#### Integrating Tidal Modeling and Facies Analysis for the Miocene, Northwest Borneo, South China Sea\*

Daniel S. Collins<sup>1</sup>, Peter A. Allison<sup>1</sup>, Howard D. Johnson<sup>1</sup>, Alexandros Avdis<sup>1</sup>, Jon Hill<sup>1</sup>, and Matthew Piggott<sup>1</sup>

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#### **Abstract**

Coastal sedimentary dynamics reflect the complex interaction of tidal, fluvial and wave processes. Palaeotidal modeling allows understanding of the sensitivity of tidal sedimentary dynamics to inferred control parameters in predictive process-based models for coastal sedimentary deposition. Integrating facies analysis and palaeotidal modeling in turn permits semi-quantification of tidal forcing along ancient coastlines, and deconvolution of parameters that control sedimentary architecture at an outcropreservoir scale. We use Fluidity-ICOM to model tides and associated bed shear stress of the South China Sea during the Oligo-Miocene. Palaeobathymetric uncertainty has been evaluated through a suite of sensitivity tests.

Results show that diurnal tides dominate and the predicted tidal range along palaeocoastlines of the developing South China Sea was higher (meso-macrotidal) relative to the present day (micro-mesotidal). A wider Luzon Strait and lack of through-flow across the Sunda Platform facilitated a larger transfer and storage of tidal energy from the Pacific Ocean. The higher ambient tidal potential, coupled with tectonically-controlled changes in shelf width and bathymetry, set up local funneling and shoaling effects resulting in elevated bed shear stress offshore northwest Borneo, south and east Vietnam, the Beibu Gulf and Gulf of Thailand. The Miocene Belait Formation (Berakas Syncline, Brunei) represents the onshore correlative to reservoir units in the prolific, hydrocarbon-bearing Baram Delta Province. Facies associations are attributable to a complex interaction of depositional processes in a shoreface-delta front to embayed coastal setting. On an inter-sand body to parasequence scale, exposures show

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discrete arrangements of broadly wave- or tide-dominated facies, each typically preserving a subordinate mixed-process signature. On an intra-sand body scale, a clear textural control on bedform type is consistent with combined-flow phase diagrams, justifiable through integrating facies analysis with numerical modeling results. The perceived absence of 'typical' upper shoreface facies in offshore Champion Field cores can in turn be ascribed to a limitation in the shoreface facies model employed. Palaeotidal modeling therefore provides important indicative insight for predictive models of sedimentary processes and facies architecture for coastal-shelf deposition, in a given tectonic and oceanographic setting.

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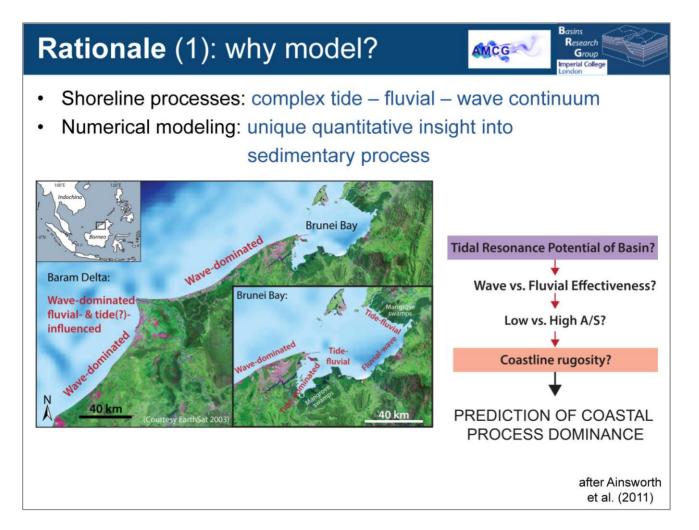












Presenter's notes: Modern shorelines are complex sedimentary systems. They may comprise a number of depositional elements each governed by a unique combination of wave-tide and fluvial power. For example, the NW Borneo Coastline in the SCS region is predominant wave to mixed wave-tide apart except in the Brunei Bay, a drowned valley system, where tide and mixed energy processes govern sedimentation. (*Presenter's notes continued on next page*)

What's more, processes along shorelines may change through time of a number of timescales.

How can we better understand the basin-region scale controls on processes acting along ancient shorelines? In particular, what controls the tidal climate in a given basin; and to what degree does coastal rugosity control tidal signal dominance? Numerical modeling can give unique quantitative insight into the controls and magnitude of processes controlling geomorphology and sedimentation along ancient shorelines.

What route do you take through predictive decision trees for coastal process?

Reconstructing process regime of ancient shorelines is complex and difficult. Typically data is limited in scale, space and time. Yet modern shorelines comprise variably mixed tide-wave-fluvial elements on different spatial scales, e.g. modern day NW Borneo wave dominated coastline vs. tide dominated Brunei Bay embayment. These in turn can change through time.

Numerical modeling can provide unique information on magnitude these processes along ancient shorelines, across a range of spatial and temporal scales. When integrated with detailed sedimentology is potentially a powerful combination for process indication and thus reservoir characterisation: tide-generated sediments are of course very different from wave generated strata.

#### Rationale (2): Integrated study AMCG Sedimentology: flow velocity & sediment supply information > Infer local-regional process regime Integrated modeling & facies analysis: predictive value for reservoir characterisation DOMINANT PROCESS secondary process tertiary process $\mathbf{F}$ , $\mathbf{f}$ , $\mathbf{f}$ = Fluvial $W_{*}w_{*}w = Wave$ T. t. t = TidalFwt Ftw Tfω Wtf Twf e.g. Lenticular-Wavy Bedding: Belait Formation, Brunei

Presenter's notes: Sedimentological observation in core and outcrop gives us an understanding of local scale flow velocity and sediment supply during sedimentation. Given enough spatial data coverage, we can therefore interpret a local to regional process regime.

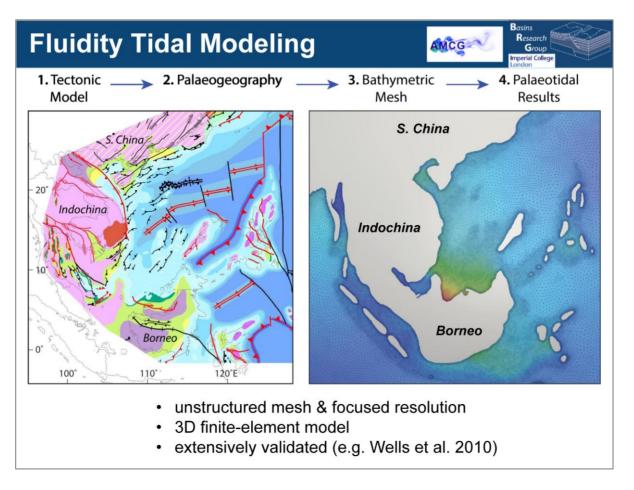
after Ainsworth et al. (2011)

Thus integrating regional-scale understanding of controls of tidal process with information of the processes preserved, we can get a predictive understanding of the pattern of process signal acquisition along an ancient shoreline, with important implications of course for reservoir characterisation.

