Turbidity Currents and River Outflows

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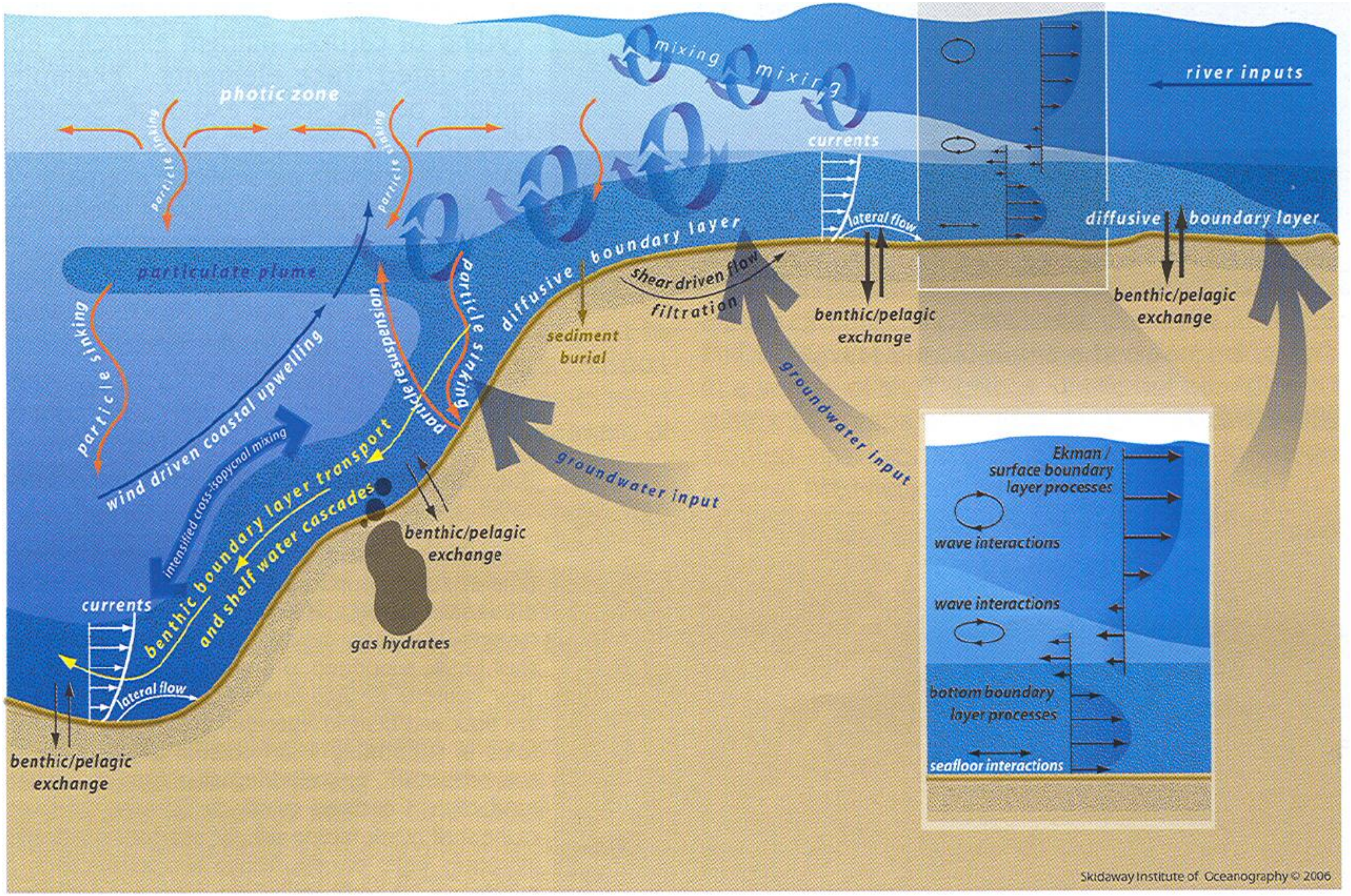
- *Motivation*
- *Governing equations / computational approach*
- *Results*
  - *turbidity currents over complex seafloor shapes*
  - *turbidity current/sediment bed interactions*
  - *turbidity current/pipeline interactions*
  - *river outflows: double-diffusive sedimentation*
- *Summary and outlook*

Coastal margin processes



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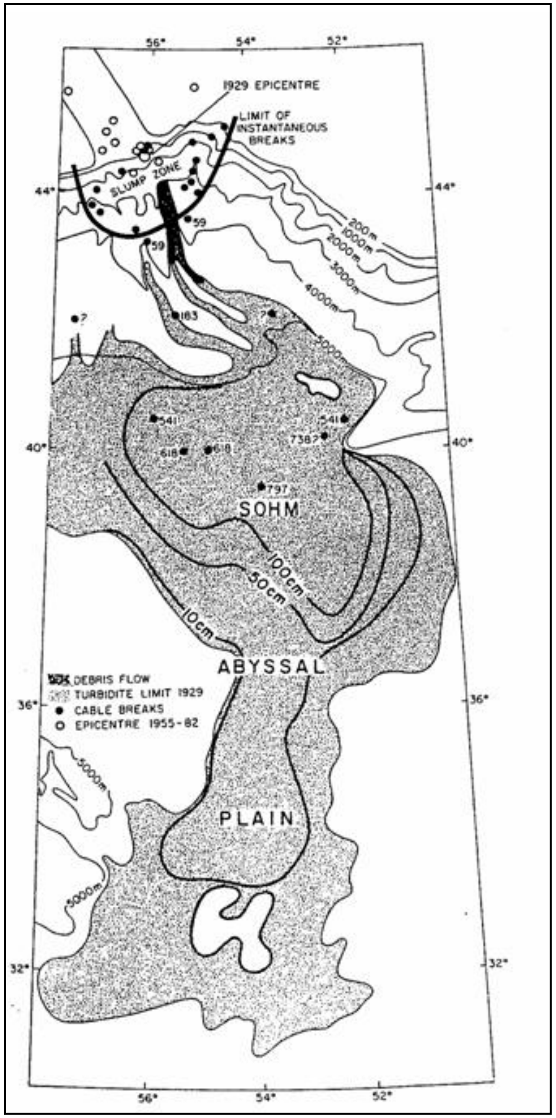
Turbidity current

- *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*

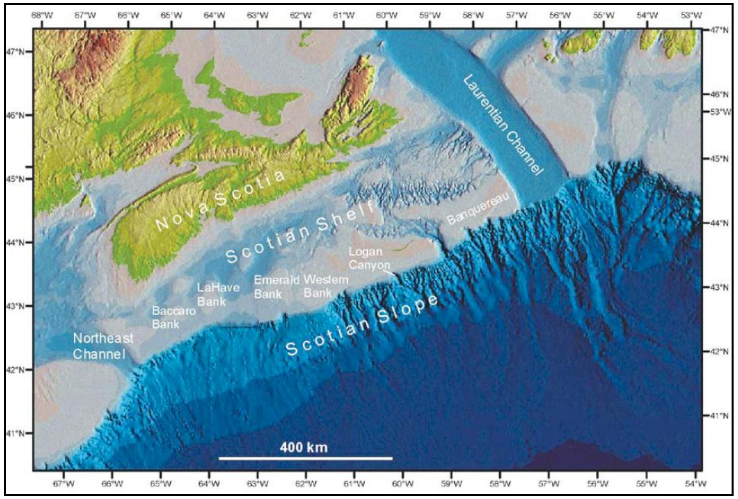
Turbidity current.

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

Turbidity current (cont'd)



Piper et al. (1984)



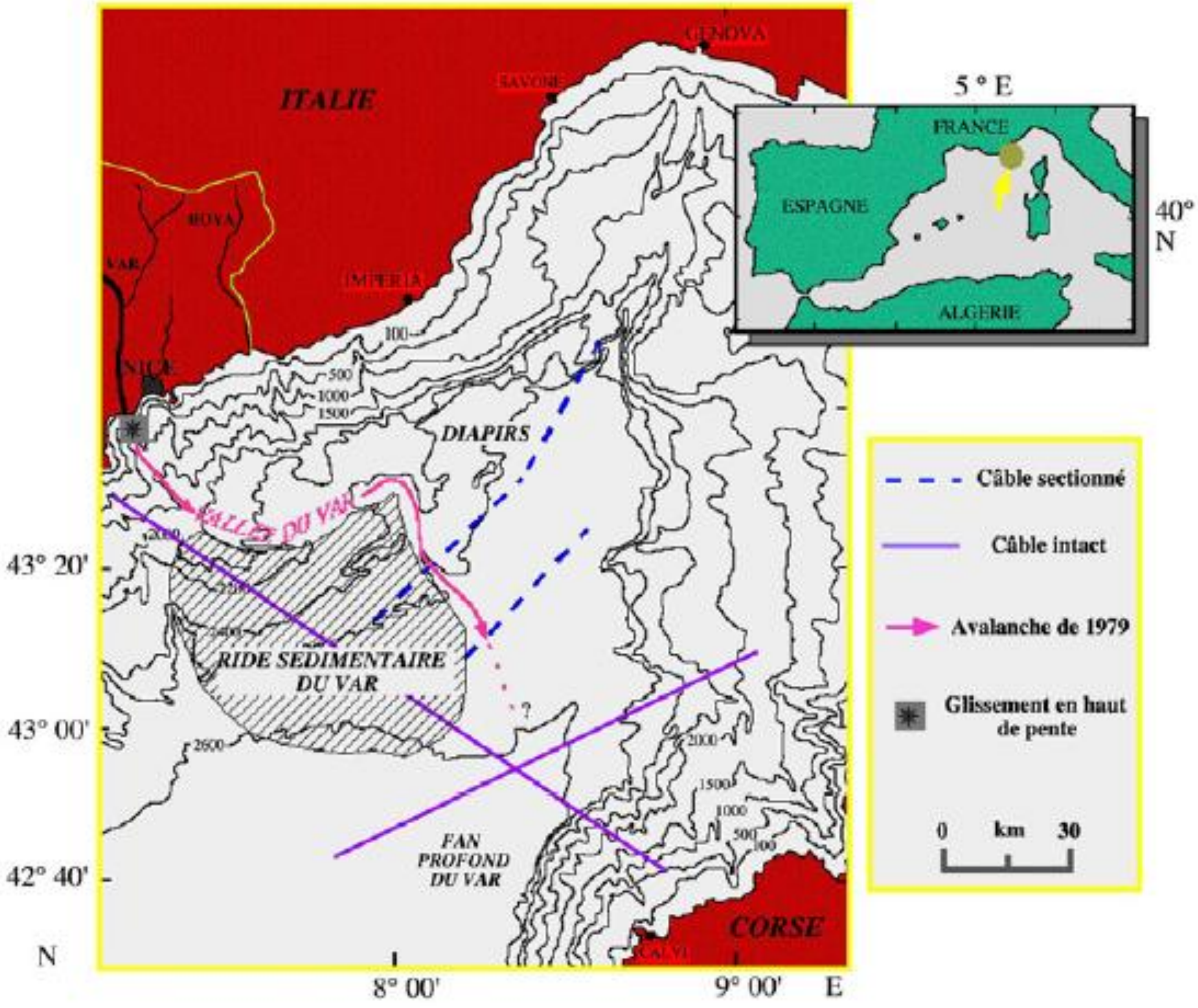
Grand Banks turbidity current historical event, Nov 18 1929 (M7.2)

- *length scale =* 10^6 *m*
- *grain size =* $\leq 10^{-1}$ *m*
- *volume of deposit =* 1.8×10^{11} m^3
- *Re =* $O(10^9)$
- *Fr = ??? Probably* ≤ 2

Turbidity current (cont'd)

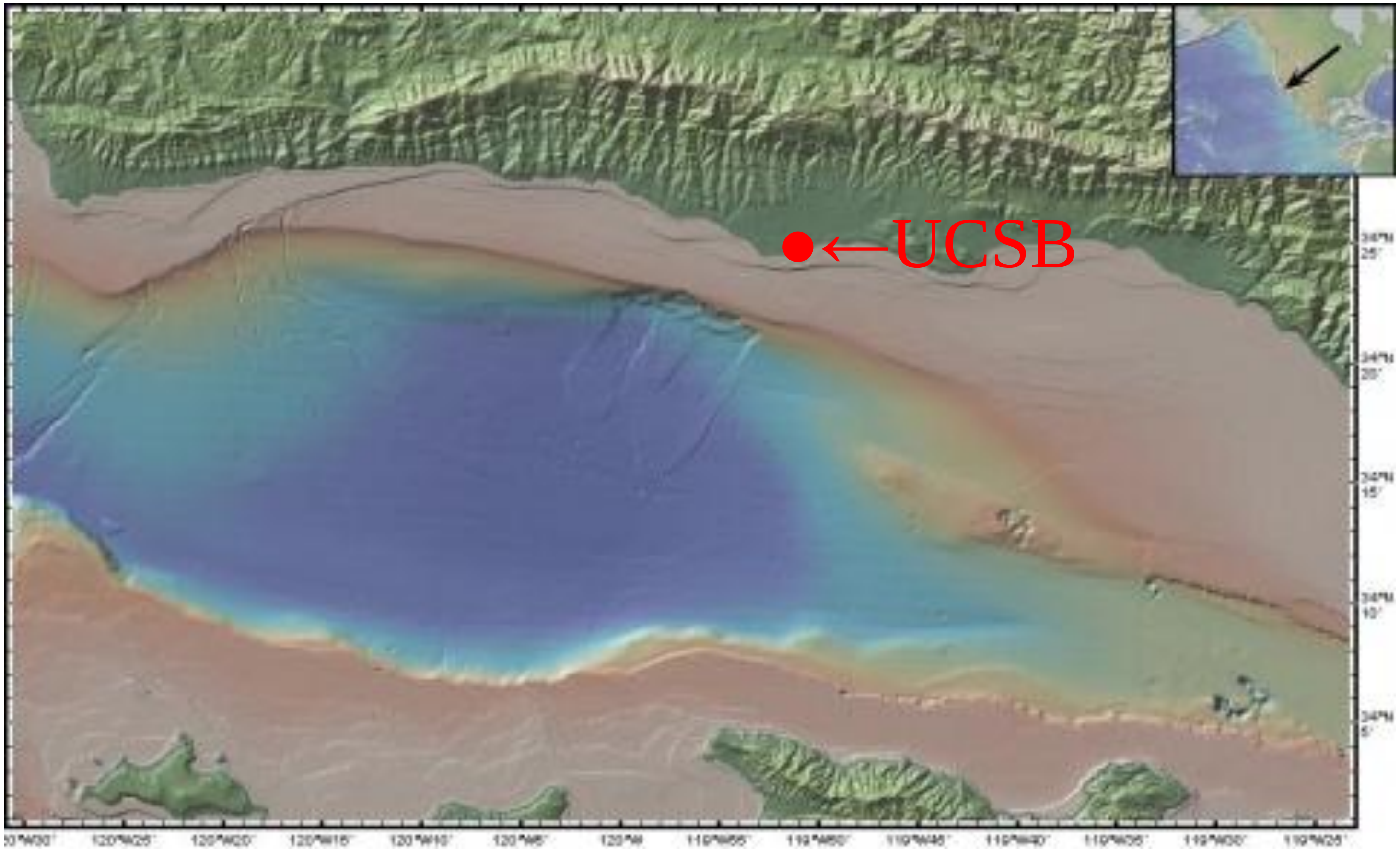
Field data – levee complex, Maastrichtian, Baja California, Mexico

