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Delivering Terrestrial Sediment to Continental Slopes: An Overview of Mechanisms*

James P.M. Syvitski[1] and Eric W.H. Hutton[1]

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[1] CSDMS Integration Facility, University of Colorado, Boulder **(james.syvitski@colorado.edu)**

Abstract

The main mechanisms for moving large volumes of sediment to, and down continental slopes include 1) Sediment delivery by hypopycnal-plumes: effective on wide shelves when sea level is near the shelf-slope break. The mechanism is effective for higher stages of sea level if the shelf is narrow and discharge is large, and is affected by the magnitude of the discharge, Coriolis deflection, winds, and Ekman transport. 2) Hyperpycnal discharge: limited to small and medium-sized rivers that drain mountainous terrain capable of generating hyper-elevated sediment concentrations. 3) Sediment gravity flows generated through wave-current interactions on relatively steep continental shelves that are subjected to ocean storms. Upwelling versus downwelling conditions are important constraints. 4) Density-cascading where shelf water is made hyper-dense, flows off the shelf, converging and accelerating. Shelf waters are made dense through cooling (e.g., cold winds), or through salinity enhancement (e.g., evaporation through winds, brine rejection under sea-ice). These bottom boundary currents can effectively erode the seafloor and carry sediment downslope either as a tractive current, or through conversion to a turbidity current. 5) Sediment failure may result from sediment loading and/or oversteepening of the upper-slope deposits. Subsurface drainage and ground accelerations can greatly influence the size and extent of the failure surface. The failed sediment mass will transition to either a debris flows or turbidity current. 6) Theory also suggests that internal waves breaking on the upper slope may also mobilize seafloor sediment. Many other mechanisms can influence the transport of sediment down continental slopes, but they are not considered volumetrically significant.

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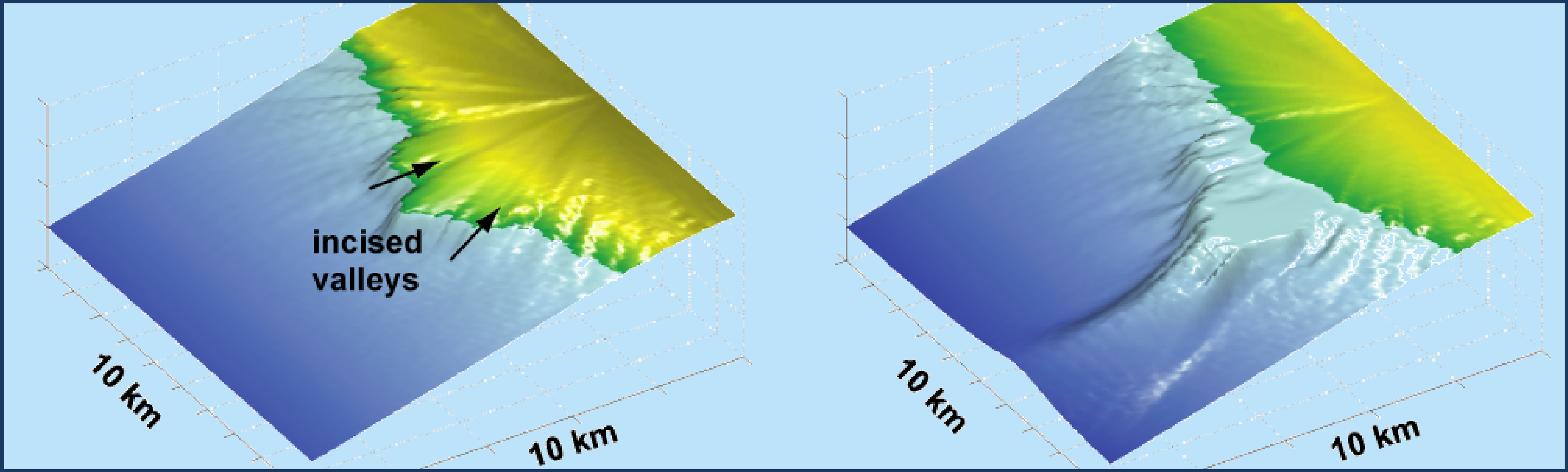
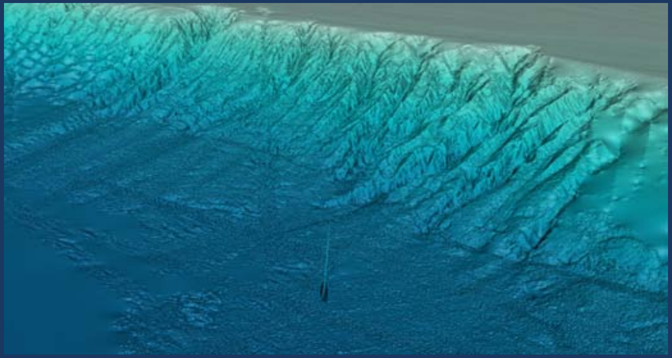
James P M Syvitski & Eric W.H. Hutton
CSDMS Integration Facility
U. Colorado—Boulder



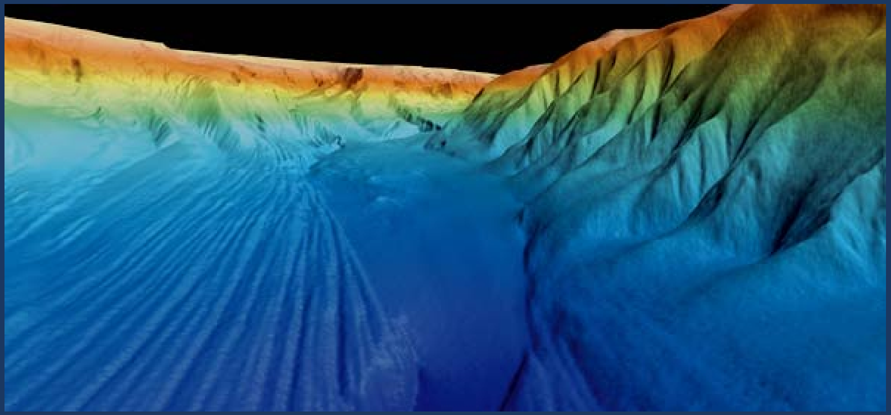


Community Surface dynamics
CSDMS
Modeling system

Syvitski & Hutton, 2008 AAPG/SEPM, San Antonio

Main mechanisms for moving sediment to & down continental slopes

1) Sediment delivery by hypopycnal (surface) plumes (2)
2) Hyperpycnal discharge (3)
3) Wave-supported bottom-boundary flows (3)
4) Density-cascading (2)
5) Sediment failure leading to sediment gravity flows (3)
6) Internal waves resuspending upper slope sediment (1)



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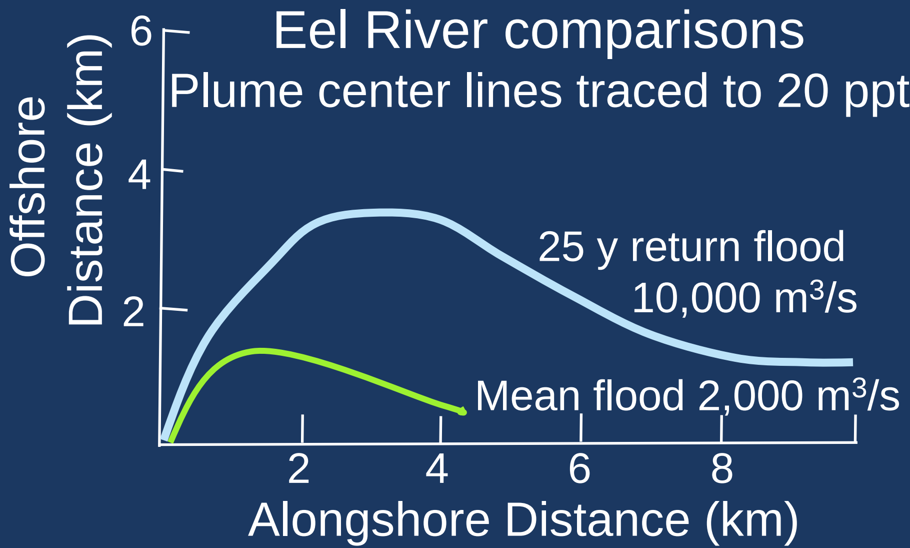
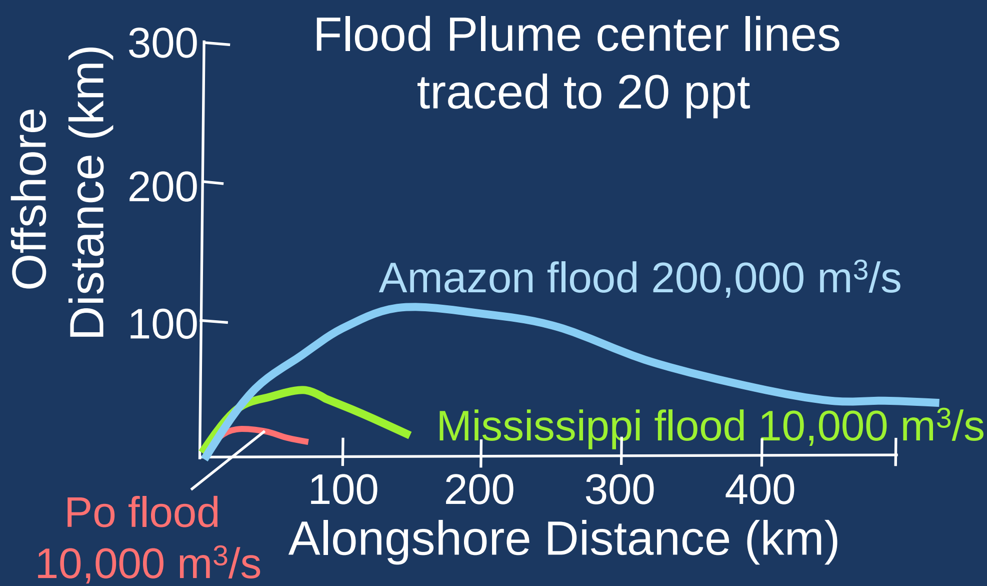
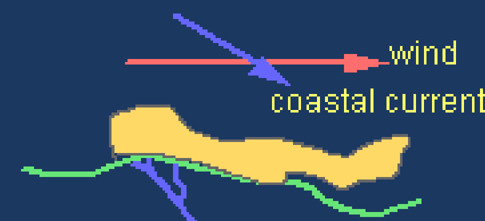


Hypopycnal plumes — effective when sea level is near to the shelf-edge, or during highstands if shelf is narrow, or discharge is large.

