Mixed Wave-, Tide- and Fluvial-Influenced, Tropical Coastal-Shelf Deposition: Miocene-Recent Baram Delta Province, Northwest Borneo*

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Abstract

Evaluating the spatial and temporal evolution of ancient, mixed-energy clastic coastal-deltaic systems requires integration of detailed facies analysis with local- to regional-scale geological factors (tectonics, climate, sediment supply, etc.) and basin physiography (e.g. water depth, shape, orientation, etc.), which together determine tide, wave and fluvial effectiveness. This approach is applied to Middle to Late Miocene coastal-deltaic successions in the low-latitude (c. 5° N), tectonically-active Baram Delta Province (BDP) of Northwest Borneo, utilising outcrop sedimentology, well-constrained paleogeographies and paleotidal modeling. In the eastern BDP, the Belait Formation initially records fluvial-dominated coastal-deltaic progradation above outer shelf to slope mudstones. Thickening- and coarsening-upwards, 4-8 m thick, parasequences are sparsely-bioturbated throughout, contain abundant climbing current-ripple cross-lamination, dewatering structures and soft-sediment deformation, attesting to high rates of current-dominated sedimentation, hyperpycnal flows, substrate instability and mouth bar collapse. The overlying Belait Formation contains abundant, 10-50 m thick, upward-coarsening successions interpreted as prograding storm-, tidal- and river flood-influenced delta front deposits, indicating greater variability of coastal processes. Seismic evidence for tectonic inversion and paleotidal modeling suggests that a large-scale (10-100 m) stratigraphic change from relatively wave-dominated to more tide-dominated facies successions reflects the development of protected embayments with suppressed wave energy. In the western BDP, the Lambir Formation is partitioned into mainly mixed fluvial- and tide-influenced sandstones that erosionally overlie subordinate wave-dominated (storm-reworked) prodelta to delta front successions. The overlying Miri Formation displays a change towards greater storm-wave energy and the development of storm-flood deltaic parasequences. This reflects a gradual decrease in fluvial and tide effectiveness, consistent with regional paleotidal model results. Numerical modeling of paleo-oceanic processes have been applied in order to better decipher the relative interplay of autogenic vs. allogenic controls on sedimentological and stratigraphic architecture in these variable, mixed-energy clastic coastal-deltaic successions.

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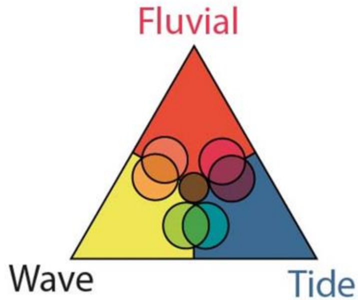
Presenter’s notes: In this talk, I will present an example of a Miocene coastal succession that demonstrates how tectonically-induced changes to basin morphology has caused variations in sedimentary processes within the coastal-shelf depositional setting.

Process prediction

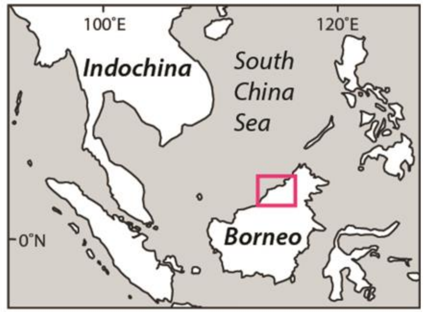
Challenge 1: **Facies analysis**

Determining the relative proportion of tide, wave and fluvial facies indicators



Challenge 2: **Geological setting**

Evaluating the controls on the relative strength of tides, waves, rivers and storms



Challenge 3: **Time**

Understanding temporal changes in process controls and facies preservation

Presenter's notes: Any evaluation of the depositional processes in ancient paralic successions faces three main challenges:

1. Determining the relative proportion of wave, tide and fluvial facies indicators, based on the analysis of facies, sedimentary structures and ichnological characteristics.
2. Evaluating the regional controls on the relative strength of tides, waves, rivers and storms, based on basin-scale considerations, such as basin morphology, shelf hydrodynamics and palaeoclimate.
3. Assessing how these process controls, and associated preservation potential, change over different temporal scales.

For this study, we have selected a study area, the Baram Delta Province in NW Borneo, SE Asia, that allows these 3 challenges to be interrogated at a range of scales.

Baram Delta Province (BDP)

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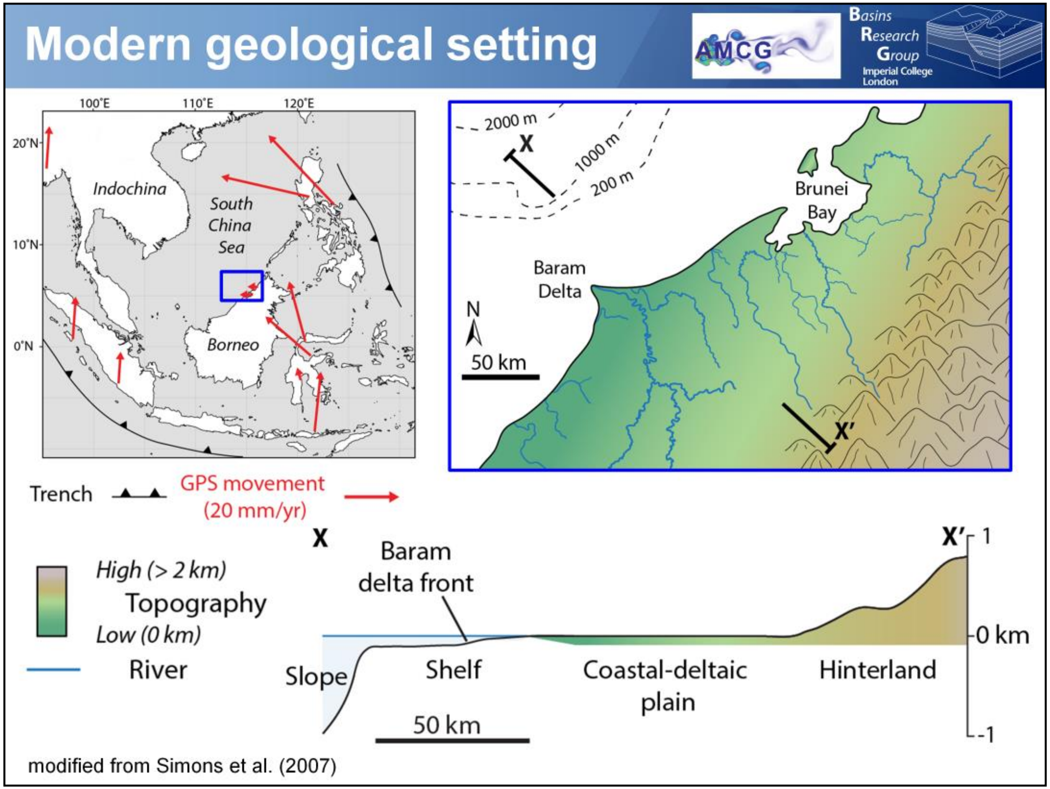
1. Modern system analogous to ancient
2. Up to 12 km sedimentation in 15 Ma
3. Dataset appropriate to interrogate the three challenges:
   - Seismic stratigraphy
   - Chronostratigraphy from well, core and outcrop
   - Outcrop facies analysis

- Evaluate the tectonic controls on coastal morphology, process variation and preservation

Presenter's notes: The Baram Delta Province has been selected for this study because it combines the following:
Firstly, the modern system is directly analogous to the ancient system, and vice versa. This system has been active for around 15 Myr in a consistent tectonic and climatic setting.
Secondly, during the past 15 Myr, up to 12 km of sediment has accumulated. The stratigraphic succession reflects high levels of accommodation, sediment supply and preservation.
And thirdly, it enables integration of a wide range of geological scales and topics, including seismic stratigraphy, biostratigraphy and outcrop facies analysis.
This rich availability of geological data reflects >100 years of petroleum exploration in what is a multi-billion barrel petroleum province.



