Sedimentology of Paralic Reservoirs: Recent Advances and their Applications

18-19 May 2015

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# Sedimentology of Paralic Reservoirs: Recent Advances and their Applications

## PROGRAMME

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<td>11.40</td>
<td><strong>Joseph Lambiase (Chulalongkorn University)</strong>&lt;br&gt;Sand-Body Geometry and Connectivity in Transgressive-Phase Deltaic Reservoirs</td>
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<td>12.00</td>
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16.00 Marcello Gugliotta (University of Manchester)  
Assessing the Importance of River Discharge Variations Versus Tidal Signals on Architecture in Paralic Reservoirs

16.20 Marijn van Cappelle (Imperial College London)  
Spatial Changes in Depositional Processes in a Progradational Mixed-Influence Deltaic Succession, Jurassic Lower Ile Formation, Halten Terrace, Offshore Norway

16.40 Daniel Collins (Imperial College London)  
Autogenic, Allogenic and Mixed-Process Controls on Stratigraphic Architecture in the Baram and Champion Delta Systems, NW Borneo

17.00-19.00 Finish followed by Wine Reception

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Day Two

08.30 Registration
08.50 Welcome

Session Three: Tidal Heterogeneity in Paralic Systems  
Session Chair: Ron Steel

09.00 Shahin Dashtgard (Simon Fraser University)  
The Broader Implications of Sedimentological- and Associated-Trends Across the Tidal-Fluvial-Transition of the Fraser River, Canada

09.20 Murray Gingras (University of Alberta)  
Inclined Heterolithic Stratification in Estuaries: Origins and Distributions

09.40 Stephen Hubbard (University of Calgary)  
Large Tidally Influenced Meandering River Systems of the Cretaceous McMurray Fm., Athabasca Oil Sands, Canada: A Key Component of an Immense Reservoir

10.00 Donatella Mellere (Premier Oil)  
A Tidally Influenced Shallow Delta System in the Middle Jurassic of the Søgne Basin, Norwegian North Sea

10.20 Silje Skarpeid (BG Group)  
Architecture of Wave and Tide Influence in Jurassic Shorelines, Northern North Sea

10.40 Break and Poster Session

Session Four: Analogue Studies  
Session Chairs: Bruce Ainsworth and Tony Reynolds

11.10 Keynote: Brian Willis (Chevron)  
Shallow Marine Depositional Complexes

11.40 Boyan Vakarelov (University of Adelaide)  
Megafan-Shoreline Systems: A Case Study of the Mitchell River Delta, Gulf of Carpentaria, Australia

12.00 Peter Johannessen (Geological Survey of Denmark and Greenland)  
How Can a 15 M Thick, 14 Km Long and 5 Km Wide Marine Barrier Island Reservoir Sandstone be Developed? – A Case Study from the Holocene to Recent Rømø Barrier Island, Danish Wadden Sea.

12.20 Adrian Hartley (University of Aberdeen)  
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12.40 Lunch and Poster Session

13.10 Meeting for Contributors to Special Publication

13.40 Guy Plint (University of Western Ontario)  
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### POSTER PROGRAMME

**Day One**

#### Session One: Paralic Reservoir Characterisation

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<td>Alireza Morshedian (Badley Ashton &amp; Associates)</td>
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<td>Miquel Poyatos-Moré (University of Manchester)</td>
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<td>David Hodgson (University of Leeds)</td>
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## Day Two

### Session Three: Tidal Heterogeneity in Paralic Systems

**Paul Carling (University of Southampton)**
Sedimentology of a Tidal Bar within the Fluvial-Marine Transition; River Severn Estuary, UK

**Sergio Longhitano (University of Basilicata)**
Deflected Steep-Marginal Deltas in Confined Tidal Straits: An Outcrop Analogue from the Upper Miocene Amantea Basin, Southern Italy.

### Session Four: Analogue Studies

**Julia Mulhern (University of Utah)**
Relating Modern Analogs and Process-Based Facies Models to Ancient Deposits: A Mixed-Energy Estuary from the Cretaceous Straight Cliffs Formation, Southern Utah

**Cari Johnson (University of Utah)**
Reservoir Facies Characterization and LiDAR Model of a Mixed-Energy Estuarine-Tidal Succession, Cretaceous Straight Cliffs Formation, Southern Utah

**Tore Grane Klausen (University of Bergen)**
Meanders to Ribbons: Basin-Scale Deltaic Evolution in the Barents Sea Offshore Northern Norway

**Victorien Paumard (University of Western Australia)**
Stratigraphic Evolution of the Barrow Deltas, Northern Carnarvon Basin, North West Shelf, Australia

**Stephen Flint (University of Manchester)**
Up-Dip to Down-Dip Evolution of Palaeovalleys Incising Deltaic Systems in Foreland Basin Settings.

**Helena van der Vegt (Delft University of Technology)**
The Application of Process-Based Computational Models to Identify Proximal to Distal Trends in Deltaic Sediment Distributions.
Oral Presentation Abstracts
(Presentation order)
Monday 18 May
Session One: Paralic Reservoir Characterisation
Sedimentology of Paralic Reservoirs: Recent Advances and their Applications

Keynote Speaker: Paralic Reservoirs

Tony Reynolds
BP, Sunbury-on-Thames, Middlesex, TW16 7LN, UK

Sedimentology plays a pivotal role in unravelling the complexities of paralic reservoirs: it delivers the language and concepts that allow complex successions of sandstone bodies deposited at or near to sea level, to be described, differentiated and quantified.

At a large scale, paralic successions respond sensitively to sea-level change, commonly by shifts in facies belts across sequence stratigraphic surfaces. As a result, the environments that comprise paralic successions, deltas, estuaries and shoreline-shelf systems, are often interleaved in highly layered successions. This strong layering and the wide range of sandbody types that comprise associated sub-environments (for example channels, splays, or shoreline sands) control the distinctive nature of paralic oil and gas fields.

Most directly layering results in stacked reservoirs. In turn, distinct sandbody types drive a range of reservoir shapes and dimensions. Thick extensive sandstones have structurally defined spill points, and commonly display extensive aquifers and good reservoir properties. Such sands have high recovery, good reservoir performance, and form primary completion targets. By contrast, thin laterally restricted, isolated sandstones have low recovery factors and poor performance. Each isolated sand may have its own set of hydrocarbon contacts, and a distinct outline that reflects both structural and stratigraphic trapping. Such sands form secondary completion targets. Fault compartmentalisation is a recurring risk. Sealing faults increase the number of reservoir compartments and may decrease performance and recovery. They can also generate traps.

At a small scale, paralic reservoirs are distinctive in being dominated by laminated sandstones. The nature of these laminae (thickness, grain size, angle, shape, sorting) is commonly indicative of depositional environment, allowing sand-body type to be inferred. In addition, their impact and that of associated shales on permeability anisotropy and resulting fluid flow is increasingly well understood.

Indeed, heterogeneity in paralic reservoirs is increasingly well understood at all scales. Applications of sequence stratigraphic concepts, ichnology, use of analogue databases, and increased integration have all played roles. Continued progress may lie in: quantification of depositional processes and resulting improvements in analogue choices; time-lapse satellite imagery; a renewed focus on grain size and its link to transport mechanism, bedload, jet or plume; computer models of depositional processes; integration with palynology; open-source data; 3D models of outcrops, and improved links with geomorphologists.
Paralic systems make significant, yet commonly challenging, reservoirs throughout the World. This complexity comes from the stratigraphic architecture which is in turn controlled by a variety of factors including, depositional process, and the accommodation/supply (A/S) ratio. While the importance of these factors have been known for several decades, recent advances in outcrop data acquisition techniques (lidar, UAVs and virtual outcrops) and the use of freely available remote sensing data from modern systems (GoogleEarth etc) have significantly improved our understanding of how these parameters interact to control reservoir architecture.

Depositional process at the shoreline is a function of the relative importance of waves, tides and fluvial input. Modern systems provide an insight into the plan view geometries that result from different combinations of these parameters. A global mapping of shorelines based upon mean wave and tidal range data, combined with a parameter that describes proximity to river mouths and the size of the fluvial drainage basins, has been undertaken. The results of this allow the quantification of global shoreline proportions and their distribution with respect to shelf width, climate, latitude and tectonic setting. The method also provides an excellent tool for finding appropriate modern analogues for ancient systems.

In addition to depositional process, the accommodation/supply regime at the shoreline is critical. The first-order classification is upon whether the shoreline system lies within a sedimentary basin. Shorelines within basins have the capacity to preserve sediment which will ultimately become part of the rock record, however 77% of the Earth’s coastline lies within areas of net erosion where sediment is removed and passed along shore or offshore. Such systems have no preservation potential but are commonly not excluded from analogue studies. The second-order parameterisation of shorelines is whether they are in net progradation or net transgression. Transgressive shorelines produce significantly different deposits (barriers and estuaries) than their progradational cousins (shorefaces and deltas). Finally the progradational systems can be further subdivided based on the shoreline trajectory - rising, straight or falling). The A/S ratio also controls the partitioning of sediment at the intra-parasequence scale. During base-level rise, paralic systems are dominated by fluvial aggradation, while during stable or falling sea-levels the main focus of the sedimentation is within the shallow marine sandbodies.

This presentation will focus on two aspects. Firstly the stratigraphic and processes based classification of paralic systems will be illustrated with examples from the global study of modern shallow marine systems, combined with detailed virtual outcrop studies in which reservoir models have been built and flow simulated to test the impact of various heterogeneities on reservoir performance. Secondly we will examine new methodologies for identifying suitable modern and ancient analogues, leading to the automated extraction of geometric data for object based models and image based data for multipoint statistical modelling, ultimately providing better analogue derived models.
Sedimentology of Paralic Reservoirs: Recent Advances and their Applications

Sedimentological Characterisation, Impact and Modelling of Clinoforms in Shallow-Marine Reservoirs

Gary J. Hampson¹, Gavin H. Graham², Nicholas E. Holgate³, Jenny E. Morris⁴, Stefano Patruno⁵, Richard P. Sech⁶, Steen A. Petersen⁷, Christopher A-L. Jackson¹, Matthew D. Jackson¹ & Howard D. Johnson¹

¹Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, UK
²present address: Total Geoscience Research Centre, Aberdeen, UK
³present address: Shell International, London, UK
⁴present address: Statoil, London, UK
⁵present address: PGS Reservoir Services, Weybridge, UK
⁶present address: Chevron Energy Technology Company, Houston, USA
⁷Statoil Research Centre, Bergen, Norway

Clinoforms are a ubiquitous feature of regressive shallow-marine strata, representing the preserved portions of sloping depositional surfaces at or close to the shoreline. These palaeo-geomorphological surfaces may be associated with significant permeability heterogeneity, which typically cuts across layer-cake reservoir zones defined by facies-based well correlations, and that may strongly influence reservoir behaviour under certain production scenarios. This presentation draws on an inventory of outcrop analogues and subsurface reservoir examples to illustrate how shallow-marine clinoforms are expressed sedimentologically, how they may impact reservoir drainage and recovery, and how they may be incorporated in reservoir models.

The geometry, distribution and lithological character of clinoforms in shallow-marine reservoirs are a function of depositional process regime and high-resolution (intra-parasequence) stratigraphic architecture. Near-linear plan-view geometries, nearly parallel clinoform orientations, and strongly ordered facies transitions across clinoforms reflect the predominance of wave and storm processes. Lobate plan-view geometries, non-parallel spatial configurations, and variable facies transitions across clinoforms are characteristic of river-dominated deltaic shorelines. The interaction of river-mouth and basinal (wave, storm, tide) processes can result in development of three dimensionally complex “compound” clinoform geometries that contain elements of both clinoform styles described above.

Significant uncertainty exists in characterising clinoforms in the subsurface. Forward seismic modeling of outcrop analogues indicates that clinoforms may be imaged in seismic data where they are: (1) spaced wider than the tuning thickness; (2) marked by pronounced interfingering of facies with different acoustic properties; and/or (3) lined by relatively thick cemented layers. These last two criteria can be corroborated using core and wireline-log data, where available. Reservoir simulation studies indicate that the extent and magnitude of permeability contrasts across clinoforms may also give rise to diagnostic production behaviours in late field life, such as breaks in hydrocarbon saturation and pressure, that can be used to refine geological understanding and calibrate reservoir models. Simulation studies also indicate that the impact of clinoform-related heterogeneity is typically larger than that of other geological heterogeneities, regardless of reservoir engineering decisions. Incorporation of clinoforms in simulation models of shallow-marine reservoirs requires model construction to be strongly guided by geological interpretation of stratigraphic surfaces, which can be facilitated (and largely automated) by the use of surface-based modelling algorithms and careful grid design. The prize is more accurate prediction of hydrocarbon recovery and drainage patterns.
Defining Geobody Geometries and Architectural Elements within Fluvio-Deltaic Depositional Systems: a Quantitative Analysis of the Paralic Mungaroo Fm, NW Australia

Georgina Heldreich¹, Jonathan Redfern¹, Keith Gerdes² & David Hodgetts¹

¹School of Earth, Atmospheric and Environmental Science, The University of Manchester, UK; ²Shell International Ltd.

Defining geobody dimensions and architecture in paralic reservoirs is a major challenge. Published width, thickness and sinuosity relationships have a huge range and the use of terminology is often confused. The resolution of typical subsurface datasets; core, wireline and seismic, adds further challenges to interpretation. Commonly outcrop studies are used as analogues, but again they are often scale limited, as many channel belt / channel belt complexes can be far larger than most exposures. It is the integration of data, utilising the potential to image geobodies at a range of scales on 3D seismic, that offers a way forward to build predictive models that are statistically meaningful.

This study examines the Triassic fluvio-deltaic Mungaroo Formation, the main reservoir in the multi-TCF gas play offshore Northern Carnarvon Basin, NW Shelf, Western Australia. A high resolution 3D seismic volume, covering approximately 17,500 km², located NW of the Exmouth and Barrow sub-basins, has been analysed in order to extract geobody geometries using amplitude analysis and blended frequency decomposition volumes. Integration with a full suite of well log data from 21 wells and detailed sedimentological description of conventional core from 8 wells has enabled characterisation of the reservoir architecture and revealed a range of geobody geometries.

The dominant facies associations identified from core and well log analysis include; single and multi-storey fluvial channel sandstones, overbank and floodplain lake mudstones and siltstones and coal intervals. Intercalated, bioturbated mudstone, siltstone and very fine grained sandstone are indicative of lagoonal/ restricted embayment and periodic marginal marine depositional settings. Spatial and temporal characterisation of the depositional environment has defined alternating periods of transgression and regression within an overall transgressive system.

Seismic attribute analysis images a range of geobody morphologies and dimensions, from sinuous, small scale (100 - 200 m wide) through to dominantly straight to low sinuosity large scale (approx. 1 - 2 km wide) geobodies, which are interpreted as individual channels and channel belts/ complexes respectively, and are the principal reservoir units in this succession. Detailed statistics have been extracted from a series of iso-proportional slices that reveal the distribution, classes and evolution of the system both temporally and spatially (proximal to distal).

