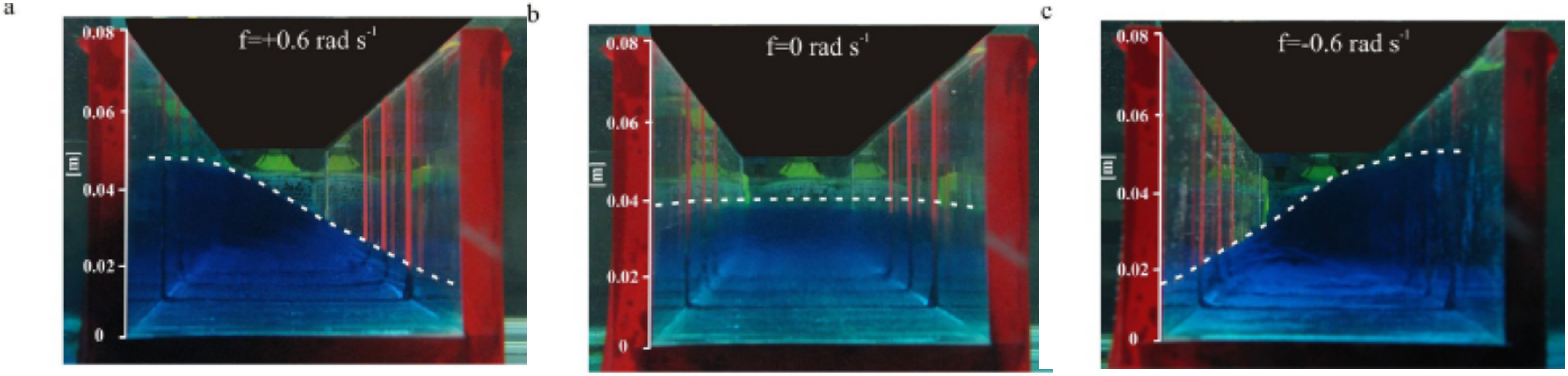
How coriolis forces influence turbidity currents.



Mathew Wells and **Remo Cossu**,
University of Toronto, Canada

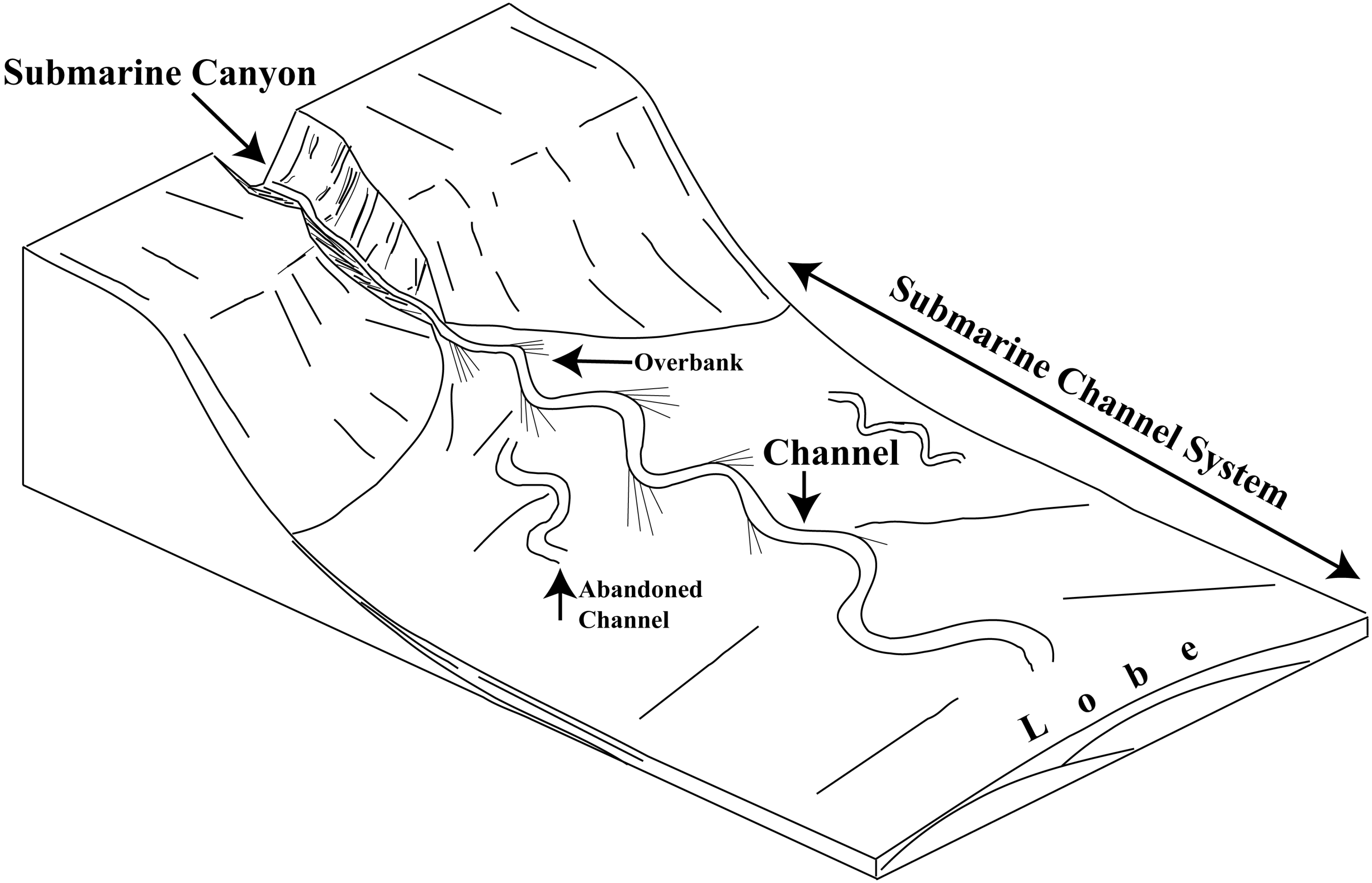
Anna Wåhlin,
Göteborg University, Sweden

Jeff Peakall,
University of Leeds, UK

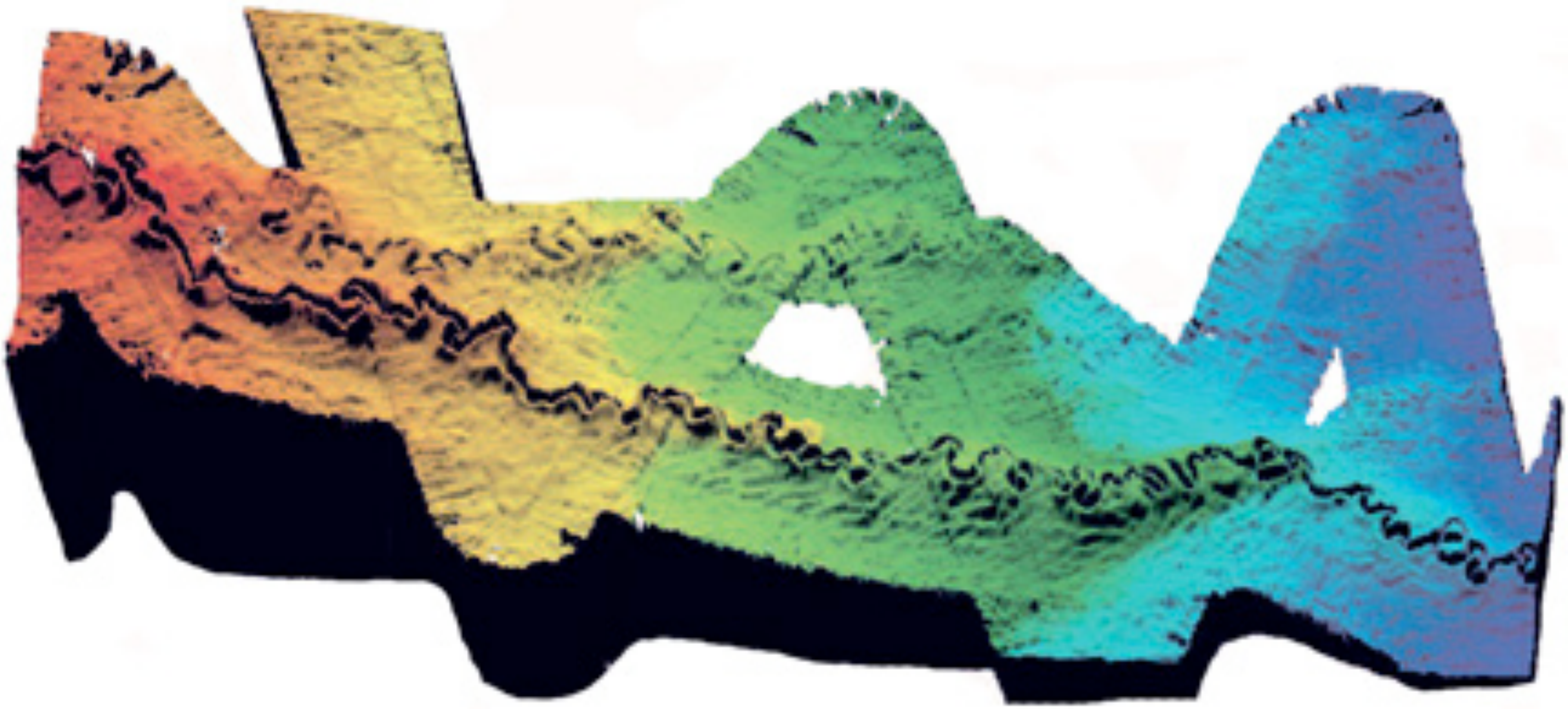
Questions

1)How does the Coriolis force change the circulation patterns of gravity currents in straight and bent channels?

2)How could these circulation patterns influence submarine channel evolution?

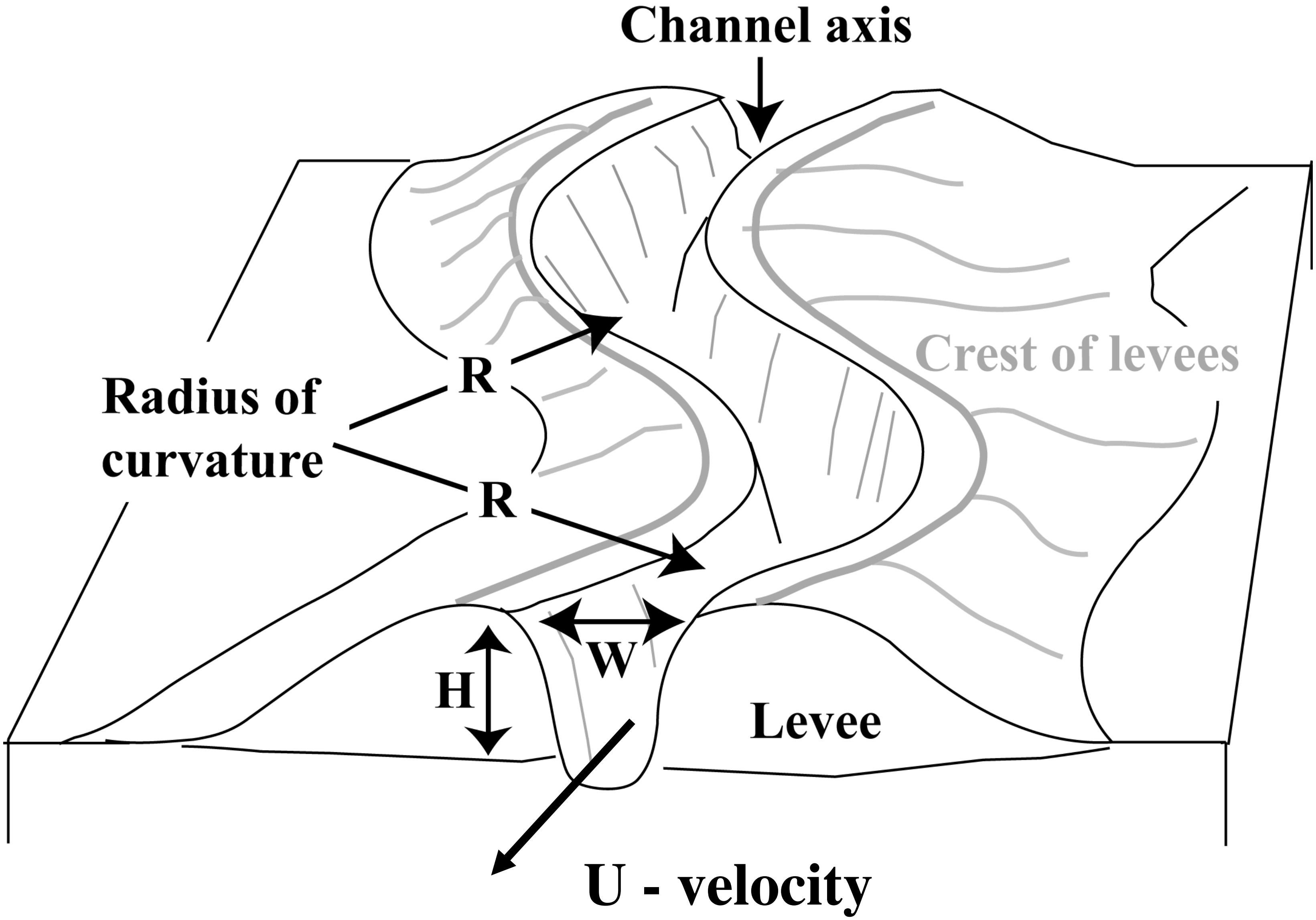


- Submarine channel systems form some of the largest sedimentary features on ocean floor, often spanning 1000s of km.
- The resulting turbidites account for a large portion of the sedimentary rocks in the geological record.

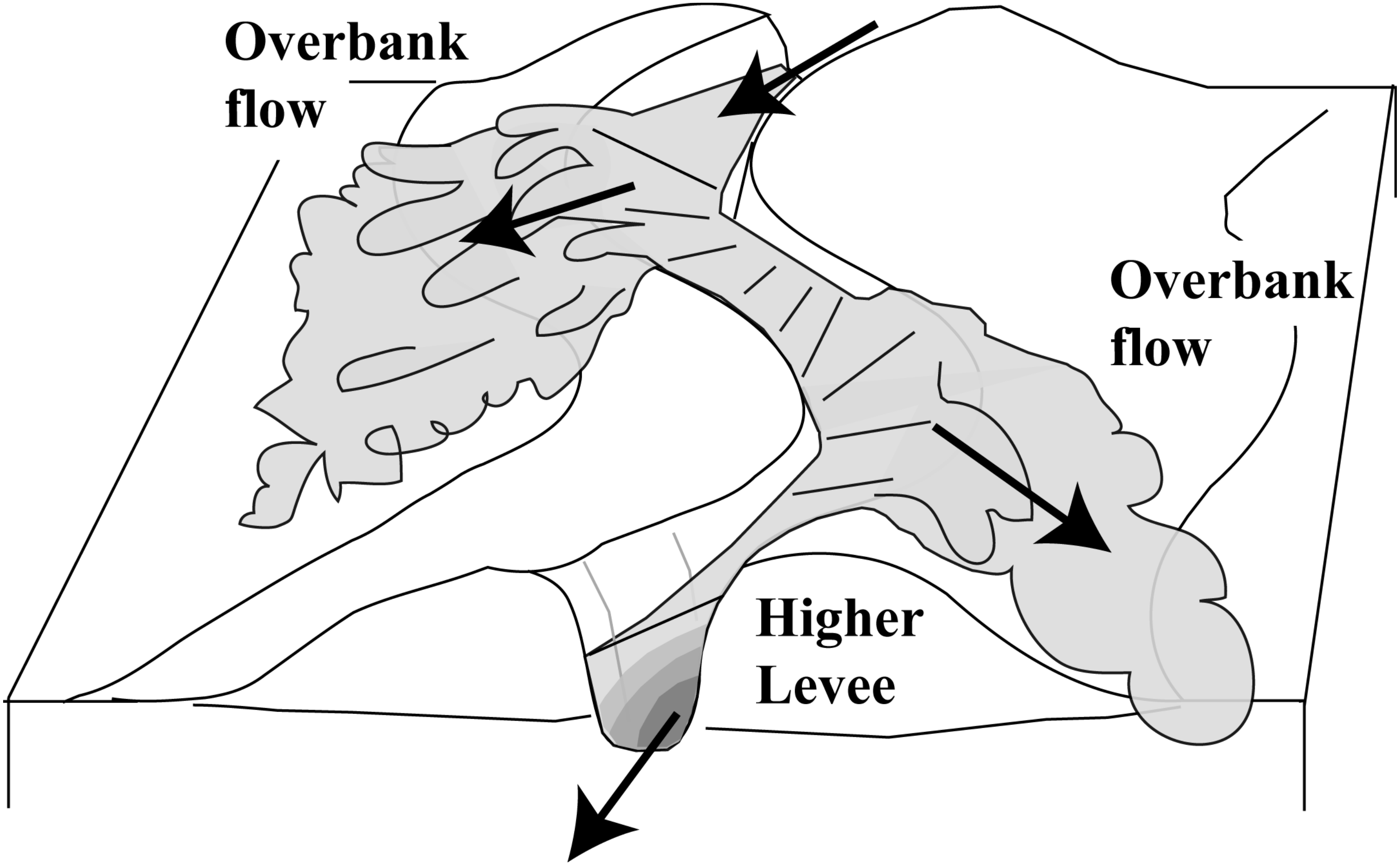


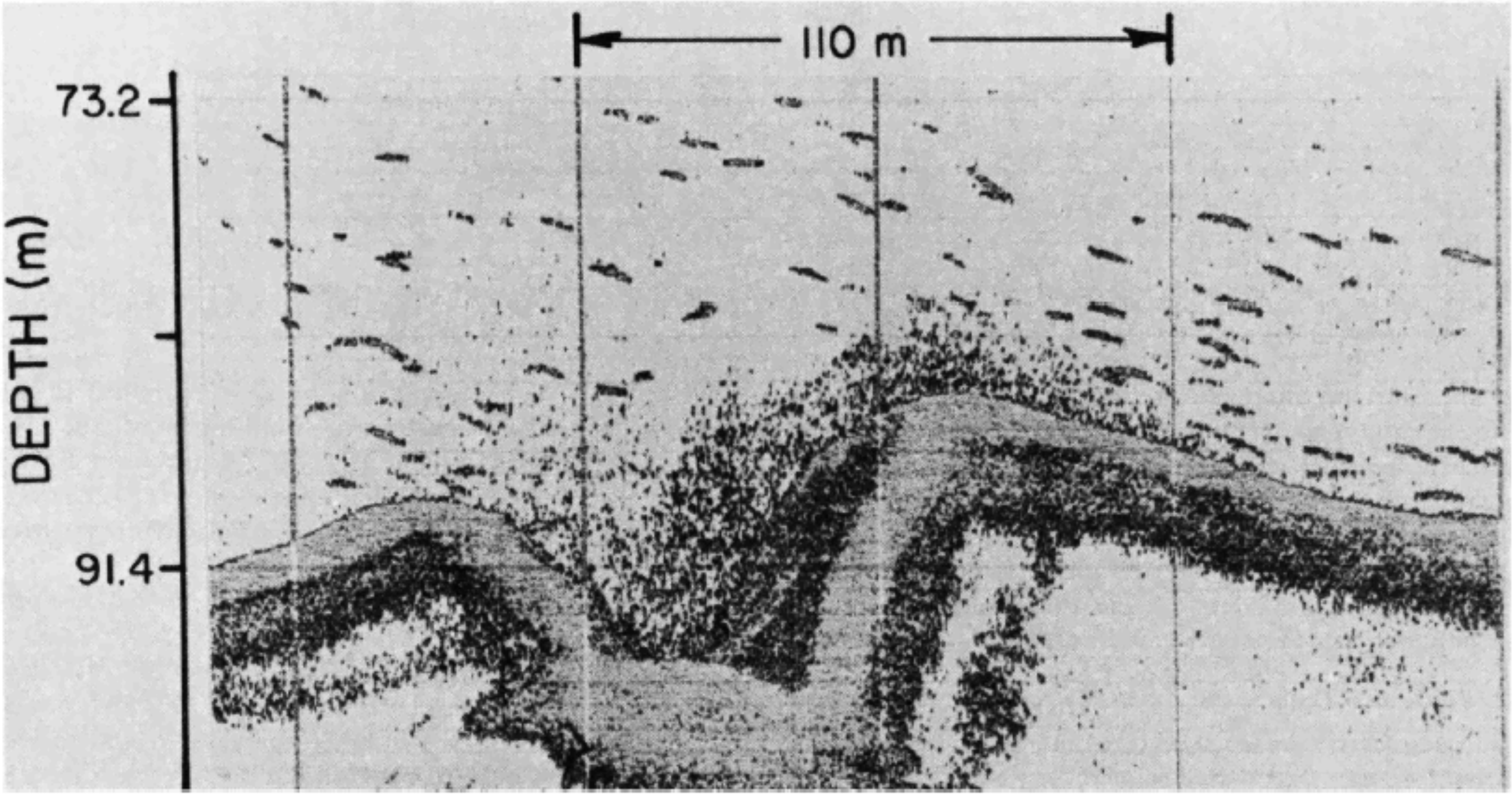
Over the last 75,000 years sediment from the Amazon River has created this 800 km long channel beneath the Atlantic. The image shows a 200 km long 4 km wide section of the channel with banks 100’s m high.

Amos and Peakall (2006) Savoye, IFREMER.



