Coriolis forces influence the secondary circulation of gravity currents flowing in large scale sinuous submarine channel systems

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Introduction

We wish to explain a more recent observation (Peakall et al., 2011) that submarine canyons at high latitudes tend to be less sinuous than systems at low latitudes (Figure 1).

We present results from rotating experimental gravity currents and describe how the internal velocity structure changes with a varying Coriolis parameter f (defined as $f=2\Omega\sin(\phi)$) representative of low and high latitude systems.

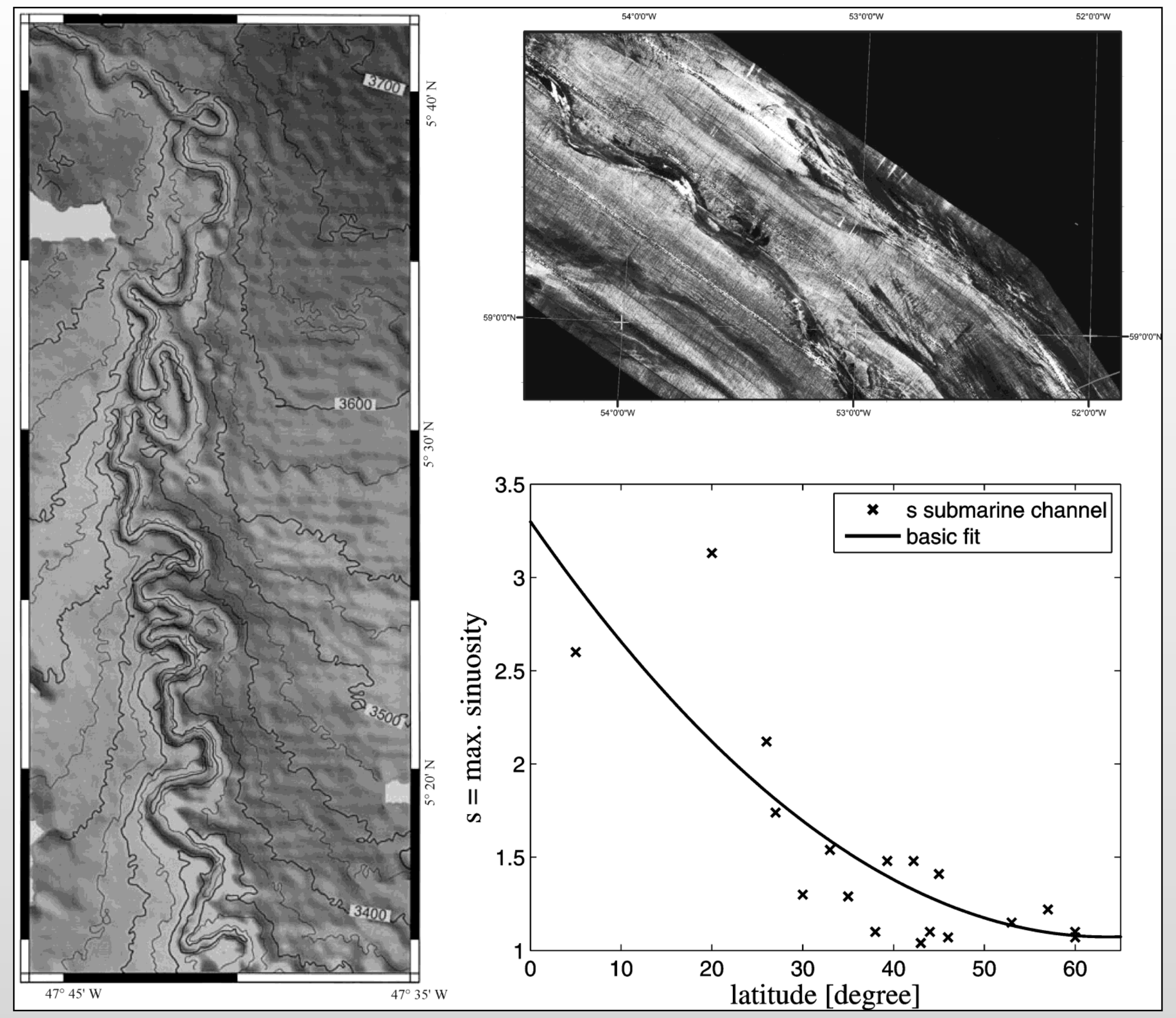


Figure 1:

Left-hand: Bathymetry of the Amazon submarine channel close to the equator with an average sinuosity of 2.6 (after Imran et al., 1999).

