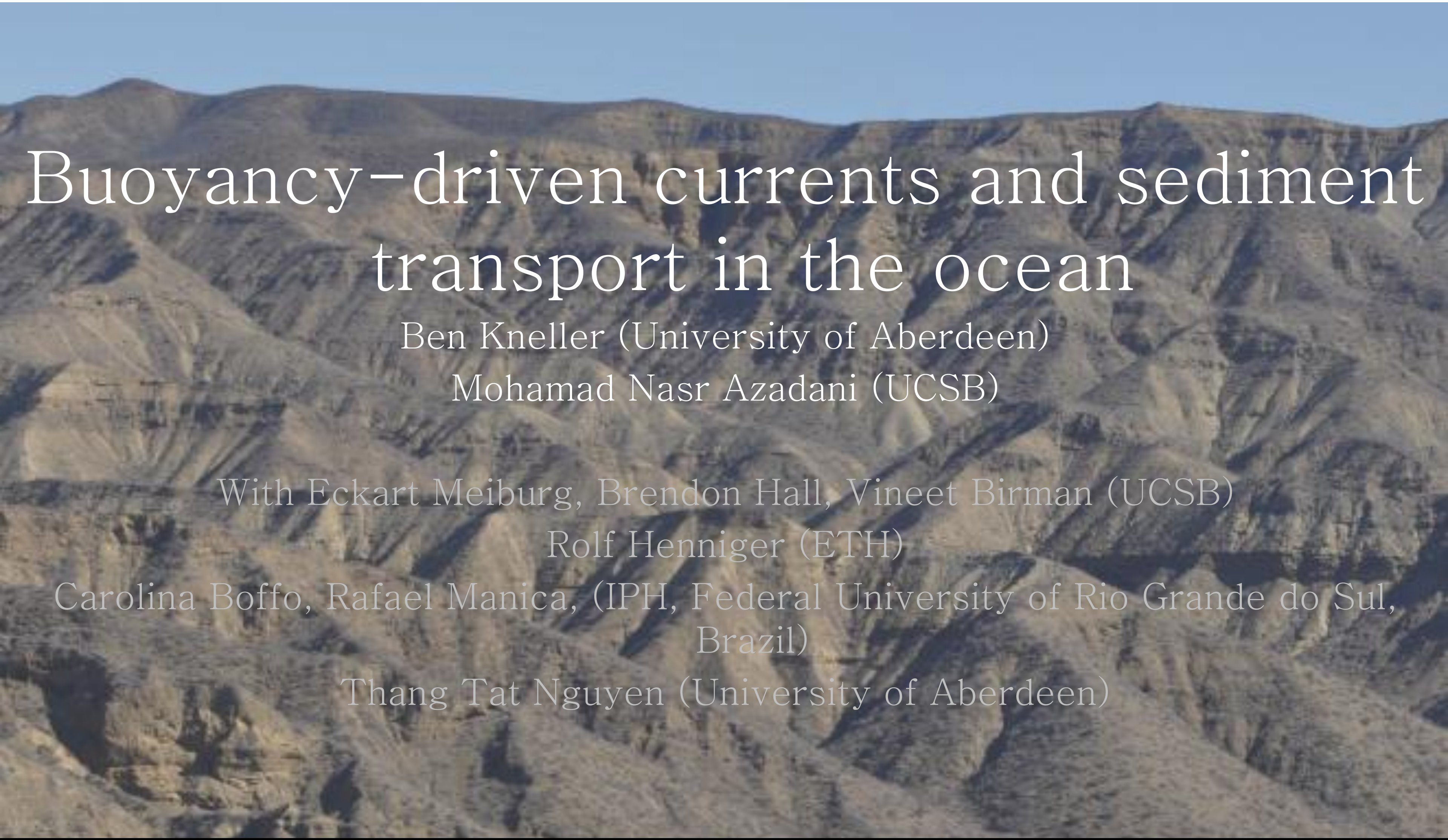
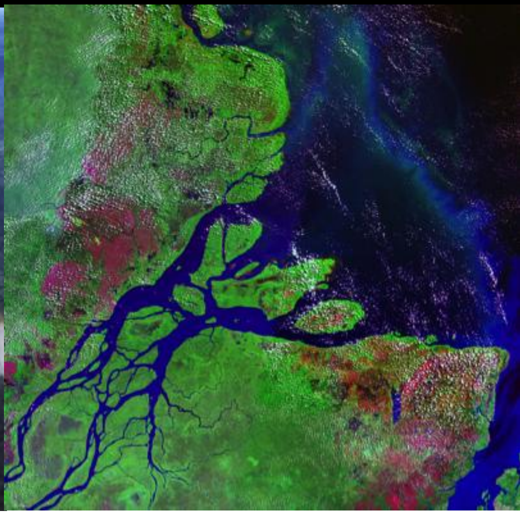


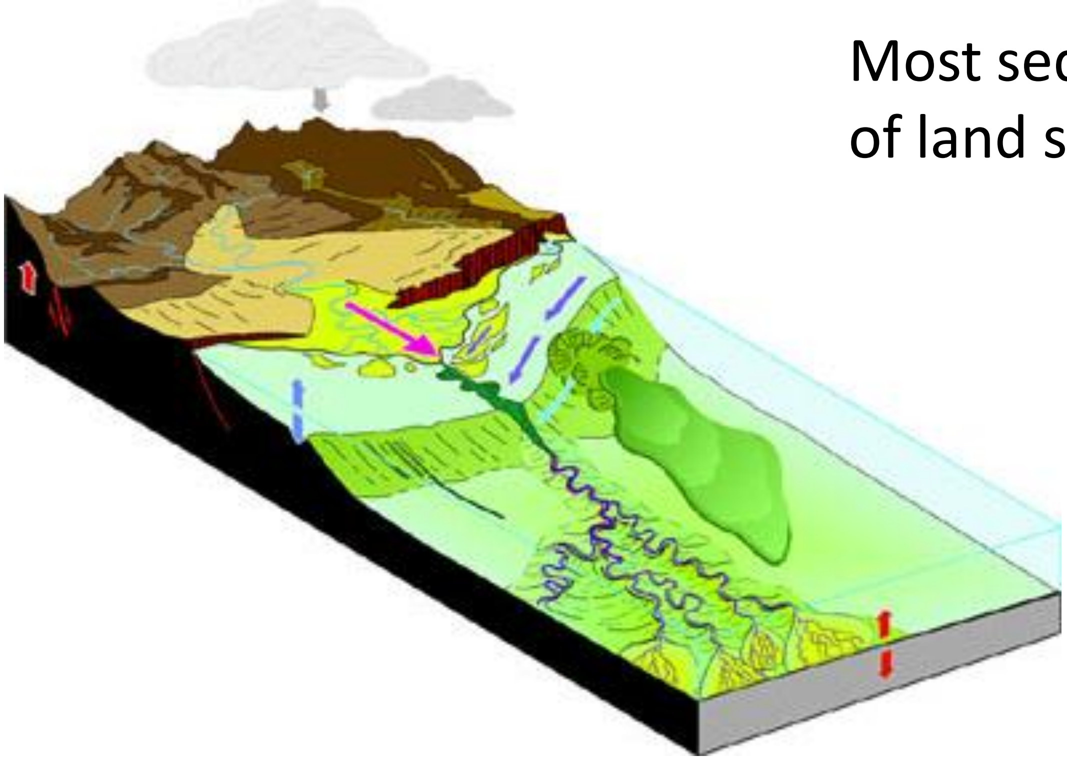
Buoyancy-driven currents and sediment transport in the ocean

Ben Kneller (University of Aberdeen)
Mohamad Nasr Azadani (UCSB)

With Eckart Meiburg, Brendon Hall, Vineet Birman (UCSB)
Rolf Henniger (ETH)
Carolina Boffo, Rafael Manica, (IPH, Federal University of Rio Grande do Sul, Brazil)
Thang Tat Nguyen (University of Aberdeen)

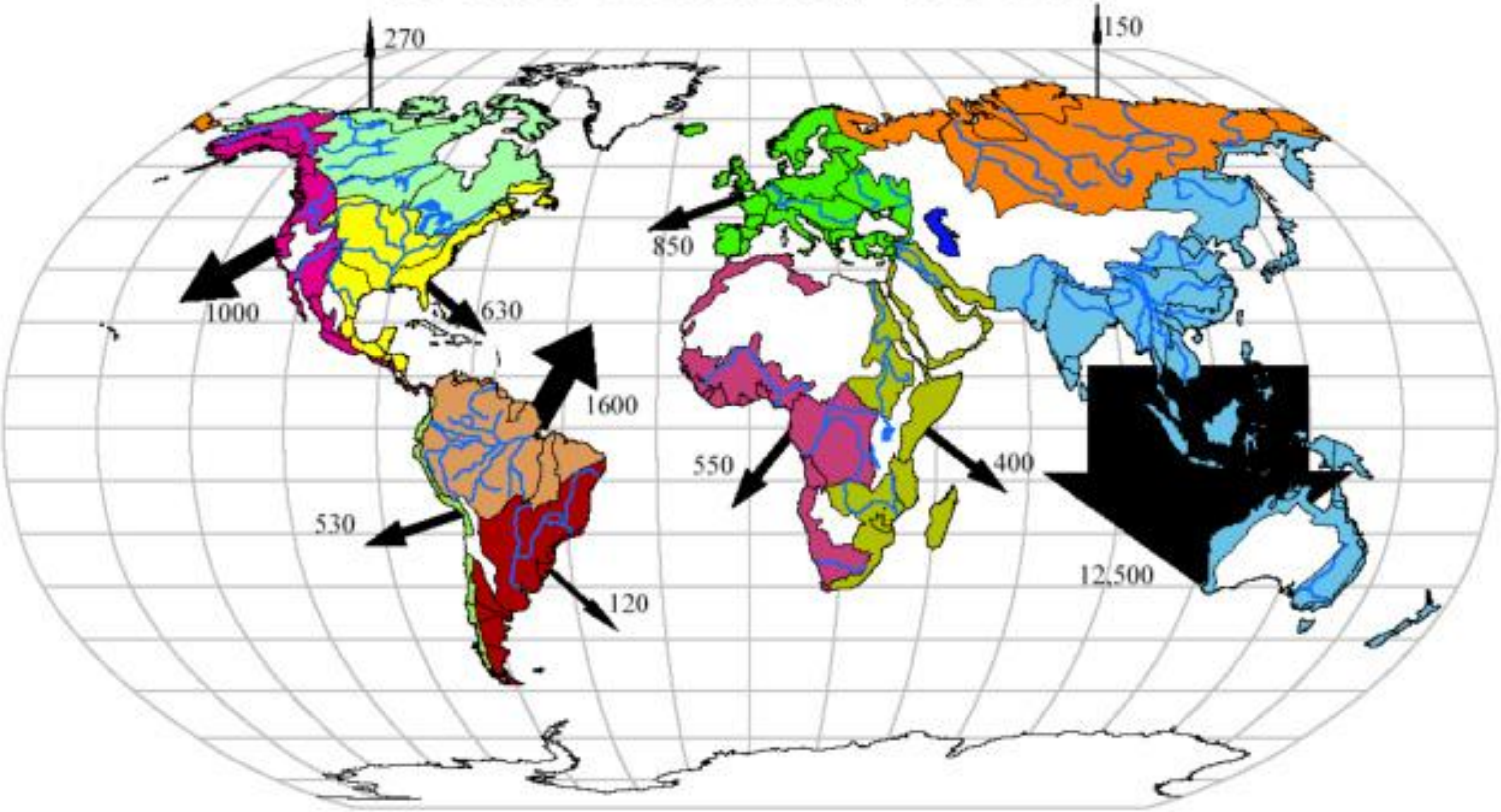
Context





Most sediments derived from erosion of land surfaces reach the ocean

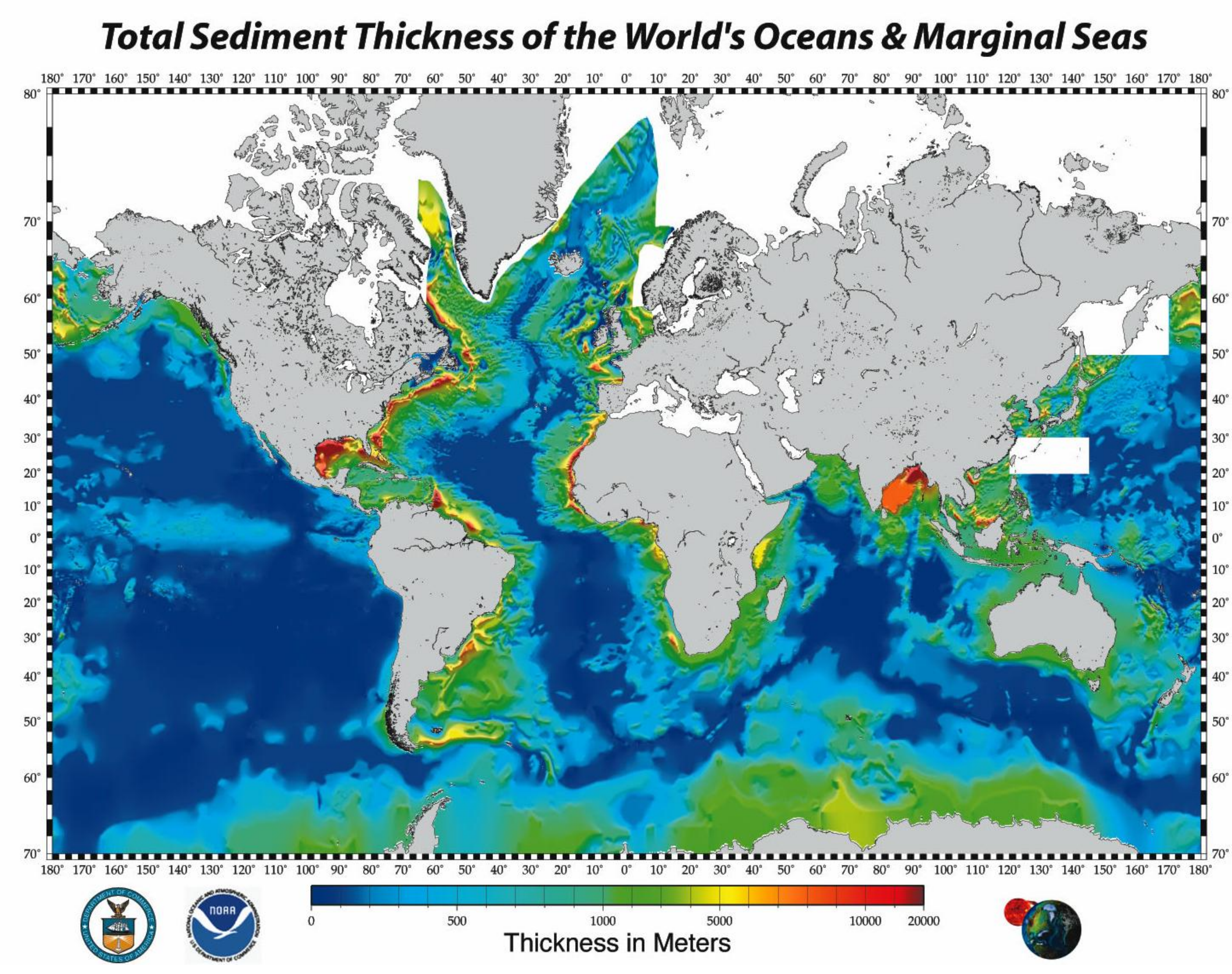
Context



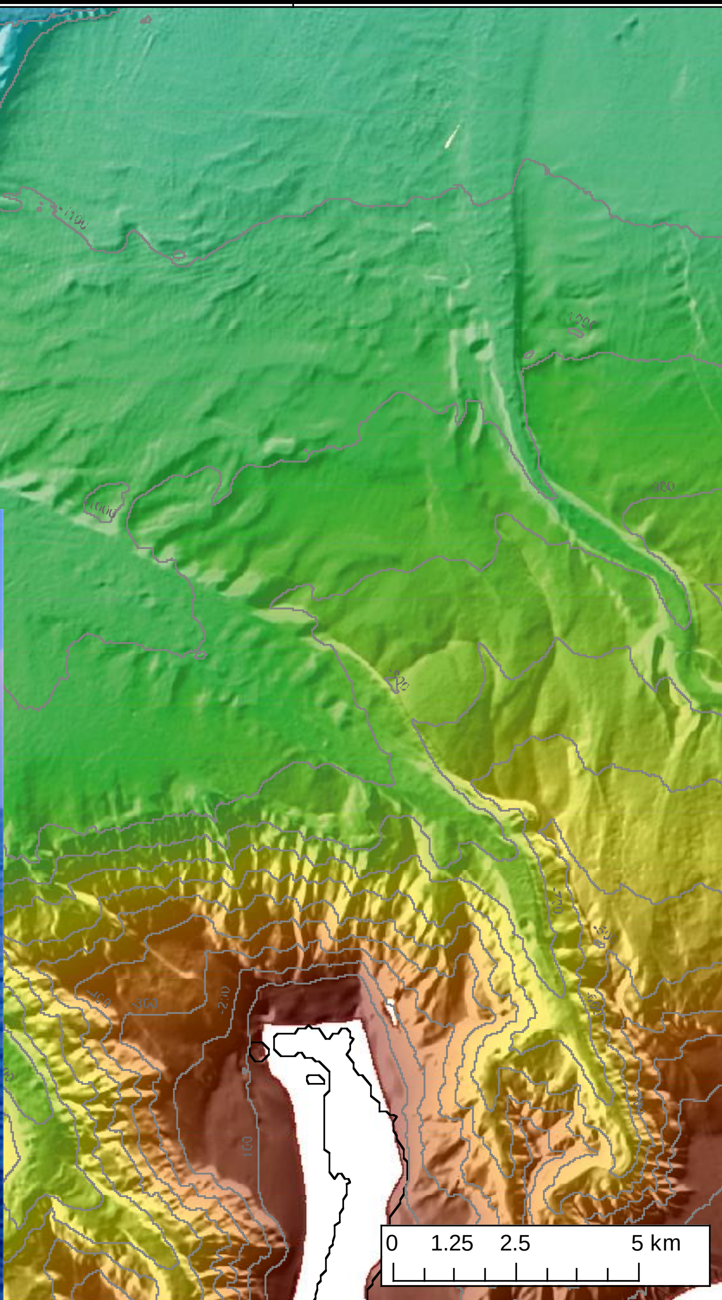
Fluvial Discharge of Suspended Sediment to the Coastal Ocean

