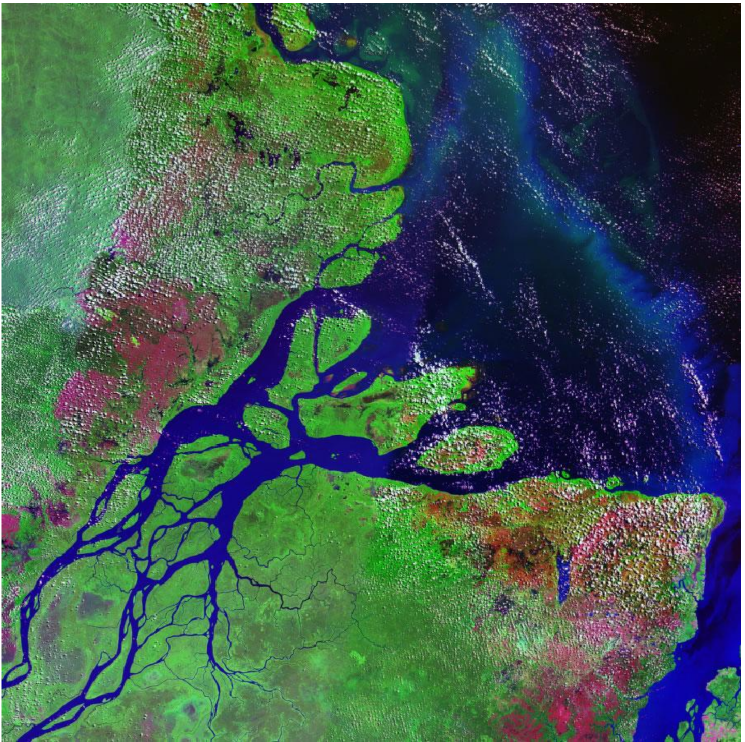
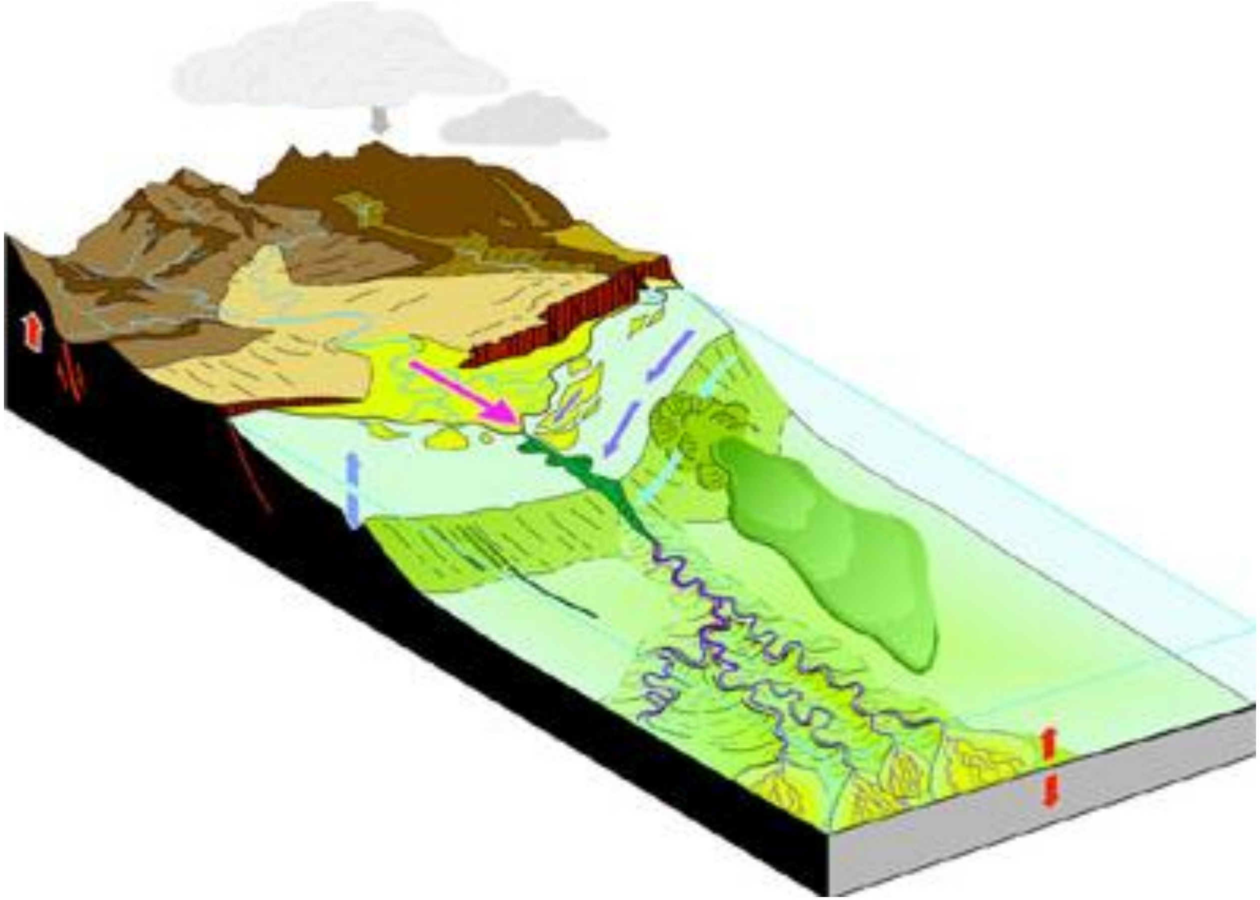
Buoyancy-driven currents and sediment transport in the ocean

Ben Kneller

With Mohamad Nasr Azadani, Eckart Meiburg, Brendon Hall, Rolf Henniger, Vineet Birman, Carolina Boffo, Rafael Manica

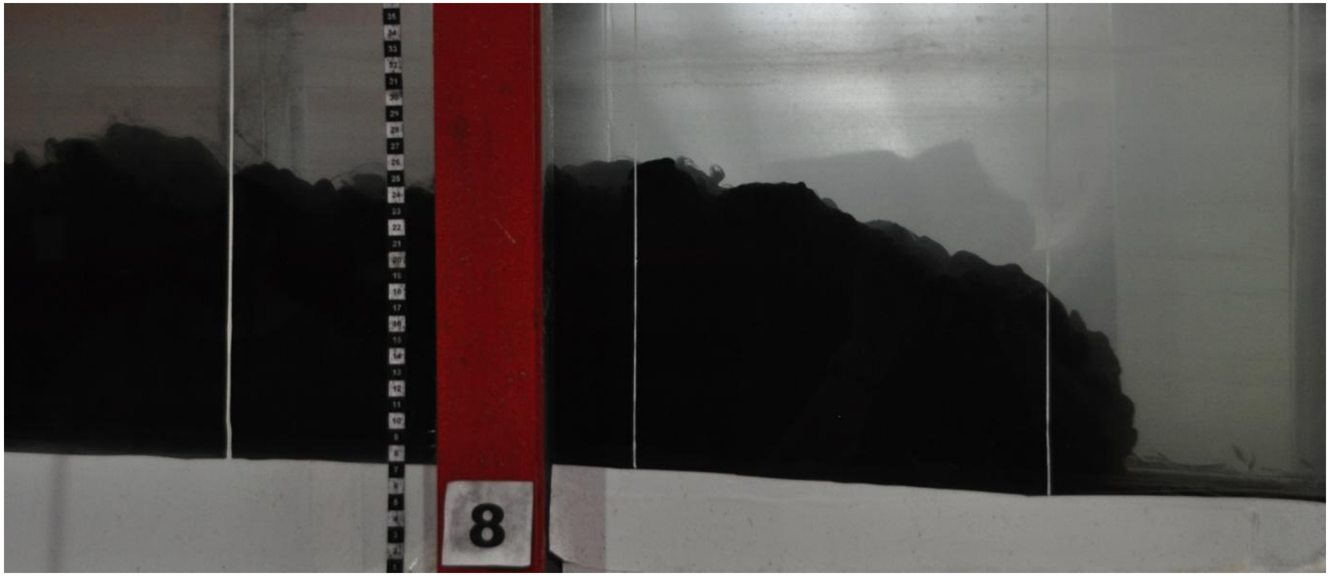


- Most sediments derived from erosion of land surfaces reach the ocean
- Much remains trapped near the shoreline
- Two buoyancy-driven processes transfer sediment to the deep ocean – the ultimate sediment sink

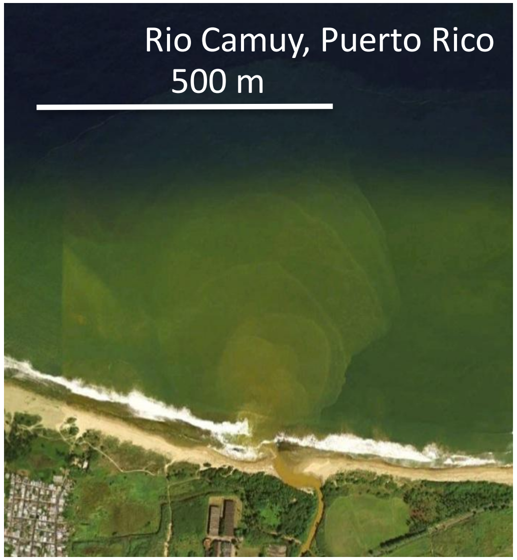


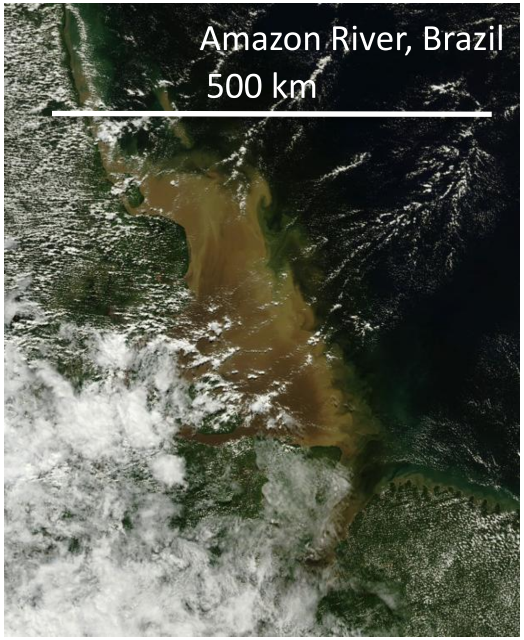
Transfer of sediment to deep water

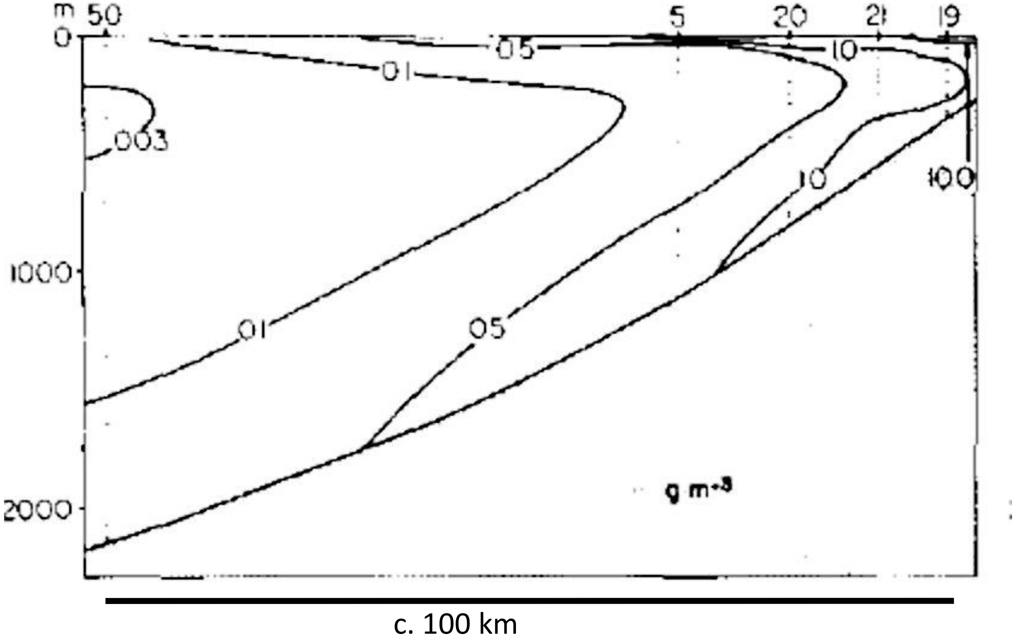
- **River plumes** and **turbidity currents**
- Both buoyancy-dominated
- Turbulence maintains sediment suspension, affecting buoyancy
- Between them these two processes account for most of the sediment in the deep sea



River plumes

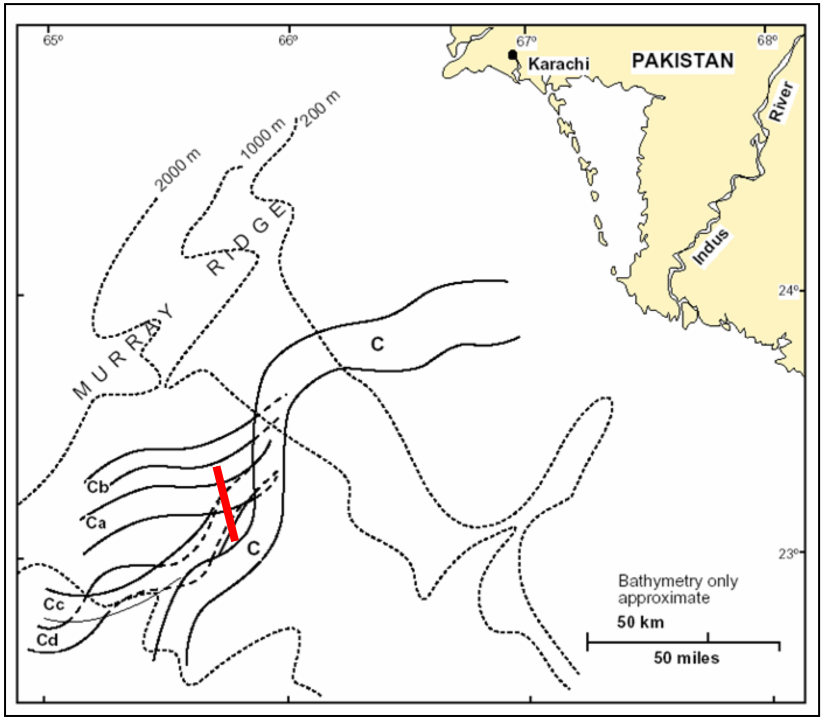






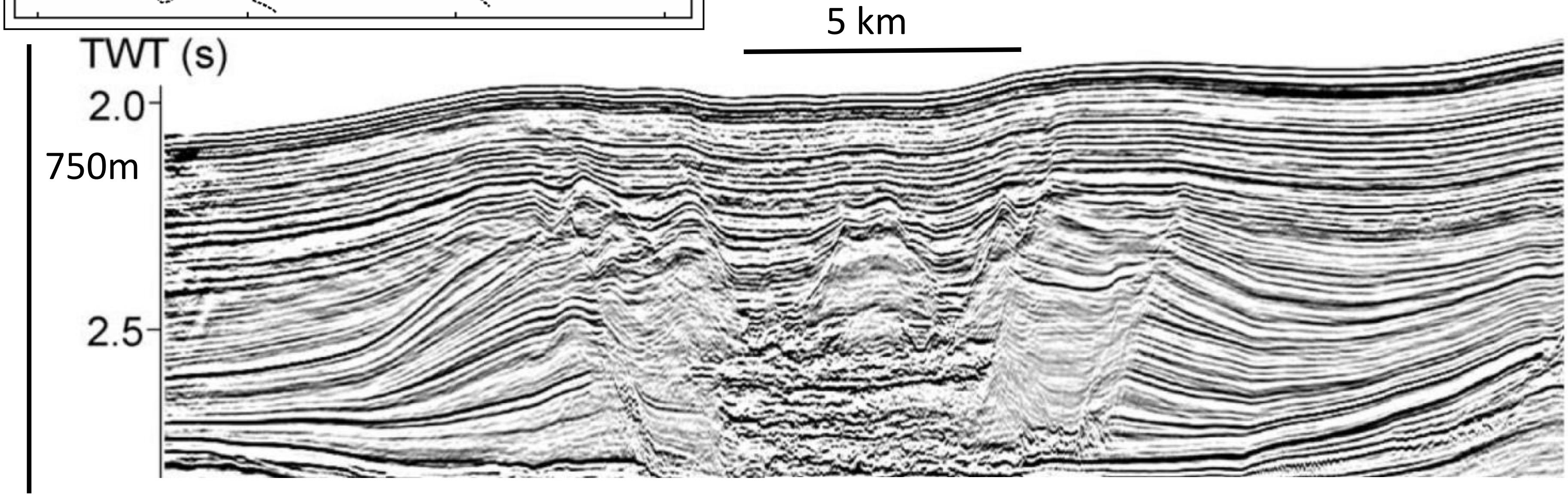
Particulate matter in Congo River plume. Eisma & Kalf, 1984