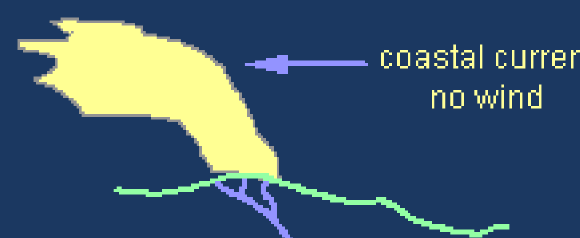
Contributing factors — magnitude of discharge, Coriolis deflection, wind conditions, ocean currents, coastal up- downwelling, and plume injection.



Coast-hugging Plume
(Kelvin Wave-influenced)



Detached Coastal Plume



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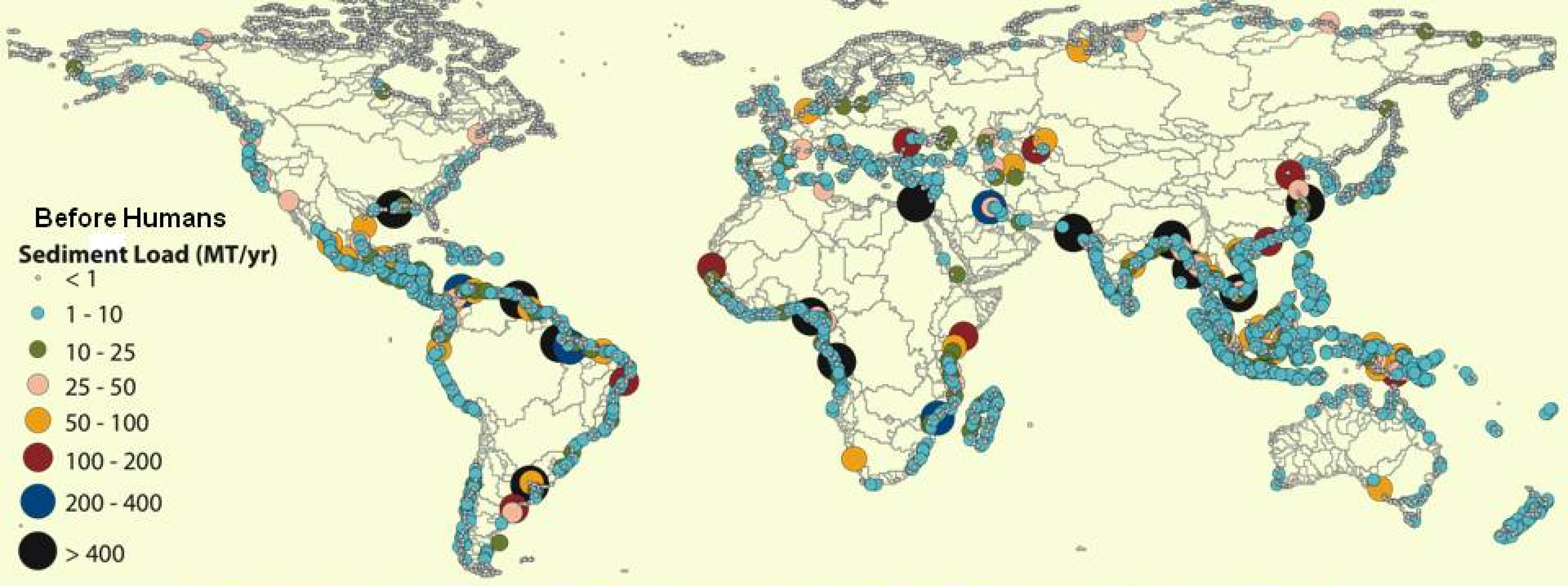

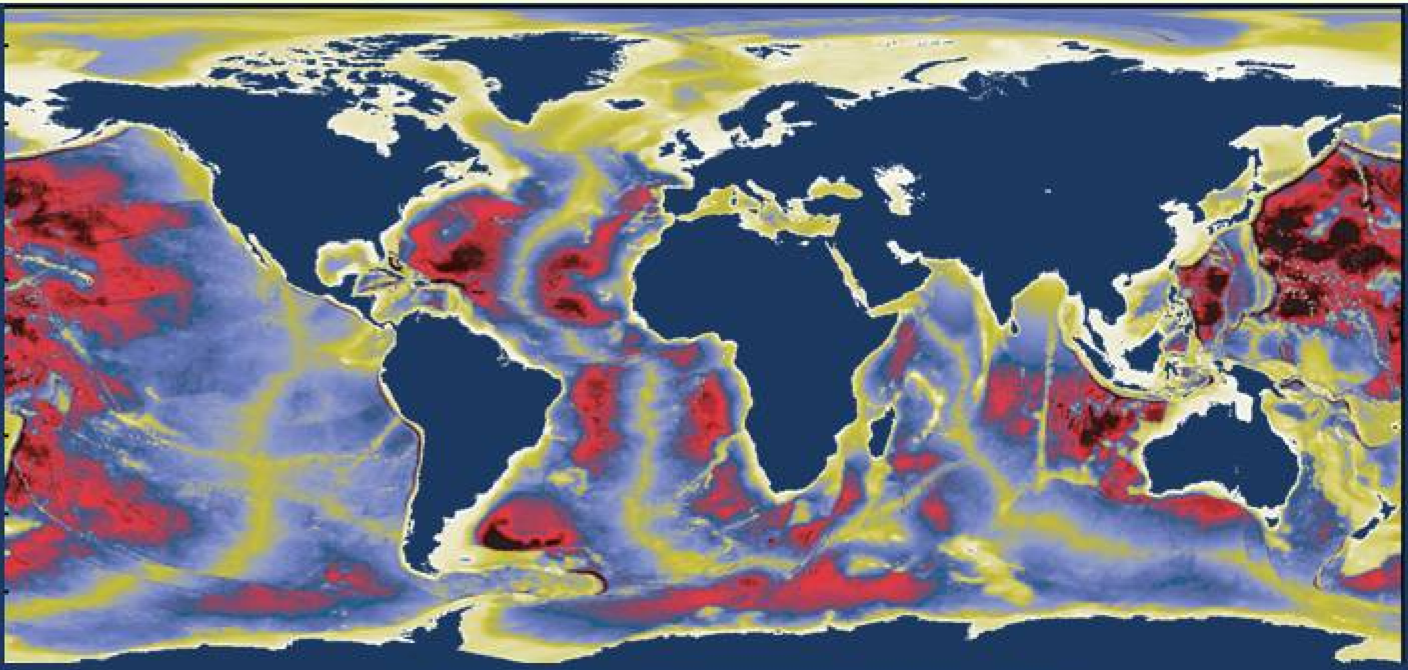

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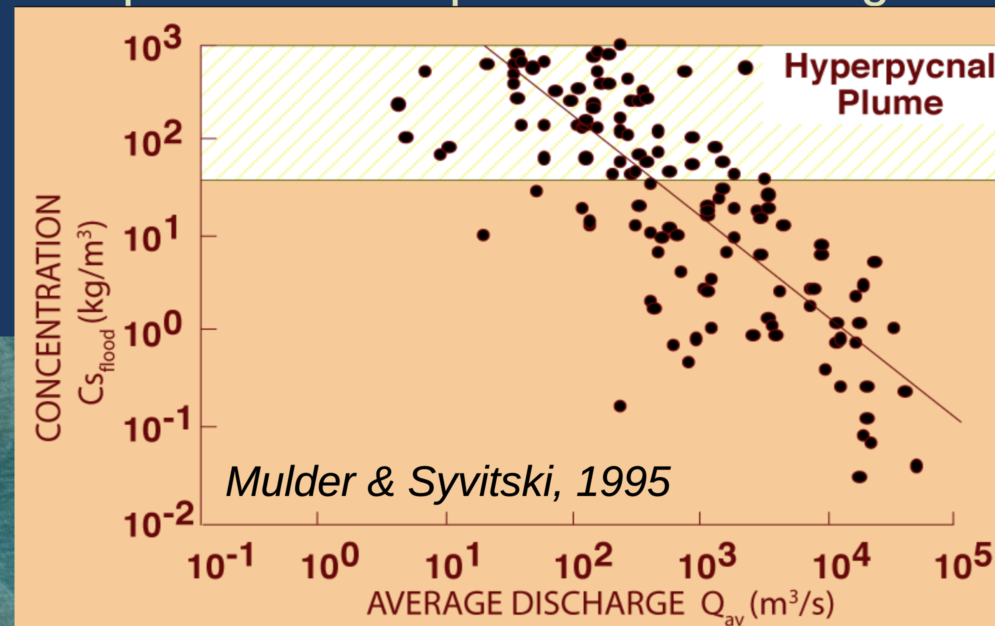
Hyperpycnal discharge is limited to small & medium-sized rivers that drain mountains capable of generating hyper-elevated sediment concentrations during infrequent high-energy floods.

