Mixed-Energy, Coupled Storm-Flood Depositional Model: Application to Miocene Successions in the Baram Delta Province, NW Borneo*

Daniel S. Collins[1], Howard D. Johnson[1], and Peter A. Allison[1]

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Abstract

Lateral (10–100 km) variations in process dominance in mixed-energy coastal-deltaic systems need not reflect significant allogenic changes in regional or local basin physiography. However, in tectonically active mixed-energy settings, deciphering between the multitude of both autogenic and allogenic-forced process variations is very challenging. We integrate paleogeographic interpretation, paleotidal modeling and stratigraphic facies analysis in order to deconvolve allogenic vs. autogenic controls on two contrasting late-mid Miocene outcrop successions in the Baram Delta Province (BDP): (1) the Lambir Formation (western BDP), and (2) the Belait Formation (eastern BDP). The Lambir Formation records deposition during rapid early coastal-deltaic progradation and comprises fluvio-tidal sandstones that are sharp-to-erosionally juxtaposed on wave-dominated (storm-reworked) prodelta to delta front successions. In tidal channel bodies (4–15 m thick), abrupt vertical changes from sandier facies, through heterolithic facies, to bioturbated mudstones reflect rapid autogenic changes in local sediment supply, with varying degrees of fluvial and marine energy during abandonment. Proximal parasequence sets also contain 4–17 m scale, erosive-based fluvial channel bodies and wave-tide influenced muddy sandbar deposits. Regional paleotidal modeling indicates that local autogenic deltaic processes controlled wave vs. tidal effectiveness. The Belait Formation was deposited under significant tectonic influence within a narrow (5–20 km), fault-bounded embayment (Berakas Syncline). This sub-basin configuration and its high rate of accommodation creation formed an effective sediment trap, with high aggradation and a steeply rising shelf trajectory. Abundant upward coarsening successions are interpreted as prograding storm- and river flood-influenced delta front deposits. Storm reworking of tidal bars and intercalated tidal sand bodies further indicate mixed-energy processes. However, larger-scale (10–100 m) partitioning of stratigraphic architecture into relatively tide- and wave-dominated

successions suggests temporal changes in process dominance. Paleotidal modeling confirms allogenic-forced changes to an embayed coastline resulted in tidal amplification. We illustrate how numerical modeling of paleo-oceanic processes places important constraints on understanding autogenic vs. allogenic control on sedimentological and stratigraphic architecture in coastal-deltaic successions.

References Cited

Gartrell, A., J. Torres, N.M. Hoggmascall, 2012, A Regional Approach to Understanding Basin Evolution and Play Systematics in Brunei - Unearthing New Opportunities in a Mature Basin: SPE 15171-MS, 5 p. Web accessed 14 November 2012. http://www.onepetro.org/mslib/servlet/onepetropreview?id=IPTC-15171-MS.

Guilpain, P., H.D. Johnson, and A.R. Damit, 2007, Reservoir Characterization of Low Permeability Lower Shoreface Facies in the Baram Delta Province, Brunei Darussalam: AAPG Annual Convention and Exhibition, Long Beach, CA, April 1-4, 2007. http://www.searchanddiscovery.com/abstracts/html/2007/annual/abstracts/lbGuilpain.htm.

Sandal, S.T., 1996, The Geology and Hydrocarbon Resources of Negara Brunei Darussalam: Brunei Shell Petroleum Company/Brunei Museum, Syabas Bandar Seri Begawan, Brunei Darussalam, 243 pp.

Swift, D.J.P., and J.A. Thorne, 1991, Sedimentation on continental margins, I: a general model for shelf sedimentation: in Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies, International Association of Sedimentologists Special Publication, No. 14, p. 3-31.

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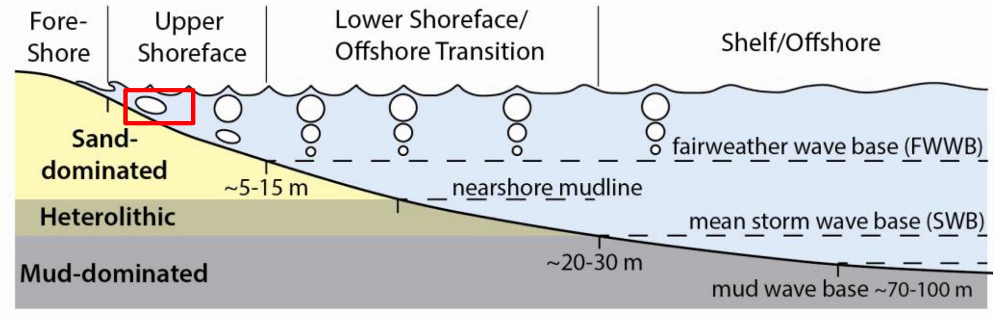
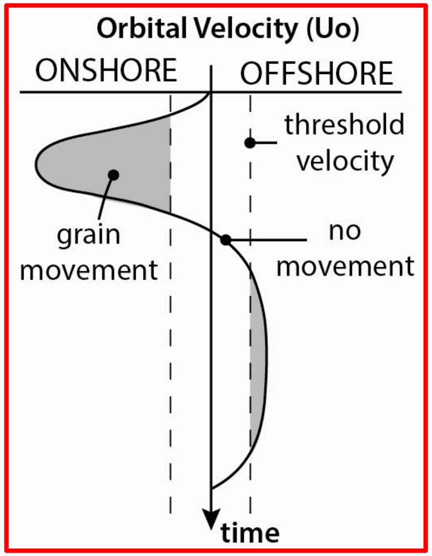
Presenter's notes: I'll be discussing today a new coupled storm-flood depositional model for the Miocene-modern NW Borneo coastal system.

Rationale



1. Standard shallow-marine facies model is a simple two-dimensional coarsening- and shallowing-upward, wave-dominated succession
   - However, extensive variability reflects differences in texture, process regime & preservational mode
2. Seaward sand transport requires flows to overcome the 'littoral energy fence':
   - This exerts a fundamental control on stratigraphic architecture, reservoir volume and connectivity



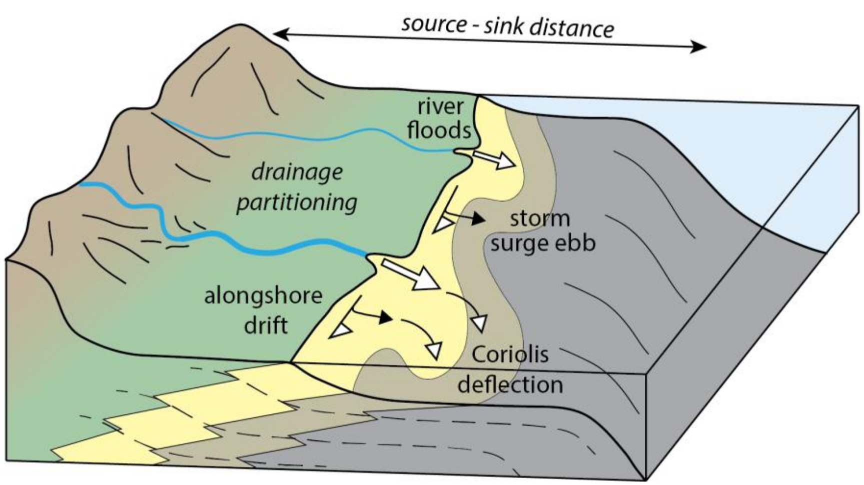
Presenter's notes: Standard, very widely used shallow marine facies model equals two-dimensional, upward coarsening, upward shallowing facies succession for a wave-dominated coastline. (Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

However, extensive variability both vertically and laterally within upward shallowing successions reflect changes in grain texture, process regime and preservational mode during relative sea level cycles. A dominant control on this stratigraphic architecture and resulting reservoir volume and connectivity is the seaward transport of sand, which requires flows to overcome the net landward velocity and bed shear stress induced by shoaling and breaking fairweather and storm waves, the so called ‘littoral energy fence’.