Sediment deposited from river plumes

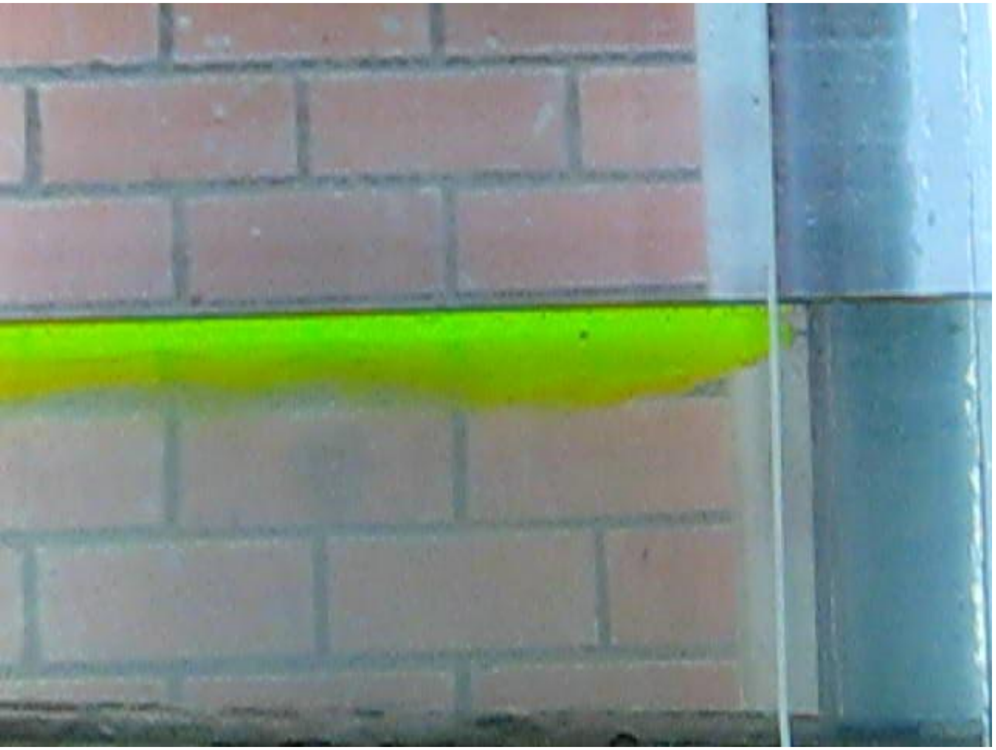


McHargue, 1991

Deptuck et al., 2003



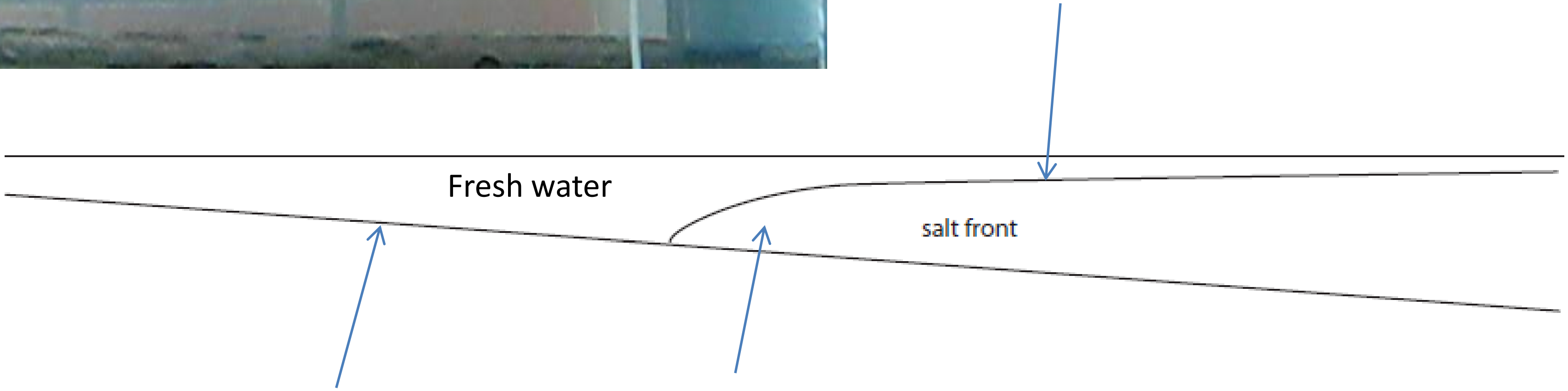
Positively buoyant surface plume



Stability of lower boundary is given by a gradient Richardson number Ri_g.

Typically the stratification is stable for $Ri_g >$ 0.25.

$$Ri_g = \frac{\left(g \dfrac{\partial \rho / \partial z}{\rho_a} \right)}{\left(\partial u / \partial z \right)^2}$$



Turbulence generation in shear layer?

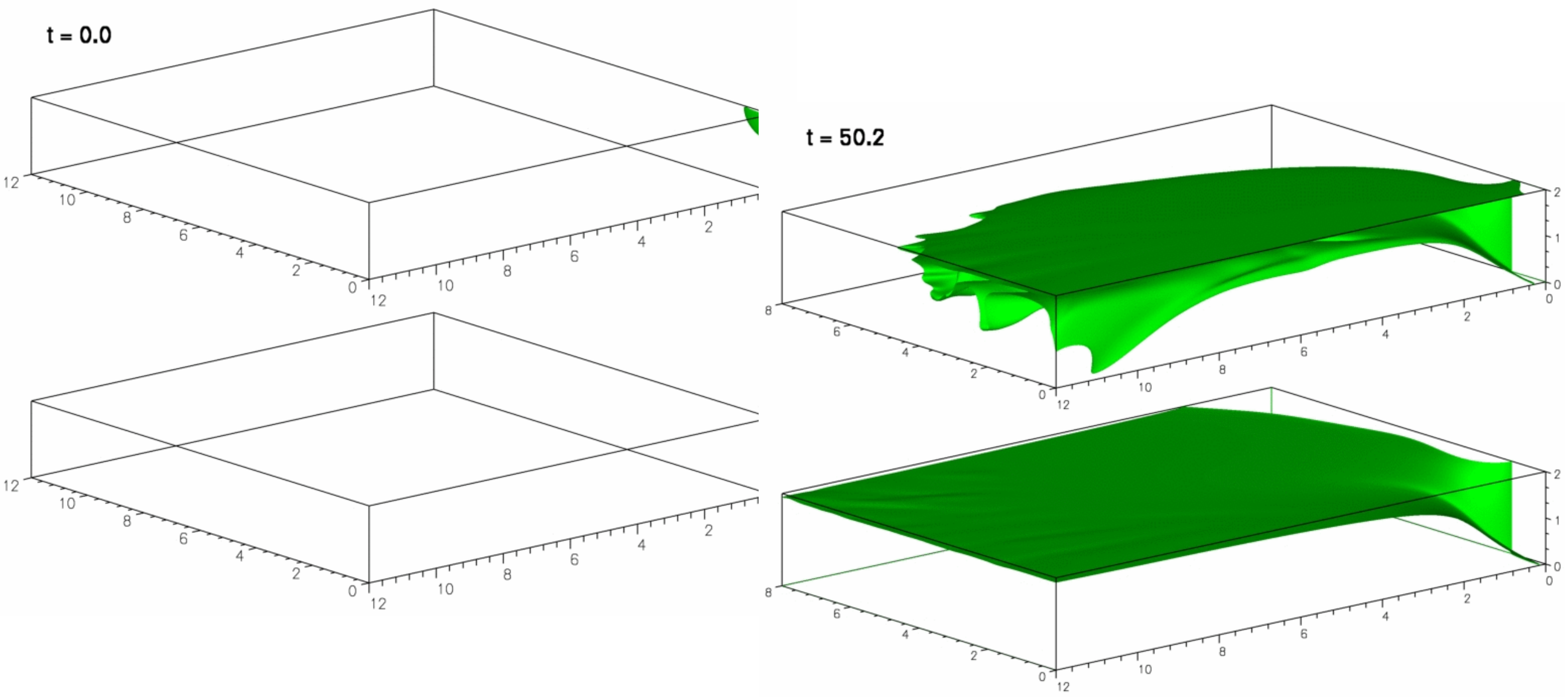
Fresh water

salt front

Turbulence generation at lower boundary when attached to bed

TURBIDITY MAXIMUM associated with turbulence decay

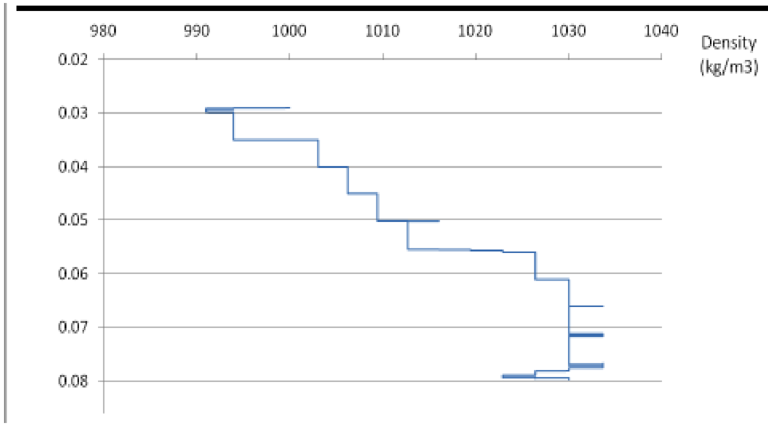
Plume lower boundary stability - DNS



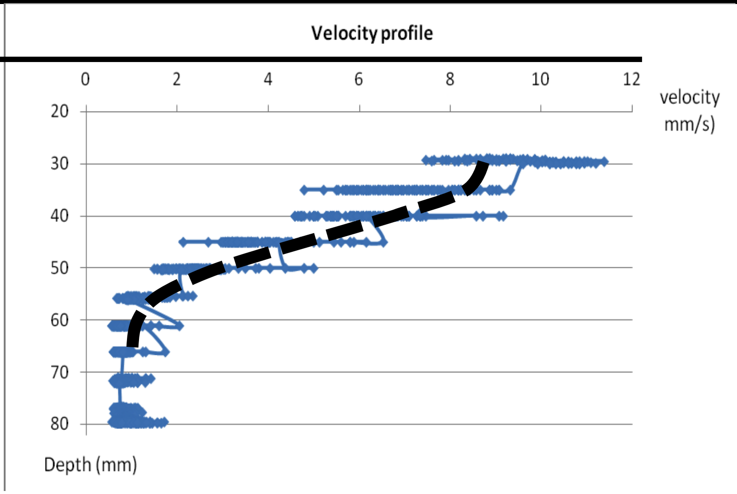
Courtesy of Rolf Henniger, ETH

Plume lower boundary stability – laboratory experiment

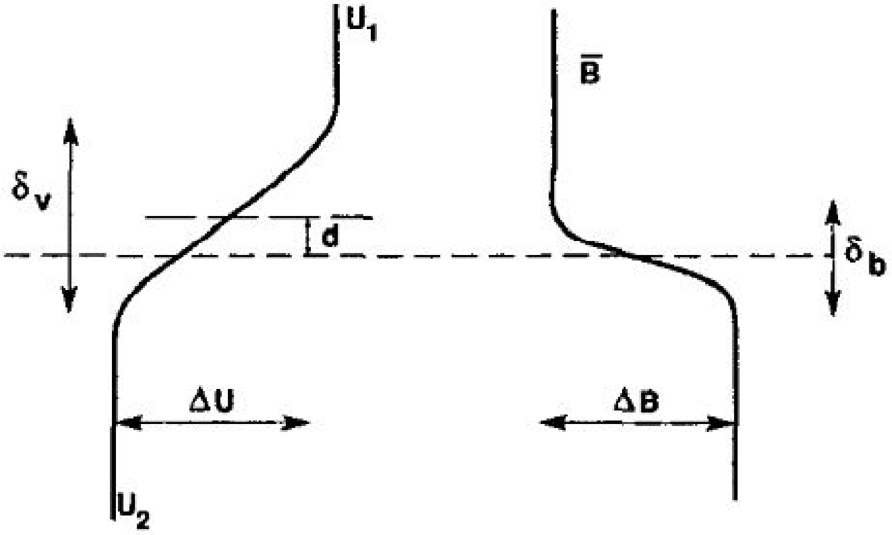
Plume lower boundary stability – laboratory experiment



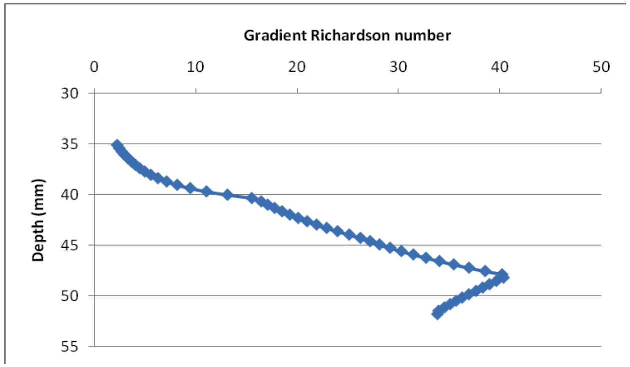
Calibrated resistivity probe



Constant Temperature Anemometry (‘hot wire’ probe)



Fernando 1991

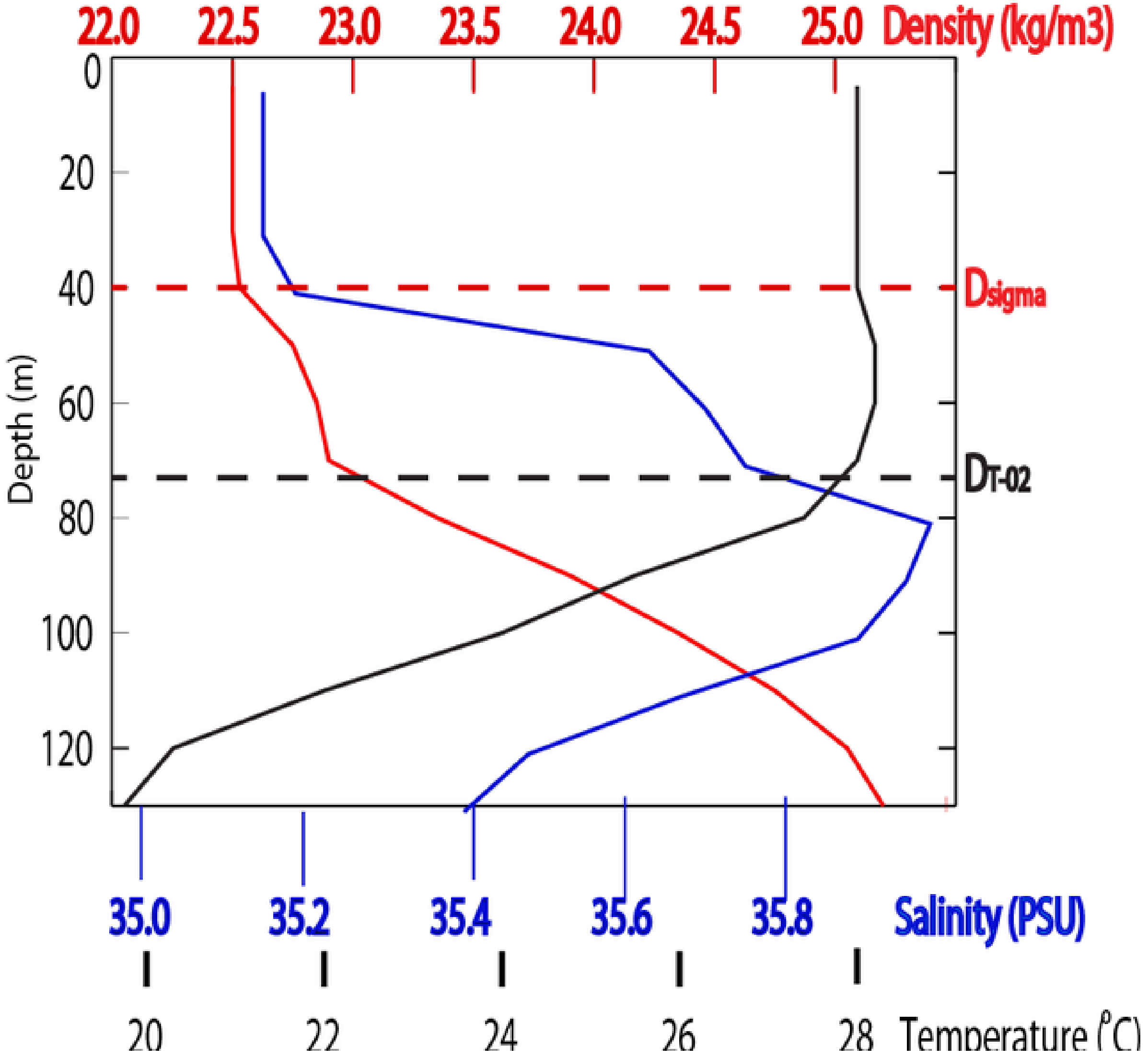


Stability of stratification suggests that long-range sediment transport by river plumes depends upon wave-generated turbulence