#### **Aims** · Basin-scale paleogeographic controls on tidal dynamics during Oligo-Miocene evolution of South China Sea Independent process sedimentology: Belait Formation. NW Borneo · Geological applicability of integrated numerical tidal modeling & facies analysis: ➤ Basin- vs. local-scale control on process signal acquisition & preservation Simon et al. (2007)

Presenter's notes: Thus the aims of this study are to understand basin to regional scale controls on tidal dynamics in a tectonically evolving basin. The Oligo-Miocene evolution of the SCS presents the perfect case study, with its tectonically complex situation between 4 major plates having resulted in rapid and pronounced basin physiographic changes, with potentially fundamental implication for process regime.

Integrating independent process sedimentological observations will in turn give us a sense for the geological applicability of integrated modeling and facies analysis in understanding basin and local-scale controls on process signal acquisition and preservation.



Presenter's notes: The tidal model used is called Fluidity and has been developed in house at Imperial College over a number of years. The methodology employed for simulations was to first construct a GDE for each timeslice. These are underpinned by the getech geodynamic plate model and the marine environments, shown here in shades of blue are calibrated to depth and based on modern environments. We then interpolate between these contours to form a palaeobathymetric grid, and interpolate from the surface on a sphere in order to form the corresponding 3D bathymetric mesh, shown here.

(Presenter's notes continued on next page)

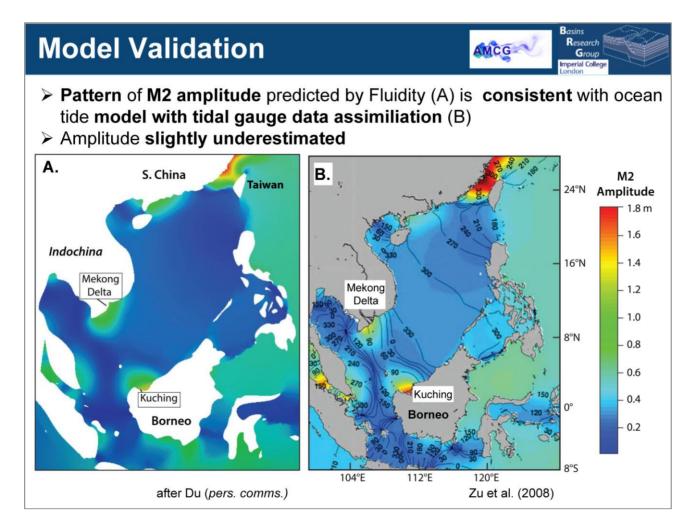
These meshes are highly advanced. They are unstructured, meaning coastlines are rendered nice and smooth, and are also focused in areas of bathymetric complexity and along shorelines. They form the boundary conditions for paleotidal simulation using fluidity, which is a 3D finite-element model and has been extensively validated, most notably for the N Se and Med. However, validation is also ongoing for the SCS.

High resolution detailed gross depositional maps, underpinned by the getech plate tectonic model. Shades of blue are below base level; pinks and greens are above. Marine environments are depth delineated and interpolation between contours produces a paleobathymetic grid too which a 3D spherical mesh is extruded.

Resulting meshes are unstructured, 3D and have focused resolution in areas near coastlines and complex bathymetry. This mesh forms the boundary conditions for astronomically-forced global tidal simulation using Fluidity, a 3D finite-element model which has been extensively validated for the modern day tidal height and bed shear stress.

#### BETTER MESH FIGURE

- Take tectonic base map and integrate public available data to produce a gross depositional map
- Environments correspond to bathymetric depth range in standard facies models, such as this although terminology somewhat varies, for instance in the definition of the shoreface
- These depths are then used to produce a bathymetric map (shown) which can then be extracted, for the entire globe, to produce an adaptive 3D mesh (shown) with the coastline as the 0 m contour
- this then forms the boundary conditions for tidal simulation from which are produced parameter maps

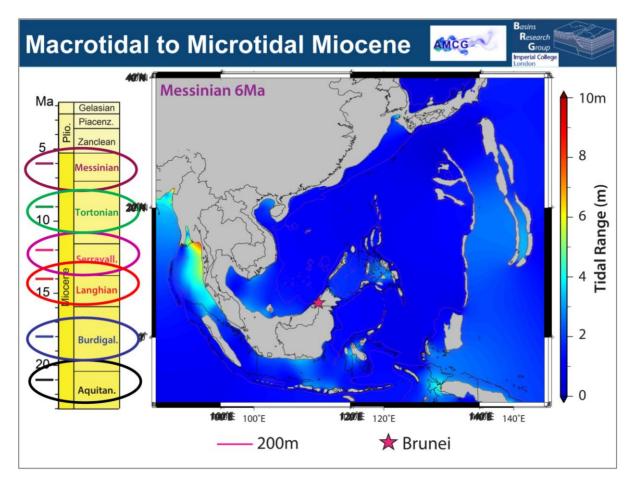


Presenter's notes: The map shown here are the modeled results using fluidity for the amplitude of the M2 tidal phase, that is the tide produced twice daily due to the gravitational attraction of the moon. We observe highs in the Kuching embayment NW Borneo, near the Mekong Delta SE Vietnam & in the strait between Taiwan and S. China. This pattern is very similar to that (*Presenter's notes continued on next page*)

observed in results using a numerical which assimilates actual measurements for tidal guages. However, Fluidity does slightly underestimate but this can be appreciated given the fact tidal guage measurements are highly localised and may have been influenced by amplification on a smaller scale than the bathymetric grid and mesh used for fluidity runs.

Modeled height of M2 tidal component using fluidity. Highs: Kuching Embayment, NW Borneo; SE Vietnam Mekong Delta region; Strait between Taiwan & S. China. If we compare to alternative model that includes assimilation of tidal guage data for the region, we see that the pattern in M2 amplitude is very similar, key areas of elevation are captured by Fluidity.

The magnitude is slightly underestimated by Fluidity. However, tidal guage measurement are highly localised and measurement of tidal height in coastal areas of tidal amplification, at a scale below the resolution of the grid used in fluidity, can explain



Presenter's notes: Let's take a look at some results. 7 timeslices were modeled for the Miocene. In chronological order, starting 21 Ma, this is a map of tidal range for combined tidal components. Model results show very large tidal ranges in the enclosed SCS in the early Miocene, and as we go through into the mid Miocene with significant changes in basin physiography comes a drop in the basin-scale tidal range, and with progressive flooding westwards into the seaway, microtidal conditions predominant into the latest Miocene. (*Presenter's notes continued on next page*)

Model results for tidal range for 6 timeslices through the Miocene.

