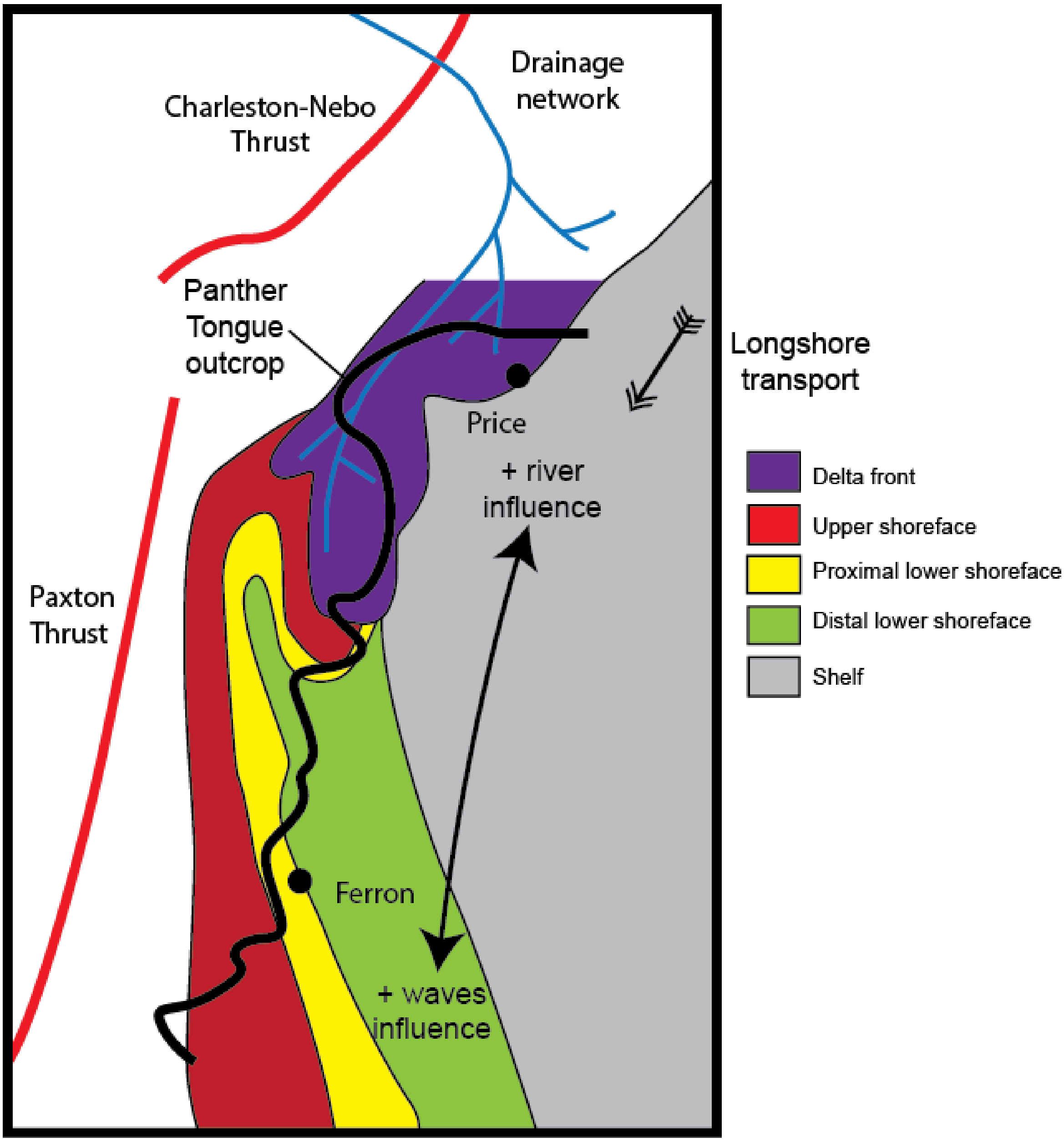


Figure: mapped and interpreted facies belt extent at maximum regression for the Panther Tongue-parasequence Ksp040 in the Wasatch Plateau, active thrusts, and interpreted drainage network feeding the Panther Tongue deltaic system.

NOTES

Climate change, sediment supply and the deep water record

Peter D. Clift and Yuting Li
Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA

Liviu Giosan
Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02540, USA

Tim Henstock
National Oceanography Centre Southampton, University of Southampton, UK

The traditional sequence stratigraphic model predicts that deepwater sedimentation is limited to periods of falling or low eustatic sea level. Conversely, when sea level is rising then high clastic sedimentation is restricted to the continental shelf. New data from the coastal and offshore parts of the delta, canyon and fan of the Indus River in Pakistan contributes to the growing body of literature that challenges this simplification. The Asian monsoon is the greatest single control on the delivery of sediment to the ocean because this modulates the rate and patterns of erosion in the source regions, especially in the Western Himalayas. Intensified mass wasting caused by stronger summer rains delivers large quantities of sediment to the large deltas in South Asia, partly as a result of reworking of previously eroded material from terraces both in the floodplains and in the mountain sources. This results in the shoreline moving out into the basin even during periods of rising sea level during the early Holocene (8-14 ka). Although sedimentation on the upper submarine fan does appear to become inactive at around 11 ka, sedimentation in the submarine canyon is known to continue until much more recently, at least until around 7 ka and through the period of rising sea levels. What is presently unclear is whether the sediment in the canyon is being delivered directly from the river mouth or whether this is reworked either by the transgression itself or as a result of localized mass wasting from the canyon walls. Shelf clinoforms are developed during sealevel highstand periods but never have the opportunity to reach the shelf edge so that sediment delivery to the slope is presumed to reflect reworking of both new and older sediment on the shelf driven by bottom currents and storm waves. Shelf edge deltas are restricted to formation during times of falling sealevel. The example of the Indus River shows us that climatically modulated sediment supply can be more important than sea level in controlling the location of deposition on a continental margin, even when the width of the continental shelf is significant. Although both sea level and climate are linked to Milankovich cycles they do not co-vary in phase with one another and do not necessarily cancel the effects of one another.

NOTES

A 'source-to-sink' perspective on sequence stratigraphy: Accommodation vs sediment supply as drivers of depositional sequences

Rob Gawthorpe and William Helland-Hansen and Patience Cowie

Department of Earth Science, University of Bergen, Bergen, Norway

Sequence stratigraphic methodology revolves around the identification and mapping of genetic packages of strata bounded by key stratal surfaces, across which genetic facies relationships break down. The advantages of this approach is that it can be applied to a wide range of data types, at scales ranging from the well-bore to the basin, which has enabled geologists to a obtain a better view of the genetic breakdown of the sedimentary record. Today, more than 30 years after its introduction, this branch of stratigraphy is less disputed after many years of confusingly diversified concepts and a degree of rivalry amongst its various schools of thought, particularly regarding nomenclature and the mechanisms driving depositional sequences and their component stratal units.

Most published sequence stratigraphic interpretations emphasise relative sea- or lake-level changes driven by tectonics or eustasy/climate as the dominant control on depositional sequences, i.e. controls within the basin 'sink'. In contrast, relatively few sequence stratigraphic interpretations clearly address, or quantify, the role of temporal and spatial variations in sediment supply, yet the relative roles of both accommodation and sediment supply are fundamental to the development of facies stacking patterns and some key stratal surfaces. Geomorphological studies of river catchments address the role of tectonics and climate in landscape evolution and associated sediment efflux. These 'source' studies suggest that the response time of the eroding landscape is of the order of 10^5 to 10^6 years, particularly for tectonic perturbations, resulting in buffering of the sediment supply from even relatively small catchments subject to high-frequency tectono-climatic perturbations. In larger sediment routing systems, with potential for sediment storage in different routing segments, such as in wide floodplains or on marine shelves, high frequency source signals will be buffered and transformed even further.

A challenge for the future development of sequence stratigraphic concepts is to adopt a source-to-sink approach and to address, more fully, the temporal and spatial variations in sediment supply and the staggered response in the stratigraphic record of tectono-climatic and sea- or lake-level perturbations. Recent analogue and numerical modelling studies of coupled catchment – depositional basin systems provide insights into this coupled system, but detailed studies of relative young, well-constrained catchment - sedimentary basin systems are needed that have chronology of high enough resolution so that the preserved stratigraphic product can be tied to specific climate and geomorphic perturbations.

NOTES

The Problem with Sequence Boundaries: Insights from Late Quaternary Systems and Experimental Studies

M. Blum[1] & J. Martin[2]

[1] *Department of Geology, University of Kansas, Lawrence, Kansas 66049, USA (mblum@ku.edu)*
[2] *Shell International Exploration and Production, Houston, Texas 77082, USA*

The sequence boundary underpins much of sequence stratigraphy. It is defined as an unconformity (and its correlative conformity) that everywhere separates bounding strata in time. Within incised-valley systems, the sequence boundary is most commonly defined by the base of fluvial incision. The presumed predictive power of this surface is derived from a model for fluvial incision and sediment bypass during relative sea-level fall: fluvial deposits that rest on the sequence boundary are commonly assumed to represent filling of an empty container during late lowstand or early transgression.

A number of problems with the sequence boundary concept have been identified by studies of Quaternary and experimental systems, where deposits can be dated independent of an interpretive model. First, the model of fluvial incision and sediment bypass during relative sea-level fall cannot be verified, and in most cases it can be falsified. Second, sediment bypass and deposition within incised valleys are not mutually exclusive: erosion and channel-belt deposition continuously redefines the valley shape over the duration of a base-level cycle. Third, extension of valleys across a newly emergent shelf is accompanied by linked channel-belt deposition and delta progradation. And fourth, the morphodynamics of the lower reaches of river systems makes it is difficult to envision how valley incision can actually propagate all the way to a lowstand shoreline, or any shoreline.

We suggest the sequence boundary remains a useful stratigraphic concept, but it is in need of major refinement to repair longstanding misconceptions about how fluvial systems respond to relative sea-level fall. In the bedrock or coastal-plain reaches of paleovalley systems, construction of the erosional sequence boundary by valley incision is diachronous, and it does not exist as a geomorphic (landscape) surface at any point in its evolution. Nevertheless, mechanistically, the valley base meets the criteria for a sequence boundary as originally conceived. However, definition of the sequence boundary as an erosional truncation surface fails in downdip reaches, due to a necessary switch in the balance between erosion and deposition in sediment-transport systems, even during base-level fall. In the cross-shelf part of the system, the classically-defined sequence boundary would be continued basinward as the base of fluvial incision. However, as incised valleys transition to net depositional fluvio-deltaic and nearshore environments as they approach their contemporaneous shoreline, this has the unfortunate consequence of disconnecting genetically-related strata, which violates criteria for definition of an unconformity. In fact, sediment mass-balance considerations indicate that the stratigraphic signal of the sequence boundary updip must change to a depositional record in the basinward direction. Quaternary and experimental incised-valley systems demonstrate that the most faithful sequence-bounding disconformity is the composite downlap surface at the base of prograding clinothems, which demarcates cross-shelf transit of fluvio-deltaic systems.