Ocean mixing layer

Turbulent homogenisation by surface wave-breaking and wind-induced shear

Indian Ocean

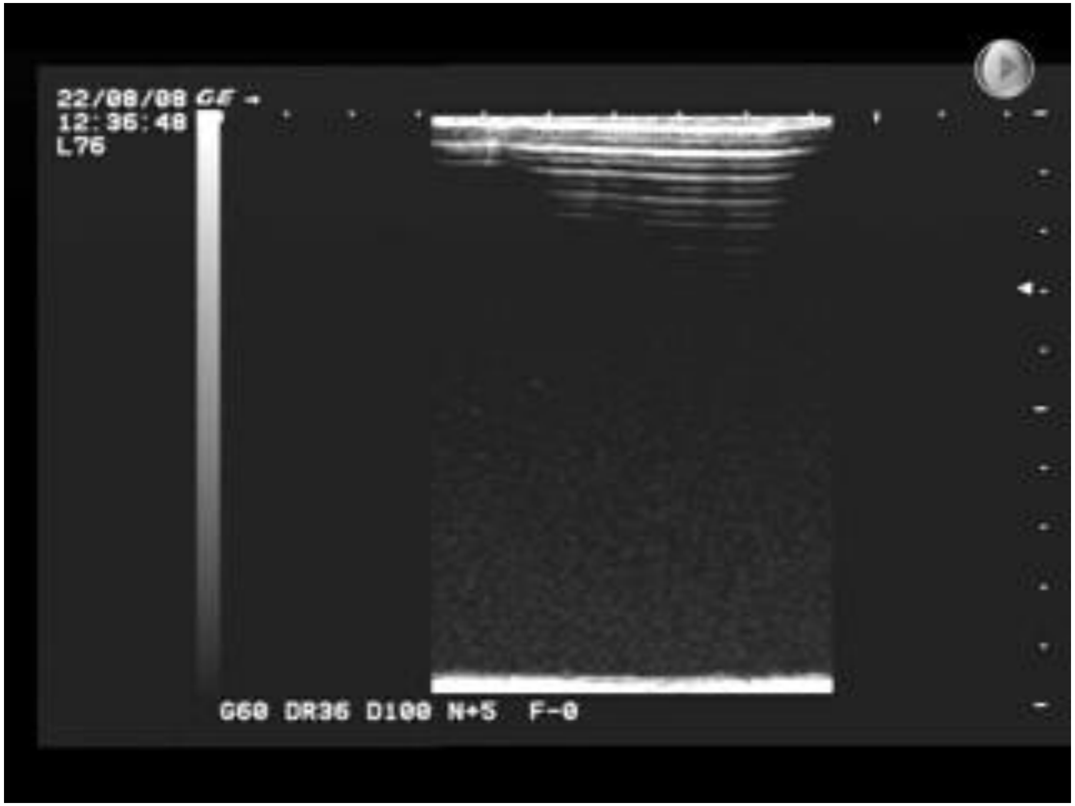


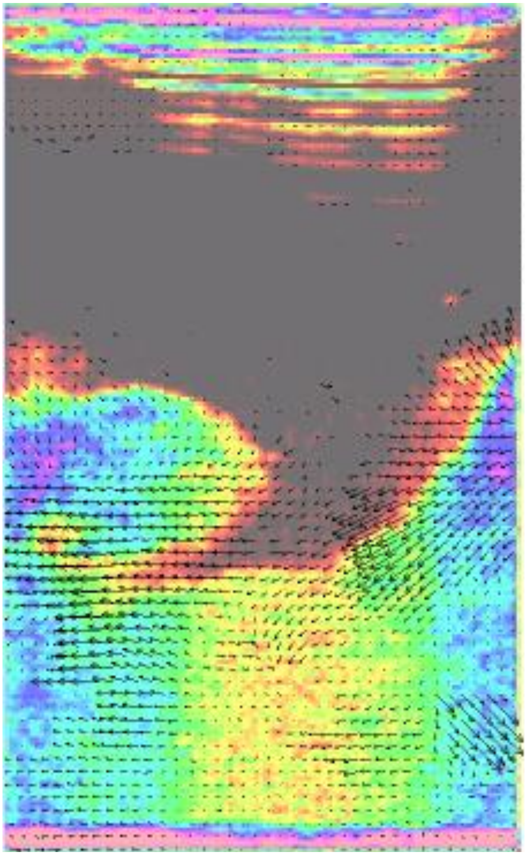
Turbidity current – laboratory experiment

Unstable stratification - Kelvin-Helmholtz instabilities

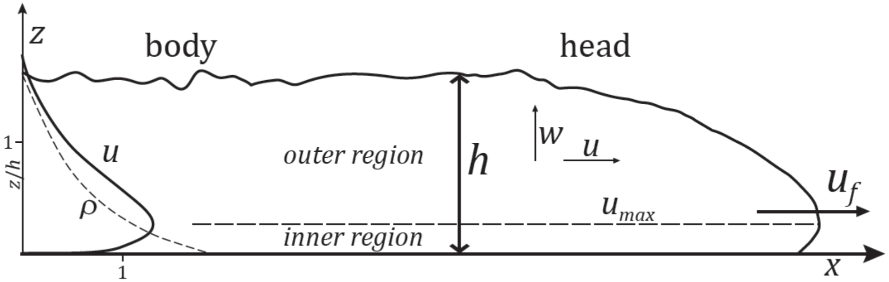
Laboratory turbidity current; crushed coal in water, imaged by medical ultrasound

vector map generated by particle image velocimetry





Carolina Boffo, UFRGS



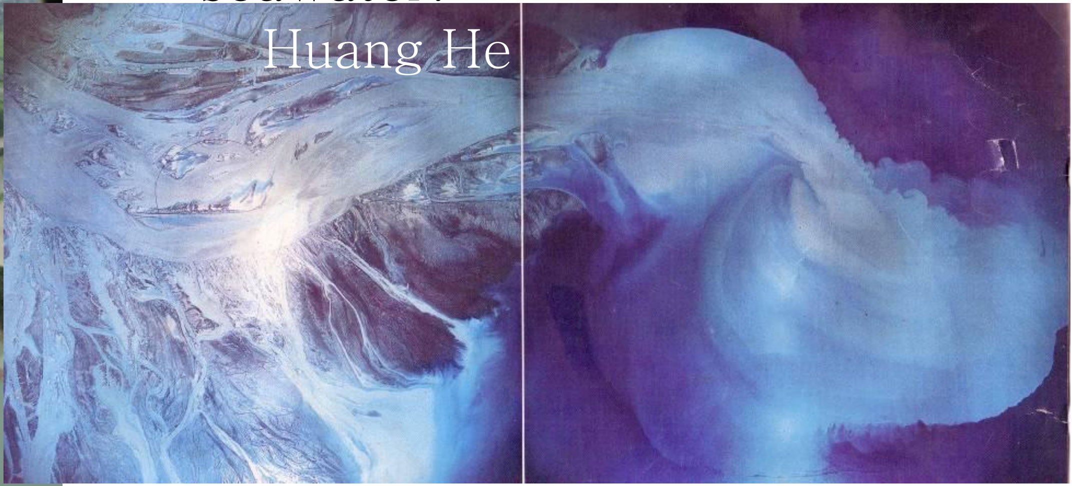
$$Ri_g = \frac{\left(g\,\dfrac{\partial\rho/\partial z}{\rho_a}\right)}{\left(\partial u/\partial z\right)^2}$$

Generation of turbidity currents by river floods

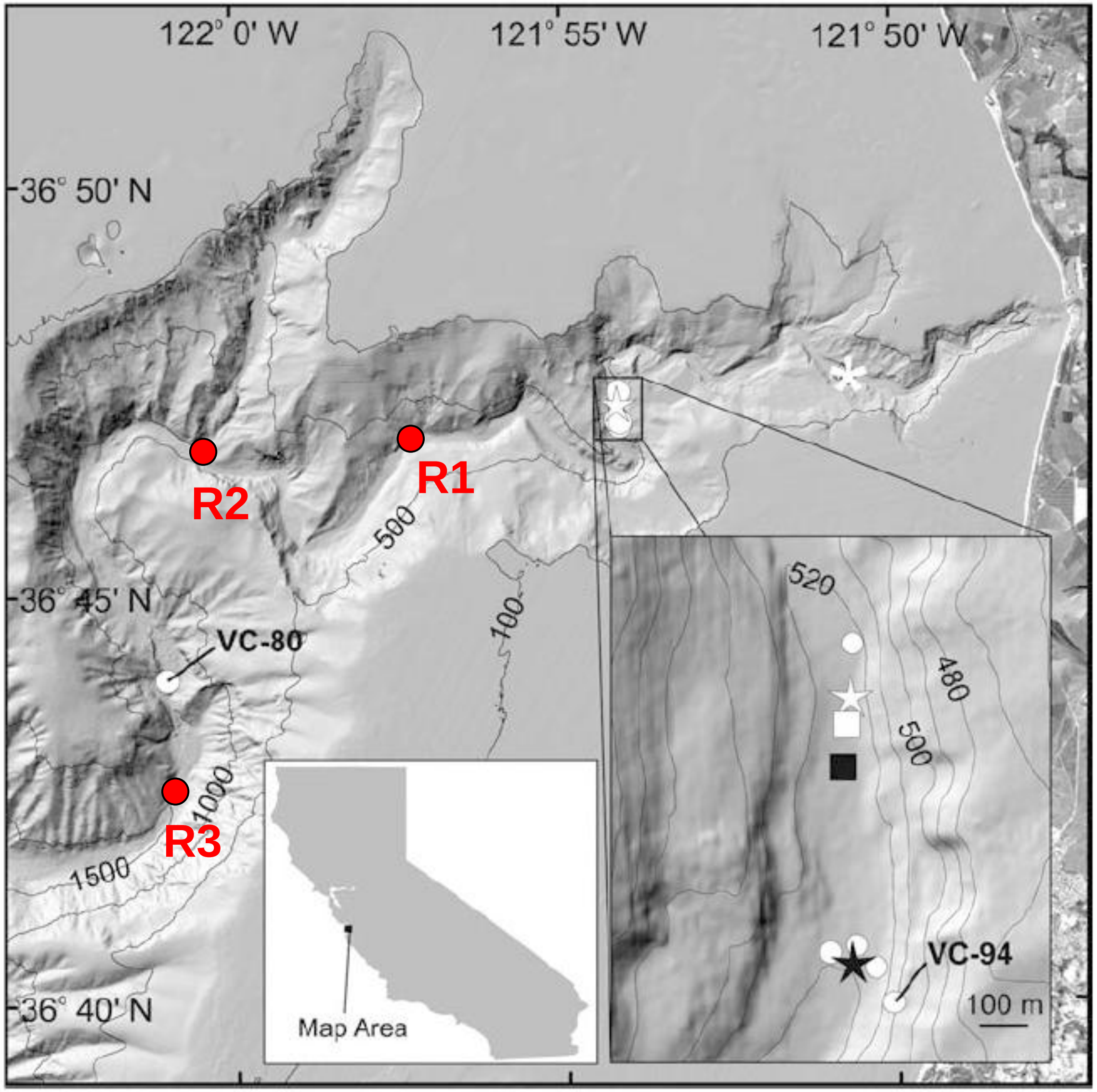
Sediment-laden rivers easily plunges into a freshwater lake

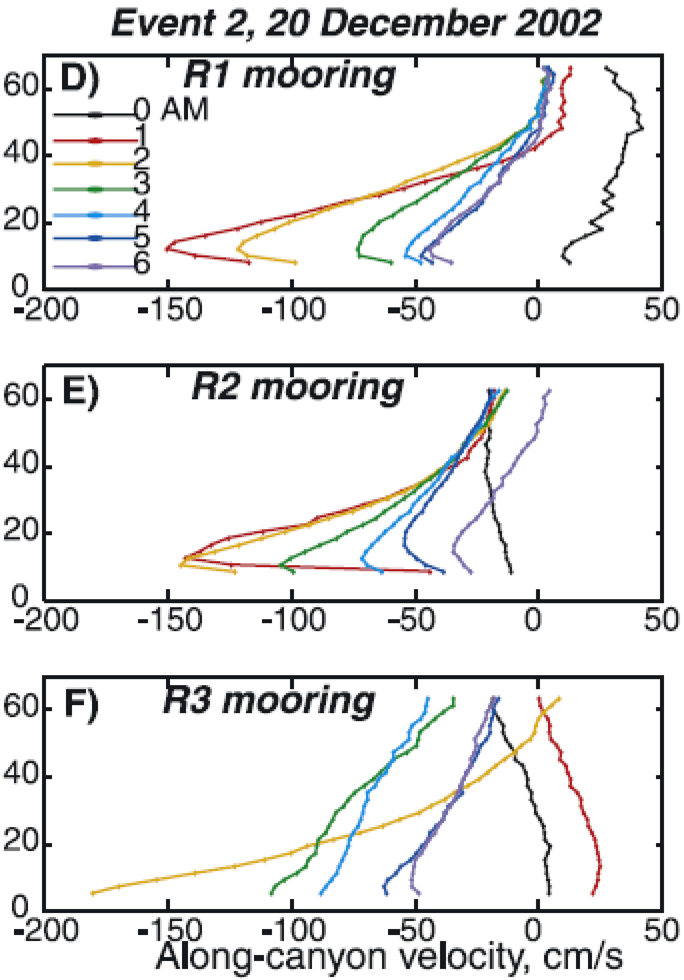

Reuss River, Switzerland

Rivers must be heavily charged with sediment in order to plunge directly into seawater.


Huang He

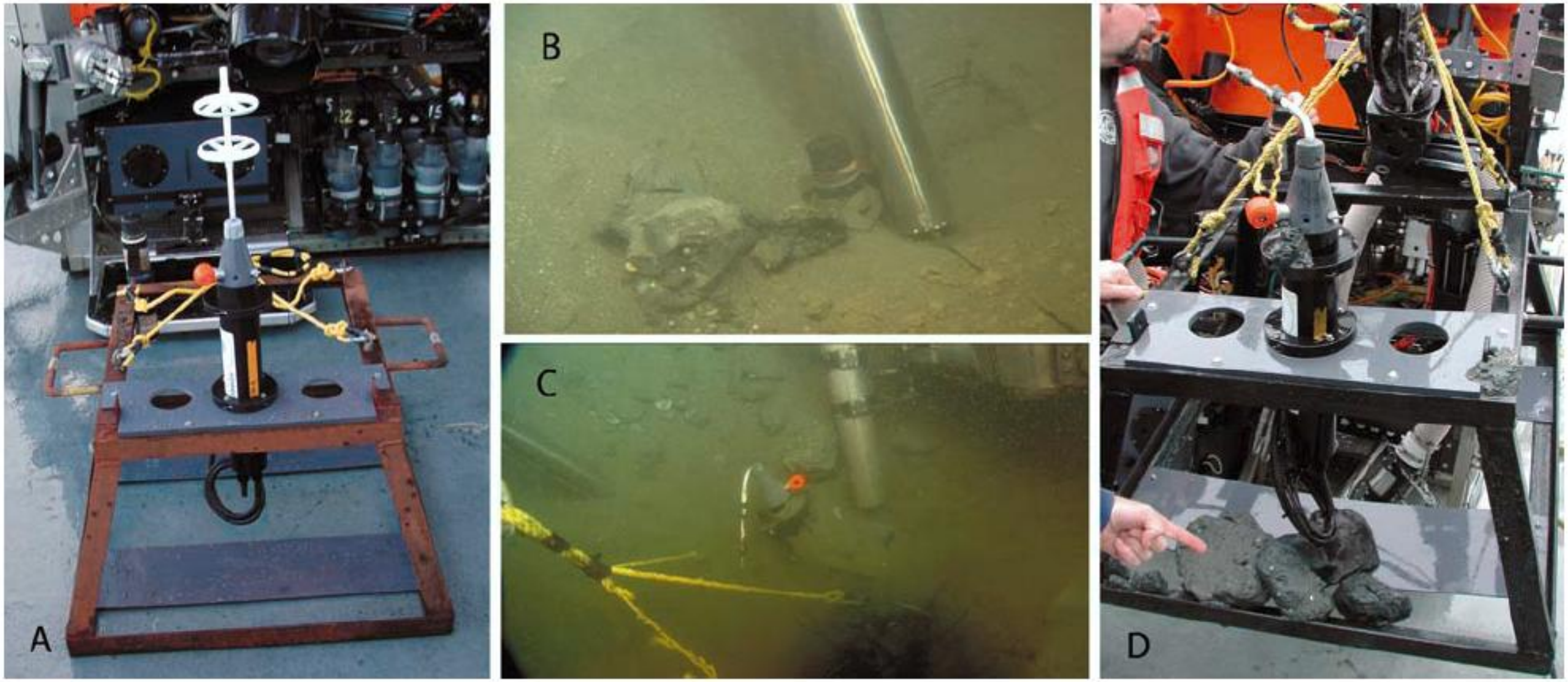
Generation of turbidity current by storm





