Dynamics of Gravity and Turbidity Currents

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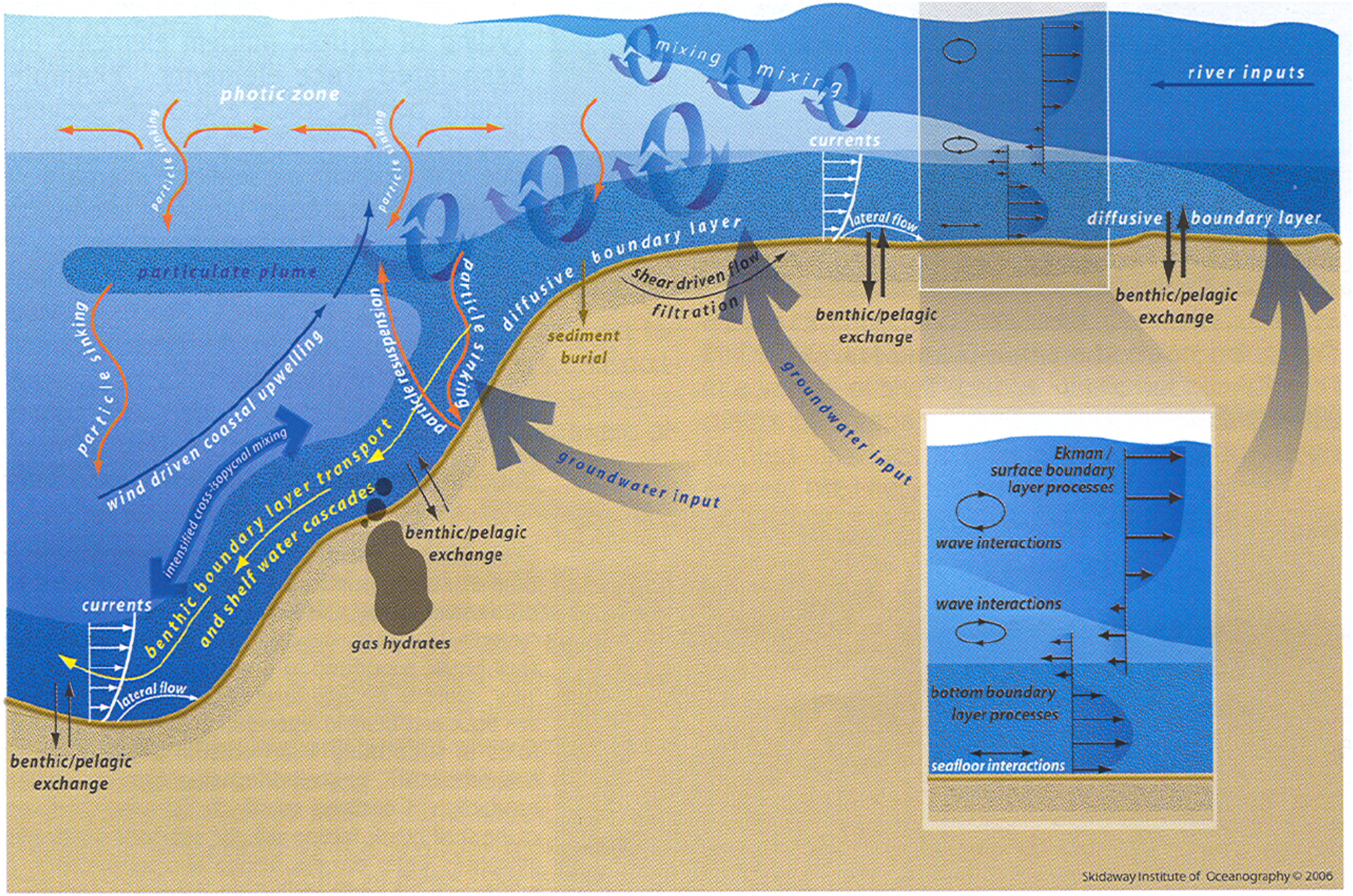
- *Introduction*
- *Gravity and turbidity currents*
- *Influence of complex topography*
- *Grain-resolving erosion simulations*
- *Current/structure interactions*
- *Outlook*

UCSB

Coastal margin processes



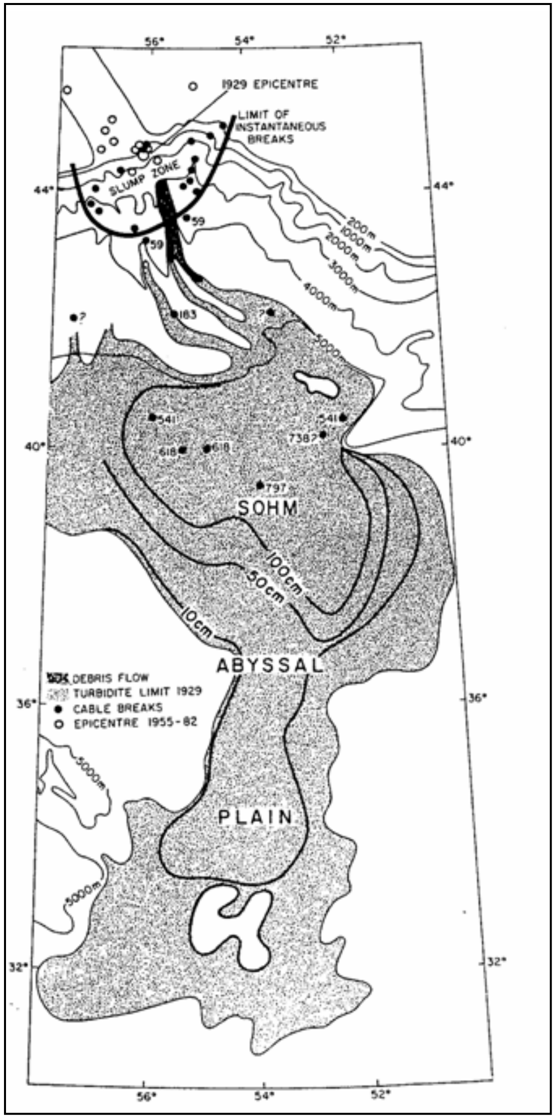
Turbidity current

- *Underwater sediment flow down the continental slope*
- *Can transport many km^3 of sediment*
- *Can flow O(1,000)km or more*
- *Often triggered by storms or earthquakes*
- *Repeated turbidity currents in the same region can lead to the formation of hydrocarbon reservoirs*
- *Properties of turbidite:*
  - *particle layer thickness*
  - *particle size distribution*
  - *pore size distribution*

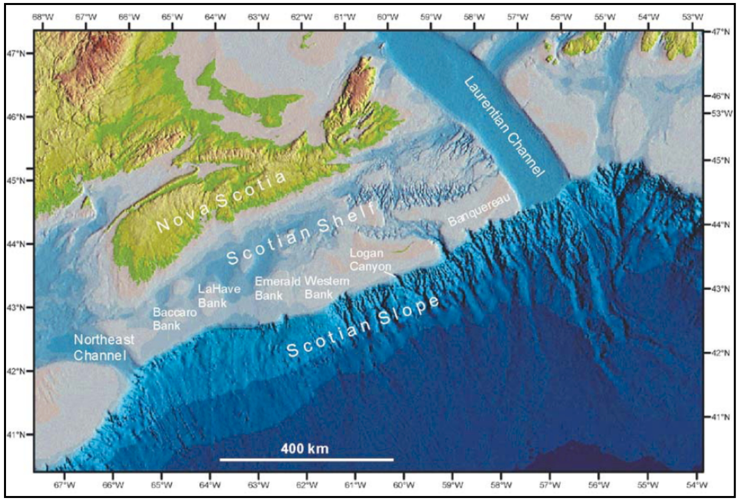
Turbidity current.

http://www.clas.ufl.edu/

Turbidity current (cont'd)



From Piper et al., 1984



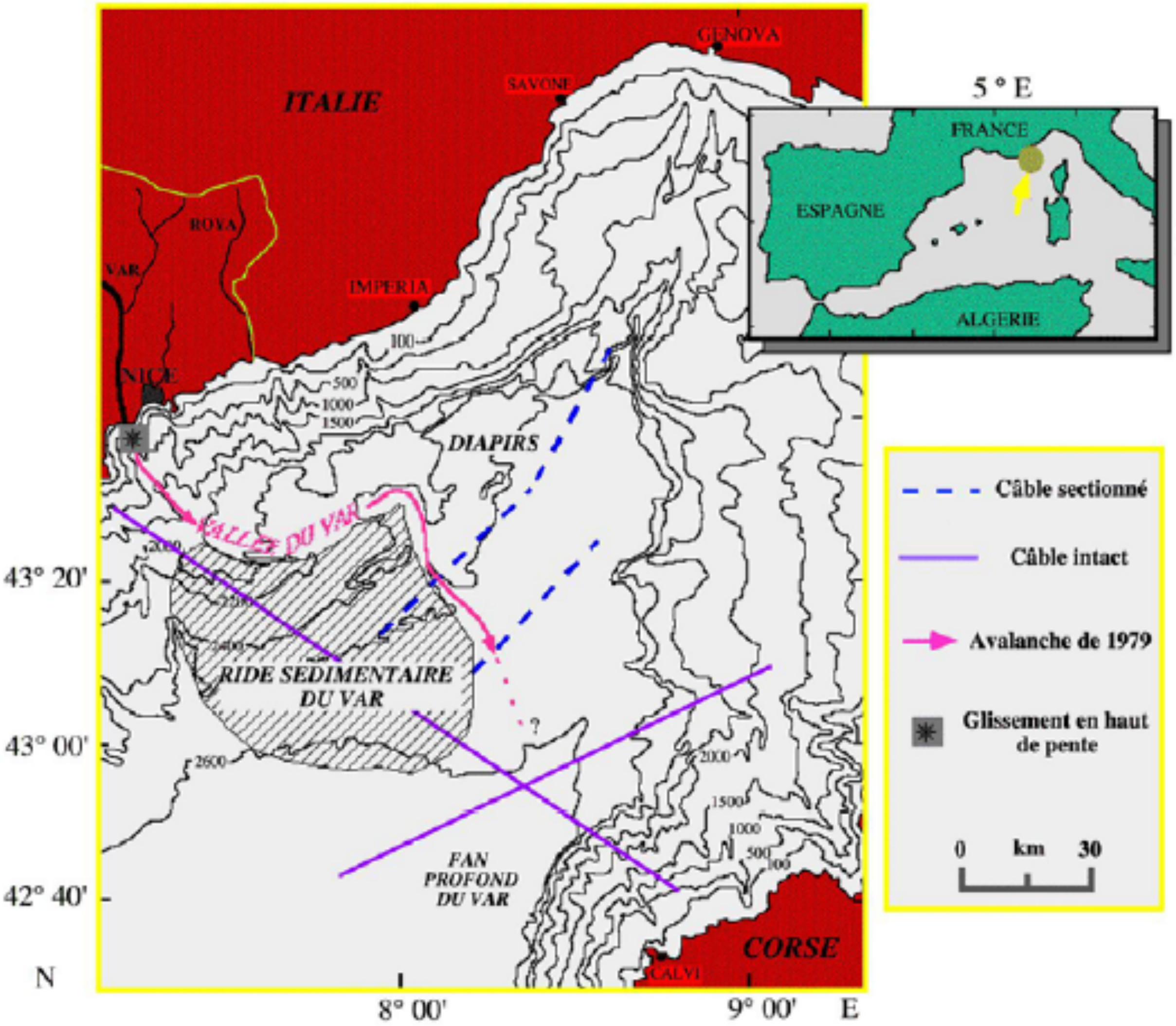
Grand Banks turbidite
historical event, Nov 18 1929 (M7.2)

Length scale = 10^6 m
Grain size = $\leq 10^{-1}$ m
Volume of deposit = 1.8×10^{11} m^3
Re = O (10^9)

Turbidity current (cont'd)