NOTES

On the Challenge of Coupling Sequence Stratigraphy and Dynamic Landscape Evolution in Deep Time

Ole J. Martinsen
Statoil Exploration Excellence,
Bergen, Norway

The most valuable asset of sequence stratigraphic models is that they provided researchers with the enhanced understanding that stratigraphic sections are not the result of continuous deposition, but are broken by extensive allogenic erosion surfaces/unconformities and omission/non-depositional surfaces. Prior to seismic stratigraphy, there was little appreciation among field geologists of the geomorphic significance and duration of stratigraphic breaks, largely as a result of the nature and scale of the studied data. This appreciation existed among industry geologists who worked seismic data and understood that stratigraphic breaks led to improved prediction of lithology both within and outside the areas the seismic data covered. Seismic stratigraphy evolved into sequence stratigraphy because of the need to convert the seismic data/subsurface acoustic response into lithological understanding of basin fill. Still, sequence stratigraphy alone remained and still to a large degree is a two-dimensional methodology, because of the stratigraphic focus. Application and use of outcrop data as the primary means by many to advance sequence stratigraphy thus caused a significant flaw in our ability to couple stratigraphic observations to landscape evolution in deep time. In the multitude of sequence stratigraphic papers published, too few have had data, ability or attempted to reconstruct block diagrams where the static, snap-shot, plan-view interpretation of the spatial extent of for instance an observed unconformity in an outcrop would have been an interpretation of the landscape at the time of formation. Nevertheless, the ultimate aim, the temporal and long-term evolution of the plan-view/geomorphological aspect of both stratigraphic units and their intervening breaks has in too few instances been attempted.

The advent of 3-D seismic in the 1990's provided seasoned sequence stratigraphers with an almost automated, instant technology to combine stratigraphic observations with geomorphology, albeit initially mainly for deep-water sedimentary environments where the contrast in acoustic properties between various lithologies was much more marked than for other, shallower and continental depositional settings. With time, technology and resolution have improved so that this challenge hardly exists anymore, but the initial focus led to a significant bias in research directions and application. Furthermore, remote sensing data and wonderful and very useful tools such as Google Earth have completely altered our appreciation and insight into geomorphology and landscapes. This ironically has almost flip-flopped the situation so that these types of data are now used many times at the expense of fundamental stratigraphic insight.

A response to this fundamental challenge is the *Source-to-Sink* methodology because it includes both a geomorphic as well as a stratigraphic component. It also includes source/catchment areas not normally studied by stratigraphers. Furthermore, this approach includes the necessity to use other sciences such as geodynamics/tectonics and paleoclimatology in building a complete synthesis. Resolution remains a key challenge – but this time keeping a first-order overview is critical to not get bogged down in software, methodology and detail and to allow for successful application to subsurface settings.

NOTES

The effect of ultra-large rivers on marine sequence development

David I.M. Macdonald

School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK (d.macdonald@abdn.ac.uk)

The inputs into the sequence stratigraphic model as expressed in the classic work by the Exxon Production Research Company are: amount, rate of change, and direction of eustatic sea-level change; amount, rate of change, and direction of subsidence (or uplift); and amount of sediment delivery. In most text-book presentations of the model, sedimentation rate is held constant and one basin-normal cross section is a proxy for the behaviour of the whole basin. Although some authors have attempted margin-parallel sections across point-sourced sediment input sites, they are intended as guides to recognition of surfaces within a single third or fourth-order cycle. This paper addresses the question of the effect of ultra-large rivers on sequence development from the viewpoint of routing system longevity; sediment supply; reduction of input elsewhere on the margin due to capture; and scale of sediment input versus the scale of other model parameters. The paper is based on research on the Amur, Niger, and Colorado (USA/Mexico) rivers.

Ultra-large rivers drain significant areas of their continents – generally more than 10% of the continental area, although this approaches 40% in the case of the Amazon. Most ultra-large rivers have a geological history spanning millions or tens of millions of years (Colorado, 6 Ma; Amur, 25 Ma; Niger, 130 Ma), with stable entry points into their receiving basins. As a result, the effects of these rivers spans multiple third or fourth order cycles. Although sediment yield per square kilometre in the catchments of ultra-large rivers may be an order of magnitude lower than that of small steep mountain rivers, the sheer scale of the catchments means that sediment supply to the basin is high. Many ultra-large rivers also span more than one climatic zone, buffering them against all but the most extreme climate change. Capture of the headwaters of other rivers reduces input elsewhere on the basin margin, changing the dynamic of sedimentation in the basin. The scale of the sediment input from ultra-large rivers can dwarf the other factors that contribute to the creation of accommodation space in the sequence stratigraphic model, so the deltas of these rivers can behave counter to the predictions of the sequence stratigraphic model and make correlation of sequences impossible. The input problem is exacerbated by the fact that the majority of tests of the sequence stratigraphic model come from the relatively low-accommodation basins of the western US.

These problems are explored in the context of the sequence stratigraphic model. An alternative numerical model is presented that shows how limits to progradation of the depositional parts of such ultra-large systems come from factors such as the decreasing shoreline growth which is a consequence of adding constant sediment increments to a growing radial cone into progressively deeper water.

NOTES

Variations in sediment flux at the million-year time scale: implications for sequence stratigraphy

Nikolaos A. Michael[1] and Philip A. Allen[2]

1. Geological Technology Team, EXPEC Advanced Research Center, Saudi Aramco, Dhahran, Saudi Arabia, nikolaos.michael@aramco.com

2. Earth Sciences and Engineering Dept., Imperial College London, London, United Kingdom, philip.allen@imperial.ac.uk

We have conducted a sediment budget of a geological sediment routing system from the mid-late Eocene (41.6 to 33.9 Ma) of the southern foreland of the Pyrenees in order to evaluate the effect of sediment supply variations on the stratigraphy of the basin-fill. The sediment routing system derived sediment from catchments in the tectonically active Pyrenean orogen and dispersed it westwards over a distance of *ca.* 200 km in a structurally controlled wedge-top setting. Depositional environments passed westwards from basin margin fans, fluvial systems, coastal and shallow marine, slope and deep-sea.

The Escanilla palaeo-sediment routing system has been subdivided into three time intervals, each of 2.5-2.6 Myr duration. For each time interval, we calculated the depositional volumes and grain-size fractions at a number of stations in the downsystem direction and transformed these data into a mass balance framework. Four thousand cubic kilometers of sediment, sourced principally from two feeder systems in the high Pyrenees, was deposited in a period of 7.7 Myr.

Over time, there was a progressive westward progradation of coarse-grained facies driven by increasing sediment supply from the rapidly eroding Pyrenean orogen. Changes in the rate of downsystem fining of grain-size, percentages of grain-size fractions in preserved stratigraphy, position of moving boundaries, and evolution of gross-depositional environments are related to variations in the volume of sediment supplied, the grain-size mix of the supply, and the spatial distribution of tectonic subsidence generating accommodation.

The time-averaged sediment discharge from source areas increased from ~250 $km^3\ Myr^{-1}$ to 700 $km^3\ Myr^{-1}$ over the 7.7 Myr interval investigated. This temporal increase in sediment supply caused major westward progradation of facies belts and led to substantial sediment bypass through the terrestrial routing system to the (initially) marine Jaca Basin. The grain-size mix, measured as size fractions of gravel, sand, and finer than sand, also changed over the three time intervals. Integration of volumetric and grain-size information from source to sink provides an estimate of the long-term grain-size distribution of the sediment supply, comprising 9% gravel, 24% sand, and 67% finer than sand.

The 7.7 Myr duration of the three time intervals of the Escanilla palaeo-sediment routing system covers 5 third-order sequences thought to be global (Haq *et al.*, 1987; Hardenbol *et al.*, 1998). At the time scale of a third-order sequence, we recognize the overwhelming impact of changes in the sediment budget driven by variations in the flux supplied by mountain catchments. Such variations, combined with changes in the grain-size mix supplied to the depositional basins, explain features such as the position of the gravel front, coastal progradation and the bypass of sediments to the deep sea, without recourse to any eustatic effects. This does not negate the possibility of eustatic change at the million-year time scale, but makes eustasy unnecessary to explain the mid-upper stratigraphy of the Escanilla system.

Recent publications:

Michael, N.A., Whittaker, A.C. & Allen, P.A. (2013) The functioning of sediment routing systems using a mass balance approach: Example from the Eocene of the southern Pyrenees. *Journal of Geology*, 121/6, 581-606, doi:10.1086/673176.

Michael, N.A., Whittaker, A.C., Carter, A. & Allen, P.A. (2014) Volumetric budget and grain-size fractionation of a geological sediment routing system: Eocene Escanilla Formation, South Central Pyrenees. *Bulletin Geological Society of America,* doi:10.1130/B30954.1.

Michael, N.A., Carter A., Whittaker, A.C. & Allen, P.A. (2014) Erosion rates in the source region of an ancient sediment routing system: Comparison of depositional volumes with thermochronometric estimates. *Journal of the Geological Society,* 171, 401-412, doi:10.1144/jgs2013-108.

NOTES

Posters

Monday 22 September 2014

1. **Divergent stacking patterns and complex responses to sea level change across a reef-rimmed greenhouse carbonate shelf: Danian of the western Pyrenean basin, N Spain**

Juan Baceta *(Basque Country University,Spain)*
V.P Wright (National Museum of Wales, UK)
A Berreteaga (Basque Country University, Spain, National Museum of Wales, UK, and The University of Manchester, UK)

2. **Carbonate sequence stratigraphy across a Middle Jurassic platform to basin transect, Southern England.**

Thomas Butt *(University of Birmingham, UK)*
James R Wheeley (University of Birmingham, UK)

3. **Climate change, sediment supply and the deep water record**

Peter Clift *(Louisana State University, USA)*
Yuting Li (Louisana State University, USA)
Liviu Giosan (Woods Hole Oceanographic Institution, USA)
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4. **CSI Spain: The usefulness of sequence stratigraphy in the study of dinosaur sites.**

Carlos de Santisteban Bové *(Universitat de València, Spain)*
Nicolaas Molenaar (Vilnius University, Lithuania)
Andrés Santos-Cubedo (Grup Guix, Spain)
Begoña Poza Falset (Grup Guix, Spain)

5. **Sequence stratigraphy of the Middle-Upper Triassic carbonate ramps of Minorca. Significance for the reconstruction of W. Tethys evolution.**

Maria José Escudero-Mozo *(Universidad Complutense de Madrid & Instituto de Geociencias, Madrid, Spain)*
J. Martín-Chivelet ((Universidad Complutense de Madrid & Instituto de Geociencias, Madrid, Spain)
J. López-Gómez (Instituto de Geociencias, Madrid, Spain)
P. Gianolla (Università degli Studi di Ferrara, Italy)
A. Goy (Instituto de Geociencias, Madrid and Universidad Complutense de Madrid, Spain)

6. **Tectonic subsidence of the passive margin of South America from global models of mantle flow and lithospheric stretching**

Nicolas Flament *(The University of Sydney Australia)*
Michael Gurnis (California Institute of Technology, USA)
Simon Williams ((The University of Sydney Australia)
Maria Seton (The University of Sydney Australia)
Jakob Skogseid (Statoil ASA, Norway)
Christian Heine (The University of Sydney Australia)
R. Dietmar Müller *(The University of Sydney Australia)*

7. **A revision of the Triassic sequence stratigraphic framework of the Dolomites (Italy). The impact of climate, volcanics, tectonic and changes in the carbonate factories.**

Piero Gianolla *(University of Ferrara, Italy)*
N. Preto (University of Padova, Italy)
G. Gattolin (University of Padova, Italy and ENI S.p.a, Italy)
M. Caggiati (*University of Ferrara, Italy)*
A. Breda (University of Padova, Italy)

8. **Testing Sequence Stratigraphic Concepts in 3D on a Mega Scale: Lateral variation of key stratal surfaces from 3D seismic analysis of the Late Cenozoic Southern North Sea**

Rachel Harding (University of Manchester)

Tuesday 23 September 2014

9. **Sequence Stratigraphy in deep-water? Time transgressive key surfaces and the progradation of basin-floor fans**