Predictive 3D reservoir models, conditioned to both seismic data and well control, have been developed in order to better understand and predict reservoir architecture, heterogeneities and connectivity through time. The insights into reservoir architecture, stacking patterns and potential connectivity within the Mungaroo Formation, have significant implications for our understanding of geobody distribution in other paralic depositional systems.
Keynote Speaker: Ichnological Applications to the Characterization and Assessment of Paralic Reservoirs

James A. MacEachern

Applied Research in Ichnology and Sedimentology (ARISE) Group, Department of Earth Sciences, Simon Fraser University, Burnaby, V5A 1S6, BC, Canada

Ichnological analysis has increasingly come to be recognized as an essential component of any high-resolution evaluation of reservoirs in paralic successions. While trace fossil data are unique, they complement classical sedimentological datasets. Ichnological evaluation tends to reside in two broad arenas of inquiry: ichnofabric analysis and ichnofacies characterization. Each contributes meaningfully to our understanding of paralic reservoir units.

Ichnofabric analysis focuses on details of tiering position and emplacement order of biogenic structures, as well as the palaeoecological aspects of the benthic community at the bed or (more rarely) bedset scale. Constituent diagrams are valuable in assessing the percentage of bioturbated fabric, the trace fossil suite, and the cross-cutting relationships between the different tiers. Details of oxygenation, uniformity of deposition rate, presence of subtle autogenic hiatal surfaces, evidence of stratal omission, and characterization of flow pathways through bioturbated media can be assessed using ichnofabric analysis. In tight reservoirs, ichnofabric studies can be critical for assessing the storativity and deliverability of hydrocarbons. Nevertheless, up-scaling such data to the field scale and of assessing the lateral persistence of such fabrics are problematic, and solutions remain elusive.

Ichnofacies characterization resides at a higher hierarchical level than ichnofabrics, and while founded on similar datasets, focuses mainly on bioturbation intensity, uniformity of burrowing, identification of ichnological suites at the bedset and facies scale, and identification of omission highlighting stratigraphic breaks, with the goal of interpreting the depositional environment. As such, ichnofacies are suited to subsurface mapping, stratigraphic correlation, and integration with process-response models derived from the lithofacies. Taken together, integrated ichnological-sedimentological facies models can be constructed to showcase the complex animal-sediment relations of various depositional environments. Up-scaling of this data to the reservoir level is comparable to that required for depositional lithofacies.

New insights into animal-sediment relations in the paralic realm have come to light from the more careful scrutiny of facies in order to identify the evidence of mixed process systems. The integration of ichnological data with recently published mixed process classification schemes have demonstrated that trace fossil suites are highly effective in helping to discern animal responses to the relative importance of waves, storms, tides, river-sediment input, and fluvial discharge in the coastal zone. Environmental stresses imparted by bedload transport of fluid mud, rapid deposition of flocculated clay, elevated and/or fluctuating fluvial influx, and other dynamic processes prevalent in the nearshore realm can be recognized from the combination of sedimentological and ichnological aspects of the facies. Correspondingly, earlier evaluations of muddy and heterolithic bedsets as being necessarily distal can now be reassessed, and many assigned to considerably more inshore settings such as prodeltas, distal delta fronts, brackish bays, and nearshore mud belts. Within such mixed process frameworks, the significance of ichnological observations can be realized and assist in the high-resolution assessment of facies and facies associations constituting the paralic reservoirs and their internal heterogeneities.
Sand-Body Geometry and Connectivity in Transgressive-Phase Deltaic Reservoirs

Joseph J. Lambiase

Petroleum Geoscience Program, Chulalongkorn University, Bangkok, Thailand

Two sandstone facies with significant reservoir potential are common within transgressive-phase deltaic successions in SE Asia. Distributary-fill sandstones occur in outcrop and core as 10 - 20 m thick fining-upward channel sands that become increasingly marine upward, although the amount of marine influence varies considerably. Seismically, they appear as elongate, coastline-perpendicular sand bodies with variable thicknesses and a back-stepping stratigraphic architecture that comprise part of relatively thin aggradational units within larger-scale progradational delta lobe successions. The depositional mechanism is a progressive decrease in sediment transport capacity and competence as ongoing relative sea level rise continually reduces water surface slope, which fills the available accommodation with progressively finer, fluvially-derived sediment until the channel becomes inefficient and avulses.

As distributary-fill sandstones have thicknesses comparable to regressive-phase fluvial point bar deposits, it is nearly impossible to distinguish them solely with wireline data, plus the two facies often are laterally adjacent within the deltaic stratigraphic complex. The geometry, total volume and reservoir quality of distributary-fill sandstone reservoirs also is highly variable because it is determined by the number, size and three-dimensional connectivity of the distributaries plus the amount of tidal influence, which often reduces porosity and permeability. In addition, sandstone thickness is controlled by avulsion so there is no relationship between thickness and channel width, making reservoir volume estimation even more difficult.

Transgressive-phase shoreline sandstones are shoreline-parallel and in the low-energy marine receiving basins of SE Asia their lateral extent is often controlled by inherited, pre-transgression delta morphology and their width and thickness are a function of relative sea level history and wave energy. They also fine upward and can easily be misinterpreted as fluvial successions on wireline logs when they occur within sequences dominated by progradation. Although often relatively thin, transgressive-phase shoreline sandstones can increase reservoir volume and connectivity significantly wherever they immediately overlie pre-transgression sandstones.
Early Cretaceous Mixed-Influence Deltaic Deposits of the Zubair Formation, SE Iraq: Depositional Controls on Reservoir Performance

Martin Wells¹, David Kitching¹, Boris Kostic², Daniel Finucane¹, Richard Brown¹, Carlos Santos¹ & Andrew Bowman¹

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The Early Cretaceous (Barremian-Aptian) Main Pay Member of the Zubair Formation is the main producing reservoir in the supergiant Rumaila oil field in southeast Iraq. Whilst the field has been on production for c. 60 years, significant resources remain. Key to their economic development is an improved understanding of the geological controls on reservoir performance and how this impacts reservoir management decisions.

A rich dataset has recently become available including nearly 1 km of historical core and 100’s of historical to modern open hole logs. These data have been augmented by the acquisition of wireline image logs, formation pressure tests and cased hole saturation logs. Synthesis of these diverse static and dynamic data has enabled a new and integrated understanding of the subsurface description.

Detailed core sedimentology and biostratigraphic analysis enable the identification of two ~50-60m thick fourth-order regressive-transgressive cycles in the Main Pay Member. These cycles highlight the phased advance and retreat of a large river-dominated, tidally-influenced, delta. A typical regressive-transgressive cycle comprises three parts.

The base of a typical cycle is marked by a few metres of pro-delta mudstones representing the early phase of deltaic advance. These mudstones tend to be laterally extensive (up to 10s of km) and provide the foundation for the stratigraphic description. They form widespread pressure baffles and are capable of holding back bypassed oil with swept zones above.

The middle part of a typical cycle comprises dominantly aggradationally stacked, fine- to medium-grained cross-bedded sandstones, deposited in amalgamated lower delta plain channels. In a gross sense sweep within these higher N:G packages is good, small-scale geological heterogeneities influence water-flood behaviour and sweep efficiency. Grain sizes tend to reduce towards the north of the field, with a more complex interlayering of sand and shale, representing a wide-range of more distal depositional environments (distributary channels, mouthbars, sand-flats and a range of lower delta plain to delta front mudstones). Together with the presence of a tar mat, this geological heterogeneity complicates fluid flow behaviour in this area of the field.

The upper part of a typical cycle comprises a few metres of heterolithic, often highly bioturbated transgressive deposits capped by a flooding surface. These lower reservoir quality sandstones contain considerable bypassed oil.

Detailed knowledge of the reservoir architecture has influenced critical aspects of the field depletion plan, for example a completion strategy which prohibits co-mingling across pro-delta shales which display a pressure break. It has also profoundly advanced our knowledge of the distribution of remaining hydrocarbons in this mature field, influencing well targeting and helping to maximise recovery. Future challenges include developing a deeper understanding of fine-scale heterogeneities to aid the recovery of bypassed oil in the south and optimising production from the more stratigraphically complex north.
Yoredale Sandstone Architecture in the Breagh Field (UK SNS)

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The exploration, appraisal and development wells in the Breagh gas field have provided fourteen penetrations of the Lower Carboniferous Yoredale formation with an average of over 500 ft of stratigraphic section. They cover an area of about 40 km² within the Breagh Field.

The Yoredale formation is dominated by very fine grain size sediments, argillaceous siltstone and shales. Reservoir quality sandstones form about 20% of the sequence and have a remarkably uniform thickness of about 30ft (10m).

The end-members of the paralic depositional system are marine limestones and freshwater coals. The limestones and coals have the potential to allow a detailed subdivision and correlation of the sequence, but the correlation is made ambiguous in places by the variable erosion level of the base Permian unconformity. Chemostratigraphic interpretation has been used to solve ambiguous correlation options.

Reliable correlation has then allowed an understanding of the architecture of the sandbodies. This has shown that both widespread sheet sands and single well isolated sandbodies are present but are not easy to differentiate based on log signatures alone. However by integrating connected volumes interpreted from well test pressure transient analysis with permissible sandbody architecture within the correlation it has been possible to predict the extent of otherwise indeterminate sandbodies.
Monday 18 May
Session Two: Process-Based Classification of Paralic Systems
Keynote Speaker: What Flavour is Your Body? New Age Classification of Paralic Depositional Systems

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Recent detailed studies of modern paralic depositional environments and ancient paralic strata have revealed complexities that existing 20th Century classification systems are unable to capture and describe. Furthermore, concurrent advances in 3D modelling software capabilities have enabled these complexities and details to be captured in reservoir models.

In order to harness these developments, new and improved methods of description and classification of these systems are required. Any new classification must be able to describe the natural hierarchies that exist in paralic depositional systems and that can be mimicked by most 3D reservoir modelling packages. Hence an architectural classification of depositional bodies built around a natural hierarchy is a first step in any new classification. Once a body has been defined and placed in an architectural hierarchy, the ‘flavour’ of that body must then be described. The key ‘flavour’ in paralic systems is the depositional process or combination of processes that were responsible for deposition of the body. Three key processes need to be considered in the paralic realm; waves, tides and fluvial processes. Each process can act individually or in combination at the coastline depending on a number of regional and local variables. A simple classification of process dominance combinations is described by a one, two or three letter acronym with the most dominant process being placed first. For example a single letter would describe a system only generated by one process (eg, Fluvial-dominated; F). Two letters would describe a mixed process system generated by two processes (eg, Fluvial-dominated, wave-influenced; Fw). Three letters would describe a mixed process system generated by three processes (eg, Fluvial-dominated, wave-influenced, tide-affected; Fwt). Fifteen discrete process combinations are thus available to describe the process variability observed in paralic depositional systems.

The process classification is important since the process or process combination defines the geometry of the depositional body identified in the hierarchical architectural classification. For example, a mouthbar depositional body generated by fluvial processes alone (F-Mouthbar) will have a very different geometry and internal heterogeneities from a mouthbar generated by a combination of wave and fluvial properties (Wf-Mouthbar), which will in turn be different from a mouthbar generated by a combination of tidal and fluvial processes (Tf-Mouthbar).

In terms of the architectural hierarchy, paralic systems self-organise into regressive and transgressive units on the scale of a shoreline progradation and retrogradation respectively. In the ancient, this would be represented by one forward-stepping unit(s) overlain by a backstepping unit(s) or flooding event (high frequency sequence). In the modern, this would be equivalent to the progradation of a system through the Holocene and a subsequent flooding. Studies of Holocene progradational systems are therefore direct analogues for the regressive portions of ancient regressive high frequency sequence cycles. This is also fortuitous since most reservoir flow units in paralic systems are represented by these high frequency sequences which are usually bounded top and bottom by flooding shales. The architectural classification must therefore apply to both scales smaller than the high frequency sequence (intra-sequence scales) and scales larger than the high frequency sequence (inter-sequence scales) that describe sequence stacking patterns and shoreline trajectories.

At an intra-sequence scale, key architectural bodies are defined by fluvial avulsion events (parasequences). Internal to these bodies, architecture can be sub-divided to a bed and bedset.
level which is a critical scale for defining reservoir heterogeneities that can influence fluid flow in reservoirs. Another important flavour is accommodation. Differentiation must be made between high frequency sequences deposited in shallow water (low accommodation) conditions and those deposited in deeper water (high accommodation). Progradational cycles in high accommodation systems are represented by vertical stacking and compensational offsetting of fluvial avulsion driven bodies (parasequences) whilst low accommodation systems exhibit lateral offset parasequence stacking relationships.

NOTES
Management of Depositional Environment Uncertainty in Marginal Marine Systems: Allowing For Multiple Plausible Interpretation Scenarios

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The typical workflow for depositional environment interpretations in the subsurface using core involves: (1) making observations of lithofacies, ichnology and other paleoenvironmental indicators; and (2) using facies models, in addition to user experience, to make interpretations. Depositional environmental interpretation is important, as it is commonly used to determine geobody dimensions, assess reservoir quality, and predict the distributions of barriers and baffles in the subsurface.

While this approach has stood the test of time, it can have important limitations: (1) the quality of interpretation can be greatly affected by user experience; (2) a single interpretation, rather than a range of valid alternative interpretations, is the typical outcome; and (3) the interpretation can be consciously or subconsciously biased by the background of the researcher. The full range of depositional uncertainty of a system is, therefore, often not considered, even when the availability of data is limited. Such gravitation towards a single solution generally leads to misinterpretation of the depositional environment, and unconsidered alternative scenarios are revealed ultimately as a superior solution.

A modification to the workflow provides an effective methodology for managing depositional uncertainty in marginal marine systems. The approach uses categories from the WAVE Process and Architectural Classification (Ainsworth et al., 2011 and Vakarelov and Ainsworth 2013; AAPG Bulletin). This classification utilizes a hierarchical approach, wherein specific categories belonging to different hierarchical levels can be linked to one another by means of parent-child relationships: e.g., what specific facies association types (children) can occur in a given depositional system (parent). Such linkages can be made by considering such variables as the types of the architectural units in question and their associated processes.

Physical sedimentary structures in a core or an interval of outcrop are first related to the possible depositional processes — wave-, tide-, and fluvial-generated flows —that may have been responsible for their formation. This typically results in a non-unique solution, because individual stratification types can be generated by more than a single process. The resultant process combinations are then related to a finite number of element complexes (facies associations) that could have been formed under such conditions. This yields a range of interpretation uncertainty (i.e., multiple applicable solutions). Ichnology, facies models, or other relevant information can be employed to further decrease this uncertainty. Parent-child relationships between the identified element complexes and their possible parent depositional systems can then be utilized to further characterize the system and make predictions about additional facies associations that might occur laterally in the same system away from known data points. This new workflow can be easily standardized, partially automated and integrated with software systems.
Autogenic Process Change in Modern Deltas: Lessons for the Ancient

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River deltas are usually interpreted in terms of fluvial-, wave- or tide-dominated process regimes and are thought to undergo change mainly by unsteady external forcing conditions. However, modern deltas show significant autogenic process changes over relatively short temporal and spatial scales (hundreds to thousands of years; km to 10s of km) during their Holocene progradation. These deltaic stratigraphic responses were autogenic because late Holocene external forcing was relatively steady (constant rates of relative sea level rise, and sediment supply). Responses over longer time intervals would likely be allogenic due to the increased probability of unsteady external forcing over longer time scales. Nevertheless, the short temporal and spatial scales by themselves are not a condition for the autogenic response of deltaic environments, but the steady external forcing is.

