

Advective Sediment Transport on Mud-Dominated Continental Shelves: Processes and Products*

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Abstract

Mud is the dominant sediment present on both recent and ancient continental shelves. Muddy shelves commonly are also sites of significant natural carbon burial. Organic carbon-rich mudstones act as source rocks and shale-gas reservoirs. Unfortunately, dark-colored, fine-grained rocks, such as these, are commonly fissile and reveal few obvious sedimentary structures under casual examination. These attributes cause most geologists to assume that these materials were deposited in low-energy settings, by continuous settling out of suspension from dilute buoyant plumes.

Recently, this paradigm has been challenged by data from three lines of investigation: (a) detailed in-situ observations of fine-grained sedimentary rocks using petrographic techniques, (b) flume experiments of mud transport, and (c) studies on modern shelves. These data demonstrate that these natural, fine-grained materials contain a great deal of small-scale evidence of erosion and advective sediment transport, where they have not been homogenized by biological activity. Moreover, physical modeling demonstrates that unconsolidated mud commonly forms ripples in conditions previously thought to allow only sand deposition.

Detailed examination of shelfal mud and mudstone from Proterozoic to Recent revealed several recurring bed types, each with distinctive lithofacies associations and successions of lamina geometries. Although they share broad aspects of deposition from waning episodic flow, these bed types record different flow-evolution pathways among sediment-gravity, traction, and suspension transport. Until now it has not been possible to investigate the relative importance of wave-, tide-, or storm-induced mud-dispersal processes in any particular succession because the characteristic microfabrics produced by the different mechanisms had not been

fully documented. As a first step to resolving this problem, we here illustrate and compare microfabrics present in mudstones from the ancient record that likely accumulated by storm set-up and geostrophic flows, waves, and wave-enhanced sediment-gravity flows of fluid. Products of wave-enhanced sediment-gravity flows, a newly recognized class of combined-flow, appear effective in transporting sediment downslope in muddy shelfal environments; they are relatively common in the ancient record. Key criteria enable their recognition and differentiation from other types of fluid-mud deposits, turbidites, and classical tempestites.

References

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Introduction

- Mud is the dominant sediment present on both recent and ancient continental shelves. Much research is being undertaken to investigate the origin of this material, with interest in unconventional shale plays being at an all time high.
- Mud is challenging to study by conventional logging and field techniques, because it is: fine-grained, dark-colored, and water soluble. It exhibits little obvious hand specimen-scale variability.
- Many investigators resort to the analyses of proxies to investigate the origin of mudstones.
- It is commonly assumed that these materials were either deposited in a) low-gradient, low-energy settings, by continuous settling out of suspension from dilute buoyant plumes, b) as the distal deposition products of storms or c) by deposition as turbidites on slopes.

Jet Rock: “laminated and organic -rich”



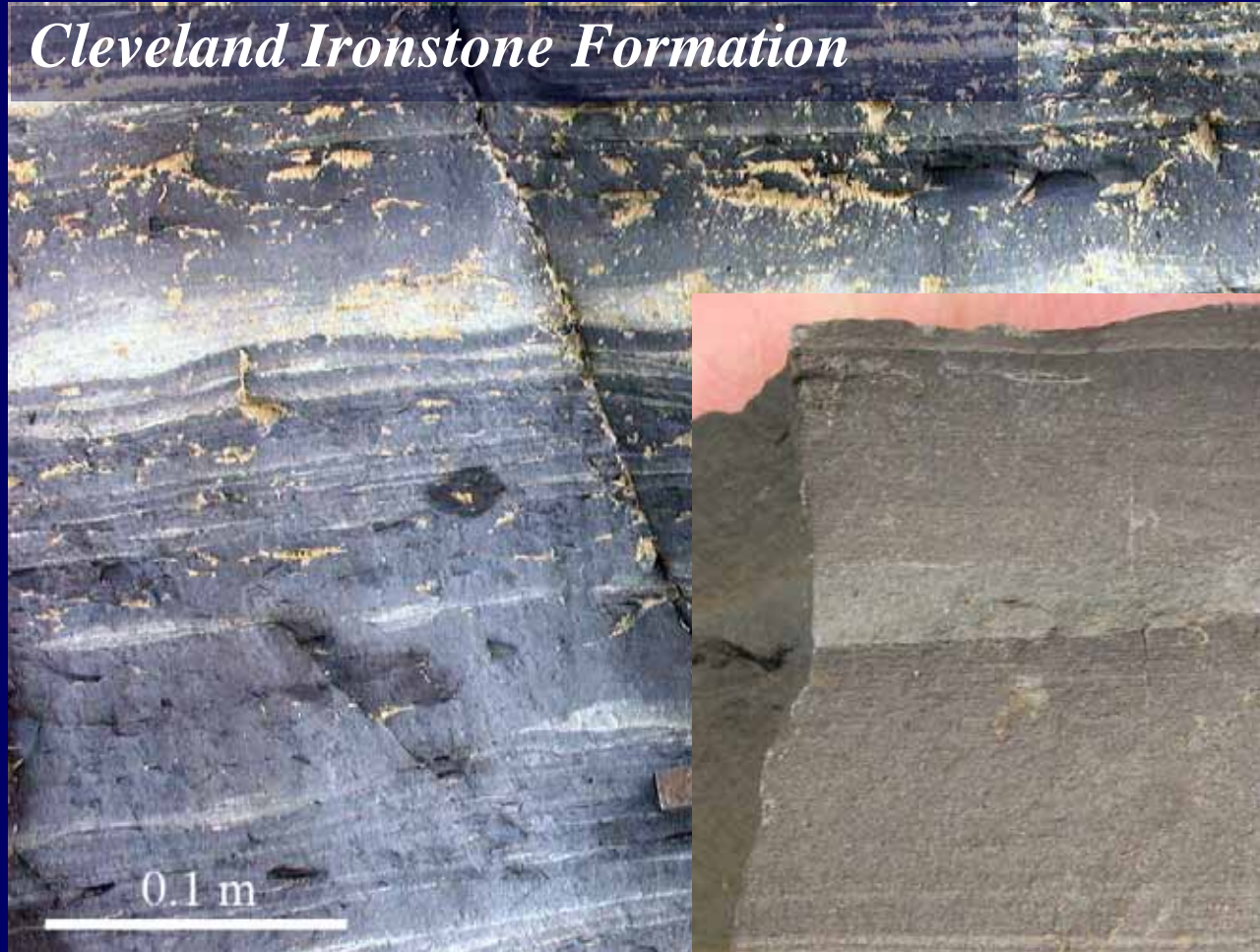
Variations on the “lam-scram” / distal tempestite theme