Coriolis parameter **f** = $2\Omega \sin \theta$

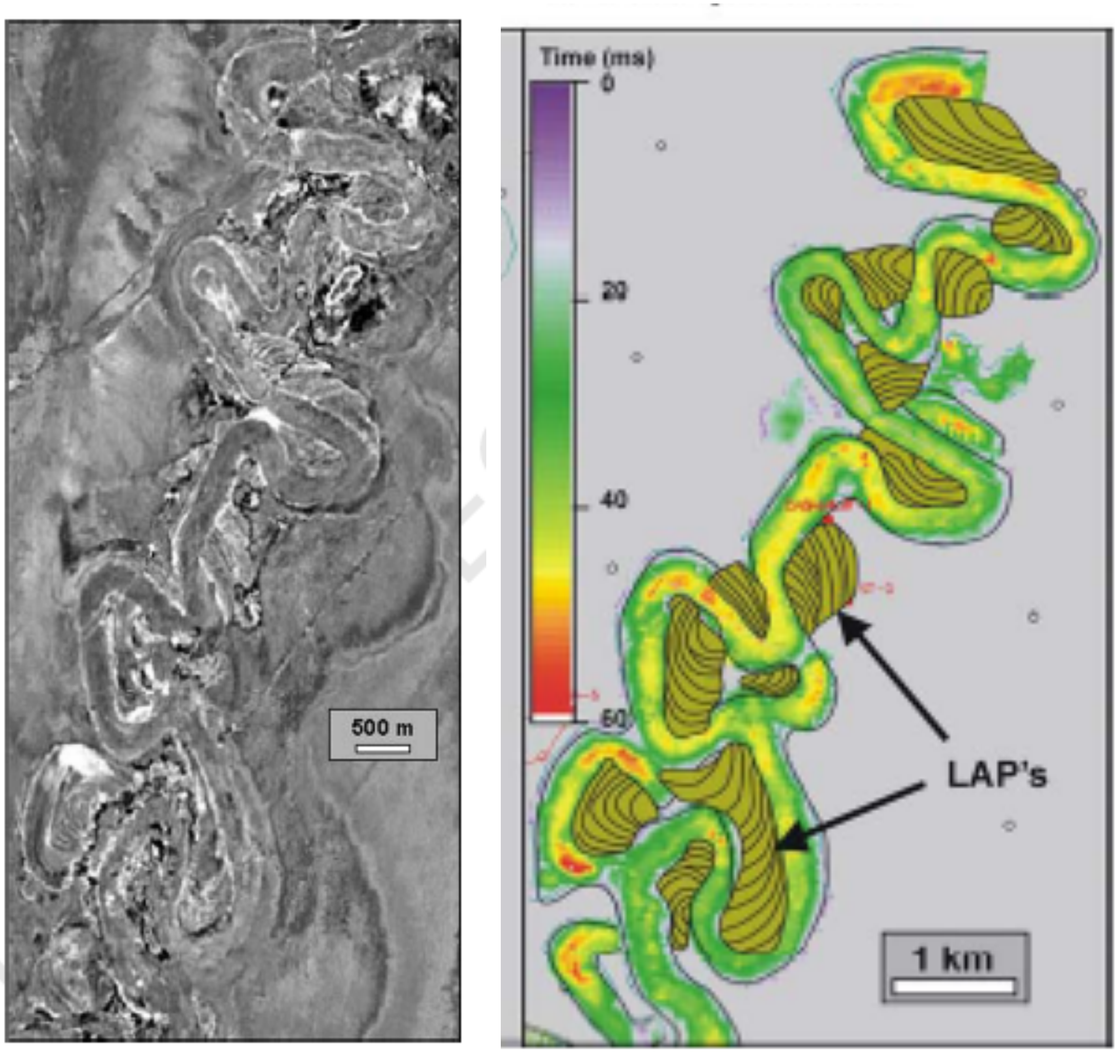

Overbank flow
Overbank flow
Higher Levee



- A seismic backscatter image of a turbidity current formed from mining tailing in Rupert Inlet.
- We are looking downstream, and the channel is turning to the left.
- Centrifugal forces deflect the interface to the right, and some of the current spills over levee, increasing their size.

From Hay 1987 JGR.

Meandering channels at low latitudes

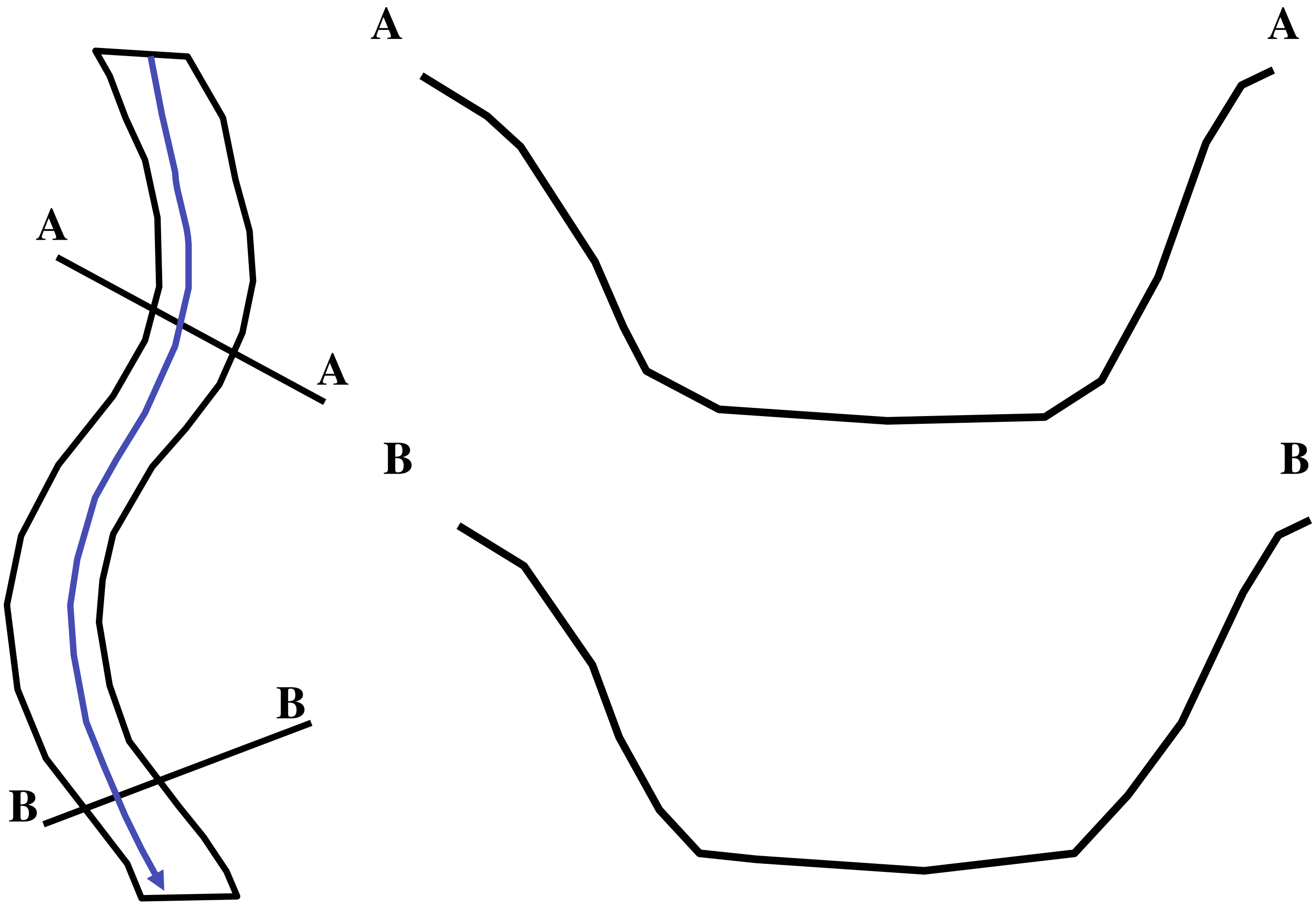


Abreu, Sullivan, Pirmez, Mohrig (2006)

Lateral accretion packages LAPs form at the inner bend and lead over time to increase in sinousity.

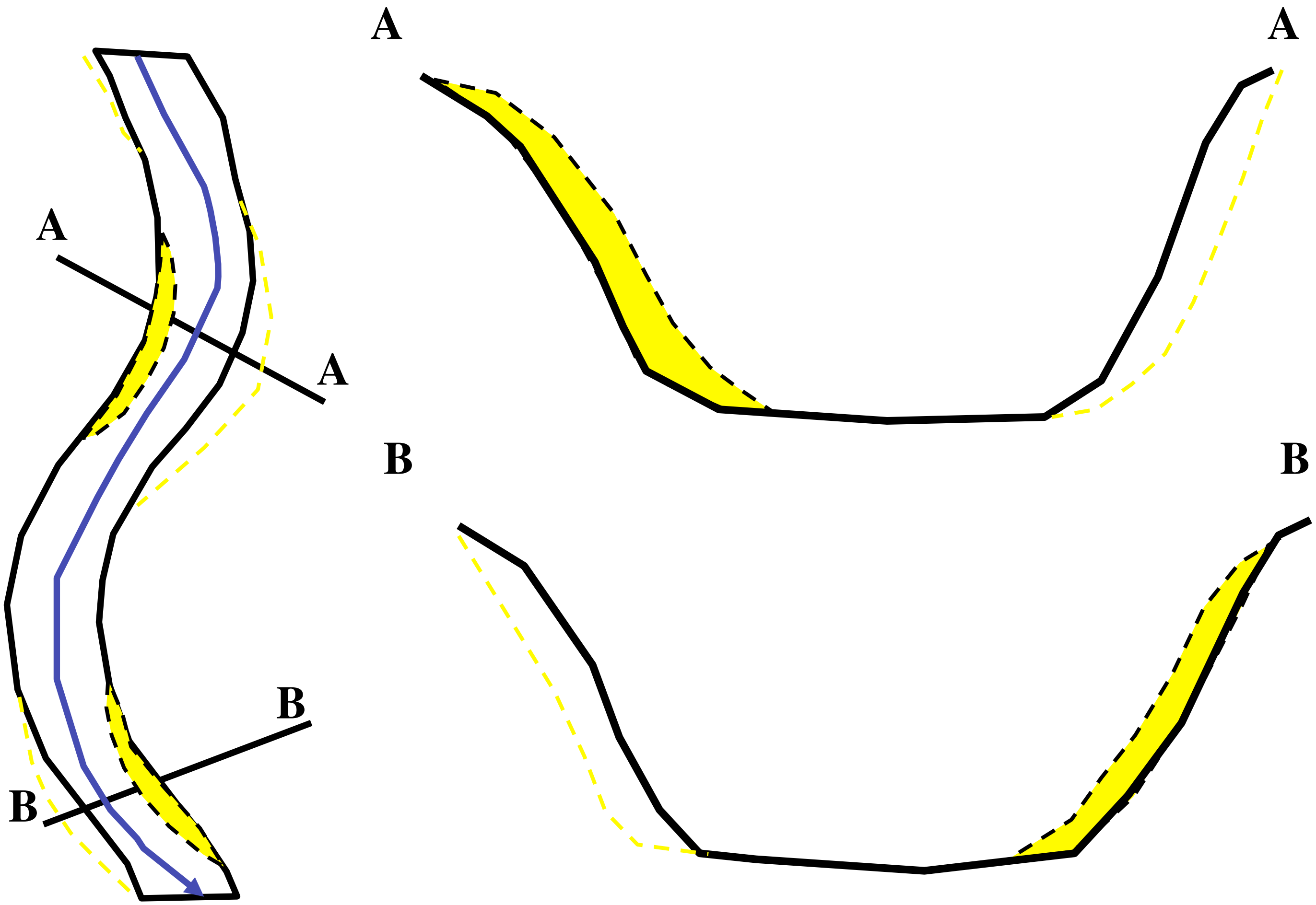
Image shown from Zaire submarine channel.

What causes sinuosity…

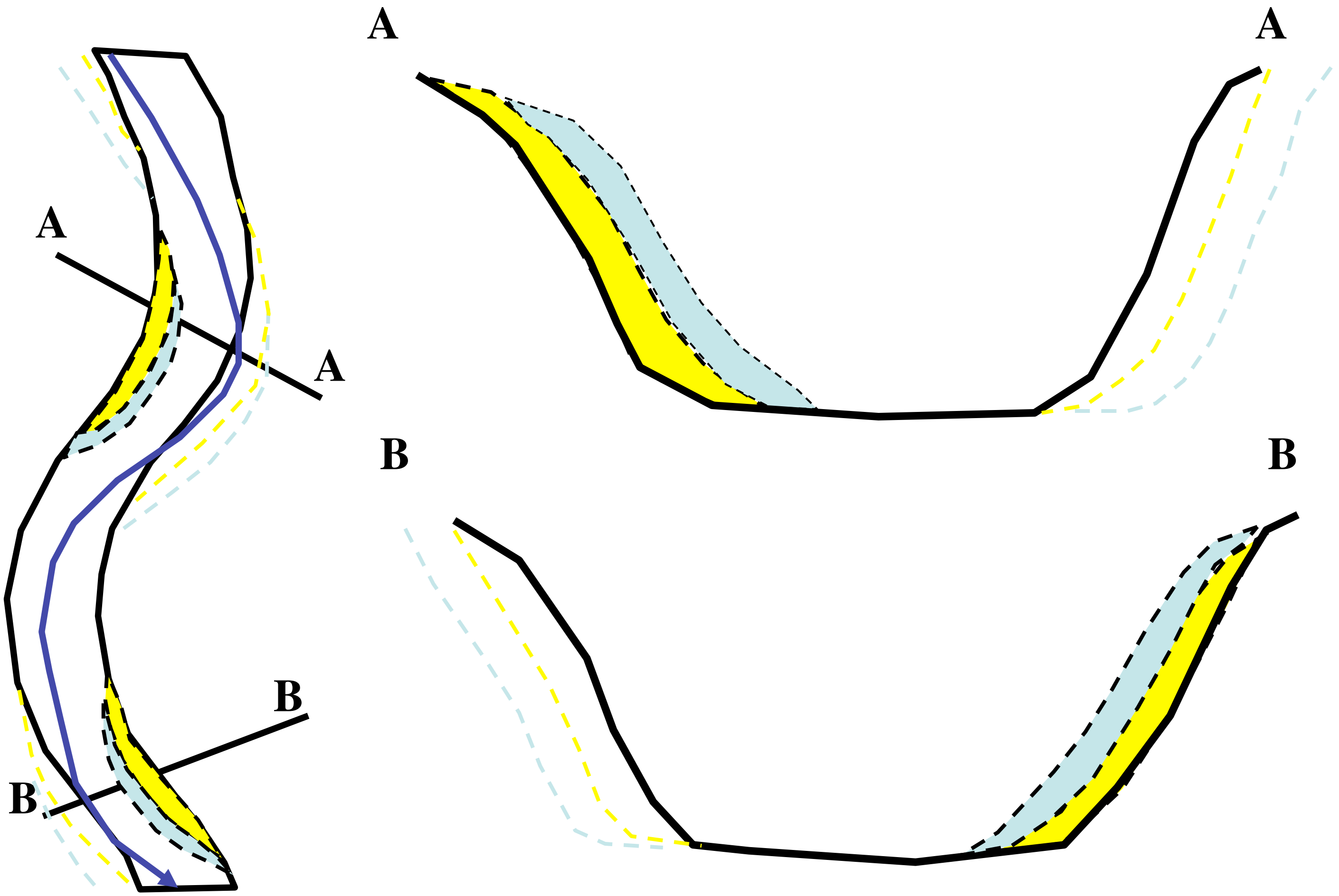


maximum velocity at the bottom

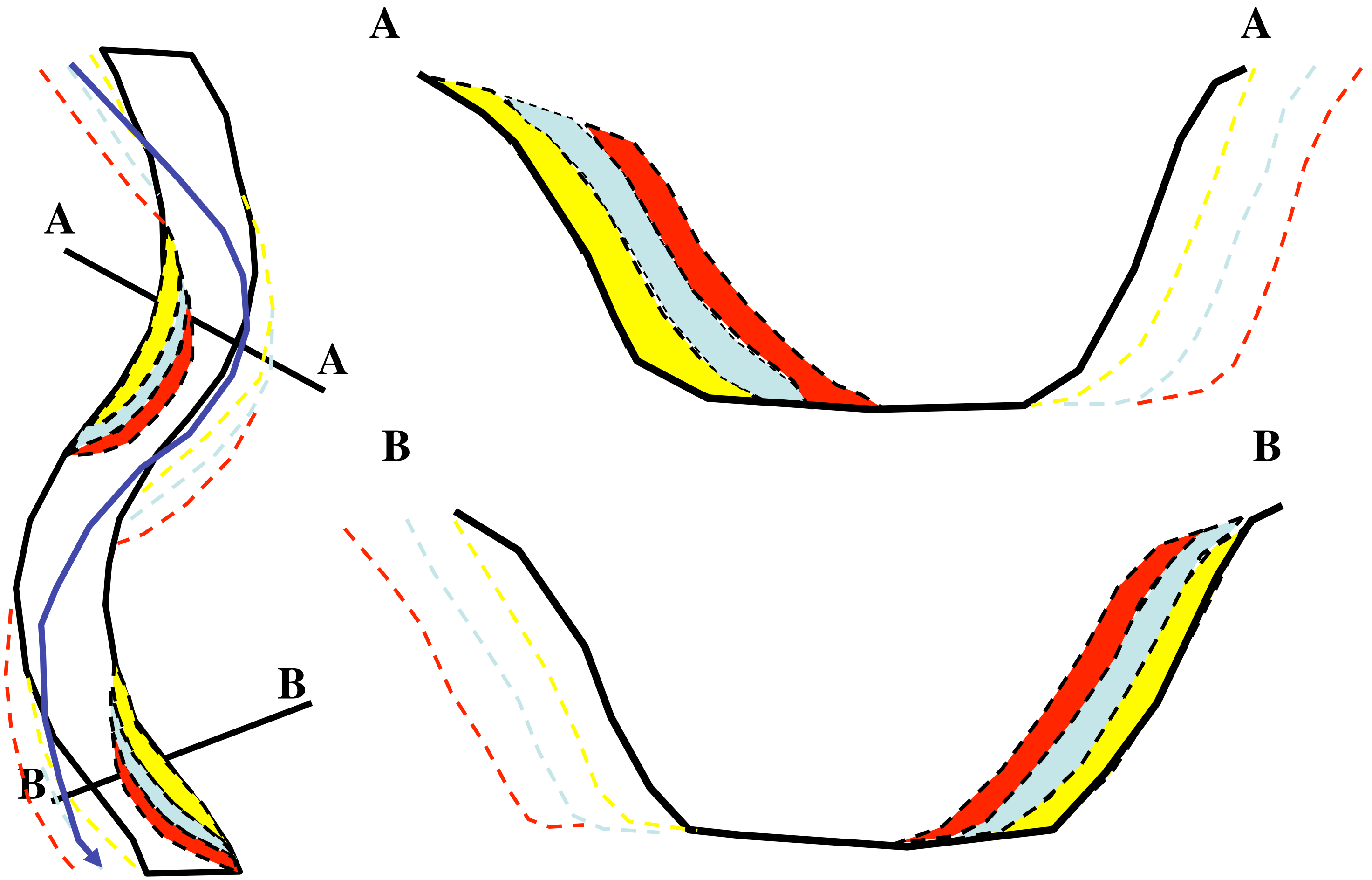
Perturbations by centrifugal forces



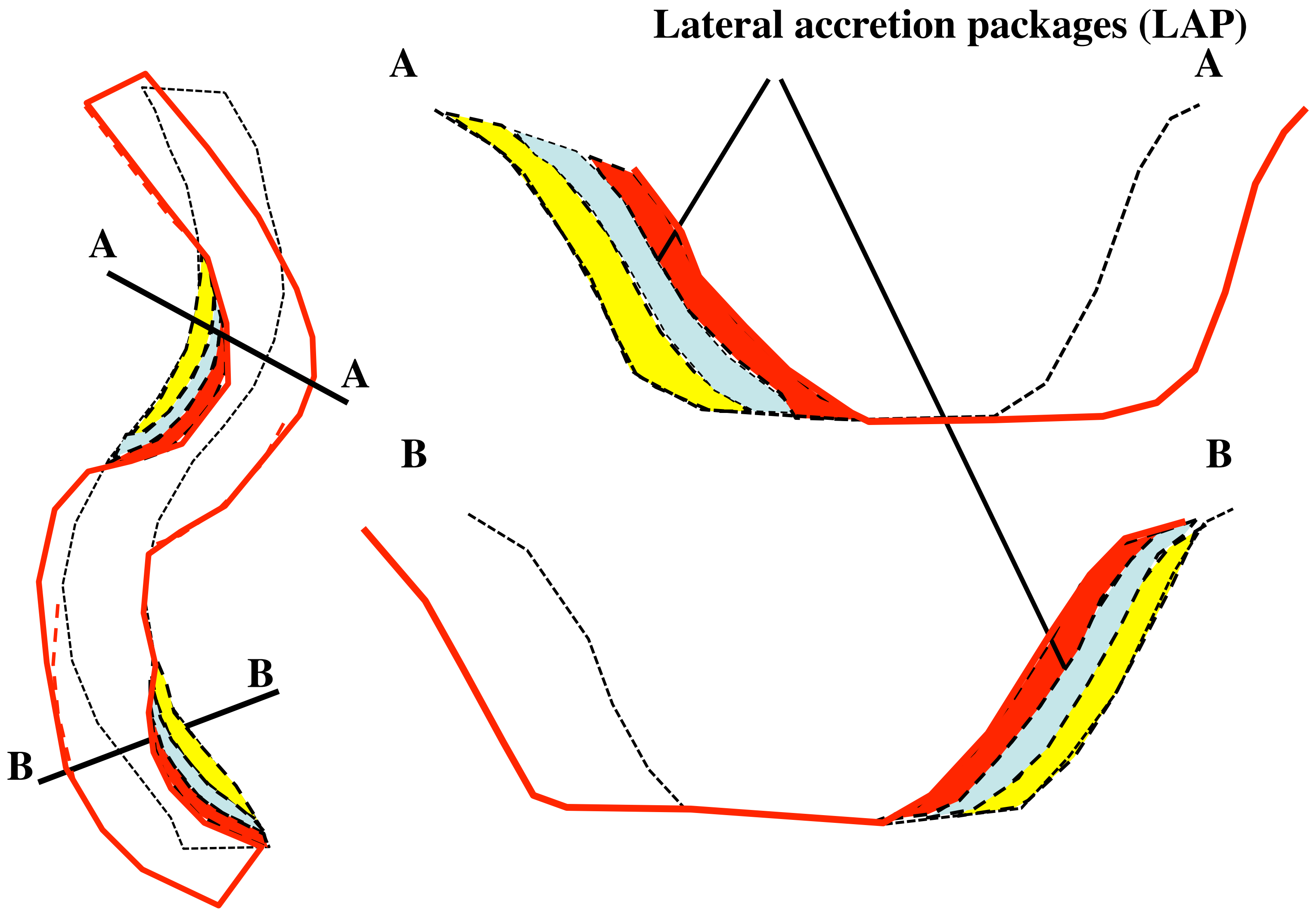
Perturbations by centrifugal forces



Perturbations by centrifugal forces



Lateral migration of channels



Due to centrifugal forces, sinuousity increases with time

The earth rotates once a day, i.e. its rotation rate is 7.3×10^{-5} rad s^{-1}

The Coriolis parameter varies with latitude as $f = 2\Omega\sin(\theta)$ where θ is the latitude.