The dominant depositional process can change down depositional dip as the delta progrades across the shelf and into slightly deeper water, or can change laterally because of shifting fluvial discharge or because of oceanographic differences between distributaries. The three most common types of process change seen in Holocene deltas are from fluvial- to wave-dominance (Mississippi and Danube deltas) from tide- to wave-dominance (Mekong Delta) or from fluvial- to tide-dominance (Mahakam Delta). Particular segments of large delta complexes can also show these changes.

The pervasive and rapid process changes seen in Holocene deltas suggest that such changes were also common in ancient deltas, expressed by changes in the character of the deltaic succession, especially on the delta front, the regime-defining segment of the delta. Such changes should be considered more as a rule than an exception. Campanian and Maastrichtian delta deposits from the Western Interior Seaway and Laramide Washakie Basin show clear evidence of such changing process regimes. A reasonably good time framework in the rock record is needed to aid discussion of whether observed stratigraphic responses are autogenic or allogenic, and it is important to make this distinction because of local or regional implications for stratigraphy. A common theme seen in shelf-delta stratigraphy is spatially extensive flooding surfaces bounding a deltaic complex of 1-300ky duration, but with great lateral, between-lobe variability within such units. The main flooding-surface bounded interval, the allogenic response, is the overall cross-shelf regression and transgression of the delta complex, whereas the great internal variability reflects autogenic spreading of the lobes during the cross-shelf transits.
Seismic Geomorphology of a Tide or Wave Dominated Shelf-Edge Delta (NW Australia): Process-Based Classification from 3D Seismic Attributes and Implications for the Prediction of Deep-Water Sands

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Shelf-edge deltas (SEDs) forming during periods of relative sea level fall and lowstand are generally efficient in transferring sediments to the slope and basins, and their identification in subsurface data is often considered a good indication of coeval development of slope and basin-floor turbidite reservoirs. This study uses high resolution 2D and 3D reflection seismic data to investigate the seismic stratigraphic evolution of forced and normal regressive shelf-edge deltas that accumulated on the edge of the NW Australian margin (Bonaparte Basin) during the late Quaternary.

The data allow reconstruction of the main episodes of delta progradation and understanding of the extrinsic and intrinsic controls on their deposition. The lack of a significant turbidite system forming off the shelf-edge delta throughout the Quaternary is a striking feature of the Bonaparte self-edge deltas. Instead, slope sedimentation is dominated by the accumulation of plume-derived mud belts and their reworking through mass-transport processes.

Seismic geomorphology permits interpretation of the process regime of the youngest shelf-edge depocentre by applying the process-based shallow-marine classification scheme developed by the WAVE consortium (Ainsworth et al., 2011; Vakarelov and Ainsworth, 2013) to the 3D seismic attribute data. Results suggest either a tide or wave dominated delta with fluvial processes being of tertiary significance. A tide or wave-dominated, fluvial-affected shelf-edge delta classification is consistent with the paleogeographical reconstruction of the margin during the last glacial maximum (ca. 25 ka BP).

The comparison of this mixed-process shelf-edge delta with fluvial or wave-dominated counterparts linked to significant sandy slope deposits (Quaternary Gulf of Mexico and Cretaceous Barrow Delta) emphasizes the potential of assessing the process regime of shelf-edge deltas as first approach for predicting the presence or absence of coeval slope and basin-floor reservoirs.
Comparison between a fluvial or wave dominated (Fw / Wf) shelf-edge delta (A - Fuji-Einstein, Gulf of Mexico; Sylvester et al., 2012) and a tide or wave dominated (Twf / Wtf) shelf-edge delta (B - Bonaparte, NW Australia) using shaded-relief image (A) and coherency attribute analysis (B) of the present-day seabed draped over the cumulative thickness map of the shelf-edge delta deposits (from Bourget et al., 2014). Close-up (C) shows a seismic trace-shape map highlighting the direct connection between a fluvial dominated delta plain and delta front and a prodelta gully (Sylvester et al., 2012). This contrasts with the lack of slope channel development off the mixed-process Bonaparte shelf-edge delta, dominated by extensive fine-grained mud-belt deposits. Fuji-Einstein seismic data is courtesy of CGG Veritas and was downloaded from the Virtual Seismic Atlas (www.seismicatlas.org). Bonaparte seismic data is courtesy of Woodside Energy Ltd.
Recognizing Seasonal Fluvial Influence in Ancient Tidally Dominated Environments

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Seasonal changes in rainfall affect water and sediment discharge in fluvial systems. This is recorded within the rock record by changes in (a) flow processes and structures created, and (b) the composition and volume of sediment. Near river mouths this is readily seen within channels, but has not yet been widely recorded in tide-dominated environments outside of channels. This study demonstrates that high resolution sedimentologic studies in channel and overbank environments can reveal a seasonal fluvial influence. The rocks studied are part of almost continuous recorded tidal deposition. They belong to the Pleistocene Erin and Talparo Formations on Trinidad, which were deposited by the Palaeo-Orinoco River under tropical, tidally-influenced fluvial and estuarine palaeoenvironments.

Using time series analysis on the rock data, semidiurnal tidal patterns were identified within the channel and overbank deposits. The effects of seasonal changes in fluvial flow could also be recognized. Some sedimentary structures indicated periods of relatively higher discharge. The content of organic matter gradually varied from month to month in a tropical seasonally influenced cycle. Bioturbated beds also show a periodic pattern, which was interpreted as representing changes in water conditions due to seasonal fresh water discharge.

This study recorded the seasonal cyclicity of lithology, bioturbation, organic content and sedimentary structures which suggest evidence of significant reservoir heterogeneity. Identification of these changes in periodicity and reservoir characteristics such as porosity and permeability, help to understand and predict reservoir producibility. This can therefore act as an analogue for similarly deposited reservoirs.

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Assessing the Importance of River Discharge Variations versus Tidal Signals on Architecture in Paralic Reservoirs

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Heterolithic deposits consisting of interbedded and/or interlaminated sandstones and mudstones are commonly interpreted as tidal in origin; however, they may also form in purely fluvial settings due to variations in river discharge on a seasonal or shorter time scale. Moreover, tidal processes and seasonal discharge signals often coexist in the lower reaches of modern rivers and may be recorded in their deposits (e.g. Fraser River delta, Canada), making it difficult to decouple the two signals. The facies characterization of seasonal deposits is poorly constrained, leading to misinterpretation and overestimation of tidal processes in the rock record with consequently less accurate facies and reservoir model reconstructions.

Large scale outcrops of the Middle Jurassic Lajas Formation (Neuquén Basin Argentina) contain well-known tidal indicators, but also signs of periodic variations river discharge. Unconfined (mouth-bars and crevasse mouth-bars) and confined (side-bars and point-bars) deposits show 0.10-0.40 m-scale interbedding of sandstones and siltstones or of coarser- and finer-grained sandstones that repeat regularly, but lack ordered rhythmicity. The coarser-grained dm-scale sandstone beds are usually slightly erosively based, structureless or more rarely show cross-bedding and contain abundant mud clasts. Evidence of tidal action (e.g. drapes, rhythmicity and bidirectionality) or brackish salinity conditions (e.g. such as body or trace fossils) are commonly absent or greatly reduced in abundance relative to the intervening deposits. The deposits interbedded with these erosively based sandstones can consist of finer-grained sandstones or siltstones or a mixture of both and may show mud or carbonaceous drapes forming mm-scale rhythmical couplets with bidirectional ripples and brackish-water trace fossils.

The erosively based sandstone beds are interpreted as the deposits of river floods at high river stage, whereas the intervening deposits with evidence of tidal action and brackish salinity conditions are interpreted as interflood deposits formed during low river stage. The seasonal signal is not preserved in mud-rich deltaic deposits because of the lack or sporadic nature of the river input in these areas and also is poorly defined in channel thalwegs and proximal mouth-bars and crevasse mouth-bars because the high energy during river floods results in removal of the interflood deposits.

When conditions are ideal for preservation, seasonality is the controlling signal in the Lajas deposits as the interbedding is distinctive while tidal indicators are primarily restricted to the interflood deposits. Conversely, a system dominated by tidal processes would intensely or completely overprint the seasonal signal showing tidal indicators through the whole deposit.

Distinguishing between seasonal discharge signals and tidal processes as the main control on deposition is crucial in improving and refining reservoir models both at facies scale and in the prediction of larger-scale geometries and could be an helpful tool for paleoenvironmental reconstructions when other approaches (e.g., palaeobotanic, palaeontological) are not effective.
Spatial Changes in Depositional Processes in a Progradational Mixed-Influence Deltaic Succession, Jurassic Lower Ile Formation, Halten Terrace, Offshore Norway

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Recognition of depositional processes in clastic coastal-deltaic deposits forms the basis for predicting their key reservoir properties, including dimensions, geometries, orientations and the three-dimensional distribution of petrophysical properties and reservoir heterogeneities. The application of this well-established approach can be problematic in mixed-energy coastal-deltaic systems, in which process interpretation is weakly constrained. We have addressed this problem through a detailed sedimentary facies analysis of exceptionally well-preserved and widely distributed cores, calibrated with their wireline log signatures, which enable confident process and environmental interpretations in all preserved parts of the depositional system. This study focusses on the lower, progradational part of the Lower to Middle Jurassic Ile Formation in the southern part of the Halten Terrace on the Norwegian shelf.

The 100 m thick Ile formation forms the top of a 300 m thick megasequence, comprising progradational to aggradational deltaic sediments, which are overlain by a succession of retrogradational coastal deposits. The progradational to aggradational succession contains three types of regressive parasequences: (1) mixed-wave-tide influenced parasequences consist of bioturbated mudstones, which coarsen upward from micro-hummocky cross-stratified sandstones and mudstones, through intervals with increasing bidirectional current-ripple cross-lamination and into cross-bedded sandstones with mud-draped foresets and toesets; (2) mixed-wave-fluvial influenced parasequences consist of mudstones that coarsen upwards through micro-hummocky cross-stratified fine-grained sandstone and mudstone into poorly sorted coarse- to very coarse-grained sandstone; and (3) wave-dominated parasequences consist of bioturbated mudstones which pass upwards into mudstones interbedded with hummocky cross-stratified sandstones that amalgamate upwards. Parasequences observed in core have a thickness varying between 3 and 28 m, with a decrease in thickness upwards. The number and thickness of parasequences are variable laterally. The mixed-wave-fluvial influenced and mixed-wave-tide influenced parasequences are found in close association with each other, and represent active and abandoned parts of the delta, respectively. Wave-dominated parasequences are interpreted as linear coastlines lateral to the deltas.
Autogenic, Allogenic and Mixed-Process Controls on Stratigraphic Architecture in the Baram and Champion Delta Systems, NW Borneo

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Exceptional rates of subsidence (up to 3000 m/Ma) and sediment supply (from a tectonically-active hinterland) have preserved a >6 km stratigraphic record of Mio-Pliocene coastal-deltaic sedimentation in the Baram Delta Province (BDP) of NW Borneo. The present-day coastal equivalents of these systems (e.g. Baram, Trusan and Padas deltas) display substantial temporal changes on a decadal to kyr timescale. However, deconvolving allogenic and autogenic controls on the evolution of these systems is challenging and necessitates a pragmatic approach to the interpretation of their stratigraphic record. This is illustrated in two contrasting late-mid Miocene outcrop successions in the BDP, which are characterized by facies associations deposited under a wide spectrum of fluvial-tide-wave energies: (1) the Lambir Formation (western BDP), and (2) the Belait Formation (eastern BDP).

The Lambir Formation represents deposition during the initial phase of rapid coastal-deltaic progradation and comprises fluvio-tidal sandstones that are sharp-to-erosionally juxtaposed on wave-dominated (storm-reworked) prodelta to delta front successions. Single and multi-storey channel bodies comprise: (i) sand-dominated bars and dunes (2-9 m thick); (ii) laterally migrating, elongate tidal bars (inclined heterolithic strata, 1-6 m thick); and (iii) mud-dominated carbonaceous heterolithic strata (1-2 m thick). Inclined heterolithic strata grade laterally into muddy carbonaceous heterolithics on a <10 m scale. Abrupt vertical changes in facies within a given channel body produces an intermittent fining upward trend from sandier facies to vertically accreting bioturbated mudstones and are interpreted to reflect rapid autogenic changes in local sediment supply, with varying degrees of fluvial and marine energy during abandonment.

Proximal parasequence sets are also characterised by large-scale (4-17 m), erosive-based single and multi-storey fluvial channel bodies and localised wave-tide influenced, muddy sandbar deposits, the bases of which represent local flooding or wave ravinement surfaces during channel abandonment. The Belait Formation displays more abundant storm-flood deltaic and/or shoreface successions and was deposited under significant tectonic influence within a narrow (5-20 km), fault-bounded embayment (preserved as the Berakas Syncline). This sub-basin configuration, with its high rate of accommodation space creation, formed a highly effective sediment trap, which is manifested by decreasing progradation rate, high aggradation and a steeply rising shelf trajectory. The abundant upward coarsening successions are interpreted as prograding storm- and river flood-influenced delta front deposits. Evidence of storm-reworking of tidal bars and intercalated channelised tidal sand bodies also indicate mixed-energy processes during different depositional phases. However, larger-scale (10-100 m) partitioning of stratigraphic architecture into relatively tide- and wave-dominated facies successions suggests temporal changes in process dominance, most likely in response to allogenic-forced changes in shoreline geometry.

The autogenic and allogenic controls on these two time-equivalent and geographically-adjacent coastal-deltaic successions will be compared in the light of (1) their different sedimentological and physical stratigraphic expressions and (2) the significance of their broader BDP settings.
Tuesday 19 May
Session Three: Tidal Heterogenity in Paralic Systems
The Broader Implications of Sedimentological - And Associated-Trends across the Tidal-Fluvial-Transition of the Fraser River, Canada

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Sedimentological, ichnological, palynological, and geochemical trends defined across the tidal-fluvial transition (TFT) of the lower Fraser River, Canada (Fig. 1) are applicable to both modern and ancient estuarine and deltaic successions. Sedimentological trends include sand-mud rhythmicity, and the frequency and thickness of mud beds within bars. The amount of mud deposited on bars, and the rhythmicity of sand and mud beds is directly linked to fluvial discharge and saltwater incursion in the channel. Ichnologic trends mainly reflect the persistence of saline water, where higher and more stable interstitial salinity is recorded by an increase in the bioturbation intensity and size of traces, as well as a higher diversity of burrows. The presence of marine dinocysts in the sediments indicates tidal influence irrespective of salinity, although the resolution of dinocyst distributions is too low to identify the TFT. Finally, geochemical signatures overwhelmingly reflect sediment source and cannot be used to establish relative position within a channel.

The trends defined in the Fraser River reflect natural flow conditions, and hence a wide range of estuarine and deltaic systems should exhibit similar trends across their respective TFTs. However, we hypothesize that these trends will vary markedly with: variations in the grain size of sediments delivered to the coastline, the cause of lithologic cyclicity (e.g., snowmelt-induced freshet vs hurricane- or monsoon-induced floods), sedimentation rate, and the density contrast between the receiving basin water and fluvial discharge. More mud-rich source sediment will result in more mud-rich deposits in the channel. Hurricane-induced floods will transport more sediment to the coastline in a less predictable and shorter time period than snowmelt-induced freshets, and the duration of low salinity related to the flood event will be reduced. Higher sedimentation rates will overwhelm infauna resulting in a severe reduction in bioturbation, and masking of the marine dinocyst and marine geochemical signatures. Finally, homopycnal systems are likely to concentrate more mud in the TFT, and hyperpycnal systems are unlikely to have appreciable mud deposits on channel bars.