Top right-hand: Bathymetry of the North Atlantic Mid-Ocean Channel (NAMOC) with an average sinuosity of 1.1 at a latitude of 55º N (from Skene et al., 2002).

Bottom right-hand: Sinuosity of several channel systems plotted against the latitude (data modified from Clark and Pickering, 1996). At high latitudes submarine canyons show little sinuosity compared to their equatorial counterparts.

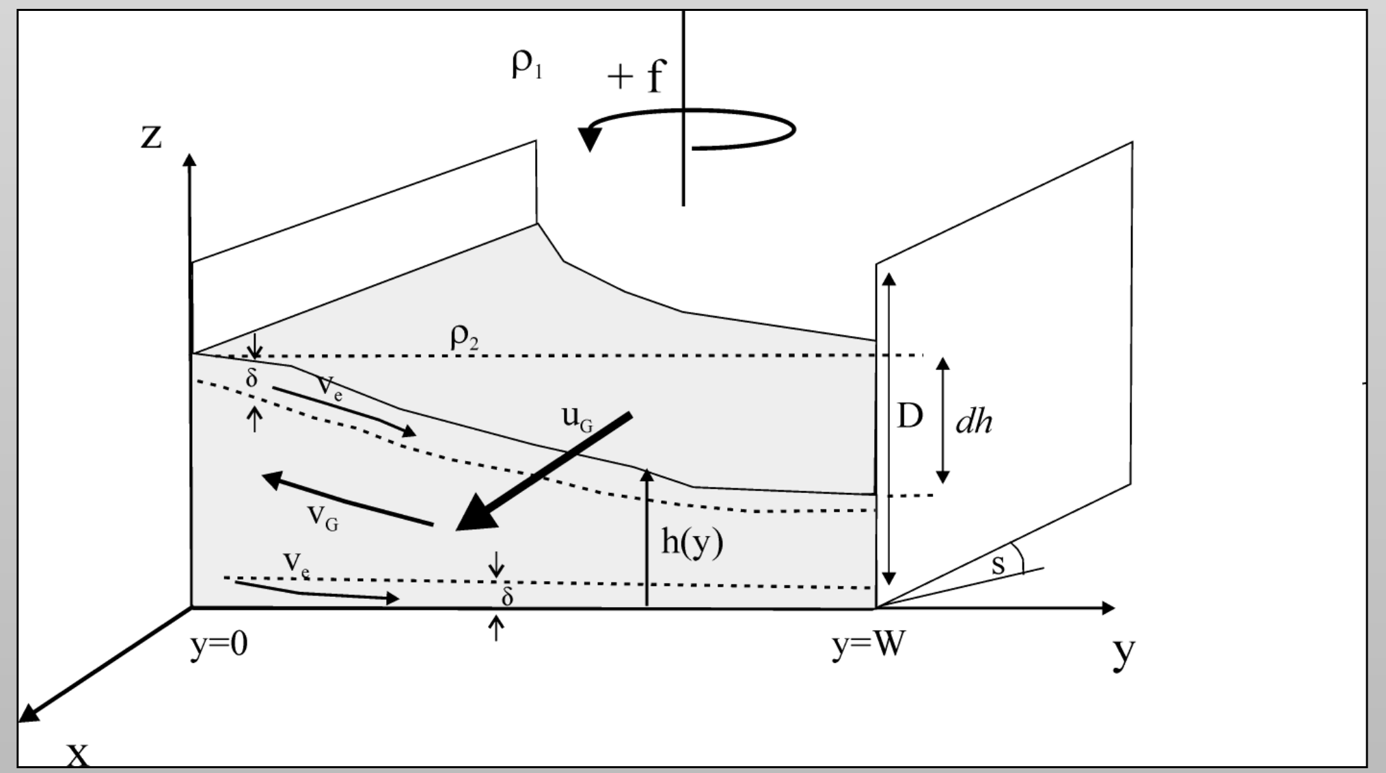


Figure 2:
Schematic sketch (from Cossu et al., 2010) of a density current flowing down a submarine channel with the gradient s, the channel height D and the channel width W (looking upstream).

The density of the ambient fluid and the gravity are ρ_1 and ρ_2 respectively, with $\rho_2>\rho_1$. The main downstream flow is u_G while there is also a significant transverse motion consisting of the interior flow v_G and bottom and interfacial currents v_e.

The thickness d of the Ekman boundary is small in comparison to the entire thickness of the flow $h(y)$.

The difference of $h(y)$ between the left and right channel wall is dh. See also Figures 4,5 and 6.

Methods

- analog modelling; rotating gravity currents flowing down a channel model
- saline density currents as surrogates for fine mud turbidity currents (e.g. Keevil et al., 2006; Sequeiros et al., 2010; Amos et al., 2010).
- Metflow Ultrasonic Doppler Velocity Profiler (UDVP) and a Nortek acoustic Doppler Velocimeter (ADV).