Critical Marine Concentrations

Equatorial: $Cs^* > 36\ kg/m^3$

Sub-tropical: $Cs^* > 39\ kg/m^3$

Temperate & Sub-polar: $Cs^* > 42\ kg/m^3$



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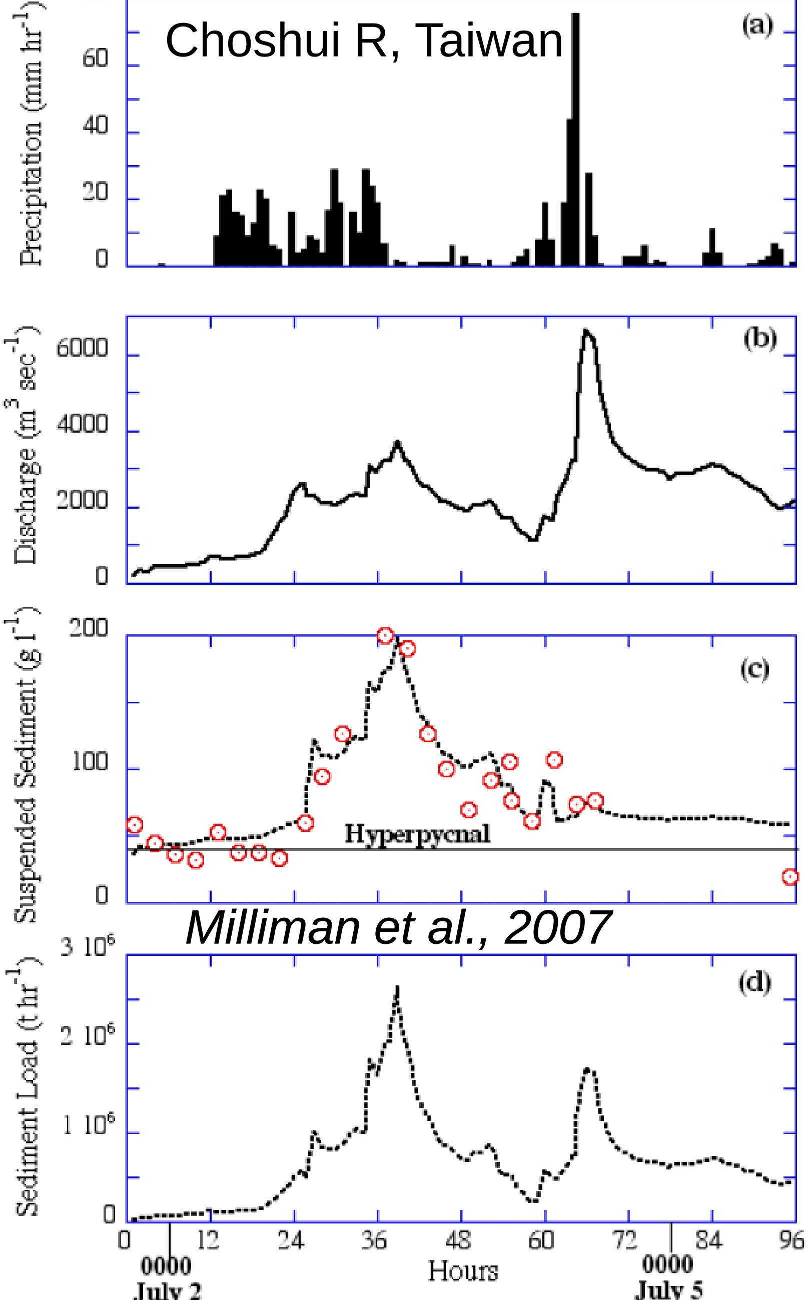

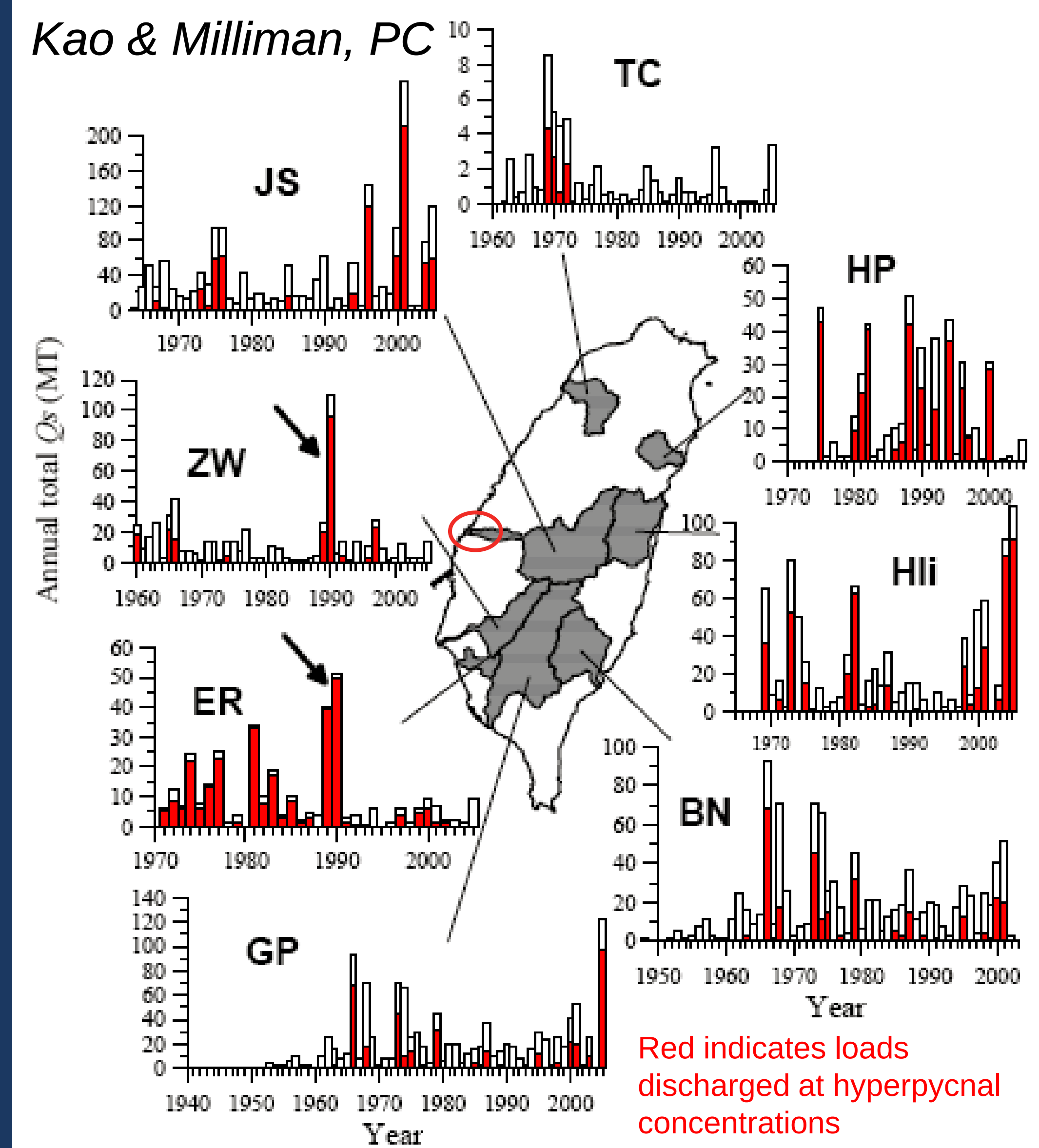

Taiwanese Rivers go hyperpycnal every few years, aided by earthquakes and typhoons.

