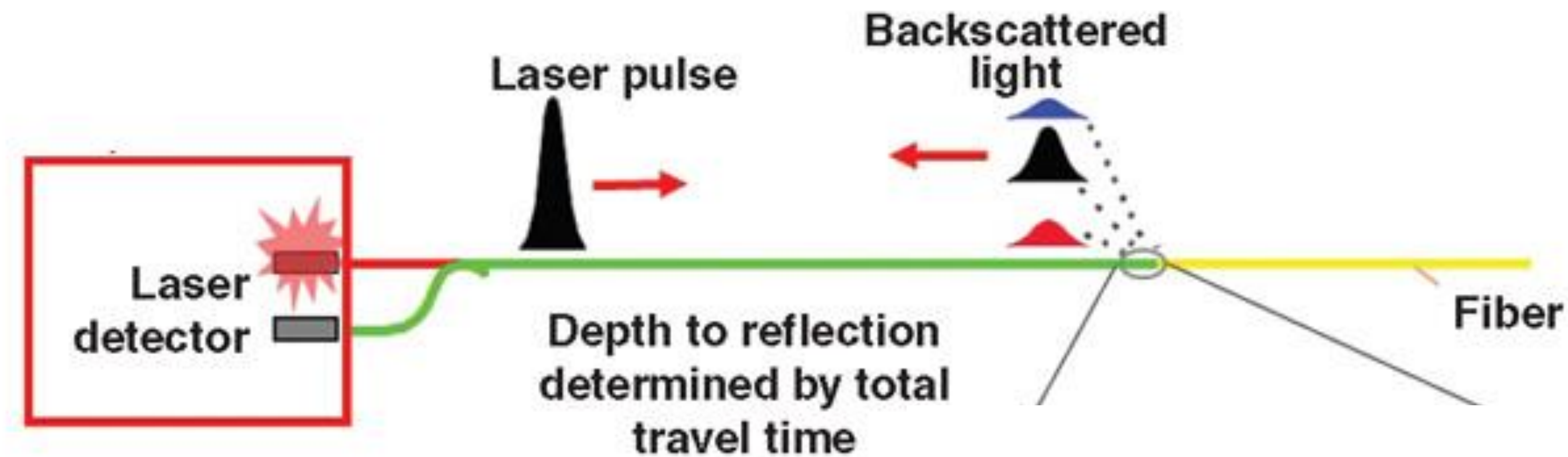
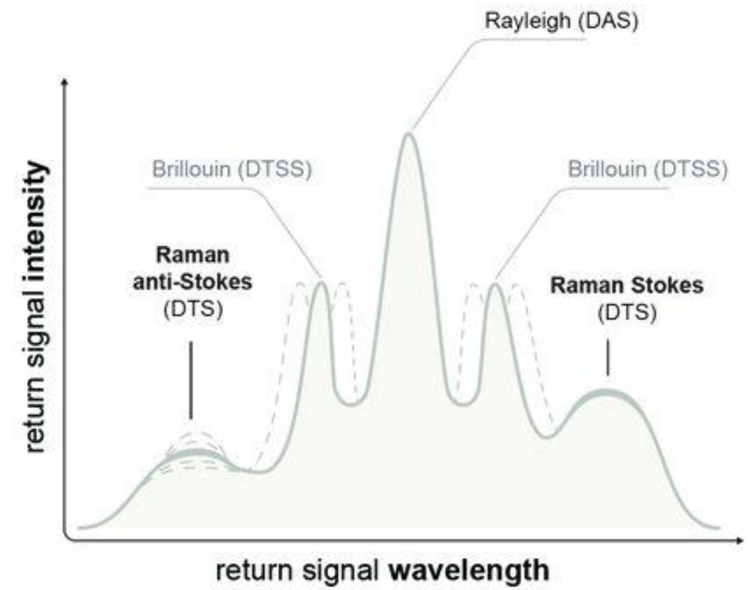
La Fibre optique comme capteur

Olivier Coutant (Isterre) / Diane Rivet (GéoAzur)