Heterolithic, thin-bedded shelfal reservoirs are volumetrically important zones of bypassed pay in many conventional reservoirs But the source and mechanism of sand delivery of sand offshore

River mouth bypassing



modified after
Swift & Thorne (1991)

- Tectonically-active margin with short (100-300 km) source-sink distance
- Humid, tropical, monsoonal climate
- Supply-dominated shelf
- Predominance of river mouth bypassing

Presenter's notes: For the setting under investigation, the key factors governing the dynamics of this critical seaward transport of sand are:

a tectonically active margin, with active hinterland uplift near the shoreline
- resulting in a short source-sink distance on the order of 100-300 km

(Presenter's notes continued on next slide)

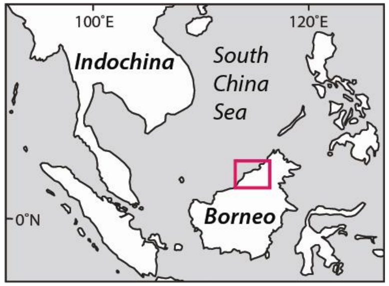
(Presenter's notes continued from previous slide)

- A humid, tropical climate under the influence of monsoons
- A supply dominated shelf
- Thus the predominance of river mouth bypassing: storm reworking of fluvially-delivered sand

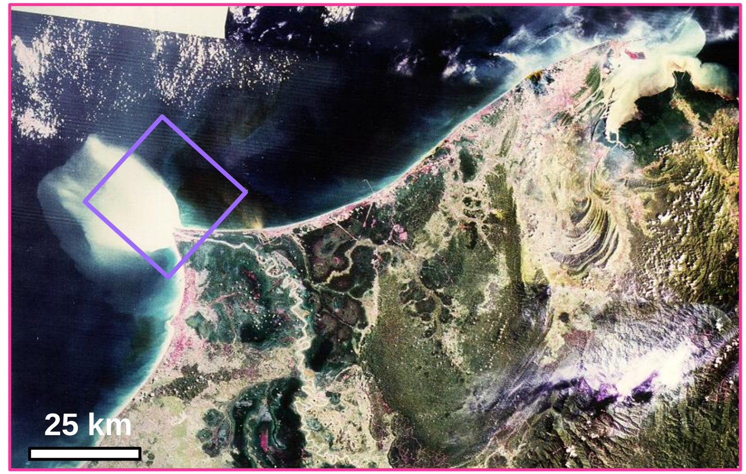
On supply-dominated shelves, sediment may bypass river mouths during floods and be reworked offshore by subsequent storms. However, in tropical systems, storms and river flooding may be closely coupled during 'storm-floods', affecting sand delivery and preservation offshore. Major differences in sediment supply dynamics and preserved stratigraphic architectures exist between active- and passive-margin deltaic systems

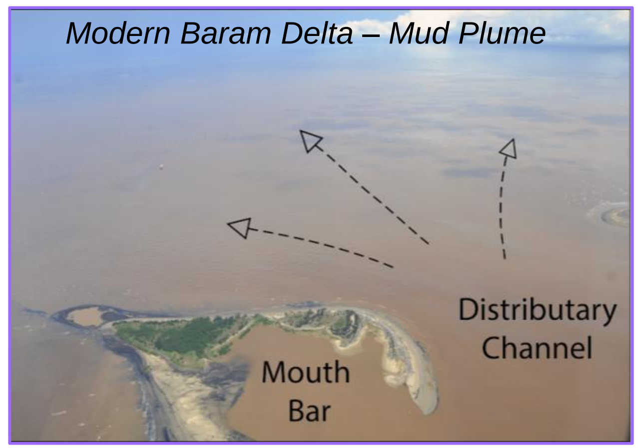
- Mechanism
- We'll be looking at one particularly variant of shallow marine system, upward coarsening succession
- Modern vs. ancient setting

Aim & outline



1. Modern NW Borneo Coastal System
2. Miocene facies successions, eastern Baram Delta Province
3. Coupled storm-flood depositional model
4. Significance & Implications





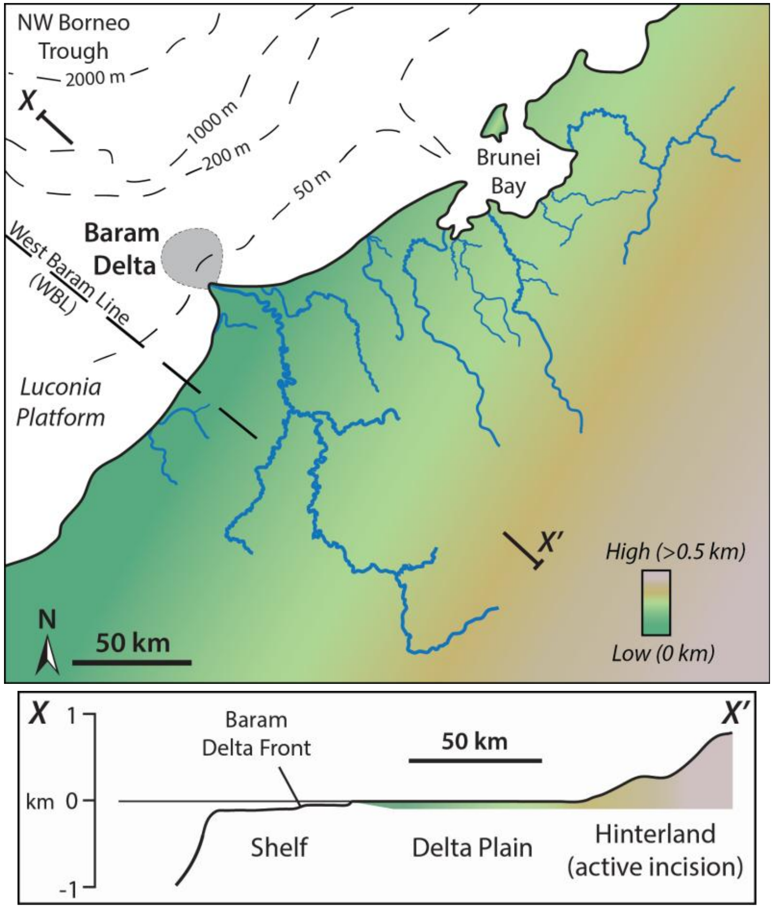
Sandal (1996)

Presenter's notes: The aim of this study is to understand the mechanism and preservation of sand delivered offshore along the Miocene-modern NW Borneo coastal system. This system is situated in SE Asia, near the equator, at the southern margin of the South China Sea. Firstly, we will understand the modern coastal system in more detailed, (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

with active delivery of suspension dominated sediment offshore evidence by the extensive mud plume in front of the modern Baram Delta. We will then observe and interpret the dominant ancient succession preserved in Miocene successions of the Baram Delta Province, deposited as part of this same coastal system. We will integrate the modern and ancient understanding into a couple storm-flood depositional models. Lastly, we will discuss the significance.
A schematic of the NW Borneo coastal system, shaded for topography, is shown here.

Modern NW Borneo



- Steep eroding hinterland (2-4 km elevation)
- Multiple short-headed rivers with separate drainage basins
- Narrow coastal plain (50-100 km)
- Humid tropical climate
  - Intense weathering
  - High precipitation
  - High river discharge

Presenter's notes: The key topographic and hydrological characteristics are:

- A steep, actively uplifting and eroding hinterland, 2-4 km in elevation

(Presenter's notes continued on next slide)

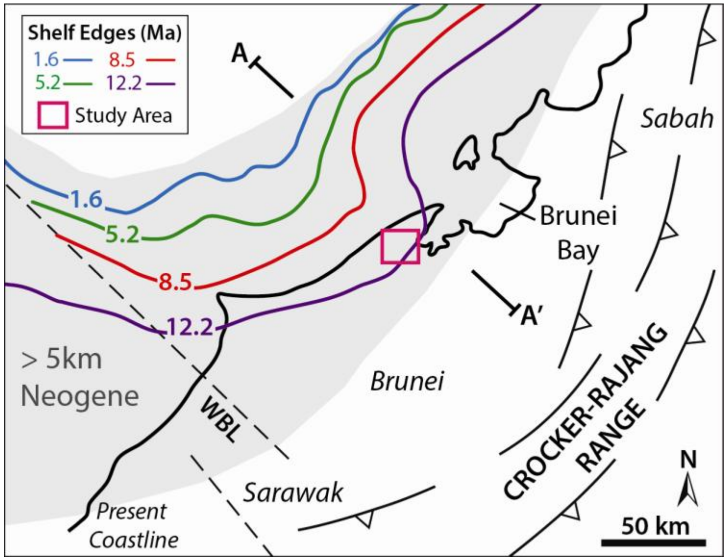
(Presenter’s notes continued from previous slide)