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)

$$\nabla \cdot \vec{u}_f = 0$$

$$\frac{\partial \vec{u}_f}{\partial t} + \left(\vec{u}_f \cdot \nabla\right) \vec{u}_f = -\nabla p + \frac{1}{Re} \nabla^2 \vec{u}_f + c\, \vec{e}_g$$

effective density

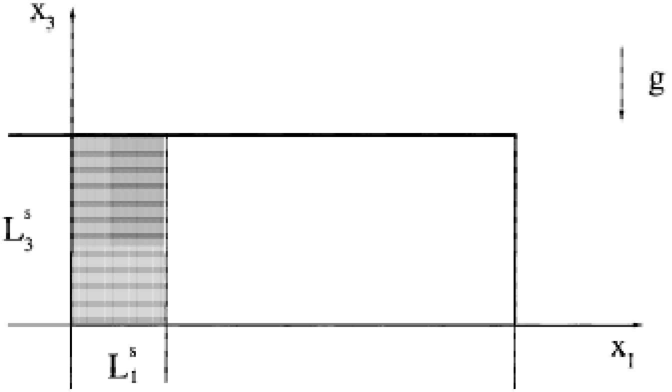
$$\frac{\partial c}{\partial t} + \left[\left(\vec{u}_f + \vec{U}_s\right) \nabla\right] c = \frac{1}{Sc\, Re} \nabla^2 c$$

settling velocity

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

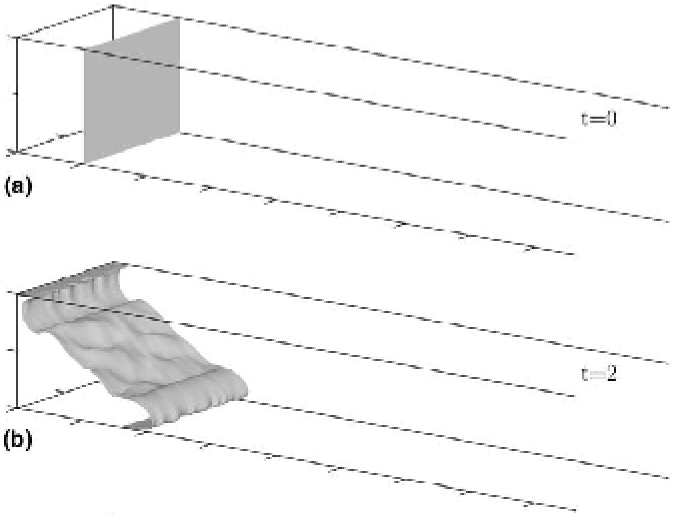
Model problem

Lock exchange configuration



Dense front propagates
along bottom wall

Light front propagates
along top wall

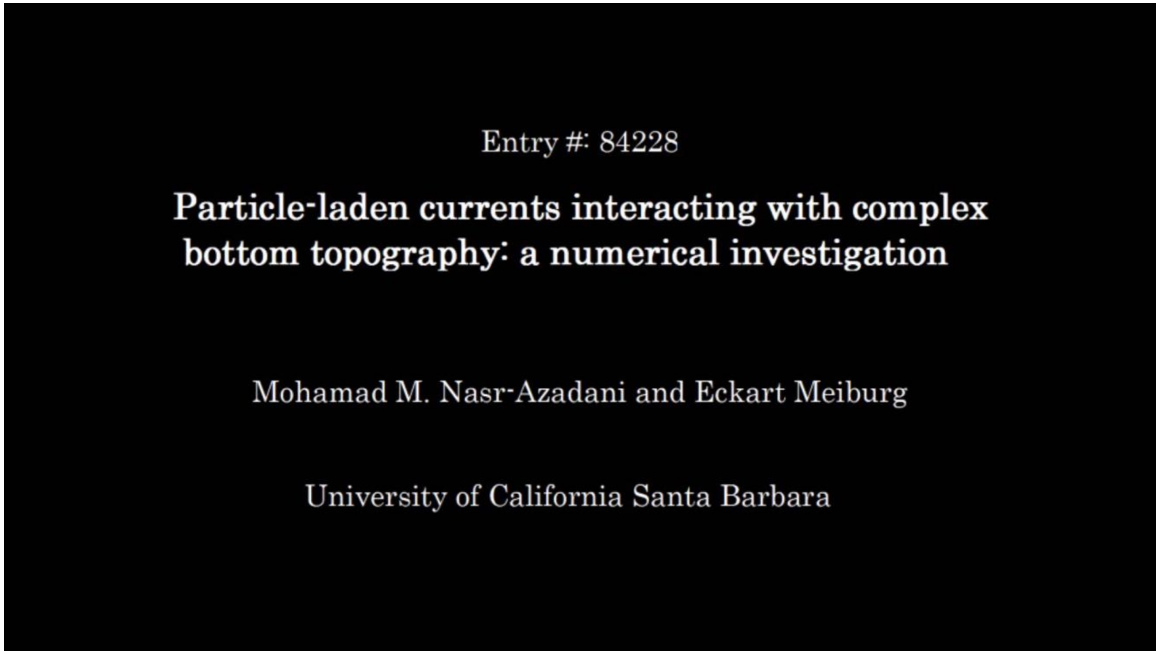


Complex seafloor topography (with M. Nasr-Azadani)

- *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

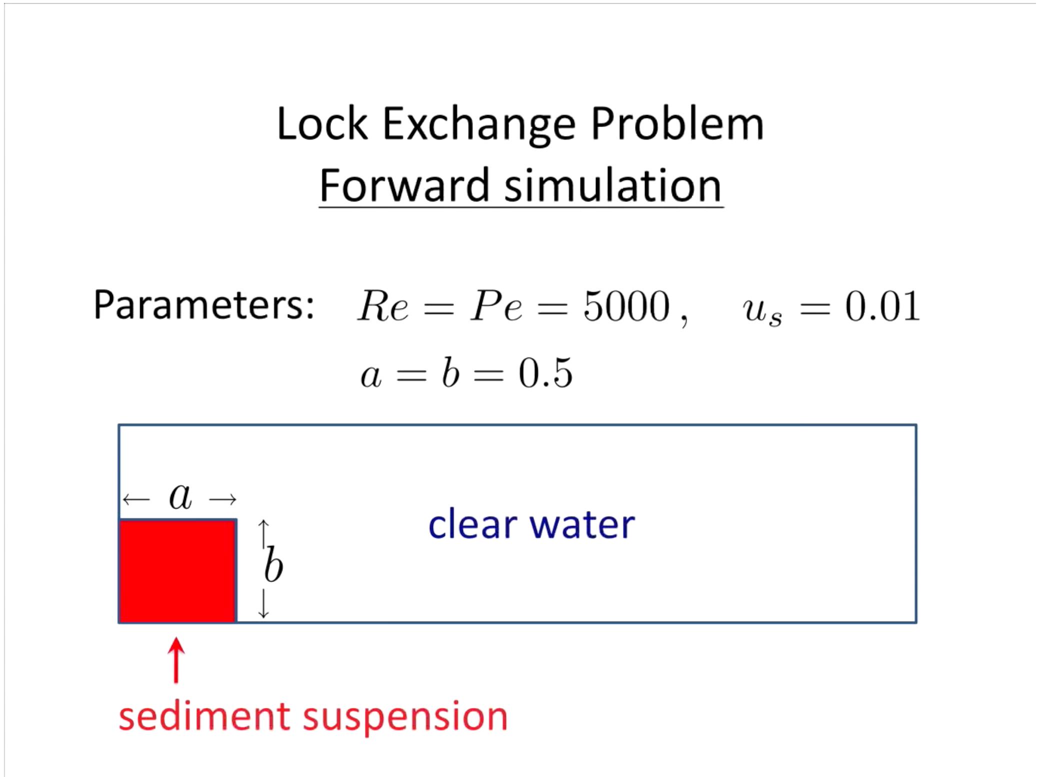
University of California Santa Barbara

- *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!*

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



Lock Exchange Problem

Forward simulation

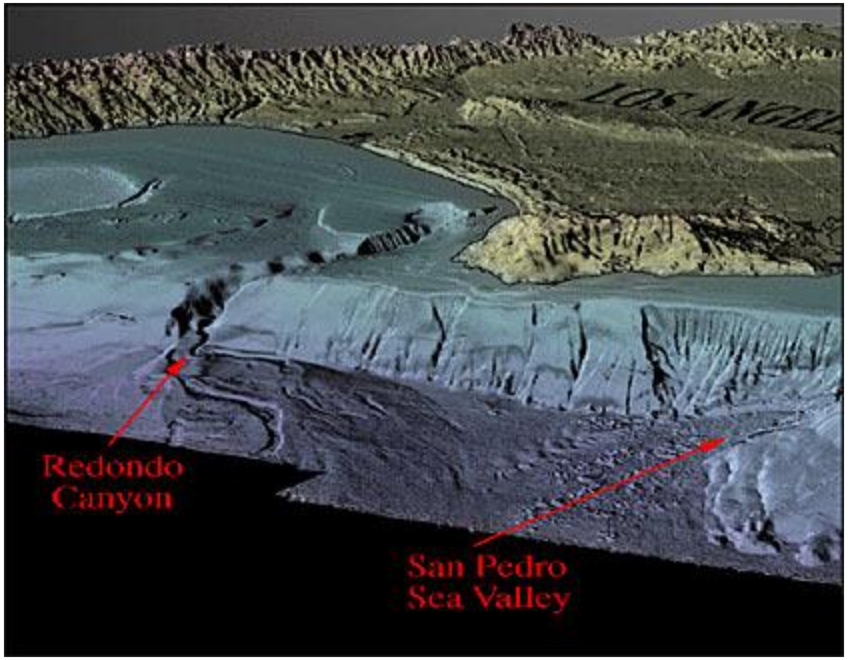
Parameters: $Re = Pe = 5000\,, \quad u_s = 0.01$

$a = b = 0.5$

- *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*

Channelization by turbidity currents: A Navier-Stokes based linear instability mechanism (with B. Hall, B. Kneller)

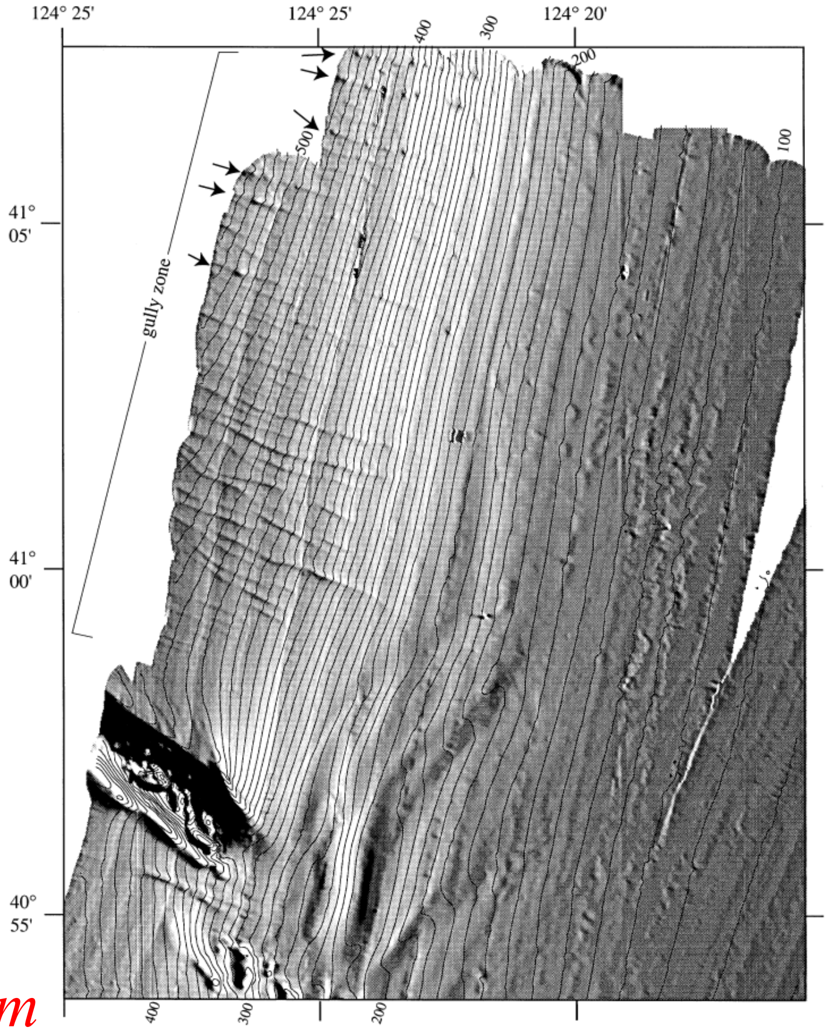
Field data show regularly spaced channels along the ocean floor



- *Hydrodynamic instability?*

Channelization by turbidity currents (cont'd)

- *Northern California margin:*



Shaded relief bathymetry; Field et al. (1999)

- *Spacing: 100's of meters to a few km*
- *Depth: O(1-100) m*
- *Mechanism for formation? Hydrodynamic instability?*

