Study of polar ice caps and coastal glacier dynamics with seismology: preliminary results from the Astrolabe glacier in Terre Adélie and the Greenland ice sheet at EastGrip drilling site.

D. Zigone

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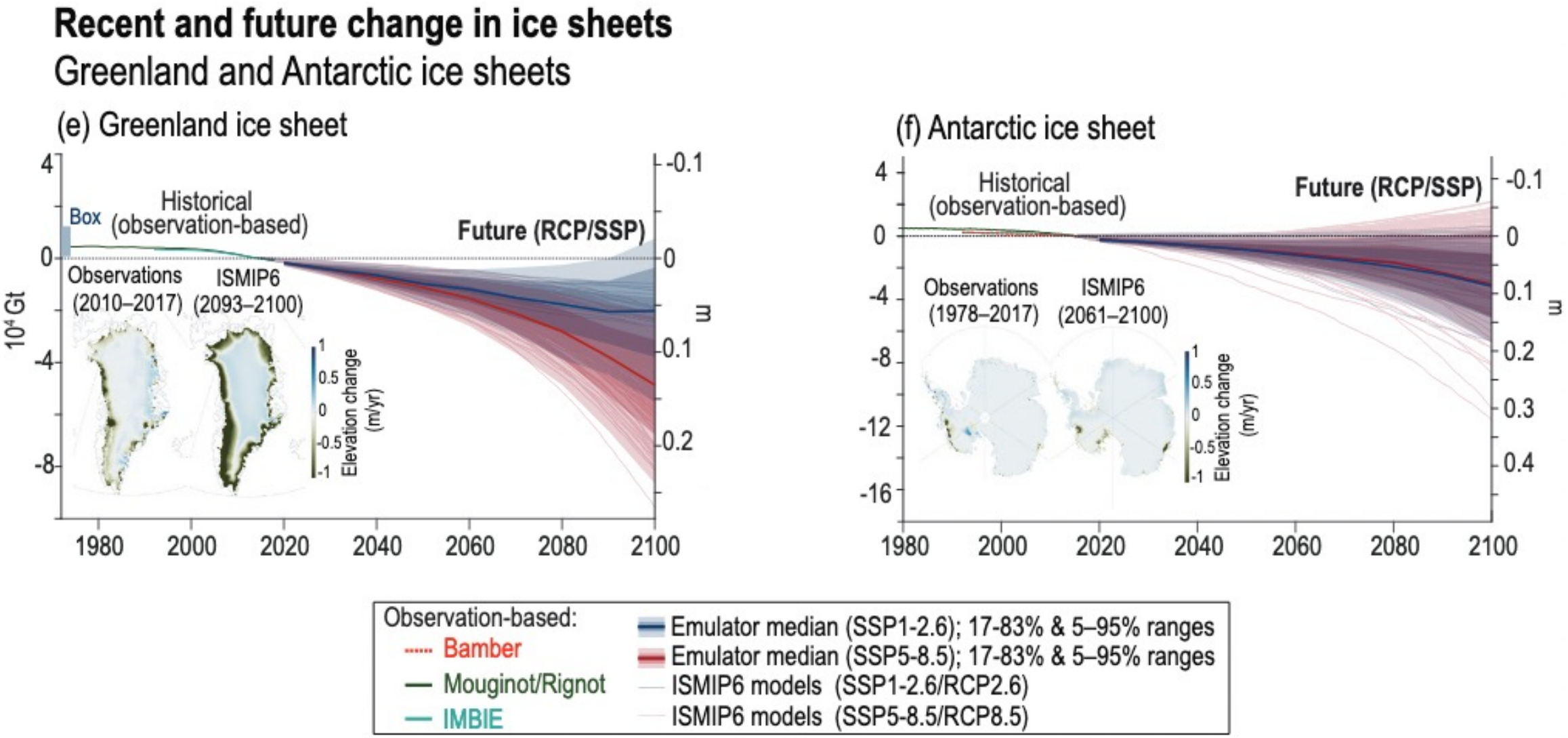
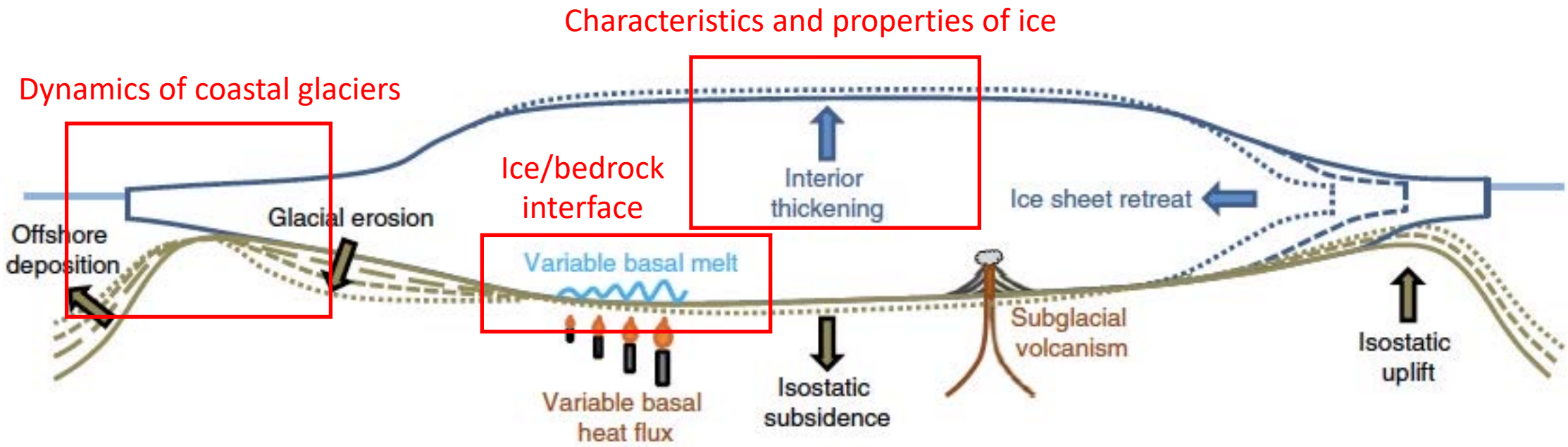
E. Pearce, C. Groult, A. Maggi, O. Eisen, G. Barruol, F. Provost, A. Fichtner, C. Hofstede, C. Hibert, E. Le Meur, J-P. Malet, A. Bernard, J-Y. Thoré, M. Bes de Berc

1. General Context



IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte et al.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

1. General Context



Summary of the interactions between the solid Earth and the Antarctic ice sheet (Whitehouse *et al.*, 2019).

Correct interpretation & predictions:

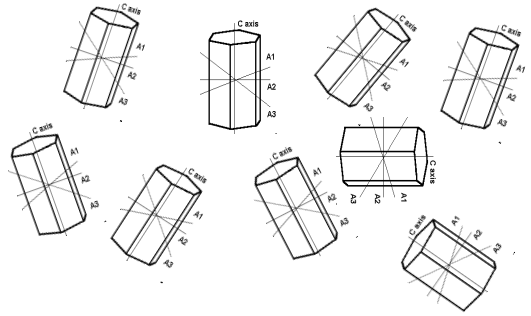
- Get ice dynamics right
- Know ice properties and subglacial conditions

⇒ on-site observations => CHIPSM

2. Study of ice sheet with seismology

- Ice anisotropy

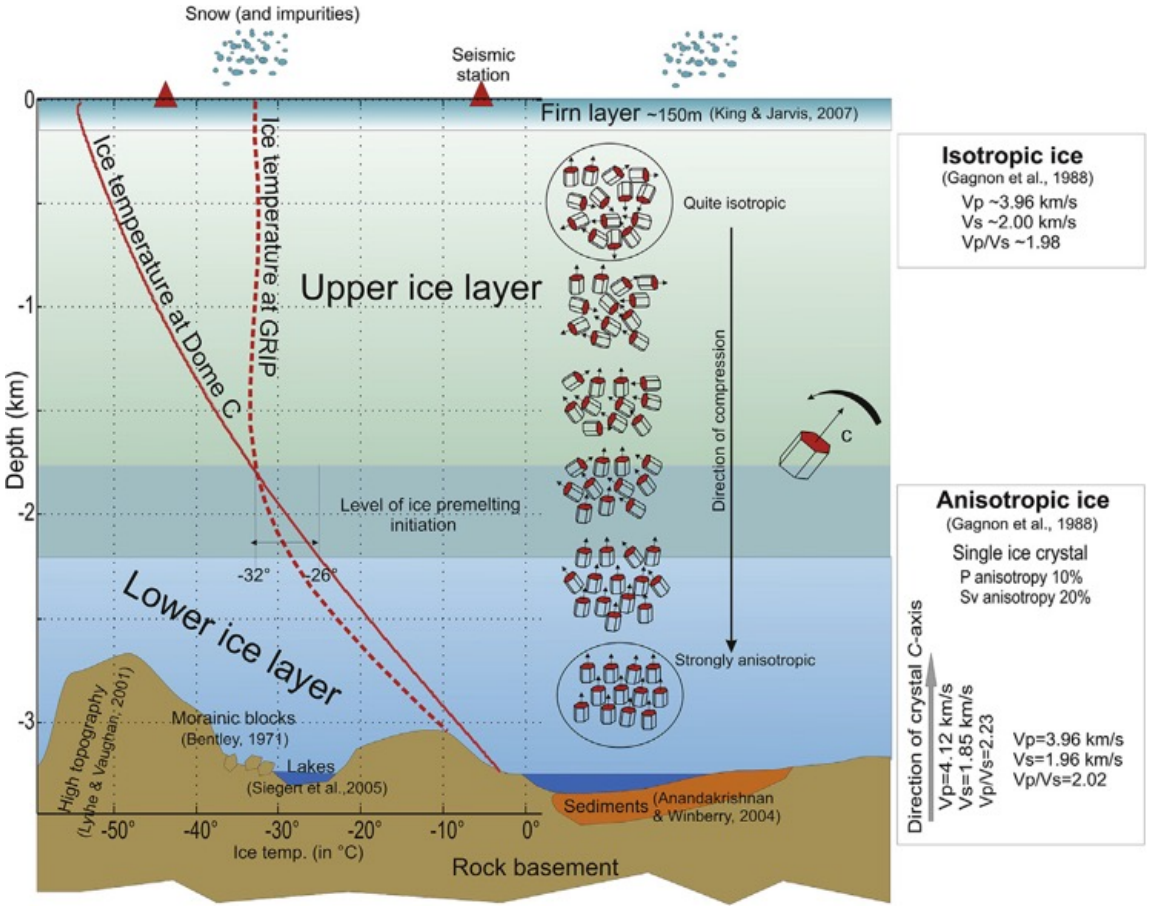
Direction of crystals: hard vs soft



- Subglacial conditions

Bedrock or soft sediments?

Frozen or melting?



Wittlinger et al., 2012, 2014

⟶ Use geophysics to observe in-situ

2. Study of ice sheet with seismology

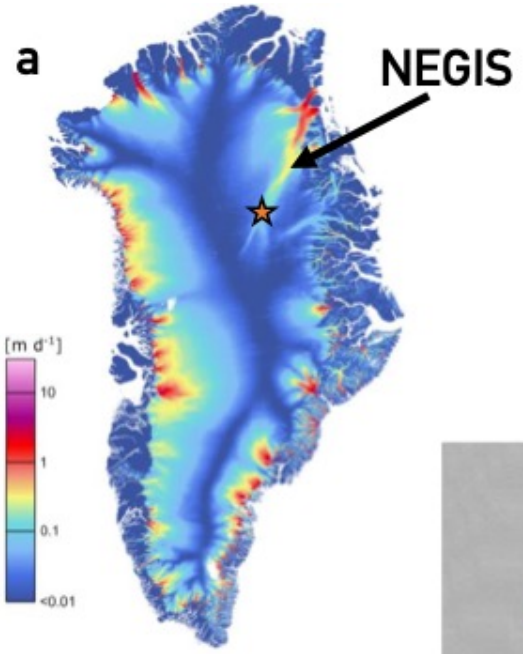
- **Project:** Characterizing ice-sheet properties and processes with novel seismic monitoring technology at EGRIP (CHIPSM-EGRIP)
- **Who:** O. Eisen (AWI, ITES), D. Zigone (ITES)
  - In the field: A. Fichtner – DAS (ETH), C. Hofstede – seismics (AWI)
  - project: E. Pearce, C. Hibert (TES), A. Booth (Uni Leeds), P. Christoffersen (SPRI)
  - Funding: USIAS/Uni Strasbourg, AWI, ETH
- **Objectives:**

- Distributed physical properties (anisotropy continuously)
- Imaging of upper layers of substrate
- (final goal: real-time location of drill above bedrock)

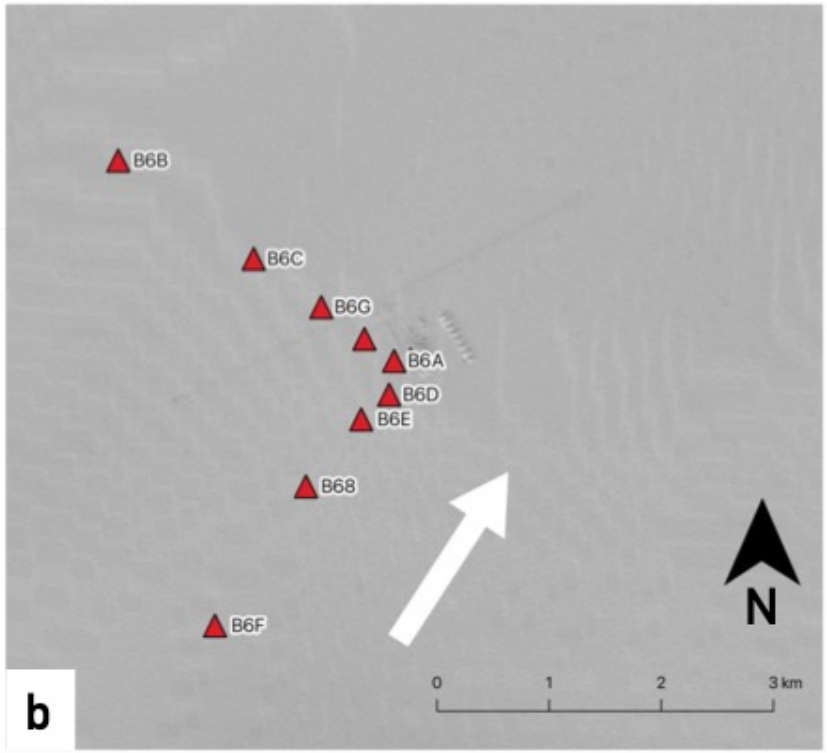
- **Methods:**

- Seismics while drilling (SWD) and **Noise correlations** with DAS and seismometers at surface
- **DAS in borehole** after drilling with surface sources**.**

2. Example of preliminary results from EastGRIP



(a) Ice velocity of the Greenland Ice Sheet 2019-2020, *(ENVEO, 2020)*. Orange star marks EGRIP drilling site.



(b) Map of the EGRIP field site, showing geophone deployment in red triangles. White arrow: approx ice flow direction. Background: Sentinel-2 NIR image, captured 7/7/19

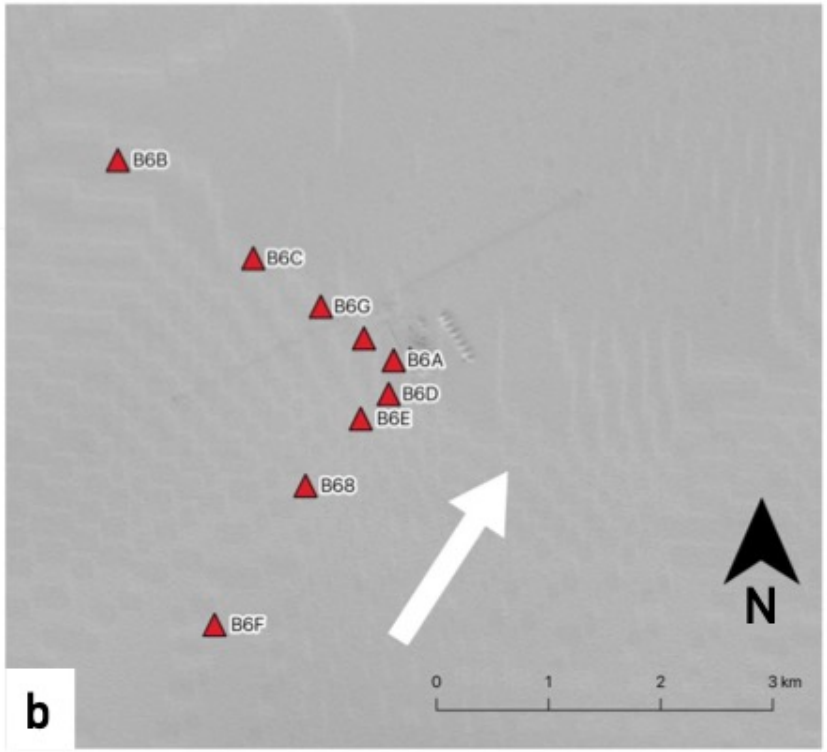
Northeast Greenland Ice Stream (NEGIS)

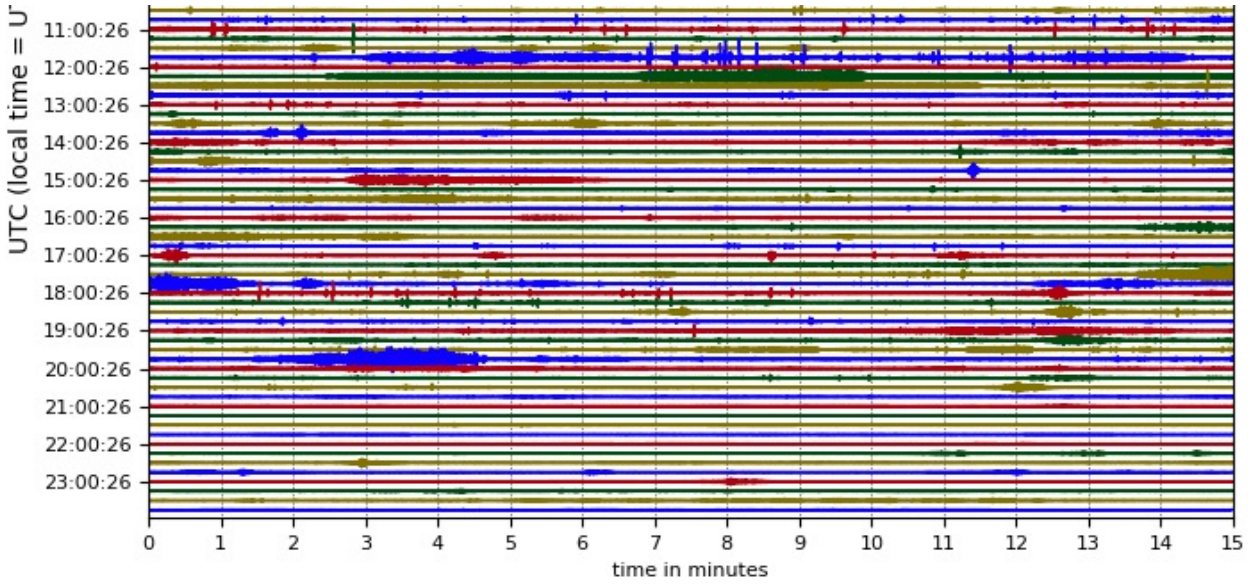
- NEGIS is the largest active ice stream in the Greenland Ice Sheet.
- Nearly 600 km long, starting close to the ice divide.
- Discharging ~12 % of the total ice sheet mass into the North Atlantic.
- Significant contribution to accelerated mass loss of the ice sheet.