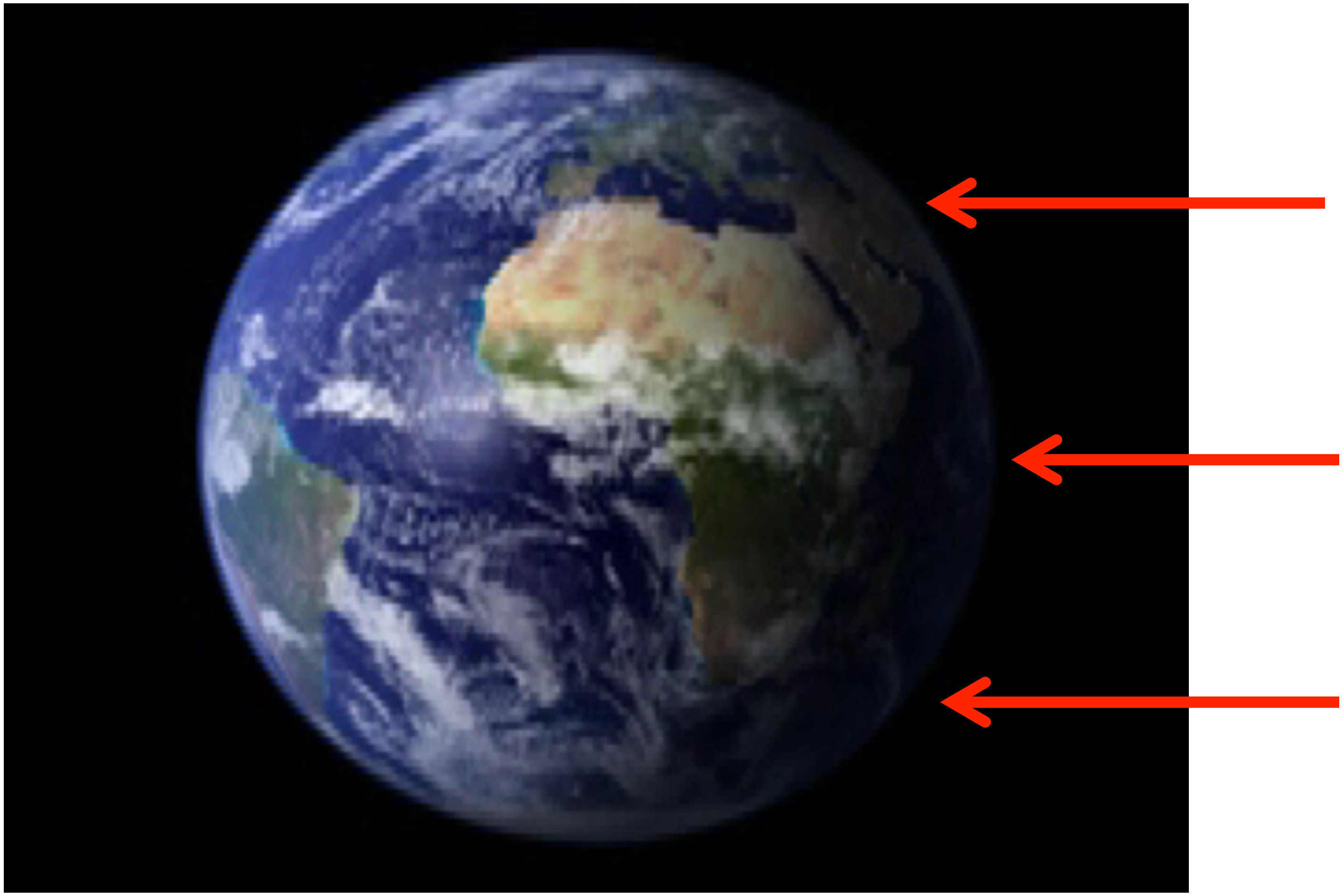
At North pole $f = 2\Omega = 1.5\times10^{-4}$ rad s^{-1}
At 40°N $f \sim 1\times10^{-4}$ rad s^{-1}
At equator $f = 0$.

In southern hemisphere f is negative.

Coriolis acceleration is given by

$$du/dt = fv$$
$$dv/dt = -fu$$

Coriolis acceleration is to the right in Southern Hemisphere, and to the left in Southern Hemisphere.
There are no Coriolis forces at the equator, and when an object is stationary,



Less than 10% of surface lies North of 45 ° N

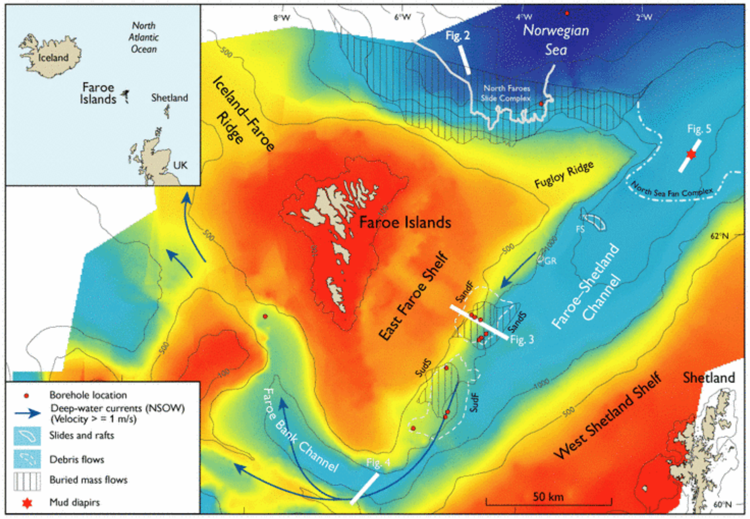
Most channels are "equatorial", i.e. Zaire, Congo, Amazon or GOM.

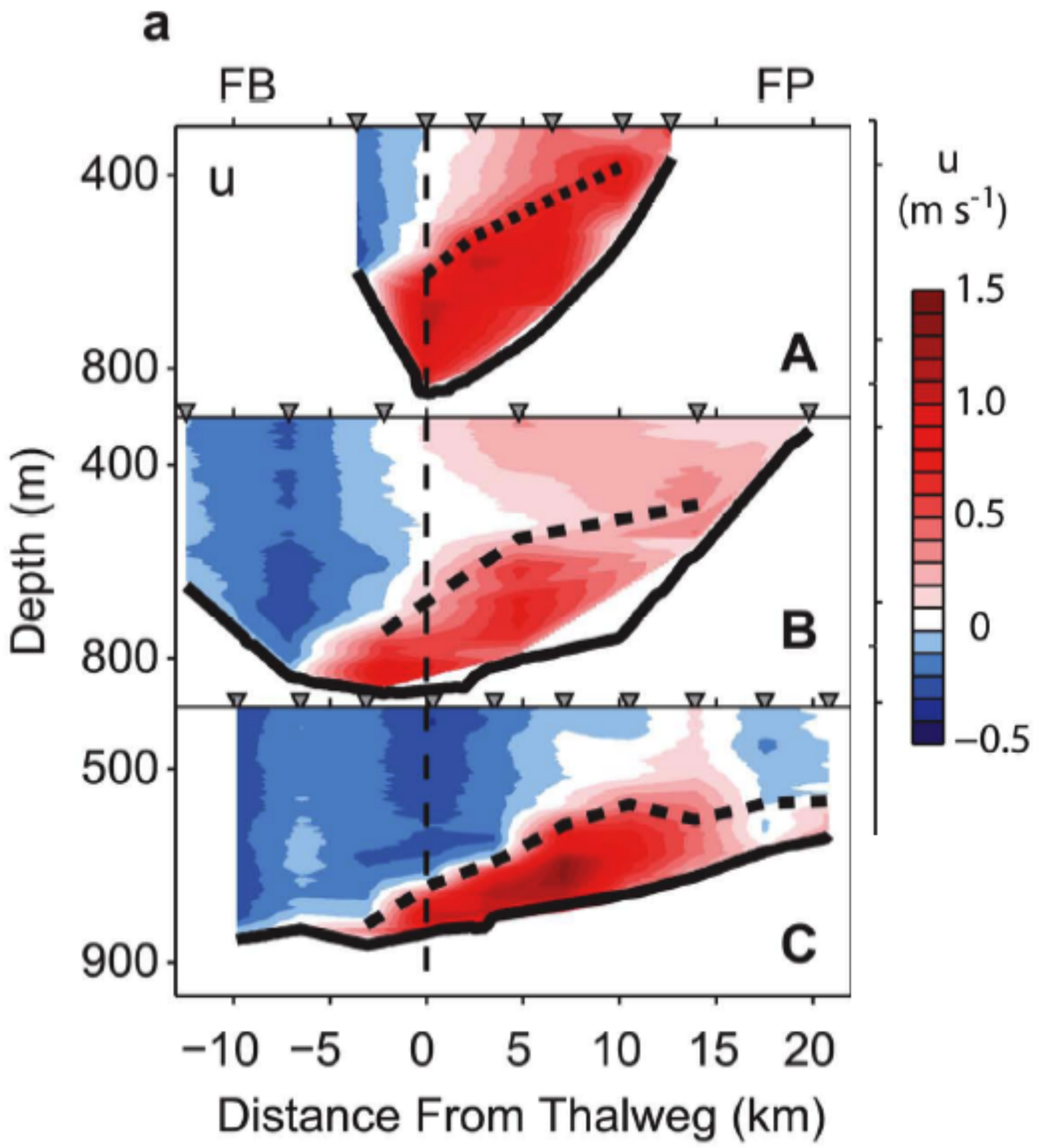
Less than 10% of surface lies south of 45 ° S

Coriolis forces are only strong at higher latitudes, which means that most turbidite systems are "equatorial" and not greatly affected for this process.

For oceanographers most major density currents are at high latitudes and are critical for describing global thermohaline circulation.

For instance the large density currents in the Faroe bank overflow is strongly deflected to the right hand side of channel.





Images from Fer et al (2010) looking downstream.

Rossby-Number

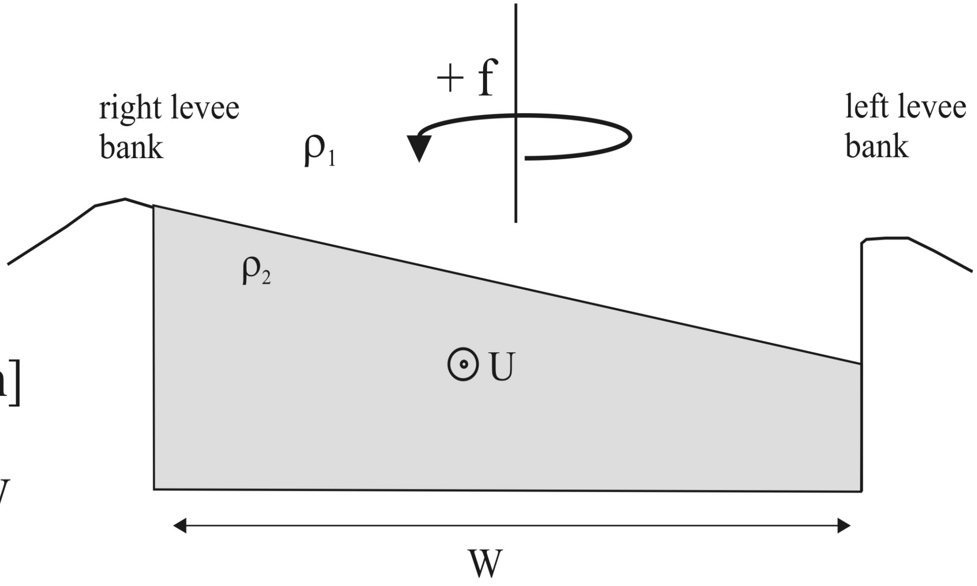
Rossby number:

$Ro = U/ (L\ f)$

U mean velocity [$m\ s^{-1}$]
f Coriolis parameter [$rad\ s^{-1}$]
L characteristic length scale [m]

Submarine channel system L=W

$Ro = U/ (W\ f)$



When would Coriolis forces become comparable to centrifugal accelerations?

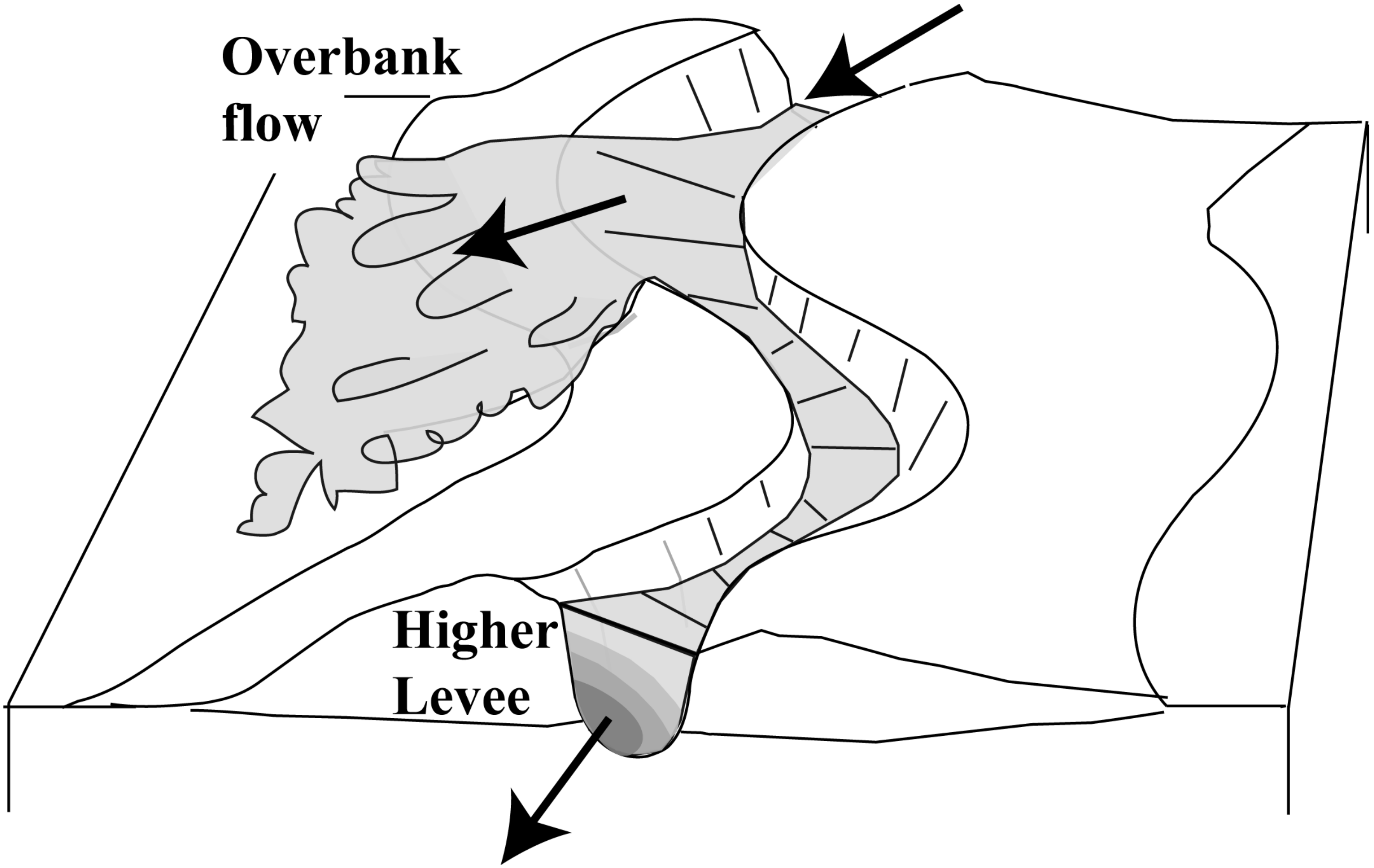
$$U^2/R \approx Uf \rightarrow R_{cor} \approx U/f$$

At mid latitudes the Coriolis parameter is $f \sim 1\text{x}10^{-4}\ \text{s}^{-1}$ and typical velocities of gravity currents are of the order of 1 m/s

Hence Coriolis forces become more important than centrifugal forces at mid-latitudes when the radius of curvature is greater than R_{cor} >> 10 km.

R_{cor} is the length scale at which the Rossby number is of order one.

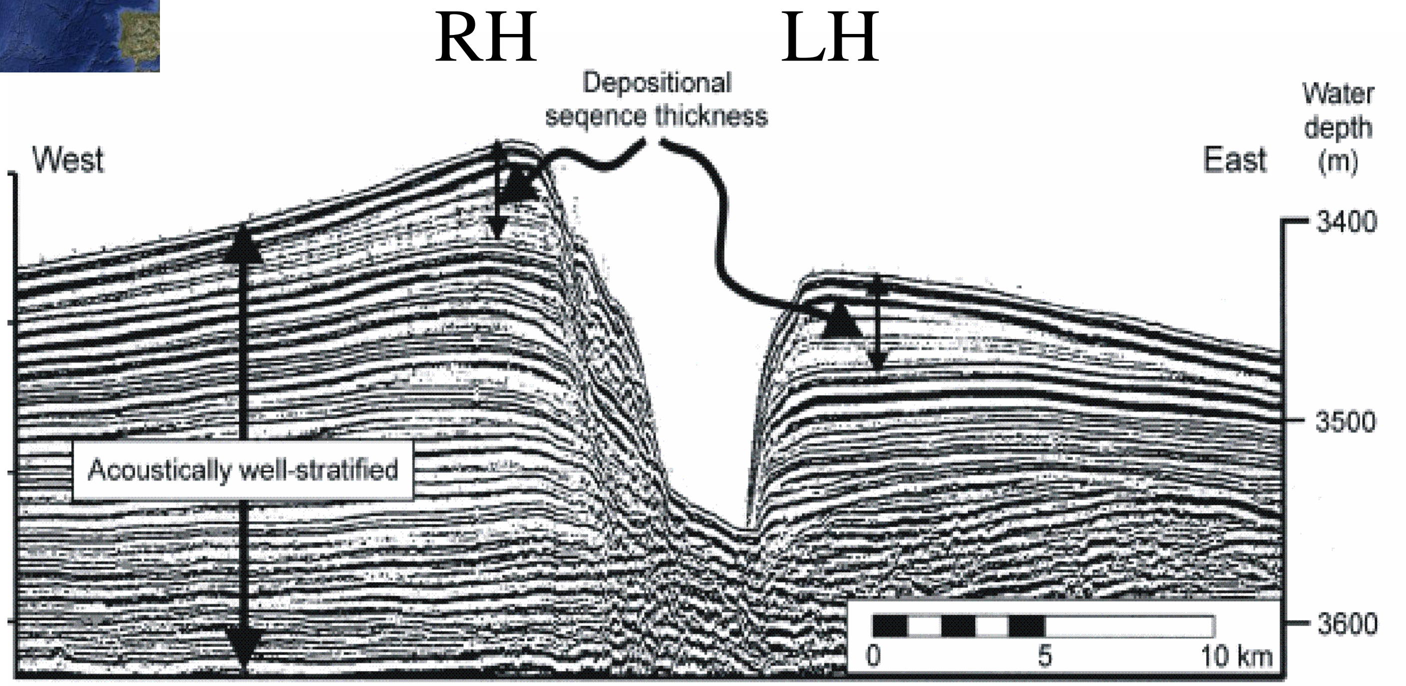
$$Ro = U/fL \approx O(1)$$



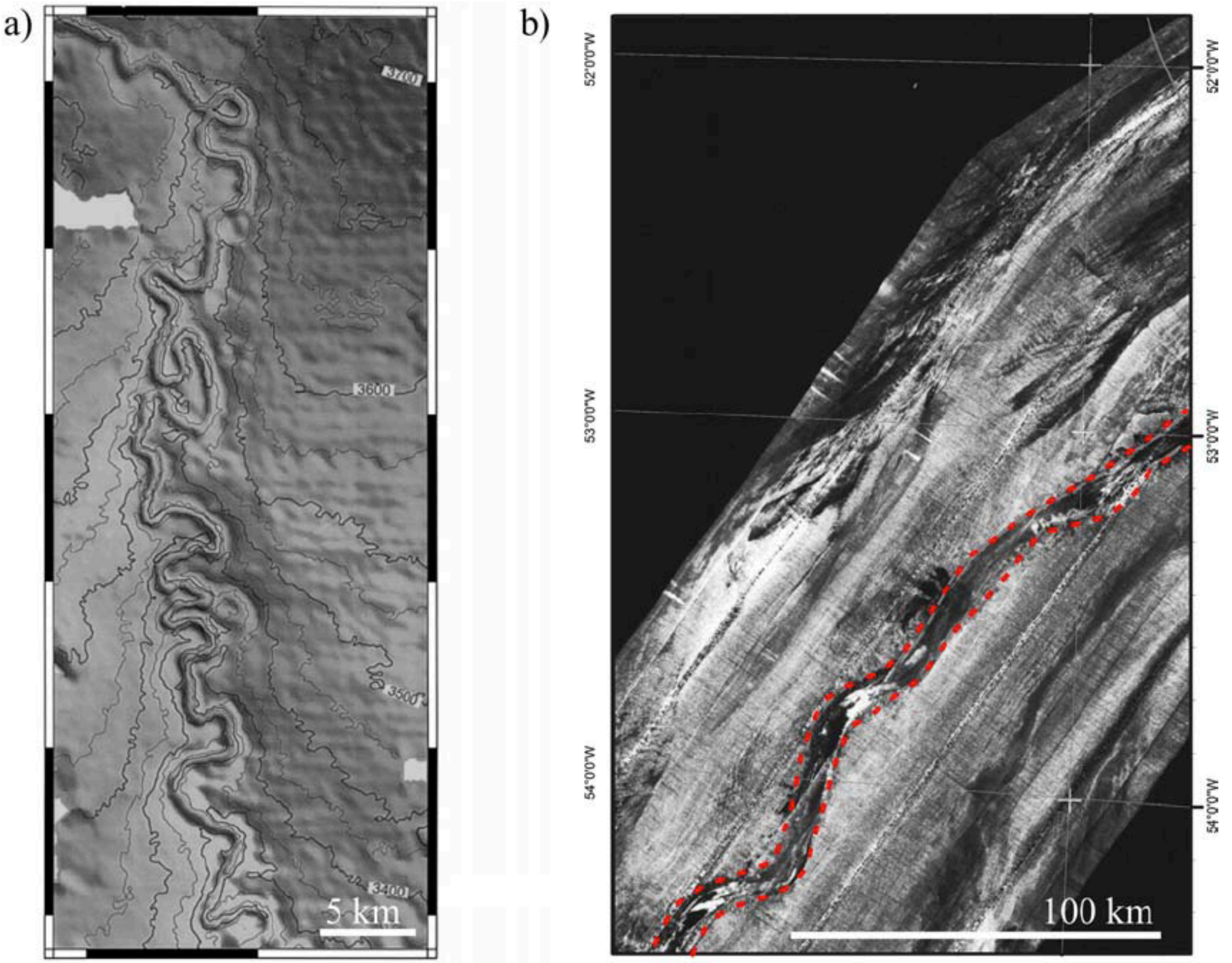
- At high latitudes Coriolis forces will deflect flow to right hand side (looking downstream) in the Northern hemisphere.