Total = 19 x 10^9 tonnes per year (Milliman and Farnsworth, 2011)

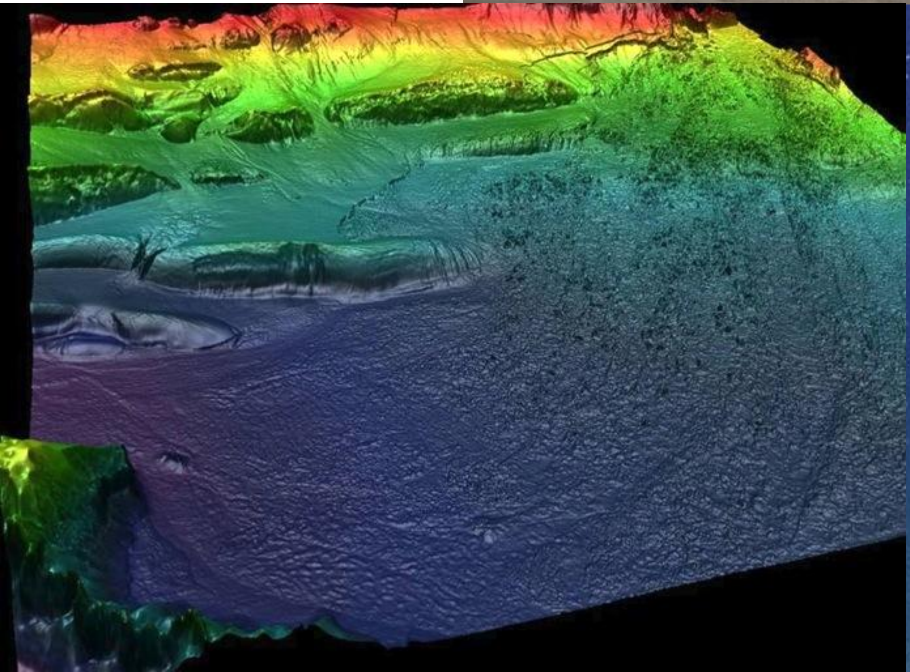
Context


Total Sediment Thickness of the World's Oceans & Marginal Seas
180° 170° 160° 150° 140° 130° 120° 110° 100° 90° 80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180°
80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70°
0
500
1000
5000
10000
20000
Thickness in Meters
NOAA

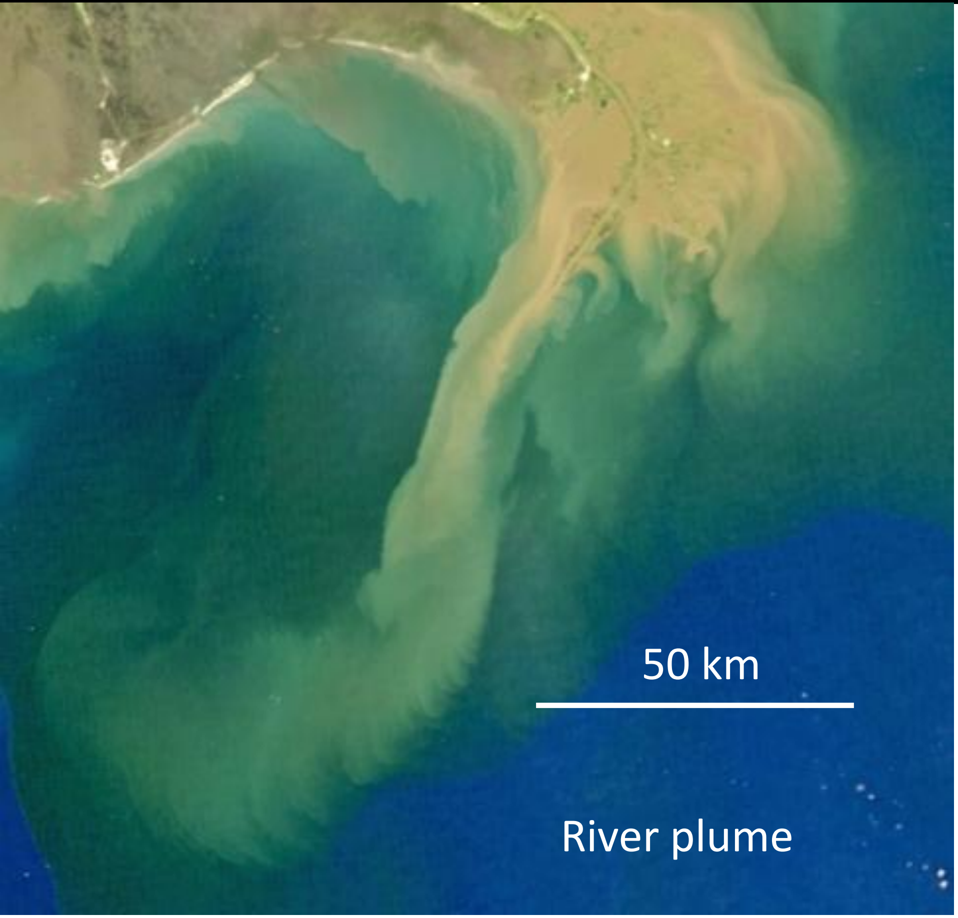
Context



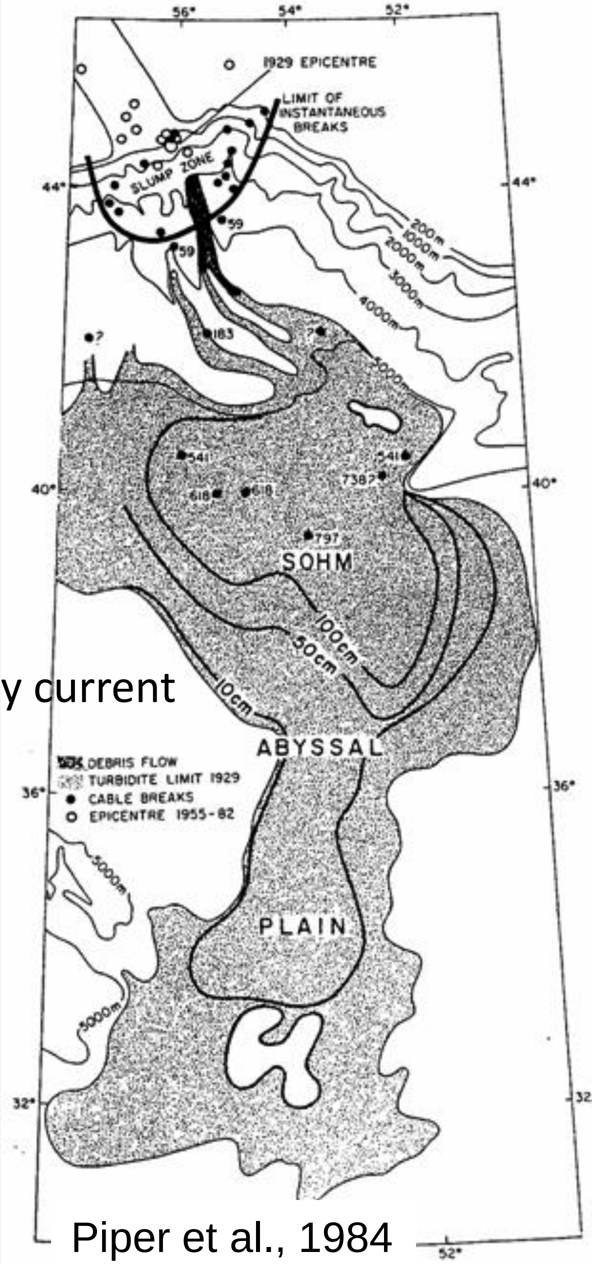
submarine landslides, ice-rafted debris, pelagic settling



Fluid-mediated transport of sediment to deep water



Turbidity current



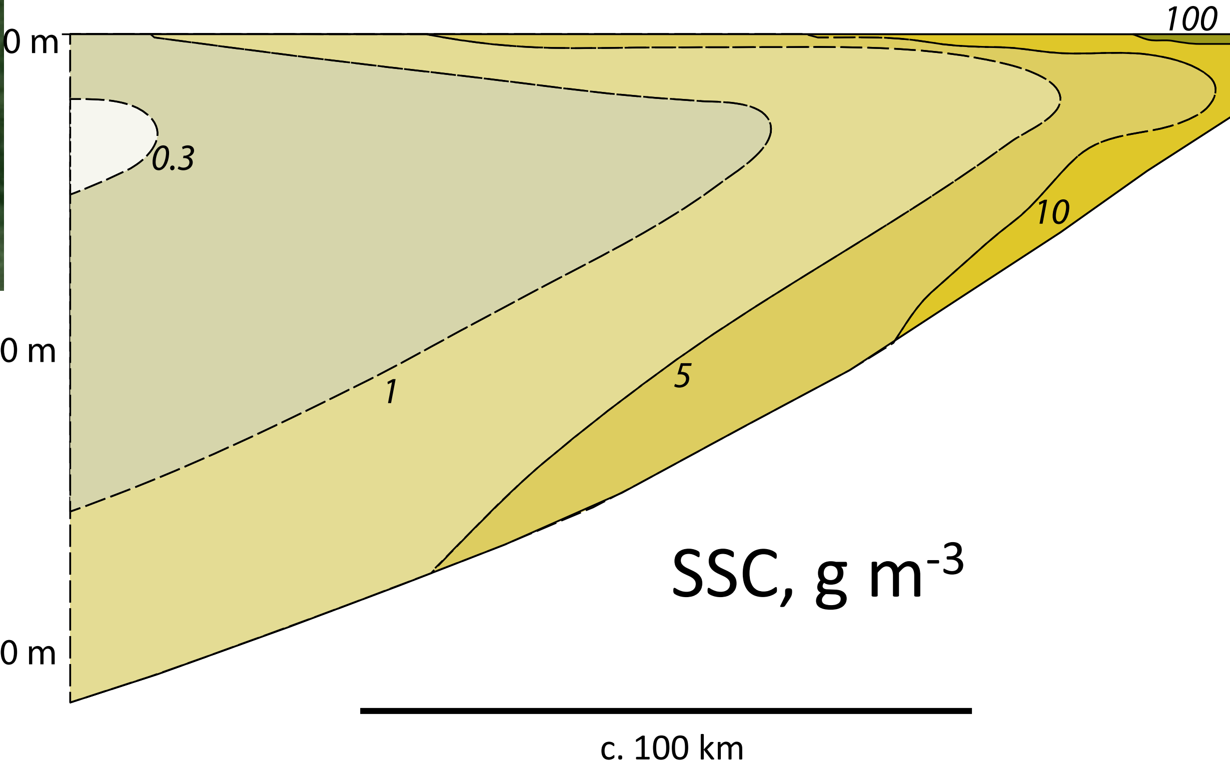
Piper et al., 1984

- Both buoyancy-driven
- Turbulence maintains sediment suspension, affecting buoyancy
- Between them these two processes account for most of the sediment in the deep sea

River plumes

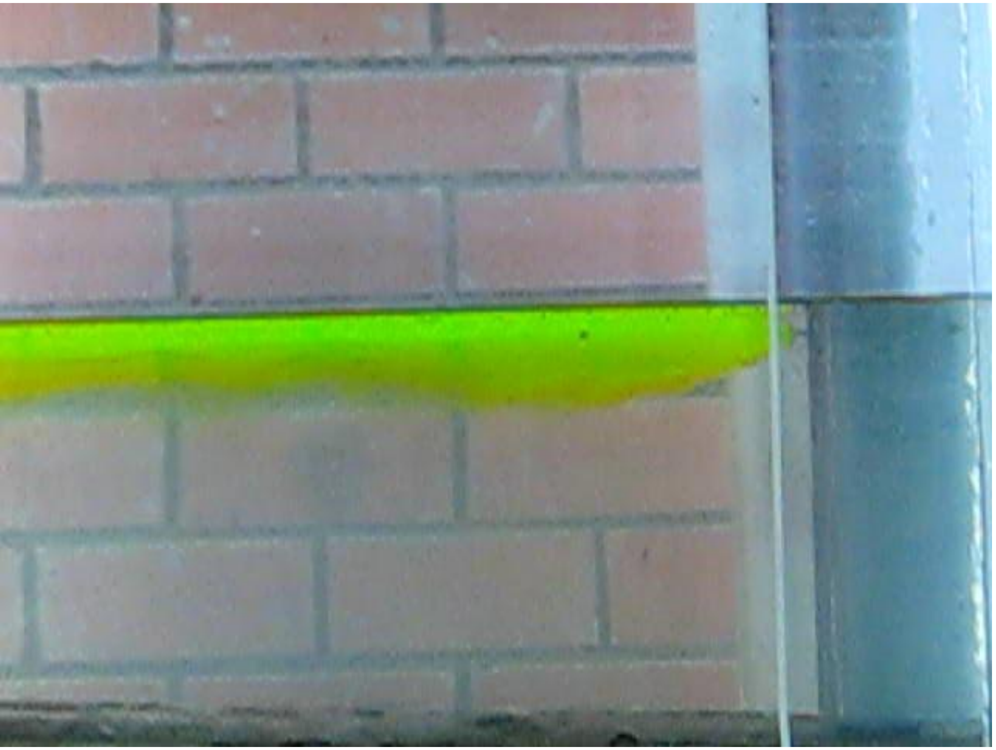
How do they go so far?

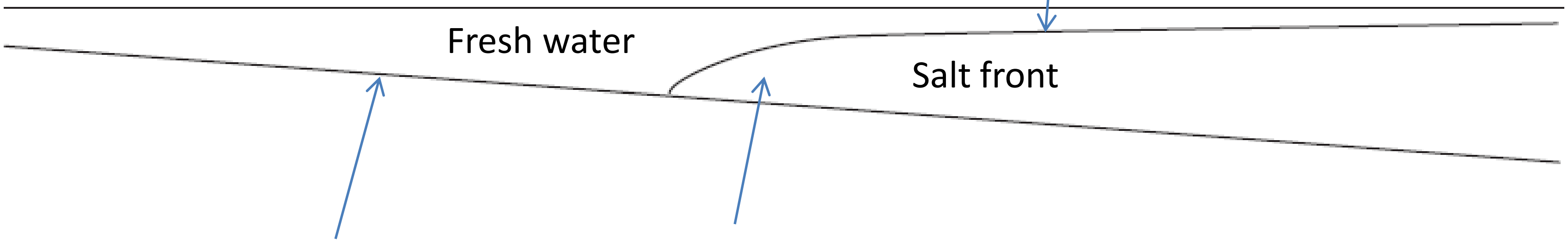
What maintains suspension?



Particulate matter >5 μm in Congo River plume.
Eisma & Kalf, 1984

Positively buoyant surface plume





Turbulence generation in shear layer?

