High Resolution Simulations of Sediment Transport by Turbidity Currents

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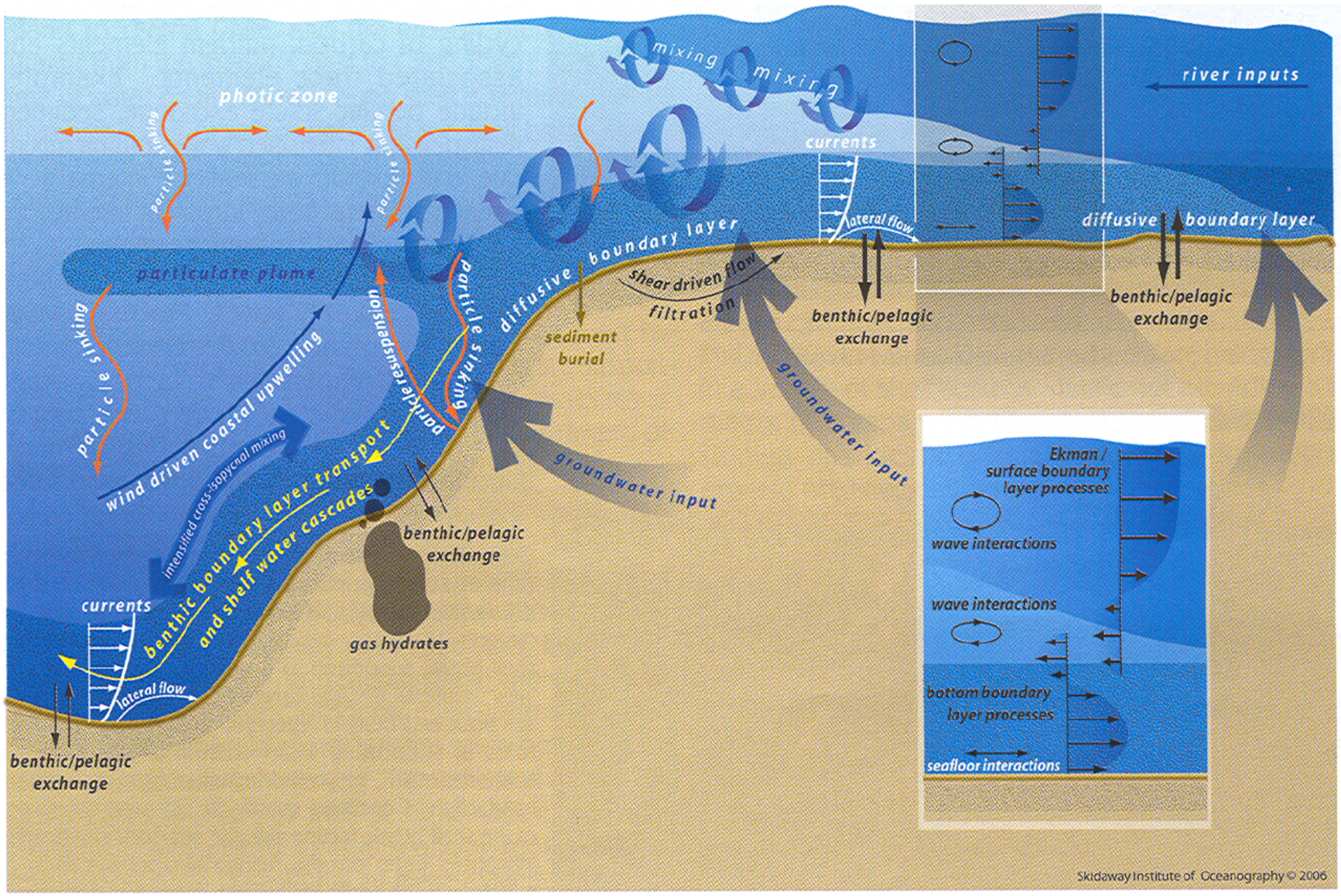
- *Motivation*
- *Governing equations / computational approach*
- *Results*
  - *particle driven gravity currents*
  - *gravity currents with erosion and resuspension*
  - *formation of channels, gullies, sediment waves*
  - *current extensions*
- *Summary and outlook*

Coastal margin processes

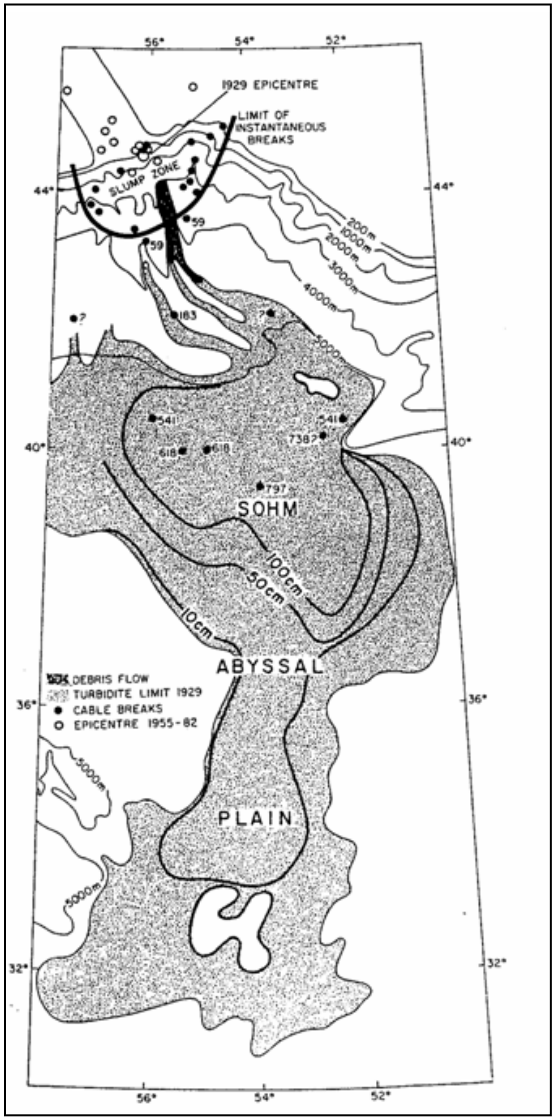


Turbidity current

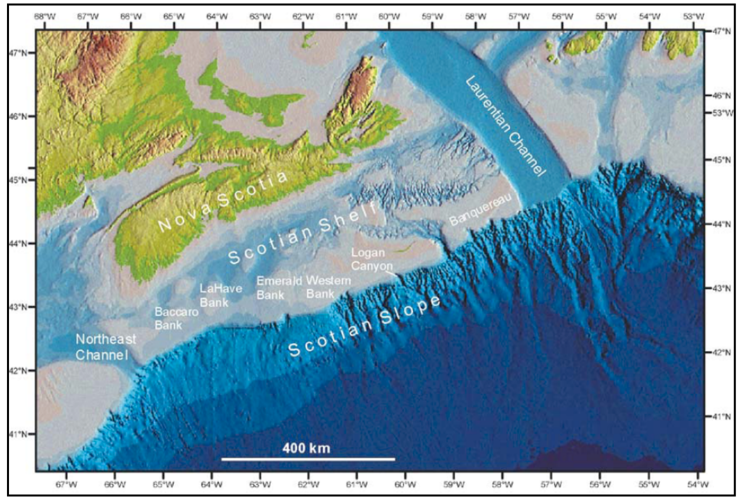
- *Underwater sediment flow down the continental slope*
- *Can transport many km^3 of sediment*
- *Can flow O(1,000)km or more*
- *Often triggered by storms or earthquakes*
- *Repeated turbidity currents in the same region can lead to the formation of hydrocarbon reservoirs*
- *Properties of turbidite:*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



<u>Grand Banks turbidite</u>

<u>historical event, Nov 18 1929 (M7.2)</u>

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

Framework: Dilute flows

Volume fraction of particles of $O(10^{-2} - 10^{-3})$:

- *particle radius « particle separation*
- *particle radius « characteristic length scale of flow*
- *coupling of fluid and particle motion primarily through momentum exchange, not through volumetric effects*
- *effects of particles on fluid continuity equation negligible*

Moderately dilute flows: Two-way coupling

Mass fraction of heavy particles of O(10%), small particle inertia (e.g., sediment transport):

- *particle loading modifies effective fluid density*
- *particles do not interact directly with each other*

Current dynamics can be described by:

- *incompressible continuity equation*
- *variable density Navier-Stokes equation (Boussinesq)*
- *conservation equation for the particle concentration field*

→ *don't resolve small scale flow field around each particle, but only the large fluid velocity scales ('SGS model')*

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

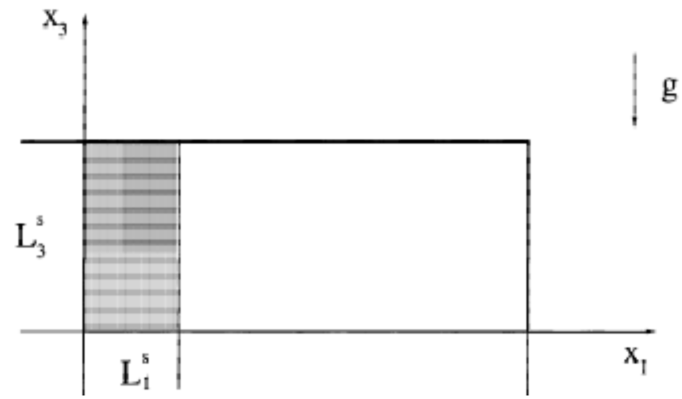
$$\frac{\partial c}{\partial t} + \left[\left(\vec{u}_f + \vec{U}_s\right) \nabla\right] c = \frac{1}{Sc\,Re}\nabla^2 c$$

settling velocity

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

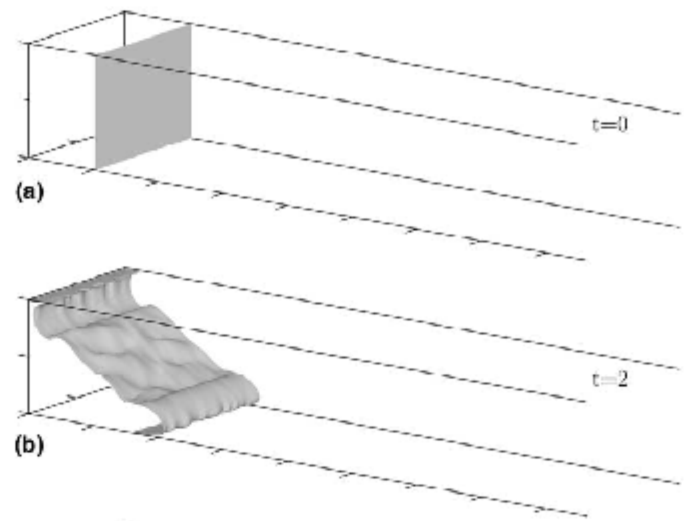
Model problem (with C. Härtel, L. Kleiser, F. Necker)