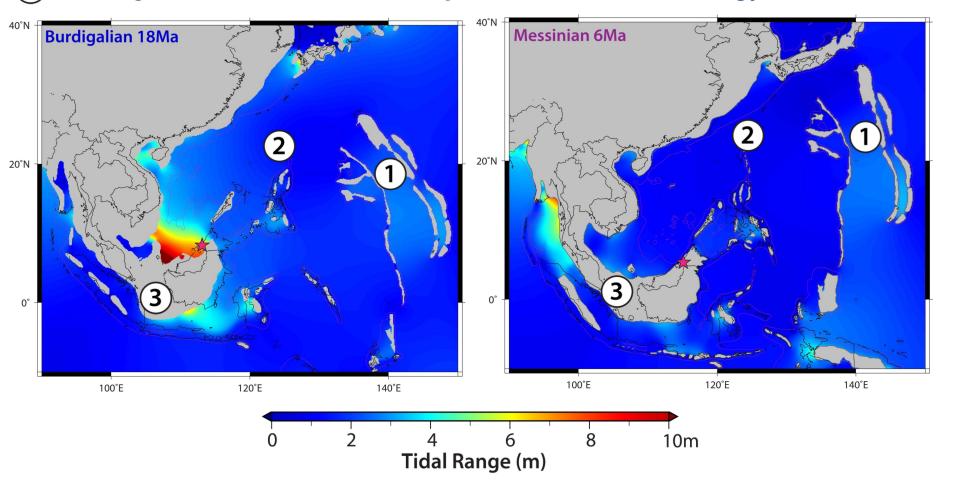
Running through chronologically, model results show basin-scale trend from macrotidal through to meso and microtidal. With macrotidal conditions at the head of the seaway, disconnected from the Indian Ocean. With gradual deepening and transgression into the Gulf of Thailand, between peninsular Malaysia and SE Vietnam, overall decreasing maximum tidal ranges translate westwards. Until the Messinian when tidal heights are regionally less than 3m similar to the present day. How can we explain this dramatic change in tidal dynamics within the evolving basin? Comparing the Early Miocene Burdigalian timeslice with the Messinian.

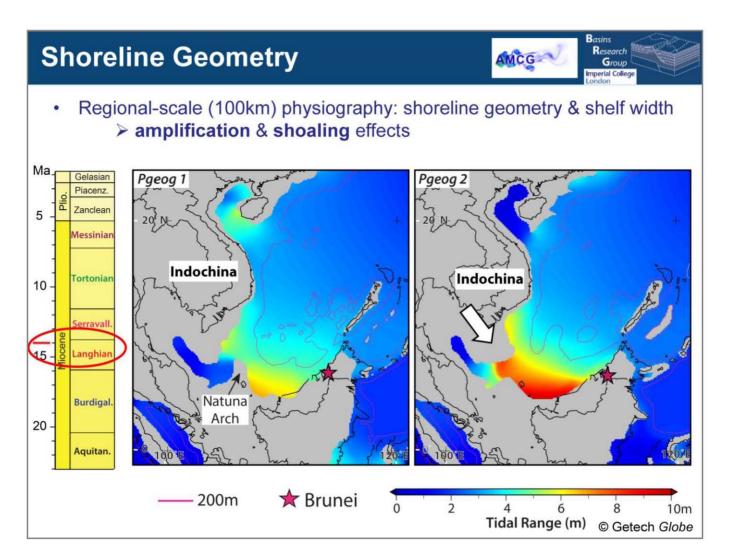
# Controls on Boundary Tide





- 1) Position & elevation of Izu-Bonin Arc = tidal energy reaching Luzon Strait
- 2 Wider Luzon Strait = more tidal energy entering basin
- (3) Emergent Sunda Platform = sequestration of tidal energy within basin

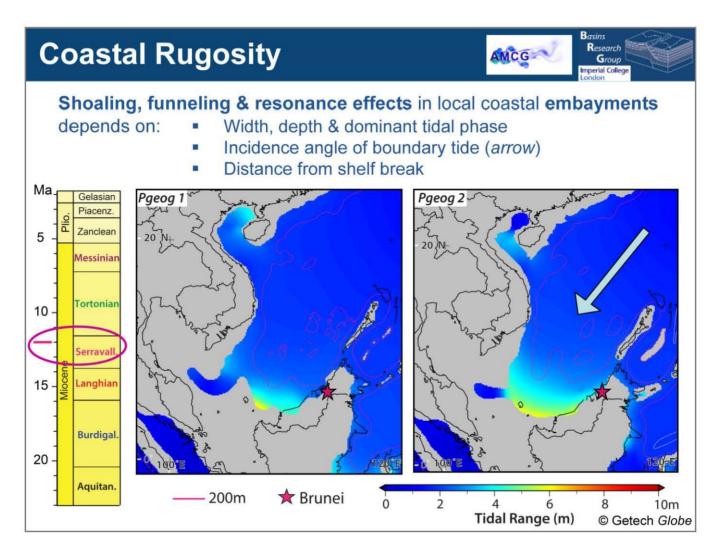




Presenter's notes: More regional to local factors also influence shoreline tidal dynamics. In particular, shoreline geometry can have a large influence by amplifying the co-oscillating boundary tide. (*Presenter's notes continued on next page*)

This is illustrated by this sensitivity test comparing two alternative pgeogs for the Langhian. In pgeog 1, partitioning of the incoming tidal by the Natuna Arch to both the NW and SE results in only local amplification in the region of NW Borneo. Compare that to PGEOG 2 where all of the incoming energy is forced into a much narrow seaway by a dramatic change in shoreline orientation in S. Indochina, thus amplifying the tidal range significantly. Thus it is very important that for a given basin, key differences between interpretations and the impact on tidal processes are understood.

Sensitivity to shoreline geometry is established by comparing two different palaeogeographies. The palaeogeography left infers a N-S peninsula, the Natuna Arch and a NE-SW coastline offshore present day Vietnam (LABELS/POINT). The palaeogeography right lacks the Natuna Arch and instead infers a prominent south facing headland offshore SE Vietnam. This geometry in Pgeog 2 sets up funneling of the SW directed boundary tide entering through the Luzon Strait, causing amplification of tide height into the abruptly narrower closing seaway. This degree of amplification is not seen in Pgeog 1 as tidal energy can propogate into the developing gulf of Thailand embayment before significant funneling to the SE of the Natuna Arch



Presenter's notes: On a smaller scale still, tidal dynamics are sensitive to degree to which coastlines are embayed which can cause significant funneling and resonance effects. However, the presence of an embayment does not always result in tidal amplification. Aspects of understanding are shown in this sensitive test to (*Presenter's notes continued on next page*)

alternative pgeeogs for the Serra timeslice. In pgeog 1, no amplification in observed in the prominent GOT embayment, which faces the incoming direction of the boundary tide from the Pacific. This likely reflects the fact that embayments have to have a certain width configuration for the incoming tidal phase in order for resonance and funneling to cause amplification. In pgeog 2, a different situation is seen. The embayment now faces eastwards and it is likely that not all of the energy from the incident tide can now diffract into the embayment, contributing to a lack of amplification. Distance from the shelf break will also control the position of amplification by shoaling due to frictional dampening.