Principe de la mesure

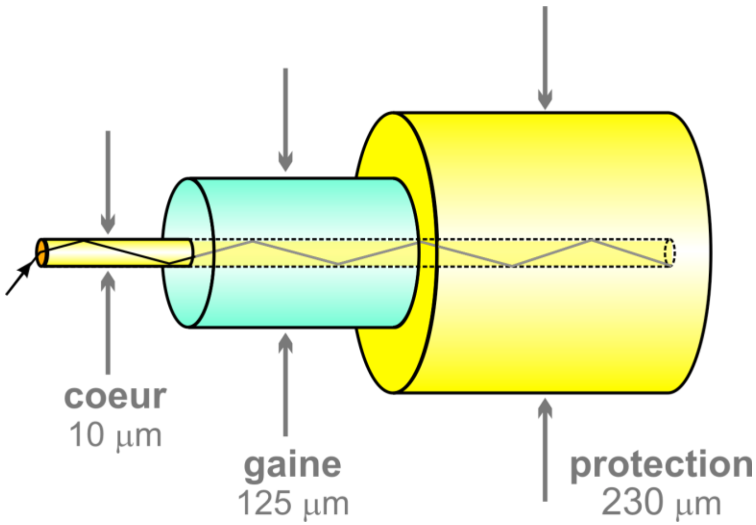




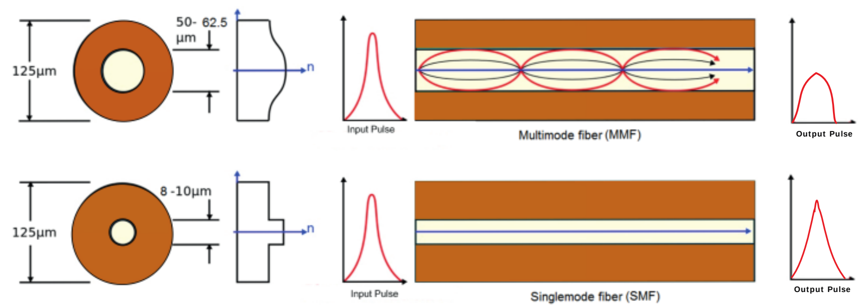
Rayleigh: diffraction élastique

Brillouin, Raman: diffraction anélastique
décalage en longueur d'onde

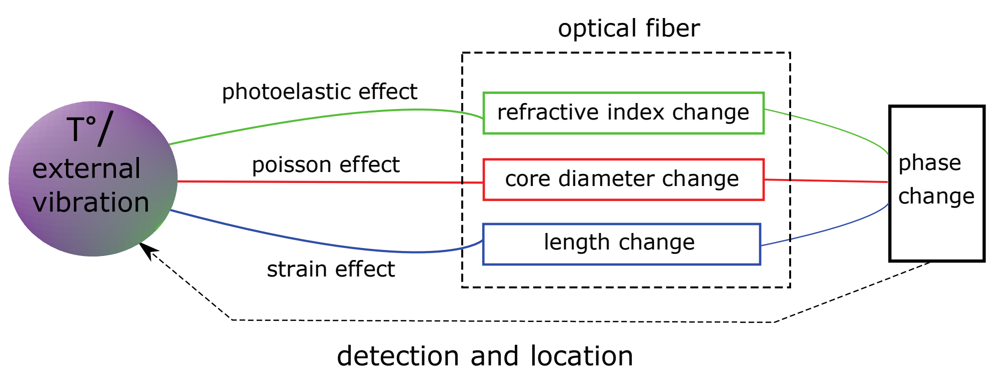
A quoi la fibre est-elle sensible?



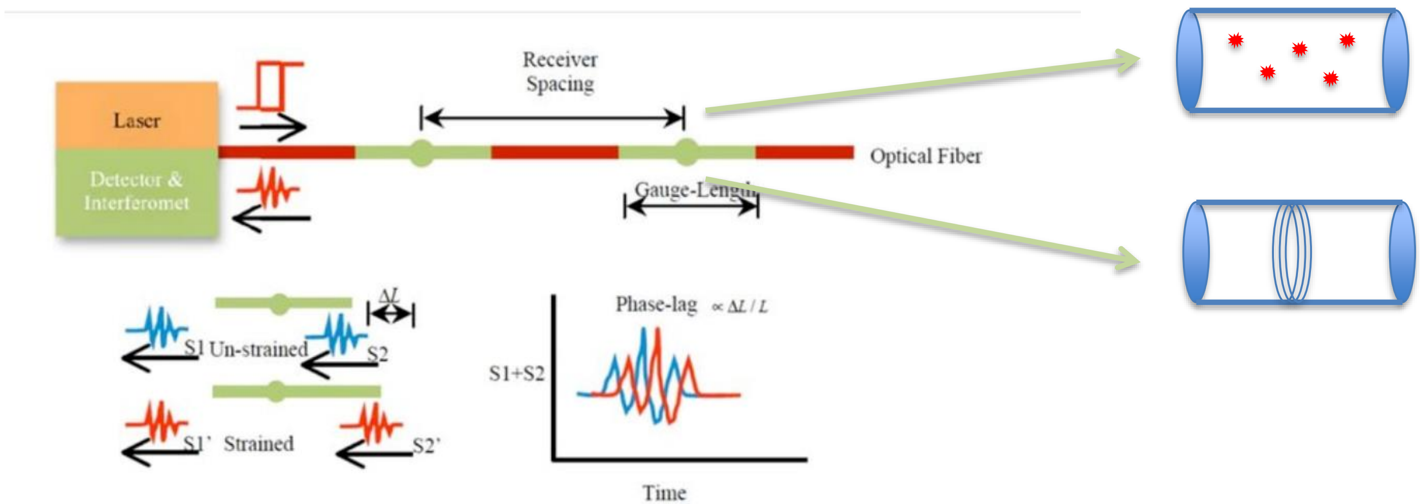
Core	cladding	coating



<u>Diffraction Rayleigh</u>



A quoi la fibre est-elle sensible?



Impuretés DAS (mesure temps)

Réflecteur Bragg (mesure λ)

<u>Sensibilité ramenée à une déformation</u>

Température (indice)	7.8 με /°C
Déformation (élongation+indice)	$\dot{\varepsilon}_{mes} = 0.78\,\dot{\varepsilon}$
Pression (indice)	0.3 με / bar

