Warnemünder Turbulence Days 30.08. – 3.09.2015

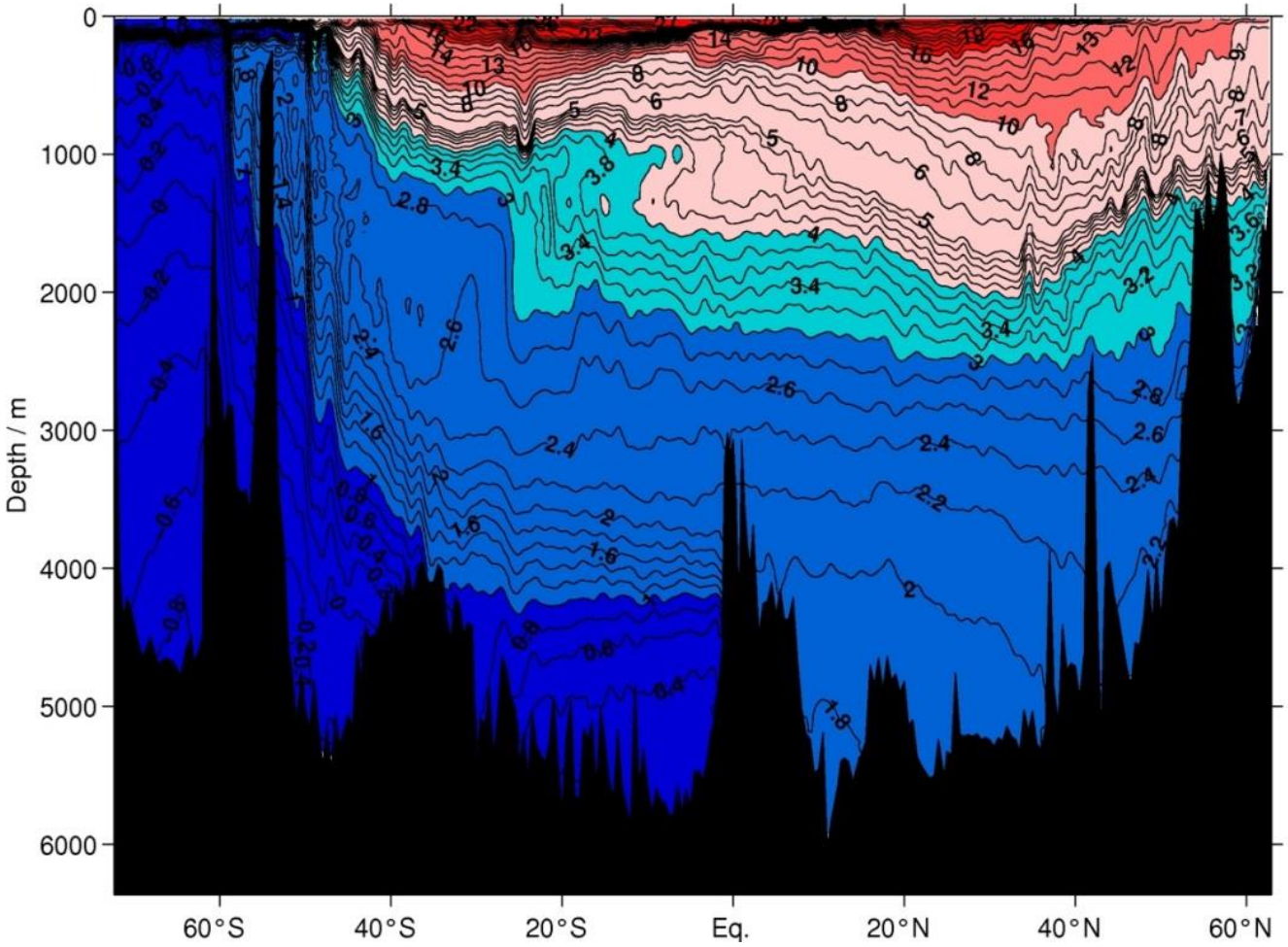
Overflow induced turbulence in a deep ocean channel

Sandra Tippenhauer, Marcus Dengler, Tim Fischer, Torsten Kanzow

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

GEOMAR

Mixing in the Ocean



Meridional temperature distribution across the Atlantic (Kanzow and Visbeck, 2009).

Continuously stratified

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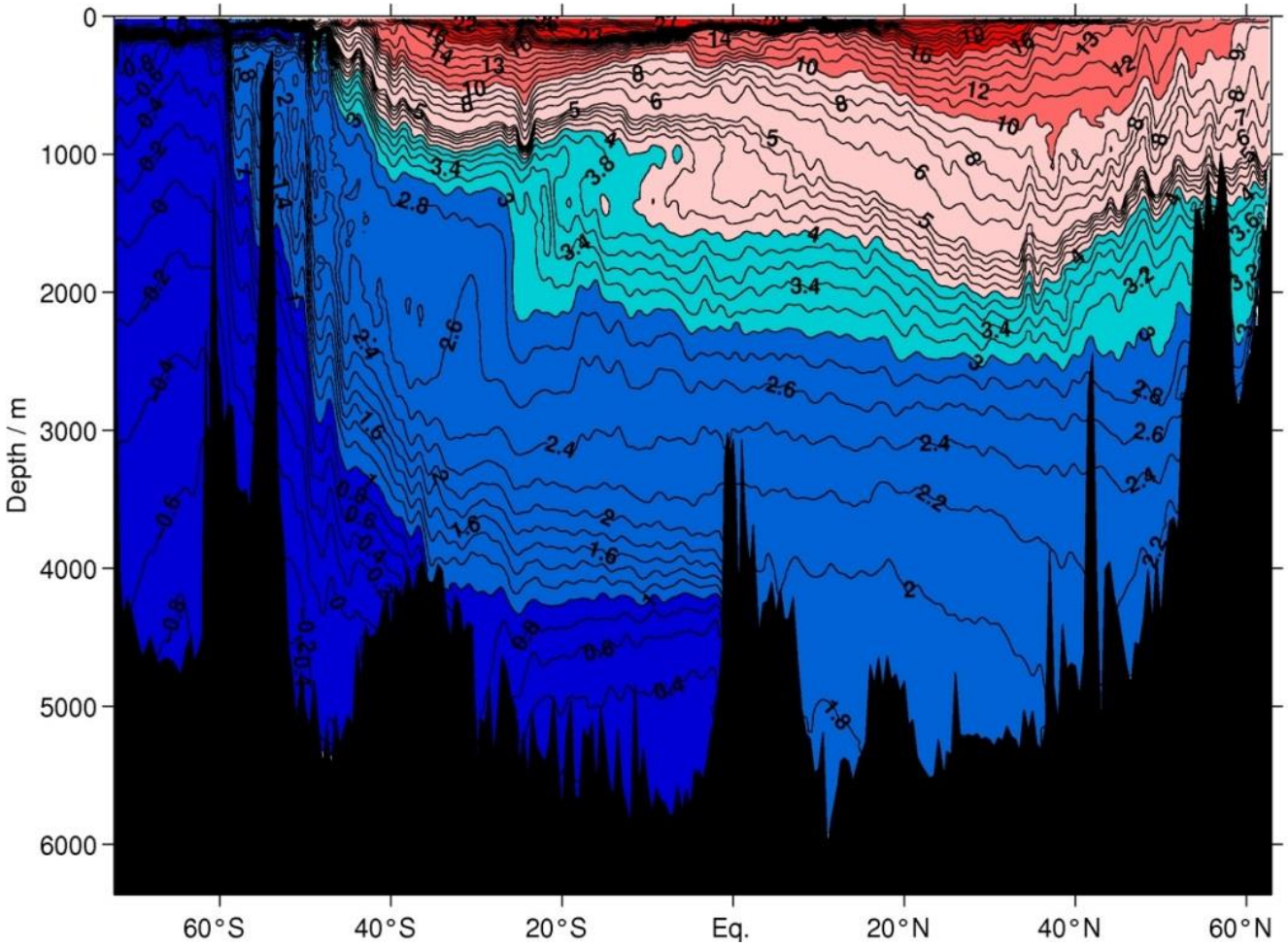

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Continuously stratified

To maintain the stratification of the deep ocean and to close the global meridional overturning circulation (MOC) there has to be diapycnal mixing.

Mixing in the Ocean

- Diffusivity of $K = 10^{-4}$ m²/s if mixing is distributed uniformly (Munk, 1966).
- Only $K \sim 10^{-5}$ m²/s observed (Ledwell et al. 1993, Toole et al. 1994).

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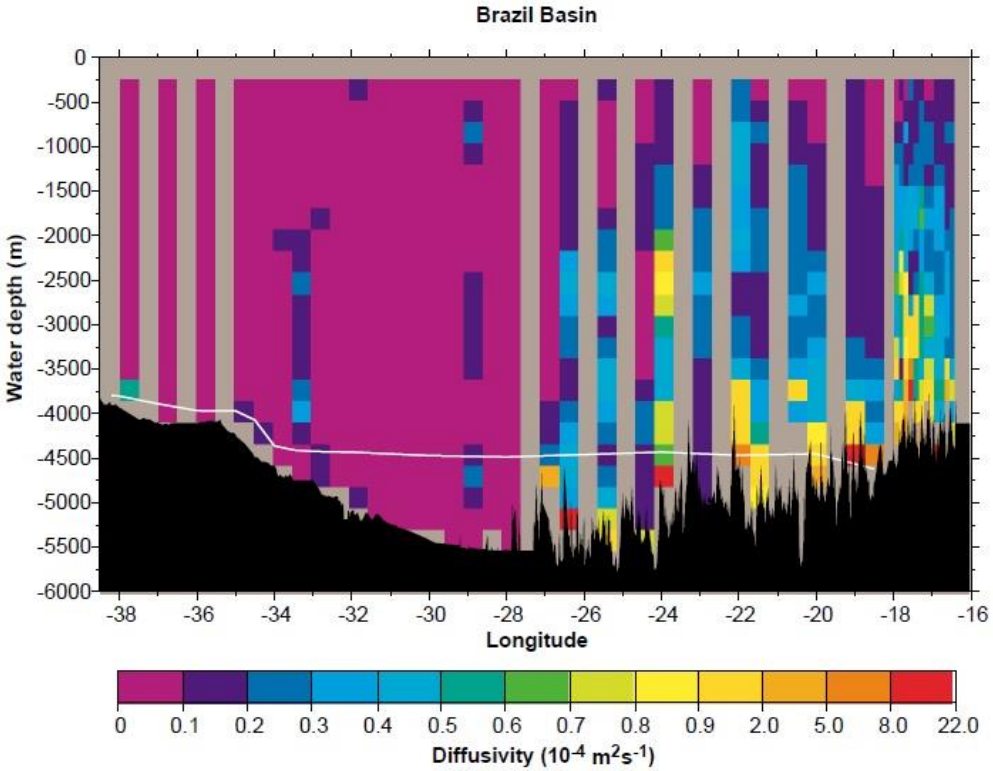
  Elevated close to rough topography of e.g. Mid-Ocean ridges.



Diffusivity $K = {}^{\gamma\varepsilon}/_{N^2}$ (Osborn 1980)
ε – observed dissipation rates,
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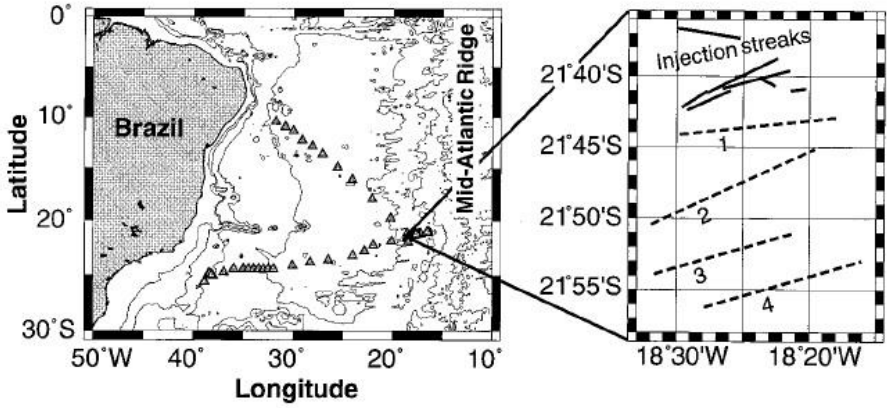
Diapycnal diffusivity in the Brazil basin. White line marks 0.8°C surface (Polzin et al., 1997).



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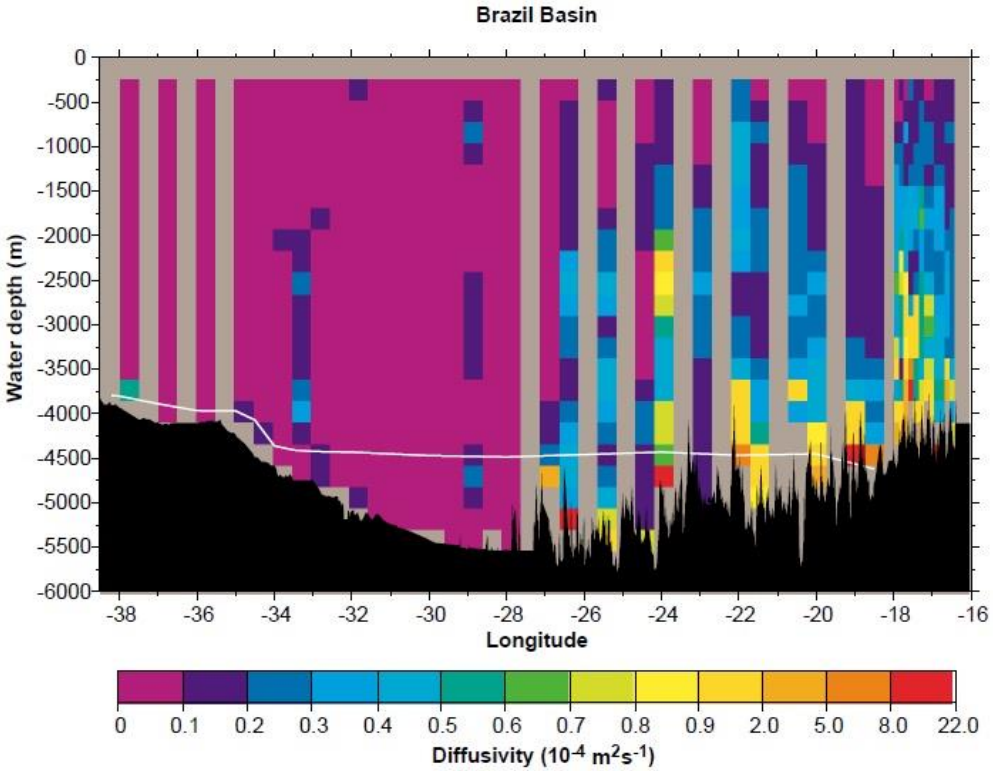
  Elevated close to rough topography of e.g. Mid-Ocean ridges.
- Commonly explained by topography-induced breaking of internal waves.



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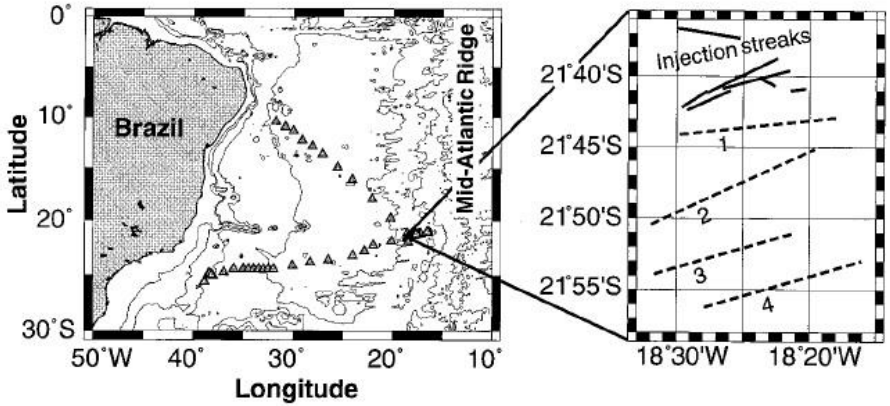

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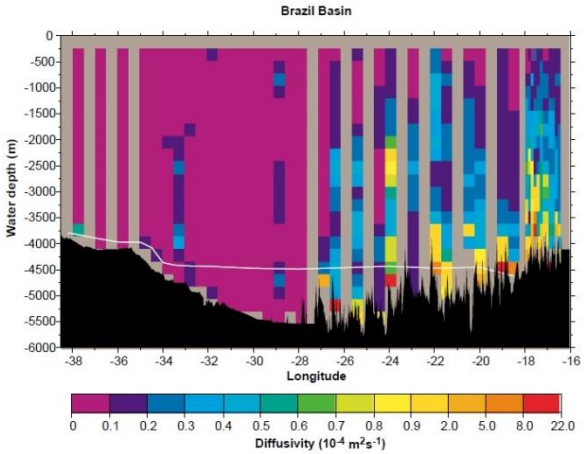
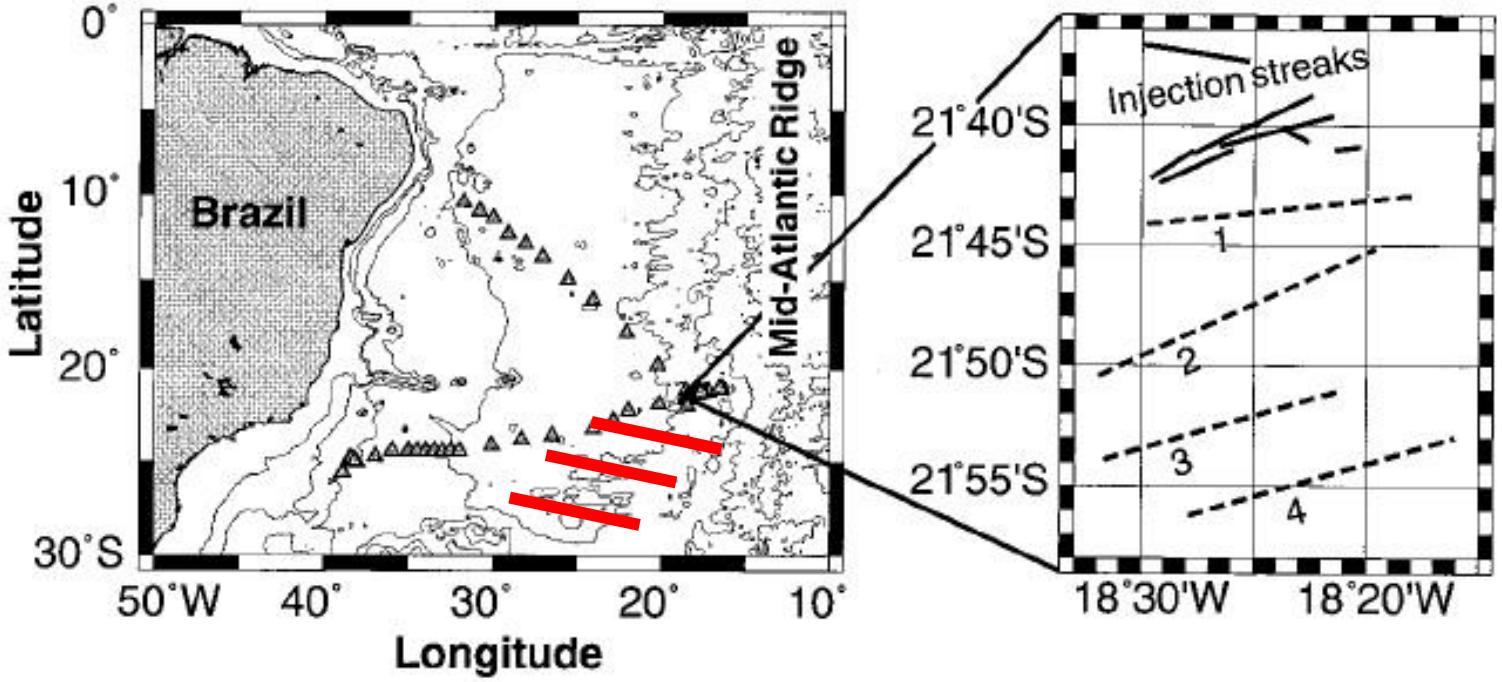


Diapycnal diffusivity in the Brazil basin. White line marks 0.8°C surface (Polzin et al., 1997).

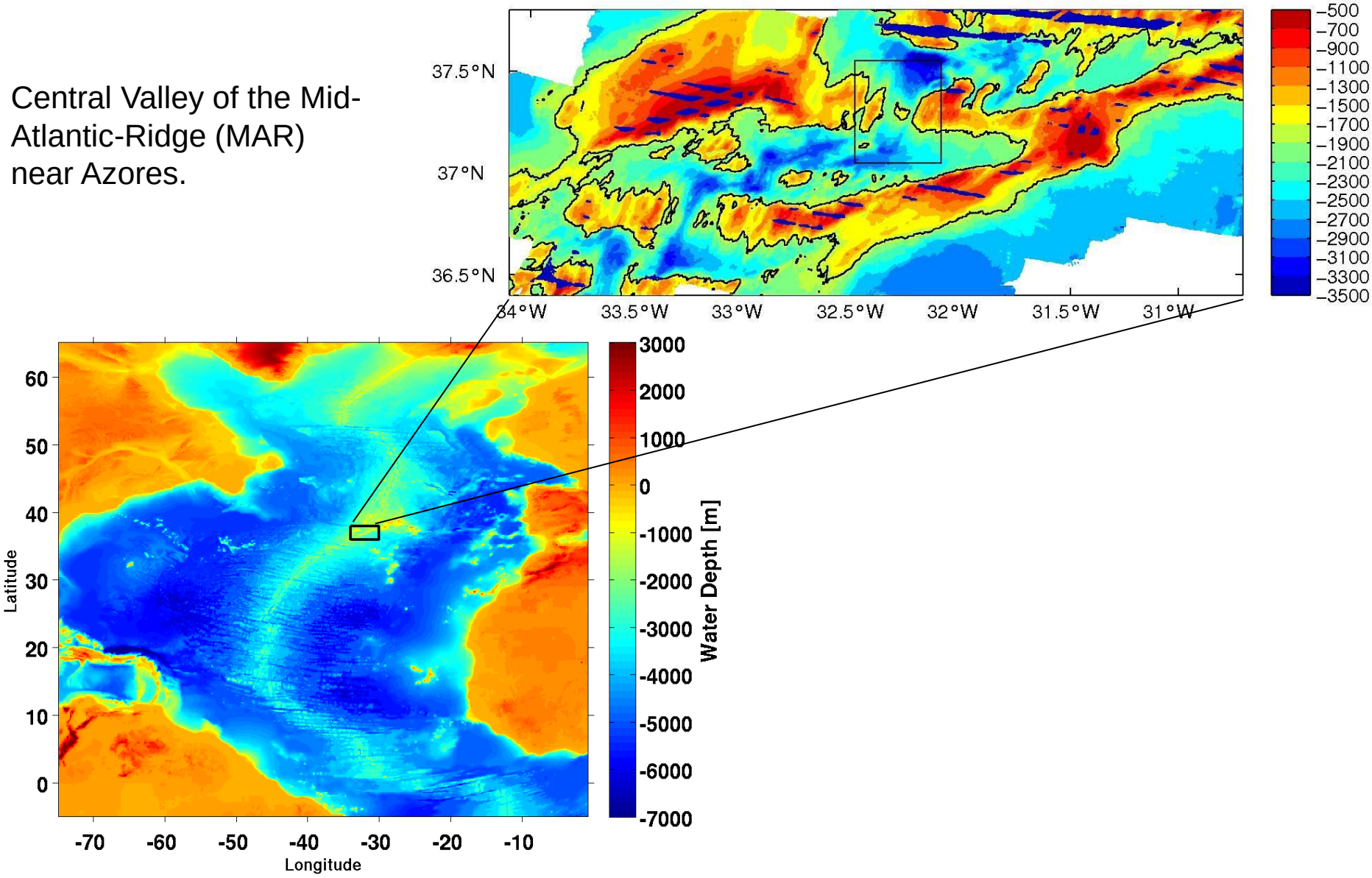
High mixing rates in canyons of mid-ocean ridges.