David Hodgson *(University of Leeds, UK)*
Ian Kane (Statoil ASA, Norway)

10. **Utility of Palaeomagnetic and Magnetostratigraphic Data in Sequence Stratigraphy Investigations**

Joseph Liddicoat (Columbia University, USA)

11. **Nearshore erosional surface in a wave-dominated delta system: example from Holocene Godavari delta, India**

Yoshiki Saito *(Geological Survey of Japan, Japan)*
Kakani Nageswara Rao (*Andhra University, India)*
K.Ch.V. Nagakumar (*Andhra University, India)*
G. Demudu (*Andhra University, India)*

A.S. Rajawat (Space Applications Centre, India)
Sumiko Kubo (Waseda University, Japan)
Zhen Li (SKLEC, East China Normal University, China)

12. **Using sequence stratigraphy to understand the taphonomy of dinosaur sites in the Arcillas de Morella Formation (Lower Cretaceous, Eastern Iberia, Spain).**

Andrés Santos-Cubedo *(Grup Guix, Spain)*
Carlos de Santisteban Bové (Universitat de València, Spain)
Begoña Poza Falset (Grup Guix, Spain)
Nicolaas Molenaar (Vilnius University, Lithuania)

13. **The use of chemostratigraphy to refine ambiguous sequence stratigraphic correlations in marine shales. An example from the Woodford Shale, Oklahoma, USA.**

Bryan Turner *(University of Oklahoma, USA)*
R.M Slatt (University of Oklahoma, USA)
J.A Tréanton (Noble Energy, Houston, USA)

14. **A hierarchical approach to marginal marine classification: linking the scales of sedimentology and sequence stratigraphy**

Boyan K. Vakarelov *(The University of Adelaide, Australia)*
R. Bruce Ainsworth (Australian School of Petroleum, Adelaide, Australia

15. **The challenges associated with sequence stratigraphy in the glacial environment**

Paul van der Vegt (PanTerra Geoconsultants, Netherlands)

16. **The influence of hydrodynamic-morphodynamic interaction on sequence stratigraphy in deltaic deposits**

Helena van der Vegt *(Delft University of Technology, Netherlands)*
Joep E. A. Storms (*Delft University of Technology, Netherlands)*
Liang Li (*Delft University of Technology, Netherlands)*

Poster Presentation Abstracts

Divergent stacking patterns and complex responses to sea level change across a reef-rimmed greenhouse carbonate shelf: Danian of the western Pyrenean basin, N Spain

Baceta, J.I. 1, Wright, V.P. 2, Berreteaga, A. 1-3

1: Dept of Stratigraphy and Paleontology, Basque Country University, Apdo. 644, E48080, Bilbao, Spain, juanignacio.baceta@ehu.es
2: Geology, National Museum of Wales, Cathays Park, Cardiff, CF10 3NP, Wales, UK
3: School of Earth, Atmospheric and Environmental Sciences, The University of Manchester, Williamson Building, Manchester M13 9PL, UK

The framework for understanding stratal architecture and stratigraphic sequences in carbonates is now well constrained, both for use in outcrop studies and for reservoir characterization and modelling. One critical factor is that the spatial variability in carbonate production creates different and complex responses to external forcing. To fully assess such factors well constrained large outcrops are needed, and this study focusses on a detailed correlation of numerous vertical sections for more than 90km across an almost complete early Cenozoic tropical platform system in the Danian of the Urbasa-Andia plateau, in the western Pyrenees. This 40-45km wide and 150-300m thick carbonate platform evolved from a ramp to a flat-topped rimmed shelf, following the appearance and spread of coralgal reefs along seaward margins. However, this evolution was discontinuous, punctuated by 3rd and higher order relative sea level changes that created three complete depositional sequences (Ma-Da, Da-1 and Da-2) and a myriad of m-scale shallowing-up units. This contribution focus on the HST of the Da-2 sequence, a 90-200m thick sedimentary package that represents the peak of the rimmed shelf growth stage.

The large-scale stacking pattern of the upper Danian HST is one of its more remarkable features. Depending on the position on the shelf, the succession develops three different coeval depositional trends: progradational at the reefal margin, aggradational at the shallow outer shelf lagoon and retrogradational at the interior tidal flat (Fig. 1). This divergence in growth pattern, that contradicts the typical aggradational to progradational pattern of facies belts established for third-order highstands, is interpreted in terms of significant variation in the rates of sediment production and accumulation across the shelf, with a highly prolific skeletal factory operating at the margin and a progressively less-productive mixed factory, defined by skeletal and non-skeletal carbonates, dominating the lagoonal and tidal flat areas.

The retrogradational trend seen in the innermost tidal flat succession confirms the prevalence of relative rising sea levels during the development of the Da-2 HST. Despite this transgressive trend, rates of carbonate production/accumulation of the reefal factory clearly exceeded any additional accommodation space created, allowing almost continuous basinward progradation of the shelf margin for about 6km. Production rates in the outer shelf lagoonal area were lower but also relatively high, as this setting became progressively wider but was still able to maintain shallow conditions, developing almost continuous aggradation with time. The interior, highly restricted tidal flat deposystem recorded the lowest rates of sediment production and accumulation within the system, only tracking the prevalent rising trend in relative sea level as a retrogradational system.

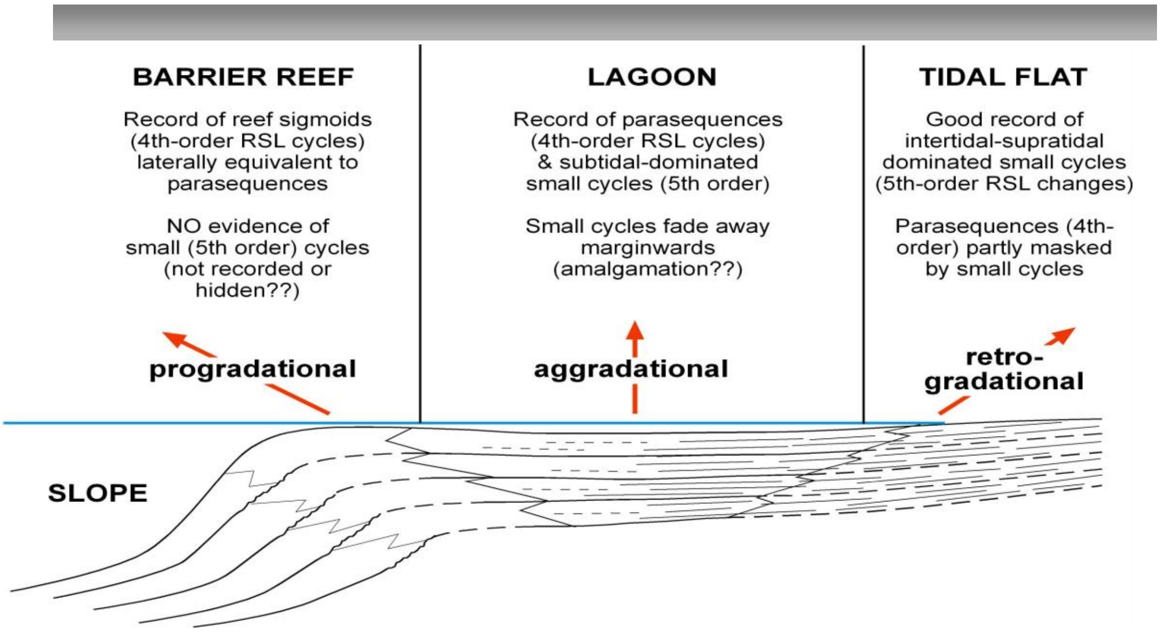


Figure 1. Synthetic stratigraphic model of the Da-2 HST flat topped shelf, emphasizing main evolutionary trends and distribution of the two orders of internal shallowing upwards facies cycles.

The large-scale depositional trends of the Da-2 HST shelf exhibit a complex succession of internal facies cycles, arranged in two superimposed shallowing-upward motifs: *m-thick small facies cycles* hosted within *parasequence sets*. The former (5^{th} order-style) are best developed in the innermost shelf, tidal flat settings, disappearing progressively by amalgamation across the lagoonal area and the transition to the shelf margin. This and the significant lateral variation in the number of small cycles per parasequence set suggest that most, if not all, developed limited lateral extent, in the range of 5-10km. In contrast the parasequence sets, bounded by exposure surfaces, are laterally continuous for more than 30kms across the shelf, from the shelf margin through to the innermost settings. It is tempting to interpret the parasequence sets as eustatic, especially as estimates of their likely duration fall within eccentricity periodicity and they are capped by distinct exposure surfaces. However, any higher frequency eustatic signal is masked in areas of higher sediment production suggesting a predominant local control. Spatial variability in carbonate production makes deciphering sea level behaviour, whether at 3^{rd} or higher order scale, difficult and requires an evaluation of more than just local successions.

Acknowledgements: This study is sponsored by BG International LTD. It is also a contribution to the research project CGL2011-23770 from the Spanish Ministerio de Ciencia e Innovación

Carbonate sequence stratigraphy across a Middle Jurassic platform to basin transect, Southern England.

Thomas J. Butt & James R. Wheeley

School of Geography, Earth and Environmental Sciences, University of Birmingham.
tomjbutt@aol.com, j.r.wheeley@bham.ac.uk.

A sequence stratigraphic interpretation along a NE-SW platform-basin transect through the Middle Jurassic of southern England is taken to determine whether sedimentation variation through the study interval was controlled by regional production rates of the carbonate system or by global base sea level changes. Sedimentary logs were compiled for five sites across the south of England through the Jurassic successions at Winterborne Kingston, Biddestone, Hornsleasow Quarry, Chipping Norton and Upwood. The pattern of sedimentation was interpreted into a sequence stratigraphic framework for each locality and more detailed data was collected for Hornsleasow Quarry, the focal point for the investigation. Petrographic, ooid, micropalaeontological and quartz abundance analysis was used to build up a detailed picture of the platform environment at Hornsleasow Quarry before applying mixed carbonate and siliciclastic sequence stratigraphic principles to produce an interpretation across the transect.
From the sequence stratigraphic analysis, sea level curves were constructed and compared to the literature. This comparison shows that sea level was predominantly controlled by global and regional base level changes and not through regional production variation. Third and fourth order cyclicity is recorded across the transect. Third order cyclicity is controlled by upwelling of magma plumes to the south and west between the Gulf of Mexico and West Africa. Fourth order cyclicity is on a similar scale to that of the obliquity Milankovitch cycle forcing glacio-eustatic controls.