- There are multiple short headed rivers with independent drainage basins all actively delivering sediment to the shoreline
- The coastal-deltaic plain is narrow, less than 100 km
-

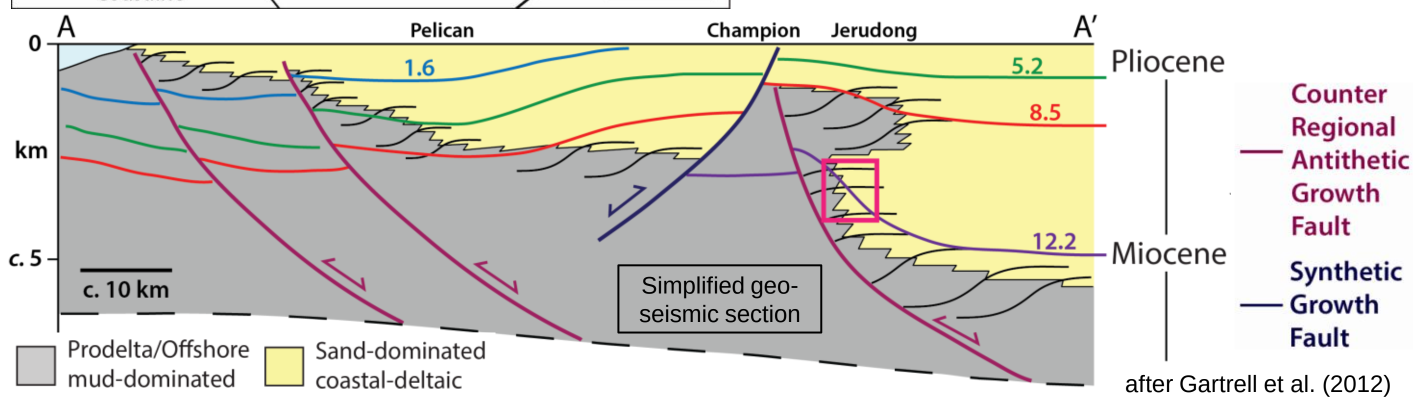
Climatically, the humid tropical climate results in intense weathering, with high rates of precipitation associated with tropical storms and orographic effects of the steep hinterland, which results in high river discharges, especially during storms. This source-sink system has been active from at least the mid-Miocene, for the last 15 Ma:

- High intensity and localised rainfall: individual rivers in flood;
- Exceeds 4000 mm in the hinterland, 2000 mm on average

Regional geologic setting



- This source-sink system has been active throughout the past 15 Ma (mid-Miocene to Recent)
- Stratigraphic consequences:
  - ➢ High sediment supply
  - ➢ High sedimentation rates (up to 6000 m/Myr)
  - ➢ 5-9 km Neogene strata
  - ➢ Progradational to strongly aggradational sequences



after Gartrell et al. (2012)

Presenter’s notes: With active uplift and intense tropical weathering of the hinterland resulting in high sediment supply across a narrow coastal plain to a tectonically active shoreline and shelf. (Presenter’s notes continued on next slide)

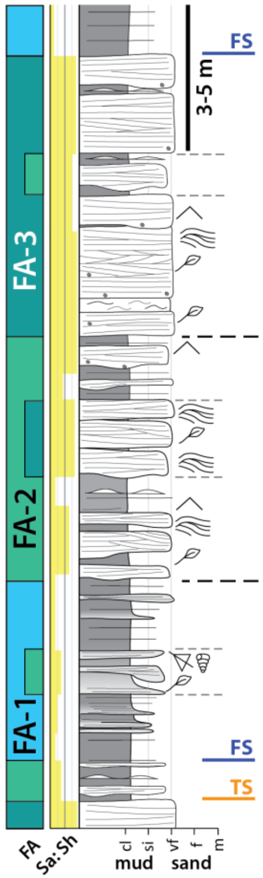
(Presenter's notes continued from previous slide)

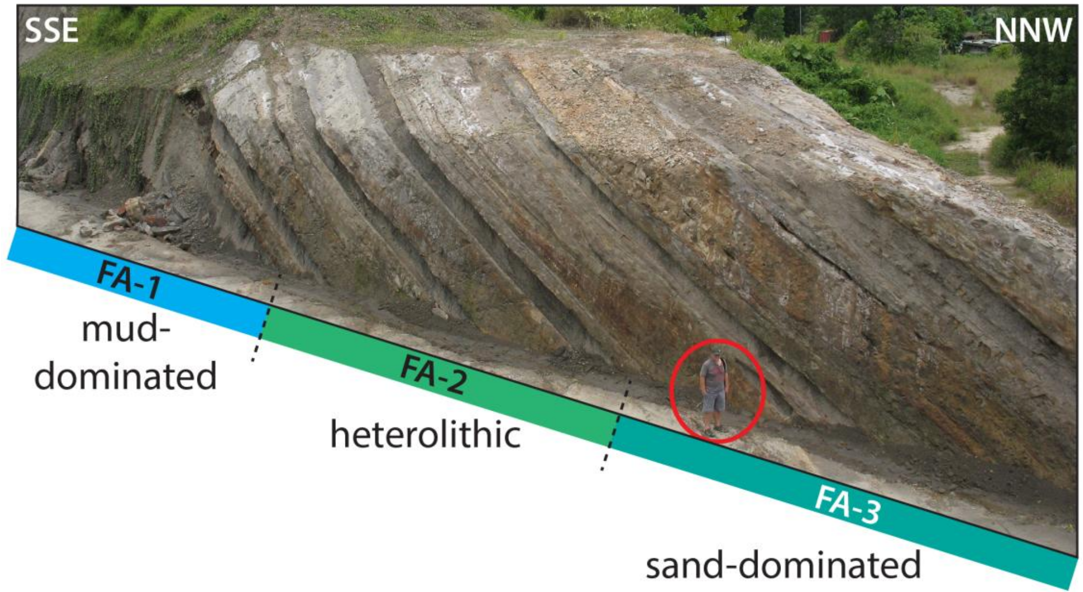
In a simplified geo-seismic cross section through the eastern Baram Delta Province, the stratigraphic consequences of this high sediment supply and tectonically active setting are:

- high sedimentation rates, particularly in high accommodation areas in the hanging walls of antithetic, basement-linked counter regional faults, downthrown to the SE, and synthetic growth faults downthrown to the NW.
- This has resulted in 5 to up to 9 km of sediment deposited in roughly the past 15-20 Ma and…
- progradational to strongly aggradational sequences, with only around 50 km net shelf edge progradation since the late mid Miocene.

The specific outcrop study area is in the eastern BDP, comprising strongly aggradational sequences of the inverted hanging wall of a major growth fault.

Dominant facies succession





- This is the **dominant reservoir-scale facies succession** observed in both **outcrop** and **core** data across the whole **NW Borneo Margin**

Courtesy of J.P. Tromp

Presenter's notes:

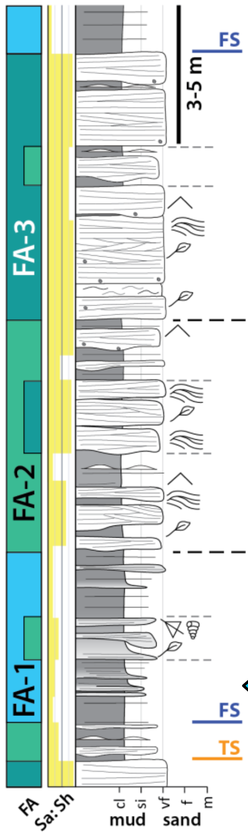
- The dominant outcrop succession observed in the study area is representative of the dominant reservoir-scale facies succession observed in outcrops and core data from across the whole NW Borneo margin.