Lock exchange configuration



Dense front propagates
along bottom wall

Light front propagates
along top wall



Results: 3D turbidity current – Temporal evolution

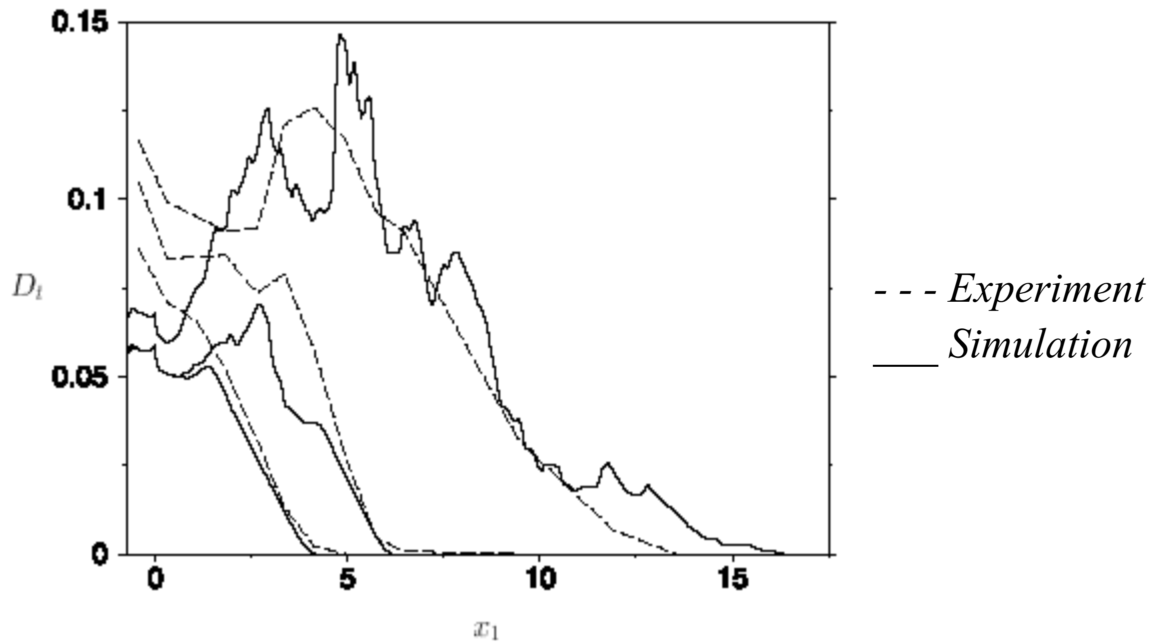
DNS simulation (Fourier, spectral element, 7x10^7 grid points)

Necker, Härtel, Kleiser and Meiburg (2002a,b)

- *turbidity current develops lobe-and-cleft instability of the front*
- *current is fully turbulent*
- *erosion, resuspension not accounted for*

Results: Deposit profiles

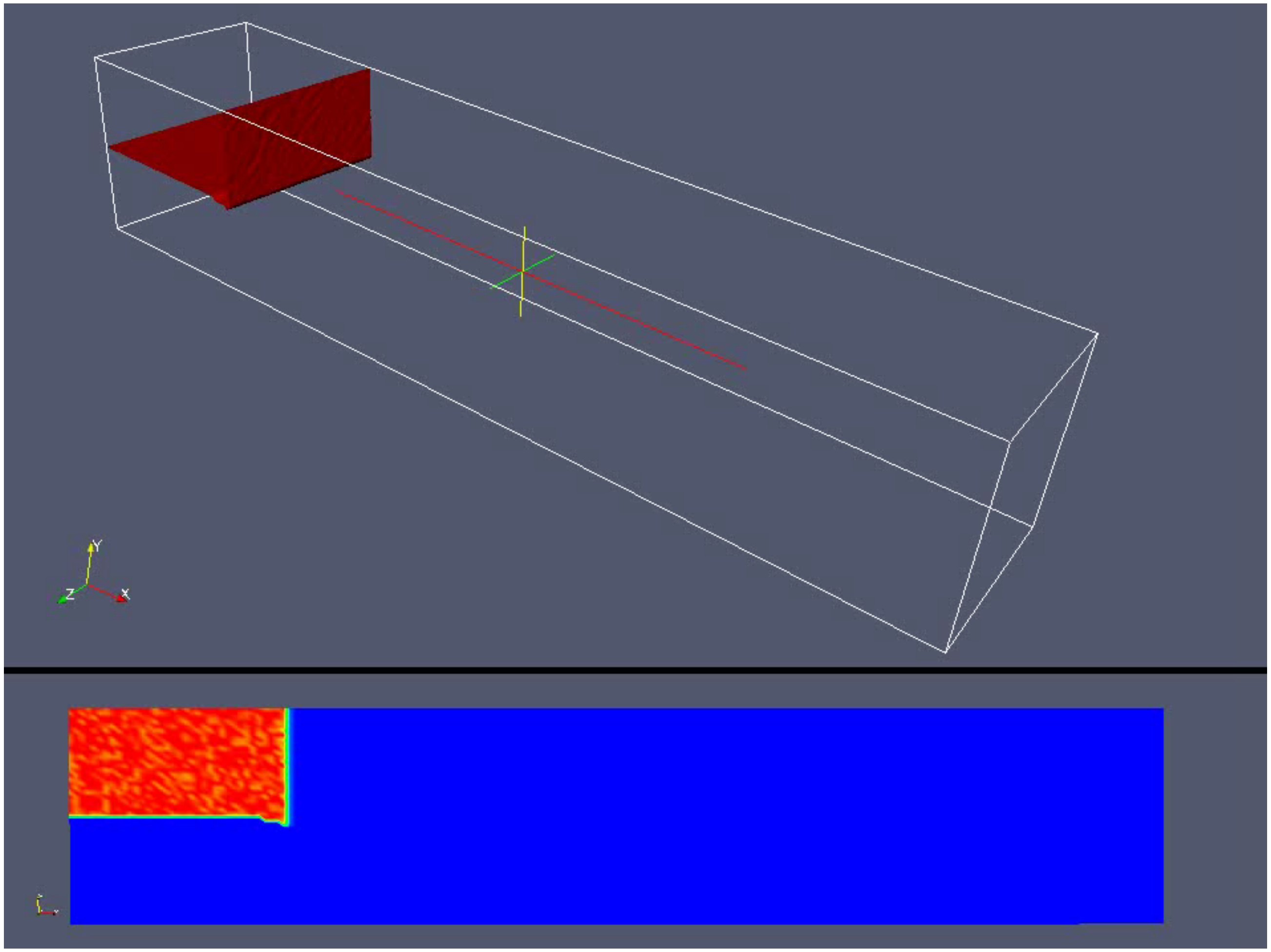
Comparison of transient deposit profiles with experimental data of de Rooij and Dalziel (1998)



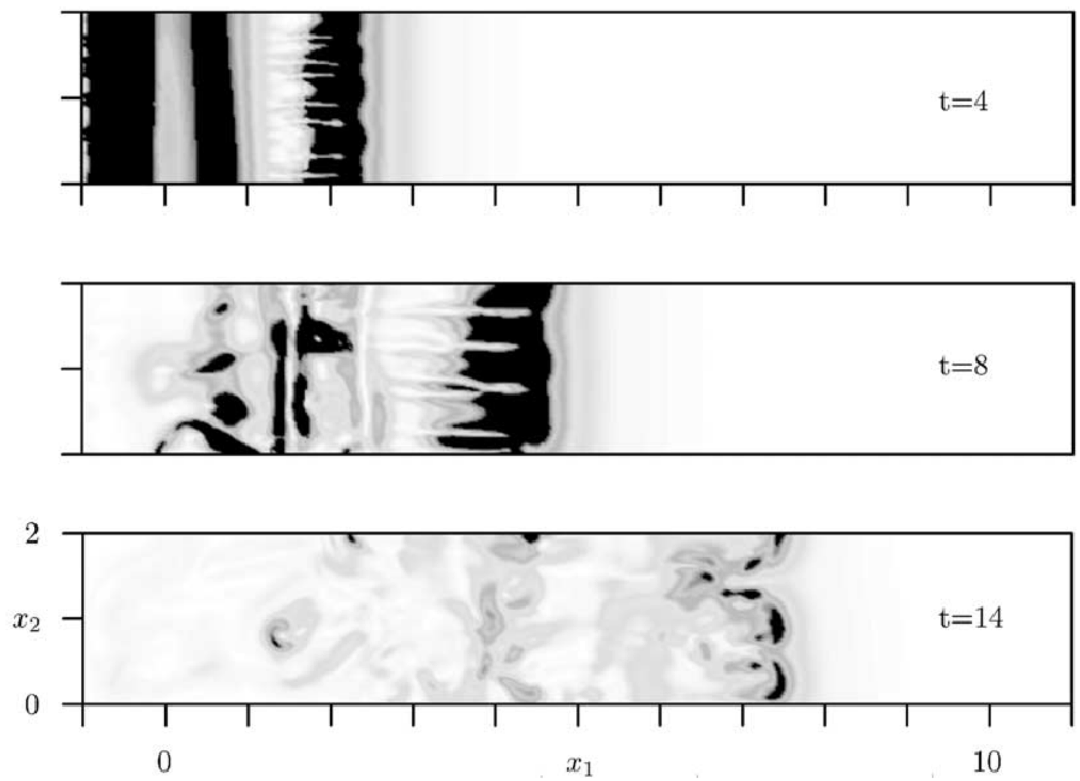
• *simulation reproduces experimentally observed sediment accumulation*

Filling of a minibasin (w. M. Nasr, B. Hall)

Interaction of gravity currents with submarine topography:



Results: Bottom wall shear stress



- *wall shear stress distribution reflects spanwise and streamwise flow structures*
- *allows prediction as to where particle bed erosion may occur*

Erosion, resuspension of particle bed (with F. Blanchette, M. Strauss, B. Kneller, M. Glinsky)

Experimentally determined correlation by Garcia & Parker (1993) evaluates resuspension flux at the particle bed surface as function of:

- *bottom wall shear stress*
- *settling velocity*
- *particle Reynolds number*

Here we model this resuspension as diffusive flux from the particle bed surface into the flow

Erosion, resuspension of particle bed (cont'd)