Presenter's notes: Firstly this is a re-appraisal of the modern Baram Delta Province geological setting. The map on left shows active plate movement in the SE Asia region and shows that Borneo is moving N and Westwards into the stable core of Indochina creating an active compressional along NW Borneo.

The BDP is shown in the blue box. Active compression has resulted in uplift of a steep and high hinterland within 100 km of the shoreline.

The narrow coastal plain comprises a number of relatively small, independent drainage basins. Combined with intense tropical weathering and high rainfall, these systems result in efficient transfer of sediment from the hinterland to the shoreline.

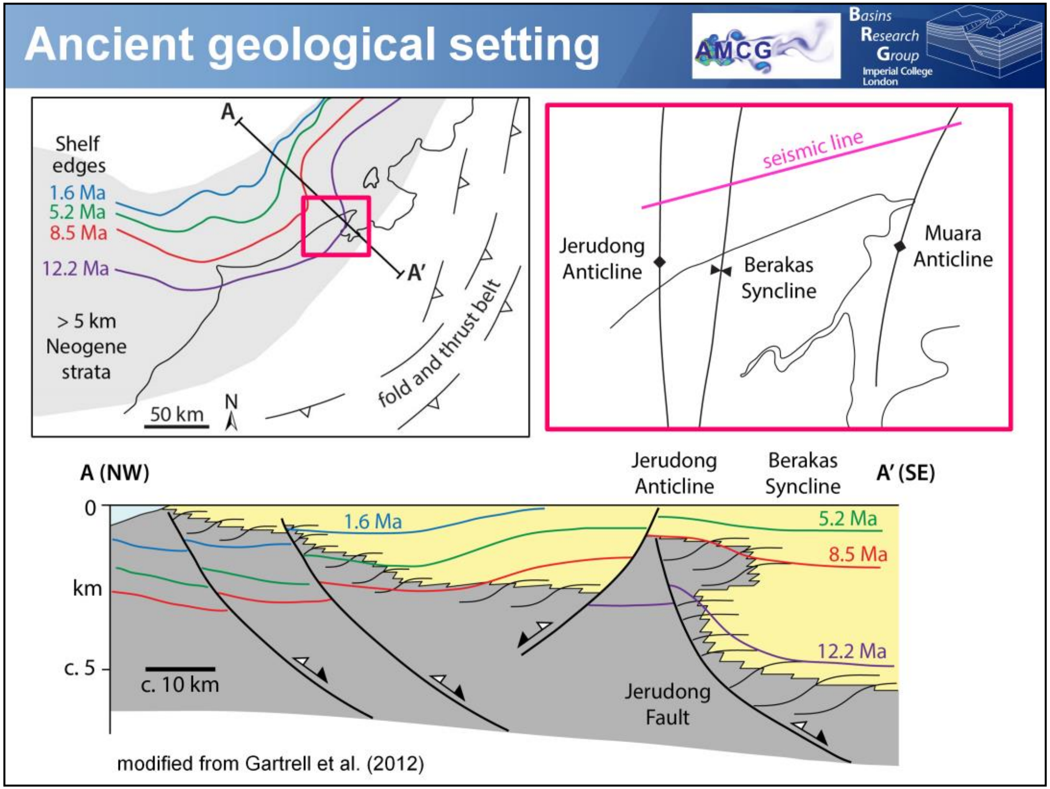
In general, this system has high fluvial power, high wave and storm power – given its position on the open SCS coastline – and low tide power because the SCS is microtidal. Furthermoore, large tropical storms tend to simulatenously eddfect the coastal and hinterland regions, causing coupling of high fluvial discharge and stormy shelf conditions; we refer to these events as storm-floods.

The modern Baram Delta Province is situated along an active tectonic margin in the tectonically complex SE Asia region. There is active compression along NW Borneo due to overall northward movement into the stable core of Indochina.

This has resulted in uplift of a high and steep hinterland, fronted by a narrow coastal plain and narrow shelf, which combined with high rates of tropical weathering, results in very high and efficient sediment transfer from source to sink through multiple, independent drainage basins.

In general, the BDP is characterised by high fluvial power, high wave power – given its position on the open South China Sea coastline subject to monsoons – and low tidal power because the South China Sea is microtidal.

- Active tectonic margin – compression due to overall northward movement into Indochina
- High, steep, actively uplifting hinterland
- Narrow coastal plain with multiple independent drainage
- Narrow shelf width
- = high sediment supply, high fluvial power
- Low tidal power because the SCS is microtidal
- But high wave power along the open monsoon-influenced coastline



Presenter's notes: This is a re-appraisal of the ancient geological setting. This map shows the present coastline relative to the position of seismically-mapped palaeo-shelf edges, > 5 km thick Neogene sediment accumulation and a NW-SE cross section in the eastern study region.

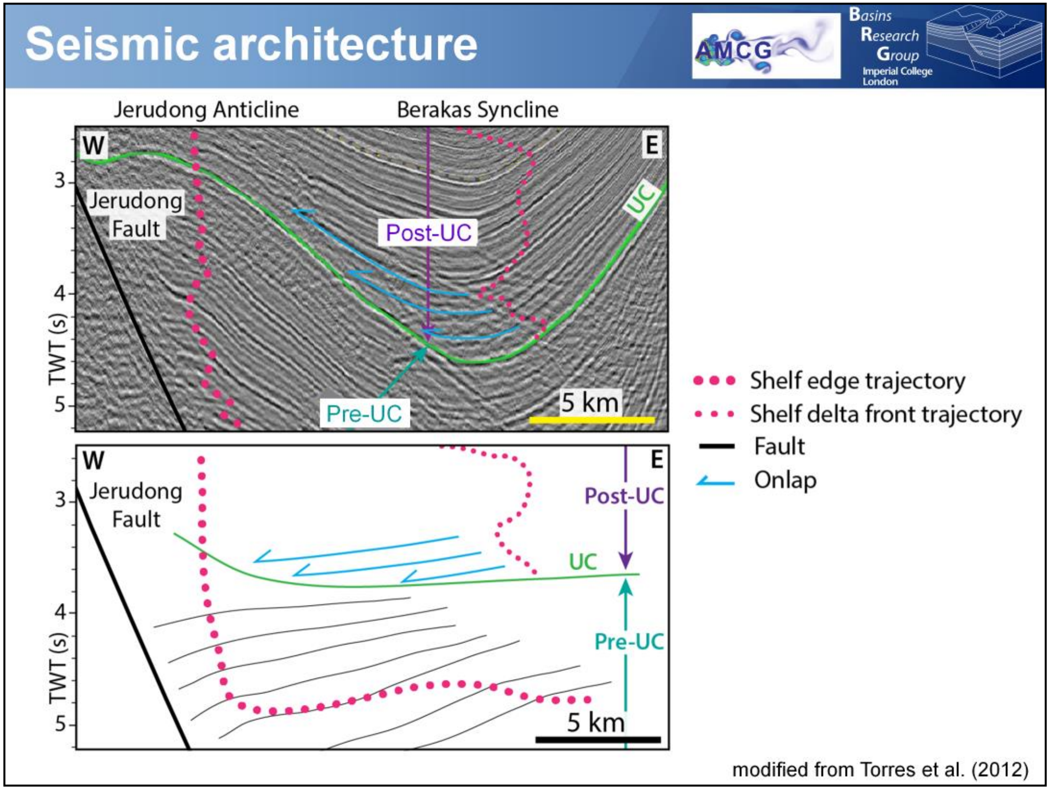
There has been exceptionally high sediment accumulation in a broadly NW prograding deltaic system.