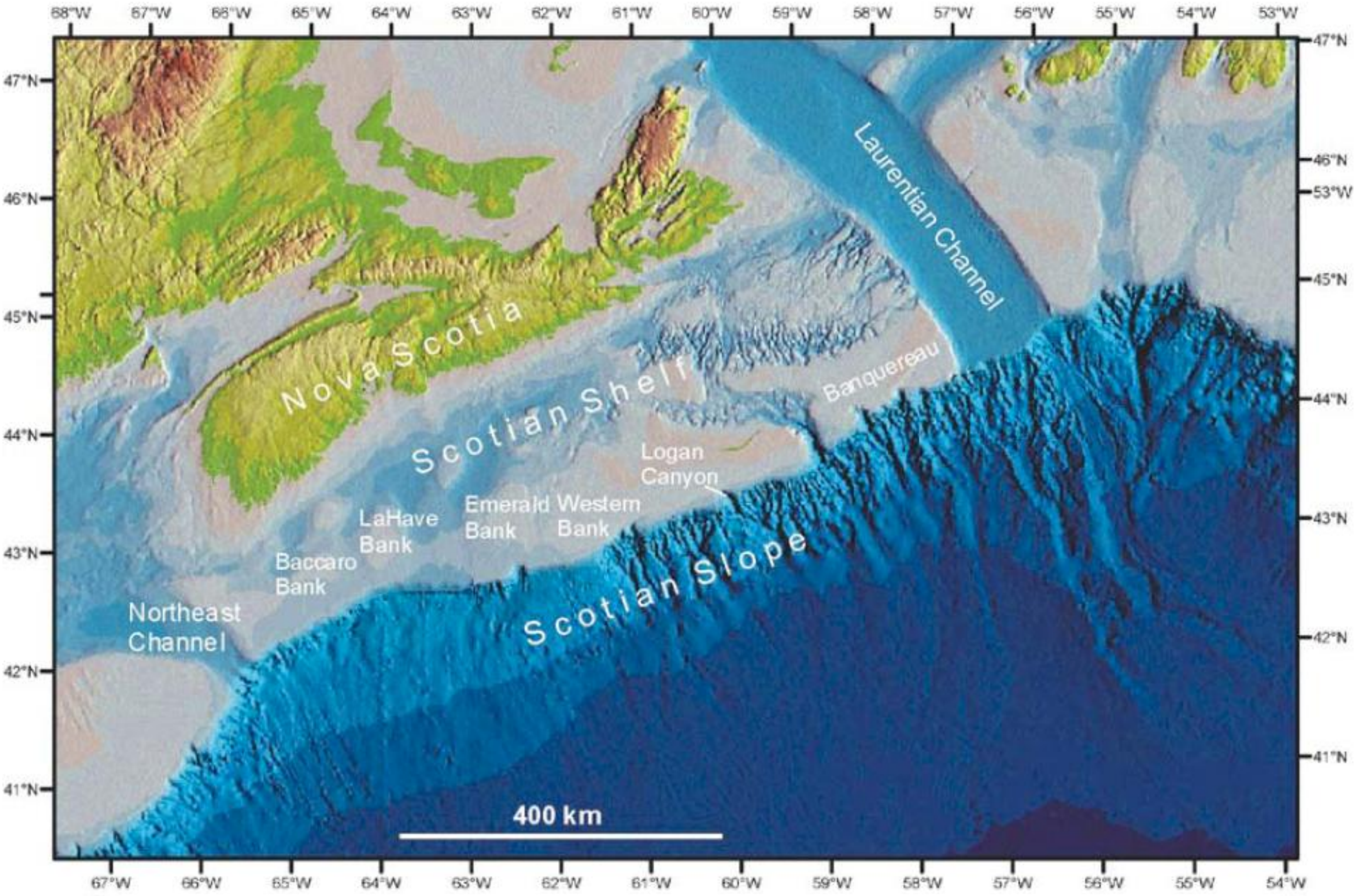
Xu et al., 2004

Generation of turbidity current by storm



Paull et al., 2003

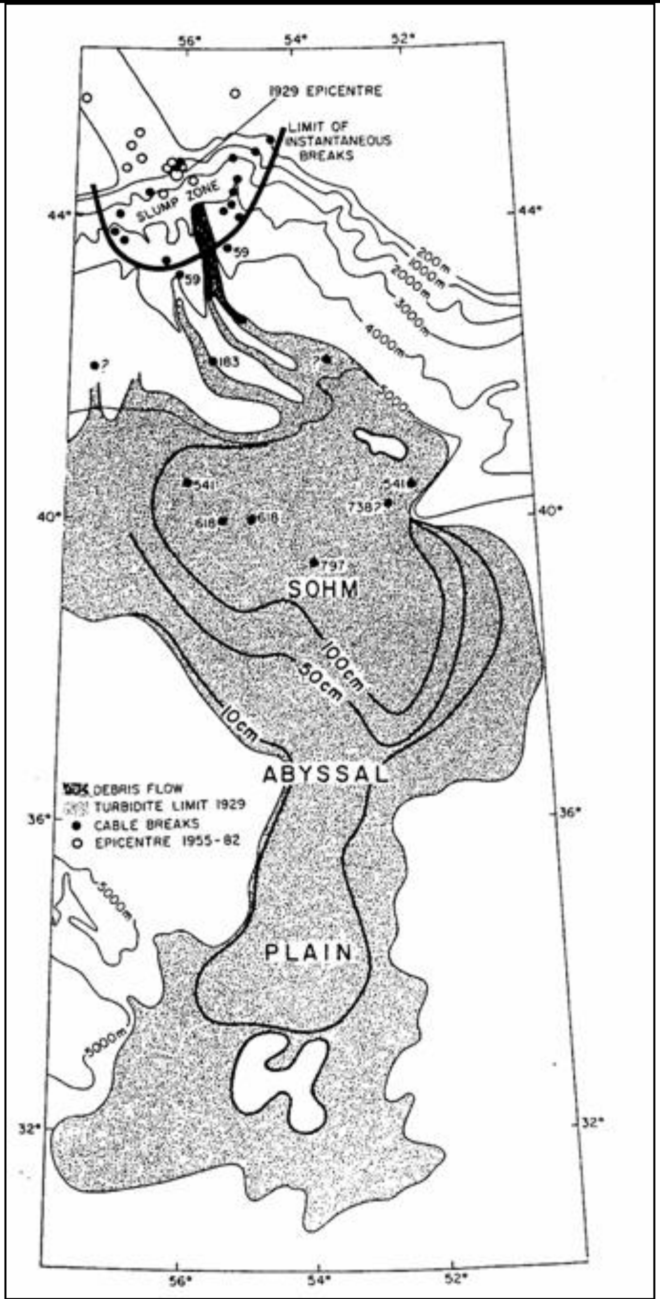
Generation of turbidity current by earthquake-triggered slope



Sea-bed morphology of the Scotian margin   Campbell et al., 2004

Generation of turbidity current by earthquake-triggered slope

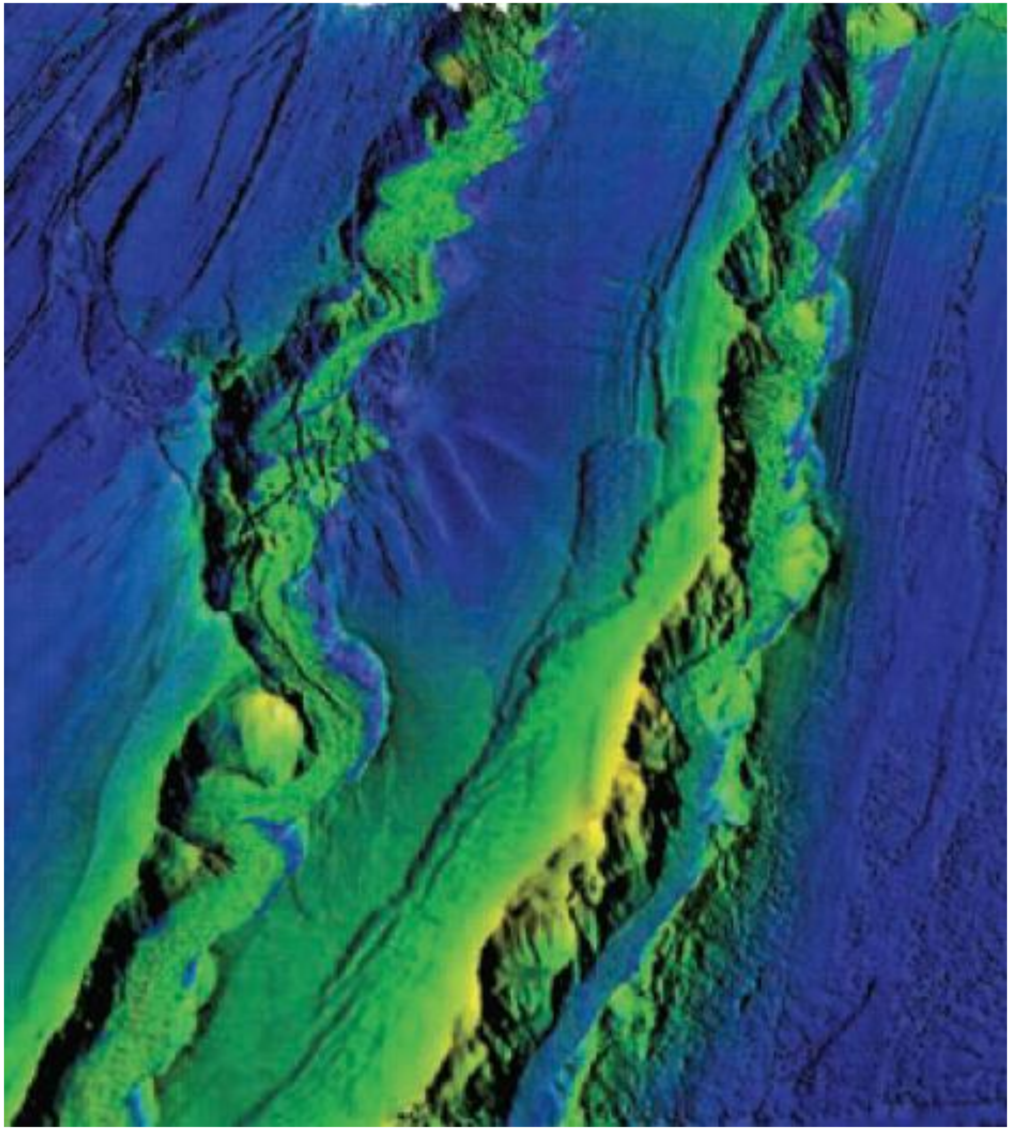
Grand Banks turbidite, 1929



Volume of deposit on basin floor about 180 km^3

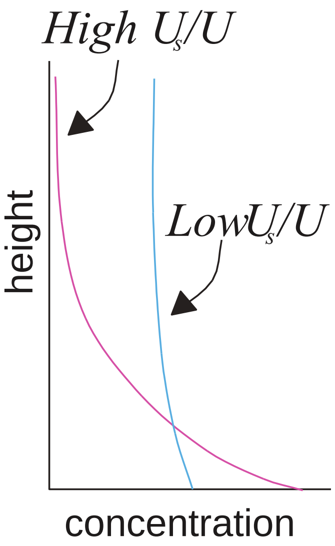
Piper et al., 1984

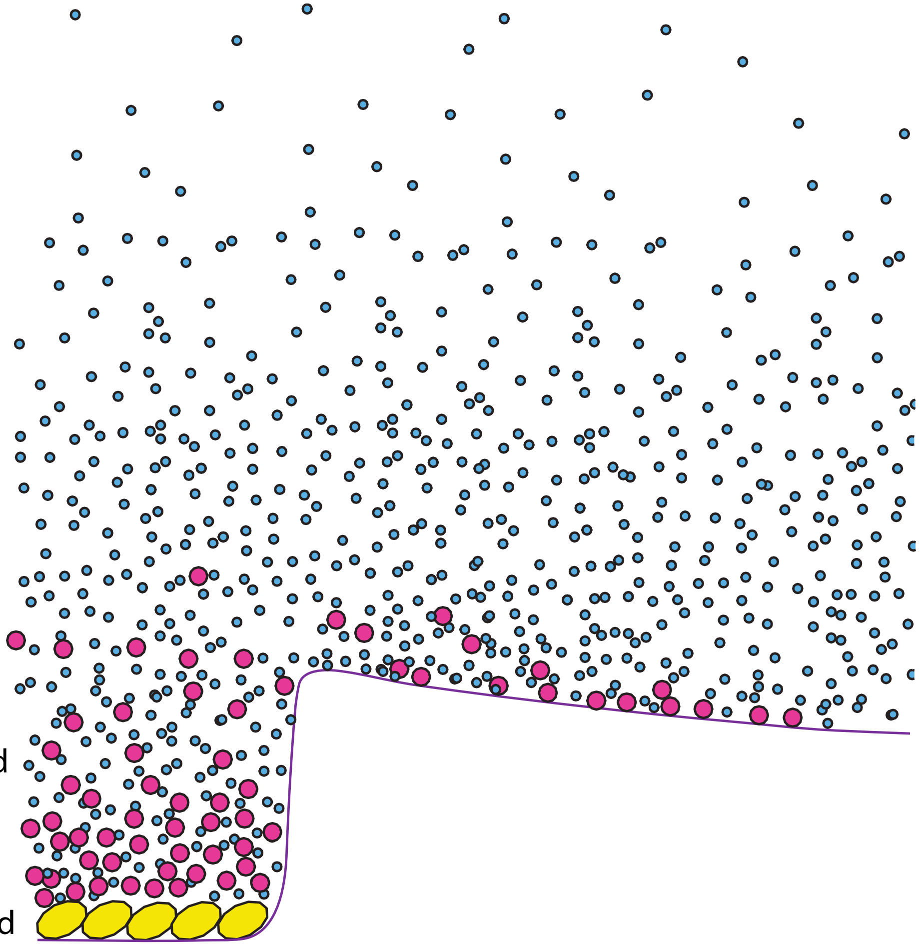
Formation of levees on deep sea channels



NE Gulf of Mexico. Sylvester et al., 2012

Overbank flow





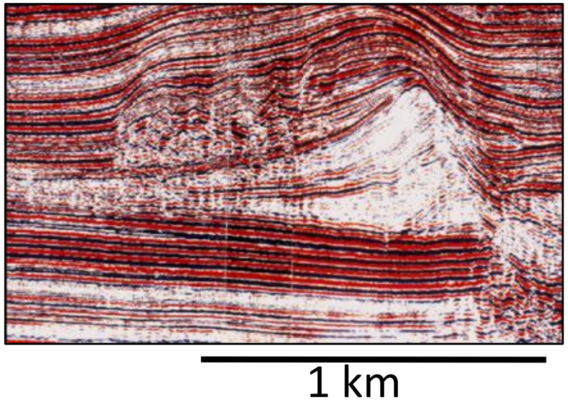
Finer-grained suspended load overbanks

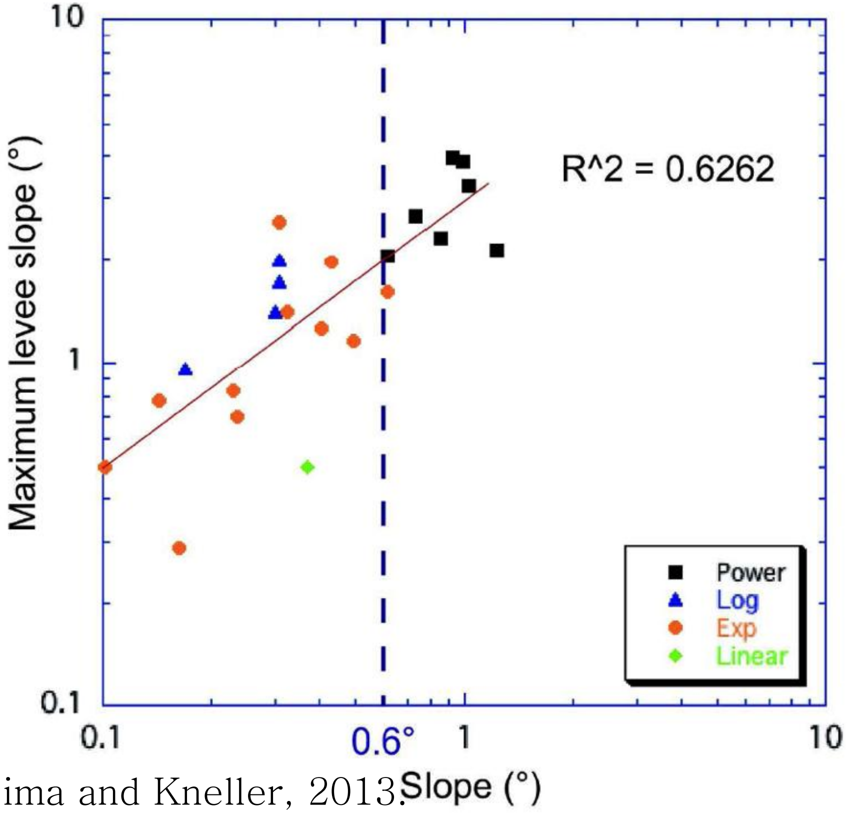
Coarse-grained suspended load confined to channel