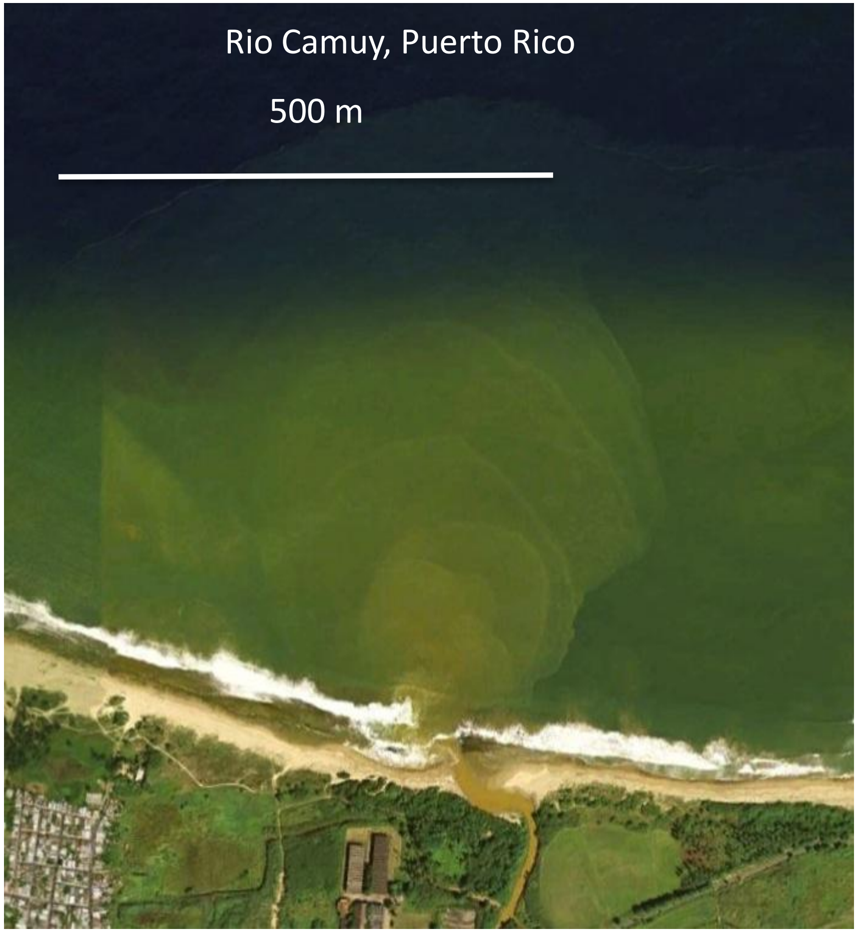
Fresh water

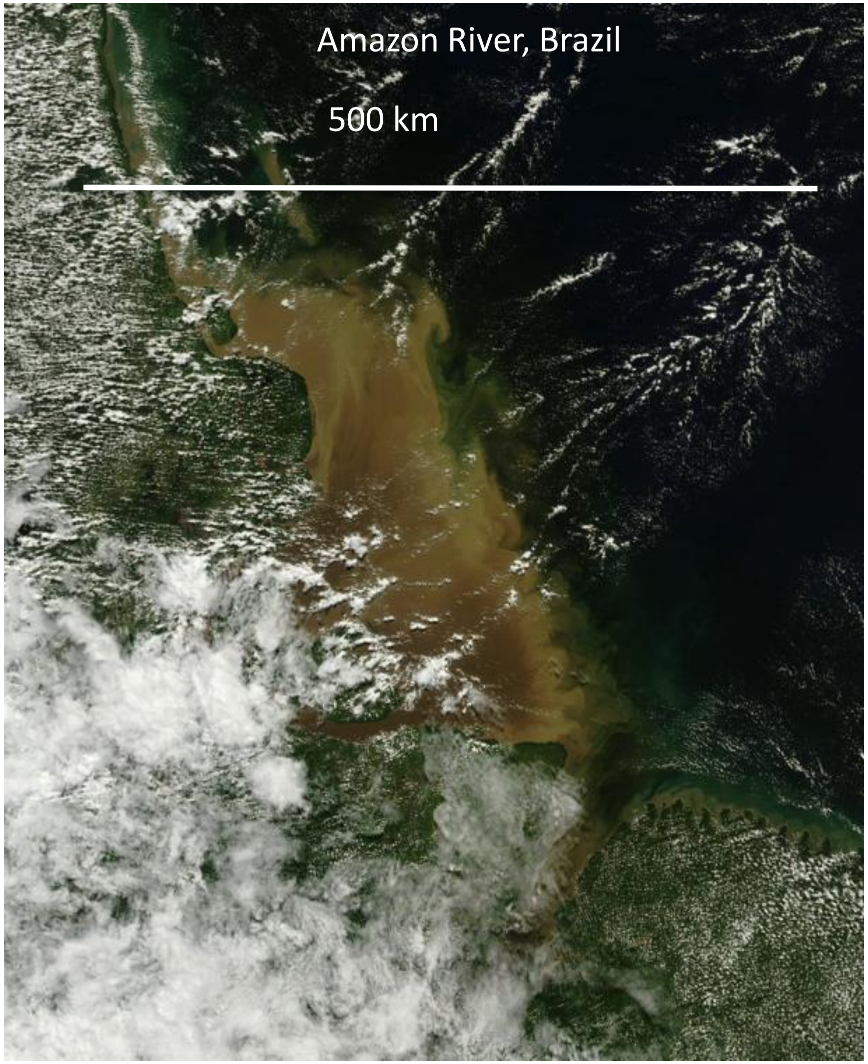
Salt front

Turbulence generation at lower boundary when attached to bed

TURBIDITY MAXIMUM associated with clay flocculation and turbulence decay

River plumes



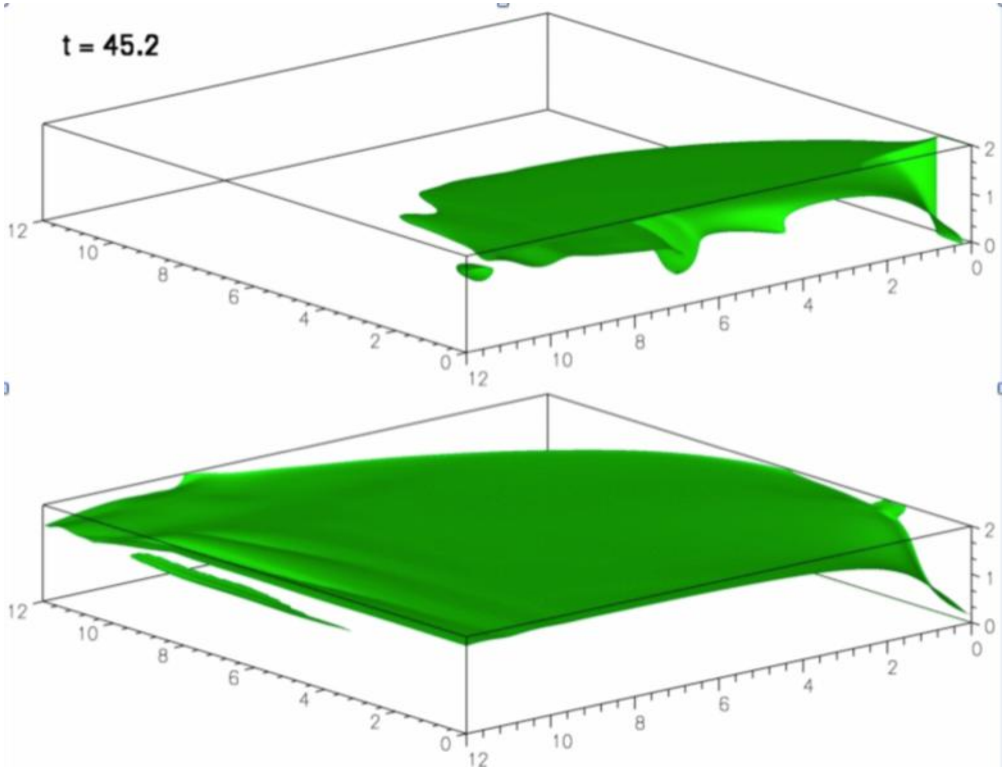


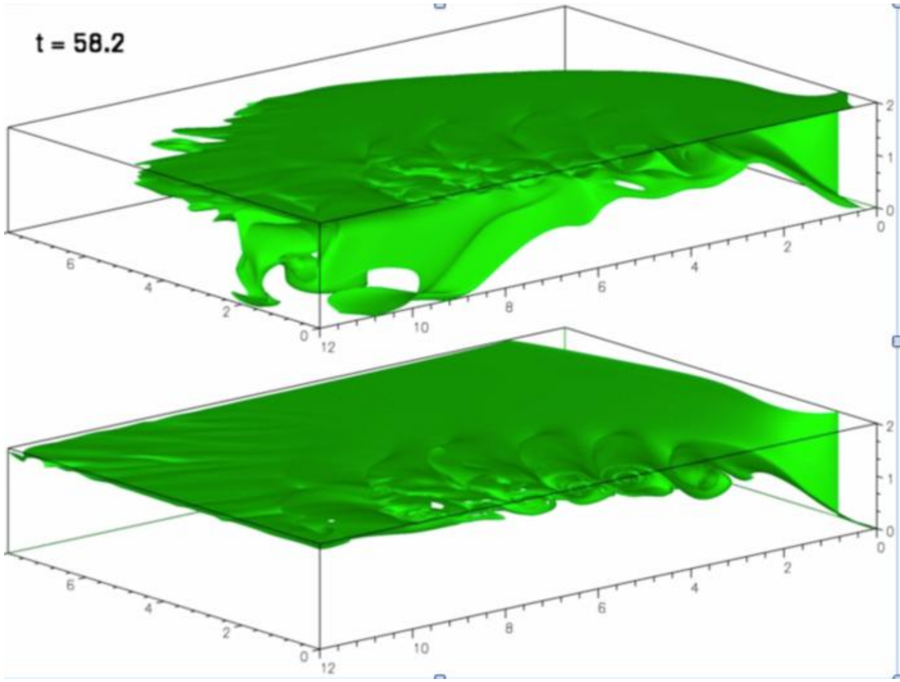
Plume lower boundary stability – numerical simulation

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

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

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

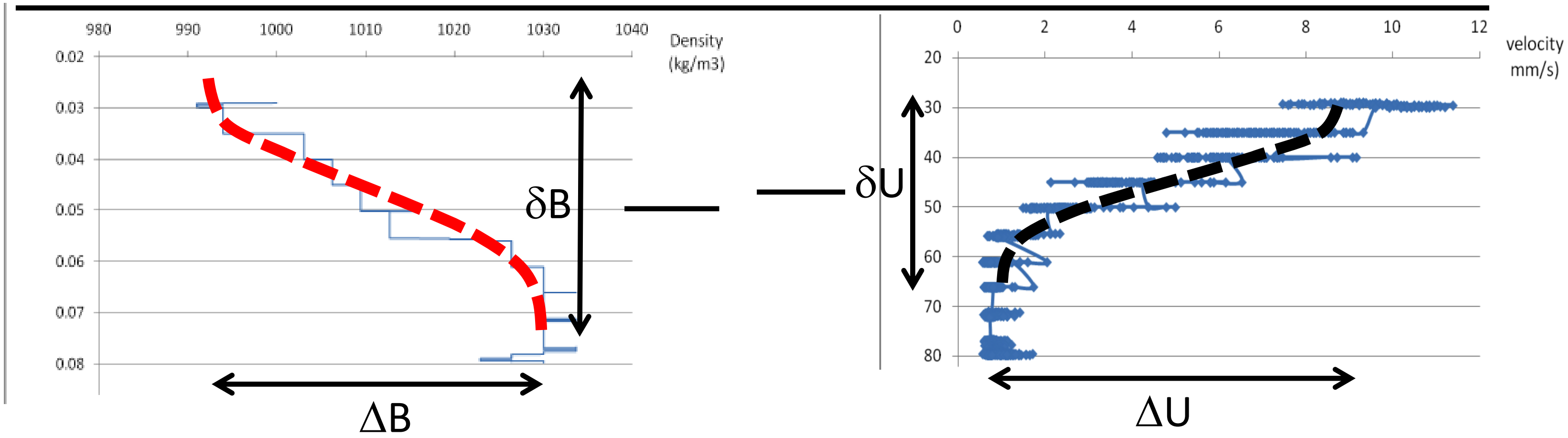




Courtesy of Rolf Henniger, ETH

Plume lower boundary stability – laboratory experiment

Plume lower boundary stability – laboratory experiment



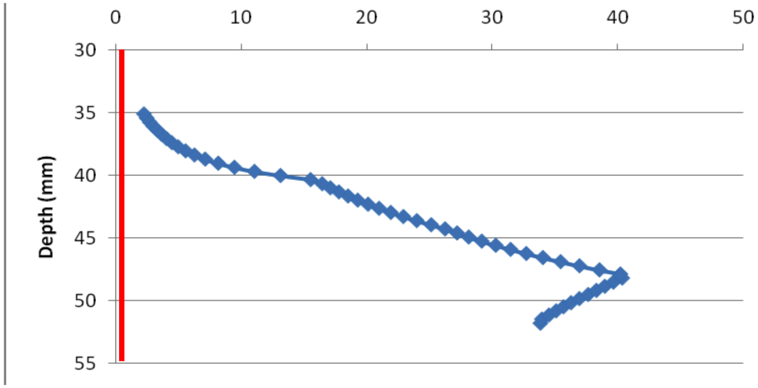
Density

(calibrated resistivity probe)

Velocity

(Constant Temperature Anemometry - 'hot wire' probe)

Gradient Richardson number

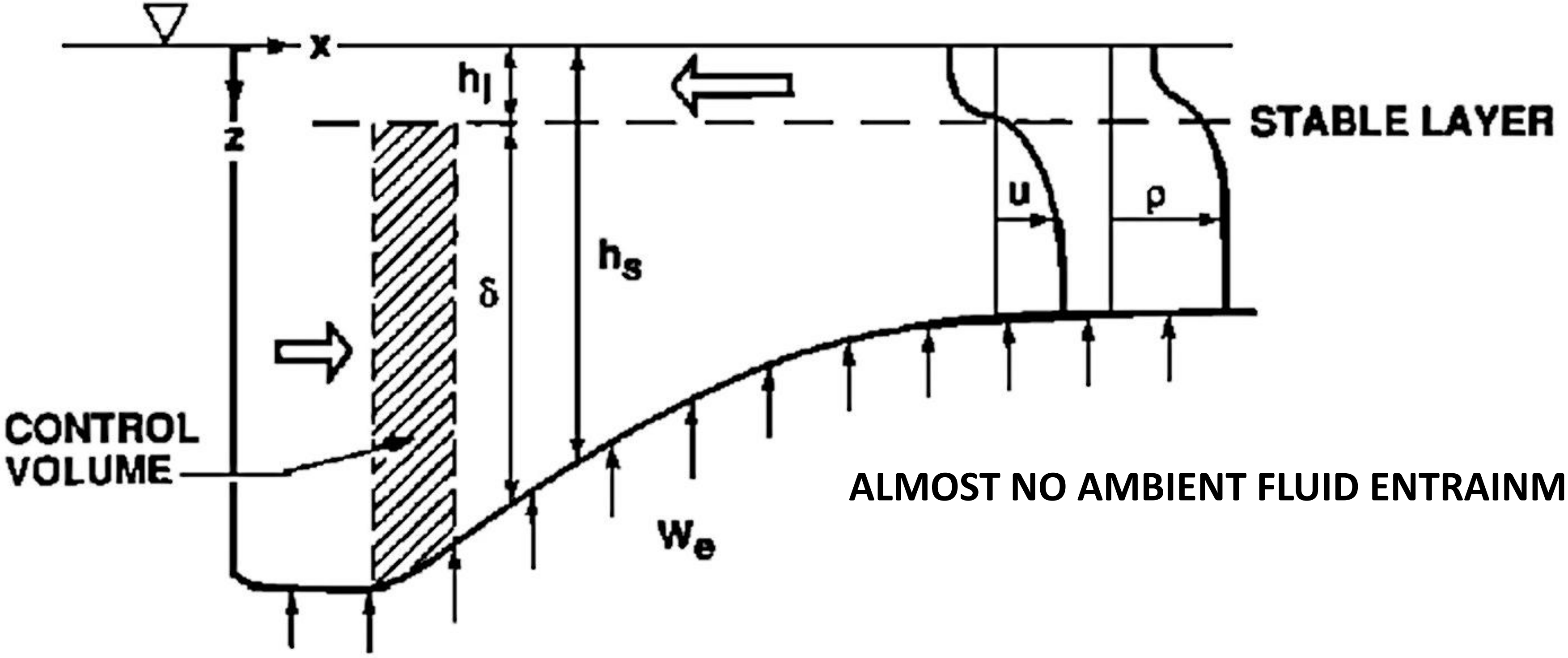


$$Ri_g = \frac{\left(g\,\frac{\partial\rho/\partial z}{\rho_a}\right)}{\left(\partial u/\partial z\right)^2}$$