A range of architectural styles has been controlled by high sediment supply and high accommodation, which is related to active movements – both extension and inversion – across basemenet linked and gravity driven growth faults.

In the eastern study area, shown here in the pink box, the main structural elements are the basement-linked Jerudong Fault, which has undergone inversion to form the Jerudong Anticline. The Berakas Syncline sub-basin is bound by the Jerudong Anticline and the Muara inversion anticline.

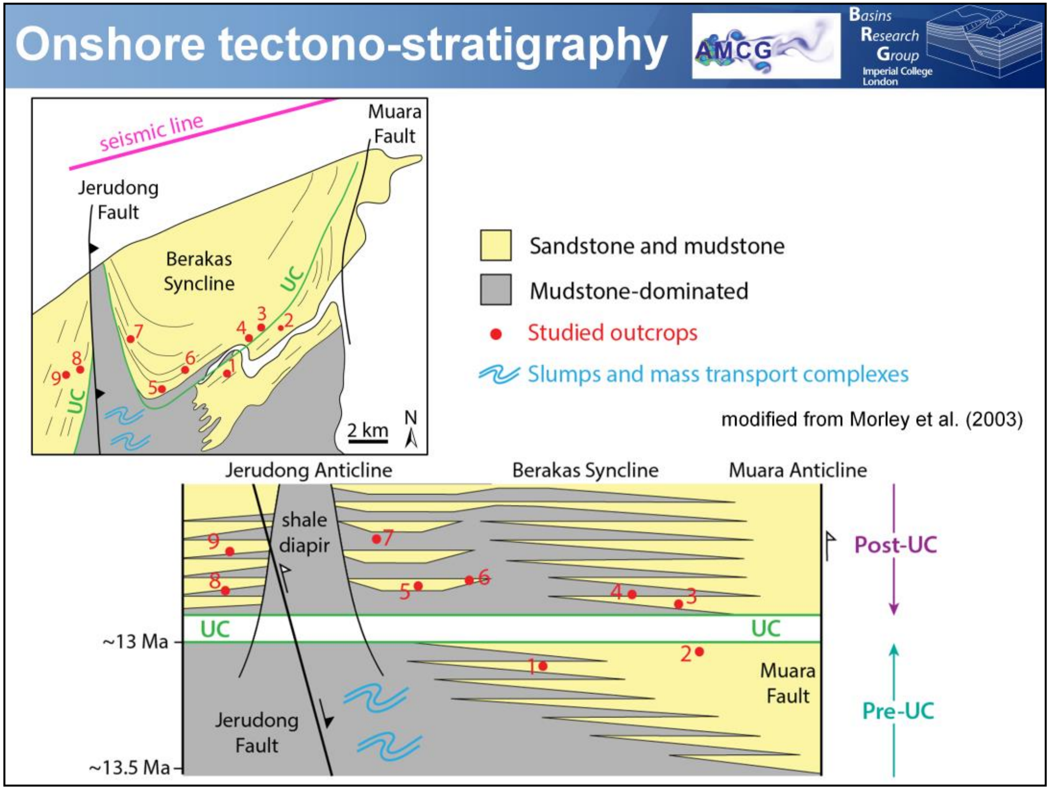
The next slide shows a simplified 2D seismic line approximately 10 km offshore and running roughly E-W across these tectonic elements.

- Palaeo-shelf edges, area of > 5 km Neogene strata and, below, a NW-SE cross-section through the eastern part of the province
- Exceptionally high rates of sediment accumulation in NW prograding delta
- Range of architectural styles: high S and high A – active movements along: Basement-linked faults and gravity-driven deltaic growth faults
- Focused study area, eastern BDP: Berakas syncline sub-basin bounding by the fault-related Jerudong Anticline in the west and Muara anticline in the east… Seismic line across these tectonic elements
  - This is that same map area but now showing the palaeo-shelf edge positions and area of > 5 km Neogene strata. And a NW-SE cross section through the eastern area.
  - Since c. 15 Ma, there has been exceptionally thick sediment accumulation along the broadly NW prograding deltaic margin
  - There are a range of architectural styles reflecting the interplay of high sediment supply from an active fold-thrust-belt and high accommodation due to movements along basement-linked faults, for instance the Jerudong Fault in the eastern BDP, and gravity-driven deltaic growth faults.
  - The focused study area is in the eastern BDP and this is a simplified tectonic element map. The Berakas Syncline formed a major sub-basin flanked by the Jerudong Anticline and Muara Anticline, each of which are related to basin-bounding faults.
  - The seismic line (next slide) spans approx. E-W across these tectonic elements.



Presenter's notes:

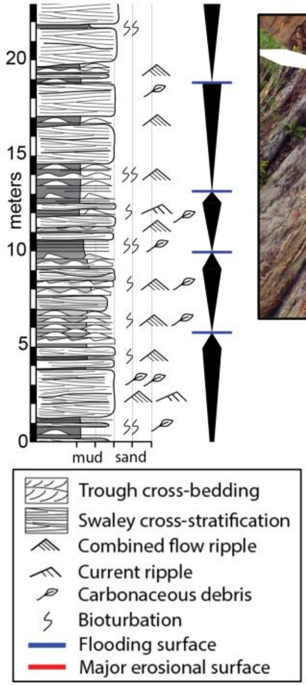
- This is a time migrated seismic section between 3–5 TWT with a c. 4 x vertical exxageration. At these depths 1 TWT is equivalent to between 1–1.5 km thickness. The seismic scale stratigraphicv architecture is exquisitely imaged. There is a chronostratigraphically and biostratigraphically defined unconformity (shown in green), calibrated to core and well data, and mappable across the Jerudong Anticline and Berakas Syncline. This is one of several important regional unconformities.
- We undertook shelf edge and shelf delta front trajectory analysis. And the figure below shows a schematic and flattened diagram of the key observations and interpretations.
- Below UC = strongly aggradational shelf margin accretion controlled by expansion of Jerudong Fault
- Across the unconformity, locus of sedimentation shifts 15-20 km eastwards, which is palaeo-landwards. The bottom sets of the initially progradational shelf deltas appear to onlap the Jerudong Anticline, followed by retorgradational to aggradational shelf delta accumulation
- We interpret the unconformity to reflect the onset of inversion along the Jerudong Fault, formation of the Jerudong Anticline, associated subsidence and formation of accommodation space in the Berakas Syncline, and resulting shoreline transgression.
- *Across this unconformity, we recognise a translation from strongly aggradational accretion of a shelf edge margin close to Jerudong Fault below the UC … to progradational, retrogradatonal and aggradational shelf deltas approximately 15-20 km eastwards, which is palaeo-landwards.*
- *Seismic-scale stratigraphic architecture exquisitely imaged and is shown to illustrate two sequences separated by a regional unconformity, one of several regional unconformities throughout the Neogene*
- *We have undertaken shelf-edge and shelf-delta trajectory analysis*
- *And this figure is a schematic interpretation of the seismic stratigraphy*
- *Pre-UC sequence has a strongly aggradational shelf-edge trajectory controlled by expansion along the Jerudong Fault*
- *Across the unconformity, the locus sedimentation shifts eastwards (palaeolandwards) by c. 15 km*
- *This reflects accommodation creation and formation of the Berakas Syncline sub-basin due to inversion along the Jerudong Fault and formation of the Jerudong Anticline.*
- *The post-UC sequence comprises progradational to aggradational accumulation in shelf deltas on the pre-existing shelf.*

