Earth-surface Dynamics Modeling & Model Coupling

A short course

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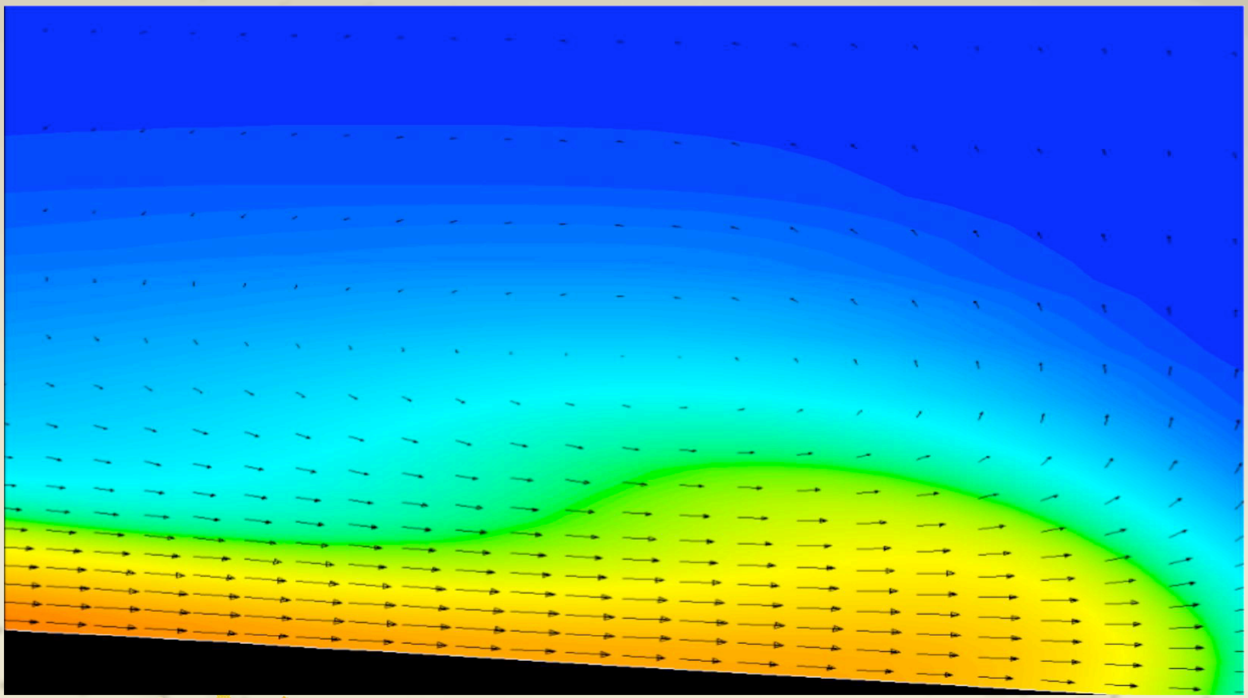
With special thanks to Jasim Imran, Gary Parker, Marcelo Garcia, Chris Reed, Yu'suke Kubo, Lincoln Pratson



after A. Kassem & J. Imran

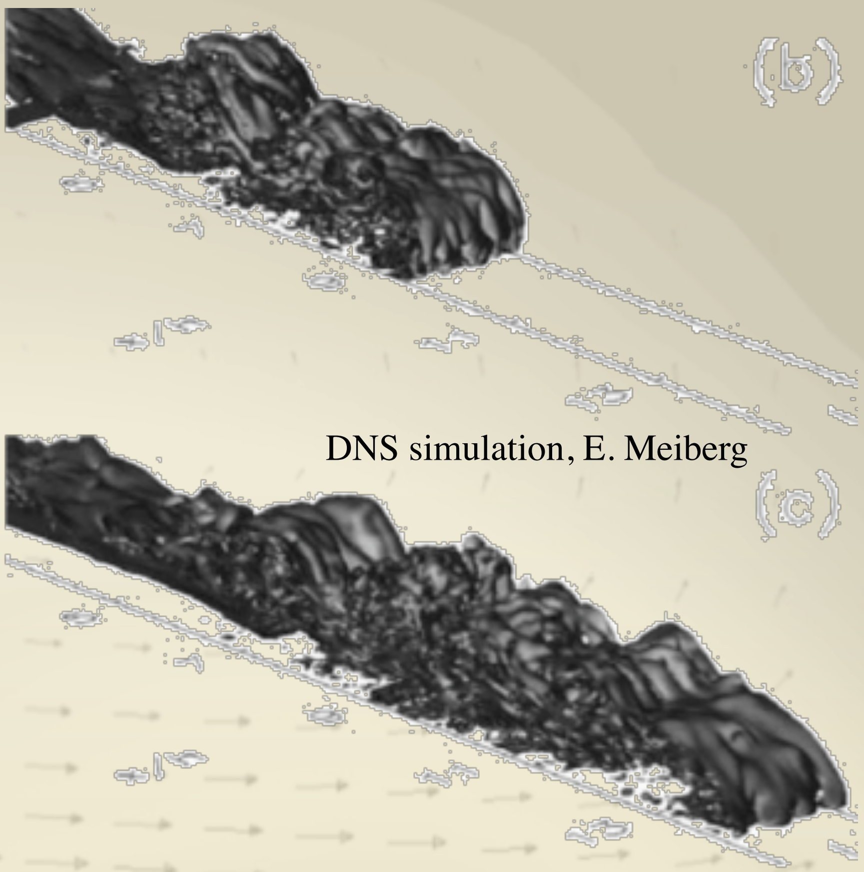
University of Colorado at Boulder

COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

University of Colorado Boulder

Module 6: Density Currents, Sediment Failure & Gravity Flows

ref: Syvitski, J.P.M. et al., 2007. Prediction of margin stratigraphy. In: C.A. Nittrouer, et al. (Eds.) Continental-Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. IAS Spec. Publ. No. 37: 459-530.



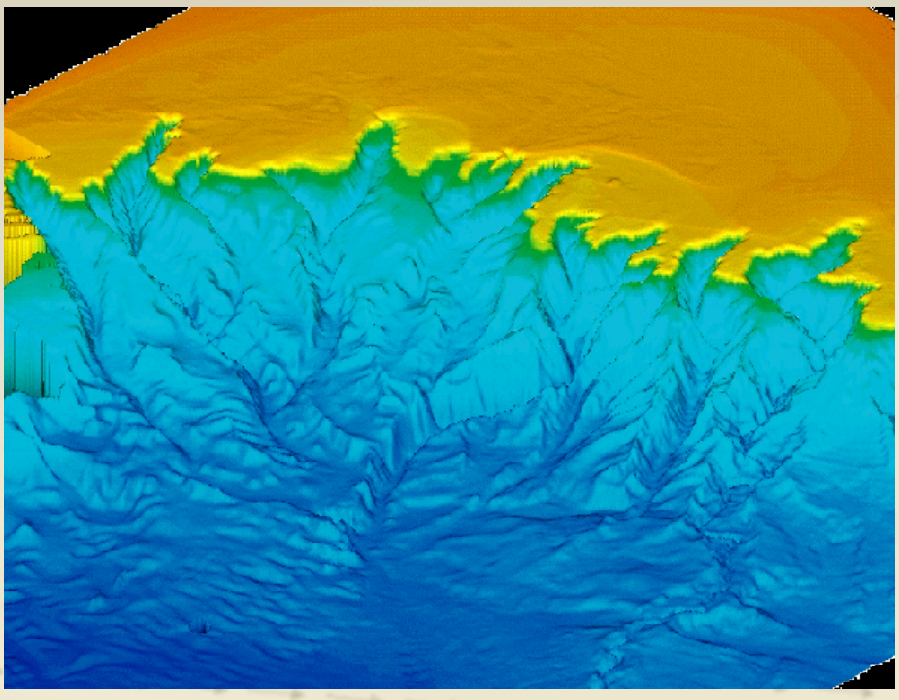
DNS simulation, E. Meiberg

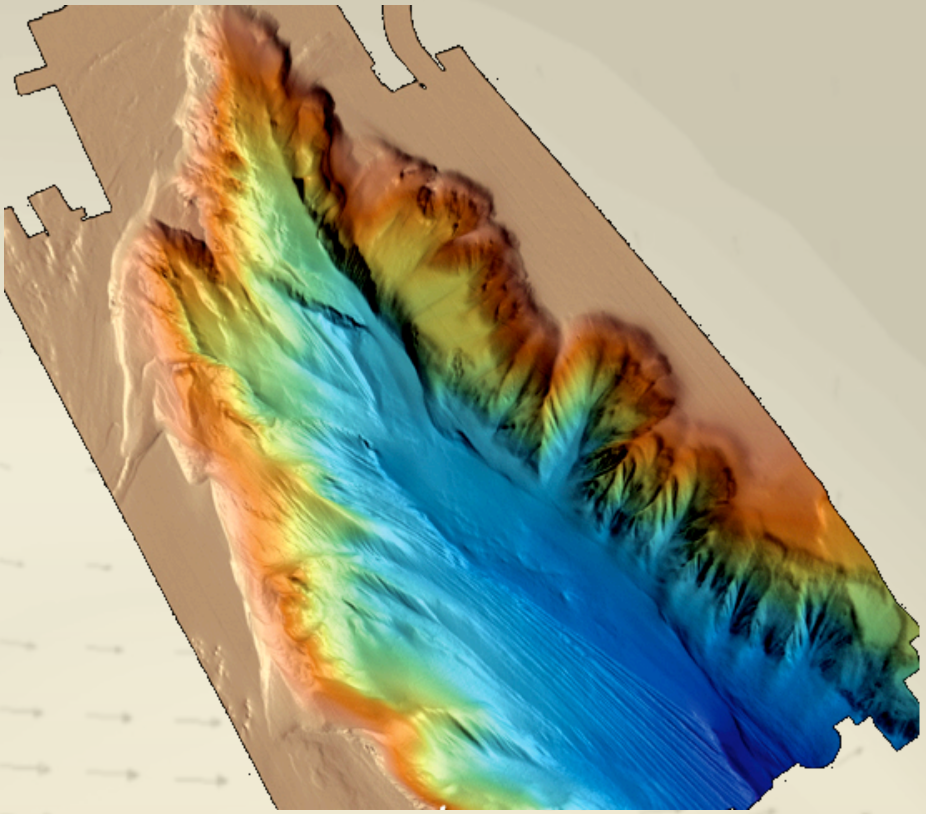
Density-cascading occurs where shelf waters are made hyper-dense through:

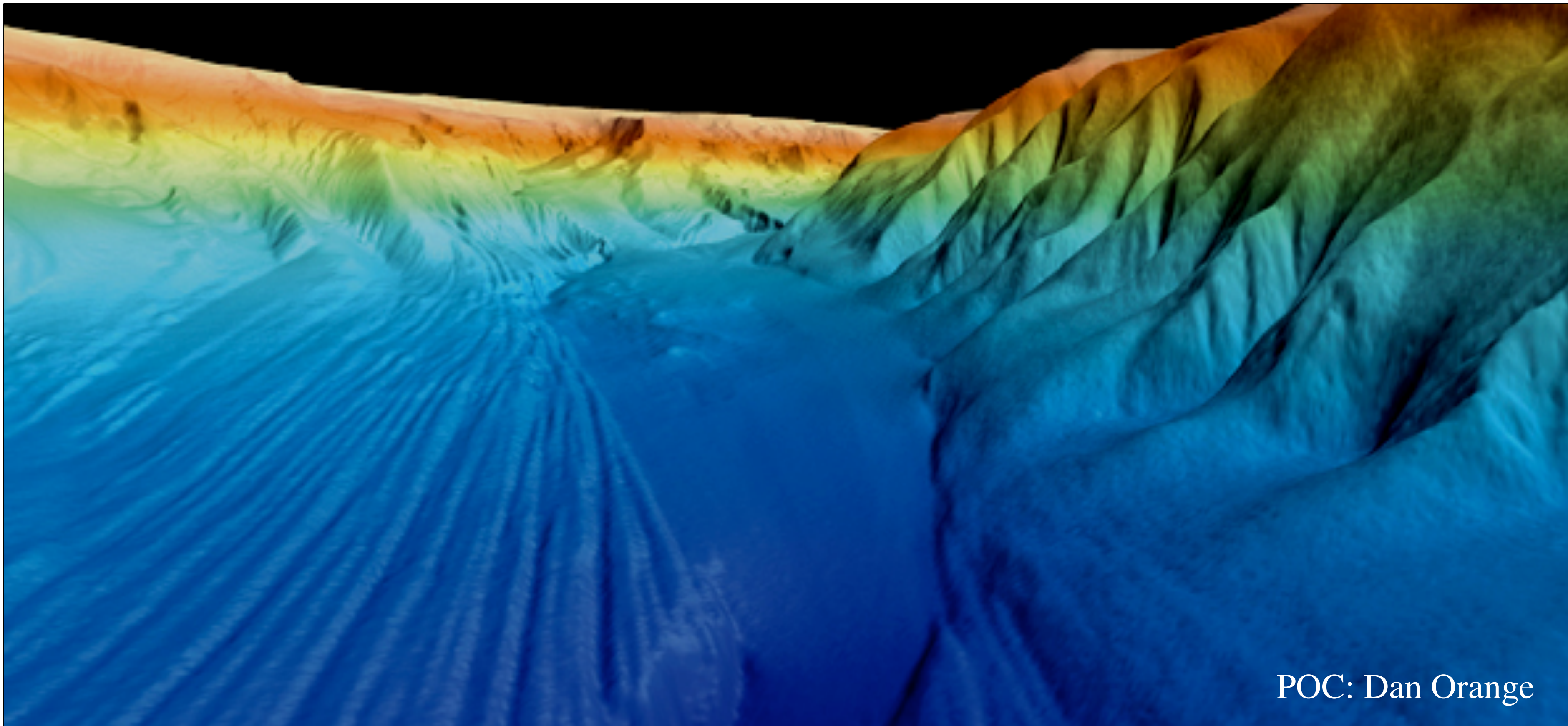
- cooling (e.g. cold winds blowing off the land), or
- salinity enhancement (e.g. evaporation through winds, brine rejection under ice)

Shelf Flows converge in canyons and accelerate down the slope.

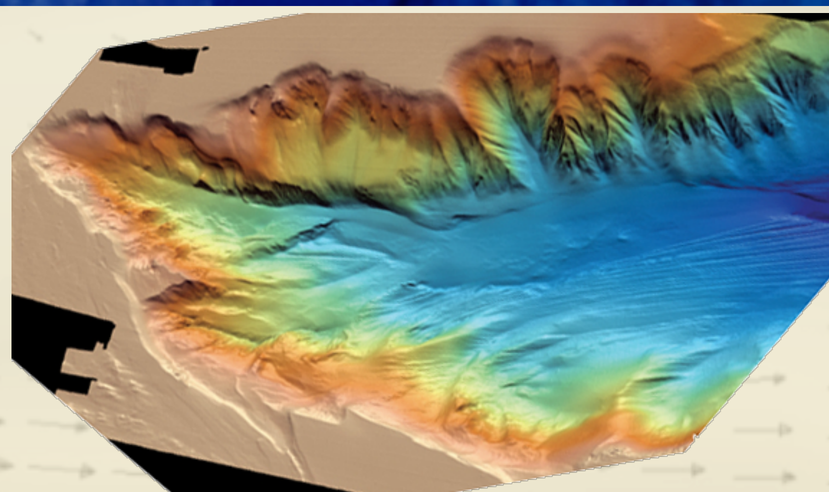
Currents are long lasting, erosive & carry sediment downslope as a tractive current, or as turbidity current.





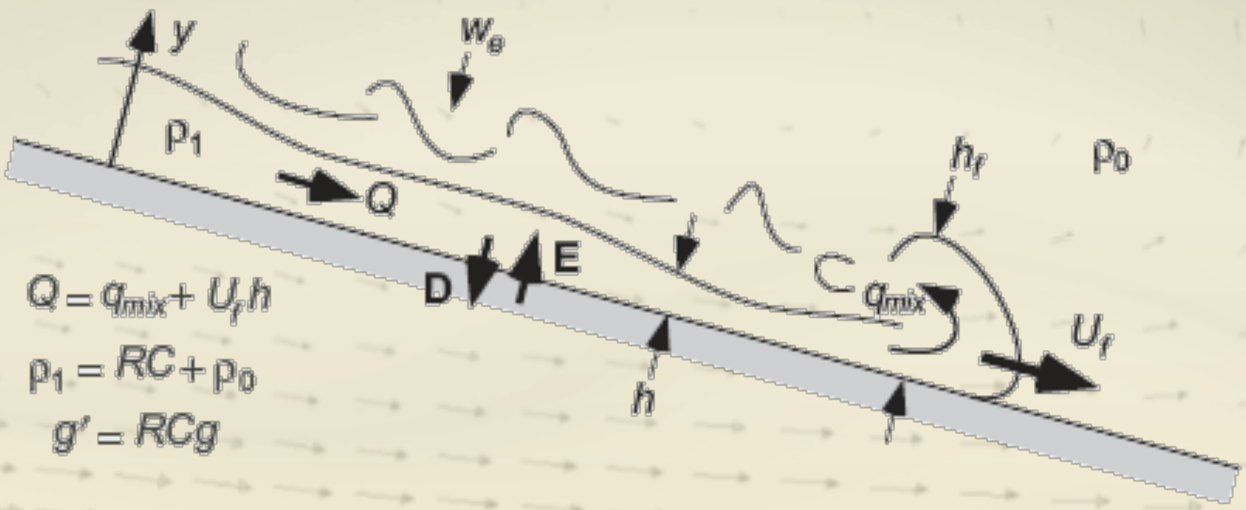


Cold water enters canyon across south rim. Erosive current generates furrows. Sand and mud carried by currents.



SAKURA for modeling hyperpycnal flows after Y. Kubo

- Dynamic model based on layer-averaged, 3-equations model of Parker et al. (1986)
- Able to simulate time-dependent flows at river mouth
- Data input: RM velocity, depth, width, sediment concentration.
- Predicts grain size variation within a turbidite bed
- Applicable to complex bathymetry with upslope



The model employs...

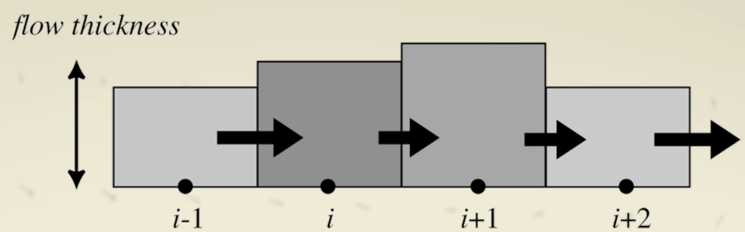
1. layer-averaged, 3-equations model with variation in channel width

$$\frac{du}{dt} + u\frac{du}{dx} + \frac{u^2}{2w}\frac{dw}{dx} = g\Delta\rho CS - \frac{g\Delta\rho}{2hw}\frac{d}{dx}\left(Ch^2 w\right) - \frac{C_{\mathrm{d}}u^2}{h} + \nu(1+2.5C)\frac{d^2u}{dx^2}$$

$$\frac{dh}{dt} + \frac{1}{w}\frac{d}{dx}(uhw) = E_{\mathrm{w}}u$$

$$\frac{dCh}{dt} + \frac{1}{w}\frac{d}{dx}(uChw) = F_{\mathrm{erosion}} - F_{\mathrm{deposition}}$$

2. Eulerian type (fixed) grid, with staggered cell

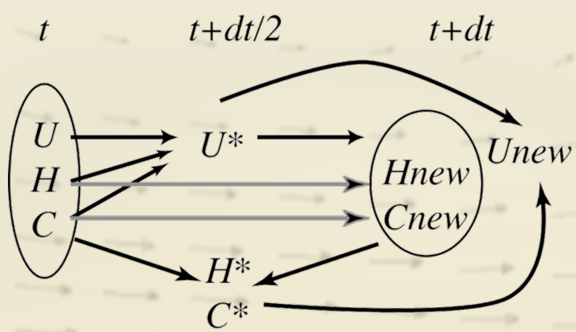


$C, H \longrightarrow$ cell center

$U \longrightarrow$ cell boundary

Good for mass conservation

3. Two-step time increments



Mixing of freshwater and seawater

Hyperpycnal flows in the marine environment involve freshwater and the sediment it carries mixing with salt water. River water enters the marine basin with a density of 1000 kg/m^3, where it mixes with ocean water having a density typically of 1028 kg/m^3. This mixing increases the fluid density of a hyperpycnal current, and alters the value of *C and R, where*

$$\frac{\partial \rho}{\partial x} = \frac{e_w}{h}(\rho_{sw} - \rho), \quad C = \frac{\rho_f - \rho}{\rho_s - \rho}, \quad R = \frac{\rho_s - \rho}{\rho}, \quad \rho_f = (1 - C)\rho + C\rho_s$$

where ρ is density of the fluid in the hyperpycnal current, ρ_{sw} is density of the ambient seawater, ρ_f is density of the hyperpycnal current (sediment and water), and ρ_s is grain density

4. TVD scheme for spatial difference uses...

· Uses 1st order difference scheme for numerically unstable area and higher order scheme for stable area

· Avoids numerical oscillation with relatively less numerical diffusion

· Possibly causes break of conservation law →used only in momentum equation.

5. Automatic estimation of *dt*

dt is determined from $\alpha\, dx/U_{max}$ at every time step

with the value of safety factor α given in an input file.

6. Variable flow conditions at river mouth

· Input flow conditions are given at every SedFlux time step

· When hyperpycnal condition lasts multiple time steps, a single hyperpycnal flow occurs with is generated from combined input data.

Equations for rate of deposition

1. Removal rate, λ

$$F_{\mathrm{deposition}} = C\,H\,\lambda\,dt$$

2. Settling velocity, w_s

$$F_{\mathrm{deposition}} = C_b\,w_s\,dt$$

$$(C_b = 2.0\,C)$$

→ Steady rate of deposition regardless of flow conditions

$$F_{\mathrm{deposition}} = C_b\,w_s\,dt\,(1-\tau/\tau_c)$$

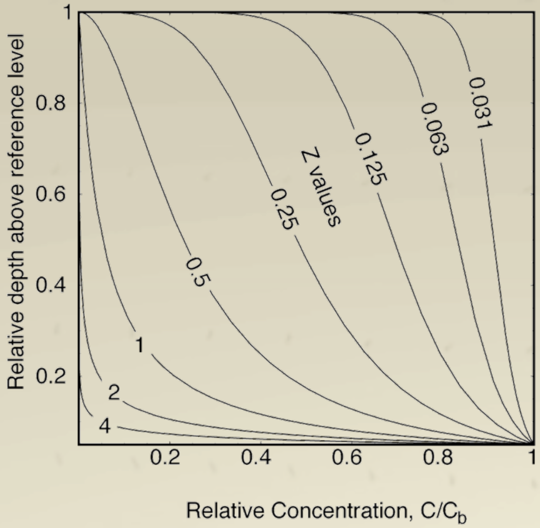
→ Critical shear stress τ_c is not reliable

3. Flow capacity, Γ_z

$$F_{\mathrm{deposition}} = w_s\,dt\,(C\,H - \Gamma_z)\,/\mathrm{H}$$

Flow capacity, Γ_z

Steady state profile of suspended sediment



$$Z = U_* / (\kappa \beta w_s)$$

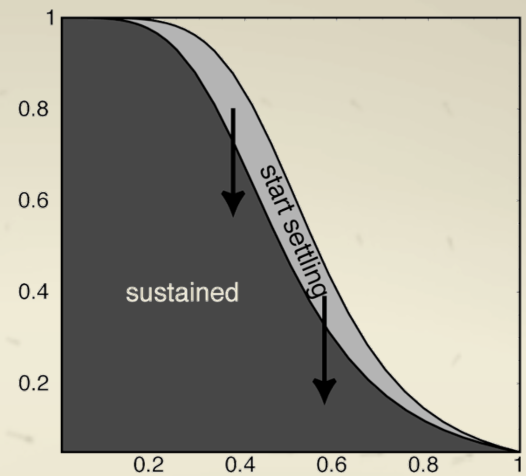
$$\frac{C}{C_b} = \left(\frac{H_1 - y}{y} \frac{H_0}{H_1 - H_0} \right)^Z$$