East Greenland Ice Core Project (EastGRIP)

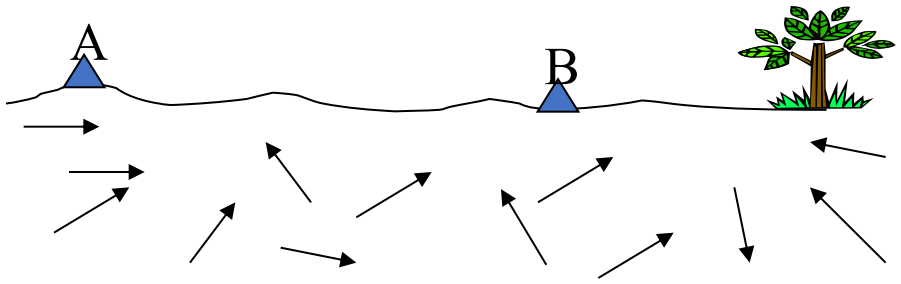
- First attempt to retrieve a deep ice core from an active ice stream.
- Located in upstream part of NEGIS (ca. 76°N, 36°W).
- Ice thickness: ca. 2660 m.
- Flow velocity: ca. 55 m / year.
- Goals: constrain climate history and deformation patterns at depth.

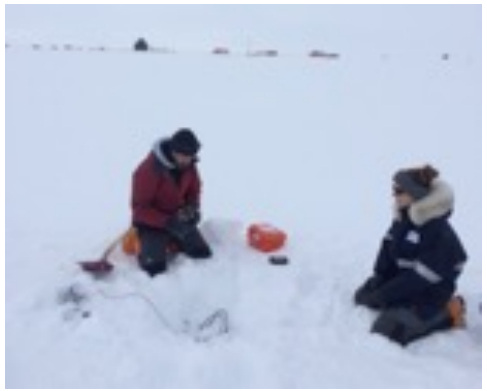
2. Example of preliminary results from EastGRIP





- We use the ambiant noise to compute cross-correlation functions





Mathematically, for a random wave field:

$$\partial_\tau C_{AB}(\tau) = -\frac{\sigma^2}{4a}(G^+(A,B,\tau) - G^-(A,B,-\tau))$$

where G^+ and G^- are the causal and anti-causal Green's functions.

The Correlation is equivalent to a recording during an active experiment

2. Example of preliminary results from EastGRIP

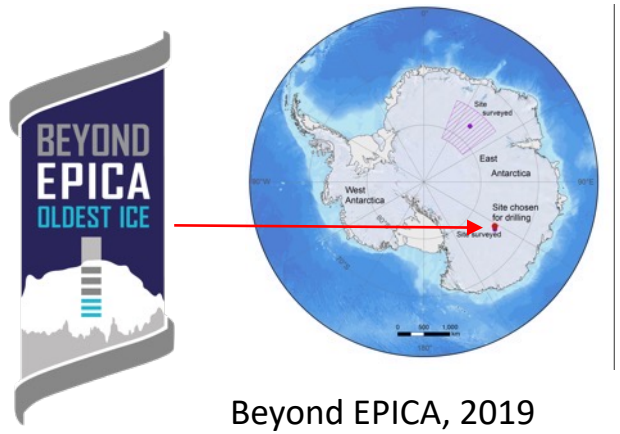
Not available

Summary and Future Plans

- Preliminary results suggest that simple, short duration (2-3 weeks), passive seismic deployment and environmental noise-based analysis can be used to determine the structures and anisotropy of the upper part of ice masses.

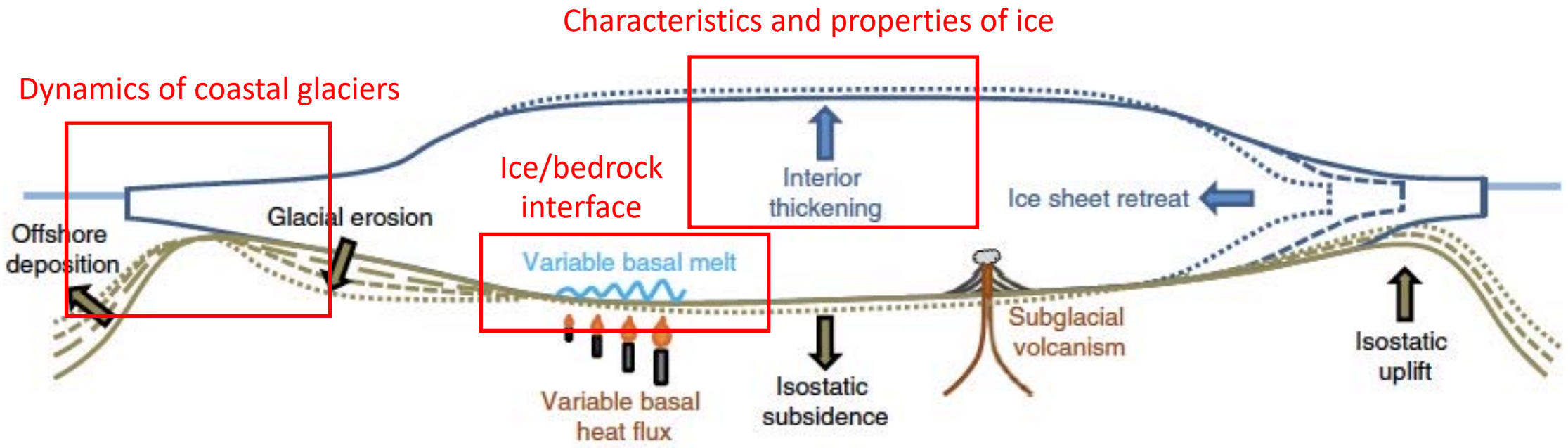
- DAS measurements look very promising.

- Similar experiments in Dome C and Little Dome C in the next few years.



Beyond EPICA, 2019

3. Dynamics of outlet glaciers



Summary of the interactions between the solid Earth and the Antarctic ice sheet (Whitehouse *et al.*, 2019).

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⇒ on-site observations => CHIPSM

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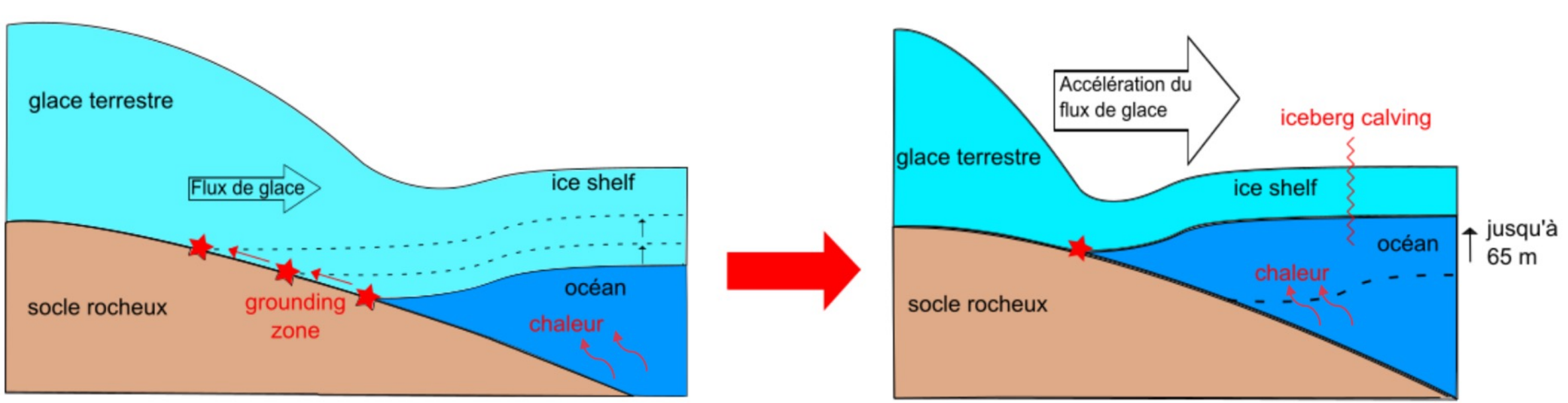
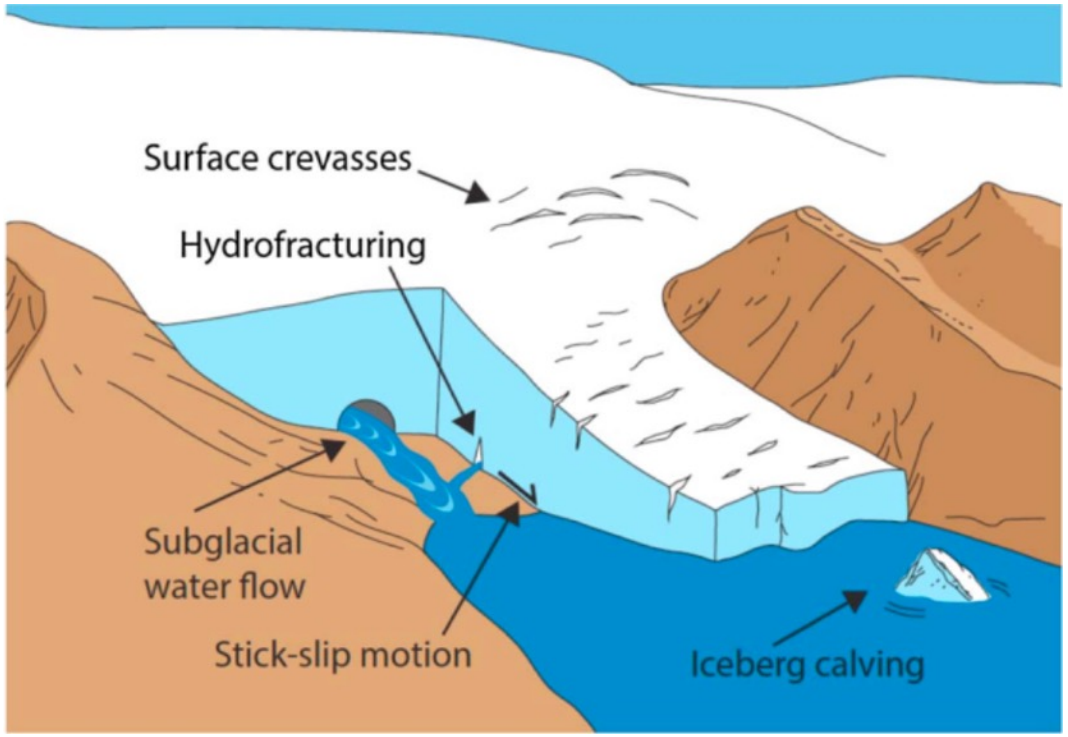


- <u>Vulnerability of Antarctic coastal glaciers to climate change:</u>

  - **Presence of floating tongues** => **sensitive to ocean dynamics** (tides, swells), and **its warming**. Warm subglacial water intrusion influences basal melting and increases the vulnerability of the ice sheet.
  - Remote sensing studies provide key information on large-scale ice flow and grounding line positions, but do not describe **the small-scale processes that control Antarctic coastal glacier dynamics** (topography, crevasses, geological, frictional, and hydrological properties of bedrock).

3. Dynamics of outlet glaciers

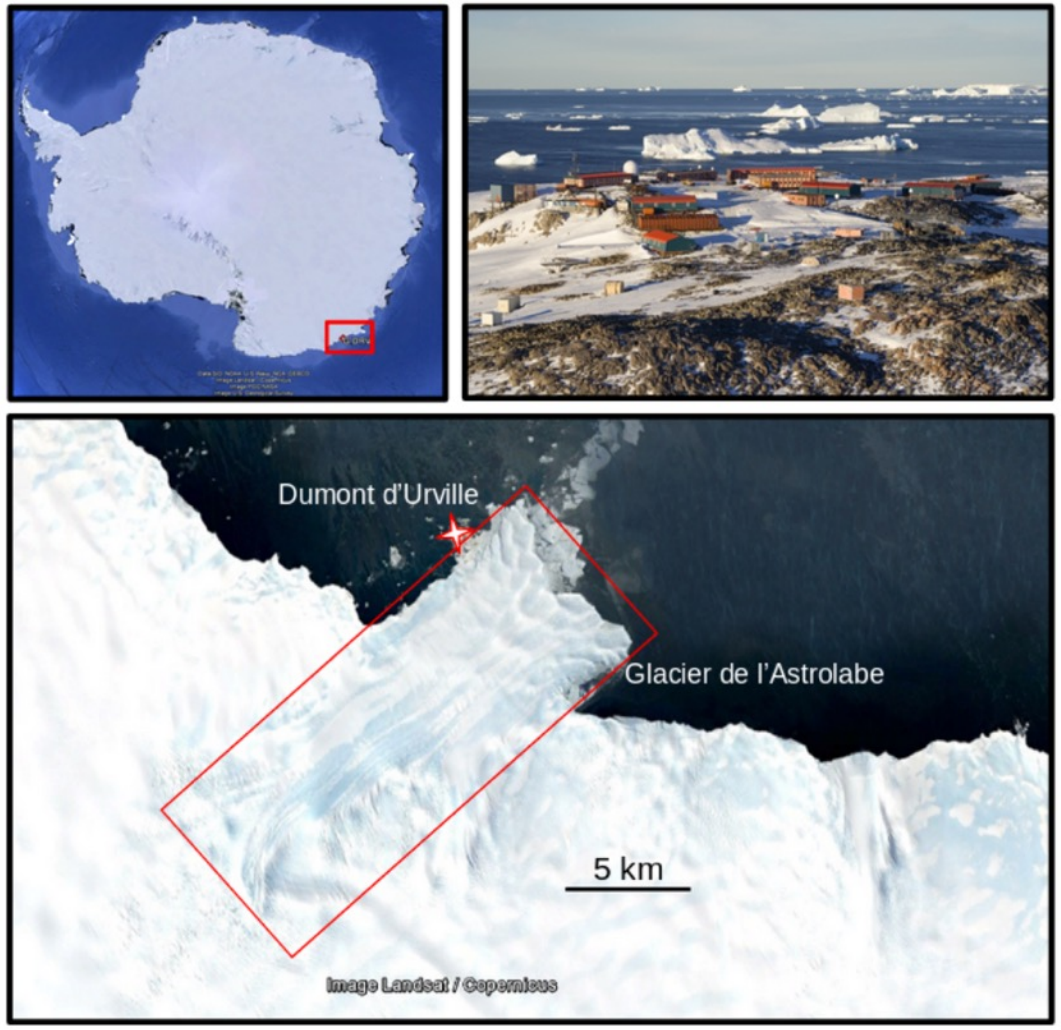


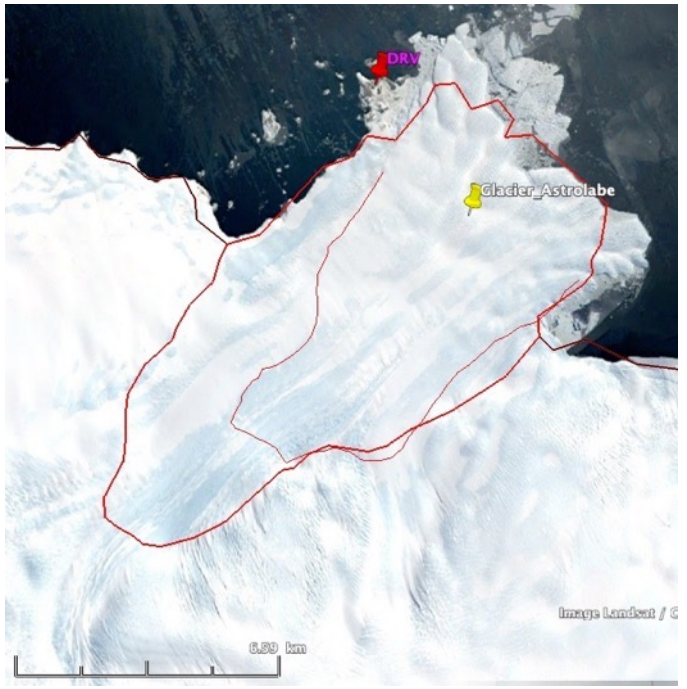
(Podolskiy & Walter, 2016).

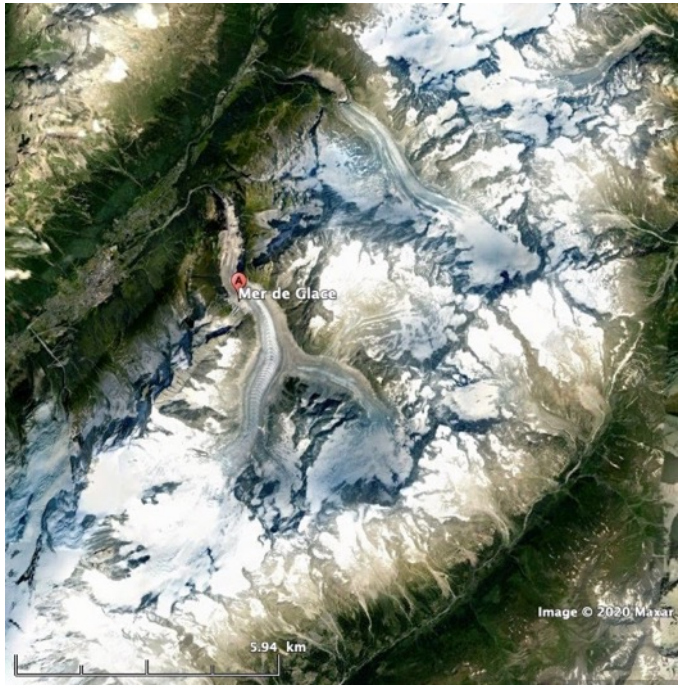
- The cryosphere is seismicaly active:
  - Icequakes
  - basal events
  - glacial tremors
  - Calving events

- There is a need for new methods to detect, classify and later locate all these seismic signals.