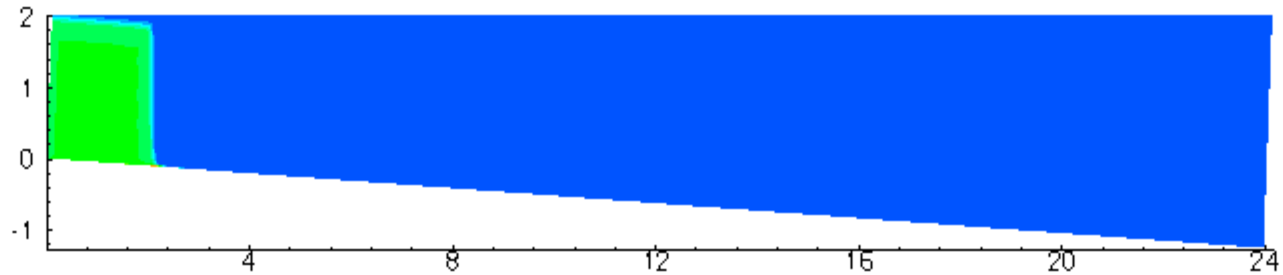
$\rho_p = 1.5 g/cm^3$, $r_p = 50 \mu m$, $\nu = 10^{-6} m^2/s$

current height $= 1.6m$

initial concentration $= 0.5\%$

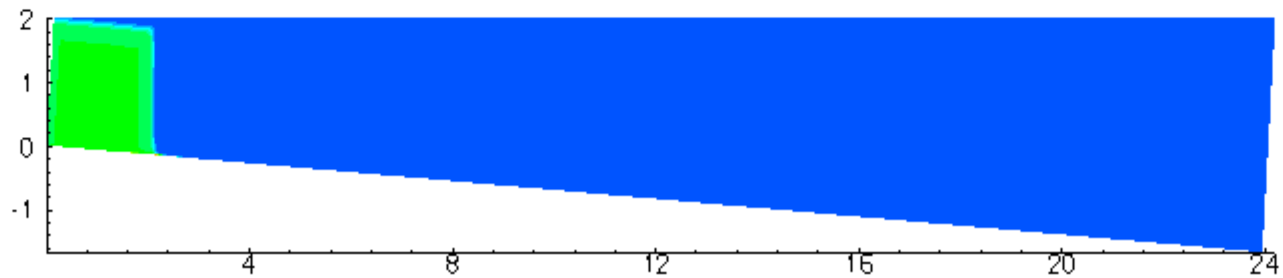
Re $= 2,200$:

slope angle $= 3^o$:



deposition outweighs erosion: decaying turbidity current

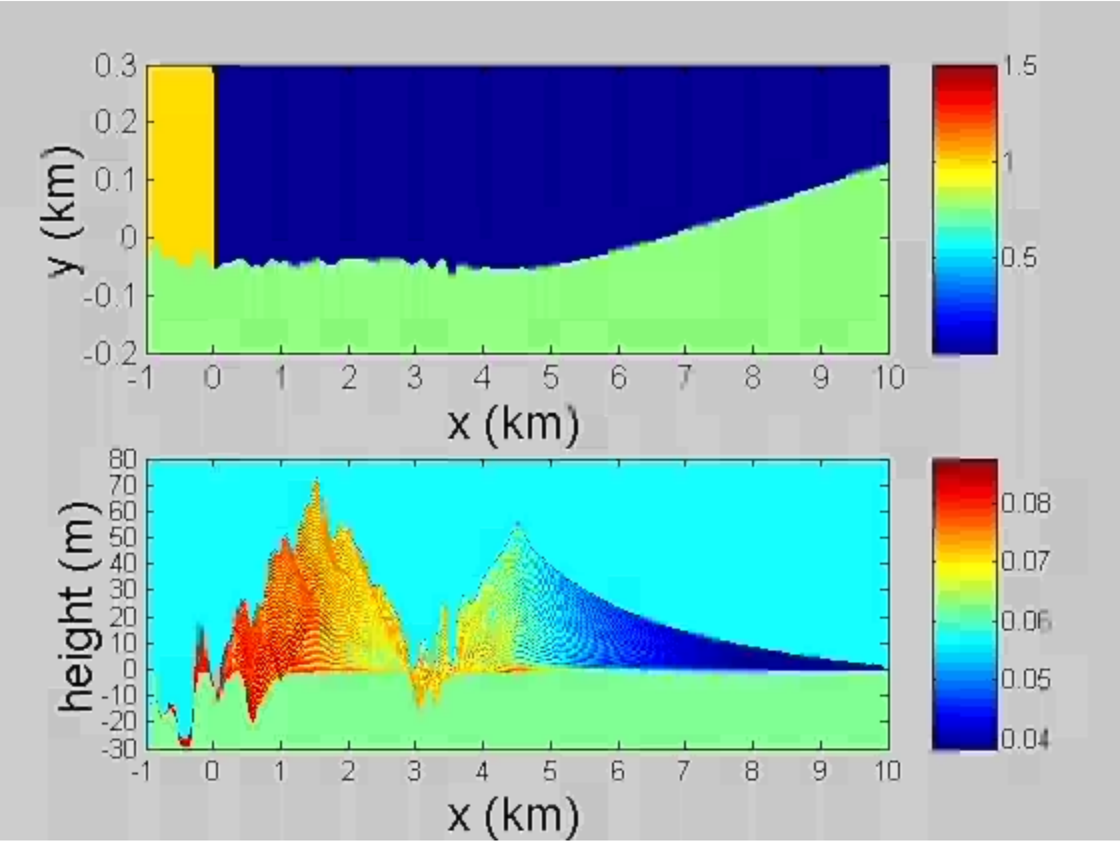
slope angle $= 4^o$:



erosion outweighs deposition: growing turbidity current

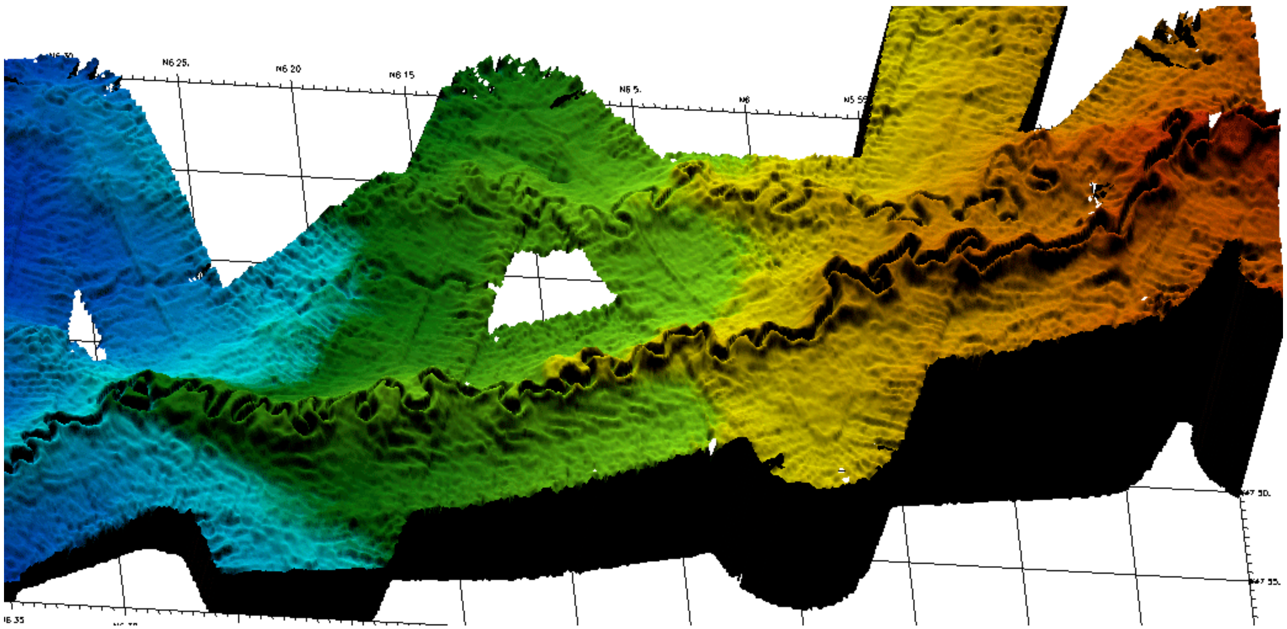
Erosion, resuspension of particle bed (cont'd)

- *multiple, polydisperse flows*
- *feedback of deposit on subsequent flows*
- *formation of ripples, dunes etc.*



Turbidity current/sediment bed interaction

Formation of submarine channel-levee systems



Amazon submarine channel

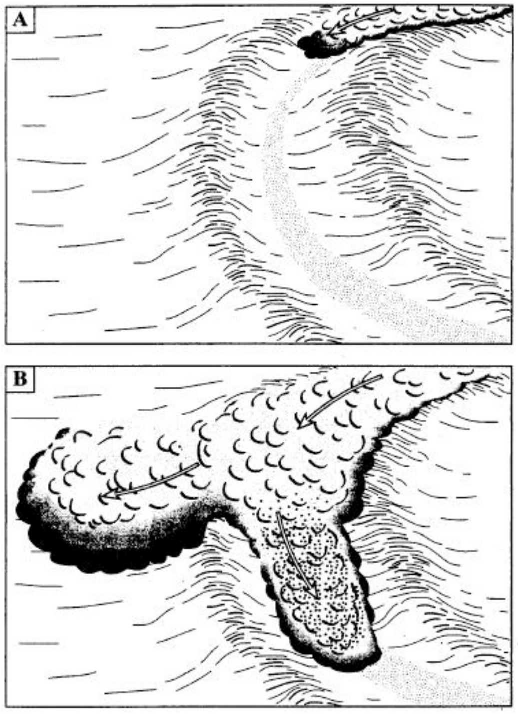
Turbidity current/sediment bed interaction

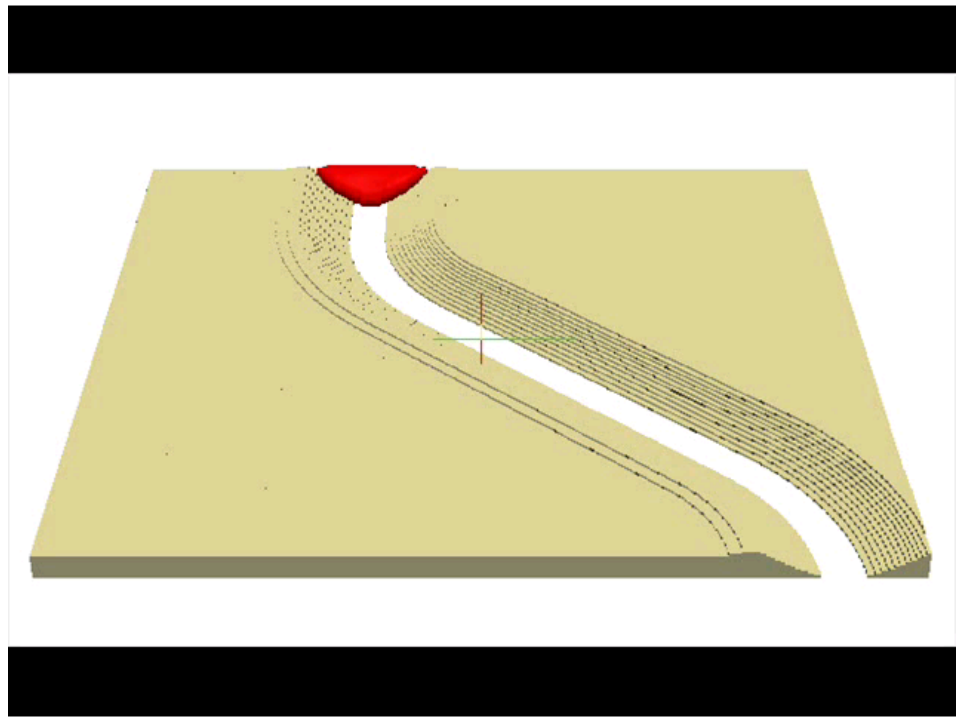
Formation of submarine channel-levee systems