(Hiscott, 1994)

Amount of suspended sediments that a flow can sustain

$$\Gamma_z = \int_{H0}^{H_1} C dy = C_b H_1 \int_a^1 \left(\frac{1-Y}{Y} \frac{a}{1-a} \right)^Z dY \qquad Y = y / H_1, \; a = H_0 / H_1$$

$$\Gamma_z \approx C_b H_1 \exp\left(-(0.124 \log_2 Z + 1.2)^4 \right)$$



$$C_b = 2.0 \; \overline{C}, \; a = 0.05$$

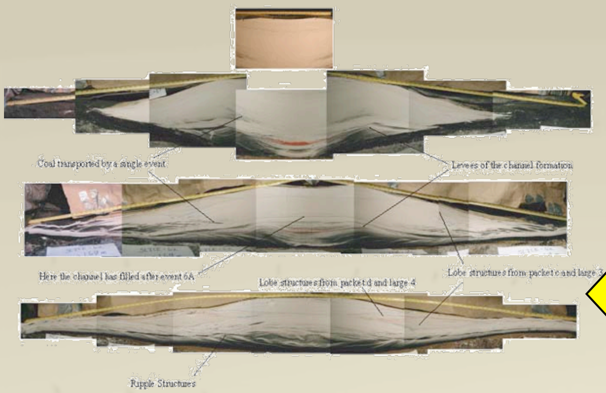
Critical flow velocity

$$Z \cong 0.20 \quad \Rightarrow \overline{U} = 198 w_s$$

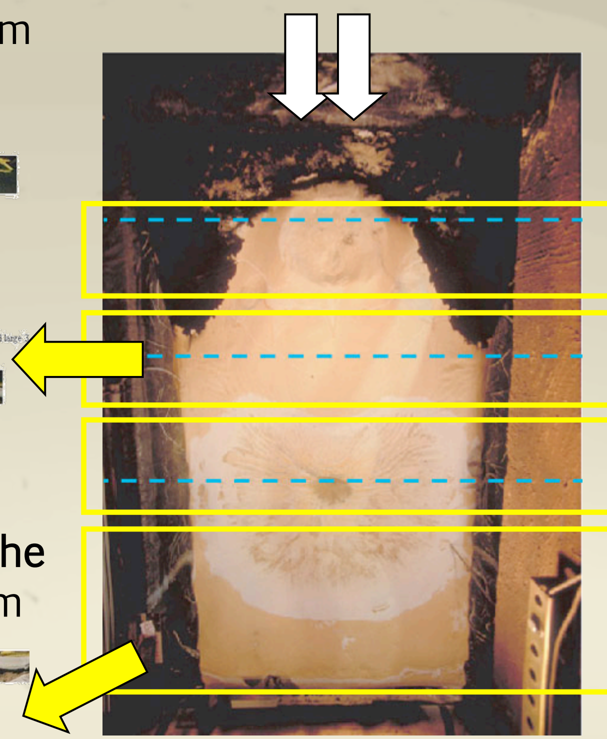
The excess amount of suspension start depositing when the total amount of suspended sediments exceeds the capacity.

Experimental Results

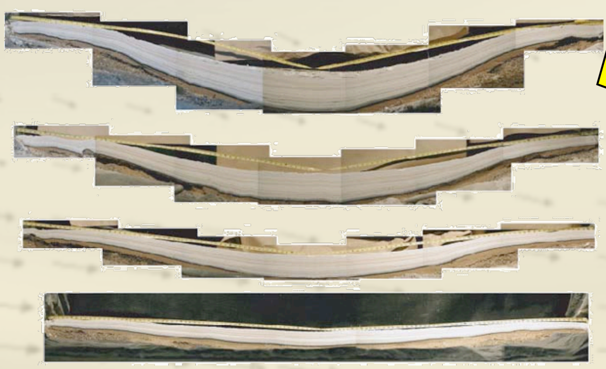
0.6, 0.9, 1.2 m from the source
0.3 m < thickness < 0.5 m