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

Plume lower boundary stability – environmental measuremer

Leschenault Estuary, Koombana Bay, Western Australia



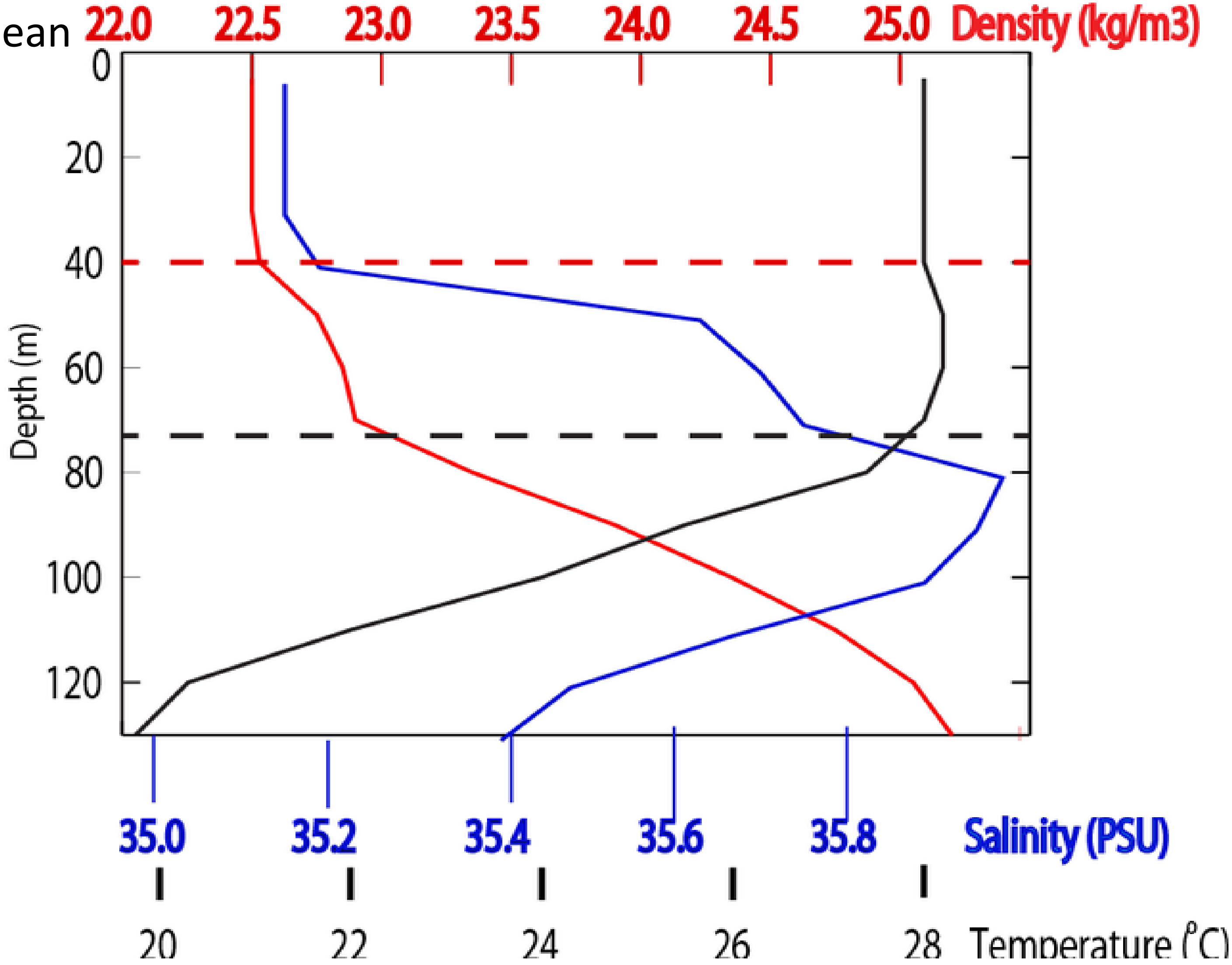
ALMOST NO AMBIENT FLUID ENTRAINMENT

Luketina & Imberger, 1989

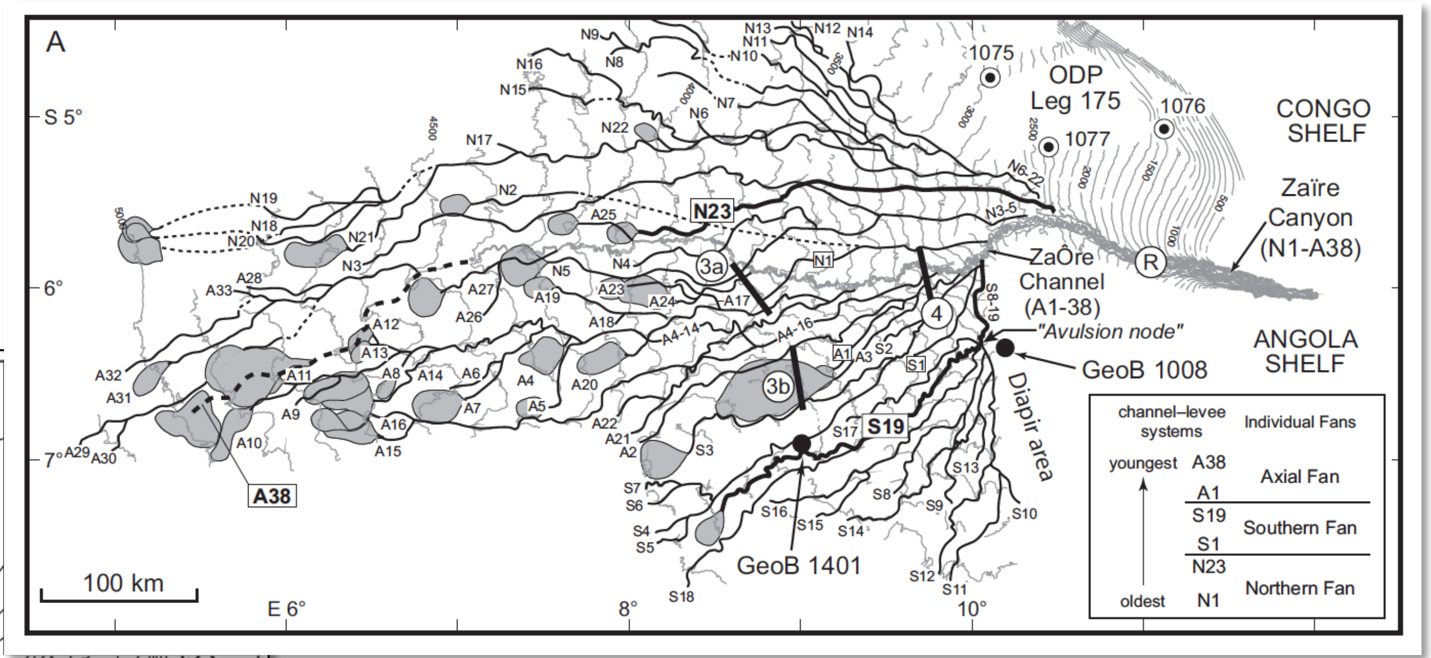
Ocean mixing layer

Turbulent mixing by surface waves and wind-induced shear

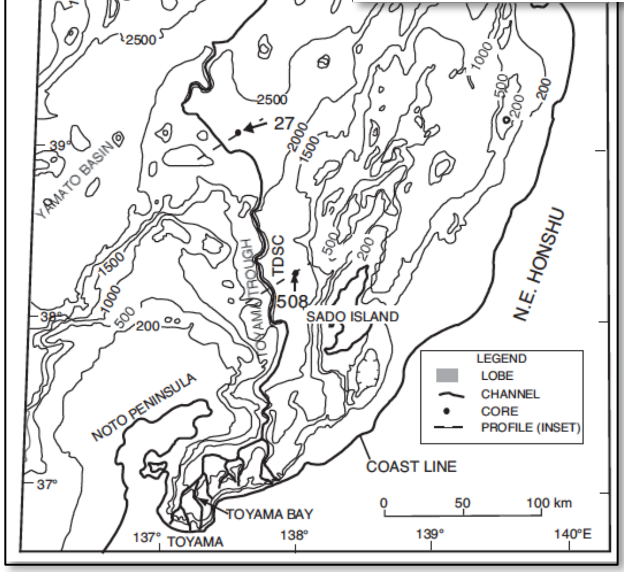
Indian Ocean



The problem of large submarine fans



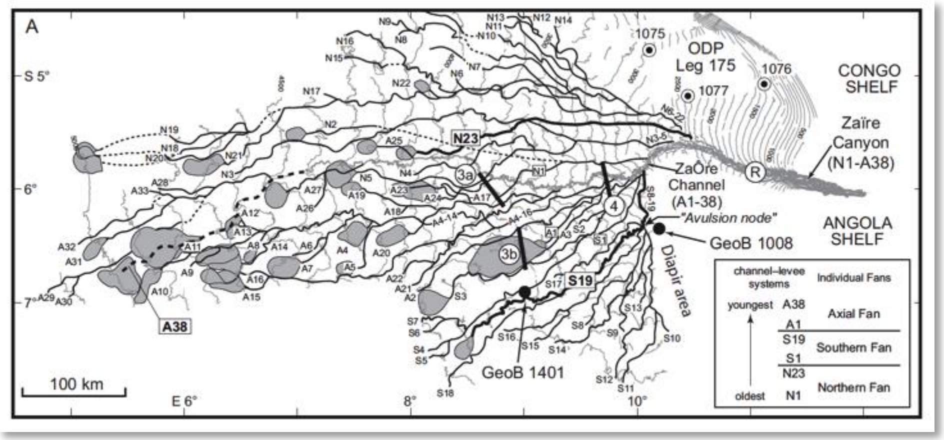
Congo fan. Marsset et al., 2009



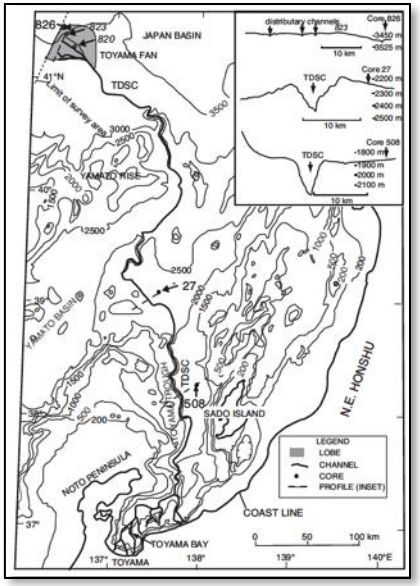
Turbidity currents apparently carry sediment in suspension through channels over very low gradients for 500 km…

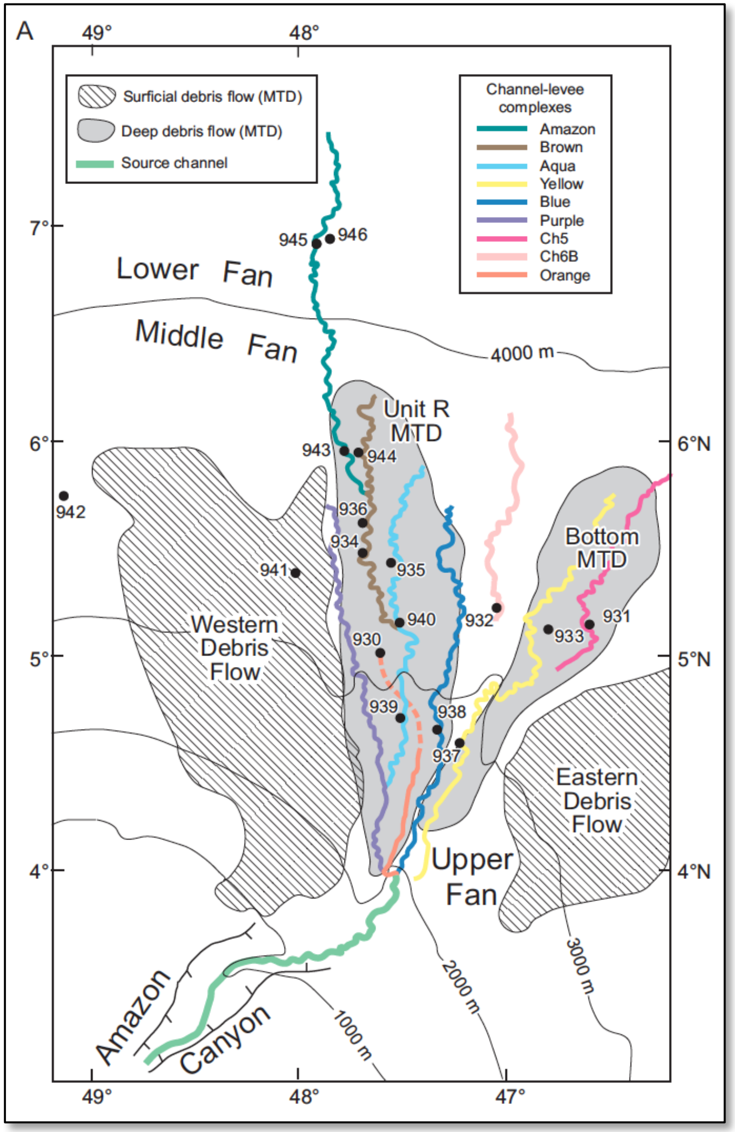
Toyama channel. Nakajima, 2009

The problem of large submarine fans



…1000 km…



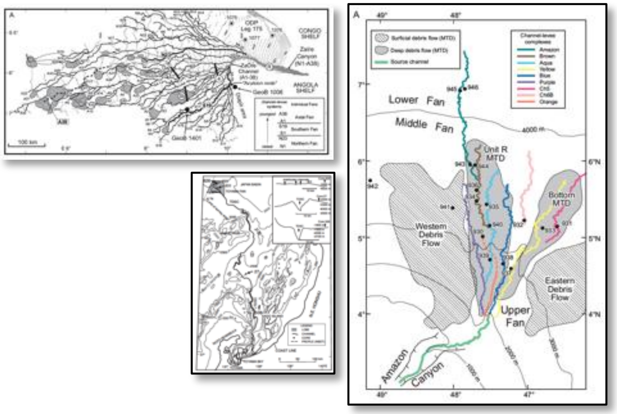


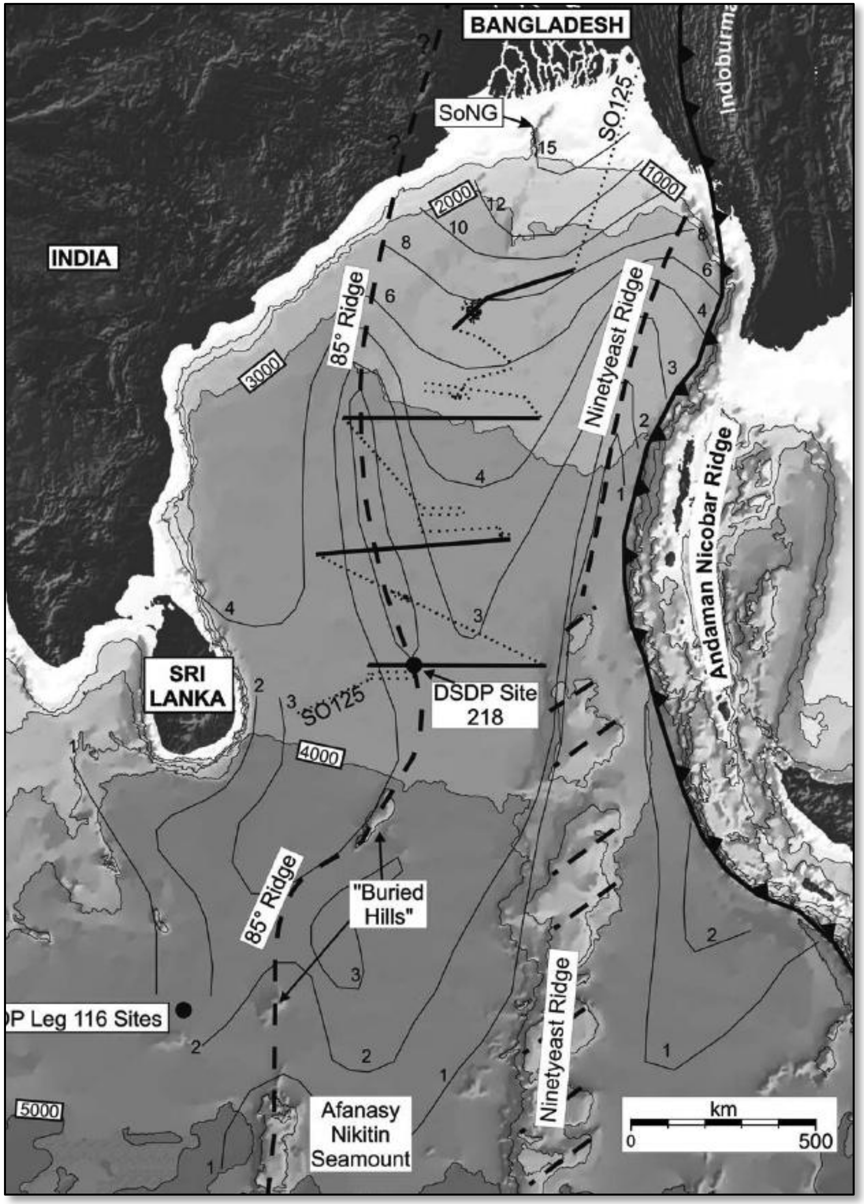
Amazon fan. Maslin, 2009

The problem of large submarine fans

…even 3000 km

How?

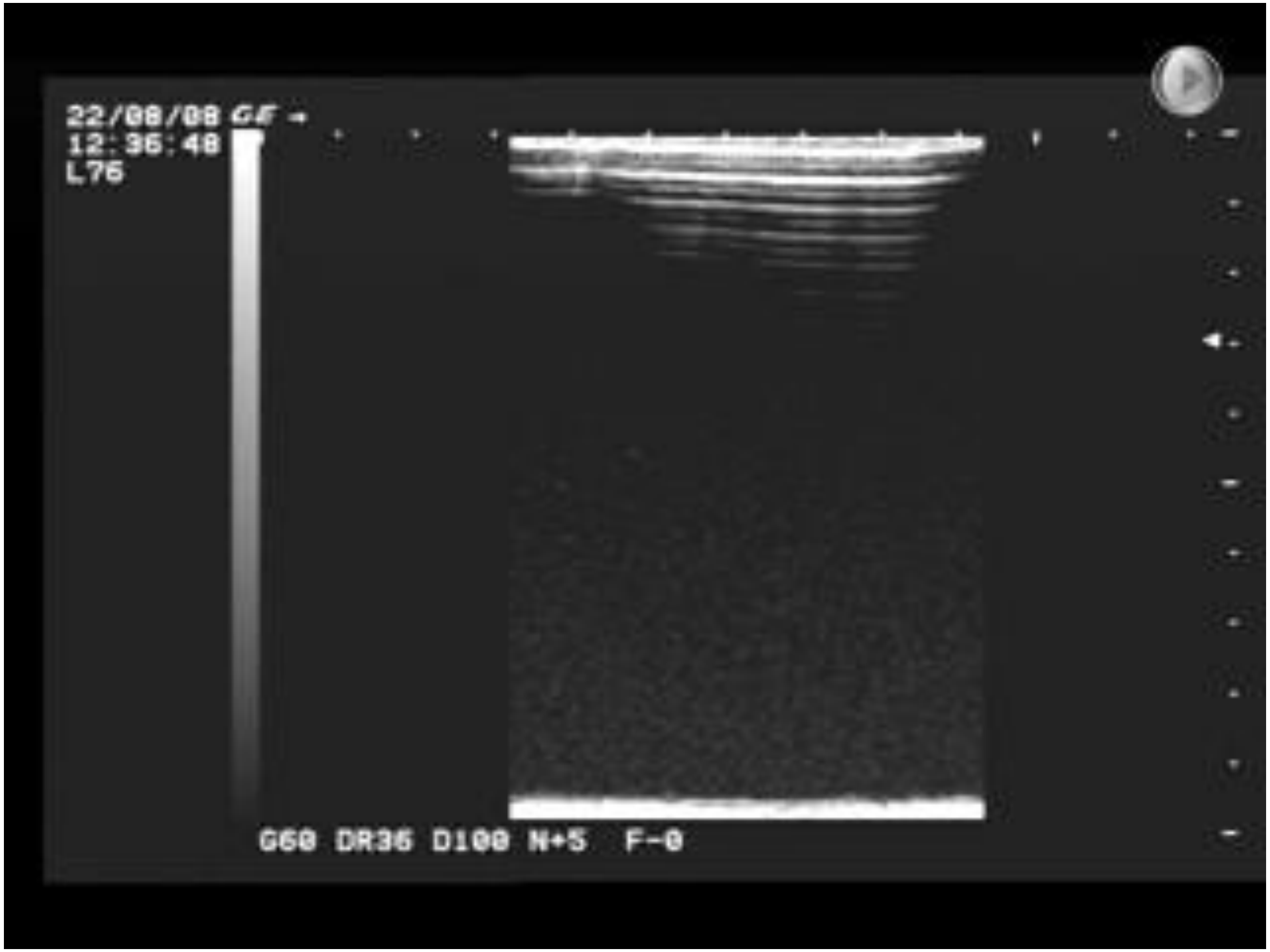




Bengal fan. Schwenk & Spieß, 2009

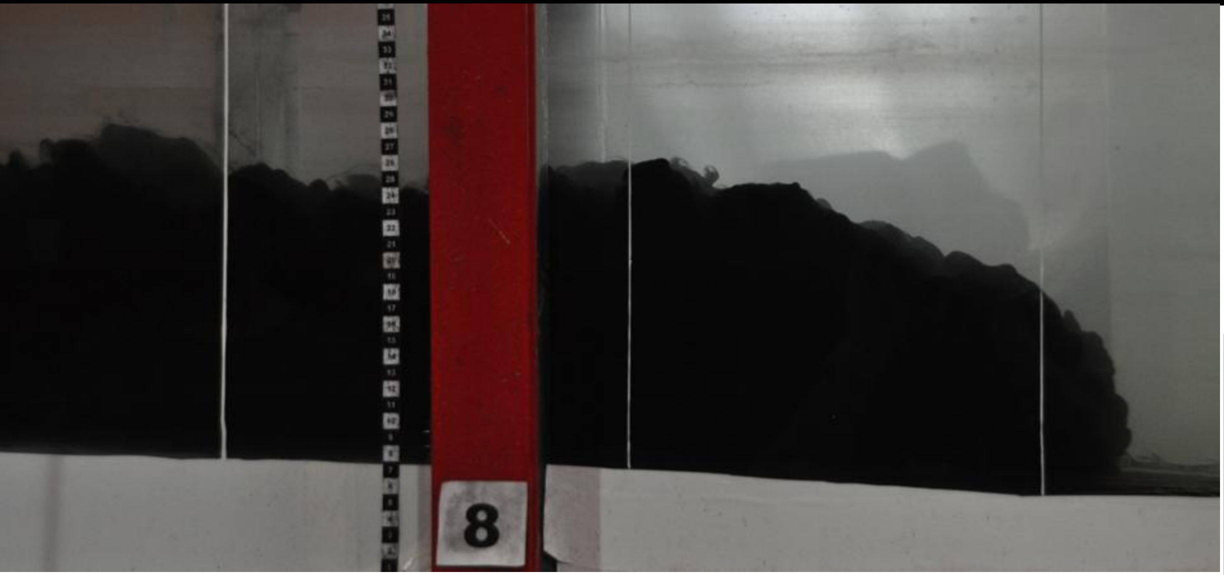
Unstable stratification - Kelvin-Helmholtz instabilities