With increasing research of estuarine and deltaic channels, it will be possible to define the range of sedimentological, ichnological, palynological, and geochemical trends that can develop across the TFT. From these data, we can produce robust models for constraining the general position of sediments relative to the TFT to statistically predict where mud is likely to be concentrated on channel bars, and to parameterize the distribution and lateral continuity of mud beds.
Summary diagram of sedimentological, ichnological, palynological, and geochemical trends across the tidal-fluvial transition of the lower Fraser River, Canada (from La Croix and Dashtgard, in review).
Inclined Heterolithic Stratification in Estuaries: Origins and Distributions

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Inclined Heterolithic Stratification (IHS) is commonly associated with paralic reservoirs. Within such reservoirs, the primary modes of IHS are as laterally accreted point- and channel-bars, and as vertically accreted channel fills. IHS has been observed in a range of sedimentary environments. It is common in bays, estuaries and deltas, and to a lesser degree in fluvial settings.

This synthesis focuses on the nature and character of IHS in tidally influenced settings, wherein IHS tends to have widely variable sedimentological expressions. Examples of IHS in tidally influenced settings are presented from several modern and ancient examples. Using a number of techniques, some observations pertinent to IHS interpretation and occurrence have been arrived at.

1. Rhythmicity in tidally influenced IHS: although evidence of tidal influence can be observed in IHS, the dominant mode of sedimentation results from seasonal variations in sediment distribution. Unlike in fluvial settings, estuary-IHS does not necessarily indicate substantial differences in hydraulic energy, and IHS may simply result from changes in sediment flux into the estuary. For example, if fluvial discharge into an estuary is increased, the overall increase in the tidal prism volume may be fractional, but mud-plume associated with the river may expand substantially. As such, in the inner estuary, sandstone is associated with high-river flux and mudstone with low-river flux. This relationship is reversed in middle estuary locales, where sandstone is tidally transported during low fluvial flux and the mudstone is deposited during high riverine discharge. These two scenarios, inner versus middle estuary, can in some cases be determined, in the rock record, on the basis of trace-fossil distributions.

2. Distribution of IHS: the nature of tidal and fluvial sediment sources, the volume of the tidal prism and the volume of fluvial flow each strongly influence the distribution of IHS in estuaries. The distribution of IHS in estuaries is therefore predictable, as IHS-prone belts start at the tidal limit and extend into the middle-, and in rare cases outer-estuary. Proximal-distal relationships within IHS can be, to a degree, resolved using trace-fossil distributions, ichnofossils size-diversity trends, and through ethological analyses.

3. Bed thickness of IHS: in estuaries IHS bed thickness is in part a sedimentological response to channel size, proximity to the fluvial system, and fluvial sediment flux. In general, thickly bedded (i.e. dm scale) IHS is an indicator of greater fluvial influence, whereas smaller tide-dominated channels characteristically display cm-scale IHS. Notably, even in tide-dominated scenarios, IHS tends to be an indicator of annual sedimentary cyclicity.

The above observations help to formulate interpretations from IHS that contribute to better understanding the sedimentary environment for paralic reservoirs, help to predict the distribution of heterolithic belts in strata dominated by estuary sedimentation, and to better understand reservoir heterogeneity ascribed to channel-associated IHS.
Large Tidally Influenced Meandering River Systems of the Cretaceous McMurray Fm., Athabasca Oil Sands, Canada: A Key Component of an Immense Reservoir

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The Athabasca Oil Sands contain hundreds of billions of barrels of bitumen within a diverse spectrum of Cretaceous (McMurray Fm) paralic deposits that derive from marginal-marine deltaic through fluvial settings. Deposition took place in a low-accommodation, distal foreland basin setting that was sensitive to subtle fluctuations in relative sea level; this resulted in a complex amalgam of deposits that extend over hundreds of km, and exhibit complex crosscutting relations though tens to hundreds of meters of strata. Paleogeographically, the approximately north-south oriented basin axis was influenced by a southerly catchment that at times extended across much of the continent, and an intracontinental seaway that inundated the area from the north (Benyon et al., 2014; Blum and Precha, 2014). The most widespread depositional elements are immense point bars that range up to 40–50 m thick and preserve evidence of extensive meanderbelts. These point bars have been described from outcrop (Mossop and Flach, 1983), and imaged in high-quality seismic data (Hubbard et al., 2011; Musial et al., 2012). Seismically constrained stratigraphic architecture indicates a dynamic, fluvially controlled meanderbelt was the primary influence on sediment distribution. However, siltstone drapes and beds, rare marine palynomorphs, and trace fossils suggest that the river system experienced periodic tidal influence, and potentially, brackish-water inundation. The prevalence of tidal / brackish features in cores and outcrops, in absence of seismically constrained depositional elements, has led to numerous interpretations of more open, brackish-water sedimentation in estuaries or bays.

An ideal modern tidal-fluvial transition (TFT) analogue for the Cretaceous strata is elusive, although aspects of several modern systems provide clues as to the nature of the deposits in the McMurray Fm. The morphological, sedimentological and ichnological characteristics of sediments deposited in the TFTs of modern river systems show differences at various scales of observation in response to changing relative influence of tidal and fluvial flow, sediment grain size and sedimentation rate, and climactic conditions. Meandering rivers of the magnitude interpreted from the McMurray Fm are commonly associated with high discharge and a sediment load dominated by fine sand and mud (e.g., Mississippi River); these rivers tend to have low depositional slopes at the coastline, and experience tidal inundation hundreds of kilometers up river. In big river systems, fluvial meanderbelts are prevalent at the landward limit of saltwater incursion and in the tidal backwater zone. Seasonal variation in fluvial discharge, however, strongly influences the volume and caliber of sediments that are transported by the various stages of river flow, and the distance that saltwater incurs upriver. Seasonal variability is manifest in river systems that experience large temperature differences between the summer and winter, or have distinctive wet and dry seasons. We posit that seasonal variation in fluvial discharge, and accordingly, seawater inundation of meanderbelts, was an important control on McMurray Fm sedimentary processes. During periods of high discharge, fluvial processes overwhelmed tidal influence and the paleoenvironment was dominated by meandering river deposits. During periods of low discharge, tidal damming and possibly saline water inundation in the tidal backwater zone resulted in deposition of mudstone drapes and beds, colonization by opportunistic organisms, and the landward transport of dinocysts (e.g., Czarnecki et al., 2014).
References:


A Tidally Influenced Shallow Delta System in the Middle Jurassic of the Søgne Basin, Norwegian North Sea

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The Middle Jurassic Bathonian to Callovian Bryne and Sandnes Formations are two of the principal reservoirs in several fields across the Norwegian and Danish sectors of the North Sea. Traditionally, the Bryne Formation has been considered as a coal-bearing fluvial system, whereas the Sandnes has been described as a tidal-influence barrier-lagoon system. Recent investigations on well 3/7-4, in Trym Field, show the widespread occurrence of tidal influence and tidal dominated deposits, across the overall studied stratigraphic interval. In particular, the Bryne cores reflect deposition by a tidal influenced delta onto a shallow tidal platform (both supratidal and intertidal) that likely was occupying the majority of the Søgne Basin. Near Trym Field, fluvial deposits are only subordinate to the tidal ones. Three broad facies associations were identified:

(1) Fluvial to tidal dominated channel fill deposits. They consists of sharply based, blocky to fining-upward sandstone units that lie onto erosional surfaces that possibly can be traced across wells. The infill ranges from fluvial (with tidal overprint on top), to distinctly tidal dominated with tidal bars. The deposits merge upwards into the mud-prone intertidal to supratidal platform. These deposits record important basinward shift of facies across the basin and are associated to major sequence boundaries.

(2) Shallow tidal platform, subdivided into supratidal (with palaeosols, coaly shales, coal and rooted horizons) and intertidal, dominated by sand flat, tidal creeks and tidal point bars.

(3) Coarsening-upward, tidal to fluvial-dominated mouth bar deposits prograding into the coaly shales and the sand flats of the infratidal platform. Fluvial to tidal influenced mouth bars within the Bryne interval are only 0.5-2 m thick. Fluvial dominated, tidally influenced mouth bars in the Callovian section (Sandnes Formation) are up to 8 m thick.

We noted very little wave and storm reworking, at least during Bathonian time. The only wave-generated features are limited to rare and equivocal wave ripples and some hints of low angle cross stratification that mimic hummocky cross strata, especially at the top of the succession. This suggests that the Bathonian Bryne fines were deposited on a tidal platform and only during moment of maximum regression, on a coastal plain dominated by rooted palaeosols.

The Søgne basin around Trym underwent to limited wind fetch due to the restriction of the basin confined between the Mandal High to the west and eroded areas to the east and consequent very low wave energy. Moreover the basin was likely to have a very shallow water depth, as indicated by the thickness of the mouth bar and by the widespread occurrence of tidal marsh deposits. This low wave energy allowed substantial tidal reworking of the river system throughout the Bathonian basin evolution.

The cored succession records an important change at the Bathonian-Callovian boundary. The Callovian deposits form a composite valley fill unit, occupied by fluvial channels, tidal channels and bars and by thick bay head delta units. The composite valley fill can be traced across the overall Søgne Basin, from the Danish sector to the Ula Field, on a distance of 80-100 km, attesting the different infill stages of a large estuarine embayment.
Architecture of Wave and Tide Influence in Jurassic Shorelines, Northern North Sea

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The Cook Formation comprises a variety of shallow marine and locally deeper water depositional environments and is of Pliensbachian to Toarcian age. More specifically, within the Knarr Field, NNS, the Cook Formation represents tidally-influenced and shoreline to shelf sediments with a restricted Late Pliensbachian age, encompassing the late part of the Marginatus and the entire Spinatum ammonite zones. A variety of data types have been integrated to produce a detailed understanding of the reservoir interval with application at both field and exploration scales.

The Cook Formation overlies the Burton Formation and is overlain by the Drake Formation, which all form part of the Dunlin Group. In the Knarr area the Cook Formation is informally divided into Lower and Upper successions. The Lower Cook comprises Sands 1, 2 and 3, and the Upper Cook Sands 4 and 5. Sands are separated by intraformational mudstones, which display remarkably consistent thicknesses across the field. Intraformational flooding surfaces are commonly chronostratigraphically constrained with MFS J15 (sensu Charnock et al., 2001) separating the Lower and Upper Cook. Sands 1 and 2 are separated by MFS J14, Sands 4 and 5 by MFS J16a and the top of the Cook Formation drowned by a relatively condensed interval including MFS’s J16b and J18.

The Lower Cook is interpreted as a series of stacked, tide-dominated bar and channel complexes; while the Upper Cook represents shoreface to shelf deposits. The tide-dominated Lower Cook is notably heterolithic with intricate intercalation of sandstone and mudrock lithologies, highly variable current- and wave-generated sedimentary structures, significant grain size variation within sandstones successions and highly variable degrees and type of bioturbation. Specifically, the tidally-dominated sediments of the Lower Cook Formation are characterised by the trace fossils Asterosoma and Rosselia. The Upper Cook Formation comprises a series of relatively organised, coarsening upwards cycles that display the systematic changes in lithology, sedimentary structures and ichnology expected for a shoreface succession. The distribution of palynomorphs confirm these observations and suggest that the Lower Cook was deposited in brackish water conditions, while the presence of more marine fossils in the Upper Cook suggests an increase in marine influence.

Superimposed upon on this primary heterogeneity the reservoir quality of the Cook Formation is further complicated by clay mineral diagenesis. High quality Cook reservoir is located at depths between 3700–3800 m as porosity has been preserved due to grain-coating chlorite inhibiting quartz overgrowth development. At a field scale variations in reservoir quality is controlled by depositional facies and grain size

The Cook Formation within the Knarr Field comprises a highly heterogeneous tidally-influenced and shoreline to shelf succession, which is punctuated by biostratigraphically constrained intraformational flooding surface, to form a complex but predictable reservoir architecture.

We would like to acknowledge BG Norge and partners Idemitsu, RWE Dea and Wintershall for their support and allowing the presentation of this work.
Tuesday 19 May
Session Four: Analogue Studies
Keynote Speaker: Shallow Marine Depositional Complexes

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Early sequence stratigraphic models applied to shallow marine successions revolutionized methods of reservoir prediction and characterization. In the decades following introduction of these methods, there have been fundamental improvements in our understanding of depositional process controls on reservoir architecture and internal facies variations defined within a sequence stratigraphic context. Such improvements reflect not just a better understanding of how changes in dominant depositional process control depositional facies patterns, but also recognition of process changes during long-term regression and transgression of shorelines including differential preservation as areas along the shoreline are locally abandoned by river avulsion and reworked by shoreline and shelf processes during larger-scale shifts in sediment supply.

A classification of shallow marine stratigraphic successions is presented based on: 1) dominate depositional process (river, wave, tide), 2) shoreline trajectory, and 3) relative preservation of regressive deposits following transgression related to accommodation to sediment supply ratios. Although all shallow marine deposits reflect variable interaction of river and marine processes, and there is a gradation between extremes of shoreline trajectory, we define specific reservoir complex types: 1) to highlight reservoir element variations within a range of systems, 2) as a framework for the organization of outcrop and subsurface analog examples, 3) to provide a structure for development of a reservoir element dimensional database, and 4) to guide stratigraphic correlation framework.

Thirteen shallow marine complex types are shown relative to their position within a regressive-transgressive clastic wedge formed during deposition of either a higher or lower long-term accommodation growth sequence. Although such classification involves some simplification and generalization, our goal is to define classes broadly enough to span the full range of shallow marine reservoir systems and to highlight contrasts in stratigraphic correlation styles and facies trends that need to be considered to characterize reservoirs within diverse types of shallow marine deposits. A catalog of examples is presented to show the definition of each complex type, key stratigraphic surfaces, and stratigraphic position within longer-term regional sequences. General correlation concepts important for prediction of facies variations within each class are highlighted by presenting outcrop and subsurface examples. Examples in this catalog show the broad range of reservoir types that can form in shallow marine settings.

Collection of outcrop and modern analog data on the depositional geometry of reservoir bodies observed in different complex types provides key input for reservoir models. Application of previous compilations of geobody dimensions are hindered by lack of clear depositional environment, stratigraphic setting and hierarchy definition, systematic separation of allo- and litho-stratigraphic body measurements, and variability of measurements by different practitioners on various data types. The result is wide variance in defined relationships (e.g., thickness to width) and results that have little predictive value. More work classifying these types of data to clearly separate apples from oranges is needed. As part of our ongoing efforts to define more predictive relationships we have focused on better methods to catalog our
analog data and archive all measurements collected. Such an archive allows previously collected data to be reassessed and allows additional measures to be added as new modelling questions arise.

NOTES
Megafan-Shoreline Systems: A Case Study of the Mitchell River Delta, Gulf Of Carpentaria, Australia

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Megafan-shoreline systems are understudied, despite their common occurrence in modern settings. The Mitchell River delta is a superbly exposed, architecturally complex megafan-shoreline system. The delta is fed by a radial network of modern and palaeo-distributary channels that drain a wet-dry monsoonal catchment into the low gradient Gulf of Carpentaria. Detailed mapping, sonic coring, trenching and topographic surveying have been used to characterise the palaeodistributary channel belts on the megafan and the depositional elements which comprise the delta plain. Chronologic investigations have refined the development of the megafan and delta to discrete periods within the Holocene.