Bedload

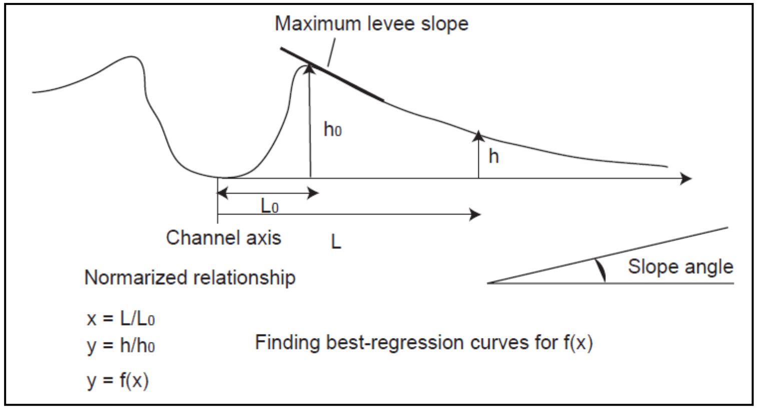
Overbank flow

Dependence of levee shape on slope gradient





Nakajima and Kneller, 2013



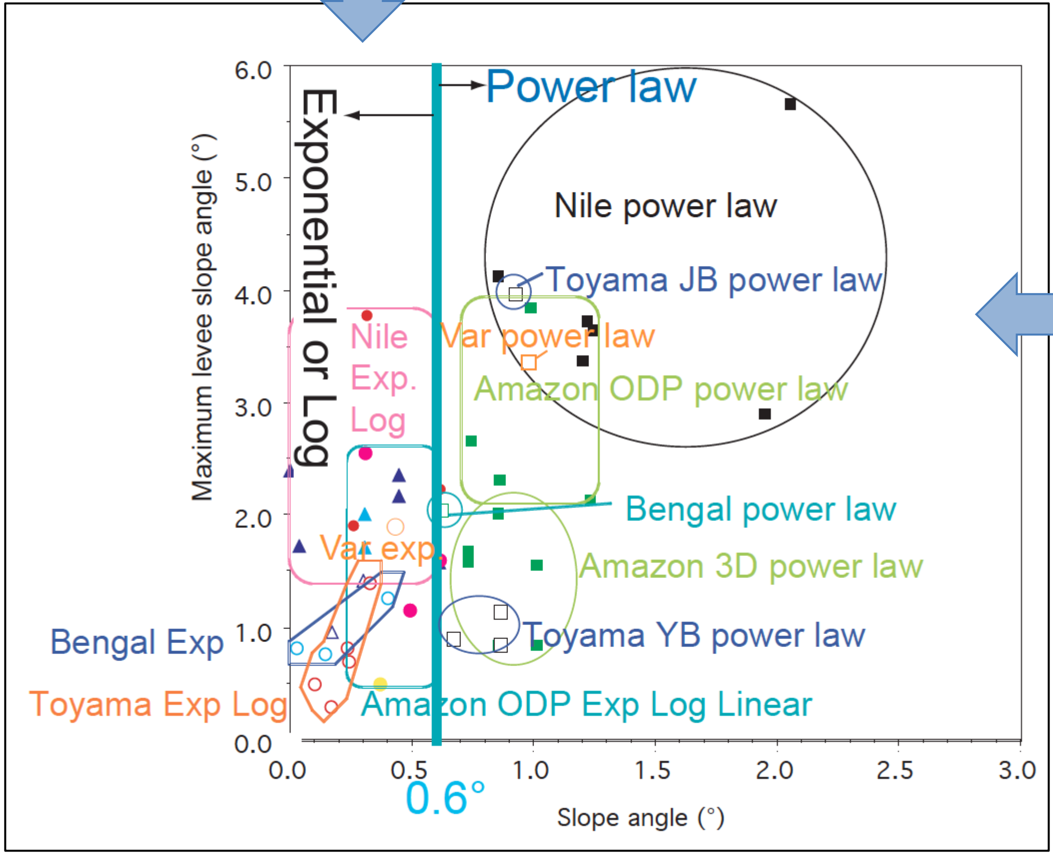
- Gradients of levee scale with regional slope
- Levee decay is power law on slopes >0.6°
- Commonly exponential on slopes <0.6°

2

$$f(x) = f_0 e^{-\left(u_s / u h_0 \right) x}$$

Low gradient,
exponential decay,
no entrainment,
No K-H instabilities

Slope controls presence or absence of entrainment



1

$$f(\hat{x}) = f_0 \left(u h_0 / \hat{x} \right)^{\frac{-u_s + E_0}{E_0}}$$

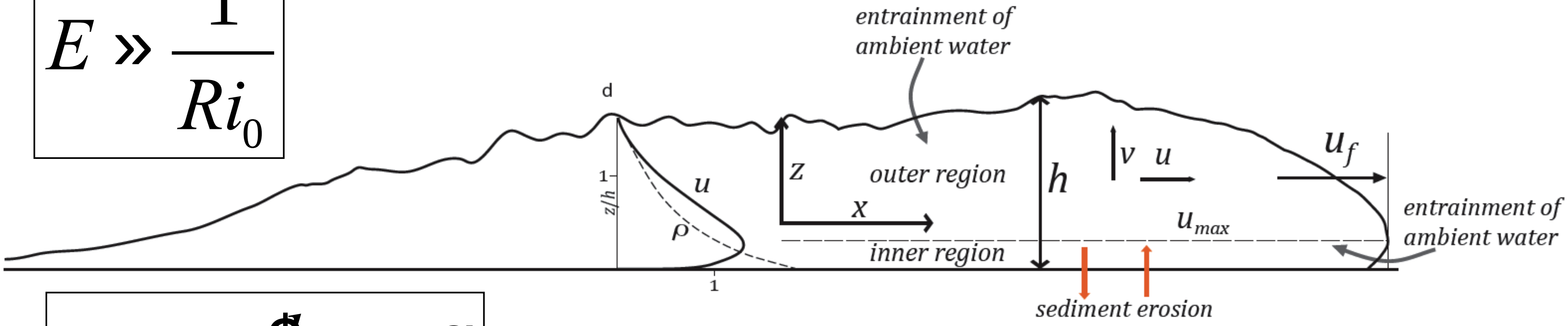
High gradient,
power law decay,
entrainment
via K-H instabilities

Birman et al., 2009

Nakajima & Kneller, 2013

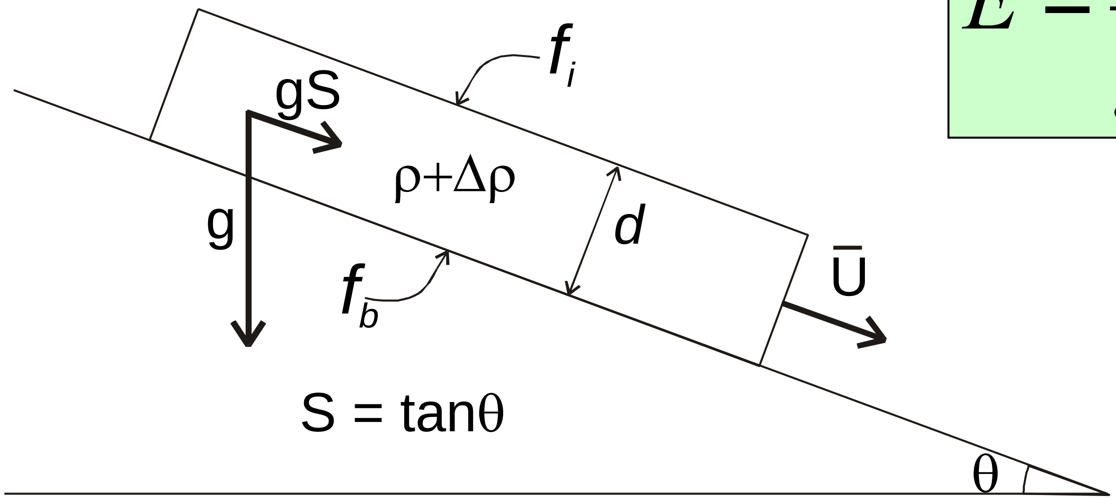
Gradient dependency of entrainment rate

$$E \gg \frac{1}{Ri_0}$$



$$Ri_0 = \frac{g\text{¢}h\cos q}{U^2}$$

$$E = \frac{U^2}{g\text{¢}h\cos q}$$

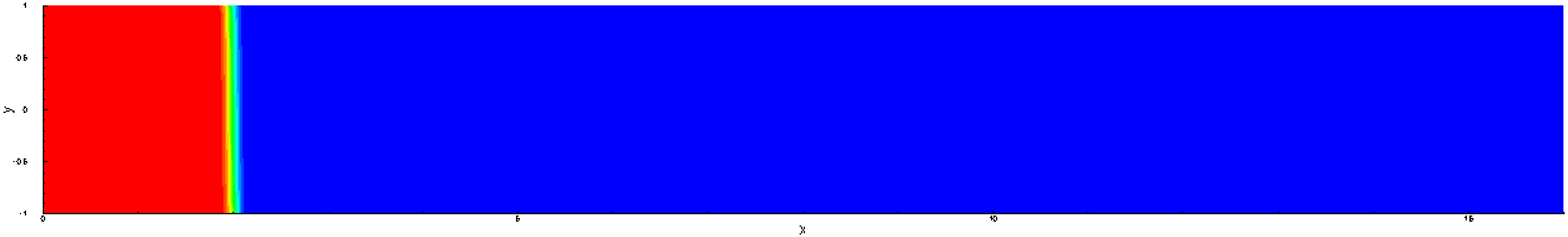


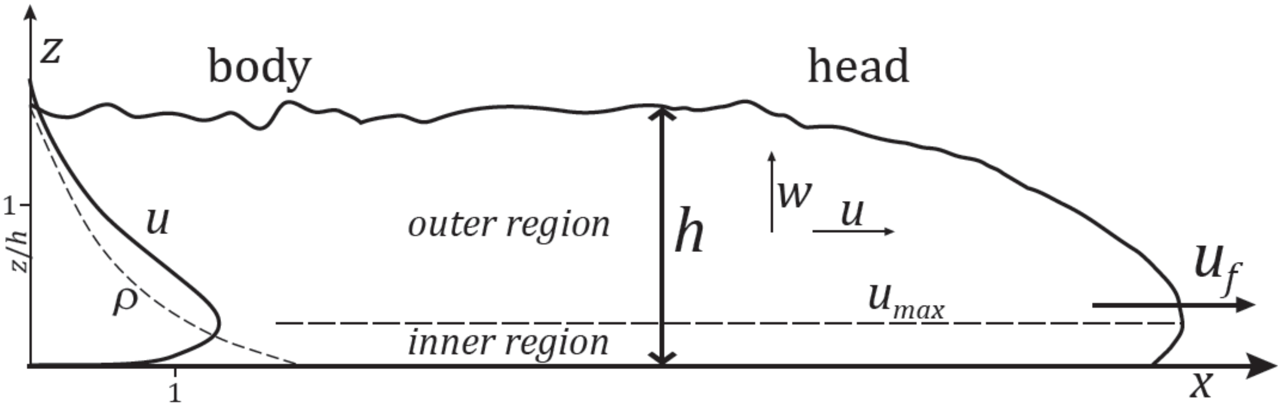
Kelvin-Helmholtz instabilities in supercritical flow

Kelvin-Helmholtz instabilities generated at upper flow boundary when $Ri_g < 0.25$

$$Ri_g = \frac{N^2}{\left(\partial u / \partial z\right)^2} = \frac{\left(g \dfrac{\partial \rho / \partial z}{\rho_a} \right)}{\left(\partial u / \partial z\right)^2}$$

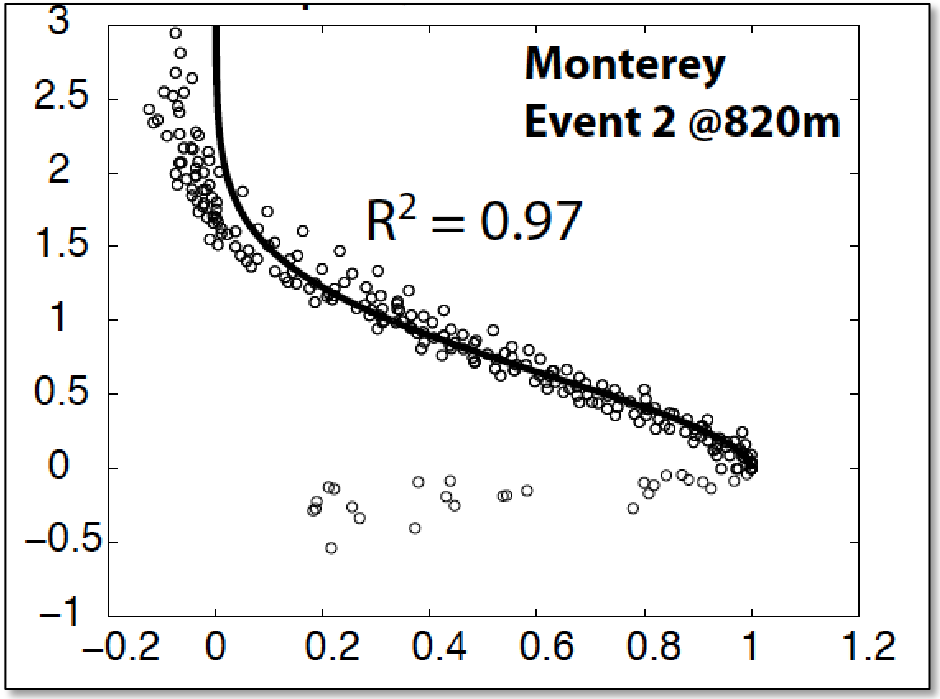
Large eddy simulation of turbidity current,
Brendon Hall, UCSB