Previous stability-oriented work

- *Smith & Bretherton (1972), Izumi & Parker (1995, 2000), Imran & Parker (2000), Izumi (2004), Izumi & Fujii (2006):*

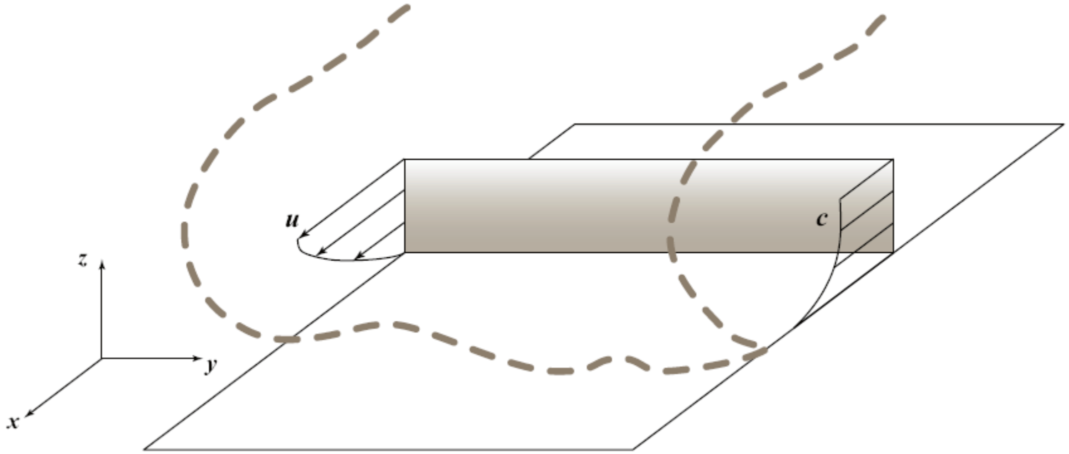
  - depth averaged equations; don't capture internal velocity and concentration structure of the current, and its coupling with the sediment bed

- *Colombini (1993), Colombini & Parker (1995):*

  - externally impose secondary flow structure on the current

Present approach

Focus on unidirectional flow some distance behind the head:



- *fully developed velocity and concentration profiles*

- *consider two-dimensional, three-component perturbation flow field, allow for full two-way coupling between flow and sediment bed*

Moderately dilute flows: Two-way coupling

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

effective density

settling velocity

At surface $\eta(y,t)$ of the sediment bed: no-slip boundary conditions.

$\eta(y,t)$ evolves due to:

a) Settling of particles

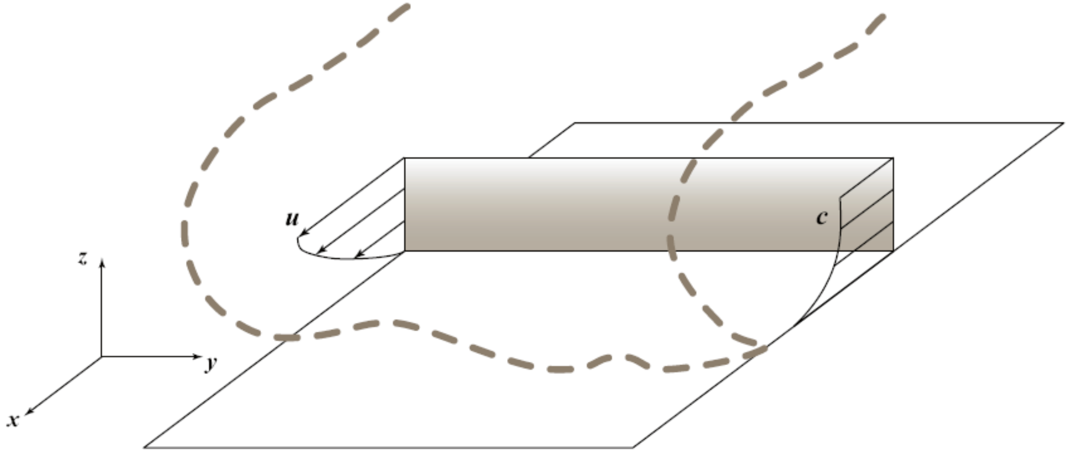
$$\frac{\partial \eta}{\partial t} = w_s\, c|_{z=\eta}$$

a) Erosion of particles

$$D \frac{\partial c}{\partial n}\bigg|_{z=\eta} = -\beta\, \tau_n \quad , \quad \frac{\partial \eta}{\partial t} = -\beta \frac{\tau_n|_{z=\eta}}{n_z}$$

Base flow profile

Unidirectional flow some distance behind the head:



Fully developed velocity and concentration profiles:

$$u_0(z) = 1 - e^{-z/L} \quad , \quad c_0(z) = \frac{N\,Pe}{L\,c_\infty} e^{-z} + 1$$

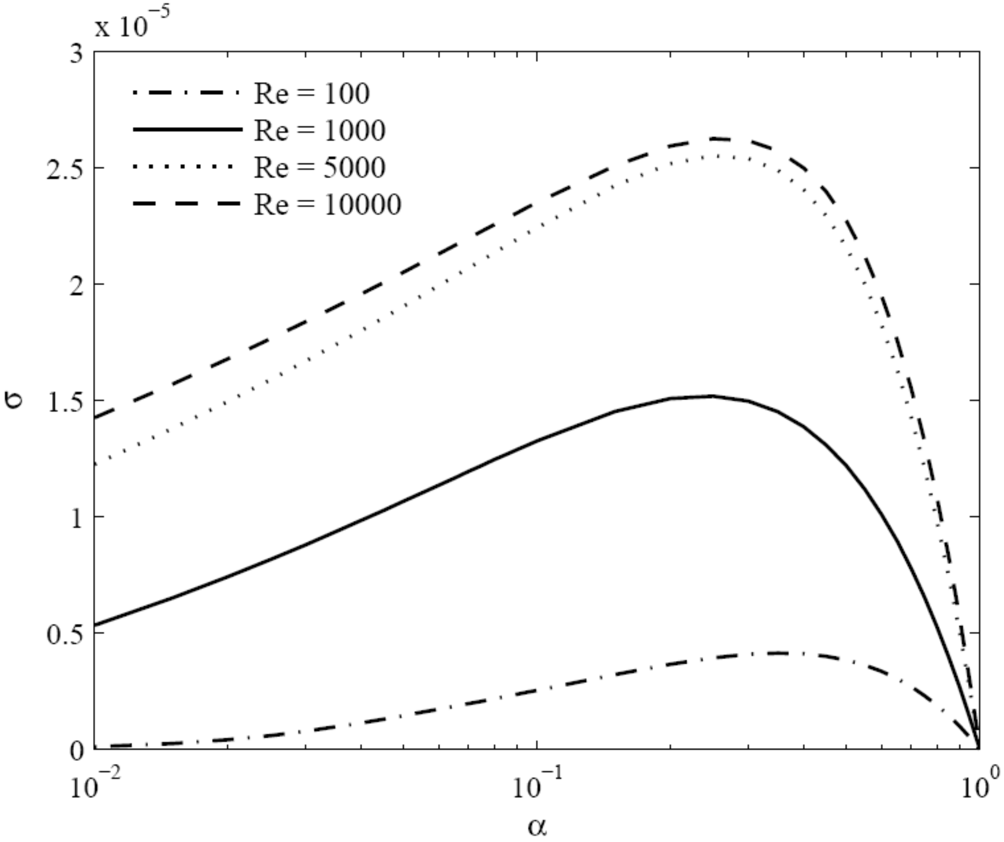
Important parameter:

L = length over which u_0 decays / length over which c_0 decays

Results: Influence of Re

Dispersion relations:

$$
\begin{aligned}
L &= 0.5 \\
G &= 0.1 \\
c_\infty &= 10^{-2} \\
N &= 10^{-5}
\end{aligned}
$$



- *larger Re are destabilizing*
- *most amplified wave number α~0.25*

Results: Instability mechanism (cont'd)

Main criterion for instability:

$$L < 1$$

base flow shear has to decay faster than base concentration profile

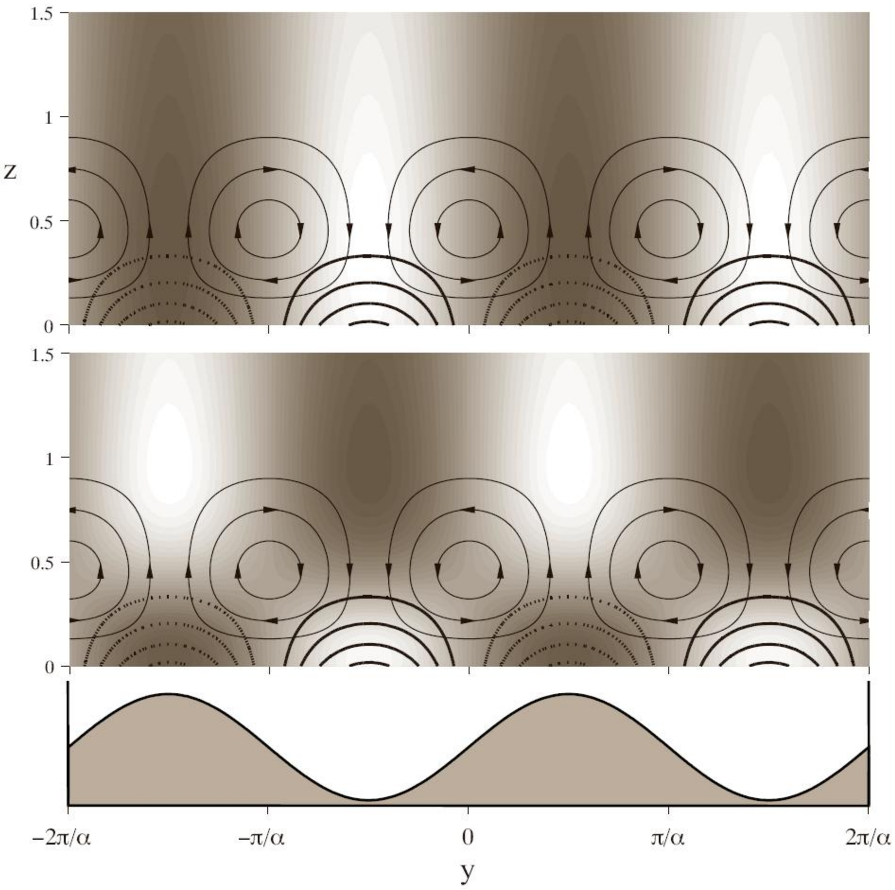
- *if base shear decays faster than base concentration profile:*
  - *an upward protrusion of the sediment bed will see less shear (less erosion), but still substantial sedimentation → will grow*
  - *a valley of the sediment bed will see higher shear (more erosion), but not much more sedimentation → will grow*

- *if base shear decays more slowly than base concentration profile: perturbations will decay*

Results: Eigenfunctions

Influence of secondary flow structure:

$$\begin{aligned} \alpha &= 0.24 \\ L &= 0.5 \\ Re &= 1,000 \\ G &= 0.1 \\ c_\infty &= 10^{-2} \\ N &= 10^{-5} \end{aligned}$$



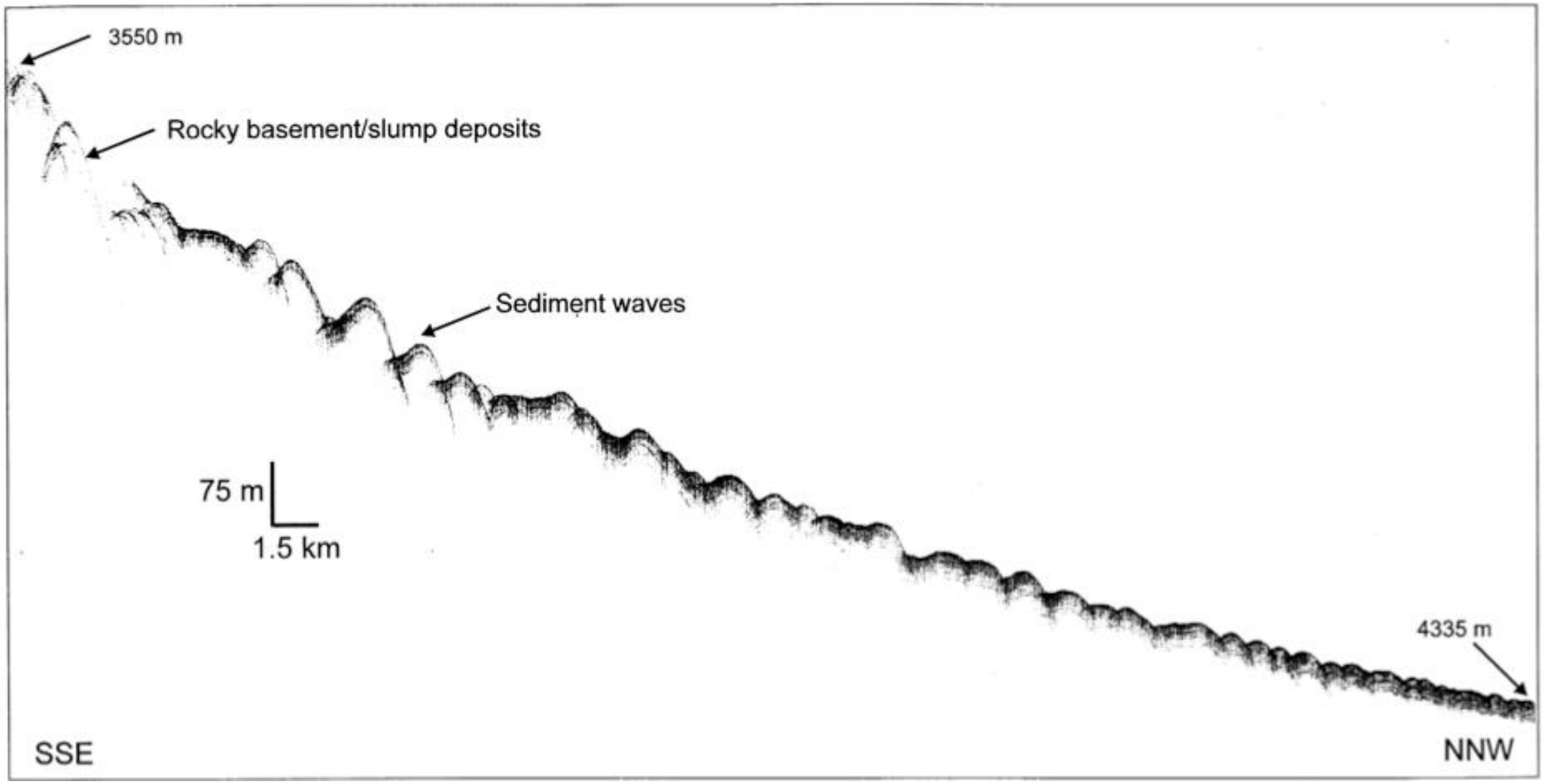
perturbation u-velocity

perturbation shear stress

secondary flow structure reduces shear stress at peaks, increases shear stress in valleys → perturbation shear stress is destabilizing