The delta has prograded up to 20 km in response to a 1.5 m sea level fall. Changes in the relative influence of wave, tide and fluvial energy during the last 6,000 years have had a major impact on delta morphology and sediment distribution. Coastal processes, including waves and tides, cause reworking of sediment at the coastline, while fluvial processes cause shifts in depositional loci through avulsion. Calculations of backwater length demonstrate that avulsion nodes are mostly concentrated in the upstream portion of the backwater zone; however, the hydraulic apex of the megafan is located well above direct base-level influence. Avulsions upstream of the backwater limit are attributed to flashy discharge during monsoonal months and the lateral restriction of channel adjustment caused by indurated surfaces which have formed from chemical alteration in this wet-dry climate. Thus, two distinct types of avulsions have been characterised: (1) avulsions on the fan, which are associated with large scale subdelta development backwater avulsions, which cause local cycles of lobe development, abandonment and minor coastal erosion, and (2) avulsions on the fan, which are associated with large scale subdelta development.

The Holocene deposits of the Mitchell River delta can be considered a natural laboratory for examining the lateral relationships between architectural units within one reservoir flow unit in a complex mixed-influence megafan-shoreline reservoir analogue.
How Can A 15 M Thick, 14 Km Long And 5 Km Wide Marine Barrier Island Reservoir Sandstone Be Developed? – A Case Study from the Holocene to Recent Rømø Barrier Island, Danish Wadden Sea

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Barrier islands are usually regarded to develop during a relative sea-level rise resulting in preservation of thin and narrow marine sandstone units, which are not suitable as reservoirs. A detailed case study of the Holocene to Recent Rømø barrier island in the Danish Wadden Sea (North Sea) illustrates how a 15 m thick, 14 km long and more than 5 km wide marine reservoir sandstone unit have been developed, creating a 1 km³ reservoir sand body.

The Rømø barrier island is situated in the easternmost “inner part” of a broad tidal bay, fringed by a string of barrier islands along the North Sea. The barrier island is 14 km long, 4 km wide and c. 15 m thick. It is a very sand-rich system as it receives coastal drift sand from north and south along the shoreface. It is separated from the mainland by a 8 km wide lagoon. The Rømø barrier island experiences a tidal range of c. 1.8 m. During strong westerly storms, the water level increases considerably, up to 5 m above mean sea-level.

The barrier island initiated for c. 8000 years ago and is still active, which allows detailed studies on recent sedimentary processes. Stacking geometries of different sand units have been unraveled based on: Seven c. 25 m long sediment cores, 35 km ground penetrating radar (GPR) reflection profiles, and dating of 70 core samples using optically stimulated luminescence (OSL) providing a unique stratigraphic framework.

Based on the high resolution dataset, ten sedimentary units within the Holocene barrier-lagoonal system are identified: Shoreface sand clinoforms with swash bars, beach ridges and swales, washover sand fans, tidal inlet channel sands, aeolian sand dunes, swamps, lakes, salt marsh and lagoons. The architectural elements are mostly composed of fine-grained sand.

Due to the detailed knowledge of the stratigraphic framework, depositional environments and precise ages, a detailed palaeo-geographic reconstruction of the Rømø barrier island has been carried out. The barrier island initiated as a short and narrow island. The first 5000 years the barrier island sand aggraded because sedimentation kept pace with the relative sea-level rise. The last 3000 years the barrier island prograded seawards, because the rate of relative sea level rise decreased. This aggradational-progradational development has resulted in thick and broad reservoir sand body. The few and thin muddy intervals only cause minor hydraulic barriers within the reservoir.

Barrier islands formed during rising sea-level, do not necessarily back-step, preserving only a thin transgressive sand unit. On the contrary, if there is a surplus of sand, a barrier island can aggrade and even prograde during a sea-level rise, creating thick barrier island, shoreface and lagoonal successions.

This full-scale natural “laboratory” provides a unique dataset which may improve our understanding of detailed barrier island development and may be used as an “analogue” to deep-seated hydrocarbon reservoirs where data often are limited.
Using a Global Database of All the Large Modern Deltas to Predicting Controls on Paralic Reservoir Distribution

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We have compiled a global database of all (n=97) the large (>30 km in length from apex to toe) modern day marine deltas using remotely sensed imagery. The dataset is the most comprehensive available for comparison with ancient paralic successions. It should at least in part be representative of the rock record and useful in constraining what the controls are on sand distribution in ancient paralic reservoir successions.

Deltas were classified according to dominant process – wave, fluvial, tidal or mixed, and modifiers were applied depending on the influence of subordinate processes e.g. wave (tidal). Although there is a complete overlap between different delta types, some general observations can be made. Wave dominated deltas account for 60% of the dataset, mixed process deltas are uncommon (10%) and tidal influenced and fluvial influenced deltas both account for 15% each. Most large deltas occur on passive margins and delta type is strongly influenced by latitude, climate and shoreline physiography.

All deltas comprise a radial, distributive fluvial system (DFS) centred on the delta apex. Large, non-fluvial deltas (>75 km) show a disconnect between the DFS and shoreline although this distance varies depending on scale of fluvial system. Smaller non-fluvial deltas (30-75 km) generally show a good connection between the DFS and shoreline, again dependent on fluvial system scale. The significance of this observation is that small non-fluvial deltas supply sand directly to the shoreface whereas larger deltas do not. Fluvial-dominated deltas supply sand directly to the marine realm.

Locating the apex of a delta – the point at which channels either bifurcate from or avulse from – is important as the majority of the transported sand is dropped immediately downstream of the apex. The backwater effect (the distance upstream of the delta mouth to where the base of the channel intersects sea-level) has been highlighted as a key controls apex location in modern deltas. Analysis of our dataset suggests that the backwater effect has no control on the apex location of large rivers, instead, the primary control on apex location of virtually all of the large deltas studied is relict topography.

It is recognised that any study of modern systems as analogues to the rock record is hampered by a lack of understanding of preservation potential and the fact that the Quaternary has experienced rapid climatic fluctuations which may not be appropriate for Greenhouse climate conditions. However, analysis of the datasets suggests that the main controls on paralic sandstone body distribution are likely to be climate, predominant basinal process, distance from apex to shoreline and size of catchment. The distribution of these controls are, in part, predictable.
Macro-Stratigraphy and Micro-Facies of Cretaceous Marine Mudrocks: Implications for Dispersal Processes and Basin Evolution, Western Canada Foreland Basin

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Marine ‘offshore’ mudstones dominate the fill of the Western Canada Cretaceous foreland basin. Over the past 30 years, systematic outcrop and wireline log-based allostratigraphic studies of the regional-scale (i.e. 100-200,000 km2) stratigraphy of mudstone-dominated units, ranging from Middle Albian to early Campanian, has shown that superficially monotonous mudrock successions show wide variability in their internal stratal organization on length scales of hundreds of km. Some mudrock units show pronounced downlap along the basin axis, others onlap against the distal forebulge whereas others show persistent parallelism. The dispersal of mud particles to distances of hundreds of km from shore raises the question of transport mechanism.

Three contrasting case studies will be discussed. The Middle Albian Harmon Formation was deposited at the southern end of an embayment connected only to the Arctic Ocean. Mudrocks are mainly strongly bioturbated, with some preserved graded silt and very fine sand storm beds. Stratigraphic analysis shows that allomembers thin and become more clay-rich to the NE away from the foredeep, but show no lap out pattern. Near the southern margin of the embayment, the log signatures become more sandy, and lobate river-dominated deltaic packages, 3-6 m thick can be mapped. The Harmon appears to represent a close balance between sediment supply and accommodation, characterized by essentially vertical aggradation across a remarkably flat ramp. Apparently low wave energy at the coast might reflect a high suspended mud concentration. The mid-Cenomanian Dunvegan Formation was deposited soon after the Boreal Ocean and Gulf of Mexico joined in the early Cenomanian. The Dunvegan is a mud-dominated delta complex that prograded to the SE along the axis of the foreland basin. Muddy prodelta clinothems, ~ 100 km long, downlap onto a phosphatic condensed section. Thin-section and SEM analysis of oriented samples from prodelta mud reveals mm-scale, graded beds of silt and clay aggregates that form distinctive ‘triplets’. Silt forms combined-flow ripples that migrated directly down the clinothem; overlying laminated and structureless silt and clay microfacies suggest deposition from decelerating flows of dense fluid mud. The direct evidence of downslope flow, coupled with externally symmetrical wave-formed silt ripples suggests that mud was dispersed seaward (SE) by ‘wave-enhanced sediment gravity flows’. The Lower to Middle Turonian Kaskapau Formation was deposited in a broad, through-going Interior Seaway following the major Turonian transgression. The Kaskapau forms a prismatic wedge that thins towards the NE from ~900 m in the foredeep to ~ 150m 200 km seaward. Subtle onlap against the forebulge is evident in some allomembers but in general, strata show no lap-out and no evidence for topography on the ramp. Microfacies analysis of mudstones deposited ~200-250 km offshore reveals combined-flow silt ripples and graded beds of silt and clay-size intraclastic aggregates that lack ‘triplet’ organization. Mud is inferred to have been transported by storm-driven combined flows in which gravity played little or no role.
Detailed Anatomy of an Axially-Incised Valley Fill System, Late Cretaceous of Southern Utah

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A compound incised valley system is preserved in Upper Cretaceous strata of the Sevier foredeep in the Kaiparowits Plateau, southern Utah, USA (Santonian-early Campanian John Henry Member of the Straight Cliffs Formation). This study investigates composite stratigraphic surfaces and the role of antecedent topography on the formation and preservation of transgressive tidal deposits. Additionally, this study expands regional correlations, documents along strike variability along a mixed wave- and tide-dominated shoreline, and discusses allogenic and autogenic process governing stratigraphic architecture.

There are four regressive-transgressive cycles preserved, each discussed in detail, with emphasis on the transgressive phases of deposition. At Main Canyon, the subaerial unconformity (SU) is associated with the development of incised valleys that formed sub-parallel to the underlying shoreline during a stepped forced regression in the “A-B-C” shoreface intervals. Basinward, the correlative unconformity is preserved as sharp-based wave-dominated shorefaces that are detached from the preceding shoreface sandstones. During the following transgression (“D and E” intervals), valleys at Main Canyon were backfilled with high-energy, upward-fining, tidal-estuarine facies (locally >25 m thick) that removed the majority of the falling-stage and lowstand fluvial deposits. Additionally, associated tidal currents modified the valley walls and margins, generating a composite stratigraphic surface. The basinward flank of the compound incised valley hosts thick (>38 m) accumulations of lagoonal and washover fan deposits. Their preservation indicates an accretionary transgressive shoreline trajectory with balanced rates of sediment supply and accommodation. Autogenic and allogenic processes are considered as controls on stratigraphic architecture for successive regressive-transgressive cycles.

Aside from the excellent outcrop expression, which permits detailed studies of internal architecture, facies associations, and reservoir-scale geobody relationships, this case study is interesting and notable because: 1) There is evidence that tidal ravinement significantly modified the initial valley shape during transgression, a process not fully recognized in most conceptual models of valley formation and fill; 2) The valley system incised in a basin-axial position (NNE/SSW), subparallel to the thrust front and nearly orthogonal to the orientation of pre-valley-formation shorefaces, which prograded from west to east. Axial systems are well-known as major transporters of sediment in large foreland basins, and yet most incised valley models imply a direct and oversimplified relationship between up-dip (source area and tectonics) and down-dip (base level) controls. In this case, supporting provenance data indicate that source areas other than the Sevier fold-thrust belt exerted major controls on sediment supply, potentially independent of the primary controls on accommodation; 3) The major subaerial unconformity and bypass surface occurred at a higher (younger) stratigraphic position than previously interpreted. The changes in regional correlations necessitated by this discovery impact more broad predictions by prominent sequence stratigraphic models; 4) Finally, correlations down dip along the axial valley system indicate a steep topographic slope of 0.011, with 47% expansion of the whole John Henry Member over ~14 km from south to the north. This suggests structural control on sediment transport and deposition, with high ‘lateral’ variability in accommodation parallel to the fold-thrust belt.
Core Description, Markov Chain Analysis and AVO Modeling Of a Lagoon/Tidal To Fluvial Transition Zone in the Cretaceous Straight Cliffs Formation, Southern Utah

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Tidal successions are comprised of a complex mixture of fluvial, tidal, and marine lithofacies. Because tide-dominated and tidally-influenced reservoirs account for an increasingly significant portion of petroleum reserves, adding to the list of available analogs studies lends valuable insights into reservoir prediction from subsurface data. Outcrop analog studies are particularly important because subtle changes in the transition from tidal to fluvial deposits make lithofacies differentiation from subsurface wireline log and seismic reflection data problematic. Furthermore, coupling forward seismic reflection modeling based on rock physics measurements derived from cores with a predictive facies model framework from outcrops provides important learnings for interpreting subsurface data.

The Cretaceous John Henry Member (Straight Cliffs Formation), located in the Kaiparowits Plateau of southern Utah, reveals excellent outcrops of fluvial and tidally-influenced deposits, and offers an opportunity to improve our understanding of wireline log interpretation and seismic imaging in similar subsurface petroleum reservoirs. The focus of this study is a 240 m core that captures a progradational succession from shoreface through tidally-influenced lagoon to fluvial deposits. The full spectrum of lithofacies stacking patterns present in the core is captured with a Markov Chain analysis. Benchtop measurements were performed on 1 inch core plugs (57 total; 25 from the coastal plain succession and 32 from the tidal succession) to obtain physical rock properties (Vp, Vs, density, permeability and porosity) for each lithofacies. The rock properties show a wide range of values as a direct result of the highly heterolithic nature of these deposits. Although measurements from different lithofacies are overlapping, we observe a slight offset between fluvial and tidal rock properties. To test our ability to observe the tidal to fluvial transition with seismic imaging, average rock properties for each lithofacies were used to generate synthetic seismic reflection models for different expressions of upward-fining packages from the Markov Chain analysis. This investigation elucidates variations in amplitude versus offset signatures as a function of the degree of tidal influence. The number of overlapping values highlights the complications associated with interpreting these deposits in subsurface data. However, the modeling shows promise in differentiating the end member packages, along with a gradational trend for intermediate packages consistent with the sedimentology of transitioning from more marine influence to more terrestrial influence.
Analysing Facies, Geobody Geometries and Architectural Elements within Open Shelf to Non-Marine Transitional Deposits: A Case Study from the Karoo Basin, South Africa.

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In coastal and shallow marine systems the deposition is complex, dominated by the interaction between different continental and marine processes. These act in different ratios depending on the position on the coast, shaping and modifying architecture and varying what can be observed both spatially and temporally.

In the Karoo Basin, South Africa, NW-SE oriented continuous exposure of more than 200km length, in the Tankwa depocentre, allows the study of stacking patterns and both dip and strike variability. More than 2500 measured palaeocurrents show a dominance of unidirectional values to the N-NE, with local E-W and NE-SW bidirectional values, confirming that the section is a strike to oblique-strike orientation. Eight 500m thick log sections spaced at 4-15km along a 70 km section were measured, and correlated with field observation and detailed panoramic photos. The SL-1 borehole drilled in the south of the area improves and details the facies classification and description.