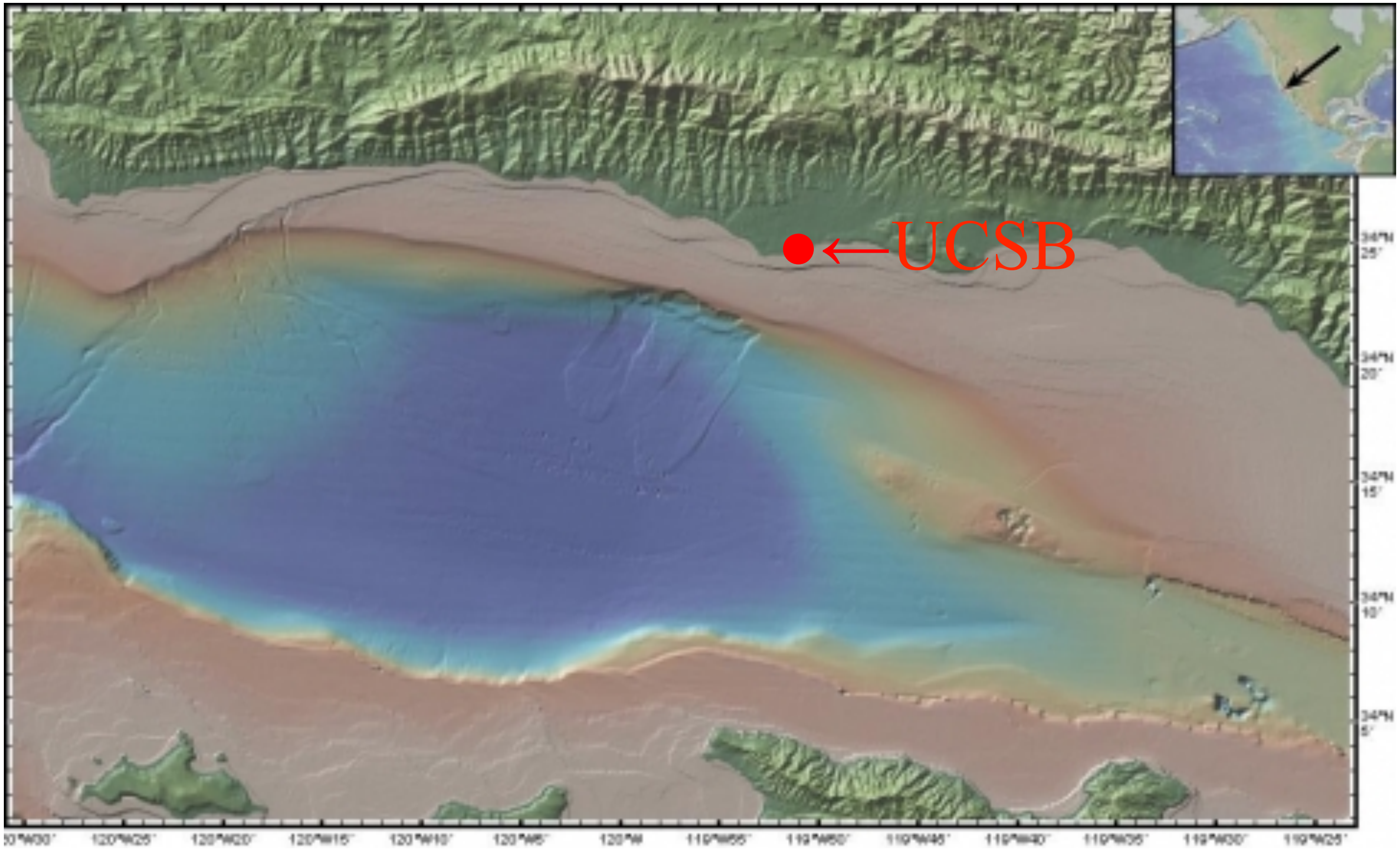
Field data – levee complex, Maastrichtian, Baja California, Mexico

Turbidity current (cont'd)



Var Fan, off Nice coast, caused in 1979 by airport construction accident

Turbidity current (cont'd)



Off the coast of Santa Barbara/Goleta

Framework: Dilute flows

Assumptions:

- *volume fraction of particles < O(*10^{-2} *-* 10^{-3}*)*
- *particle radius « particle separation*
- *small particles with negligible inertia*

Dynamics:

- *effects of particles on fluid continuity equation negligible*
- *coupling of fluid and particle motion primarily through momentum exchange, not through volumetric effects*
- *particle loading modifies effective fluid density*
- *particles follow fluid motion, with superimposed settling velocity*

Moderately dilute flows: Two-way coupling (cont'd)

$$
\begin{aligned}
\nabla \cdot \vec{u}_f &= 0 \\
\frac{\partial \vec{u}_f}{\partial t} + \left(\vec{u}_f \cdot \nabla\right) \vec{u}_f &= -\nabla p + \frac{1}{Re} \nabla^2 \vec{u}_f + c\, \vec{e}_g \\
\frac{\partial c}{\partial t} + \left[\left(\vec{u}_f + \vec{U}_s\right) \nabla\right] c &= \frac{1}{Sc\, Re} \nabla^2 c
\end{aligned}
$$

effective density

settling velocity

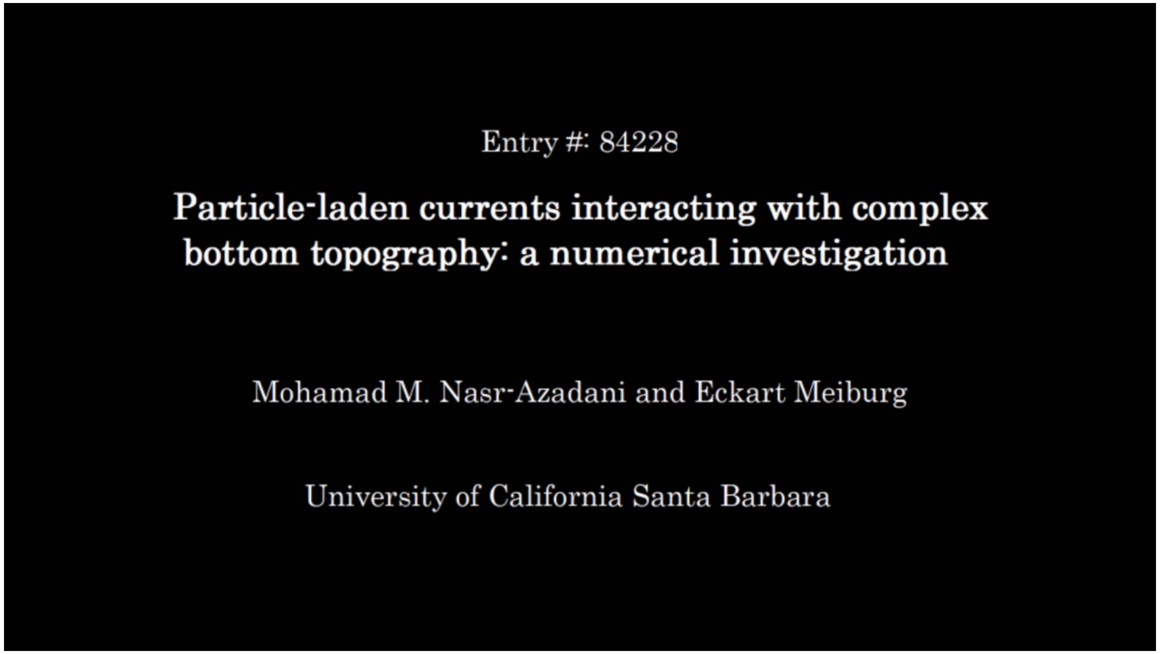
$$
Re = \frac{u_b\, L}{\nu} \quad , \quad Sc = \frac{\nu}{D} \quad , \quad U_s = \frac{u_s}{u_b}
$$

Numerical method

- *second order central differencing for viscous terms*
- *third order ENO scheme for convective terms*
- *third order TVD Runge-Kutta time stepping*
- *projection method to enforce incompressibility*
- *domain decomposition, MPI*
- *employ PETSc (developed by Argonne Nat'l Labs) package*
- *non-uniform grids*
- *immersed boundary method for complex bottom topography*

Lock exchange configuration (with M. Nasr-Azadani)

Flow of turbidity current around localized seamount



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Particle-laden currents interacting with complex bottom topography: a numerical investigation

Mohamad M. Nasr-Azadani and Eckart Meiburg

University of California Santa Barbara

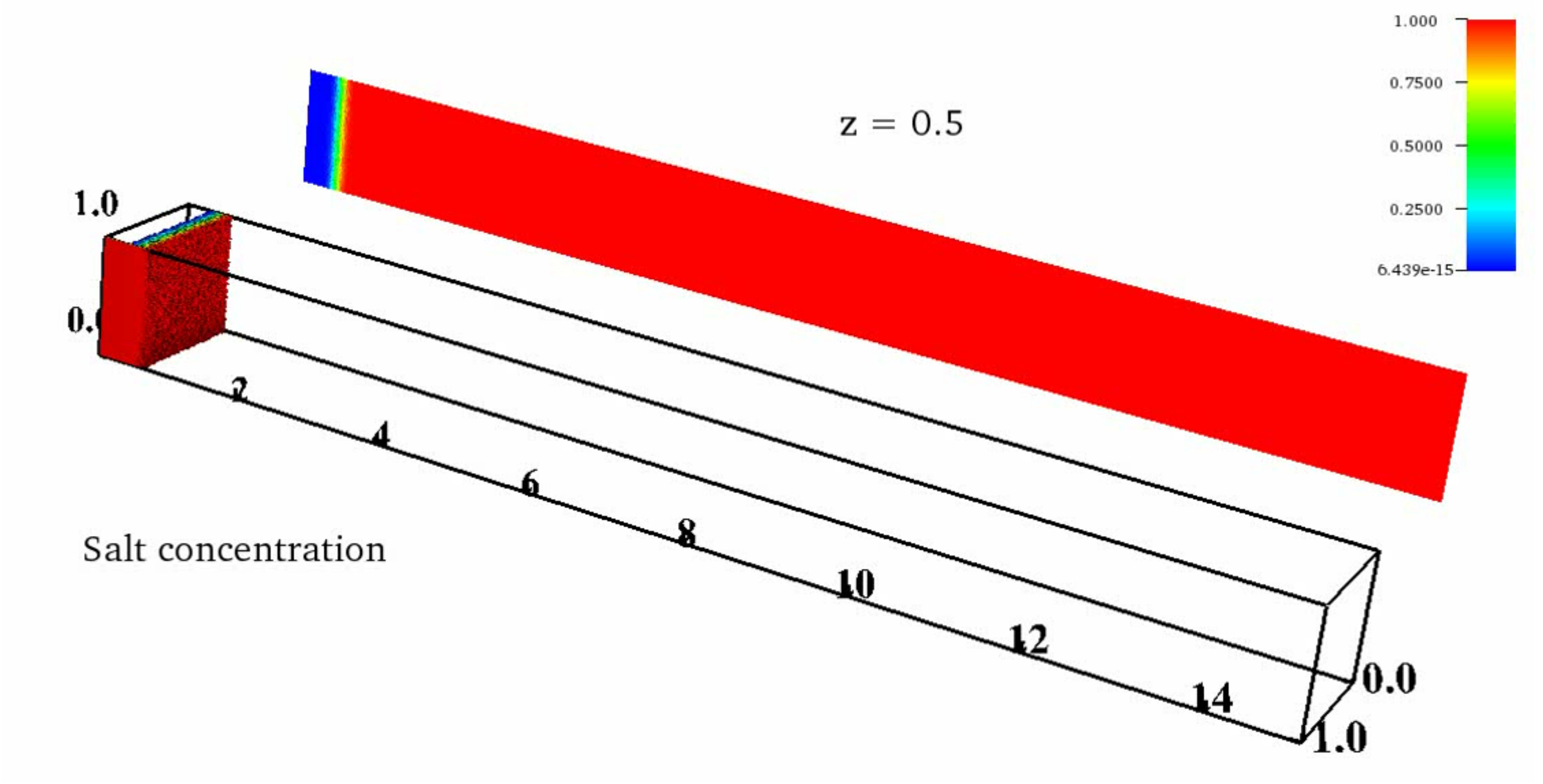
- *turbidity current develops lobe-and-cleft instability of the front*
- *current dynamics and depositional behavior are strongly affected by bottom topography*

$$Re_{sim} = 2,000 : \;\; u_b \approx 2cm/s \;, \;\; L \approx 10cm \;, \;\; \nu \approx 10^{-6} m^2/s$$