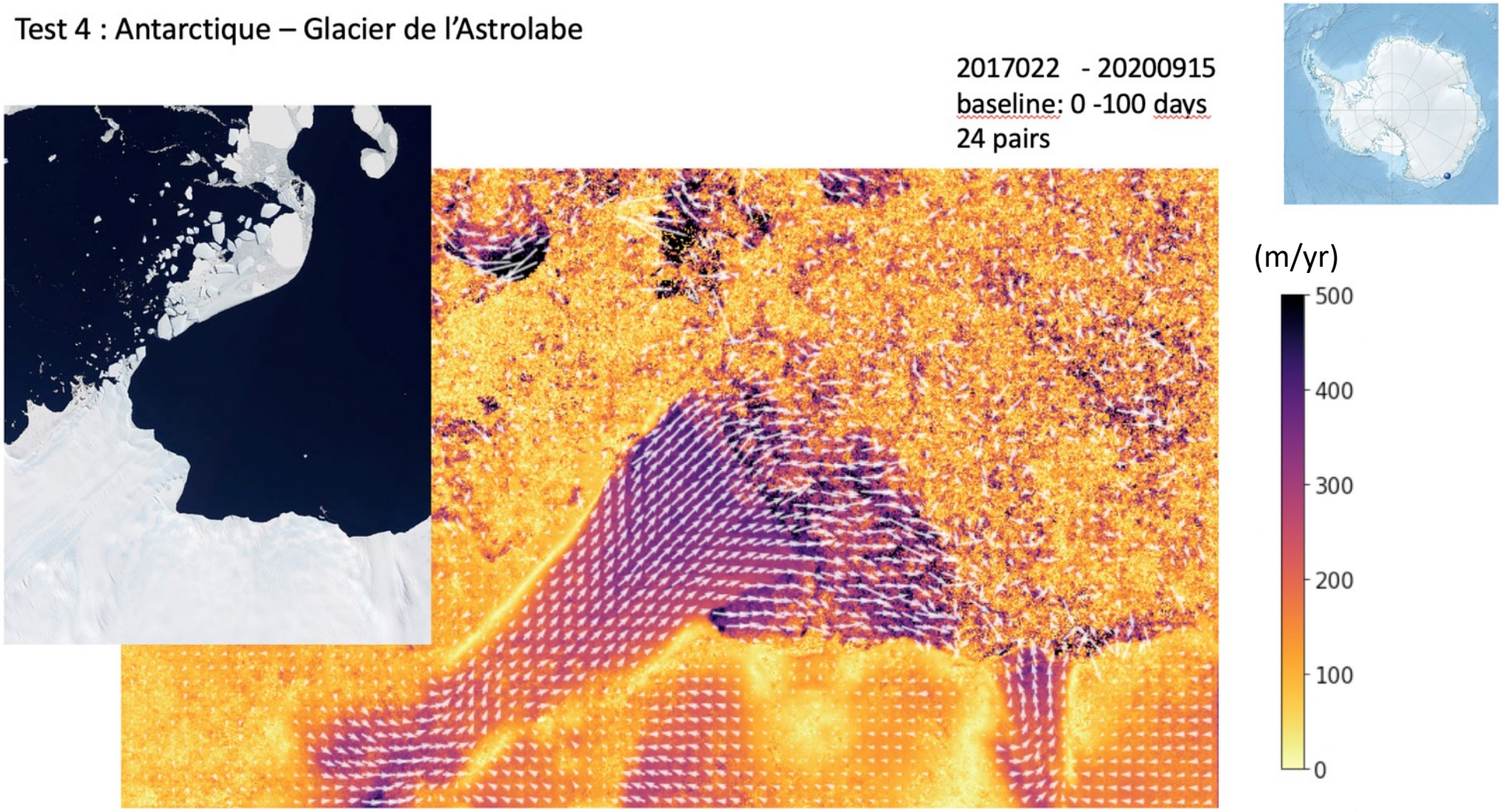
The Astrolabe Glacier





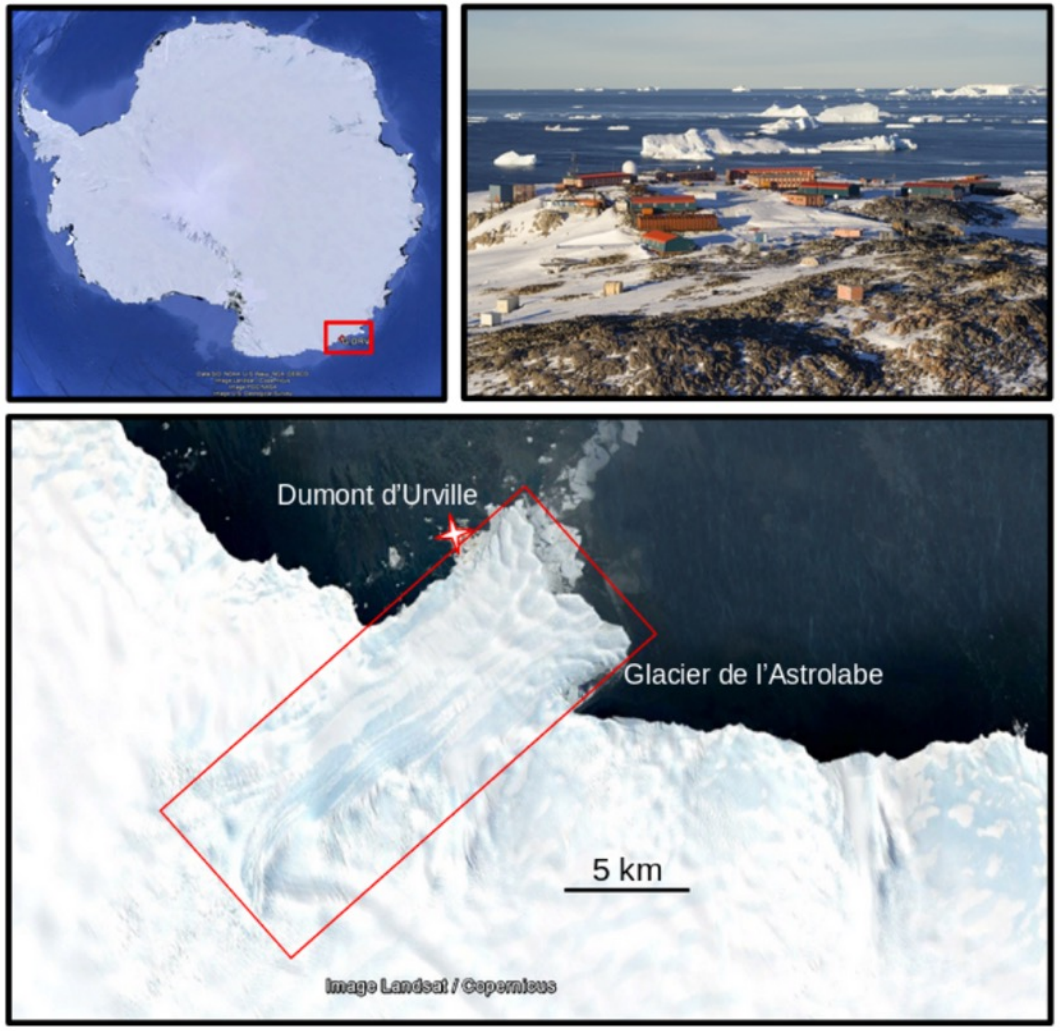


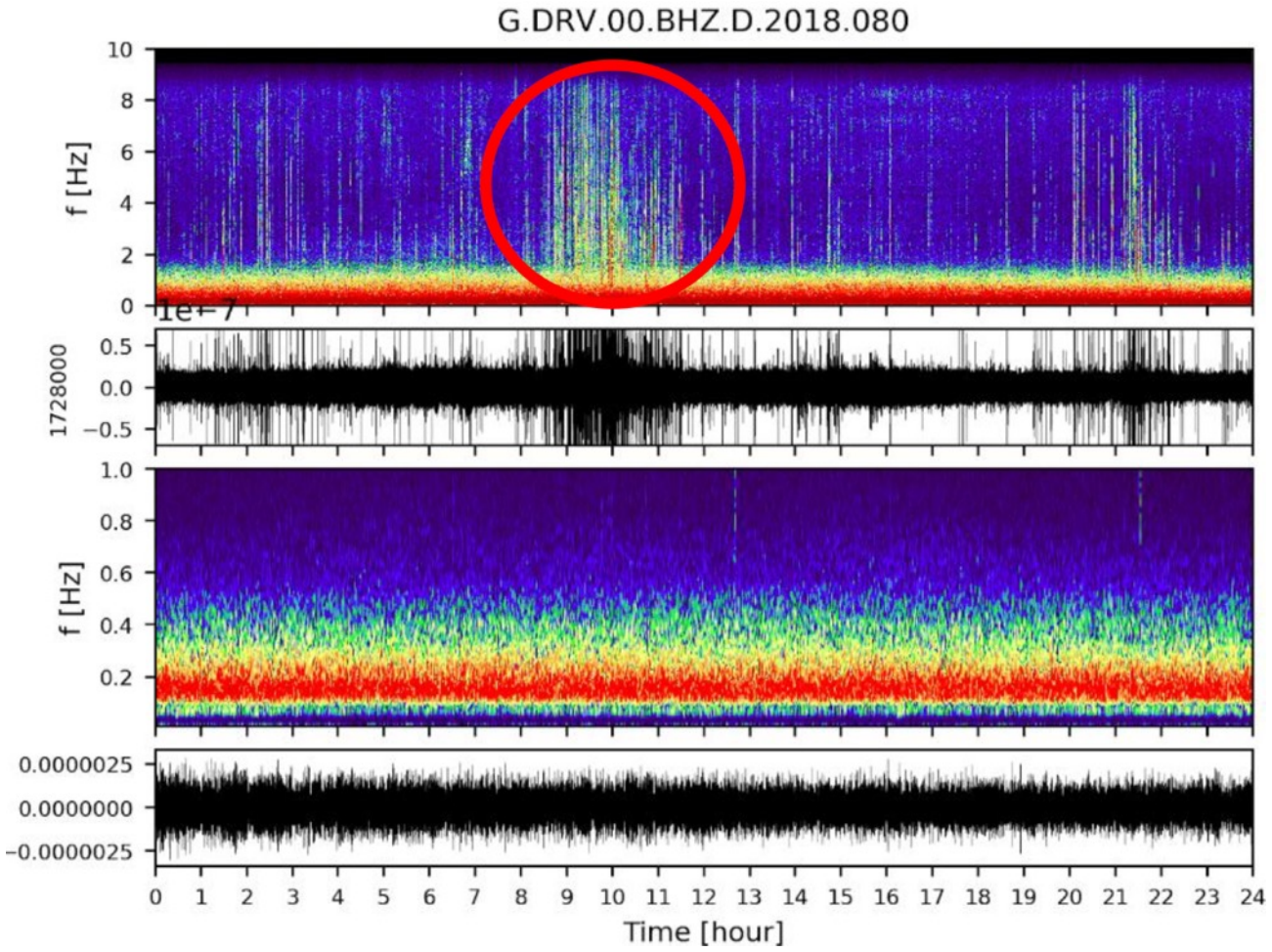
The Astrolabe Glacier



From F. Provost & J-P. Malet (pers. Communication)

Cryosismicity





- Clear burst of seismic activity between 2 and 8Hz
- Duration ~ 2-3h
- 1 to 3 times a day
- Visible of consecutives days with a time shift
- Appear all year round with seasonality

Cryosismicity

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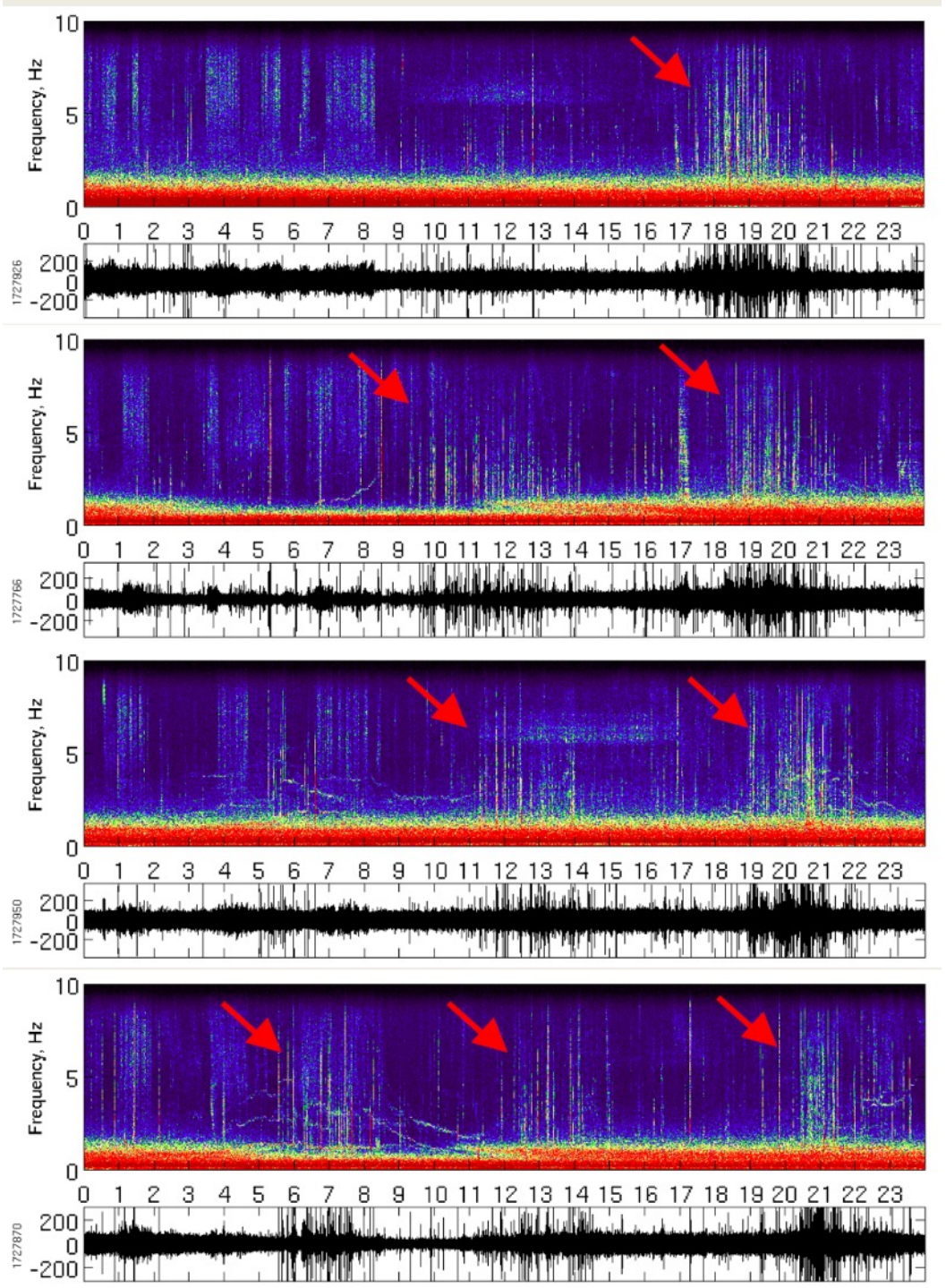


29 Jan. 2018

30 Jan. 2018

31 Jan. 2018

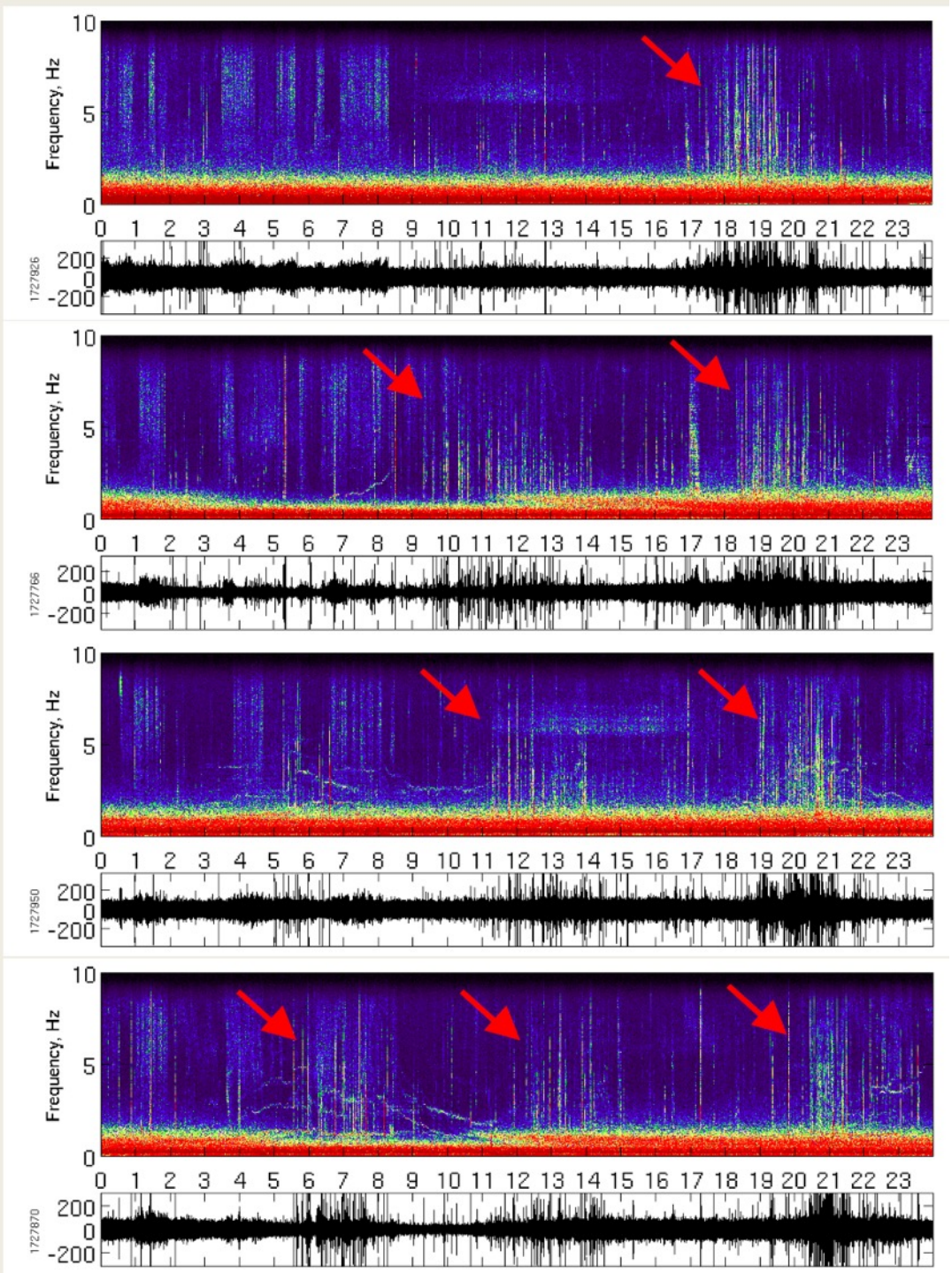
01 Feb. 2018

Cryosismicity

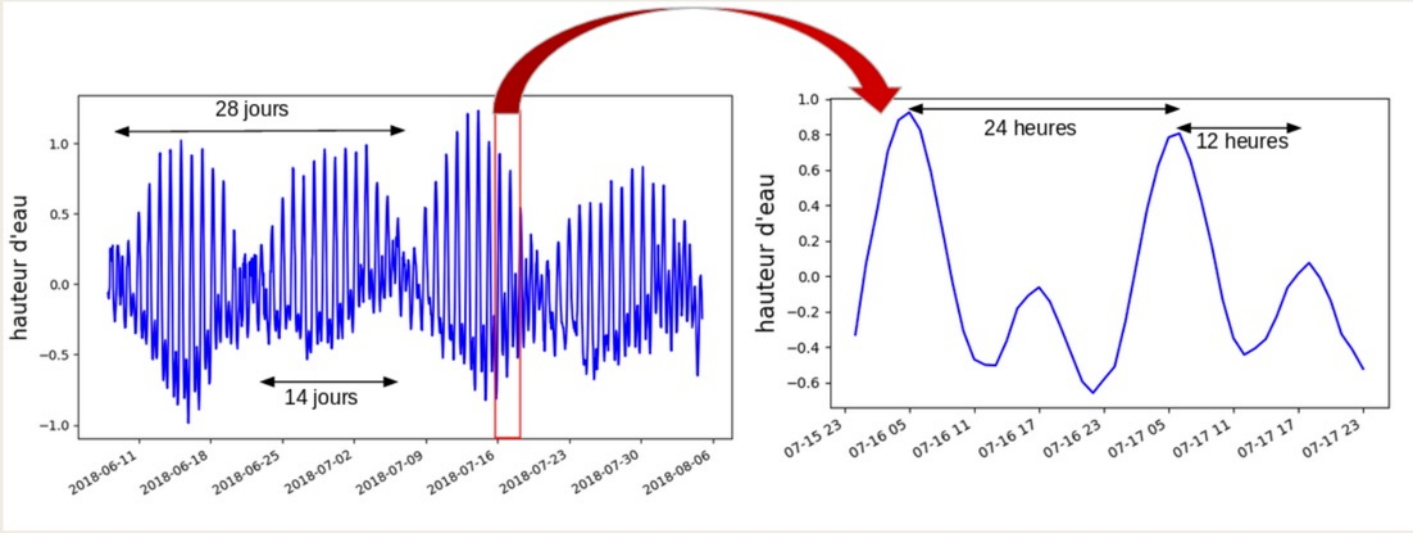
- Clear burst of seismic activity between 1 and 8Hz
- Duration ~ 2-3h
- 1 to 3 times a day
- Visible of consecutives days with a time shift
- Appear all year round