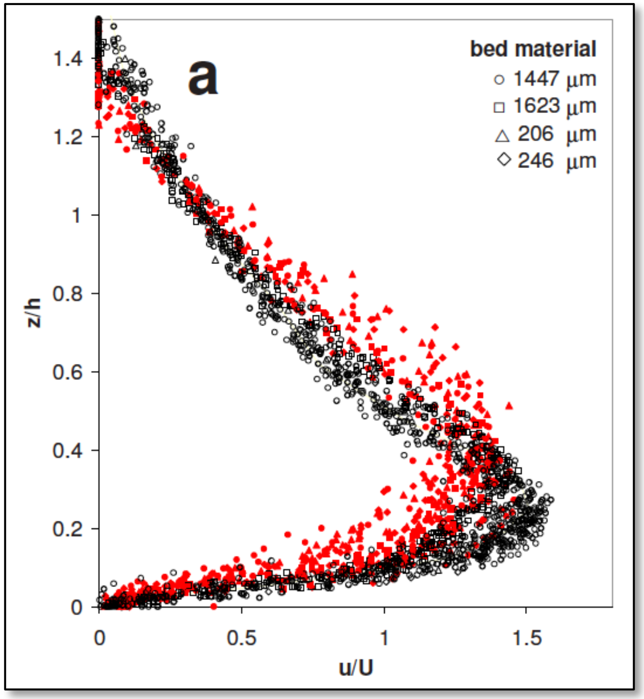


Meiburg & Kneller, 2010

The classic view – velocity profiles



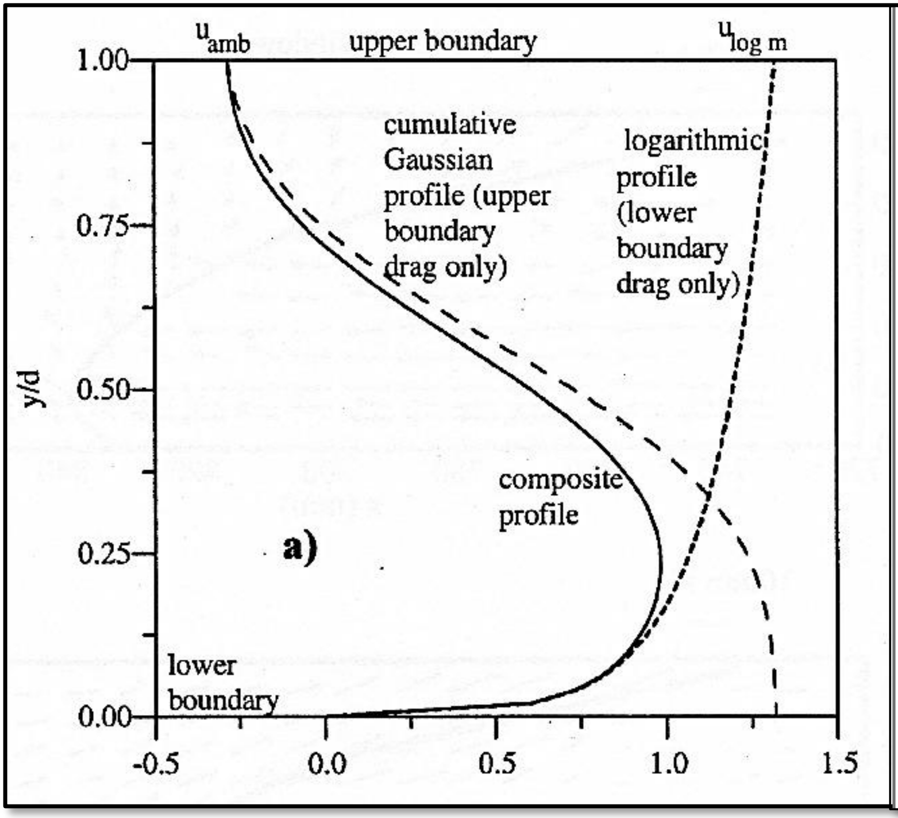
Natural current
Xu, 2010



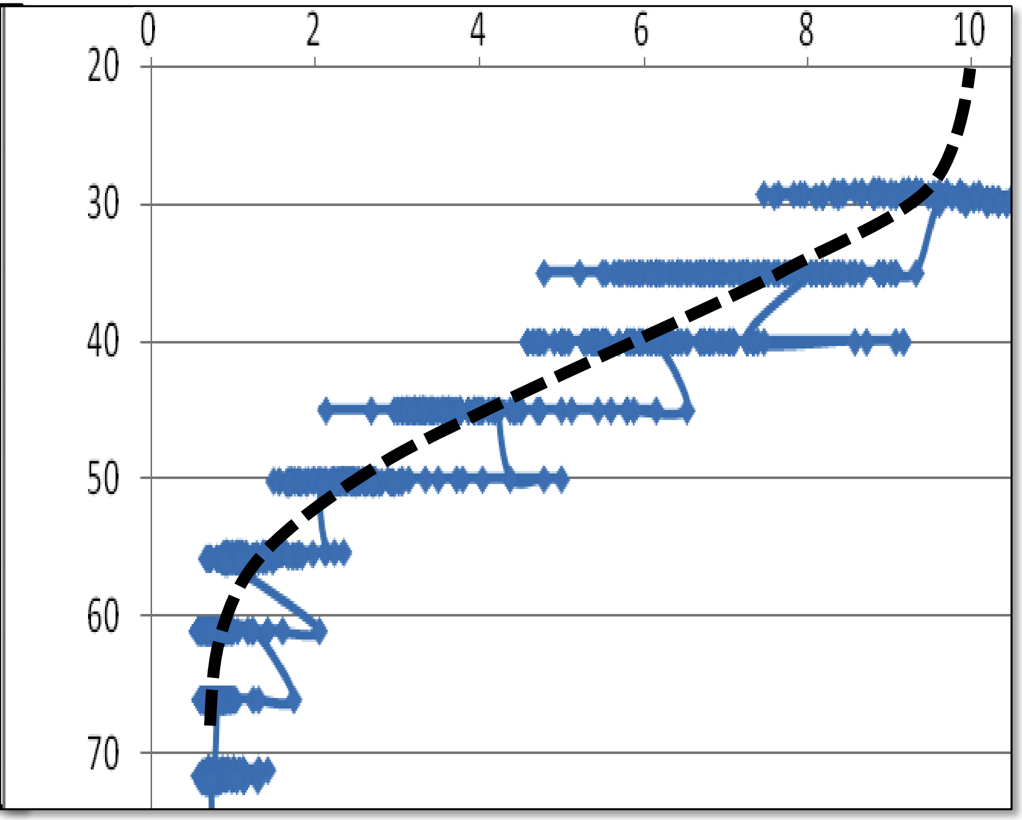
Experiments on super-critical flow
Sequeiros et al. 2010

Most of the drag is at the top, so
u_{max} is near the bottom

Origin of the velocity profile



Kneller et al., 1999

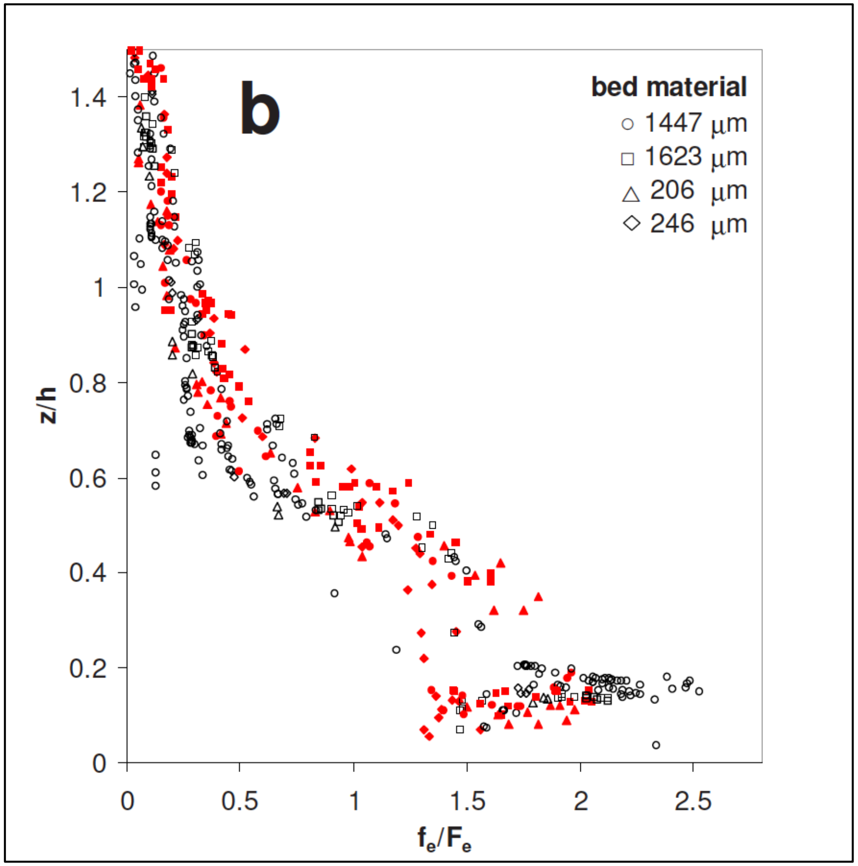


Buoyant plume velocity profile
Kneller & Manica, unpublished

Velocity profile can be treated as sum of logarithmic boundary layer profile, and symmetrical shear layer profile that extends to the bed where there is high turbulent drag

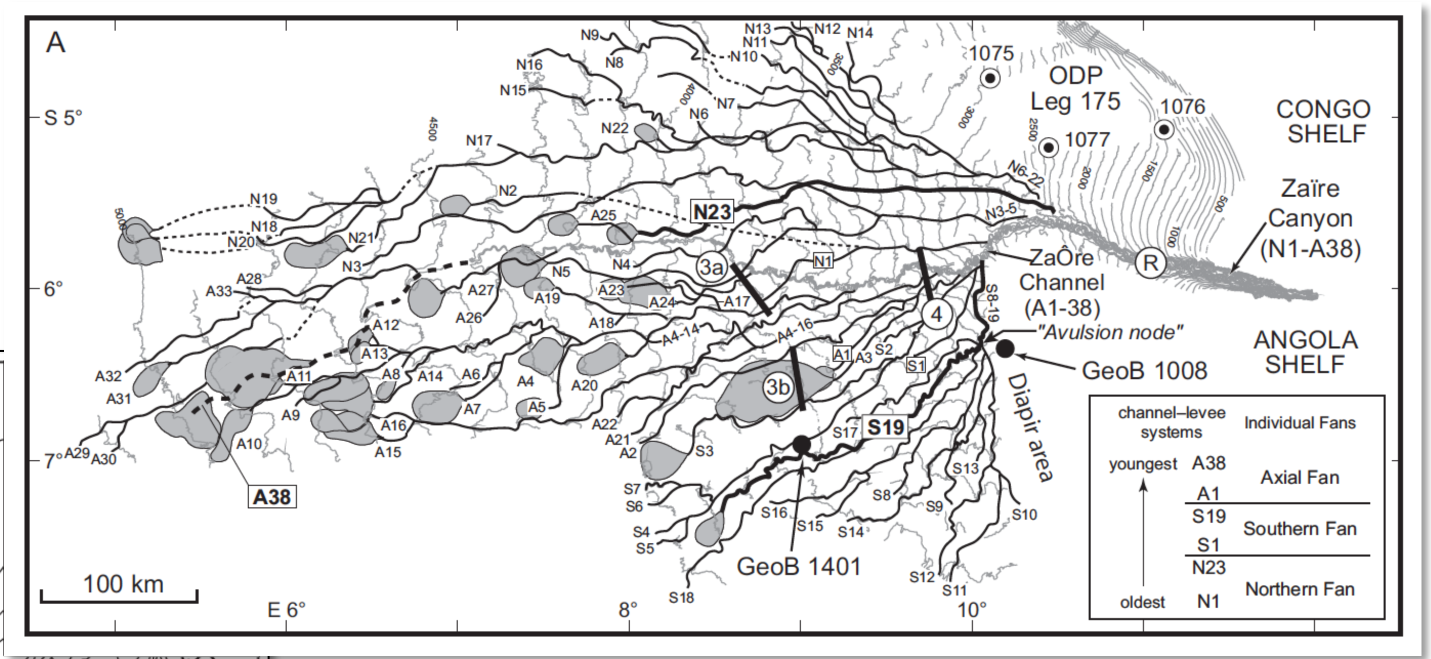
The classic view – density profile

Strongly density stratified

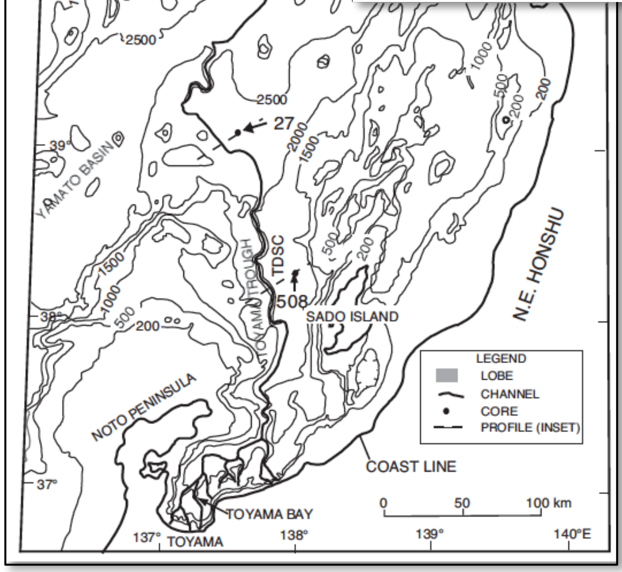


Experiments on super-critical flows
Sequeiros et al. 2010

The nature of the problem



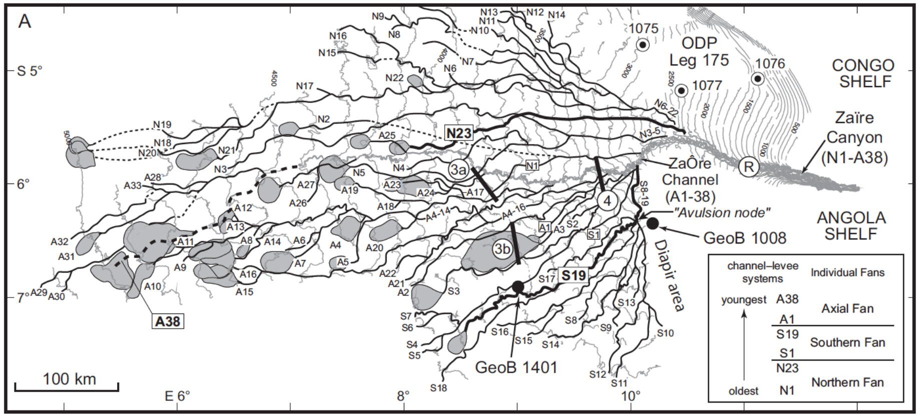
Congo fan. Marsset et al., 2009



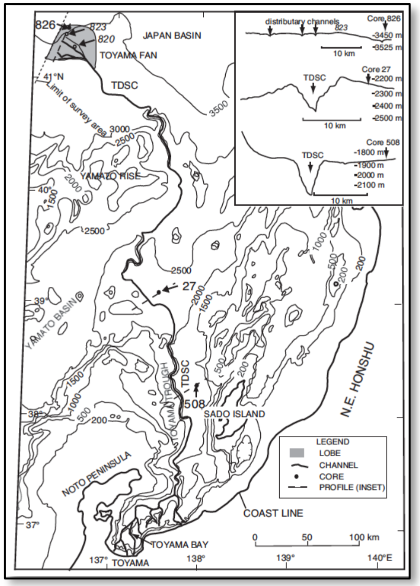
Toyama channel. Nakajima, 2009

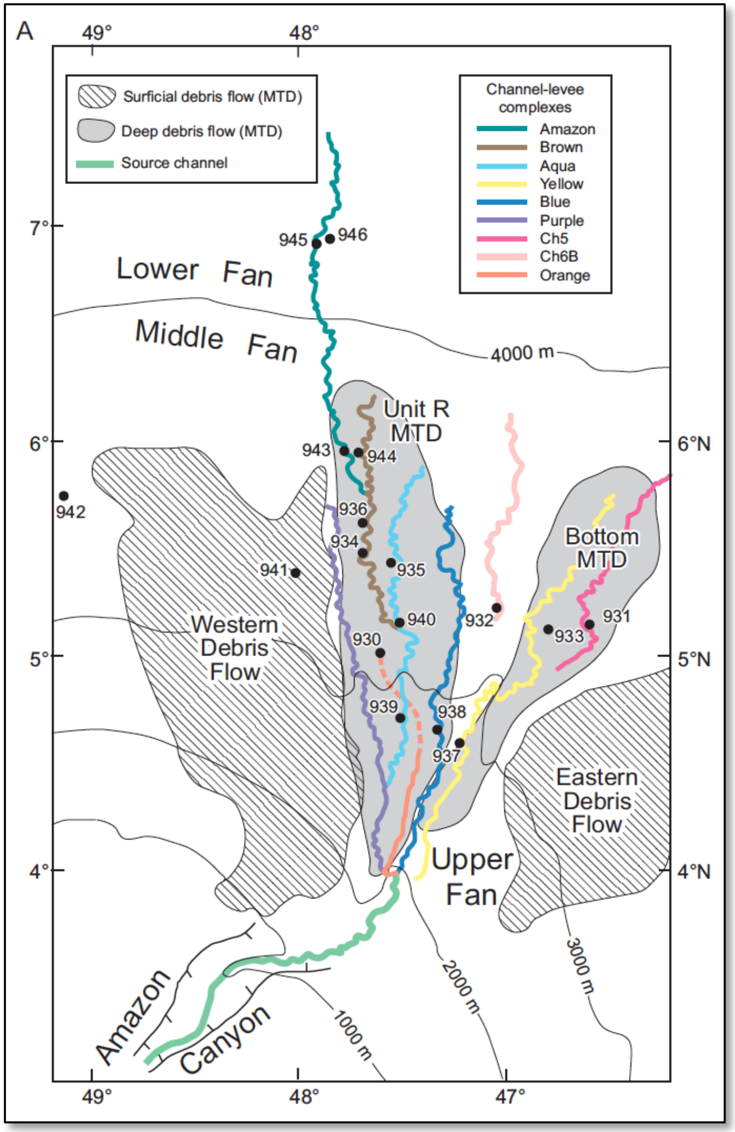
Turbidity currents apparently carry sediment in suspension through channels over very low gradients for 500 km…