→ *simulation corresponds to a laboratory scale current, not field scale!*

LES simulation: reversing buoyancy turbidity current

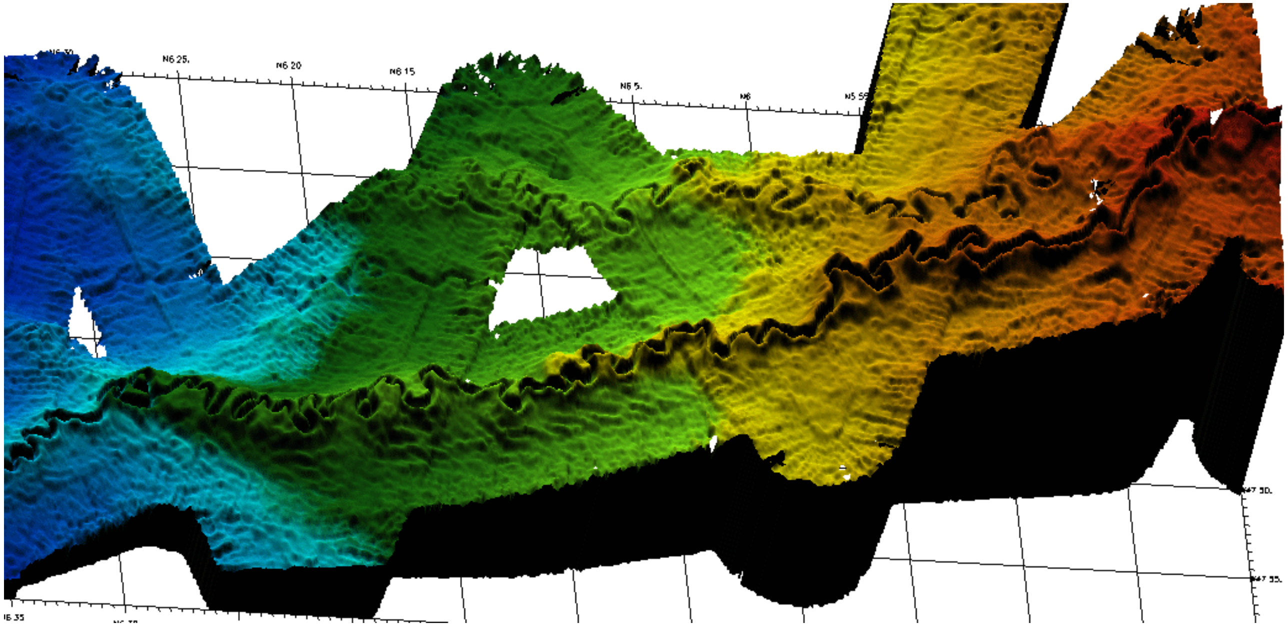
Initially the current propagates along the seafloor



- *after some sediment has settled out, the current lifts up and becomes buoyamt*

Turbidity current/sediment bed interaction

Formation of submarine channel-levee systems



Amazon submarine channel

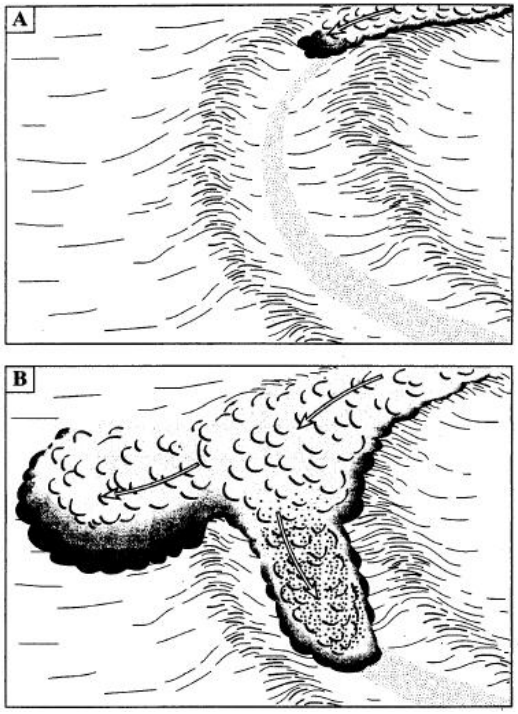
Turbidity current/sediment bed interaction

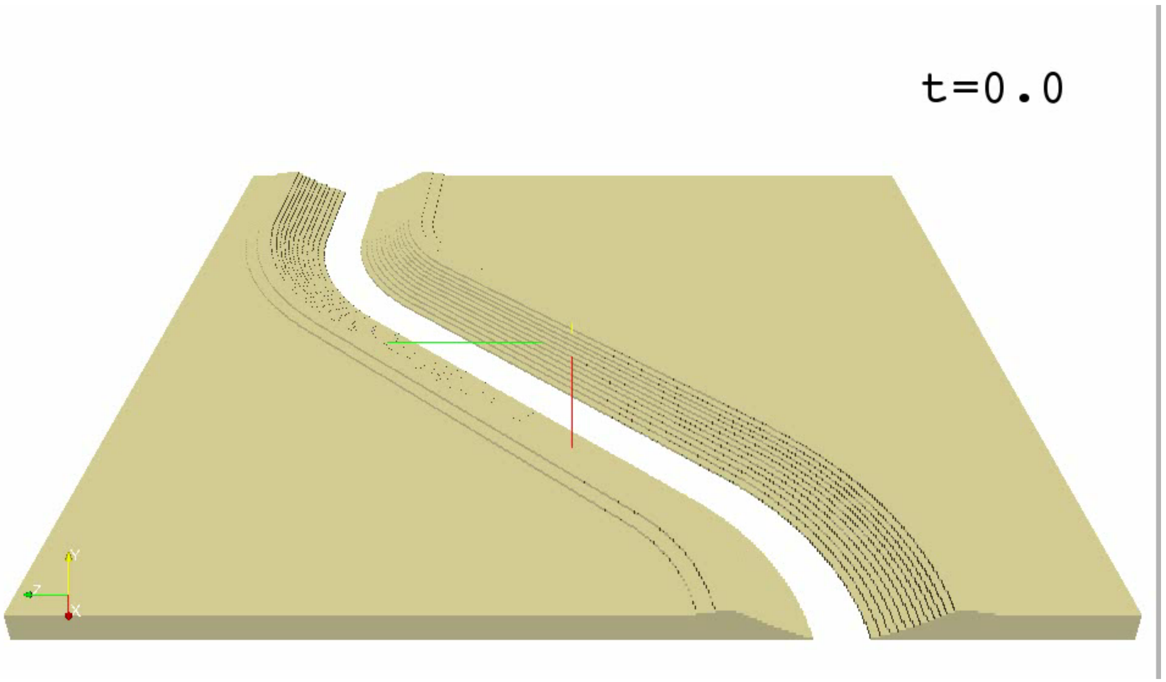
Formation of submarine channel-levee systems

Monterey Canyon fan

Turbidity current/sediment bed interaction (w. M. Nasr)

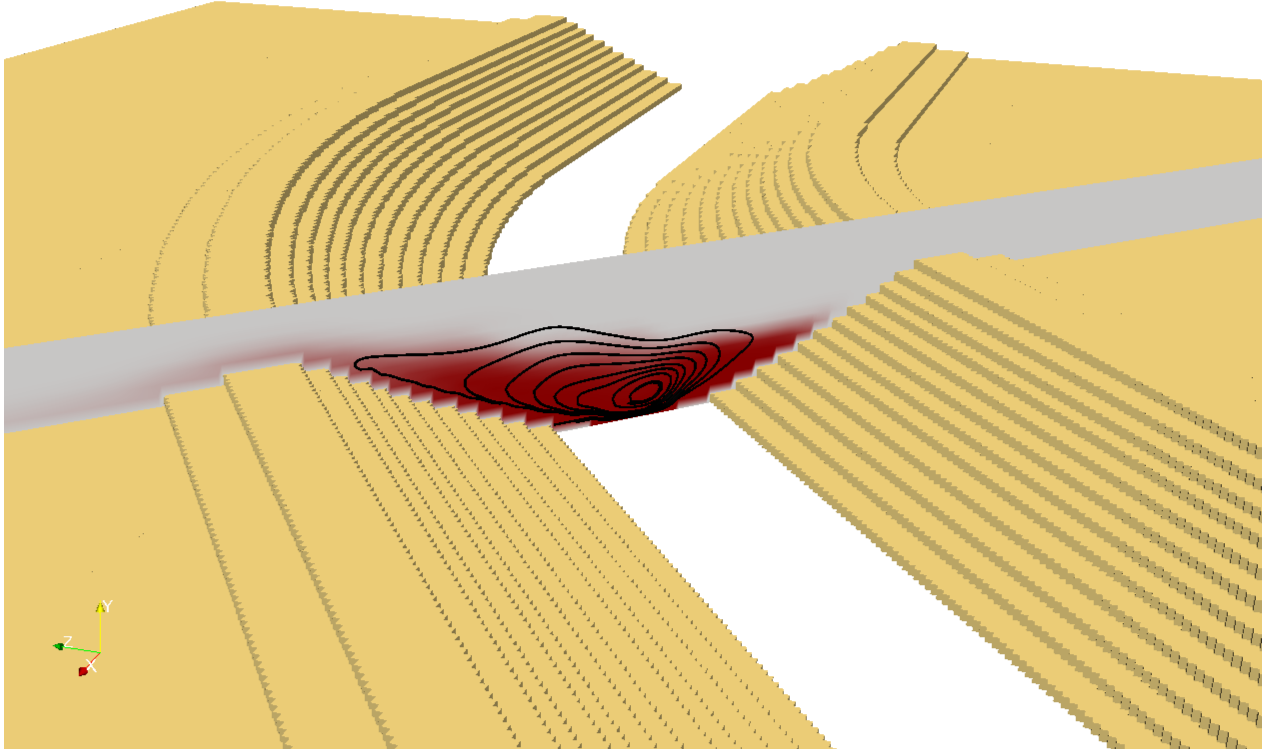
‘Flow stripping’ in channel turns: lateral overflows





Turbidity current/sediment bed interaction

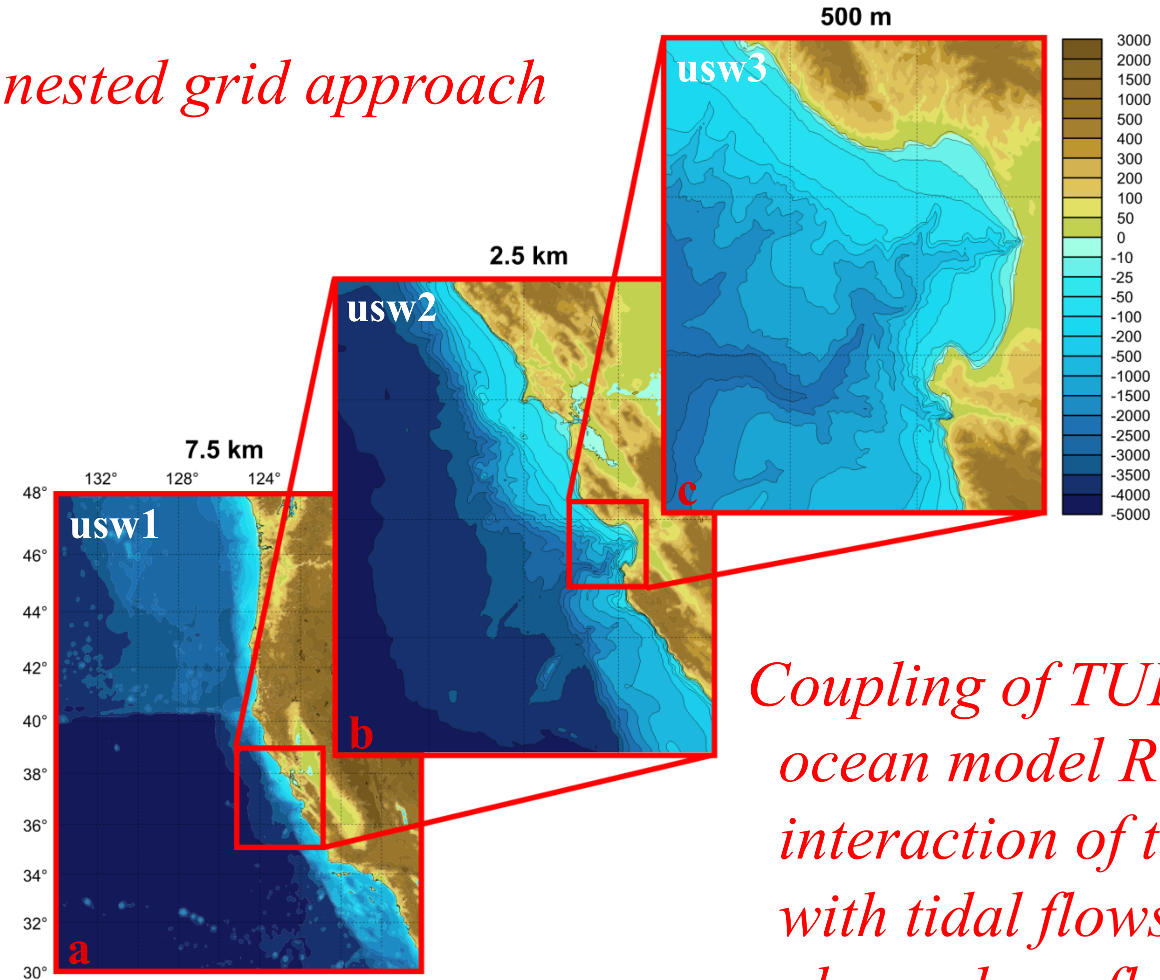
Secondary flow in submarine canyon bends