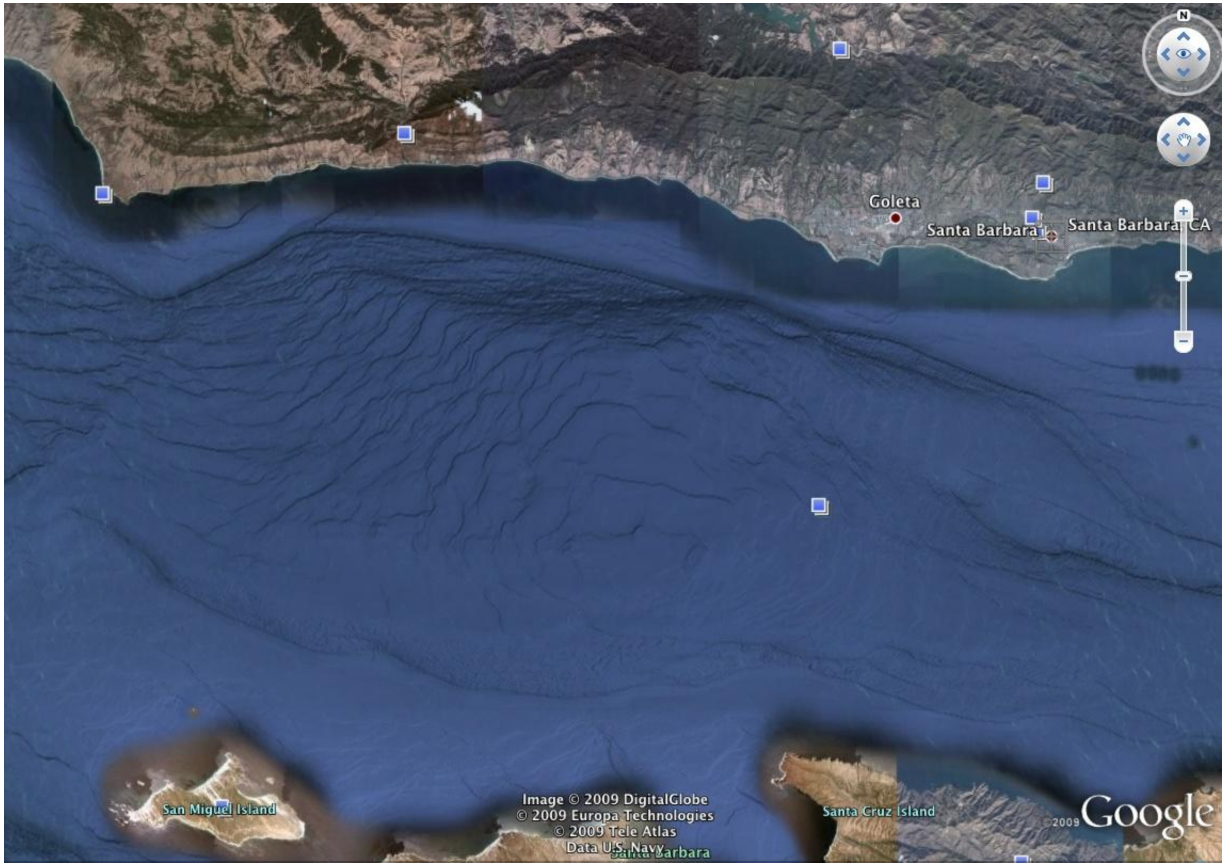
Sediment wave formation by turbidity currents (w. B. Hall, L. Lesshafft, B. Kneller)

Large scale sediment wave forms at the ocean floor



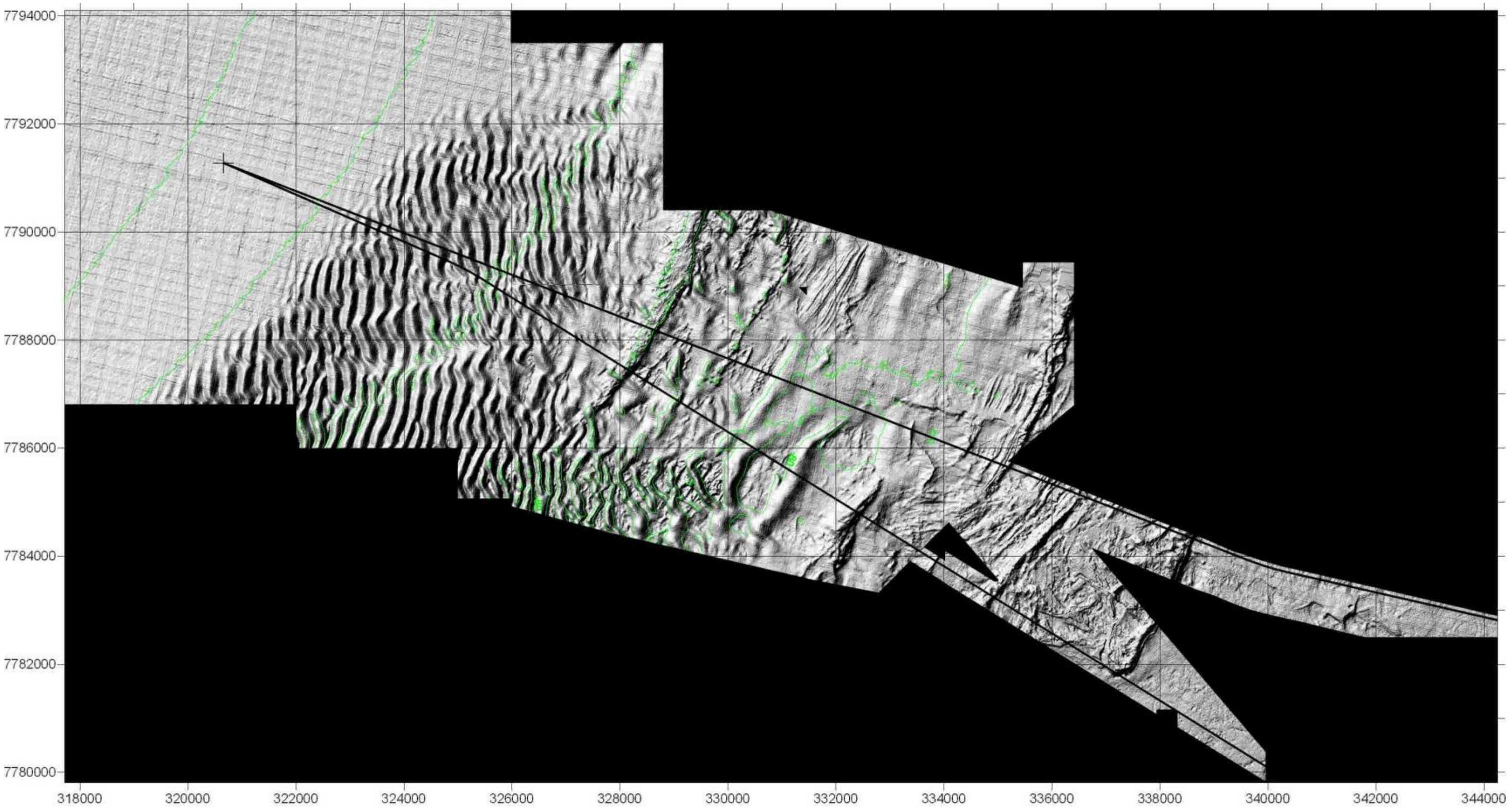
- *sediment waves are prime targets for oil reservoir formation*
- *formed by turbidity currents and bottom flows; mechanism?*
- *traditional assumption: lee waves, but no rigorous stability analysis available*

Sediment wave formation by bottom currents



Santa Barbara channel

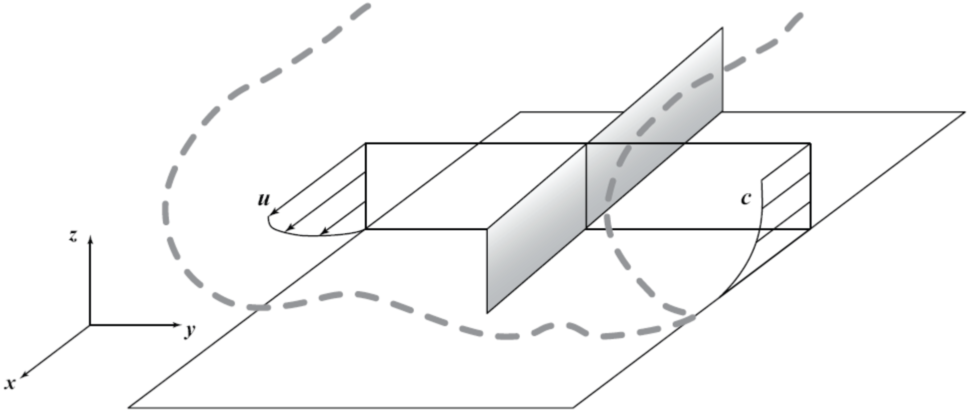
Sediment wave formation by bottom currents



Australian coast

Base flow profile

Unidirectional flow behind the head:



Fully developed velocity and concentration profiles:

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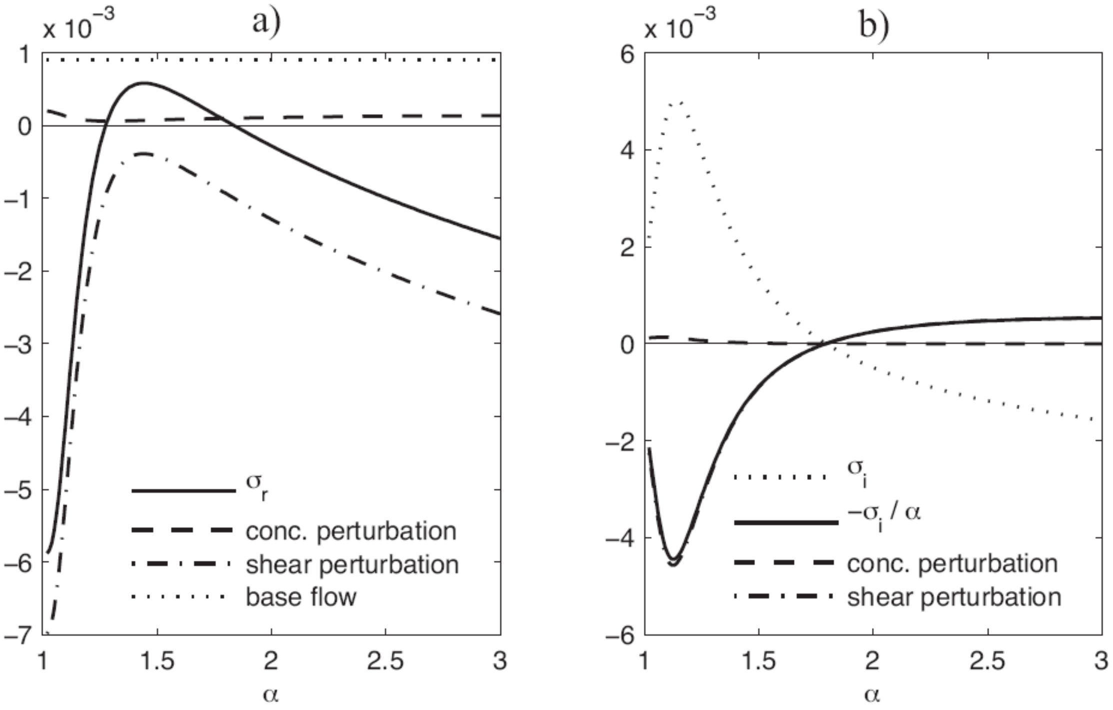
Important parameter:

L = length over which u_0 decays / length over which c_0 decays

Linear stability results

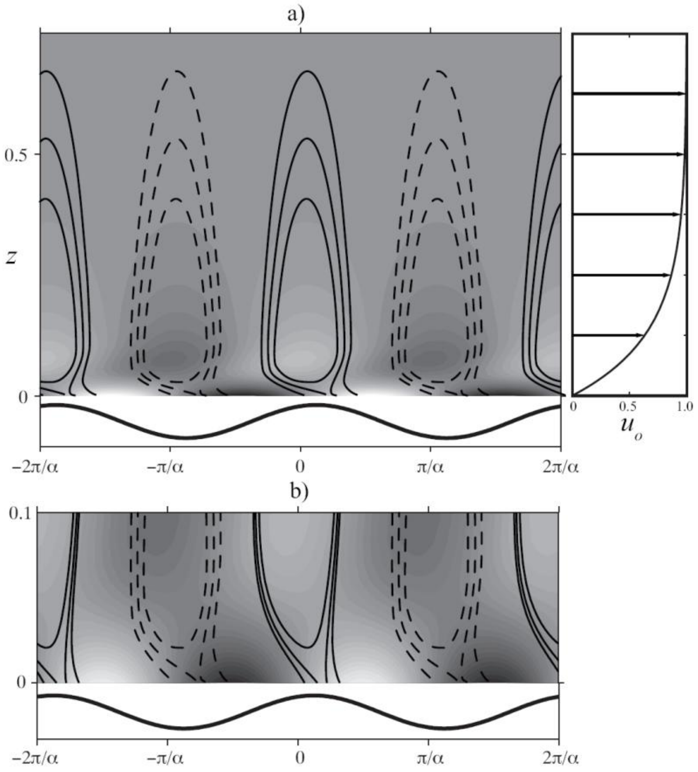
Dispersion relations:



- *most amplified wave number α~1.44*
- *base flow has main destabilizing effect*
- *sediment waves migrate upstream*

Results: Eigenfunctions

Influence of secondary flow structure:



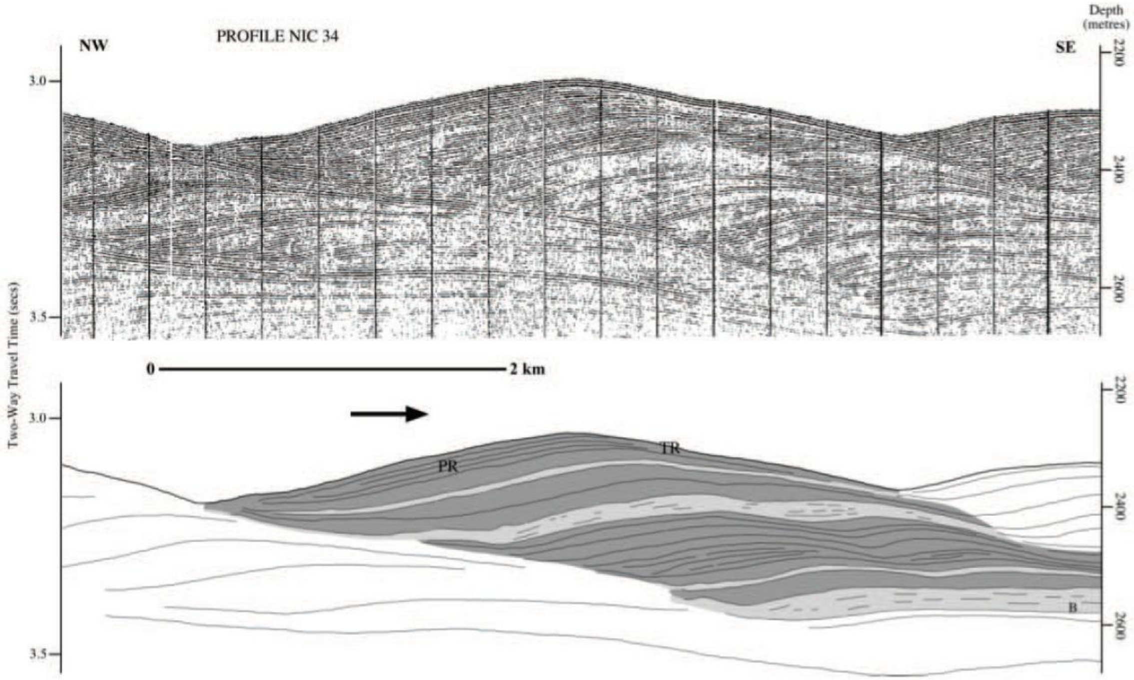
shading:
perturbation
shear stress

line contours:
perturbation
concentration

- *perturbation shear larger on downstream side of peak than on upstream side → more erosion on downstream than on upstream side → upstream migration*
- *perturbation concentration is larger at peak than in trough → more sedimentation at peak than in trough → growth of wave amplitude*

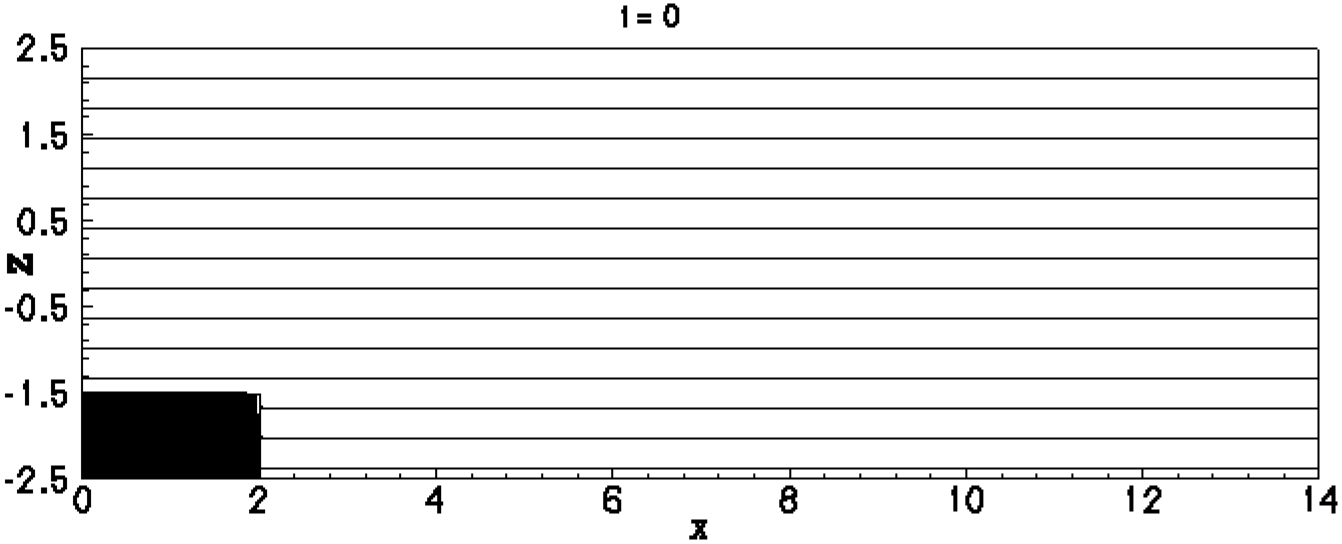
Field observation of sediment bed structures

Net deposition is stronger on the upstream side



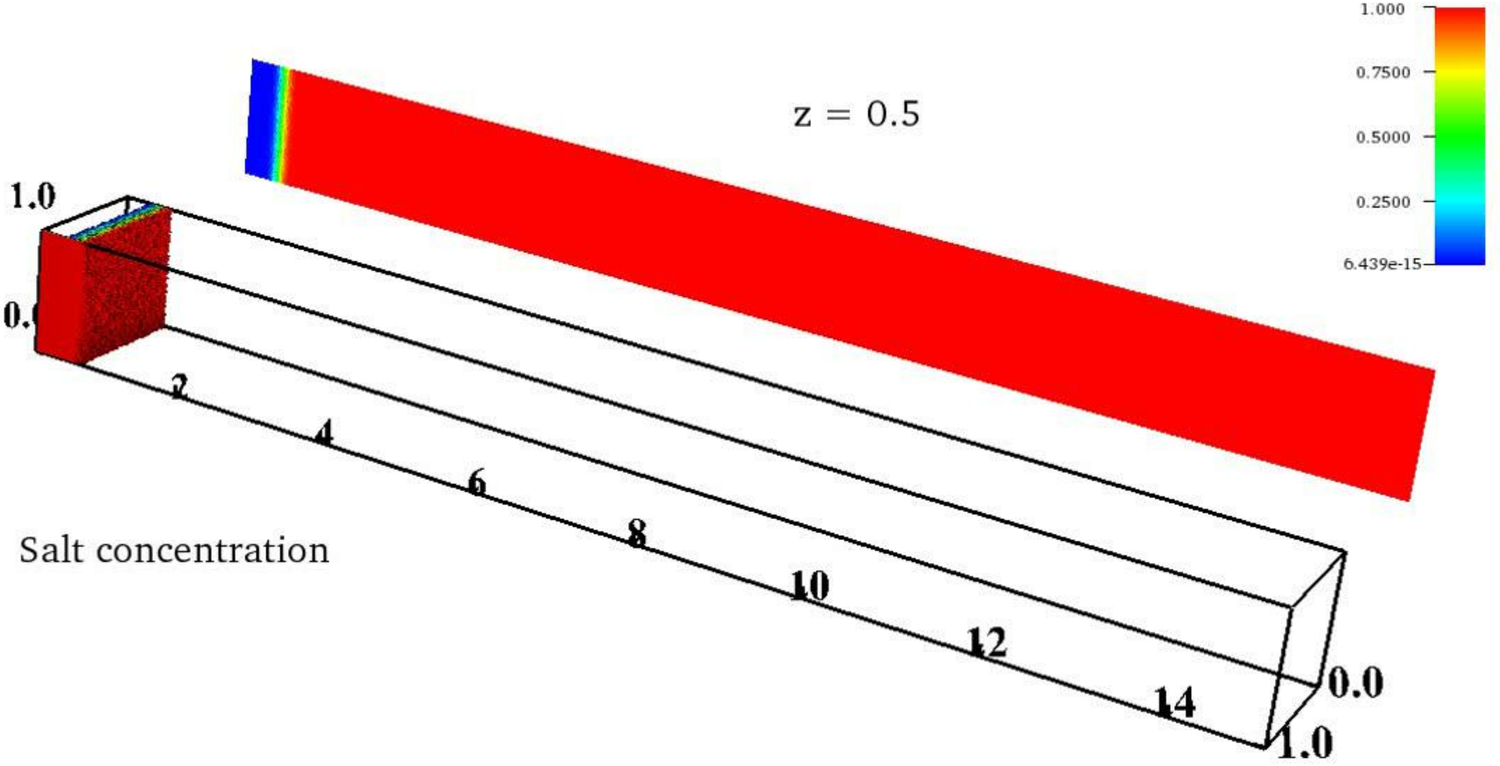
upstream migration

Stratification: Internal wave generation



- *Excitation of internal waves in the ambient fluid*

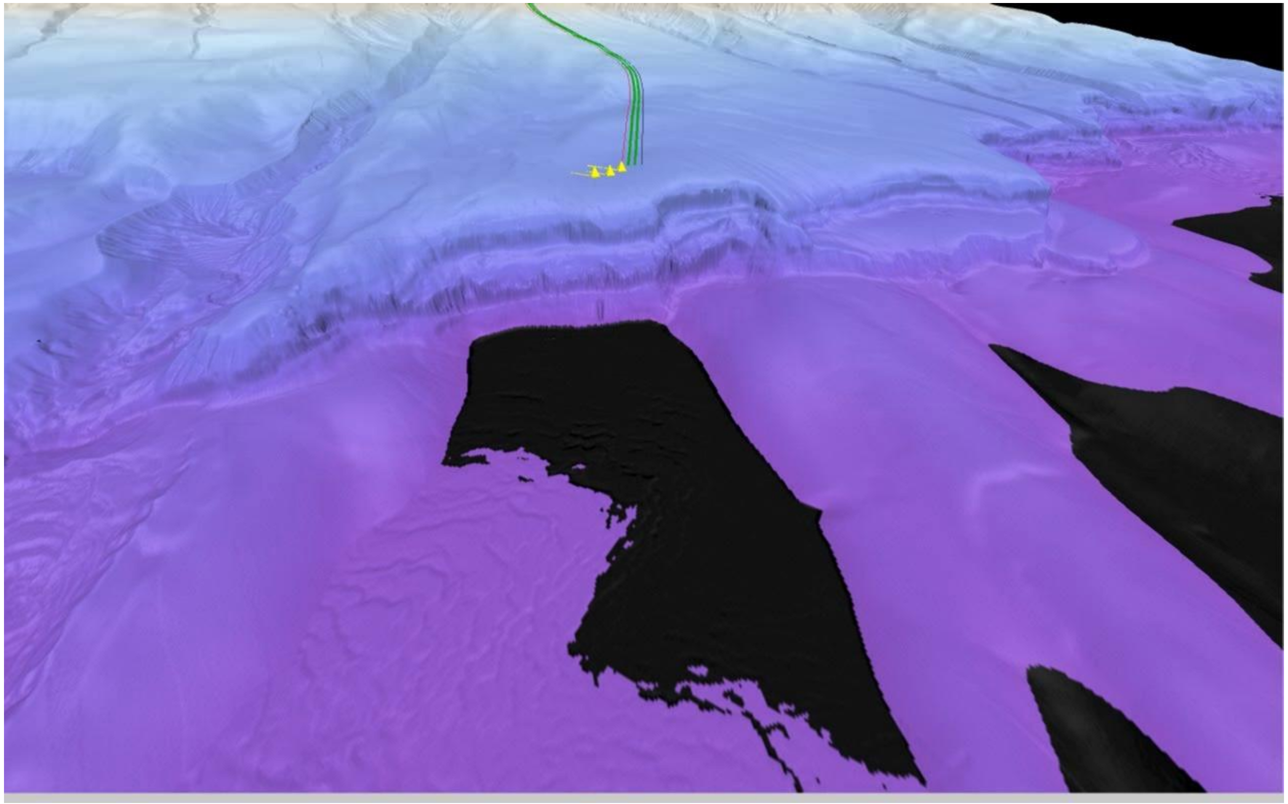
Reversing buoyancy (M. Boekels, E. Lenk, S. Radhakrishnan)



- *propagates along bottom over finite distance, then lifts off*
- *subsequently propagates along top*

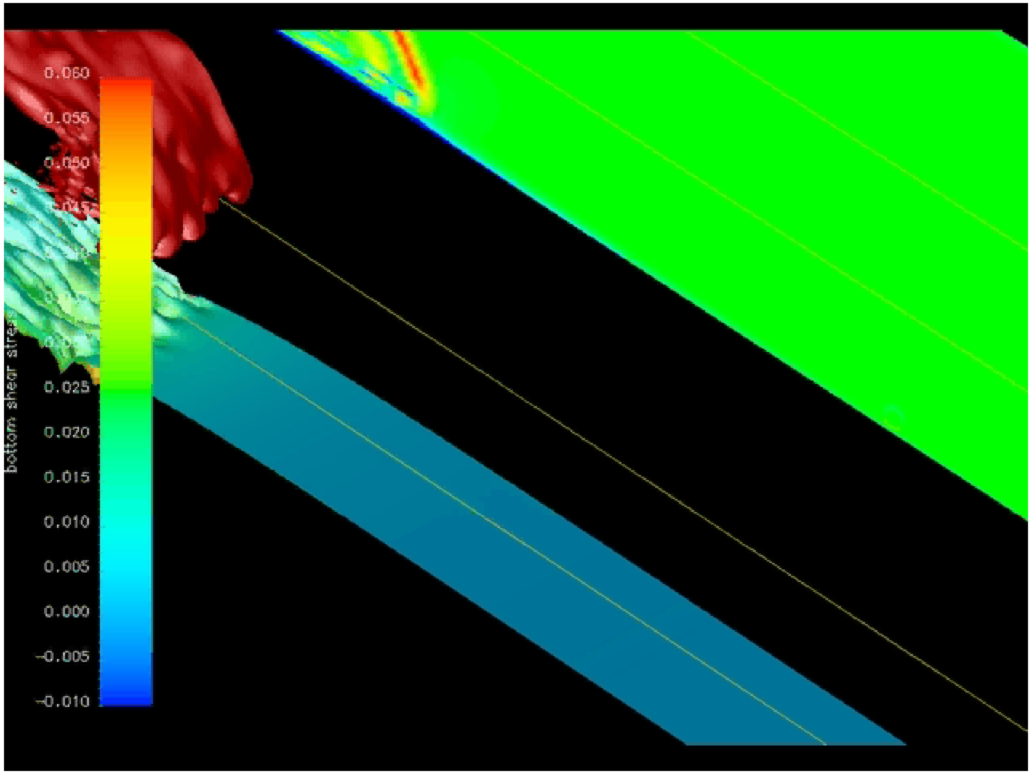
Hazards posed by gravity and turbidity currents (with E. Gonzales, T. Tokyay, G. Constantinescu)