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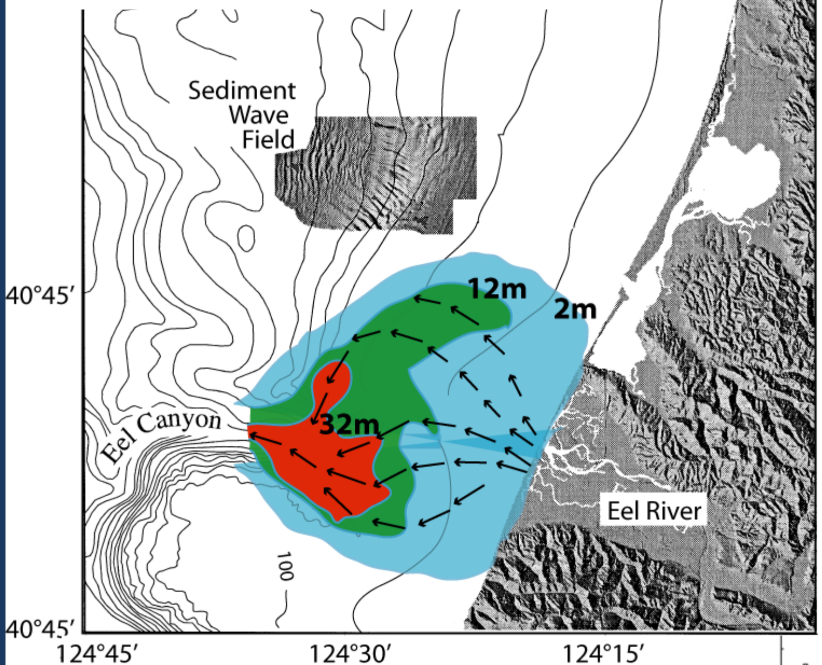
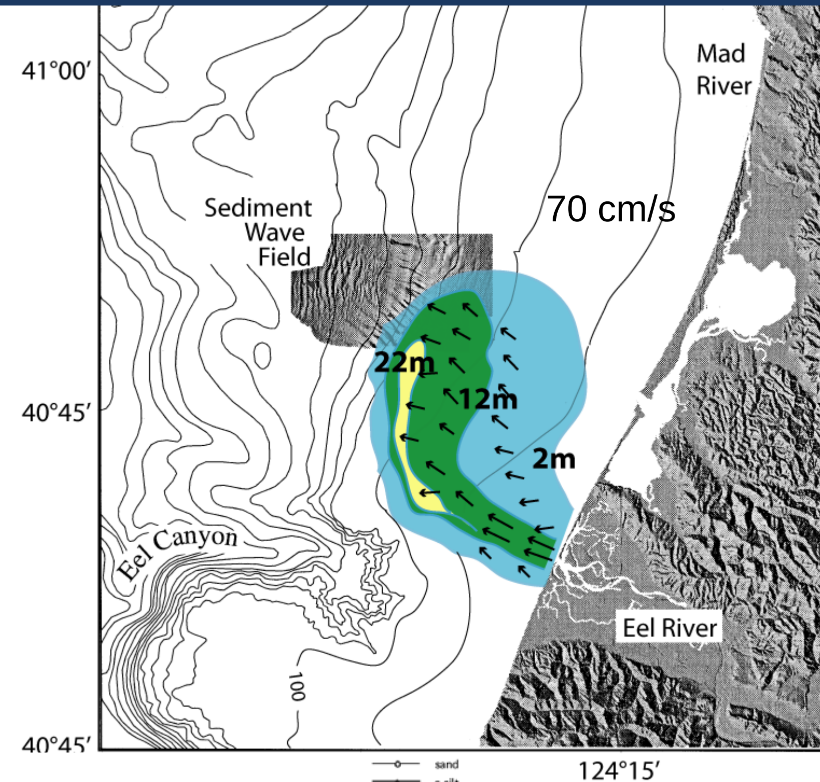
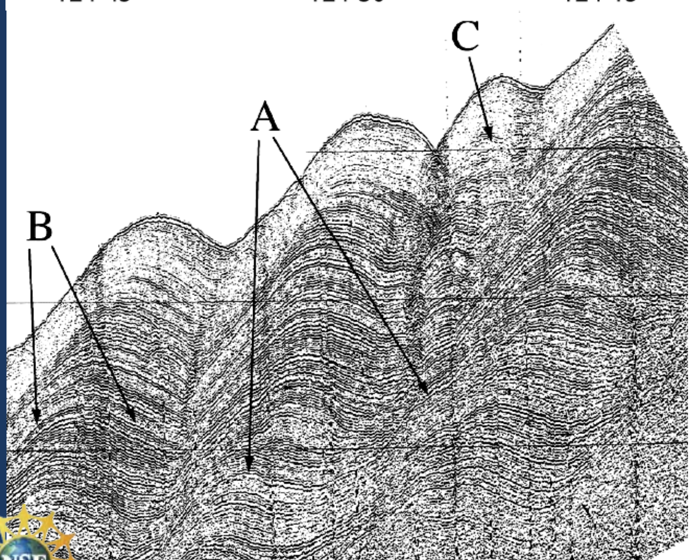
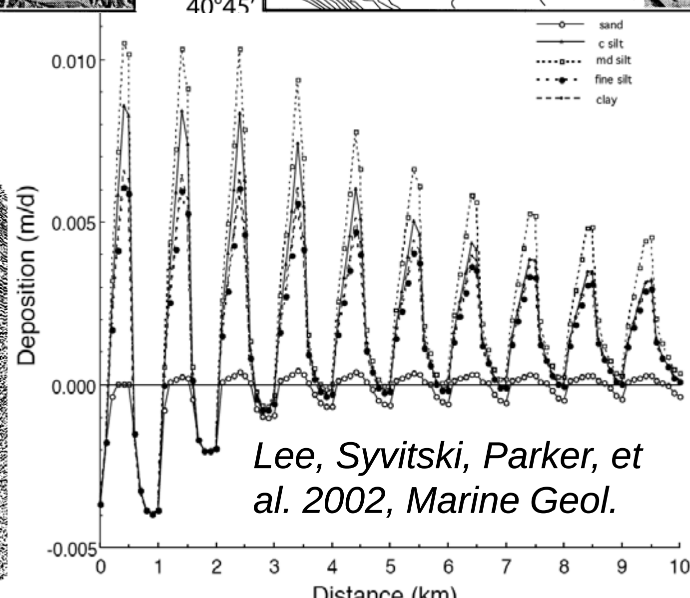
Imran & Syvitski, 2000, Oceanography









Lee, Syvitski, Parker, et al. 2002, Marine Geol.

Hyperpycnal flows are influenced by along shelf currents & bathymetry.

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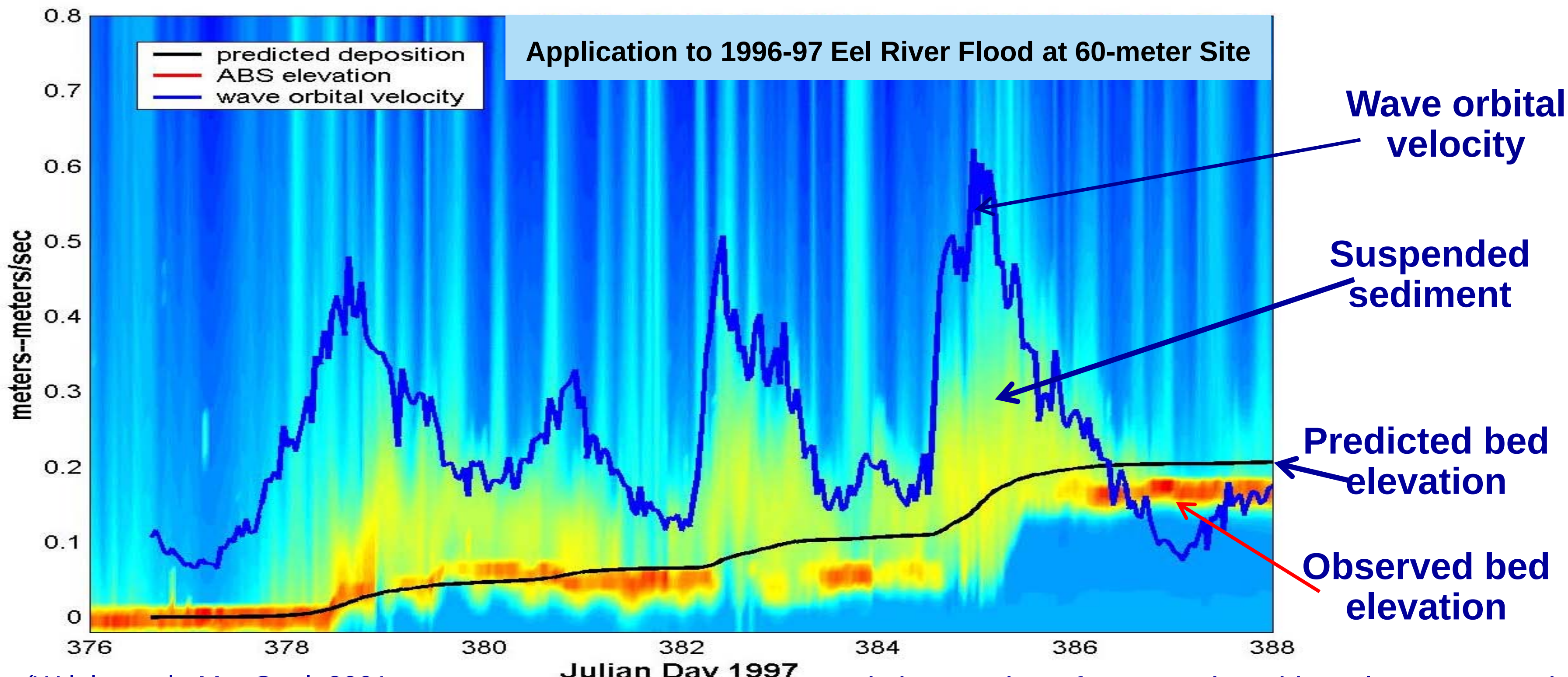
Sediment gravity flows generated through wave-current interactions on relatively steep continental shelves subjected to large ocean storms

$$Deposition = \frac{Ri_{cr}^{\ 2}}{(1-P)C_d gS} \frac{d}{dx}\left(\alpha U_{max}^{\ 3}\right) \qquad U_{max} = \sqrt{U_w^{\ 2} + V_C^{\ 2} + U_{grav}^{\ 2}}$$



(Wright et al., Mar.Geol. 2001

(Observations from Traykovski et al., CSR 2000)