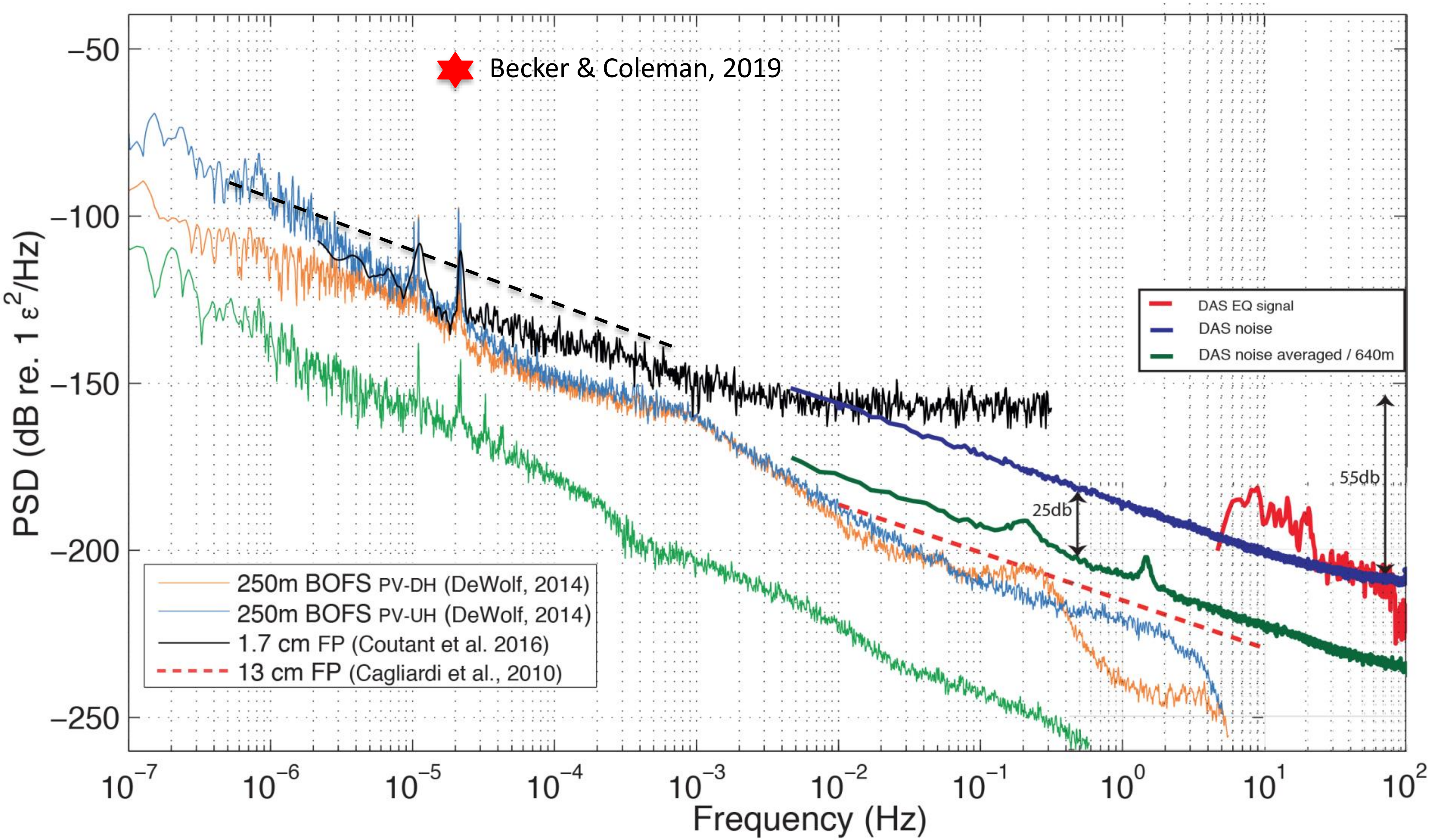
A quoi la fibre est-elle sensible?

- Les fibres monomode atténue la lumière avec la distance, utilisable jusqu'à 50km
- À 50km, le pas d'échantillonnage min est de 2*50 km / 2.e5 km/s = 50msec ⇔ 2kHz
- Longueur de gauge typique 10/20m
- Un capteur tous les mètres sur 1 km @ 2KHz