Facies include: current ripple laminated, wave reworked, thin-bedded inverse to normally graded and dirty siltstone (St)-sandstones (Sd); 10-20m thick Sd packages forming channelized, tabular and amalgamated bodies; deformed Sd-St; and structureless or laminated fines (St-M). Seven regionally mapped units include: (1) prograding prodelta and mouth bar facies; (2) a laterally variable unit including lower delta plain channels (Fig.1) passing to shoreface or shoreline deposits; (3) shoreface-offshore transition thin prograding cycles with storm and wave reworking; (4) laterally variable shoreline deposits from lower/upper delta plain amalgamated channels to strand plain or coastal sand deposits; (5) lower–upper delta plain bay-interchannel flood plain facies, (6) upper–lower delta plain deposits accumulating thick deposits of fines and (7) upper delta plain - fluvial deposits.

This well-exposed example, records an overall prograding basin fill across a low-gradient shelf or ramp, comprising two progradational cycles. Which record the interplay of allogenic forcing and autogenic processes.

The Tankwa-Karoo succession records the transition from mixed influence shoreline systems to marginal and non-marine deposits in a moderate to high latitude, non coal bearing setting. It provides a new outcrop analogue to constrain architectural heterogeneities in paralic reservoirs.
Keynote Speaker: Moving Toward Theoretical Facies Models for Depositional Environments

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Facies models are an important tool for interpreting depositional environments in the geologic record. These models are commonly developed from empirical observations of outcrops and modern environments, yet their application to interpreting the rock record is not trivial. This occurs in part, because facies models are derived from the incomplete stratigraphic record and are subject to significant uncertainty. In this talk I advocate for using physics-based morphodynamic modeling to refine existing facies models. Morphodynamic models can simulate environmental change at time scales up to 10,000 years, providing predictions of stratal body size, shape, and connectivity, spatial/temporal change in grain size, and distribution of key stratigraphic surfaces. A theoretical approach to simulating facies has two distinct advantages. First, one can potentially creating more robust conclusions by verifying key stratigraphic observations with theoretical predictions. Second, theoretical facies models allow scenario testing to evaluate the range of conditions that can create the observed stratigraphic patterns and understand how other variables (e.g. median grain size) influence facies-scale stratigraphy.

Towards this end, I use case-studies to demonstrate how such an approach can lead to novel insights about the facies character in coastal, fluvial, and deltaic reservoirs. In particular I will show that physics-based models make predictions about variability in deltaic channel and coastal sand body size that is consistent with the modern and ancient record, but not accounted for in facies models. Moreover, I will demonstrate how model simulations guide a re-interpretation of the morphology of the Kf-1 parasequence set of the Cretaceous Last Chance delta, a unit of the Ferron Sandstone near Emery, Utah, USA, from clinoform dip data, clinoform concavity, and variance of dip directions.

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The formation and subsequent development of a delta is the result of interaction between a suite of depositional environments (e.g. distributary channels, tidal channels, mouth bars, subaqueous and aqueous levees, interdistributary bays, crevasse splays, delta plain, prodelta and delta front, as well as wave-formed beaches and associated shorefaces, etc.). These depositional environments are all driven by a temporal and spatially varying fluvial and marine forcing as well as vertical movement of the substrate. Some parts of the delta may be aggrading or prograding while simultaneously other parts of the delta may be degrading. In case marine processes are present, local flow will be either unidirectional, bidirectional or orbital and highly variable. The relative importance of fluvial versus wave and tidal forces determines for the most part the geometry of the delta. In addition grain size, and the ratio between cohesive and non-cohesive sediments affect the delta morphology, channel density and the type of shoreline (Orton and Reading, 1993). It should therefore be no surprise that the deposits associated with delta formation are very heterogeneous and poorly predictable.

Given this apparent complexity and the relevance to understand and predict deltaic deposition, numerous approaches to modelling three dimensional delta formation have been undertaken during the past decennia. Given the complexity stated above, realistic heterogeneity can only be expected from the most detailed models because of their detailed description of the hydrodynamics and the sediment transport and because of their refined grid.

Delta modelling using the physics-based simulation model Delft3D has shown that essential processes driving delta formation under progradational settings can be reproduced, such as mouthbar formation, channel bifurcation, channel abandonment and infill, avulsions, delta plain delta slope, prodelta and clinoform development. Figure 1 shows key processes for a river-dominated delta formation. Figure 2 shows two cross sections through the delta illustrating the heterogeneous sediment body highlighting this stratal complexity. In addition to these simulated fluvial-dominated sedimentary systems, we observe expected behavior in delta plan view as the ratio between fluvial, tidal and wave forcing and cohesive vs. non-cohesive sediment is altered.

While recent Delft3D modelling efforts appear to be quite successful, the modelled delta morphology does not necessarily exemplify deltas as can be observe today. While critically reviewing the simulated deltas, we have to infer that coupled hydrodynamic and sediment transport processes alone are crucial steps in delta modeling, but by itself insufficient to fully reproduce modern-day delta morphology and stratigraphy. The absence of long term measurement data of hydrodynamics and sediment transport as well as morphological development (both aqueous and subaqueous) in deltas hampers a better knowledge of processes relevant at decennia to centennial scales and lacks the opportunity for direct validation of the models. We can only compare the model to the incomplete, partially preserved end product, c.f. the delta as it is observed now. In order to make progress in process-based delta simulation, we will need better validation data. This can be accomplished by setting up research programs to study in more detail the past and present-day delta development in a range of basinal settings or to start to link experimental work with numerical simulations and find solutions for potential scaling issues. While there are still many challenges, physics-based
modelling has huge potential to predict deltaic stratigraphy in much more detail as can be done today.

Figure 1. Shoreline comparison between t=31 months (grey) and t=45 months (black isobaths). The red lines denote depositional processes and environments typical for a deltaic environment. The difference between the grey and black indicated how dynamic the delta development is at different locations. Three lobes can be distinguished as separated by blue dotted lines in the graph. The active lobe is highly dynamic, the mature lobe shows predominantly stable channels and accretion while the abandoned lobe shows very little sedimentation and a stable shoreline. The dotted orange line shows the position of the cross section (Fig 2). For details on the simulation, see Geleynse et al 2010.

Figure 2. Cross section (for location see fig 1J) showing the sand (orange) to clay (blue) ratio. The substrate composition ratio is 0.5 (yellow). The sand is predominantly linked to distributary channels and subaqueous levees. The fringes of the sediment body consist of prodelta and delta front clays which are deposited in a clinoform geometry. Clinoform angles are maximum 0.86 degree. For details on the simulation, see Geleynse et al 2010.
Ancient Backwaters and Baylines: Slope Magnitude and Its Control on Facies Partitioning In Ancient Fluvio-Deltaic Systems

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A common observation in many ancient clastic wedges is that shoreline deposits are commonly significantly finer than associated fluvial deposits. Abrupt downstream fining in rivers, and increase in tidal or marine influence, may mark the backwater and bayline limits, which are controlled primarily by slope, tidal range, and river discharge. The backwater distance, from the shoreline, is defined as the ratio of river depth versus slope, whereas the bayline is the tidal range divided by the slope. In Modern continental-scale low slope river systems (i.e. Slope < 0.0001), such as the Mississippi and Amazon, backwaters may reach many hundreds of kilometers upstream, whereas they may be on the order of a few kilometers in steeper gradient systems.

Ancient deltaic systems of the Cretaceous interior seaway of North America, including the micro-tidal Turonian Ferron Sandstone Member in Utah, show coarse-grained pebbly-sandstone bedload river deposits that feed medium-to fine-grained sandy shorelines. Cross-sections allow estimates of channel depth and width, which can used to calculate the cross-sectional area of a channel. Grain size and bedforms can be used to estimate flow velocity. When multiplied by the channel area, the velocity can be used to estimate discharge. Ferron trunk channels are on the order of 5-9 m deep with discharge (Qw) of less than about 1500 m³/s. This suggests moderate size upstream drainage basins and a propensity for downstream, distributary channels to produce hyperpycnal deltaic deposits.

Within the Ferron clastic wedge, the pebble-to sand transition lies several kilometers from coeval shoreline deposits, suggesting a short backwater length. Slope estimates can also be made based on onlap distances of associated coastal prisms, as expressed in stratigraphic cross sections. For the Ferron, slopes > 0.001, are an order-of-magnitude steeper than for the low-gradient continental scale systems, like the Mississippi. This explains the position of the transition from pebble- to sand in the fluvial systems, at a few versus hundreds of kilometers from the shoreline, as well as the lack of pebbles in co-eval shorelines. Onlap limits of bay and lagoon deposits, of several tens of kilometers, mark the bayline and suggest an average tidal range of < 2m.

The Cenomanian Dunvegan Formation, in Alberta, contains trunk streams on the order of 10-28 m deep. Discharge estimates are correspondingly about 3 times larger that the Ferron sandstone. Brackish water indicators have been found several tens of kilometers inland, suggesting the bayline was about 30km from the shoreline. Previous estimates of Dunvegan valley slopes are on the order of 0.0004, higher than the Mississippi, but lower than the Ferron. The gravel-sand transition lies considerably farther landward as well, suggesting backwater distances might have been on the order of 100 km.

Estimation of slope and discharge thus can be made in ancient clastic systems and allow prediction of the partitioning of coarse versus fine-grained facies at choke-points, as defined by the backwater and bayline limits.
Quantitative Use of Analogs in the Pursuit of Subsurface Characterization of Coastal River Deposits

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Analog-based reasoning refers to the use of modern (or ancient) depositional systems as a proxy for the scale and motif of a subsurface target. A well-chosen analog (or finite set of analogs) acts as a useful representation of the expected scales of stratigraphic objects and lithofacies. Juxtaposition of these scales with the field scale provides a powerful visual of the range of stratigraphic heterogeneities that may be encountered. In an analytical framework, analogs can provide a quantitative basis for interpretation, estimation, and prediction in subsurface settings.

Quantitative comparison between a subsurface target and potential analogs works well in fluvial systems, where geometric and hydraulic scaling of channels is robust. This permits scale information embedded subsurface data to be integrated with voluminous information available for modern river geometry. In coastal reaches, however, this comparative framework is complicated by the addition of shoreline controls on water and sediment fluxes. The effects on channel morphology, kinematics, and depositional patterns appear to be significant.

Herein we explore how quantitative analog selection may be approached in coastal river reaches, where development of a backwater curve or tidal modulation may result in breaks in channel scaling and significant changes in depositional patterns. We will discuss how such breaks may be leveraged to signify important process controls in subsurface data. Lastly, we speculate on the power of leveraging modern analogs and ancient deposits to connect short-term depositional effects in within coastal rivers to long-term stratigraphic accumulation of channel belts.
Poster Presentation Abstracts
Permeability Heterogeneity in Bioturbated Sediment, Cardium Formation, Pembina Field, and implications for successful waterflooding of complex tight oil reservoirs

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Bioturbated sediments representing distal expressions of paralic depositional environments are increasingly being exploited for oil in the supergiant Cardium Formation reservoir, Pembina Field, Alberta, Canada. These sedimentary strata were previously considered unproductive due to the limited vertical and horizontal connectivity between permeable beds. In these “tight oil” plays (0.1 – 10 md), sand-filled burrows connect bioturbated and parallel laminated sandstone beds creating hydrocarbon migration pathways exploitable via horizontal drilling and multi-stage fracking. As the exploitation of bioturbated strata progresses, waterflooding is being considered, although the response to enhanced oil recovery schemes in unconventional plays is limited. To assess the viability of waterflooding the bioturbated strata of the Cardium Formation, a regional-scale core-based study was undertaken.

Thirty-eight cores were logged and seven lithofacies identified, including four bioturbated facies that range from 5-75% total sandstone and siltstone content. An additional 170 wells were evaluated to ensure correct stratigraphic correlations and to maximize the number of bulk permeability (plug and full diameter) data points. An additional 629 Pressure Decay Profile Permeametry (microperm) measurements were acquired from three of the bioturbated facies in eleven wells distributed throughout the study area (Figs. 1 and 2). Microperm values enable correlation of bulk permeability from plugs and full diameter samples to the heterogeneous permeability distributions in intensely bioturbated strata. Bulk and microperm permeability data are graphically compared, and permeability distributions are mapped across the field. Using isopach thicknesses of bioturbated facies, production data, and permeability data, “sweet spots” are identified for placement of effective waterfloods.

Production information for recently drilled horizontal wells in the Pembina field demonstrate that bioturbated muddy sandstones and sandy mudstones in paralic environments can be economically exploited when sand-filled burrows provide connectivity between sand beds. However, well performance within these poorly understood unconventional tight oil plays can better be predicted with an in depth characterization of their facies and complex permeability heterogeneities. Based on our results, it is clear that micropermeability analysis can be effectively employed to differentiate between economic and sub-economic plays, identify areas with high effective permeability, and to high-grade areas for enhanced oil recovery schemes.
Integrated Ichnological-Sedimentological Model of a Forced Regressive Asymmetric Delta Reservoir, Lower Cretaceous Viking Formation, AB, Canada

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The Lower Cretaceous (Albian) Viking Formation of western Canada is a prolific hydrocarbon-producing interval. Its relatively thin expression belies its internal complexity. Owing to low-accommodation conditions in the basin, the latter half of the Viking contains no less than 4 regionally extensive sequence boundaries that saw the shoreline shift from western Alberta to central Saskatchewan, a distance of some 450 km.

In the Kaybob/Fox Creek field area, the main reservoir units occur within a sharp-based forced regressive shallow-marine succession that overlies a mappable regressive surface of marine erosion, demarcated by firmground omission trace fossil suites of the Glossifungites Ichnofacies. The reservoir facies consist of coarsening- and cleaning-upward, sporadically bioturbated muddy sandstones and sandstones, with locally abundant dark, fissile mudstone interbeds and interlaminae. Ichnological suites are diverse, with fully marine elements such as Phycosiphon, Zoophycos, Asterosoma, Schaubcylindrichnus coronus, Bergaueria and Rhizocorallium, in addition to numerous facies-crossing forms. BI values vary considerably, with successions showing BI 0-5 at the bed and bedset scale. BI values decrease upwards in all sections as sandstone contents increase. Wave- and storm-generated physical sedimentary structures dominate, characterized by micro-HSC, HCS, SCS, oscillation ripples and rare combined flow ripples. Mudstone laminae and interbeds are carbonaceous, drape sandstones and generally show BI 0-1. They are consistent with rapid deposition and/or other physico-chemically stressful conditions and ascribed to mud supplied by rivers. Using the WAVE classification scheme, the coarsening-upward successions yield a process classification of Wf (wave-dominated, fluvial influenced).