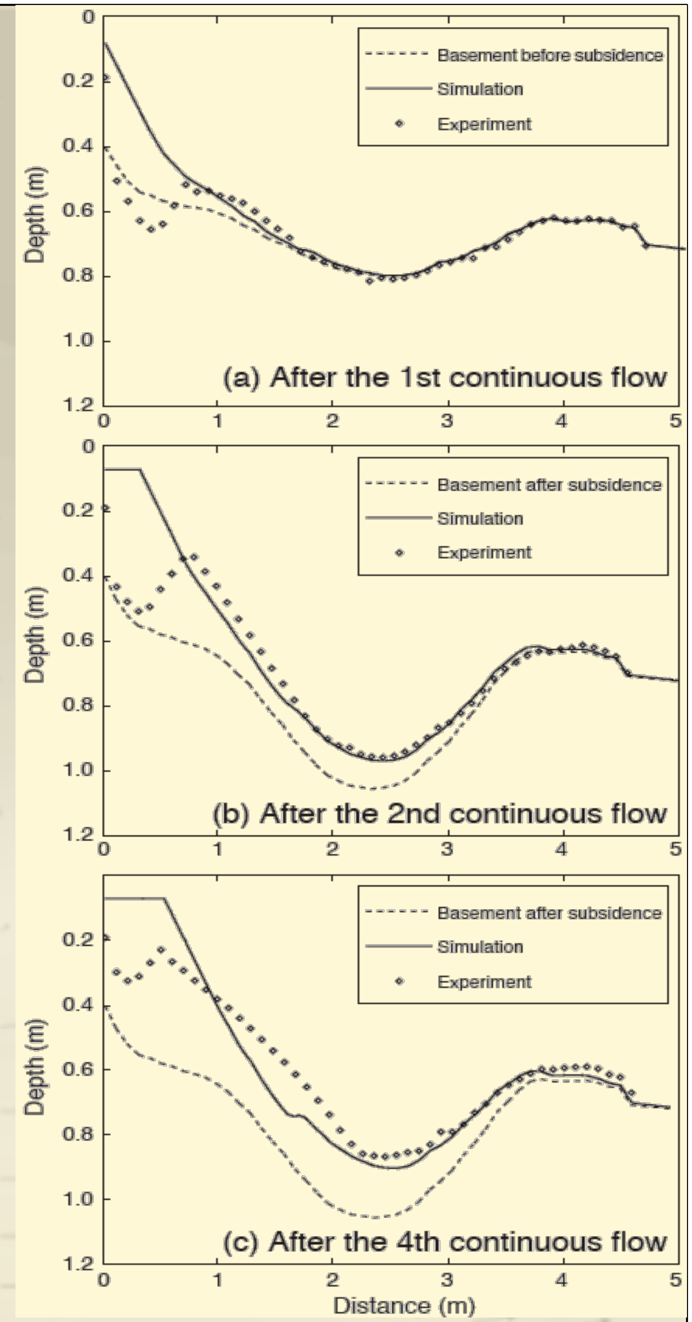


input



2.4, 3.0, 3.3, 3.6 m from the source thickness < 0.2 m

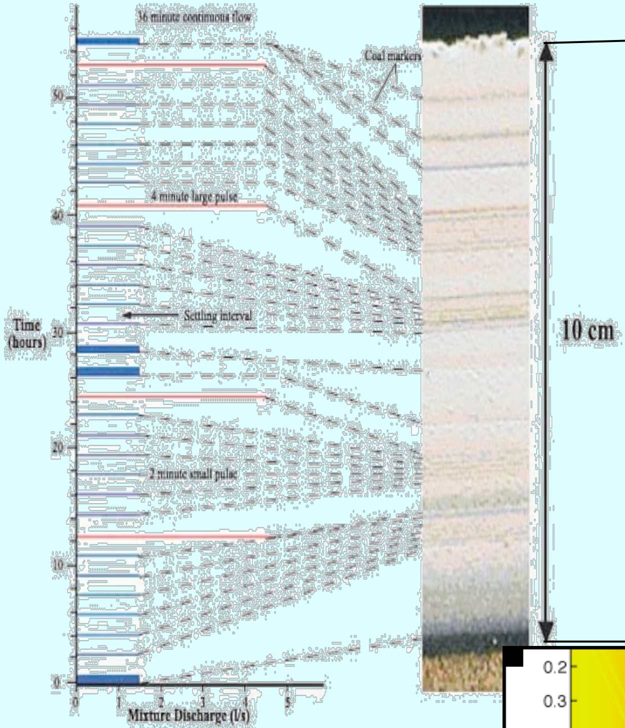


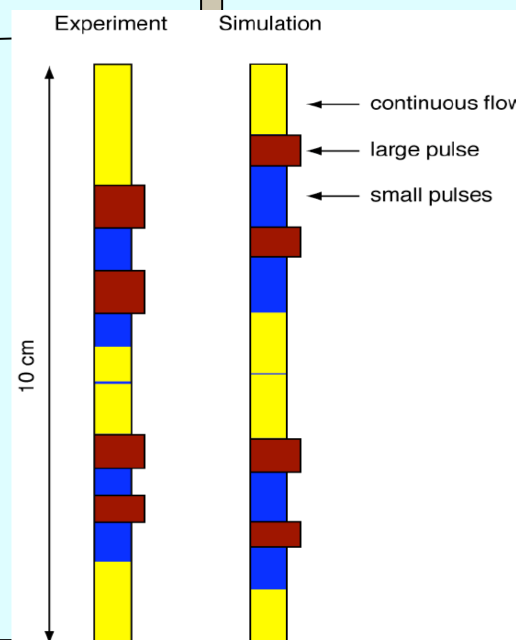


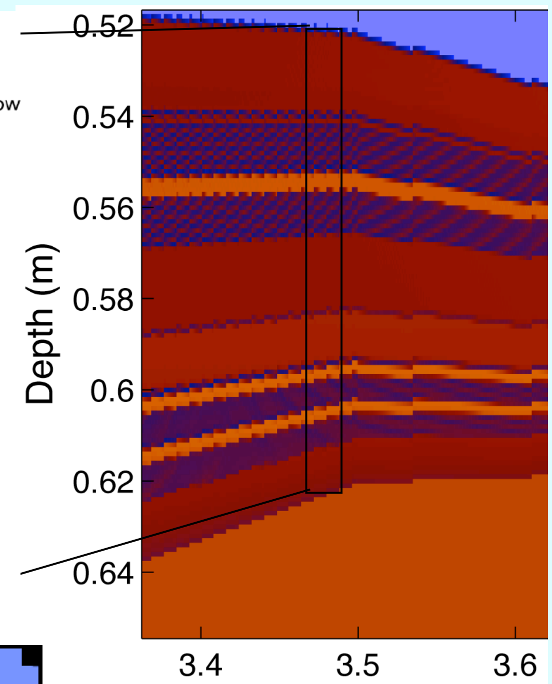
Jurassic Tank

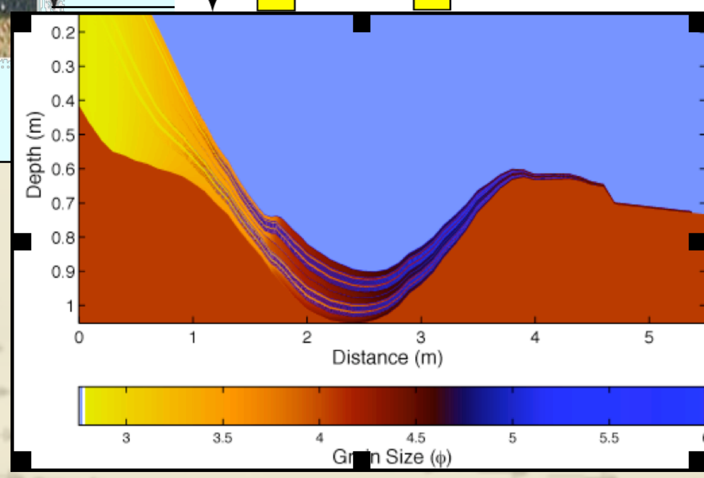
SedFlux

Continuous flow
Large pulse
Small pulses

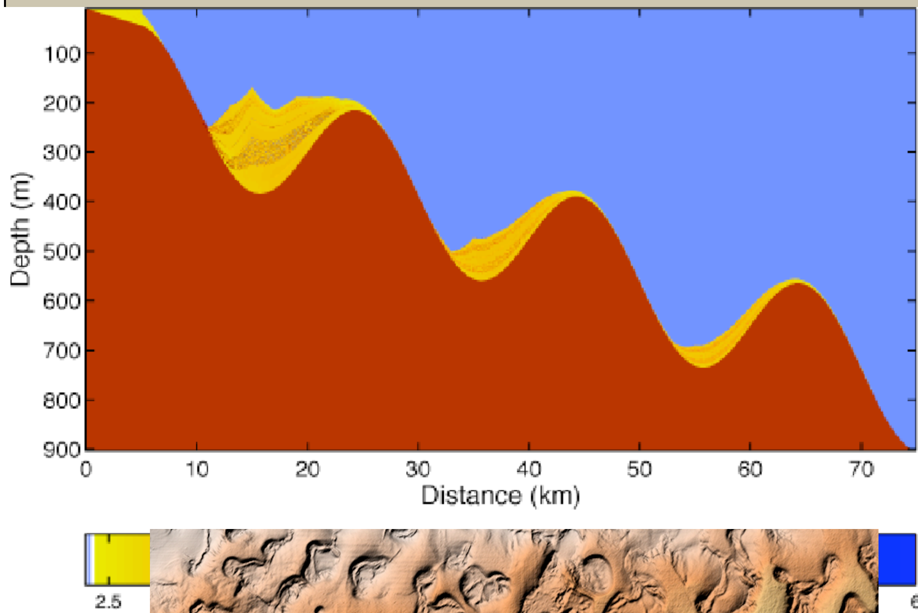


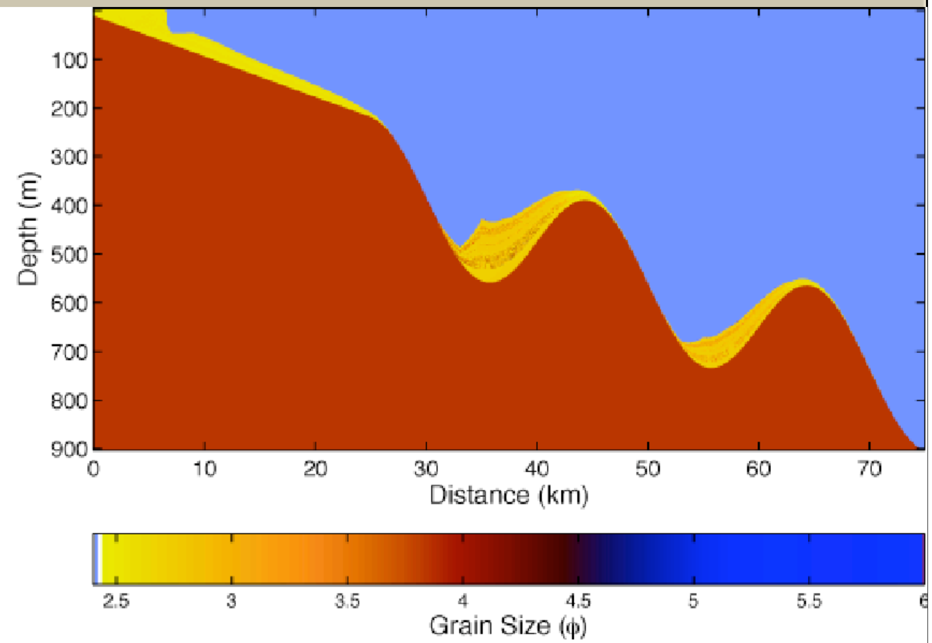


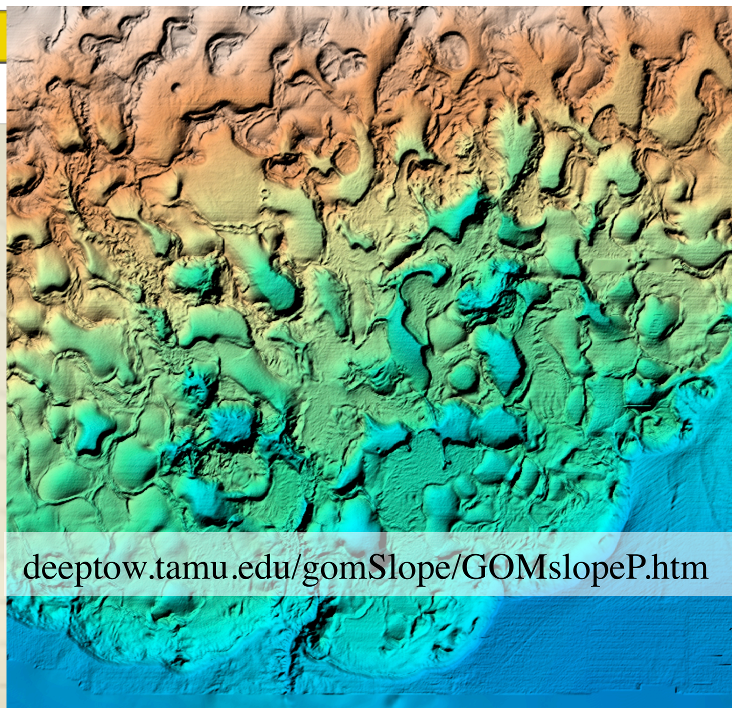


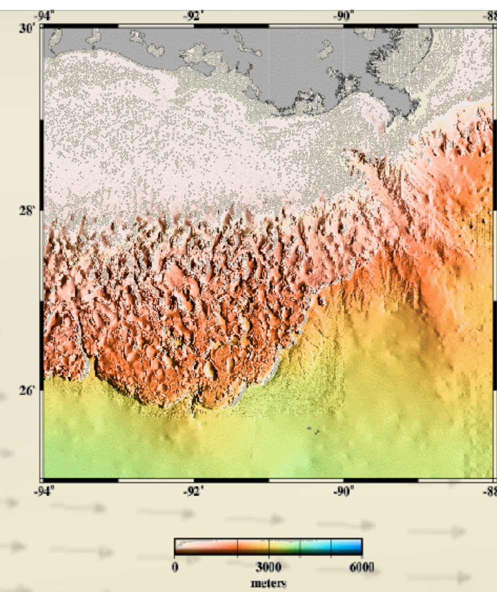


Multiple basins --- of the scale of Texas-Louisiana slope

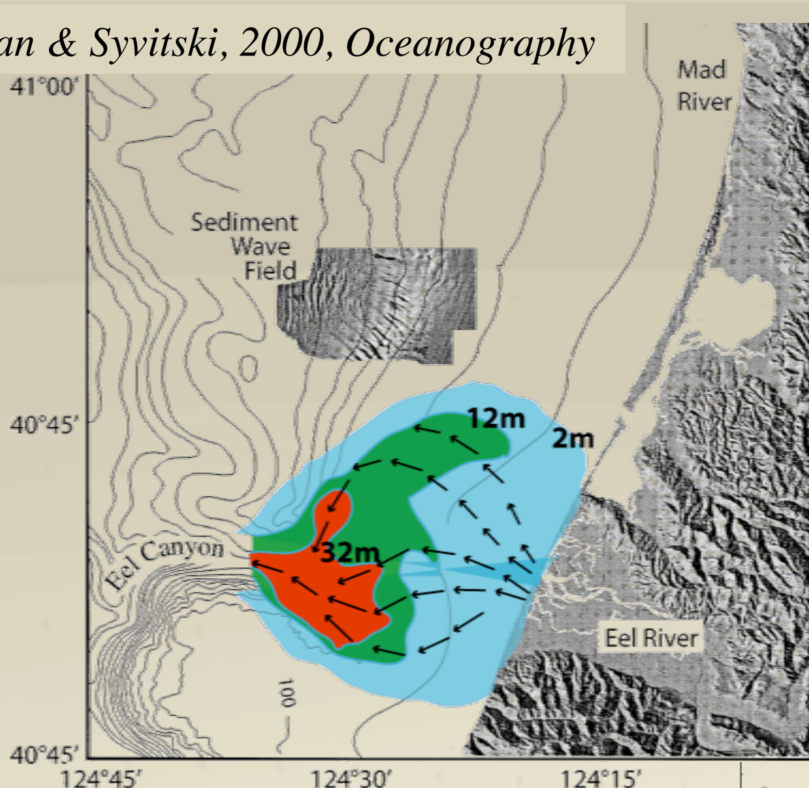




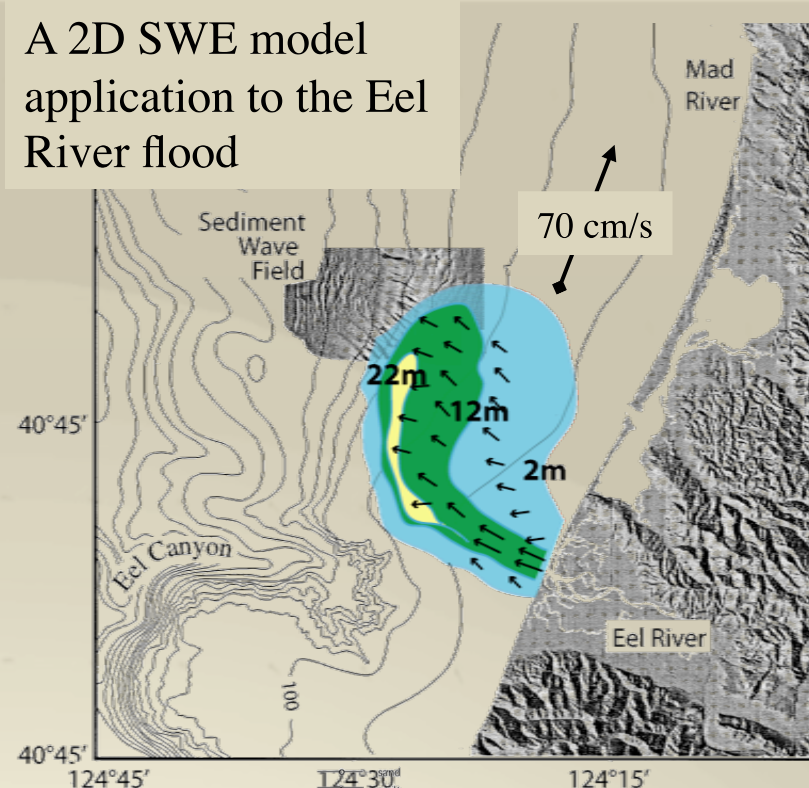


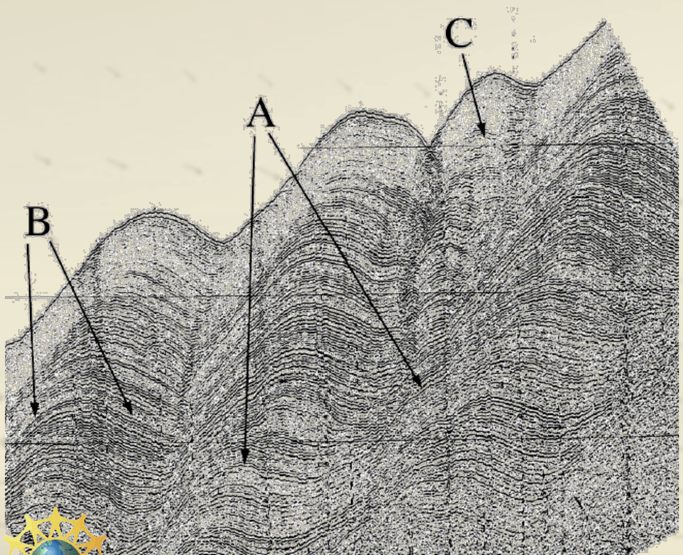


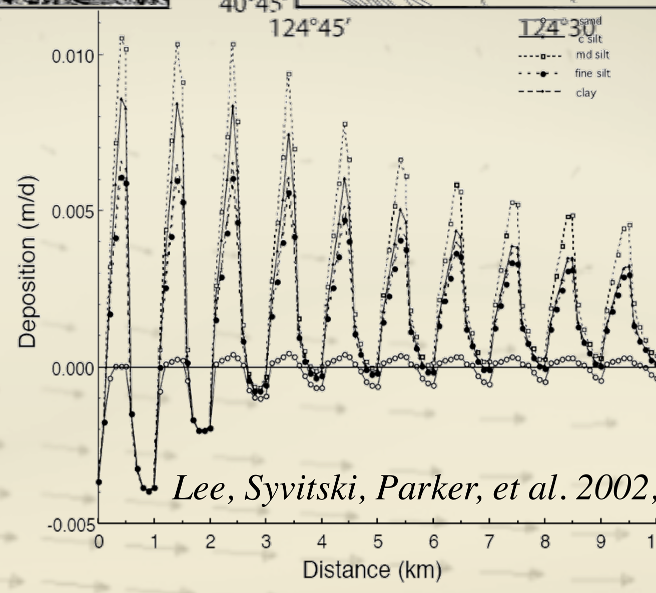
Imran & Syvitski, 2000, Oceanography



A 2D SWE model application to the Eel River flood





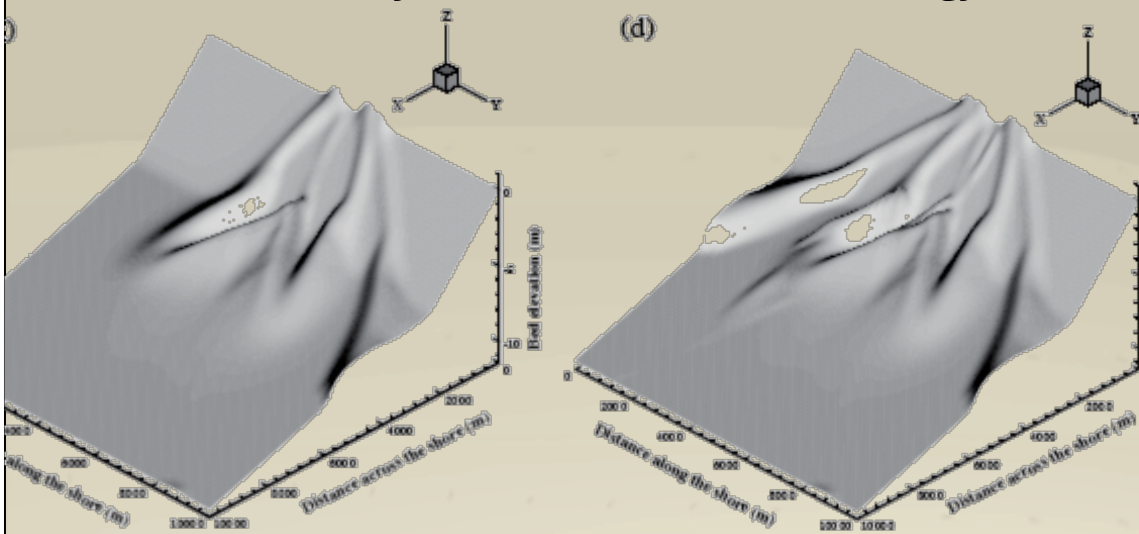


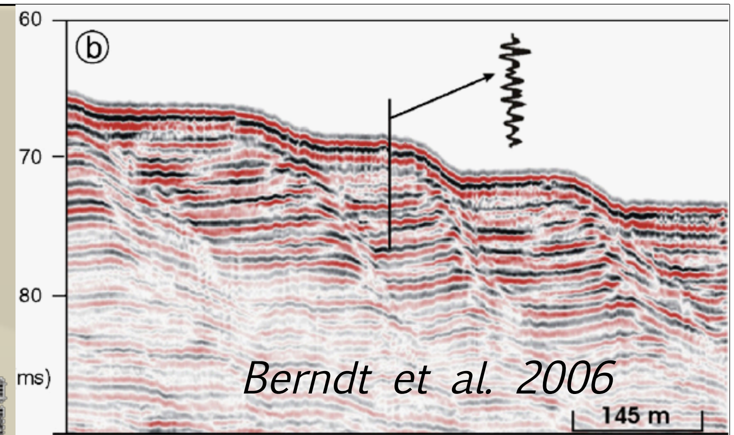
Lee, Syvitski, Parker, et al. 2002, Marine Geol.

A 1D integral Eulerian model application to flows across the Eel margin sediment waves

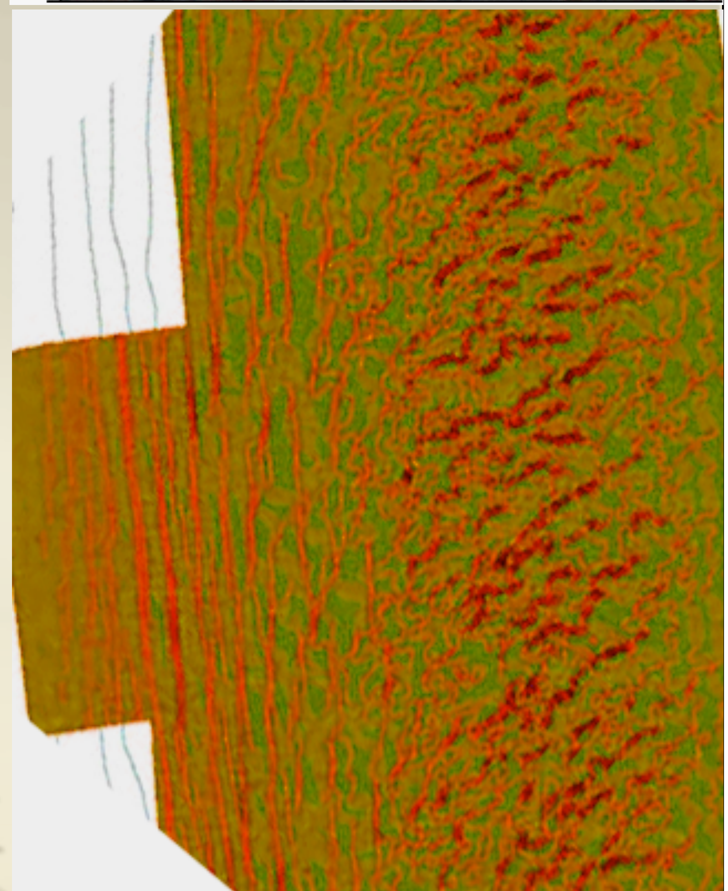
FLUENT-modified FVM-CFD application

Khan, Imran, Syvitski, 2005, Marine Geology





Berndt et al. 2006



SEDIMENT FAILURE MODEL

1) Examine possible elliptical failure planes
2) Calculate sedimentation rate (m) at each cell
3) Calculate excess pore pressure u_i

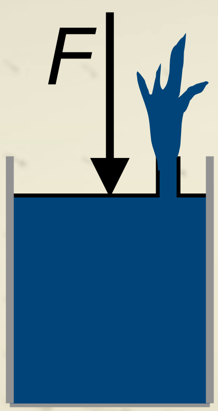
Gibson $u_i = \gamma' z_i A^{-1}$

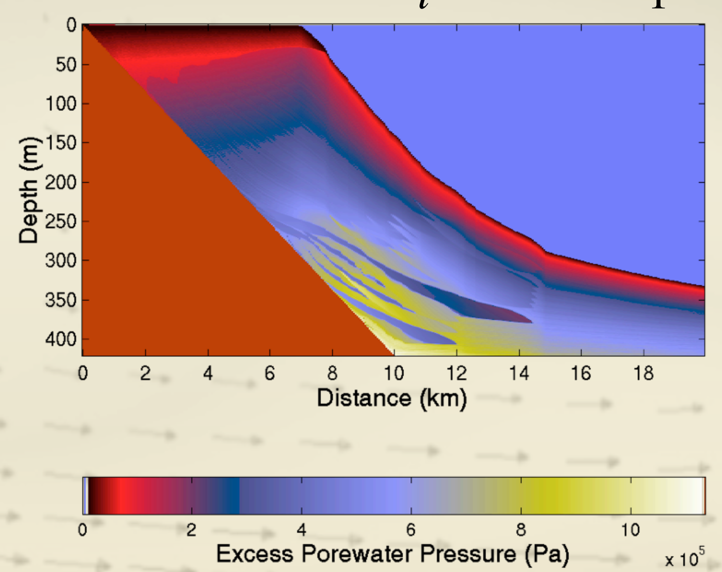
where $A = 6.4(1-T/16)^{17}+1$

$T \approx m^2 t / C_v$

and C_v = consolidation coefficient

or use **dynamic consolidation theory** $u_i = 1 - c_1 e^{-c_2 T_v}$





SEDIMENT FAILURE MODEL

4) Determine earthquake load (horizontal and vertical acceleration)
5) Calculate JANBU Factor of Safety, F: ratio of resisting forces (cohesion and friction) to driving forces (sediment weight, earthquake acceleration, excess pore pressure)

JANBU METHOD OF SLICES