1 journée ~ 1To de données

Niveau de bruit

La résolution est inversement proportionnelle à la longueur de mesure



Exemple: enregistrement « Large-bande », moyenne sur 1200m

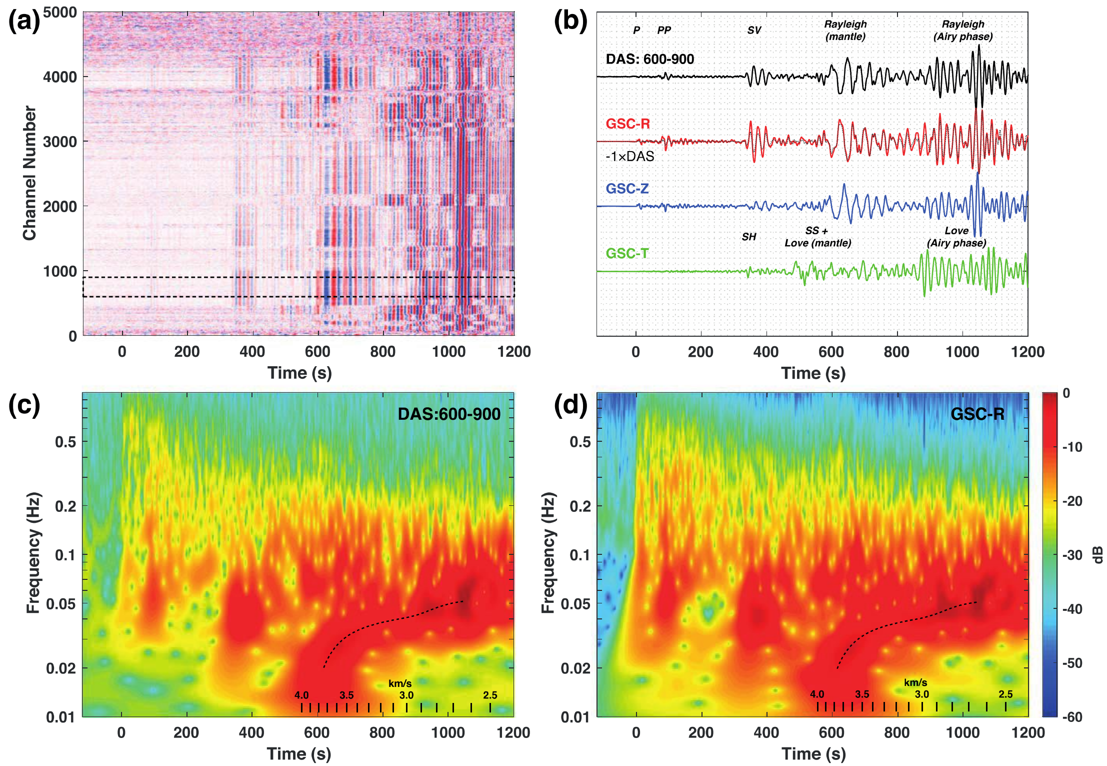


Figure 2. Data from the 2018 M7.5 Honduras earthquake recorded on DAS channels and GSC broadband seismometer. (a) Waveform data of all ~5,000 DAS channels from the Goldstone OpticaL Fiber Seismic experiment. The channel spacing is 4 m. (b) Comparison between selected DAS strain and GSC particle velocity. The GSC waveforms are rotated into vertical, radial, and tangential components after removing the instrument response. Waveforms are band-pass filtered between 0.01 and 2 Hz. Amplitudes are normalized to unity by the peak amplitude of DAS strain and radial GSC velocity, respectively. The selected DAS strain is stacked from channels 600–900. For better comparison, polarity-reversed DAS strain (dash line) is also plotted, overlying the radial GSC velocity. (c, d) The spectrograms of the stacked DAS strain and radial-component GSC velocity, respectively. The dash line tracks the Rayleigh wave group velocity dispersion. The group velocity scale is shown at the bottom. DAS = distributed acoustic sensing.

GRL, 2019, The Potential of DAS in Teleseismic Studies: Insights From the Goldstone Experiment
C Yu , Z Zhan , N. J. Lindsey ,J. B. Ajo-Franklin , and M. Robertson, UC Berkeley

Exemple: détection d'une zone de faille

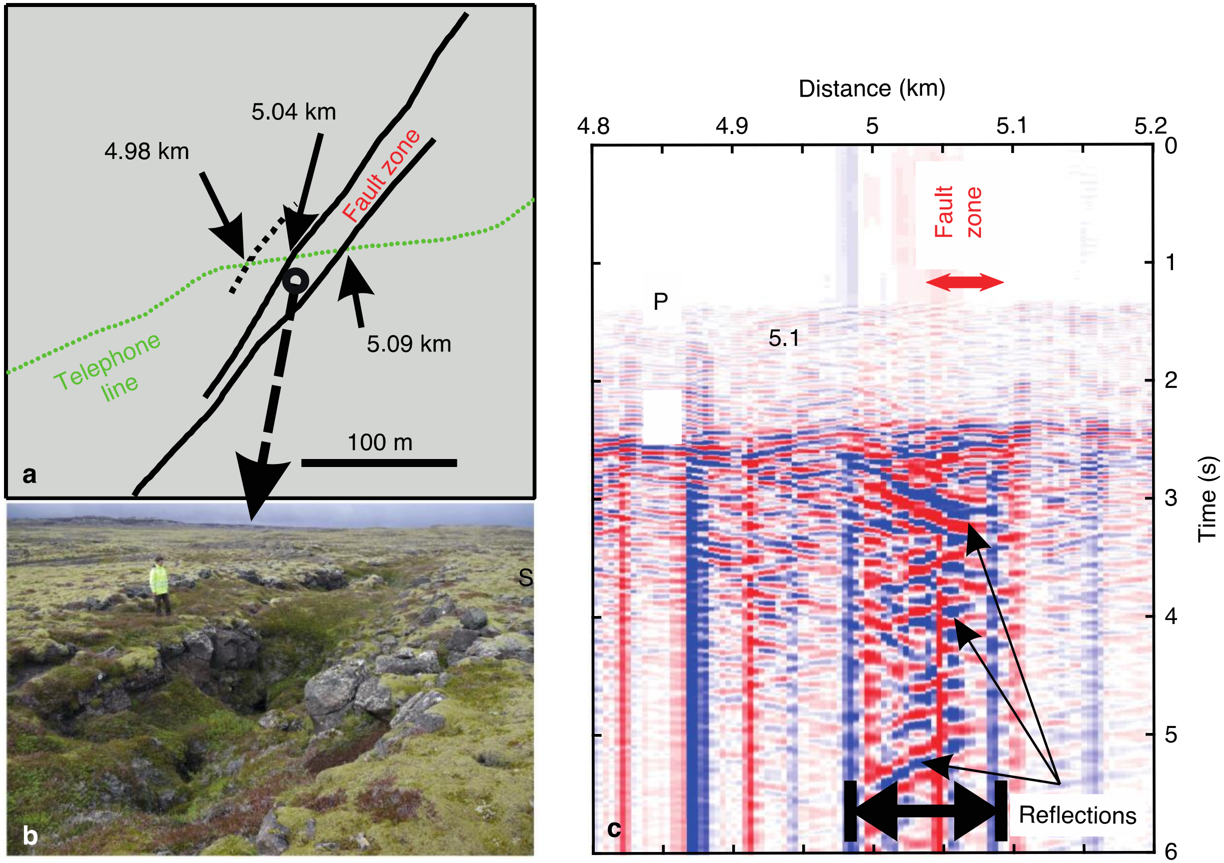


Fig. 7 Structure of a fault damage zone within an active geological rift. a The road and the cable (distance ~5 km) cross several faults, e.g. a clearly visible fault zone with more loose material in the field (between 5.04 and 5.09 km). b The fault damage zone is visible by the ~50–60 m wide depression area (picture taken at ~100 m SW of the road, looking towards SW). Note that at the cable location no depression area is visible. The depression is only the surface expression at the position of the picture (Picture Martin Lipus, GFZ). c Short record (6 s) of strain phases from a local earthquake (Fig. 5) trapped in the fault damage zone. Phases are reflected until ~4.98 km, which may indicate a hidden fault with surface expression. Waves inside and outside the fault zone have different apparent velocities