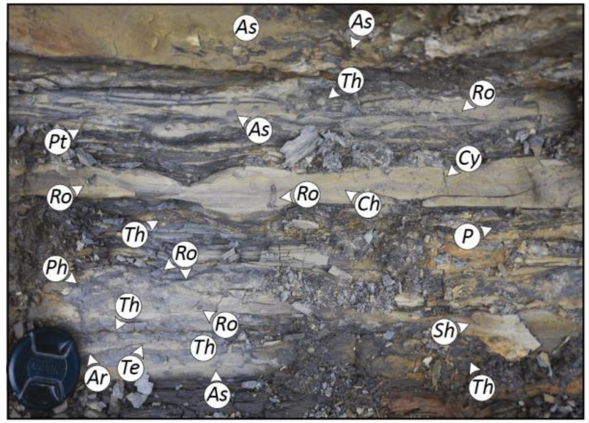
(Presenter's notes continued on next slide)

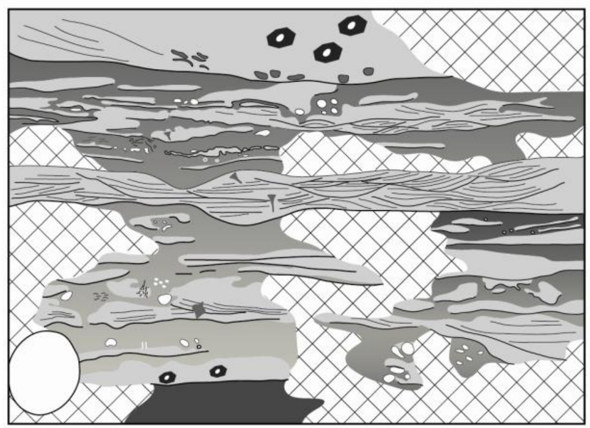
(Presenter’s notes continued from previous slide)

- The upward sanding succession from mud dominated, through heterolithic to sand-dominated facies, correlatable laterally on a 100 m to km-scale.
- The succession shows little upward coarsening of sand, with the sandstone bed fabric being consistent throughout and dominated by swaley cross stratification. Sandstone beds only get thicker and more amalgamated upwards.
- Mudstone intervals occur vertically throughout these typically 10-40 m sequences, along with carbonaceous debris and minor wave ripples.

Mud-dominated FA-1







- BI 1-3, low-moderate diversity, impoverished *Cruziana* ichnofacies
  - Physio-chemical stress
- High, mm-scale preservation, oscillatory-dominated ripples
  - High sedimentation rates

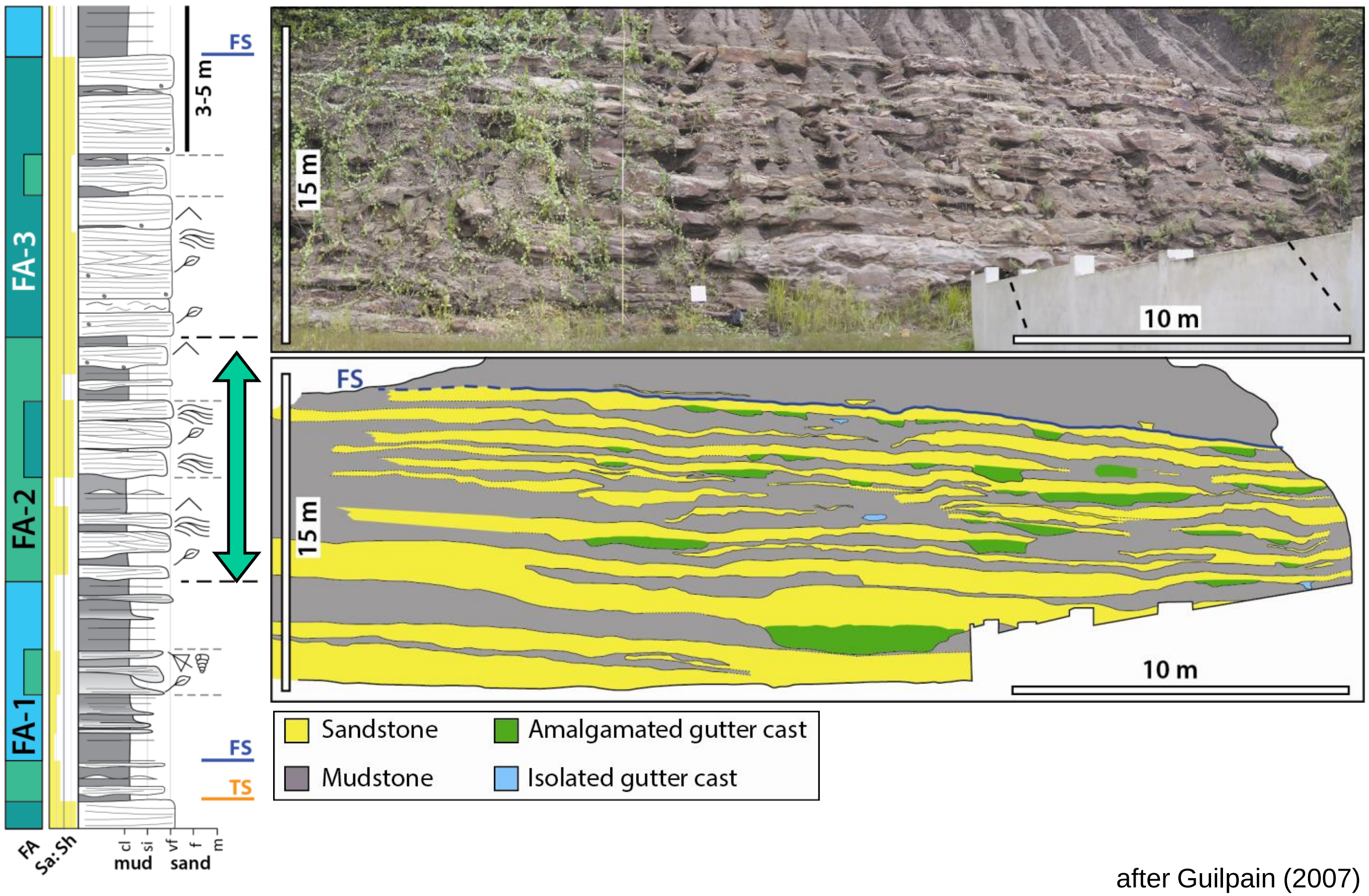
Presenter's notes:

- Well-preserved muddy heterolithics generally show low to modest bioturbation intensities of 1-3, with this particular example being of the most bioturbated. (Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

- The diversity of ichnofauna represents a slightly impoverished *Cruziana* ichnofacies and in general, a degree of physio-chemical stress was present during deposition of the mudstone-dominated intervals.
- Cm-scale sandstone interbeds display a well-preserved, mm-scale oscillatory-dominated ripple lamination, suggesting high sedimentation rates by storm-flows relatively distal to the main sediment source.
- The supply of mudstone and additional salinity stress may reflect suspension-dominated fluvial influence typical of the modern shoreline.

Heterolithic FA-2



after Guilpain (2007)