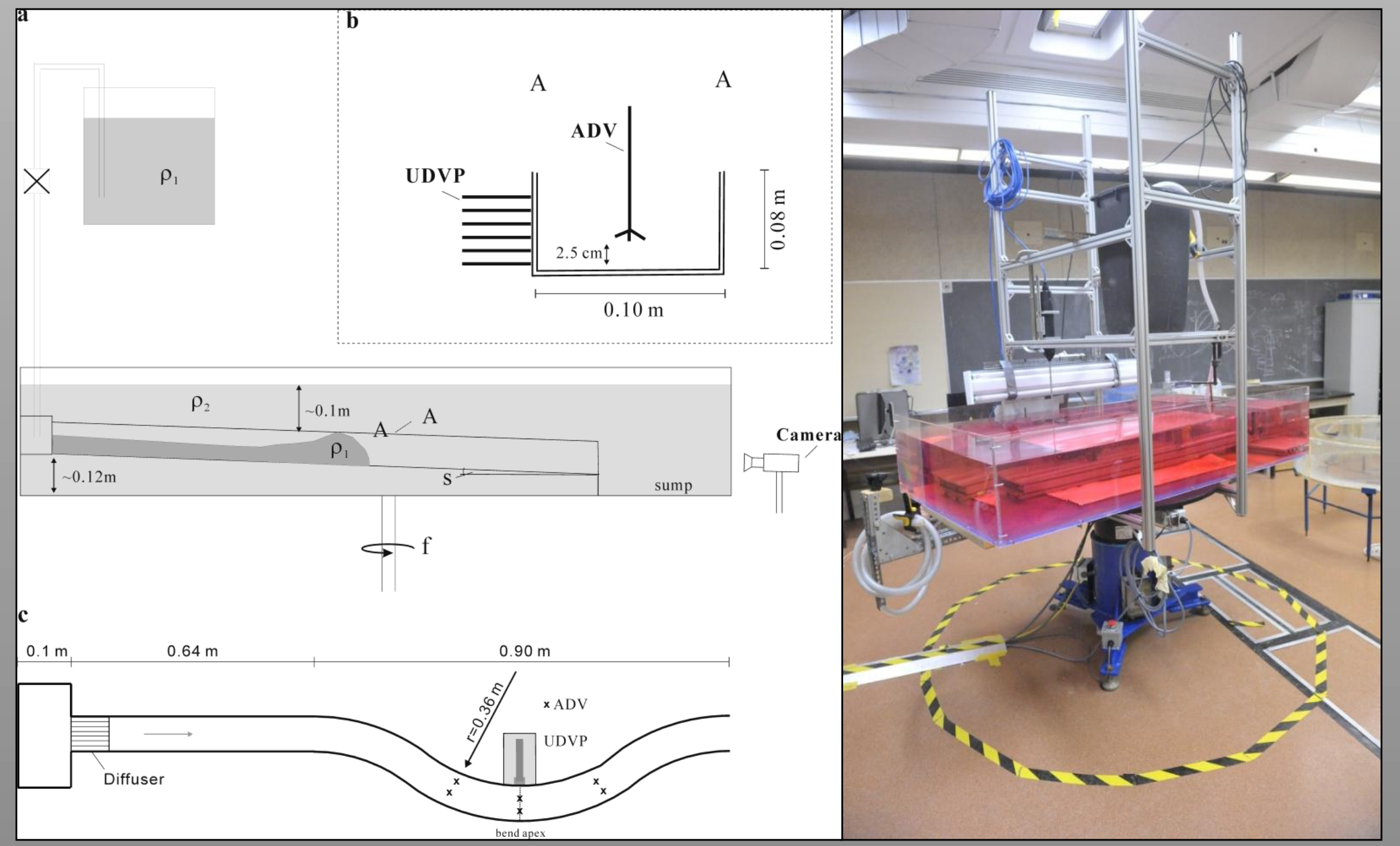


Figure 3:
a) Curved channel model that can be rotated in either the Northern or Southern Hemisphere sense. The Coriolis parameter was varied from f = 0 to ±0.5 rad s^{-1}.

b) Positioning of measuring instruments in the bend apex.

c) Planform geometry of the curved channel model.