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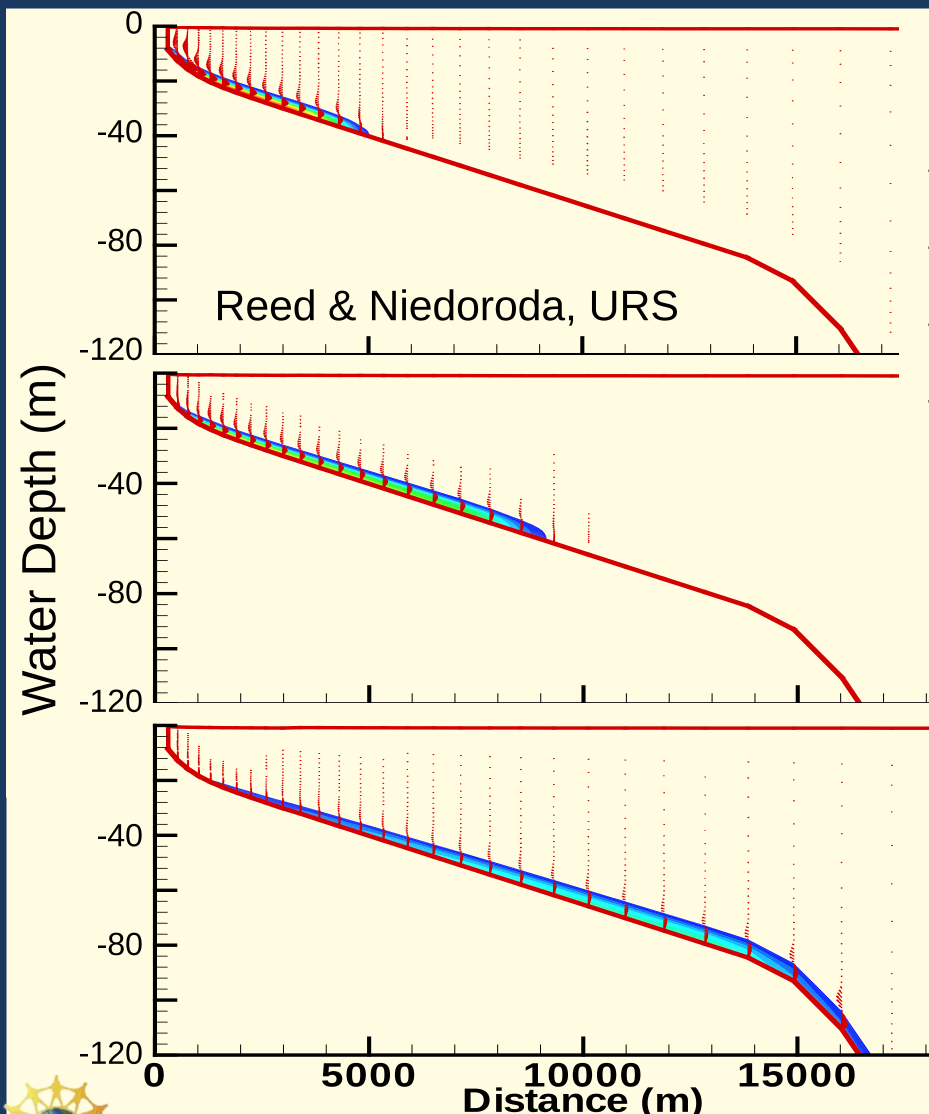
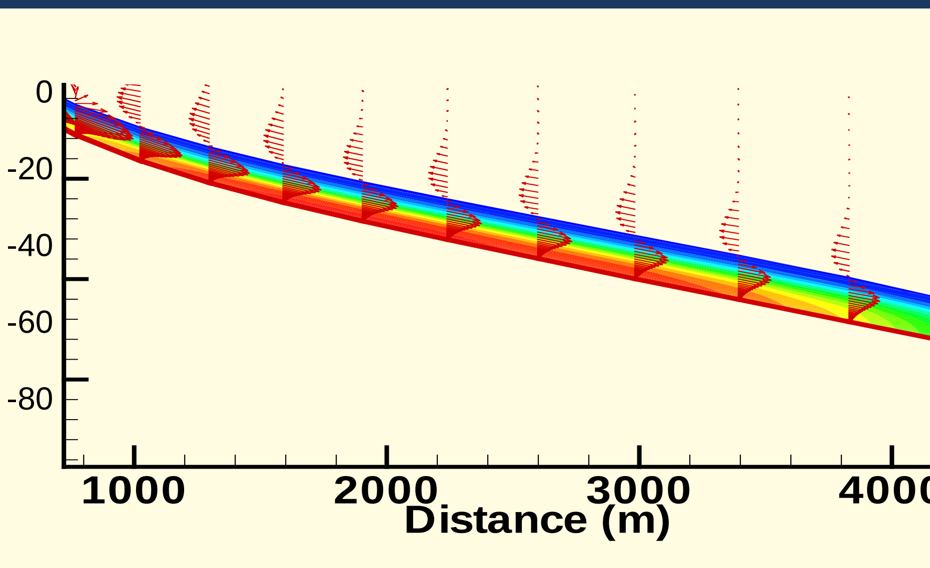
Ekman Transport (upwelling & downwelling) are important constraints on wave-supported gravity flows.





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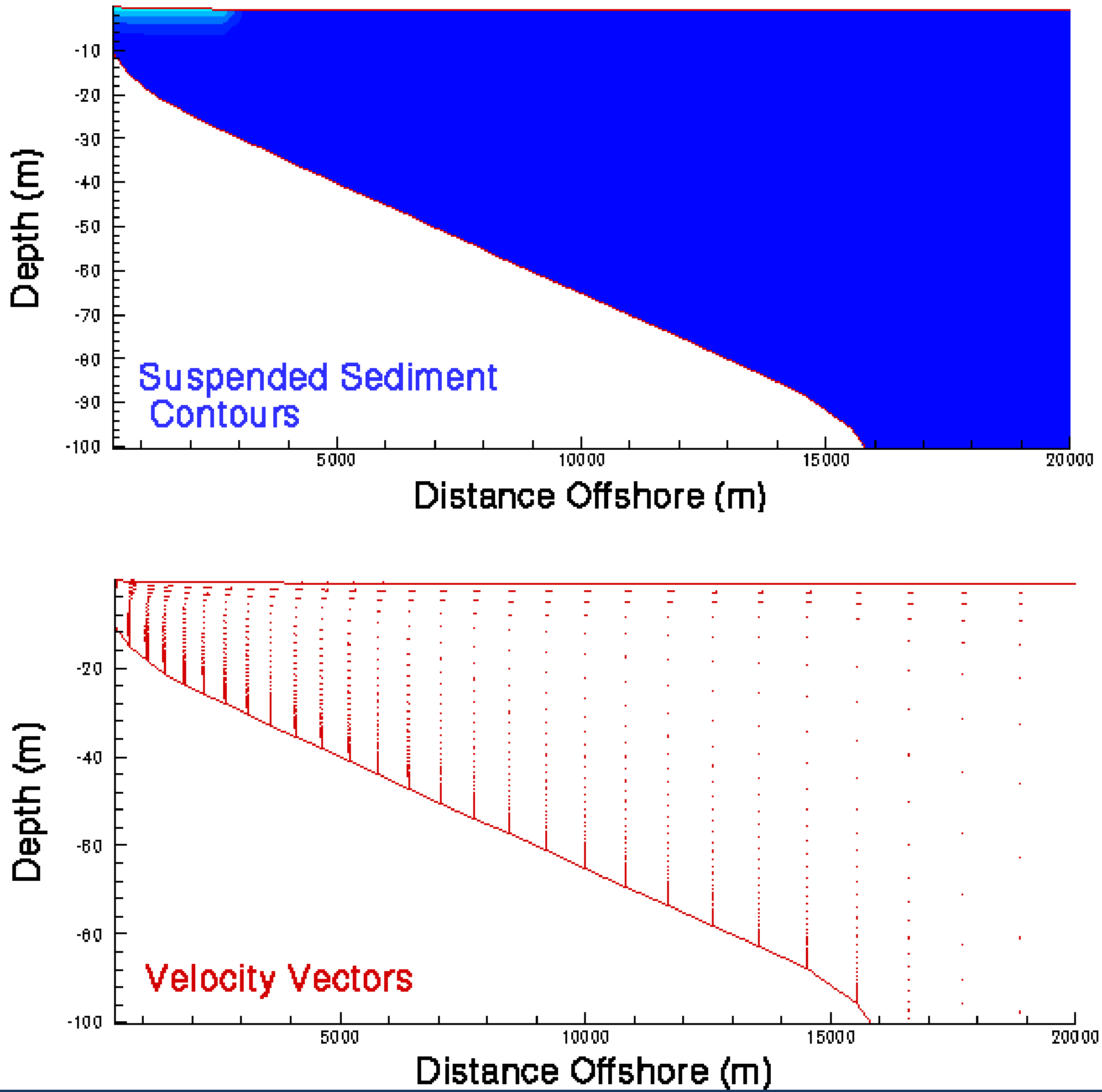


Reed & Niedoroda, URS

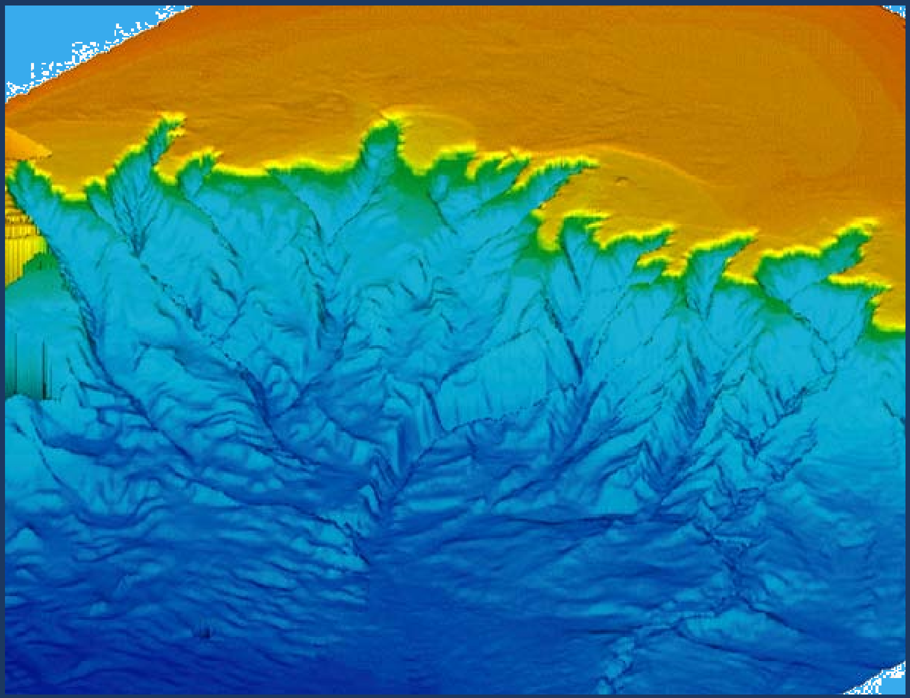
Density-cascading occurs where shelf waters are made hyper-dense through:

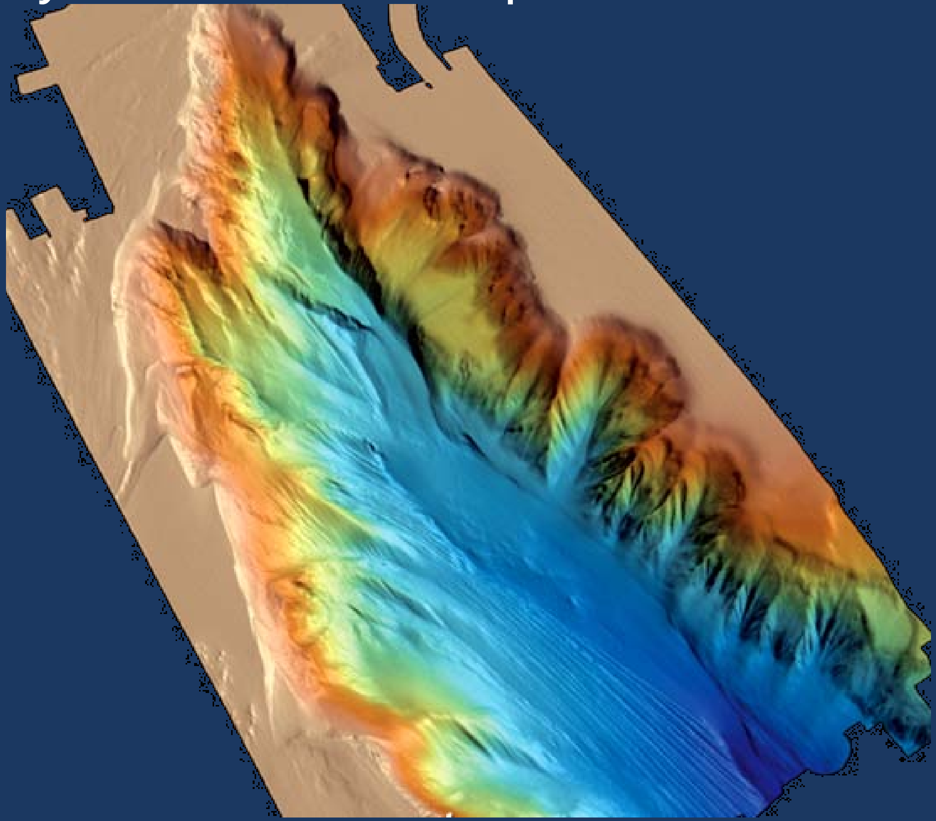
cooling (e.g. cold winds blowing off the land), or

salinity enhancement (e.g. evaporation through winds, brine rejection under ice)

Shelf Flows converge in canyons and accelerate down the slope.

Currents are long lasting, erosive & carry sediment downslope as a tractive current, or as turbidity current.





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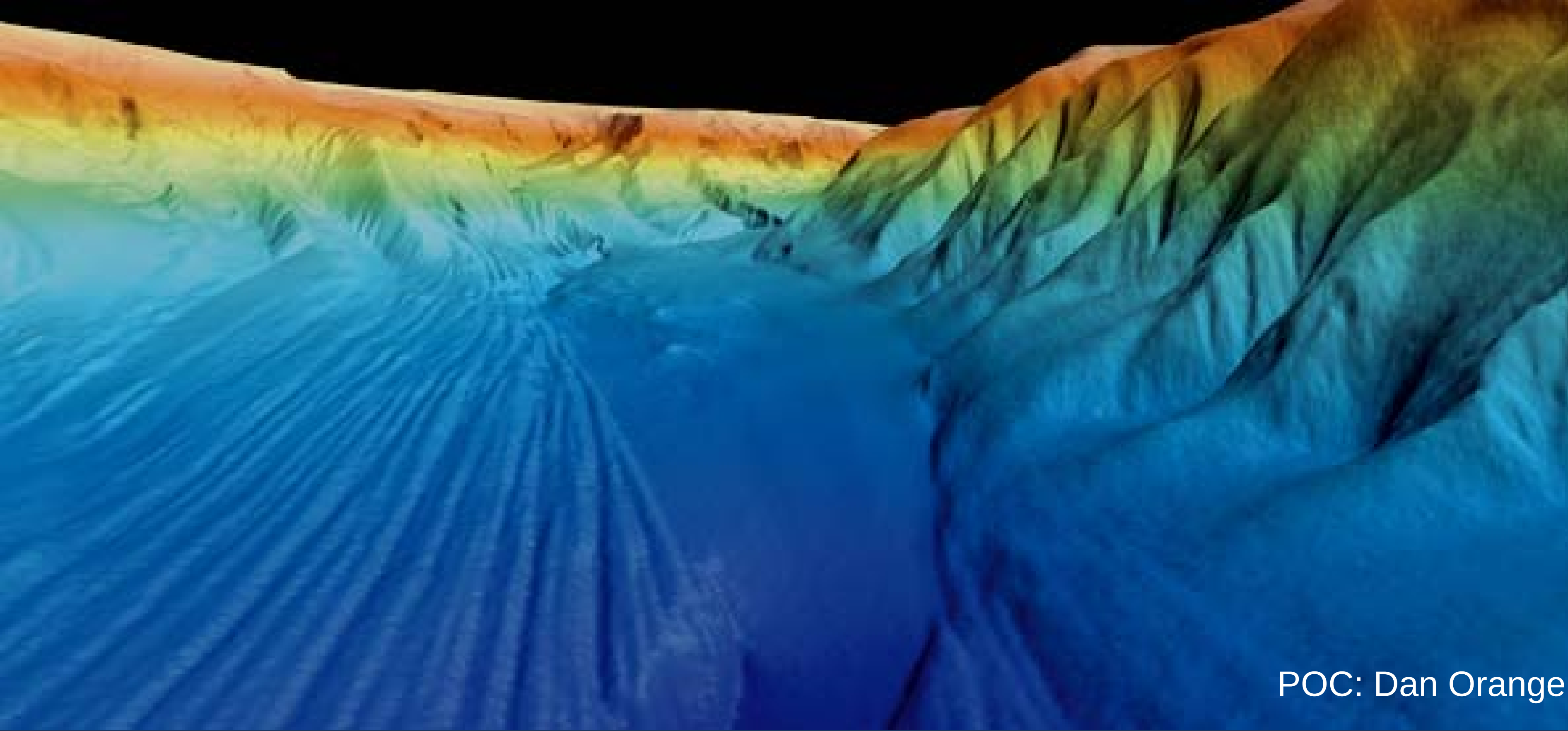
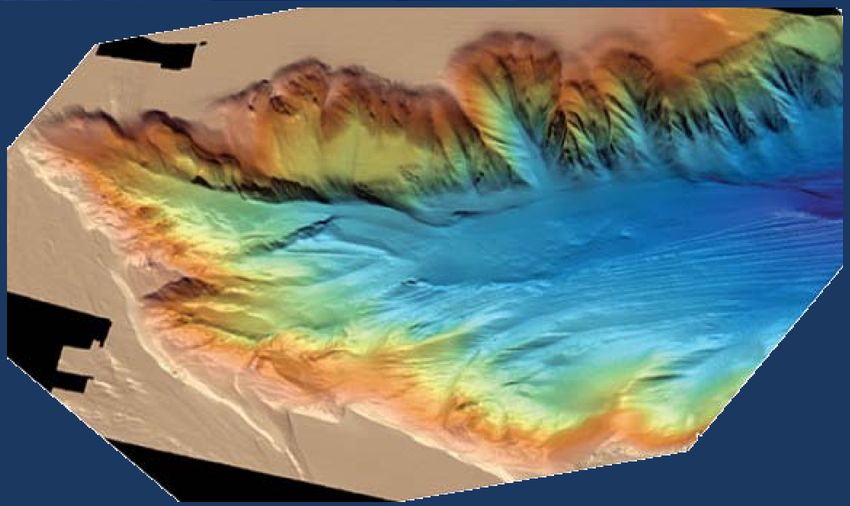
Syvitski & Hutton, 2008 AAPG/SEPM, San Antonio



Cold water enters canyon across south rim. Erosive current generates furrows. Flows are active today. Sand and mud carried by currents.



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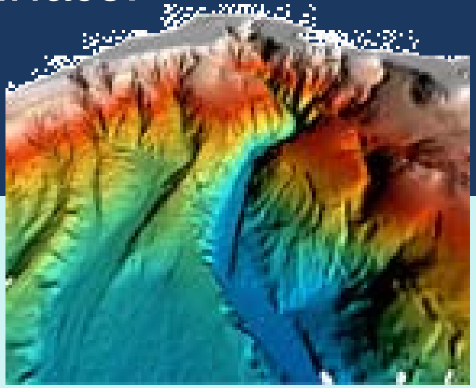
<u>Sediment failure</u> may result from sediment loading and or over-steepening of the upper-slope deposits. Subsurface drainage and ground accelerations can greatly influence the size and extent of the failure surface.