Associated to along-channel flow across sills (e.g. Thurnherr and Speer 2003, Thurnherr et al. 2005, and St. Laurent and Thurnherr, 2007).



Central Valley of Mid-Atlantic-Ridge

Central Valley of the Mid-Atlantic-Ridge (MAR) near Azores.



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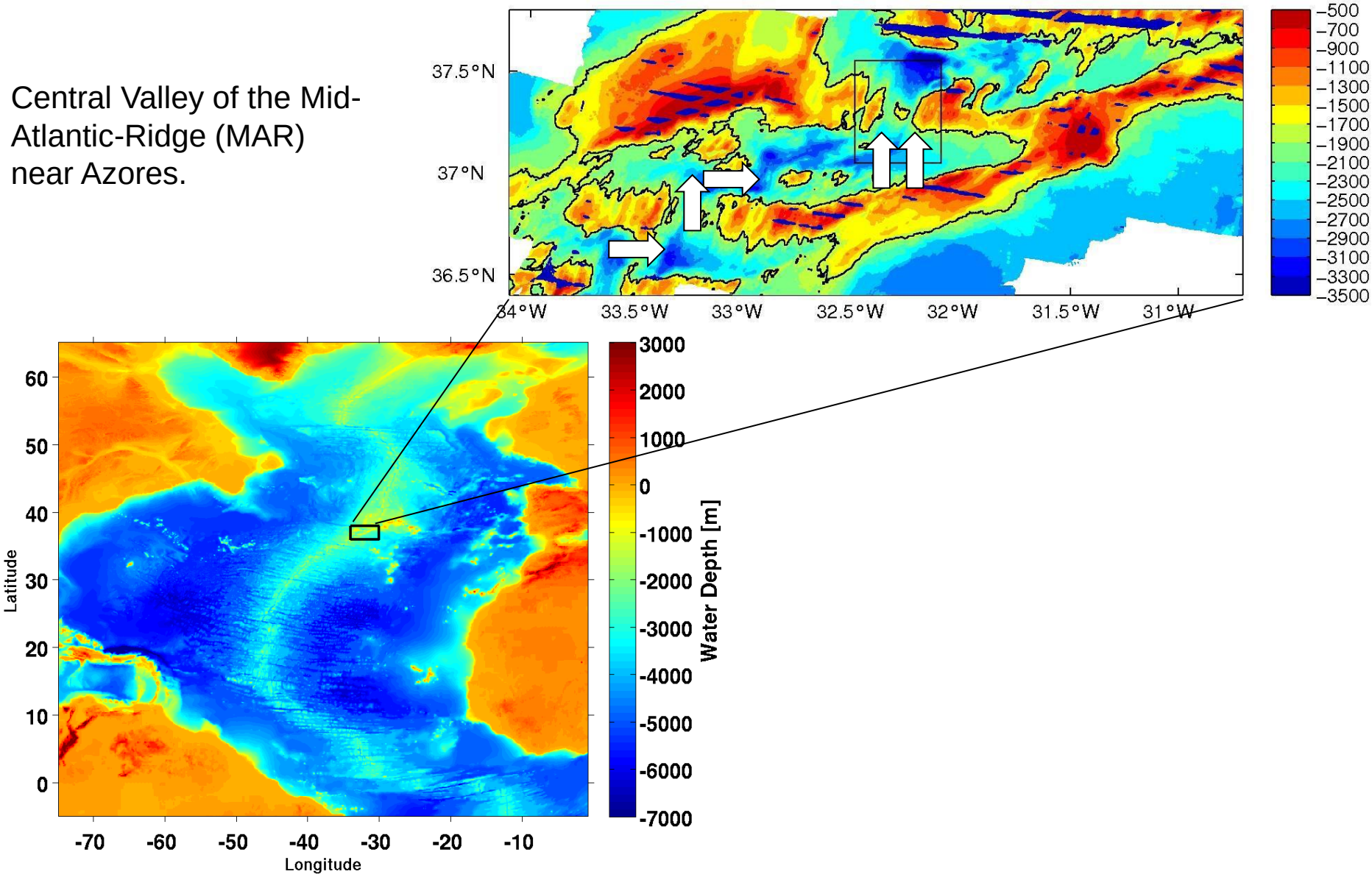

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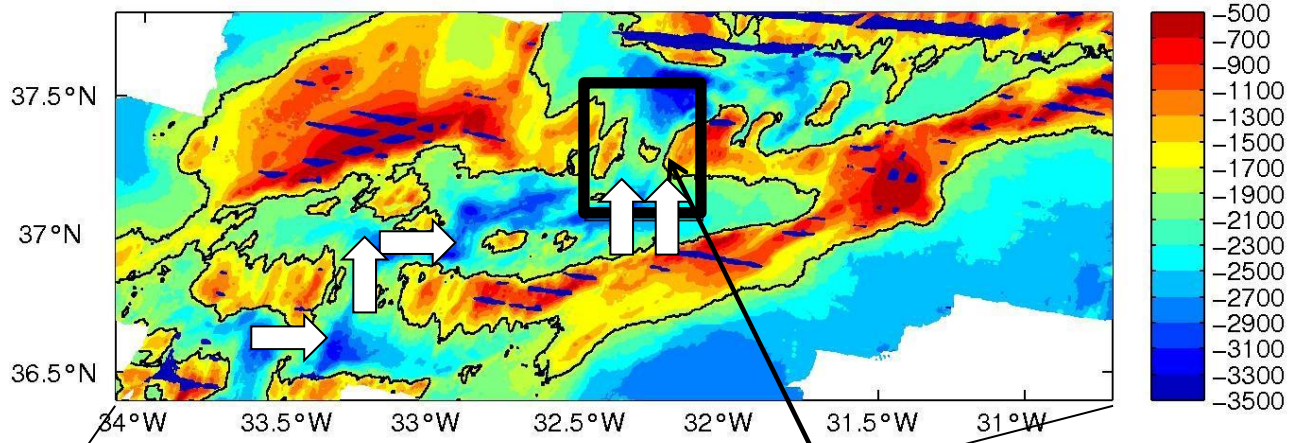
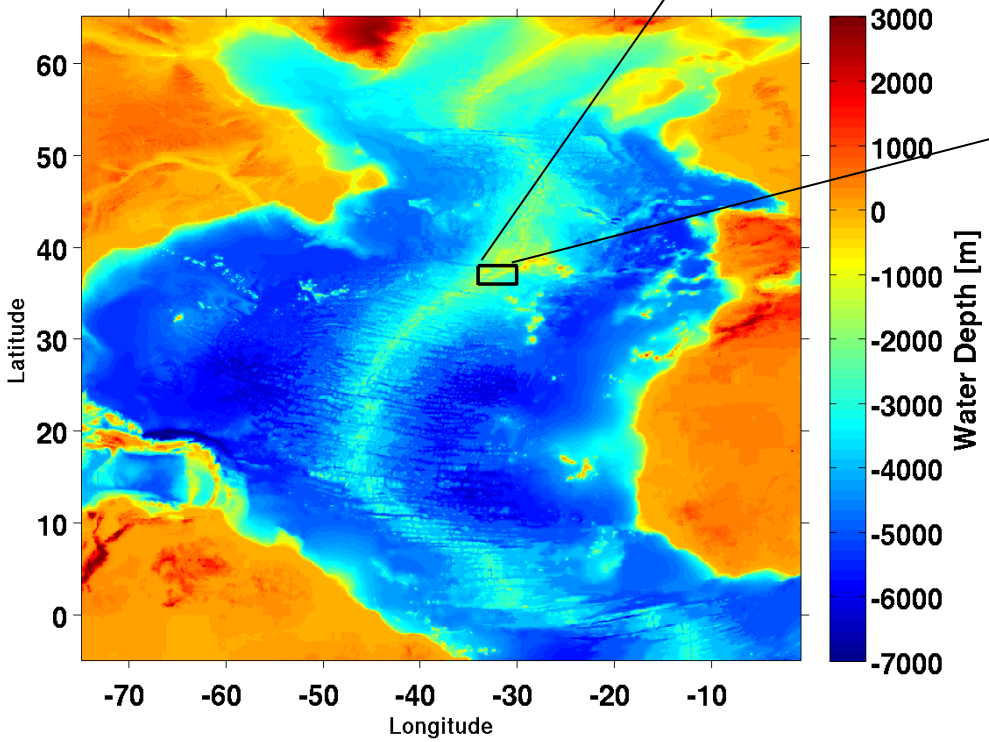
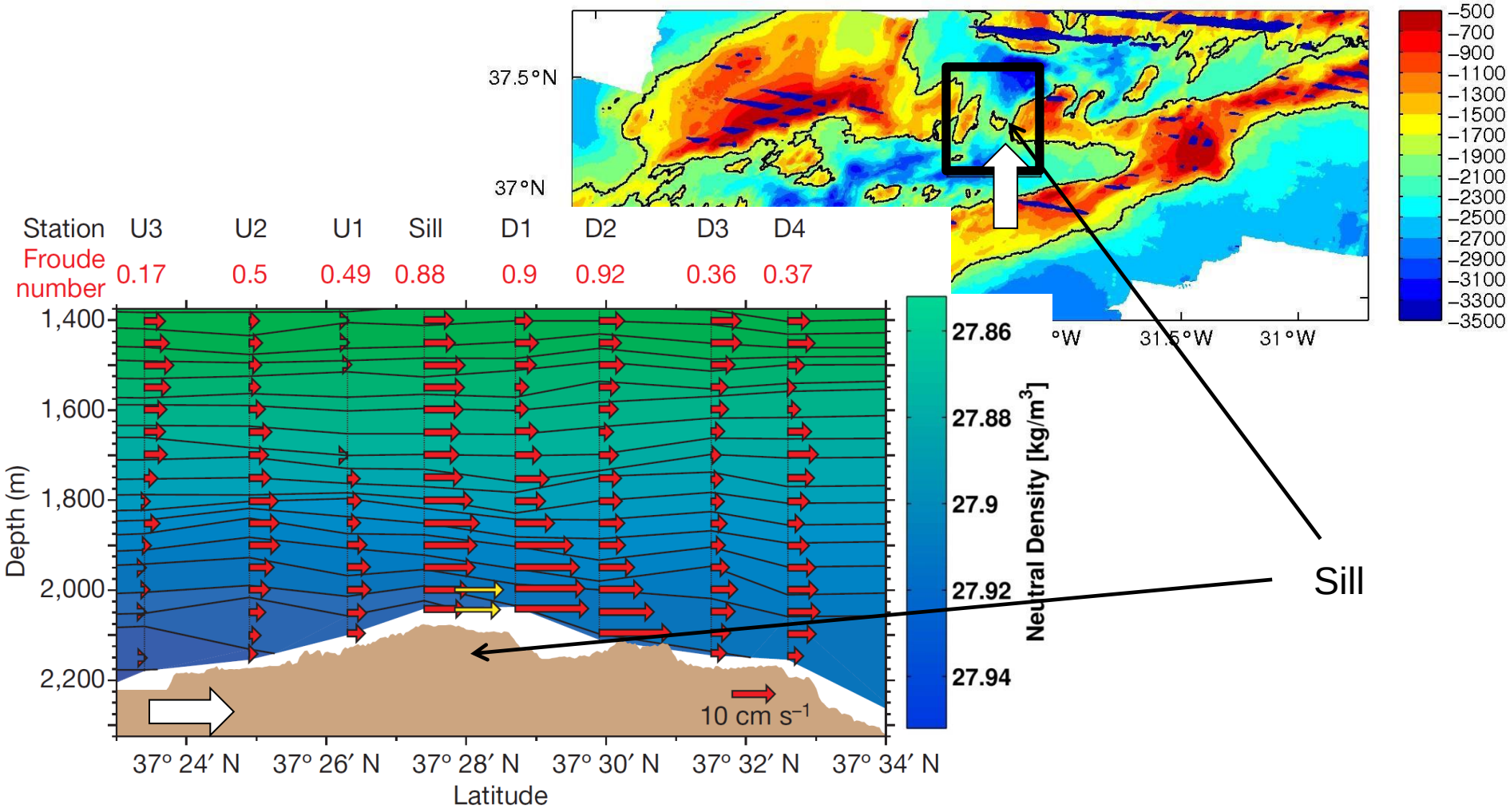




Sill

Lucky Strike segment

Circulation in the Lucky Strike Segment



Red arrows: 50-m-averaged lowered ADCP data.
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Average velocity $> 10\ ^{cm}/_{s}$
Maximum velocities $\sim 20\ ^{cm}/_{s}$

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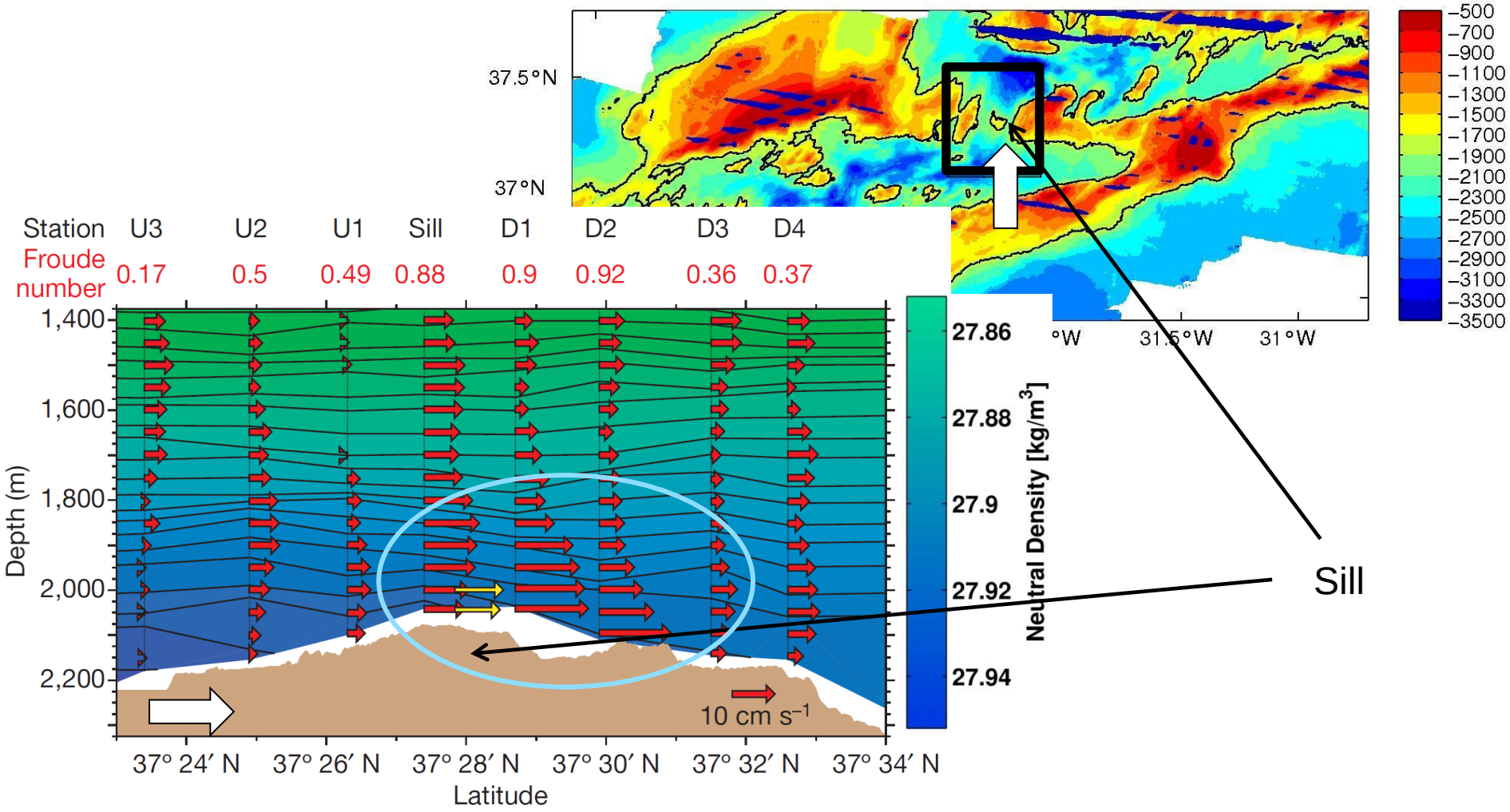

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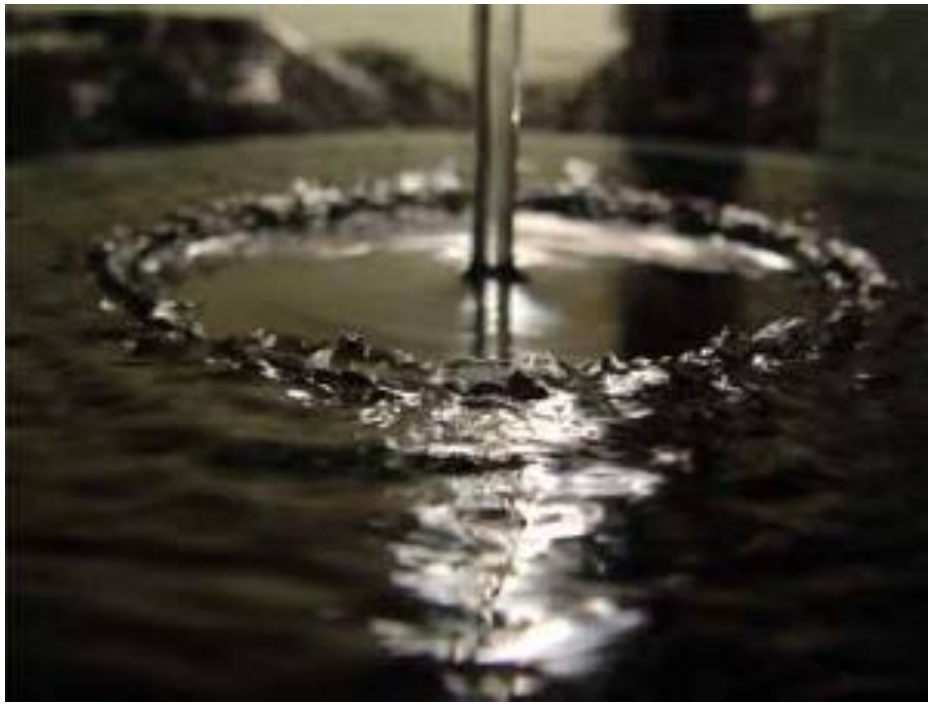
Hydraulic Jump



http://lamanto.blogspot.de/2009/05/circular-hydraulic-jump.html

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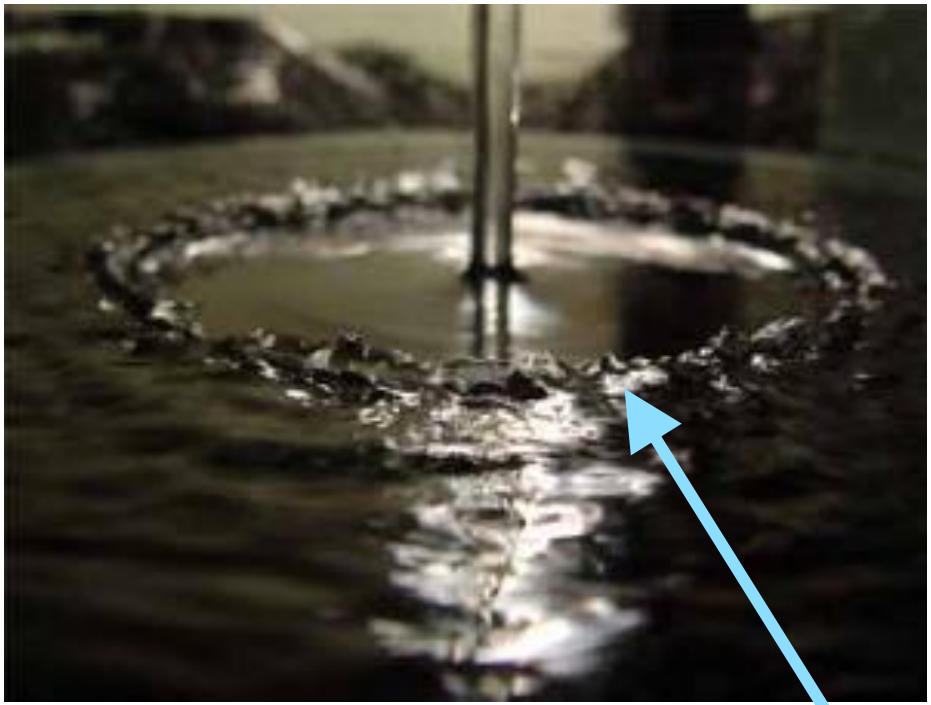

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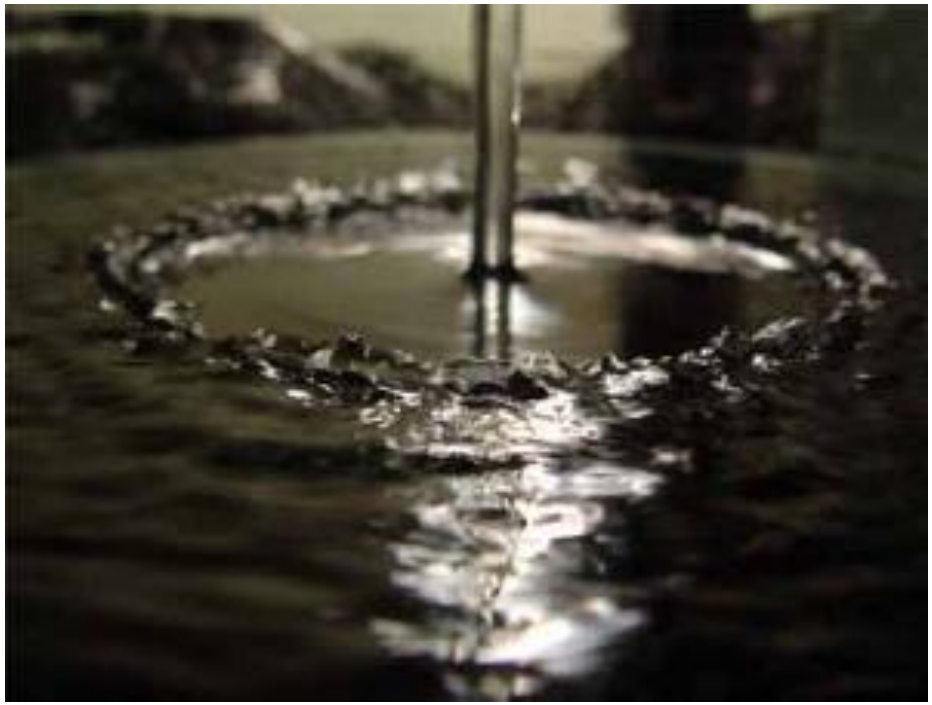

