Turbulence Modulation due to Stratification in Turbidity Currents : Numerical Modeling and Implications for Turbidites

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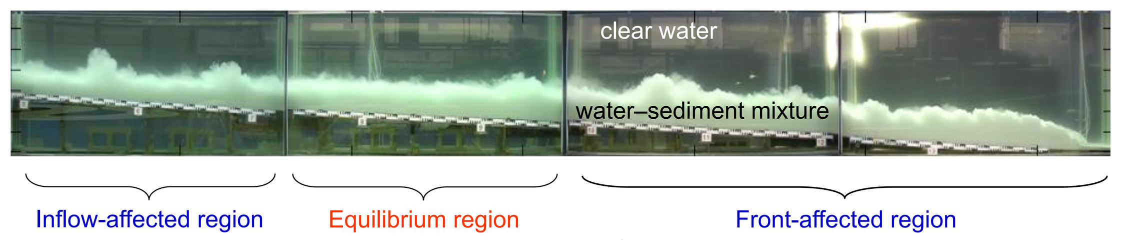
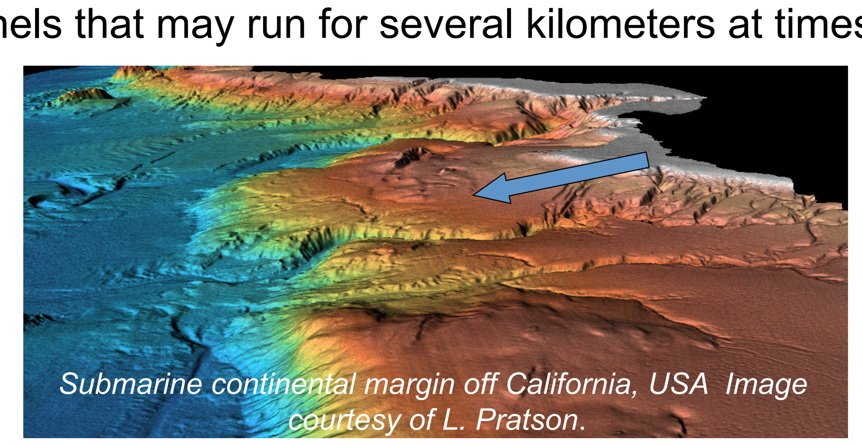
TURBIDITY CURRENTS

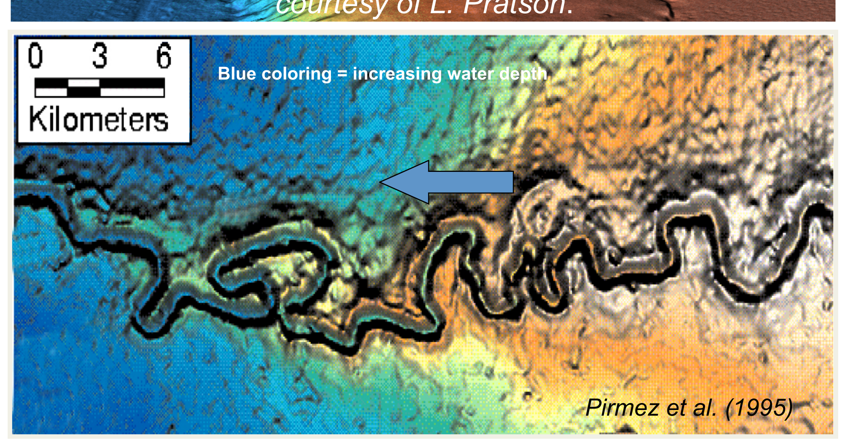


An experimental example of a turbidity current.

Turbidity currents are buoyant flow driven by suspended sediment. Turbidity currents are subset of Density or Gravity currents, which include: oceanic fronts, avalanches, lahars, pyroclastic flows, and lava flows. Along with other pyroclastic flows they can be also defined as Non-Conservative gravity currents; due to the non-conservative nature of the driving media, which is sediment in case of Turbidity currents. Turbidity currents happen often in nature (lakes and oceans), and they are known to be **one of the main mechanisms of sediment transport in the ocean environment.** Under certain conditions these flows can be sustained for hours or some times for days, and are capable of carving deep canyons in the continental shelf. Turbidity currents are also known to produce long submarine meandering channels that may run for several kilometers at times.