Cleveland Ironstone Formation



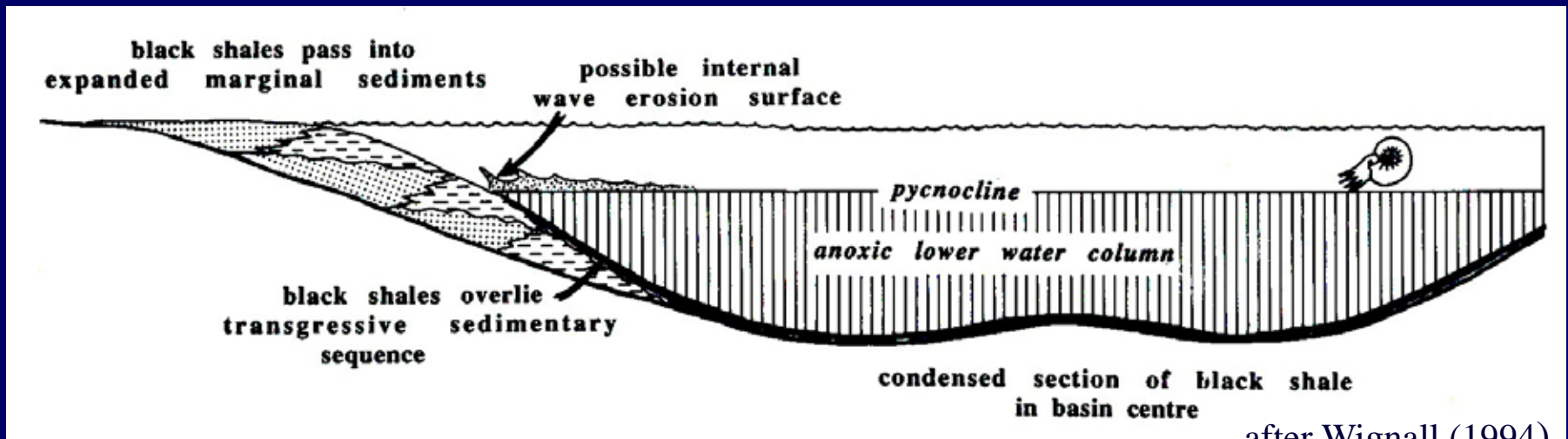
Variations on the “lam-scram” / distal tempestite theme

Cleveland Ironstone Formation



Existing models

- These assumptions have led geologists to typically assume that, away from gradients particularly associated with fluvial inputs and the shelf break, fine-grained mud deposition occurs in basin-centered deposits that exhibit bull's eye stratigraphic geometries. Under these circumstances facies distributions are typically interpreted as being controlled by variations in primary production and bottom water anoxia / dysoxia.