The Kaybob field area lies to the NW and generally shows higher BI values (BI 0-5; mainly BI 2-5), more diverse trace fossil suites, and only rare mudstone interbeds, suggesting that fluvial influence was minor. By contrast, Fox Creek successions lying to the SE are markedly heterolithic even in sand-dominated intervals, show overall lower ichnological diversity, and display reduced BI values (BI 0-3), reflecting significantly greater fluvial influence. Correspondingly, this forced regressive interval is interpreted to record a mixed river-wave influenced asymmetric delta, wherein successions from Kaybob correspond to updrift positions removed from fluvial discharge, and Fox Creek successions occupy positions downdrift of the trunk distributary, where they experienced greater fluvial influence. Continued base level fall exposed these units to subaerial exposure, leading to truncation and cementation of the upper part of the succession. Such depositional and stratigraphic distinctions are not academic only. Updrift Kaybob units, while showing only half the Kmax values of Fox Creek (albeit with similar porosities), produce both oil and gas from more homogeneous reservoirs. Fox Creek wells produce only gas and is generally a poorer reservoir. Reservoir quality decreases markedly to the south, due to erosional truncation and cementation associated with subaerial exposure during continued development of the falling stage systems tract.
Depositional Controls on Niger Delta Onshore Reservoirs

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In over 6 decades of petroleum production in the delta, the onshore Niger Delta has been identified as a prolific petroleum province. The basic insight to the prediction of depositional facies in sandstones or siliceous reservoirs within the region is the understanding of the control forming these deposits.

To further explore the environment, an approximately 15,000 ft. of the conventional cores have been taken from twenty wells on the onshore depobelts (Northern delta, Ughelli depobelt, Central Swamp, Coastal Swamp). The ages of the cored intervals which ranged from Chattian to Tortonian, was determined using biostratigraphic data, and the spatial distribution of the cored facies. The deposition suggests a mixture of tidal, fluvial – estuarine and wave influenced depositional sequences. This is dominated by a tidal and fluvial channel turbidite sandstone, and associated interfluve deposits alongside the wave formed shoreface facies. The distribution of the lithofacies showed a dominance of tidal channels facies constituting 37\% of the observed interval, fluvial channels constituted 16\%, shoreface facies is about 21\%, and 27\% made of coastal plain deposits.

The result has unraveled a distinct lithofacies distribution and depositional sequences of the reservoirs in space and time across the selected wells from the onshore settings. These cores from several producing reservoirs representing a range of paralic depositional settings, indicate biogenic structures and the lithofacies associations deposited into the formative depositional environments. Similar facies patterns present in the offshore settings could also be explained by using similar depositional control on the onshore facies that have lateral transport of tidal, fluvial – estuarine and wave sediments as a critical component for the reservoir evaluation. This has aided in a bid to understand and predict depositional trends across the main productive Agbada formation of the Niger Delta.
Defining Geobody Geometries and Architectural Elements within Fluvio-Deltaic Depositional Systems: a Quantitative Analysis of the Paralic Mungaroo Fm, NW Australia

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Defining geobody dimensions and architecture in paralic reservoirs is a major challenge. Published width, thickness and sinuosity relationships have a huge range and the use of terminology is often confused. The resolution of typical subsurface datasets; core, wireline and seismic, adds further challenges to interpretation. Commonly outcrop studies are used as analogues, but again they are often scale limited, as many channel belt / channel belt complexes can be far larger than most exposures. It is the integration of data, utilising the potential to image geobodies at a range of scales on 3D seismic, that offers a way forward to build predictive models that are statistically meaningful.

This study examines the Triassic fluvio-deltaic Mungaroo Formation, the main reservoir in the multi-TCF gas play offshore Northern Carnarvon Basin, NW Shelf, Western Australia. A high resolution 3D seismic volume, covering approximately 17,500 km², located NW of the Exmouth and Barrow sub-basins, has been analysed in order to extract geobody geometries using amplitude analysis and blended frequency decomposition volumes. Integration with a full suite of well log data from 21 wells and detailed sedimentological description of conventional core from 8 wells has enabled characterisation of the reservoir architecture and revealed a range of geobody geometries.

The dominant facies associations identified from core and well log analysis include; single and multi-storey fluvial channel sandstones, overbank and floodplain lake mudstones and siltstones and coal intervals. Intercalated, bioturbated mudstone, siltstone and very fine grained sandstone are indicative of lagoonal/ restricted embayment and periodic marginal marine depositional settings. Spatial and temporal characterisation of the depositional environment has defined alternating periods of transgression and regression within an overall transgressive system.

Seismic attribute analysis images a range of geobody morphologies and dimensions, from sinuous, small scale (100 - 200 m wide) through to dominantly straight to low sinuosity large scale (approx. 1 - 2 km wide) geobodies, which are interpreted as individual channels and channel belts/ complexes respectively, and are the principal reservoir units in this succession. Detailed statistics have been extracted from a series of iso-proportional slices that reveal the distribution, classes and evolution of the system both temporally and spatially (proximal to distal).

Predictive 3D reservoir models, conditioned to both seismic data and well control, have been developed in order to better understand and predict reservoir architecture, heterogeneities and connectivity through time. The insights into reservoir architecture, stacking patterns and potential connectivity within the Mungaroo Formation, have significant implications for our understanding of geobody distribution in other paralic depositional systems.
Paralic Reservoirs of the Lower Cretaceous Mannville Group (Sparky, Waseca, and McLaren Formations) West-Central Saskatchewan, Canada

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The Lower Cretaceous Upper Mannville Group (Sparky, Waseca, and McLaren Formations) of west-central Saskatchewan, Canada, comprise an interval up to 60 m thick deposited in shallow-marine to coastal plain/delta plain environments. Despite the abundance of core and well logs and its importance as a heavy oil producing area, a sequence stratigraphic framework for these units has not been constructed previously. The majority of earlier interpretations have relied on lithofacies analysis and well-logs characteristics. The deposits, however, exhibit marked vertical and spatial variability, owing to several autogenic and allogenic processes, which have led to a complex stratigraphic architecture. The integration of ichnological data with physical sedimentological observations yields a better understanding of the depositional framework, and can be used to discriminate the different paralic subenvironments. These data can also be employed effectively to aid in the recognition of subtle changes in relative base level, changes in degree of marine influence, identification of various discontinuities, and refinement in their genetic interpretations.

Thirteen facies are grouped into six spatially recurring facies associations. Facies Association 1 (FA1) encompasses offshore sediments deposited below fairweather wave base but above storm wave base. Facies association 2 and 3 (FA2 and FA3) form coarsening-upward successions and represent progradation of wave- and storm-dominated shorefaces and mixed river- and wave-influenced deltas, respectively. Facies Association 4 (FA4) commonly displays current-dominated fining-upward successions, and is interpreted as distributary and fluvo-estuarine channel complexes, depending upon their stratigraphic context. Facies Association 5 (FA5) is broadly similar to FA2 but is ichnologically distinct in that the succession is characterised by low-diversity, impoverished trace-fossil suites with variable bioturbation intensities, and is interpreted to record deposition in shallow brackish-water bays. Facies association 6 (FA 6) is interpreted as coastal/delta plain deposits.

The studied strata can be separated into parts of two depositional sequences. The main deposits of the lower sequence comprise two highstand systems tracts (HST), corresponding to the Sparky Formation and the Lower Waseca Member. The base of the Lower Waseca marks the onset of a transgressive systems tract (TST). A maximum flooding surface (MFS) marks the end of transgression and the resumption of progradation for the remainder of the Lower Waseca. Following highstand progradation, a relative base-level fall produced a subaerial unconformity, which marks the base of the upper sequence. Fluvial valley incision led to sediment bypass, and deposition of forced regressive and lowstand shoreface and delta complexes of the falling stage systems tract (FSST) and lowstand systems tract (LST) toward the northern part of the study area. The subaerial unconformity was transgressively modified during subsequent relative sea level rise. TST accumulation is largely confined to fluvo-estuarine infill of the incised valleys of the Upper Waseca Member. The Upper Waseca is separated from the McLaren Formation by a maximum flooding surface (MFS), with the McLaren Formation marking a return to regional shoreline progradation and formation of a highstand systems tract (HST).
Facies Analysis of Thin-Bedded Reservoirs in Mixed-Influenced Deltaic Systems

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Despite the historical assumptions that most marine “shelf” mud is deposited by gradual fallout from suspension in quiet water, recent studies of modern muddy shelves show that they are dominated by hyperpycnal fluid mud. Flume work shows that bedload transport is critical in the deposition of mud, and storm-wave aided hyperpycnal flows are common on many modern muddy shelves. We have applied these ideas to the interpretation of mud-rich prodelta deposits of the Cretaceous Western Interior Seaway depositional systems of North America. Thin-bedded heterolithic deposits contain significant sandstone and are volumetrically important zones of bypassed unconventional pay surrounding many conventional reservoirs.

The Upper Cretaceous Ferron Sandstone in Utah shows deposition by ignitive turbidity currents, hyperpycnal flows, storm surges, as well as complete bioturbation in areas away from river-influence. Ignitive turbidites show fining upward Bouma sequence. Hyperpycnites show either inversely or normal grading. Storm deposits (tempestites) fine upward and contain hummocky cross stratification (HCS) and wave ripples. Ignitive turbidity currents and hyperpycnal flows indicate fluvial-dominated depositional environments, whereas tempestites are linked to storm-wave dominated environments. Detailed measured sections, at centimeter-scale, allow the relative proportion of sedimentary and biogenic structures generated by each depositional process/event to be calculated. These were measured from a series of stratigraphic sections within a mixed wave and fluvial dominated parasequence, exposed continuously exposed along depositional strike.

The parasequence shows strong along-strike variation with a completely wave-influenced shoreface environment in the north, that contains minimal thin-beds, passing abruptly into a fluvial-dominated area with a thick heterolithic prodelta, then to an environment with varying degrees of fluvial and wave influence southward, and back to a wave-dominated environment further to the southeast. The depositional model of the parasequence is therefore interpreted as a storm-dominated symmetric delta with a large river-dominated bayhead delta system. It is thus practical to quantify the relative importance of depositional processes and determine the along-strike variation within thin-bedded heteroliths in ancient delta system using thin-bedded facies analysis, which has implications of along-strike heterogeneity of thin-bedded reservoirs.
Contrasting Processes During Fine-Grained Deltaic Progradation Along A Regional Shelf Margin, Karoo Basin, South Africa

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Commonly, shelf accommodation has been emphasised as one of the major controls on progradation of deltaic shelf margin systems and delivery of sand to deep water settings. However, a complicated interplay of factors including rate of sediment supply, shelf physiography, and lateral variability in dominant process regime challenge simple predictive models of slope sediment bypass and the development of basin-floor fans.

Three-dimensional datasets can help to deconvolve these different factors, but need to be regional in scale to capture basin margin architecture, but with detailed sub-seismic observations to capture process regimes and facies distributions. Here, the evolution of a shelf margin in the Permian Karoo basin, South Africa is investigated. More than 1000 regionally distributed sedimentary logs along a 150 km+ strike section, from basin-floor to shelf in both the Tanqua and Laingsburg depocentres provide data for stratigraphic panels that show the position of the clinoform rollover and the base-of slope through time. This helps to constrain water depth estimates, and to capture changes in slope length and gradient. This dataset has also been integrated with absolute age control and isopach mapping.

A differential subsidence pattern across the basin led to a thinner and more ramp type progradational outbuilding in the Tanqua depocentre, whereas a thicker slope succession in Laingsburg, resulted in an aggradational followed by progradational stacking pattern. Shelf margin deltaic progradation in the Laingsburg area operated by the accretion of silt through multiple parasequence cycles without the sandy part of each clinothem reaching the clinoform rollover. The downdip correlation of shelf edge deltas show that their associated slope deposits are generally less sand-rich than the underlying basin-floor stratigraphy, which points to either physiographic change in the basin margin architecture and/or process regime through time. Detailed field observations have provided criteria to define a muddy shelf to slope transition. These findings provide a facies basis for equivalent seismic expressions in cases of margin progradation via fine grained material. These investigations have demonstrated that basin margin progradation can occur without development of basin-floor fans, and address the processes responsible for transporting fine grained material across the shelf and beyond the shelf edge rollover during relative sea-level highstands.
Surprises during Rises? Shallow-Marine Process Regime, Clinoform Trajectory, and the Timing of Down-Slope Coarse-Grained Sediment Supply Offshore New Jersey

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The analysis of shelf-edge clinoform trajectory in reflection seismic datasets or outcrop-based studies has been widely employed as a tool to infer relative sea-level change, to interpret long-term factors controlling the basin margin evolution, and to predict the timing of coarse-grained sediment delivery from continents to oceans. Accommodation- or sediment supply-driven models have been emphasised, with less focus on the role of the shelf-edge process regime in operation at individual clinothems, and how the process regime change in time and space (across strike). IODP Expedition 313 collected three research boreholes that intersected a set of ocean-facing 200-300m-high Miocene clinothems offshore New Jersey that sit above the continental shelf. The objective of the expedition was to capture a complete record of relative sea-level change through integration of seismic stratigraphy, core and well logs, and high-resolution chonostratigraphy. Seismic profiles tied to cored and dated borehole data provide a means to link the depositional architecture (clinoform trajectory) to sediment dispersal processes and patterns. Top-set deposits are dominated by shoreface-to-offshore facies associations with local fluvial-influenced successions. Clinoform rollover deposits are either wave- or fluvial-dominated. Typically, where the rollover is wave-dominated there is little coarse-grained sediment in the toe-sets. However, the bottom-sets to fluvial-dominated rollovers comprise sharp-based successions of coarse-grained turbidites and debrites. This distribution of coarse sediment does not correlate with clinoform trajectory. There is no evidence of deep shelf incision by fluvial channels, which suggests periods of a wide distributive river supply system that fed sediment downslope to form a gullied apron or coalesced fans at clinoform toes. The direct relationship between river-dominated rollovers and sandy bottomsets, suggests that process regime in the shoreline controlled the transfer of sediment from top-sets to bottom-sets on the New Jersey margin during the Miocene, even a times of rising relative sea-level, and serves as a subsurface analogue to other clinothem units that prograded above deep continental shelves.
Inclined heterolithic stratification (IHS) is reported from the upper parts of a modern bank-attached bar in the fluvial-marine transition at the head of the Severn estuary. The IHS overlies largely homogenized bar sands. Although the outer estuary is macrotidal (14m tide range) within the transition tidal amplitude varies only between 3m and 0.3m. The channel bank is convex upwards with a tidal current-eroded scarp near the level of MHWN tides and continuing accretion of IHS occurring at the level of MHWS tides. All but the lowest Neap tides rework the sandy channel bar deposits which are bioturbated. Consequently, the lower portion of the bar is largely massive. Basal sands within the active tidal channel are faintly laminated with occasional ripple cross-bedding, mud flasers, reactivation surfaces and convolutions. Convolutions are ascribed to pressure fluctuations due to tidal bores. In contrast, the IHS are distinctive thin laminations of sand, silt and clay deposited by the higher Spring tides. The bar top is inundated by slow currents, with little opportunity for reworking, which explains the preservation of distinctive lamination. The influence of high river discharge is not evident in the depositional signature, probably due to the intense mixing of high concentration estuarine suspended sediment for all weather and seasonal conditions.

Allogenic controls on accommodation are outlined together with the autogenic hydrodynamic context of deposition. The stratigraphic relationship of the bar to Holocene formations, into which the bar is set, provides context. The IHS of the transitional zone sediments are contrasted to the deposits within fluvial and marine environments upstream and downstream. Although lamination occurs within the fluvial and marine sequences, lamination is much finer and regular in thickness, sand-mud couplets are not conspicuous and IHS is absent. Published studies of sandy bars in the marine-estuary have recorded interstratified beds, but also frequent cross-bedding, which abundance is not seen in the basal sands or within the HIS of the transition zone.
Deflected Steep-Marginal Deltas in Confined Tidal Straits: An Outcrop Analogue from the Upper Miocene Amantea Basin, Southern Italy.