$$F_T = \frac{\sum_{i=0}^{n} \left[b_i \left(c_i + \left(\frac{W_{v_i}}{b_i} - u_i \right) \tan\phi_i \right) \frac{\sec\alpha_i}{1 + \frac{\tan\alpha_i \tan\phi_i}{F_T}} \right]}{\sum_{i=0}^{n} W_{v_i} \sin\alpha_i + \sum_{i=0}^{n} W_{h_i} \cos\alpha_i}$$

Where F_T = factor of safety for entire sediment volume (with iterative convergence to a solution); 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;* M =*mass of sediment column,* u_i= *pore pressure.*

6) Calculate the volume & properties of the failure: in SedFlux the width of the failure is scaled to be 0.25 times the length of the failure
7) Determine properties of the failed material and decide whether material moves as a debris flow or turbidity current

Sediment Gravity Flow Decider
Debris Flow or Turbidity Current?

• Properties of a failed mass determine the gravity flow dynamics.

• If failed material is **clayey** (e.g. > 10% clay), then the failed mass is transported as a **debris flow**. Clay content is a proxy for ensuring low hydraulic conductivity and low permeability and thus the generation of a debris flow with viscoplastic (Bingham) rheology.

• If the material is **sandy, or silty with little clay** (e.g.< 10% clay) then the failed sediment mass is transported down-slope as a **turbidity current**, where flow accelerations may cause seafloor erosion and this entrained sediment may increase the clay content of the flow compared to the initial failed sediment mass. Deposition of sand and silt along the flow path may result in the turbidity current transporting primarily clay in the distal reaches along the flow path.

Governing equations of the Lagrangian form of the depth-averaged debris flow equations:

Continuity

$$\underbrace{\frac{\partial h}{\partial t}}_{(a)} + \underbrace{\frac{\partial}{\partial x}\left[U_p h_p + \frac{2}{3} U_p h_s\right]}_{(b)} = 0$$

height of flow (1a) is inversely proportional to its velocity (1b).