Monterey Canyon fan

Turbidity current/sediment bed interaction

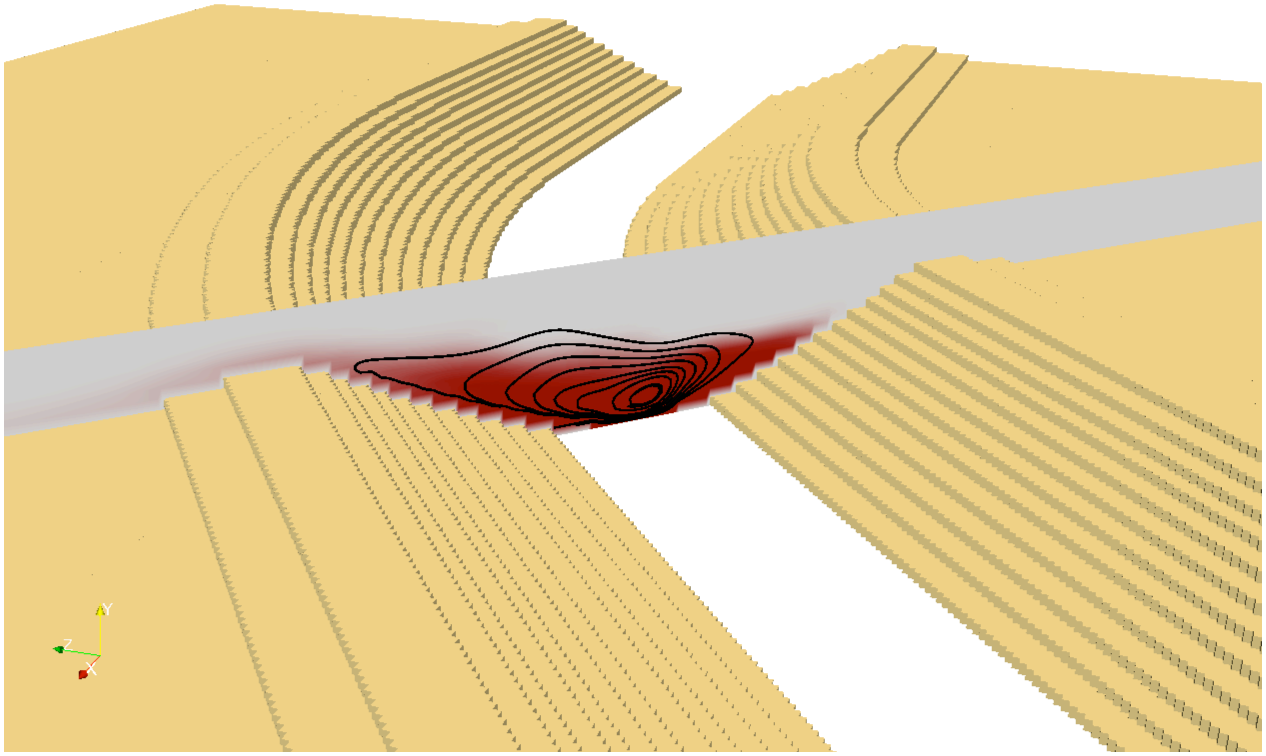
‘Flow stripping’ in channel turns: lateral overflows





Turbidity current/sediment bed interaction

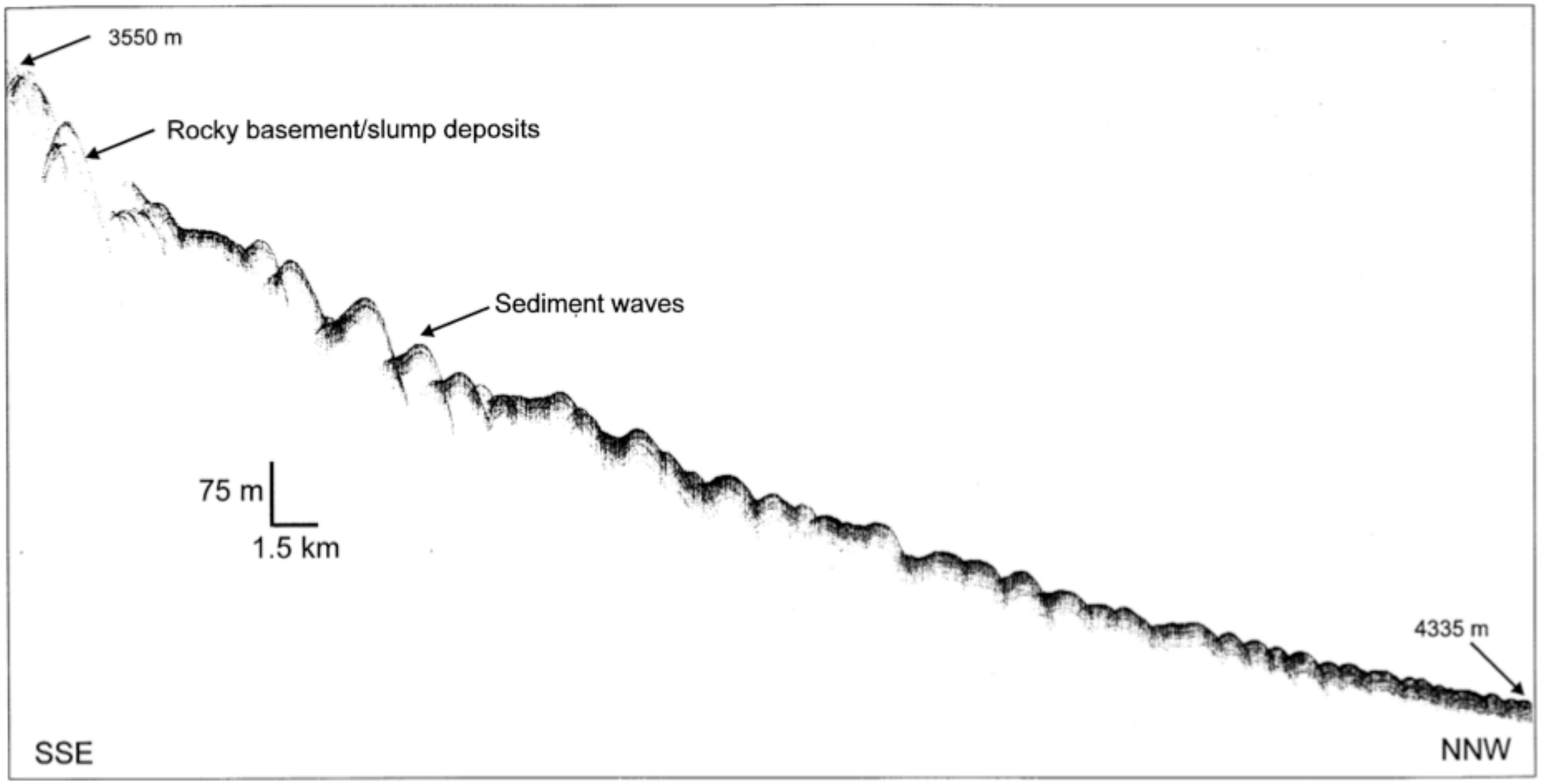
Secondary flow in submarine canyon bends



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

Turbidity current/sediment bed interaction

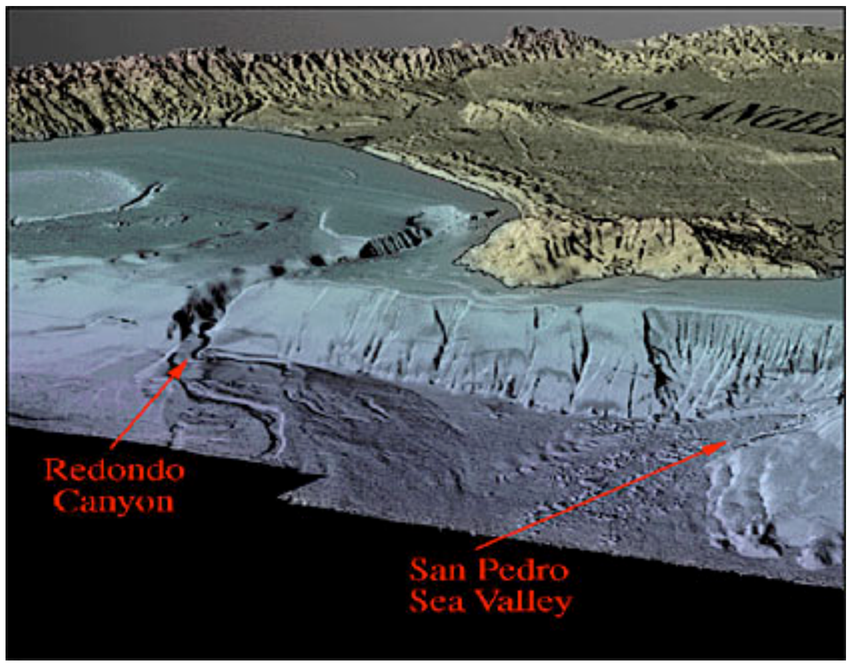
Sediment wave formation by lateral overflows



- *sediment waves are prime targets for oil reservoir formation*

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?*

Previous stability-oriented work

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

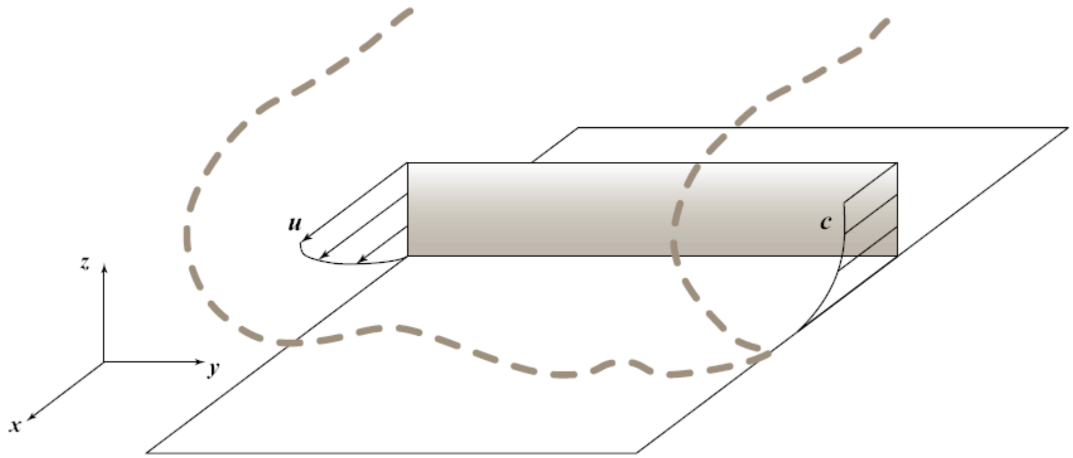
  - depth averaged equations; don't capture internal velocity and concentration structure of the current, and its coupling with the sediment bed

- *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 η(y,t) of the sediment bed: no-slip boundary conditions.