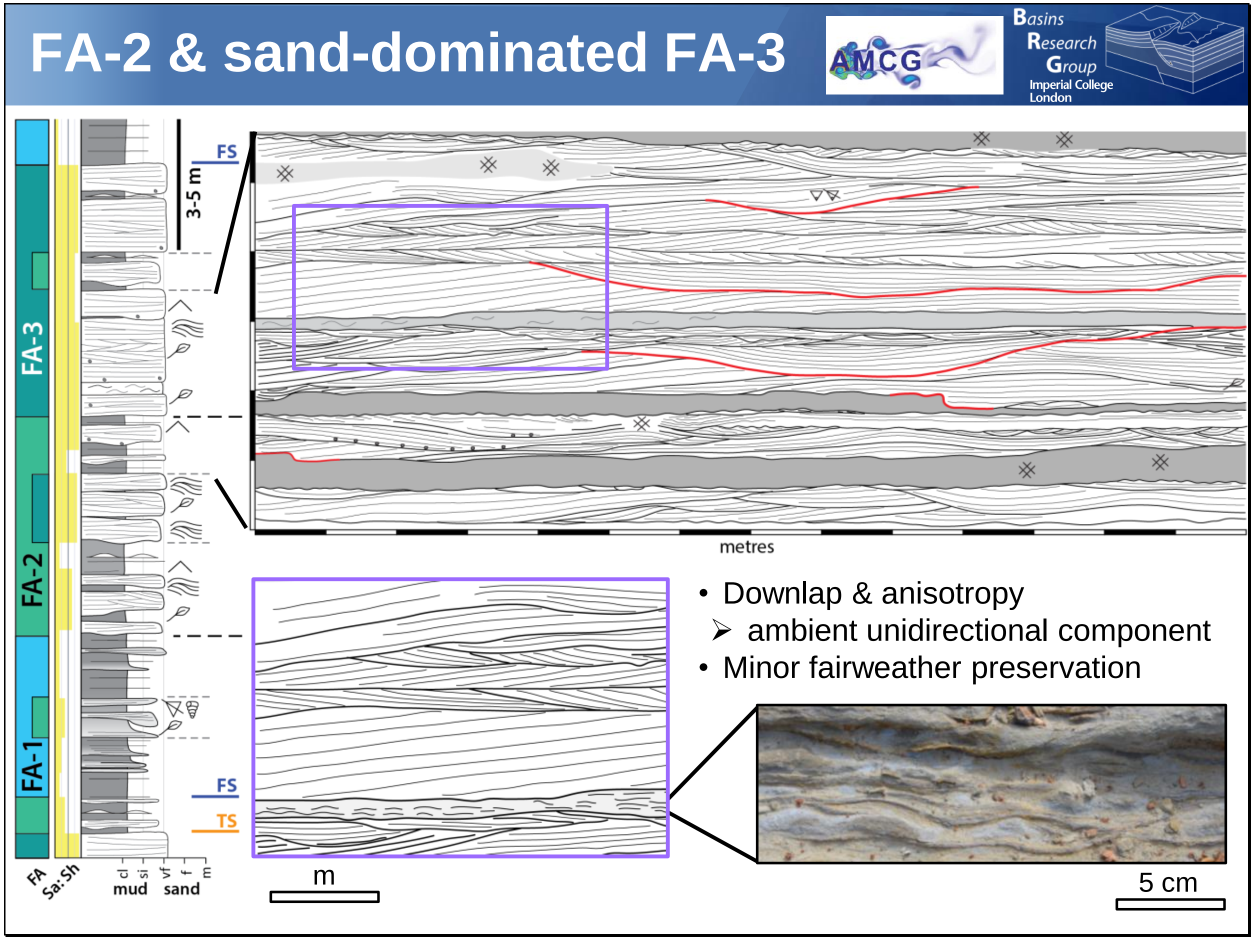
Presenter’s notes:

- Heterolithic facies successions comprise a dm to m-scale interbedding of sandstone and mudstone dominated facies.

(Presenter’s notes continued on next slide)

(Presenter's notes continued from previous slide)

- Sandstone beds are invariable sharp based and show downcutting, concave upward basal contacts, termed gutter casts, most of which are attached to an overlying bed.
- The internal fabric within the gutter casts and overlying bed is the same and apparently continuous in most cases.
- The sandstone fabric is also consistent between beds in heterolithic successions and amalgamated beds in the sand-dominated successions.



Presenter's notes:

- This line drawing through c. 6 m of heterolithic to sand-dominated succession.
- The dominant sandstone fabric is large-scale, typically metre-scale wavelength of low angle, sparsely bioturbated, swaley dominated cross bedding. (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

- Hummocks are subordinate owing to a hierarchy of internal erosive discontinuities, which indicating repeated fluctuations in energy during individual events, and erosional amalgamation of successive sandy flow deposits.
- In detail, downlapping and anisotropic SCS is common, suggesting a superimposed unidirectional component. Only minor intercalated, sometimes mud-draped, wave ripples occur indicating minor fairweather preservation
- This SCS dominated structure is ubiquitous throughout interpreted wave-dominated facies successions, from cm-scale muddy heterolithics to m-scale amalgamated sand-rich packages. Therefore, the processes controlling preservational sedimentation did not vary through section, only the magnitude.
- As well as the consistent sedimentary fabric, the other striking feature of virtually all sandstone beds and packages are the erosive downcutting bounding surfaces, shown here in red. Taking a look at these in more detail:

Gutter casts

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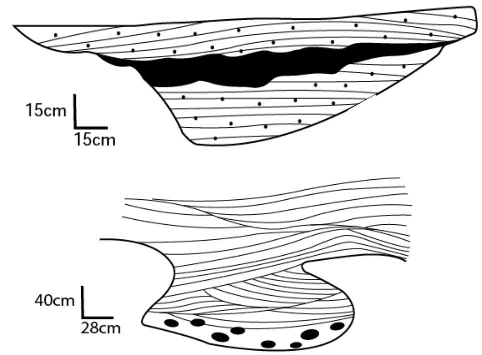
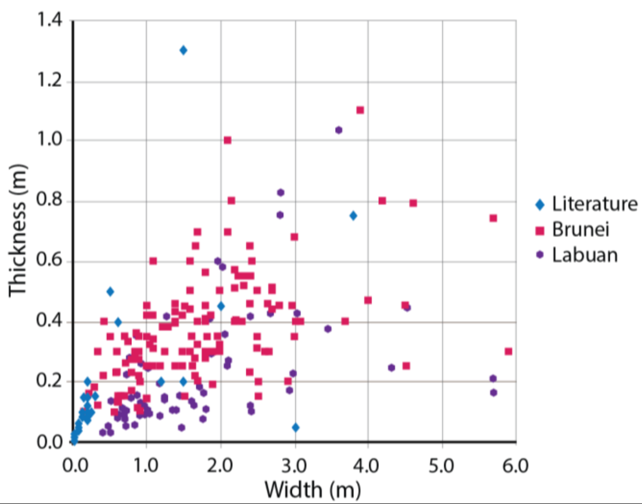
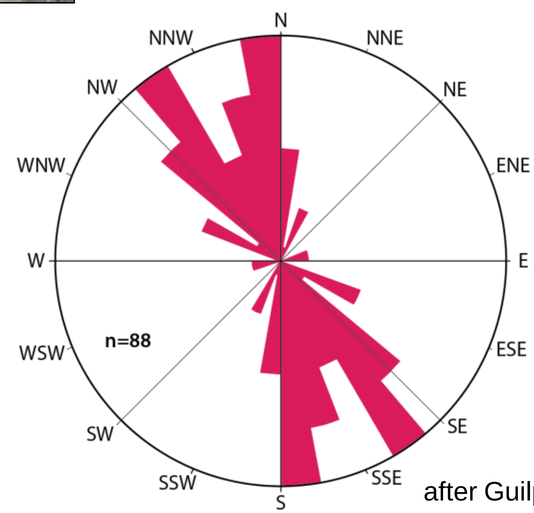


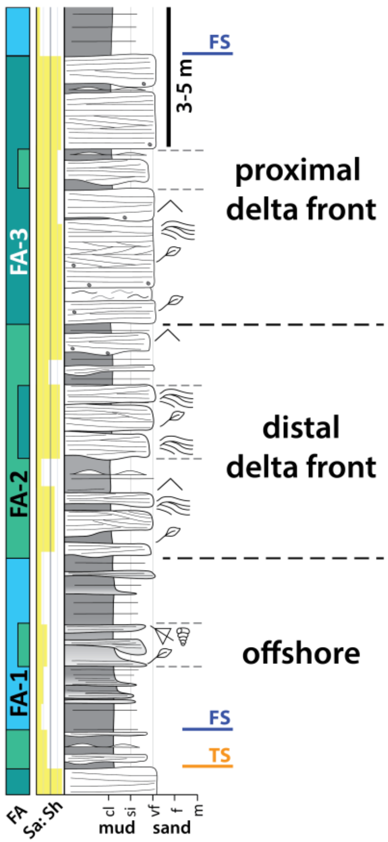




after Guilpain (2007)

Presenter's notes: Gutter casts show a wide range of geometries, from symmetric to asymmetric and steep to overhanging walls, which indicate rapid infill of an eroded cohesive substrate. Compound infills indicate repeated events and inherited topography. Gutter show a wide range of sizes within a broadly consistent aspect ratio, and may be up to 1 m thick and 4-6 m wide. 90% of gutters measured were thicker than the mean thickness of gutter dimensions previously published, which is about 20 cm.