- *creates bed shear stress that causes lateral sediment transport*

Upscaling: Embedding high-resolution simulation within coarser resolution one (w. J. Syvitski, H. Arango, C. Harris)

- *nested grid approach*



Coupling of TURBINS with regional ocean model ROMS, to include interaction of turbidity currents with tidal flows, internal waves, along-shore flows, Coriolis effects…

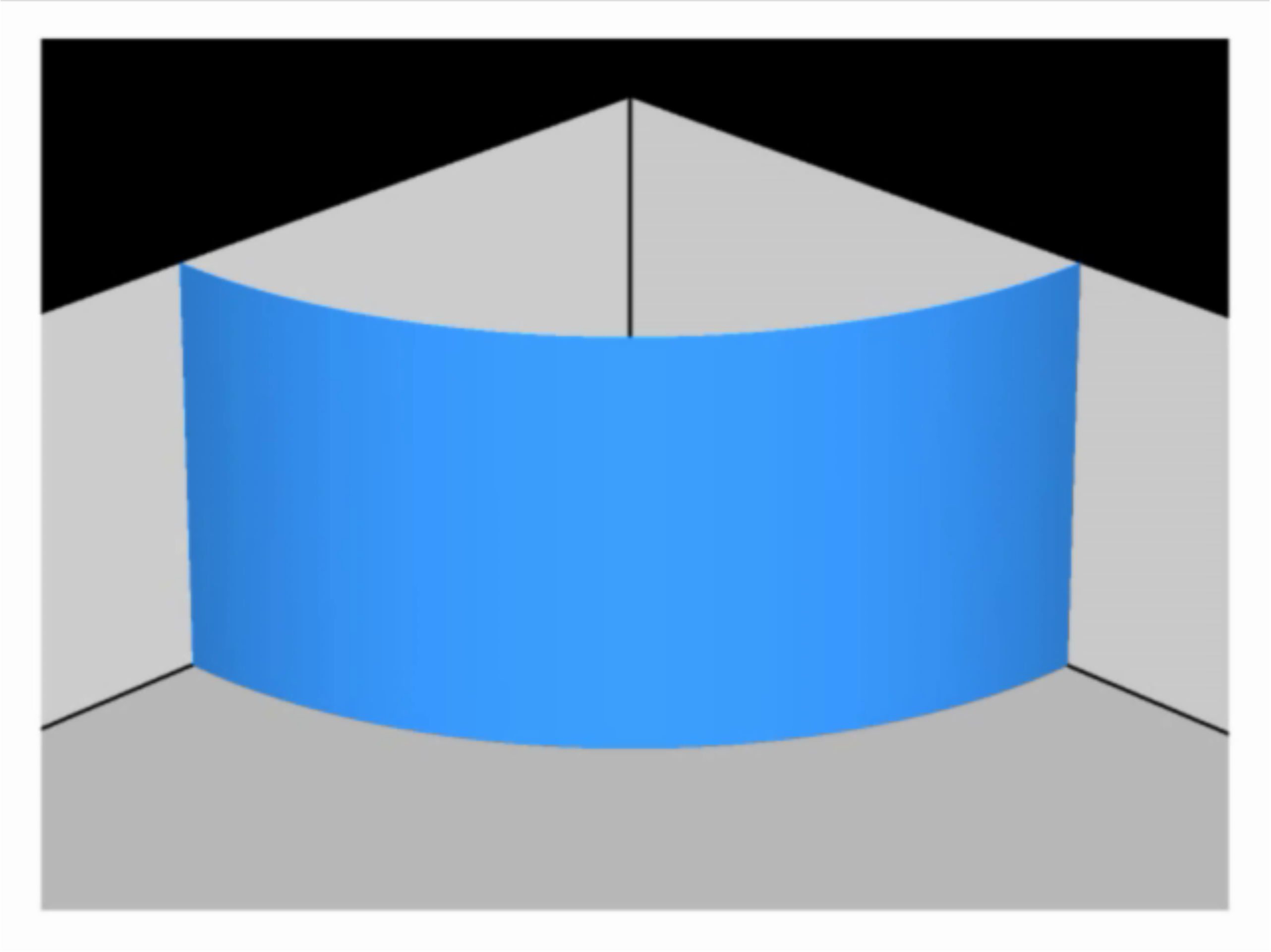
Couple turbidity current solver to reservoir simulator

Long term strategy:

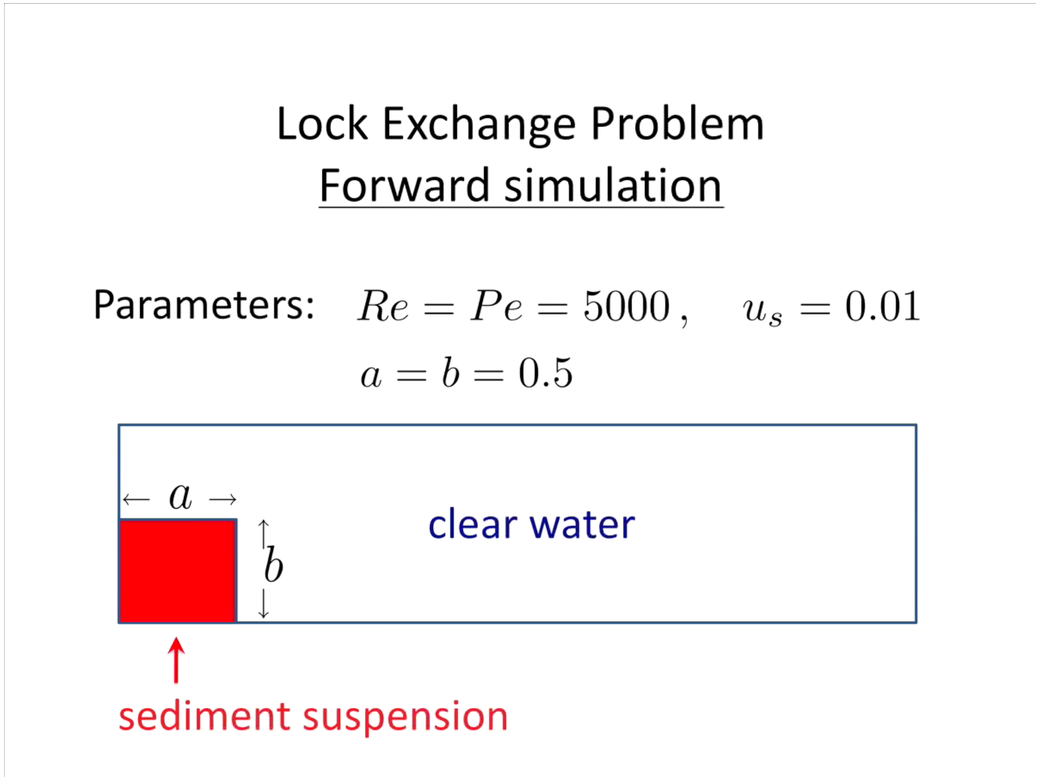
- *carry out simulation of polydisperse turbidity current*
- *obtain spatial grain size distribution of the deposit*
- *convert grain size distribution into permeability and porosity distribution*
- *feed permeability/porosity distribution into reservoir simulator*
- *carry out simulations of porous media displacement processes*

Porous media flow simulations (w. A. Riaz)

- *displacement of dense, more viscous fluid by light, less viscous one in a heterogeneous porous medium*



Inverse problem: Reconstruct current from deposit data (w. L. Lesshafft, B. Kneller)



Lock Exchange Problem

Forward simulation

Parameters: $Re = Pe = 5000\,, \quad u_s = 0.01$

$a = b = 0.5$

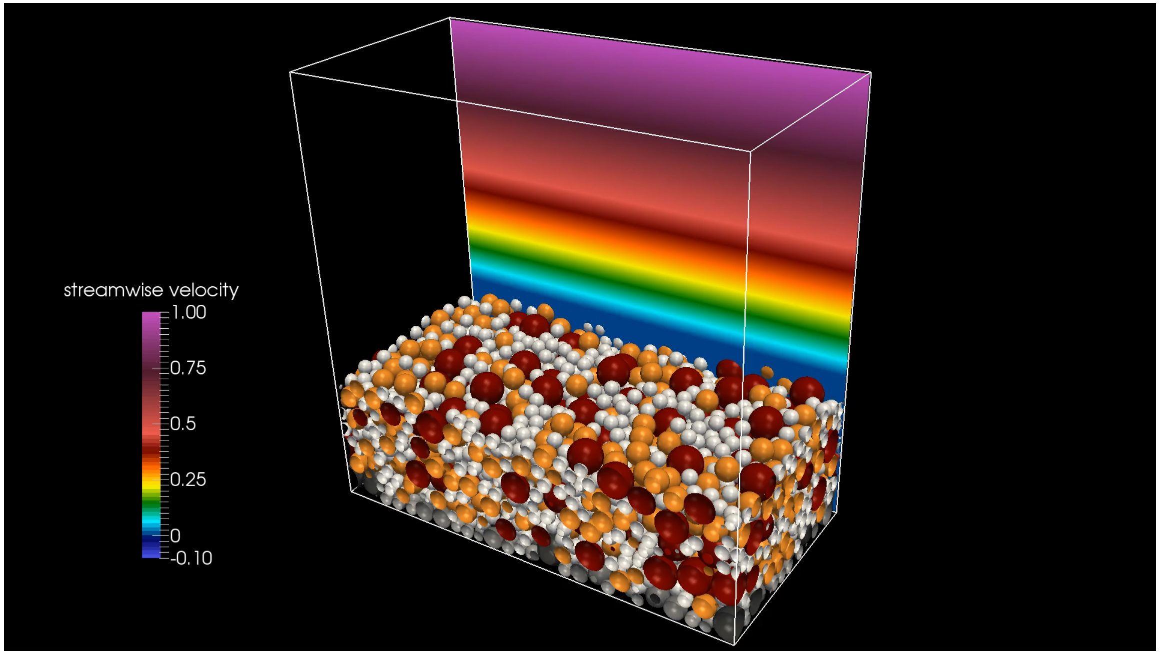
- *isolated deposit data allow reconstruction of initial conditions of turbidity current*
- *feed those initial conditions into high-resolution forward simulation*
- *obtain complete information on spatially distributed deposit configuration*
- *based on detailed deposit information, construct reservoir model*

Erosion of sediment bed (E. Biegert, B. Vowinckel)