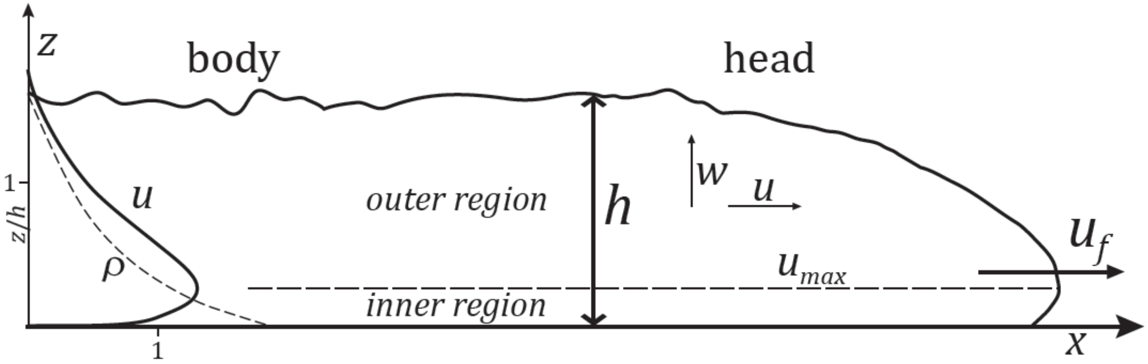
Froude subcritical laboratory turbidity current; crushed coal in water, imaged by medical ultrasound

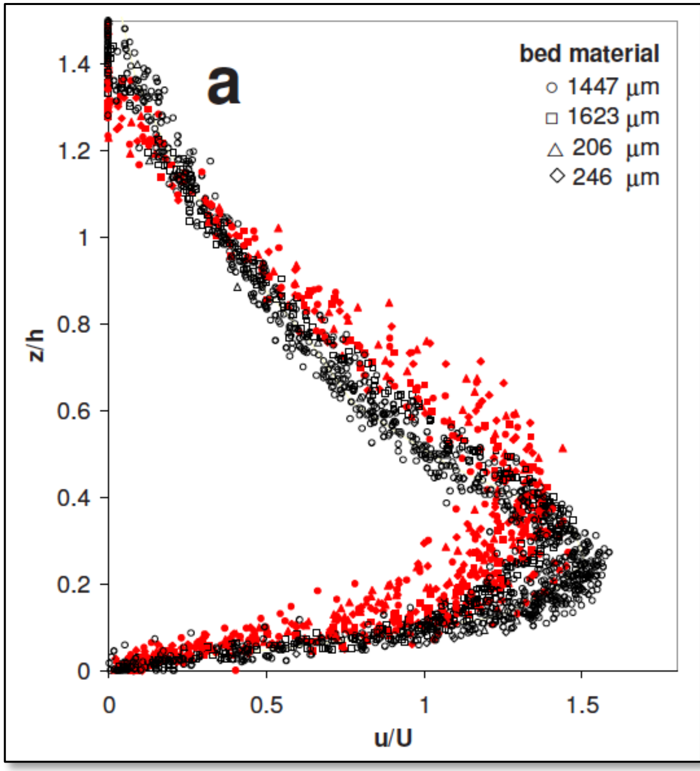


Carolina Boffo, UFRGS

The classic view – velocity profiles

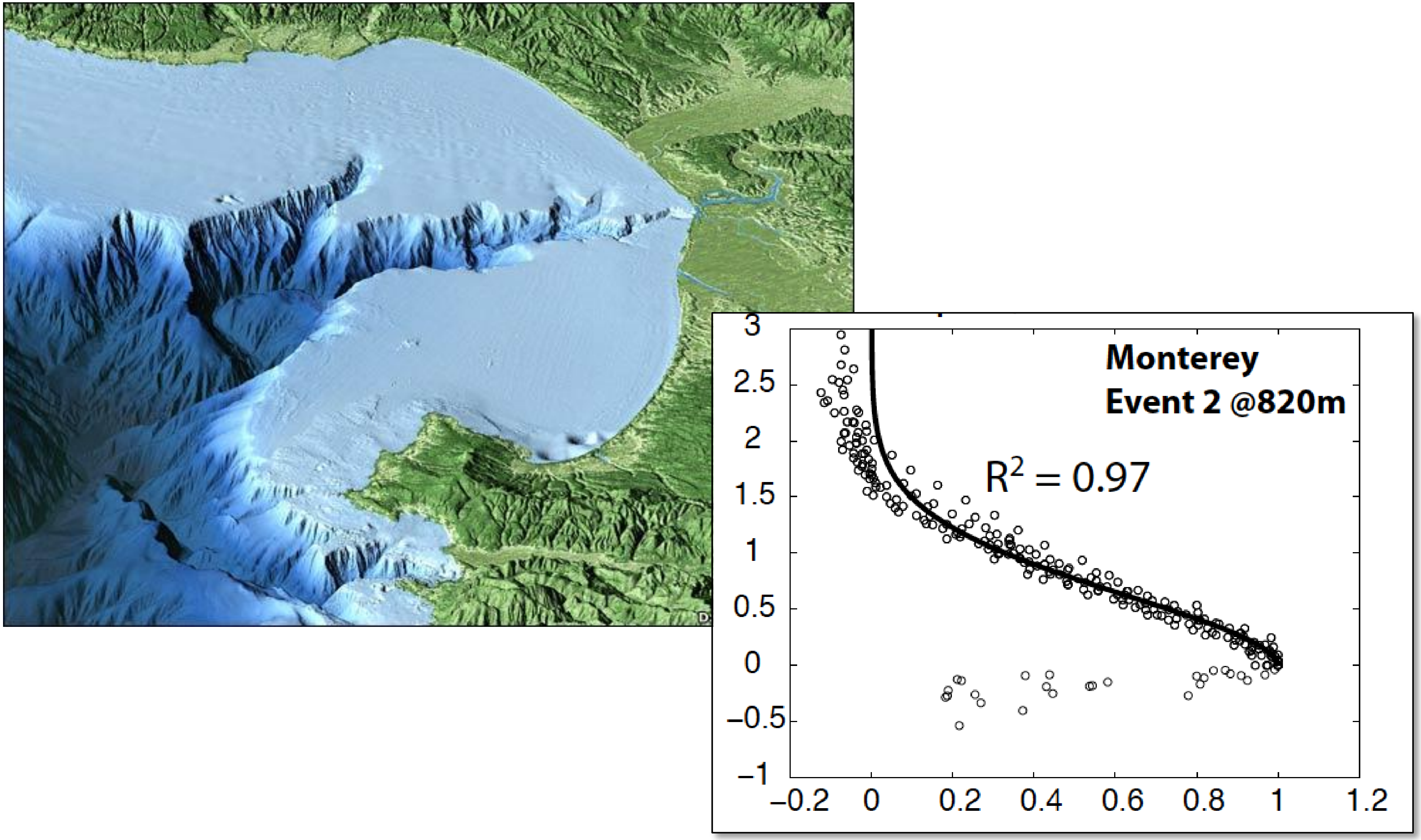






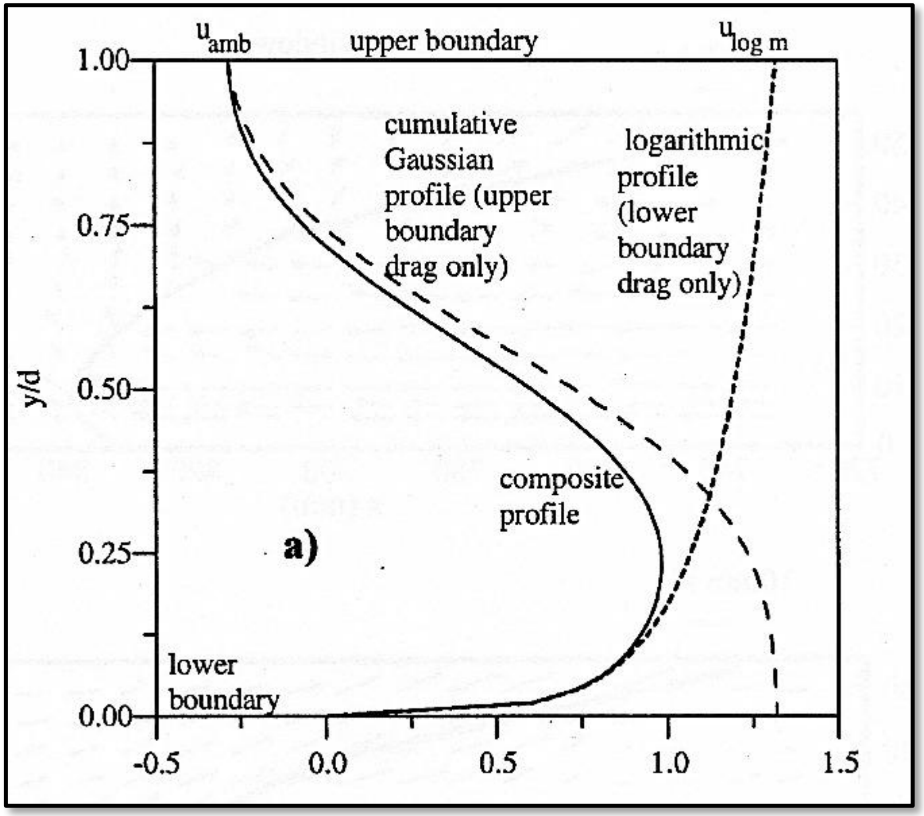
Experiments on super-critical flows
Sequeiros et al. 2010

The classic view – velocity profiles



Natural current
Xu, 2010

Origin of the velocity profile



Kneller et al., 1999

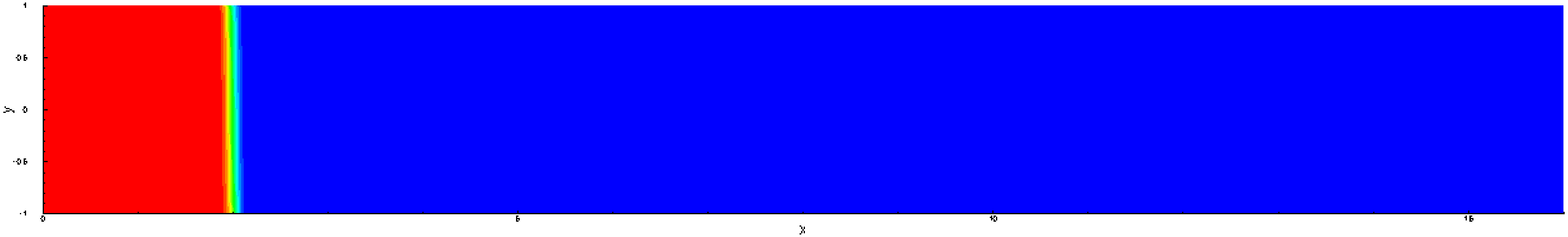
Sum of logarithmic boundary layer profile, and shear layer profile (error function) that extends to the bed where there is high turbulent drag

Kelvin-Helmholtz instabilities

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

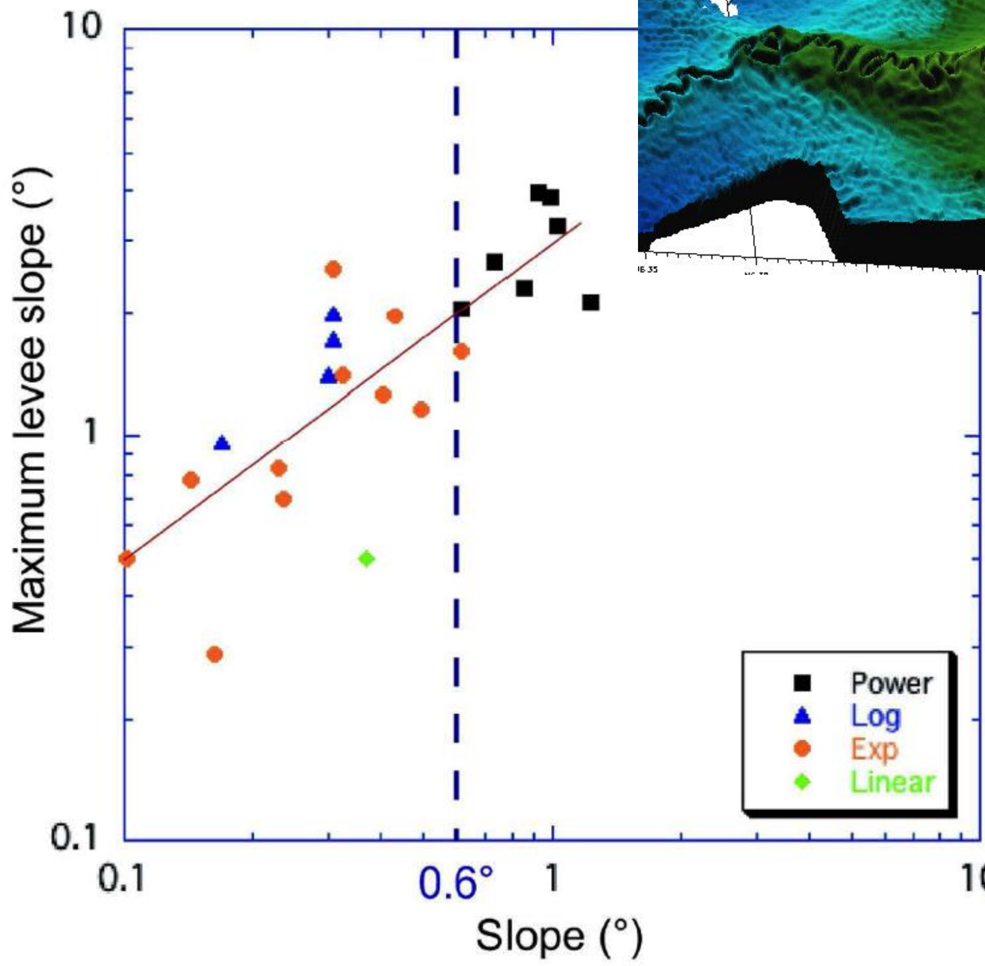
$$Ri_g = \frac{N^2}{(\partial u/\partial z)^2} = \frac{\left(g\frac{\partial \rho/\partial z}{\rho_a}\right)}{(\partial u/\partial z)^2}$$

Large eddy simulation of turbidity current,
Brendon Hall, UCSB

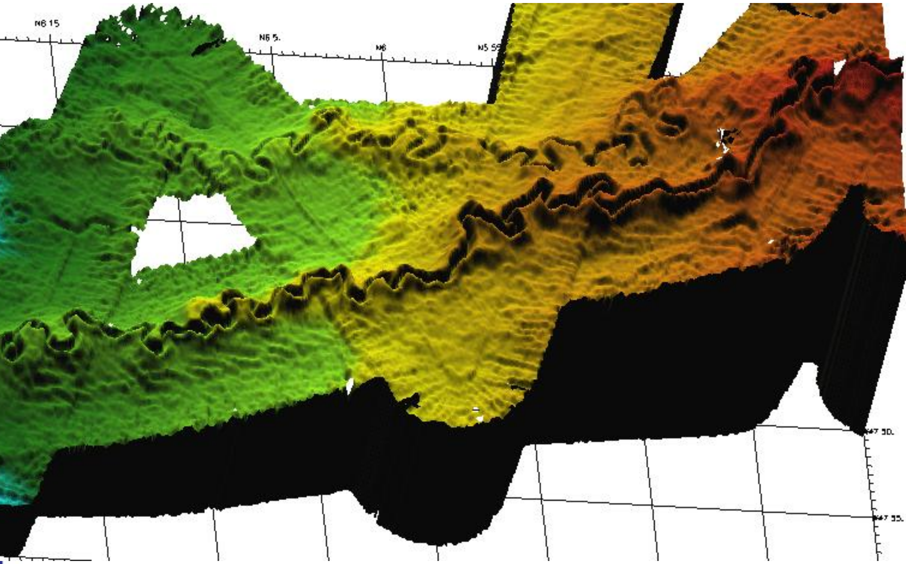


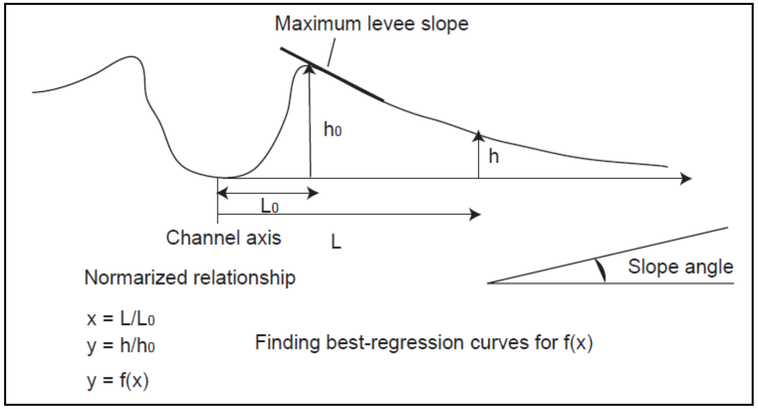
- Turbulent drag largely due to Kelvin-Helmholtz instabilities.
- Entrainment of ambient fluid mainly via KHIs that form when shear dominates and stratification becomes unstable (i.e. when gradient Richardson number is <0.25)

Dependence of levee shape on slope gradient



Nakajima and Kneller, 2013.