- This results in an asymmetry between the left and right hand levee size.

NAMOC submarine channel system



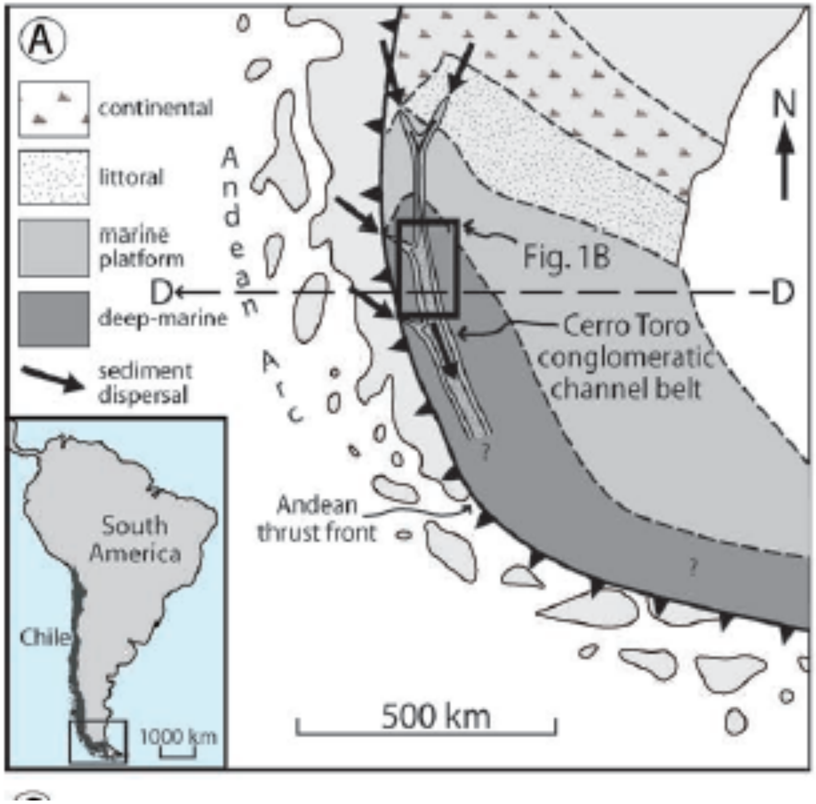
- At high latitudes most submarine channels have a higher right levee bank in the northern hemisphere, and a higher left levee bank in the southern hemisphere.

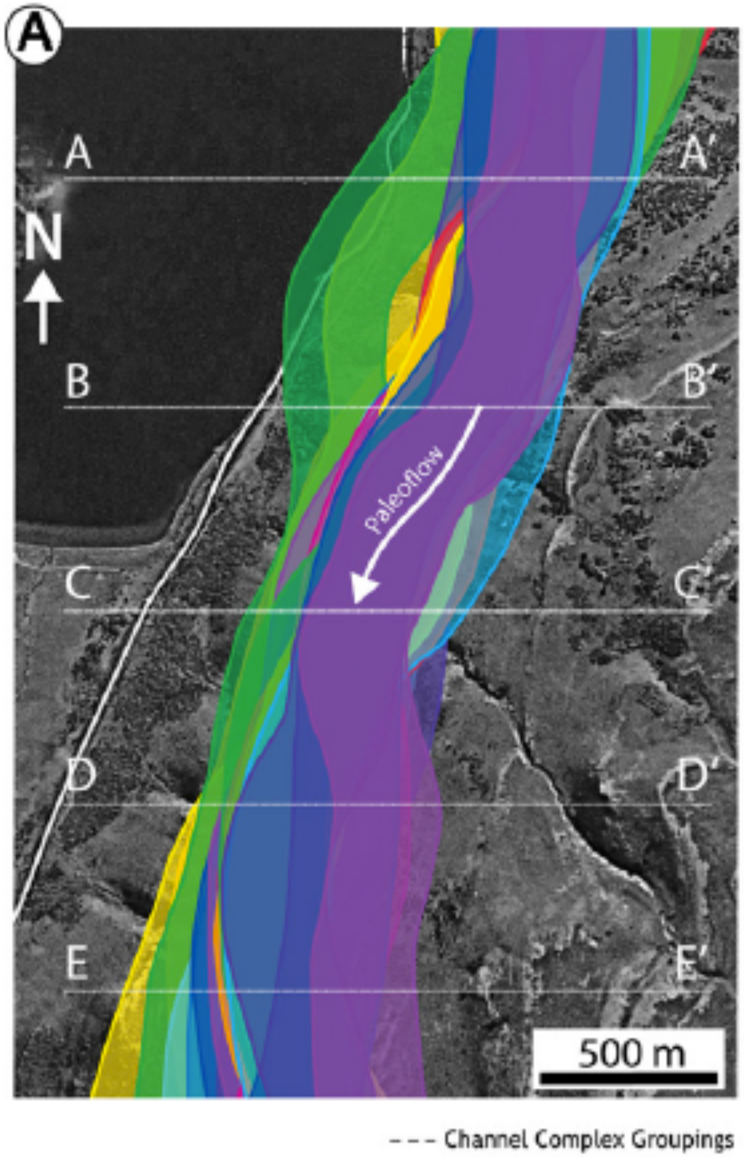


very sinuous

almost straight.

a)Bathymetry of Amazon Fan at approximately 5° N - Imran et al (1999)
b)Seismic image of the NAMOC at 60° N - from David Piper





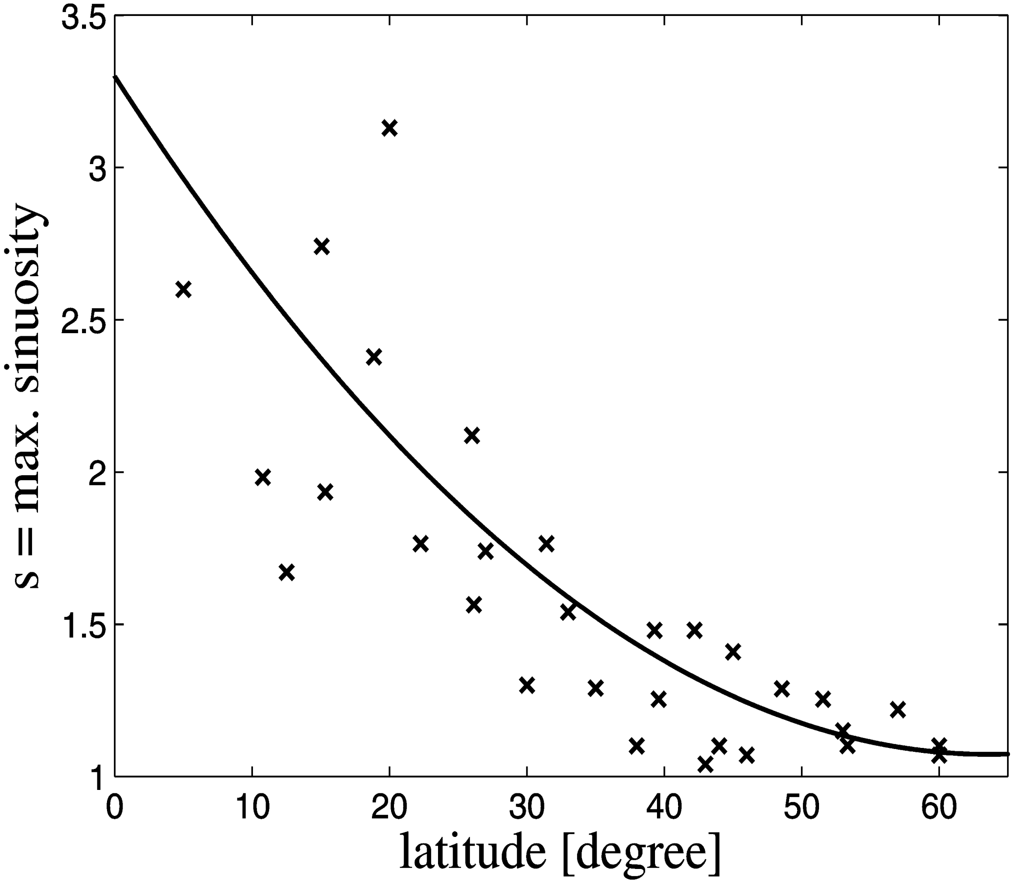
Cerro Toro formation at 55^{o}S.

Formed ~ 60 Million years ago and displays asymmetries consistent with southern Hemisphere Coriolis forces.

Sinuosity

$$s = \frac{\text{length of sinuous channel}}{\text{length of straight channel}}$$

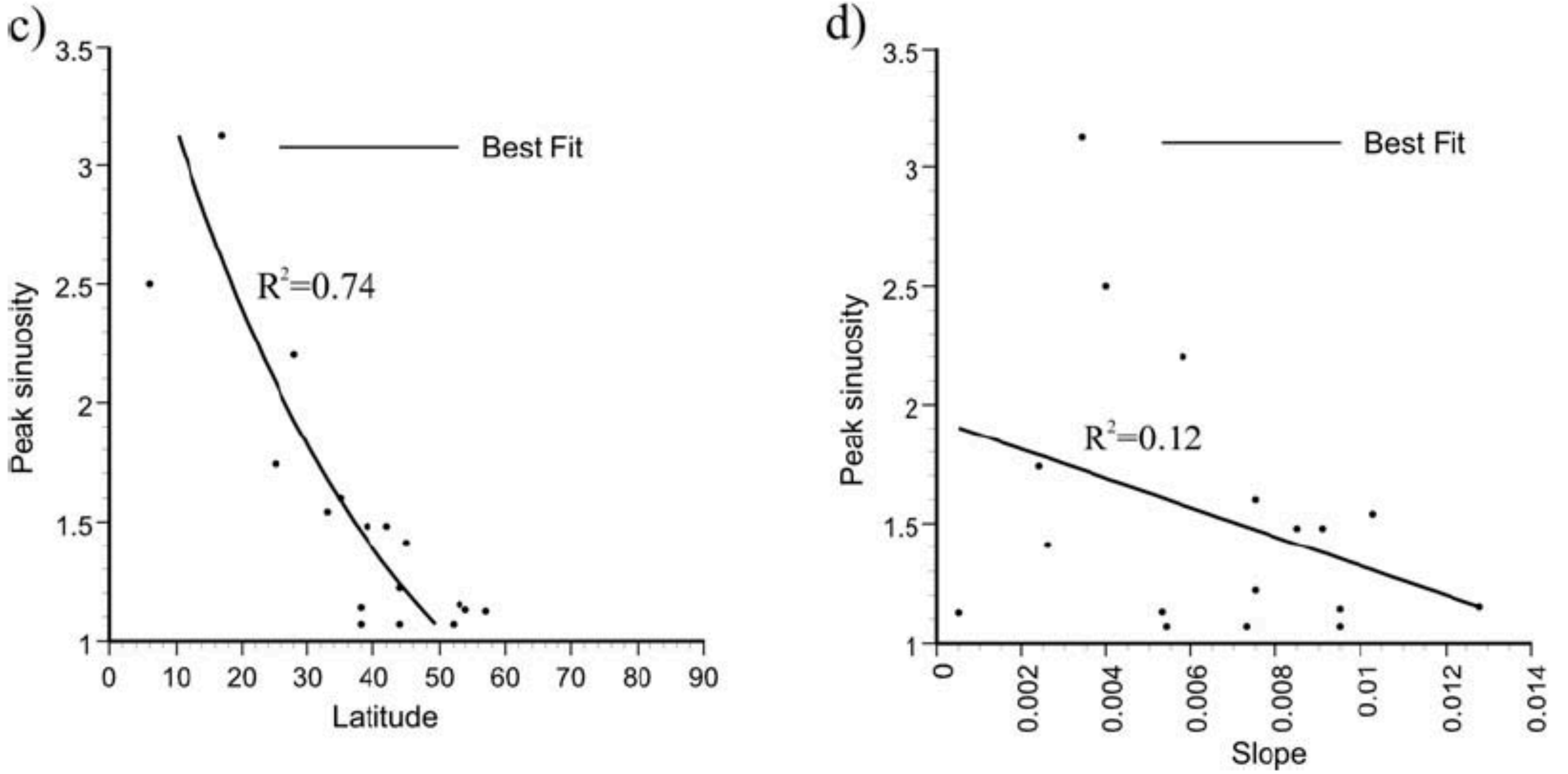
Sinuosity of submarine channels versus latitude



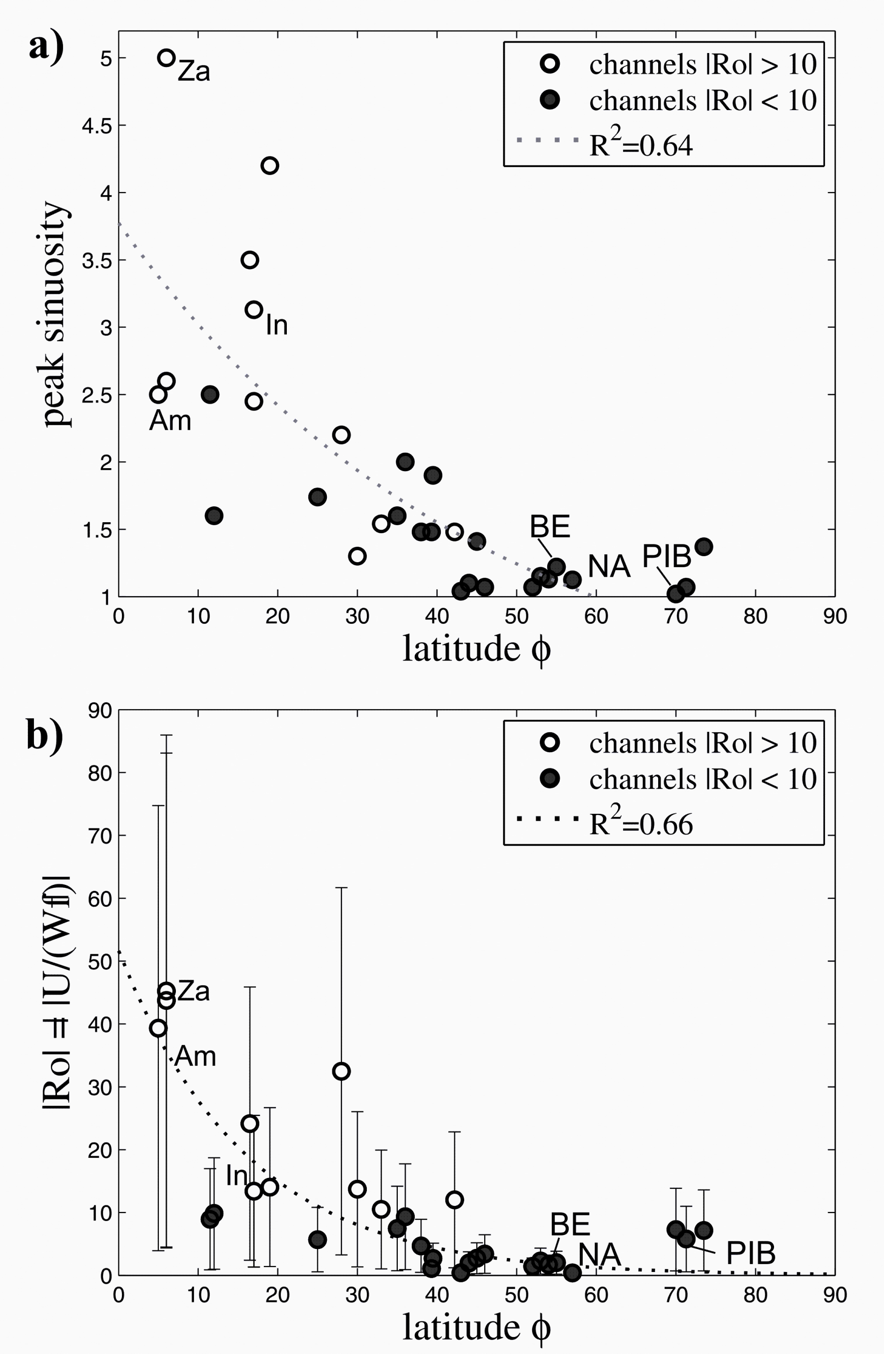
Peakall et al. (2008)

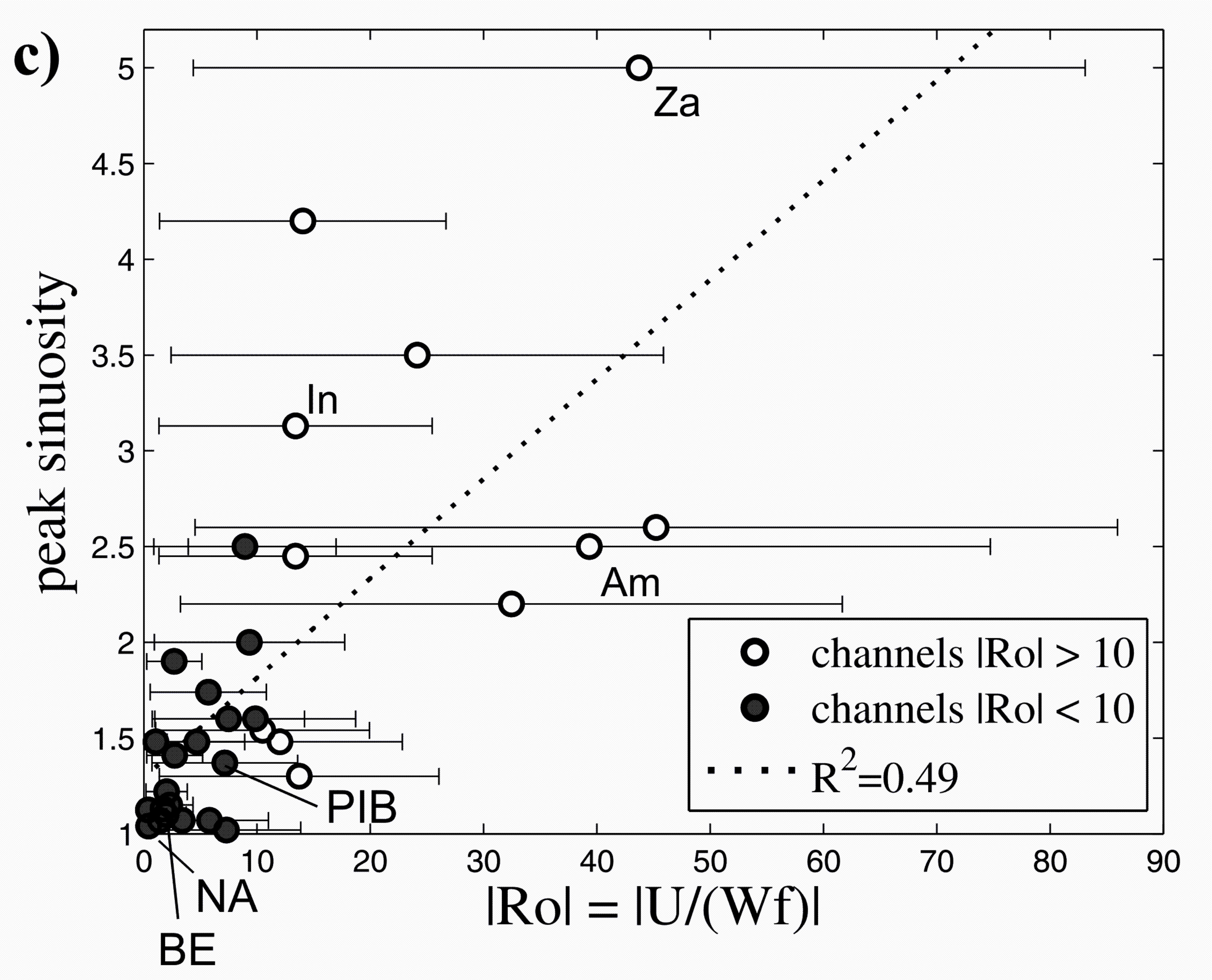
The Coriolis parameter *f* increases with latitude Θ as

$$f = 2\Omega \sin\Theta$$ where Ω is the Earth's rotation rate (1/day).