Momentum (shear (s) layer)

$$\underbrace{\tfrac{2}{3}\frac{\partial}{\partial t}\left(U_p h_s\right) - U_p \frac{\partial h_s}{\partial t} + \tfrac{8}{15}\frac{\partial}{\partial x}\left(U_p^2 h_s\right) - \tfrac{2}{3} U_p \frac{\partial}{\partial x}\left(U_p h_s\right)}_{(a)} =$$

$$\underbrace{h_s g\left(1-\frac{\rho_w}{\rho_m}\right)S}_{(b)} - \underbrace{h_s g\left(1-\frac{\rho_w}{\rho_m}\right)\frac{\partial h}{\partial x}}_{(c)} - \underbrace{2\left(\frac{\mu_m U_p}{\rho_m h_s}\right)}_{(d)}$$

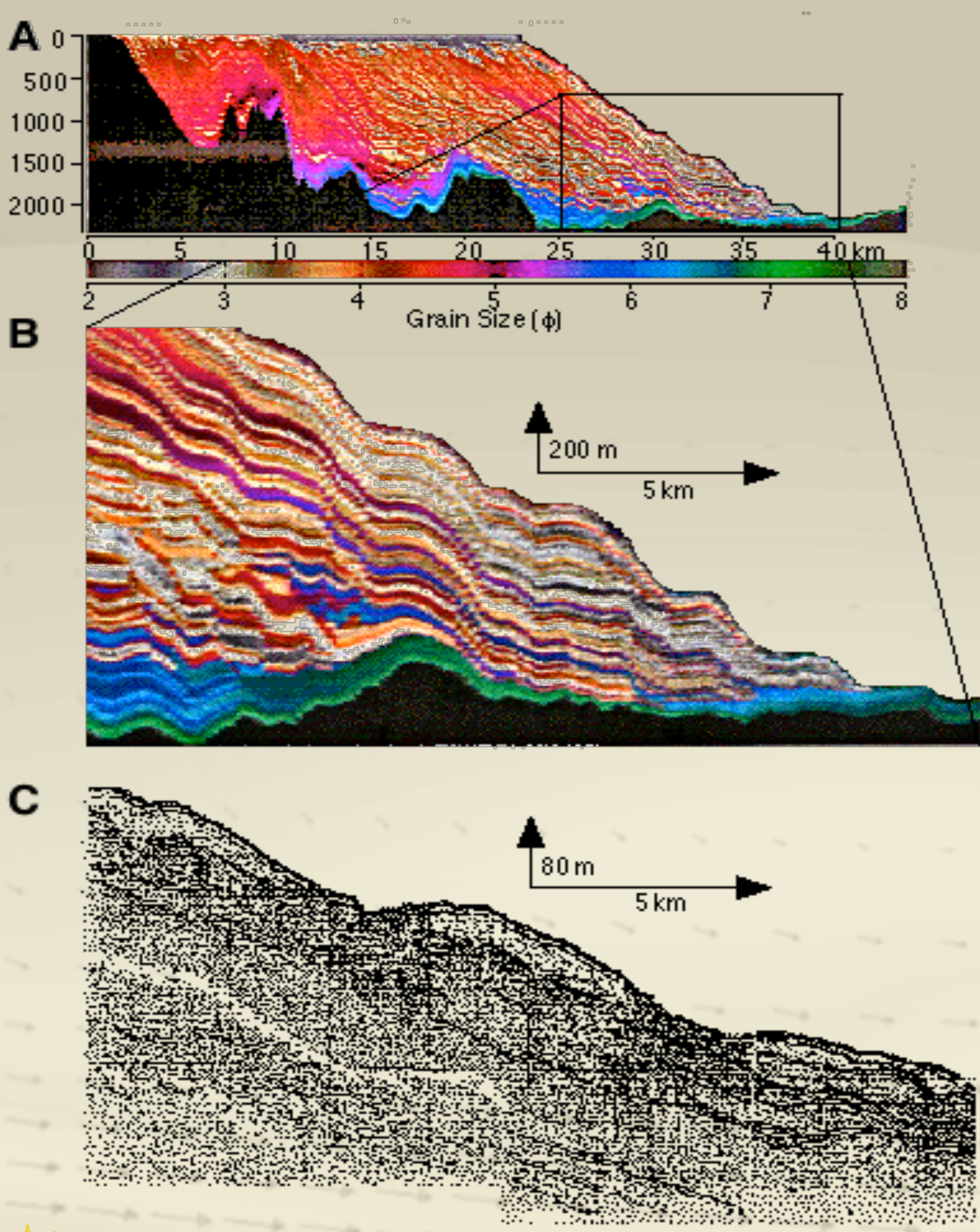
Momentum (plug flow (p) layer)

$$\underbrace{\frac{\partial}{\partial t}\left(U_p h_p\right) + \frac{\partial}{\partial x}\left(U_p^2 h_p\right) + U_p \frac{\partial h_s}{\partial t} + \tfrac{2}{3} U_p \frac{\partial}{\partial x}\left(U_p h_s\right)}_{(a)} =$$

$$\underbrace{h_p g \frac{\partial}{\partial x}\left(1-\frac{\rho_w}{\rho_m}\right)S}_{(b)} - \underbrace{h_p g\left(1-\frac{\rho_w}{\rho_m}\right)\frac{\partial h}{\partial x}}_{(c)} - \underbrace{\frac{\tau_m}{\rho_w}}_{(d)}$$

Momentum (a) is balanced by weight of the flow scaled by seafloor slope (b); fluid pressure forces produced by variations in flow height (2c); and frictional forces (d).

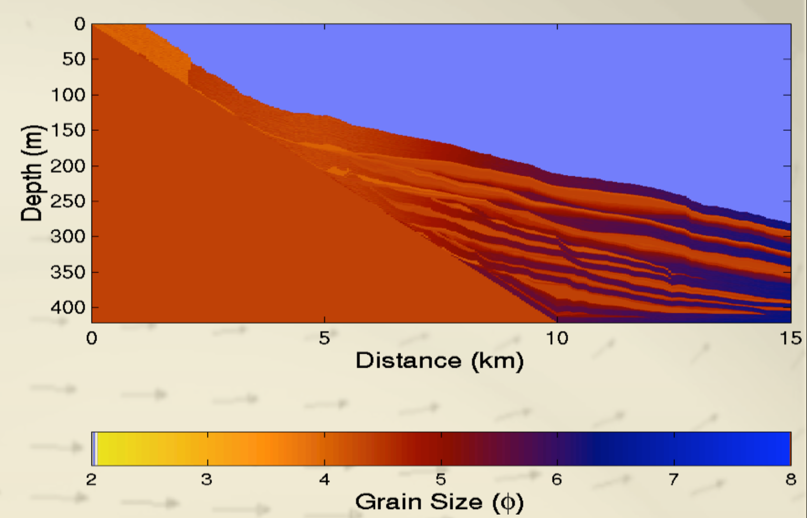
h=height; U=layer-averaged velocity; g is gravity; S is slope; ρ_w is density of ocean water; ρ_m is density of mud flow; τ_m is yield strength, and μ_m is kinematic viscosity.



Given these governing equations for a debris flow, the dynamics do not allow the seafloor to be eroded. Thus the grain size of the final deposit is equal to the homogenized grain size of the initial failed sediment mass.

Shear strength ⇑ Runout ⇑

Viscosity ⇑ Runout ⇓

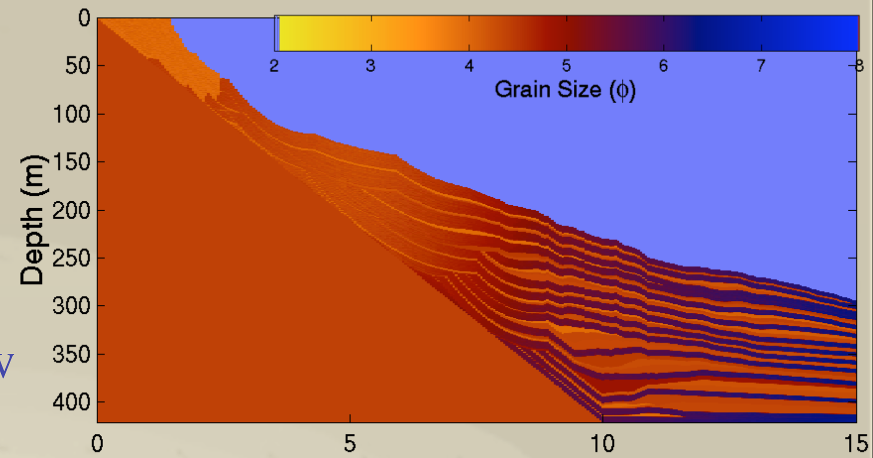


"Global" Sediment Properties

- Coefficient of consolidation
- Cohesion
- Friction angle
- Shear strength
- Sediment viscosity

Failure

Debris flow



"Local" Sediment Properties relationships on a cell by cell basis

Cohesion $c = c(\sigma, \phi, \tau)$ Shear strength $\tau = \tau(\sigma, PI)$

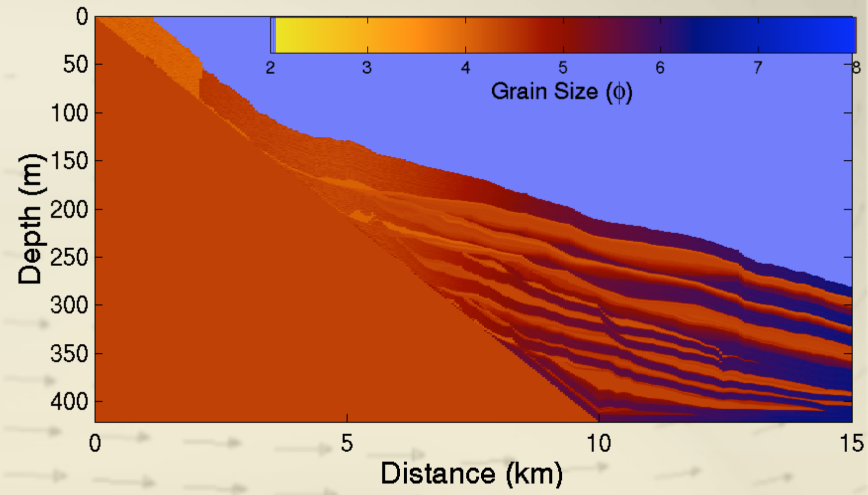
Viscosity $\eta = \eta(e)$ Friction angle $\phi = \phi(D, \rho_r)$

σ load, ϕ friction angle,

τ shear strength, e void ratio,

PI plasticity index, D grain size

ρ_r relative density



Four layer-averaged turbidity current conservation equations in Lagrangian form

$$\underbrace{\frac{\partial h}{\partial t}+\frac{\partial Uh}{\partial x}}_{(a)}=\underbrace{e_w U}_{(b)}$$

Fluid continuity (with entrainment)

$$\underbrace{\frac{\partial Ch}{\partial t}+\frac{\partial UCh}{\partial x}}_{(a)}=\underbrace{W_s(E_s-r_oC)}_{(b)}$$

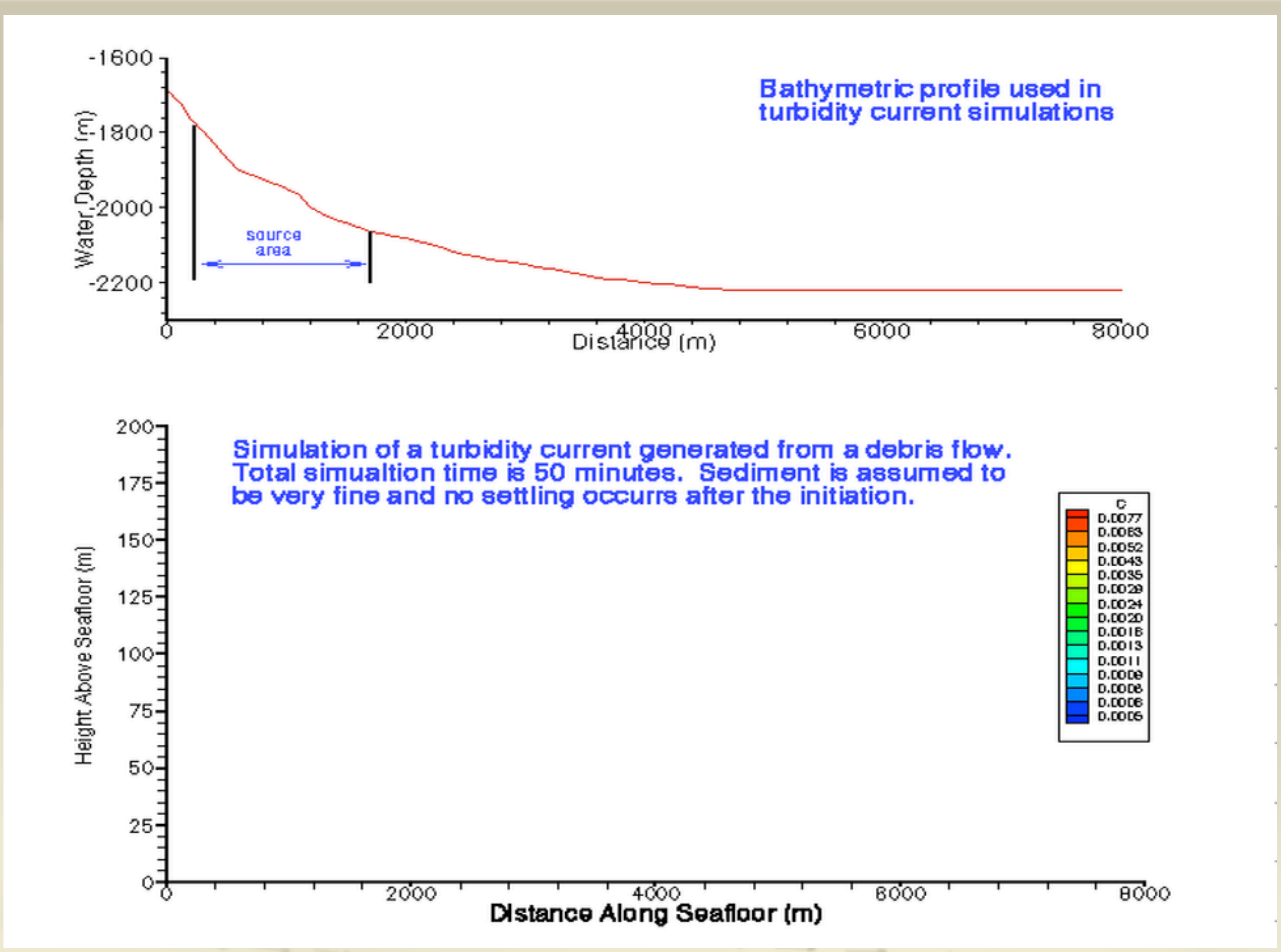
Sediment continuity Exner Equation

$$\underbrace{\frac{\partial Uh}{\partial t}+\frac{\partial U^2h}{\partial x}}_{(a)}=\underbrace{RgChS}_{(b)}-\underbrace{\frac{1}{2}Rg\frac{\partial Ch^2}{\partial x}}_{(c)}-\underbrace{u_*^2}_{(d)}$$