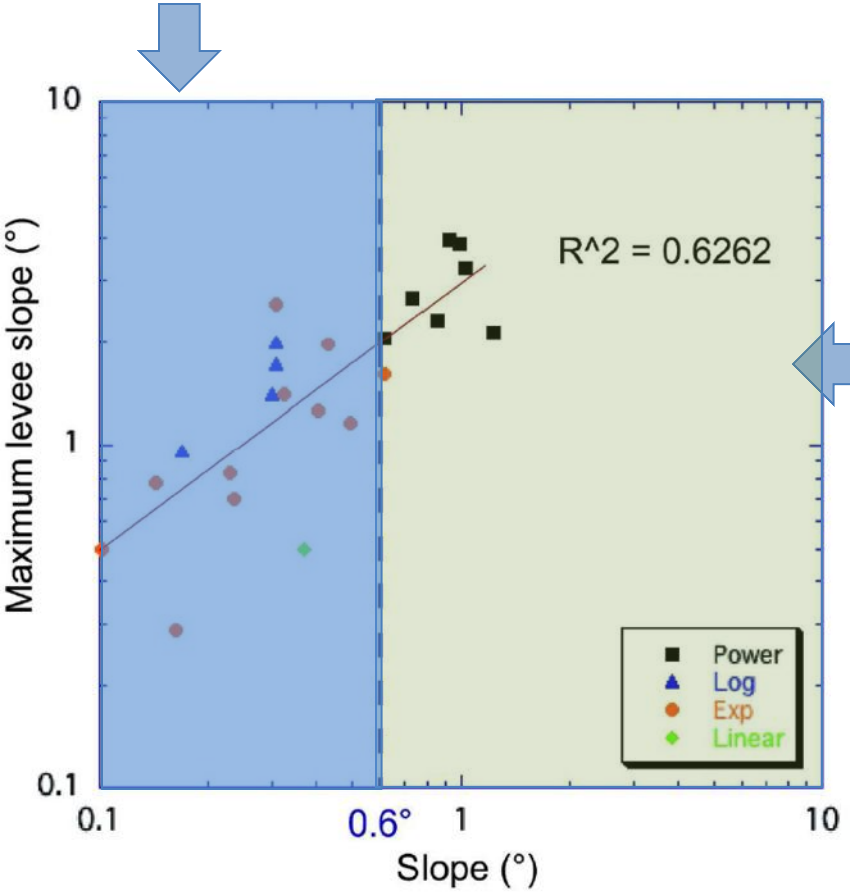


- Gradients of levee scale with regional slope
- Levee decay is power law on slopes >0.6°

Slope controls presence or absence of entrainment

$$f(x) = f_0 e^{-\left(u_s / uh_0\right)x}$$

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

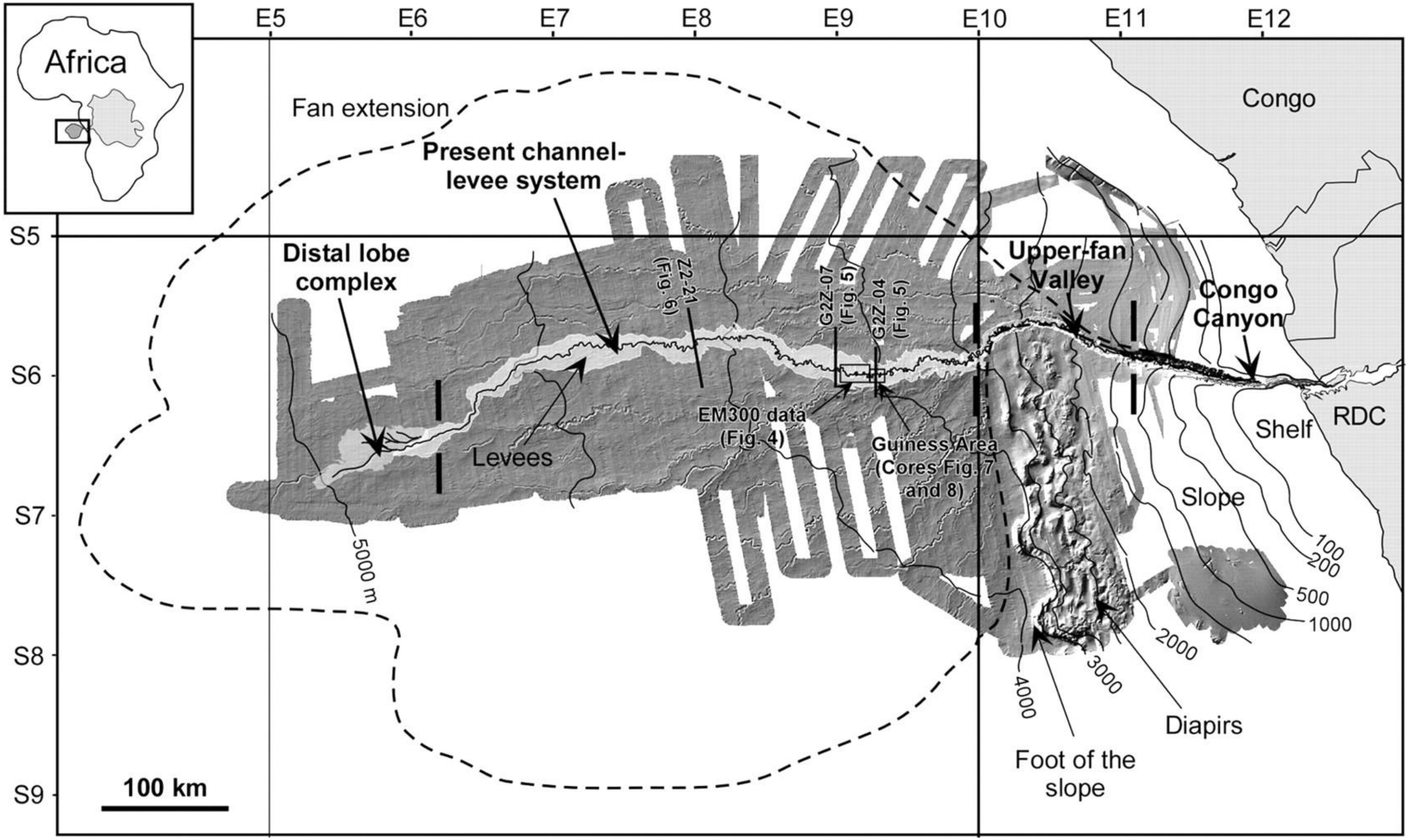


$$f(\hat{x}) = f_0 \left(uh_0 / \hat{x}\right)^{\frac{-u_s + E_0}{E_0}}$$

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

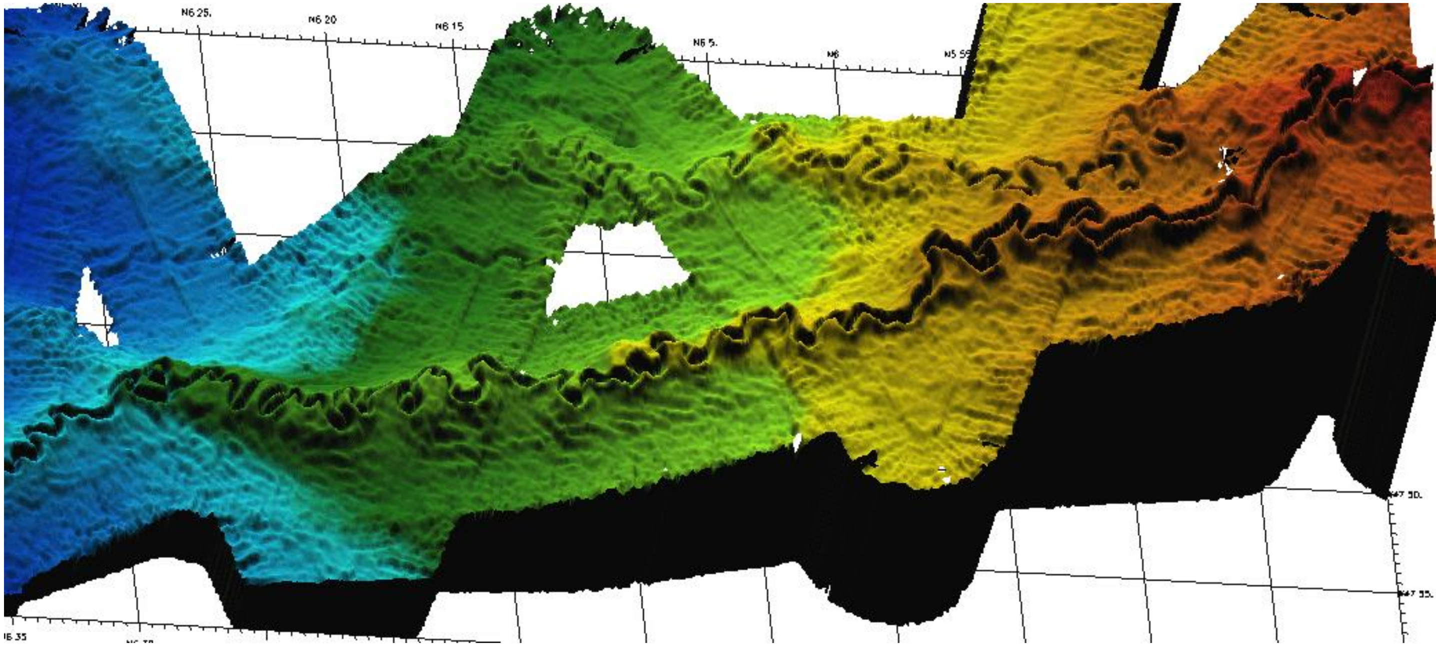
Birman et al., 2009

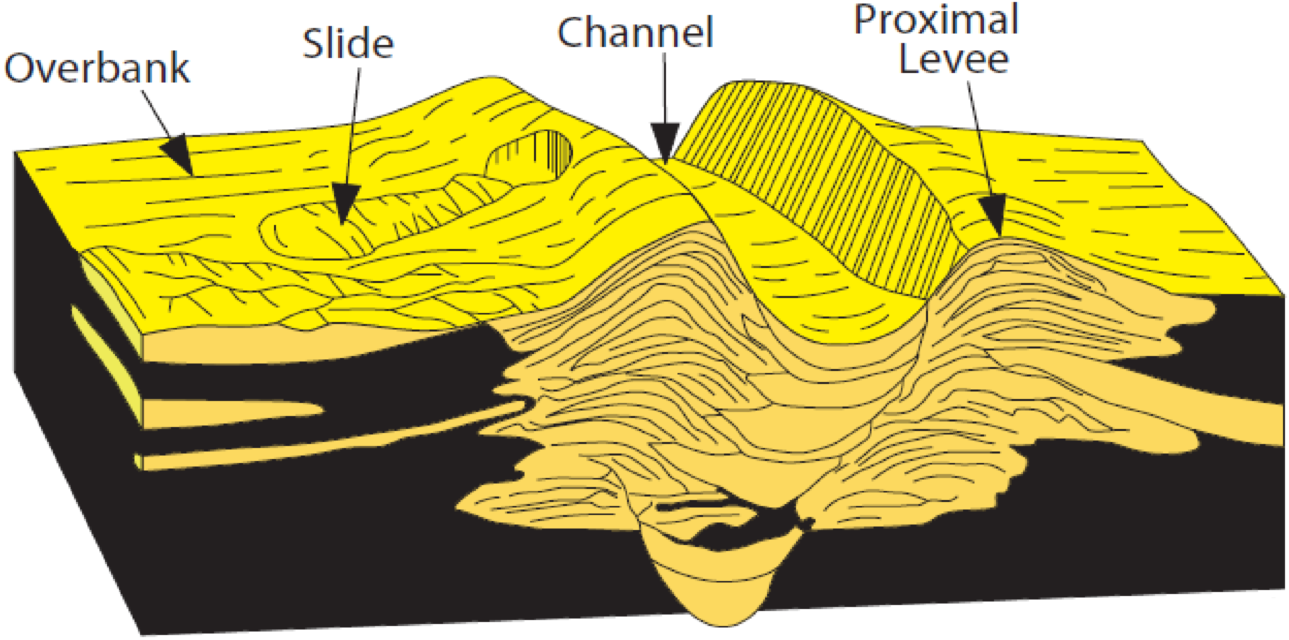
The problem of large submarine fans



Babonneau et al., 2010

Characterising flow





Characterising flow

	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
Velocity	0.7 m s^{-1} (Vangriesheim et al., 2009)		
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

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

2D Direct numerical simulation

Continuity equation: Incompressible flow

$$\nabla \cdot \mathrm{u} = 0$$

Conservation of momentum: Navier-Stokes equations in Boussinesq approximations

$$\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathrm{u} + c\mathrm{e}^g$$

Small particle size: neglect inertia

$$\frac{\partial c}{\partial t} + (\mathrm{u} + u_s \mathrm{e}^g) \cdot \nabla c = \frac{1}{ScRe} \nabla^2 c$$

2D Direct numerical simulation

Reynolds number

$$Re \mathrm{o} \frac{\hat{u}_b \hat{H}/2}{\hat{n}} \quad \text{where} \quad \hat{u}_b = \sqrt{\hat{g}\frac{\hat{r}_1 - \hat{r}_0}{\hat{r}_0}\frac{\hat{H}}{2}}$$

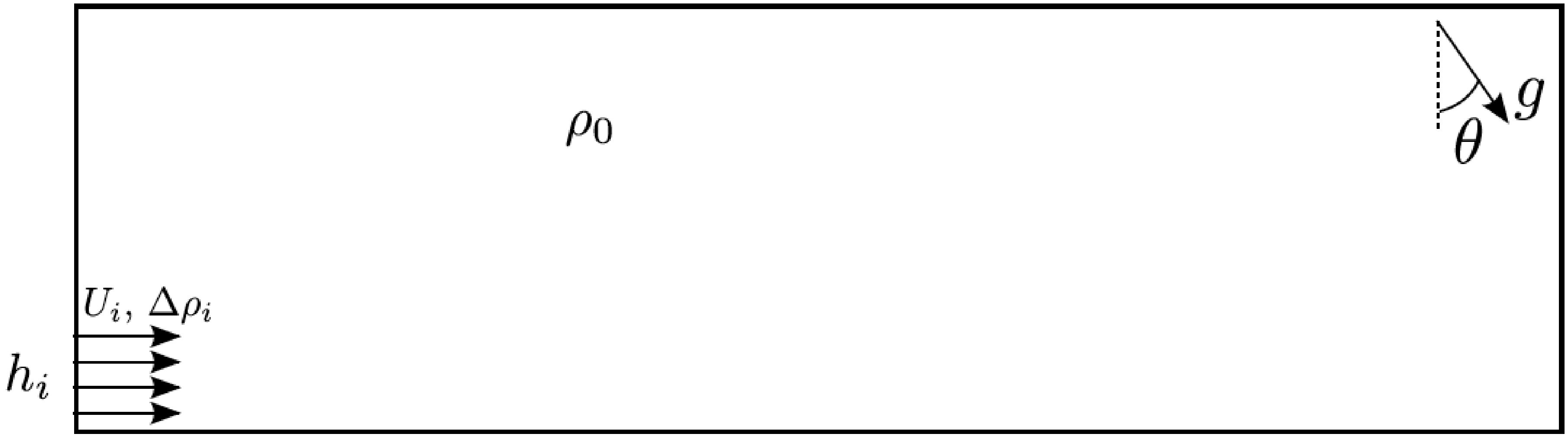
Schmidt number (no significant influence when *Sc* ≥ 1)

$$Sc \mathrm{o} \frac{\hat{n}}{\hat{k}}$$

Dimensionless particle settling speed

$$u_s \mathrm{o} \frac{\hat{U}_s}{\hat{u}_b}$$

2D Direct numerical simulation



$$Fr_i = \frac{U_i}{u_b}$$

But is a bulk Froude number appropriate in stratified flows?