The nature of the problem



…1000 km…



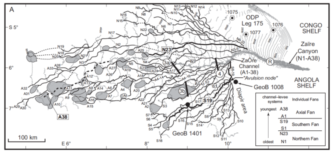


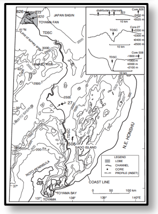
Amazon fan. Maslin, 2009

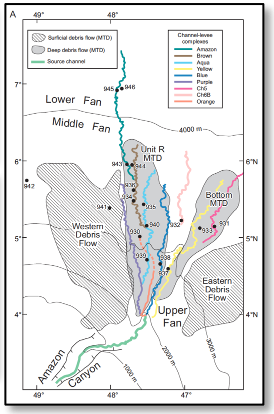
The nature of the problem

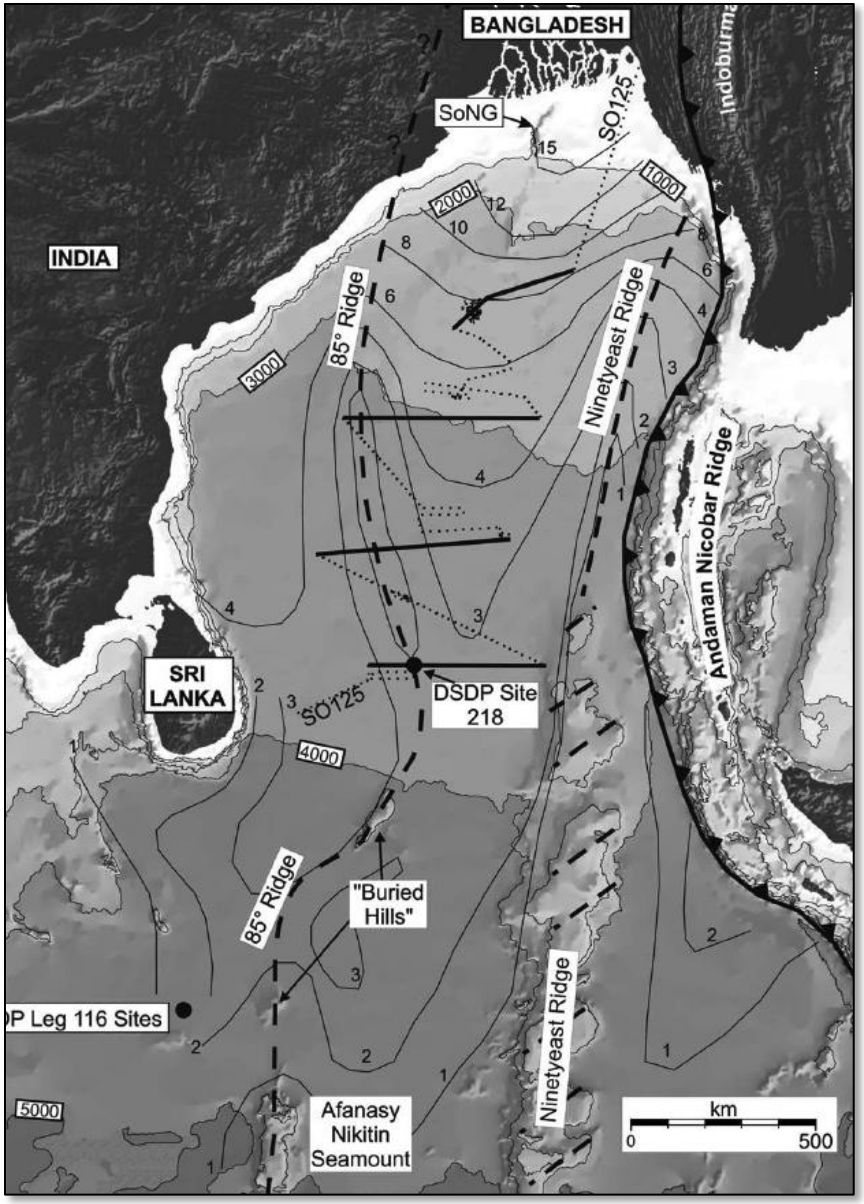
…even 3000 km

How?







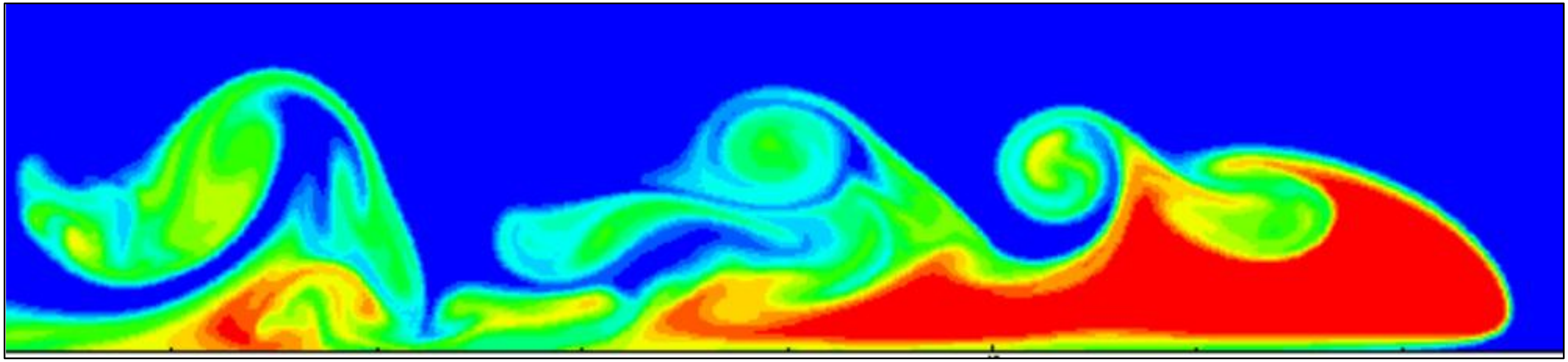


Bengal fan. Schwenk & Spieß, 2009

The nature of the problem

	Congo	**Amazon**	**Bengal**
Gradient of distal channel reaches	0.13°	0.11°	0.05°
Grain-size of lobe sediments (u_s is proxy for min. shear velocity u_*)	Medium sand	Very fine sand	Silt
Approximate height of distal levees (proxy for flow height)	100m	50m	30m
Minimum sediment conc. by volume	≥ 0.1%	≥ 0.01%	≥ 0.003%
Density difference $\Delta\rho$	≥ 1600 g/m^3	≥ 160 g/m^3	≥ 50 g/m^3

$$u_* = \sqrt{g\frac{\Delta\rho}{\rho}h\sin\alpha}$$

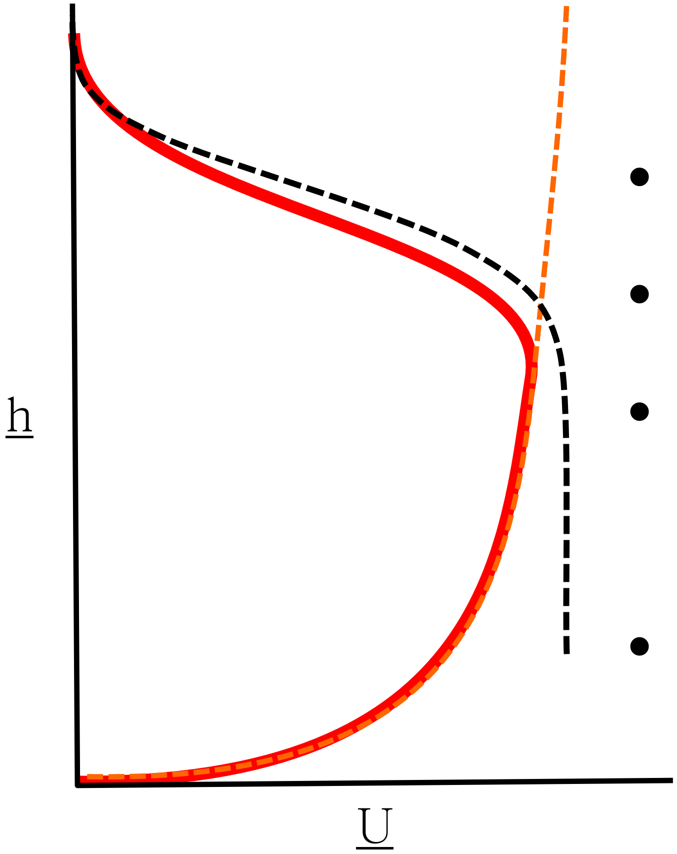


Large eddy simulation. Courtesy of Brendon Hall, UCSB

- Turbulent drag largely due to Kelvin-Helmholtz instabilities.
- Entrainment of ambient fluid mainly via KHIs
- KHIs form when the shear dominates over density gradient
- Stratification unstable when gradient Richardson number is <0.25

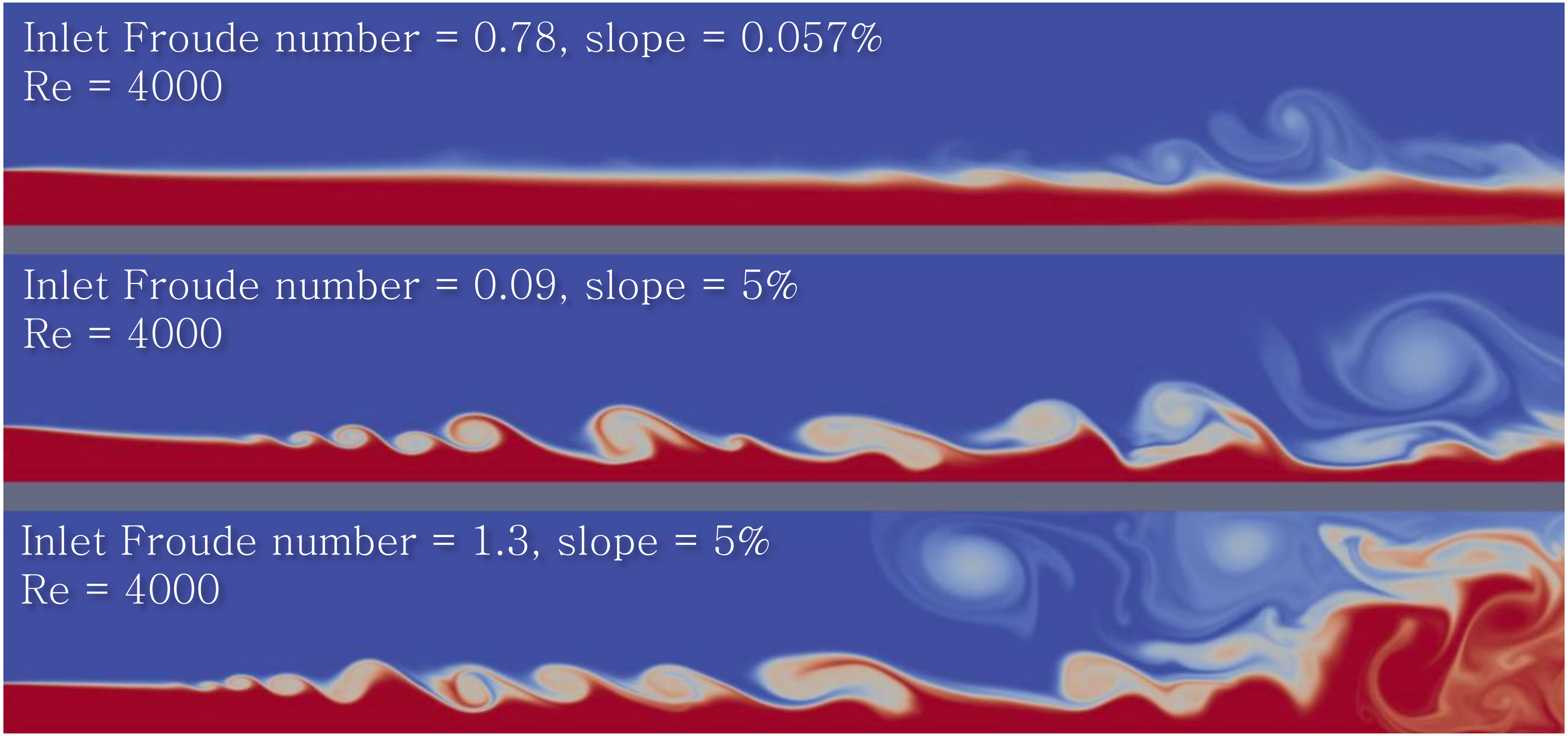
$$Ri_g = \frac{g\,\dfrac{\partial\rho/\partial z}{\rho_a}}{\partial u/\partial z}$$

Absence of Kelvin-Helmholtz instabilities…



- Substantially reduced drag
- No entrainment
- Velocity profile dominated by lower boundary
- Weak density stratification

2D Direct numerical simulation



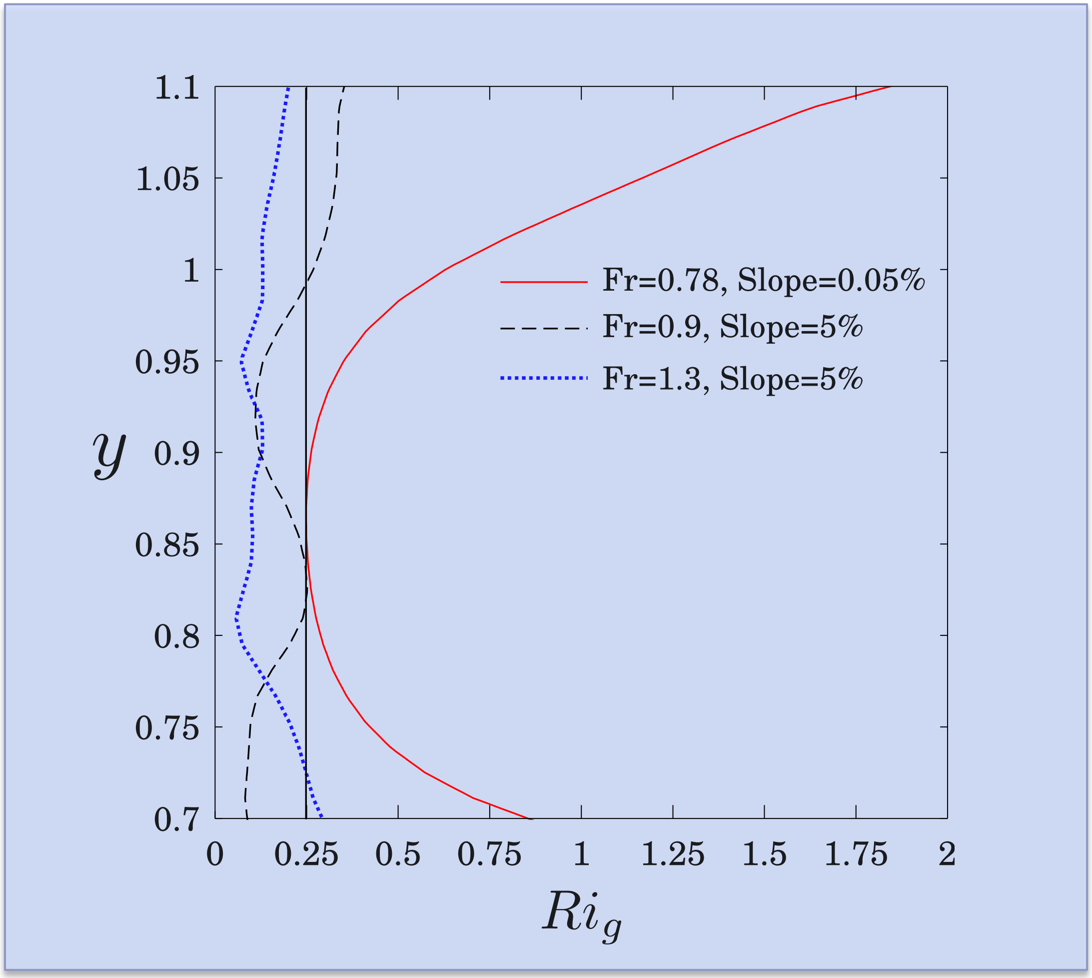
Inlet Froude number = 0.78, slope = 0.057%
Re = 4000