Thus having embayment can't automatically be associated with predictions of tidal amplification and again an actualistic understanding of tidal dynamics is needed.

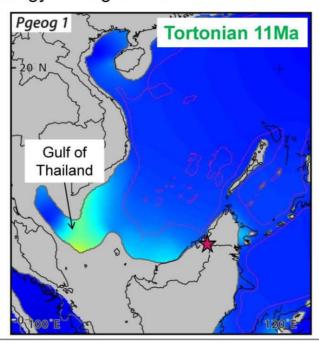
In particular, tidal amplification is common within embayments. But it is not always the case. Shoaling, funneling & resonance effects within embayments are sensitive to a number of factors, including the dimensions of the embayment, the dominant tidal component of the tidal wave entering, the incidence angle of the boundary tidal wave and also the distance from the shelf, which controls regional shoaling and frictional dampening.

### **Independent sedimentology**





- · Aim: 'Understand paleogeographic controls on tidal dynamics at a certain time'
- Ideally: 'Can we predict tidal dynamics at a certain location in time?'
- Reality: Only predictive once we understand local to regional sedimentology & integrate with numerical modeling



Presenter's notes: In spite of uncertainty in paleogeography, across sensitivity tests there is a general regional scale trend from macrotidal to microtidal as a result of fundamental changes in gross basin physiography & fulfilling the aim of understanding the regional scale paleogeographic controls on tidal dynamics at a certain time. (*Presenter's notes continued on next page*)

However, in understanding the controls, we still can't be certain in predicting tidal dynamics at a certain point in time and thus implication on sedimentology through morphological and flow changes, until we undertake independent process sedimentological observations.

Thereafter, for instance, if we identify a consistent pattern of tidal signal acquisition in sediments across a region, perhaps Tortonian sediments deposited in the Mekong Delta and opening of gulf of Thailand region, we'd be confident in our prediction of tide-dominated clastics for as yet unobserved sediments in the same region.

However, does that mean to say you don't get tidal sediments along the more microtidal coastlines further away? Let's take a look at the Belait Formation of NW Borneo, deposited around this time.

Tidal modeling – regional tidal potential: TR control on morphology. Indicative: If macrotidal, then sediments will be tidal.

Sedimentology -

Complex rapidly evolving tectonics – bathymetry changes.

Uncertainty in pgeog: challenge for paleotidal model.

RATHER THAN predicting TR at a point in time.

Our aim: understand the controls of TR at any point in time.

Integrating process sedimentological interpretations.

Local flow and sed supply characteristics: local to regional process sedimentology.

# **NW Borneo Case Study**



Indochina

South China



Pacific

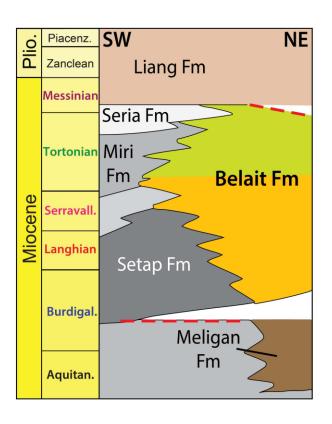
Ocean

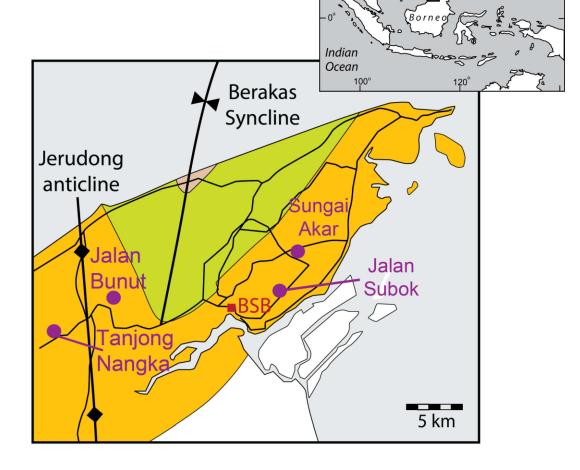
Baram Delta Province: high accommodation & sediment supply

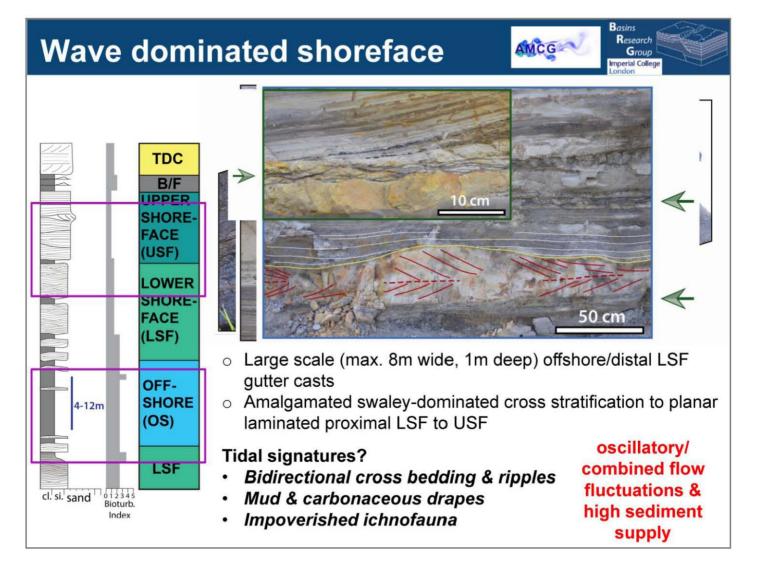
• Mid-Late Miocene **Belait Formation** (>6 km thick):

tide vs. wave dominance

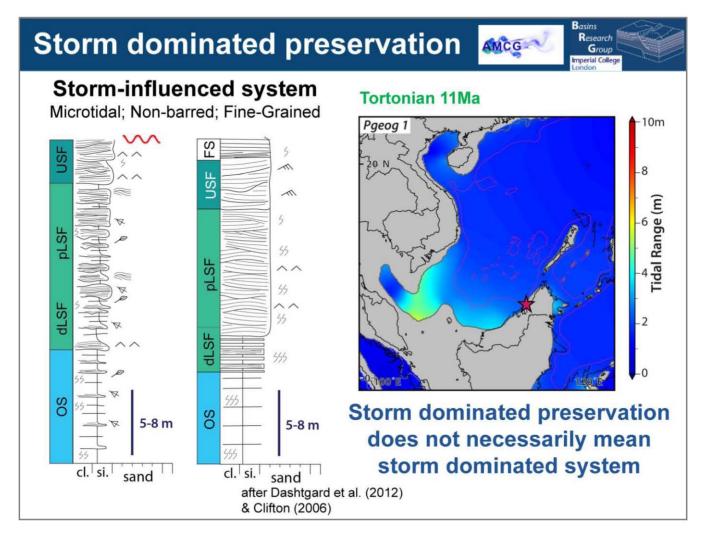
Berakas Syncline: active structural embayment