CSI Spain: The usefulness of sequence stratigraphy in the study of dinosaur sites

Carlos de Santisteban Bové[1], Nicolaas Molenaar[2], Andrés Santos-Cubedo[3] & Begoña Poza Falset[3]

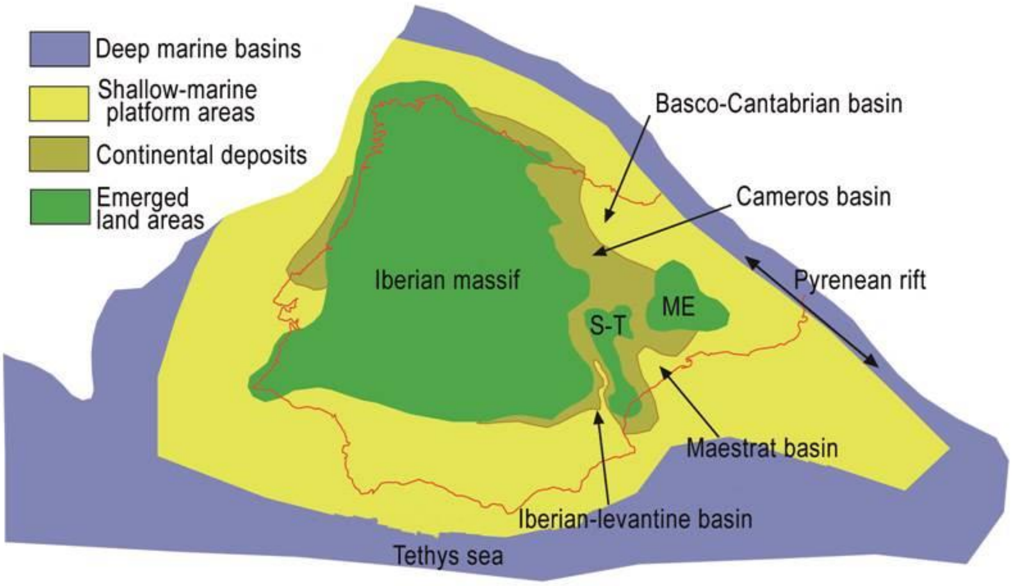
1. Departament de Geologia, Universitat de València, Av. Dr. Moliner, 50, E-46100 Burjassot, València, Spain. carlos.santisteban@uv.es
2. Department of Geology and Mineralogy, Vilnius University, K.M. Čiurlionio 21/27, LT-03101 Vilnius, Lithuania. nicolaasmolenaar@gmail.com
3. Grup Guix, C/ Santa Lucia, 75, E-12540 Vila-real, Castelló, Spain. santos.cubedo@gmail.com; begopoza@gmail.com

The use of sequence stratigraphic methods and applying these to other fields such as palaeontology has allowed in the last years to reinterpret the fossil record of many sites. Thus, new methods, concepts and protocols are very helpful in understanding how the sediments were formed, and how we must look for fossils or how we must correctly interpret that record.
Most of continental upper Jurassic-lower Cretaceous deposits that outcrop in the Iberian Peninsula were deposited along the northern and eastern margins of the Variscan Iberian Massif. Here the Iberian Trough was a subsident basin from the Late Permian to the Late Cretaceous, with an elongated NW – SE orientation. This through can be divided in several basins: Vasque-Cantabrian, Cameros, Maestrat and Iberian-Levantine Basin (also known as *Surco Ibérico Suroccidental* by some authors, due to the position of its deposits in the Iberian fold-belt, or South Iberian sub-basin).

Two areas were studied: the Ibero-Levantine basin and the Maestrat basin, both of them in the eastern part of Iberian Peninsula. The first one extends over southeastern Teruel, part of Cuenca and throughout the province of València. Deposition was constrained between the Sagunto-Teruel and the Iberian massifs (figure 1). The second one, the Maestrat basin, extends over the provinces of Tarragona, Castelló and part of Teruel. It was bounded in the north by the ranges of the Ebro Massif and in the south by the Sagunto-Teruel Massif. The northern area of the Tethys Ocean invaded Iberia through the Maestrat and the Ibero-Levantine basins. Both sedimentary basins received sediments from the margins of the massifs that bounded them laterally and, in the north, from the middle region of the Iberian System. In the Maestrat basin, sediments showed a preferred distribution to the southeast, whereas in the Ibero-Levantine basin sediments were distributed toward the southwest. These deposits contain abundant fossil sites in which remains of dinosaurs are important.

The classic interpretations of the environments where dinosaur lived and those in which they died and were preserved suggest that there were deltaic systems along the basin margins that developed at the mouth of meandering rivers. Tidal currents reworked the deltas margins, producing tidal plains and estuaries. The use of sequence stratigraphy has led us to change this point of view. In contrast to what might be expect, there have been hardly any finds of dinosaur remains in the fluvial deposits in this delta. In fact, fluvial channel deposits are far less well represented than coastal deposits, since a substantial proportion of the former floodplain has been eroded during the Upper Jurassic and Lower Cretaceous. This erosion is the consequence of the development of cyclic climatic changes. We think that these deposits were formed in a wave-dominated deltaic system subjected to relative eustatic changes. They are characterized by a stratigraphic cyclicity determined by transgressions and regressions. Regressions caused incision of the drainage systems and significant erosion. Most of the absent sedimentary record corresponds with semi-arid periods. This should be kept in mind in the interpretation of paleontological sites and they are important for understanding the taphonomy of fossil sites.

Figure 1.- Paleogeographic scheme of the Iberian Plate in the Upper Jurassic and Lower Cretaceous.



Sequence stratigraphy of the Middle-Upper Triassic carbonate ramps of Minorca. Significance for the reconstruction of W. Tethys evolution

M.J. Escudero-Mozo[a,b], J. Martín-Chivelet[a,b], J. López-Gómez[b], P. Gianolla[c], A. Goy[b,d].

[a.] Departamento de Estratigrafía, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain. (majescud@ucm.es)
[b.] Instituto de Geociencias (UCM, CSIC). c/ José Antonio Nováis 2, 28040 Madrid, Spain.
[c.] Università degli Studi di Ferrara. Dipartimento di Fisica e Scienze della Terra, via Saragat 1, 44100 Ferrara, Italy
[d.] Departamento de Paleontología, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain

Minorca was located in the westernmost Tethys area during the Triassic, in a key paleogeographic location close to the present-day Iberia, Sardinia and the Cottian and Southern Alps. The Middle-early Late Triassic carbonates of Minorca (Muschelkalk) have been studied in five sections across the northern area of the island. These units lie uncorformably on a red unit in Röt facies (top of the Buntsandstein facies), present a transitional upper contact with the Keuper facies, and show a remarkable lithological and stratigraphical homogeneity throughout the island, with a total thickness of 100-120 m. They consist of three limestone and dolostone units named: Monte Toro, Arenal d'en Castell, and Fontanelles formations, from base to top.

In order to progress in the knowledge of the Middle to Late Triassic evolution of the W. Tethys, a detailed, outcrop-based, sequence stratigraphic analysis has been accomplished (Figure 1). At a large scale, five main successive stages of carbonate platform evolution were defined and characterized: 1) Initial marine transgression and shallow ramp development (late Illyrian); 2) Carbonate platform drowning (Illyrian - Fassanian boundary); 3) Prevalence of open sea conditions (Fassanian p.p. - Longobardian - early Julian); 4) Abrupt sea-level drop and subaerial exposure (intra-Julian) and; 5) Shallow carbonate platform and transition to sabkha systems (Keuper facies). These main evolutionary stages were framed in a new sequence stratigraphic scheme, which consist of five 3rd-order depositional sequences; one in the Monte Toro Fm. of upper Illyrian age; three in the Arenal d'en Castell Fm., respectively Fassanian, Longobardian, and upper Longobardian - lower Carnian in age; and one more in the Fontanelles Fm., of lower Carnian p.p. age.

The study was supported by new biochronostratigraphic data, based on the ammonoids yielded by the Arenal d'en Castell Fm. These allowed to differentiate six successive ammonoid biozones from the lower Fassanian to the lower Carnian interval (Figure 1), which can be correlated to the standard ammonoids Zones defined by Balini et al. (2010) for the Tethys realm.
The integration of the new biochronostratigraphic and sequence stratigraphic data allows detailed interregional correlations with Iberia, central Europe, and the Alps basins; as well as to progress in the understanding of the evolution of the W. Tethys realm during the opening of the Neotethys, when important paleogeographic reorganizations caused by the northwards movements of the Cimmerian promontory took place.

This is a contribution to Project CGL2011-24408 (MINECO, Spain), and to research groups "Sedimentary systems and climate variability (CSIC-642853)"; and "Basin Analysis (UCM-910429)", and "Paleoclimate and Global Change (UCM-910198)".

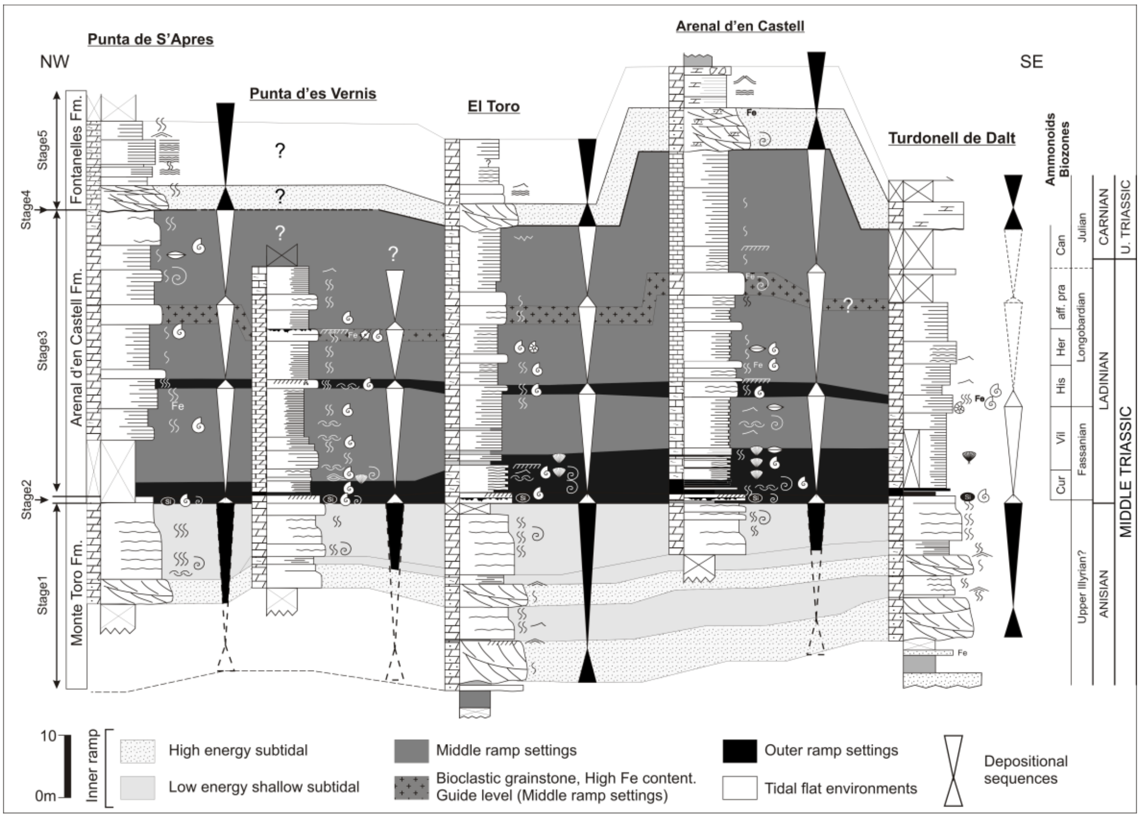


Figure 1. Depositional sequences and main stages of platform evolution of the Muschelkalk facies of Minorca,

Tectonic subsidence of the passive margin of South America from global models of mantle flow and lithospheric stretching

Nicolas Flament[1], Michael Gurnis[2], Simon Williams[1], Maria Seton[1], Jakob Skogseid[3], Christian Heine[1], R. Dietmar Müller[1]

[1] *EarthByte Group, School of Geosciences, The University of Sydney, Sydney, NSW 2006, Australia; nicolas.flament@sydney.edu.au*
[2] *Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[3] *Statoil ASA, Martin Linges vei 33, 1364 Fornebu, Norway*

The relief of the South American passive continental margin is characterized by a north-south asymmetry: it is elevated along eastern Brazil in the north, and abuts the deep Argentine Basin in the south. In addition, published tectonic subsidence curves reveal a Cenozoic post-rift acceleration of subsidence along Brazil, and a Late Cretaceous unconformity in the North Falkland Basin (Figure 1).