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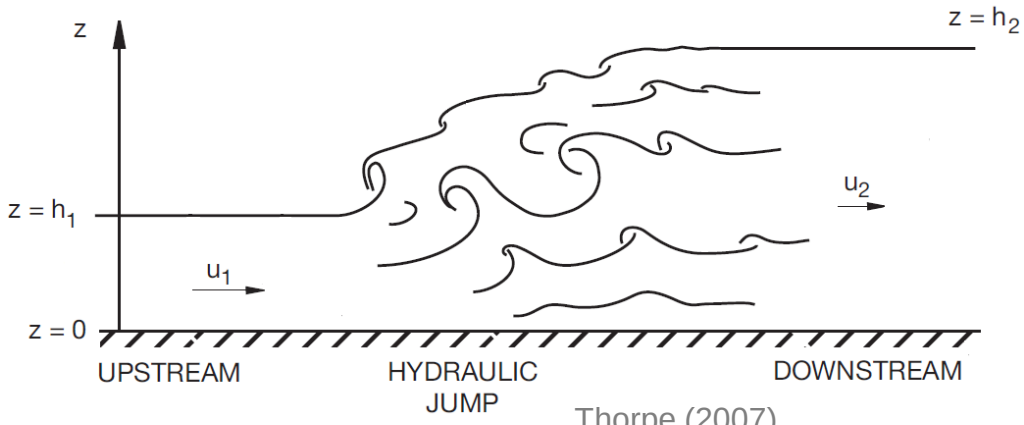

Thorpe (2007)

Hydraulic Jump

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Froude Number: ratio of flow speed to speed of waves

$$Fr = \bar{u}/\sqrt{g'H}\,,$$

$\bar{u}$ – mean flow speed,
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$Fr > 1$ *supercritical*

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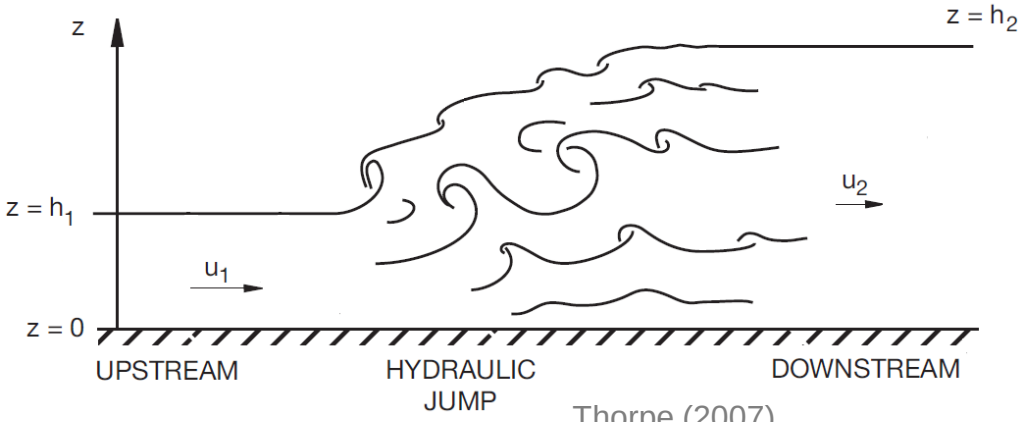

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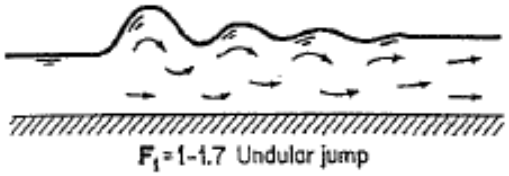

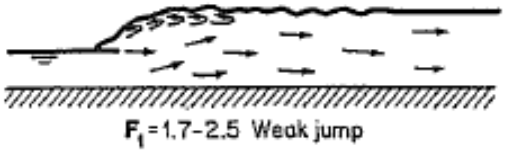

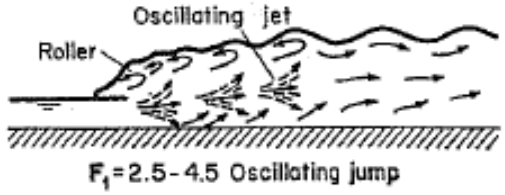

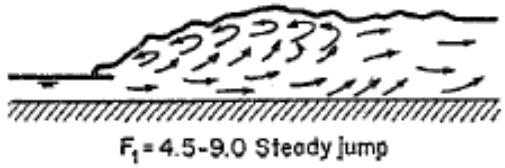

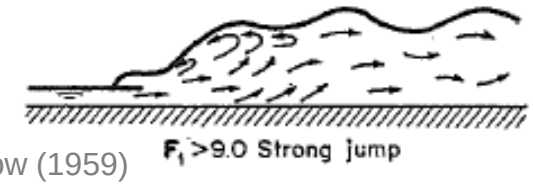

Chow (1959)

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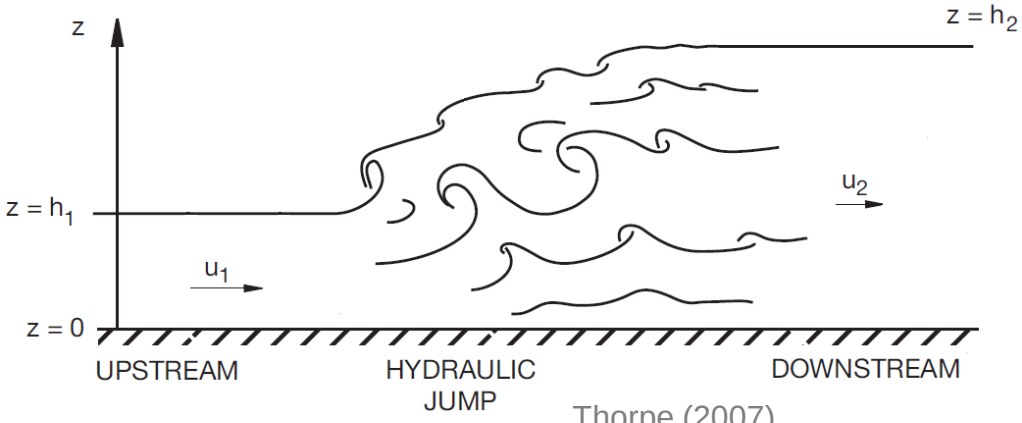

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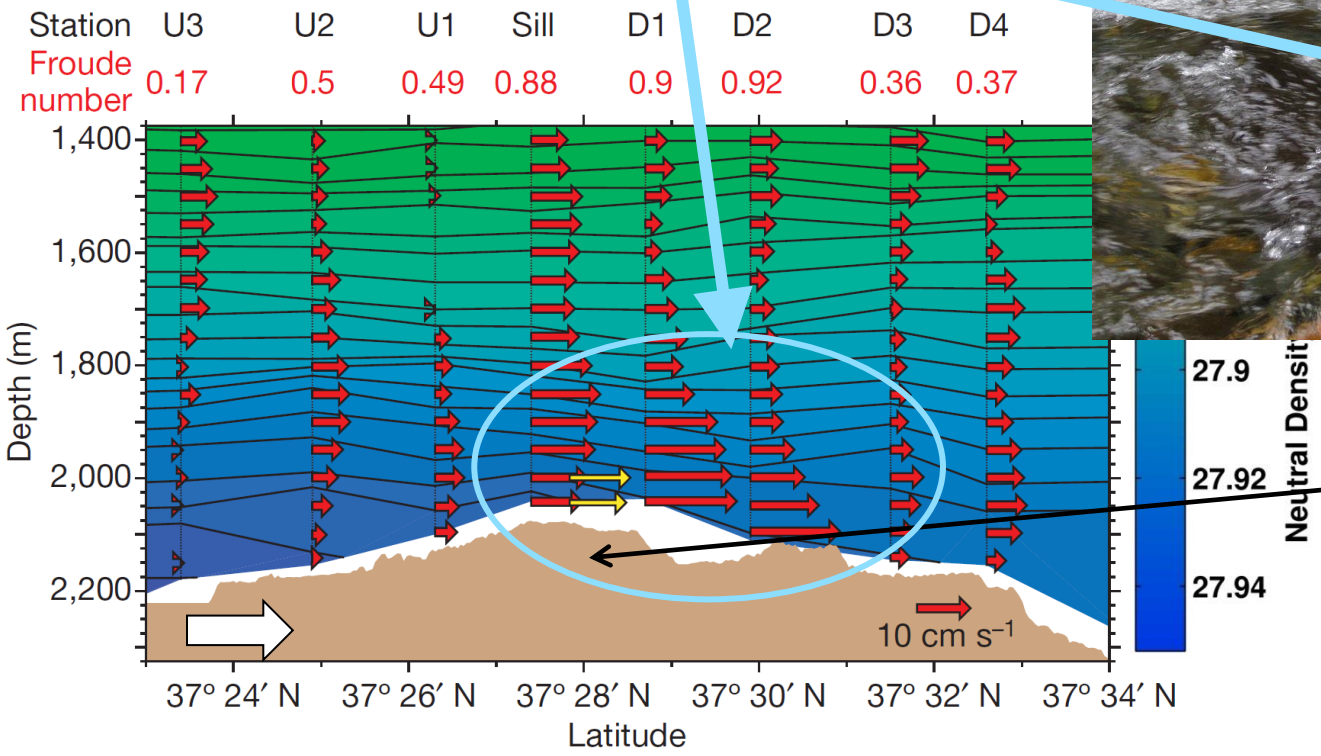

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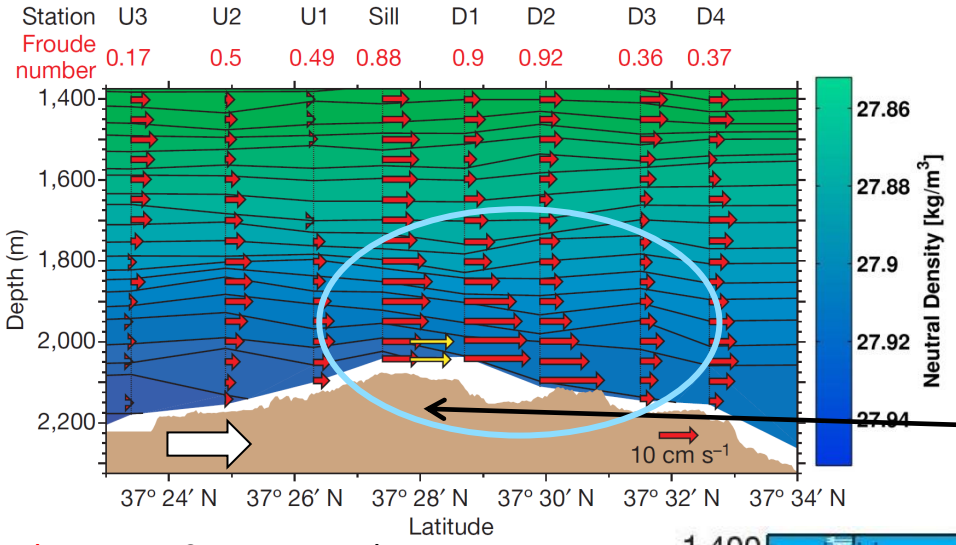

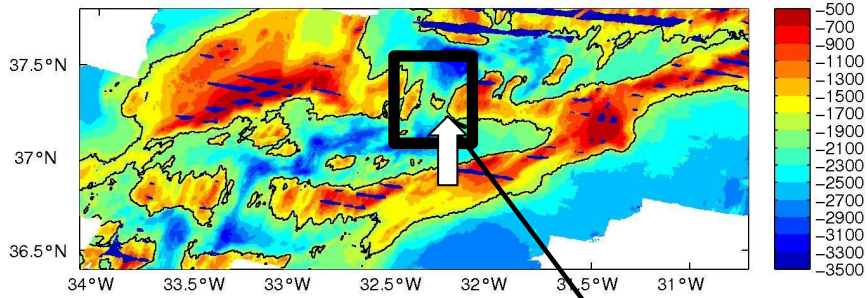

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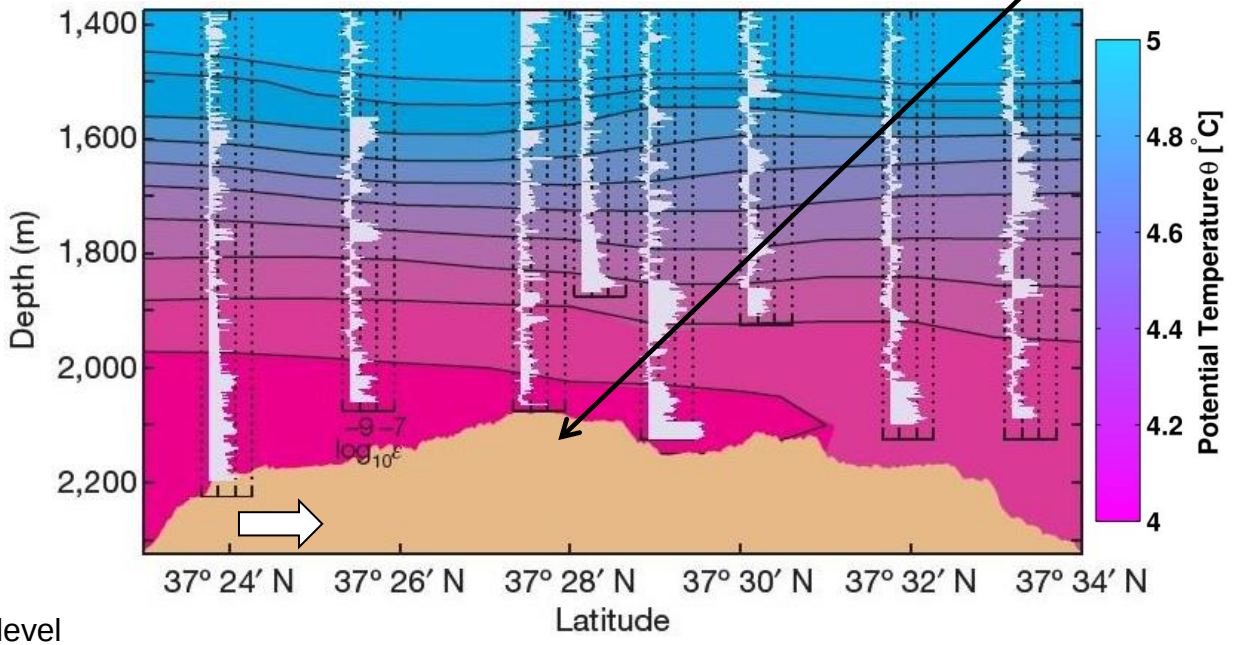

Dissipation [W/kg] along channel. Reference level $3 \cdot 10^{-10}$ [W/kg] (St. Laurent and Thurnherr, 2007).

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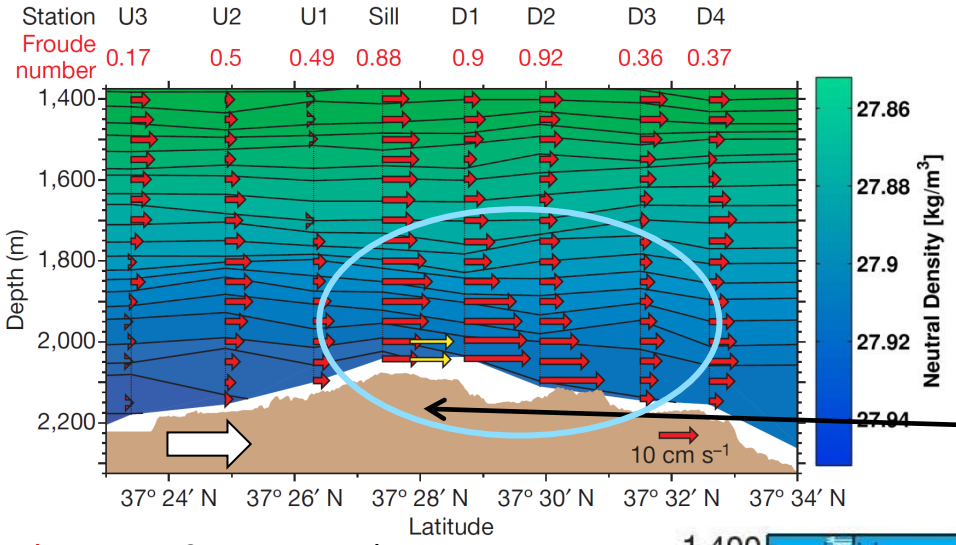

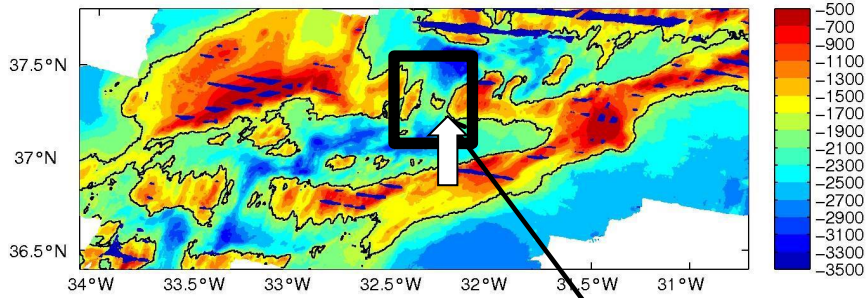

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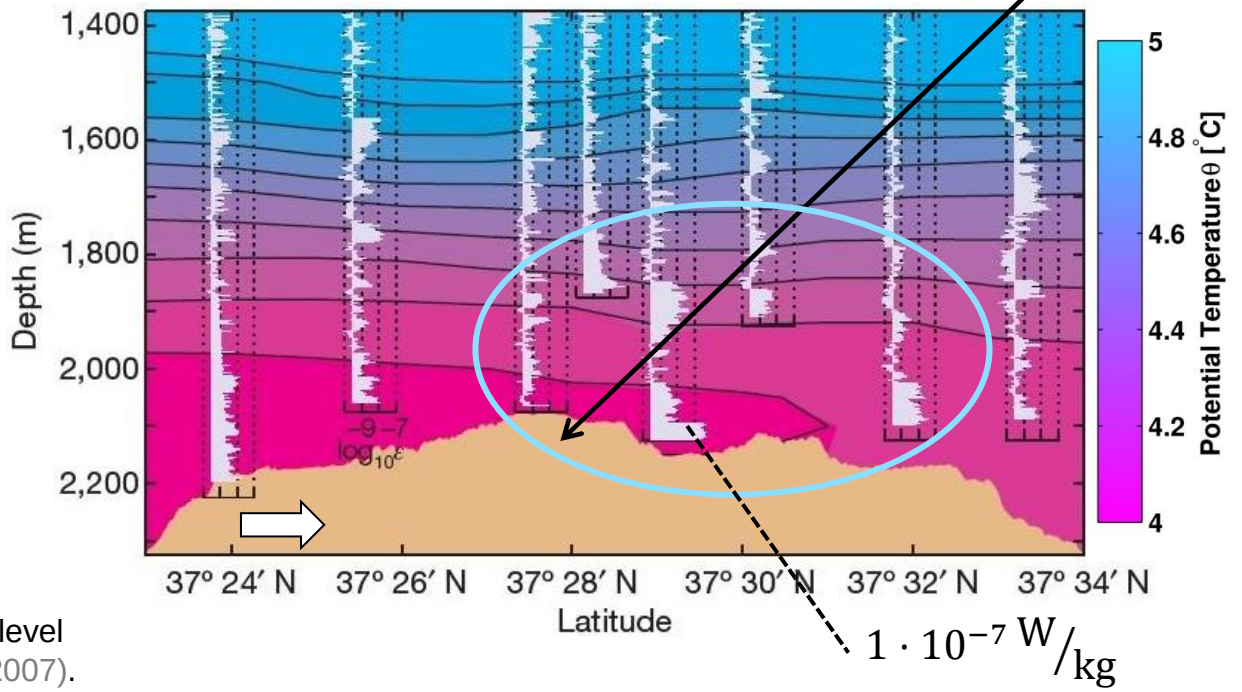

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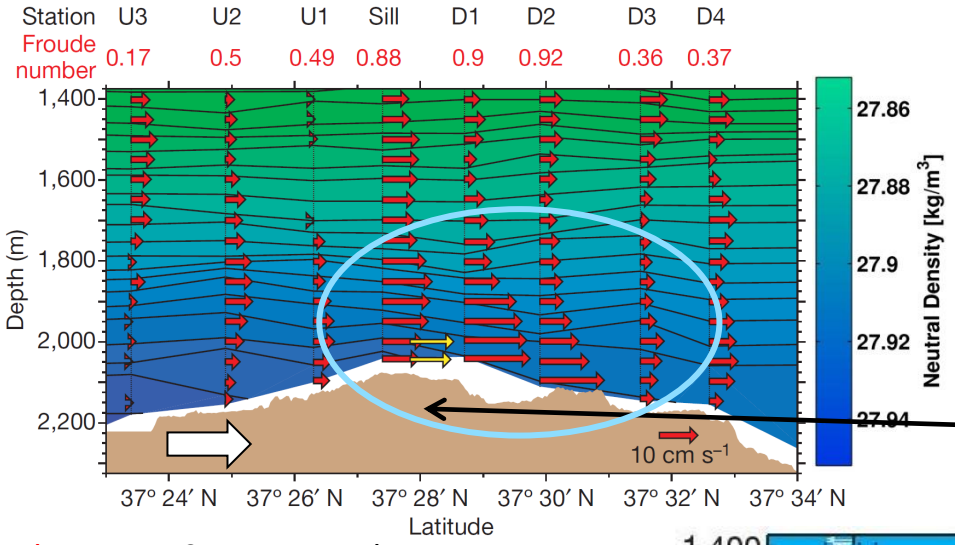

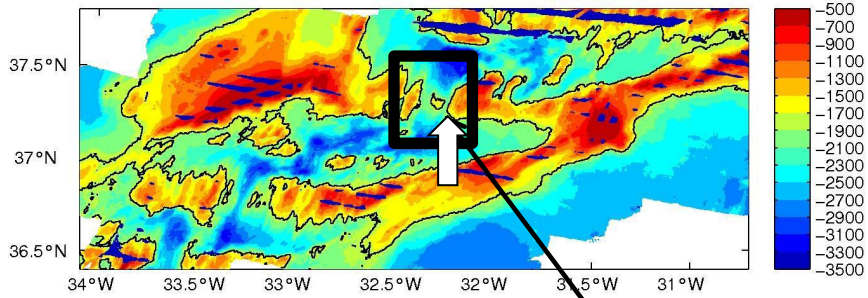

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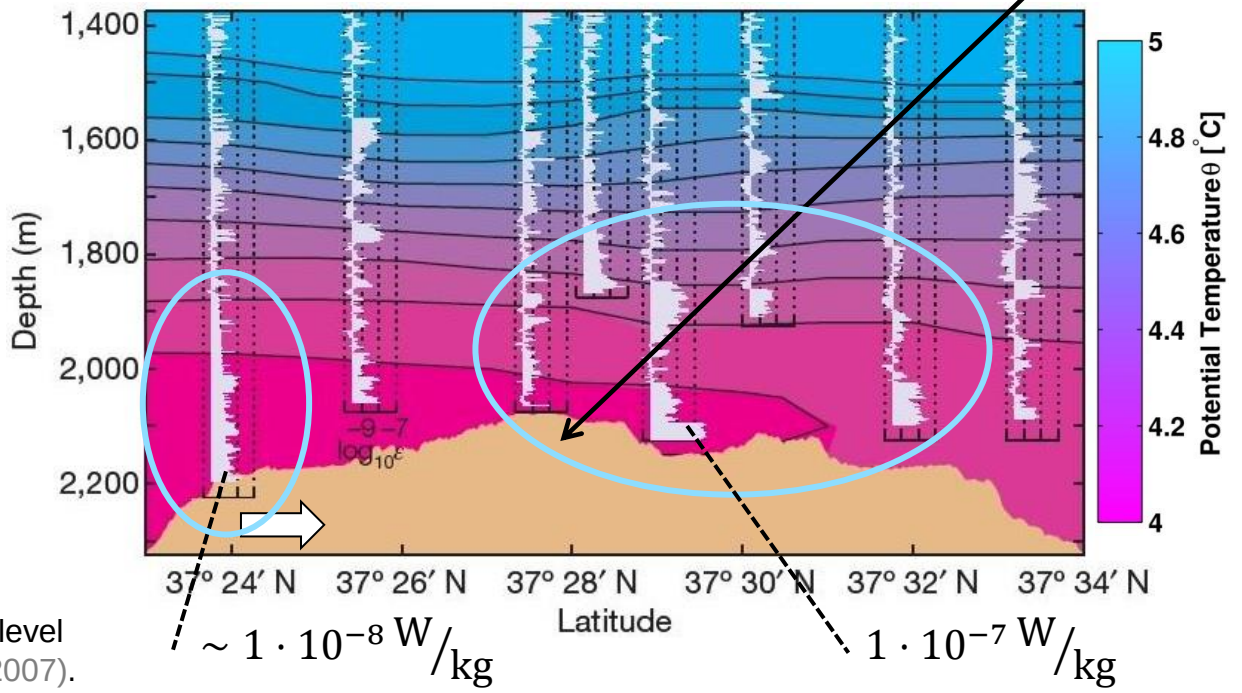