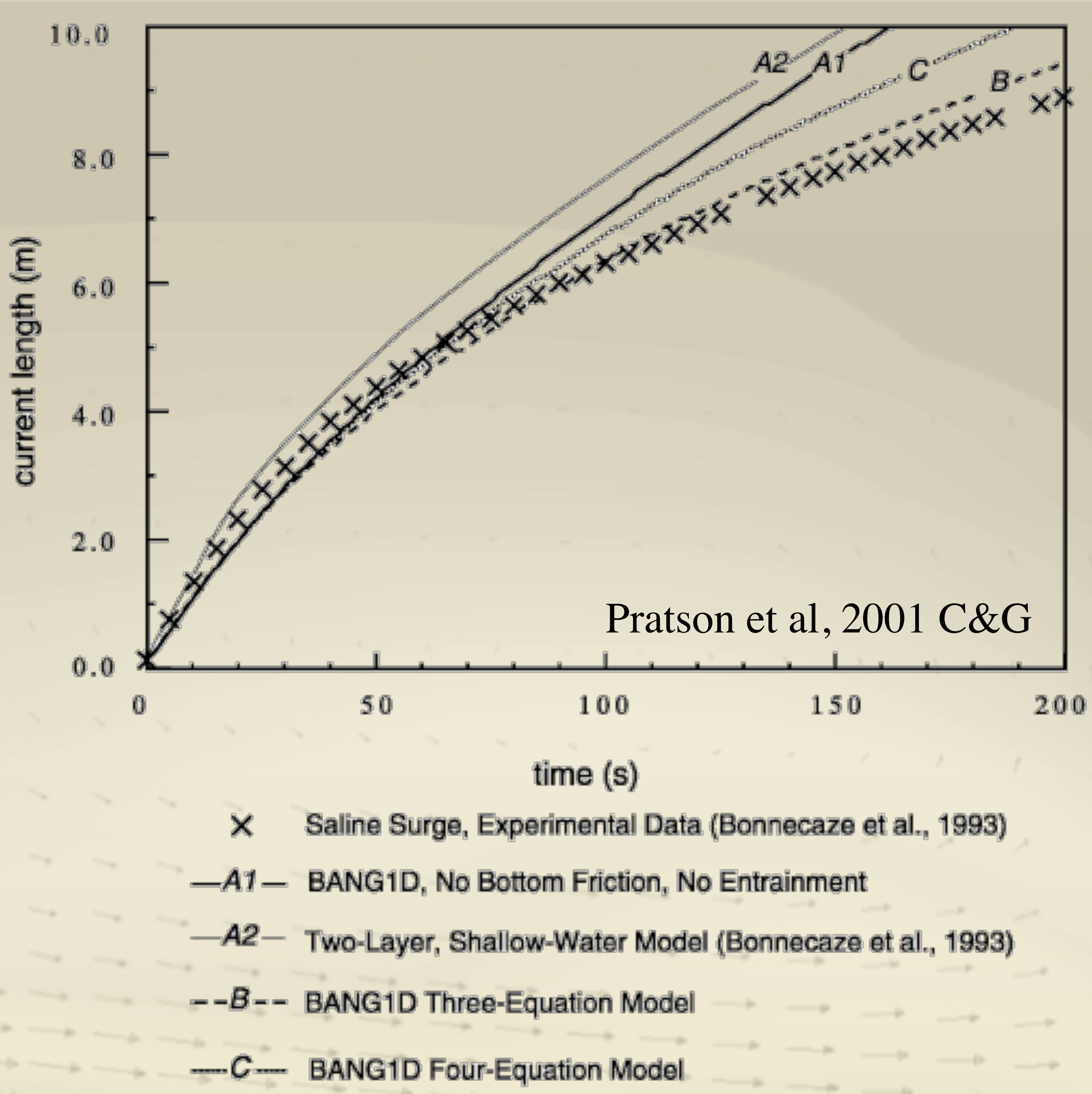
Momentum = Gravity - Pressure - Friction

$$\underbrace{\frac{\partial Kh}{\partial t}+\frac{\partial UKh}{\partial x}}_{(a)}=\underbrace{u_*^2U+\frac{1}{2}U^3e_w}_{(b)}-\underbrace{\varepsilon_o h}_{(c)}-\underbrace{RgW_sCh}_{(d)}-\underbrace{\frac{1}{2}RgChUe_w}_{(e)}-\underbrace{\frac{1}{2}RghW_s(E_s-r_oC)}_{(f)}$$

Energy | **Turbulent kinetic energy** | **Dissipat. viscosity** | **Resusp. Energy** | **Entrainment Energy** | **Bed Erosion Energy**

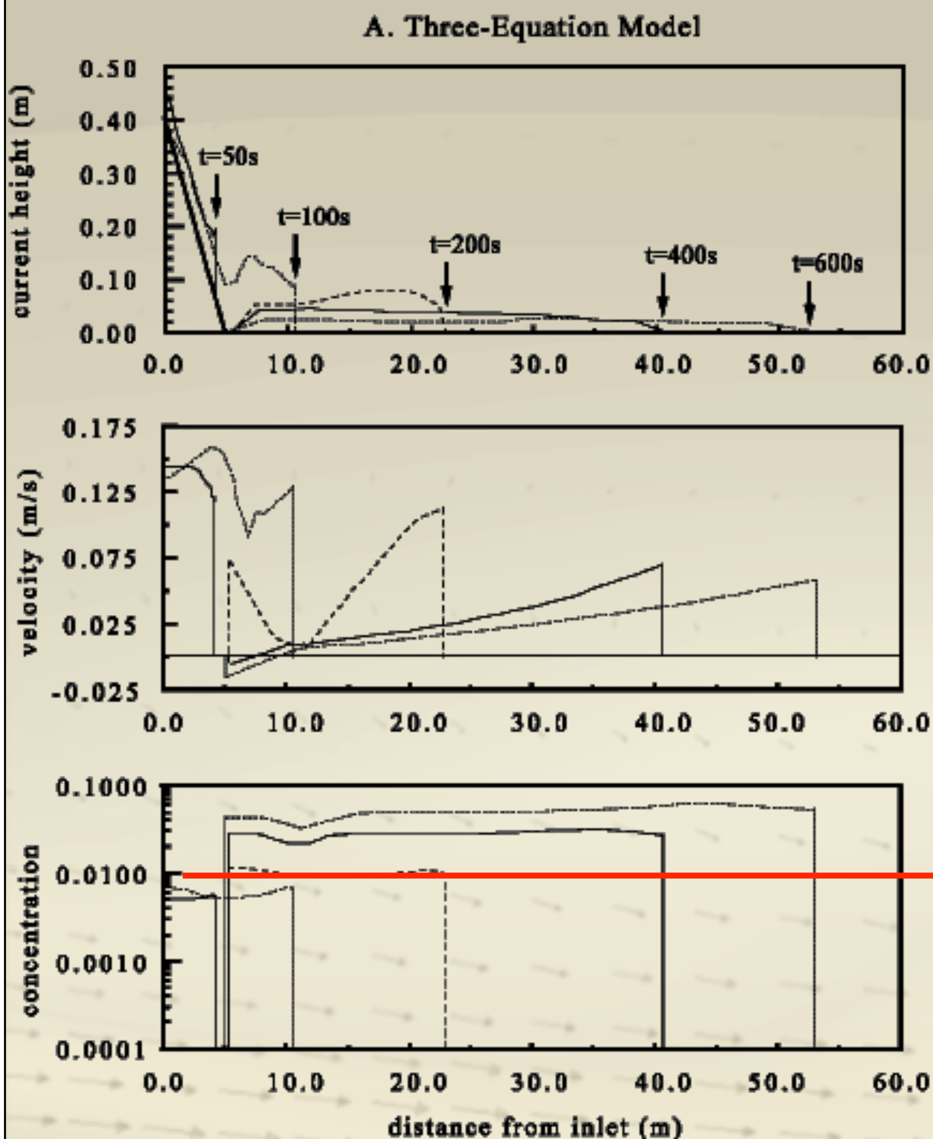


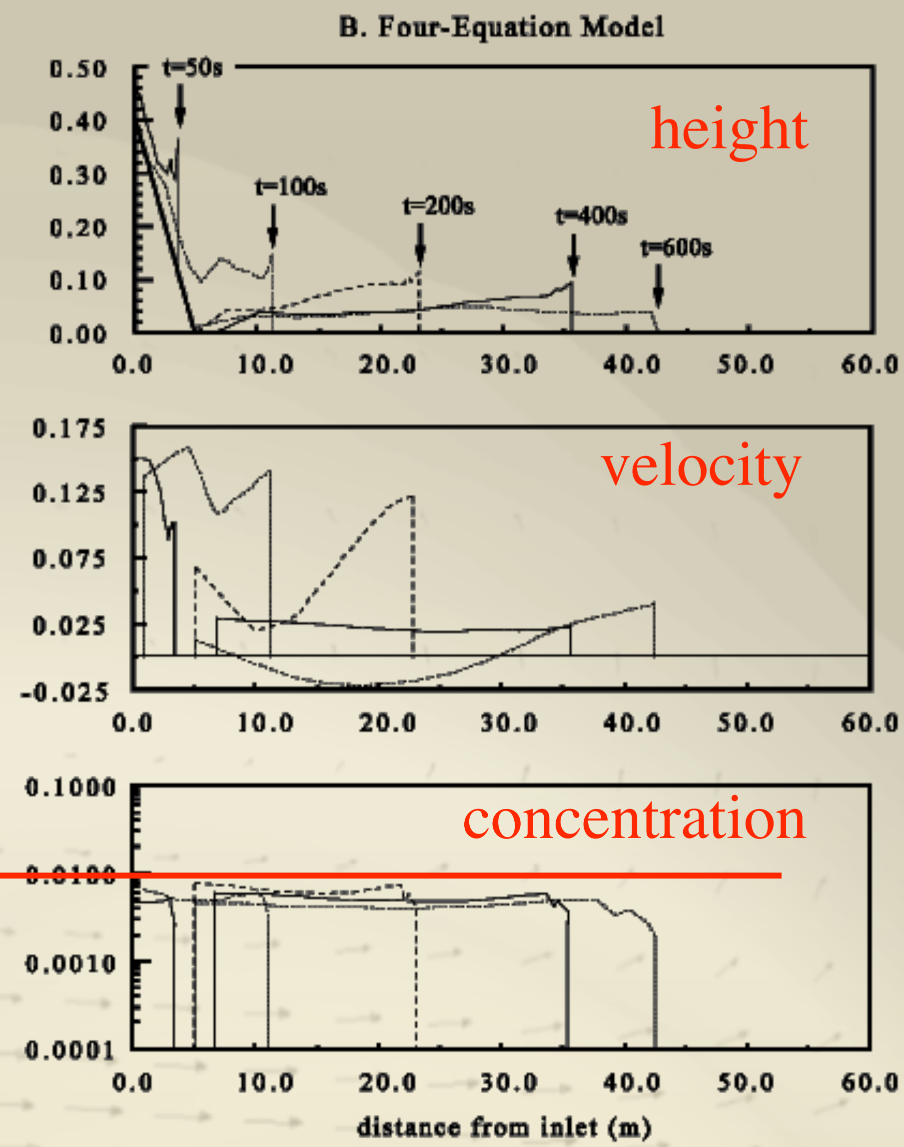
Chris Reed, URS


10.0
8.0
6.0
4.0
2.0
0.0
0
50
100
150
200
current length (m)
time (s)
A2
A1
C
B
Pratson et al, 2001 C&G
× Saline Surge, Experimental Data (Bonnecaze et al., 1993)
—A1— BANG1D, No Bottom Friction, No Entrainment
—A2— Two-Layer, Shallow-Water Model (Bonnecaze et al., 1993)
- -B- - BANG1D Three-Equation Model
----C---- BANG1D Four-Equation Model