We investigate the origin of these topographic features in the present and over time since the Jurassic with a model of global mantle flow and lithospheric deformation. The model progressively assimilates plate kinematics, plate boundaries and lithospheric age derived from global tectonic reconstructions with deforming plates, and predicts the evolution of mantle temperature, continental crustal thickness, long-wavelength dynamic topography, and isostatic topography. Mantle viscosity and the kinematics of the opening of the South Atlantic are adjustable parameters in multiple model cases (see Flament et al., 2014 for a full description of the model and model cases).

Model predictions are compared to observables both for the present-day and in the past. Present-day predictions are compared to topography, mantle tomography, and an estimate of residual topography. Predictions for the past are compared to geological constraints. Comparing predicted dynamic uplift of southern Africa to the results of a thermochronology study, we find the uplift of the Kaapvaal Craton to be best reproduced with a lower mantle that is at least 40 times more viscous than the upper mantle.

The predicted evolution of model elevation along the South American passive margin can be directly compared to tectonic subsidence inferred from backstripped borehole data (Figure 1). This comparison reveals that model predictions are within error (typically a few tens of meters and a few million years) of published tectonic subsidence curves, to the exception of the early evolution of the complex Santos Basin. In the model, the evolution of dynamic topography accounts for the acceleration of subsidence along Brazil and for the unconformity in the North Falkland Basin.

Our results suggest that pure shear thinning of the lithosphere during rifting and dynamic topography might explain much of the evolution of the South American passive margin. In addition, they suggest that the first-order features of the topography of the South Atlantic are due to long-wavelength dynamic topography, rather than to asthenospheric processes.

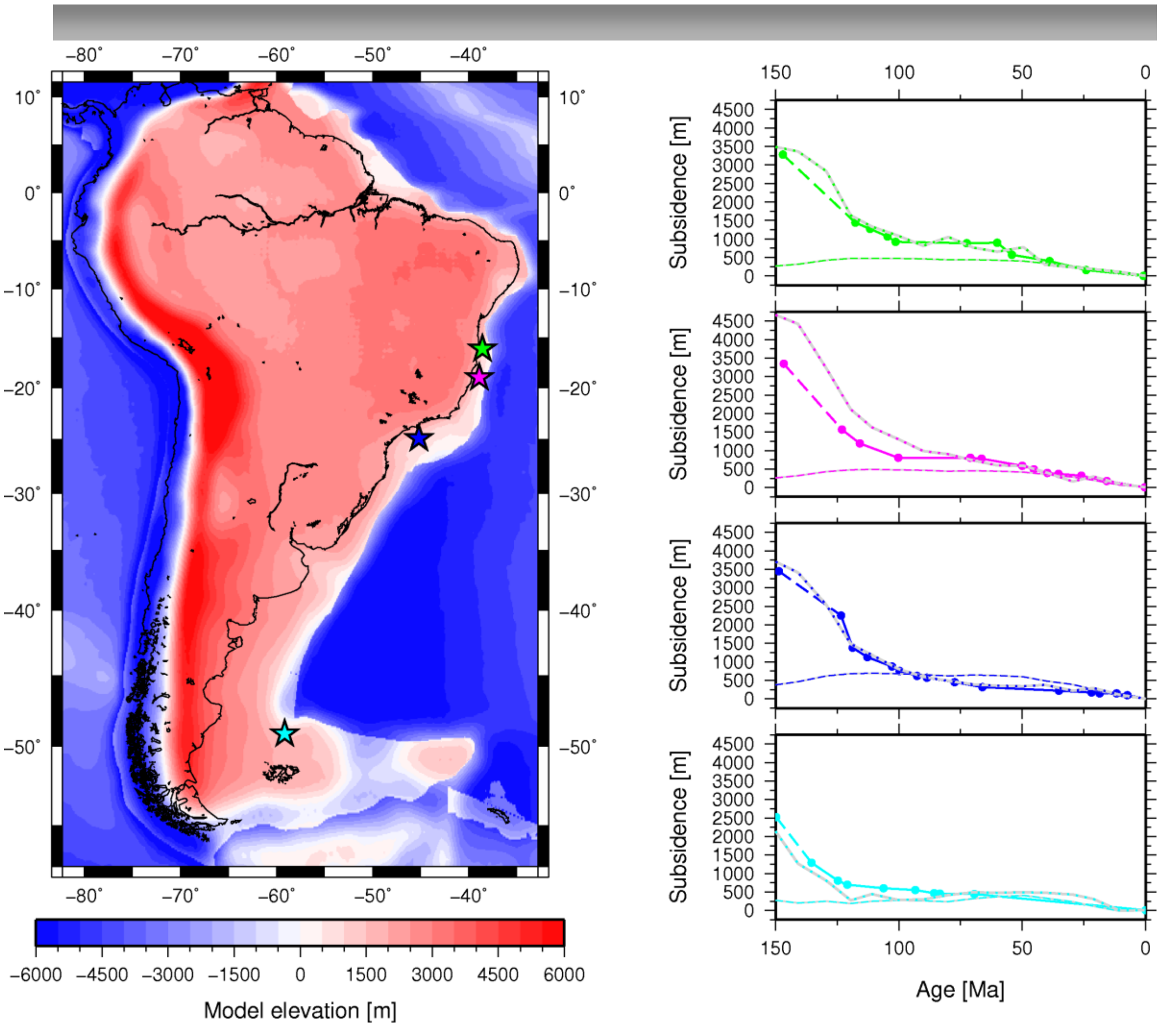


Figure 1: Predicted present-day elevation of South America (left) with coastlines in black, and coloured stars denoting well locations (green: Bahia Basin, magenta: Santos Basin and blue: Espirito Santo Basin from Chang et al., 1992; cyan: North Falkland Basin from Jones et al., 2004). Comparison between model and observation (right) colour-coded by location: tectonic subsidence inferred from observations (solid lines and disks; dashed line represents extrapolation to basement), predicted evolution of topography (grey line overlain by dotted line) and predicted evolution of dynamic topography (thin grey line overlain by dashed line).

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A revision of the Triassic sequence stratigraphic framework of the Dolomites (Italy). The impact of climate, volcanics, tectonic and changes in the carbonate factories.

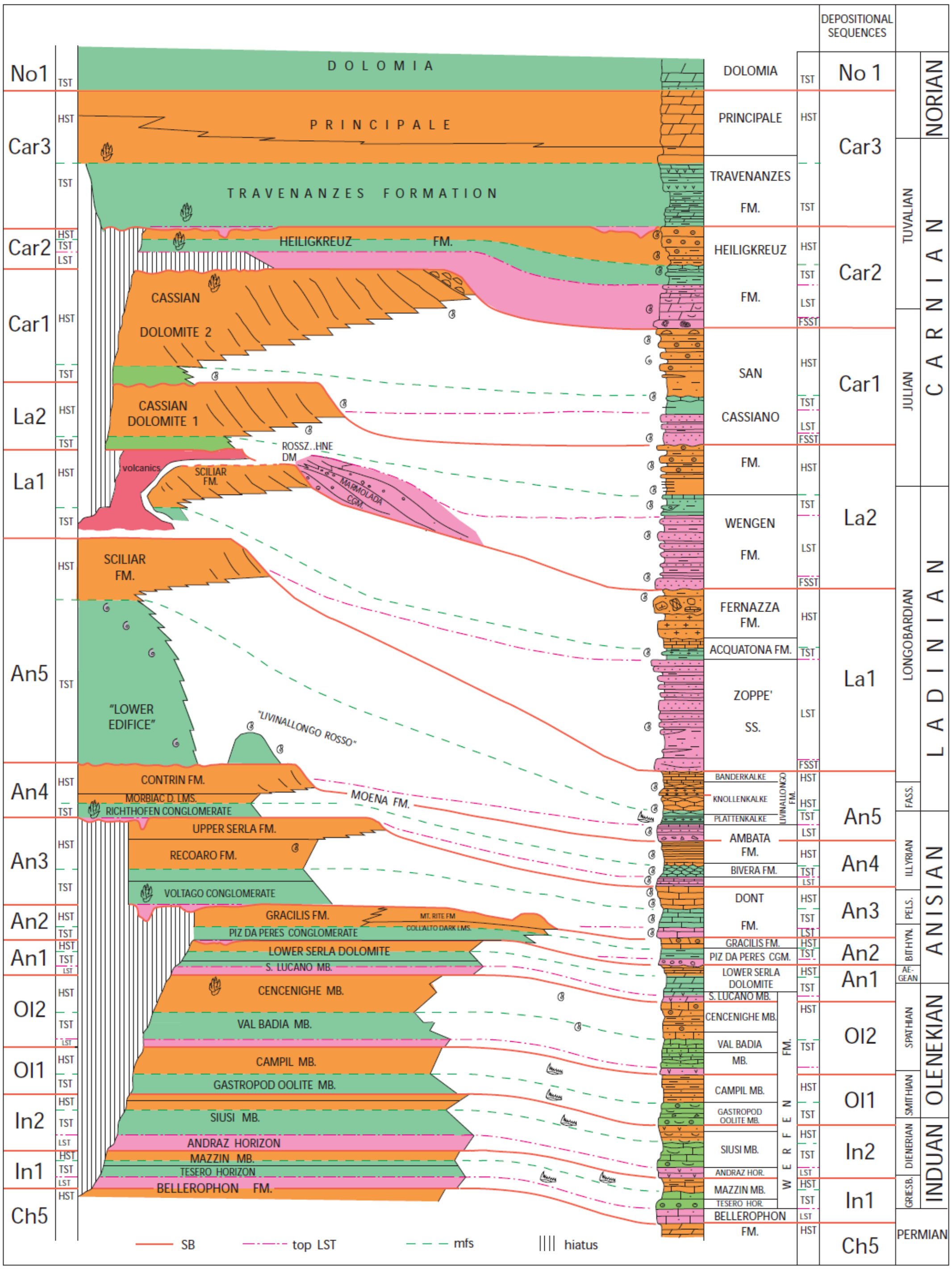
P. Gianolla*; N. Preto°; G. Gattolin°^; M. Caggiati*; A. Breda°.

** University of Ferrara, Department of Physics and Earth Sciences, via Saragat 1, 44100 Ferrara, Italy (glr@unife.it)*
° University of Padova, Department of Geosciences, via Gradenigo 6, 35131, Padova, Italy
^ Exploration and Production Division, Eni S.p.a., Via Emilia 1, 20097 San Donato Milanese, Italy

Seismic-scale outcrops, the high-resolution bio-chrono-stratigraphic framework and the scarce alpine deformation render the Dolomites (Southern Alps, north-eastern Italy) an ideal reference for the Triassic global sequence stratigraphic charts (Haq et al., 1987; Gianolla & Jacquin, 1998; Hardenbol et al., 1998). However, the Triassic of the Dolomites is the result of a complex set of forcings, which determined a large variability of the carbonate sedimentary successions that includes ramps, carbonate banks, high-relief isolated or attached carbonate platforms, with different carbonate factories. The possibility to read the coeval response of carbonate and siliciclastic depositional systems to such different sedimentary forcings as sea level oscillations, climate change and volcanic activity make this region a playground to test the limits and the potentials of the sequence stratigraphic methodology.