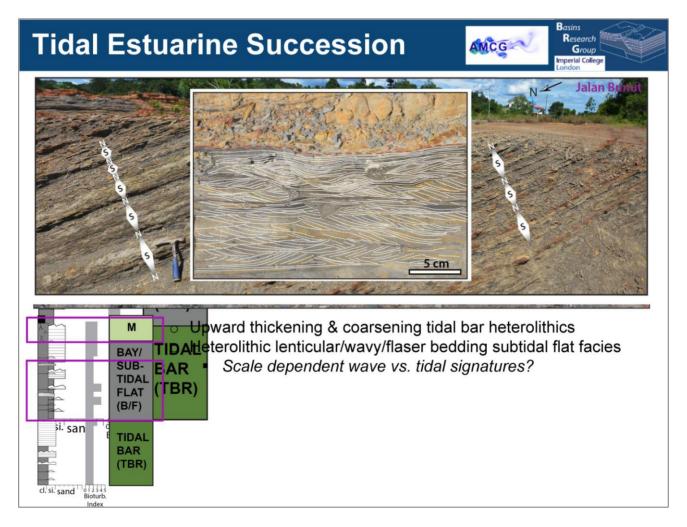
Presenter's notes: Summary logs with colour NB.



Presenter's notes: Model: fine-grain size – bias in record. Also reworking > sedimentation rate.

Tide model results: even if macrotidal, signal may be obscured.

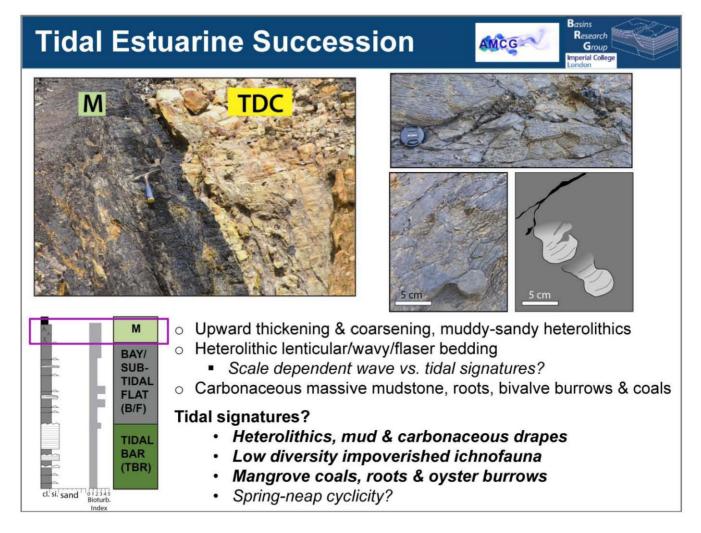
Tides only preserved as a function of grain size in high sedimentation rate e.g. mouth bar with local tidal amplification.



Presenter's notes: Overview of succession at Sungai Akar Exposure. Upward thickening and sanding heterolithic packages, dark muds; lenticular to wavy bedding; moderate bioturbation. Stacked tidal bars within embayment. Predominantly mud-rich system, and trapping of carbonaceous material. (*Presenter's notes continued on next page*)

Upward transition into through muddy heterolithics into a dark carbonaceous mud. The process signature in the subtidal flat deposits is variable & potentially scale dependent. dm-m-scale variability in sand:shale ratio, which one my interpret in terms of spring:neap tidal fluctuations, are superseded on a cm-scale by strong oscillatory wave or combined-flow signal in the form of bundled to interwoven up-building ripples.

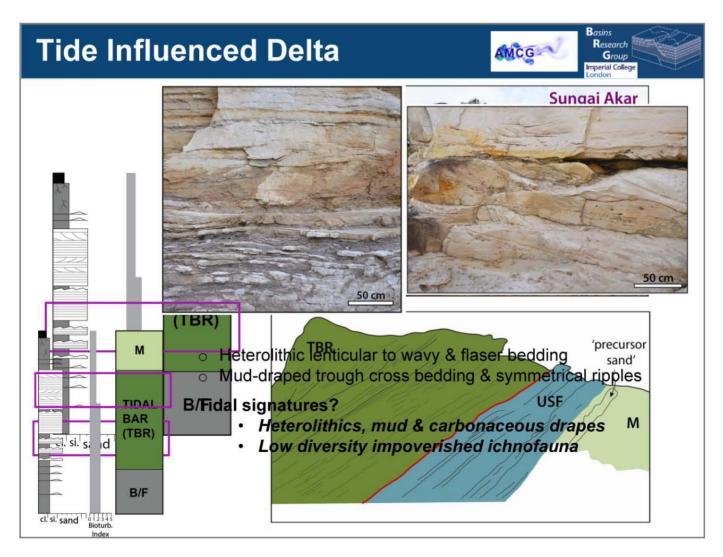
Strong tidal indicators? Strongly heterolithic facies, with mud and carbonaceous drapes; low diversity and impovershed ichnofauna; mangrove coals & roots, & mollusc burrows; tentative spring-neap cyclicities?



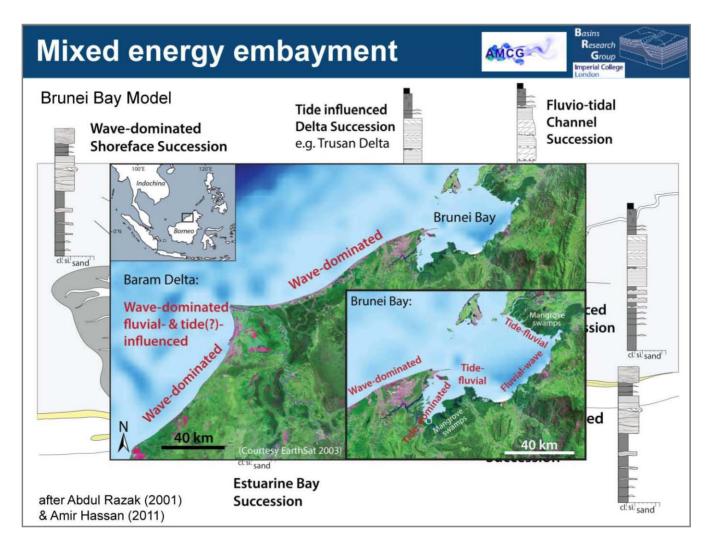
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Strong tidal indicators? Strongly heterolithic facies, with mud and carbonaceous drapes; low diversity and impovershed ichnofauna; mangrove coals & roots, & oyster burrows; tentative spring-neap cyclicities?



Presenter's notes: Sungai Akar tidal bar. Tidal indicators.



Presenter's notes: With little lateral context too exposure, poor correlation as yet, it is possible succession were deposited within a mixed energy embayment analogous to modern day Brunei Bay. (*Presenter's notes continued on next page*)

On the scale of the Berakas Embayment c. 20km, [OVERLAY] you can capture the variations in process dominance interpreted from the facies.