- *erosion models to date are mainly empirical, e.g. Garcia and Parker (1993), limited validity, not based on first principles → research at the microscopic level is needed to develop improved erosion models*
- *perform many-particle simulations, with the flow around each particle resolved*
- *employ model flows (Poiseuille), subject sediment bed to increasing shear stress until erosion occurs*
- *study mechanics of erosion from first principles*
- *derive scaling laws for improved macroscopic, continuum erosion models*

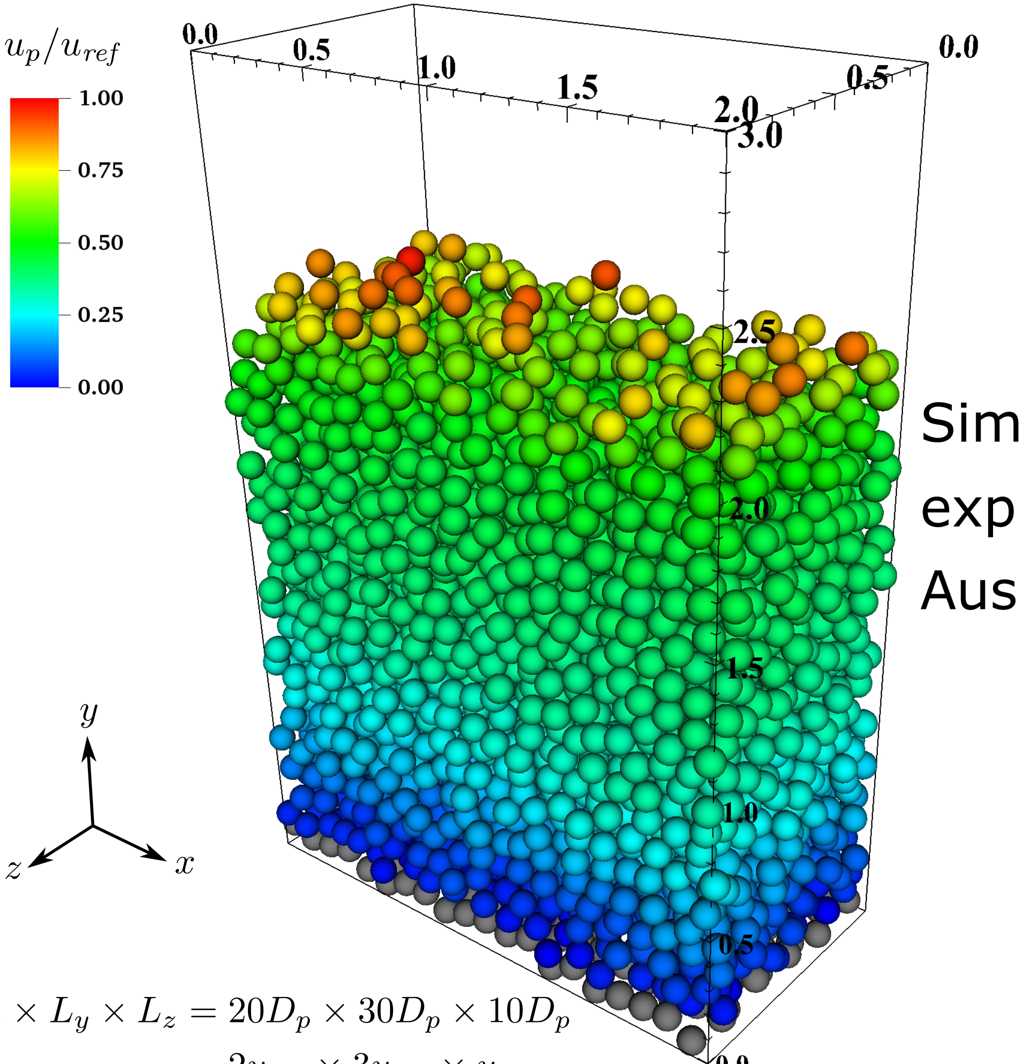
3D grain-resolving DNS simulations

Example: bedload transport for polydisperse sediment



- *resolves the flow around each grain, and in each pore space*
- *captures dynamics of high-concentration regions, hindered settling, non-Newtonian behavior*
- *currently limited to O(10^4-10^5) grains → very small scales only*
- *these simulations can provide accurate relations for the all-important erosion/resuspension rates, which are governed by grain-scale dynamics*
- *these accurate erosion relations can then be incorporated into large-scale simulations*
- *provide constitutive laws for high-concentration regions → capture non-Newtonian dynamics*

Simulation setup



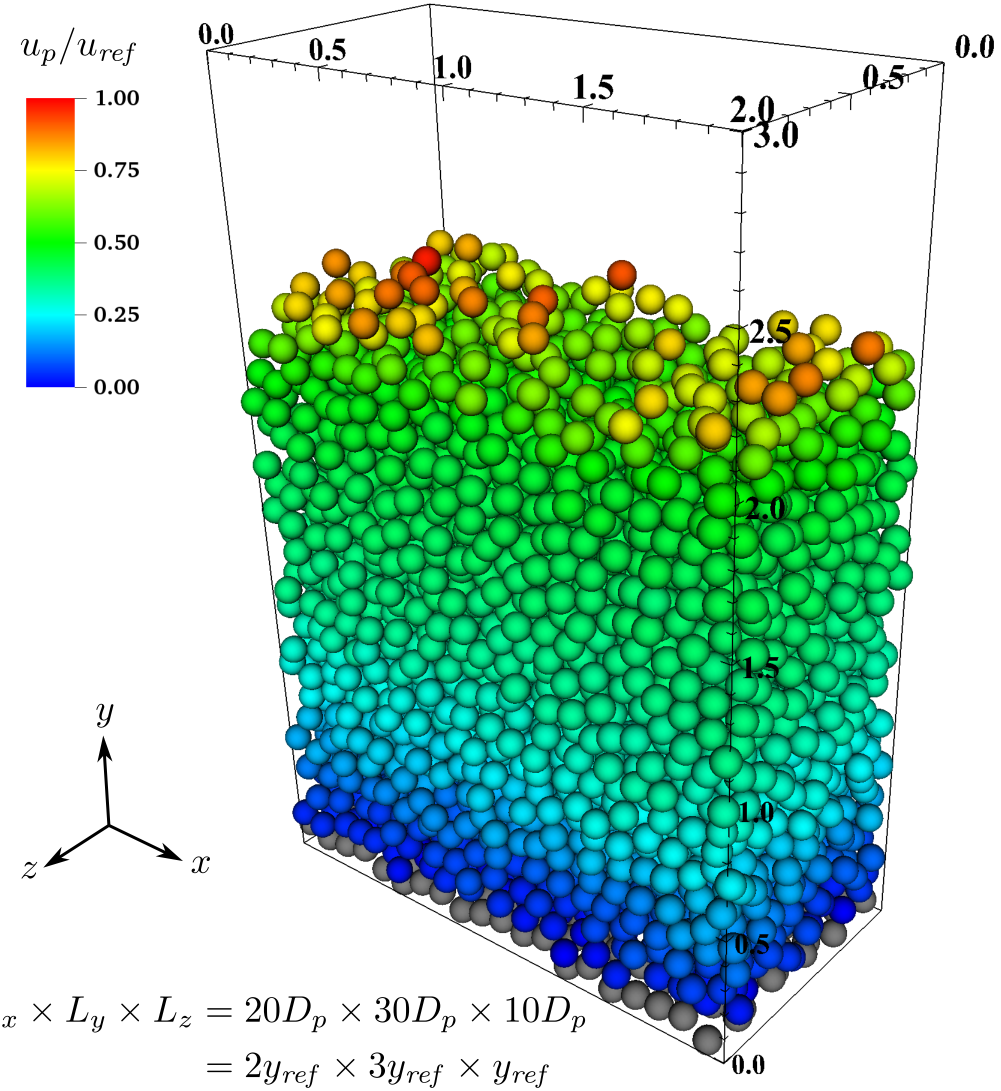
$$\frac{\rho_p}{\rho_f} = 2.10$$

$$Re_{ref} = \frac{u_{ref} y_{ref}}{\nu_f} = 67$$

Similar to experimental setup of Aussillous et al. [*JFM* 2013]

$$L_x \times L_y \times L_z = 20D_p \times 30D_p \times 10D_p$$
$$= 2y_{ref} \times 3y_{ref} \times y_{ref}$$

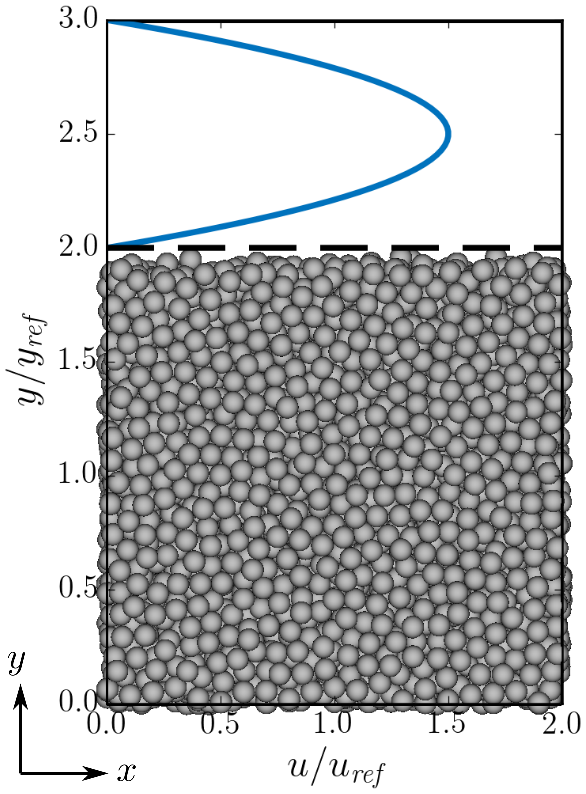
Simulation setup



$$\frac{\rho_p}{\rho_f} = 2.10$$

$$Re_{ref} = \frac{u_{ref}\, y_{ref}}{\nu_f} = 67$$

Reference Poiseuille flow:



$$L_x \times L_y \times L_z = 20D_p \times 30D_p \times 10D_p$$
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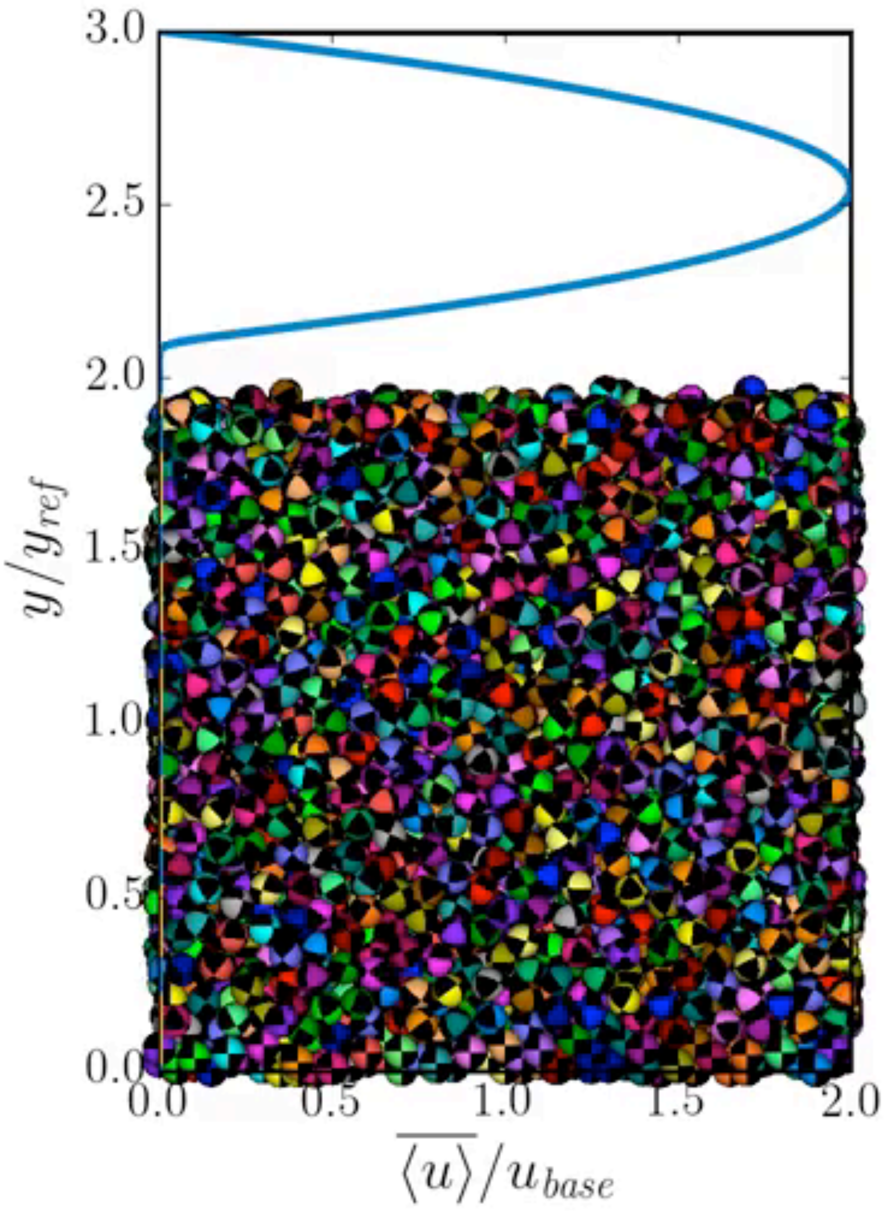
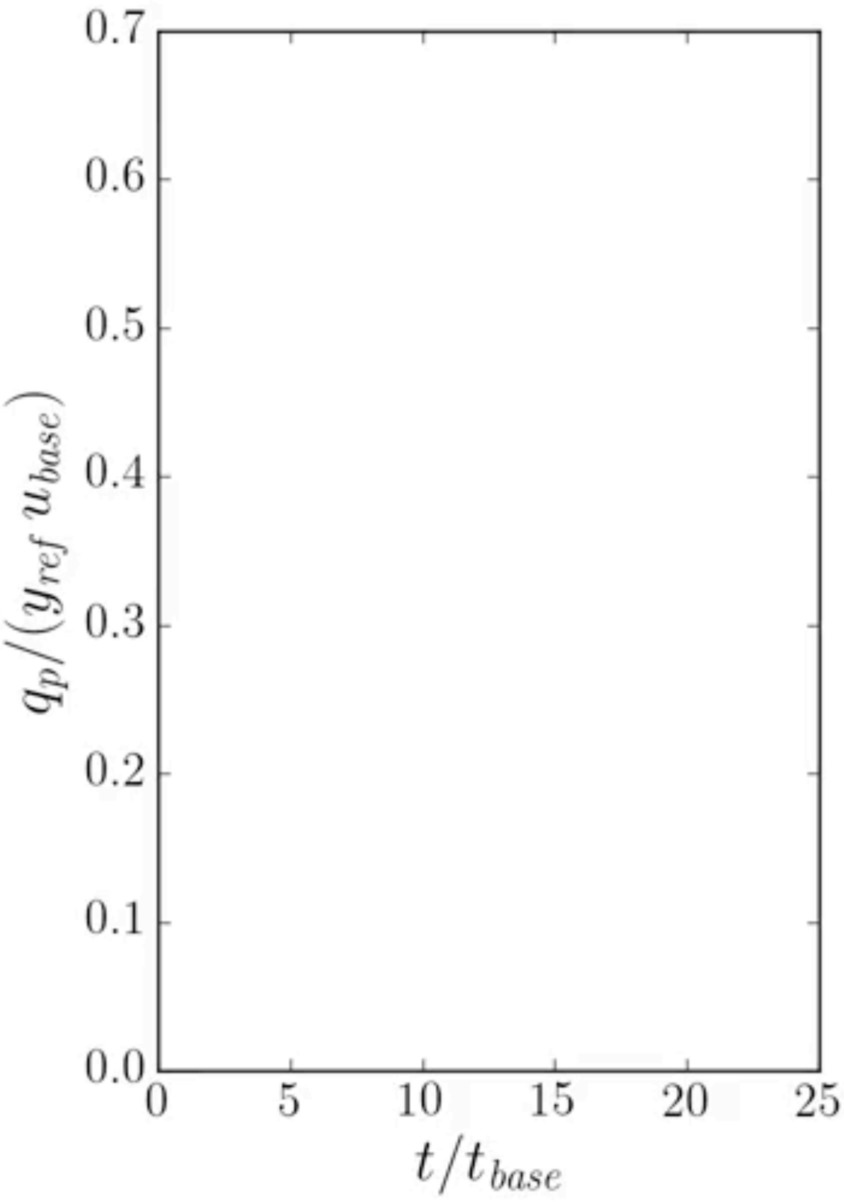

3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
y/y_{ref}
$\overline{\langle u \rangle}/u_{base}$


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
$q_p/(y_{ref}\, u_{base})$
t/t_{base}

Current extension: Cohesive sediment (w. P. Luzzatto-Fegiz, B. Vowinckel)

- *Currently preparing experiment for the International Space Station*
- *Expected to fly in later this month*
- *Goal: Study the flocculation behavior of sediment under microgravity conditions, so that interparticle forces dominate*
- *In collaboration with CASIS (Center for the Advancement of Science in Space)*

Settling of 1,261 polydisperse, cohesive particles

- *simulation setup:*

  silt in water

  [te Slaa et al., JHE, 2015]