η(y,t) evolves due to:

a) Settling of particles $\qquad \frac{\partial \eta}{\partial t} = w_s\, c|_{z=\eta}$

b) Erosion of particles $\qquad D \frac{\partial c}{\partial n}\Big|_{z=\eta} = -\beta\, \tau_n \quad , \quad \frac{\partial \eta}{\partial t} = -\beta\, \frac{\tau_n|_{z=\eta}}{n_z}$

Dimensionless parameters

Characteristic quantities:

$$\begin{aligned} l^* &= D/w_s \\ u^* &= u_\infty \\ t^* &= l^*/u^* \\ p^* &= \rho_f\,(u^*)^2 \\ c^* &= c_\infty \\ \rho^* &= c_\infty\,(\rho_p - \rho_f) \end{aligned}$$

Dimensionless parameters:

$$Re = \frac{u_\infty\, D}{\nu\, w_s} \quad , \quad Pe = \frac{u_\infty}{w_s}$$

$$G = \frac{c_\infty\,(\rho_p - \rho_f)\, g\, D}{\rho_f\, u_\infty^2\, w_s} \quad , \quad N = \frac{\beta\,\nu\,\rho_f\, w_s}{D}$$

Linearization

Linearization yields generalized eigenvalue problem:

$$-\alpha V + \frac{dW}{dz} = 0 \ ,$$

$$\sigma U + W\frac{du_o}{dz} = \frac{1}{Re}\left(-\alpha^2 U + \frac{d^2U}{dz^2}\right) \ ,$$

$$\sigma V = -\alpha P + \frac{1}{Re}\left(-\alpha^2 V + \frac{d^2V}{dz^2}\right) \ ,$$

$$\sigma W = -\frac{dP}{dz} + \frac{1}{Re}\left(-\alpha^2 W + \frac{d^2W}{dz^2}\right) - GC \ ,$$

$$\sigma C + W\frac{dc_o}{dz} - \frac{1}{Pe}\frac{dC}{dz} = \frac{1}{Pe}\left(-\alpha^2 C + \frac{d^2C}{dz^2}\right) \ ,$$

$$\sigma E = E\frac{c_\infty}{Pe}\left.\frac{dc_o}{dz}\right|_{z=0} - EN\left.\frac{d^2u_o}{dz^2}\right|_{z=0} + \frac{c_\infty}{Pe}C(z=0) - N\left.\frac{dU}{dz}\right|_{z=0}$$

base flow effect — *perturb. settling* — *perturb. shear*

with boundary conditions:

$$U(z=0) + E\left.\frac{du_o}{dz}\right|_{z=0} = 0 \ ,$$

$$V(z=0) = 0 \ ,$$

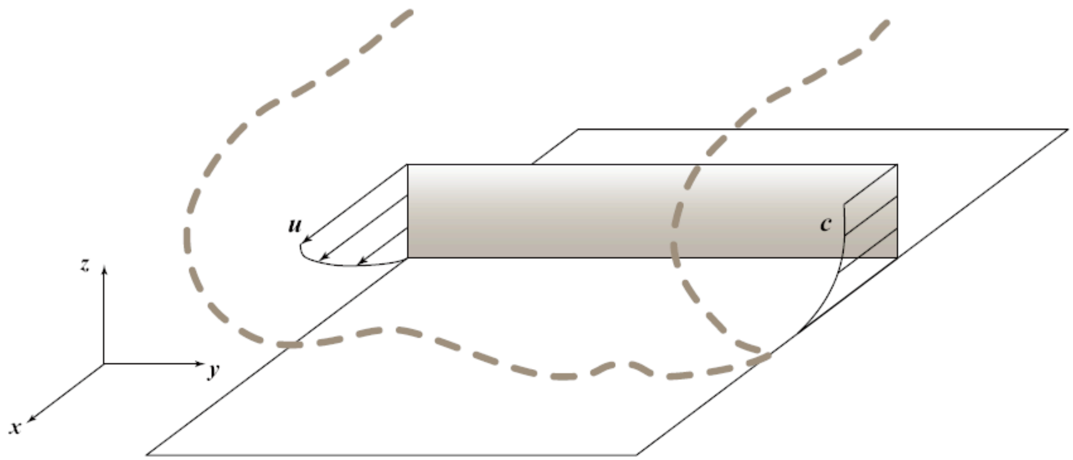
$$W(z=0) = \sigma E \ ,$$

$$E\left.\frac{d^2c_o}{dz^2}\right|_{z=0} + \left.\frac{dC}{dz}\right|_{z=0} = -\frac{NPe}{c_\infty}\left(E\left.\frac{d^2u_o}{dz^2}\right|_{z=0} + \left.\frac{dU}{dz}\right|_{z=0}\right) \ ,$$

$$U(z\to\infty) = V(z\to\infty) = W(z\to\infty) = C(z\to\infty) = 0 \ .$$

Base flow profile

Unidirectional flow some distance behind the head:



Fully developed velocity and concentration profiles:

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

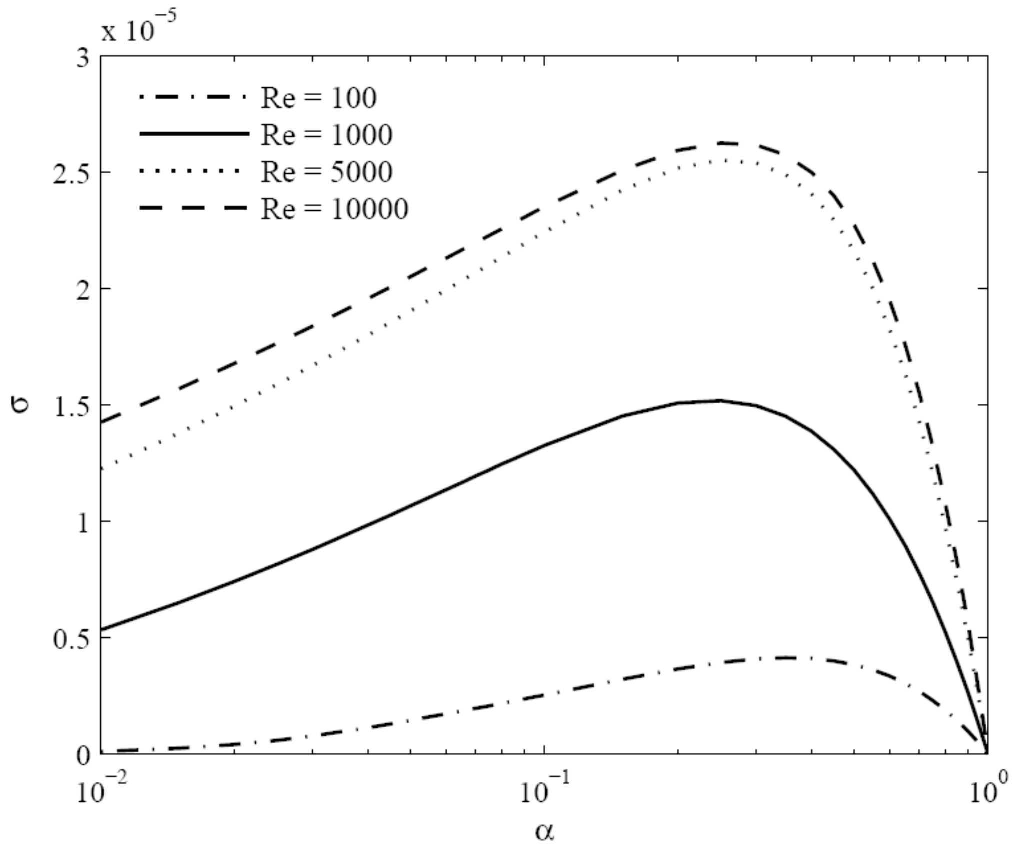
Important parameter:

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

Results: Influence of Re

Dispersion relations:

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

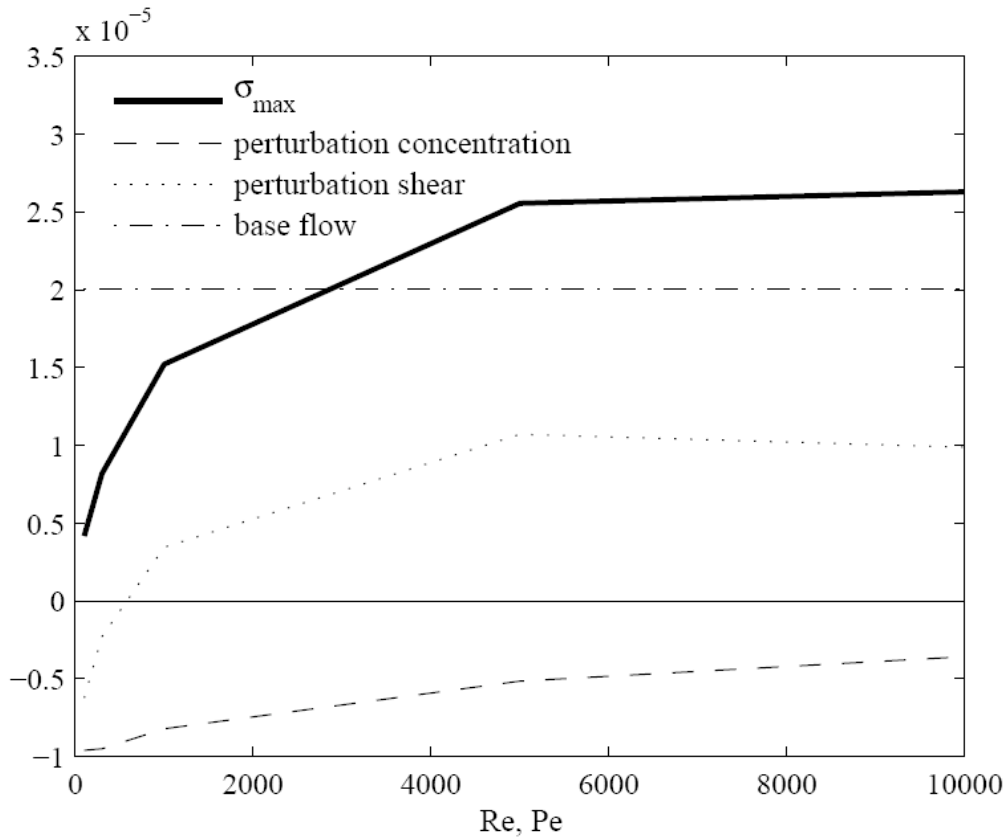


- *larger Re are destabilizing*
- *most amplified wave number α~0.25*

Results: Instability mechanism

What drives the instability?