right-hand: Photo of the rotating platform.

Results

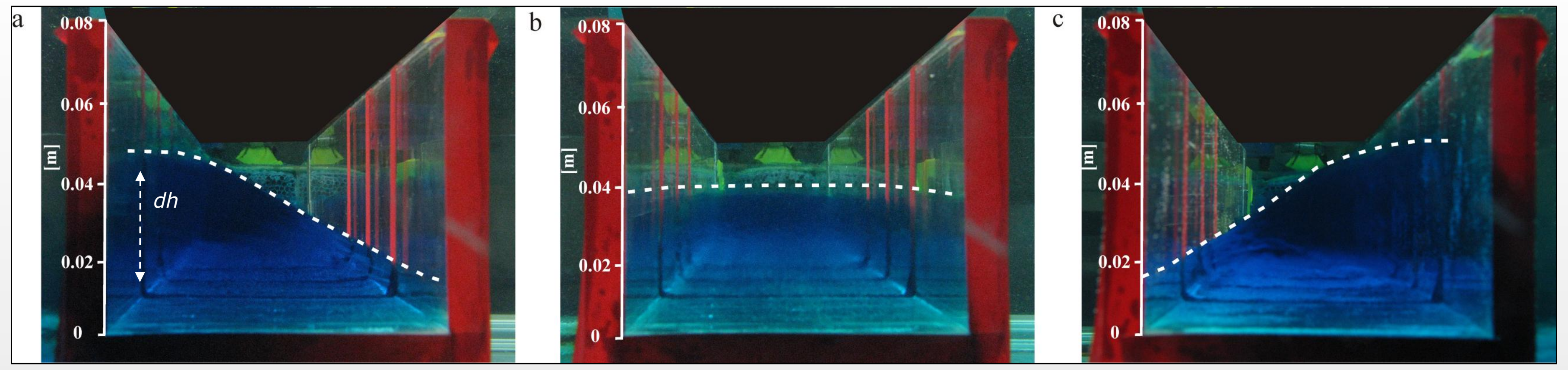


Figure 4:
Change of the density interface of experimental gravity currents in a straight channel section for various f (looking upstream).
a) f = 0.6 rad s^{-1} b) f = 0 rad s^{-1} c) f = -0.6 rad s^{-1}. Data are taken from Cossu et al. (2010).