Submarine continental margin off California, USA Image courtesy of L. Pratson.



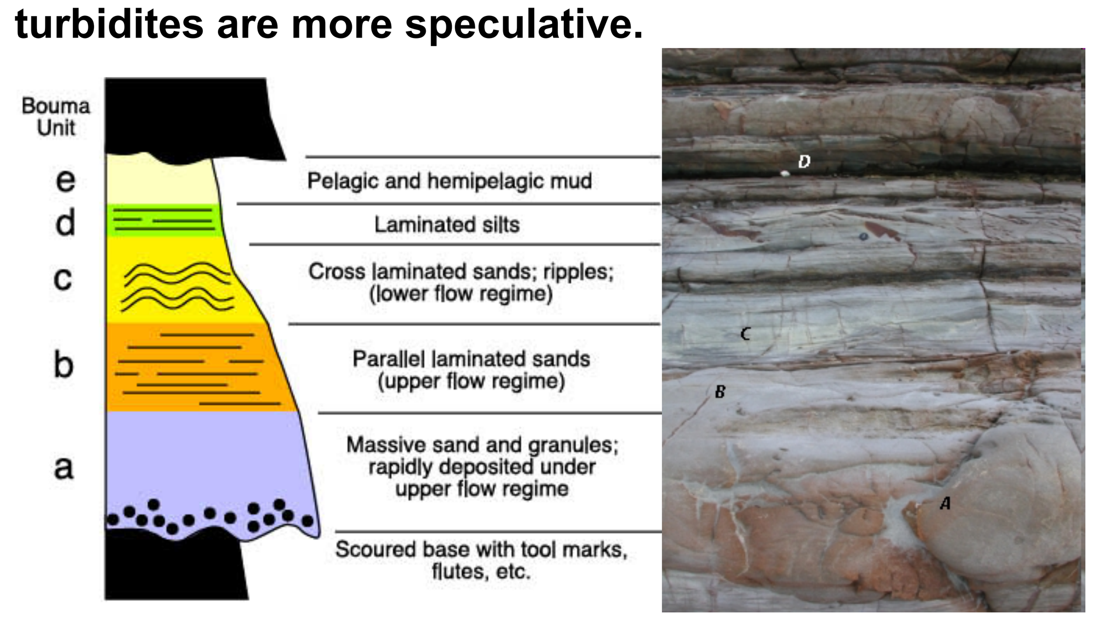
Amazon Channel System of the coast of Brazil

Deposition due to Turbidity currents

When the energy of a Turbidity current lowers, its ability to carry suspended sediment decreases and sediment deposition occurs; thus a wide range of structures in the depositional records have been emplaced as **turbidites** by turbidity currents. Turbidity currents are rarely seen in nature, thus turbidites can be used to determine characteristics of turbidity current. Often, when the local topography and the flow conditions are right, turbidity currents may produce massive deposits of sand that become oil reservoirs (Leclair and Arnott 2003) over geological time scales. Turbidites seen in outcrops are often characterized in terms of the **Bouma sequence** (Bouma 1962). **Units a to e in Bouma sequence** are interpreted in terms of a single flow event, with flow waning from bottom to top.

Gravel wave emplaced by turbidity current, Patagonia Chile

Of interest here are **units a and b**, both of which tend to be sandy. **Unit a** is "massive", i.e. either **lacking or highly deficient in depositional structure.** Parallel laminations are seen in fluvial deposits as well as turbidites, and have been reproduced in the laboratory (Paola et al 1989, Best and Bridge 1992). They are associated with upper-regime plane-bed flow. Their formation is due to the organization of sand grains into streaks according to size and orientation by the bedload layer. **Mechanisms for the emplacement of massive turbidites are more speculative.**