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



- *base flow is main driver*
- *perturbation concentration always stabilizing*
- *perturbation shear stabilizing at low Re, destabilizing at high Re*

Results: Instability mechanism (cont'd)

Main criterion for instability:

$$L < 1$$

base flow shear has to decay faster than base concentration profile

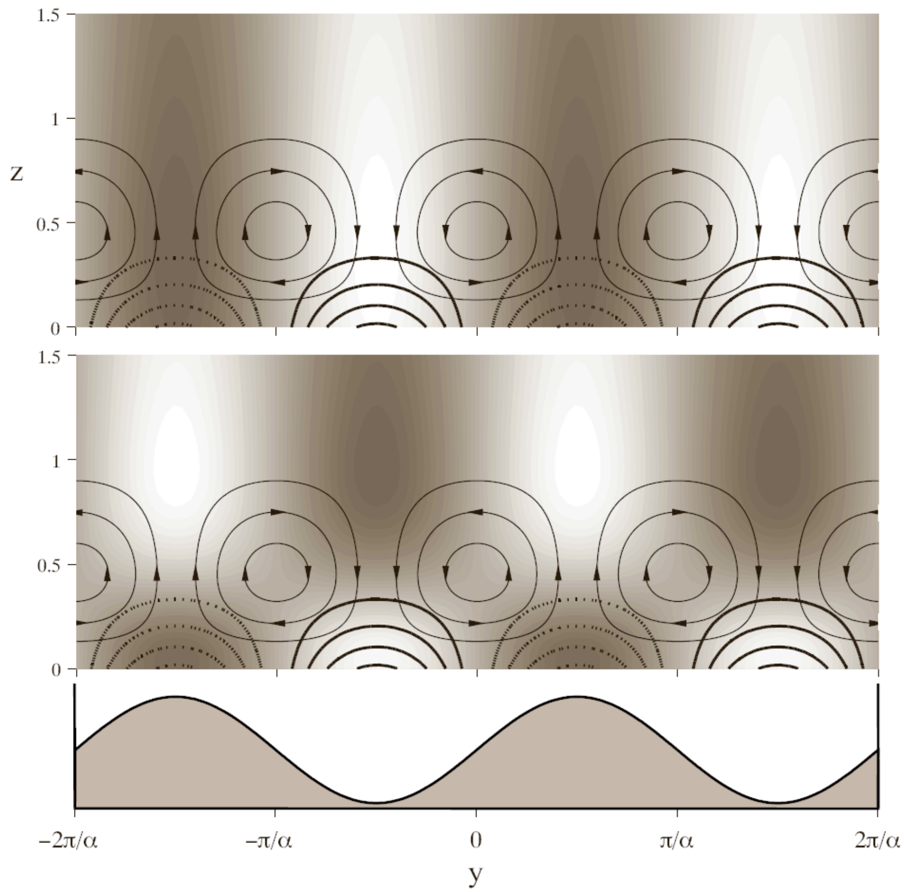
- *if base shear decays faster than base concentration profile:*
  - *an upward protrusion of the sediment bed will see less shear (less erosion), but still substantial sedimentation → will grow*
  - *a valley of the sediment bed will see higher shear (more erosion), but not much more sedimentation →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

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

Results: Eigenfunctions

Influence of secondary flow structure:

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



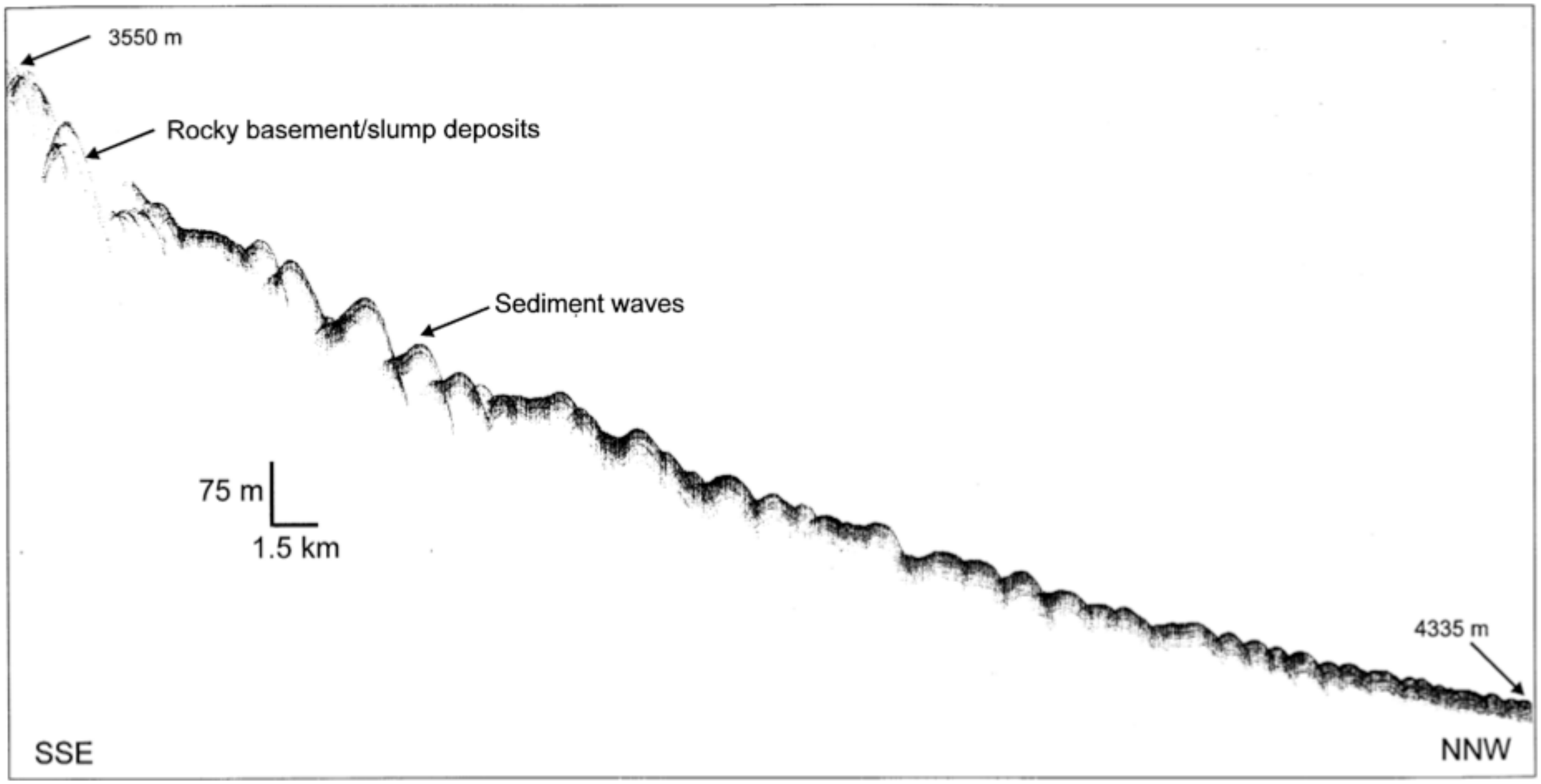
perturbation u-velocity

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

Large scale wave forms at the ocean floor

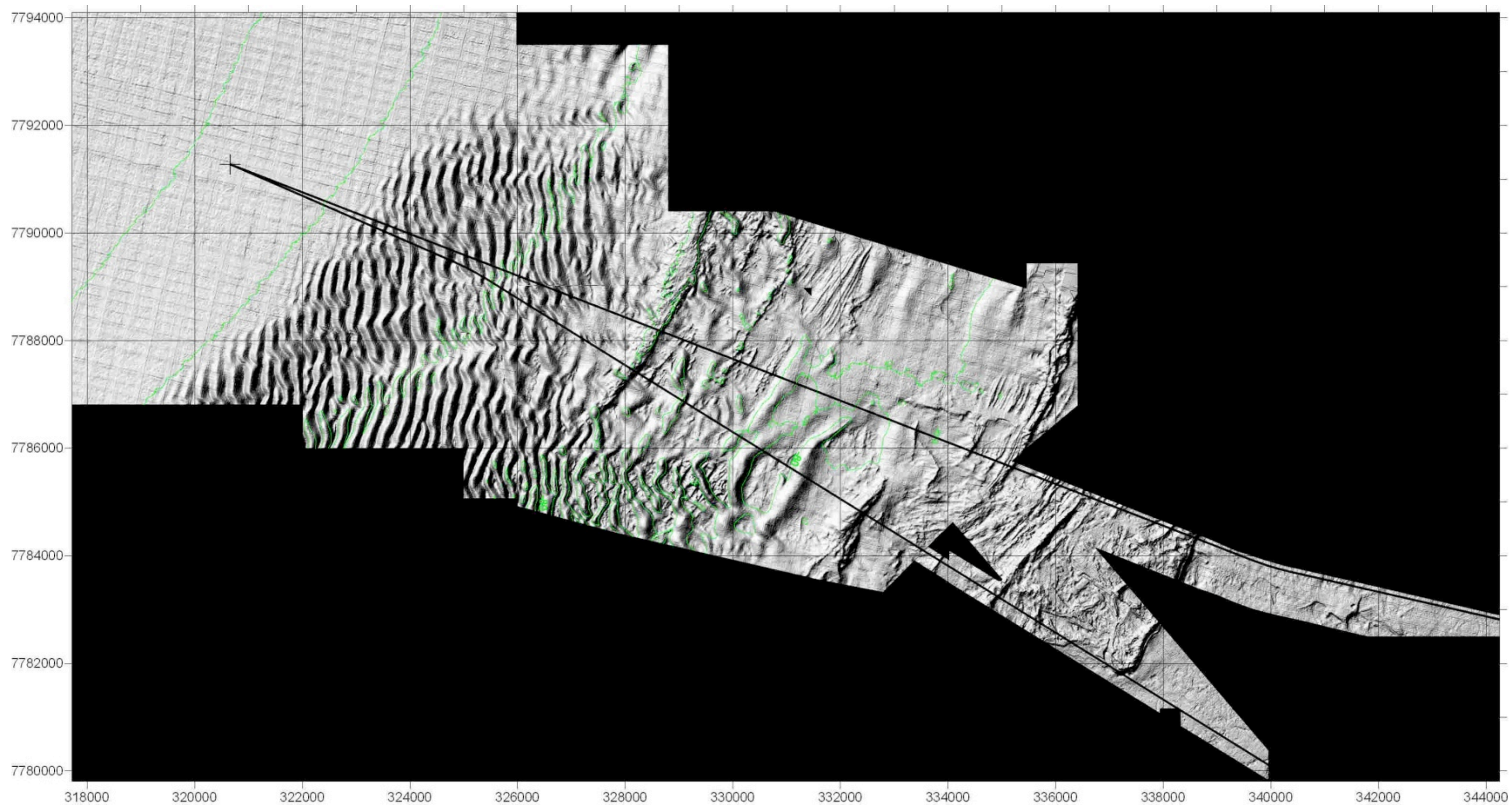


- *sediment waves are prime targets for oil reservoir formation*
- *formed by turbidity currents and bottom flows; mechanism?*
- *traditional assumption: lee waves, but no rigorous stability analysis available*