Recently, the sequence stratigraphic framework of the Dolomites was carried out according to the approaches summarized in Catuneanu et al. (2011). The revision of the depositional sequences (DSa) allowed to better define: a) the surfaces that delimit the different system tracts; b) the influence of tectonics in the timing of the DSs stacking patterns; c) the role of changing carbonate factories in the architecture of carbonate depositional systems; d) the impact of climate and/or environmental changes in the demise of carbonate systems and supply of siliciclastic sediments; e) the impact of local volcanic activity on sediment supply and carbonate production shut-off, ; and lastly g) the hierarchy of the identified depositional sequences. This led to a revised sequence stratigraphic framework (Fig. 1), characterized with respect to the original schemes (e.g., Gianolla et al., 1998) by a lower number of DSs, by the identification of FSSTs in many DSs, and by a better age control for sequence stratigraphic surfaces.

One example is the impact, in the Dolomites, of the "Carnian Pluvial Event", a global episode of climate change documented worldwide at low latitudes, that involved increased rainfall and possibly global warming. This climatic event predates a drop of sea-level and caused the demise of microbial dominated high-relief carbonate platforms that dominated the region. It was followed by the coexistence of small microbial carbonate mounds and loose arenaceous carbonates. A subsequent sea level fall brought to the definitive disappearance of microbialites and shallow water carbonates switched to ramps dominated by loose carbonate sediment. The climate-induced crisis of Early Carnian shallow water carbonate systems of the Dolomites generated a geological surface similar to a drowning unconformity, although no transgression occurred. The sudden infilling of basins at the end of the Early Carnian was the result of the climatic-induced switch from high-relief carbonate systems characterized by steep slopes to a gently inclined ramp, rather than by the continuous progradation of a high-relief microbial platform.
Results show that the evolution of carbonate systems of the Dolomites at the end of the Early Carnian cannot be interpreted in the light of sea level changes only, pointing out that ecological changes can induce significant modifications in depositional geometries.


DEPOSITIONAL SEQUENCES
No1
Car3
Car2
Car1
La2
La1
An5
An4
An3
An2
An1
Ol2
Ol1
In2
In1
Ch5
DOLOMIA
PRINCIPALE
TRAVENANZES FORMATION
HEILIGKREUZ FM.
CASSIAN DOLOMITE 2
CASSIAN DOLOMITE 1
SCILIAR FM.
"LOWER EDIFICE"
"LIVINALLONGO ROSSO"
CONTRIN FM.
MORBIAC D. LMS.
RICHTHOFEN CONGLOMERATE
UPPER SERLA FM.
RECOARO FM.
VOLTAGO CONGLOMERATE
GRACILIS FM.
PIZ DA PERES CONGLOMERATE
LOWER SERLA DOLOMITE
S. LUCANO MB.
CENCENIGHE MB.
VAL BADIA MB.
CAMPIL MB.
GASTROPOD OOLITE MB.
SIUSI MB.
ANDRAZ HORIZON
MAZZIN MB.
TESERO HORIZON
BELLEROPHON FM.
MOENA FM.
MARMOLADA CGM.
volcanics
TRAVENANZES FM.
SAN CASSIANO FM.
WENGEN FM.
FERNAZZA FM.
ACQUATONA FM.
ZOPPE' SS.
BANDERKALKE
KNOLLENKALKE
PLATTENKALKE
LIVINALLONGO FM.
AMBATA FM.
BIVERA FM.
DONT FM.
WERFEN FM.
NORIAN
CARNIAN
TUVALIAN
JULIAN
LADINIAN
LONGOBARDIAN
FASS.
ANISIAN
ILLYRIAN
PELS.
BITHYN.
AEGEAN
OLENEKIAN
SPATHIAN
SMITHIAN
INDUAN
DIENERIAN
GRIESB.
PERMIAN
SB
top LST
mfs
hiatus

Testing Sequence Stratigraphic Concepts in 3D on a Mega Scale: Lateral variation of key stratal surfaces from 3D seismic analysis of the Late Cenozoic Southern North Sea

Harding, R[1], Huuse M[1]

University of Manchester, Williamson Building, Manchester M14 9PL
Rachel.Harding@postgrad.manchester.ac.uk

'MegaSurvey' 3D seismic data and borehole data spanning the southern North Sea reveal an expanded sedimentary record for the Late Cenozoic, a period of intense climatic and eustatic changes leading to fully glacial conditions in high latitudes of the northern hemisphere.

The Late Cenozoic of the North Sea Basin was dominated by a large clastic depositional system, fed by the Baltic River System (BRS) and the proto-Rhine, -Elb and –Meuse rivers. Periodically, deltas reached the rapidly prograding shelf edge and shed sediment into the basin in the form of basin floor fans. During the Late Miocene-Pliocene (12.4-2.58Ma) the main sediment input into the basin was from the northeast. From the earliest Pleistocene (2.58Ma-1.8Ma), sediment supply from easterly and southerly directions dominated in the southern North Sea.

The lateral extent and character of sequence boundaries along strike within a sedimentary basin is a subject of debate in the literature. The spatially varying subsidence (regional and salt tectonic controls); variable sediment input (grade, volume and direction), changing climatic drivers and connection to the global ocean, in combination with extensive 3D seismic and borehole coverage, makes the Late Cenozoic North Sea a natural laboratory to test several sequence stratigraphic concepts. This includes the chronostratigraphic significance of seismic reflections, the lateral variability of sequence boundaries, and eustatic control on sequence development.

The offshore seismic expression of this sediment input is in the form of largely low angle (<2°) clinoforms. They vary in style and height, from 50 m to 500 m, prograding and downlapping onto the Mid-Miocene Unconformity (MMU). Two main structural domains are identified within the basin: in the northeast the basin geometry is dominated by accelerated subsidence; and the southwest is dominated by Quaternary salt tectonic activity. Variation in coeval sequences across the basin suggests that although there is evidence for a strong influence of 40,000 year glacial/interglacial cycles between 2.58 and 1.8Ma, the creation and destruction of accommodation space by these two tectonic actions is shaping the resulting sequences.

Maximum flooding surfaces are typically associated with downlap surfaces observed in seismic images and condensed shale layers observed in gamma-ray logs. These are the most traceable key stratal surfaces across the basin, and can be more consistently tied to the global sea level curve than erosional/onlap surfaces.

Sequence Stratigraphy in Deep-Water? Time Transgressive key surfaces and the progradation of basin-floor fans

David M Hodgson1, Ian A. Kane2

[1] *School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK.*
[2] *Statoil ASA, Research Centre, Bergen, P.O. Box 7200, NO-5020 Bergen, Norway.*
Corresponding author: d.hodgson@leeds.ac.uk

A general consensus on the sequence stratigraphic framework established for deep-water deposits relates cyclic variations in shelfal accommodation to repeated changes in the character of the lithology and stacking of depositional elements. Several factors hinder the simple translation of sequence stratigraphic terms and principles defined for shallow-water systems to the interpretation of deep-water deposits meaning that the lowstand fan concept remains contentious. Here, we integrate observations from outcrop and subsurface datasets to interpret that most key regressive surfaces formed during phases of submarine slope degradation are time transgressive. Progressive confinement on the slope results in sequential sediment gravity flows that maintain their downslope energy farther into the basin during the initial period of slope channel system formation. This way, frontal lobe deposits are incised and overlain by external levees as the channel system propagates farther into the basin and becomes more confined by a combination of erosional confinement and external levee construction. The stratigraphic response of the linked basin floor fan is growth and net progradation until a maximum basinward extent is reached, corresponding to the time of most efficient slope sediment supply, which marks a maximum regressive surface. Conceptually, this process response could be purely autocyclic, but would be amplified with an allogenically-driven waxing-then-waning sediment supply cycle. The coupled progressive confinement of the slope channel system and basin-floor fan growth will result in a strongly diachronous lithological basal surface to the system, and challenges the widely applied model whereby the deep-water sequence boundary is isochronous and passes into a correlative conformity at the base of the basin floor fan.

Utility of Palaeomagnetic and Magnetostratigraphic Data in Sequence Stratigraphy Investigations

Joseph C. Liddicoat

Barnard College, Columbia University, NY, NY 10027 USA
jliddico@barnard.edu

Two characteristics of Earth's magnetic field have application for correlating and dating stratigraphy – reversals of polarity and systematic changes in the palaeomagnetic vector. The benefits and limitations of each are controlled by several factors, and among them is the time interval. Whereas the reversal time scale (Gradstein *et al.,* 2004) covers all of Earth history, records of short- and long-term behaviour of the magnetic field (called secular variation) apply only to the Holocene and Quaternary post-Wisconsin (several hundred thousand years). Also restricting are the location and areal extent of an investigation; there are no bounds on magnetostratigraphic investigations, but secular variation is confined mainly to regions several thousand kilometres across (for example, within the Great Basin of the western U.S. or in Great Britain and Europe).

A reversal of polarity is easy to conceptualize as a stratigraphic marker because it occurs simultaneously around the world. If the magnetostratigraphy is complete to the base of the Quaternary (as in a core of lacustrine or marine sediment), dating the stratigraphy using only the reversal time scale can be done with a high level of confidence. Because secular variation is the result of a complex interaction between the dipole and nondipole fields, it is highly variable when considered worldwide. Still, where systematic changes in declination, inclination, and relative field intensity are calibrated by radiometric dates, the curves are potentially useful for correlating and dating stratigraphy on a regional scale. Rock-magnetic information, such as magnetic susceptibility, and other laboratory experiments (Thompson *et al*., 1980) designed to identify the physical properties and composition of the carrier of magnetization are akin to records of secular variation in lacustrine and marine sediments.

The results of investigations where Earth's magnetic field has been used in investigations of sequence stratigraphy will be presented. They are for dating a 3.0 m.y. record of palaeoclimate in pluvial lacustrine sediments in Searles Valley, CA (Liddicoat *et al*., 1980); dating and correlating Oligocene and younger turbidites and subareal sediments in the Ventura and Los Angles basins, CA (Liddicoat, 1990); dating and correlating Pliocene and younger lacustrine and subareal sediments in Death Valley, CA (Knott *et al*., 2008); dating and correlating Pliocene and younger terrestrial and lacustrine mammal-bearing sediments in the Nihewan Basin, China (Cai *et al*., 2013); and dating transgressive and regressive Pleistocene and Holocene marine sequences in the eastern Tyrrhenian Sea (Iorio *et al*., 2014). As well, stratigraphic sequences deposited during the Cretaceous and Cenozoic in North America in the Atlantic Coastal Plain (Virginia, South Carolina, Georgia) and Mississippi Embayment (Texas, Mississippi, Alabama) can be correlated by marine fossils and the palaeomagnetic record to sedimentary formations and palaeontology records in Europe and Asia (Liddicoat, 2012).

Nearshore erosional surface in a wave-dominated delta system: example from Holocene Godavari delta, India

Yoshiki Saito [1], Kakani Nageswara Rao [2], K.Ch.V. Nagakumar [2], G. Demudu [2], A.S. Rajawat [3], Sumiko Kubo [4], Zhen Li [5]

1. Geological Survey of Japan, AIST, Central 7, Tsukuba, 305-8567, Japan, yoshiki.saito@aist.go.jp
2. Andhra University, India
3. Space Applications Centre, India
4. Waseda University, Japan
5. SKLEC, East China Normal University, China

The Godavari delta is one of the world's largest wave-dominated deltas. The Godavari River arises in the Western Ghats near the west coast of India and drains an area of about $3.1x10^5$ km^2, flowing about 1465 km southeast across the Indian peninsula to the Bay of Bengal. The Godavari delta consists of a gentle seaward slope from its apex (12 m elevation) at Rajahmundry and a coastal beach-ridge plain over a distance of about 75 km and covers ~5200 km^2 as a delta plain. The river splits into two major distributary channels, the Gautami and the Vasishta, at a barrage constructed in the mid-1800s. The coastal environment of the deltaic coast is microtidal (~1 m mean tidal range) and wave-dominated (~1.5 m mean wave height in the June–September SW monsoon season, ~0.8 m in the NE monsoon season).