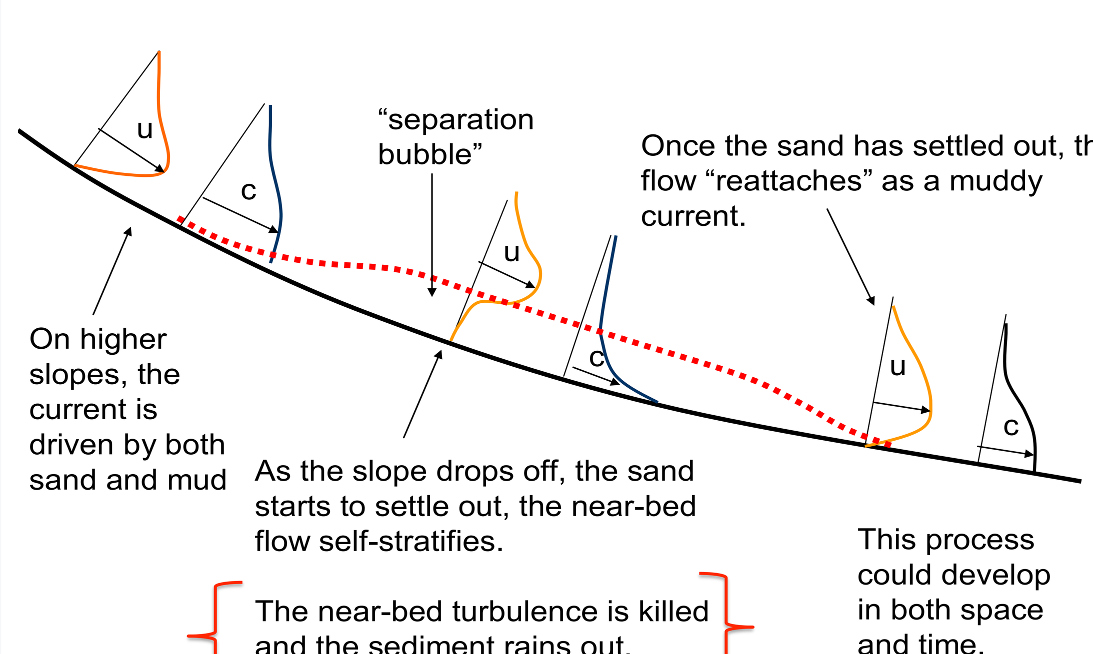


Characteristic Sedimentation Pattern: Bouma Sequence

These units (a) can be up to meters in thickness, and can be extensive in the downdip direction. They do not have fluvial analogs. A mechanism has been put forward to explain the depositional structure.

The Mechanism

NEW THEORY OF COLLAPSE OF TURBULENCE DUE TO SELF-STRATIFICATION (GARY PARKER et al.)



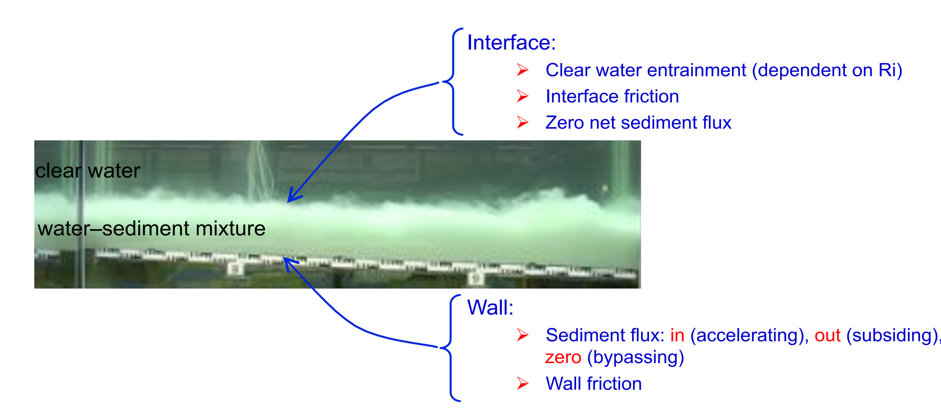
Conceptual Model

To quantify the proposed mechanism a conceptual model of a continuous inflow Turbidity current is proposed. It is called **TCR** (Turbidity Current with a Roof) and it reflects the characteristics of the **Equilibrium Region** of Turbidity currents.

Turbidity Currents – Equilibrium region

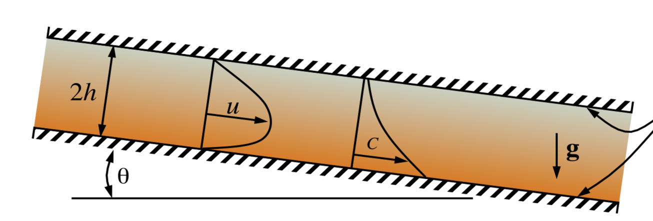
In the equilibrium region:

- Local balance between buoyant force and wall+interface friction
- Local balance of fluid mass between inflow, outflow and ambient entrainment
- Local balance of sediment mass between inflow, outflow and resuspension/ deposition