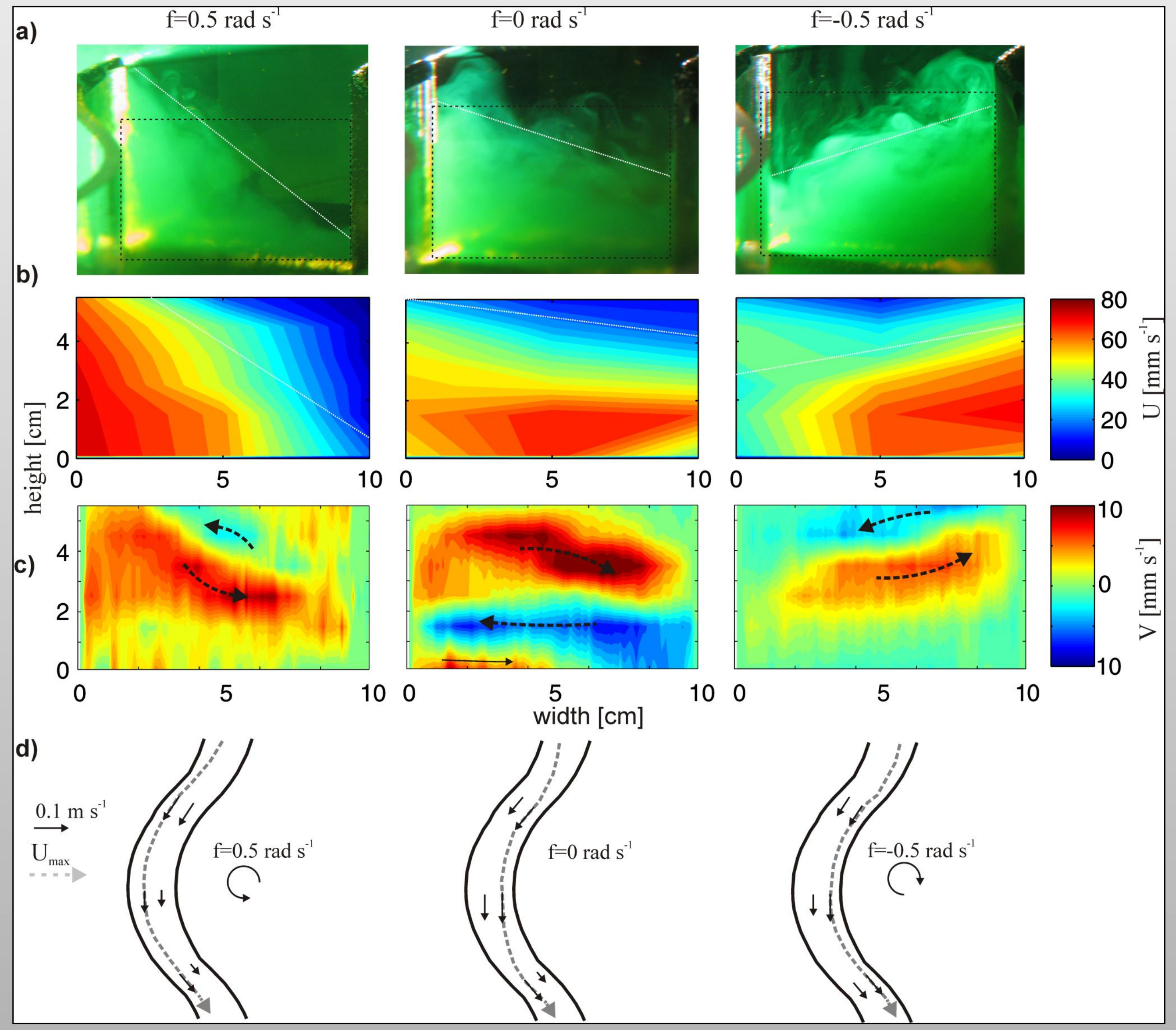


Figure 5:
A combination of centrifugal and Coriolis forces govern the internal flow structure of turbidity currents in sinuous channels.