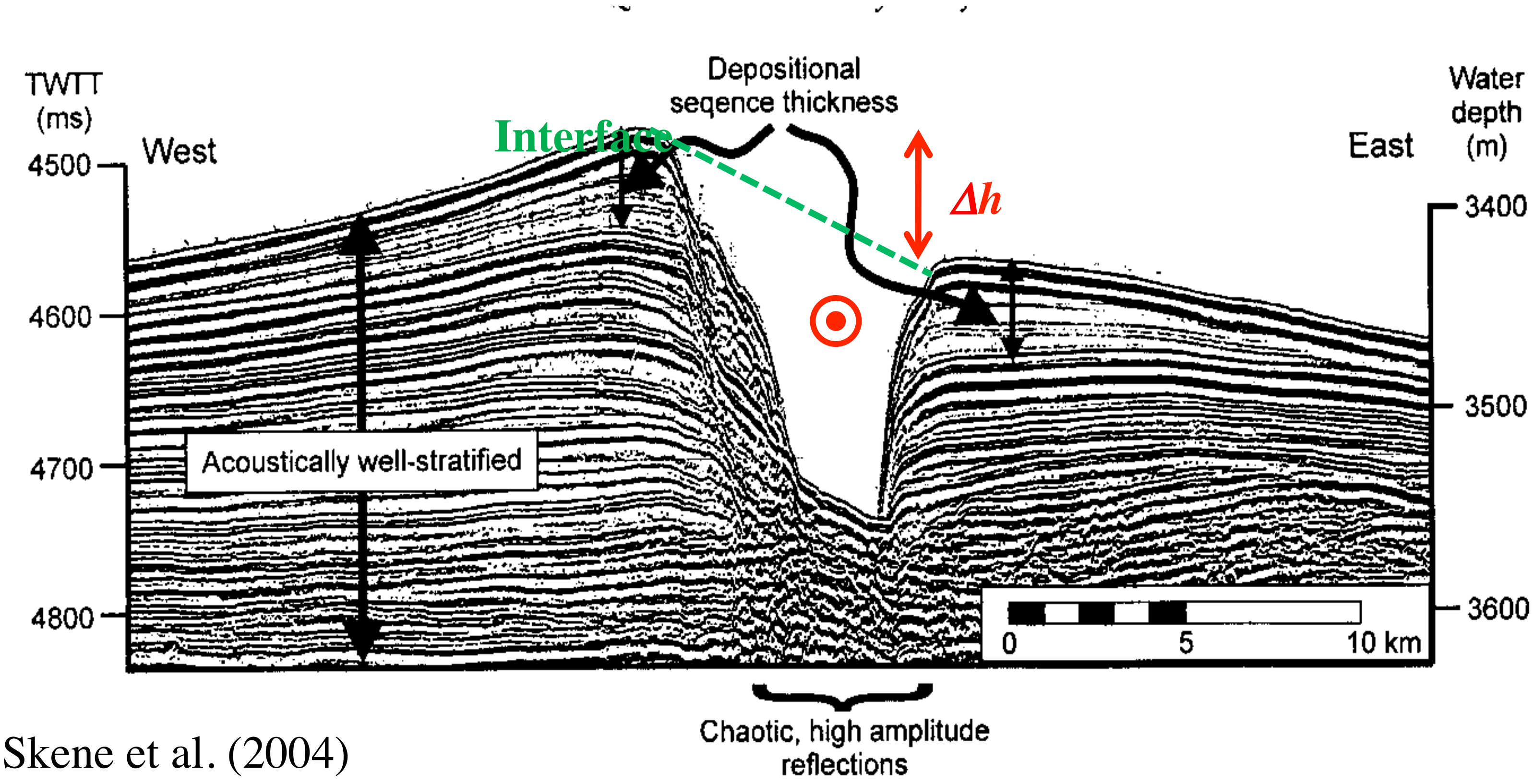


In contrast to rivers, the sinuousity of submarine channels does not depend very strongly upon the slope.


a)
peak sinuosity
latitude ϕ
channels |Ro| > 10
channels |Ro| < 10
R^2=0.64
Za
In
Am
BE
NA
PIB
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
70
80
90
b)
|Ro| ≡ |U/(Wf)|
latitude ϕ
channels |Ro| > 10
channels |Ro| < 10
R^2=0.66
Za
Am
In
BE
NA
PIB
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

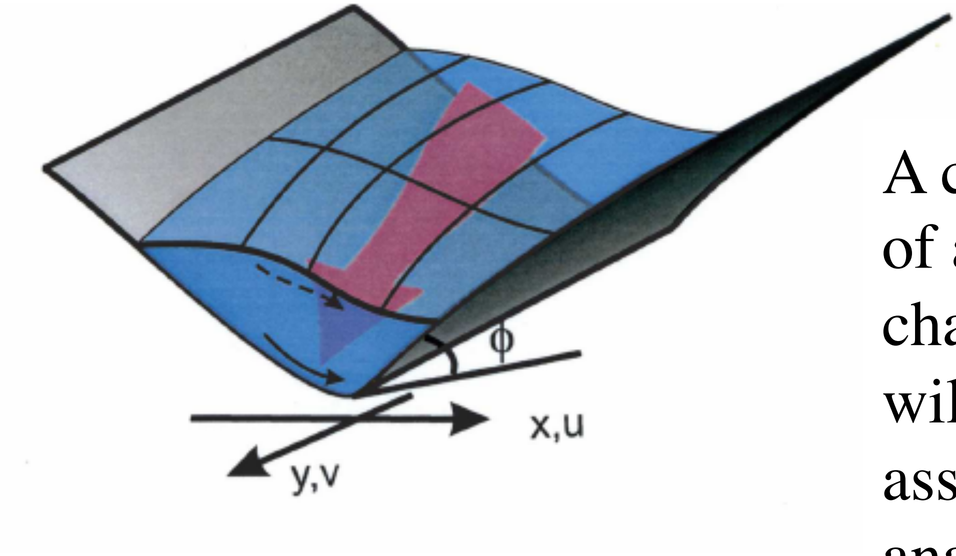


There is a good correlation between low Rossby number and low sinuosity



Skene et al. (2004)

- The asymmetry in channel levee banks is usually ascribed to Coriolis deflection of the turbidity currents.



A complete description of the flow of a stratified current in a curved channel is quite complicated, so we will have to make some assumptions in order to get an analytic solution we can compare with laboratory experiments.

$$\cancel{\frac{\partial u_n}{\partial t}} = \frac{u_s^2}{R_s} - u_s \cancel{\frac{\partial u_n}{\partial s}} - \frac{1}{\rho_0}\frac{\partial p}{\partial n} - f u_s - \cancel{\frac{\partial \langle u_n' u_z' \rangle}{\partial z}}$$

Assume the flow is steady in time

Assume the secondary circulations are constant in space

Assume we can describe friction with Ekman dynamics.

If you assume the the downstream velocity is only determined by constant Froude number condition of

$$Fr = \mathbf{u} / \sqrt{g'h} = 1$$

then Komar (1969) showed that the interface tilt will be given by,

$$-\frac{dh}{dy} = Fr^2 \left(\frac{fh}{U} + \frac{h}{R} \right)$$

So for a given geometry, tilt only depends on *U*.

a

In a straight channel $h/R=0$.

Then for a width W the deflection of the interface will be inversely related to the current speed.

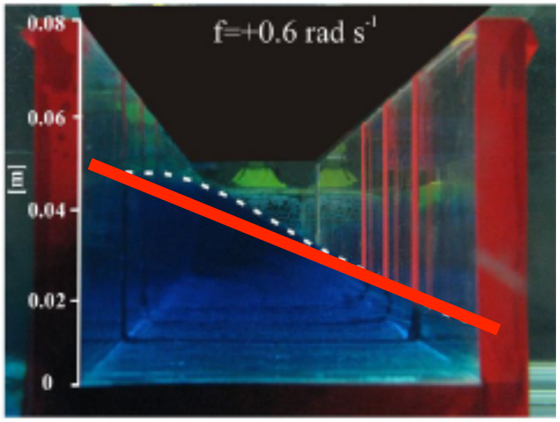
$$\Delta h_{coriolis} = Whf\,/\,U$$

This simple result had never been tested, but this result of Komar is often used to estimate speed U.

Our experiments aimed to measure U and interface slope.

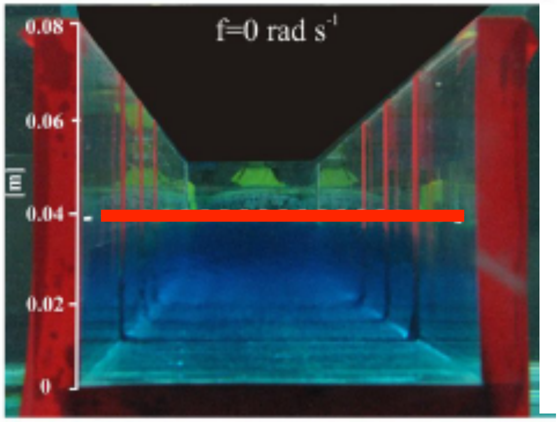
a

a



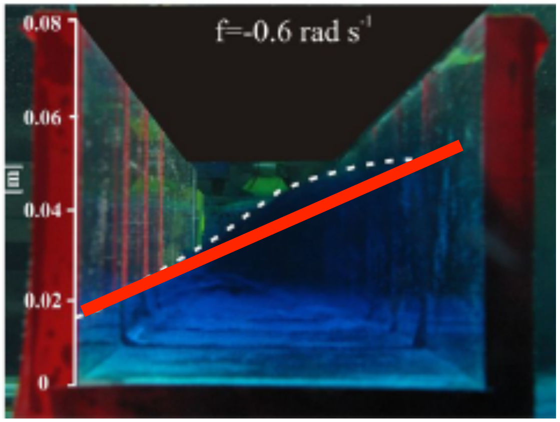
With rotation in the NH sense the interface banks upon on the RHS, looking downstream.

b



With no rotation the interface is flat

c



With rotation in the LH sense the interface banks upon on the LHS, looking downstream.

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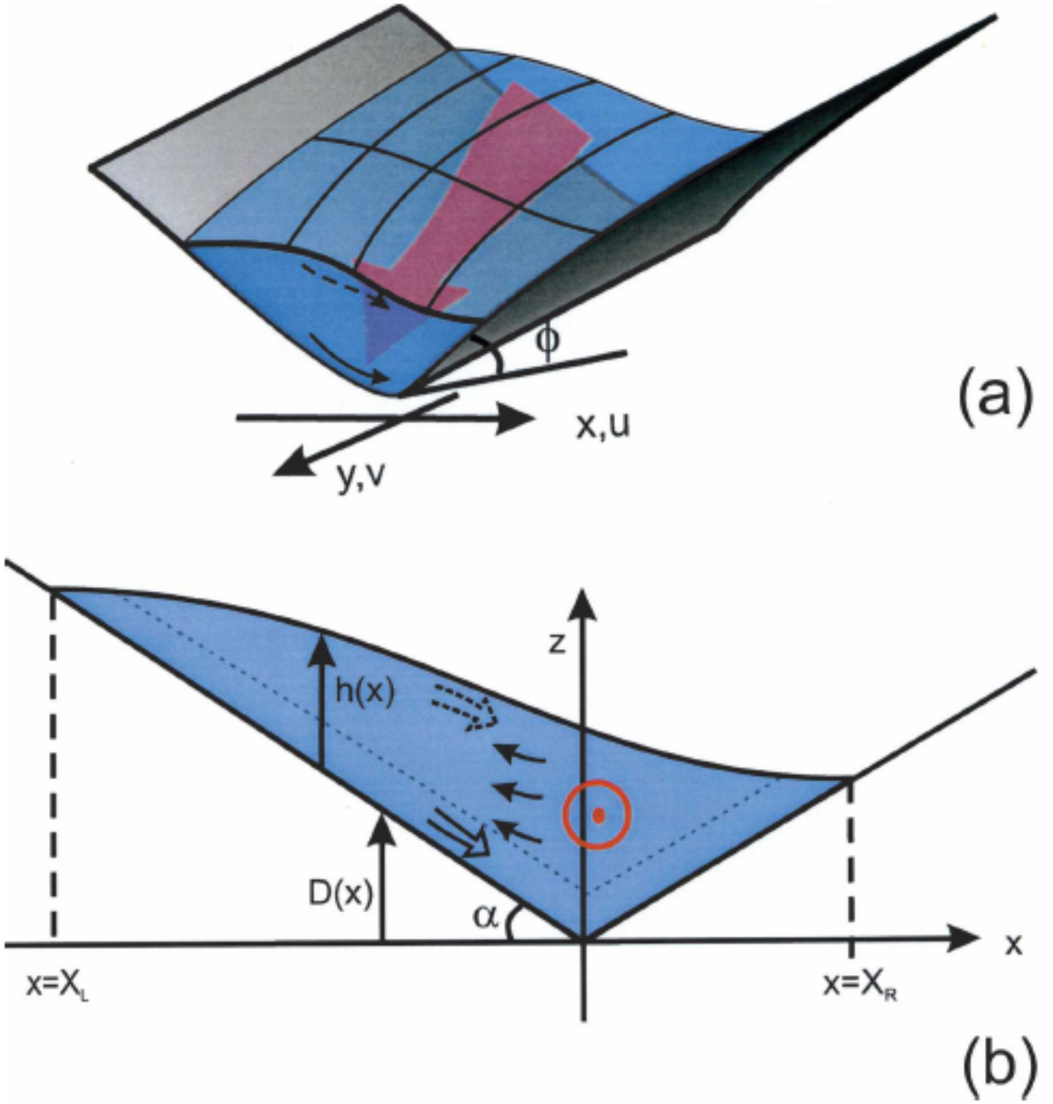


FIG. 9. Sketch of the dense current, showing the main along-channel flow (red), the bottom (solid arrow) and interfacial (dashed arrow) frictional transports, and the secondary return flow (small solid arrows). Also shown is the coordinate system and some of the notations used.

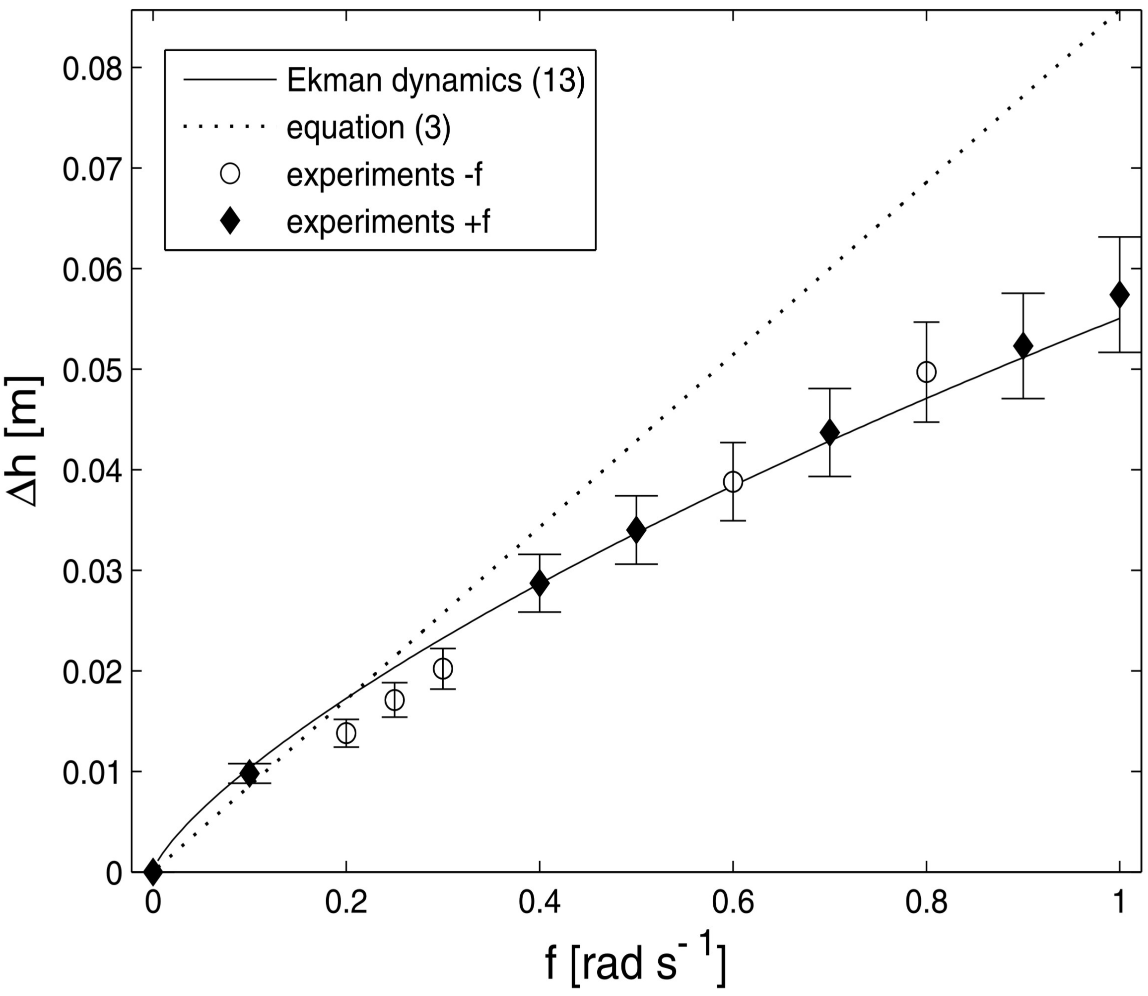
Modelling from Wahlin (2004)

$$-f \cdot \mathbf{v} = -g' s - \nu \frac{\partial^2 \mathbf{u}}{\partial z^2}$$

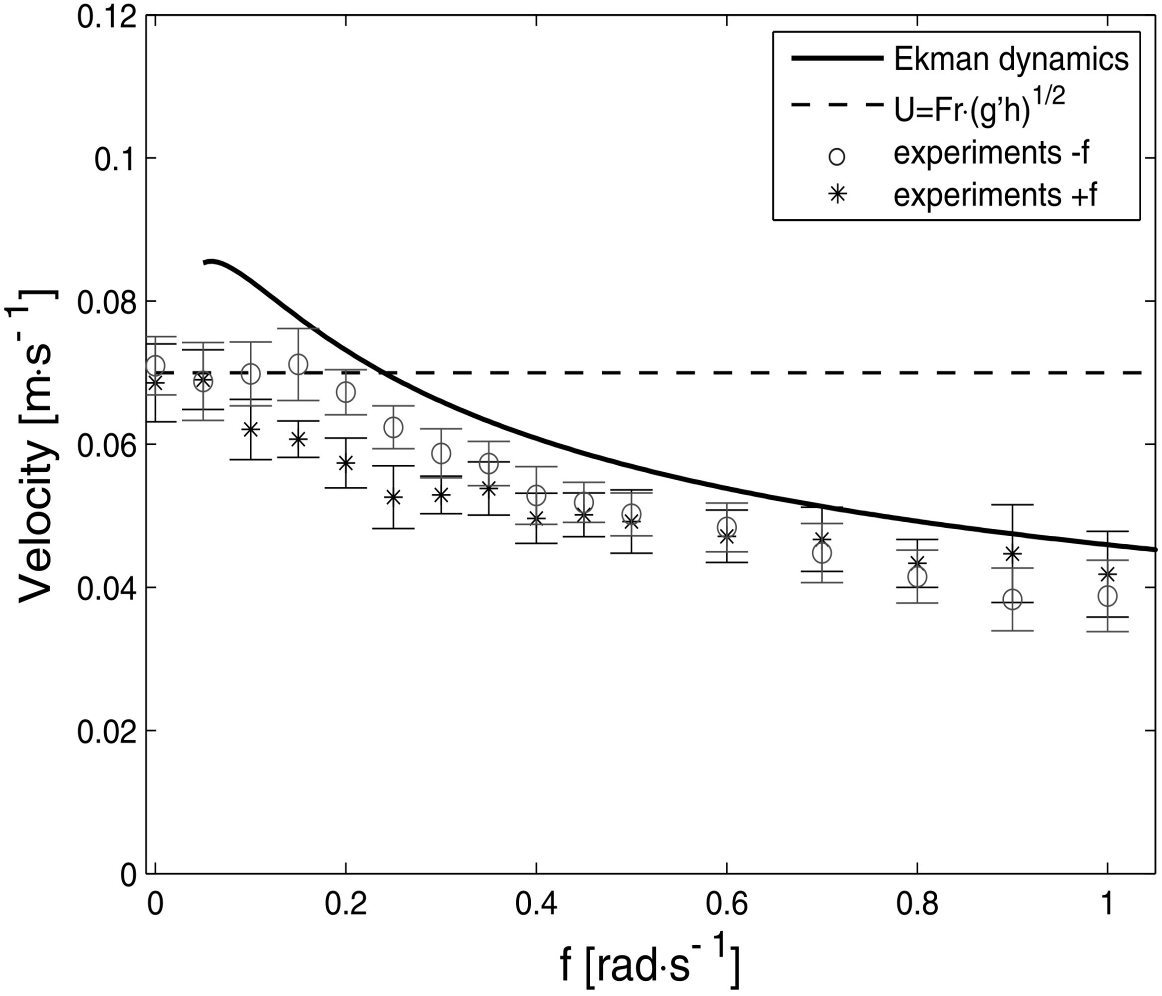
$$f \cdot \mathbf{u} = -g' h_y - \nu \frac{\partial^2 \mathbf{v}}{\partial z^2}$$

Slope of the interface with varying rotation rates

Deflection of the density interface *Δh* is better reflected for large *f* by the inclusion of Ekman dynamics.