Inlet Froude number = 0.09, slope = 5%
Re = 4000

Inlet Froude number = 1.3, slope = 5%
Re = 4000

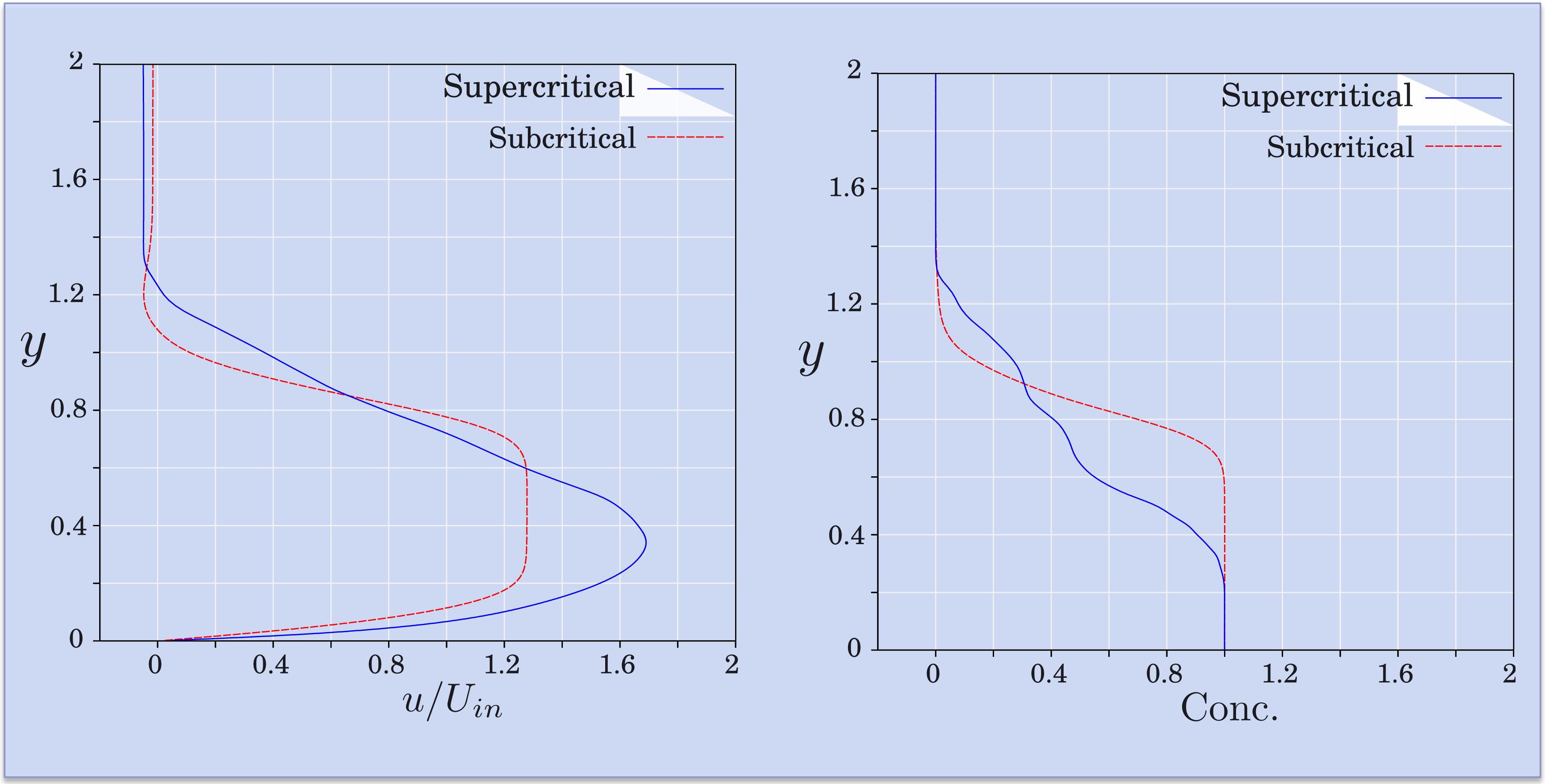
Full Navier-Stokes with Boussinesq approximation. Method in Nasr-Azadani and Meiburg, 201

2D Direct numerical simulation Gradient Richardson number



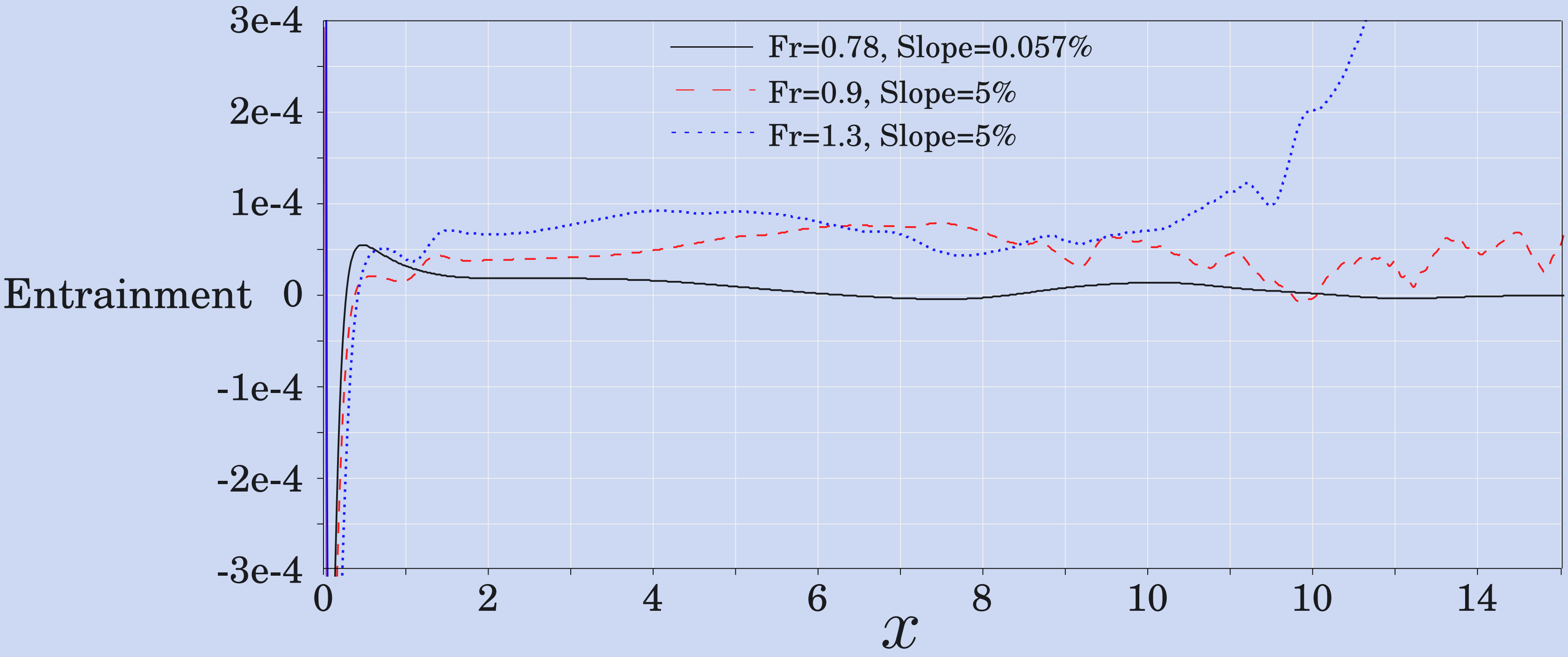
Flows on lower gradients (subcritical) have stable stratification

2D Direct numerical simulation, velocity and density profiles



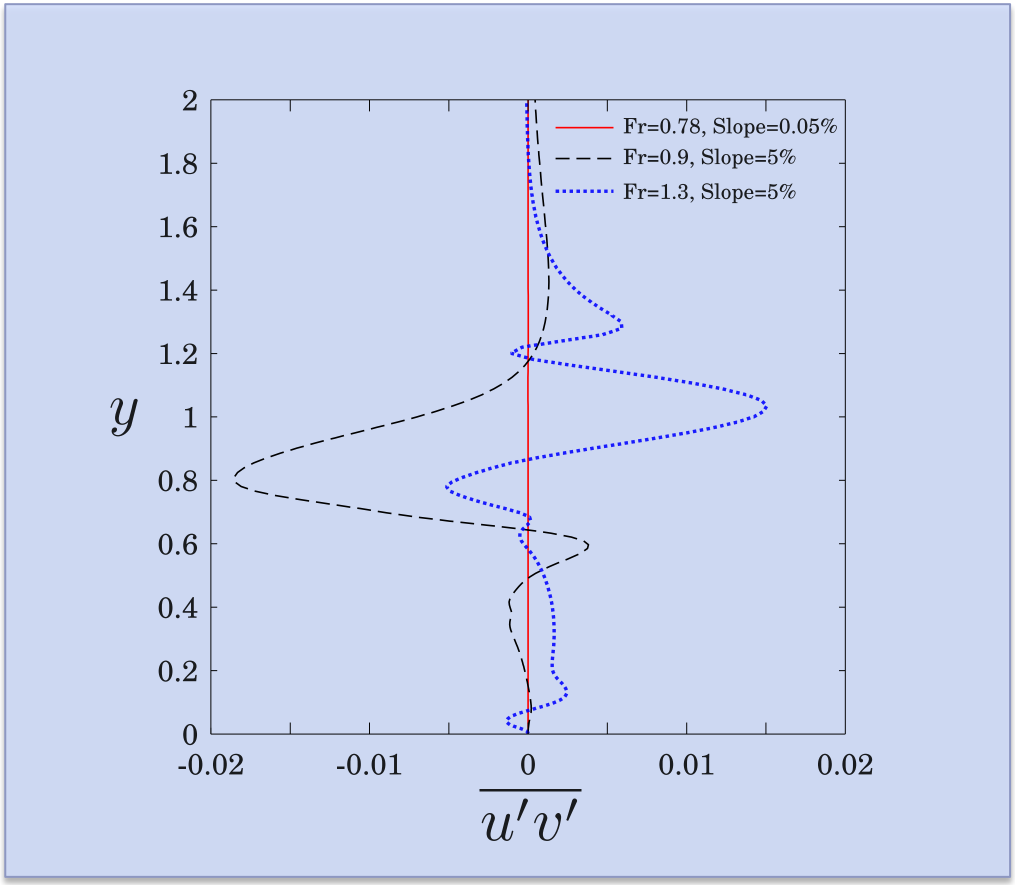
Flows on lower gradients have radically different velocity and density profiles

2D Direct numerical simulation, entrainment



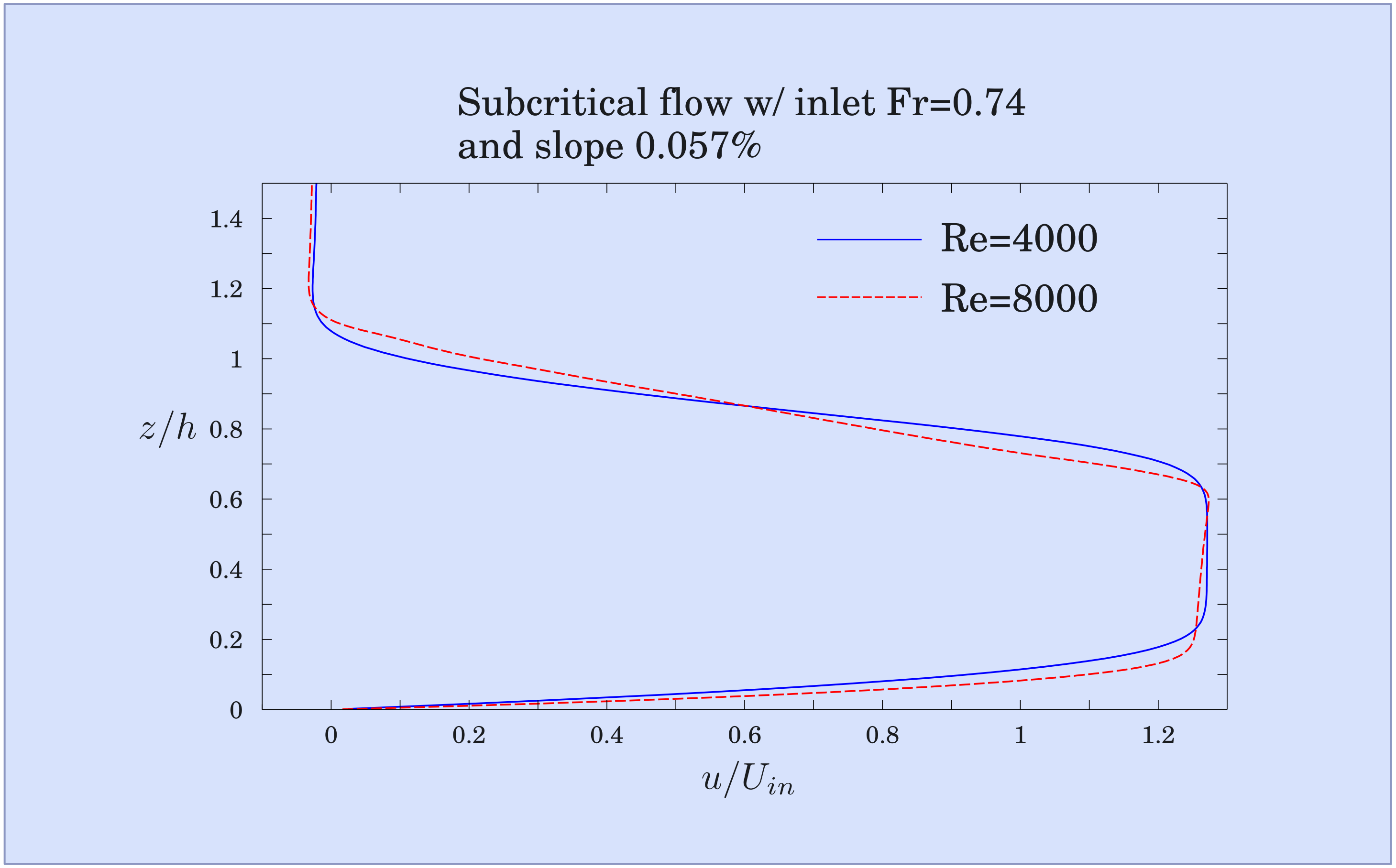
Flows on lower gradients show minimal entrainment

2D Direct numerical simulation, turbulent shear



Flows on lower gradients show minimal turbulent shear/drag

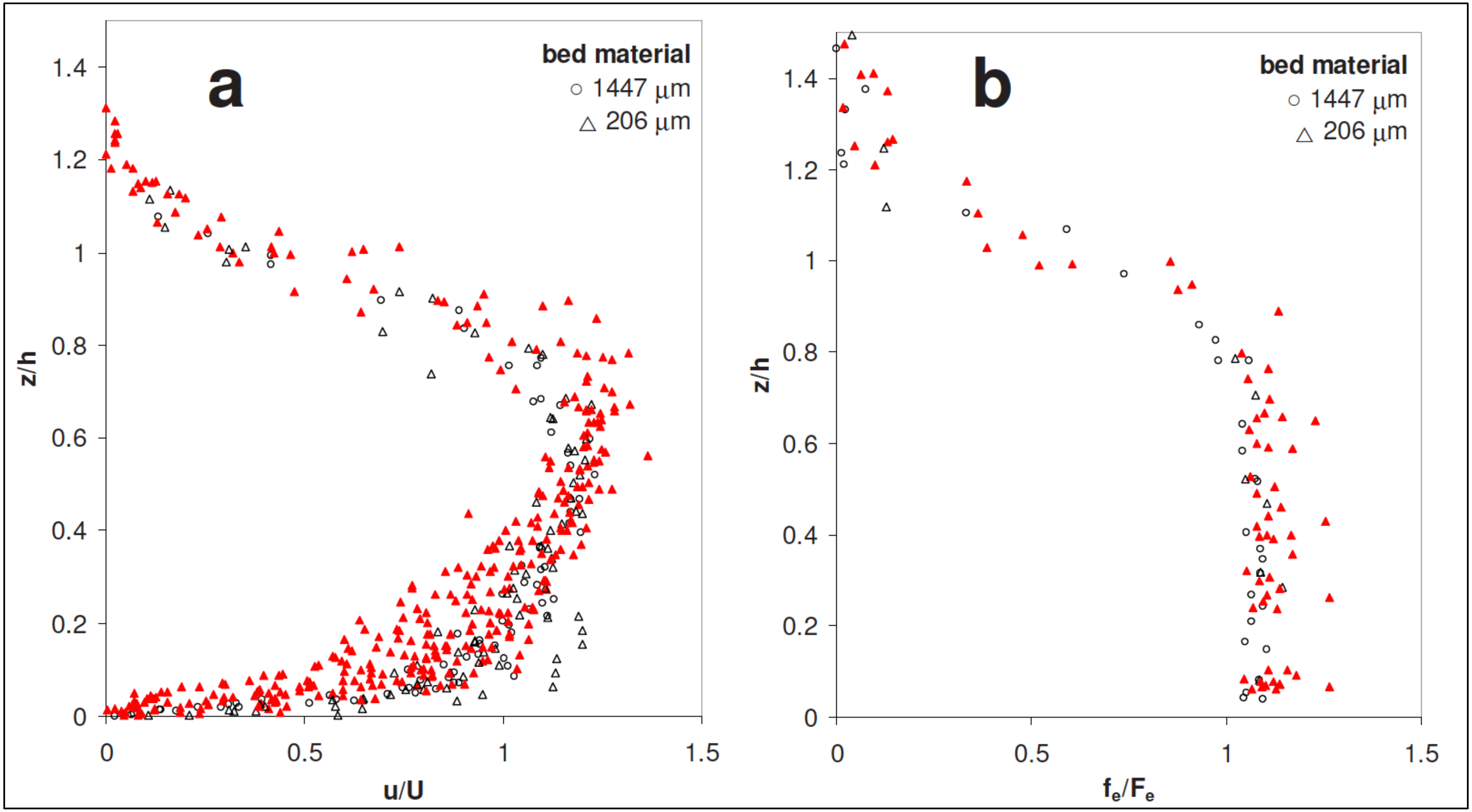
3D Direct numerical simulation, influence of Reynolds number



Velocity structure show slight Reynolds number sensitivity.

2D simulations capture most of 3D behaviour

Experimental flows show similar behaviour



Sub-critical flows. Sequeiros et al. 201

Conclusions

- Turbidity currents on very low gradients probably have stable stratification
- They do not exhibit Kelvin Helmholtz instabilities
- They experience little entrainment of ambient seawater
- They experience far lower drag than flows with Kelvin Helmholtz instabilities
- These last two probably account for their persistence over enormous distances

Thank you for listening

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