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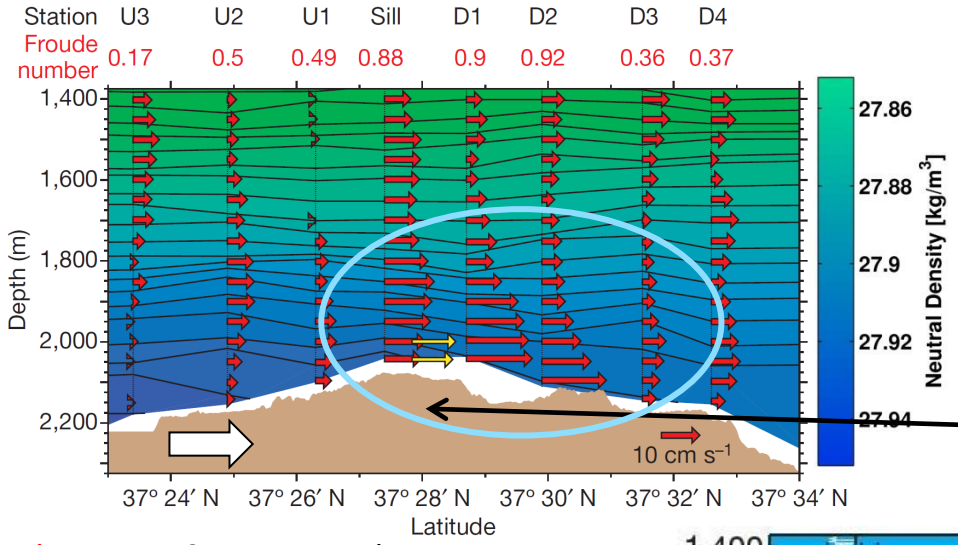

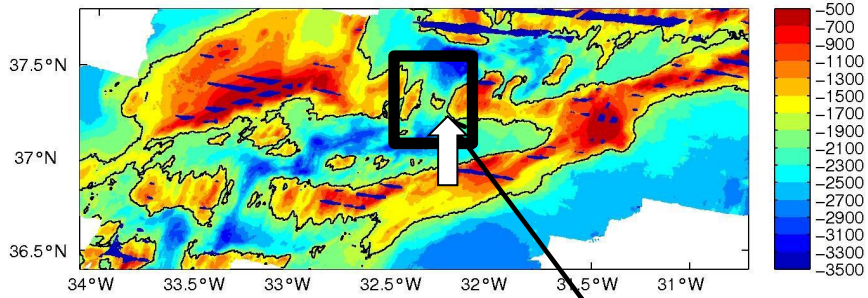

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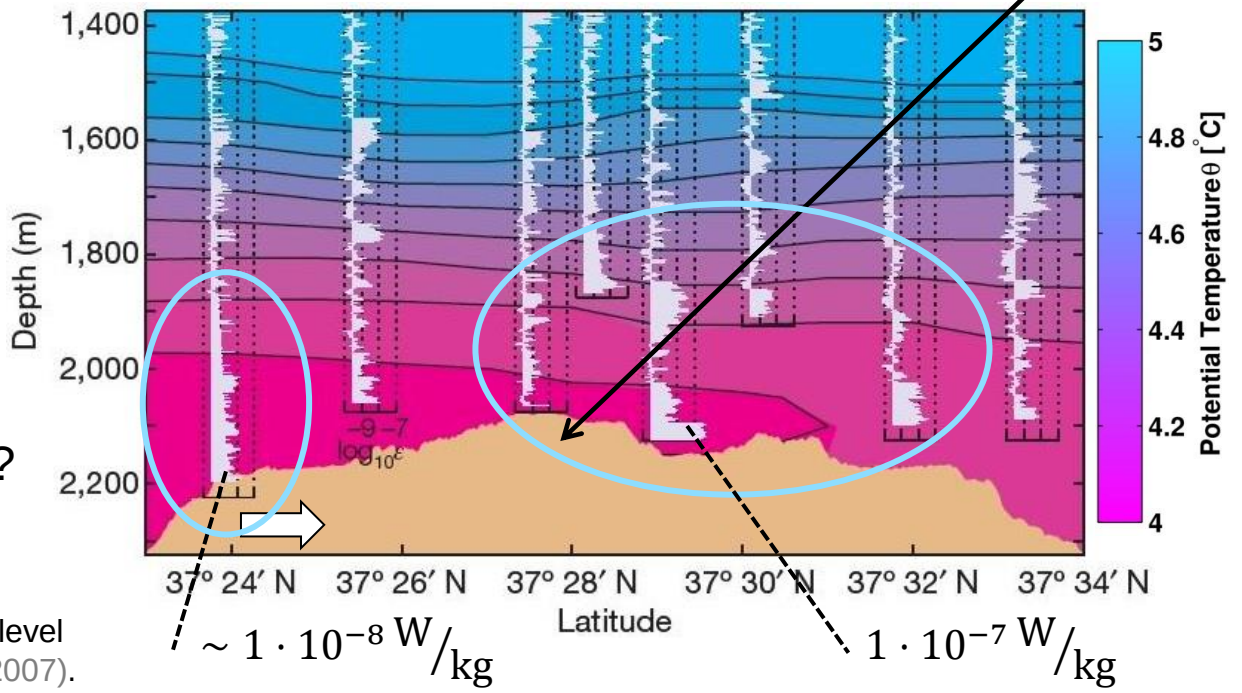

How is the dissipation rate distributed along the channel?

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Understand the physical mechanisms controlling the mixing in this channel.

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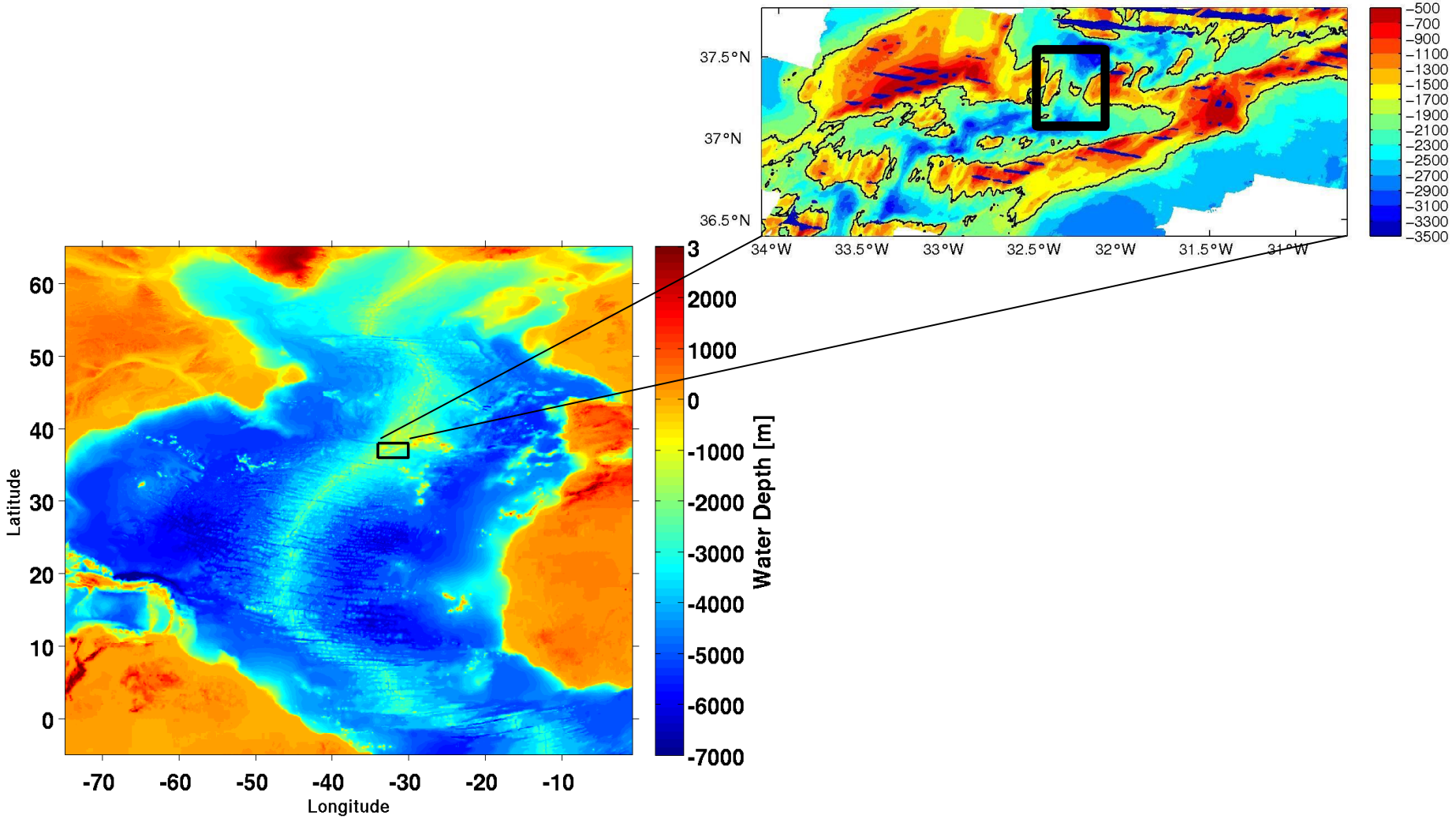

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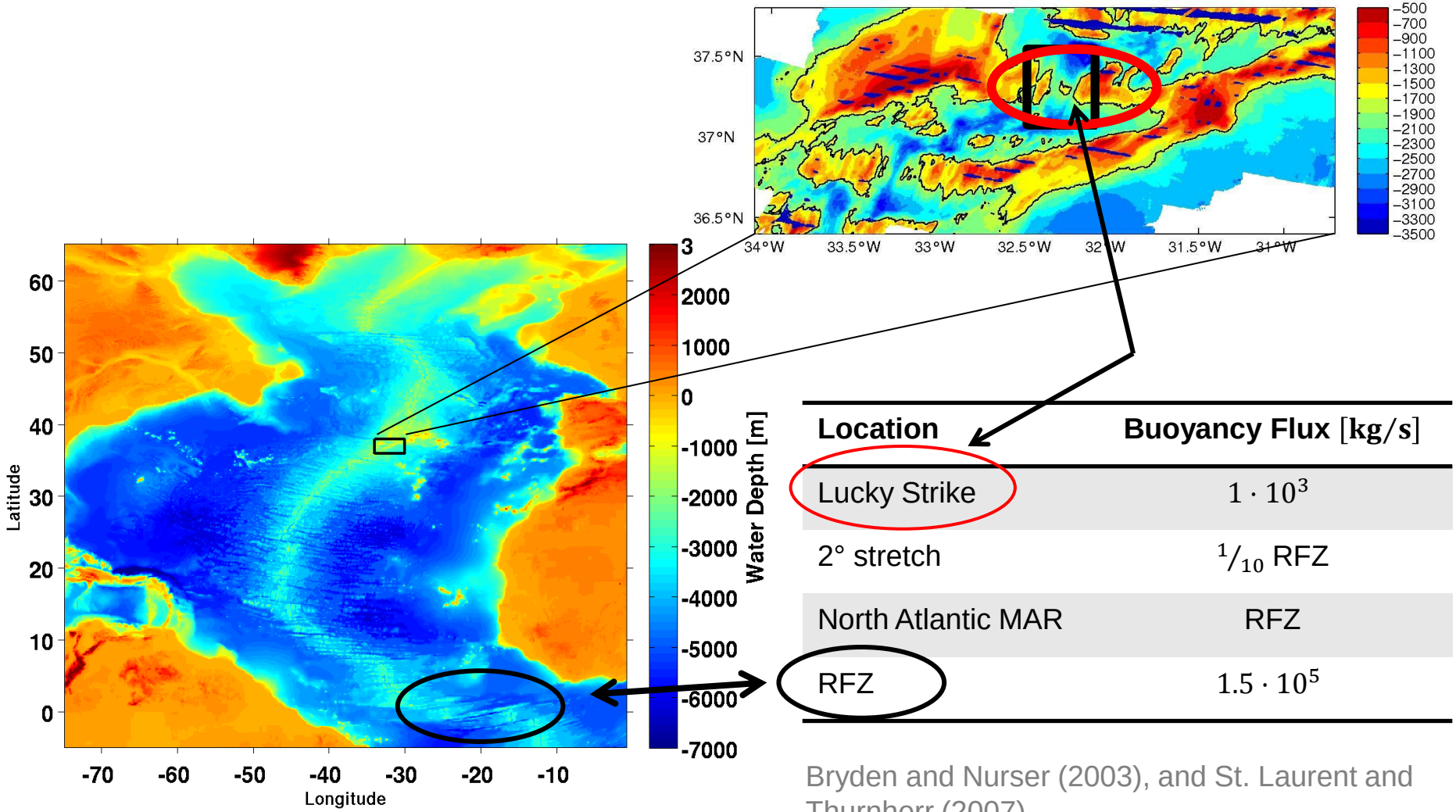

Romanche Fracture Zone (RFZ)

Location	Buoyancy Flux $[kg/s]$
Lucky Strike	$1 \cdot 10^3$
2° stretch	$^1/_{10}$ RFZ
North Atlantic MAR	RFZ
RFZ	$1.5 \cdot 10^5$

Bryden and Nurser (2003), and St. Laurent and Thurnherr (2007)

Questions addressed in this Study

Scientific questions

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- Is there evidence for hydraulic jumps?
- Do tides have an influence?

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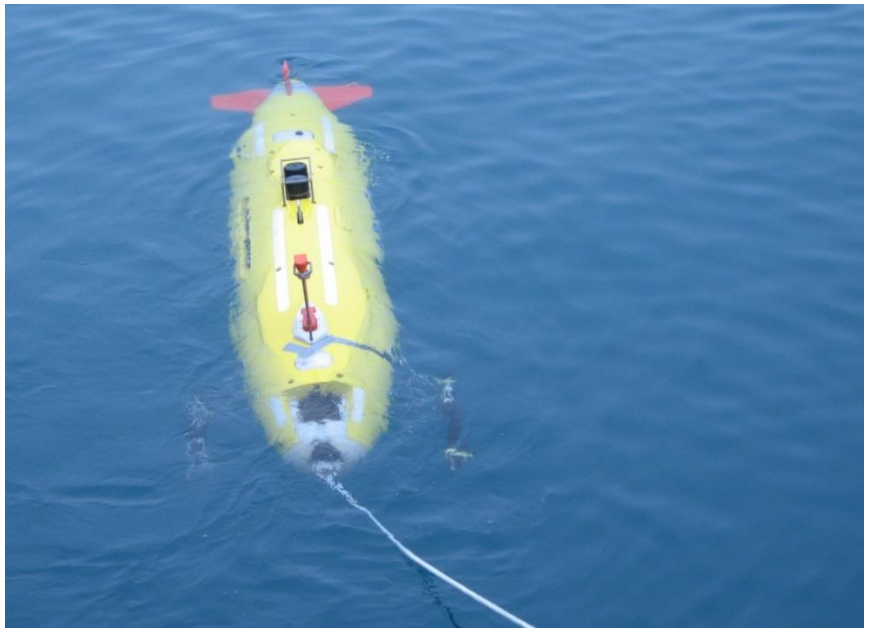
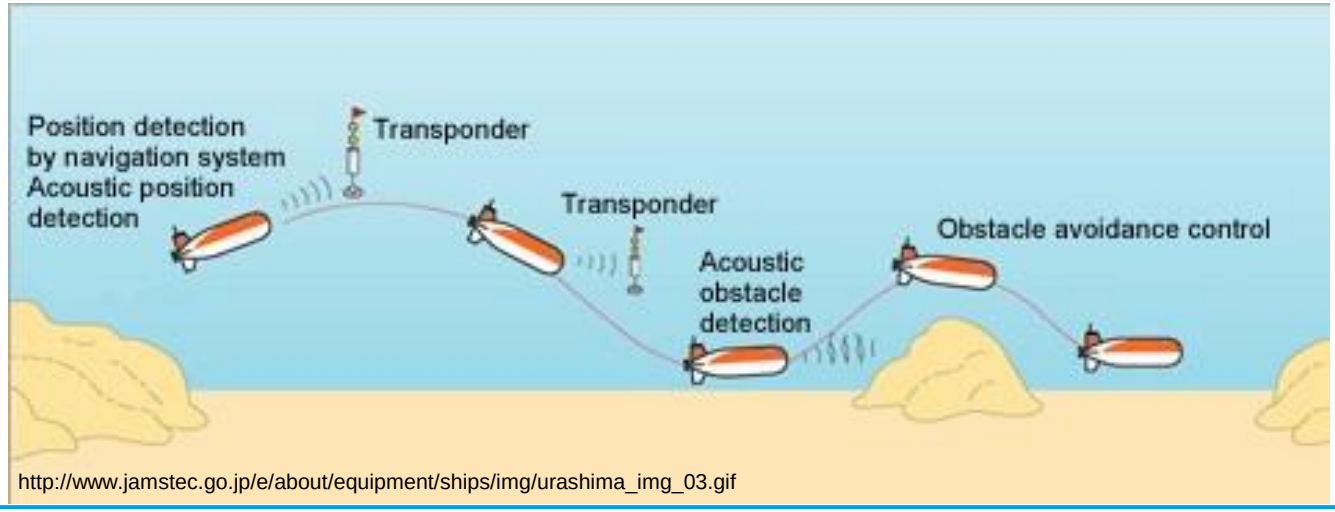
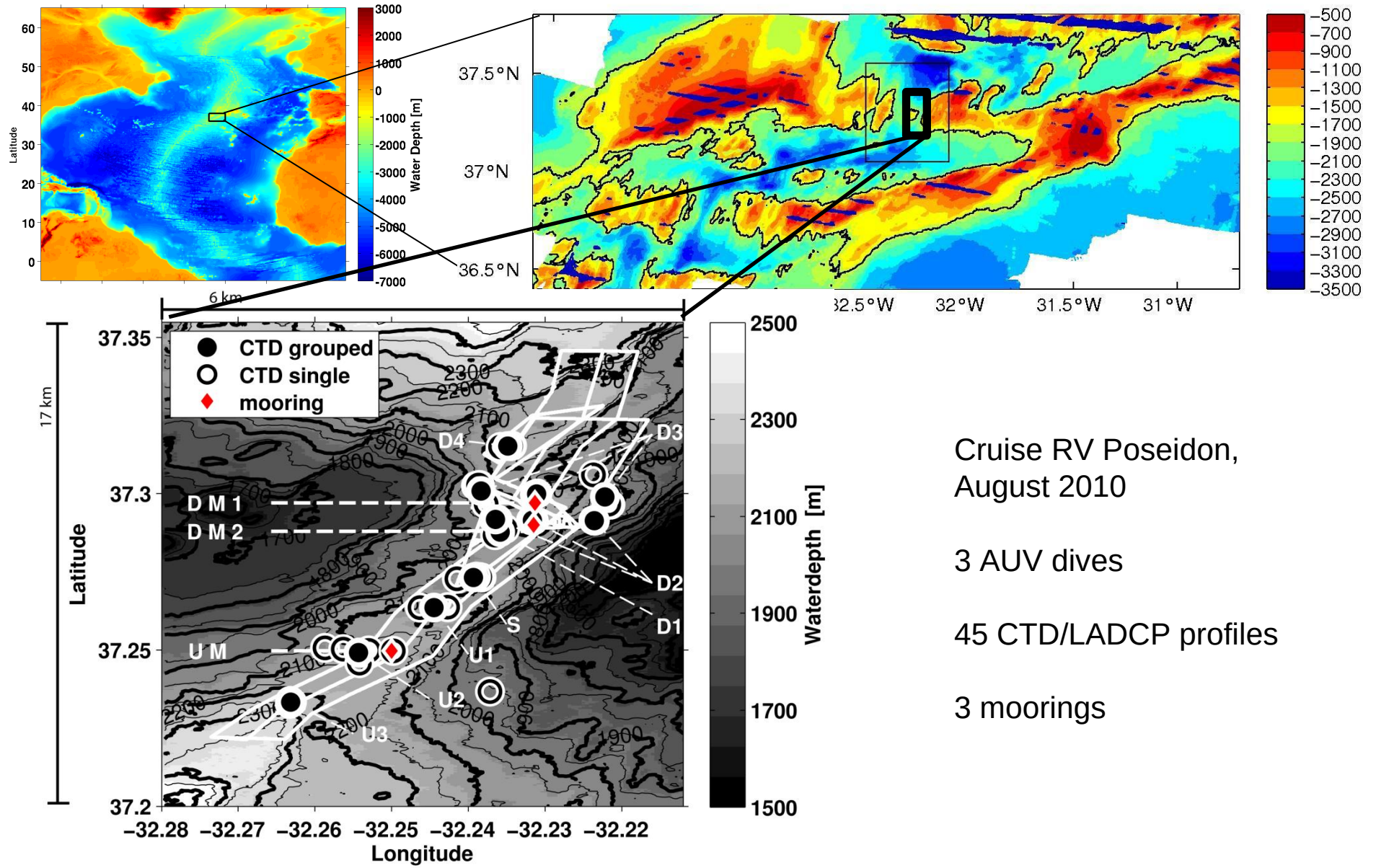


Autonomous underwater vehicle (AUV)



http://www.jamstec.go.jp/e/about/equipment/ships/img/urashima_img_03.gif

The Lucky Strike Segment at the MAR



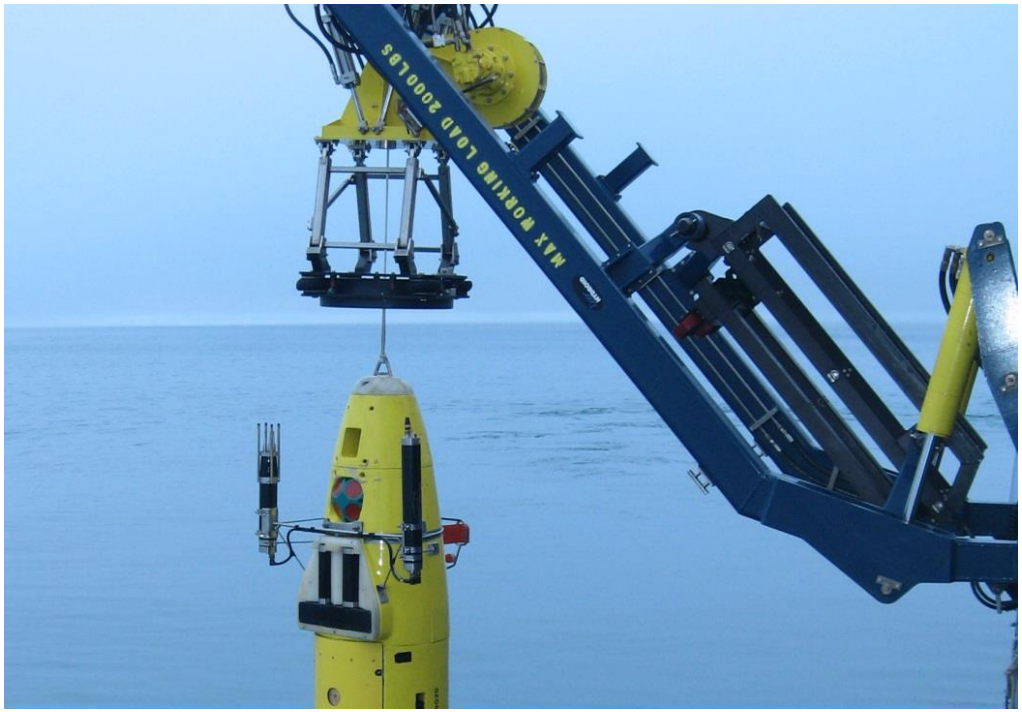
Cruise RV Poseidon, August 2010

3 AUV dives

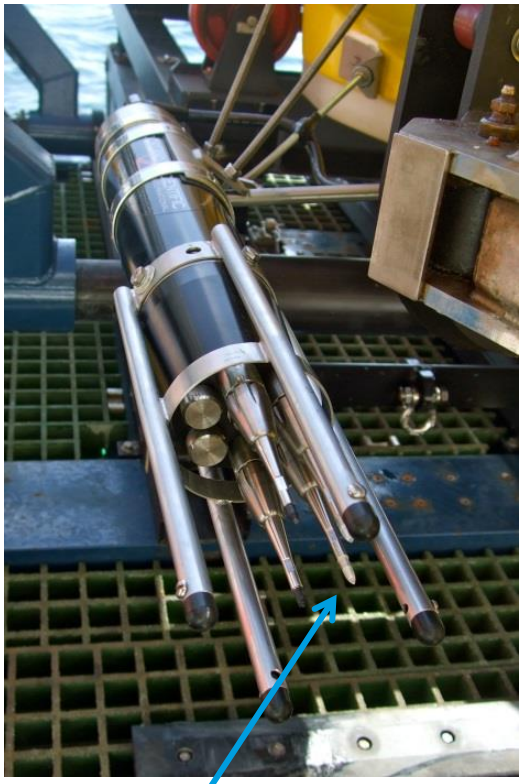
45 CTD/LADCP profiles

3 moorings

Turbulence Probe and AUV



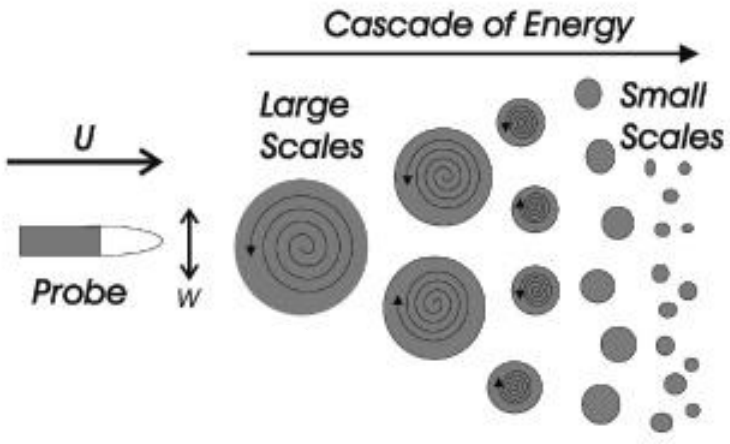
AUV Abyss (autonomous underwater vehicle).