For f=0 rad s^{-1} only centrifugal forces are important, the density interface shows a superelevation at the outside of channel bends and an internal flow structure similar to observations in Peakall et al. (2007) and Amos et al. (2010).

When Coriolis forces dominate $|f| >> 0$ rad s^{-1} the interface is always deflected to one side of the channel (e.g. to the right-hand-side in the Northern Hemisphere) and the internal flow structure changes dramatically.

Changes of the internal flow structure in a sinuous channel model are illustrated in Figure 5 a-d for various f.

a) Tilt of the density interface.

b) Downstream velocity profiles.

c) Cross stream velocity profiles.

d) Location of the downstream velocity at the bottom.

Data are taken from Cossu and Wells (2010, 2011).

$$\frac{dh}{dy} = Fr^2\left(\frac{hf}{U} + \frac{h}{R}\right) \quad (1)$$

$$Ro_W = \frac{U}{Wf} \quad (2)$$

$$\frac{dh}{h} = Fr^2\left(\frac{1}{Ro_W} + \frac{W}{R}\right) \quad (3)$$

The equation (1) of Komar (1969) can be expressed in terms of a Rossby number Ro_W.

W = width of the channel
R = radius of curvature
U = mean downstream velocity

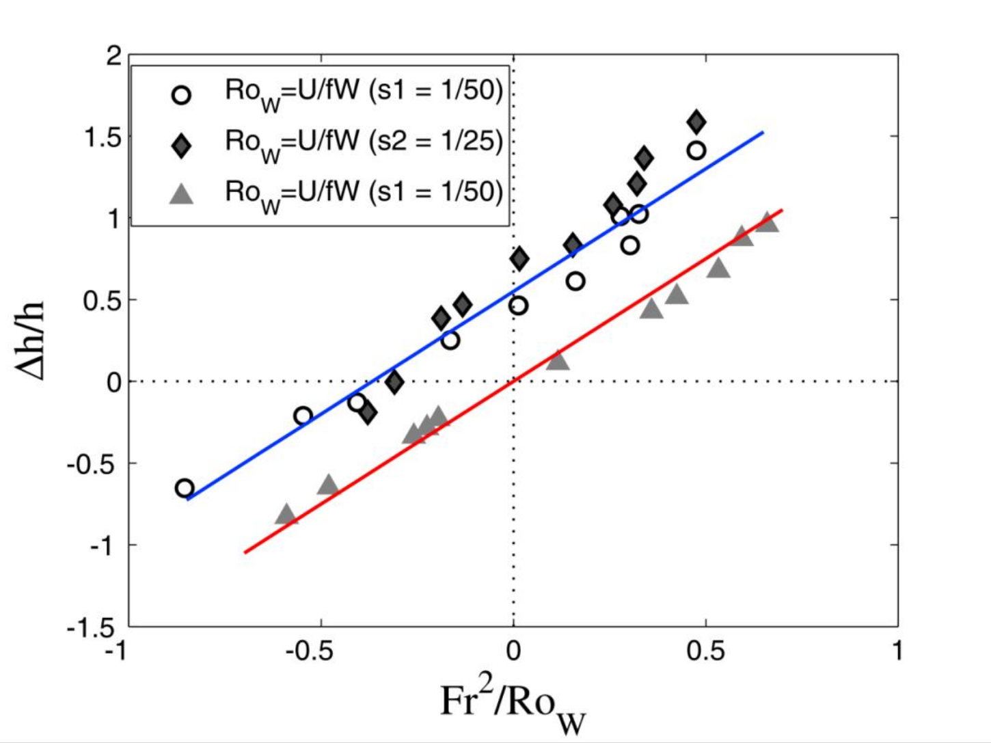


Figure 6:
Relationship between the tilt of the interface dh/h and $Fr^2/|Ro_W|$. Coriolis forces are weak when $Fr^2/|Ro_W| \sim 0$ and dominant when $Fr^2/|Ro_W| >> 0$. Data are taken from Cossu and Wells (2011).