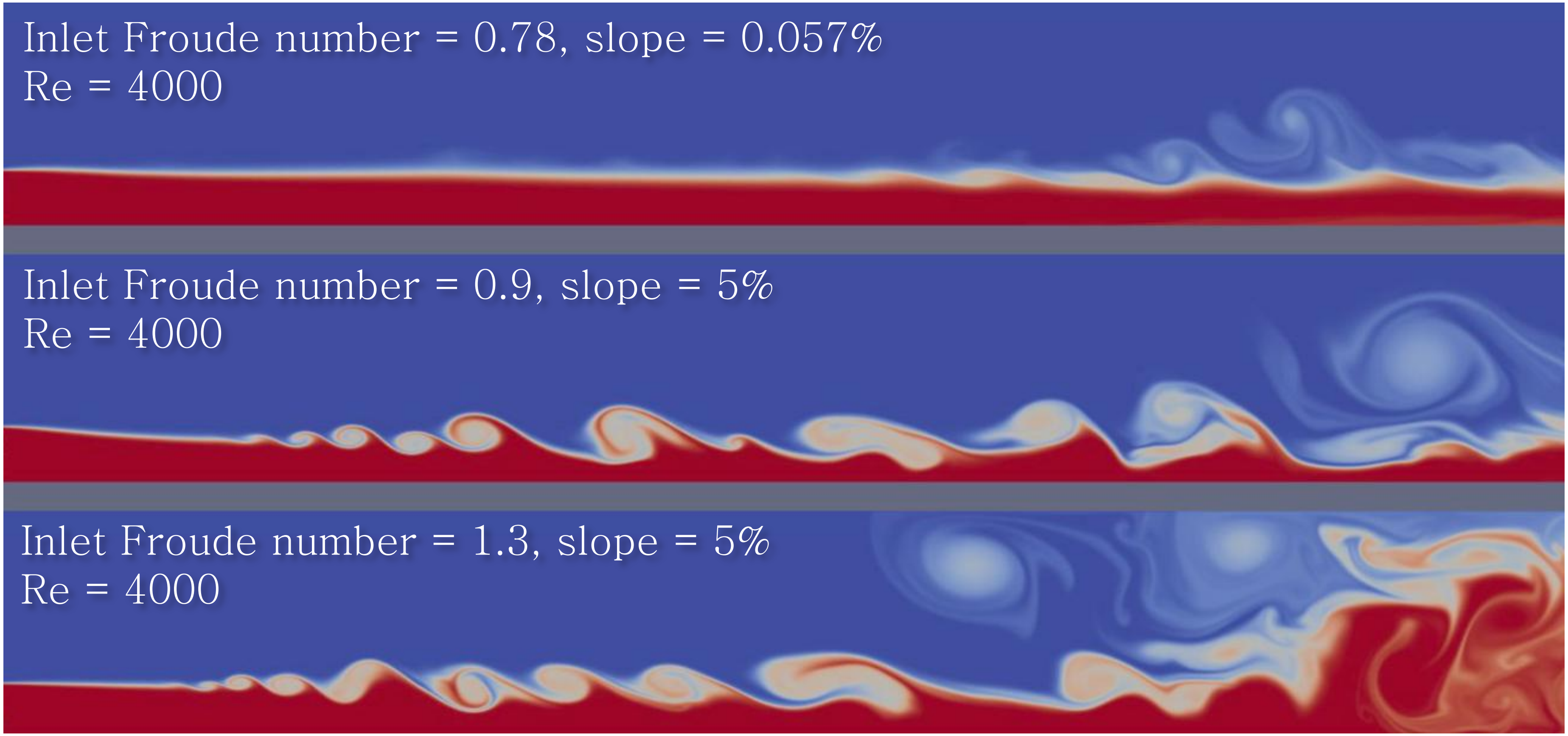
2D Direct numerical simulation; Re = 4000

Inlet Froude number = 0.78, slope = 0.057%

Inlet Froude number = 0.9, slope = 5%

Inlet Froude number = 1.3, slope = 5%

2D Direct numerical simulation



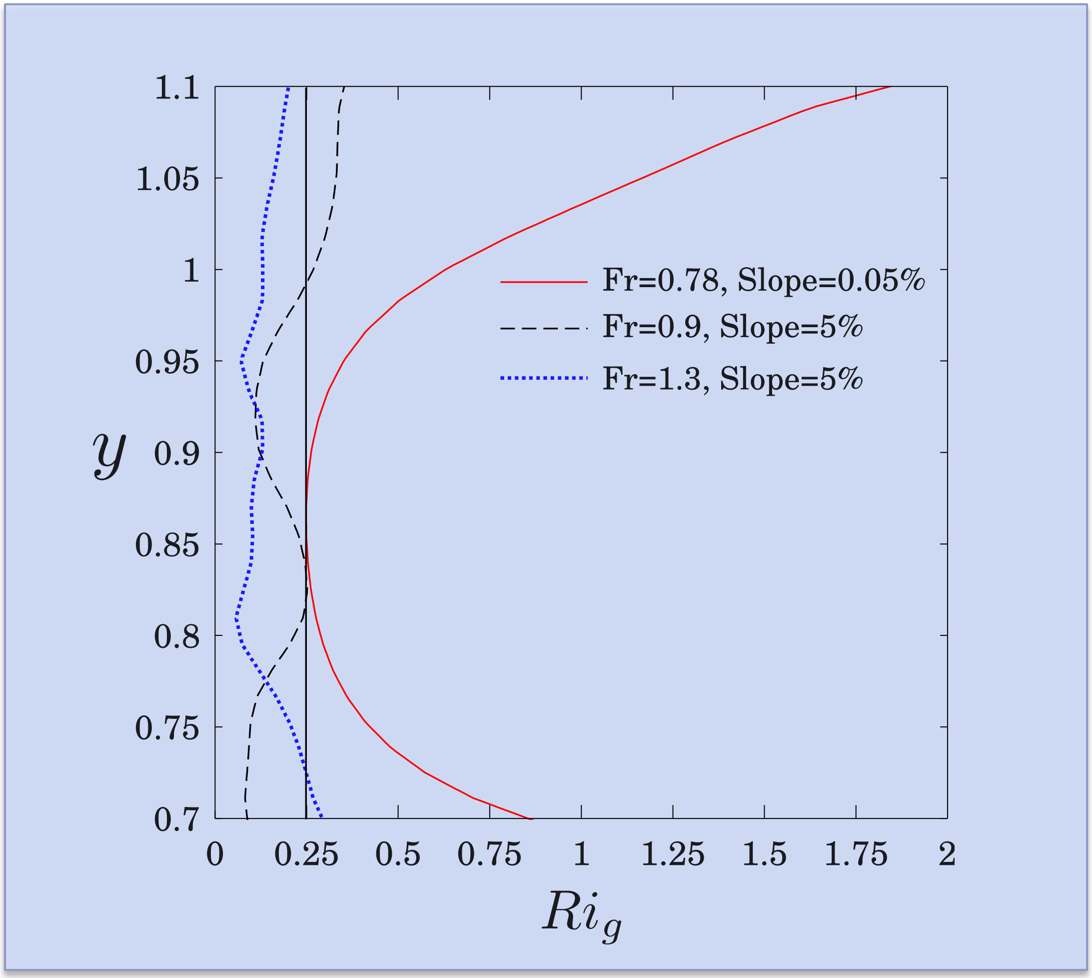
Inlet Froude number = 0.78, slope = 0.057%
Re = 4000

Inlet Froude number = 0.9, slope = 5%
Re = 4000

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

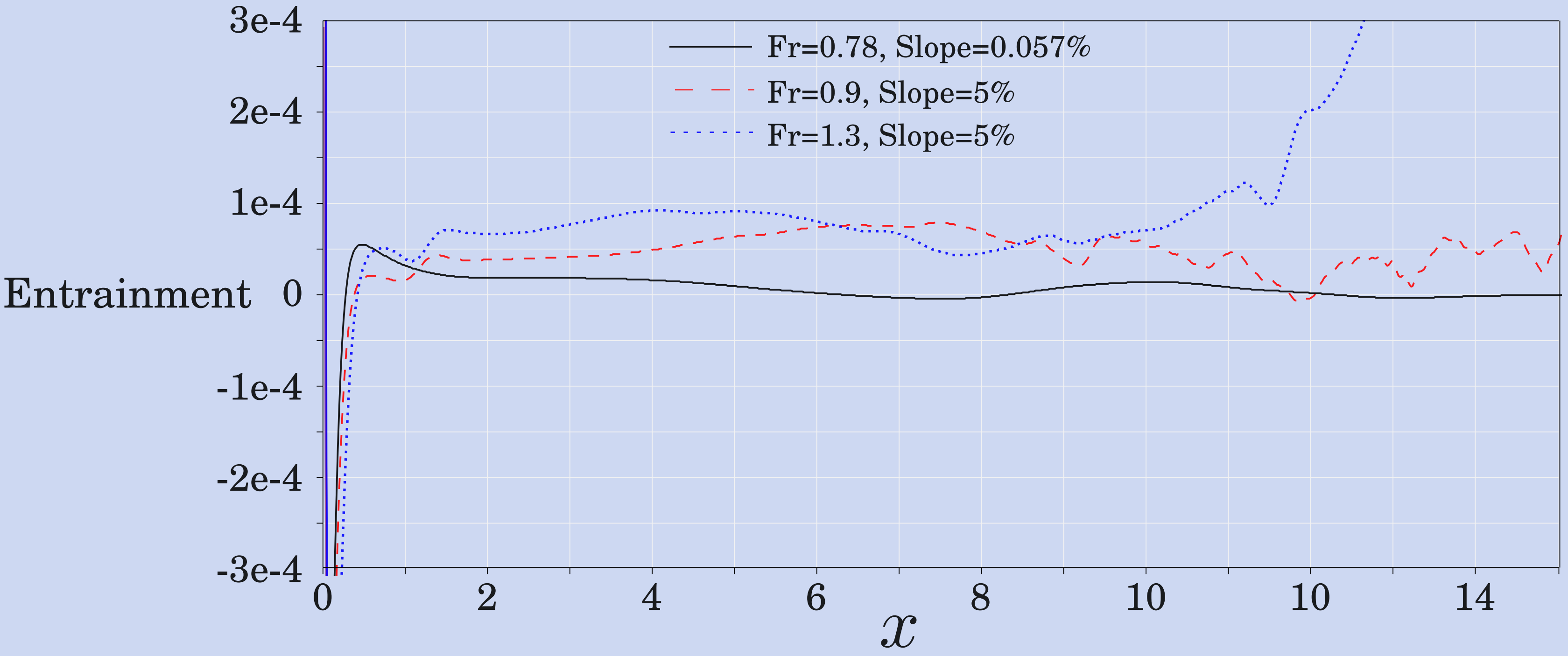
ull Navier–Stokes with Boussinesq approximation. Method in Nasr-Azadani and Meiburg, 201

2D Direct numerical simulation Gradient Richardson number



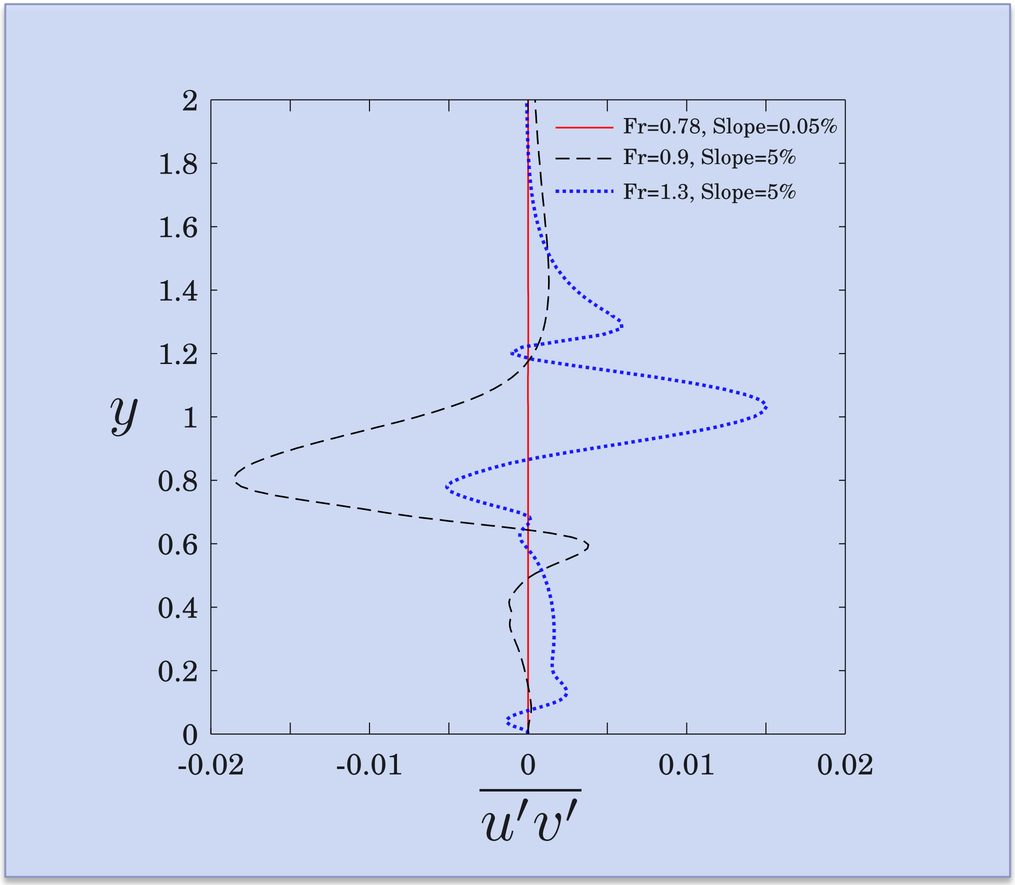
Flows on lower gradients (subcritical) have stable stratification

2D Direct numerical simulation, entrainment



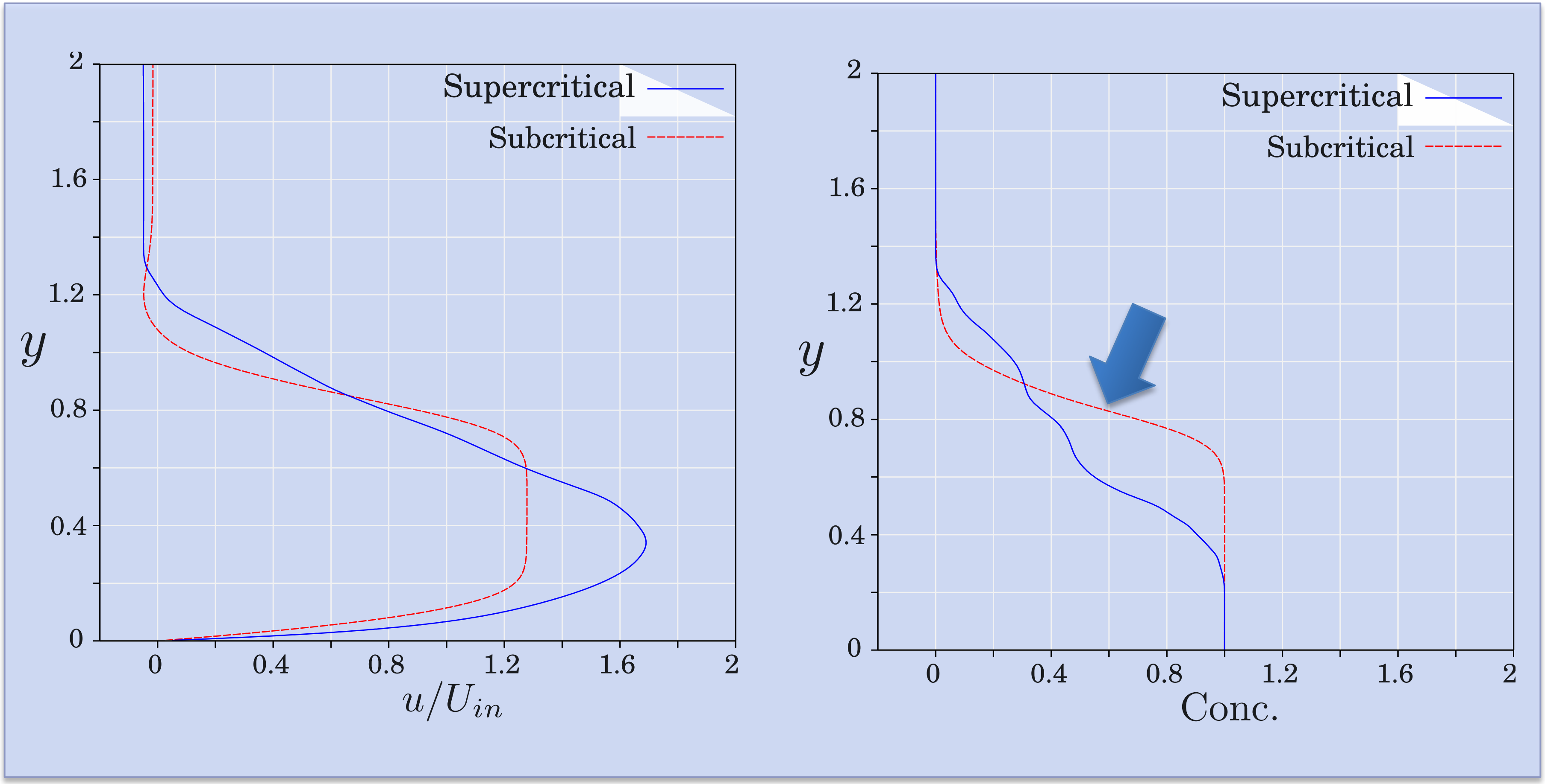
Flows on lower gradients show minimal entrainment