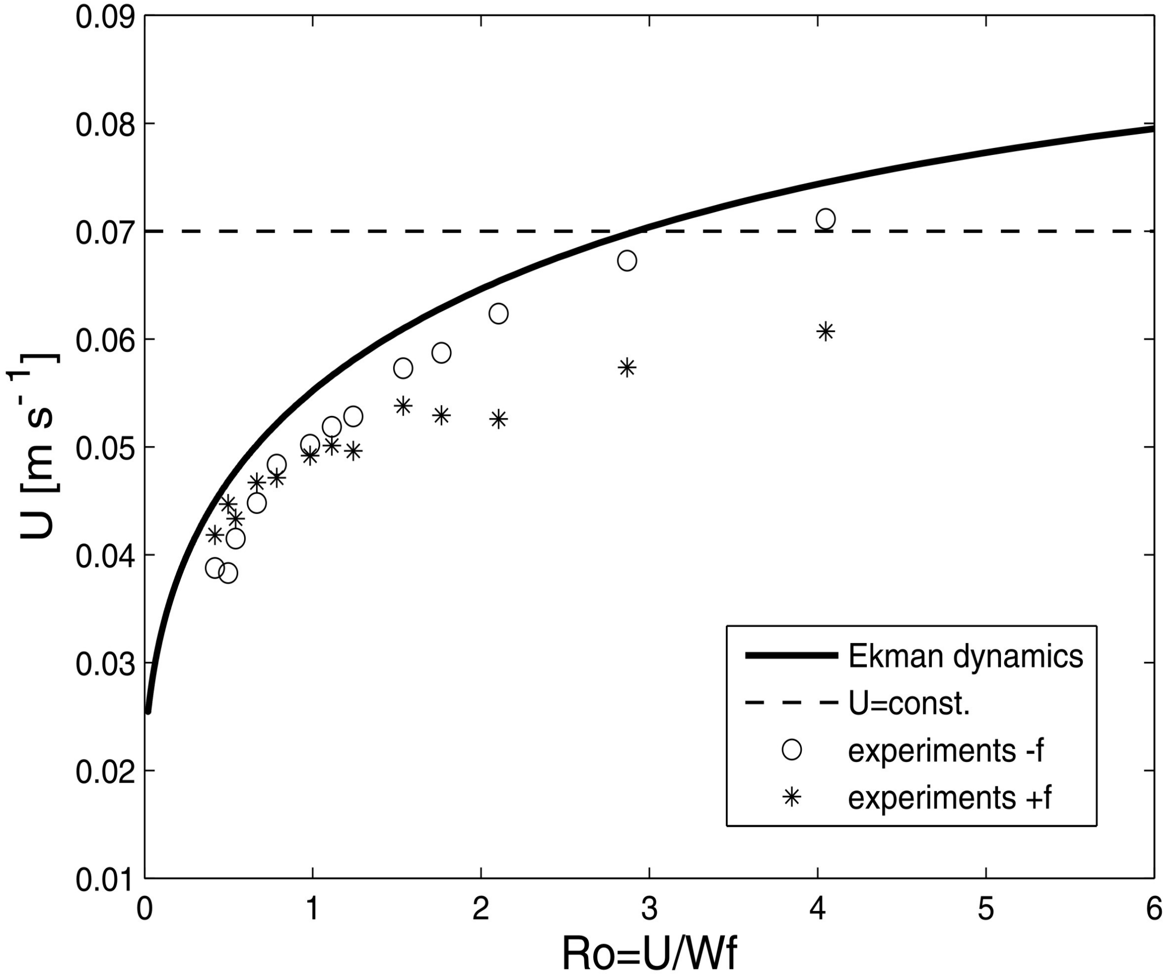
Downhill propagation speed with varying rotation rates



The velocity data can also be plotted in terms of a Rossby-Number based upon the width of the flow

For Rossby numbers smaller than 10 the Coriolis-effect becomes somewhat important

For Rossby number of order 1 it is dominant.

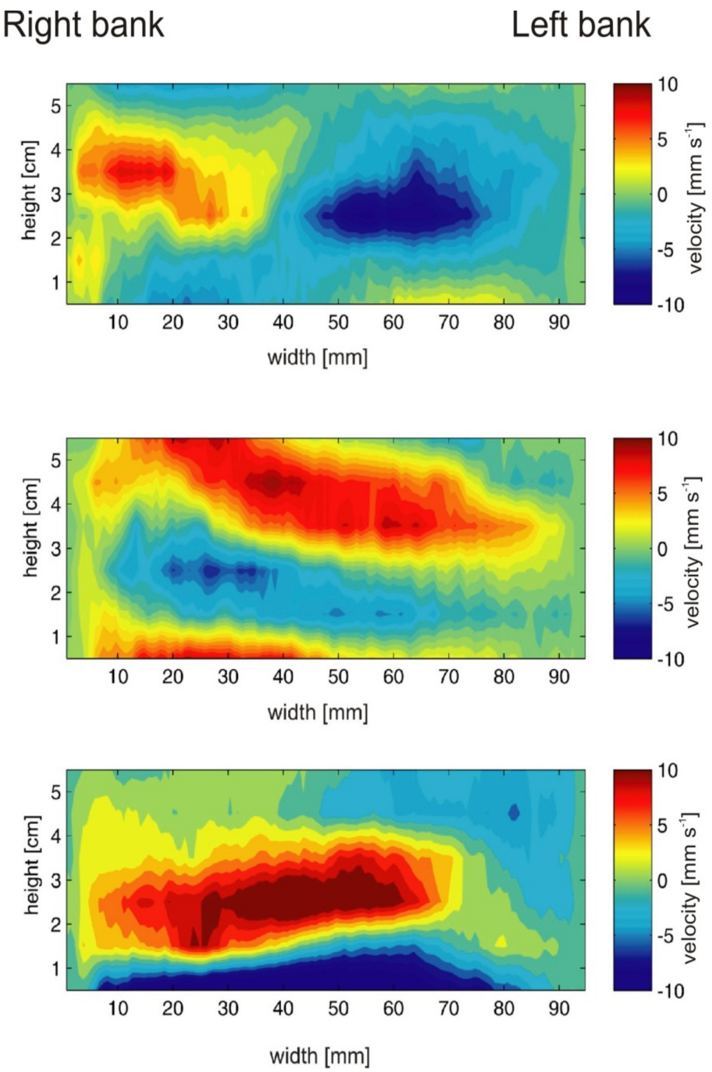


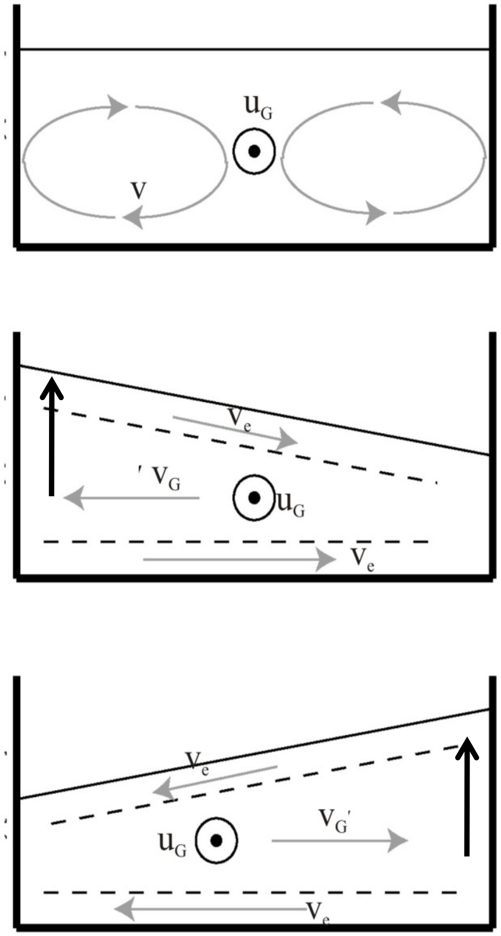
Secondary flow fields with varying rotation rates

No rotation
$f=0$ rad s^{-1}

NH
$f=+0.25$ rad s^{-1}

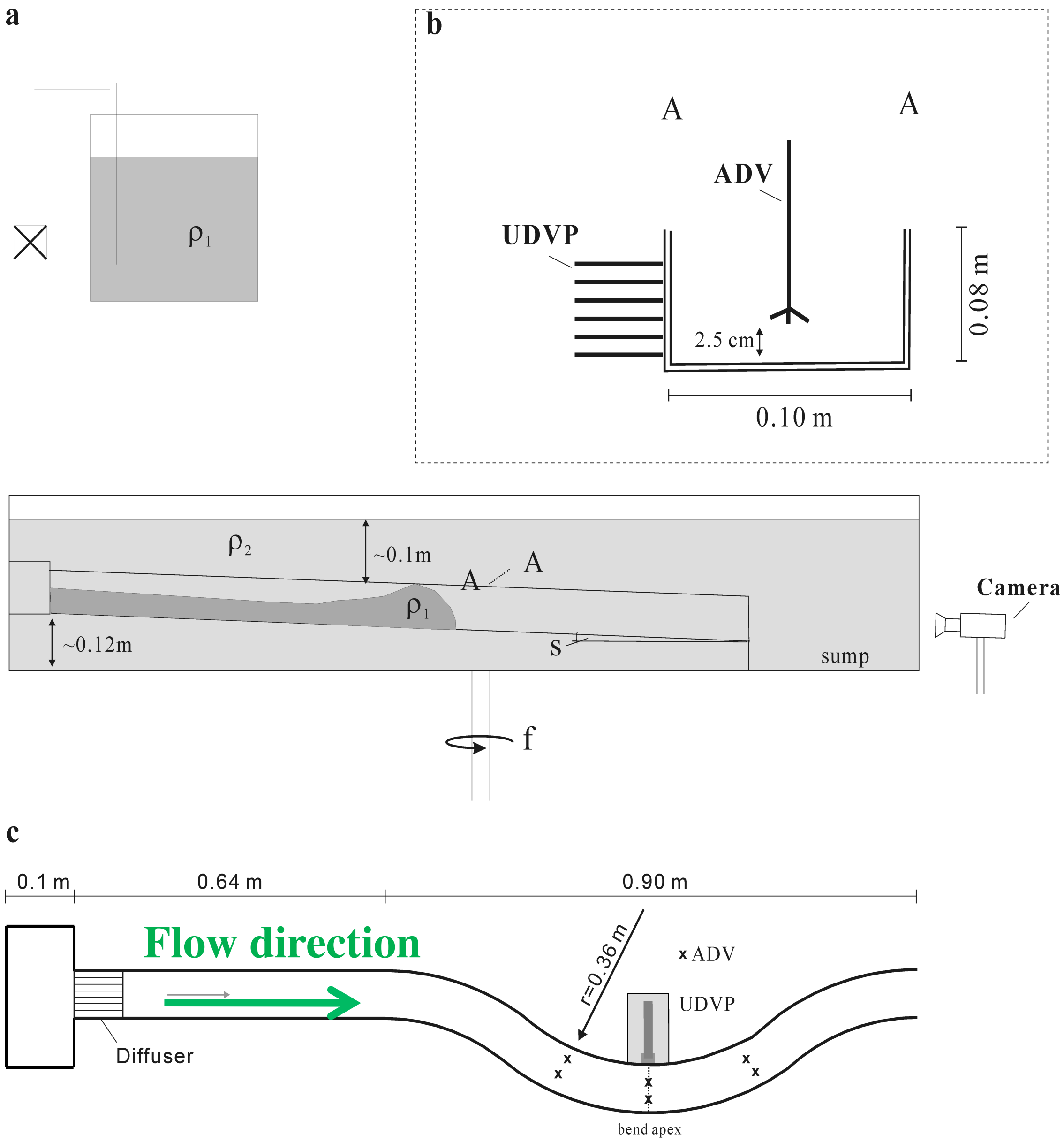
SH
$f= -0.25$ rad s^{-1}

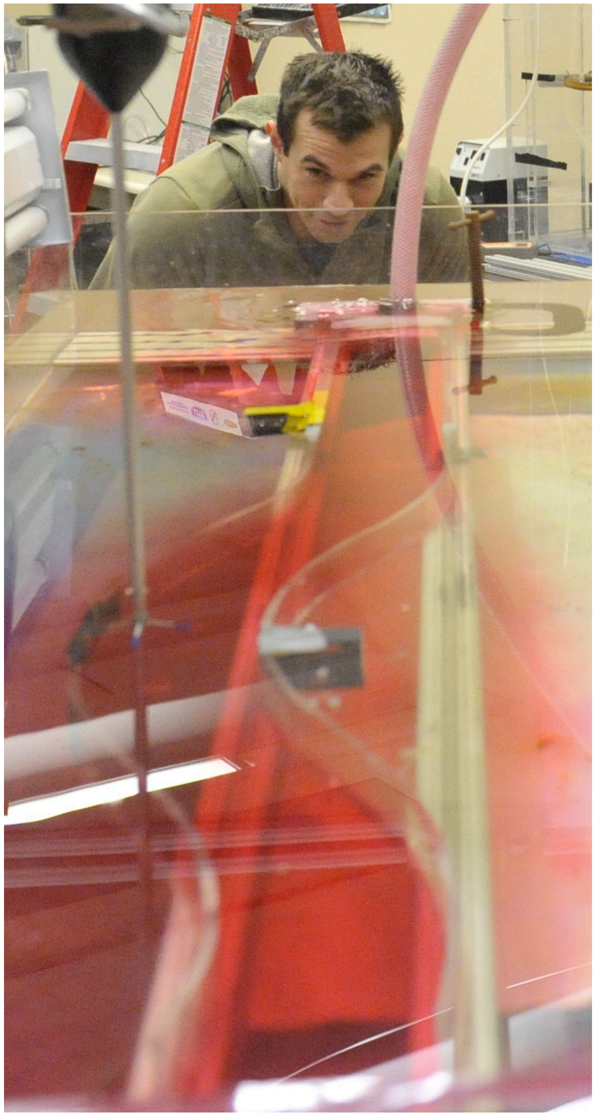


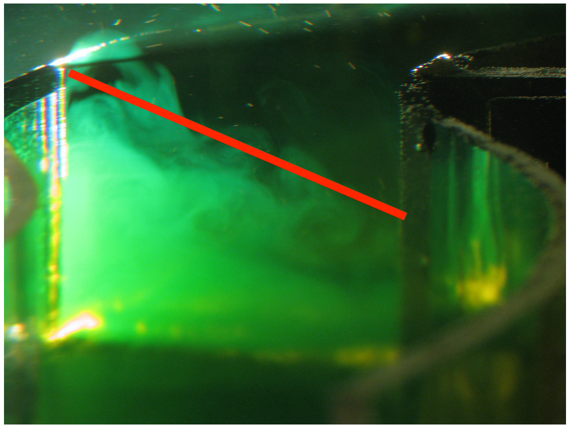


across-stream velocities are in geostrophic balance

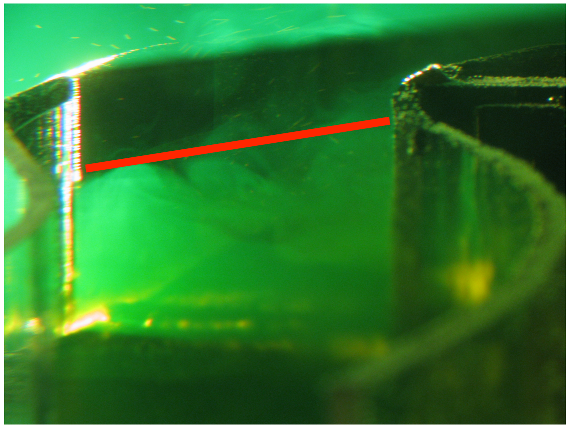
Experimental modelling of rotating gravity currents in bend



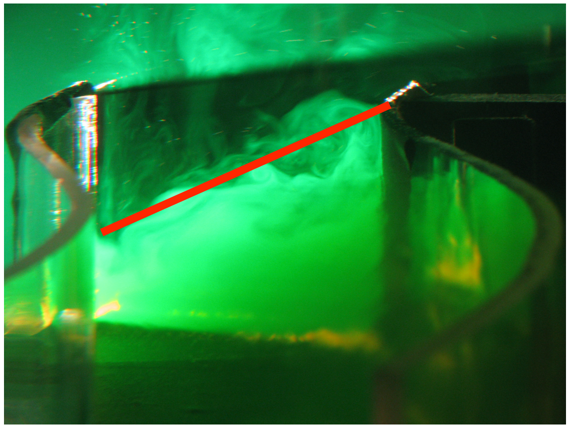




No Rotation
Interface deflected
to the outside of channel



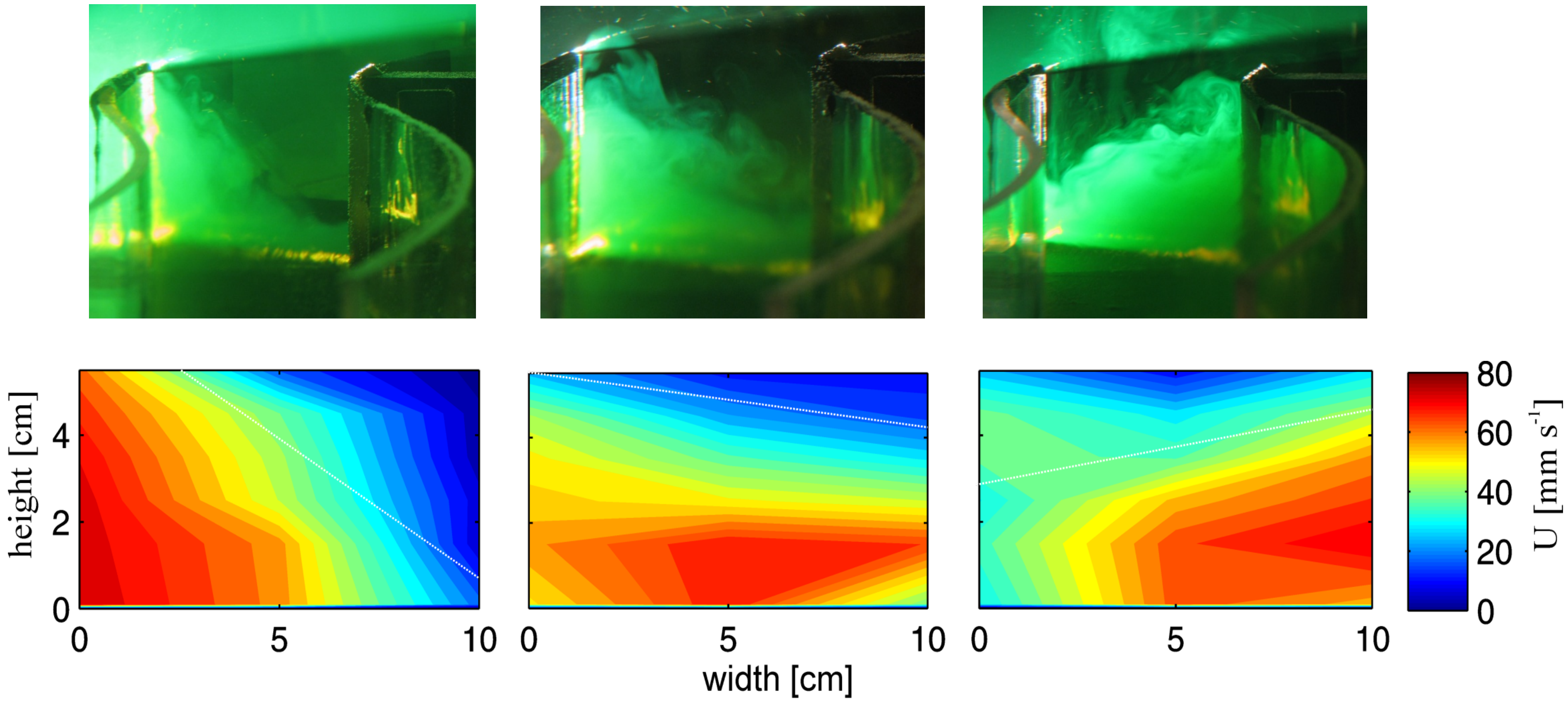
Moderate rotation
Interface deflected
to the inside of channel



Strong rotation
Interface deflected
to the inside of channel

$$-\frac{dh}{dy} = Fr^2\left(\frac{fh}{U} + \frac{h}{R}\right)$$

- •As *f* can be positive or negative, Coriolis can act with or against the centrifugal terms.
- •Interface is predicted to be flat when $Ro = U/Rf = -1$.
- •Here we introduce a second Rossby number based upon the radius of curvature as $Ro_R = U/Rf$.