Twelve borehole cores (340 m total length), taken in the coastal delta plain during 2010–2013, yielded more than 100 C-14 dates. Sediment facies and C-14 dates from these and previous cores and remote-sensing data support a new delta evolution model. The Holocene coastal delta plain is divided into two parts by a set of linear beach ridges 12–14 km landward from the present shoreline in the central part of the delta. The location of the main depocenter (lobe) has shifted during the Holocene from 1) the center to 2) the west, 3) east, 4) center, 5) west, and 6) east. The linear beach ridges separate the first three from the last three stages. These lobe shifts are controlled by river channel shifts near the apex. Just as the current linear shoreline of the central part of the delta and the concave-up nearshore topography are the results of coastal erosion of a cuspate delta, the linear beach ridges indicate a former eroded shoreline. An unconformity within the deltaic sediments also indicates erosional environments during the formation of the linear shoreline. We interpret this unconformity as a wave-ravinement surface in a regressive delta succession reflecting the decrease of sediment supply due to lobe shifts (or avulsion) and partially temporary transgression in a delta system, and not as a marine erosion surface due to forced regression. Similar erosion surface is recognized in the Yellow River delta (Saito et al., 2000), also formed by a lobe shift. Discrimination of either surface for ancient sediments and rocks in a wave-dominated setting will be important in sequence-stratigraphic interpretation.

Saito, Y. et al.: J Asian Earth Sci. 18, 489–497, 2000.

Using sequence stratigraphy to understand the taphonomy of dinosaur sites in the Arcillas de Morella Formation (Lower Cretaceous, Eastern Iberia, Spain)

Andrés Santos-Cubedo[1], Carlos de Santisteban Bové[2], Begoña Poza Falset[1] & Nicolaas Molenaar[3]

1. Grup Guix, C/ Santa Lucia, 75, E-12540 Vila-real, Castelló. santos.cubedo@gmail.com; begopoza@gmail.com
2. Departament de Geologia, Universitat de València, Av. Dr. Moliner, 50, E-46100 Burjassot, València. carlos.santisteban@uv.es
3. Department of Geology and Mineralogy, Vilnius University, K.M. Čiurlionio 21/27, LT-03101 Vilnius, Lithuania. nicolaasmolenaar@gmail.com

The Arcillas de Morella Formation (Barremian, Lower Cretaceous; Spain) is one of the most famous dinosaur fossil rich formations from Europe. In its sediments, dinosaur bones were described for the first time in Spain. After years of paleontological investigations a great number of dinosaur sites have been found. Despite of the well-known fossil fauna and flora, the sedimentology and the accumulations of the dinosaur bones remain largely unstudied, and no unequivocal paleoenvironmental framework has yet been established. The study of various bonebeds using sequence stratigraphic methods and concepts has now shed light about the complexity of taphonomic process that form the fossiliferous sites in Arcillas de Morella Formation. This also highlights the importance of understanding the taphonomic history of the fossil associations for paleontological studies.

The sediments from this formation contain abundant articulated and disarticulated remains of extinct and extant taxa, primarily dinosaurs. Most of these dinosaur remains are found in transgressive facies. Dinosaur bones commonly occur as fragments or disarticulated skeletons, but in some cases they are articulated carcass or semi-articulated ones.

The pertinent stratigraphic unit comprises sandstones, conglomerates, carbonates, marls and claystones. The succession shows a cyclic lithology pattern that corresponds to relative sealevel changes and changes in climate that developed in the western Tethys during the Early Cretaceous. The deposits were formed in a wave-influenced deltaic system, which was incised during eustatic falls and then filled during a marine transgression. Many of the sandstone bodies are beach deposits, which result of the infill of an incised valley complex. These infillings form a complex of transgressive-regressive cycles represented by alternating green marls, which contain tropical carbonates with marine fauna at the base, and red clays at the top, with prismatic calcareous paleosoils similar to the modern caliches developed in the semiarid Mediterranean regions.

The use of sequence stratigraphy has enabled us to understand the formation of dinosaur fossil sites from the Arcillas de Morella, and they led us to propose a scheme for the location of these sites in the stratigraphic succession, allowing better understanding of the complex taphonomic processes.

The use of chemostratigraphy to refine ambiguous sequence stratigraphic correlations in marine shales. An example from the Woodford Shale, Oklahoma, USA.

Turner, B.W.[1], Slatt, R.M.[1], and Tréanton, J.A.[2]

1: University of Oklahoma, ConocoPhillips School of Geology and Geophysics, 100 East Boyd St. Suite 710, Norman, OK 73019
2: Noble Energy, 1001 Noble Energy Way, Houston, TX 77070

The Woodford Shale provides an opportunity to test recent advances in handheld XRF (HHXRF) technology to develop and refine sequence stratigraphic frameworks by comparing chemostratigraphic profiles directly to gamma ray logs obtained from the same locations. Two adjacent field sites and three cores of the Woodford Shale have been scanned using HHXRF to develop a preliminary analysis of the regional variability of chemostratigraphic profiles for this formation.

Three cores from Lincoln, Pottawatomie, and Pontotoc Counties in Oklahoma and two outcrops at the Hunton Anticline Quarry (HAQ) in Murray County, OK represent both proximal and distal environments of the Woodford Shale. Clean surfaces at each area are scanned at no greater than one foot intervals using HHXRF to determine the elemental profiles. At the same resolution, a gamma ray profile is scanned using a GR scintillator or core spectral gamma ray. The lithologic description, gamma ray profile, and elemental profiles are then used to develop the sequence stratigraphic interpretation.

Stratigraphic successions that are correlatively ambiguous based on GR profiles alone are able to be properly correlated by utilizing surfaces that are recognized within chemostratigraphic profiles. Certain elements act as proxies for local depositional and environmental conditions during sedimentation. The principal elements used in this study are titanium (Ti), zirconium (Zr), silicon (Si), Calcium (Ca), strontium (Sr), phosphorous (P), aluminum (Al), potassium (K), molybdenum (Mo), and vanadium (V). Plotting these changing concentrations of elements as a function of depth in a measured section generates a chemostratigraphic profile used to develop stratigraphic frameworks.

Ti and Zr are associated with continentally derived sediment. Ca and Sr are associated with carbonate accumulation. Al and K are associated with feldspars and clays. Mo and V can be used as an indication of redox conditions. Additionally, organic matter is a principal vector for P and can bind V in sediments. Si is found in biogenic quartz, detrital quartz, feldspars, and clays. As such, it is useful to evaluate Si as a ratio between Si/Al. When evaluated 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 horizon. At several horizons in the Woodford the Si/Al value spikes, these spikes are interpreted as algal blooms at these locations. Immediately above these blooms, there is typically a sudden peak in carbonate proxies, interpreted as temporary periods of hard-ground formation. When found together, these horizons are interpreted as surfaces of non-deposition that can be used for building a correlative stratigraphic framework.

These chemostratigraphic successions are capable of resolving higher frequency cyclicity within a sequence stratigraphic framework than is typically interpreted from GR logs. By evaluating the chemostratigraphic trends, it is possible to break out 5 parasequences within the transgressive systems tract in the Lower and Middle Woodford and 2 parasequences within the highstand systems tract above the maximum flooding surface near the base of the Upper Woodford.

A hierarchical approach to marginal marine classification: linking the scales of sedimentology and sequence stratigraphy

Boyan K. Vakarelov[1], R. Bruce Ainsworth[2]

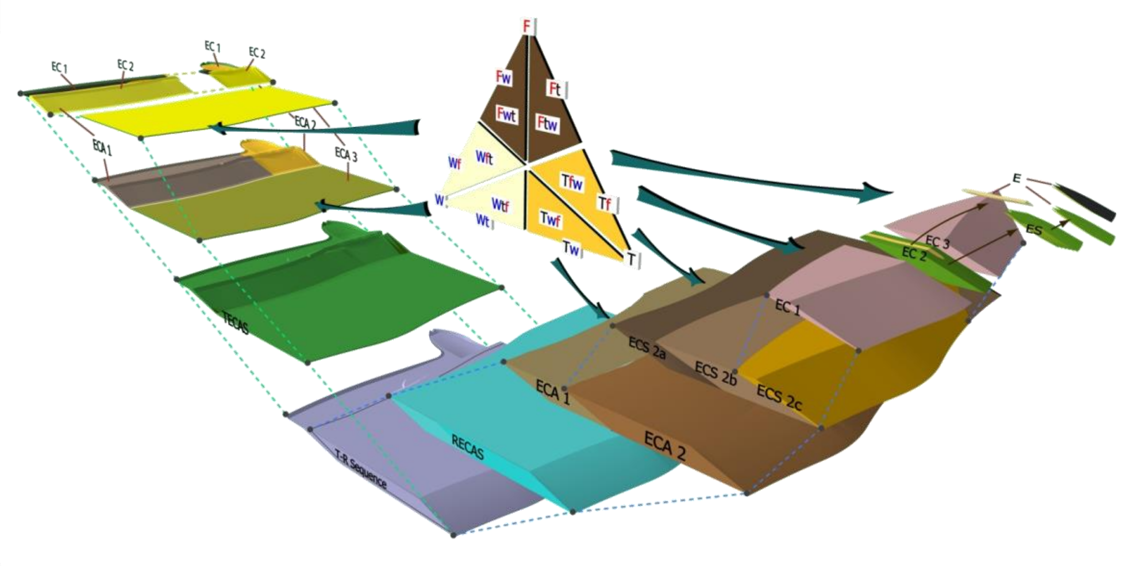
1. *WAVE Consortium, The University of Adelaide, Adelaide, SA, Australia, bvakarelov@sedbase.com*
2. *Australian School of Petroleum, Adelaide, SA, Australia*

Marginal marine systems contain a natural organization of sediment body architecture that can be used for devising a hierarchical classification scheme. Using hierarchies of different levels of architecture, linked by parent-child relationships, allows for describing the same system from the scale of an individual bed to the scale of a depositional sequence. Such a framework provides the means to describe both the inter-parasequence and the intra-parasequence architecture and heterogeneity of a unit, which has important subsurface implications.

The classification scheme clearly differentiates process from architecture. Process is determined by examining physical sedimentary structures and trace fossil assemblages that are used as proxies for ratios between wave, tide and fluvial-generated currents. Fifteen process classification categories have been defined: F, Fw, Ft, Fwt, Ftw, W, Wf, Wt, Wft, Wtf, T, Tf, Tw, Tfw, Twf (Figure 1).

Architecture refers to the different scales of sediment bodies that are formed by these processes, as well as additional allocyclic or physiographic controls. The classification consists of seven types of architectural units which are placed on five architectural hierarchy levels—Hierarchy Level I: Element (E) and Element set (ES); Hierarchy Level II: Element complex (EC) and Element complex set (ECS); Hierarchy Level III: Element complex assemblage (ECA); Hierarchy Level IV: Element complex assemblage set (ECAS); and Hierarchy Level V: Transgressive-regressive sequence (T-R Sequence). Stacking of T-R Sequences (T-R Sequence sets) under different accommodation/sediment supply regimes can be related to systems tracts and depositional sequences. E, ES, EC, ECS and ECA units are subdivided in categories that are related to depositional process. ECAS and T-R Sequence deposits are not assigned a process (Figure 1).