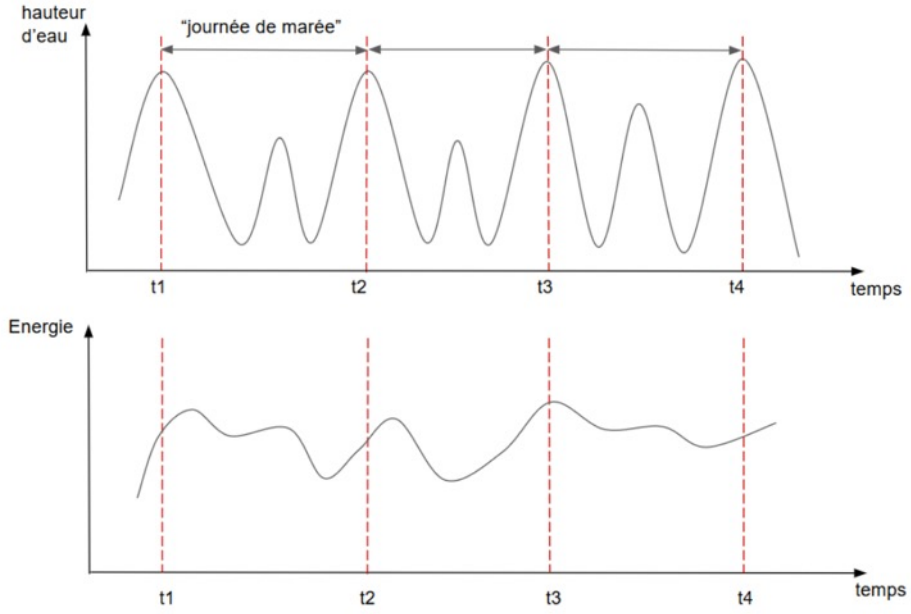
Tidal modulation of cryoseismic activity

=> Computed the seismic energies between 2 and 4Hz during 2018 to build time series that can be compared to tidal forcing



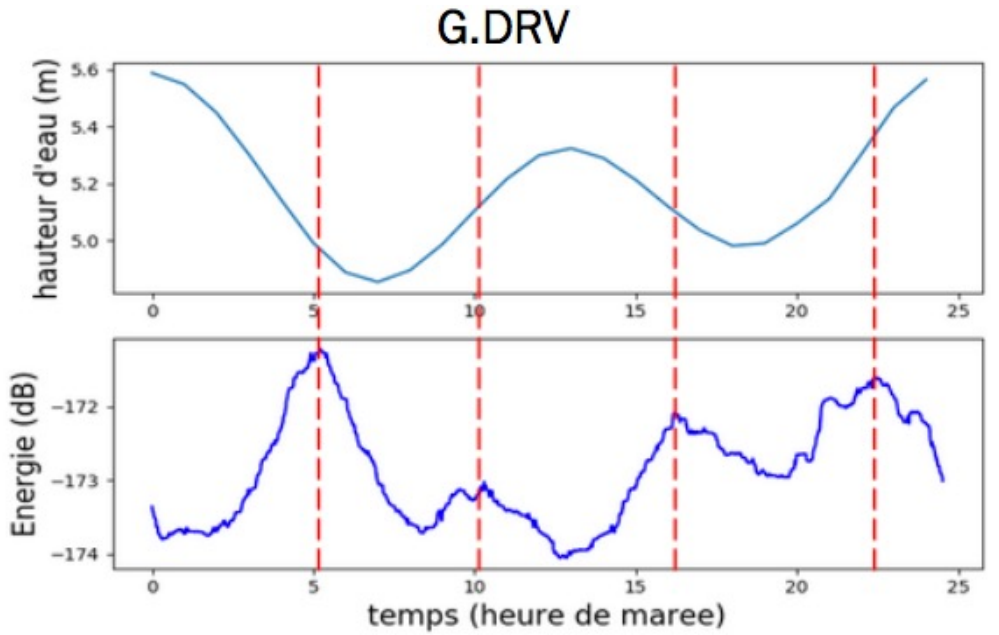
Tidal Modulation

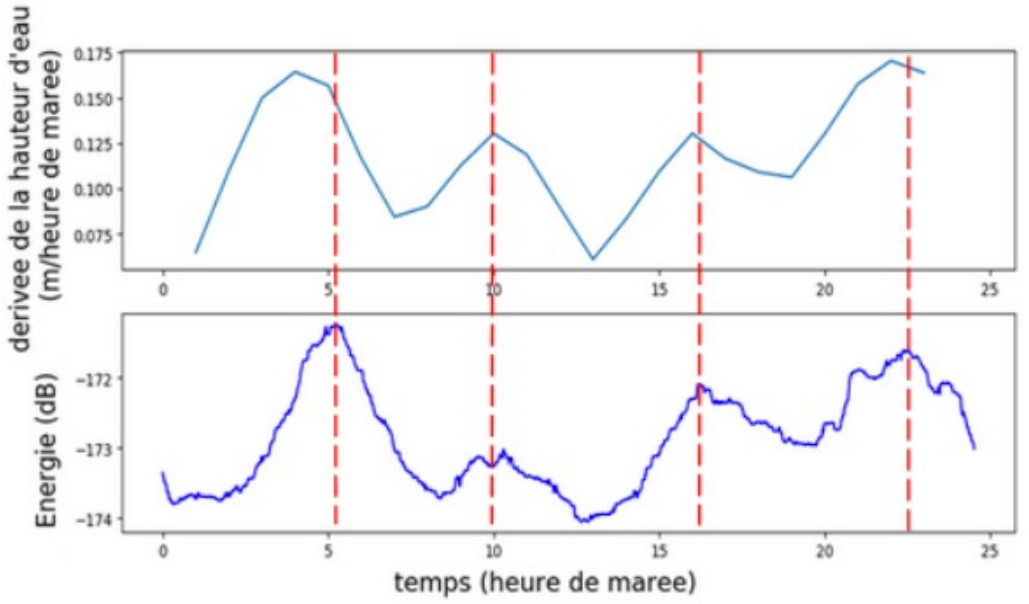




Découpage des signaux de hauteur d'eau et d'énergie sismique en « journées de marée »

Moyenne des « journées de marée » sur un an

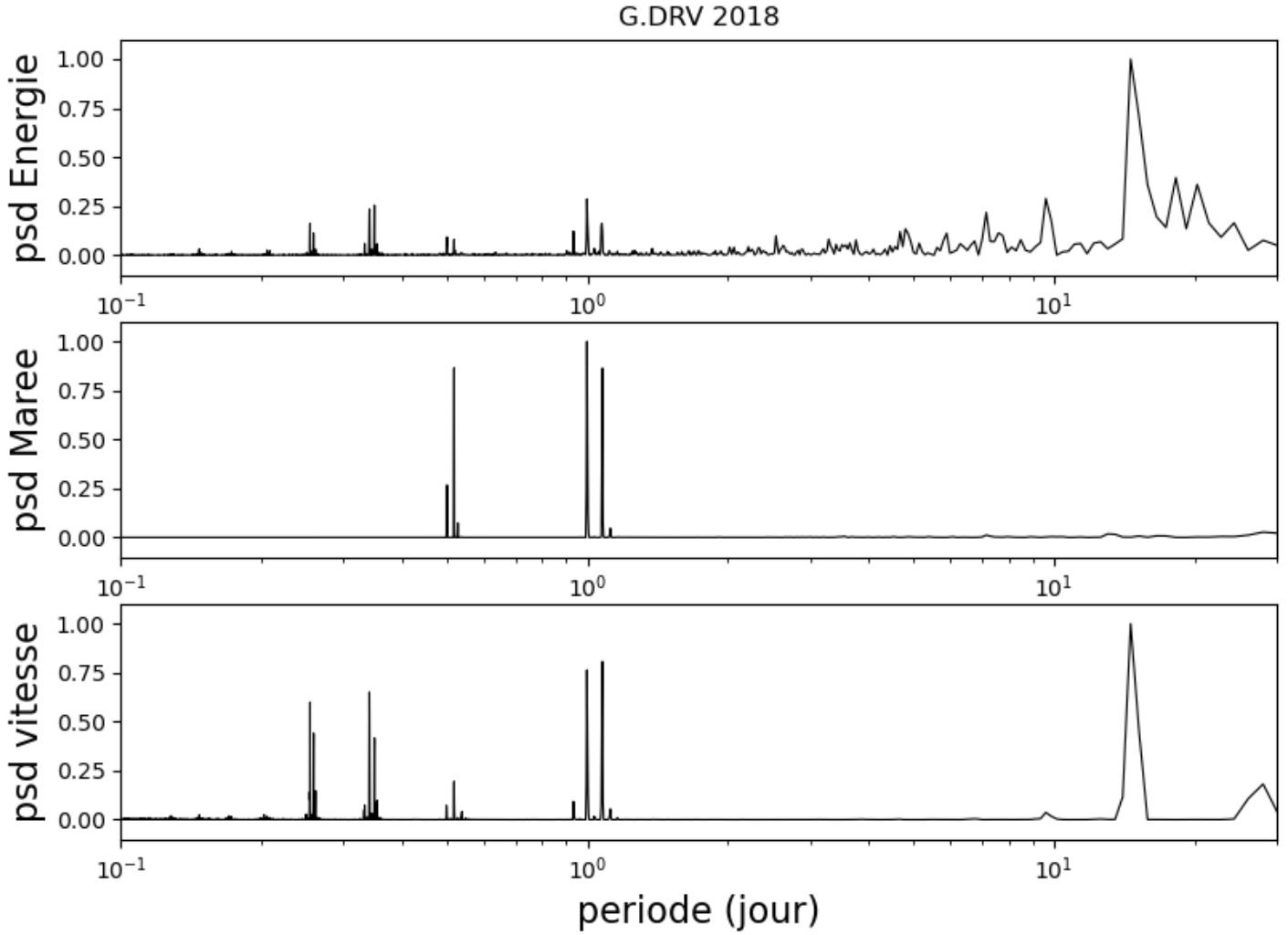


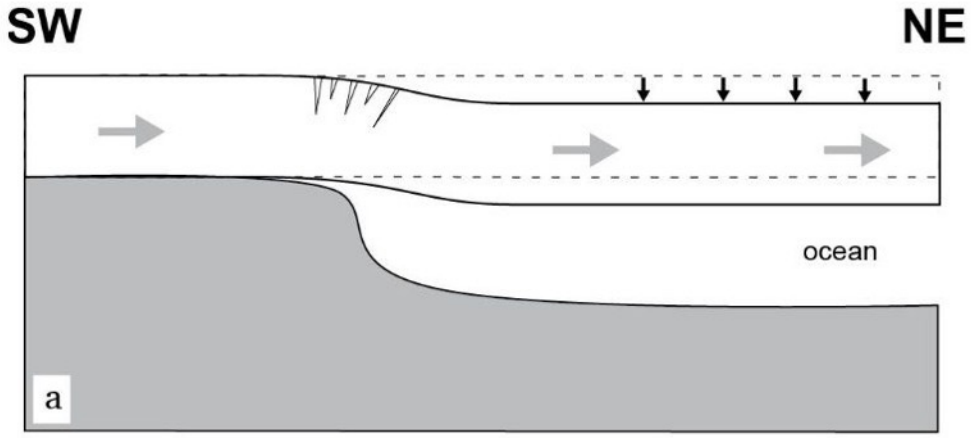


Stage M2 C. Groult

Tidal Modulation

- Clear modulation of the of cryoseismic activity by the tidal forcing with all the harmonics of the forcing recorded in the icequake activity for year 2018.

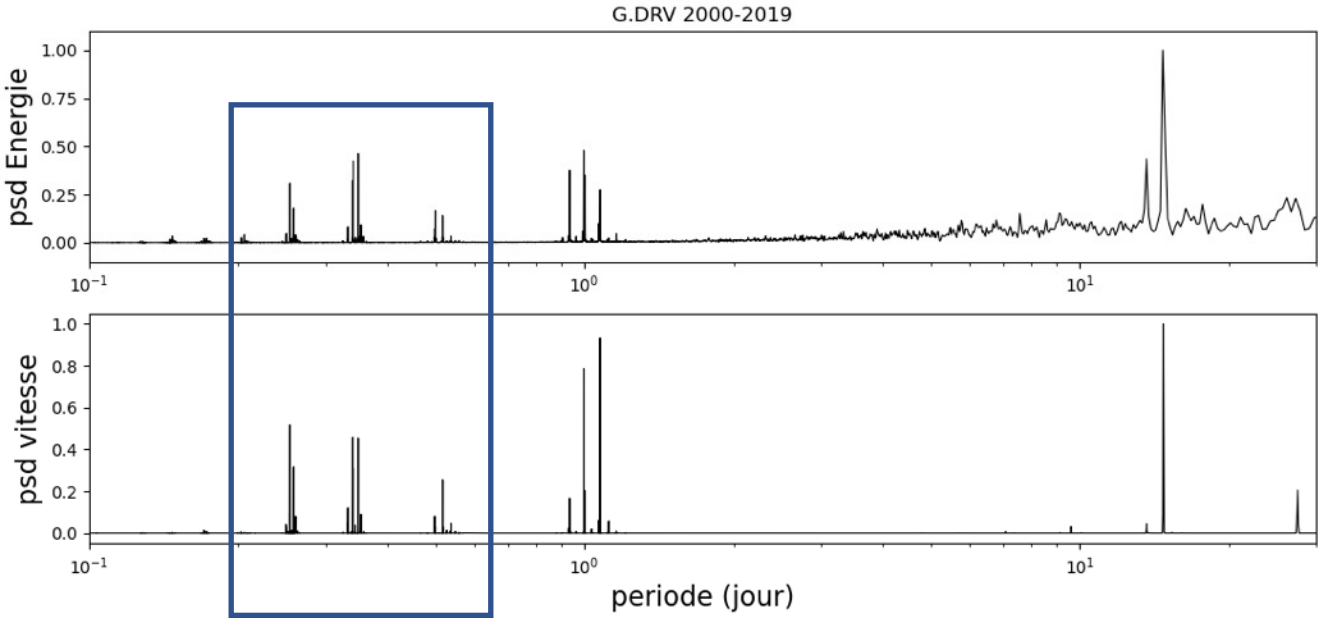


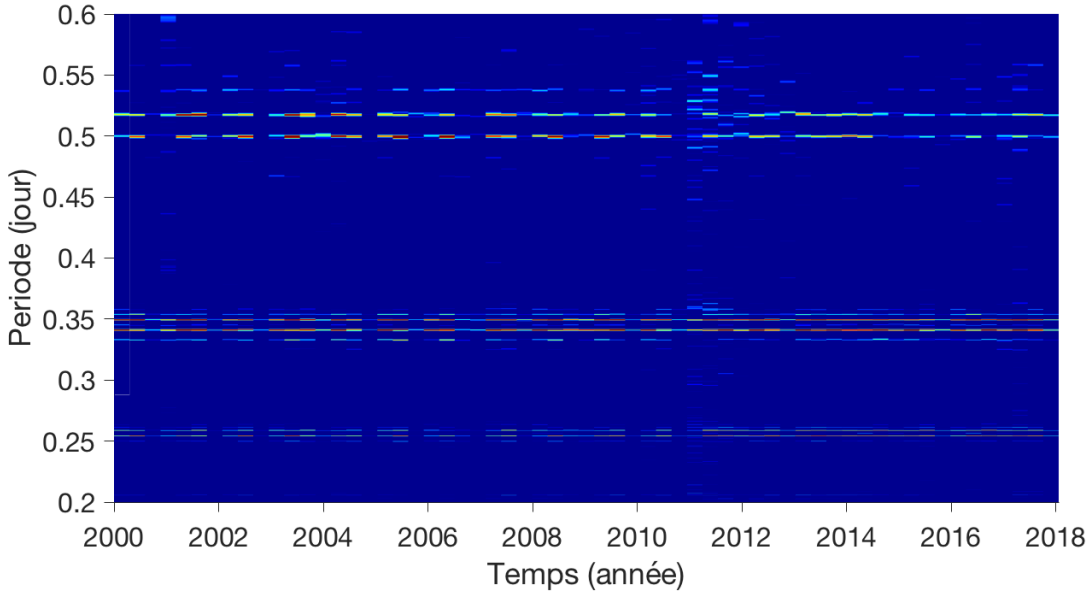


G. Barruol, communication personnelle

Strain accommodation at the grounding line?