Sediment wave formation by bottom currents

Santa Barbara channel

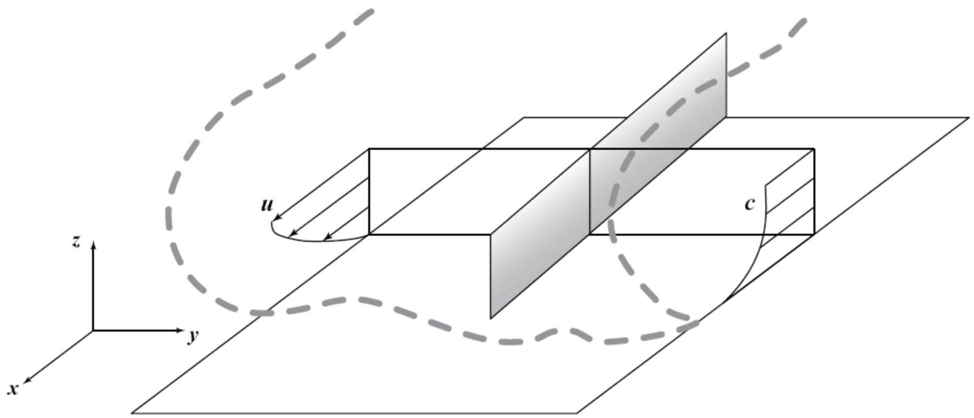
Sediment wave formation by bottom currents



Australian coast

Base flow profile

Unidirectional flow behind the head:



Fully developed velocity and concentration profiles:

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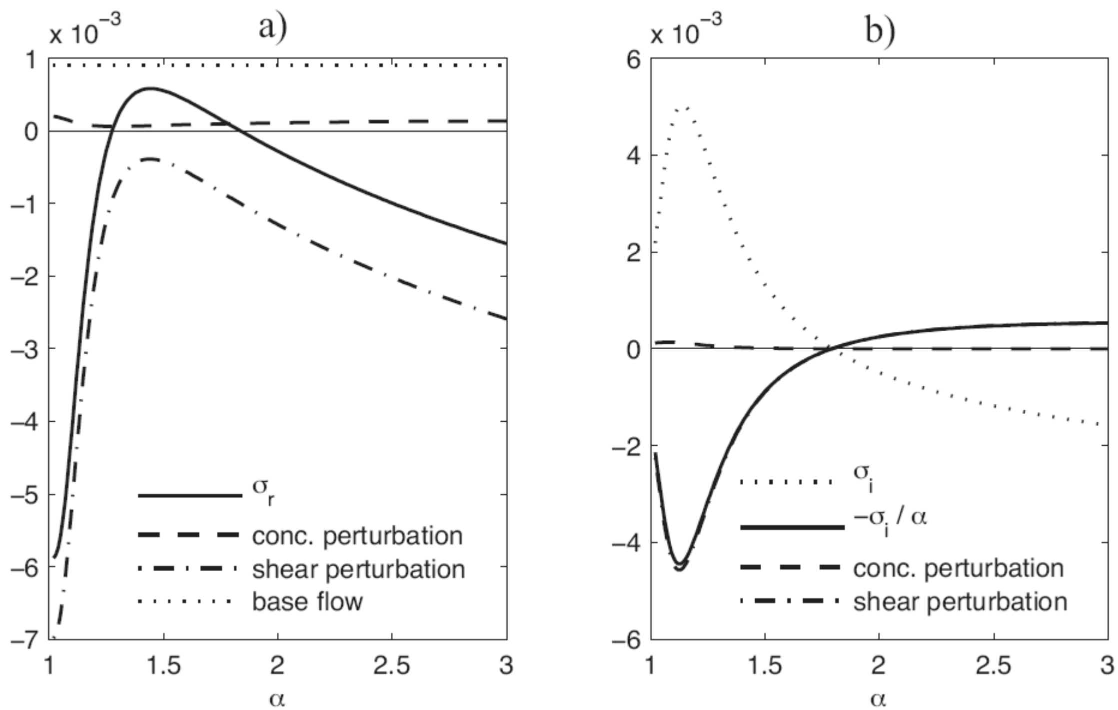
Important parameter:

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

Linear stability results

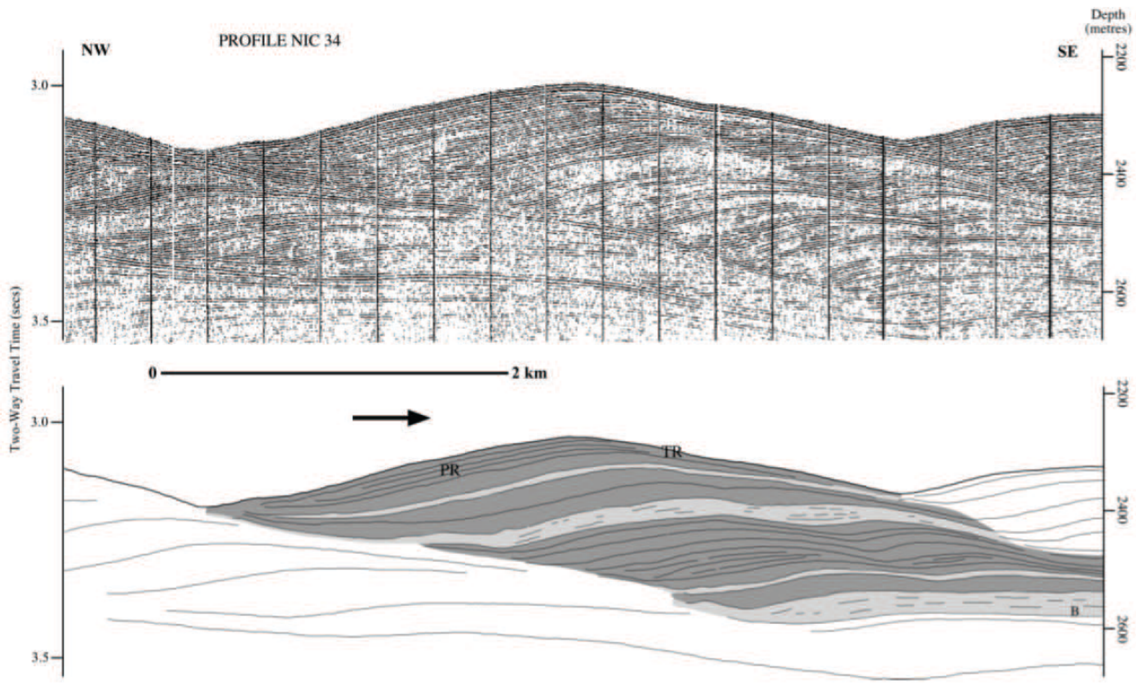
Dispersion relations:



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

Field observation of sediment bed structures

Net deposition is stronger on the upstream side

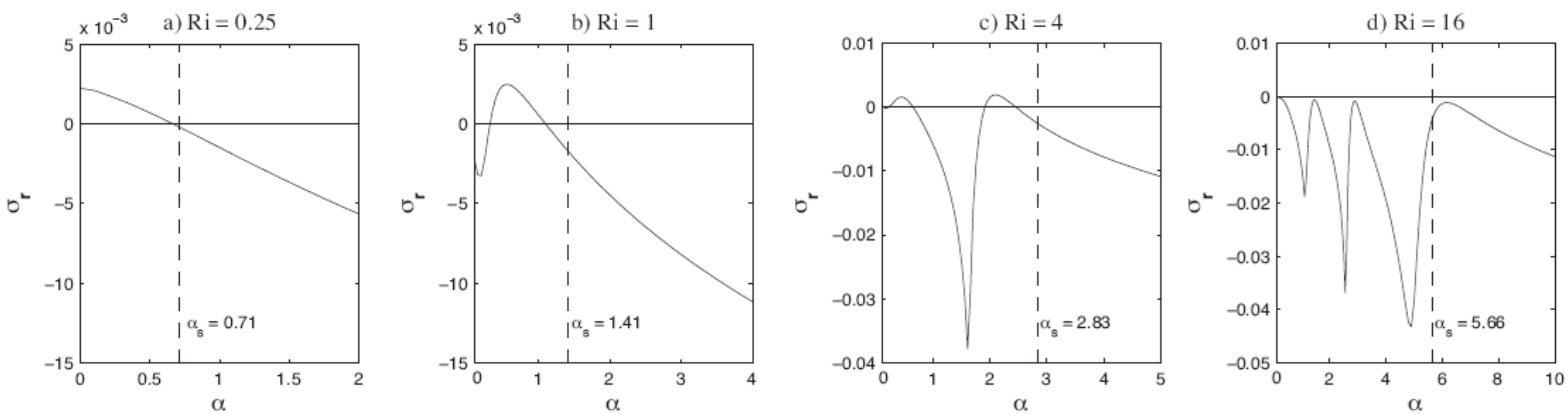


upstream migration

Linear stability results

Important parameter: Richardson number

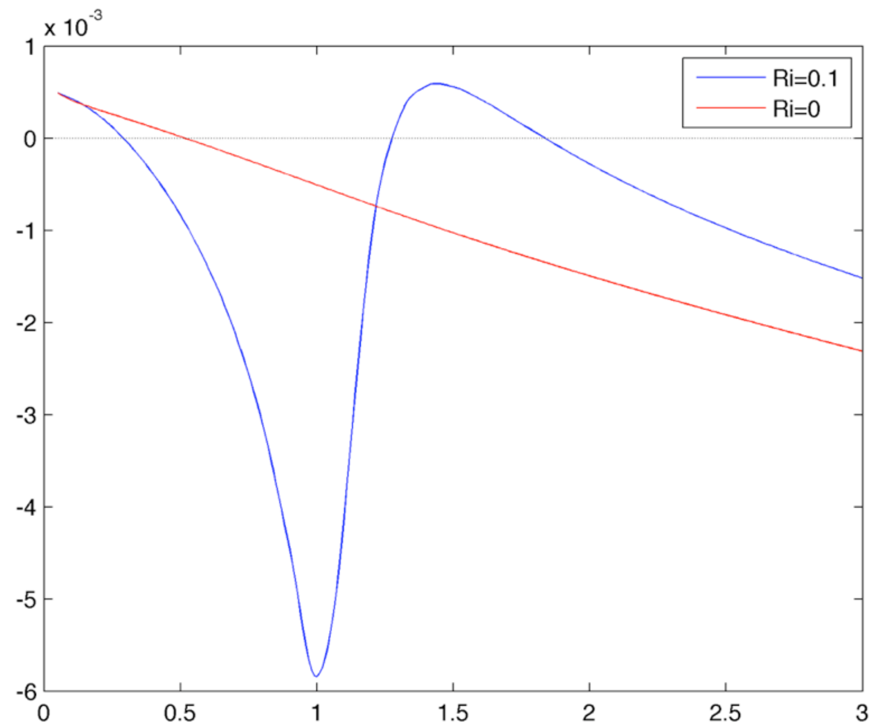
$$Ri = c_\infty g' D / u_\infty^2 w_s$$



- *as we increase Ri → more modes become unstable → instability is due to internal wave modes*