2D Direct numerical simulation, ‘turbulent’ drag



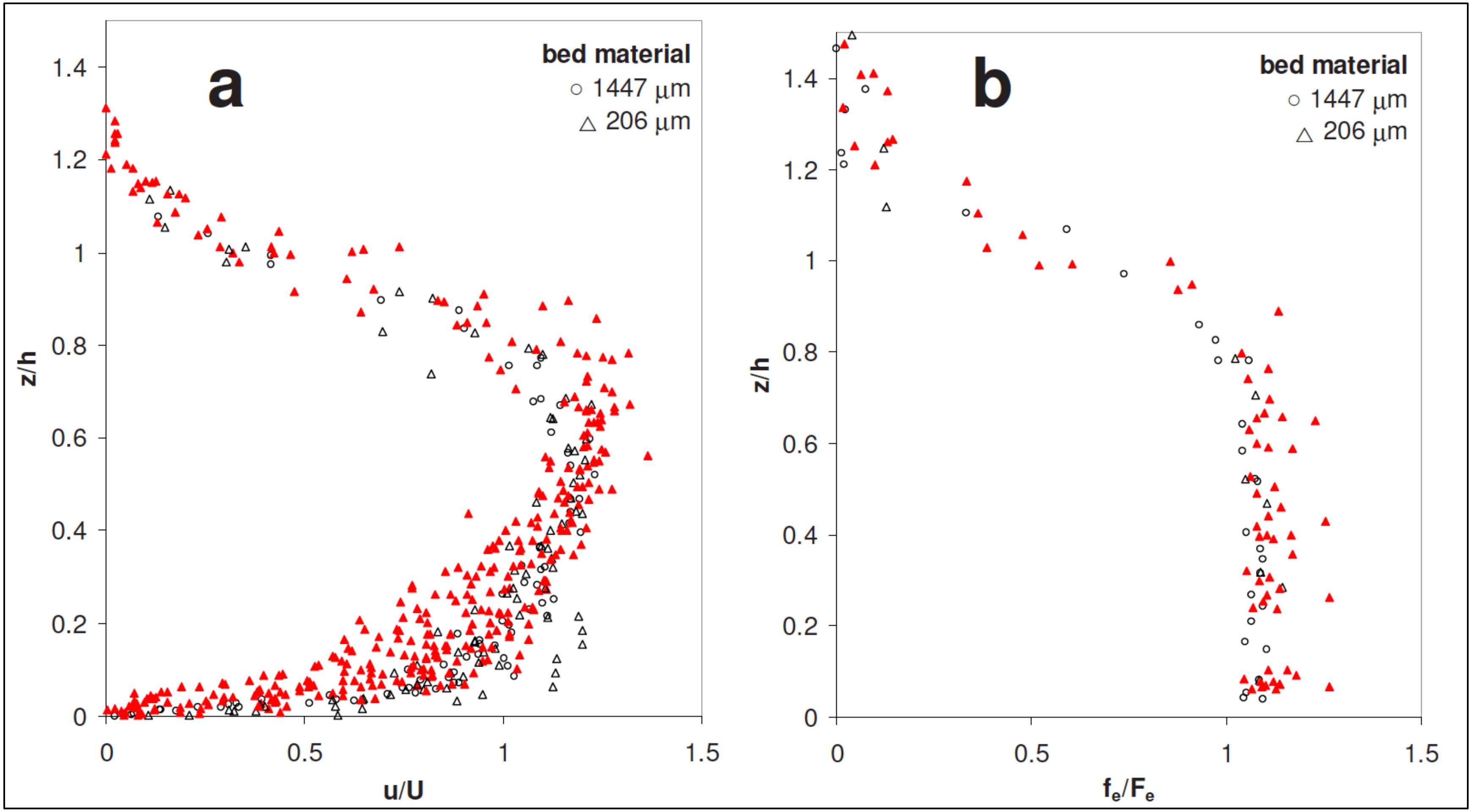
Flows on lower gradients show minimal turbulent drag

2D Direct numerical simulation, velocity and density profiles



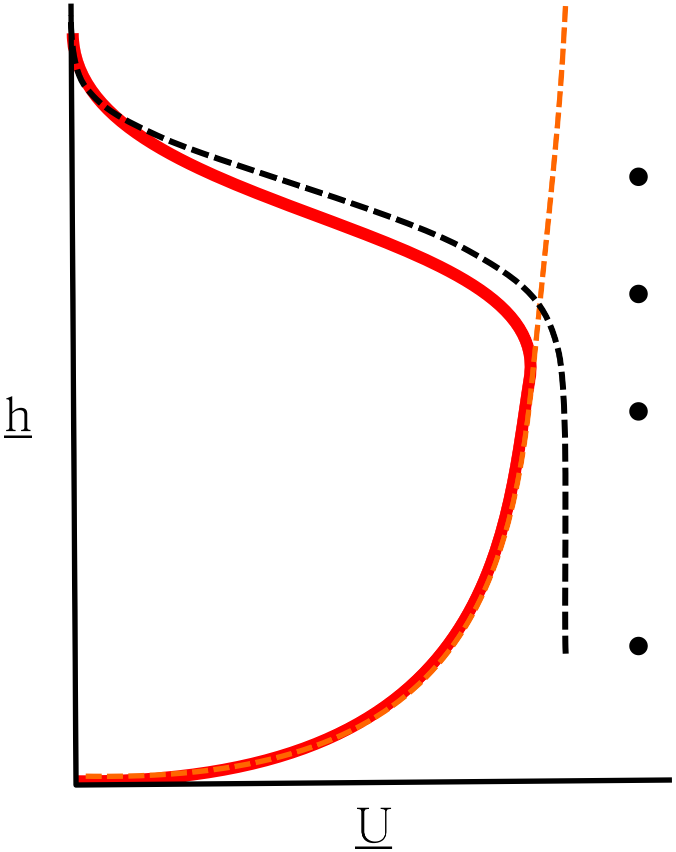
Flows on lower gradients have radically different velocity and density profiles

Experimental flows show similar behaviour



Sub-critical gravity flows. Sequeiros et al. 2010

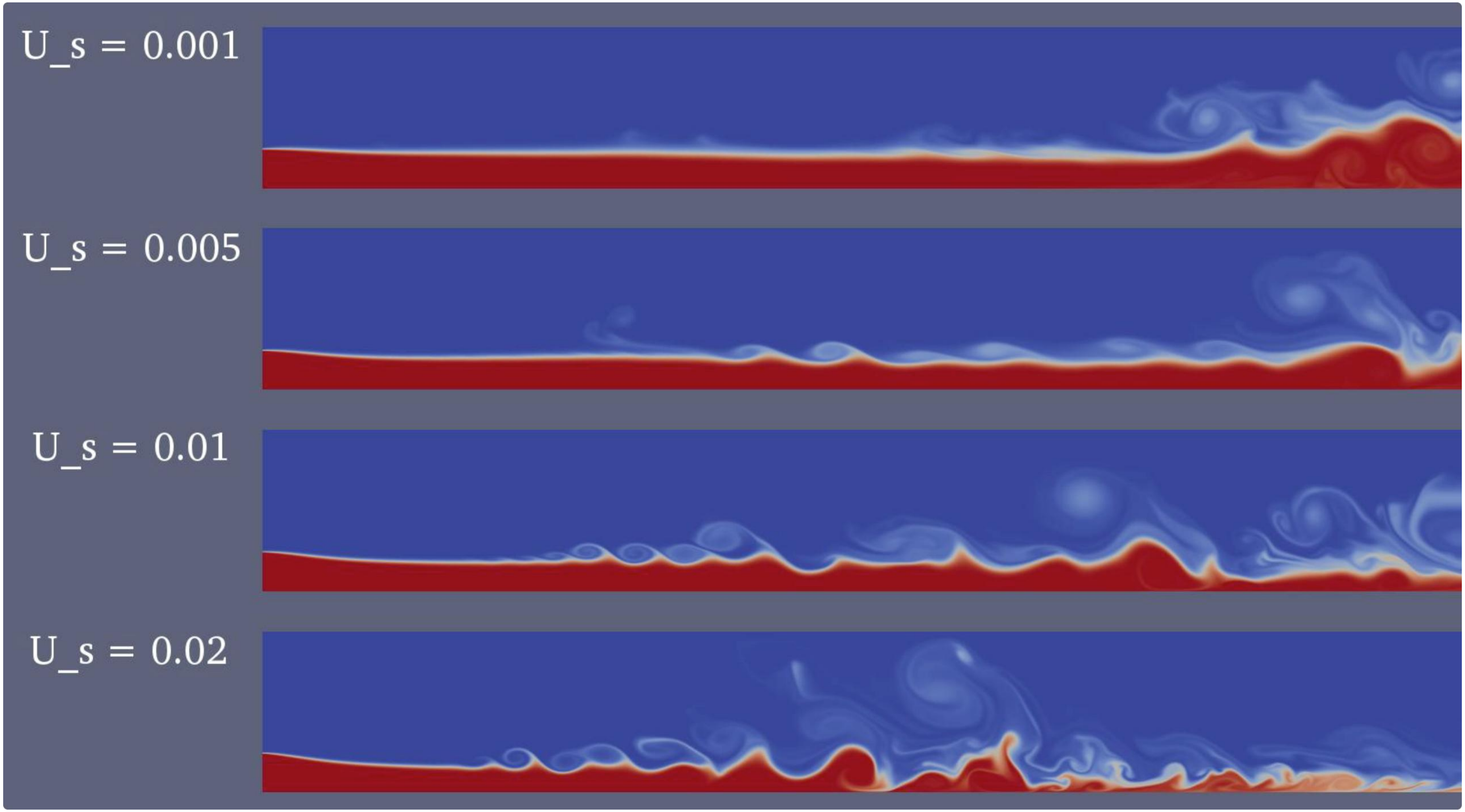
Absence of Kelvin-Helmholtz instabilities…



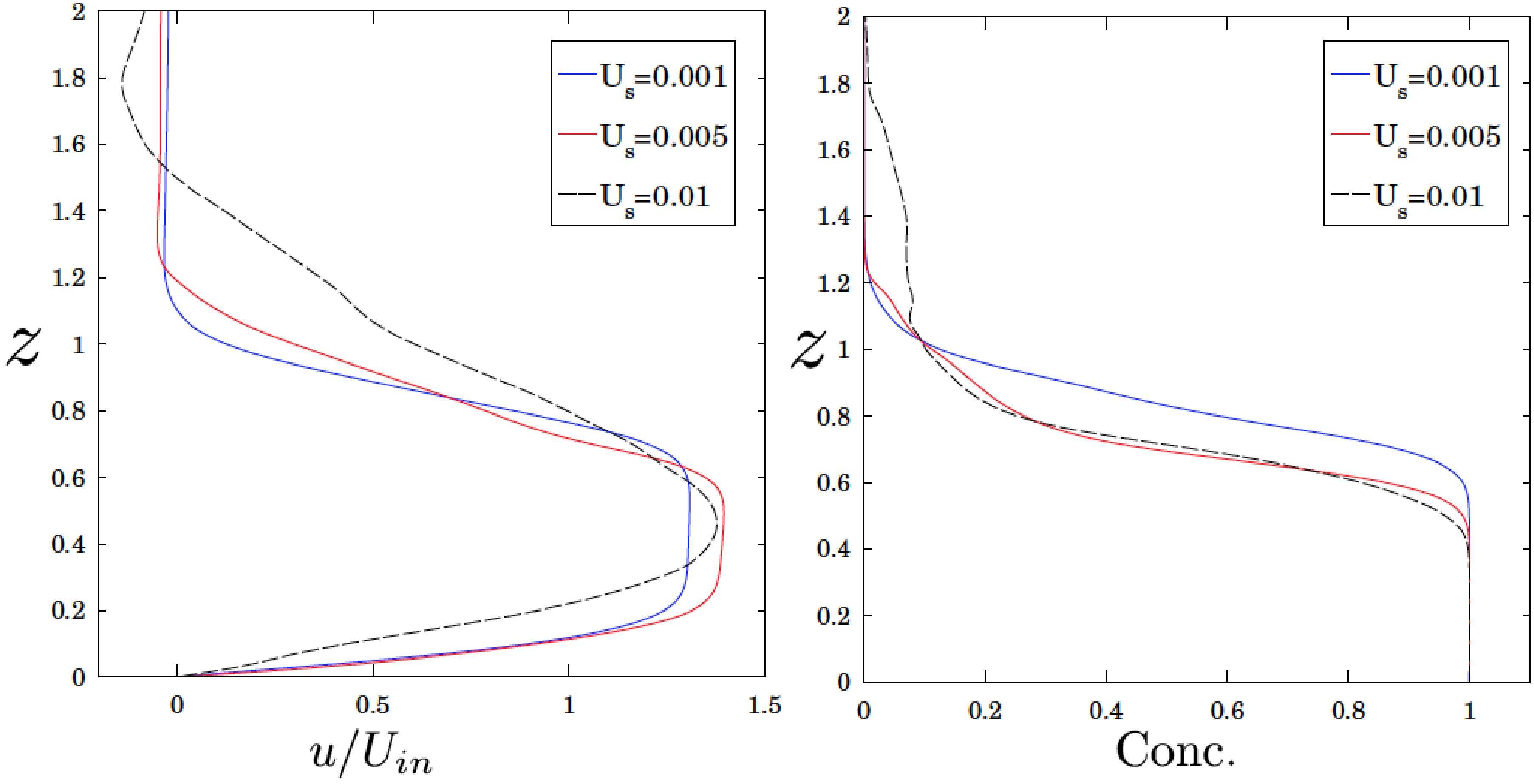
- Substantially reduced drag
- No ambient fluid entrainment
- Velocity profile dominated by lower boundary
- Weak density stratification

Influence of settling velocity

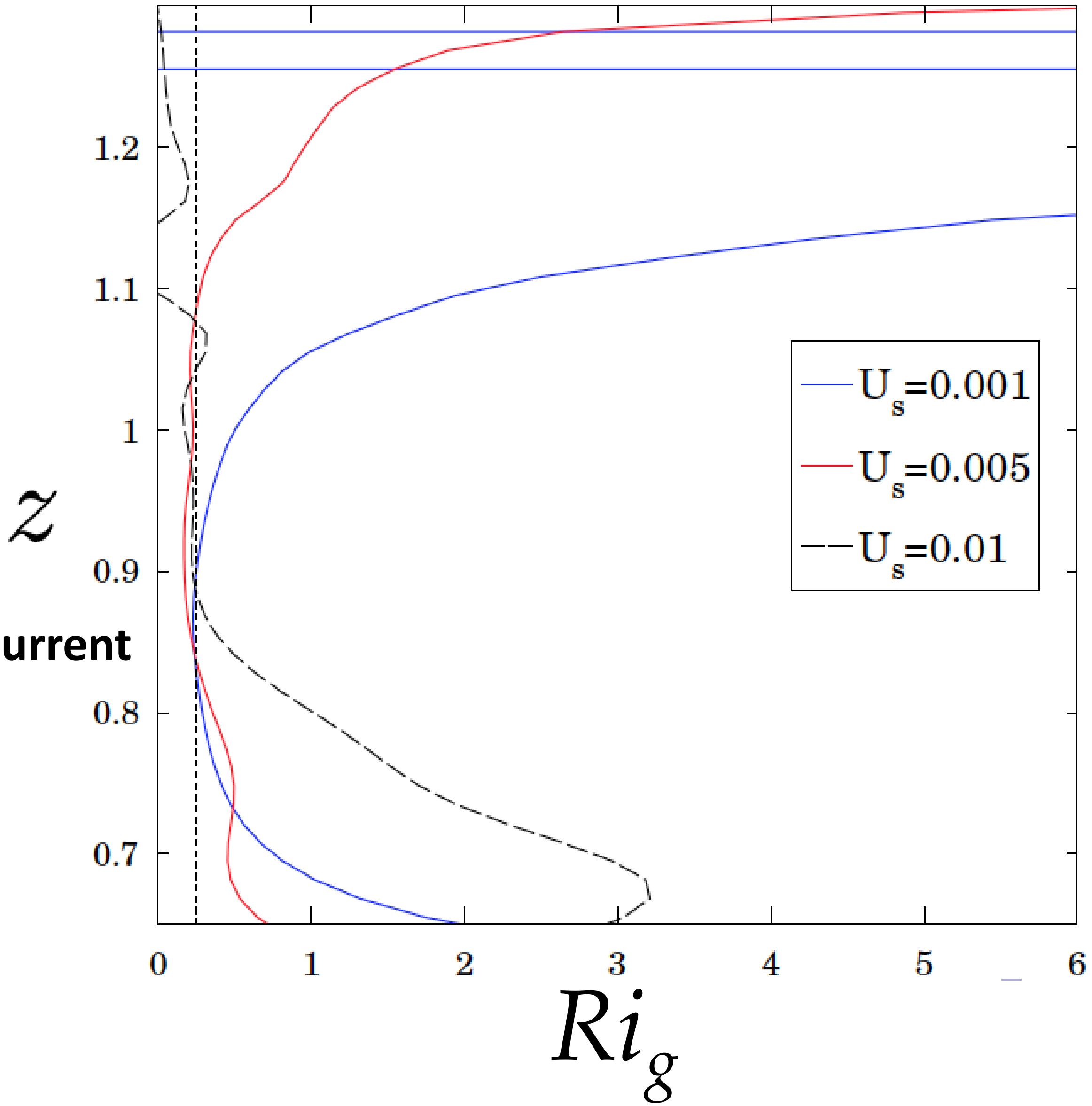
Influence of settling velocity



Influence of settling velocity on density and velocity profiles



Influence of settling velocity on gradient Richardson number



Upper part of current

Constraints on flow parameters

	u^*	U_b	SSC (u^*)	SSC (Ub)
Congo	0.037	0.87	0.03-0.1%	~1%
Amazon	0.012	0.28	0.001-0.01%	~0.50%
Bengal	0.003	0.09	0.0005-0.003%	~0.01%

Is buoyancy velocity the appropriate characteristic velocity with which to scale u_s?

Conclusions

- Turbidity currents on very low gradients probably have stable stratification, do not exhibit Kelvin Helmholtz instabilities, experience **little entrainment** of ambient seawater, and **far lower drag** than flows with Kelvin Helmholtz instabilities
- This accounts for their persistence over enormous distances
- Fundamental difference in character between flows on steep slopes and gentler slopes is driven by change in Ri_g

Thank you for listening

UCSB
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