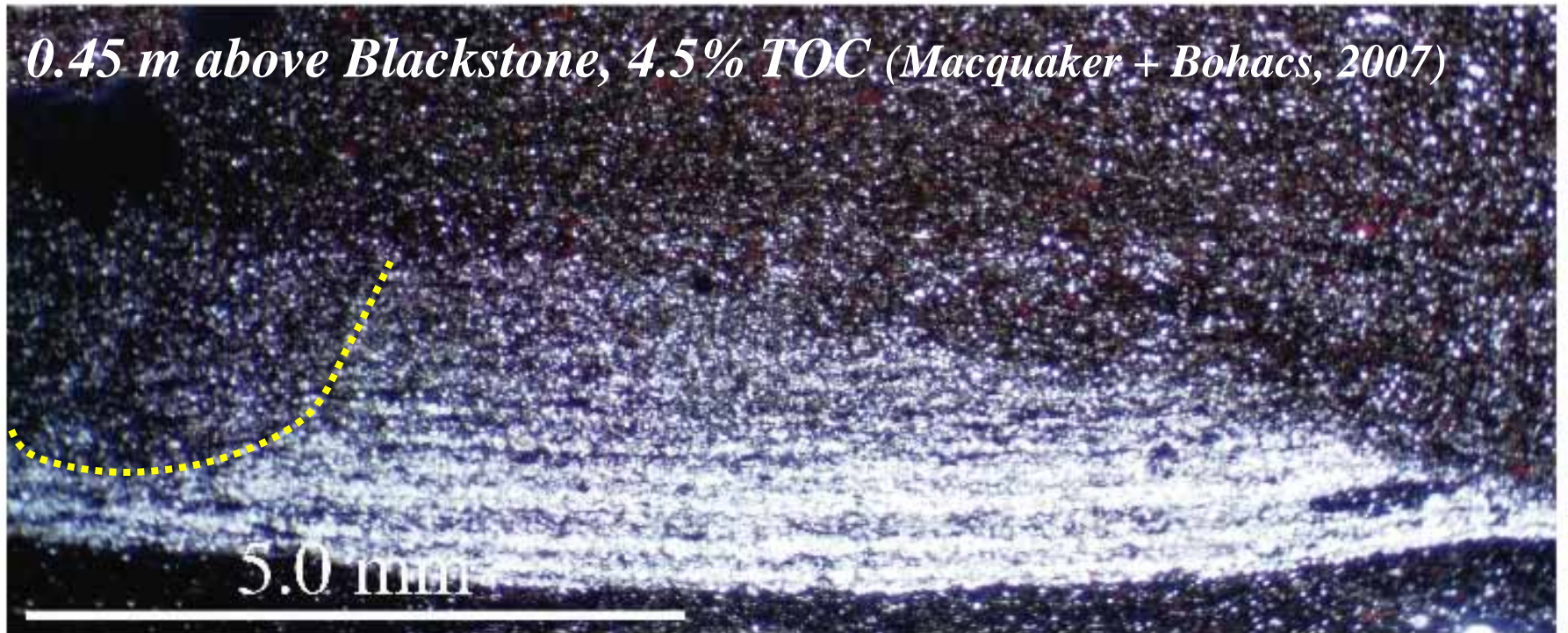


Recent micro-textural research

- Advances in both thin section manufacturing and micro-imaging techniques reveal that fine-grained distal sediments are highly heterogeneous on millimeter scales.
- Variability demonstrates significant differences in:
 - *Proportions of clastic detritus being delivered to the basin from the eroding hinterland - composition and grain size.*
 - *Primary production in the basin.*
 - *Diagenetic pathways following deposition.*
- This research *also* demonstrates that fine-grained sediments contain a great deal of microfabric information:
 - *Erosion* *✓ Advection sediment transport processes*
 - *Bioturbation* *(waves, currents, sediment gravity flows)*
- These processes interact to control textural heterogeneity.

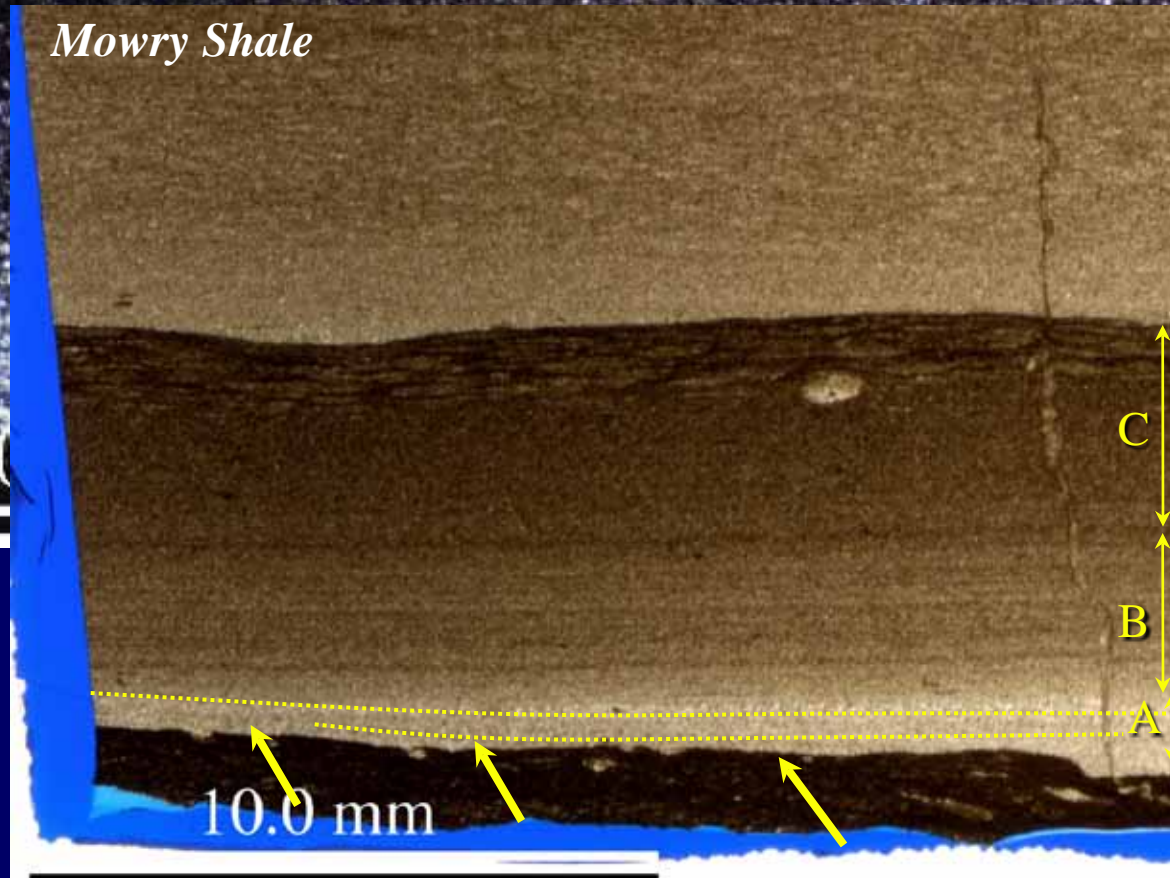
Microtextural data - starved ripples

0.45 m above Blackstone, 4.5% TOC (Macquaker + Bohacs, 2007)



Microtextural data - WESGFs

0.45 m above Blackstone, 4.5% TOC (Macquaker + Bohacs, 2007)