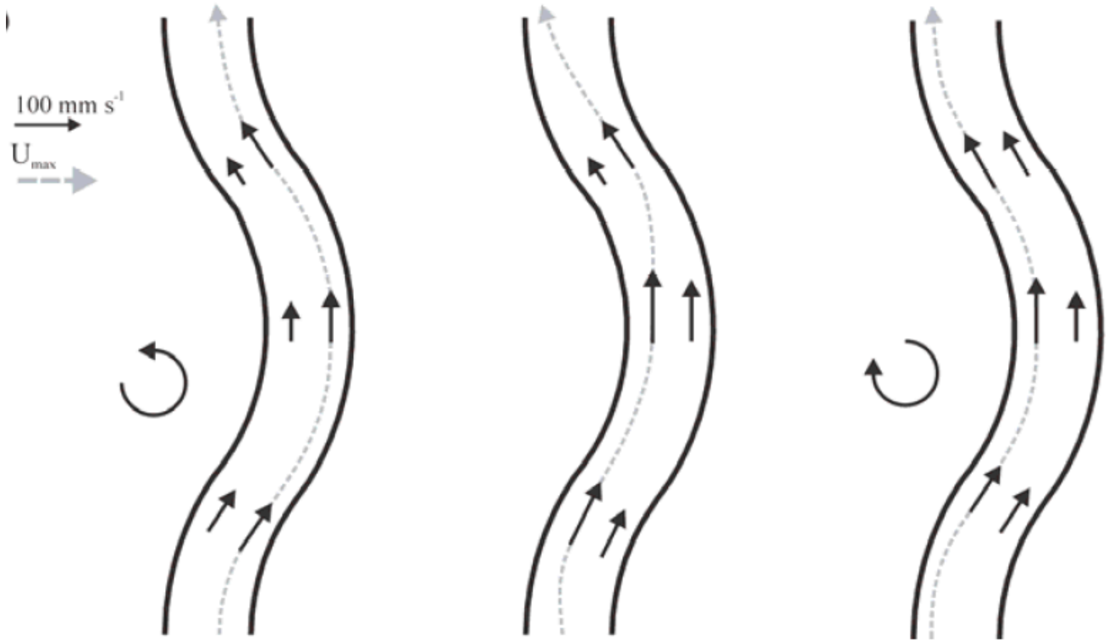
f > 0 (Northern Hemisphere)

f = 0 (at the equator)

f < 0 (Southern Hemisphere)

Core of maximum downstream velocity shifts with *f*

Location of maximum velocity in a sinuous channel subject to Coriolis



f > 0 (Northern Hemisphere)

Coriolis and centrifugal force act in the same direction

f = 0 (at the equator)

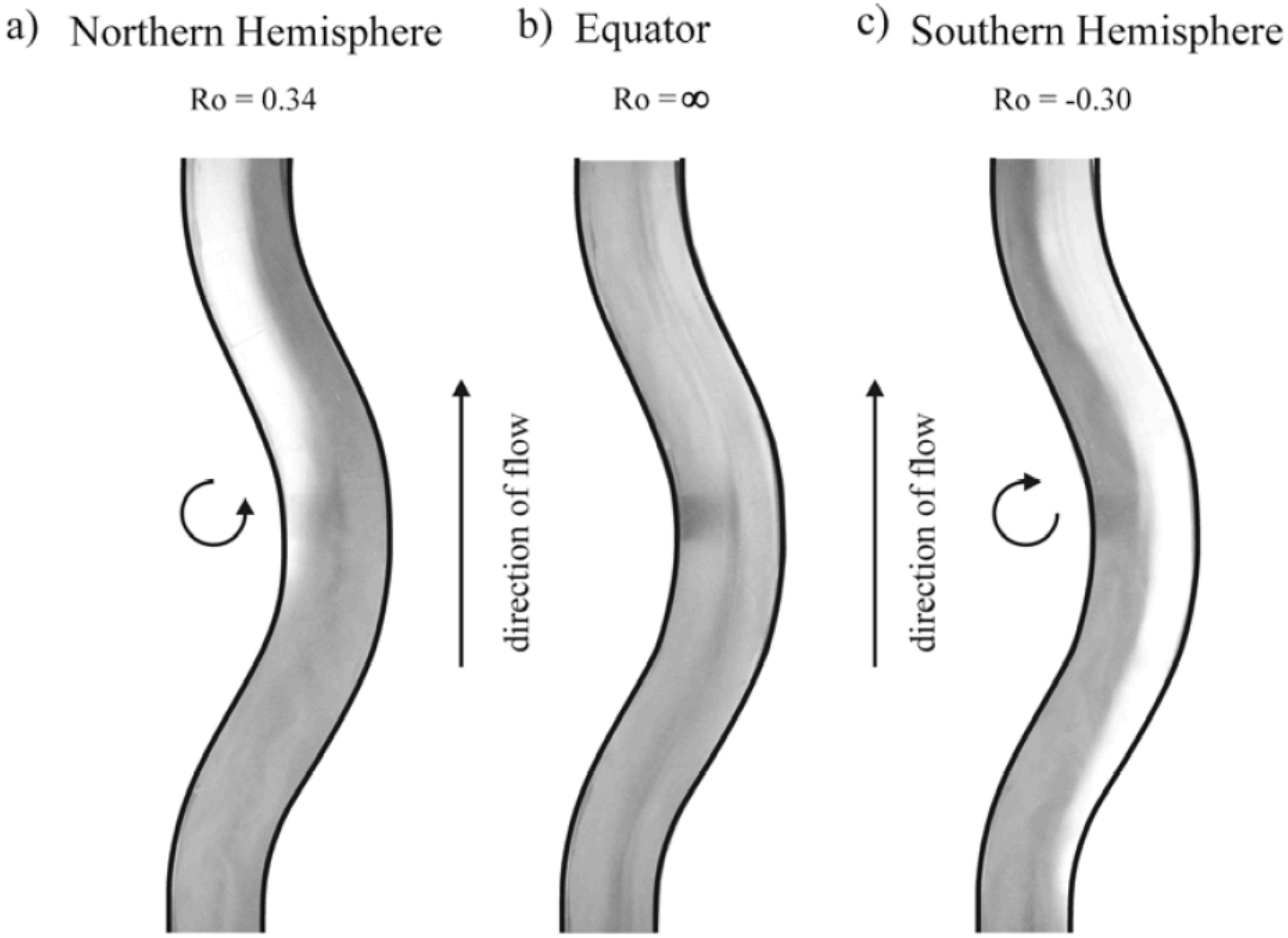
only centrifugal force causes perturbations in downstream velocity

f < 0 (Southern Hemisphere)

Coriolis and centrifugal force counteract each other

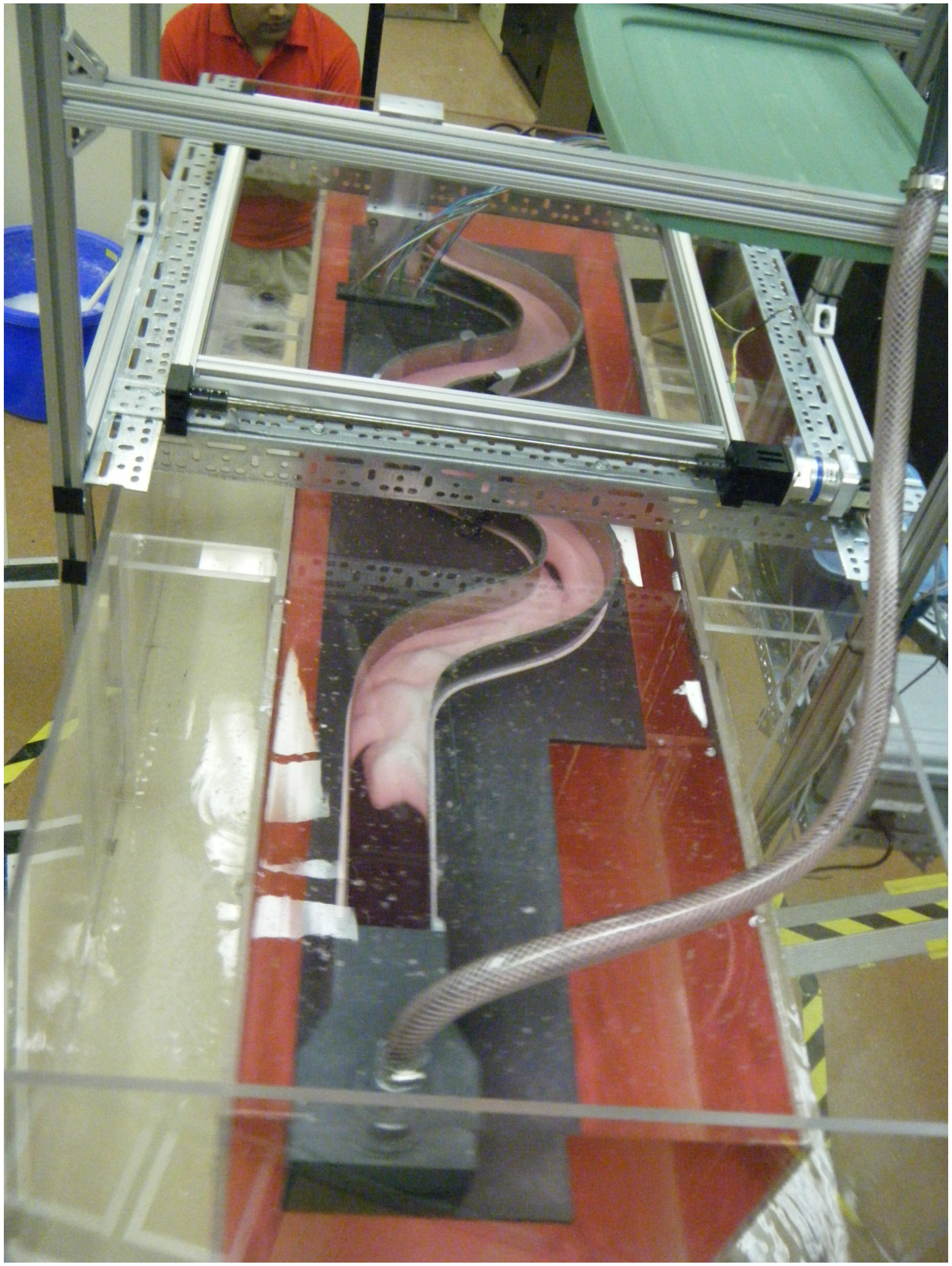
Coriolis force > centrifugal force

Depositional patterns from a seadiment laden gravity current

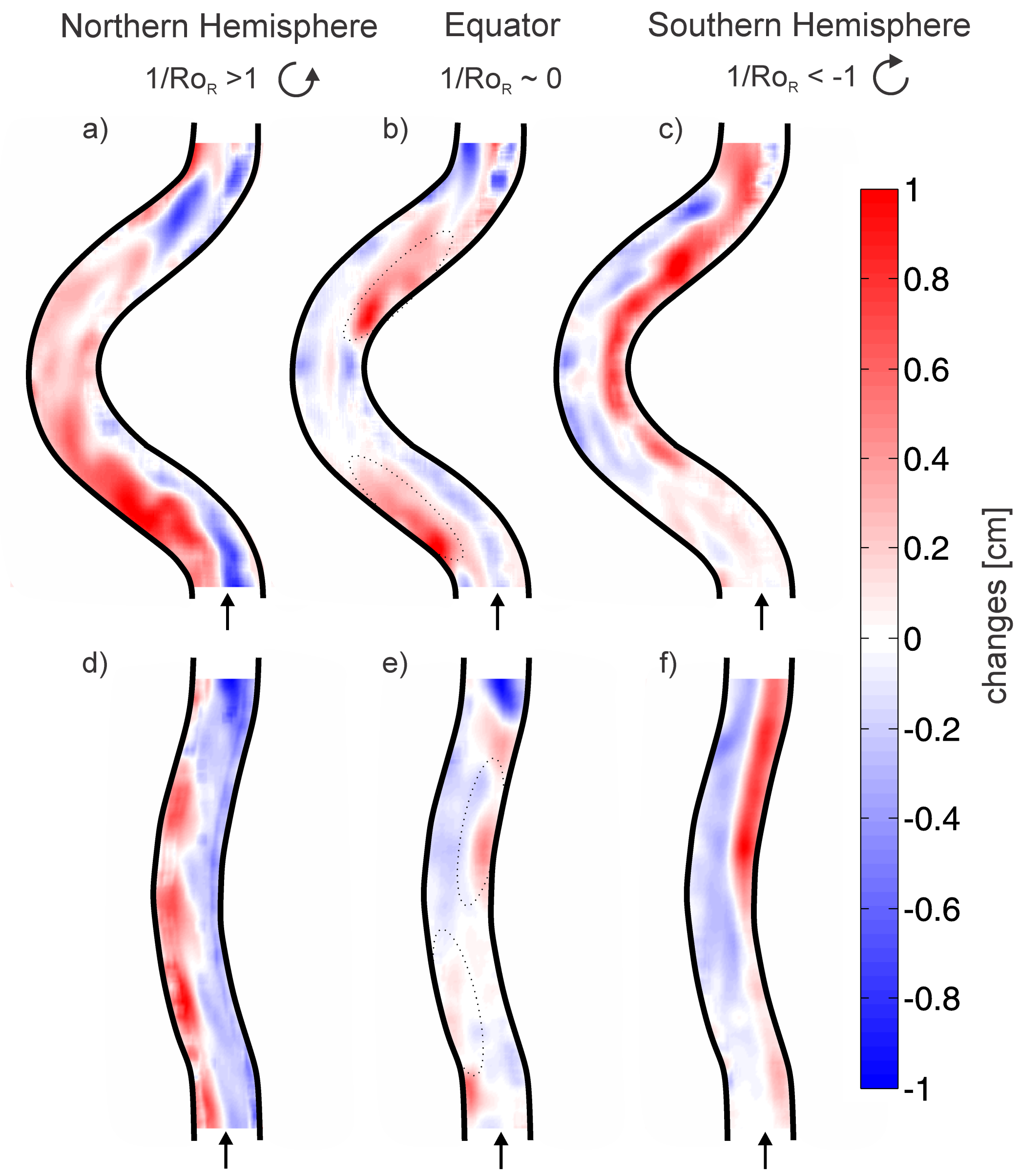


More deposition on RHS

More deposition on LHS



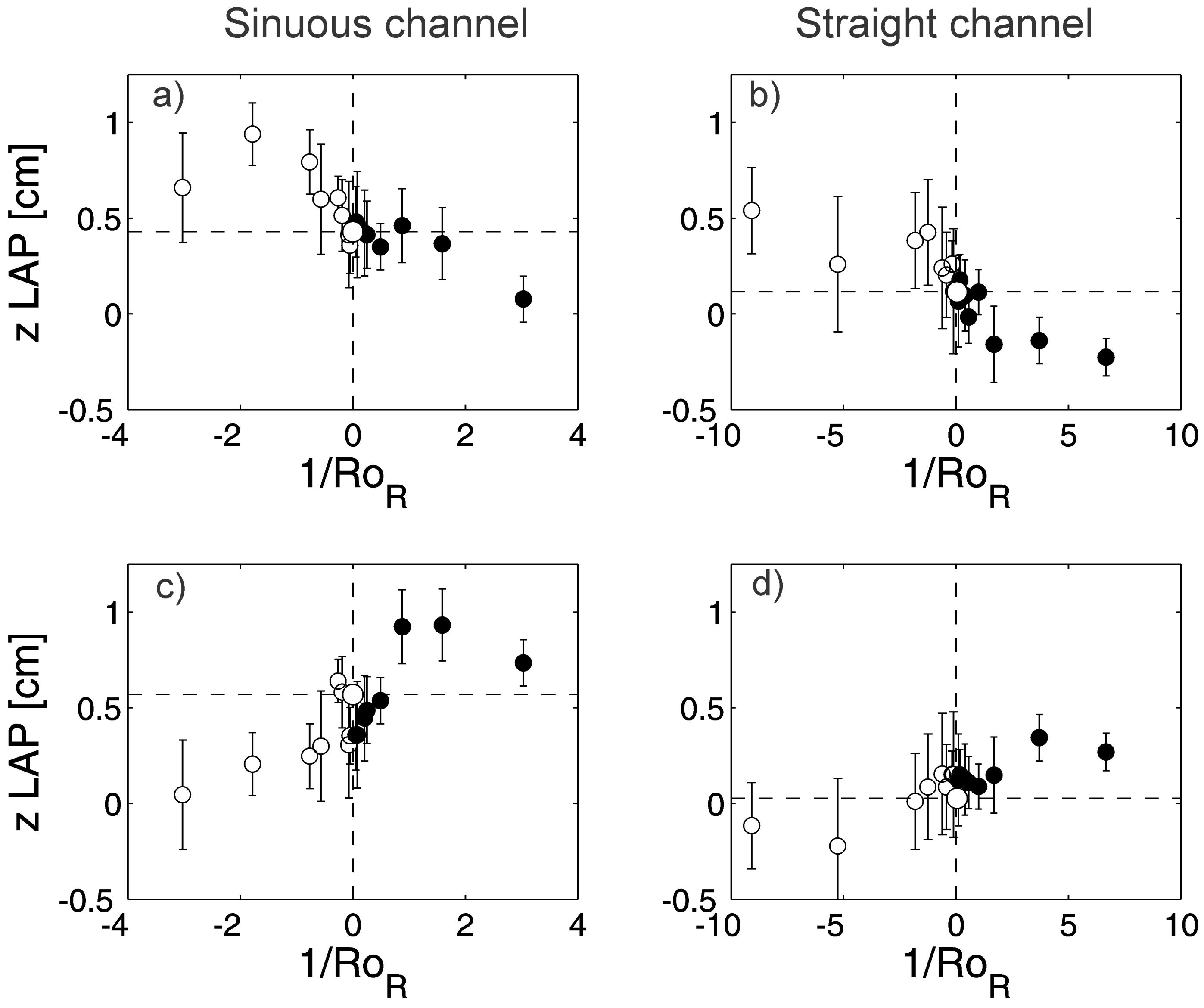
Rotating experiments with a rotating bed of low density plastic beads.



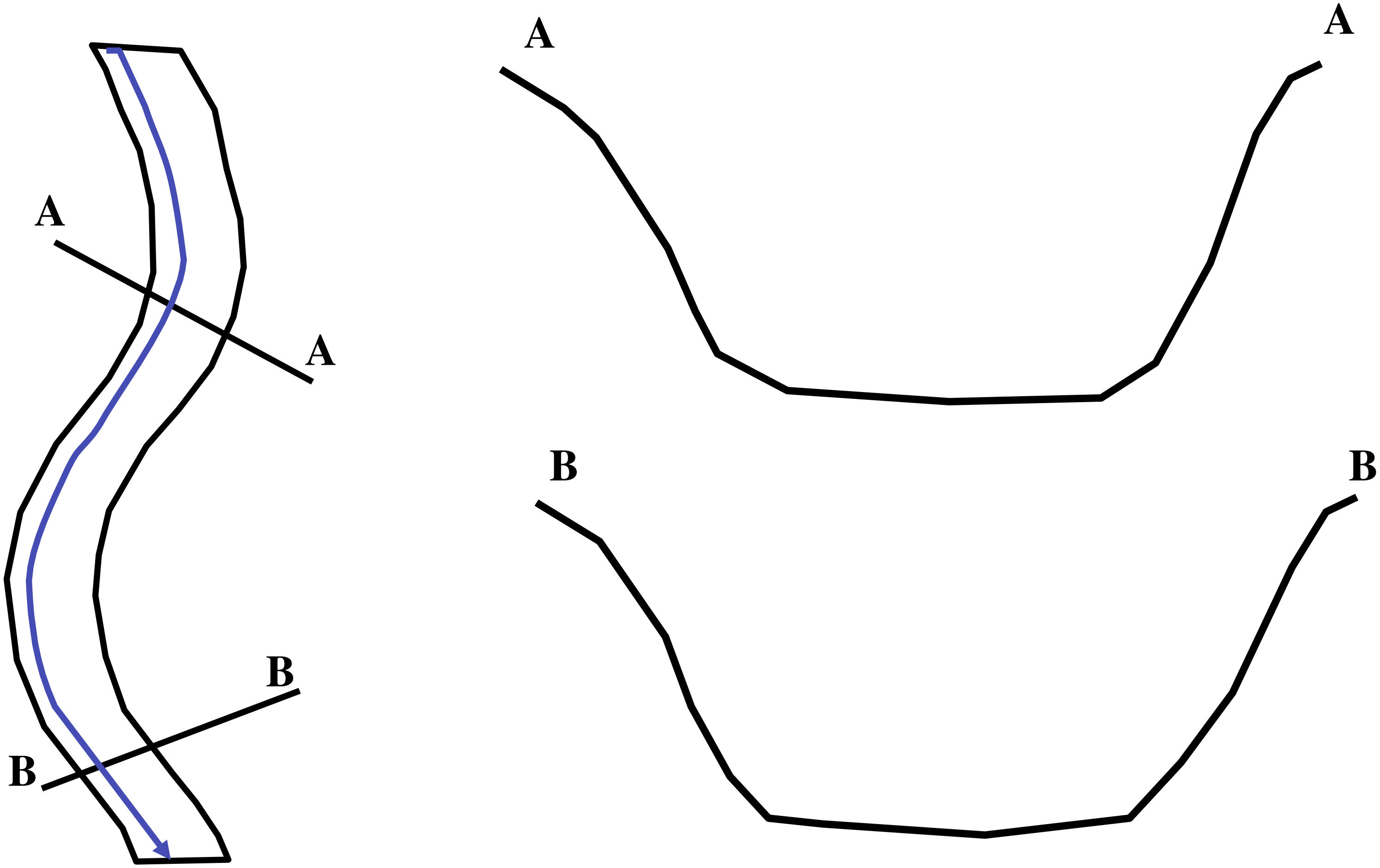
Erosion on RHS
Deposition on LHS

Alternating pattern
between bends

Erosion on LHS
Deposition on RHS

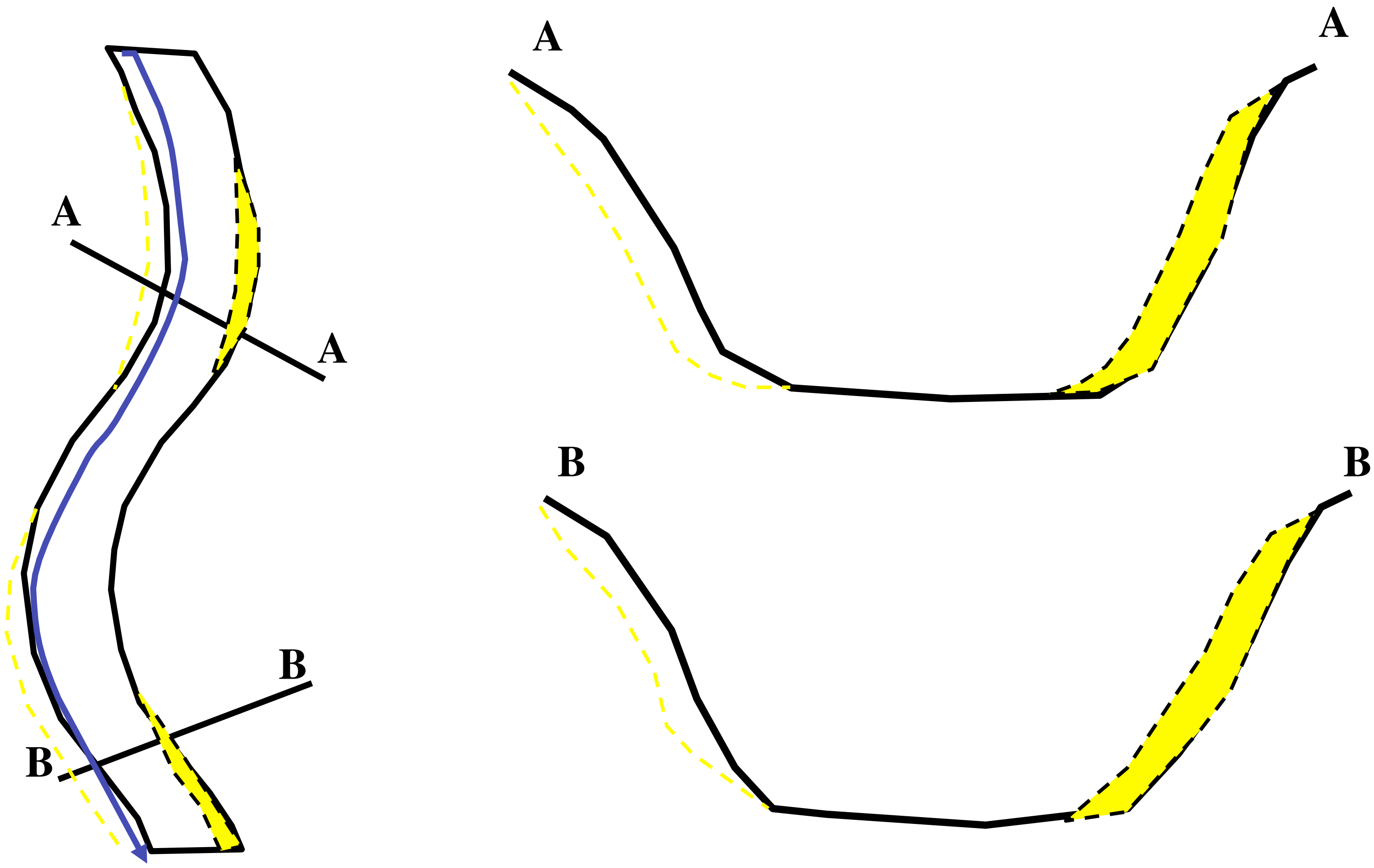

Sinuous channel
Straight channel
a)
b)
c)
d)
z LAP [cm]
z LAP [cm]
1/Ro$_R$
1/Ro$_R$
1/Ro$_R$
1/Ro$_R$
1
0.5
0
-0.5
-4
-2
0
2
4
-10
-5
0
5
10

Possible evolution of channels in high latitude systems when f >> 0 (NH).