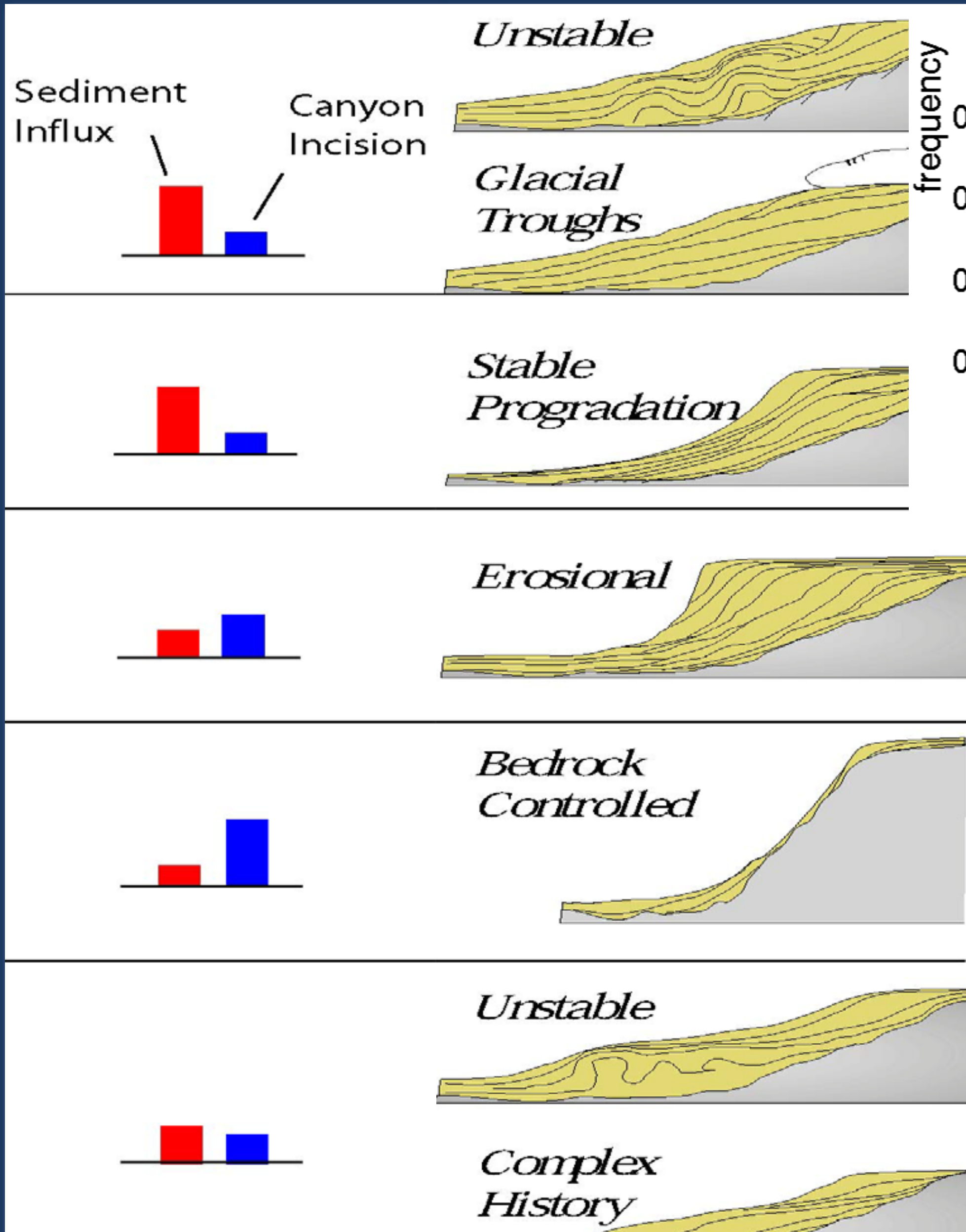
$$F_T = \frac{\sum_{i=0}^{n} b_i \left(c_i + \left(\frac{W_{vi}}{b_i} - u_i \right) \tan\phi_i \right) \frac{\sec\alpha_i}{1 + \frac{\tan\alpha_i \tan\phi_i}{F_T}}}{\sum_{i=0}^{n} W_{vi} \sin\alpha_i + \sum_{i=0}^{n} W_{Hi} \cos\alpha_i} = \frac{\mathrm{Resistance}\, Force}{Driving\, Force}$$

b_i = width of ith slice; c_i=sediment cohesion; ϕ_i = friction angle;

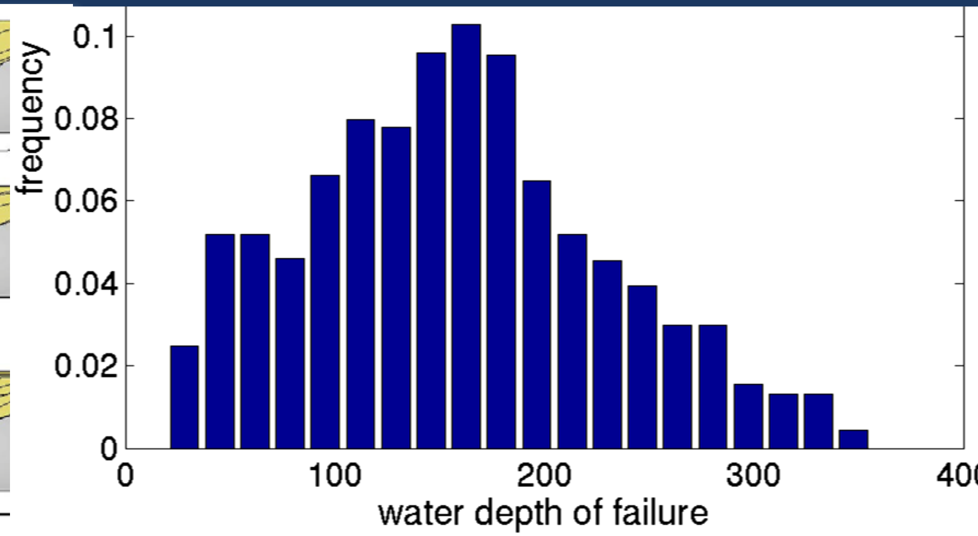
W_{vi} = vertical weight of column = $M(g+a_e)$; α = slope of failure plane;

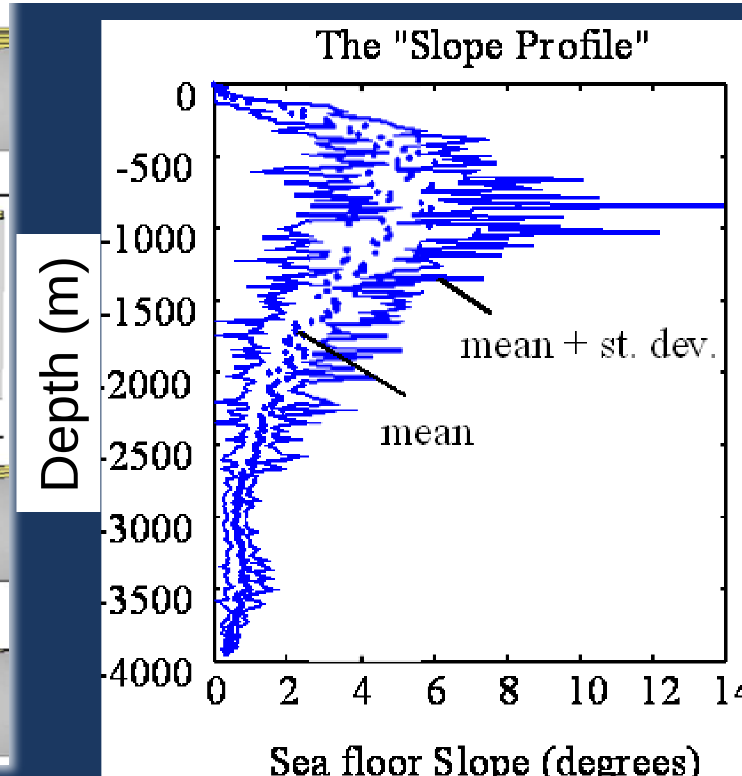
W_{hi} = horizontal pull on column = Ma_e; g = gravity due to gravity;

a_e = acceleration due to earthquake; u_i = pore pressure



O’Grady et al.





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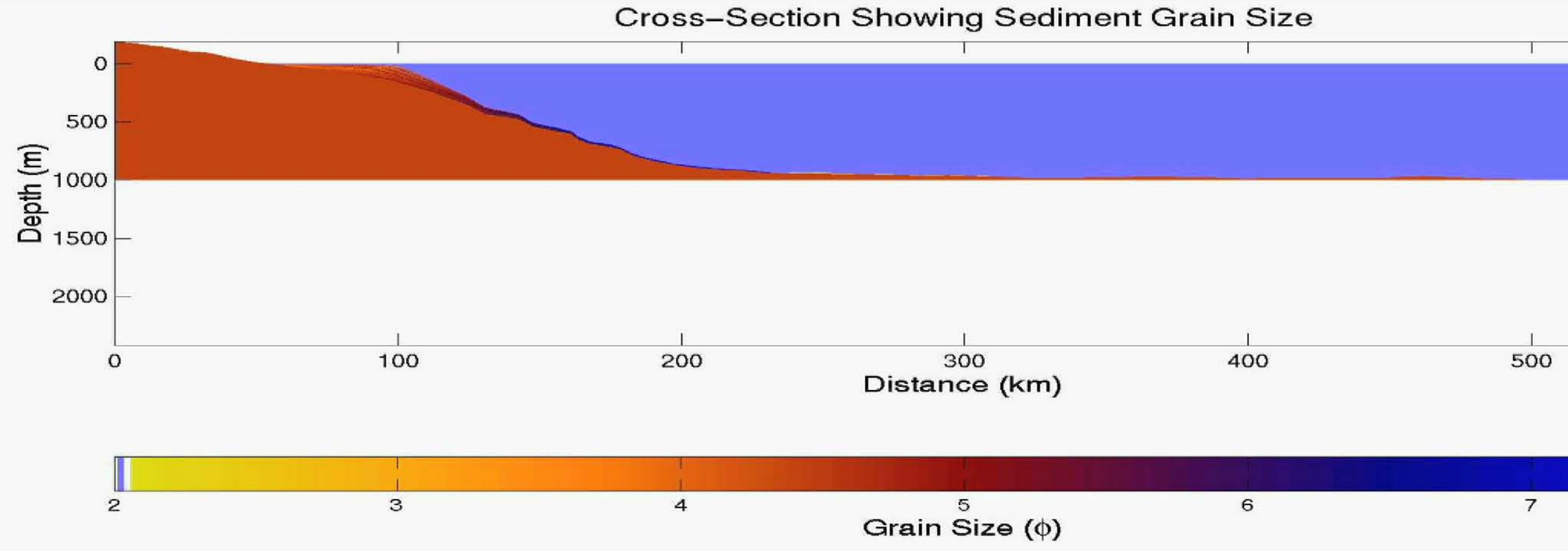

The failed sediment mass will transition to a slide, slump, debris flow or turbidity current. The science on this transition is still poorly understood, but is known to depend on the material properties (grain size, clay minerals, permeability, cohesion) of the failed sediment. Where the failed material contains significant fraction (5 to 15%) of clay size minerals, then a debris flow is likely. Silty & sandy sediment will likely liquefy and move as a turbidity current, eroding finer material along the way.