- Vibrations due to mounting and engine
- Observed by 3D-accelerometer

Velocity shear probes

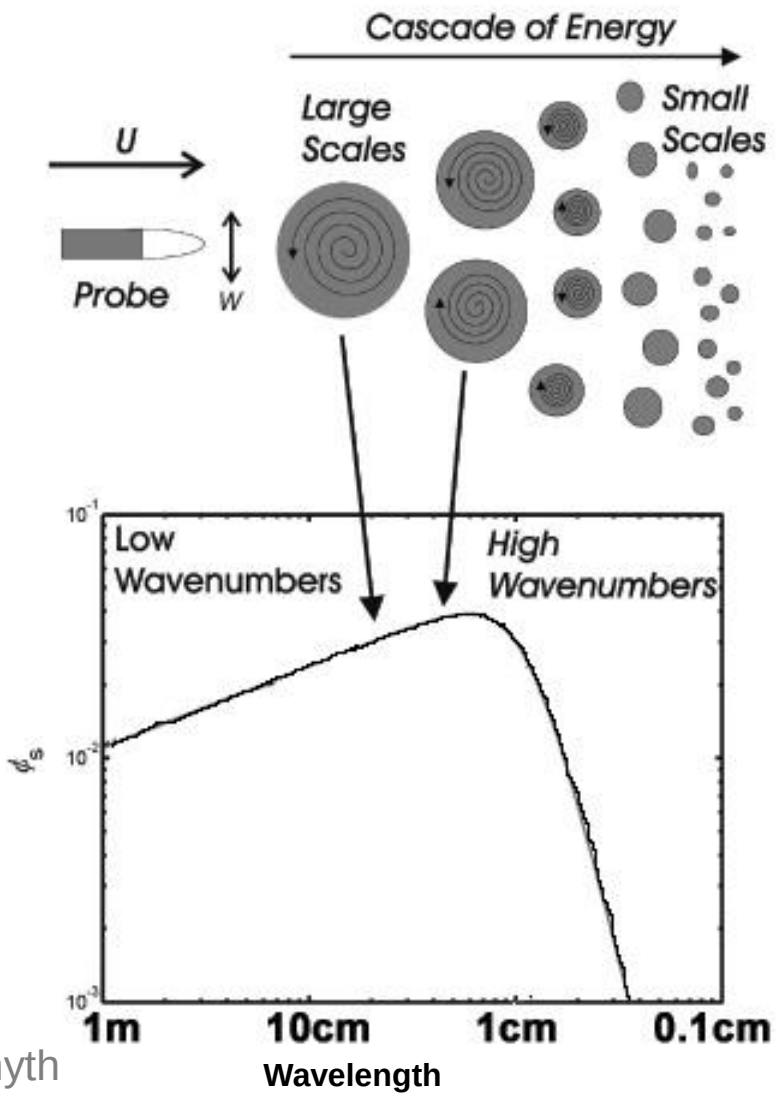
Infer Dissipation of TKE from Velocity Shear



velocity shear →

Infer Dissipation of TKE from Velocity Shear

velocity shear → spectrum Φ → dissipation rate ε



Empirical Nasmyth spectrum (Nasmyth 1970, Oakey 1982).

Infer Dissipation of TKE from Velocity Shear

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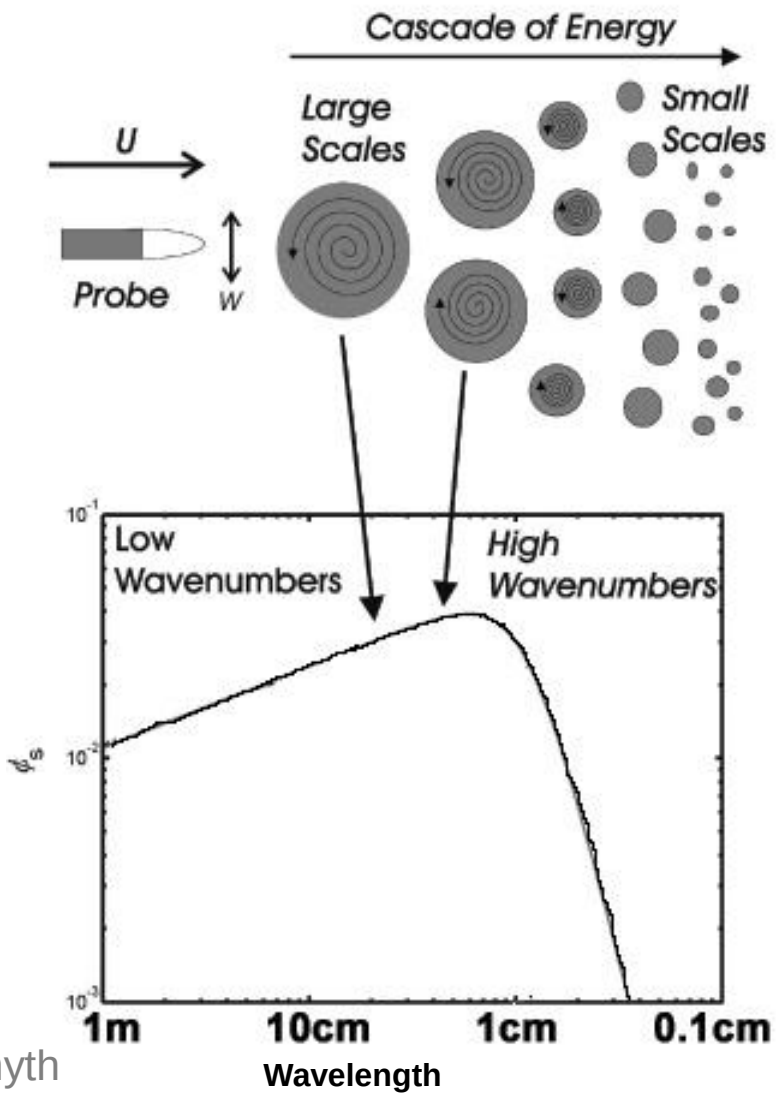
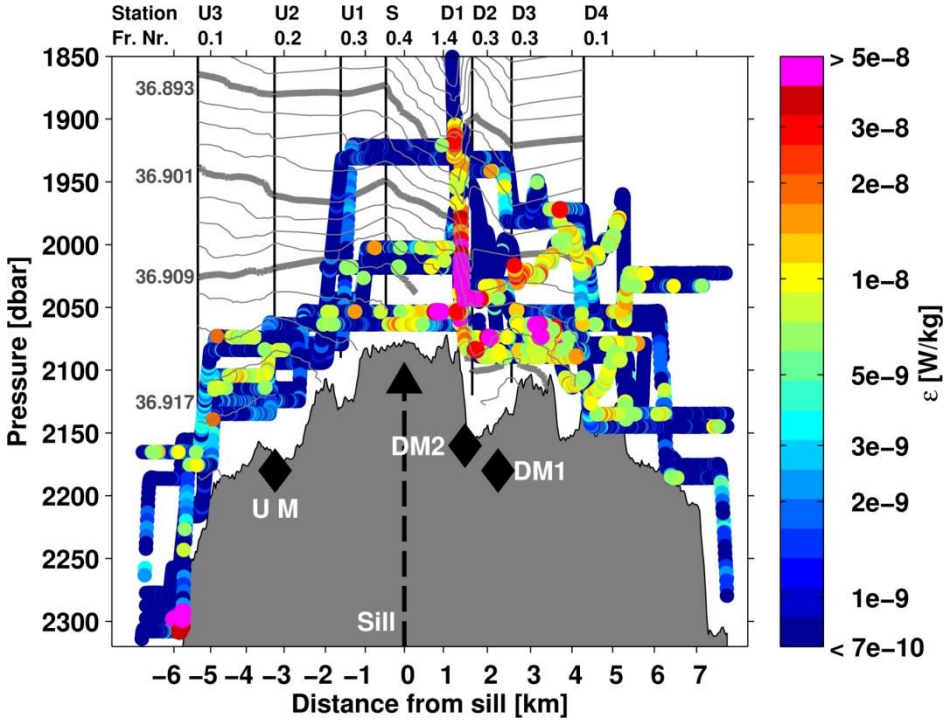
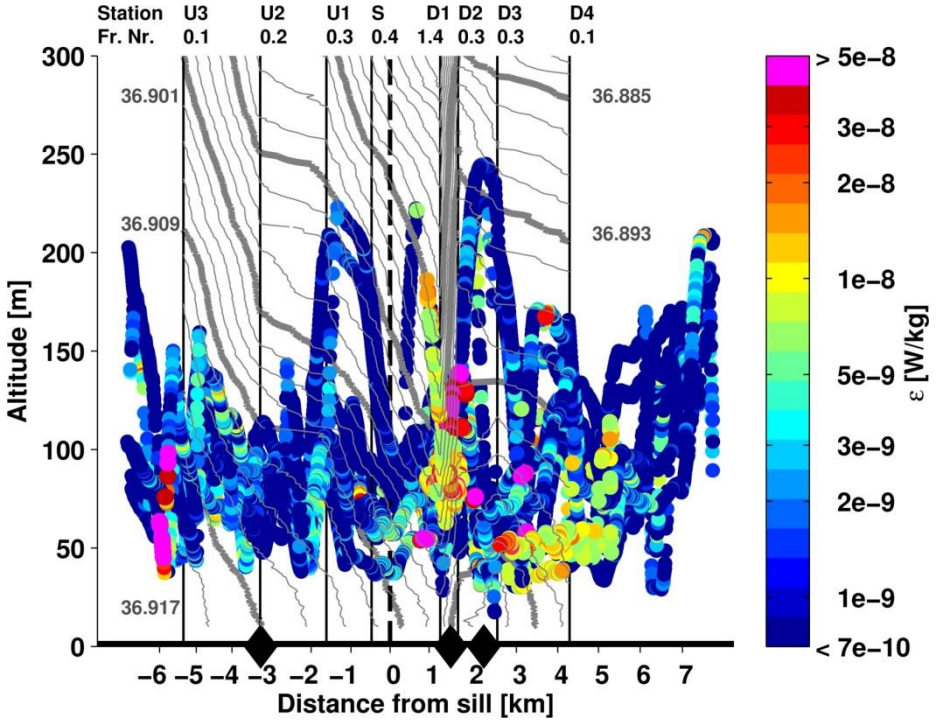


Method described in Tippenhauer et al. 2015

Empirical Nasmyth spectrum (Nasmyth 1970, Oakey 1982).

Dissipation Rate along the Channel



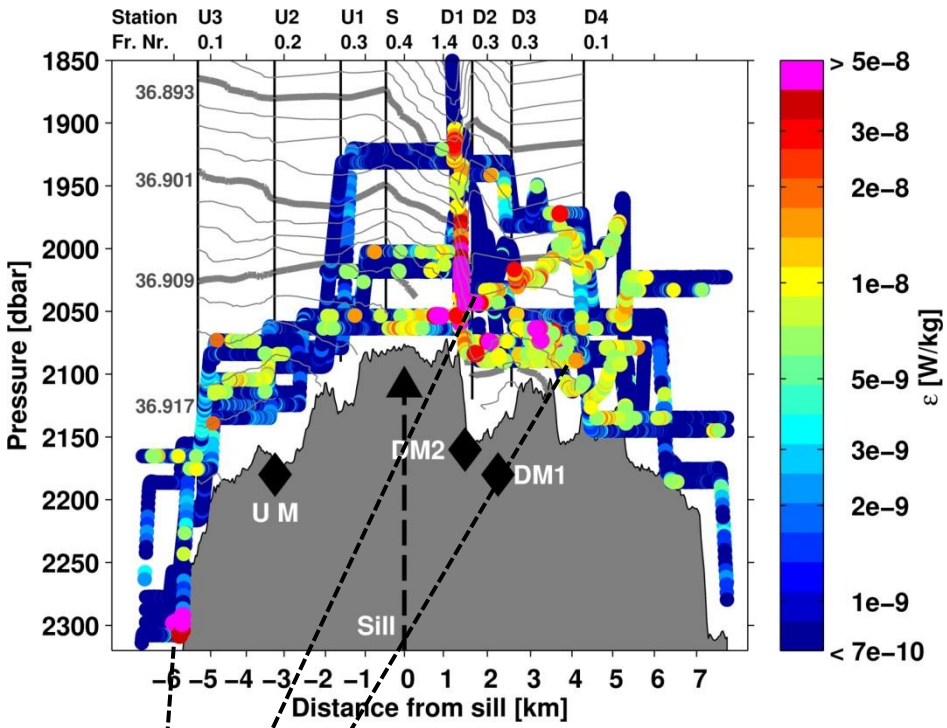


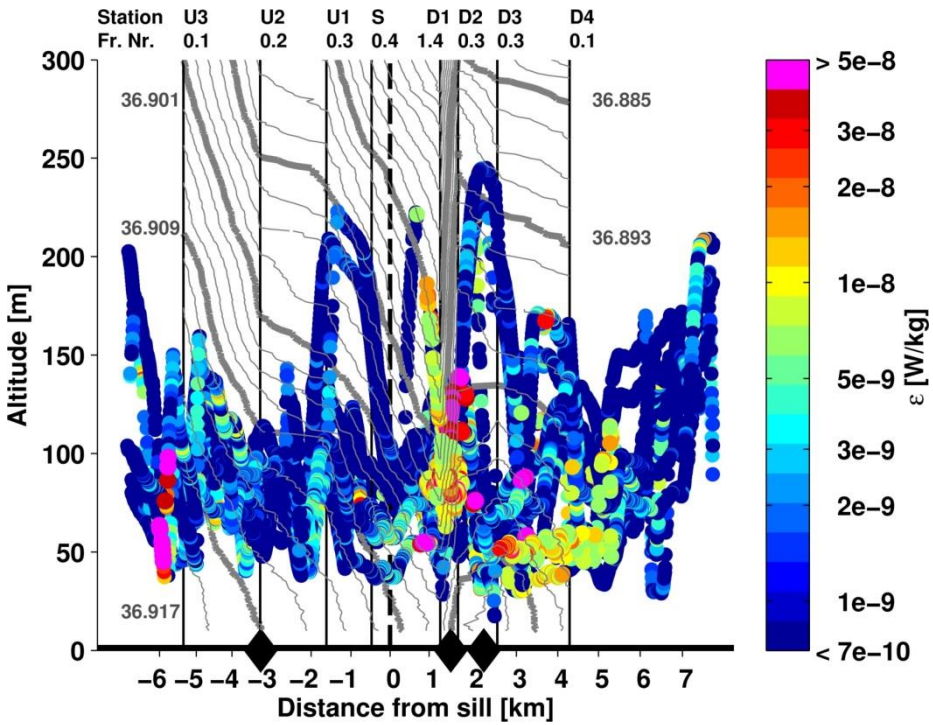
- 20 hours high resolution turbulence data (9 meter or 6 seconds)
- First successful deep ocean, AUV-based turbulence observations

- High mixing downstream of the sill mostly below 100 m altitude
- Pattern consistent with hydraulic jump downstream

Tippenhauer et al. 2015

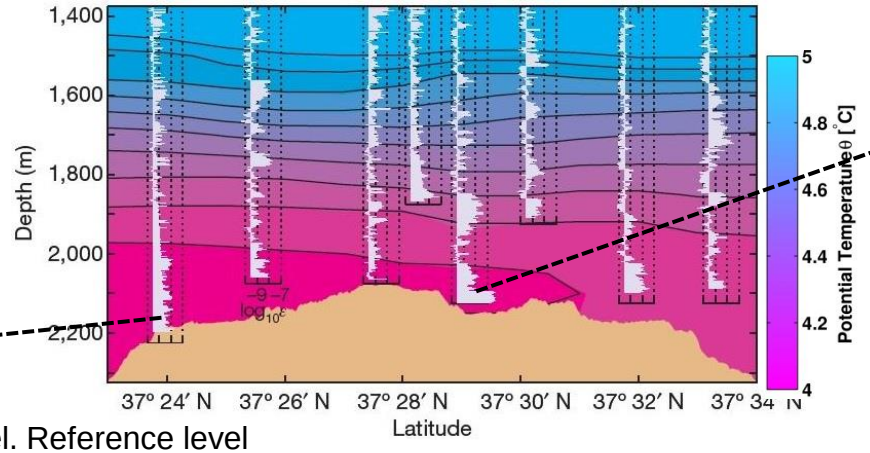
Dissipation Rate along the Channel





$> 1 \cdot 10^{-8}\ \mathrm{W/kg}$

$\sim 1 \cdot 10^{-8}\ \mathrm{W/kg}$

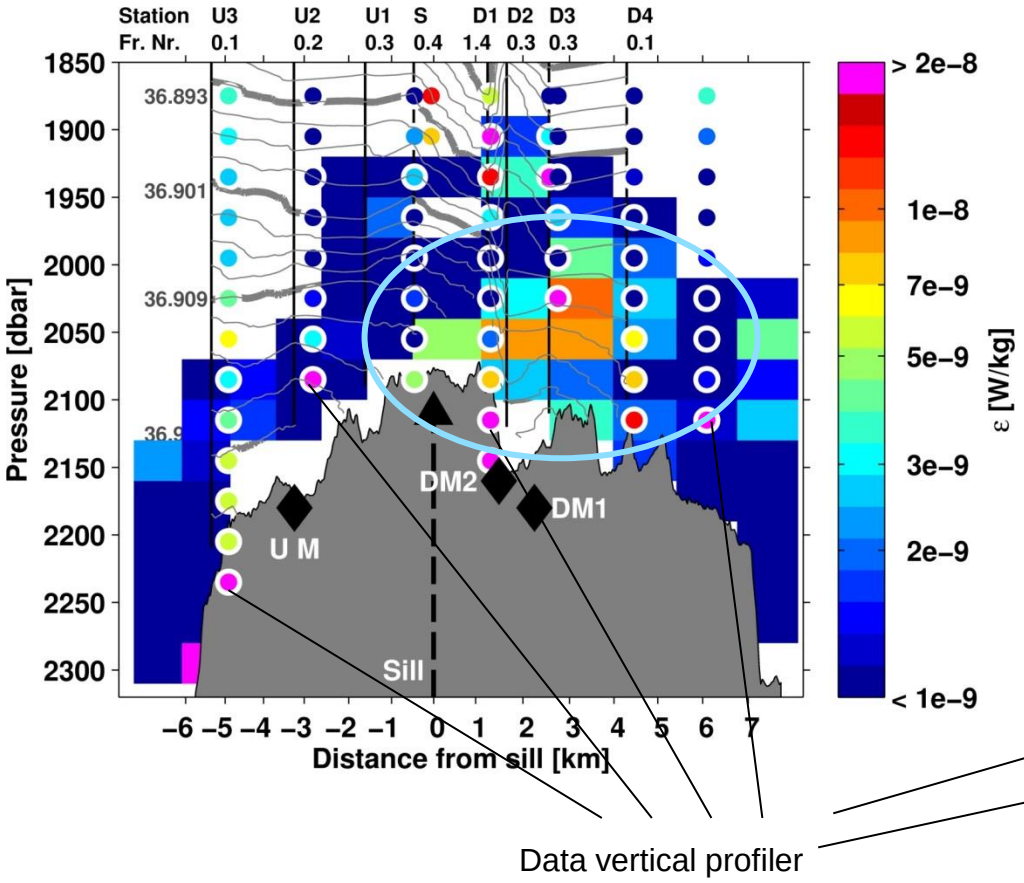


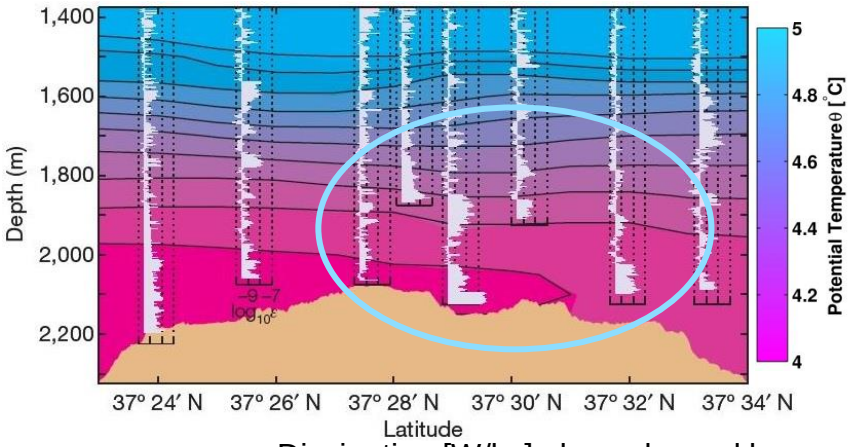
$1 \cdot 10^{-7}\ \mathrm{W/kg}$

Dissipation [W/kg] along channel. Reference level $3 \cdot 10^{-10}$ [W/kg] (St. Laurent and Thurnherr, 2007).