Conceptual and Mathematical Model

- **Ambient entrainment and model interface friction with a wall neglected**



$$\boxed{\mathbf{u} = 0 \qquad cV_z - \frac{1}{\mathrm{Re}_\tau \mathrm{Sc}}\frac{\partial c}{\partial z} = 0}$$

Conservation of momentum

$$\frac{\partial \tilde{\mathbf{u}}}{\partial t} + \tilde{\mathbf{u}} \bullet \nabla \tilde{\mathbf{u}} = -\nabla \tilde{p} + \frac{1}{\mathrm{Re}_\tau}\nabla^2 \tilde{\mathbf{u}} + \tilde{c}\ \mathbf{e}_x + \frac{1}{\tan\theta}\left(\tilde{c} - \tilde{c}^*\right)\mathbf{e}_z$$

Conservation of fluid mass based

$$\nabla \cdot \tilde{\mathbf{u}} = 0$$

$$\boxed{u^2_{*,avg} = \frac{\tau_b + \tau_t}{2\rho} = g_x \frac{\rho_s - \rho}{\rho} c^{(v)} h}$$

Conservation of mass for sediment

$$\frac{\partial \tilde{c}}{\partial t} + \nabla \cdot \left[\tilde{c}\left(\tilde{\mathbf{u}} + \tilde{\mathbf{V}}_s\right)\right] = \frac{1}{\mathrm{Sc}\,\mathrm{Re}}\nabla^2 \tilde{c} \qquad \boxed{\mathrm{Re}_\tau = \frac{u_{*,avg}\, h}{\nu}} \qquad \boxed{\mathrm{Sc} = \frac{\nu}{\kappa}}$$

The above mathematical model is solved using DNS (Direct Numerical Simulation). Details of the numerical scheme used can be found in Cantero et al. (2009). The equations were solved for different settling velocities of sand, for Re_τ = 180, Sc = 1 and θ = 5°.

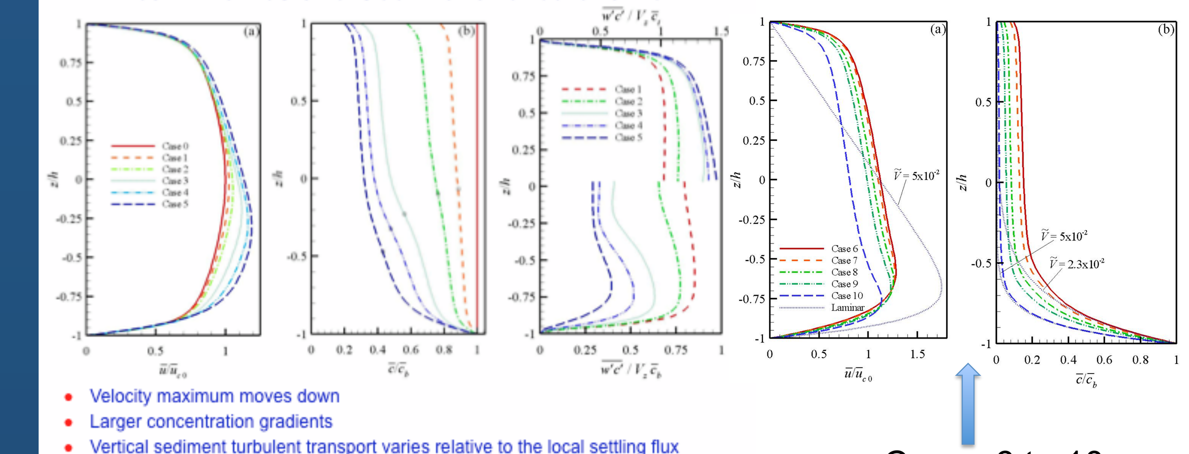
Results

The simulations has been done for 10 different cases with varying values of settling velocities (there is a case 0 for 0 settling velocity). The values of different parameters obtained from each simulation has been listed below.

Table 1. Cases studied in this work. For all cases the domain size is $L_x = 4\pi h \times L_y = 2\pi h \times L_z = 2h$, and resolution is $N_x = 96 \times N_y = 96 \times N_z = 97$. In the table $\tilde{z}_{u,max}$: location of streamwise velocity maximum, $\tilde{z}_{pyc}$: location of pycnoclyne, and $\tilde{z}_{0ReS}$: location of zero Reynolds shear stress.