Deposited in the central bay area will be estaurine bay associations [OVERLAY] – mud dominated heterlithics, tidal bars, bay head deltas; with a variable wave signature reflecting the degree of openness to the wave input.

Deposited along open embayment shoreline and by wave-dominated deltas within the embayment e.g. Lawas Delta [OVERLAY] as well as along the open regional shoreline [OVERLAY]

In central to inner embayment areas, tidal bars in mixed process tide-influenced deltas & estuary successions will be deposited [OVERLAY] e.g. the Trusan Delta and inner Brunei Bay, fringed by fluvio-tidal channel belts [OVERLAY].

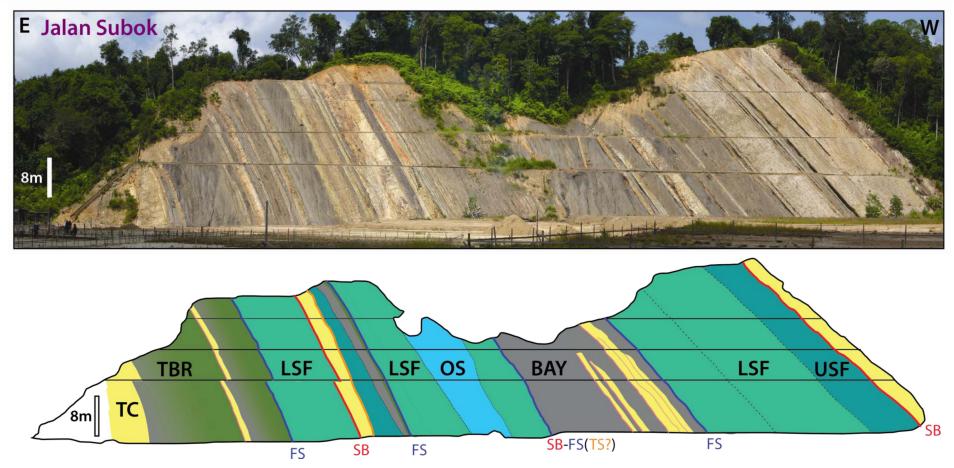
Lateral context limited

Vertical strat archiecture limited to few spectacular exposures civil engineering related.

# Vertical compartmentalisation





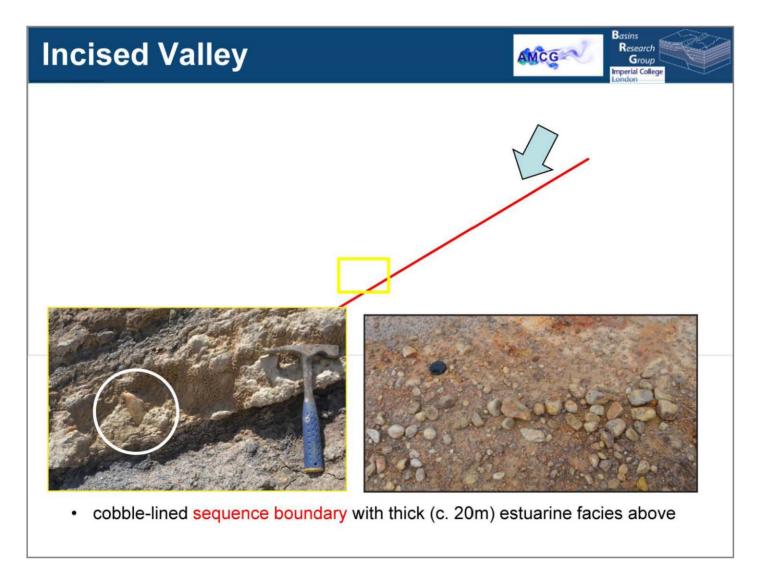


USF Upper shoreface TBR Tidal bars

LSF Lower shoreface B/F Bay/Subtidal

OS Offshore TC Tidal channels

Vertical compartmentalisation of wavevs. tide-dominated facies associations by key stratal surfaces

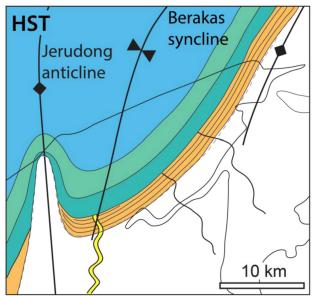


Presenter's notes: Incised valley fill.

## Change in process dominance

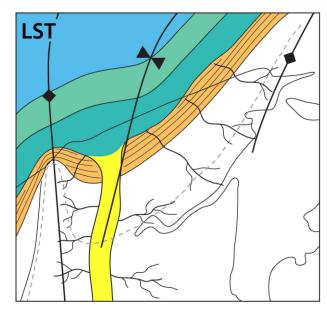


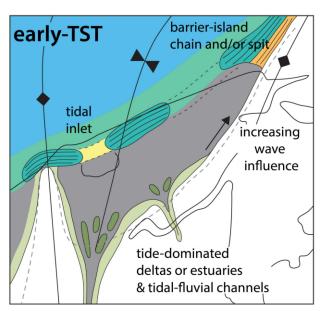




**HST:** aggrading to slightly-prograding wave-dominated shoreface

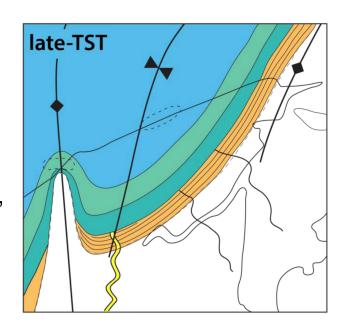
**LST:** fluvial incision & incised valley formation

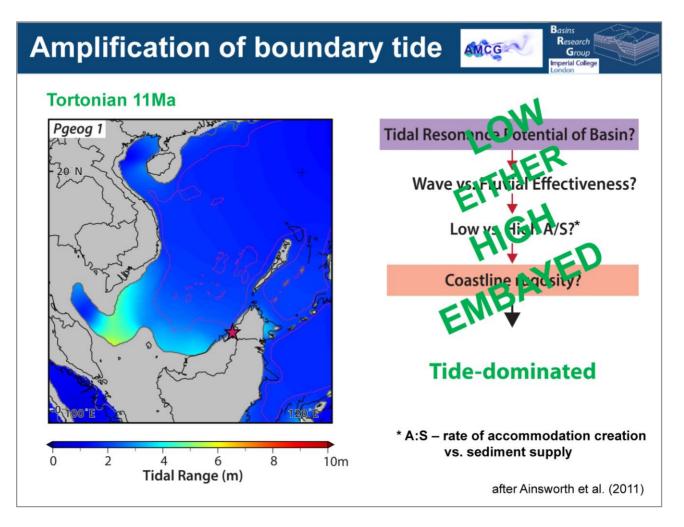




early-TST: transgressive estuary association, mixed-energy

late-TST: sediment supply ≥ accommodation, wave-dominated shoreface





Presenter's notes: So considering the tidal model results for the Tortonian, the approximate age of deposition, results indicate a low amplitude boundary tide as controlled by the regional paleogeographic configuration. So we understand the controls on the low tidal potential of basin. (*Presenter's notes continued on next page*)

However, in order for the sediments deposited along a certain point of this shoreline to be tide-dominate (CLICK), given either high fluvial or wave effectiveness (CLICK) and a high accommodation to sediment supply in the tectonically active Baram Delta Province, you need to have an embayed coastline to amplify the microtidal boundary tide.