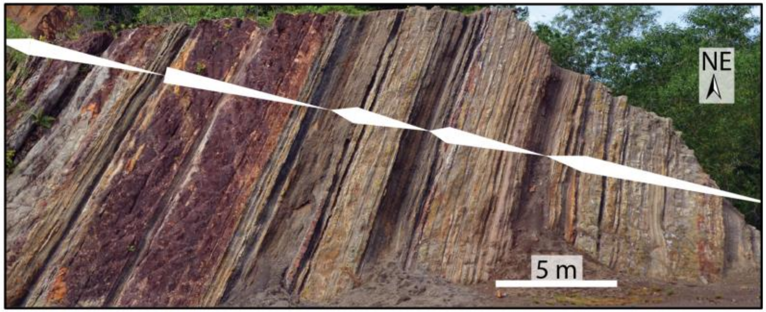


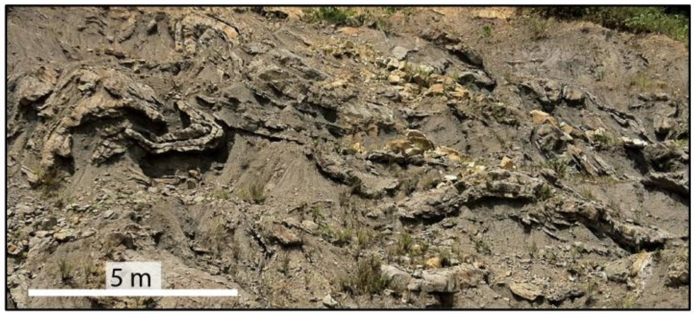
Presenter's notes:

- Through detailed outcrop mapping of the onshore Berakas Syncline we have been able to calibrate the position of seismically-mapped unconformity onshore. It is recognised by unconformable relationships in bedding strike and onlap of bedding above the correlated unconformity.
- Studied outcrop successions span across the unconformity
- Outcrop mapping of sandstone units relationships, shown simplified in the map above, and observations of the stratigraphic architecture across all studied outcrops, are shown in this schematic wheeler diagram E-W across the Berakas Syncline
- Below UC: we recognise prograding to aggrading shelf successions. Outcrops in relatively distal areas show extensive evidence of slumping and mass transport in an outer shelf to slope position adjacent to the Jerudong Fault
- Above the unconformity, facies are more laterally variable; sandstone geobodies can be correlated laterally on a 2-5 km scale but comprise variable facies, including both wave, tide and fluvial dominated sandstone geobodies with varying interpretable lateral extent. We also observe increase sandstone supply to adjacent sub-basins.
- In the next series of slides I'll show the contrasting facies and stratigraphic architectures observed in outcrops below and above the unconformity.