Tippenhauer et al. 2015

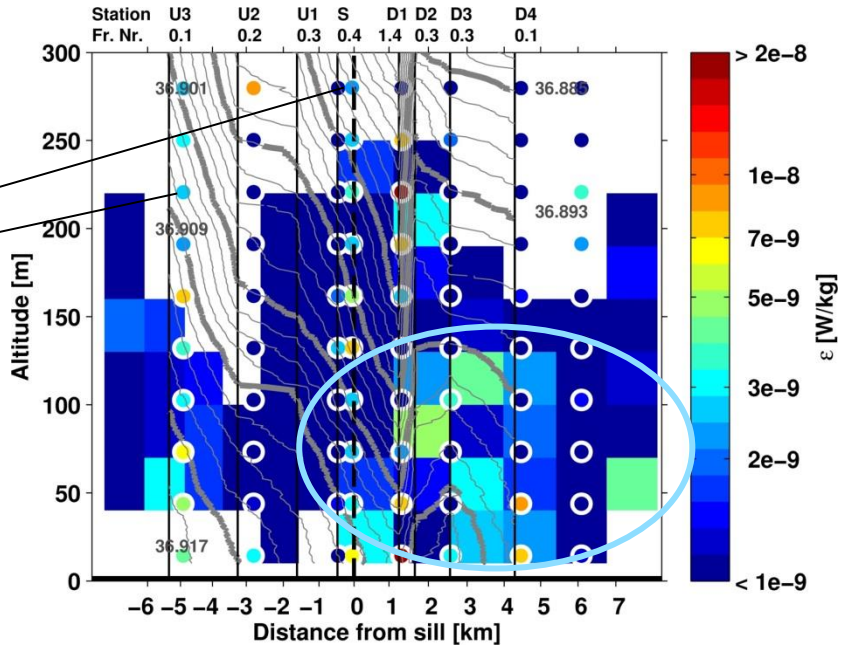
Dissipation Rate along the Channel





Dissipation [W/kg] along channel by St. Laurent and Thurnherr, 2007).

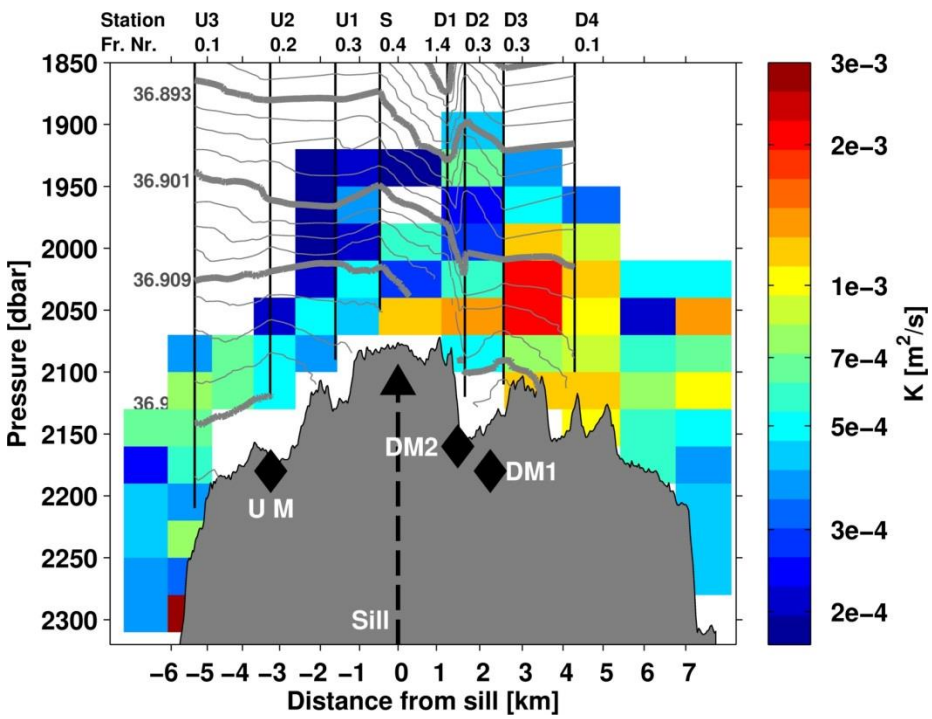
Data vertical profiler

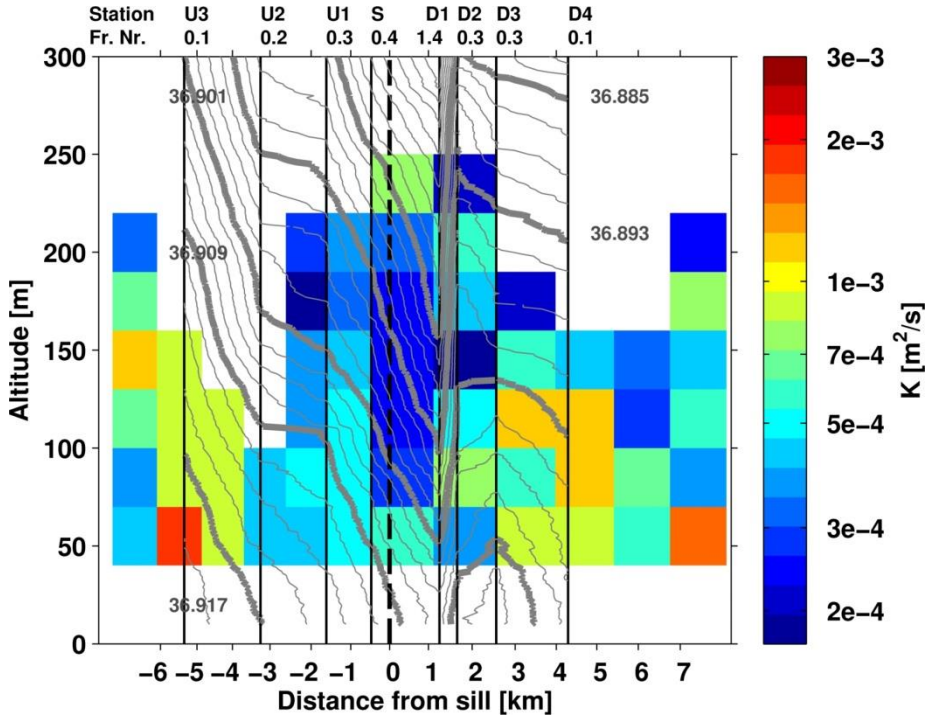


Box-average dissipation rates as function of pressure and altitude.

Tippenhauer et al. 2015

Diffusivity along the Channel





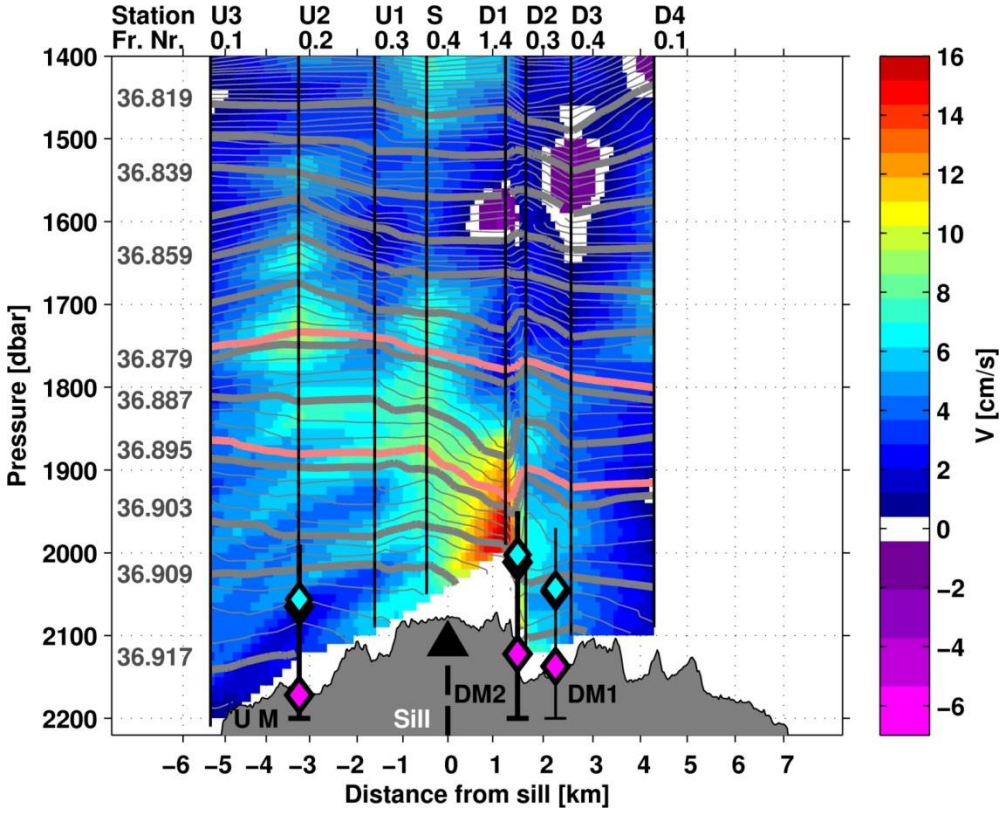
Diffusivity $K = {}^{\gamma\varepsilon}/_{N^2}$ (Osborn 1980)

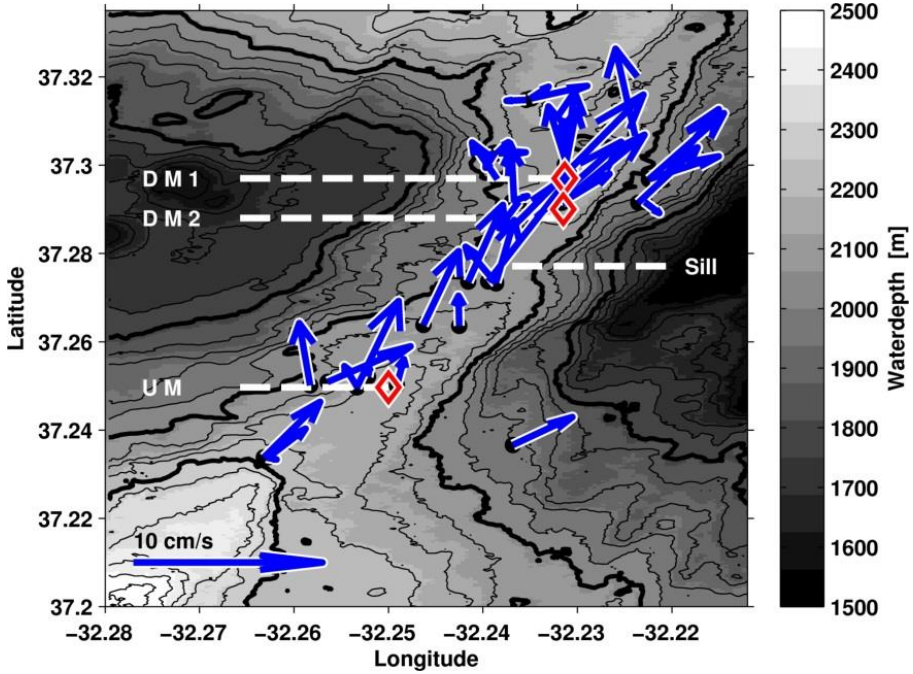
ε – observed dissipation rates,

N – buoyancy frequency,

$\gamma = 0.2$ – mixing efficiency.

Average velocity $> 8\ ^{cm}/_{s}$
Maximum velocities $> 17\ ^{cm}/_{s}$





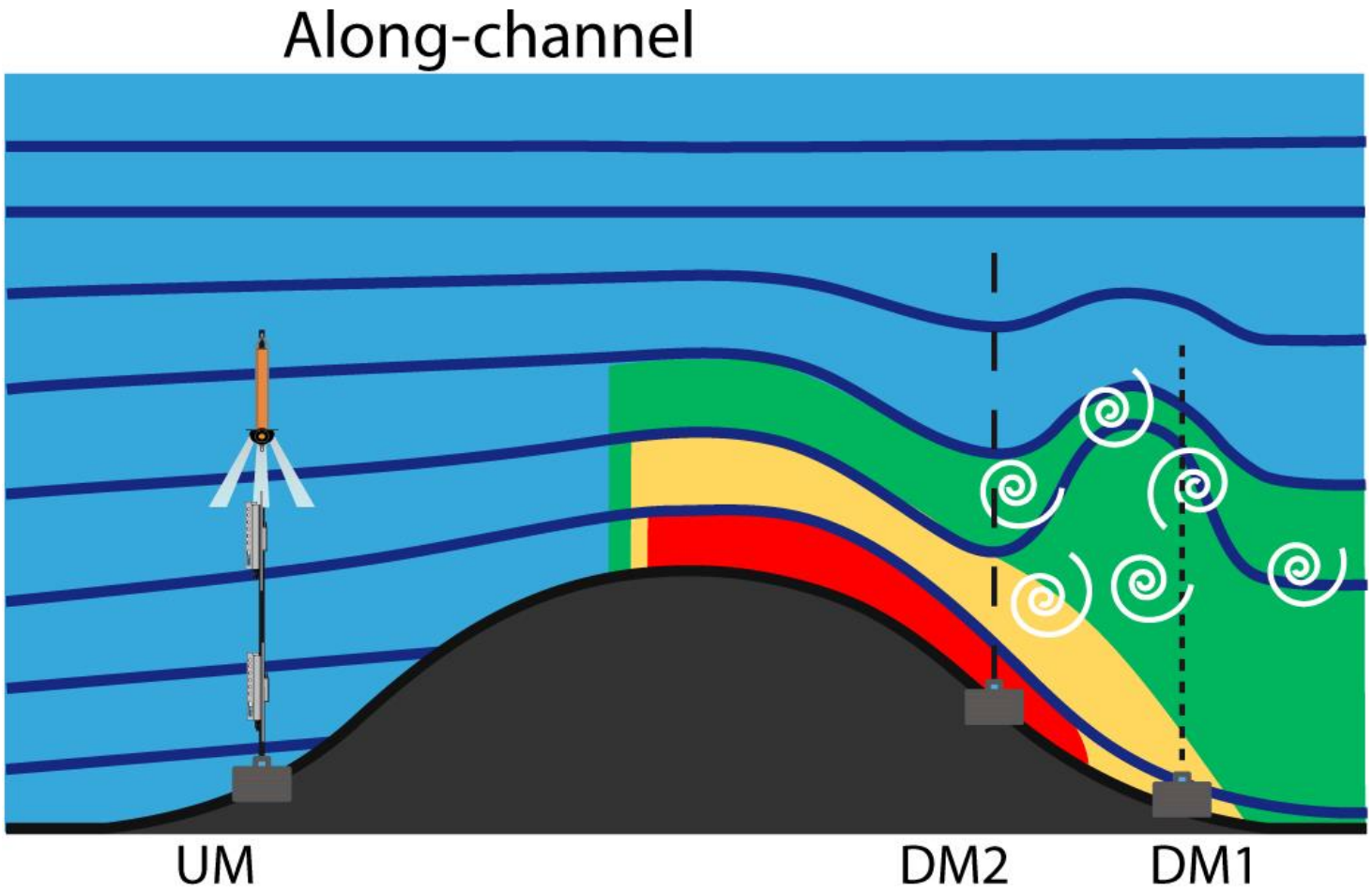
Averaged between 1800m and the bottom

Velocity along the channel.

Froude Number computed between isopycnals $\sigma_2 = 36.893$ (lower red) and $\sigma_2 = 36.877$ (upper red).

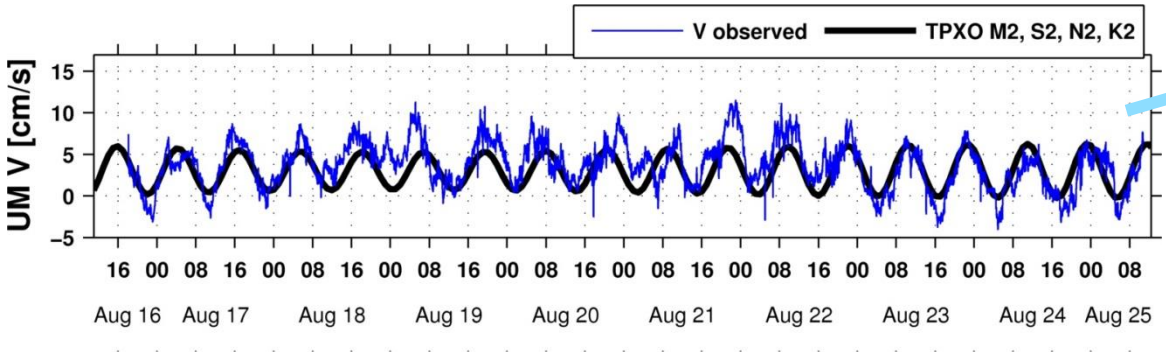
Tippenhauer et al. 2015

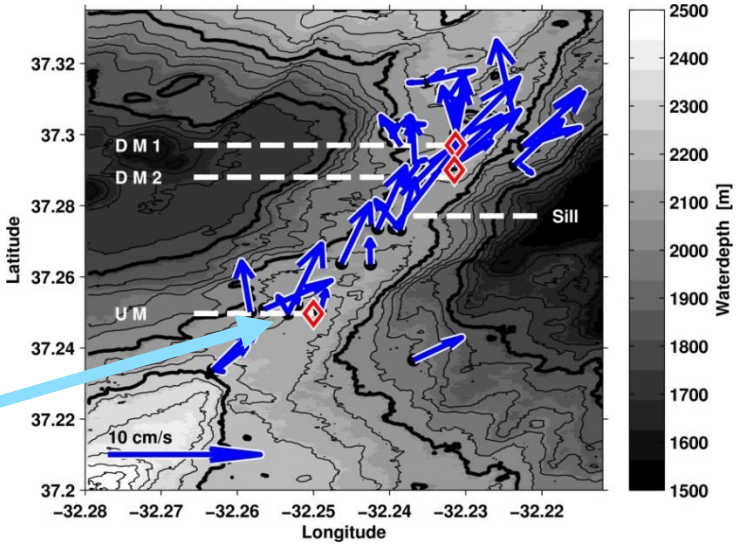
Hydraulic jumps were identified as the main source for the elevated mixing downstream of the sill.



Flow Velocity and Tides

Barotropic tides from TPXO global model of ocean tides (Egbert and Erofeeva, 2002).





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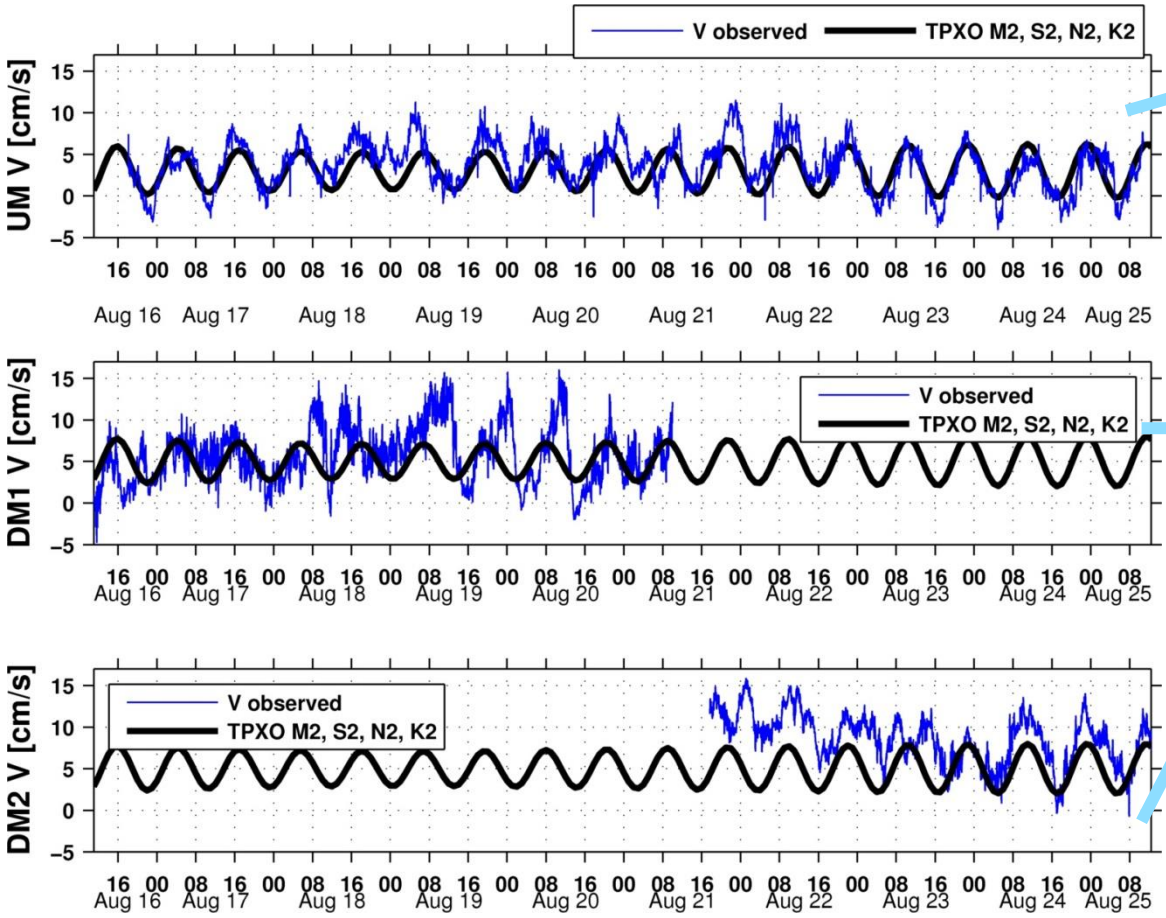