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Tidal straits are confined marine passageways connecting two adjacent basins where the tidal inversion in phase opposition generates relevant current convergence and tidal amplification. Tidal straits host important clastic accumulations. Sediments spread parallel to the strait axis, from proximal coarse-grained deposits to distal fines following the decrease of the tidal current velocities, as consequence of the progressive divergence of the tidal prism toward the seaway peripheries.

Modern and ancient tidal straits exhibit large-scale, tidal cross-stratified sandbodies, which represent the dominant physical elements of these marine systems. When preserved in the rock record, these complexes usually exhibit very good reservoir potential. However, a scarce number of case studies have documented tidal strait marginal systems (e.g., fan/braid deltas, aprons, beaches …) which, as observable in many modern examples, represent one of the most important sedimentary source to these narrow basins.

The Amantea Basin (southern Italy) was a mid-upper Miocene marine half-graben, which changed into a tidal strait during the Tortonian due to a strong tectonic-driven narrowing concurrent with a relative sea-level rise. Dune-bedded sequences dominate the succession, including tidal cross strata up to 12 m thick. Although intensely deformed by an active extensional tectonics, the northern border of the Amantea Strait also preserves a marginal paralic system, which is very well exposed along a seismic-scale section (figure).

Large-scale architectures and sedimentological features revealed a series of internal stacked sandbodies. They were initially originated by gravity-driven debris and grain flows shed from a steep, footwall margin and, subsequently, dominated by the effect of powerful tidal flows. Palaeocurrent patterns show a progressive variation in the dominant trend between the two facies associations with an average difference of ca. 60°-80°.

This succession is interpreted as a steep marginal delta prograding perpendicularly within the Amantea Strait. Early footwall-derived mass flows were progressively replaced by the dominance of tidal currents flowing axially to the seaway, which were responsible of the deflection of the delta front during a late stage of a marine transgression. This case study represents an outcrop analogue for reservoirs entrapped in tectonically-confined, narrow half-grabens.
Relating Modern Analogs and Process-Based Facies Models to Ancient Deposits: A Mixed-Energy Estuary from the Cretaceous Straight Cliffs Formation, Southern Utah

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Process-based facies models for estuaries and deltas are largely derived from modern analogs, and generally depict end-member energy settings. It is unclear how applicable these facies models, and other modern analogs, are to interpretations of the rock record, particularly in more complex mixed-energy estuarine, deltaic, and tidal environments. Such ambiguity reflects the difficulty in understanding preservation potential, the close temporal and stratigraphic interplay between end-member systems, and a general knowledge gap for both modern and ancient high-energy, sand-rich tidal settings. More generally, despite the demonstrated utility of applying the theory of uniformitarianism to link modern and ancient environments, critical differences in the temporal and physical scales of observation also pose a challenge to analog studies and their application to subsurface reservoirs.

This research presents a detailed assessment and model for outcrops of a mixed-energy (wave- and tide-dominated) estuary from the Cretaceous Straight Cliffs Formation, southern Utah, with specific modern analog comparisons. Along a 1,200 m-wide, 60 to 120 m-thick section, cm-scale measured sections, petrography, and gigapan and aerial photos are used to document vertical and lateral facies changes. The estuary consists of three depositional units (DU): (1) a lowermost interval, 20–30 m thick, of tidal bars and marsh deposits composed of carbonaceous shales and coals; (2) a middle interval, 50–80 m thick, with channelized tidally-influenced bayhead delta / tidally-dominated delta deposits; and (3) an uppermost interval, 30–50 m thick, of landward-stepping barrier island strata. The lower interval began as an open, tide-dominated estuary, perhaps similar to the modern North Carolina coast at Cape Hatteras with a barrier island partially bounding a flooded estuary (DU 1). The estuary then fills with channelized tidal sands and associated tidal rhythmites perhaps similar to Winyah Bay, South Carolina which is partially infilled and bounded by an open barrier island (DU 2). Pulsated transgression causes the infilled estuary to be bound by barrier island facies transitioning from tidal to open marine as the barrier island passes over the underlying strata (DU 3). The tidal sands have a sheet-like geometry and therefore could be preserving environments similar to Big Sarasota Pass, Florida or the East Friesian Islands, Germany, North Sea. As transgression progressed, a system similar to Cape Hatteras, North Carolina was reestablished, with DU 3 preserving the seaward side of the barrier island.

This study highlights areas for improvement in the modern to ancient to reservoir analog workflow, particularly in mixed-energy systems. For example, we illustrate the difficulties in distinguishing between bayhead and tidal deltas in outcrop, despite the importance of such distinctions for both sequence-stratigraphic and reservoir interpretations. Despite these challenges, detailed facies characterization and predictive 3-D geobody analysis does elucidate key recognition criteria for the mixed-energy system, including the preservation of both tide and wave energy indicators, tidal packages, and barrier island facies.
Reservoir Facies Characterization and LiDAR Model of a Mixed-Energy Estuarine-Tidal Succession, Cretaceous Straight Cliffs Formation, Southern Utah

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Depositional architectures in tidal successions reflect a complex mixture of fluvial, tidal, and marine environments, making their recognition and interpretation difficult. Because tide-dominated and tidally-influenced reservoirs account for a significant portion of petroleum reserves, predictive facies models derived from outcrops are invaluable. Outcrops of Cretaceous strata in Tibbet Canyon, southern Kaiparowits Plateau of southern Utah, offer insight into the regional extent and internal complexity of tidal processes. This study captures the architecture of a mixed-energy estuarine succession preserved as part of the John Henry Member fluvial to marine transition of the Upper Cretaceous (Santonian-Campanian) Straight Cliffs Formation. A detailed interpretation of an 8 m by 500 m bayhead delta is presented, highlighting its internal architecture as well as its relationship to underlying tidal bars and overlying coastal plain strata. Superficially, bayhead deltas and tidally influenced point bars have similar, IHS-dominated architectures, but they form by different processes and have different architectural expressions (progradational and coarsening upward vs. lateral accretion and fining upward, respectively). As such, they behave quite differently as reservoirs.

Terrestrial LiDAR, outcrop photomosaics, detailed measured sections, and paleocurrents were used to describe facies and facies associations and interpret architectural elements. LiDAR scans provide point clouds tied to RGB values for a photo-realistic geospatial outcrop reconstruction of a complex vertical succession. The ~65 m thick interval is an excellent example of inner-middle estuary succession consisting of elongate, sigmoidal tidal bars, estuarine point bars, bayhead deltas, and tidal flat deposits. The stratigraphic evolution of an estuarine succession from tidal bars to a bayhead delta overlain by coastal plain deposits was captured in a conceptual model. Within the bayhead delta, beds thicken and coarsen vertically, and are composed of very fine- to medium-grained trough cross-stratified, rippled (some climbing), planar laminated, and planar cross-stratified sandstones and interbedded mudstone/siltstone. Modeling results are compared to published studies of IHS point bar models to demonstrate the impact of distinct stacking patterns and geometric relations of different IHS deposits on reservoir character.
Meanders to Ribbons: Basin-Scale Deltaic Evolution in the Barents Sea Offshore Northern Norway

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Channel deposits from an extensive delta plain that occupied the present Barents Sea in Triassic times, show a clear development from wide and amalgamated deposits in upstream, proximal reaches of the delta to narrower ribbons in the downstream paralic parts. Its aerial extent (400 by 300km) is barely matched by only the largest modern counterparts, and its high level of preservation is uncommon for ancient systems of this size. Palynological data from wells, coupled with regional 2D seismic lines, allow us to constrain and correlate these deposits across the basin, whereas multiple 3D seismic datasets offers a rare insight into the details of the development of this large-scale deltaic system. Seismic data show how several cycles of river avulsion have occurred with increasing frequencies from a proximal to distal position on the delta plain, resulting in a complex network of ribbon-shaped channel deposits. The delta plain is linked to the relatively shallow basin in which it was deposited, with delta progradation taking place under conditions of relatively stable sea-level and high sediment supply in a greenhouse world.

This Triassic delta distinguishes itself from modern counterparts developed in the Quaternary and provides information about a substrate interval not easily investigated in modern deposits, which represent snapshots considered on geological time scales. Despite several differences, distribution of channel geometries and avulsion patterns appear to be similar, suggesting that delta plain deposition and development is comparable to the modern. This study considers the fluvial system in terms of potential drainage area and discusses the variability in the geometries of channel bodies in terms of the basin configuration and the underlying strata by comparison with a modern counterpart. The variability in channel geometries and associated facies distributions is argued to be controlled by strike and dip variations in accommodation. Based on this understanding, a facies model for fluvial deposits in high accommodation and high sediment supply setting is proposed, with particular emphasis on trying to bridge the shallow marine, paralic and deltaic depositional settings.
Stratigraphic Evolution of the Barrow Deltas, Northern Carnarvon Basin, North West Shelf, Australia

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The Northern Carnarvon Basin, covering a surface of ~535 000 km², is located on the North West Shelf (Fig. 1) and constitutes the most developed hydrocarbon province of Australia. The Barrow Group represents a deltaic to turbiditic slope/basin floor depositional systems of Berriasian - Valanginian age, with gas fields discovered in both shallow marine and basin-floor fan reservoirs. During the late syn-rift phase of basin extension, several very wide (>100 km) deltas prograded to the north/northwest in the Exmouth and Barrow sub-basins as well as on the Exmouth Plateau (Fig. 1). The deltaic and basin-floor systems prograded over half-graben and were overlain by a thick transgressive shale that forms the regional seal (Fig. 2).

The Barrow Group deltas formed during the transition between an active rift and a passive margin, and the complex tectonic configuration of the North West Shelf during the Early Cretaceous period most likely played a key role in the spatial distribution of the deltas (lobe switching) as well as in the source of sediment and the creation of accommodation space in the basin.

Regional 2D, 3D seismic and well data are used here to constrain the seismic stratigraphic evolution (2nd to 3rd order scales) of the deltaic systems temporally and spatially. The spatial extent of each delta will be identified via offlap break mapping.

The internal architecture of individual deltas (including mapping of delta plain and delta front from identification of depositional elements and linkages with the deep-water elements) will be then established using the seismic geomorphological analysis of the 3D seismic dataset (Fig. 3).

It is anticipated that this regional approach will highlight the relative roles of the parameters (eustasy, tectonism, accommodation, sediment supply) that controlled development of the basin-scale stratigraphic framework of the Barrow Group. This is critical for understanding the hydrodynamic controls along the Early Cretaceous paleo-coastline and, therefore, on the major depositional processes of the system.
Figure 1: Location map of the Northern Carnarvon Basin and its associated geological provinces (North West Shelf of Australia). Bathymetry and topography data (250 m resolution) comes from the Australian Bathymetry and Topography Grid (Whiteway, 2009) available on the Geoscience Australia database.

Figure 2: 2D seismic cross-section of the Barrow Group (see location on Fig. 1) showing progradation over the rift-inherited half-graben. Length of profil approx. 100 km.
Figure 3: (A) Seismic cross-section from the Charon 3D survey (see location on Fig. 1). (B) Spectral decomposition attribute map (color-blended from frequencies 20, 50 and 80 Hz) of clinoform 1. The identification of key geomorphological features suggests a fluvial-dominated, tidal-influenced, wave-affected system (Fw). (C) Spectral decomposition attribute map (color-blended from frequencies 20, 50 and 80 Hz) of the clinoform 2. The geomorphological features here suggest a wave-dominated, fluvial-influenced, tidal-affected system (Wf). (D) and (E) Schematic representative map of a Fw and Wf depositional system (respectively) from Ainsworth et al. (2011). OB = offlap break.
Up-Dip to Down-Dip Evolution of Palaeovalleys Incising Deltaic Systems in Foreland Basin Settings.

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Recent advances in our understanding of the morphological evolution of palaeovalleys, the composite nature of the associated sequence boundary and its expression in down-dip locations have been largely guided by examples from passive margins, where subsidence increases basinward. This study documents a series of incisional fluvio-deltaic sandbodies from the Pennsylvanian Breathitt Group (central Appalachian Basin, U.S.A.), which fulfil the traditional definition of palaeovalleys. The Breathitt Group was deposited in an epicontinental foreland basin setting, in which there was no shelf-slope break, and palaeovalleys can be tracked from the high accommodation orogenic margin towards the lower accommodation cratonic margin of the basin, over 100 km down-dip. Sandbody architecture has been captured through a combination of centimetre-scale sedimentary logging and annotation of photomosaics from km-long road-cuts to produce correlation panels. Sandbodies are typically 5-20 m thick, 0.5-30 km wide, and dominated by trough cross-beded medium-to-coarse grained sandstone deposited as longitudinal bars. Heterolithic strata displaying lateral accretion occur, particularly towards the tops of valley fills, as well as rarer heterolith-filled abandonment plugs, slumps and slides. Characteristic changes between the proximal, high accommodation and the distal, low accommodation sectors of the basin include: (1) the number of stratigraphic levels containing major sandstones decreases, and the sand bodies become increasingly discontinuous, suggesting an overall distributive morphology; (2) the sand bodies erode into increasingly open-marine facies; (3) the sand bodies contain an increasingly diverse, marine ichnofauna, suggesting increasing marine influence down depositional dip. Up-dip, a basinward facies shift at the bases of the palaeovalleys is not evident, whereas down-dip an unambiguous basinward facies shift at the bases of the same sand bodies clearly distinguishes them as palaeovalley fills. This contrasts markedly with models for palaeovalleys derived from passive margins, where the expression of the palaeovalley is lost down-depositional dip.
The Application of Process-Based Computational Models to Identify Proximal To Distal Trends in Deltaic Sediment Distributions.

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River deltas result in highly heterogeneous deposits which, over time, can form significant oil and gas reservoirs. In an effort to better exploit their hydrocarbon carrying potential, analogues are studied to improve understanding of these reservoirs. Modern analogues allow the study of deltaic sedimentation and is particularly good for understanding lateral continuity of deposits. However, aside from limited core data, directly measurable vertical data resolution may be limited. The data availability of ancient river delta analogues may allow more detailed study of vertical sedimentation, but lateral continuity is limited and dependent on accessibility and preservation of appropriate outcrops.

To link horizontal and vertical variation in sediment distribution over the entire delta, process-based models such as Delft3D can be employed. These models have become increasingly reliable for predicting the responses to of natural systems to their individual boundary conditions over increasing timescales. Advances over the past decades allow us to apply process-based models to test hypotheses regarding the formational process relating to ancient deposits. They can also be employed to identify trends between the conditions present at the time of deposition and the expected patterns of sedimentation.

In this study we focus on the variation of heterogeneity observed in the sedimentation when moving from proximal to distal position within the deltaic deposits. Continuous model output, generated in Delft3D, is used to extract trends based on the position within the delta. The approach also allows investigation as to how these relationships change under different hydrodynamic conditions and sediment supply.

Process-based modelling is still an underutilised tool in the oil and gas industry. Workflows for identification of trends, as shown in this study, is not the only relevant application for process-based models. The models are also applied to verify the match between observed data and a non-unique set of hypothesised depositional models. As a growing body of research highlights its applicability, process-based modelling using software like Delft3D are rapidly being established as a valuable industry tool.
Deposited sand bodies show increasing heterogeneity when moving from proximal to distal positions in deltaic depositional environments.
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