$$\mathrm{Re} = \frac{\sqrt{g' D_{50}}\, D_{50}}{\nu_f} = 1.5$$

- *particles:*

$$N_p = 1261$$

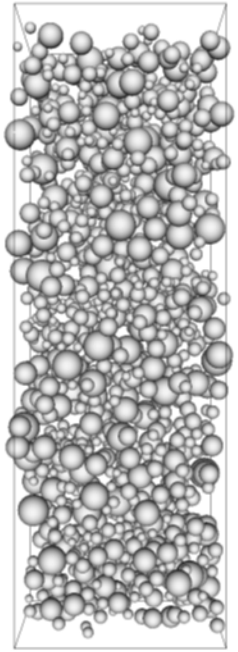
$$\max\{D\} / D_{50} = 2.4$$

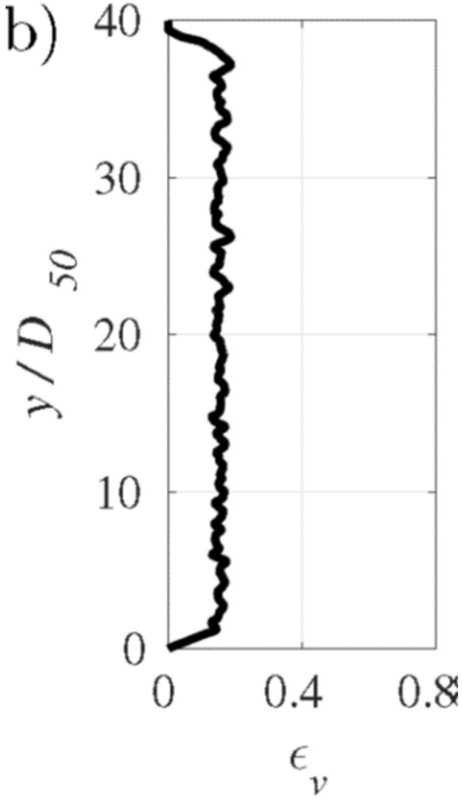
$$\min\{D\} / D_{50} = 0.6$$

- *computational parameters:*

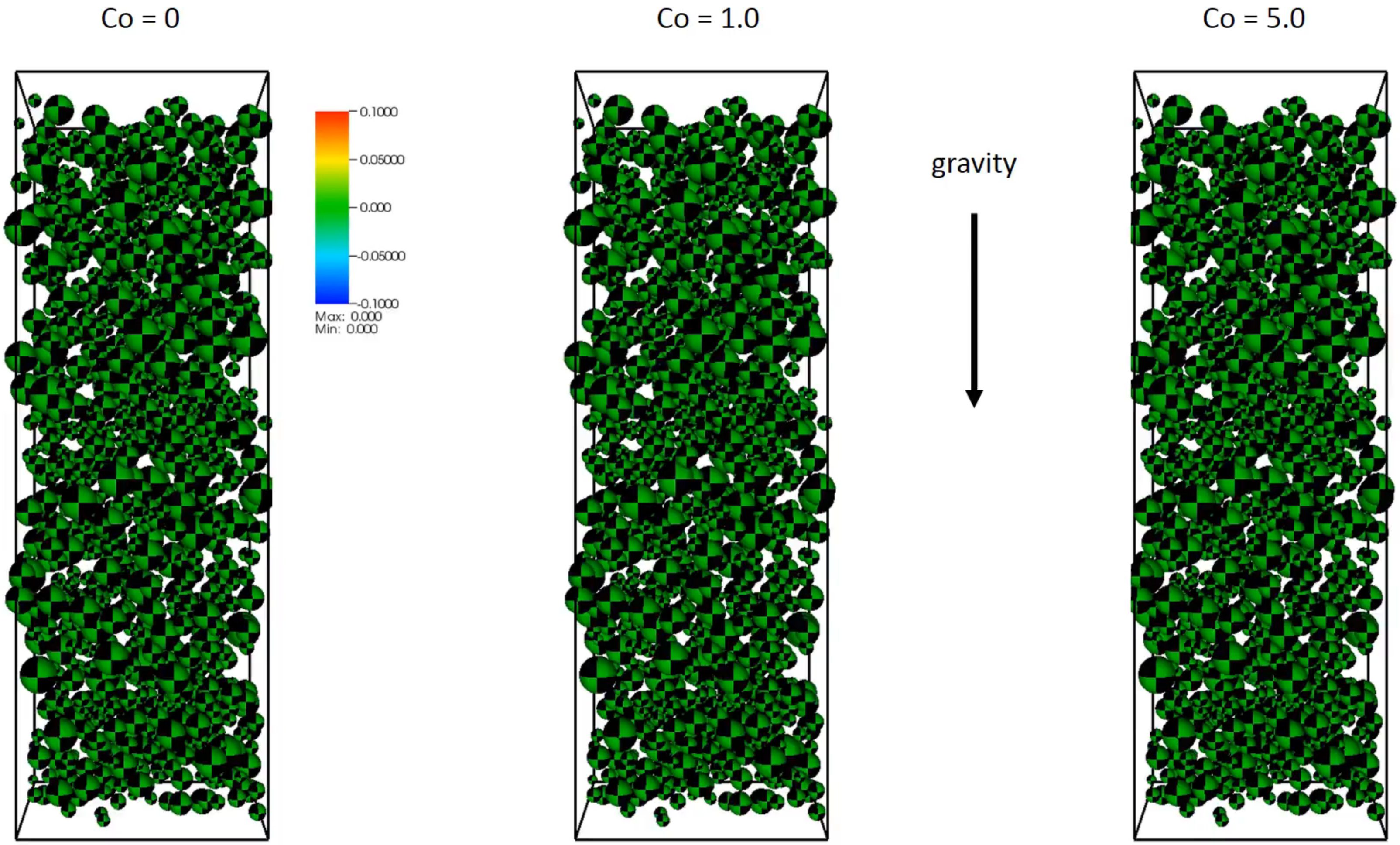
$$D_{50} / \Delta x = 18.5$$

$$\lambda = \Delta x$$





Settling of 1,261 polydisperse, cohesive particles



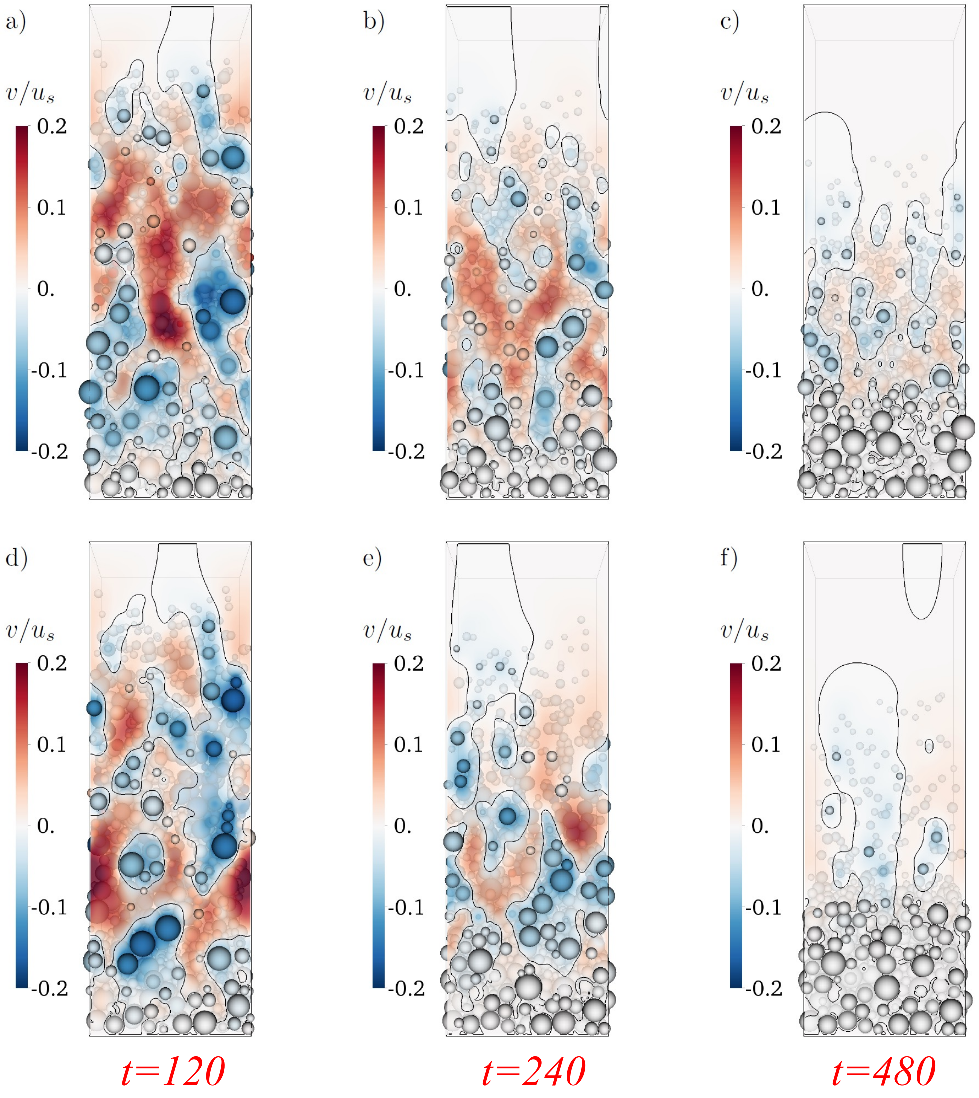
- *moderate cohesive forces accelerate overall settling process; further increasing the cohesive forces has only a minor effect*
- *key mechanism that accelerates settling: smaller particles bind to larger ones, settle with the higher velocity of the larger particles*

Settling of 1,261 polydisperse, cohesive particles

- *contours of vertical fluid velocity:*

noncohesive sediment

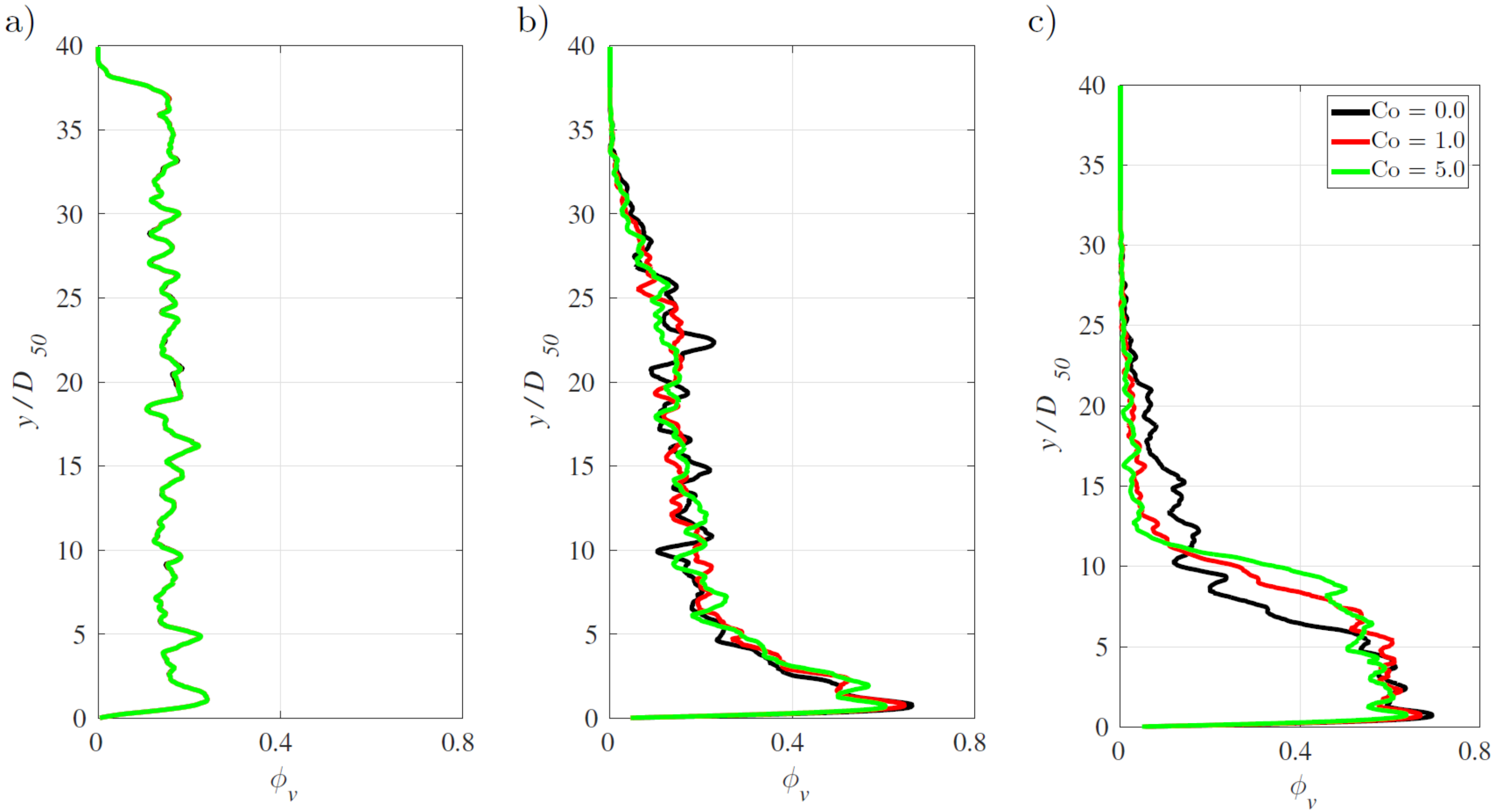
cohesive sediment



- *particle clusters are correlated with negative vertical fluid velocity*

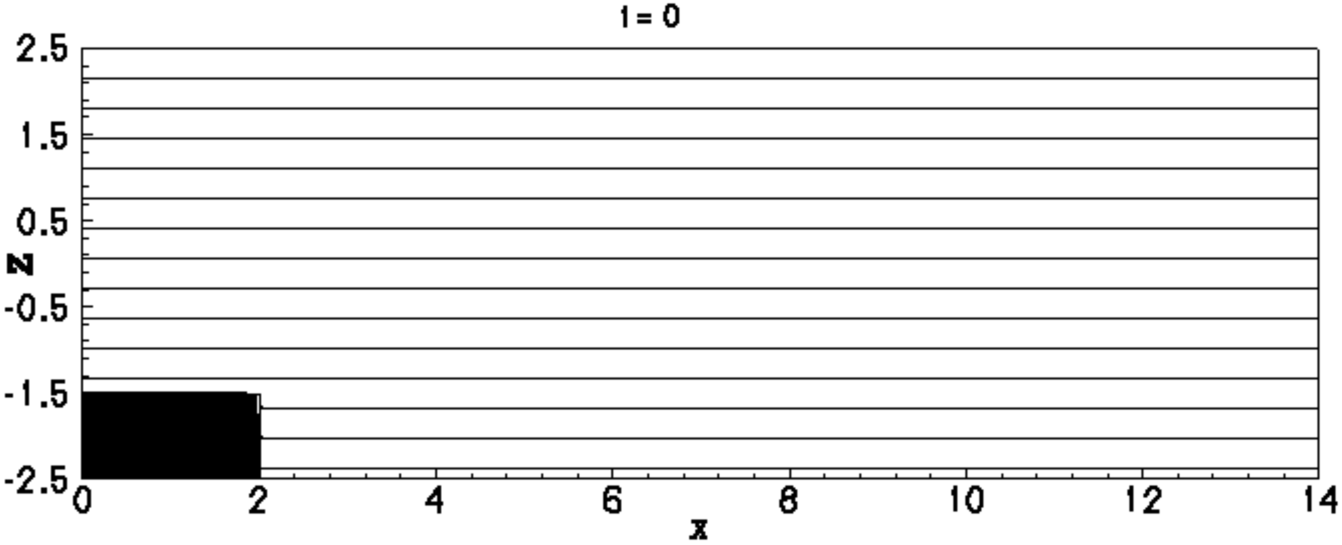
Settling of 1,261 polydisperse, cohesive particles

- *horizontally averaged particle volume fractions at different times:*



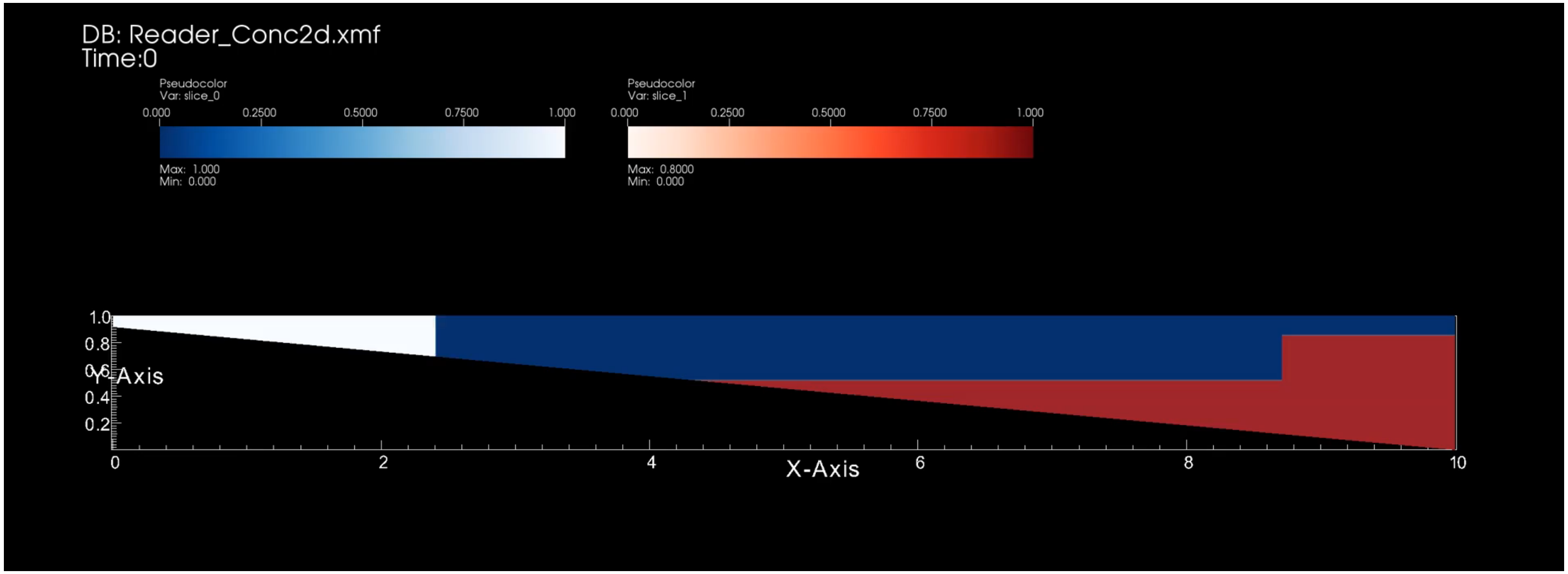
- *final time profiles consistent with accelerated settling for cohesive sediment*
- *near bottom wall, volume fraction of cohesive sediment is smaller than for noncohesive sediment, due to presence of flocs with larger pore spaces*