Use of the hierarchical classification allows for linking architectural units by means of familial relationships (parent-child, siblings, cousins). A finite number of relationships between individual architectural categories makes possible the prediction of parent, child and sibling units to a classified interval. Such an approach can be greatly simplified through use of software.



Architectural Unit Name	Acronym	Informal Abbreviated Name
Element *	E	*No abbreviation*
Element Set *	ES	*No abbreviation*
Element Complex *	EC	Complex
Element Complex Set	ECS *	Complex Set
Element Complex Assemblage	ECA *	Assemblage
Element Complex Assemblage Set	ECAS *	Assemblage Set
Transgressive Element Complex Assemblage Set	TECAS *	Transgressive Assemblage Set
Regressive Element Complex Assemblage Set	RECAS *	Regressive Assemblage Set
Transgressive-Regressive Sequence	T-R Sequence*	*No abbreviation*

* recommended form for usage

Figure 1. A summary diagram of the hierarchical, process and architectural marginal marine classification. After Vakarelov and Ainsworth (2013).

The outlined classification offers the following practical implications: (1) It covers all regressive and transgressive marginal marine depositional environments; (2) it applies equally well to modern and ancient systems; (3) each hierarchy level applies to a different scale of observation, with units covering the full spectrum of reservoir heterogeneities (entire flow units, inter-reservoir sand bodies, and intra-reservoir barriers and baffles); (4) it provides a framework for dealing with depositional uncertainty; (5) it is highly suitable for use in computer databases and computer expert systems.

References:

Vakarelov, B.K. and Ainsworth, R.B, 2013, A hierarchical approach to architectural classification in marginal marine systems – bridging the gap between sedimentology and sequence stratigraphy. AAPG Bulletin, v. 97, p. 1121-1161.

The challenges associated with sequence stratigraphy in the glacial environment

Paul van der Vegt, Evert van de Graaff

PanTerra Geoconsultants, p.van.der.vegt@panterra.nl

The investigation of glacial deposits has become increasingly important in recent decades due to its growing significance as potential hydrocarbon reservoirs. While sequence stratigraphy has been successfully implemented in correlating depositional sequences in coastal settings, the direct application of the sequence stratigraphic approach in the glacial depositional environment remains challenging. The aim of this work is to highlight the implications of uncertainties of a glacial environment on the sequence stratigraphy and suggest steps reduce these uncertainties.

Sequences derived from glacial deposits are mainly related to icehouse world conditions. An icehouse world has enhanced sea-level changes compared to a greenhouse world due to water being stored and released from the ice sheets. This increased storage potential of both water and sediment can also enhance continental and basin-scale diachronous events in deposition. Local climatic factors invariably play a large role in ice accumulation and retreat, complicating reconstructions on a geological scale. The resulting rapid changes in deposition are characteristic for the glacial regime. An example of this is the way in which continental ice-sheets are known to change in dimension, direction and hydraulic character within a single, but also between successive, ice-ages. This impacts our ability to make correlations and predictions on scales ranging from continental to even very localised regions.

Important controls for sequence stratigraphy, such as water-depth, accommodation space and sediment source significantly increase in complexity closer to the ice-sheet due to glacio-isostatic depression. This leads to differential changes in water-depth, accommodation space and sediment supply. This has an immediate effect this has on basin geometry, which differs significantly compared to non-glacial coastlines. In addition, deglaciation has a direct impact on global sea-level while the glacial rebound occurs over a longer time-scale.

Glacial processes causes shelf and continent to be severely eroded resulting in deep scours, meltwater channels and large moraines. Although these incisions occur during lowstands they can incise deeply below ‘normal’ base-level making them fundamentally different from non-glacial fluvial channels. The inherited topography from this erosion causes significant increases in accommodation space, while the increased mobilized sediment causes rapid sedimentation. This leads to the development of isolated areas where lakes of variable spatial scales may develop. In this fragmented sedimentary system these lakes can be rapidly filled with deposits of a varying nature and at different times. This will complicate correlations in basin- or local-scale reconstructions.

Currently sequence stratigraphy is generally applied on local scale for glacial deposits. Basin-scale and continental scale applications remain challenging because these are highly overprinted by local effects. Sequence stratigraphy assumes sea level to be a dominant control the position of sediment input. This is not the case in the glacial setting. A rise in water-level or a change in climate may trigger floating of the ice sheet, and cause a retreat of the basal subglacial sediment source. Alternatively, due to conditions up-ice may cause the ice to advance onward resulting in a counter intuitive forced regression, unrelated to the change in water-level. It has been suggested that the decoupling of the sediment supply and the relative sea-level is a necessary step to allow the application of sequence stratigraphy in the glacial domain.

This work aims to highlight the uncertainties and difficulties that need navigating in the interpretation and correlation of glacio-stratigraphic sequences on different spatial and temporal scales. A better understanding of these challenges can help to pave the way to a future sequence stratigraphic framework that can be applied in the glacial environment.

The influence of hydrodynamic-morphodynamic interaction on sequence stratigraphy in deltaic deposits

Helena van der Vegt, Joep E. A. Storms, Liang Li

Delft University of Technology, h.vandervegt@tudelft.nl

The intricate balance of allogenic and autogenic processes in fluvio-deltaic environments can complicate placing them in unambiguous chronostratigraphic context. In particular it is important to quantify the relative contribution from autogenic and allogenic processes.

The shoreface-shelf morphology has been found to contain considerable variation depending on its response to processes over a range of timescales. Processes acting over shorter timescales may not be discernable in the vertical facies successions, but can be responsible for differences in overall depositional geometries.

3D depositional geometries originate from morphodynamic controls at the time of deposition. The morphology evolves under control of hydrodynamic processes, while hydrodynamic processes are influenced by the morphology constraining the flow. Morphodynamics and hydrodynamics are therefore interlinked in any evolving deltaic environment. This indicates that the interaction between hydrodynamic and morphodynamics can have a marked impact on effect autogenic processes ultimately have on the stratigraphy.

Delft 3D, a hydro-morphodynamic software tool, has been well established in modelling these interactions on engineering timescales of several years to several decades. Delft3D has also been implemented to model different delta morphologies under varying balance of influencing processes including fluvial, wave and tidal forcing.

With improvements to computing capabilities it is now possible to extend these simulations both spatially and temporally. The timesteps employed in Delft3D are in the order of minutes, allowing inclusion of variation in fluvial, tidal and wave processes. It is also possible to investigate the lateral extent of the effects.

Allogenic forcing in fluvially dominated deltaic systems has been found to induce different autogenic controls. The dominance of e.g. lobe switching, avulsions and mouth bar bifurcations can depend on whether the system is experiencing transgression or forced regression. Additionally, especially during normal regression, the impact which hydrodynamic-morphodynamic interaction has on the resultant sequence stratigraphy, and therefore the balance between autogenic and allogenic processes, may be a function of basin depth.

We will show that the balance between autogenic and allogenic forcings can be influenced by interaction between hydrodynamics and morphodynamics across the genetic units. We have created a set of models in Delft3D which simulate fluvial input into a basin during transgressive and falling stage systems tracts. We investigate the results in models with and without tidal influences and the impact this has on the resulting sequences. We also look at the effect of basin geometry and in particular the relationship between basin depth and hydrodynamic influence during normal regression.

As computing power increases and modelling techniques improves, 3D process-based models will be used increasingly to optimise our understanding of the processes influencing sequence stratigraphy. We have shown how these models can be implemented to improve our understanding of sequence stratigraphy in the deltaic depositional environment through a closer study of the long term interaction between hydrodynamics and morphodynamics. The spatial resolution also allows the quantification of heterogeneity within this environment. In the future, such models can be applied to more specific hypothesis testing into the formation of specific parasequences and sequences.

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Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.
Lecture Theatre:
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.
Main Piccadilly Entrance:
Straight out door and walk around to the Courtyard.

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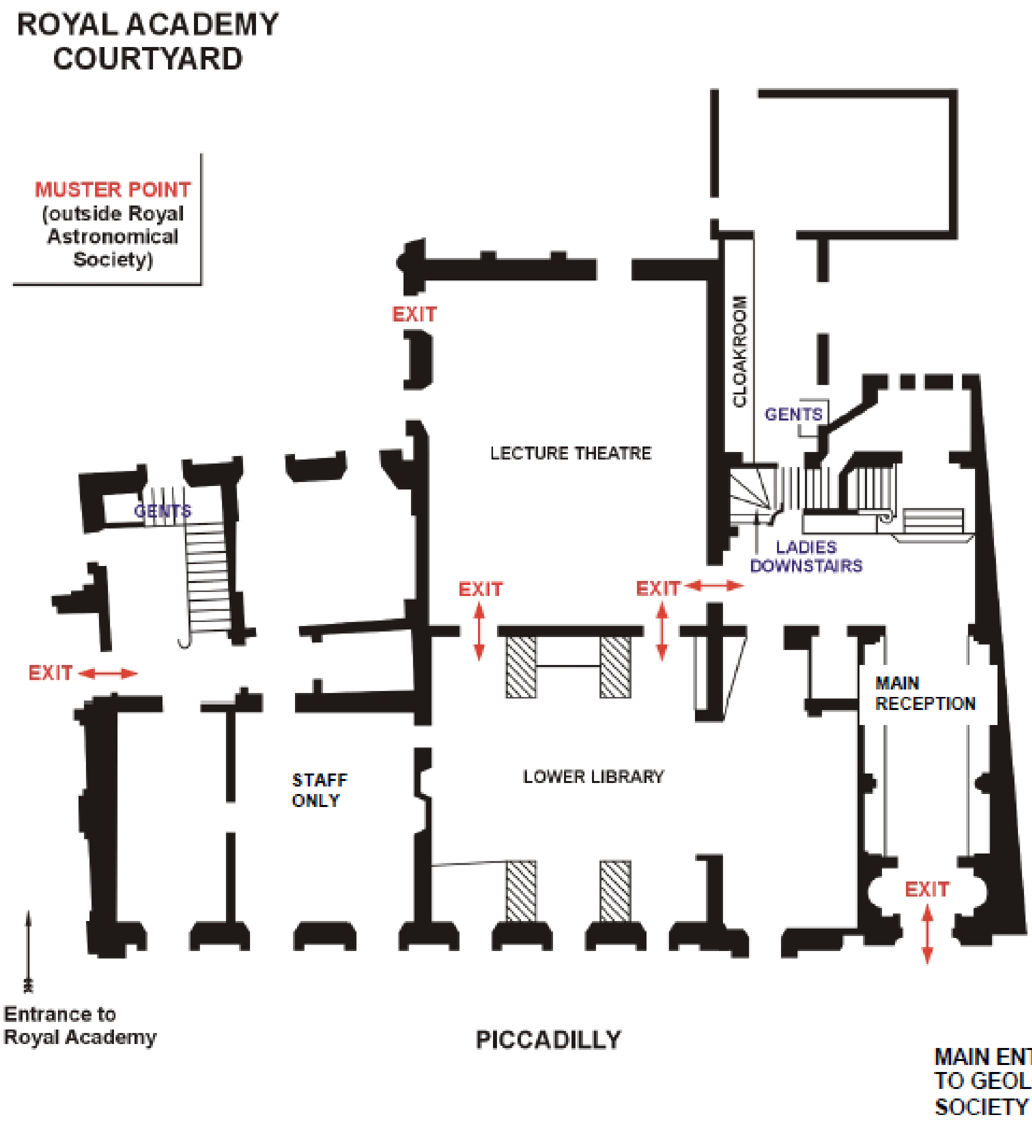
The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly



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