But as yet, this embayment is near sub-grid scale for the paleogeographic mesh. What's more, each timeslice paleogeography is a time-averaged highstand paleogeography; thus most shorelines are modeled as smooth.

## **Conclusions**





- Regional paleogeographic effects are the first-order controls on shoreline tidal dynamics
  - decrease in tidal range in the South China Sea through the Miocene due to basin-scale paleogeographic changes
- Numerical modeling gives unique quantitative understanding on effects of regional-local shoreline geometry on resonance and funneling
- Q. Why were tidal sediments deposited at this location and time?
  - e.g. Belait Formation, Berakas Syncline, Brunei:
    - > infer embayed coastline amplified a microtidal boundary tide

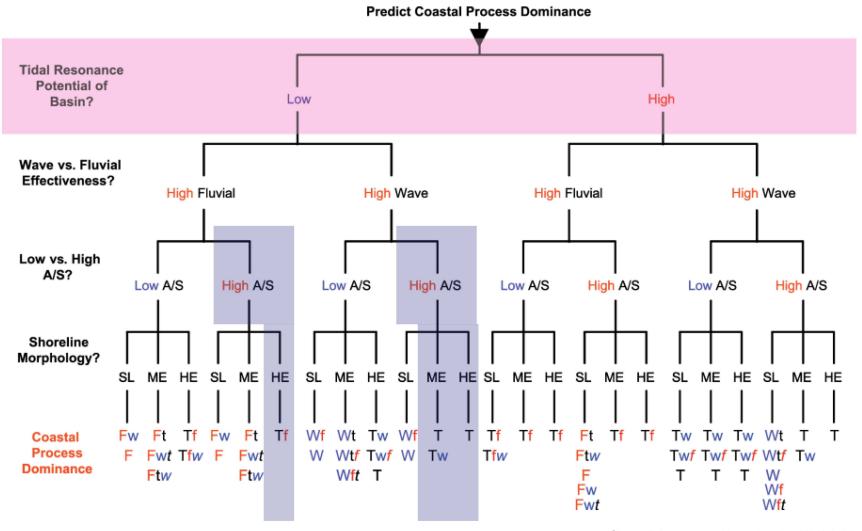
But: can we capture this using numerical modeling?

And: are model results consistent with sedimentology outside the embayment? ...

# Coastal process prediction







after Ainsworth et al. (2011)

## **Lunar Retreat**





- The Moon is receding at 3.83 cm per year. 15 Ma this equates to c. 570 km (assuming constant rate).
- Current perigee distance from Earth is 357,643 km. Current apogee distance from Earth is 406,395 km.
- Current Lunar distance varies by nearly 50,000km.
- Rather than introduce a small unknown variable we used the modern distance.





# **Rossby Radius**





- The Rossby Radius (R) defines the lengthscale of dynamic fluids at which rotational effects become important in any given basin.
- R = c/f where c = (gh)^1/2 and f is the Coriolis parameter(e.g. Leeder, 1999).
- If a basin's width exceeds 2R rotational effects become important causing the tidal wave to rotate about an amphidromic point of zero tidal range

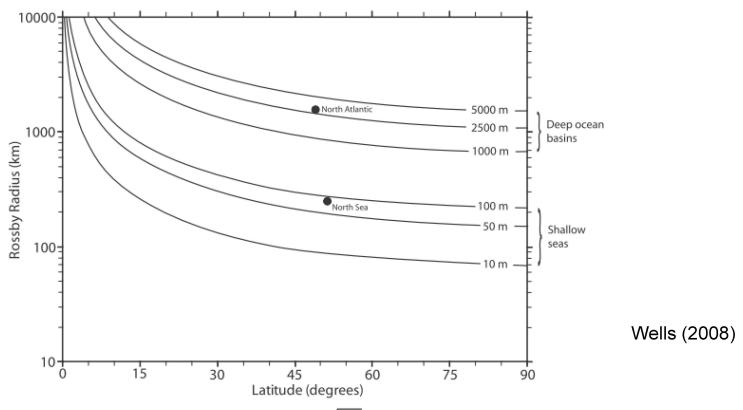
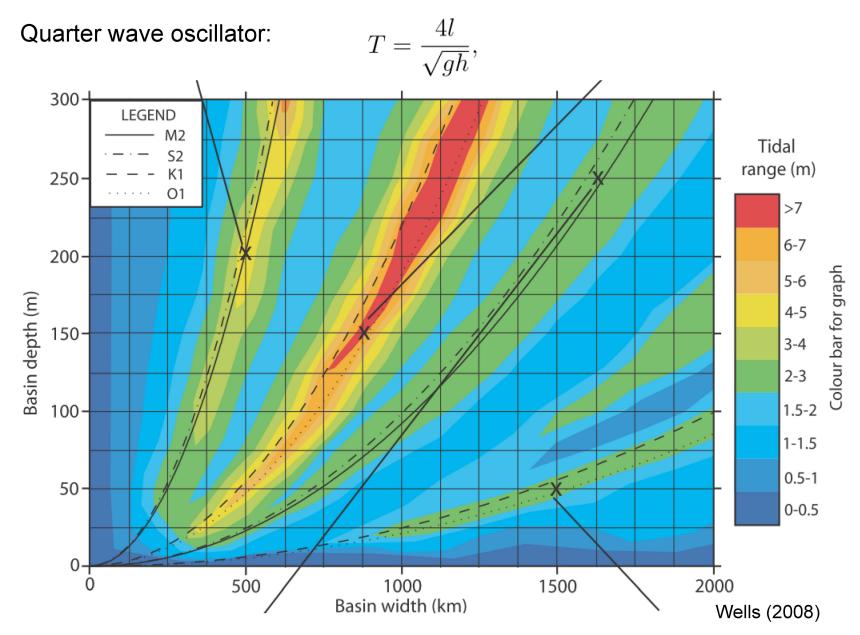


Figure 2.6: Plot of Rossby Radius,  $R = (\sqrt{gh})/(2\Omega \sin \phi)$  (see text for details) for differing latitudes (x-axis) and water depths (different lines)

# Resonance in open embayment







## **Meshes: Minimum Depth**





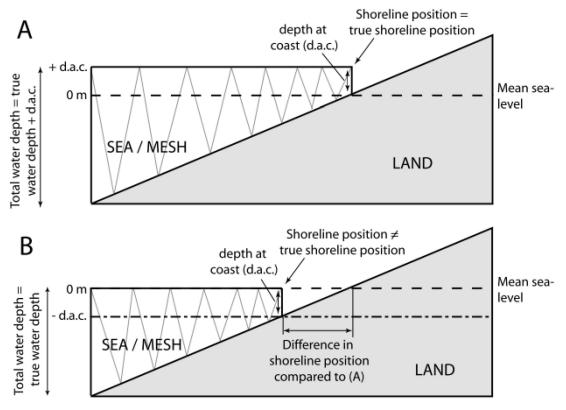


Figure 3.5: ICOM meshes must have a depth at the shoreline in order to prevent the top of the mesh going through the bottom as the free surface is lowered relative to the base level. There are two ways of achieving this: (A) use the 0 m contour (mean sea-level) to define the shoreline and raise the initial free surface elevation by a constant amount. (B) Use a contour with depth below 0 m to define the shoreline and set the initial free surface elevation to 0 m. See text for details.