Nature Comm., 2018, Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features P. Jousset et al. (GFZ)

Exemple d’enregistrement DAS terrestre (FebusOptics & ISTerre)

We have tested during 5 days in September 2018 the DAS interrogator from Fiber-Optics on a commercial telecommunication ber operated by Fibrea-Covage in the Maurienne Valley, French Alps. The cable runs along the «La Chapelle» active seismic swarm, from the valley to the St François Longchamp ski resort. Several earthquakes were recorded, we show the sections for two events of magnitude 1.2 and 1.4. (g. 1). The Fibrea ber cable infrastructure (g. 2) is theoretically not favorable to the coupling e ciency between the ground and the optical ber.

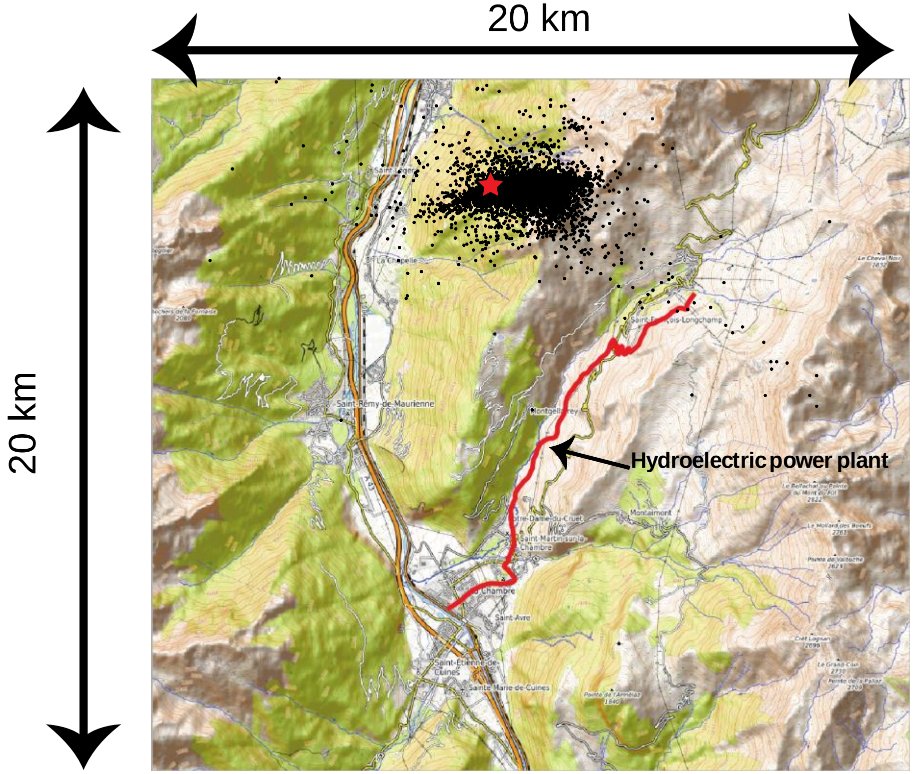


Figure 1: Telecom fiber location (red) and seismic swarm EQs locations (dots & star)