Pre-UC facies analysis

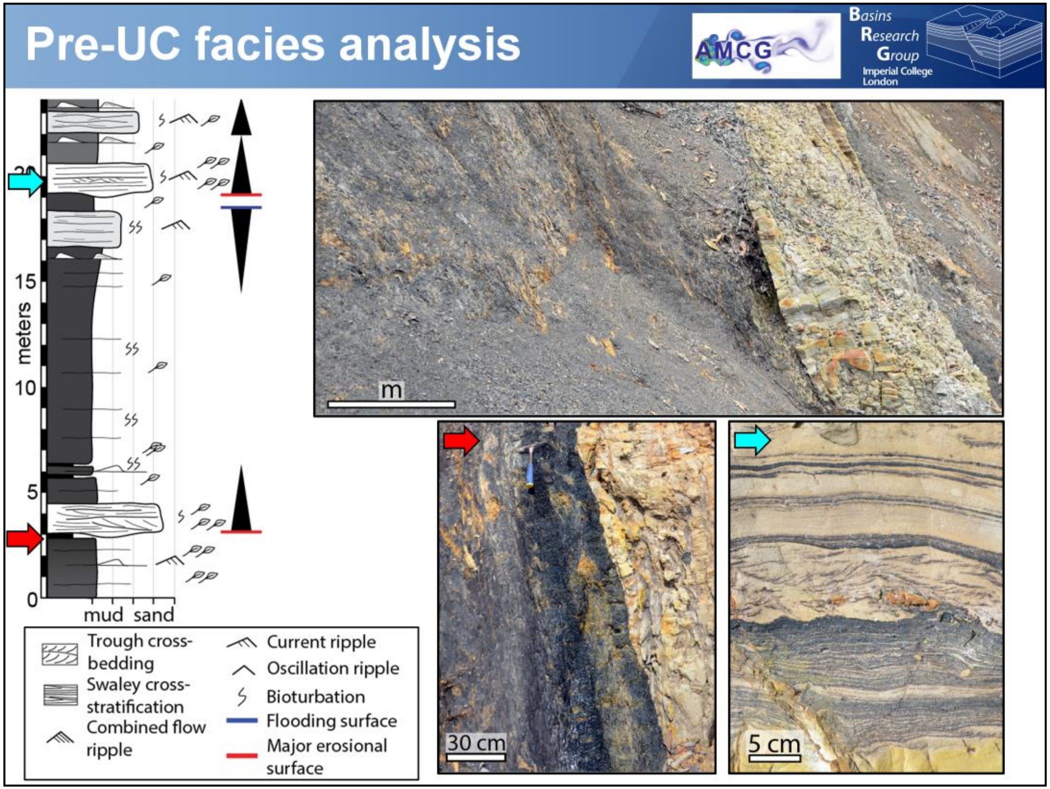






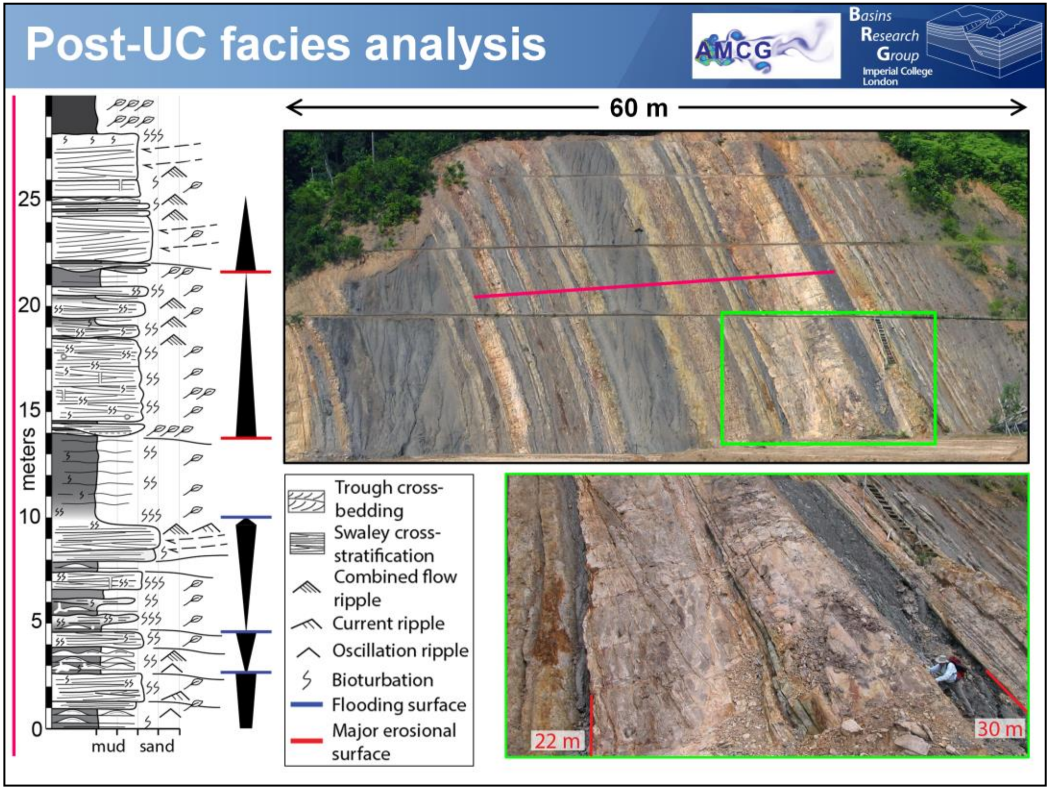
Presenter's notes:

- Representative facies architecture of pre-UC delta front successions
- 5-10 m thick upward sanding successions
- Dominated by wavy-bedded, very fine grained, sandy heterolithics displaying combined flow ripples and interstratified very fine grained, swaley cross-stratified sandstones
- Upper part of successions comprise amalgamated, metre-scale, swaley cross stratified very fine sandstone units
- Bioturbation is generally relatively low intensity and diversity but sporadically intense, which is consistent with generally high but fluctuating sedimentation in a moderately stressed environment
- Moderate to high carbonaceous debris throughout all facies and the …
- Overall character suggests wave-dominated, fluvial influenced deltaic deposition
- Equivalent sandstone facies in approximately contemporaneous, relatively distal successions are slumped on a m-decametre-scale, suggesting unstable slope position under high sediment supply and/or tectonic deformation in an outer shelf-slope position



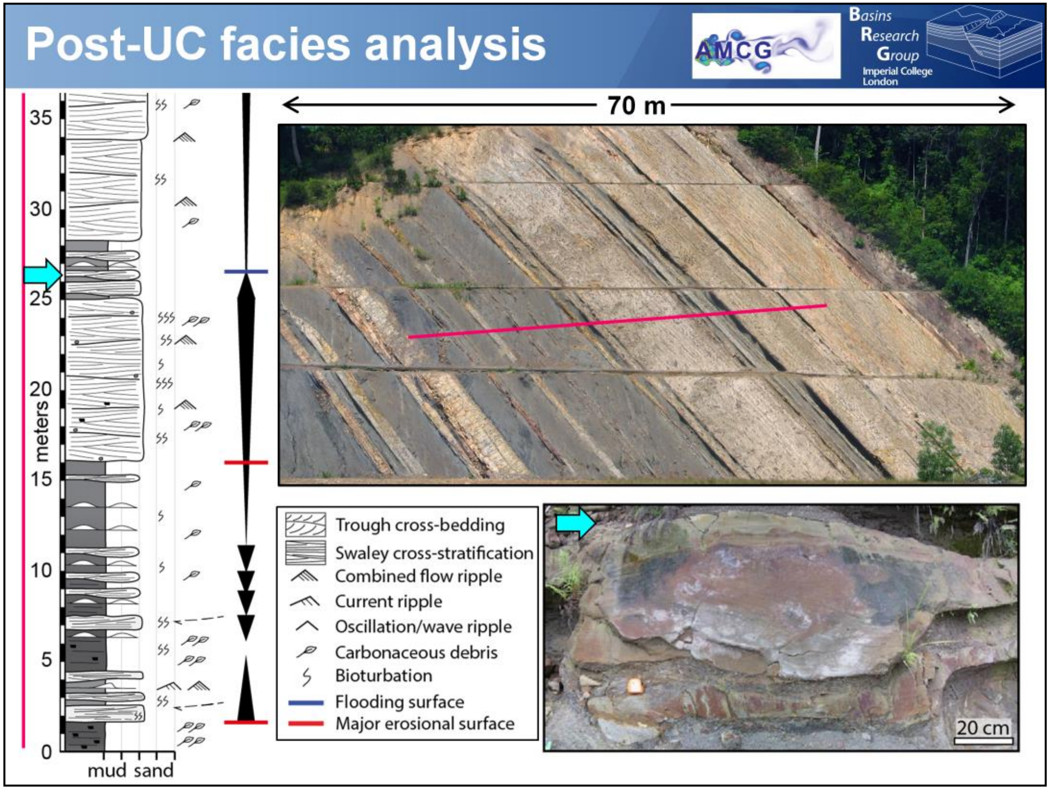
Presenter's notes:

- Relatively proximal parts of pre-UC successions display much more variable facies architectures
- Successions are dominated by thick, dark-coloured, carbonaceous rich and typically apparently structureless mudstone units and these include occasional coal horizons
    - Equivalent facies contain abundant mangrove pollen, roots and leaves and suggest deposition in a subtidal to intertidal, mangrove influenced, tide-dominated and wave-protected environment
- These mudstone units occur stratified with sharp erosional-based and channelised sandstone units with abundant mudstone drapes, mudstone and coal intraclasts and carbonaceous debris, including drapes on current ripples
    - These suggest more current dominated deposition, fluvio-tidal channels
- Mangroves are strong evidence for tide-influenced to dominated lower coastal plain proximal or lateral to the more wave-dominated delta fronts



Presenter's notes: Post-UC facies architecture within the central Berakas Syncline:

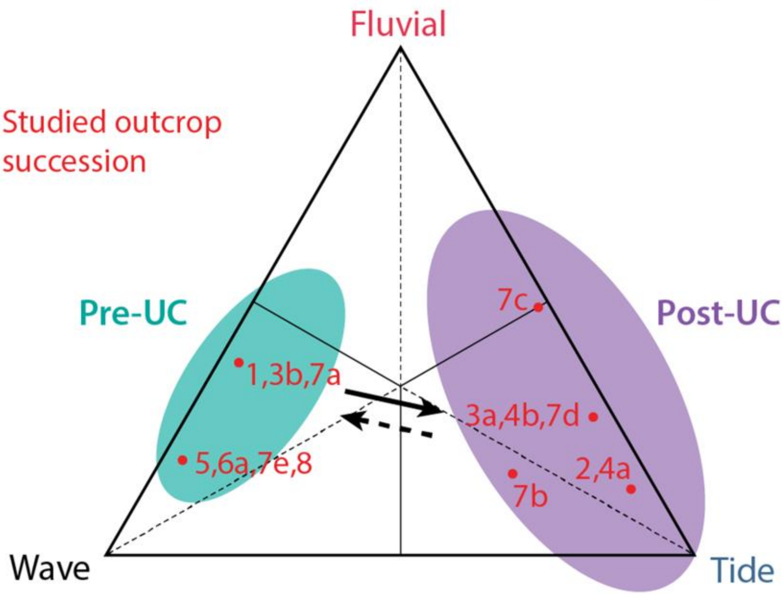
- More mud-dominated, mudstone units comprising similarly carbonaceous-rich, mangrove-influenced mudstone
- Sharp-based sandstone units predominate over thinner and more muddier upward sanding successions, and commonly form multi-storey units with internal accretion surfaces consistent with bar accretion within channels. Minor bioturbation, mud drapes and bidirectional cross-bedding suggest that these bodies represent tide-influenced fluvial channels
- Equivalent facies successions also contain heterolithic fluvial-tidal bars/deltas and far less preserved evidence for storm or wave reworking
- Abundance of thick mangrove mudstone units, associated with channels and mixed-process delta geobodies, is consistent with more restricted, tide-dominated deposition in a relatively embayed setting



Presenter’s notes:

- Vertically and laterally adjacent outcrops do contain evidence of more storm-reworked, wave-dominated deltaic deposition
- Thick upwards coarsening parasequence dominated by swaley cross stratification and contain abundant gutter casts directly overlie mangrove and restricted embayment mudstones with fluvio-tidal channels
- Evidence for progradation of wave-dominated deltas into a relatively restricted and tidal embayment

Process interpretation

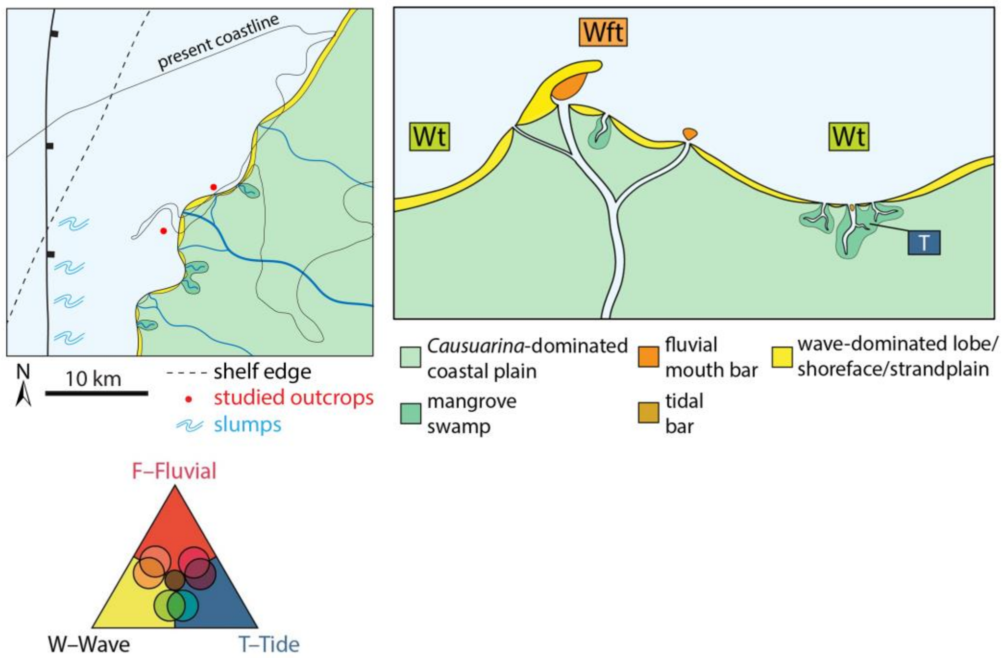


Ainsworth et al. (2011)

Presenter’s notes:

- This diagram shows the approximate process interpretation ranges for the pre- and post-UC depositional systems, and each depositional element comprising the studied successions.
- Pre-UC contains evidence for wave-domianted, fluvial-influenced deltas and tide-influenced coastal plain
- Post-UC contains evidence of more tide-dominated, wave-protected deposition and fluvio-tidal deltas and channels But also contains wave-dominated deltas
- These suggest a dramatic change in coastal morphology and process preservation across the unconf

Pre-UC depositional model

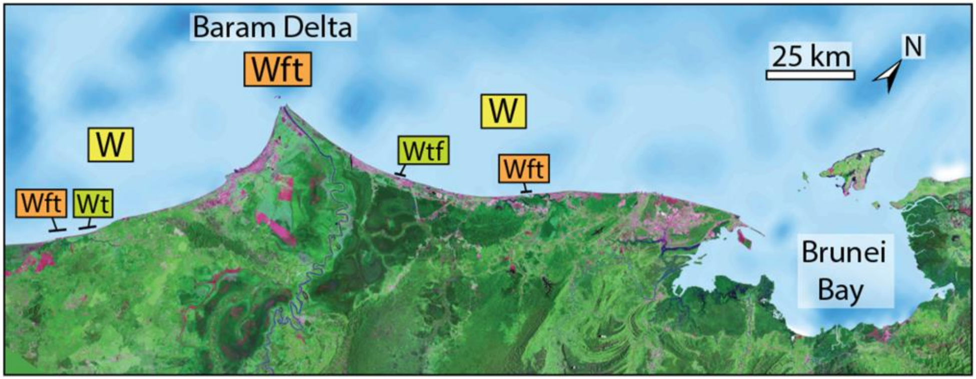


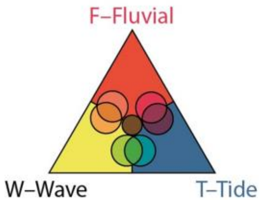
Presenter's notes: Pre-UC:

The eastern BDP comprised a multi-sourced, mixed-energy, open deltaic shoreline. High accommodation was controlled by extension along the Jerudong Fault. Sediment was supplied through multiple fluvial systems similar to the modern BDP.