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



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

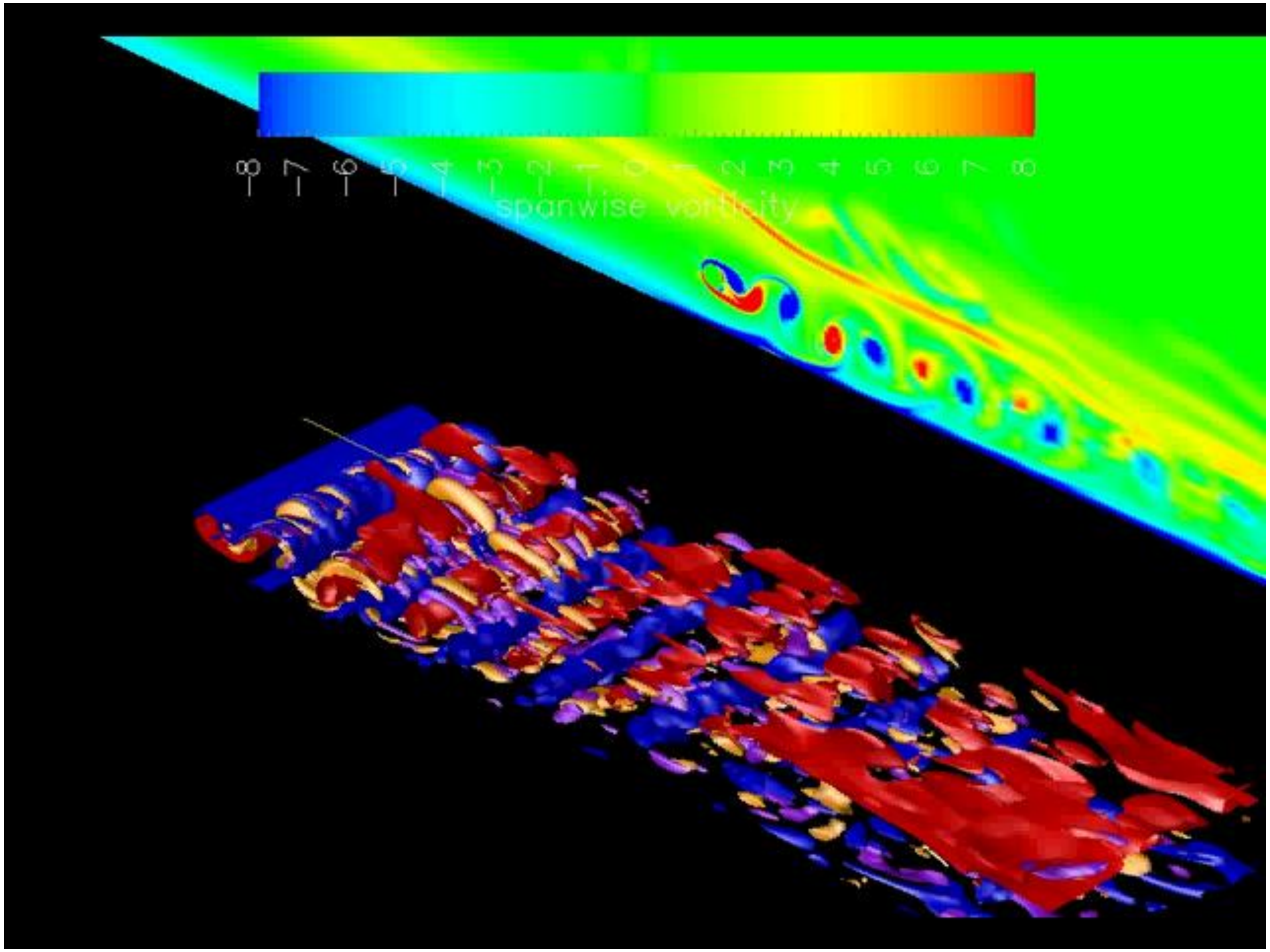
Simulation of gravity current past a model pipeline:



- *what forces and moments are exerted on the obstacle?*
- *steady vs. unsteady?*
- *erosion and deposition near the obstacle?*

Gravity current flow over elevated circular cylinder

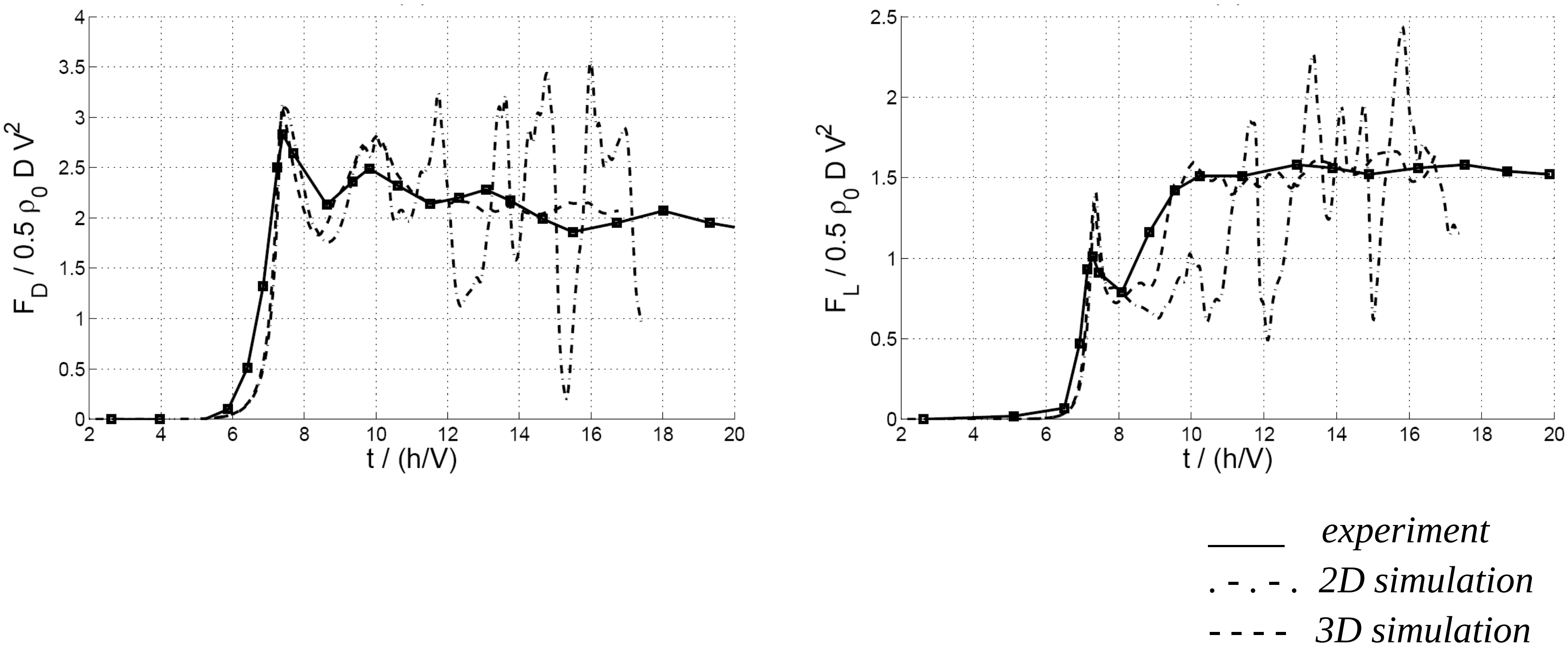
Vorticity:



- *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):



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

Sedimentation from river plumes: Motivation (w. P. Burns)

- *10^{10} tons of sediment are transported by rivers into the world's oceans every year → important to understand sedimentation in river plumes*

Mississippi river plume
drainage basin size: 3.3×10^6 km^2
annual sediment yield: 1.2×10^2 t/km^2

Santa Clara river plume
drainage basin size: 4.2×10^3 km^2
annual sediment yield: 1.4×10^3 t/km^2

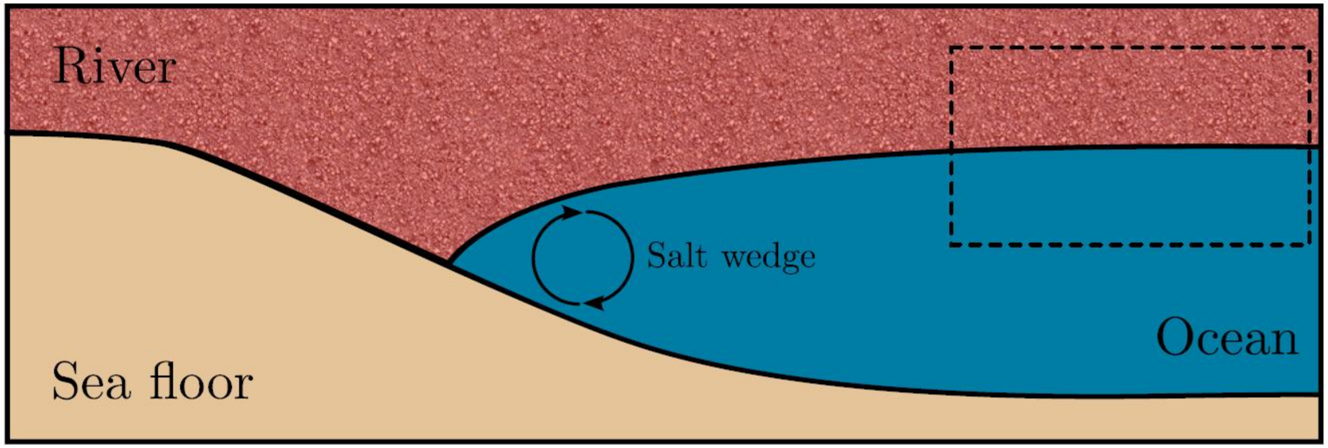
→ *a large fraction of the sediment supply into the oceans is due to small, mountainous streams*

Sedimentation from river plumes: Configuration

Hypopycnal river plumes:

density of the river (fresh water + sediment) < density of ocean (water + salinity)

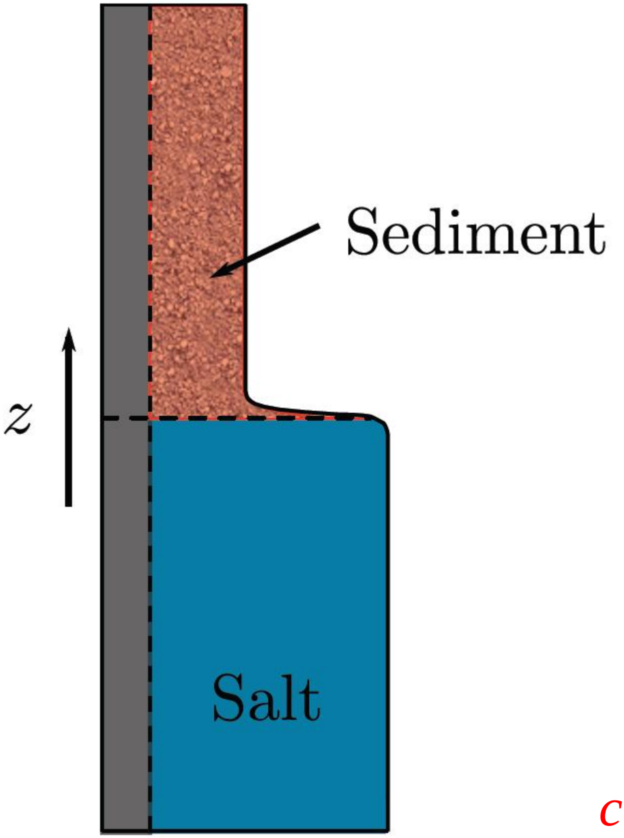
→ *river outflow propagates along the ocean surface*

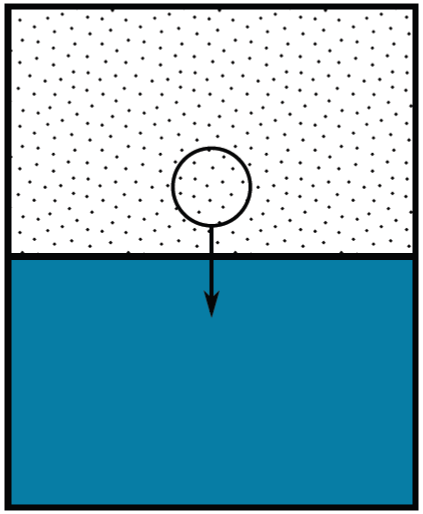


- *focus on the downstream density stratification*

Sedimentation from river plumes: Double-diffusion

Base density profile:

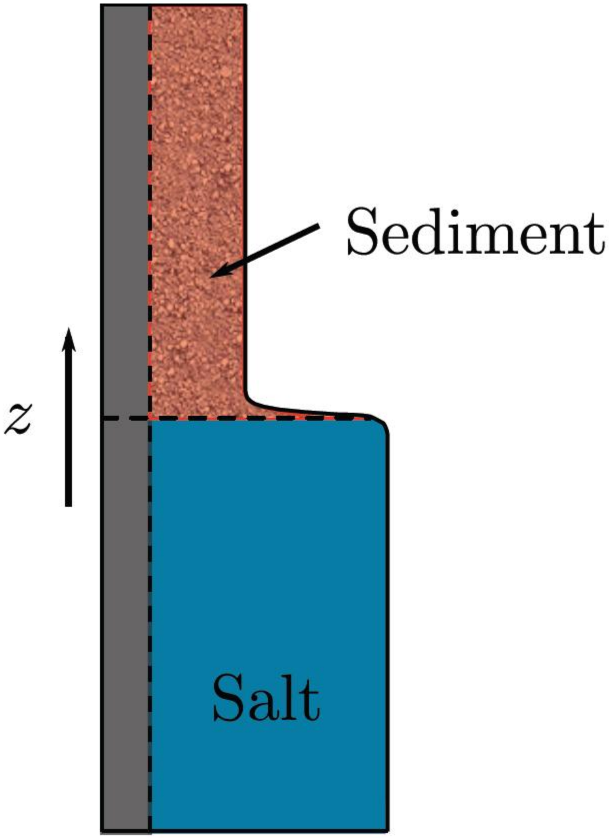


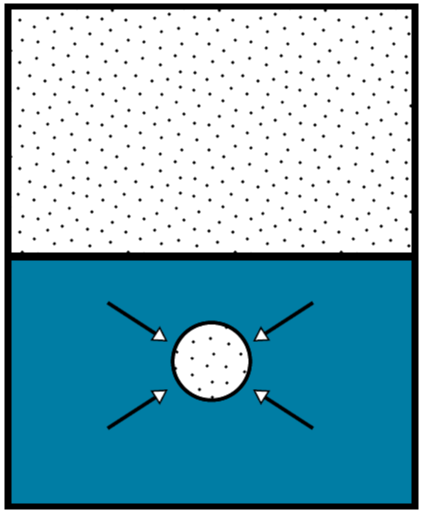


consider local downward perturbation of fluid element across opposing gradients

Sedimentation from river plumes: Double-diffusion

Base density profile:

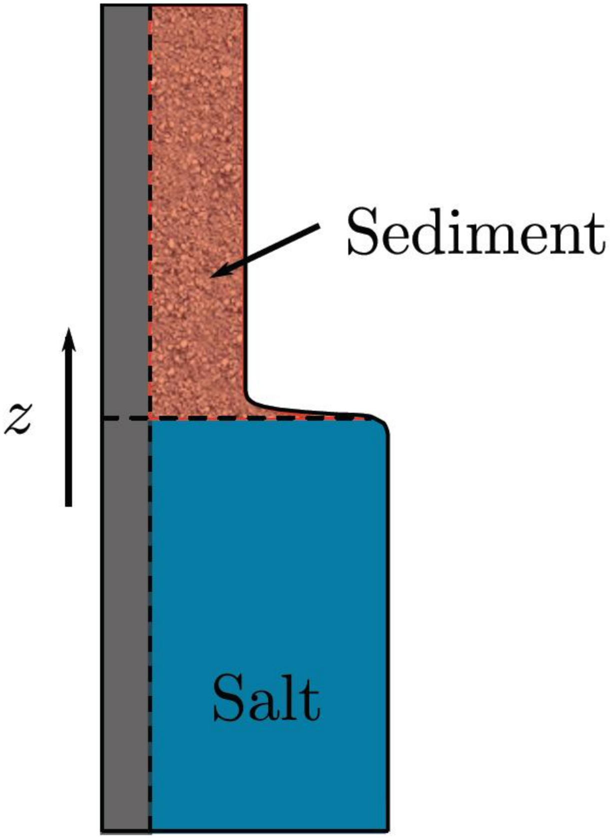


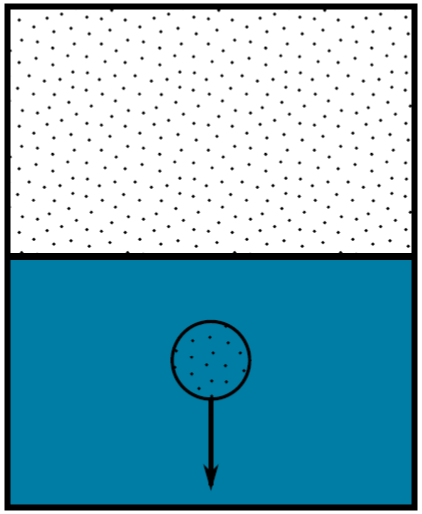


salinity diffuses inward more rapidly
than particles diffuse outward

Sedimentation from river plumes: Double-diffusion

Base density profile:

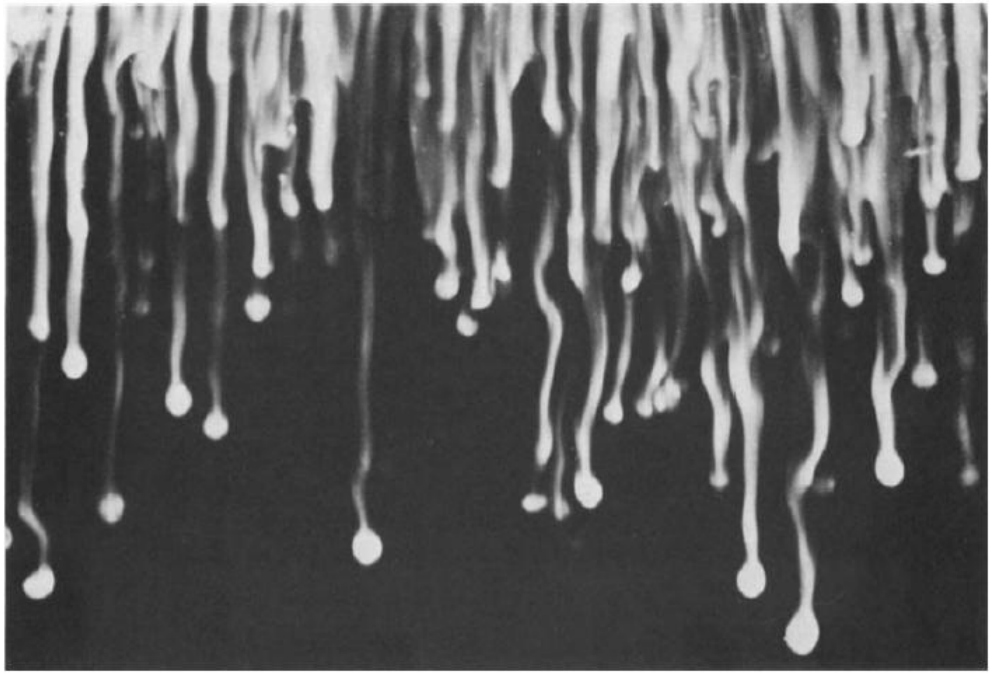




→ *fluid element will continue to sink*

Traditional case: Salt fingers

- *warm, salty water above cold, fresh water:*



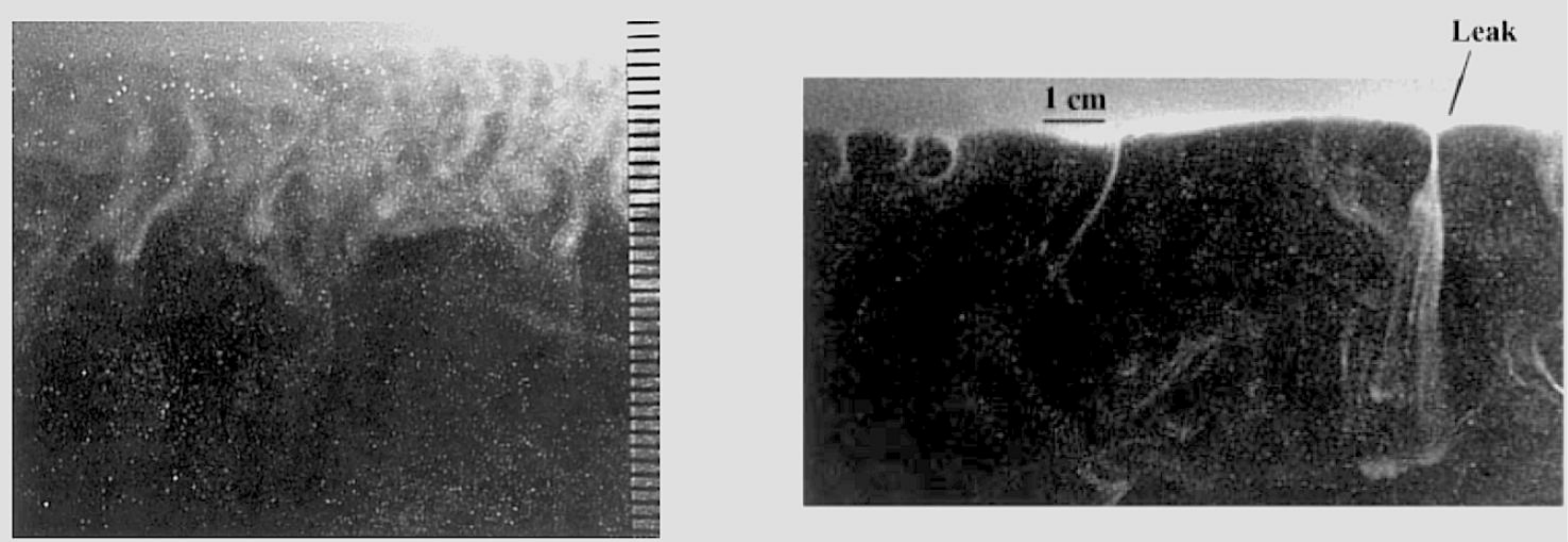
Huppert and Turner (1981)

- *dominant process for the vertical flux of salt in the ocean*
- *robust against shear*
- *believed to be responsible for the formation of the thermohaline staircase*

→ *for salt/sediment system, how does double-diffusion affect sedimentation?*

Sedimentation from river plumes: Experiments

- *previous experimental work by Parsons et al. (2001):*

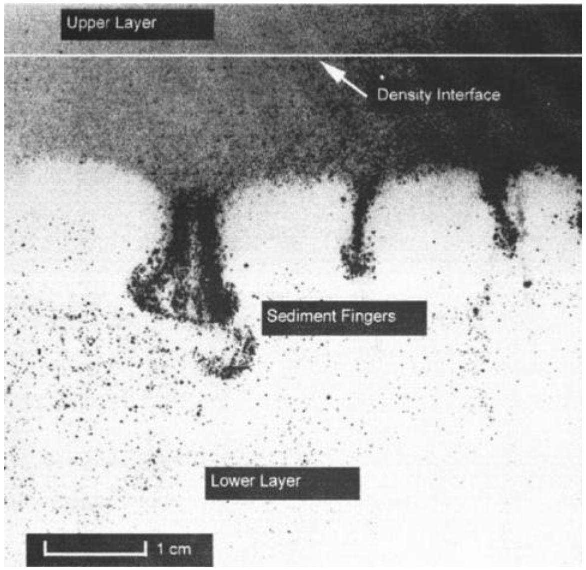


convective 'fingering' mode
space filling

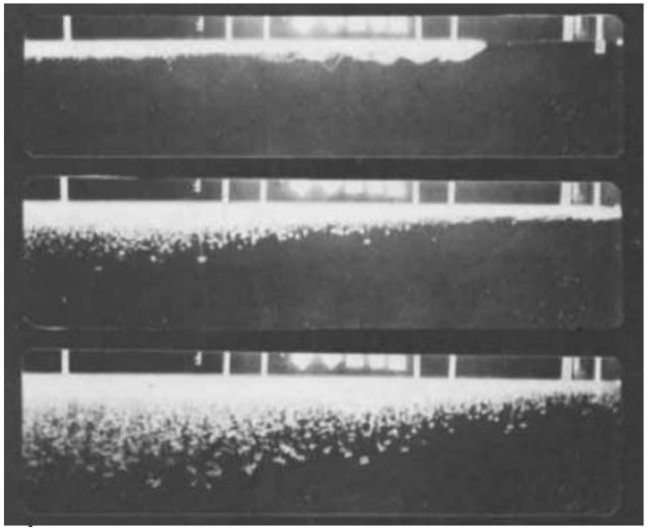
'leaking' mode
localized, structures move along interface

→ *goal: understand mechanisms driving these modes, and their influence on the effective particle settling velocity*

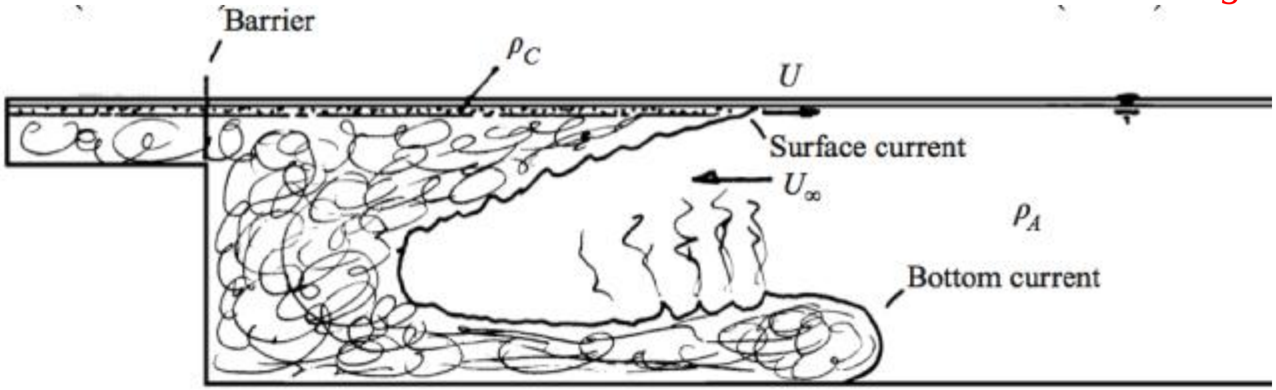
Sedimentation from river plumes: Experiments