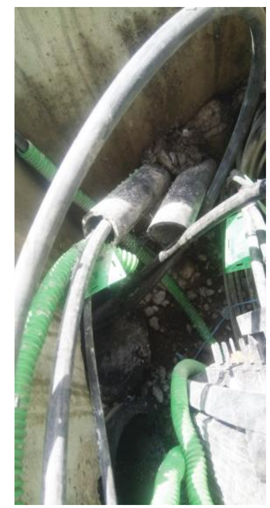
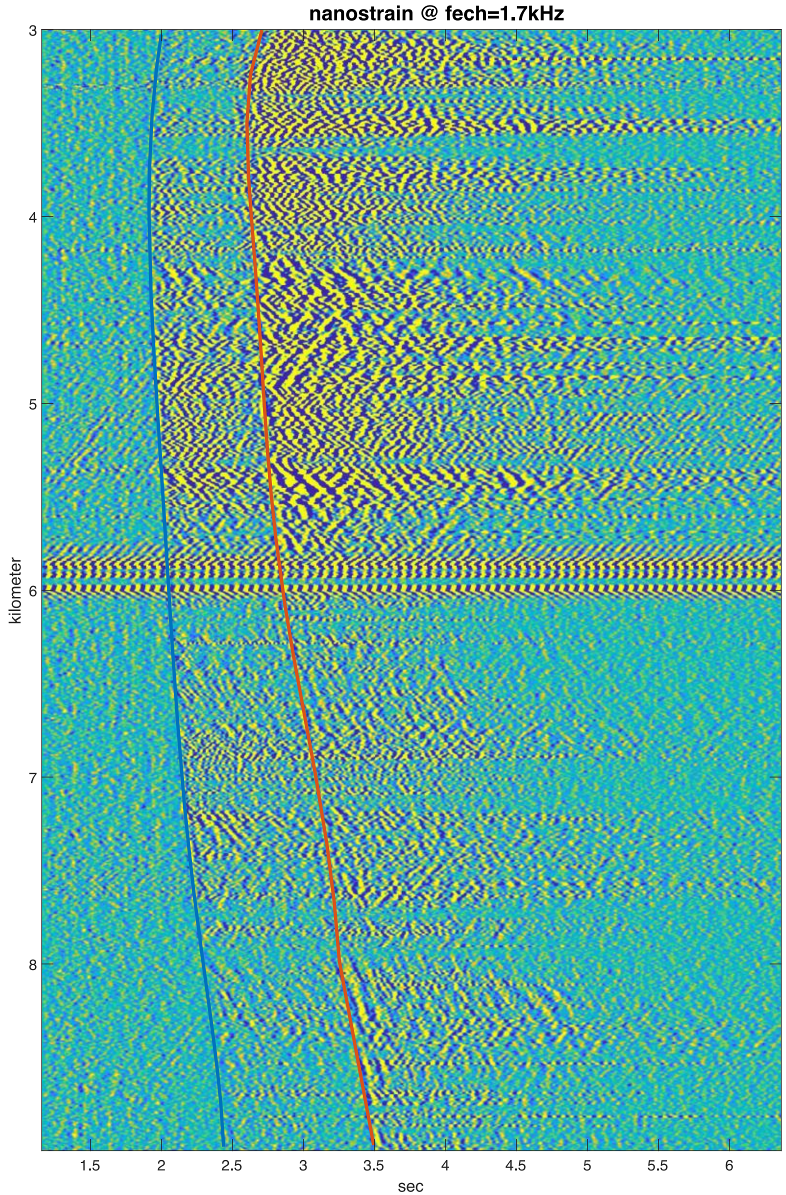
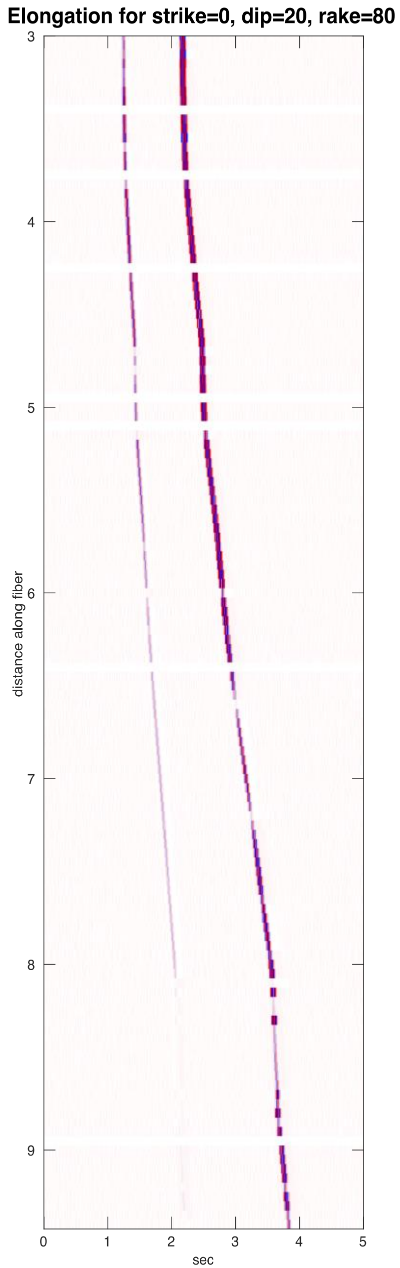


Figure 2: Fiber loose cable inside the PEHD tube (Courtesy of Fibrea-Covage)

Enregistrement d’un mag 1.5: observation / modélisation de l’élongation en milieu homogène





Perspectives

- **Acteurs industriels coté interrogateur**
  - Silixa (UK)
  - OptaSense (US)

  - FebusOptics (Fr)
  - Schlumberger; Halliburton; Fotech(UK); BandWeaver (China); ApSensing, NBG (RFA); Ziebel (US)….

Le nombre d'offres instrumentales explose

Prix 100k€ à 240k€

Tous les interrogateurs se valent-ils?

Perspectives

- **Acteurs industriels coté fibre**

En France relativement peu de fibre « noires », mais déploiement du réseau THD

Accès à la fibre via

– les opérateurs (SFR, Covage),
– les délégataires de service public,
– les collectivités (ex: département de l'Isère)

Déploiement de la fibre optique
Réalisé
2016-2017
Projet 2019
Albertville
Tours en Savoie
La Rosière Montvalezan
Bourg-Saint-Maurice
Les Arcs
La Plagne
Alton
Aiguebelle
Tignes
Val d'Isère
Col de l'Iseran
Moûtiers
Brides les-Bains
Bozel
Champagny-en-Vanoise
Épierre
Valmorel
Saint-Martin de-Belleville
Le Tania
Courchevel
Pralognan-la-Vanoise
Méribel
Saint-François-Longchamp
Bonneval sur Arc
Les Ménuires
Bessans
Val Cenis Lanslebourg
Termignon
Sollières Sardières
Val Thorens
Saint-Jean de-Maurienne
Bramans
Aussois
Les Karellis
Saint-Michel-de-Maurienne
La Toussuire
Albiez-le-Jeune
Le Corbier
Orelle
Modane
La Norme
Saint-Sorlin-d'Arves
Saint-Jean-d'Arves
Valfréjus
Valmeinier
Valloire
10 km
CRÉATEUR DE RÉSEAUX FIBRE OPTIQUE
NEUTRES ET OUVERTS EN SAVOIE

Perspectives

- Applications en géophysique et environnement: surveillance en vallées Alpines
    - Sismicité
    - Crues
    - Glissements de terrain
    - Avalanches
    - …..
- Imagerie passive entre fibres
- Monitoring des structures
- Fibres sous-marines
- …

Projets en cours:

<u>ANR SEAFOOD</u> (Seafloor Fiber Optic Observatory for Distributed measurements), ANR 2018, A. Sladen

<u>ANR MONIDAS</u> 2019->2023

Partenaires:

Febus-Optics: construction d'un DAS

ISTERRE : vallées Alpines

IPGP: cible Stromboli

Géoazur: cible sous marine

EOST: exploitation géothermique

- Quels traitements pour réduire les flux de données?
- Meilleure caractérisation du couplage fibre/sol

Distributed sensing of earthquakes and ocean-solid Earth interactions analysis using fiber optic telecom seafloor cables

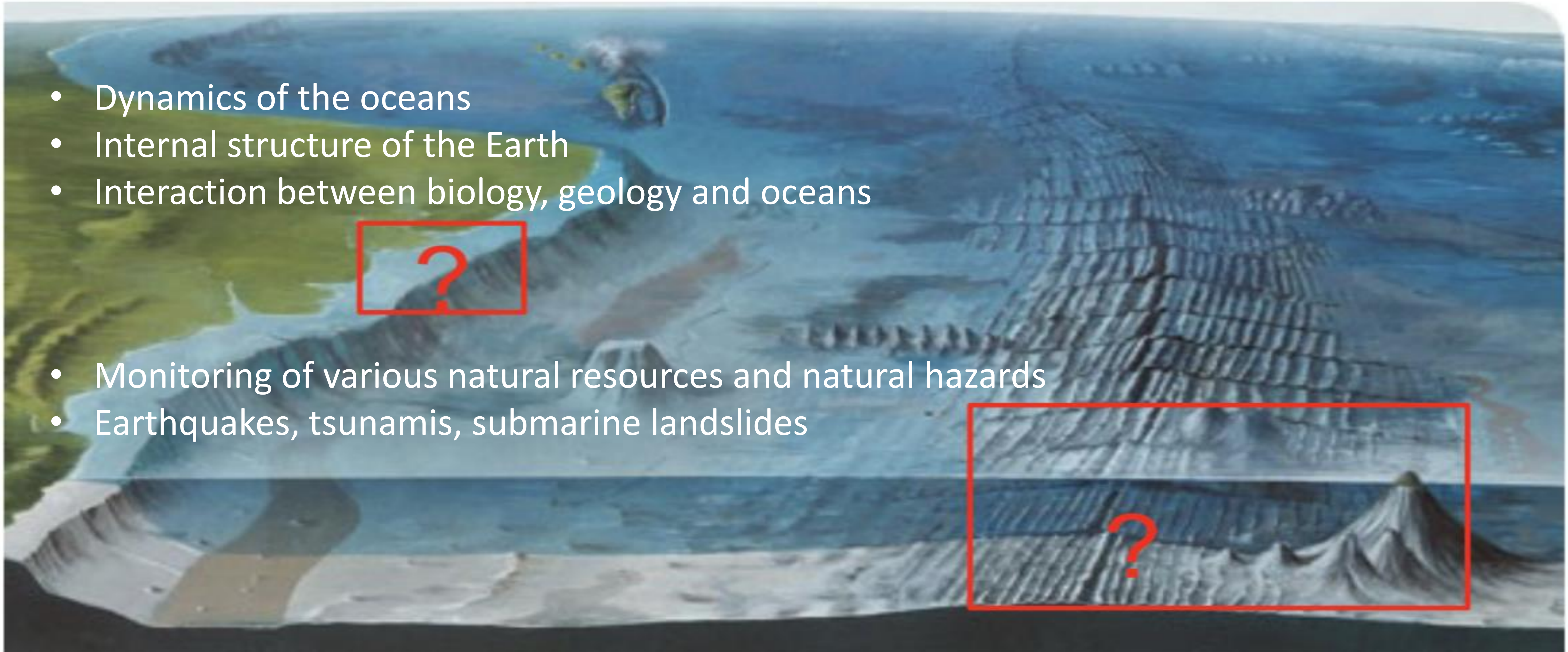
Diane Rivet

Anthony Sladen, Jean-Paul Ampuero, Louis de Barros, Yann Hello,
Gaëtan Calbris (Febus), Patrick Lamare (CPPM), Stavroula Tsagkli, Paris Pagonis (INP Demokritos)

RESIF – Novembre 2019

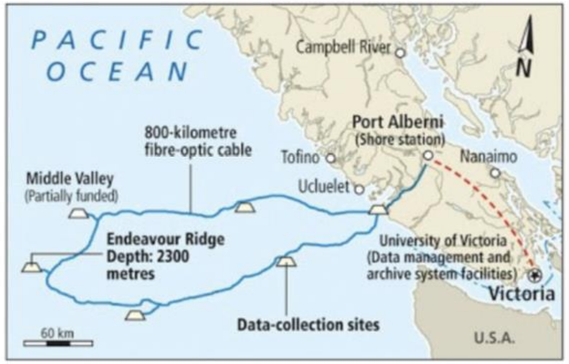
Ocean floor instrumentation holds the answers to numerous key scientific questions