Stratification: Internal wave generation



- *Excitation of internal waves in the ambient fluid*

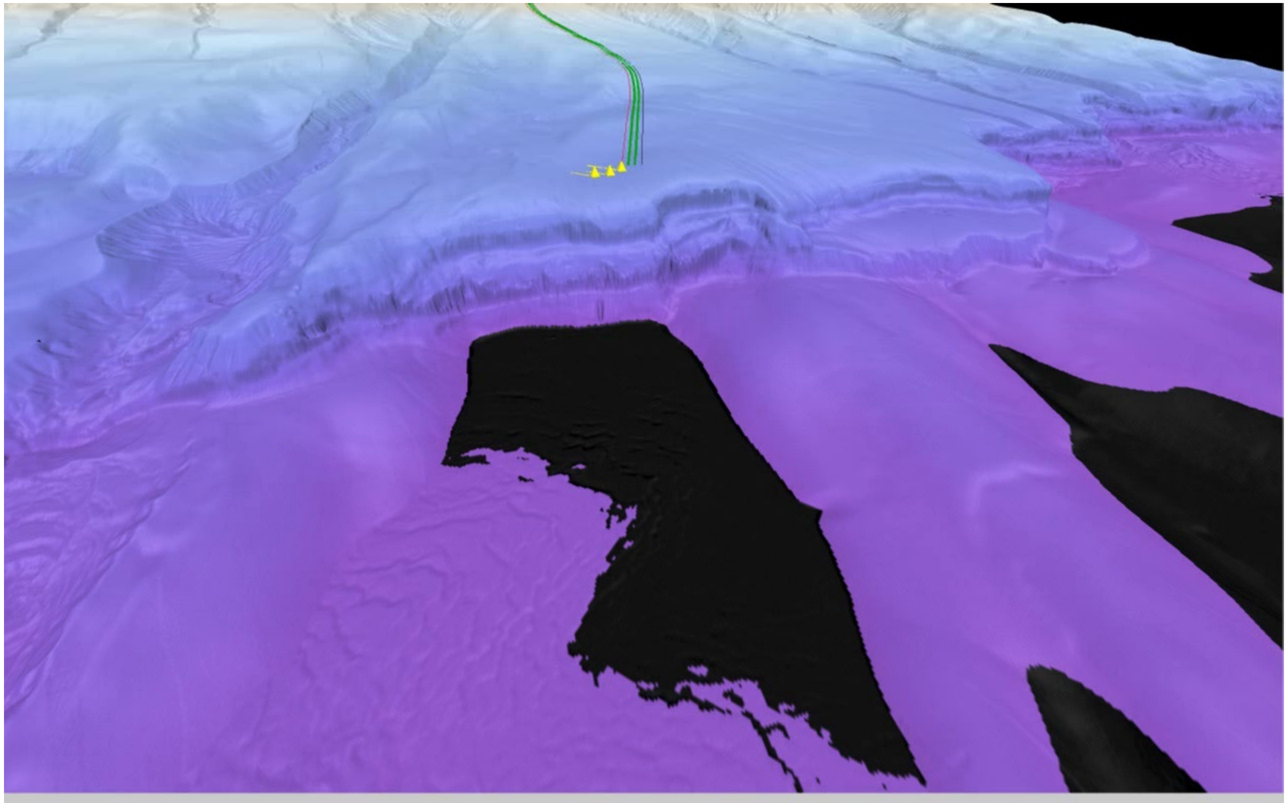
Interaction of gravity current with internal wave (w. R. Ouillon, J. Koseff, N. Ouellette)



- *"Decapitation" of current by internal wave*

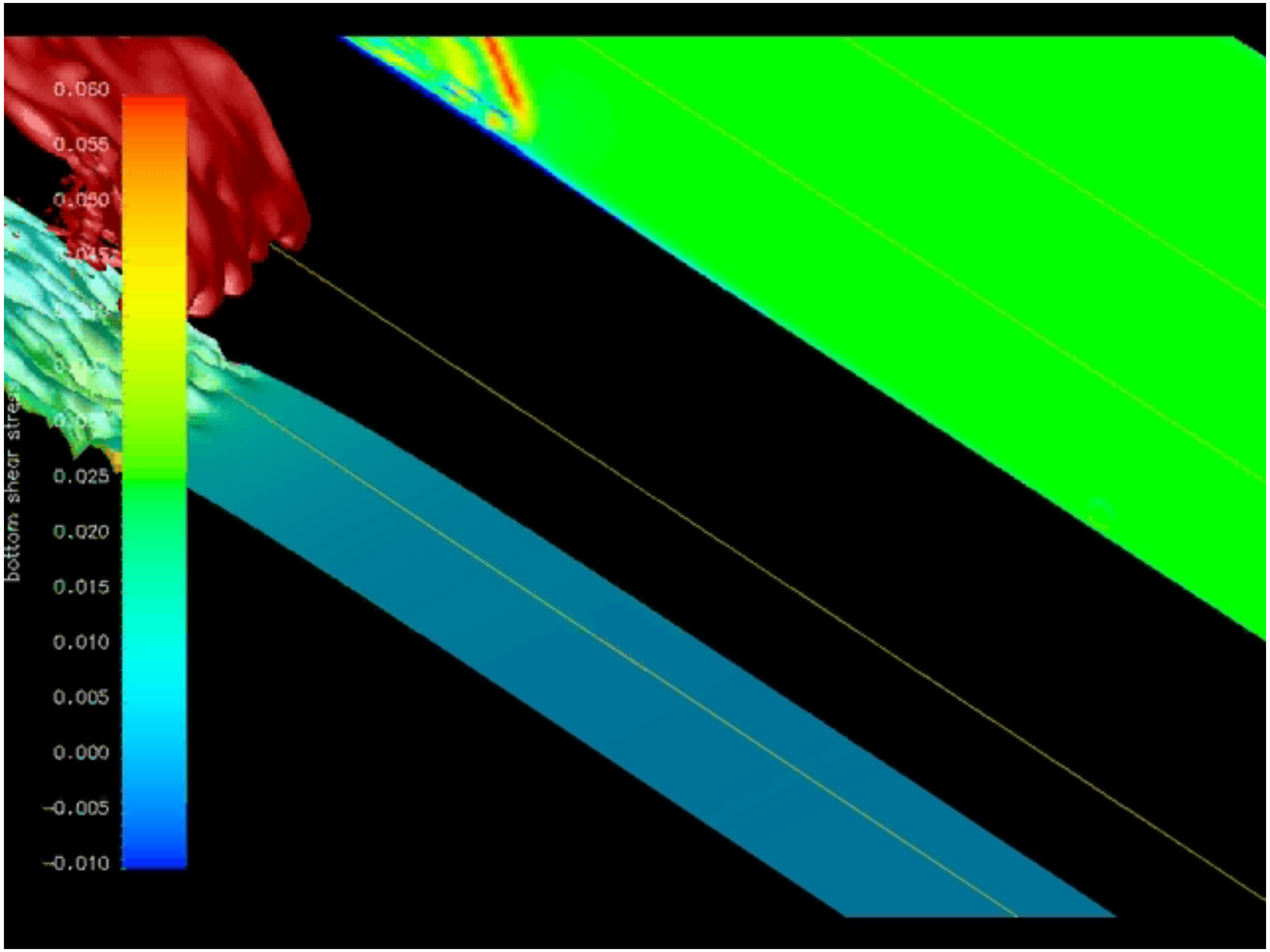
Hazards posed by gravity and turbidity currents (with E. Gonzales, T. Tokyay, G. Constantinescu)

Gravity currents may encounter underwater marine installations, Such as pipelines, wellheads etc.:



Hazards posed by gravity and turbidity currents

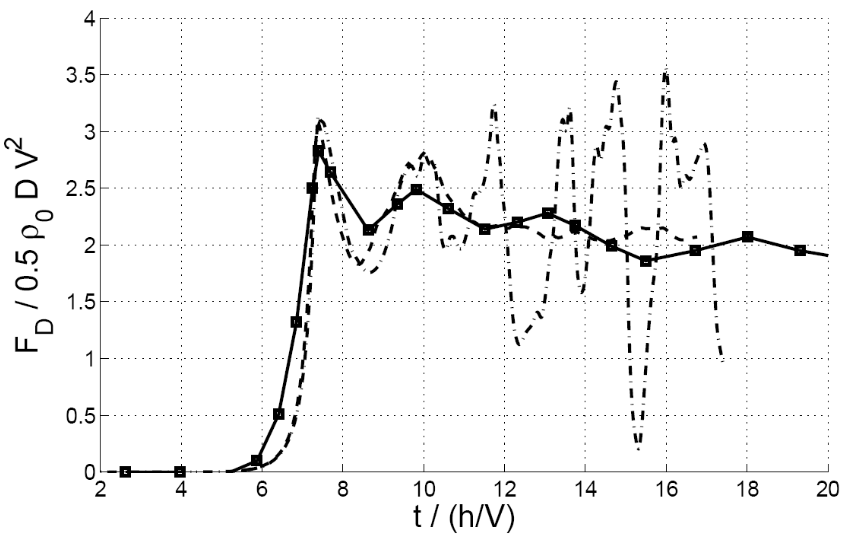
Gravity current interacting with pipeline: Vorticity and shear stress:

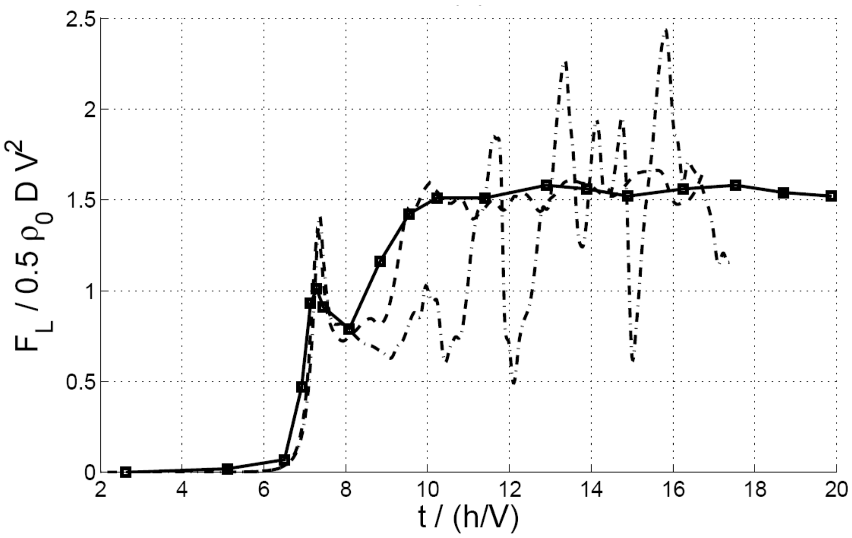


- *important for the prediction or erosion and scour*

Hazards posed by gravity and turbidity currents (cont'd)

Comparison with experiments by Ermanyuk and Gavrilov (2005):





______ *experiment*
. - . - . *2D simulation*
- - - - *3D simulation*

- *2D simulation captures impact, overpredicts quasisteady fluctuations*
- *3D simulation captures impact and quasisteady stages well*

Summary

- *high resolution 3D simulations of turbidity currents*
- *detailed information regarding erosional/depositional behavior, energy budgets, dissipation, entrainment, mixing dynamics . . .*
- *ongoing research on first-principle erosion analysis*
- *recent extension to complex seafloor topography: meandering channel/levee systems, mini-basins, local seamounts*
- *interaction of turbidity currents with submarine pipelines: forces, moments, time scales*
- *intrusions and reversing buoyancy (hyperpycnal) currents*
- *interaction of gravity/turbidity currents with internal waves*
- *inverse problem for reconstruction of current's initial conditions*
- *long-term goal: coupling to reservoir simulator*