Hoyal et al. (1999): convective sedimentation



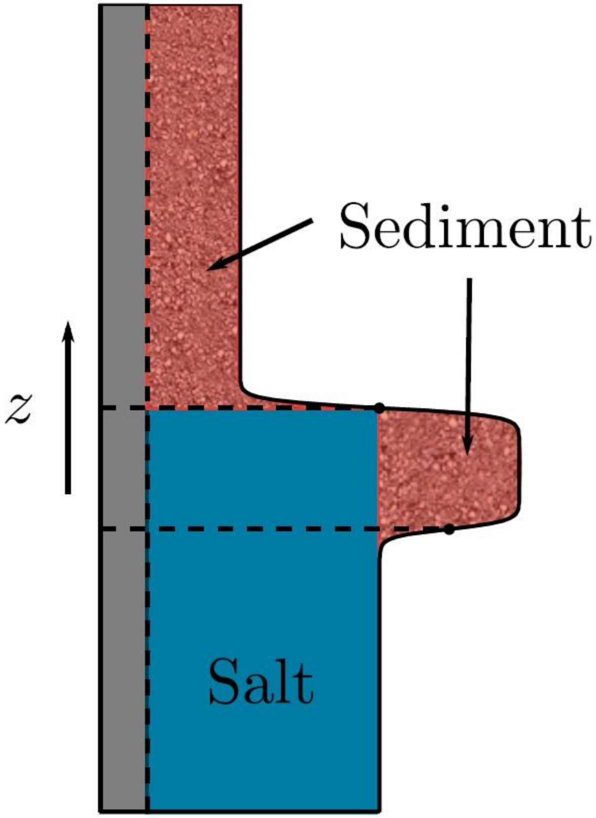
Green (1987):DDS from buoyant gravity currents



Maxworthy (1999):DDS from hyperpycnal plumes

Sedimentation from river plumes

Physical setup:



density profile

characteristic quantities:

$$\begin{aligned} V_{st}^{*} &= \frac{g d_p^2 (\rho_p - \rho_f)}{18 \mu_f} \\ g' &= \frac{\Delta \rho_c}{\rho_0} g = \gamma g \\ U^{*} &= (\nu g')^{1/3} \end{aligned}$$

dimensionless parameters:

$$\begin{aligned} V_p &= \frac{V_{st}^{*}}{U^{*}} \\ Sc &= \frac{\nu}{\kappa_s} \\ R_s &= \frac{\alpha \Delta S}{\gamma \Delta C} \\ \tau &= \frac{\kappa_s}{\kappa_c} \end{aligned}$$

Sedimentation from river plumes: Numerical simulations

- *Two dimensions:*

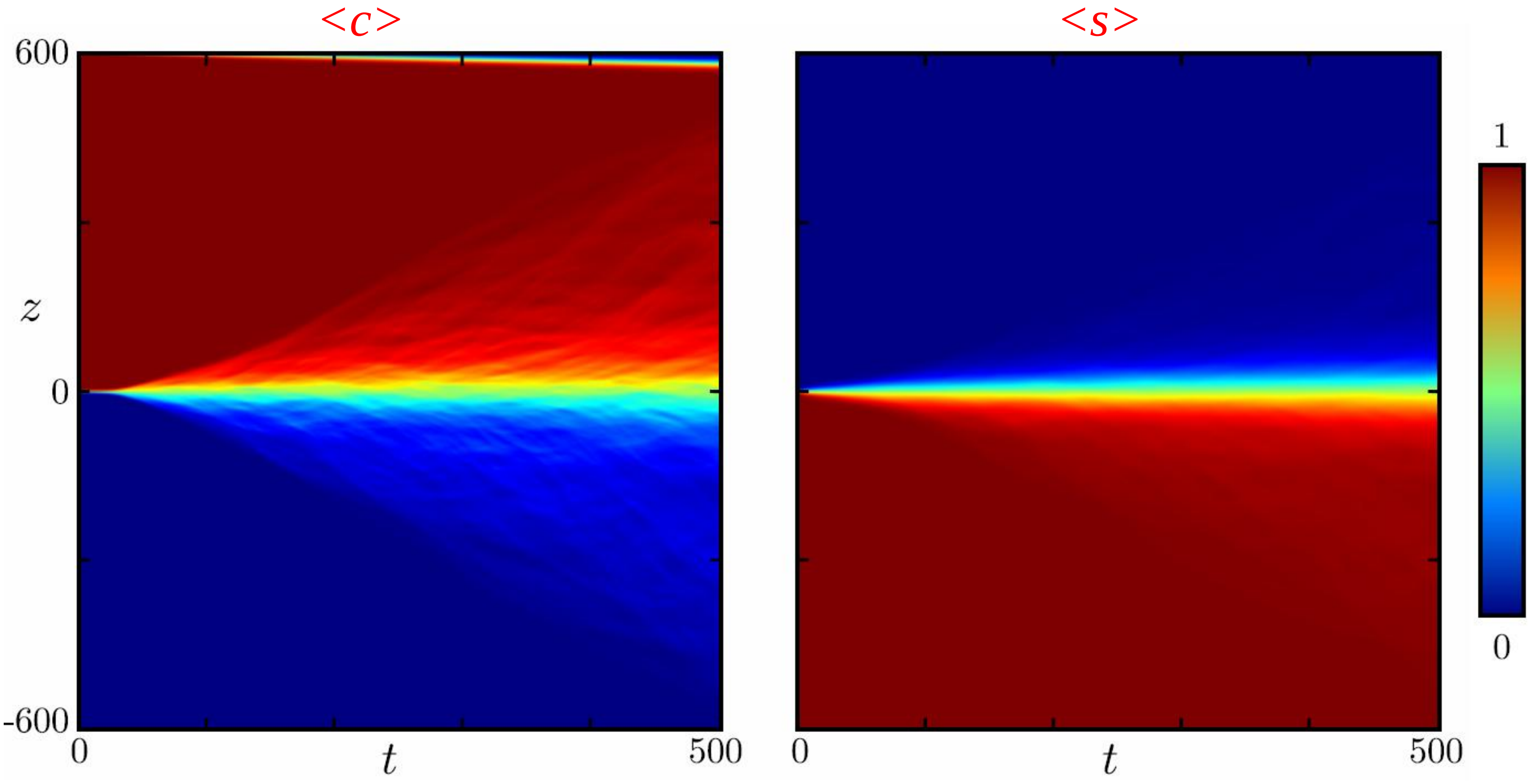
  - *streamfunction, vorticity-formulation of Navier-Stokes equations*
  - *Boussinesq approximation*
  - *spectral/compact finite differences*

- *Three dimensions:*

  - *IMPACT code (Henniger and Kleiser 2011)*
  - *primitive variable formulation of Navier-Stokes equations*
  - *Boussinesq approximation*
  - *staggered grid*
  - *6^{th} order compact finite differences*
  - *massively parallel*

Sedimentation from river plumes: Numerical simulations

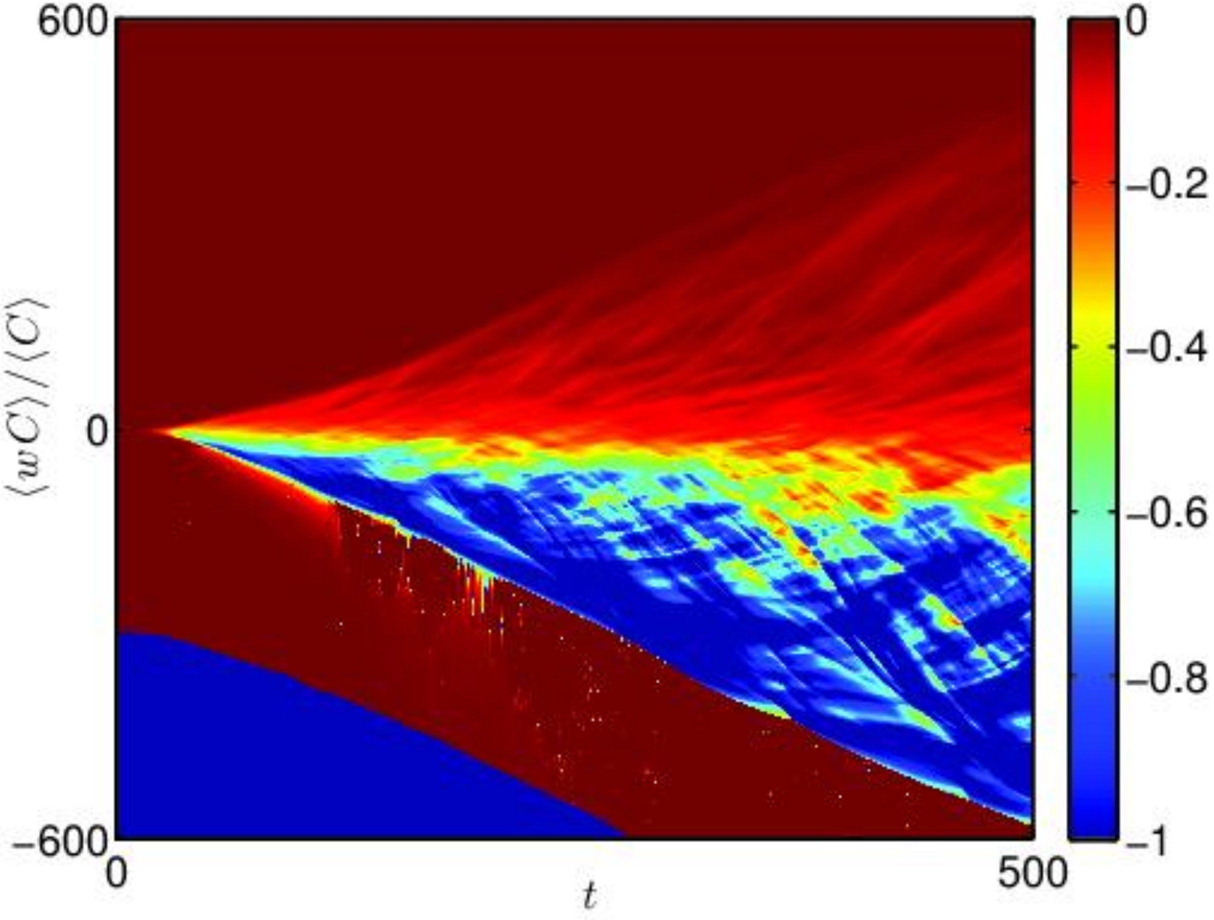
Sedimentation from river plumes: Mean fields



- *thickening of the interfacial region ~ time → convectively dominated*
- *vigorous convective motion*
- *'streaks' due to the release of buoyant plumes*

Sedimentation from river plumes: Effect on sedimentation

Settling velocity enhancement:

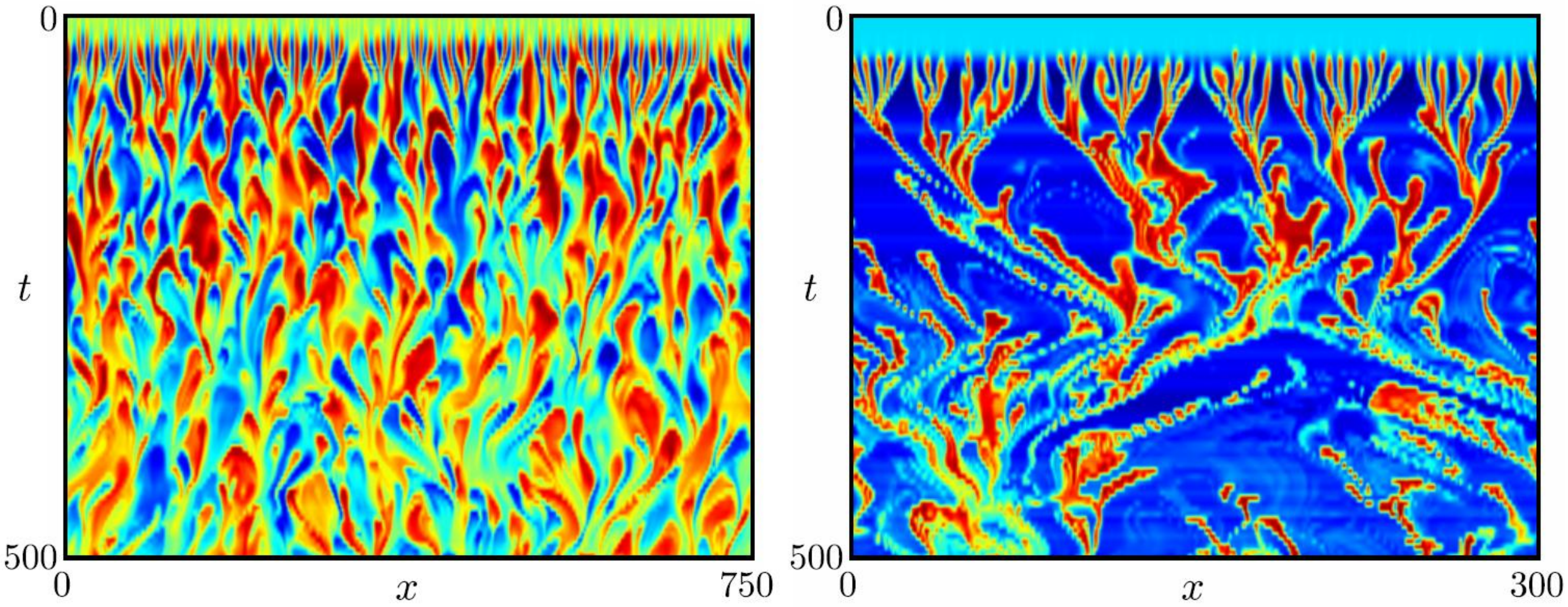


- *in the region z < 0, the effective settling velocity is O(1), rather than* $V_{st}=0.04$

Sedimentation from river plumes: Leaking mode

Sedimentation from river plumes: fingering vs. leaking

x,t-diagrams of sediment concentration at fixed vertical location:



fingering mode
weak horizontal motion

leaking mode
strong horizontal motion and merging

- *'phase locking' results in the characteristic features of the leaking mode*

Summary

- *high resolution 3D simulations of turbidity currents and river outflows*
- *detailed information regarding erosional/depositional behavior, energy budgets, dissipation, entrainment, mixing dynamics . . .*
- *recent extension to complex seafloor topography: meandering channel/levee systems, mini-basins, local seamounts*
- *linear stability analysis explains formation of channels, gullies and sediment waves, gives their dominant length scales*
- *interaction of turbidity currents with submarine pipelines: forces, moments, time scales*
- *reversing buoyancy (hyperpycnal) currents*
- *double-dffusive sedimentation in river outflows dramatically enhances the effective settling velocity*
- *convective 'fingering' vs. 'leaking' mode*