Tidal Modulation time evolution





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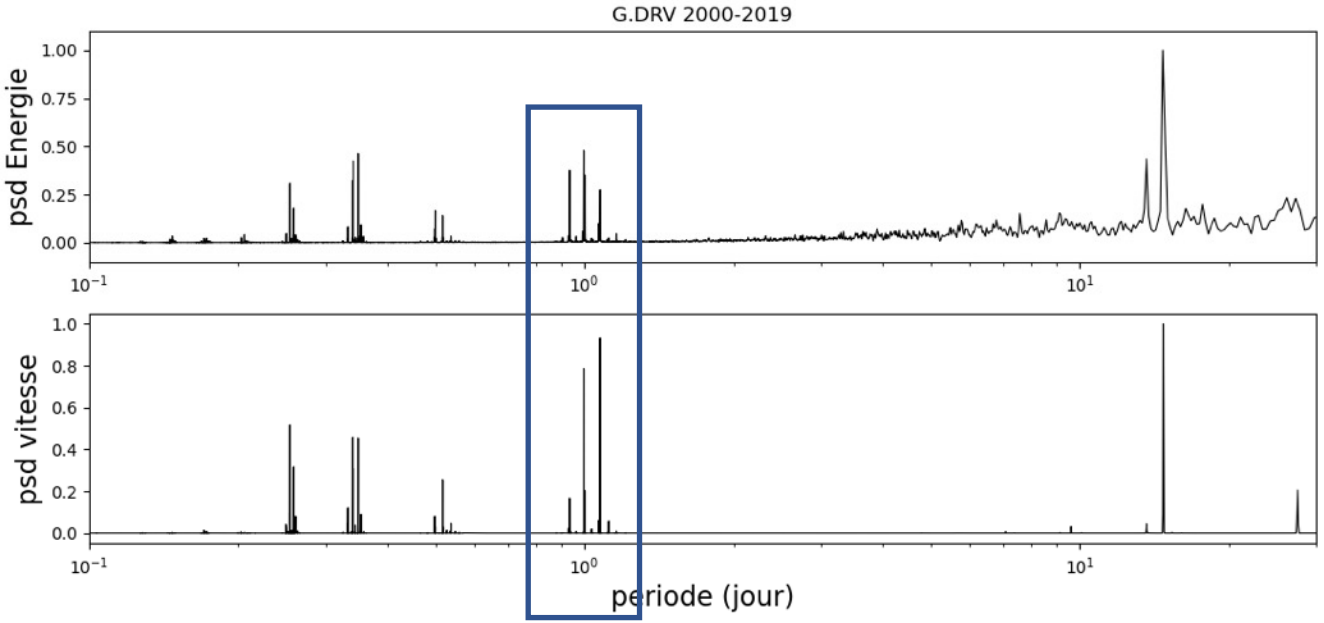

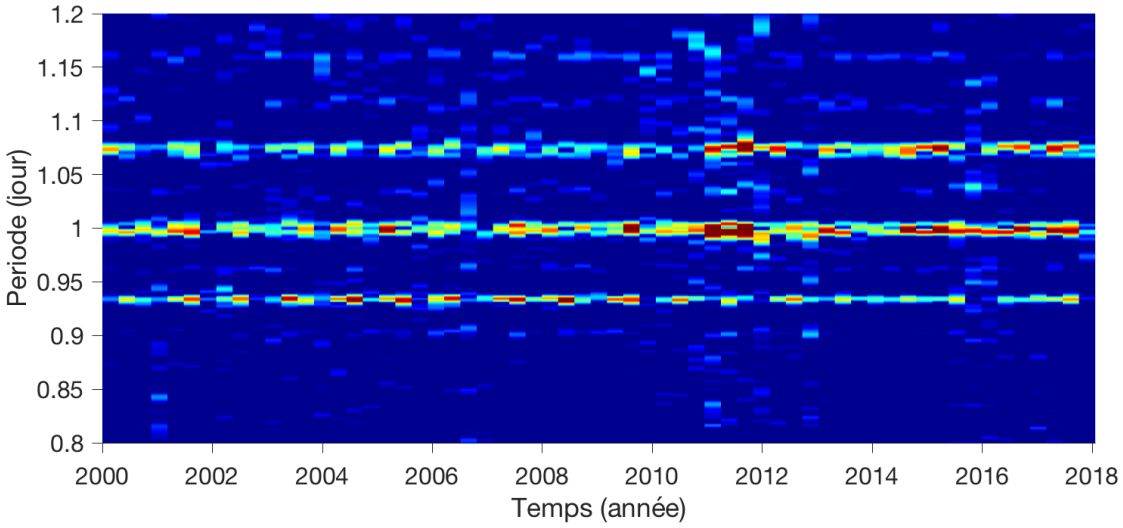

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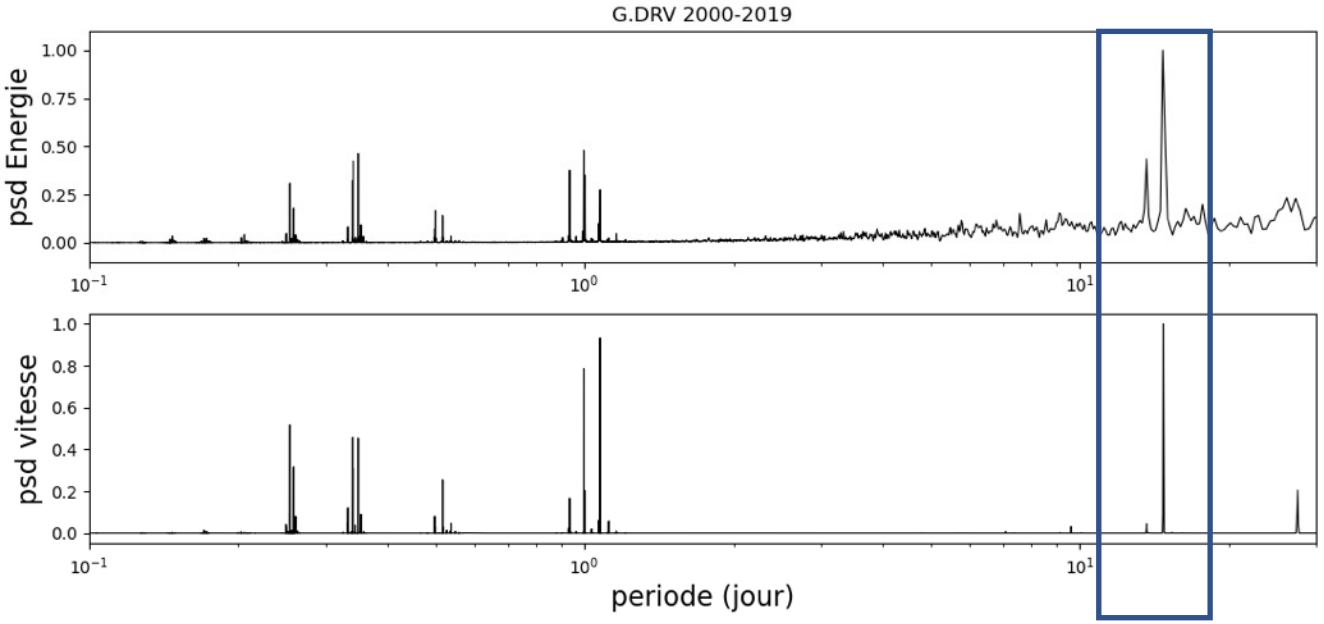
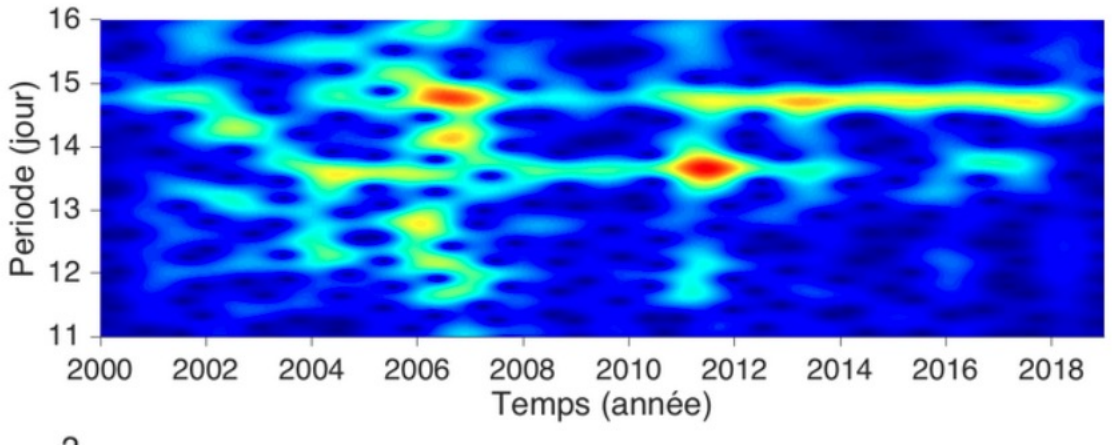
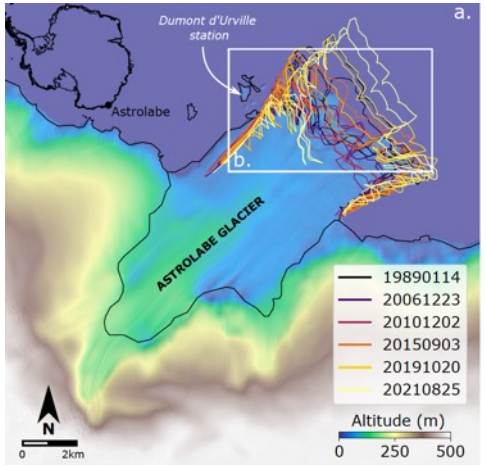


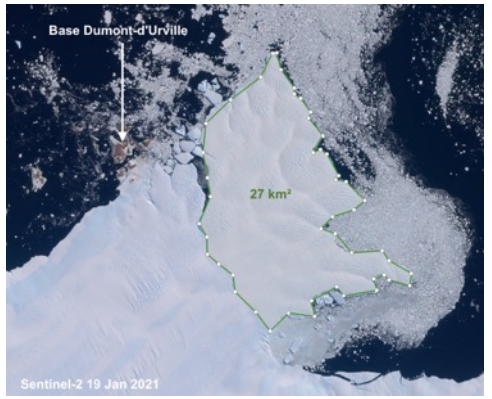


- 2 pics for the fortnightly forcing with clear time evolution

Scientific Questions:

- Which process explains those time evolution?
- Non linearity?
- Ice Rheology => role of visco-elasticity?
- Role of the geometry of the shelf?





Stage M2 C. Groult

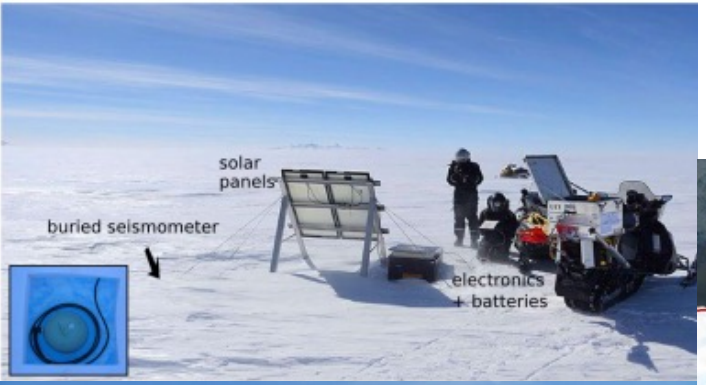
Summary and Future Plans

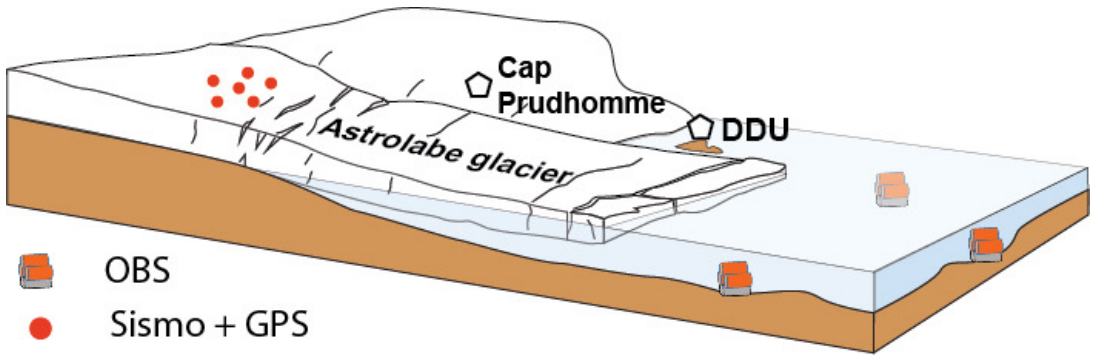
- Clear seismic cryogenic signal modulated by tidal forcing
  $\Rightarrow$ mode I fractures opening and closing during tidal charge and discharge?

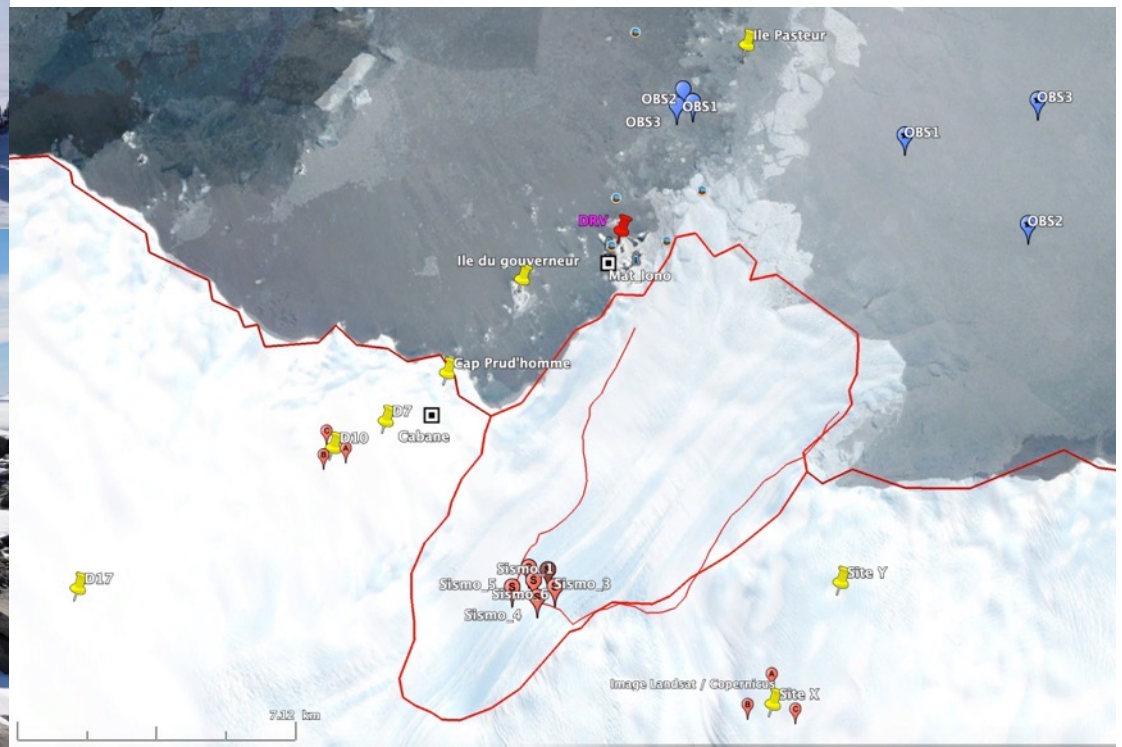
- All the harmonics of the tidal forcing visible in the seismic energy with clear time evolution for the fortnightly forcing
  $\Rightarrow$ Role of the large calving events?
  $\Rightarrow$ Role of visco-elastic Rheology?

- Now we need to better detect and classify all those signals with a better network and ML methods

Future Plans: SEIS-ADELICE & ANR CRYOS-TA
Astrolabe glacier







Projects SEIS-ADELICE & ANR CRYOS-TA

Cryoseismology on the Astrolabe glacier

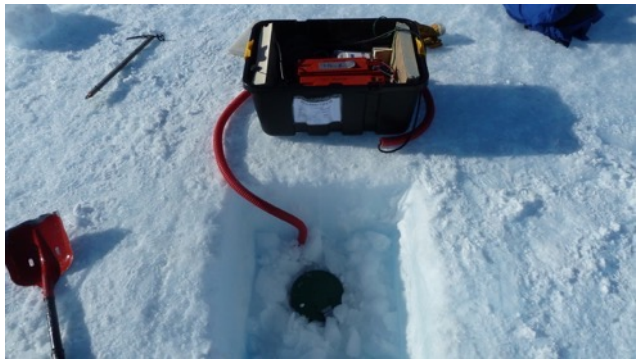
Objectives:
Brittle/ductile transition
Basal gliding
Subglacial hydrology
Ocean/ice interaction
Rifting and calving processes

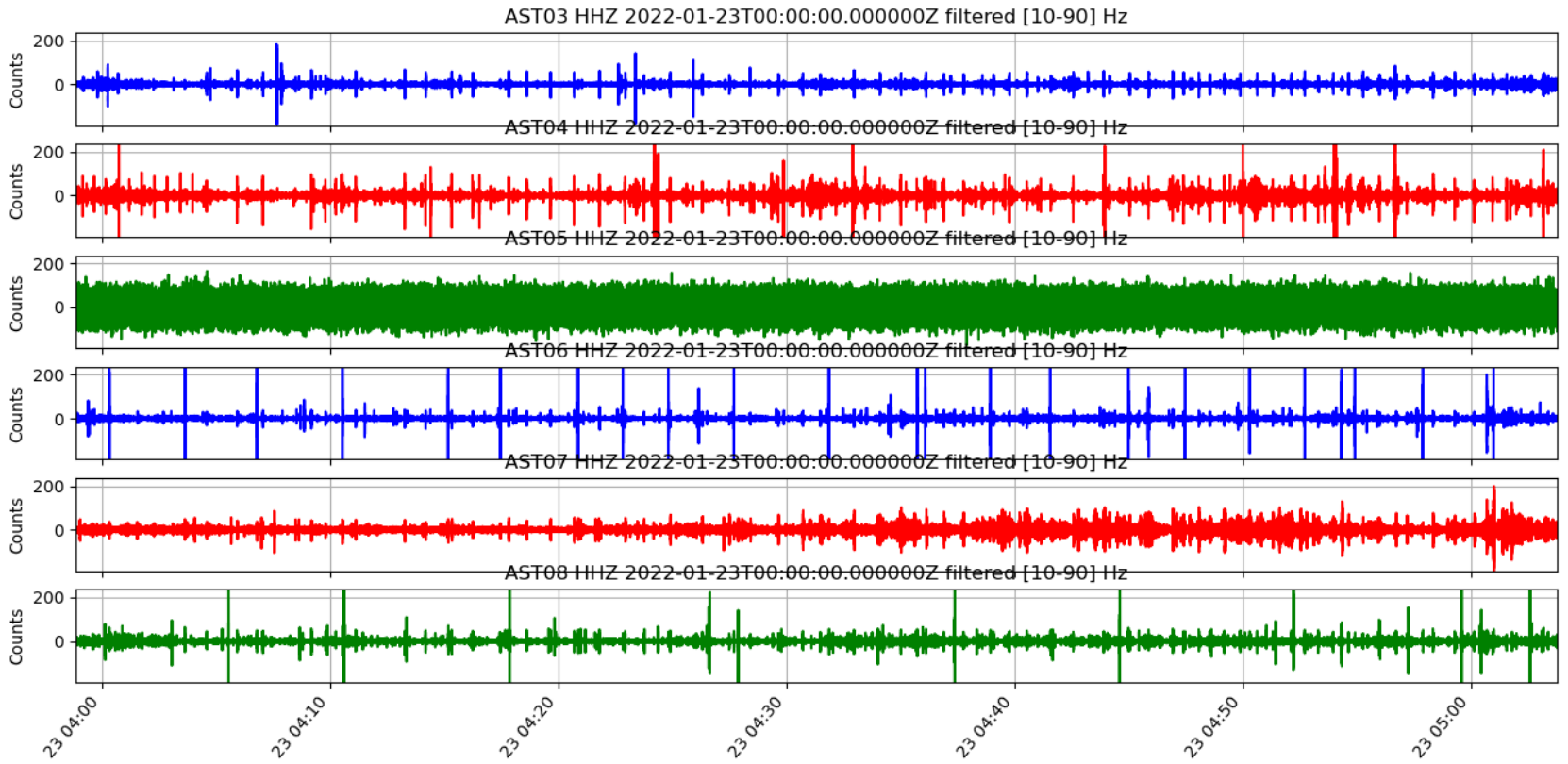
Deployment of land and ocean bottom seismometers (OBS)