Depositional model



1. Upward-cleaning successions:
   - ➢ Progradational deltaic shoreline
2. Consistent sandstone sedimentary fabric
   - ➢ Storm-dominated & minimal fairweather preservation
3. Large-scale and abundance of gutter casts:
   - ➢ Repeated erosive, sediment-laden, seaward flows
4. Modern system is a direct analogue

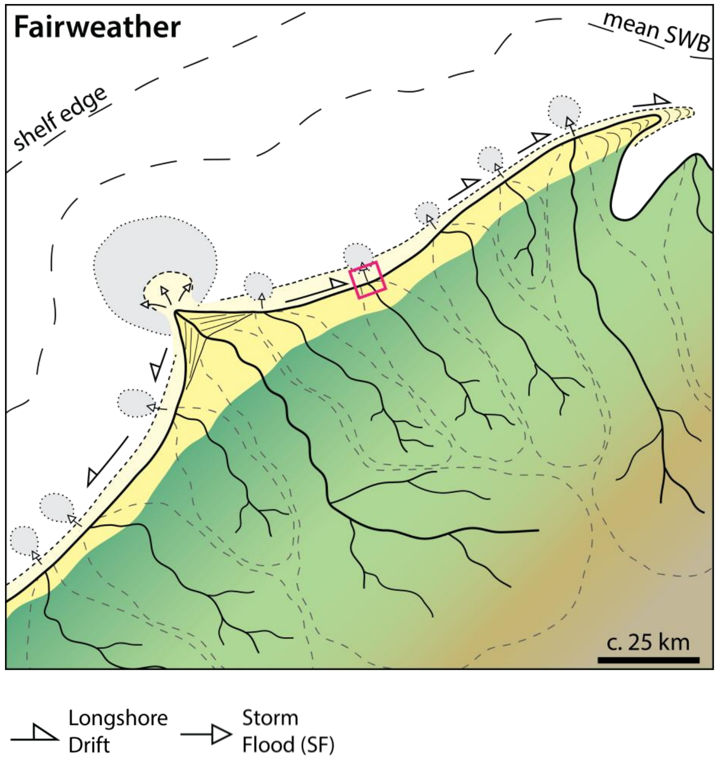
Presenter’s notes: To summarise the key features and a simple 2D depositional interpretation, upward cleaning succession from mud to sand dominated is consistent with a progradation deltaic shoreline. Consistent swaley cross-stratified sandstone fabric attests to deposition and preservation under oscillatory-dominated combined storm flows, (Presenter’s notes continued on next slide)

(Presenter's notes continued from previous slide)

with minimal fairweather preservation. The large-scale and abundance of gutter casts indicates an inherent capacity for the coastal system to generate repeated erosive sediment laden seaward flows. Lastly, the geologic history indicates that the modern system is the continuation of a system, which has been in place for at least the last 15 Ma. Therefore, we can use the modern as a direct analogue.

Fairweather conditions

- Low-moderate wave energy
- Negligible fluvial sand supply
- Alongshore transport dominates
- Sand accumulates as accreting spits in river mouths and embayments



Sand accumulation above low tide

Casuarina vegetated strandplain

100 m N

Sandy coastal plain/ strandplain (fairweather-dominated)

Coastal-Delta Plain

Delta front to flanking shoreface (storm-flood-dominated)

Prodelta/offshore (suspended sediment -dominated)

Presenter's notes: During fairweather conditions:

- Wave energies are low to moderate
- With negligible fluvial sand supply to the shoreline through any of the multiple rivers
- As a result, alongshore transport dominates and sand accumulates in accreting bars in river mouths and embayment
- Satellite imagery from a modern river mouth in 2011 shows the accumulation of a NE accreting alongshore bar across the mouth
- And as waves become attenuate, modulation of river flow and accretion of fluvial and likely tide influenced point bars

Fairweather conditions

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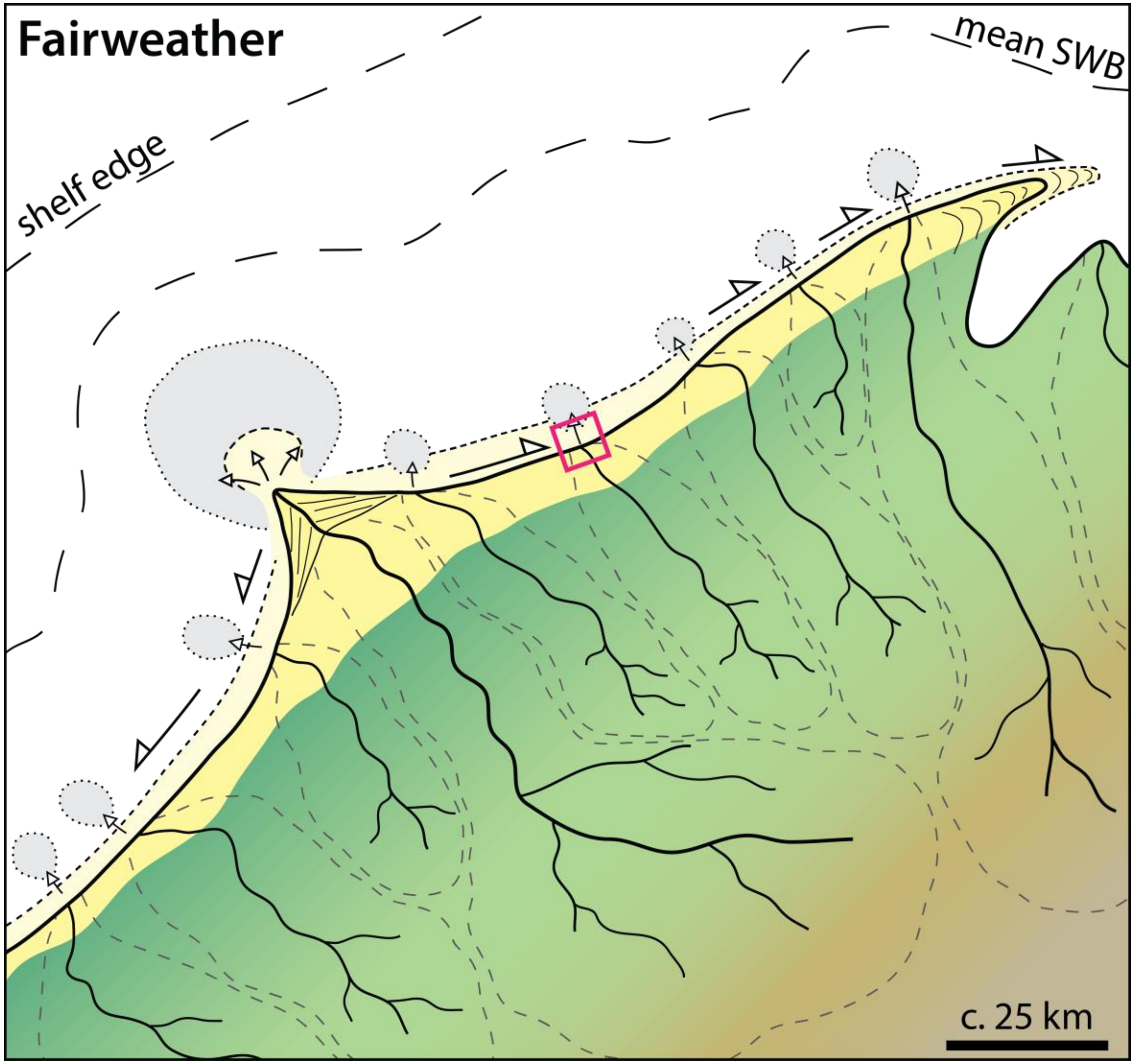

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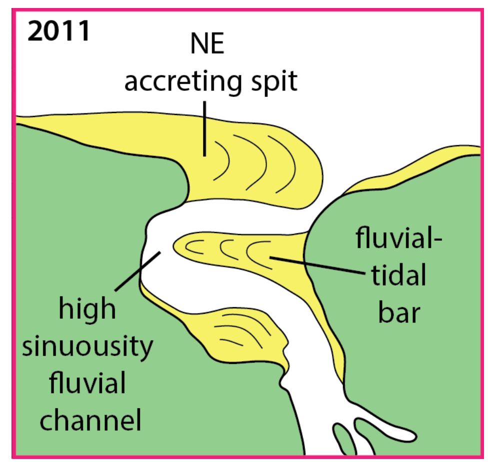


Sand accumulation above low tide

Casuarina vegetated strandplain

100 m

N

Longshore Drift

Storm Flood (SF)