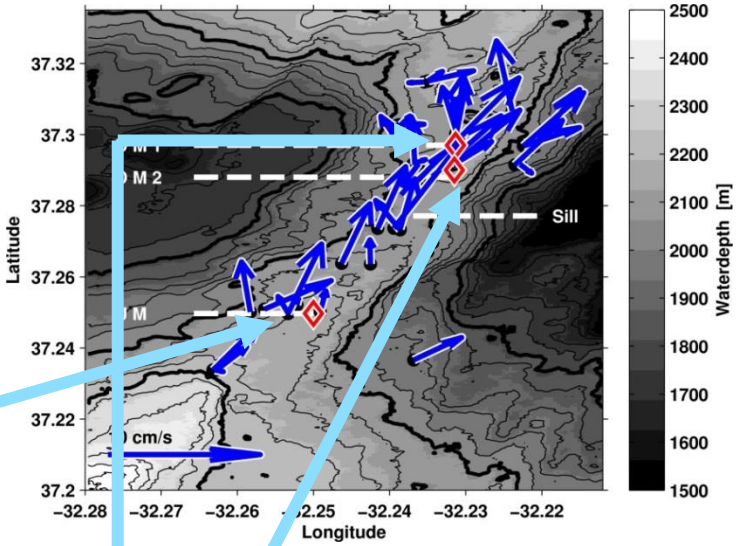

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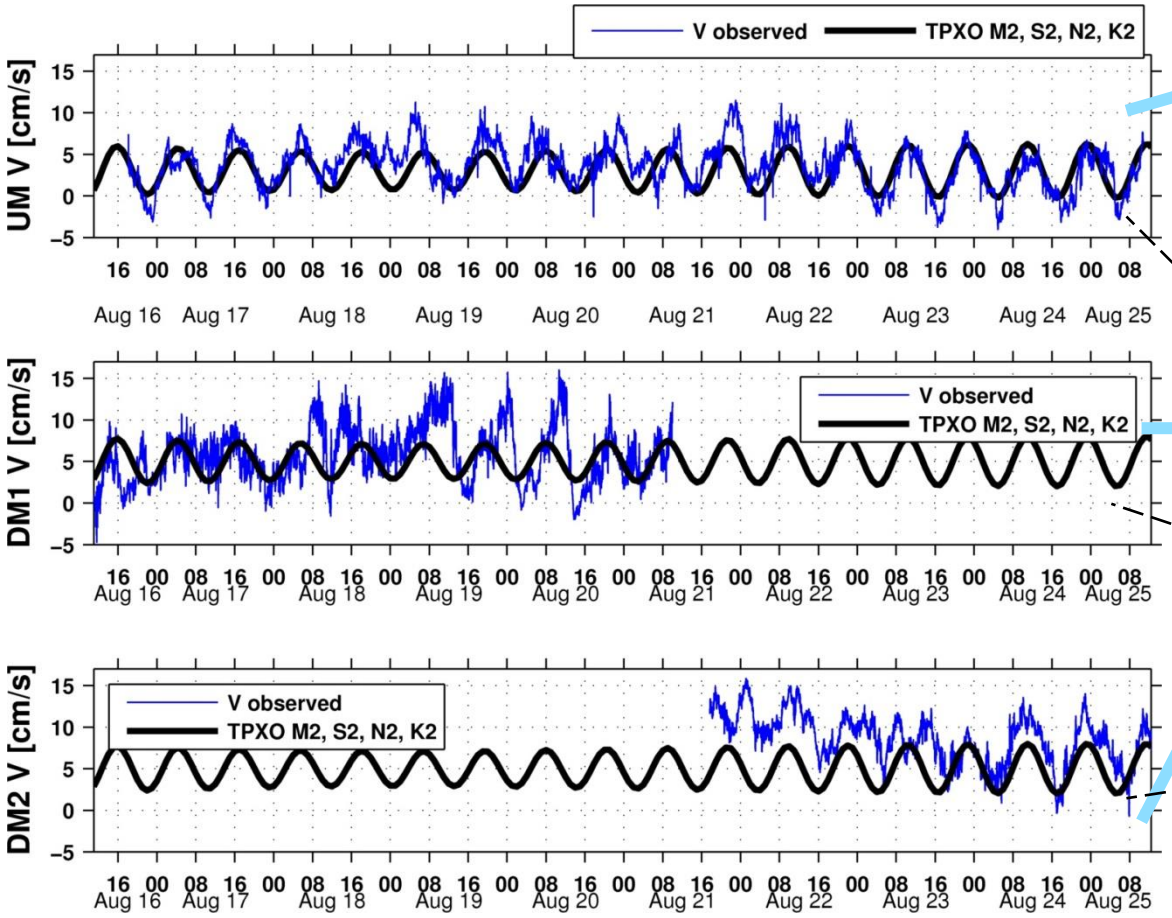
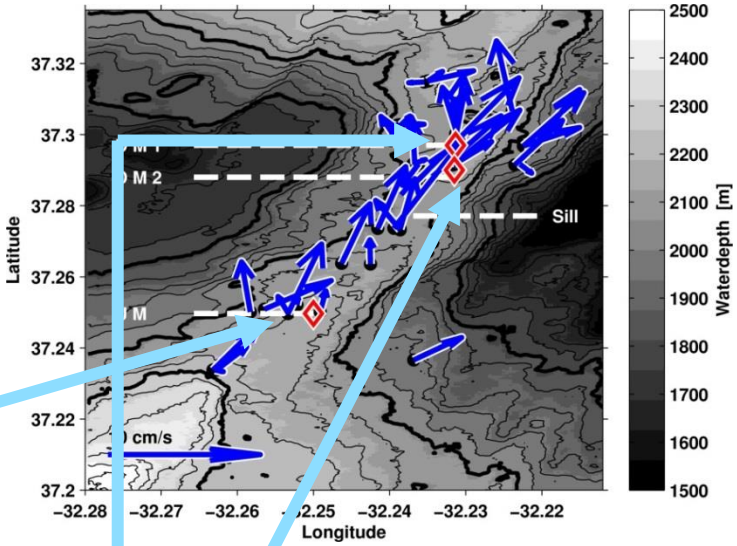




explained variance:

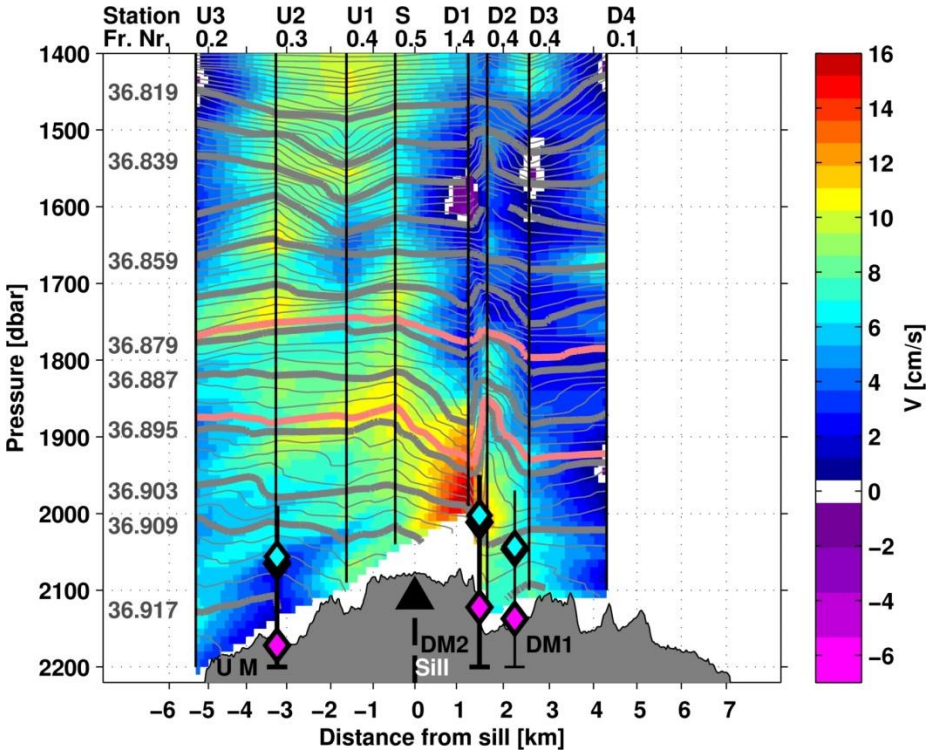
$R^2 = 0.5$

correlation not significant

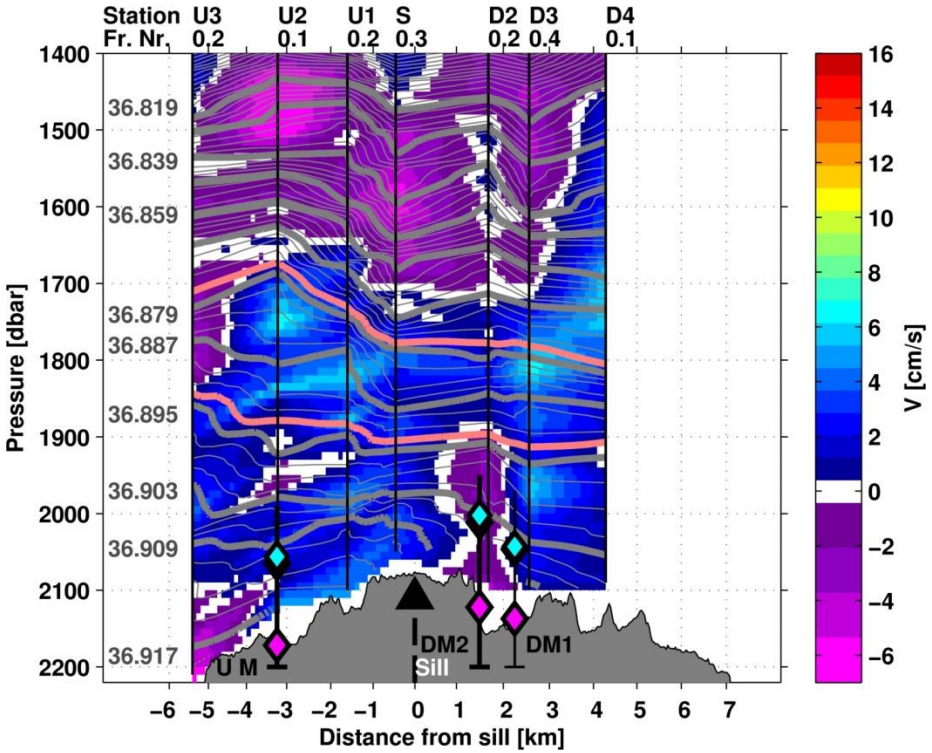
$R^2 = 0.3$

Velocity along the Channel – Tidal Cycle

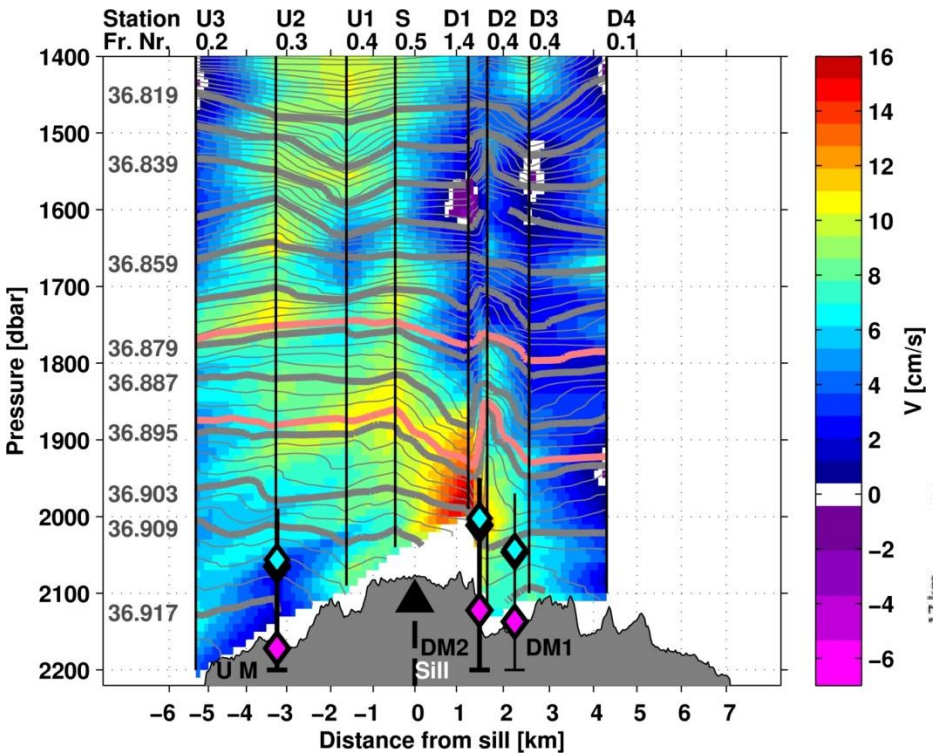
High flow velocity along the channel

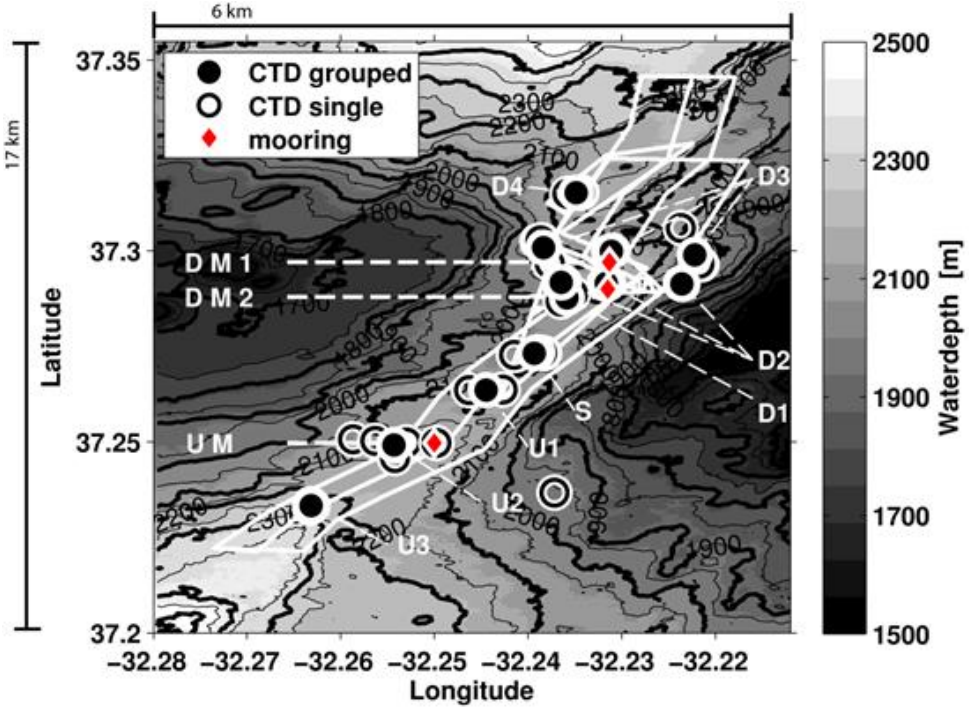


Low flow velocity along the channel



High Velocity Phase – Across-Channel Structure





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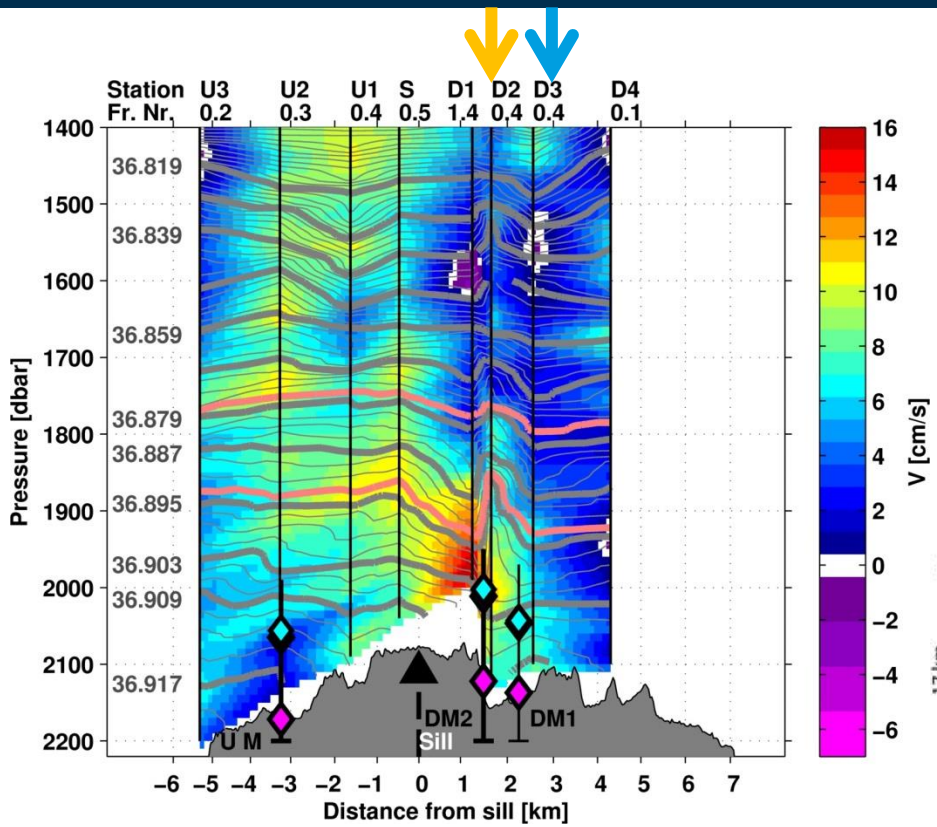
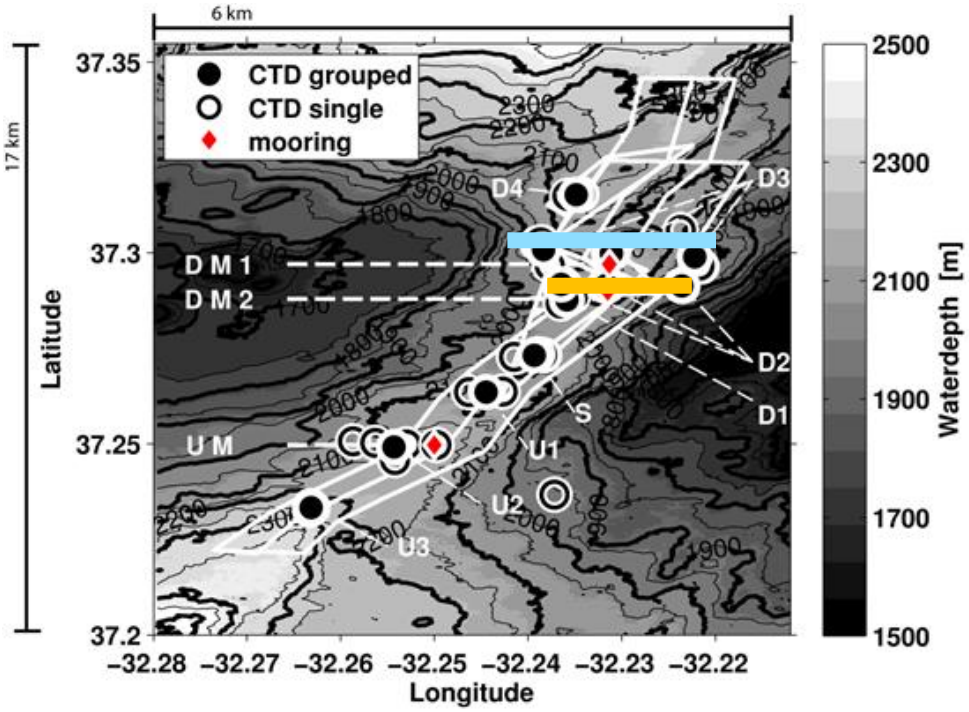
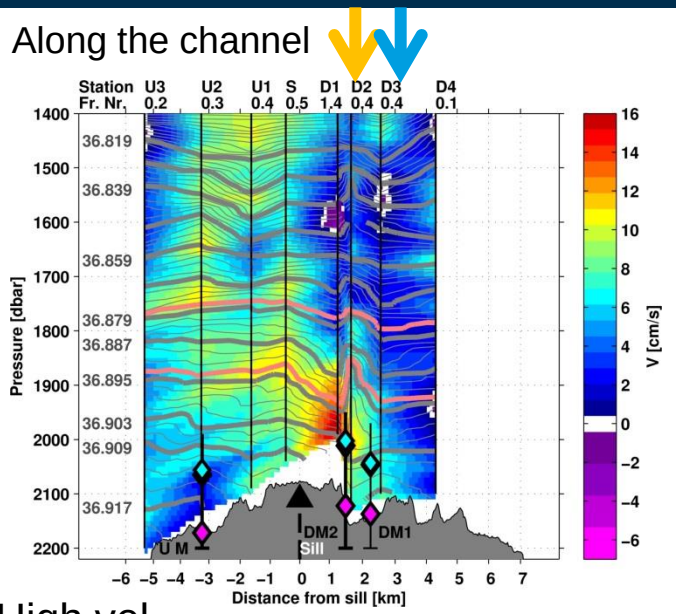




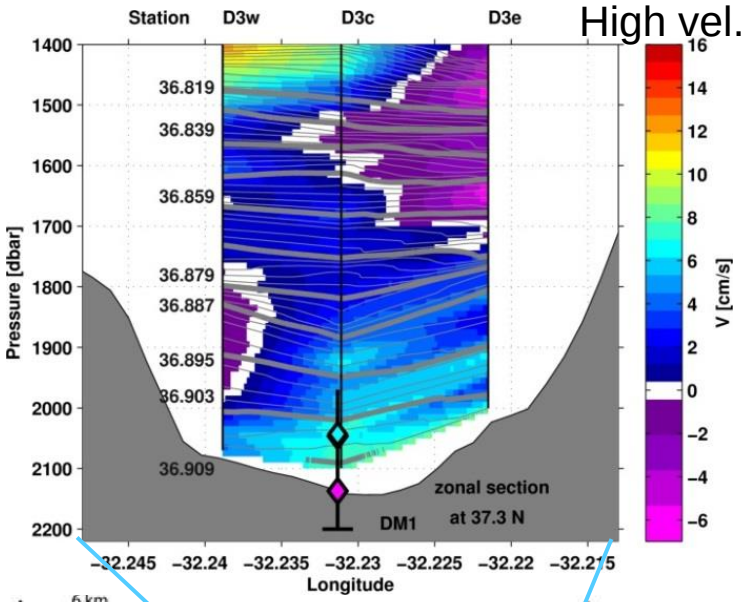
High Velocity Phase – Across-Channel Structure

Along the channel



Across the channel at D3

High vel.