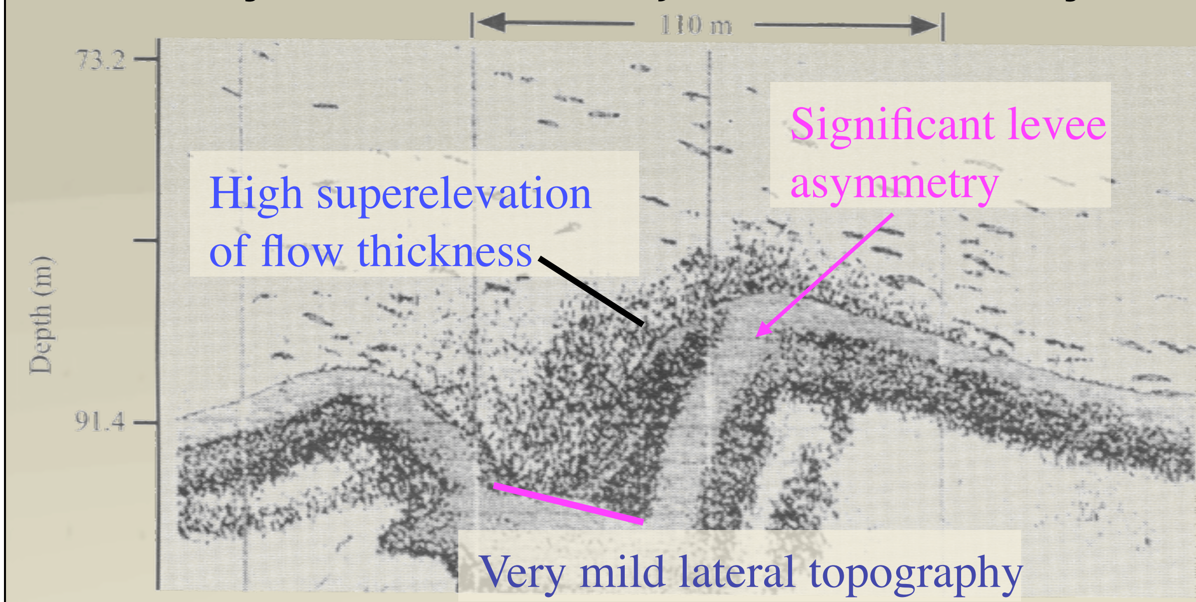
3-Equation Model

4-Equation Model

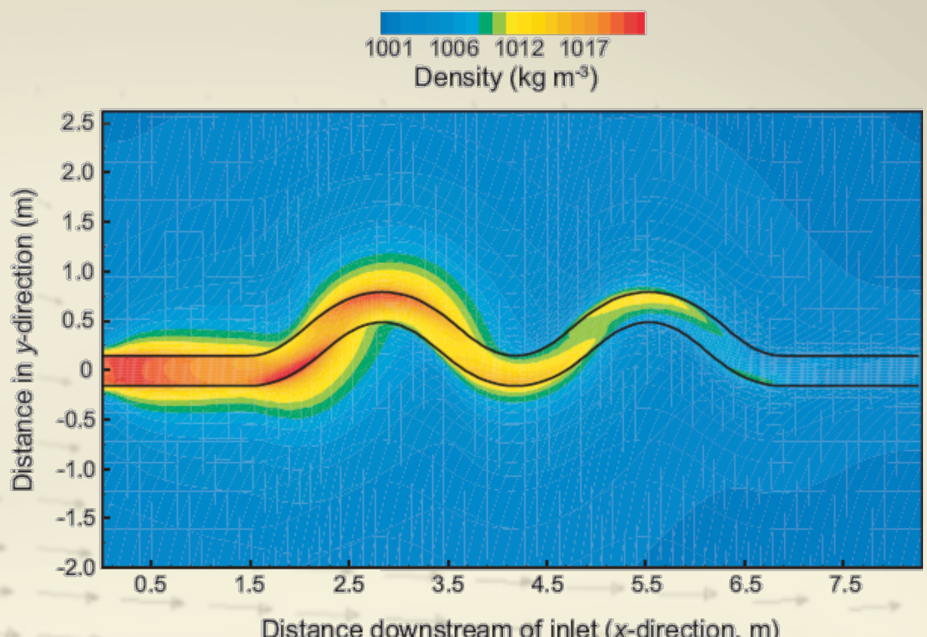




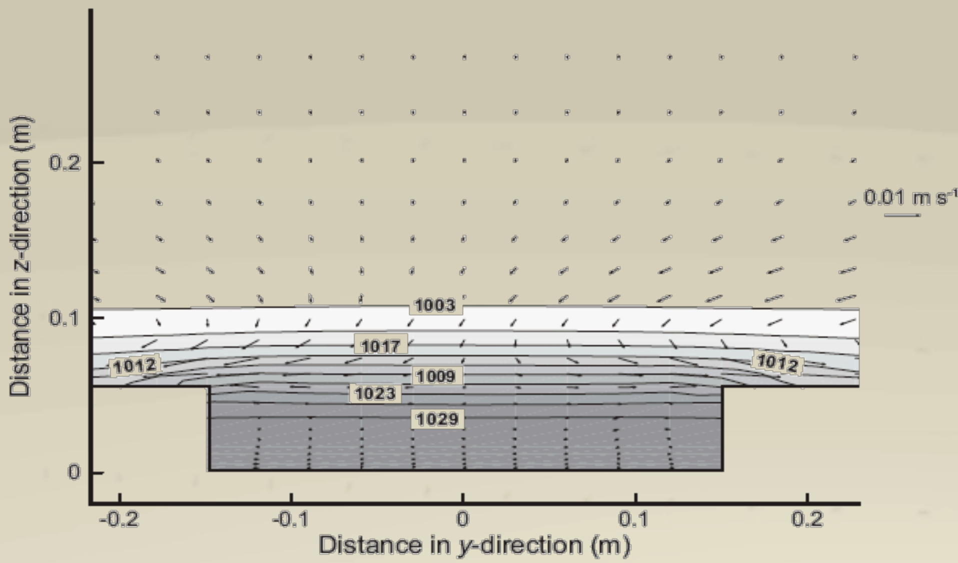
Turbidity current on a fjord bottom (Hay, 1987)



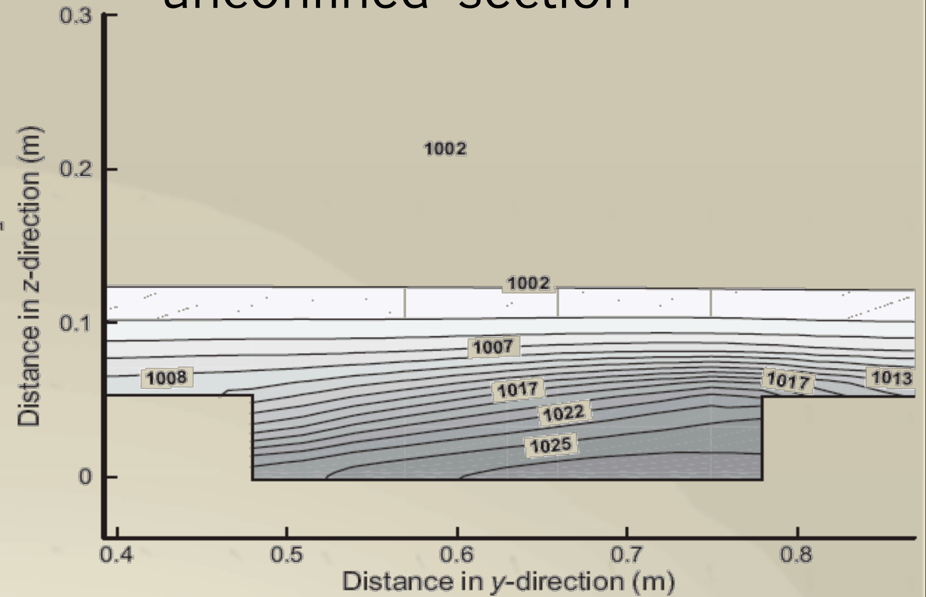
Application of Fluent 2D FVM –CFD model to modeling a turbidity current on a meandering bed (Kassem & Imran, 2004)



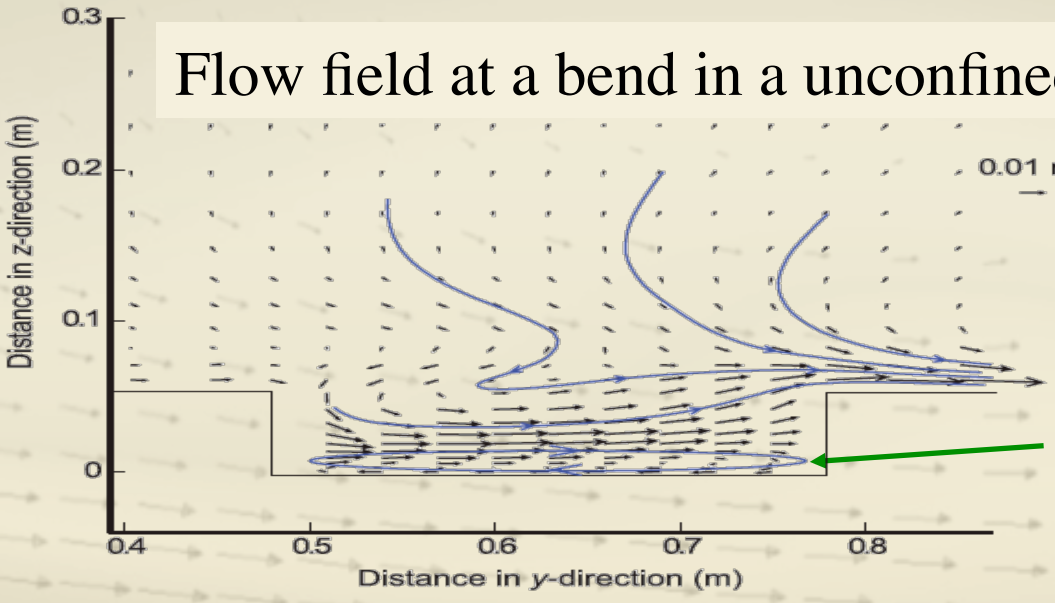
Lateral flow field in a straight unconfined section.



Density field at a bend in a unconfined section



Flow field at a bend in a unconfined section



Very weak circulation cell

Kassem & Imran, 2004

Density Currents, Sediment Failure & Gravity Flows Summary

Density Currents: may interact with seafloor: RANS?

Hyperpycnal Flow Models: 3eqn 1Dx & 2Dxy Lagrangian SWE; 3D FVM

Sediment Failure Model: Janbu MofS FofS model + excess pore pressure model + material property model

Gravity Flow Decider: material property model

Debris Flow Model: Bingham, Herschel-Buckley, Bilinear rheologies; 1Dx 2-layer Lagrangian

Turbidity Current Models: 3eqn & 4eqn 1Dx SWE; 3D FVM CFD

(as a test try to translate this slide)