Microtextural data - Tempestites

0.45 m above Blackstone, 4.5% TOC (Macquaker + Bohacs, 2007)

Mowry Shale

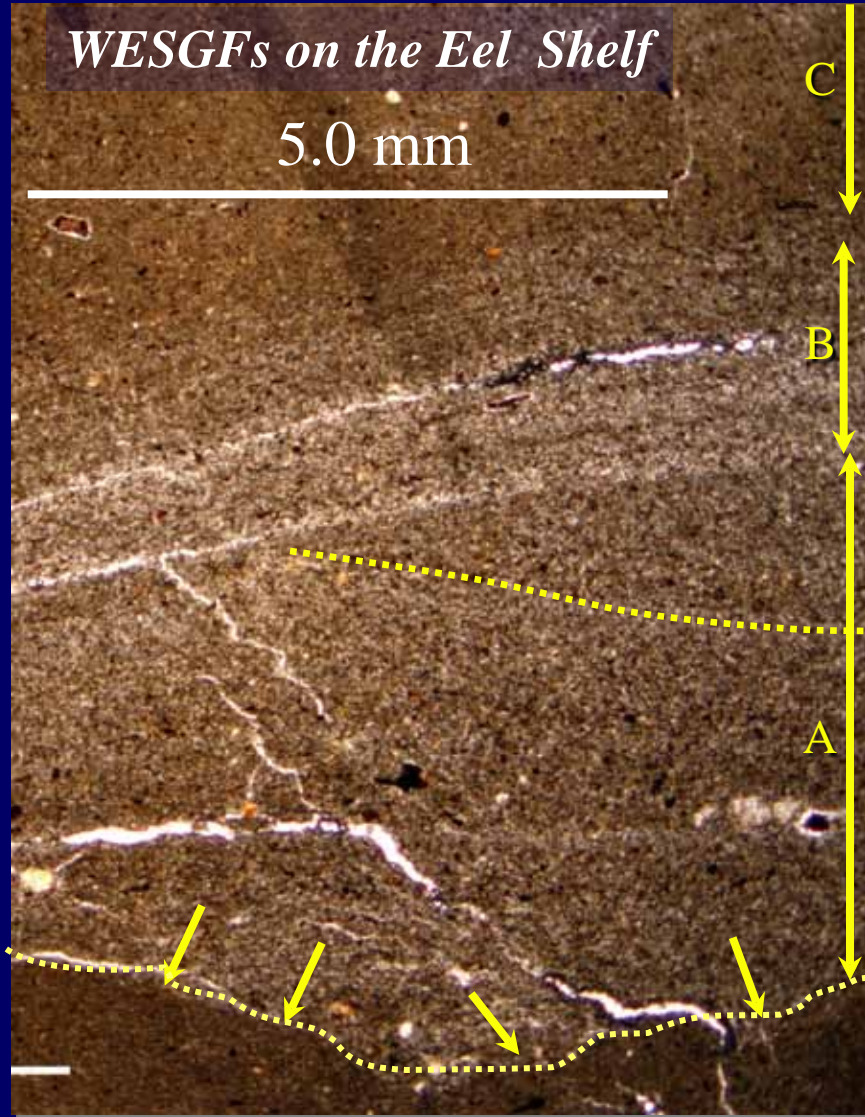
Cleveland Ironstone Formation

5.0

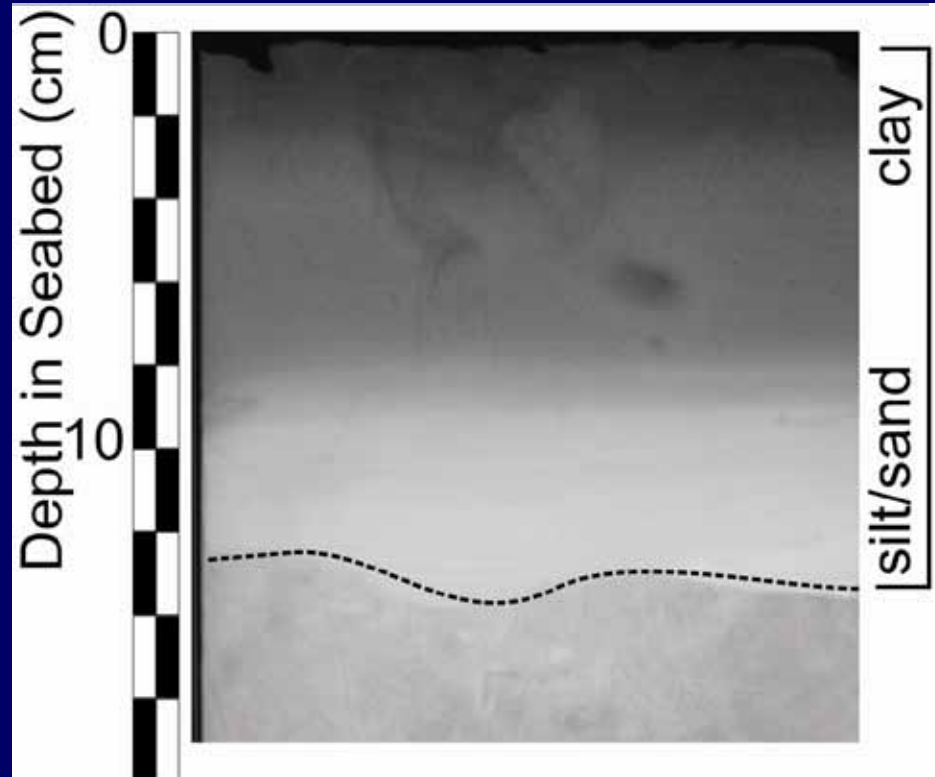
10.0 mm

10.0 mm

Recent counterparts



Hurricane Katrina “tempestites” on the Louisiana Shelf (Keen et al., 2006)



Microtextural variability - origins

- A great deal of bed-scale, micro-textural variability is present, where not destroyed by bioturbation.
- Many individual beds are:
 - *Sharp (erosionally) based,*
 - *Normally-graded,*
 - *Organized internally into lamina-sets with variety of geometries.*
- This variability suggests that different physical mechanisms are responsible for advective sediment dispersal within an overall “distal tempestite paradigm”.
- Does this small-scale variability actually matter?