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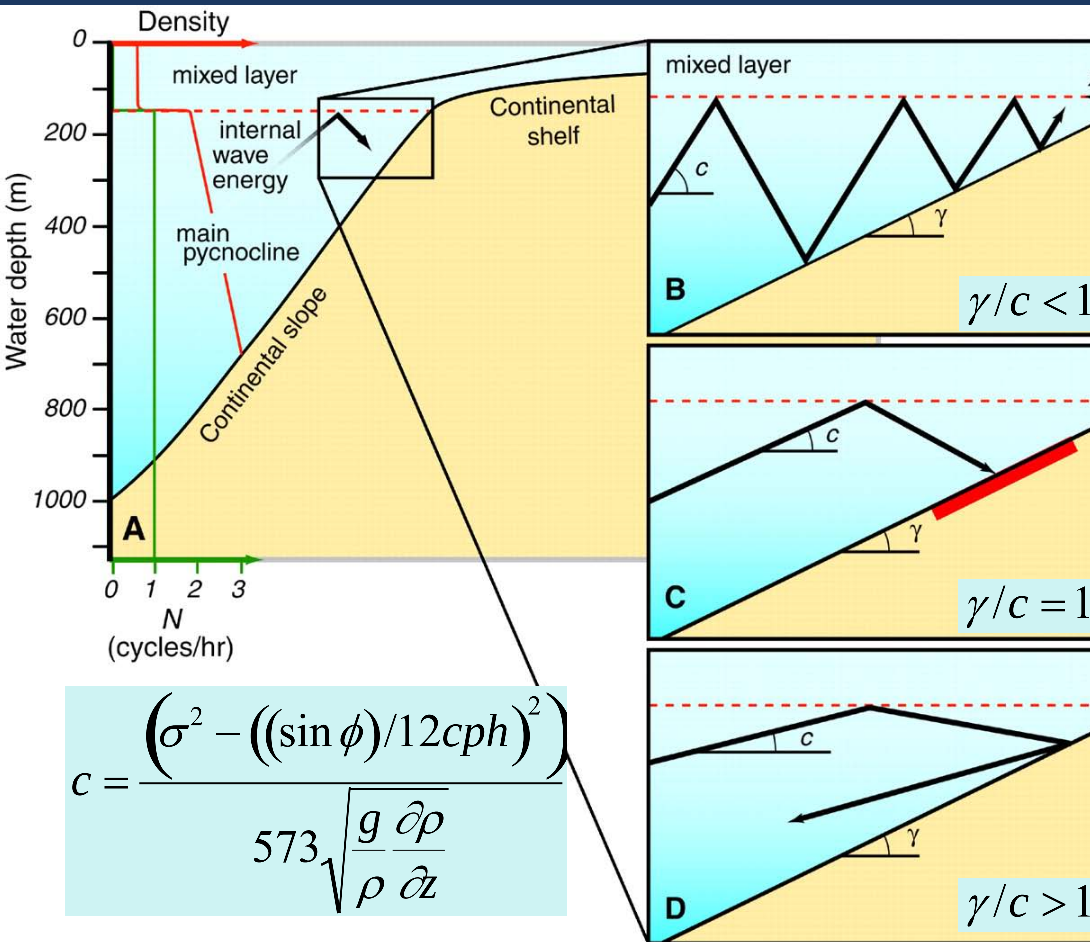
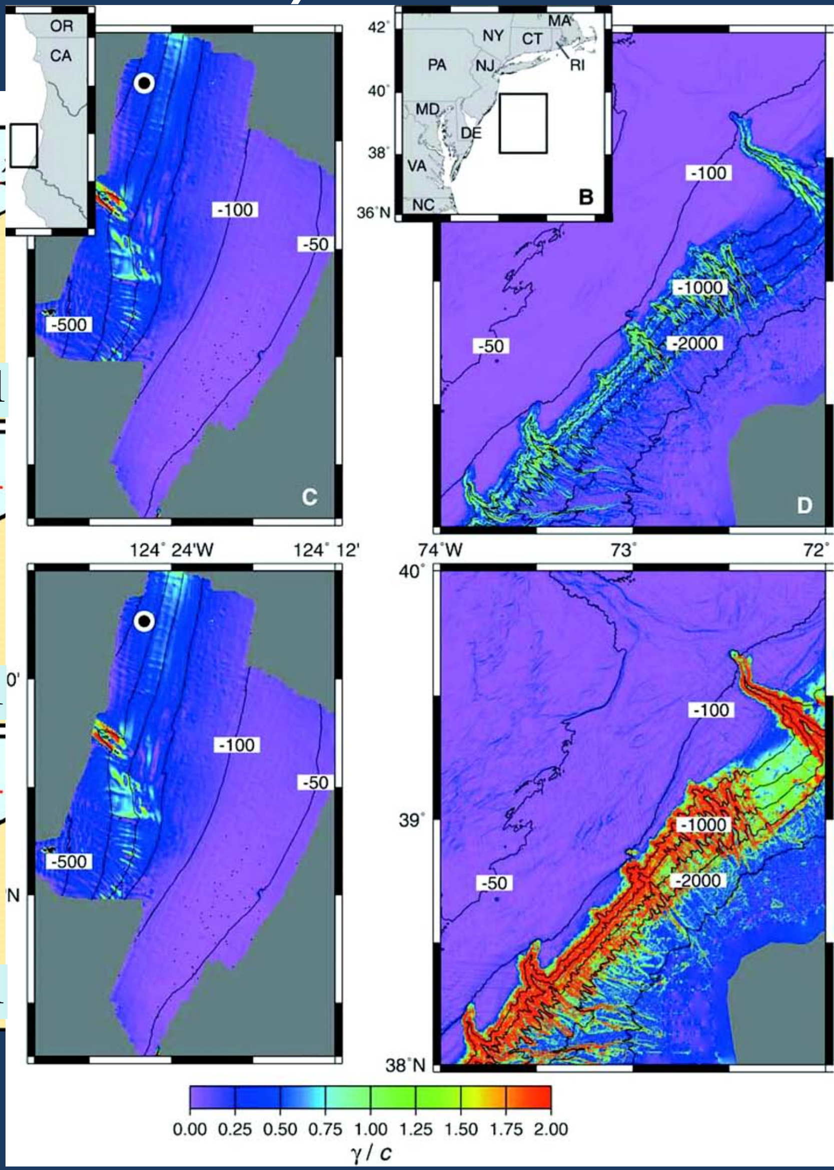
Internal waves breaking on the upper slope may also mobilize seafloor sediment (Cacchione et al, 2007 Science).



$$c = \frac{\left(\sigma^2 - \left((\sin\phi)/12cph\right)^2\right)}{573\sqrt{\frac{g}{\rho}\frac{\partial\rho}{\partial z}}}$$



$$\gamma/c = \frac{\text{seafloor slope}}{\text{internal tide angle}}$$

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SUMMARY

1) **Surface plumes:** flood discharge, shelf currents, shelf width

2) **Hyperpycnal flows:** plume concentration, shelf slope, currents

3) **Shelf fluid muds:** river supply, wave E, shelf slope, downwelling

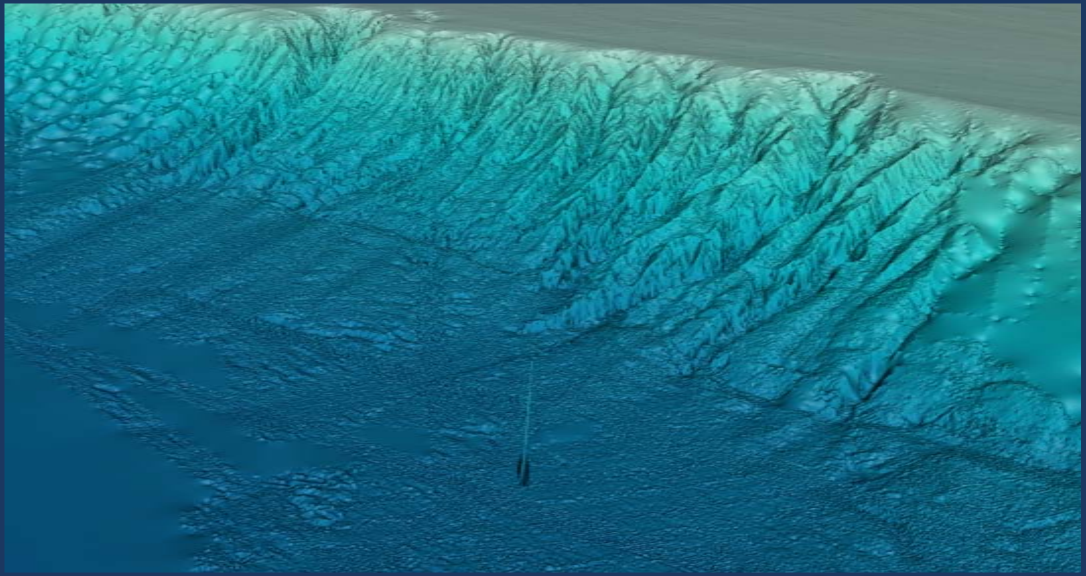
4) **Density-cascading:** climatology & oceanography

5) **Failure to gravity flows:** slope sedimentation, earthquakes, material properties, excess pore pressure

6) **Internal wave resuspension:** internal tides & seafloor slope

Other Secondary Processes

1. Nepheloid transport
2. Geostrophic currents and eddies
3. Ice sheet delivery, and iceberg & sea ice rafting



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