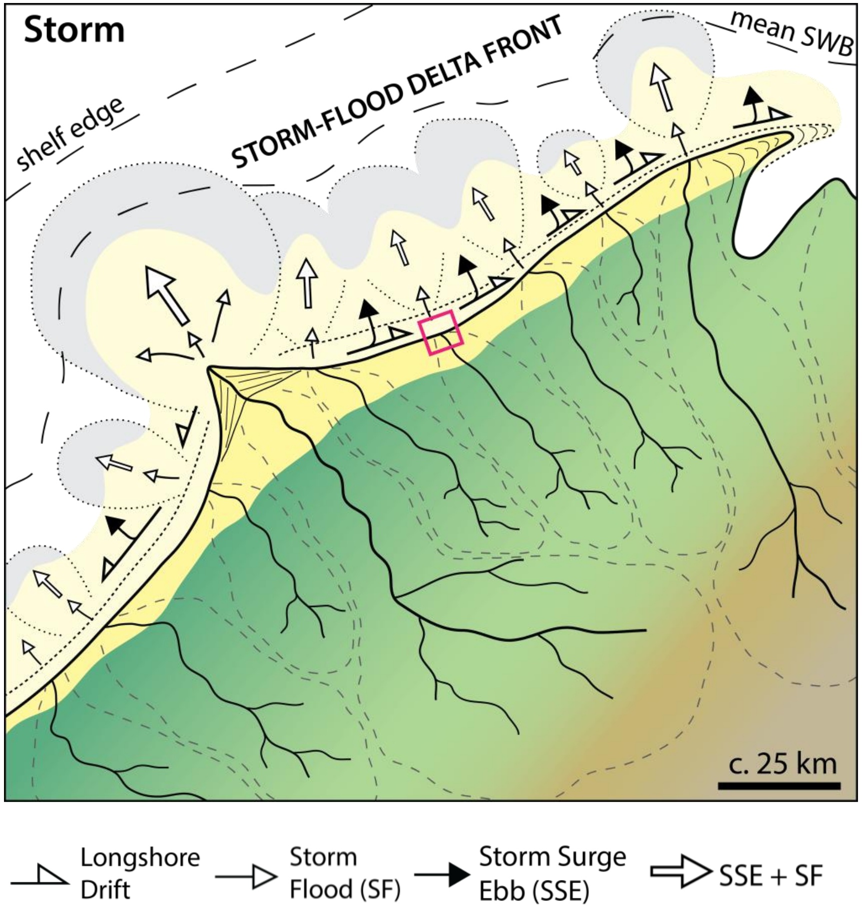
Sandy coastal plain/ strandplain (fairweather-dominated)

Coastal-Delta Plain

Delta front to flanking shoreface (storm-flood-dominated)

Prodelta/offshore (suspended sediment -dominated)

Storm conditions



- Moderate-high wave energy
- High fluvial discharge
- Offshore-directed sediment supply dominates
- Sand transport from river mouths and flanking shoreface to offshore

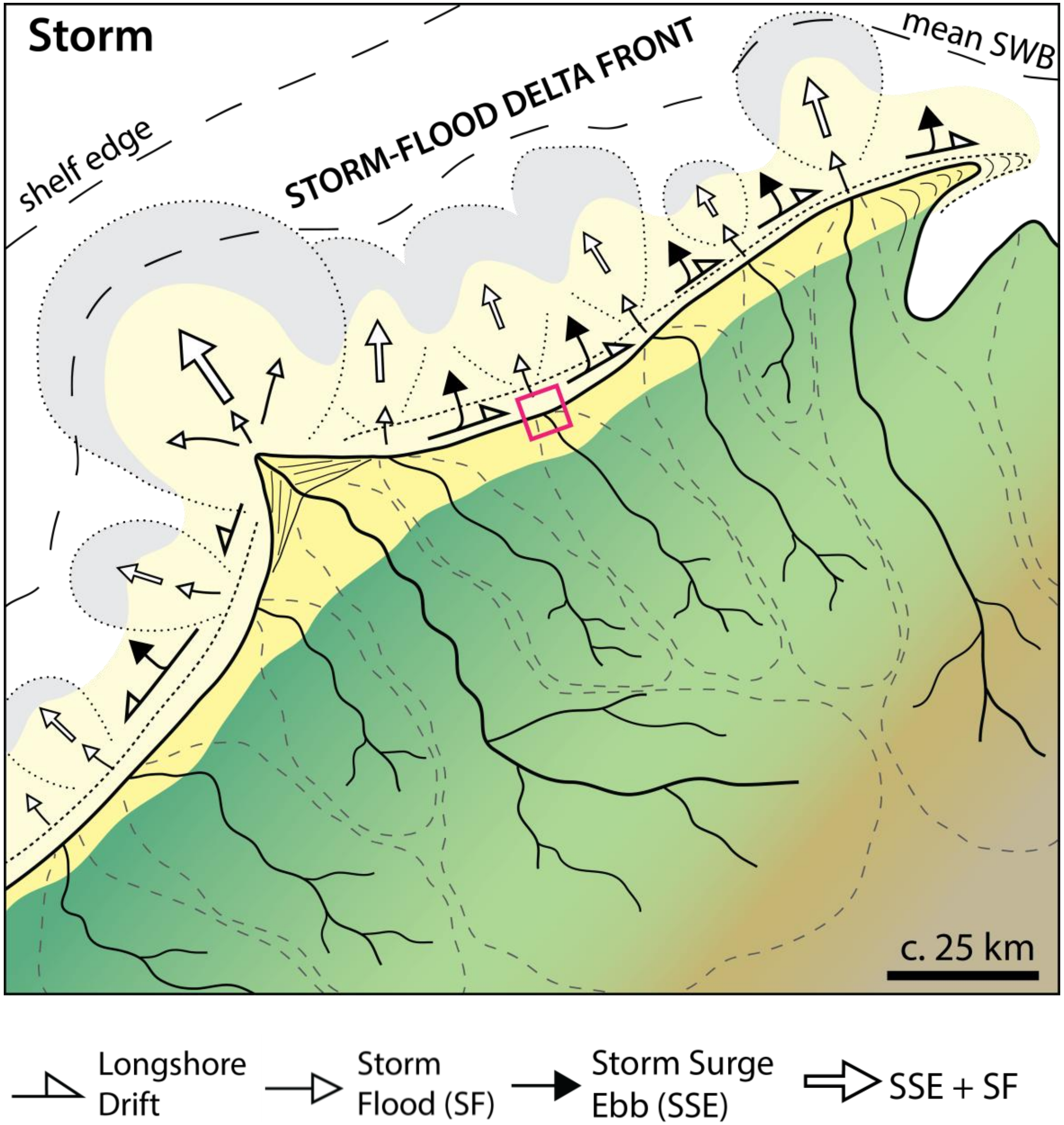
Sandy coastal plain/ strandplain (fairweather-dominated)
Coastal-Delta Plain
Delta front to flanking shoreface (storm-flood-dominated)
Prodelta/offshore (suspended sediment -dominated)

Presenter's notes: However, during storm conditions: Storms are accompanied by moderate to high wave energies and storm precipitation enhances river discharges, so called storm-floods, and fluvial sediment supply, perhaps even contemporaneous with storm waves. (Presenter's notes continued on next slide)

Presenter’s notes continued from previous slide)

Storm waves, storm surge ebb flows and storm-flood fluvial discharge actively erode the nearshore sediment in river mouths and flanking shoreface regions and offshore-directed transport will dominate. The capacity of this system to erode is illustrated in the evolution of the same river mouth from 2011 to 2012, whereby the sand distribution is massively reduced: the alongshore and fluvio-tidal bars substantially eroded and only minor updrift sand accretion. Most of that sand was likely flushed offshore and deposited under storm-dominated conditions. The nearshore and upper shoreface zones were also likely stripped and sediment redeposited with storm-dominated fabrics.