Associated with GPS from DACOTA project (E. Le Meur)

SEIS-ADELICE, 2022
Icequakes & Repetitive events

- **Icequakes** - Crevassing?
- **Repetitive events** - Stick slip?
- **Tremors** - Sub glacial hydrology



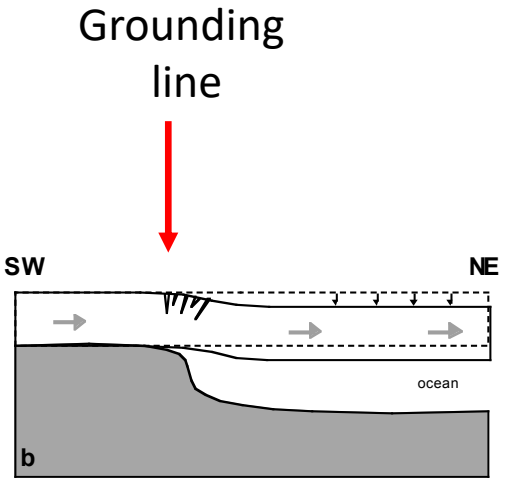


6 BB stations on the glacier, 1h of seismic record

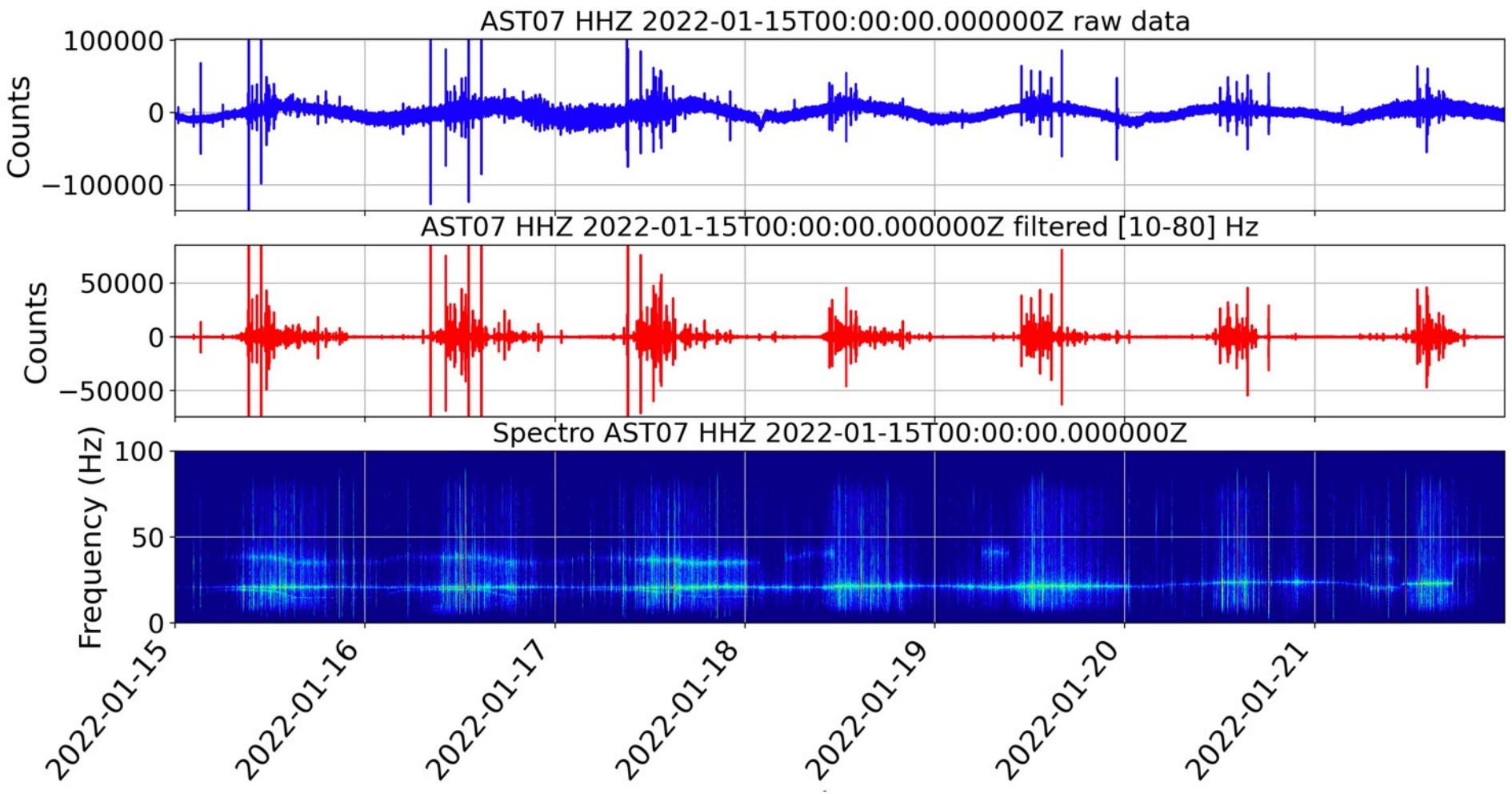
G. Barruol (Comm. Pers.)

SEIS-ADELICE
Tide-induced icequakes

- Tides induced icequakes
- Tide-modulated tremors

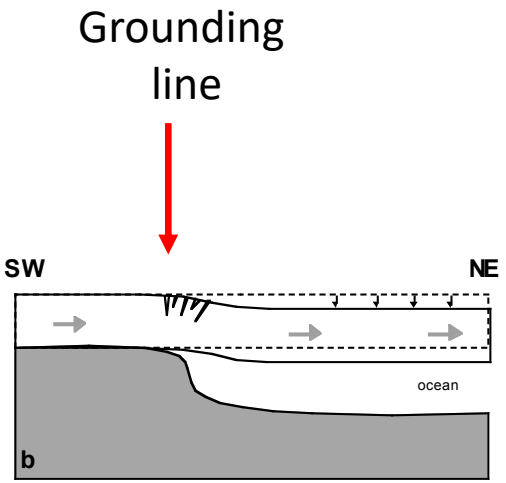


Station AST07, 1 week of seismic record

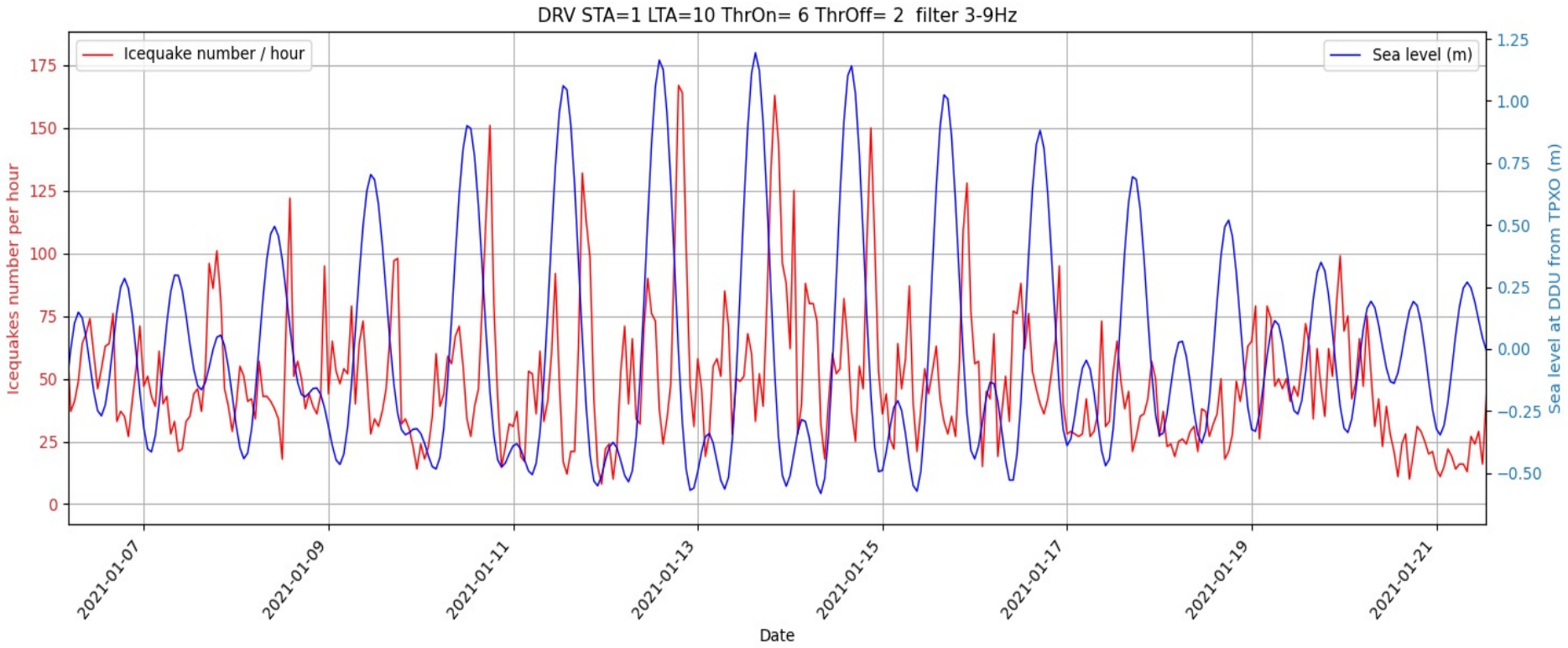


G. Barruol (Comm. Pers.)

DRV, Tide-induced icequakes



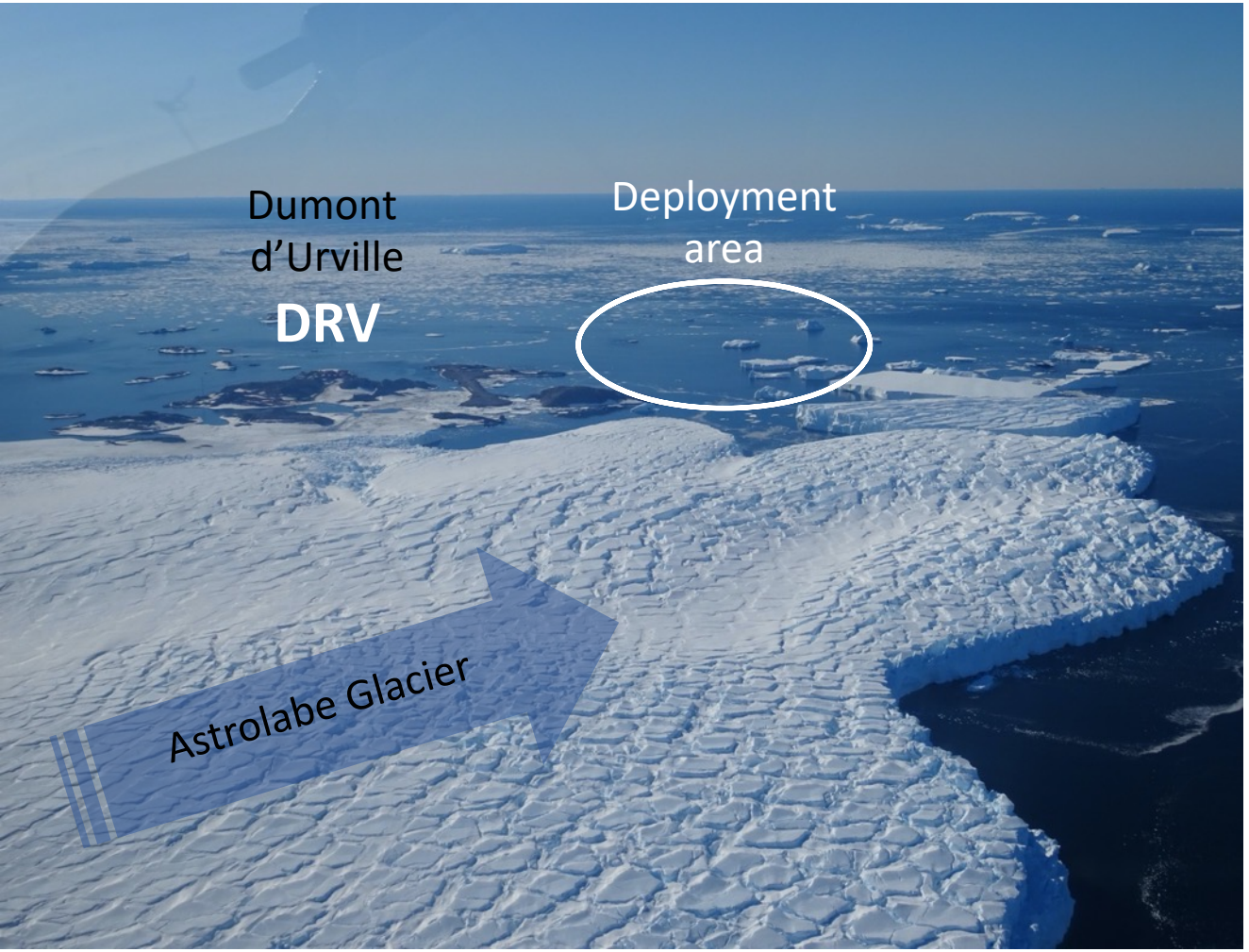
Icequakes detections and tide modulation, DRV, 2 weeks, Jan 6-21, 2021



G. Barruol (Comm. Pers.)

M2 E. Rouzaud, IPGP 2021

OBS deployments at the terminus of Astrolabe Glacier



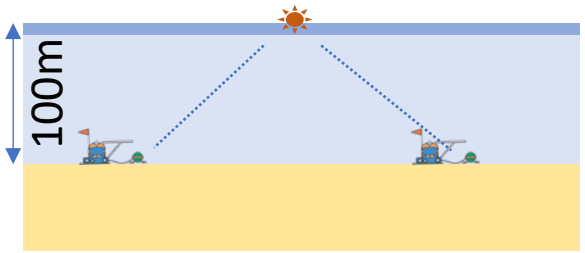
- 4 instruments for 2 to 3 weeks

- 2 instruments redeployed for 1 year

IPGP - Guralp
3 comp. Wide-band

INSU Short Period
3 geophones

Active seismics above the OBSs !



INSTITUT POLAIRE FRANÇAIS

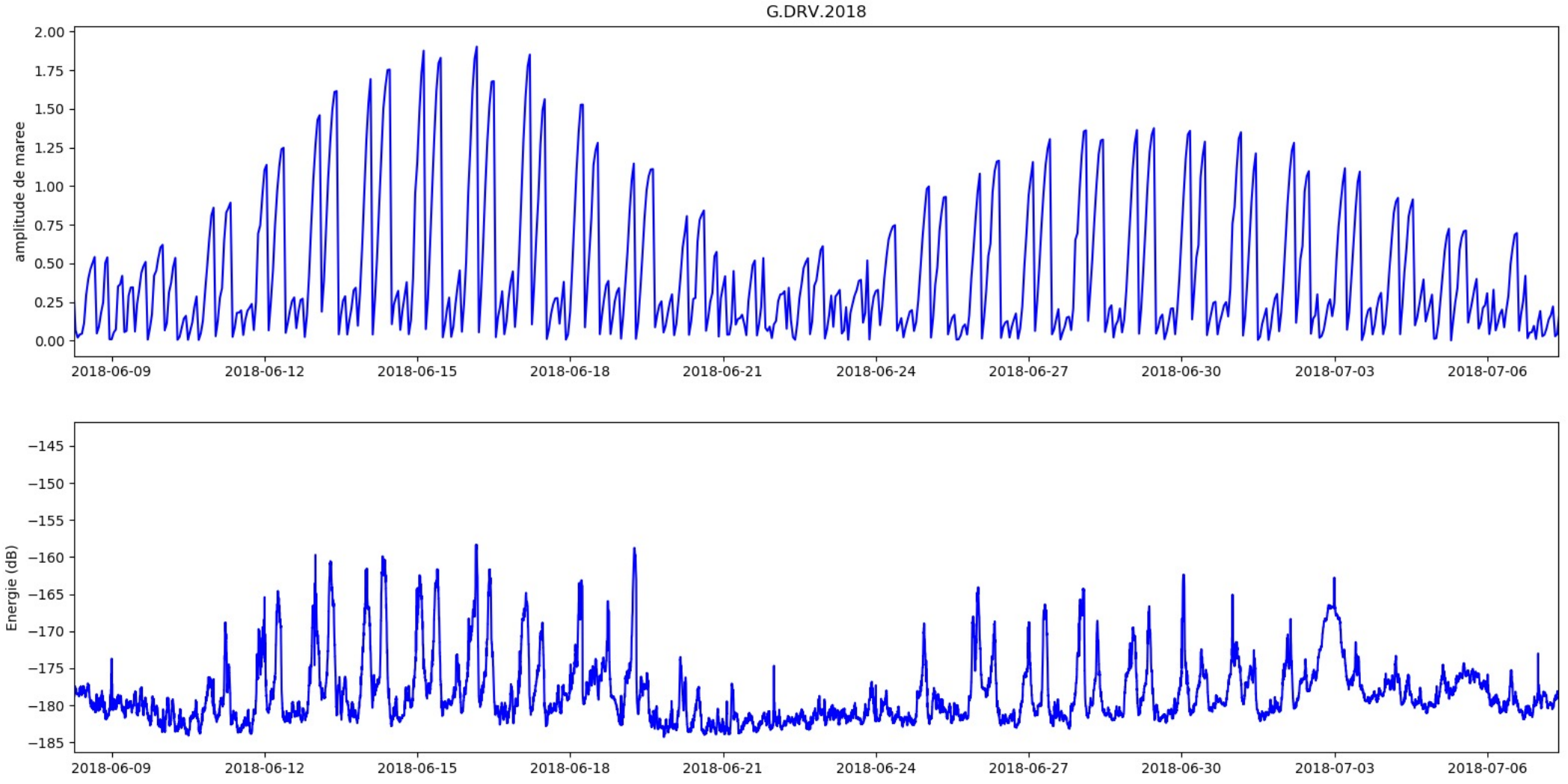
G. Barruol (Comm. Pers.)