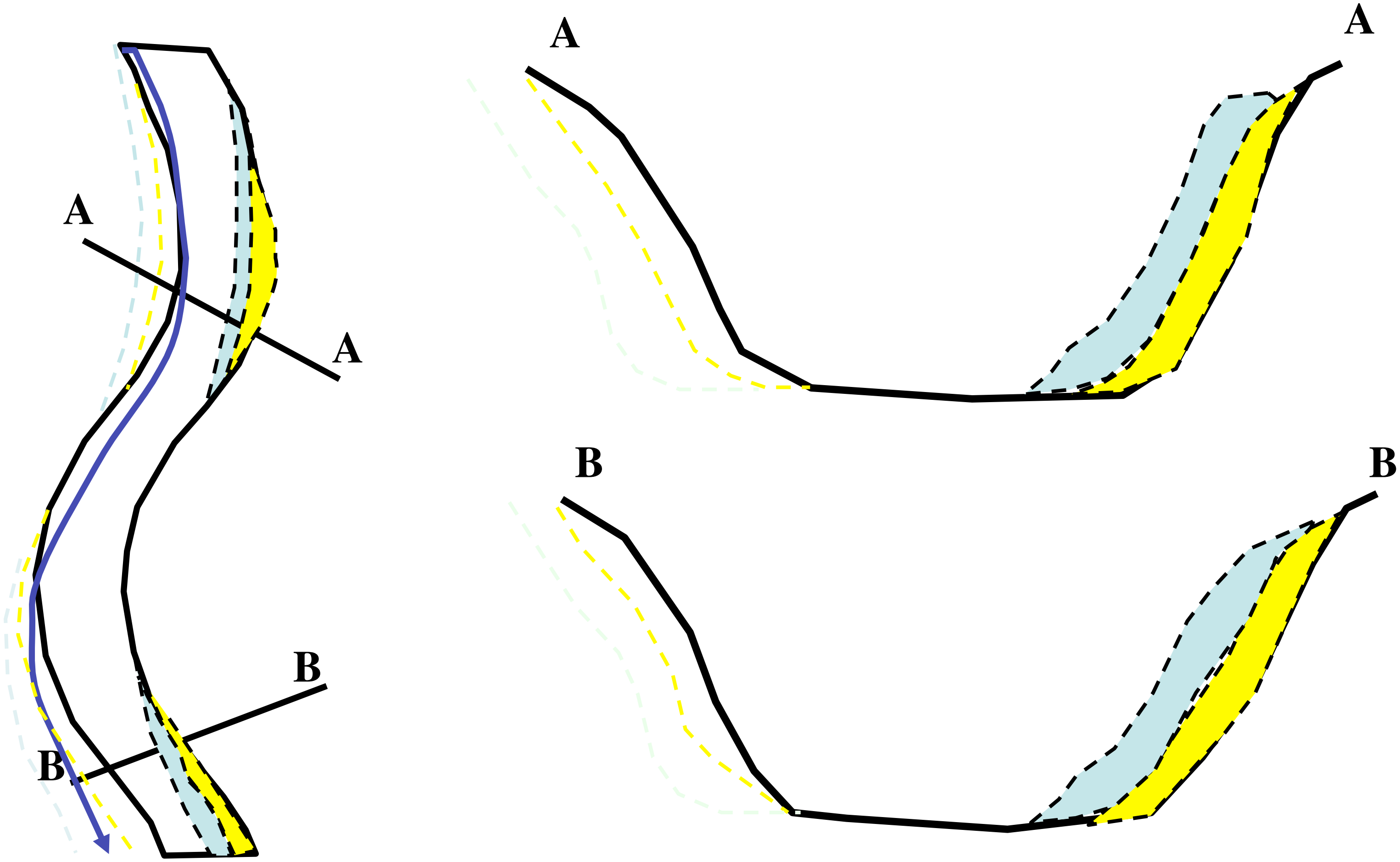
maximum velocity at the bottom
and on RHS looking downstream.

Possible evolution of channels in high latitude systems



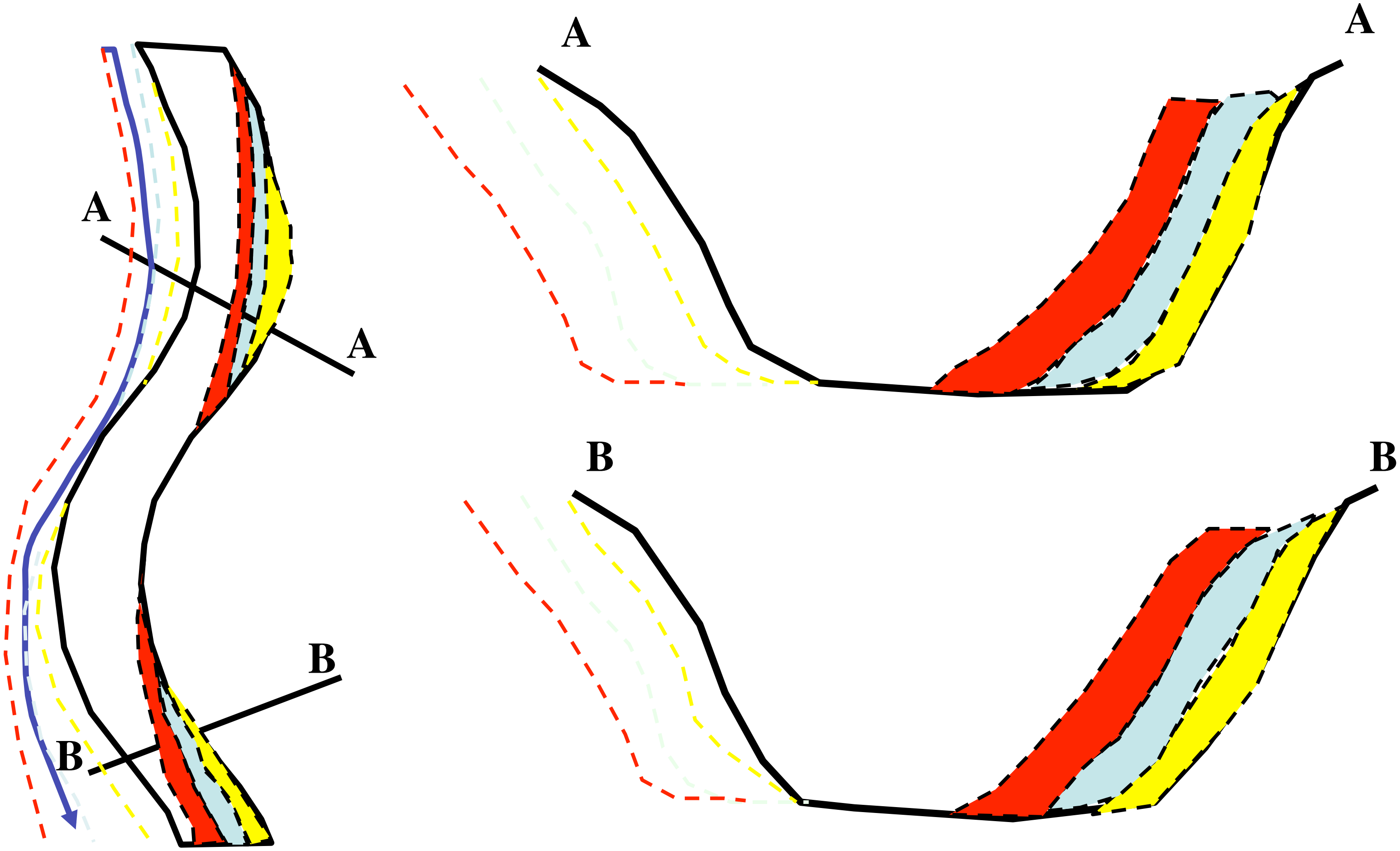
maximum velocity at the bottom

Possible evolution of channels in high latitude systems



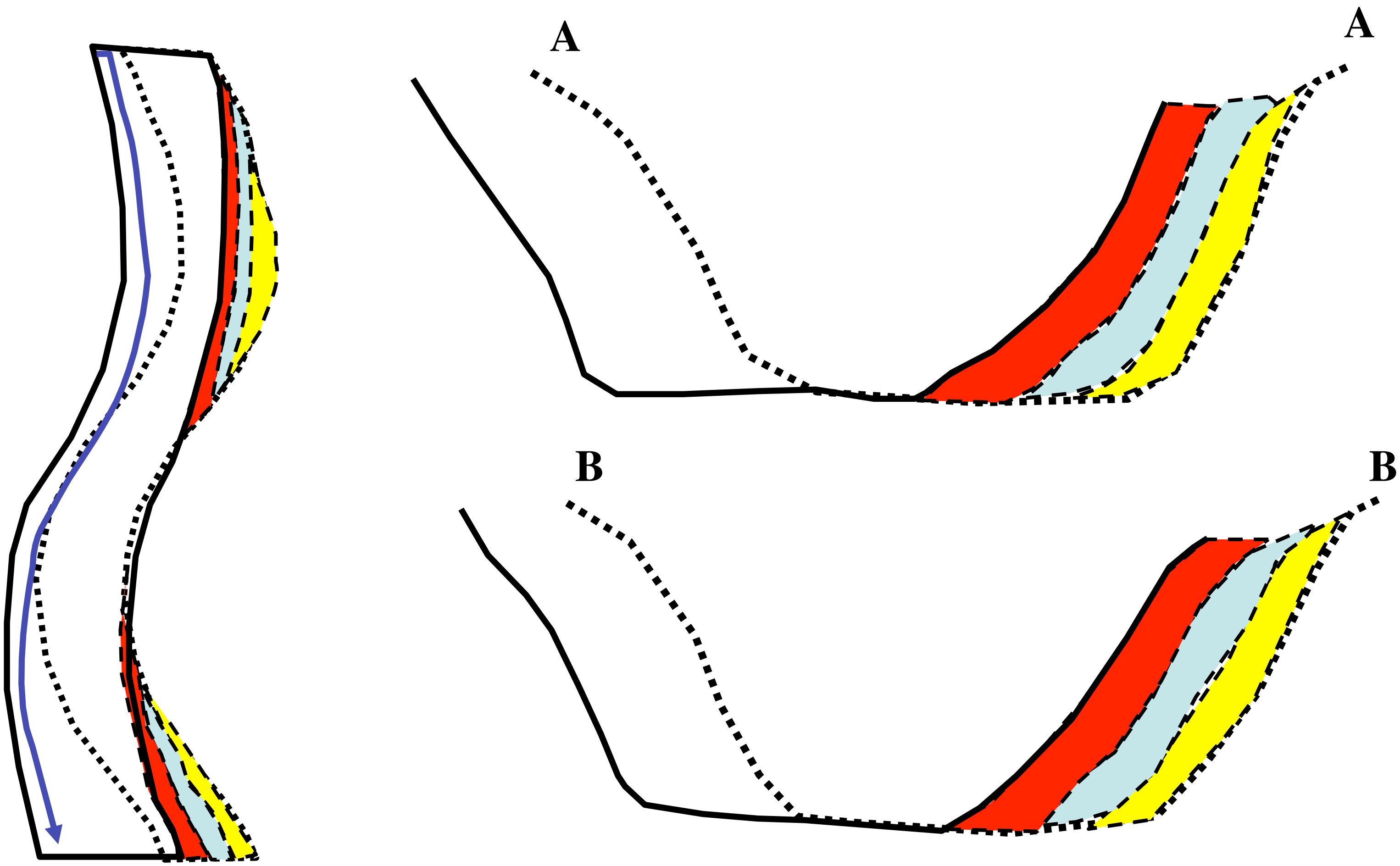
maximum velocity at the bottom

Meandering channels on submarine fans

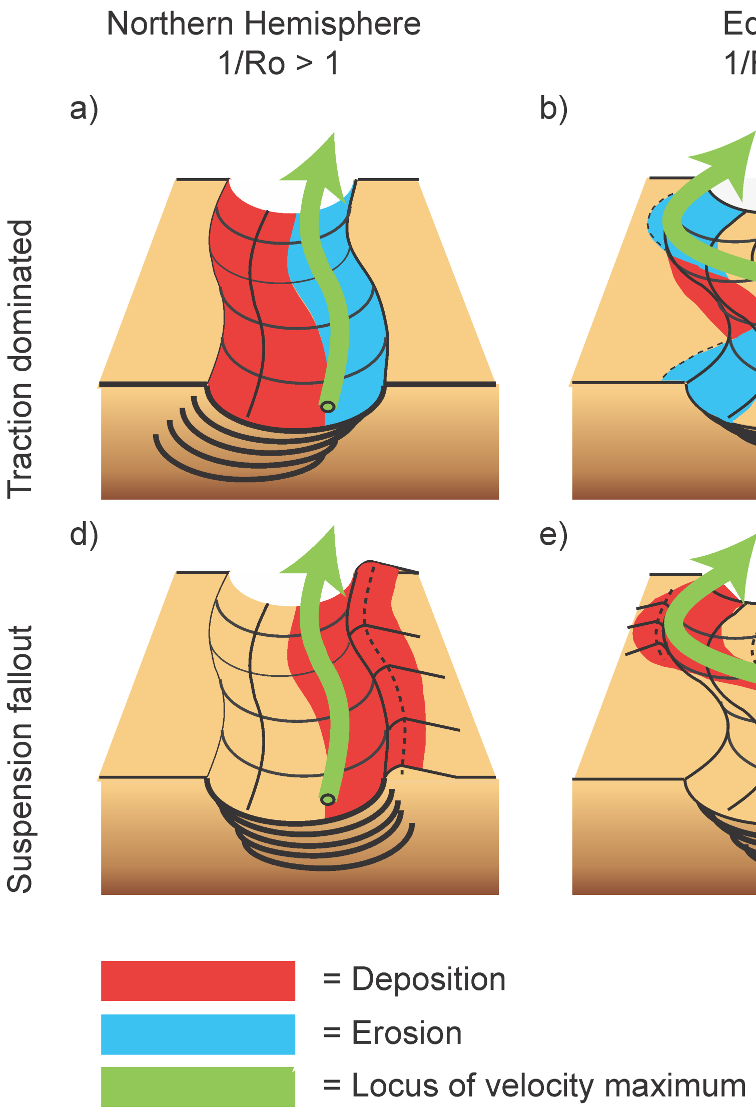


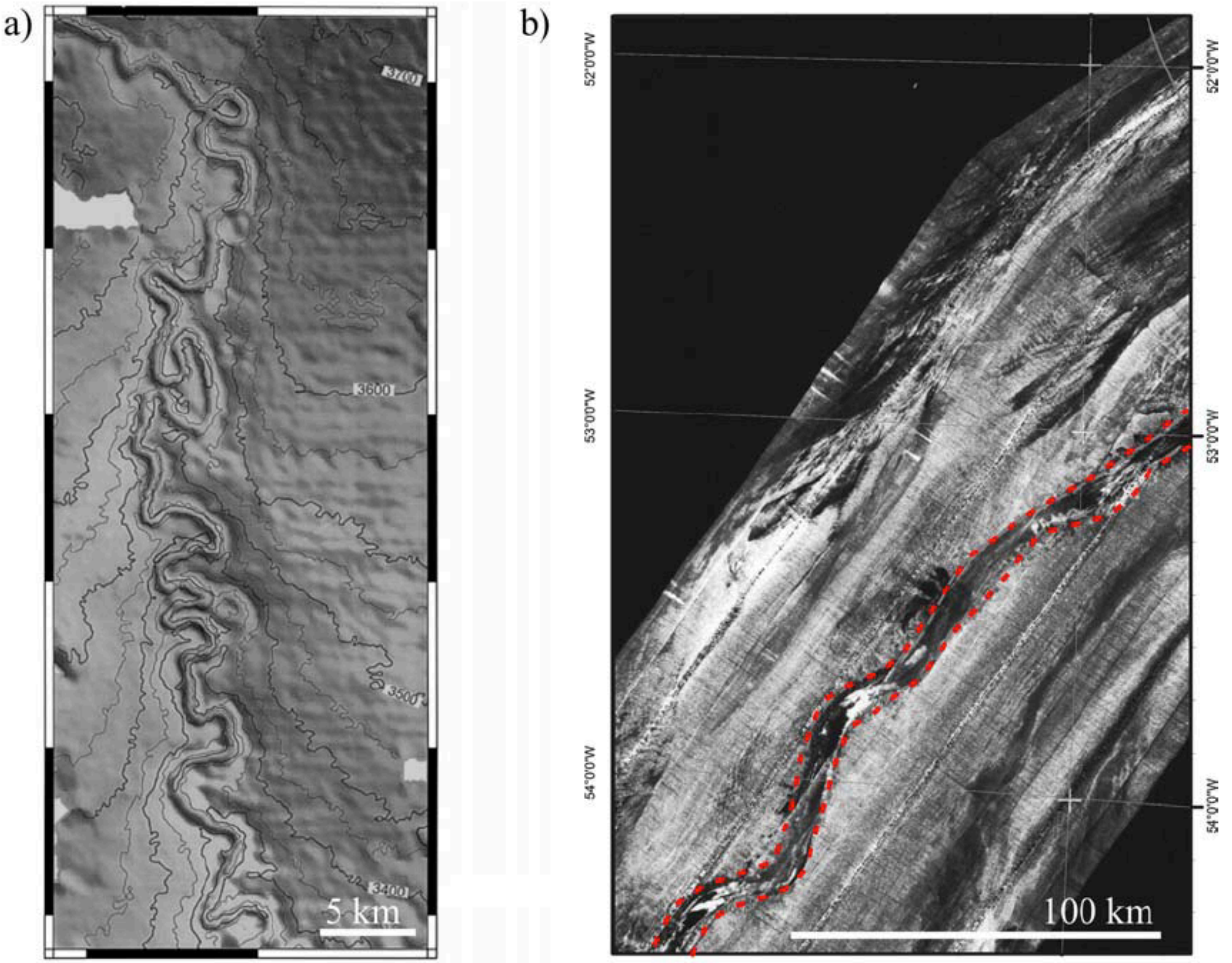
maximum velocity at the bottom

Meandering channels on submarine fans



maximum velocity at the bottom


Northern Hemisphere
1/Ro > 1
Equator
1/Ro =0
Southern Hemisphere
1/Ro < -1
a)
b)
c)
Traction dominated
d)
e)
f)
Suspension fallout
= Deposition
= Erosion
= Locus of velocity maximum



very sinuous

almost straight.

a)Bathymetry of Amazon Fan at approximately 5° N - Imran et al (1999)
b)Seismic image of the NAMOC at 60° N - from David Piper

Summary.

- The larger the rotation rate, the smaller the downhill propagation speed U.

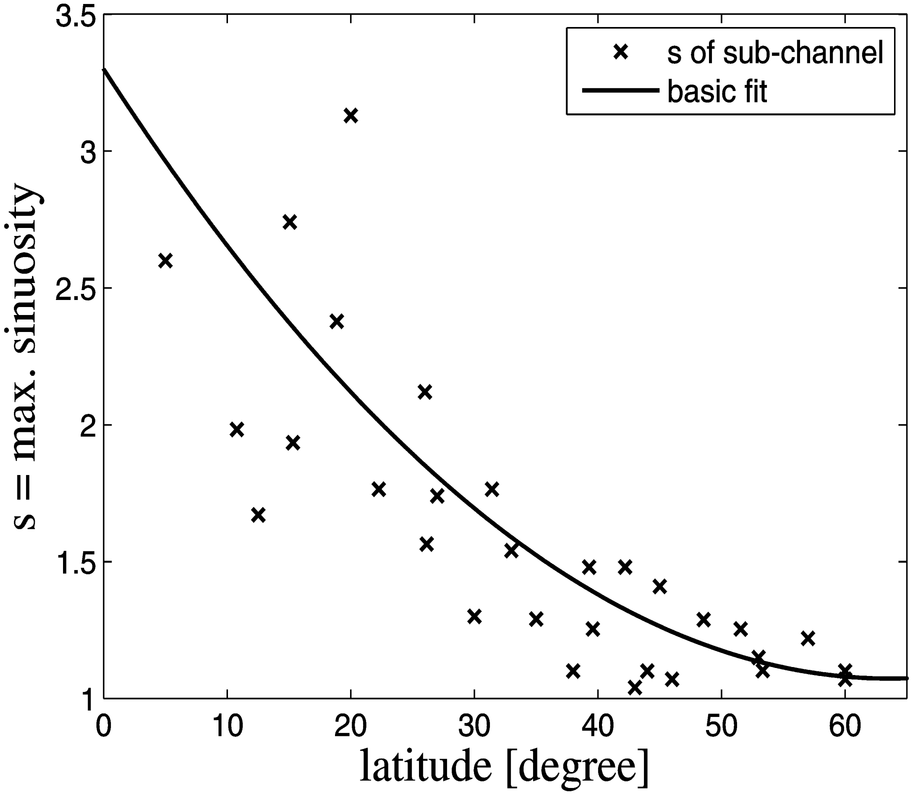
- Deflection of the density interface increases with increasing rotation.

- The magnitude and direction of secondary flow cell depends on orientation and magnitude of rotation.

- Deflection of the density current to the right (left) in the Northern (Southern) Hemisphere.

- These processes influence the sedimentation patterns in submarine channel systems and might be the key role for the apparent inverse relationship between the Coriolis parameter and the channel sinuosity.

Sinuosity of submarine channels vs latitude



Peakall et al. (2008)