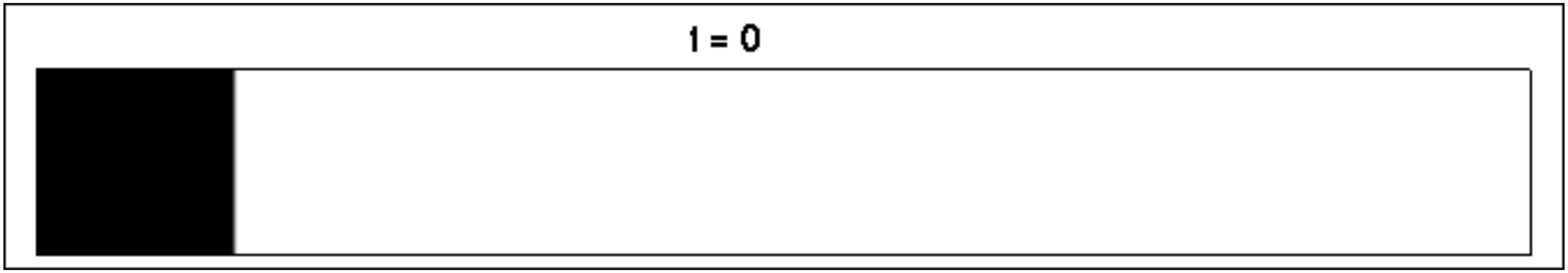
Linear stability results

Dispersion relations:



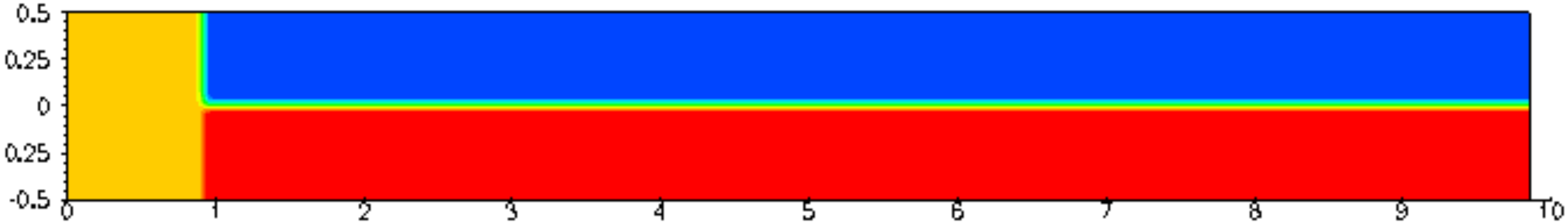
- *'turn off' stratification: high wavenumber mode disappears → linked to int. waves*
- *low wavenumber mode is caused by base flow instability mechanism*

Reversing buoyancy currents (with V. Birman)



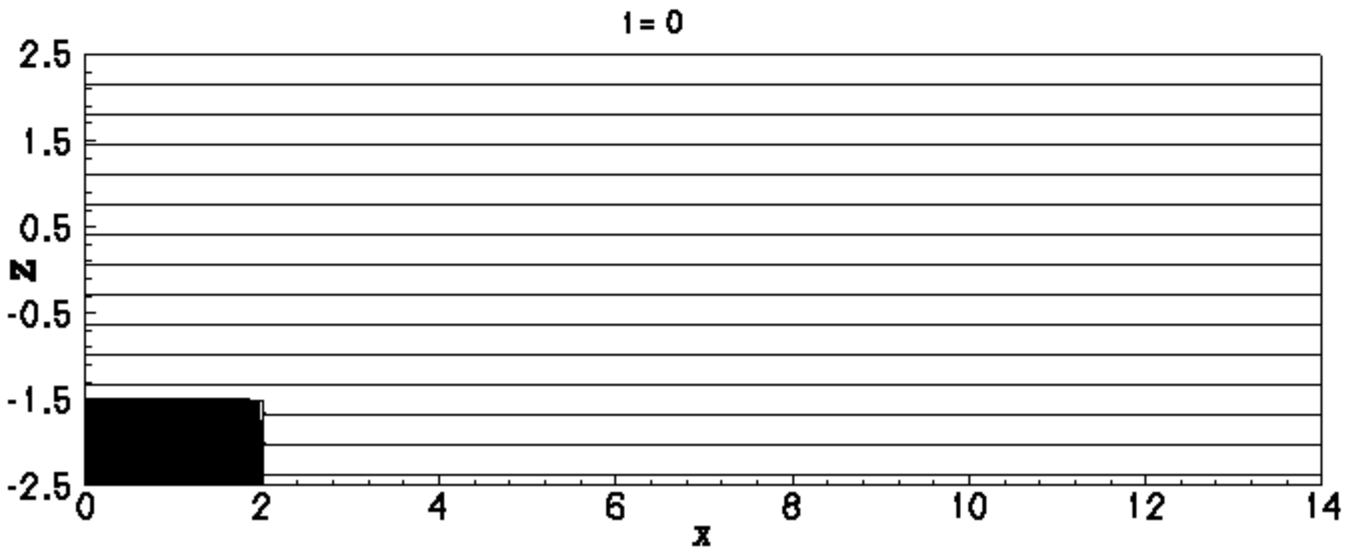
- *propagates along bottom over finite distance, then lifts off*
- *subsequently propagates along top*

Gravity currents in stratified ambients (with V. Birman, B. Sutherland)



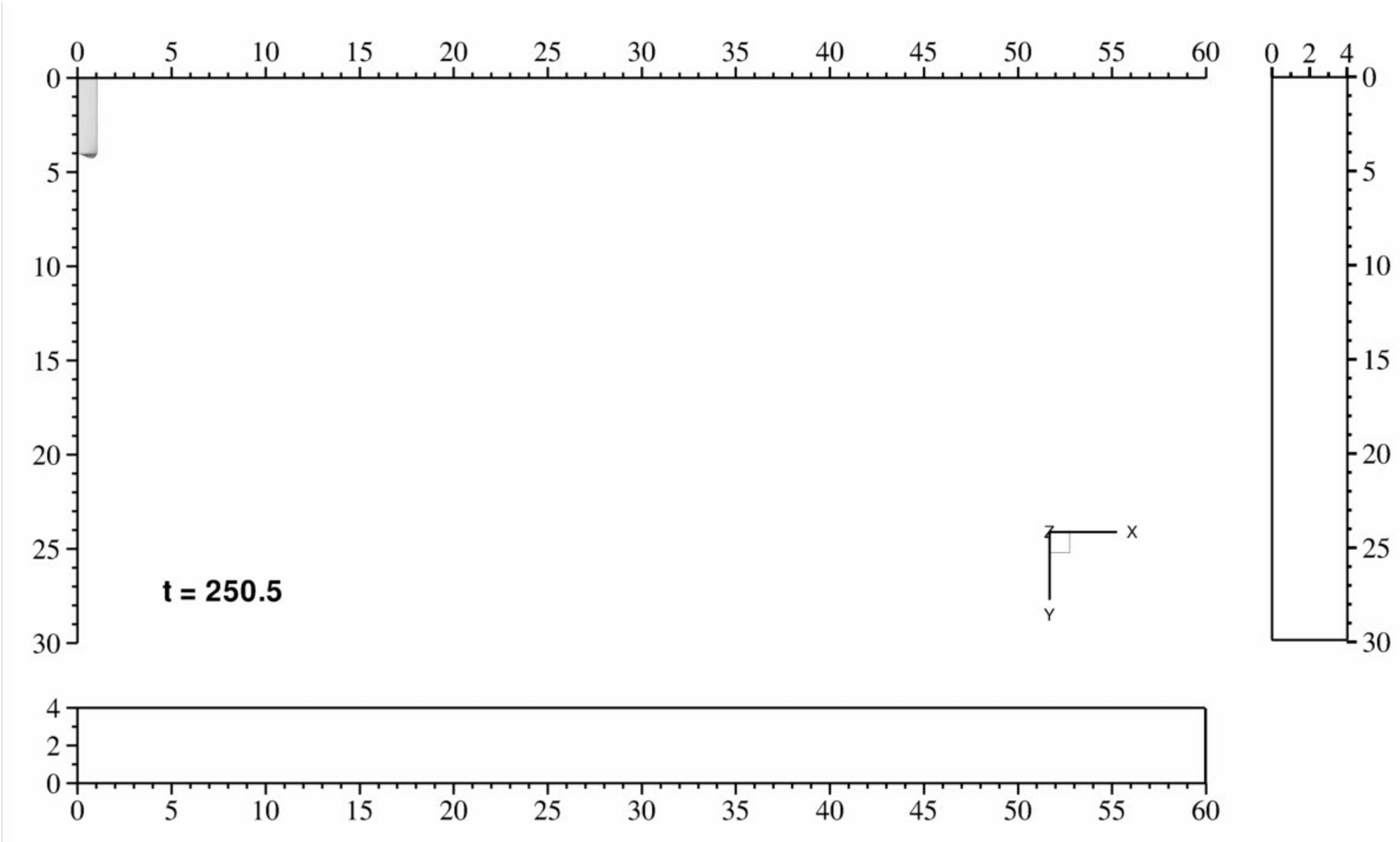
- *generation of internal waves*
- *complex interaction of the current with the stratified ambient*

Stratification: Internal wave generation



- *Excitation of internal waves in the ambient fluid*

Sedimentation from river plumes



Collaboration with Henniger and Kleiser (2008)

Summary

- *high resolution 2D and 3D simulations of gravity currents*
- *detailed information regarding sedimentation dynamics, energy budgets, mixing behavior, dissipation…*
- *extension to gravity currents flowing down a slope, complex geometries, erosion and resuspension, intrusions, reversing buoyancy, submarine structures, levees*
- *identify novel linear instability mechanism responsible for the formation of streamwise channels/gullies and sediment waves*