Institut Terre & Environnement de Strasbourg | ITES | UMR 7063 de l'Université de Strasbourg & cnrs & ENGEES

INSTITUT POLAIRE FRANÇAIS PAUL-ÉMILE VICTOR

Merci

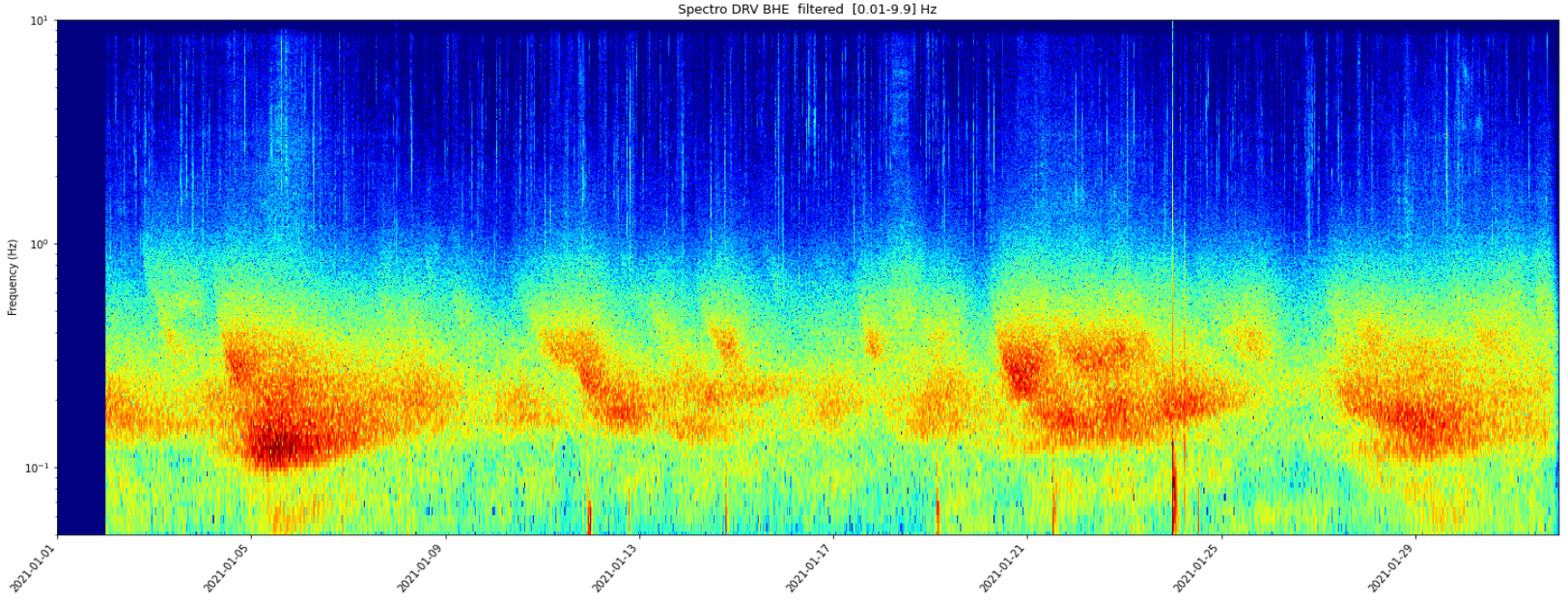
3.2 Tidal Modulation



Stage M2 C. Groult

3. Cryosismicity

DRV East seismogram



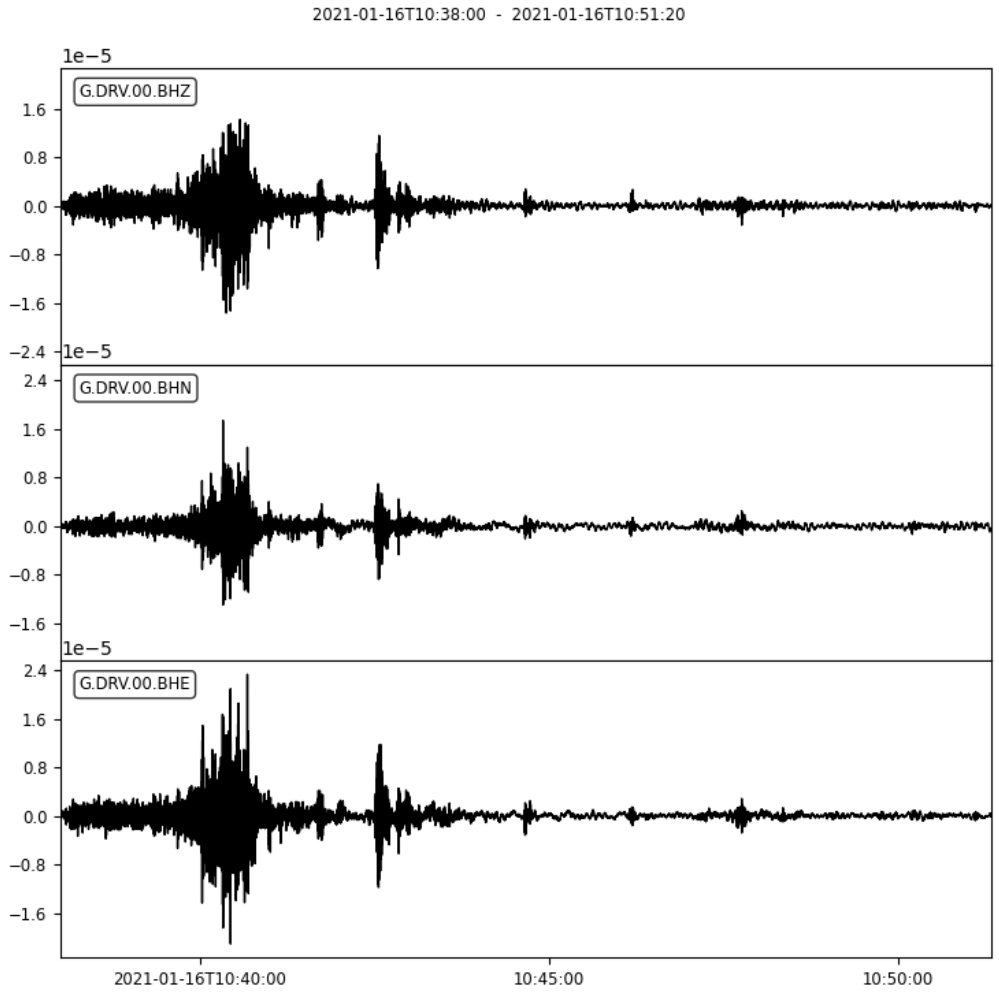
Icequakes, 1-10Hz

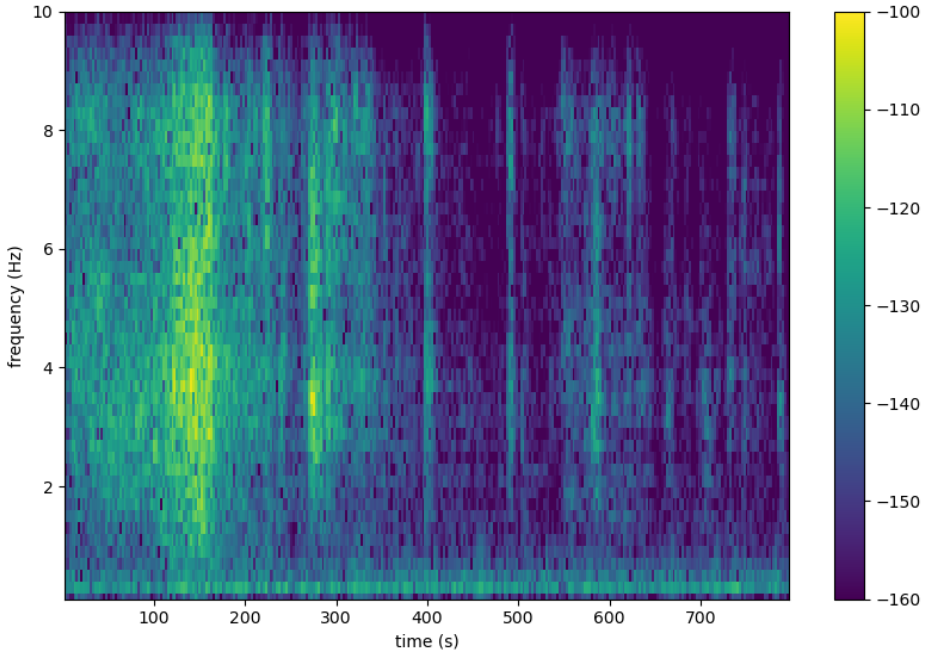
Secondary microseisms, 1-10s

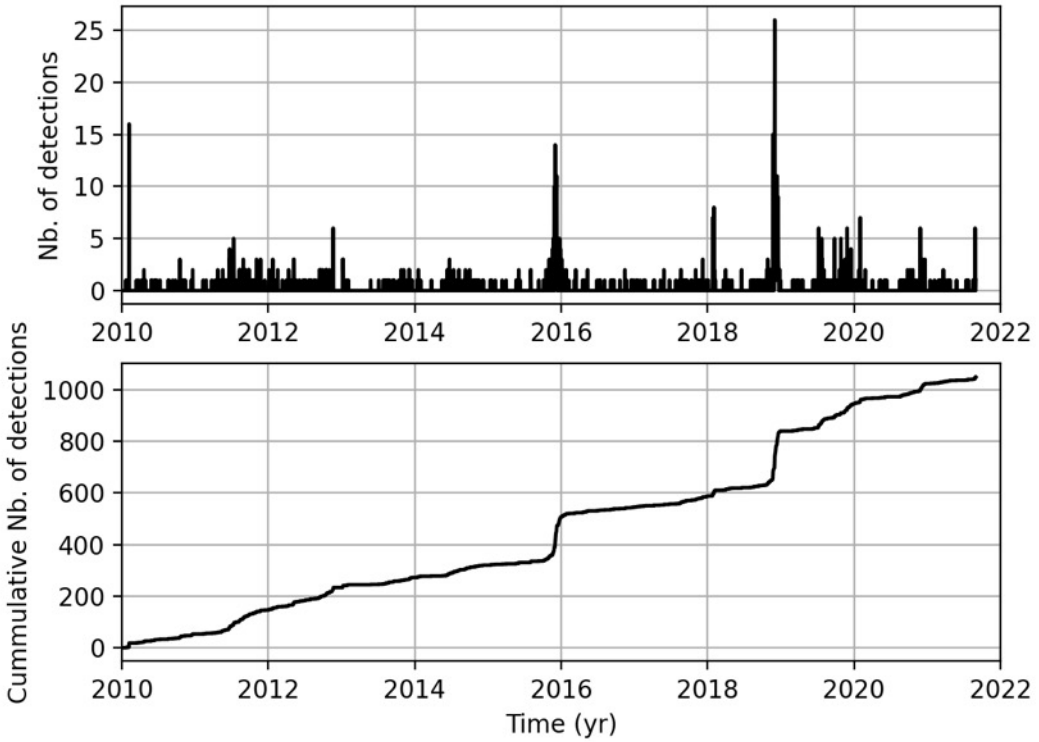
Primary microseisms, 10-20s

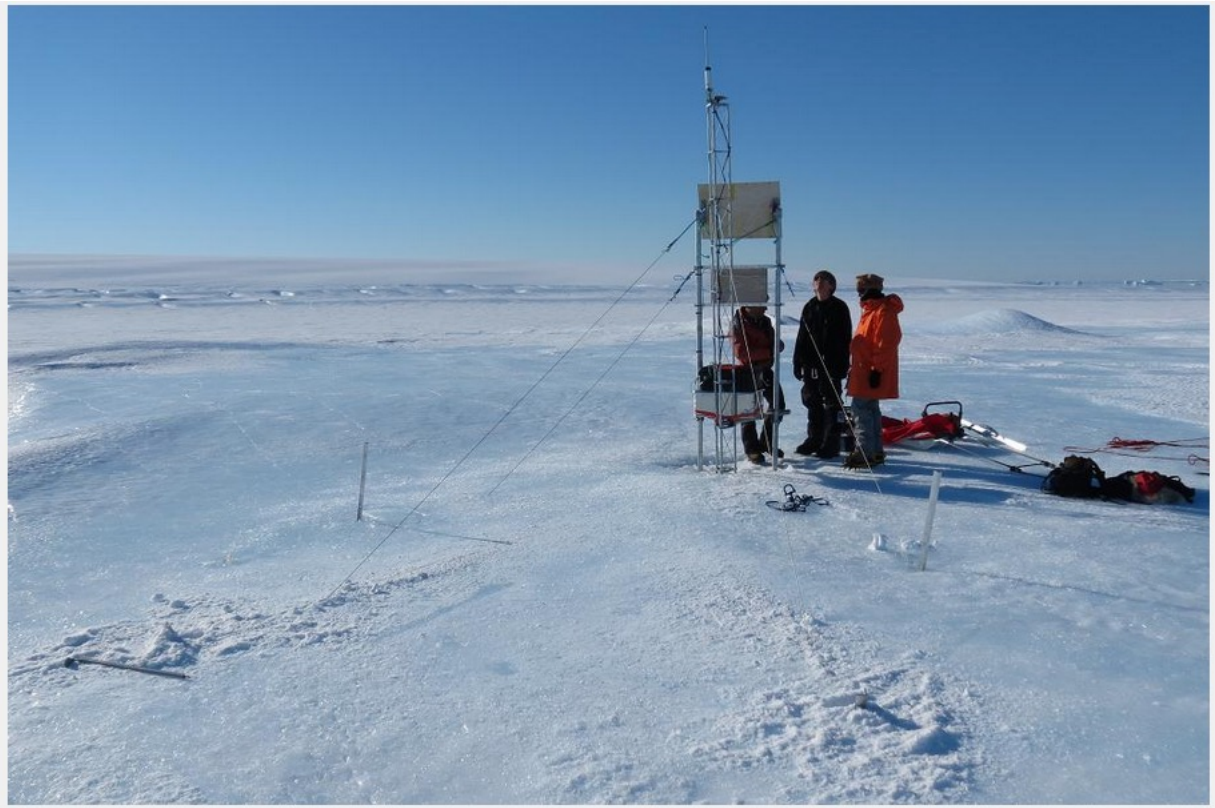
G. Barruol, communication personnelle