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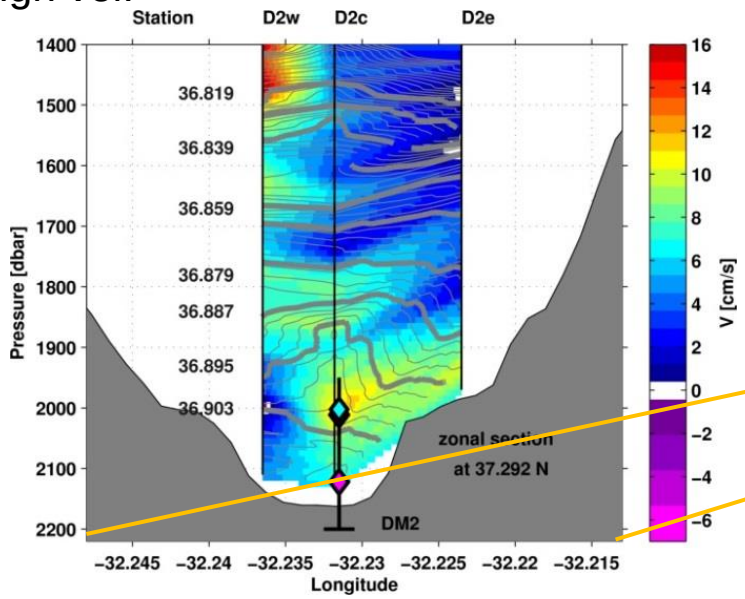
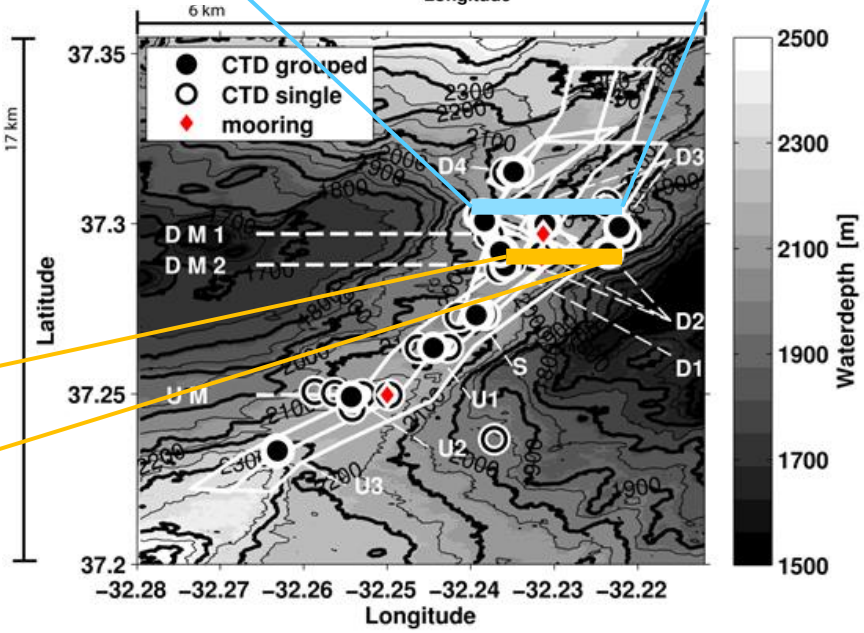
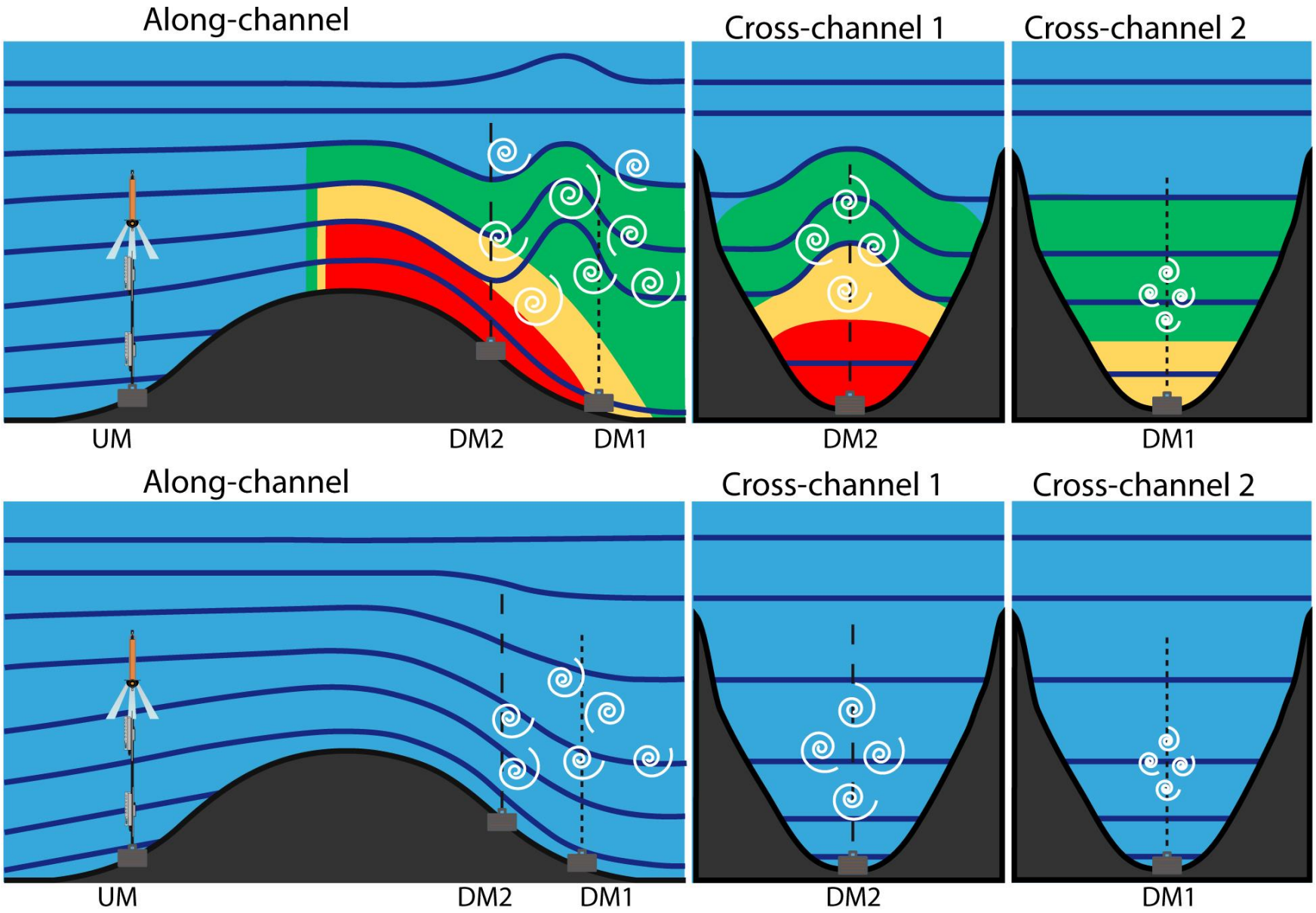


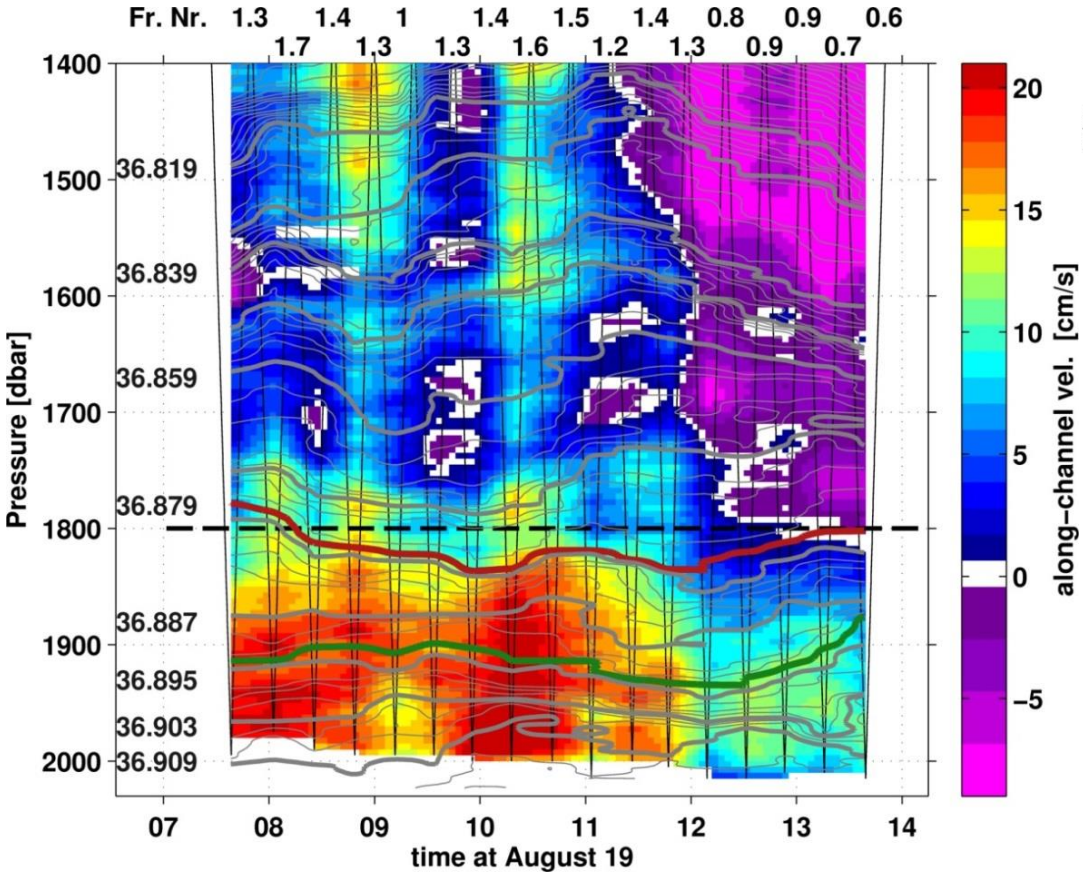
Across the channel at D2



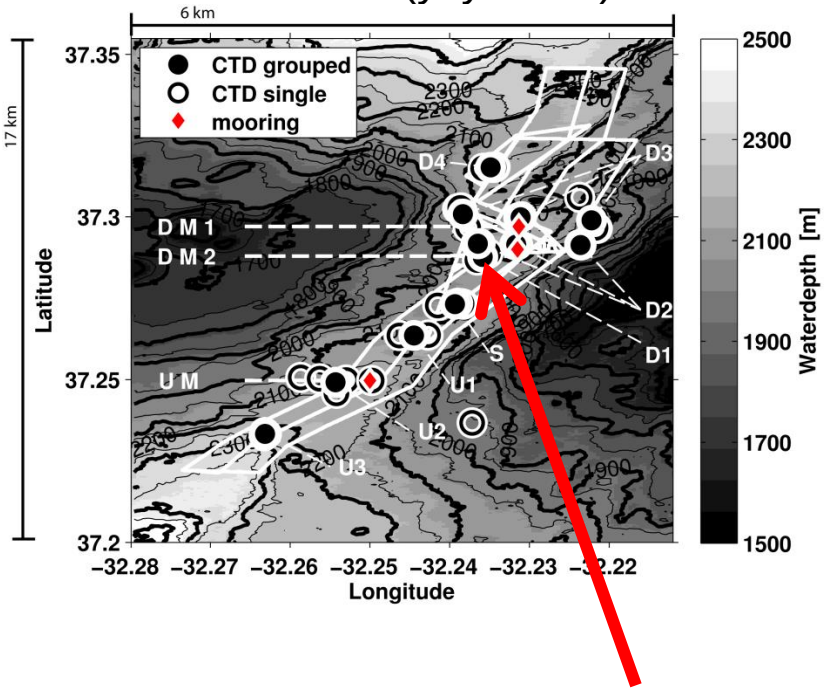
Sketches of High and Low Velocity Phases



Evolution of the Flow and Density Field



7 hour station at D1 (yoyo-cast)



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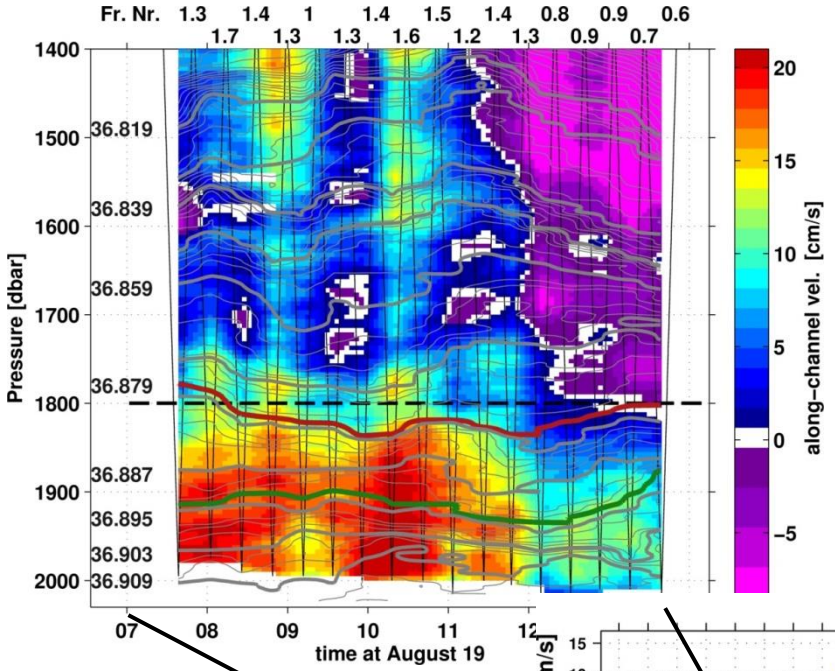

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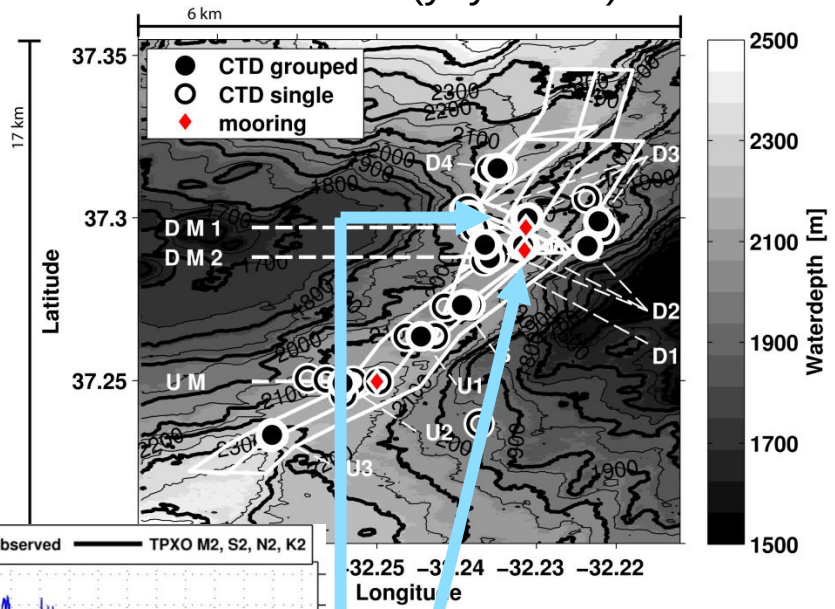
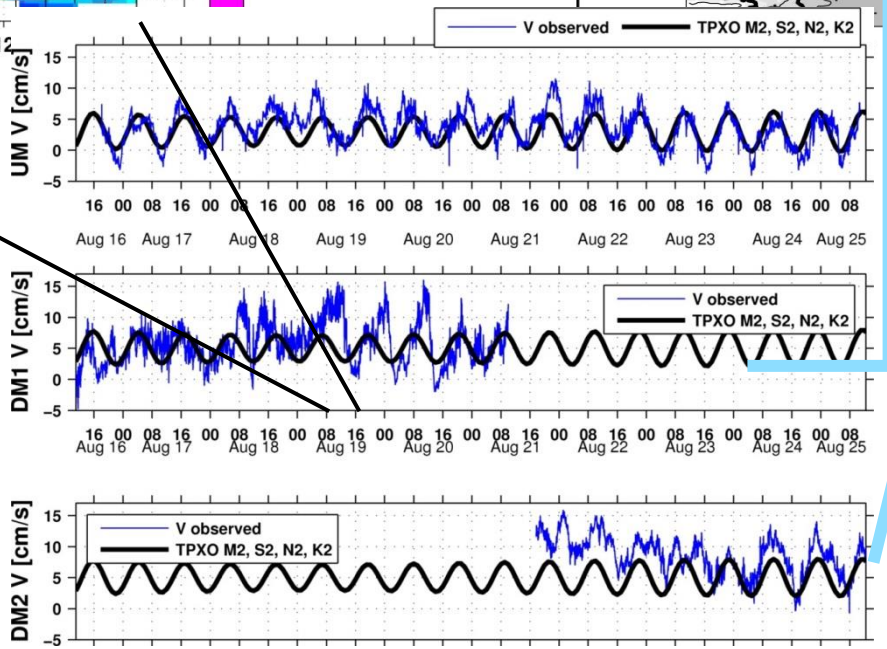
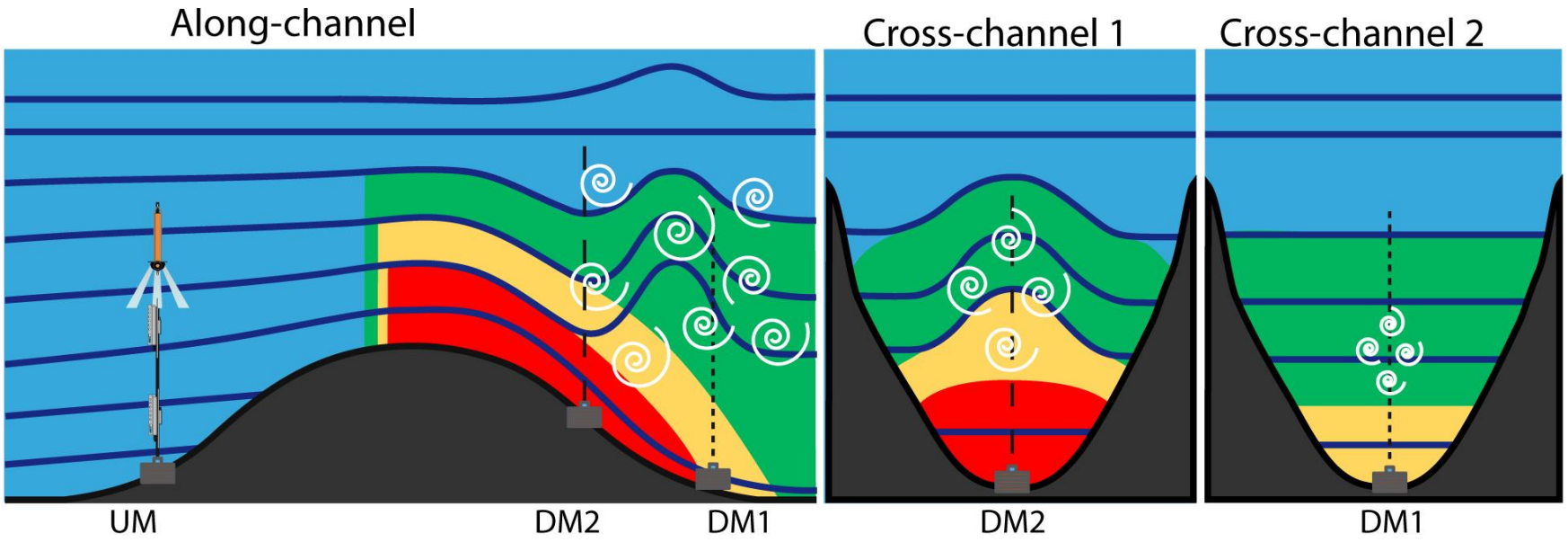




Sketch of High Velocity Phase



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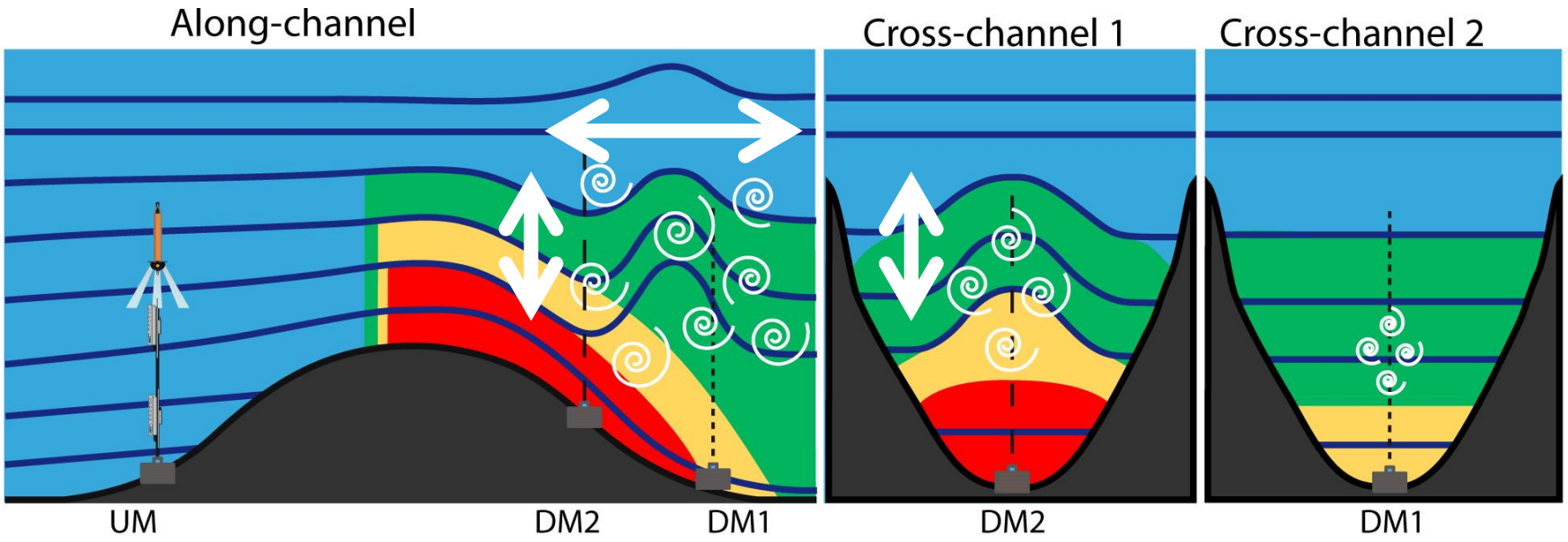
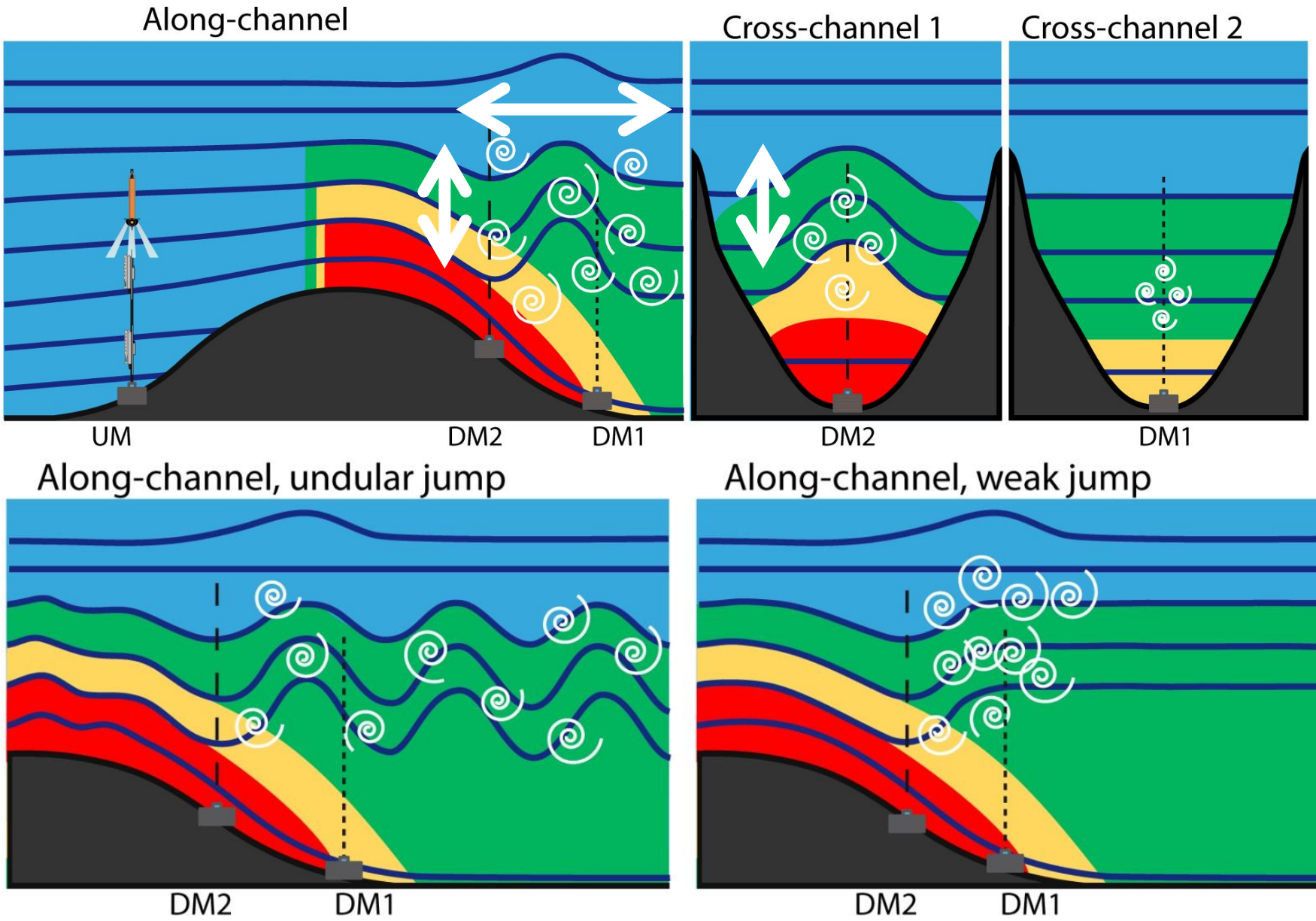


Sketch of Undular and Weak Hydraulic Jump



Questions addressed in this Study

- *How is the mixing distributed along the channel?*
  The mixing is distributed non-uniformly. Consistent with the average flow.

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<u>Open questions:</u>

- Dependence of mixing on the flow and topography conditions, especially in the tidal cycle.

- Role of upstream propagating hydraulic jumps.

- Origin of long-term variability (e.g. *Thurnherr et al.*, 2005).

Questions addressed in this Study

Scientific-technological achievements

- A new processing software was adapted.
  Filter to reduce the noise.

- AUVs are suitable for deep ocean turbulence observations. This widens the measurement range for horizontally profiling techniques especially in areas which are hard to access e.g. the
  - deep ocean or,
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Thank you for your attention