Microtextural variability - processes

- Yes!
- These mechanisms lead to some regions being:
 - *clay-rich (ductile in the subsurface where enriched in clay minerals), and others being*
 - *silt-rich (brittle in the subsurface where enriched in biogenic quartz).*
- So what processes might be responsible for the sediment dispersal patterns on mud-dominated continental shelves?
 - *Gravity, Current, Waves*
- A great deal of research has been focused on the obvious driver of these processes - storms, and their products (tempestites, HCS, etc.). These mostly address sand-dominated parts of the succession.
- Interpretations of muddy units are typically only an after-thought!

Why the mud component is important, 1

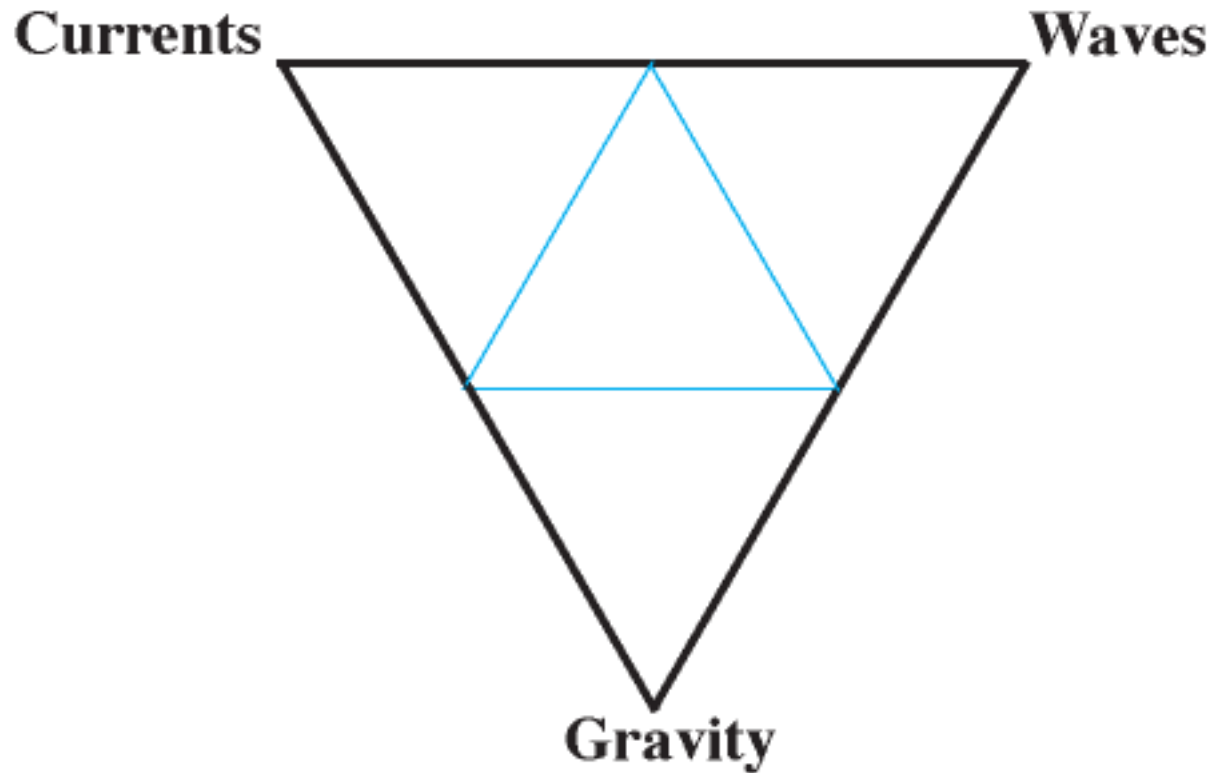
- Wave activity can resuspend the mud fraction creating a fluid mud.
- Resuspension increases the density of the bottom-water layers, forming a dense fluid-mud suspension bounded by a lutocline.
- Assuming that this material is maintained in suspension (through hindered settling and wave energy) - gravity forces become dominant and the fluid mud flow is transported down-slope by a combination of wave activity and gravity. Under these circumstances gravity forces are dominant over the Coriolis effect (Myrow and Southard, 1996).
- Following flow initiation, turbulence is dampened below the lutocline (Reynolds likely <2000), and laminar flow is established.
- Lutocline separates wave boundary layer from core flow in the water column, reducing influence of the Coriolis effect.
- The net effect is that **WESGFs** transport the clay and very fine-grained silt fractions downslope where wave activity and the low gradients dominate sediment dispersal.

Why the mud component is important, 2

- Where mud contains a significant coarse silt component, there is typically not enough wave energy to maintain all size fractions in suspension.
- Under these circumstances, as wave energy wanes, the coarse silt fraction rapidly deposits and the lutocline disperses.
- The absence of a sharp lutocline means that the whole water column remains turbulent and the basal boundary layer remains connected to the overlying water column. This
 - *Reduces water column density friction effects, and*
 - *The Coriolis effect plays a more dominant role.*
- The net effect in this case is that a Geostrophic flow, driven by a combination of storm set-up and waves, becomes the dominant sediment dispersal mechanism. A classic normally and continuously graded tempestite with a much greater shore-parallel-dispersion component is deposited.