Conclusions

At low latitudes ($Fr^2/|Ro_W| \sim 0$) centrifugal forces and inertial run-up lead to perturbations of the three-dimensional flow field. The helical flow cell reverses in subsequent bends so that lateral accretion packages (LAPs) always form on the inside of channel bends. This enables a predominantly lateral migration and leads to an increase in sinuosity (Peakall et al., 2007; Amos et al., 2010), as sketched in Figure 7a.

Our data suggest that Coriolis forces strongly influence the flow dynamics in mid and high latitude systems where ($Fr^2/|Ro_W| >> 0$). Coriolis forces suppress cross stream velocities and perturbations caused by centrifugal forces. This could counteract the formation of LAPs and impede the increase of sinuosity (Figure 7b,c).

In addition, in suspension fall-out regimes sediment will mainly be deposited on the right-hand (left-hand) side in the Northern (Southern) Hemisphere (Figure 7e,f). This implies a strong levee asymmetry and consequently a lateral migration of the channel system to only one side.

Such an evolution for a mud-dominated system has been reported for the NAMOC (Klaucke et al., 1997), as illustrated in Figure 8.

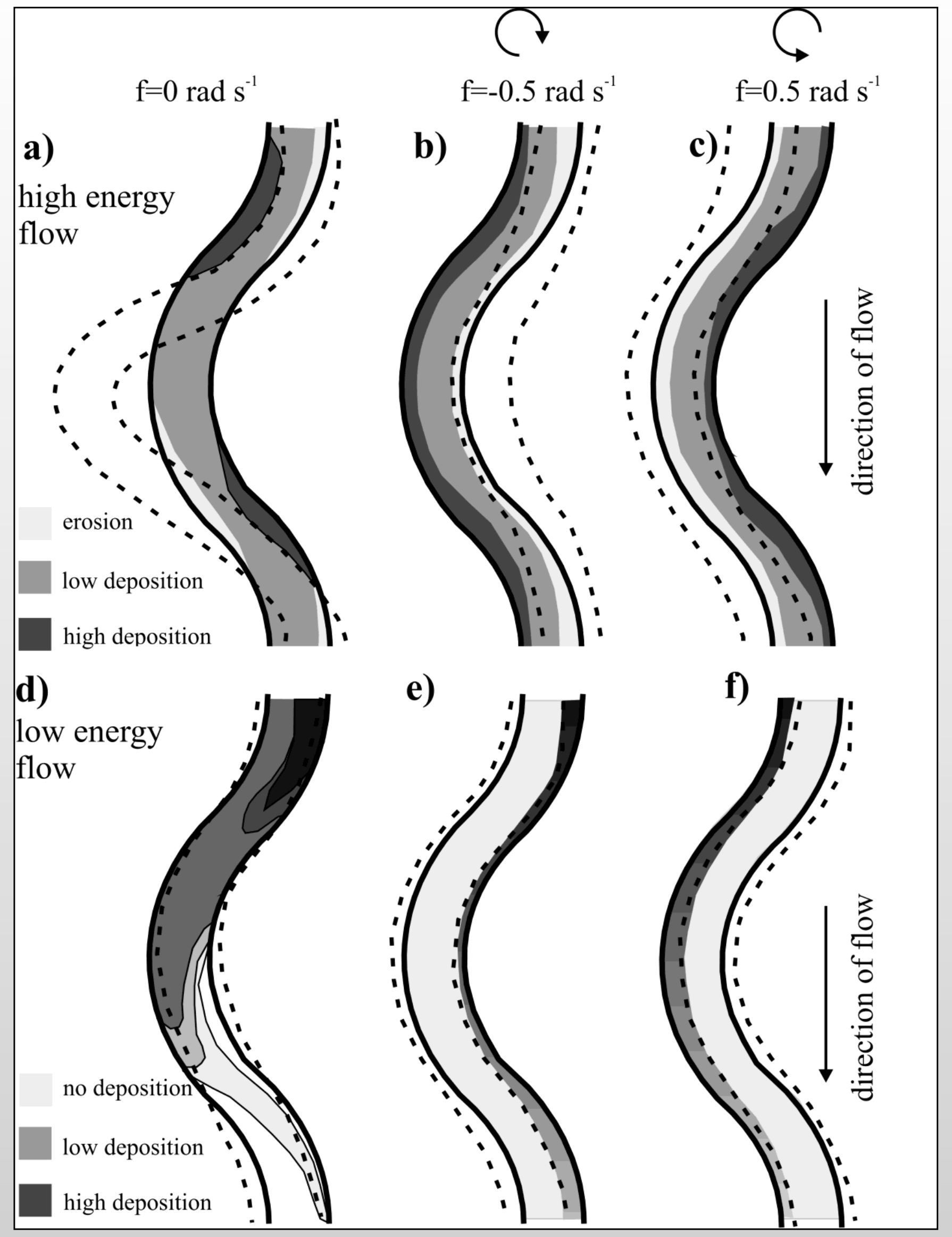
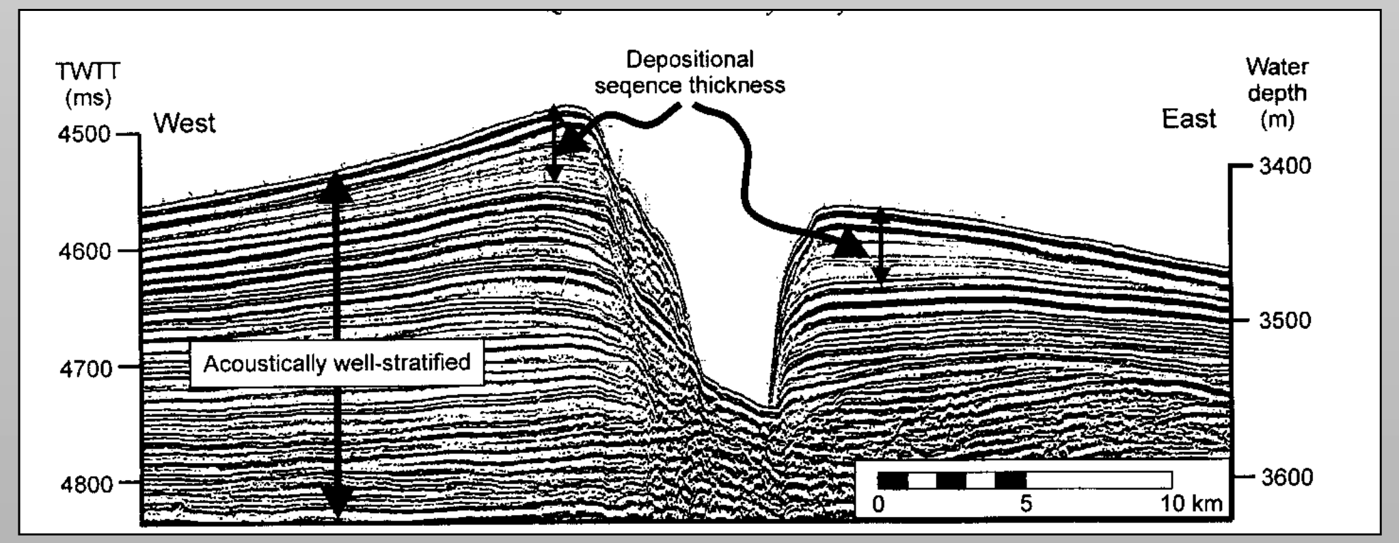


Figure 7:
Conceptual model for the evolution of submarine channels under the influence of Coriolis forces (Cossu and Wells, 2011).

Figure 8:
Airgun seismic profile across the North Atlantic Mid- Ocean Channel (looking upstream), taken from Skene et al. (2002).

The NAMOC shows a constantly higher right levee system over several thousand kilometers and can be classified as a mud-dominated submarine canyon.



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