3. First results

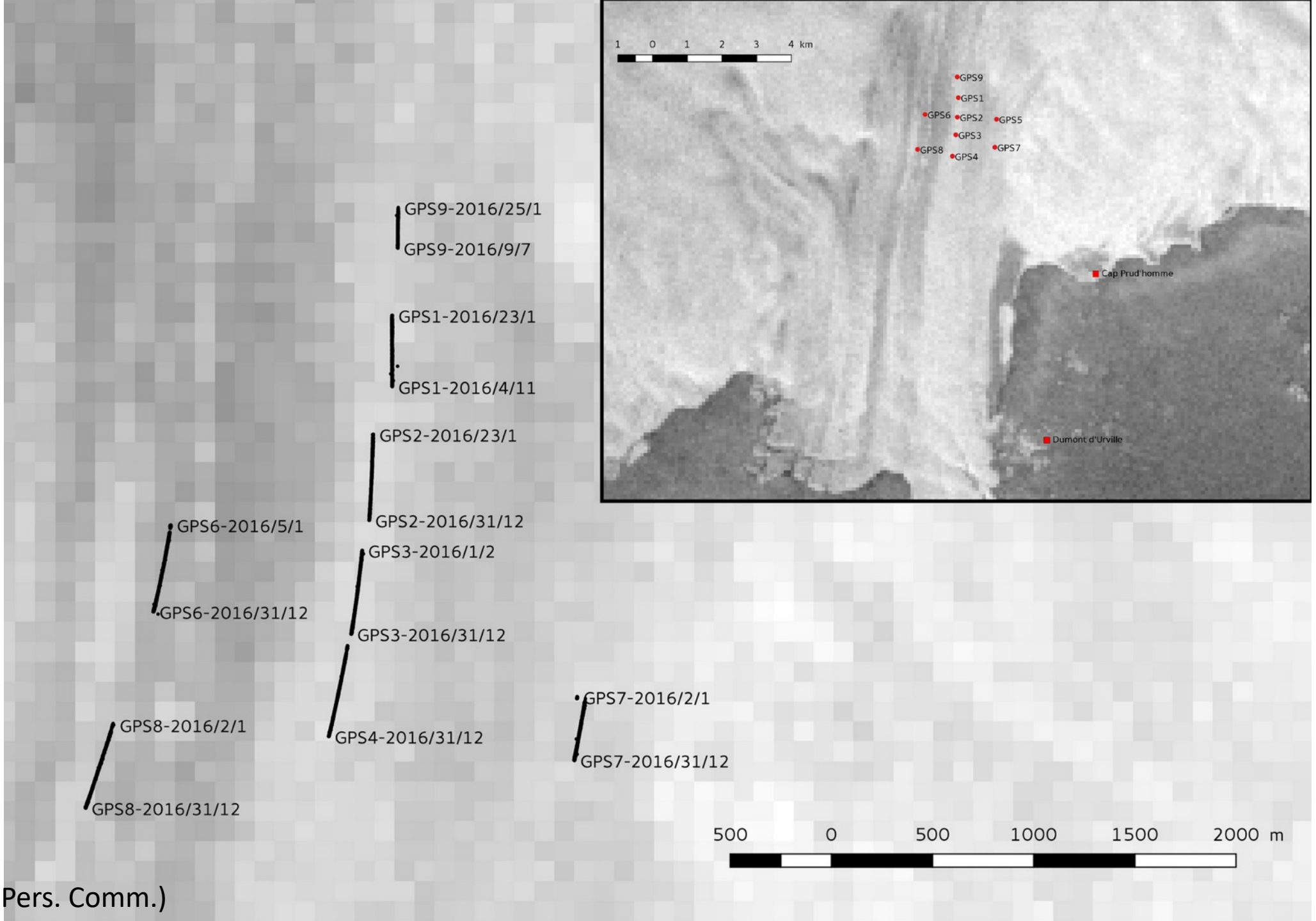




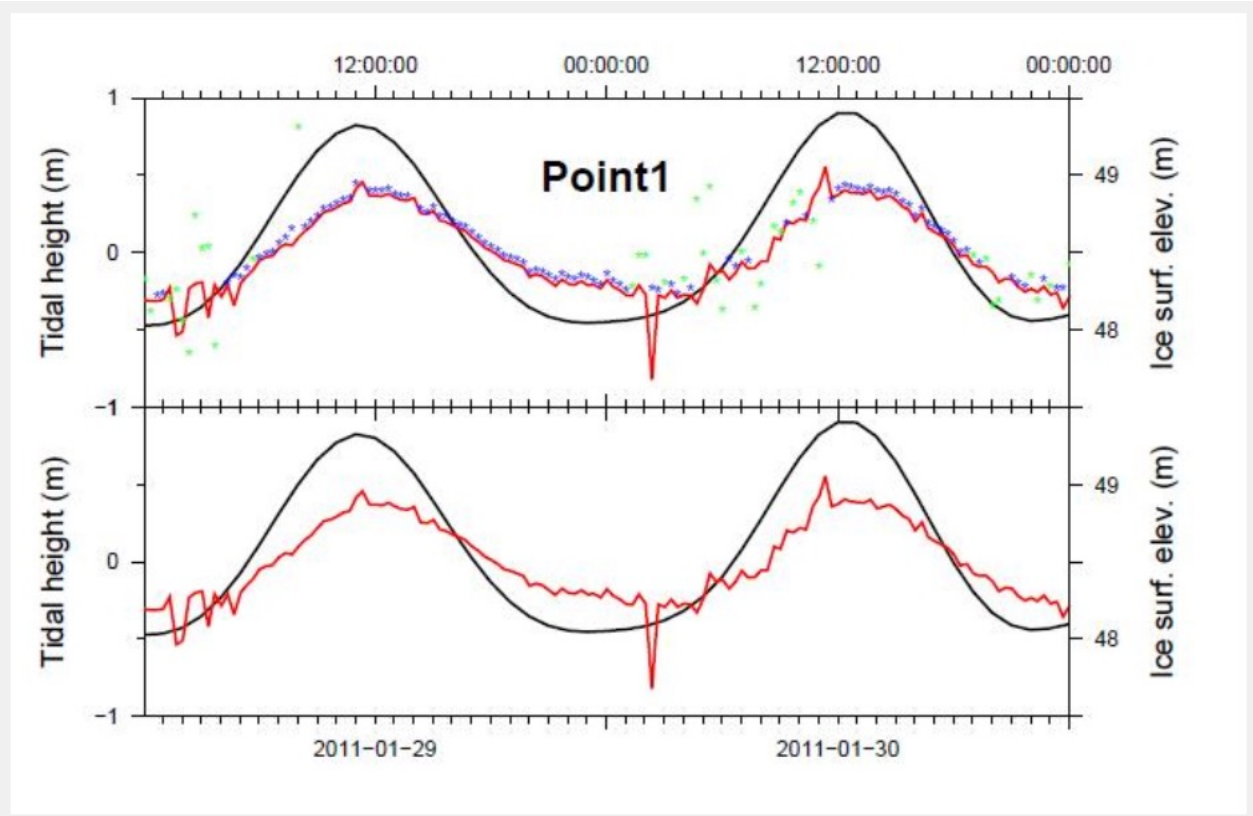




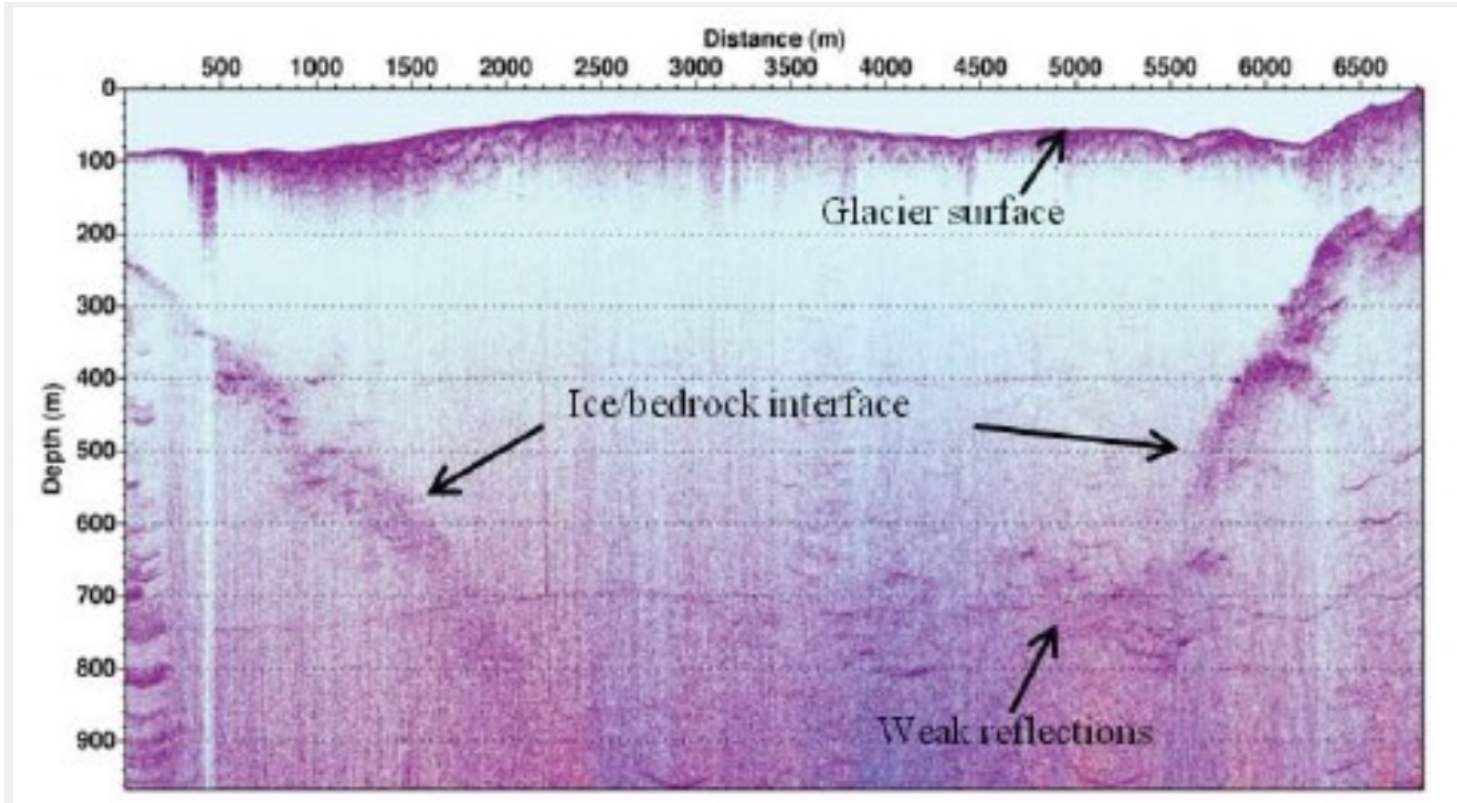
E. Le Meur (Pers. Comm.)



E. Le Meur (Pers. Comm.)

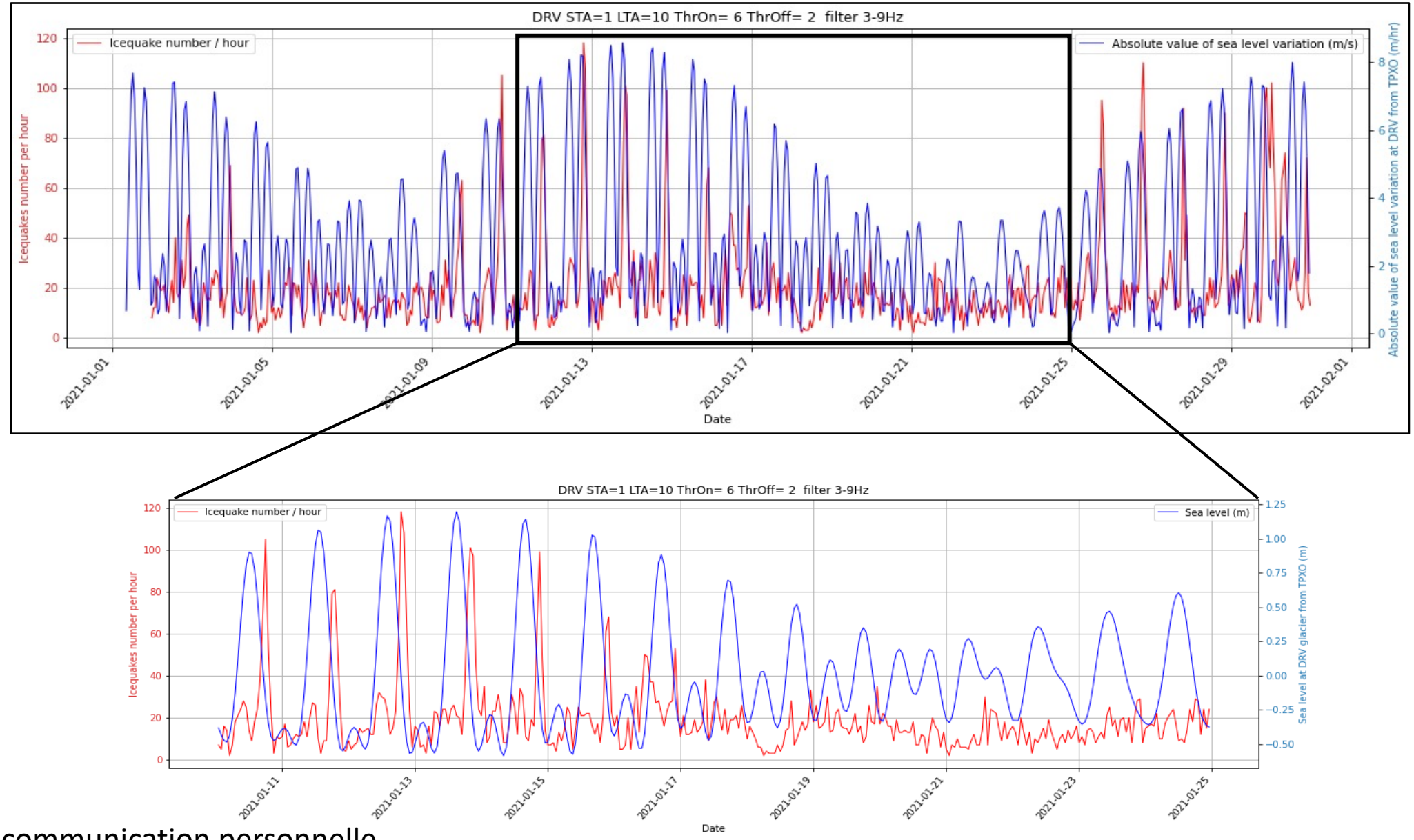


Le Meur et al. (2014)



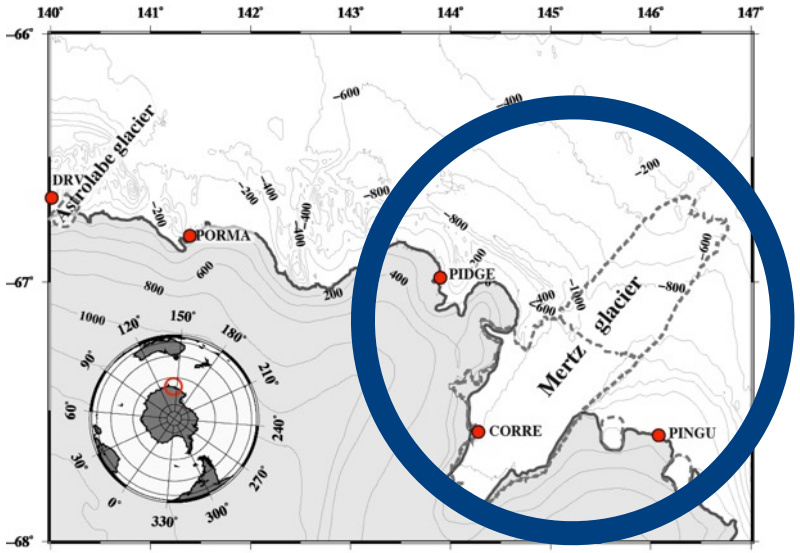
Le Meur et al. (2014)

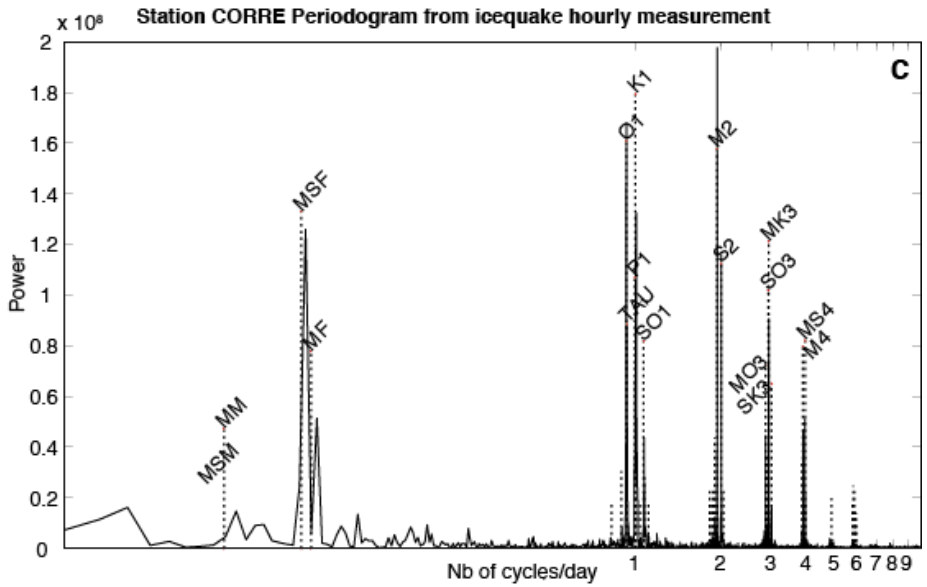
Tidal Modulation – STA/LTA

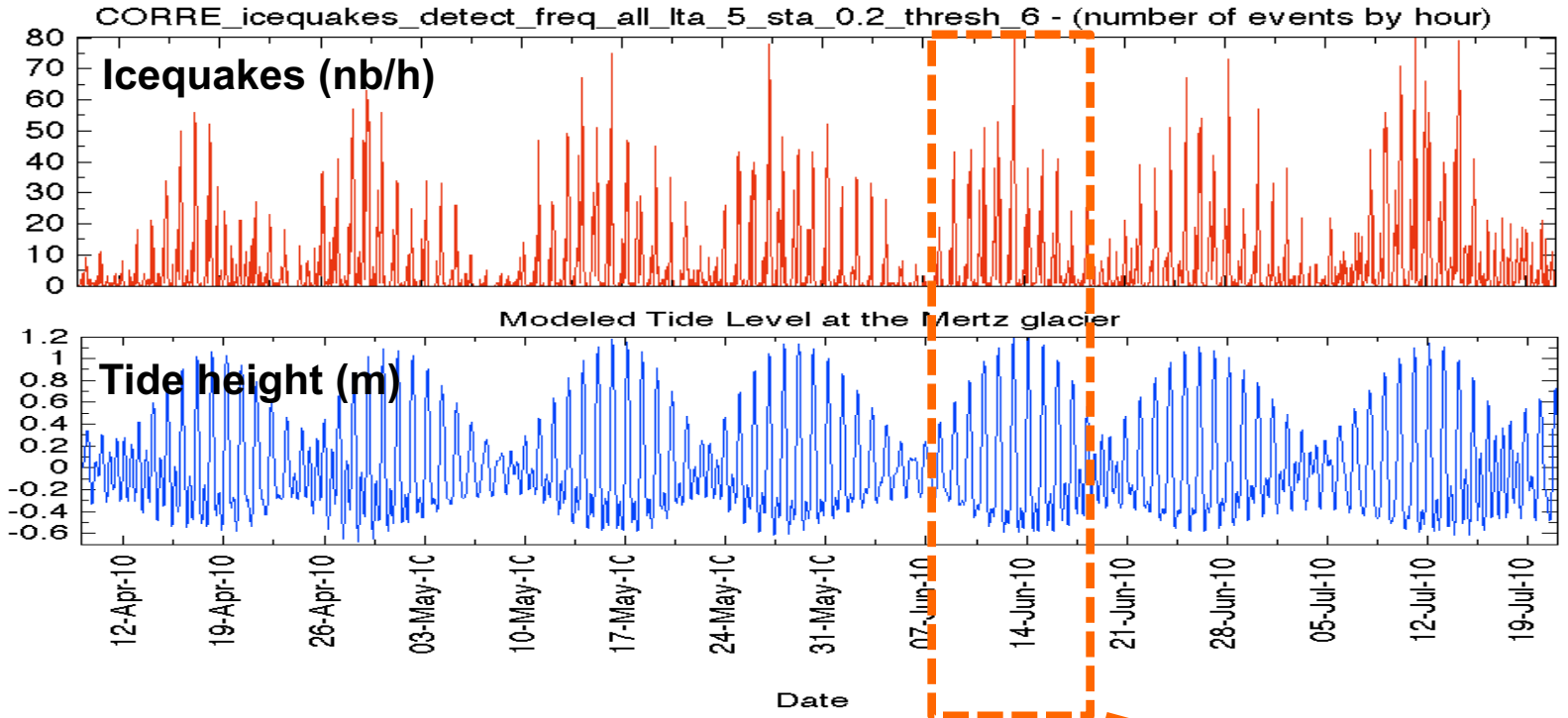


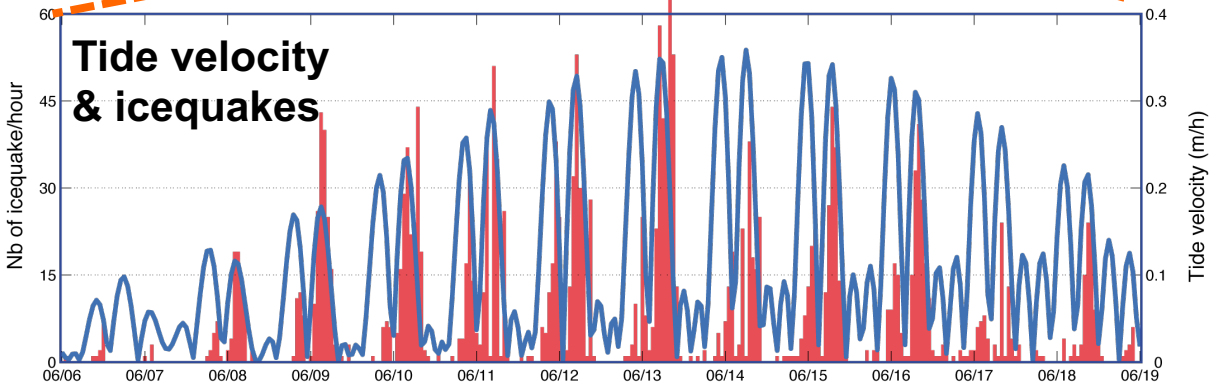
G. Barruol, communication personnelle

Tidal Modulation









Barruol et al. (2013)