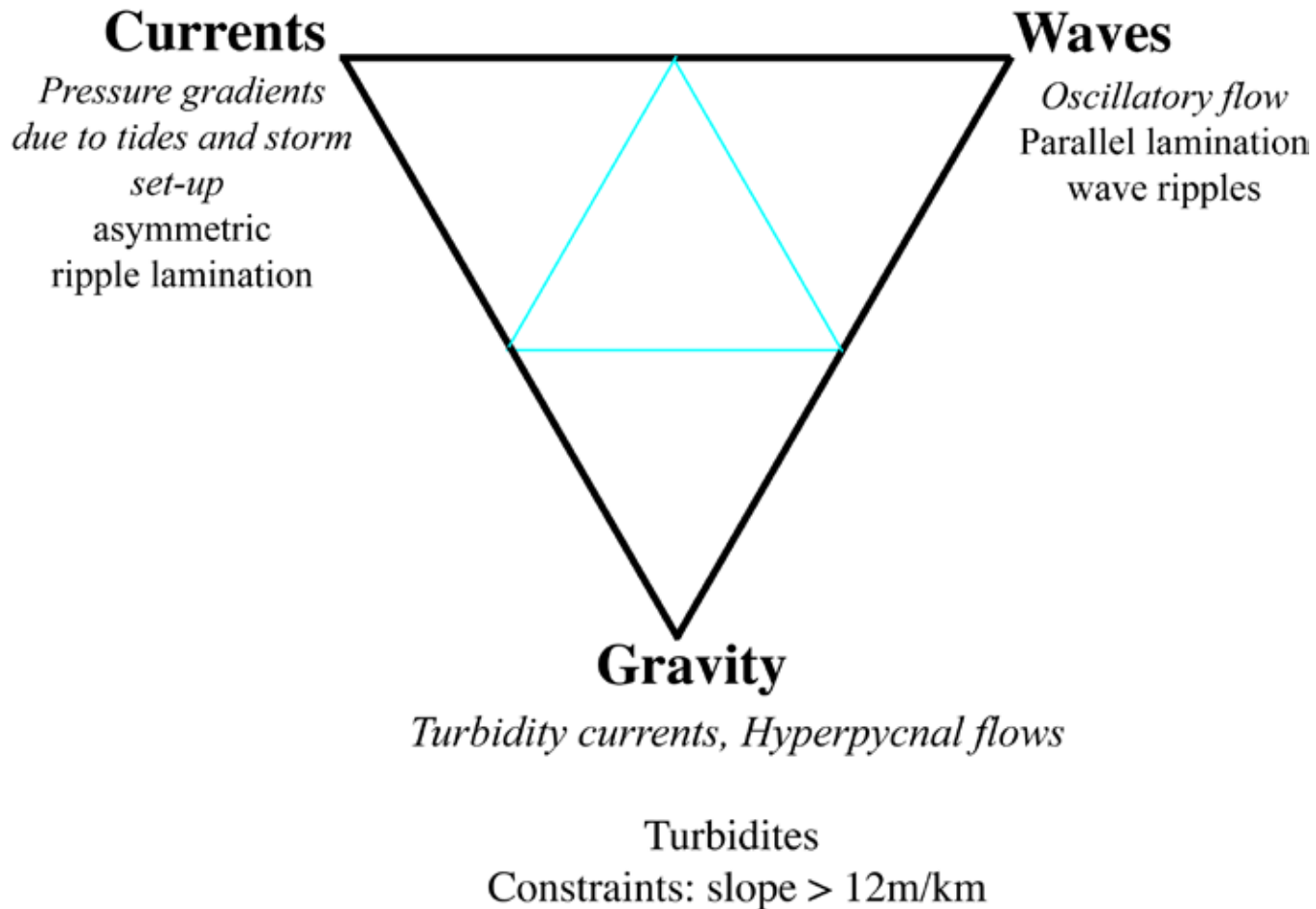
Sources of energy for shelf sediment transport