Case	$\tilde{V}$	$\tilde{T}_{avg}$	$\tilde{u}_b$	Re_b	Ri_b	$\tilde{u}_{*,t}$	$\tilde{u}_{*,b}$	$\tilde{\bar{c}}_t$	$\tilde{\bar{c}}_b$	$\tilde{z}_{u,max}$	$\tilde{z}_{pyc}$	$\tilde{z}_{0ReS}$	$\mathcal{K}_b$	B_b
0	0	160	15.38	2769	0	1.00	1.00	1.00	1.00	0.00		0.00	0.41	5.5
1	5×10^{-3}	50	15.61	2811	0.012	1.00	1.00	0.88	1.14	-0.03	-0.07	-0.03	0.35	4.0
2	10^{-2}	50	15.88	2858	0.026	0.99	1.01	0.76	1.32	-0.07	-0.10	-0.07	0.32	3.1
3	1.75×10^{-2}	50	16.46	2962	0.055	0.99	1.01	0.57	1.86	-0.20	-0.23	-0.23	0.27	1.9
4	2×10^{-2}	50	17.02	3064	0.067	1.02	0.99	0.53	2.23	-0.26	-0.32	-0.32	0.24	1.6
5	2.125×10^{-2}	50	17.48	3146	0.079	1.05	0.95	0.52	2.63	-0.29	-0.47	-0.39	0.215	1.2
6	2.3×10^{-2}	60	18.04	3247	0.141	1.05	0.94	0.43	4.45	-0.58		-0.66		
7	2.5×10^{-2}	200	17.81	3206	0.166	1.03	0.96	0.39	5.00	-0.58		-0.68		
8	3×10^{-2}	50	17.20	3097	0.243	0.98	1.02	0.29	6.58	-0.63		-0.73		
9	3.5×10^{-2}	50	16.46	2963	0.341	0.93	1.07	0.21	8.30	-0.68		-0.75		
10	5×10^{-2}	200	14.02	2524	0.825	0.77	1.19	0.07	14.26	-0.75		-0.83		

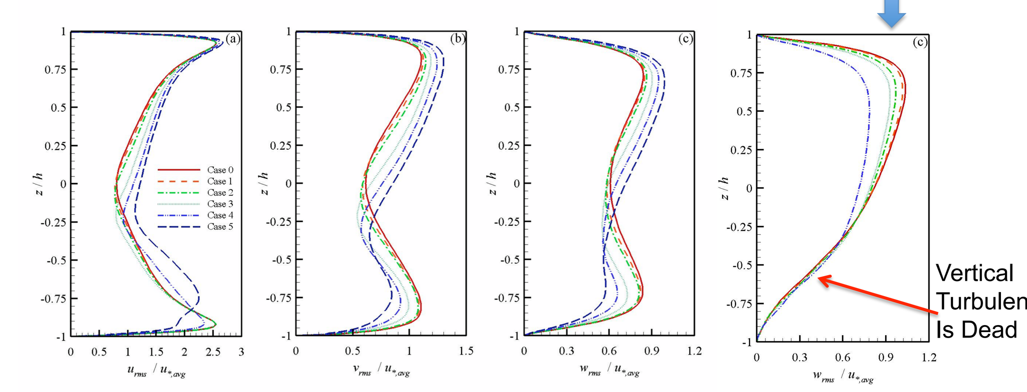
Mean Profiles and Sediment Turbulent Flux



- Velocity maximum moves down
- Larger concentration gradients
- Vertical sediment turbulent transport varies relative to the local settling flux

Cases 6 to 10

Turbulent Intensities



Conclusions

- The presence of sediment breaks the symmetry of the flow due to the tendency to self-stratify
- Self-stratification damps turbulence near the bottom wall
- Two regimens are present with a rather sharp transition from one to the other occuring for 2.22 x 10[-2] < $|V_z| / u_{*b}$ < 2.43 x 10[-2] for Re_τ = 180
- The results clearly show that the suggested mechanism works for Re_τ used in the present case. In order to fully cement the hypothesis simulations of TCR needs to be done at higher Re_τ (Parsons and Garcia 1998).
- At present DNS has its limitations due to exorbitant computation cost, so a LES (Large Eddy Simulation) model is under development to tackle the problem.

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Acknowledgments

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