Storm conditions



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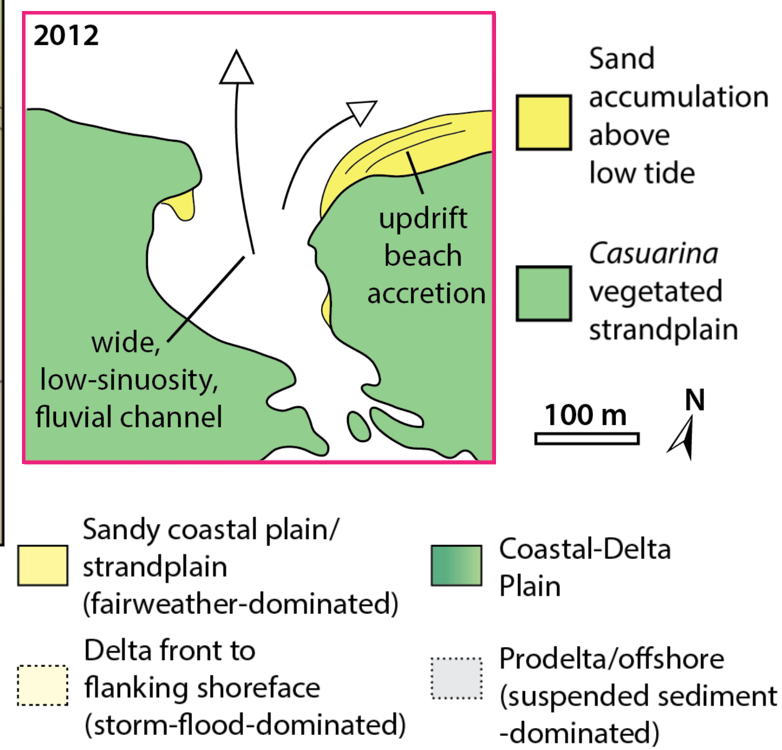

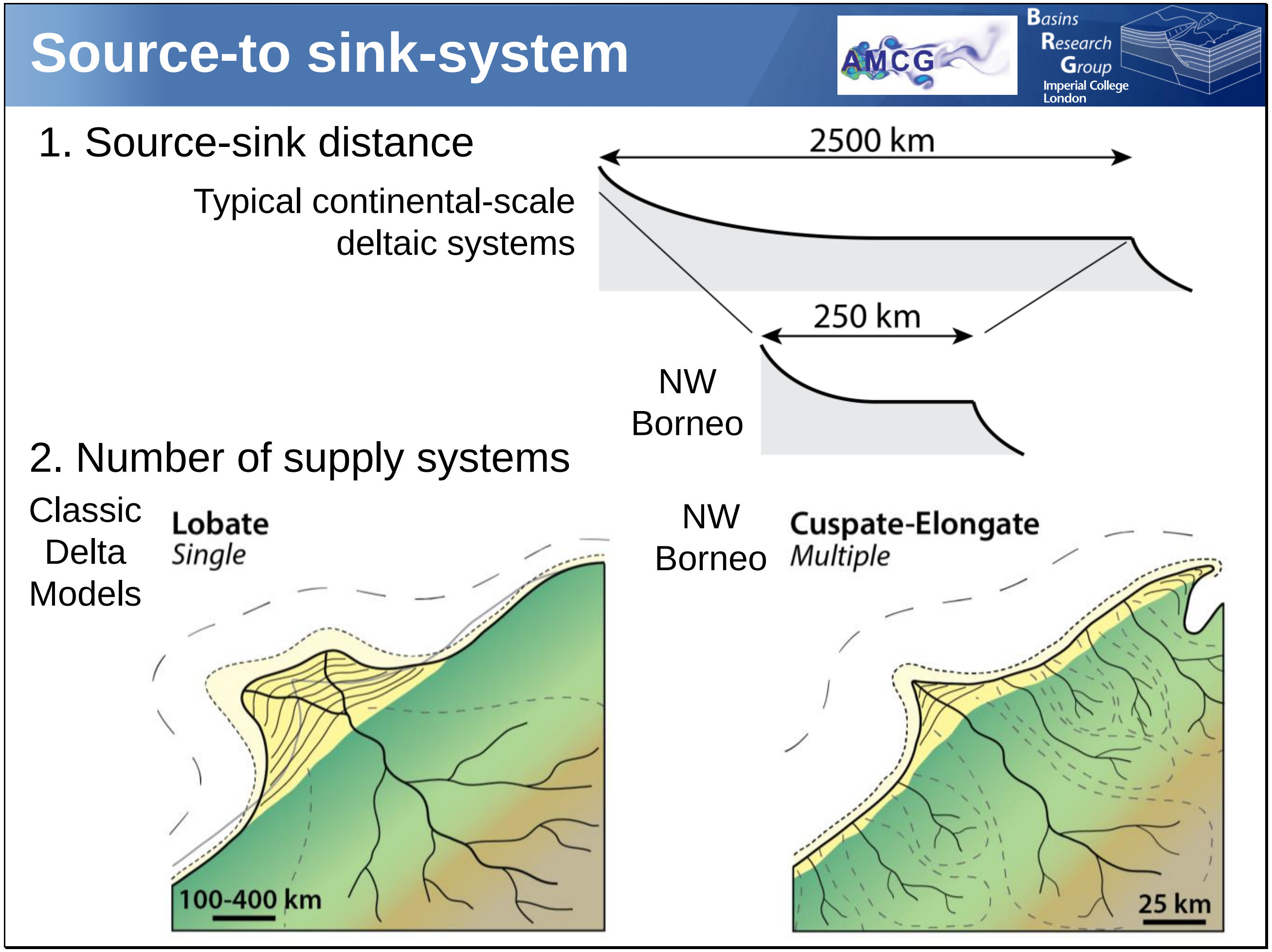

Presenter's notes: This model of the NW Borneo deltaic systems differs from classic delta models firstly in terms of:

- Source sink distance: classic delta models, for instance based on the Mississippi, Nile, Orinoco are continental scale deltaic systems with source to sink distances typically on the order of 1000's of km, whereas along the active NW Borneo margin, the source to sink distance is on the order of 100's km, making for a very efficient source to sink sediment delivery

(Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

Secondly:

- And relating to the shorted source-sink distance, the NW Borneo coastal system has multiple supply systems, whilst the classic delta models are based on single point sourced systems with a fluvial-fed distributary network.
- An important implication of this is that for a multiple supply system, sand is more evenly distributed along the shoreline, and the equilibrium shoreline shape will be a lot different.
- In effect, the laterally extensive shallow marine facies belts and succession, which characterise the ancient Baram Delta Province, may represent amalgamation of individual storm-flood delta fronts through progressive outbuilding and also autogenic channel switching and sediment redistribution.

Classic delta models:

- single-source, passive-margin deltas
- large (100-1000 km) source-delta distances

Multi-sourced, active-margin deltaic deposition along NW Borneo:

- Increasingly cuspate-elongate sand distribution

Conclusions

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1. The ubiquitous **upward-sanding facies successions** in the **Baram Delta Province** are a consequence of **prograding, coupled storm-flood, coastal-deltaic depositional systems**

2. The **factors conducive** to **storm-flood deposition** are:
   - *Humid, tropical climate*
   - *High rates of sediment supply*
   - *Multiple sediment supply systems*
   - *Short (100's km) source-sink distance*
   - *Coupling of 'coastal-shelf storms' and 'terrestrial storms'*

3. **Stratigraphic preservation** of this system was **influenced by**:
   - *Progressive uplift of a tectonically-active margin*
   - *High rates of accommodation space creation*
   - *A long-lived (c. 15 Myr) palaeotectonic/palaeogeographic setting (Mid-Miocene to Present-day)*

4. Combinations of some of these factors may make this model applicable to **comparable modern and ancient settings** elsewhere

Presenter's notes: So to conclude:

1. Ubiquitous upward-sanding facies successions in the Baram Delta Province are a consequence of prograding, coupled storm-flood, coastal-deltaic depositional systems

(Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

2. The factors conducive to storm-flood deposition are:
    - Humid tropical climate
    - High rates of sediment supply
    - Multiple sediment supply systems
    - Short source to sink distance
    - Coupling of coastal shelf storms and terrestrial storms, resulting in storm-flood fluvial discharge
3. Stratigraphic preservation of this system in NW Borneo was influenced by:
    - Progressive uplift of a tectonically active margin
    - High rates of accommodation space creation
    - A long lived c. 15 Ma palaeotectonic/palaeogeographic setting
4. Combinations of some of these factors may make this model applicable to comparable modern and ancient settings elsewhere.