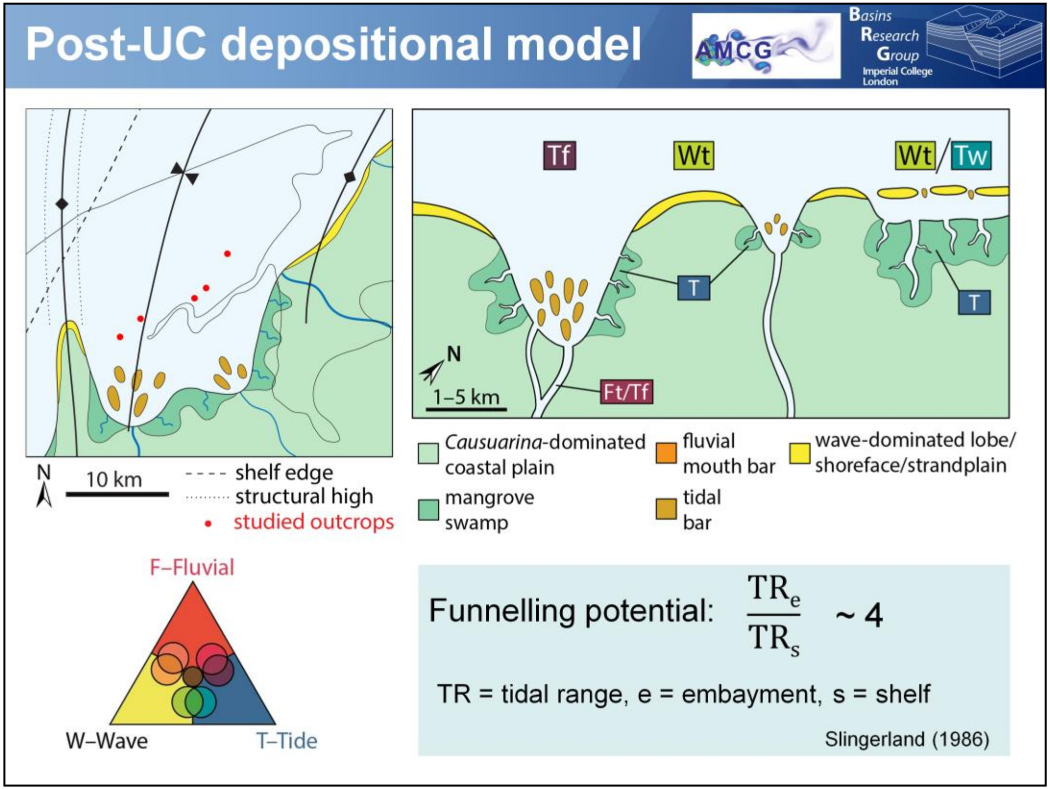
Lobate mixed wave-fluvial deltas formed. Gradually over time, channel switching across the narrow coastal plain results in lateral amalgamation of deltaic sandstones and formation of linear sandstone belts. However, lateral and vertical connectivity is disrupted by preservation of lower coastal plain deposits and by deposition muddier, more tide-influenced successions in relatively embayed areas between deltas and in tide-reworked, abandoned distributaries

Pre-UC depositional model



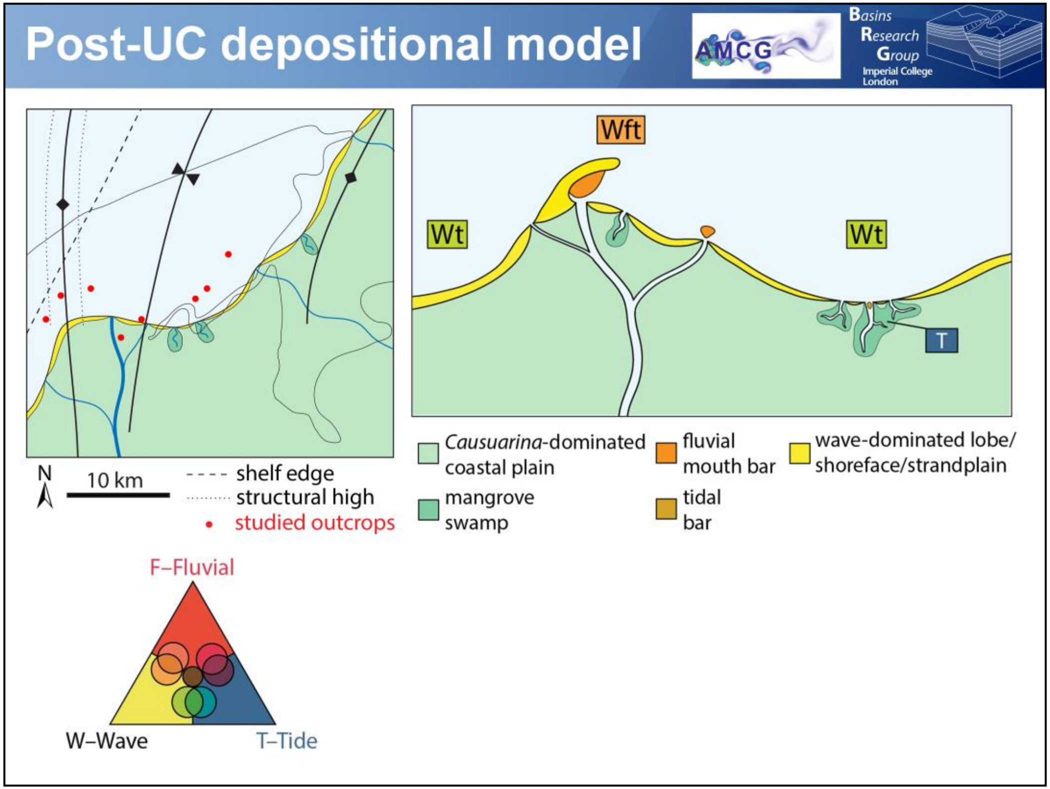


Presenter's notes: A very good analogue is the modern Baram Delta Province
Baram Delta is a wave-dominated, fluvial and tide-influenced delta
Overall the coastline is wave-dominated but smaller depositional elements are mixed process, abandoned rivers are converted to tidal channels and lagoons with associated mangrove mudstones, which form good potential intra-successional source rocks



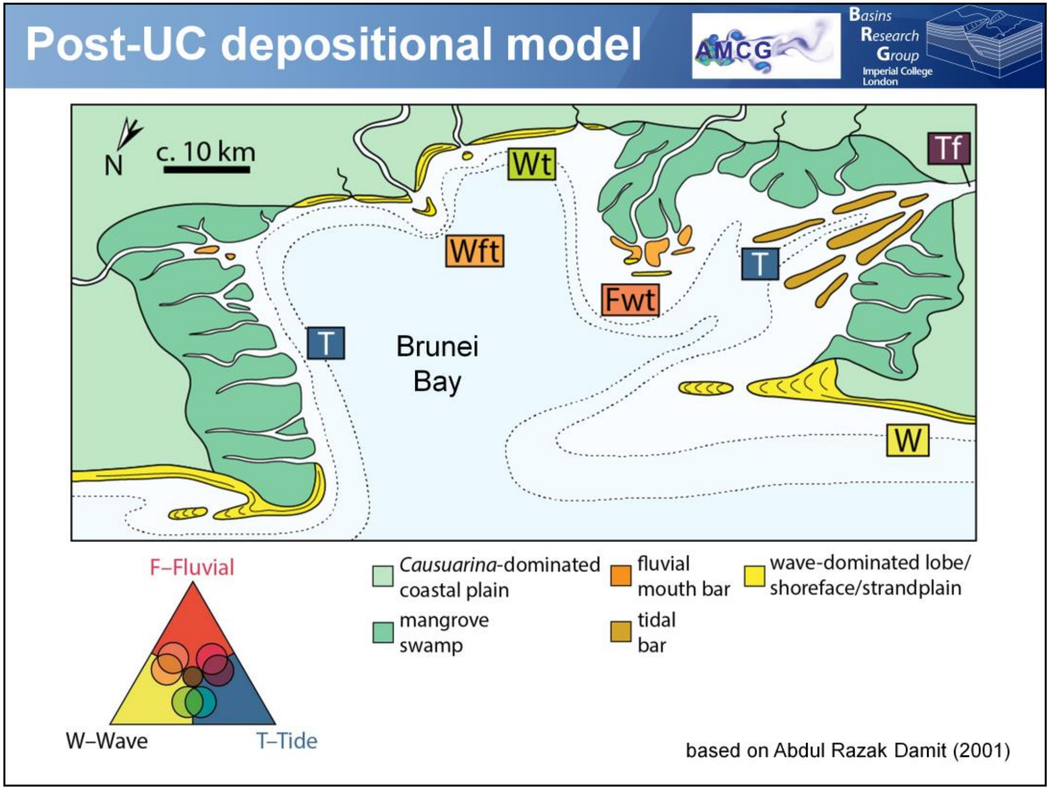
Presenter's notes: Post-UC:

- Tectonic configuration, hydrological system and coastal morphology in the eastern BDP changed dramatically
- Compression caused inversion along the Jerudong Fault, forming the Jerudong Anticline and associated structural high. The same occurred along the Muara Fault in the east.
- Associated subsidence in the Berakas Syncline may have been accentuated by shale withdrawal into the flanking anticlines, resulting in formation of a structurally-defined embayment and shoreline transgression, dampening of waves and funnelling of tides….
- *Shoreline transgression = embayment … funnelled tide, damped waves*
- The funnelling potential of this basin is relatively high, and tidal range within the embayment may have been up to 4x the TR along the adjacent open coastline
- = a more restricted complex fluvio-tide dominated depositional settings formed; high range of more laterally-restricted sandstone bodies, more vertical variability with subsidence. Observed depositional elements include tidal bars, fluvial-tidal chennels, mangrove-influenced lower coatal plain to embayment facies, and tidal channels



Presenter's notes:

- Wave-dominated delta successions in the post-UC sequence suggest progradation of the deltas into the embayment which ultimately re-established a more linear shoreline conducive to more wave-dominated or storm-reworked deposition similar to pre-UC sequence
- *However, the intermediate case, of prograding mixed-process deltas into embayment would also result in laterally disconnected sandy delta lobes surrouded by embayment mudstones*



Presenter’s notes: The modern Brunei Bay forms a very good analogue to the post-UC depositional model
Brunei Bay is a tectonic embayment laterally adjacent to the open-coastline of the wider Baram Delta Province
Several laterally adjacent depositional elements:

- tide-dominated deltas or estuaries
- Fluvial dominated mixed-process deltas
- wave and tide influenced shorefaces
- wave-dominated mixed-process deltas along the relatively open embayment coastline
- tide- and mangrove-dominated lower coastal plain

The embayment is undergoing high rates of subsidence and this complex mosaic of depositional elements and facies will be preserved. This complexity will only increase through autogenic and further allogenic changes in the position of these depositional elements.
Embayment depositional systems are much more complex sedimentologically and stratigraphically compared to the more linear, altogether sandier, storm-reworked open coastline.

Conclusions

- Syn-depositional extension and compression in the Baram Delta Province exerted a strong control on coastal morphology and depositional processes

- Pre-inversion: mixed-energy, multi-sourced, deltaic coastline coincided with basin extension (basement-linked and deltaic growth faulting) and unstable delta front slopes

- Post-inversion: compression created a more tectonically-compartmentalised basin and a restricted, mud-rich, laterally-variable depositional setting

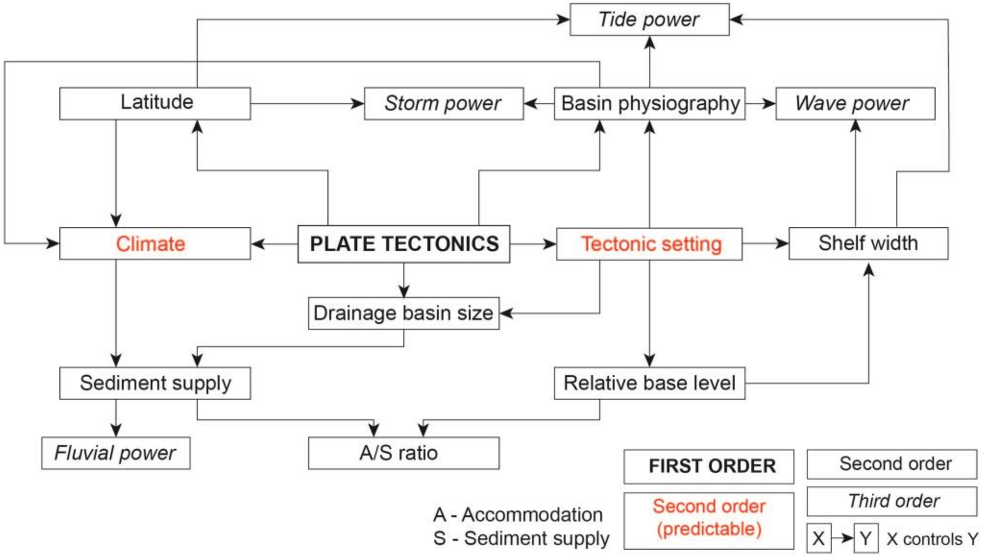
- Elements of the modern depositional system (e.g. monsoonal storm regime, nearshore sand supply & coastal morphology) can be calibrated with the Miocene facies successions

Presenter's notes: In conclusion…

Ancient process prediction

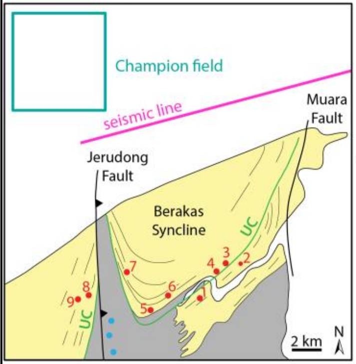
Challenge 2: **Geological setting**

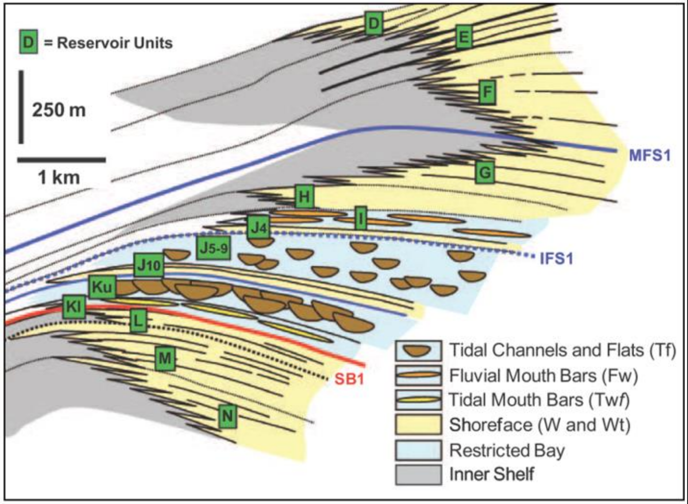
Understanding the controls on tides, waves, rivers and storms



after Nyberg & Howell (2016)

Subsurface implications





from Ainsworth et al. (2011)

Ancient process analysis (1)

Challenge 1: **Process prediction—Facies analysis**

Q. What is the relative proportion of tide, wave and fluvial facies indicators?