## **Bed Shear Stress**





Surface integral boundary condition based on quadratic friction law:  $-C_{\rm D}|\bar{u}|\bar{u}$ 

 $C_D$  = drag coefficient

$$|\bar{u}| = \sqrt{u^2 + v^2 + w^2}$$

u, v, w = velocities in x, y, z dimensions

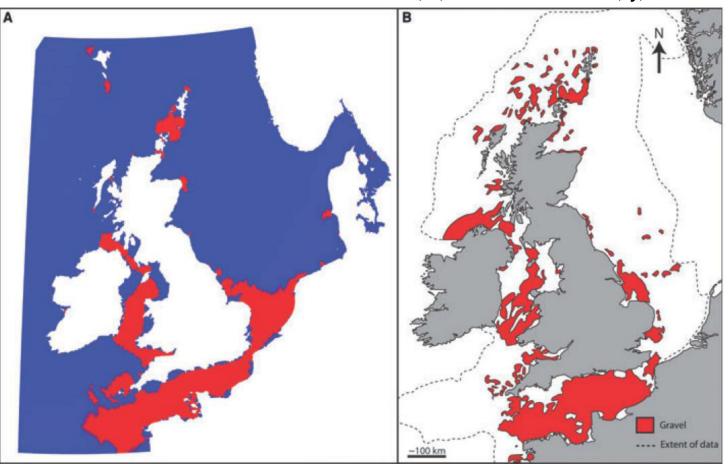


Fig. 5. ICOM prediction of bed shear stresses capable of transporting gravel (shaded red) (A) and the observed gravel grain-size distribution for the North European shelf seas (B) (modified from Graham & Straw, 1992).

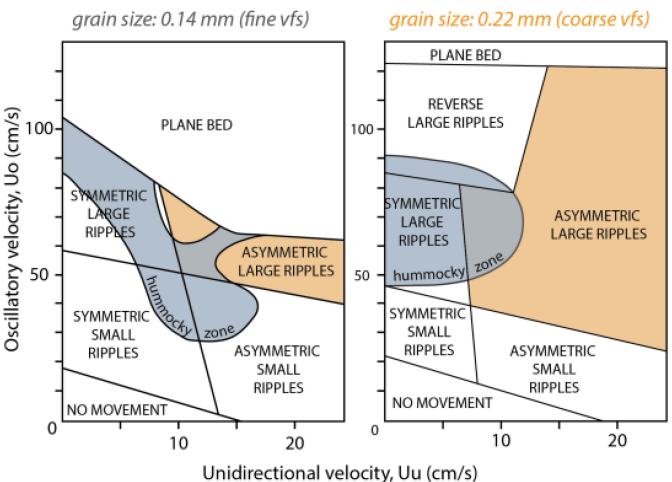
## **Product Changes**

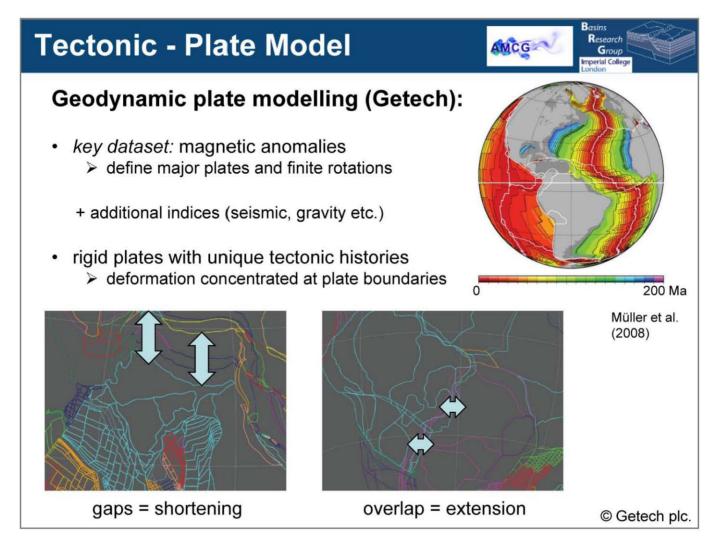




#### COMBINED-FLOW PHASE DIAGRAM:

period of oscillatory flow = 10.5 seconds





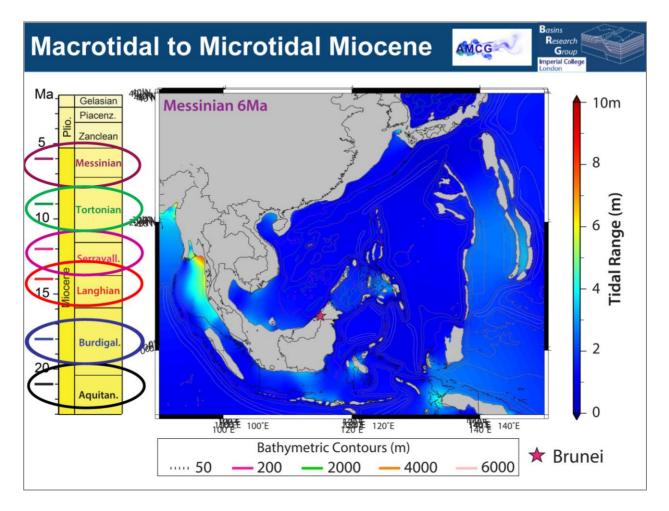
Presenter's notes: Lithosphere subdivided into rigid polygons, each with a unique appearance and disappearance age. These undergo finite rotations about a given Euler pole. ideally we'll rotate one plate relative to a fixed plate, a so called plate pair. However, we lack this information, we take multiple. (*Presenter's notes continued on next page*)

In reality, plates deform over time change shapes & plate boundaries are diffuse.

Ideally, we want to be able to model this deformation by changing our plate boundaries to match the extent of deformation.

Computationally intensive + difficult on global scale.

Simple boundary matching could be confused with positional errors.



Presenter's notes: This run was for tidal range in the Langhian (14 Ma). As you can see, tidal ranges were macrotidal in the region of SW Borneo Coast and the East Natuna Basin, offshore Vietnam – the Nam Con Son and Cuu Long and the Beibu Gulf and the Mahakam Basin offshore Indonesia and the tidal potential of the basin in general was much higher than today, where tides are macrotidal.