Universal criterion $U_c^* > U_{cr}^*$



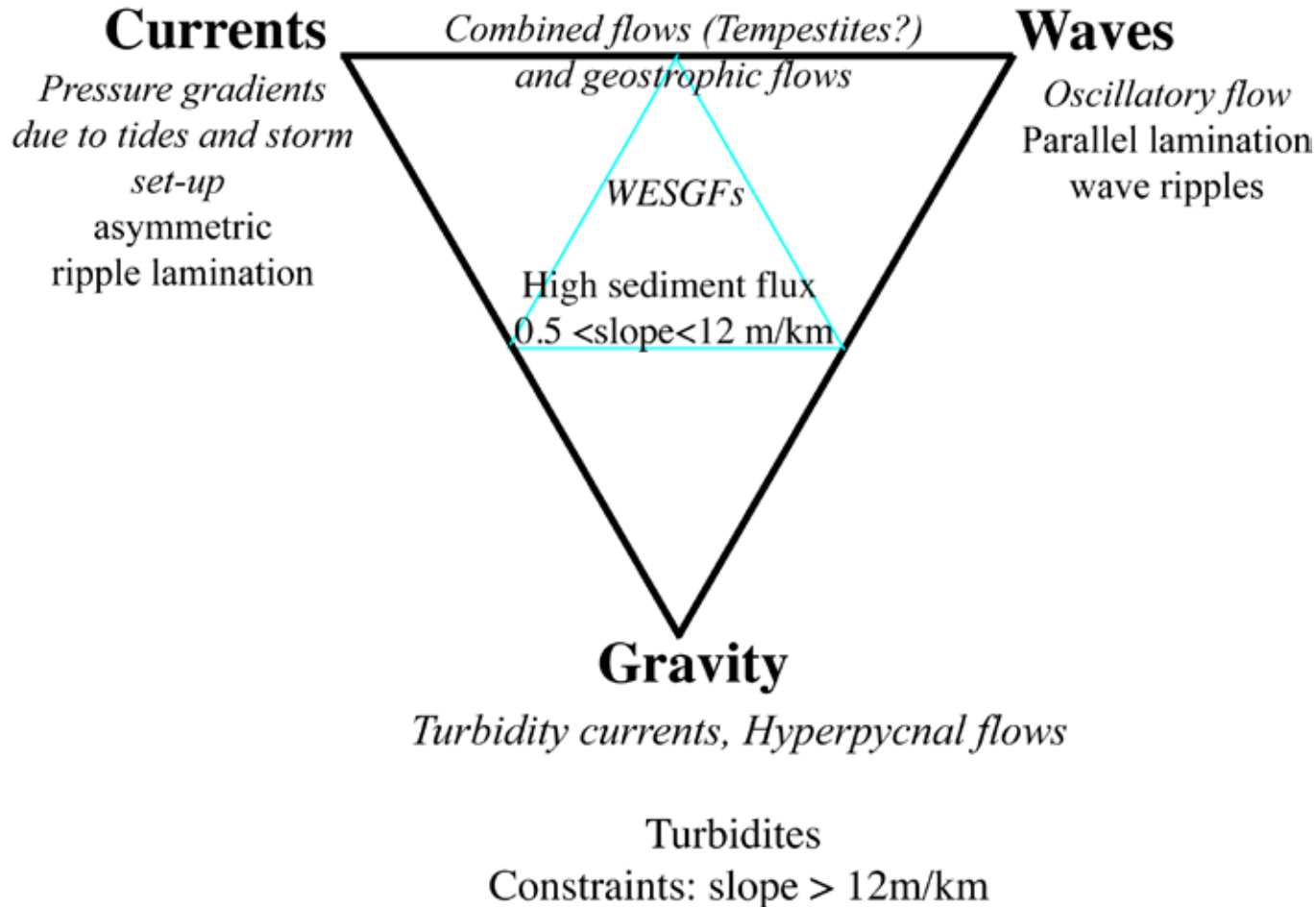
Energy and products

Universal criterion $U_c^* > U_{cr}^*$



Energy and Products

$$\text{Universal criterion } U_c^* > U_{cr}^*$$

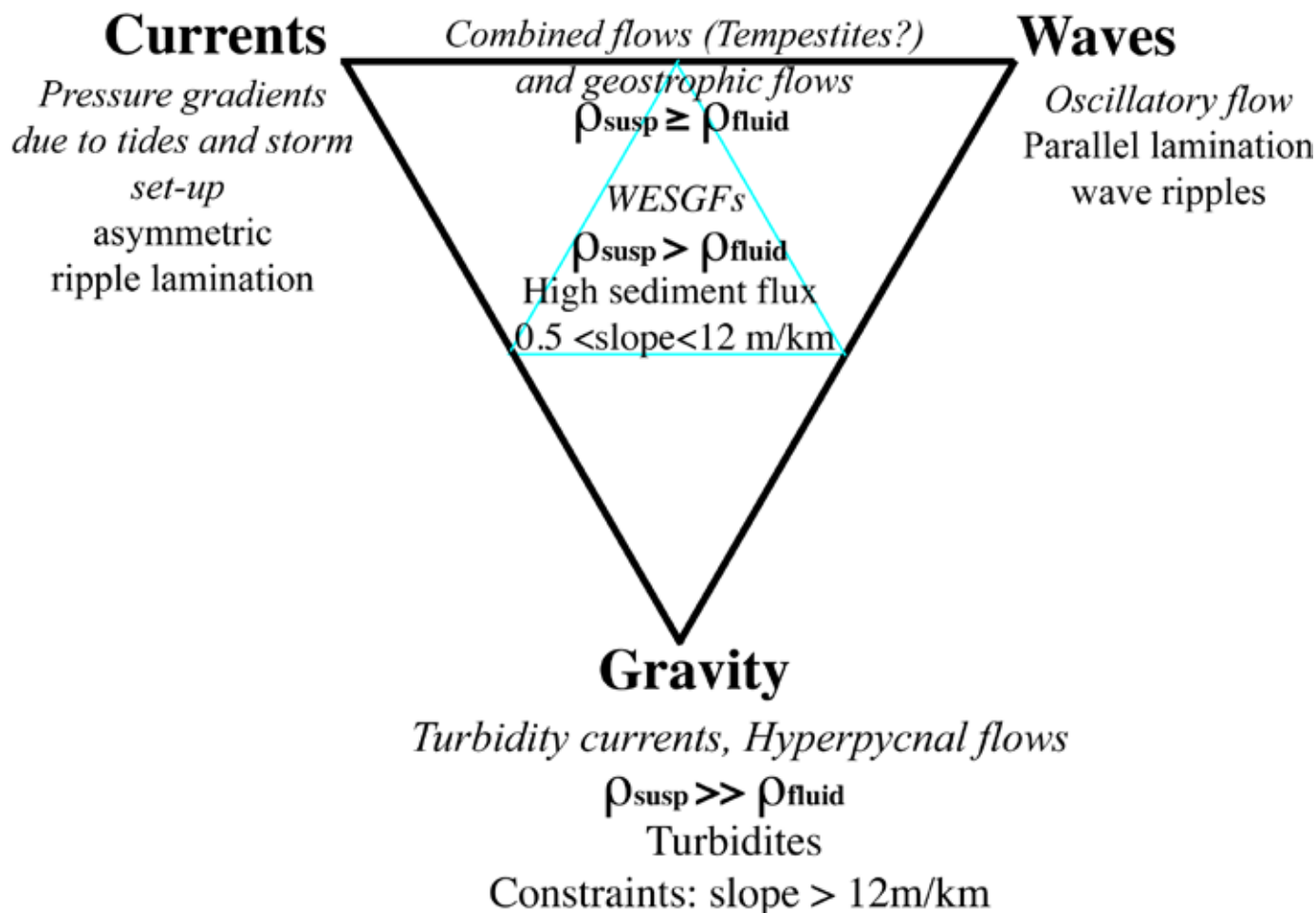


Other things to think about!

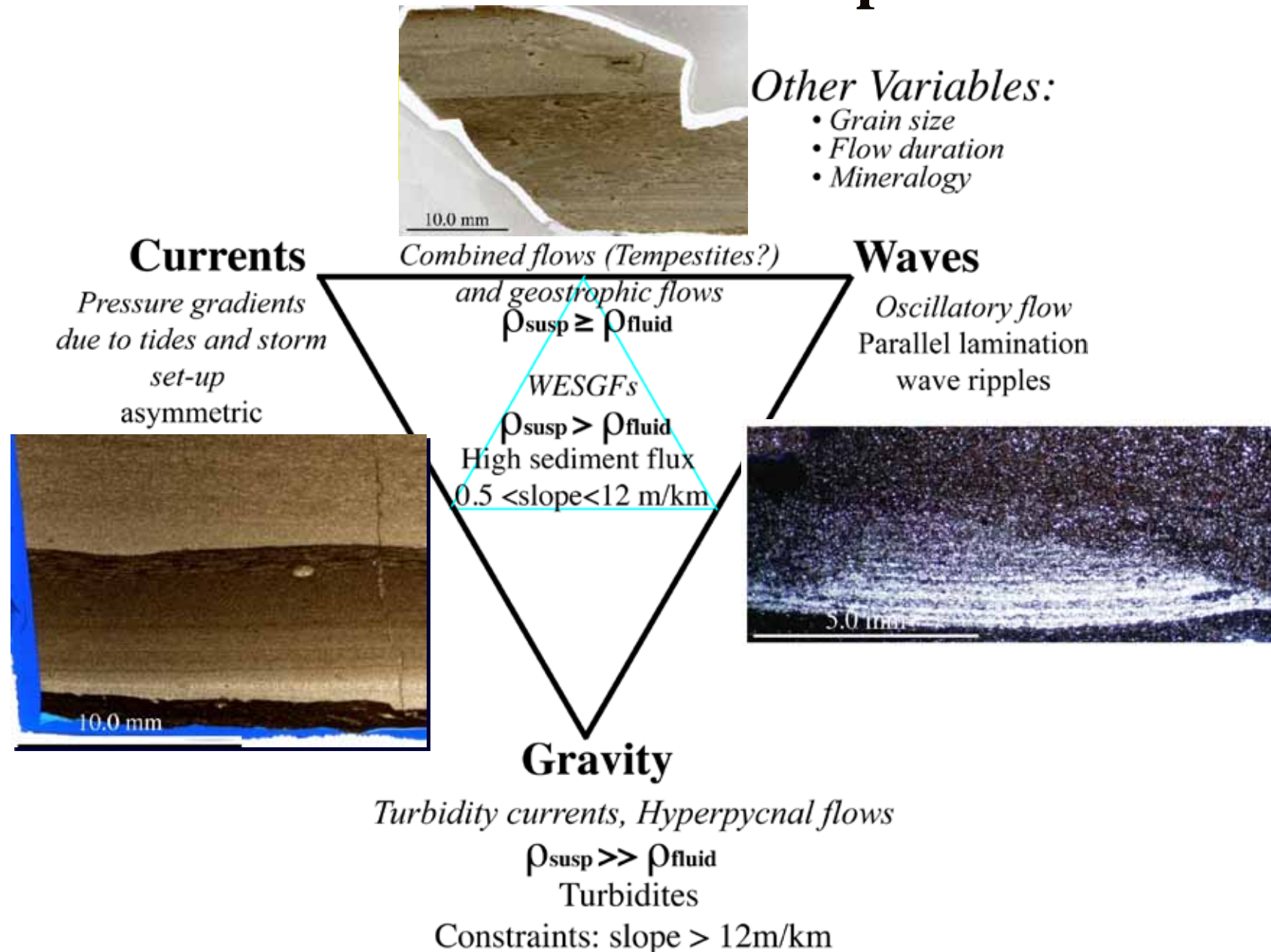
Universal criterion $U_c^* > U_{cr}^*$

Other Variables:

- Grain size
- Flow duration
- Mineralogy



Does this make a difference? Examples



A Reality Check

- Wide variety of controls interact:
 - *Gravity*
 - *Grain Size*
 - *Currents*
 - *Mineralogy (provenance)*
 - *Waves*
 - *Energy Level & Duration*
- To yield:
 - *Wide variety of products (some subtly different)*
 - *Complicated mosaic of mudstone lithofacies*
- Does NOT yield classically expected bull's eye pattern
- Interactions are broadly predictable within a sequence stratigraphic framework:
 - *Inputs of sediment & energy*
 - *Fetch*
 - *Shelf bathymetry*
 - *Systematic changes through time*