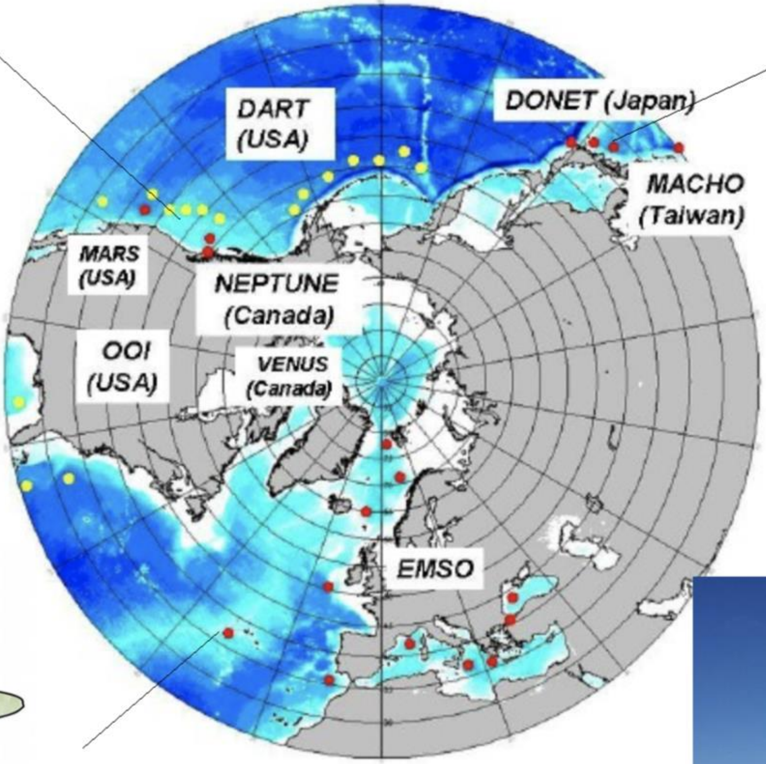
- Dynamics of the oceans
- Internal structure of the Earth
- Interaction between biology, geology and oceans
- Monitoring of various natural resources and natural hazards
- Earthquakes, tsunamis, submarine landslides

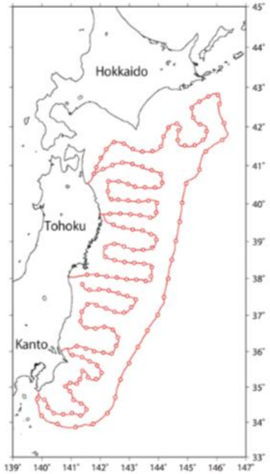


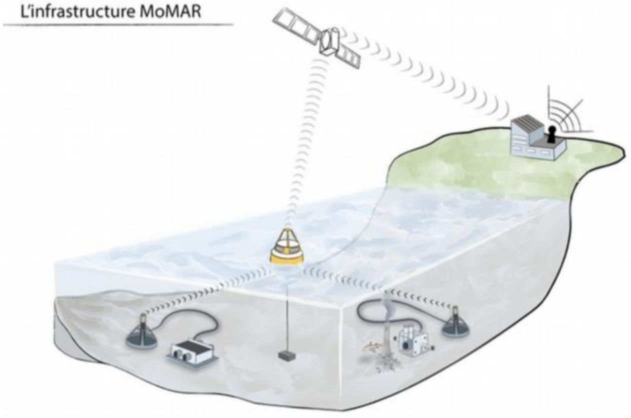
Challenging and expensive permanent instrumentation

Submarine cabled real-time seafloor observatory







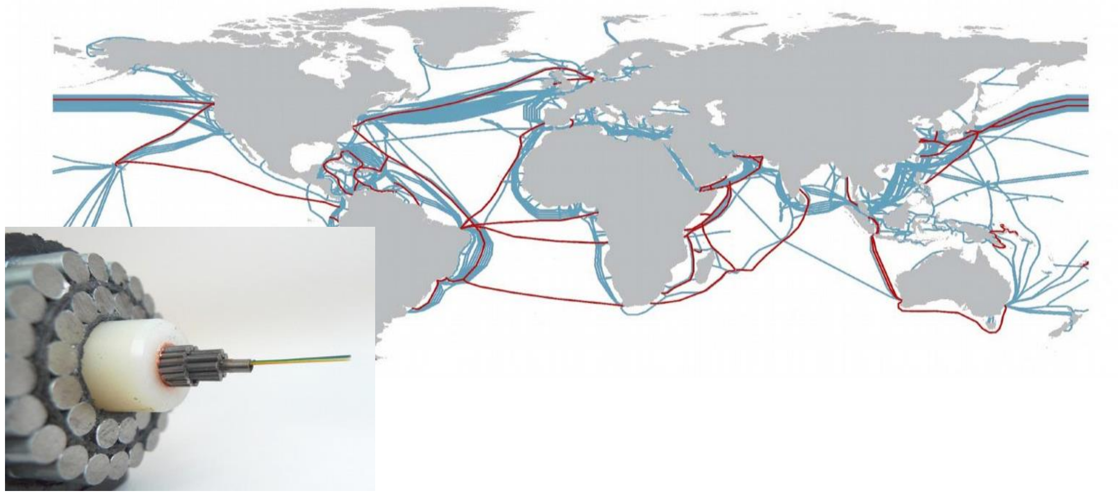


N’importe quelle fibre, mais pas n’importe quel câble

Axe 1 : sur câble dédié

Pas cher et permet de cibler la zone d’étude. Câble qui a besoin d’être protégé et couplé au fond marin.

Axe 2 : sur câbles telecom



Tapissent la plupart des océans et zones côtières mais câbles particuliers et pas emplacement imposé

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mais pas n’importe quel câble

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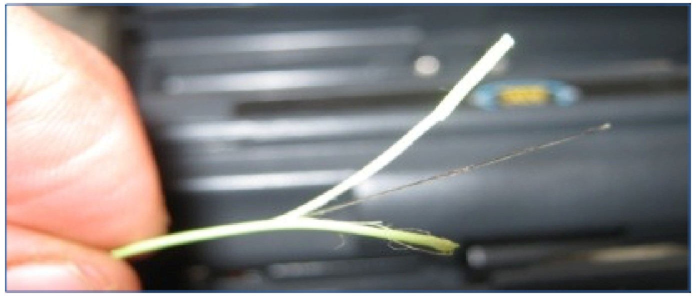

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Axe 2 : sur câbles telecom

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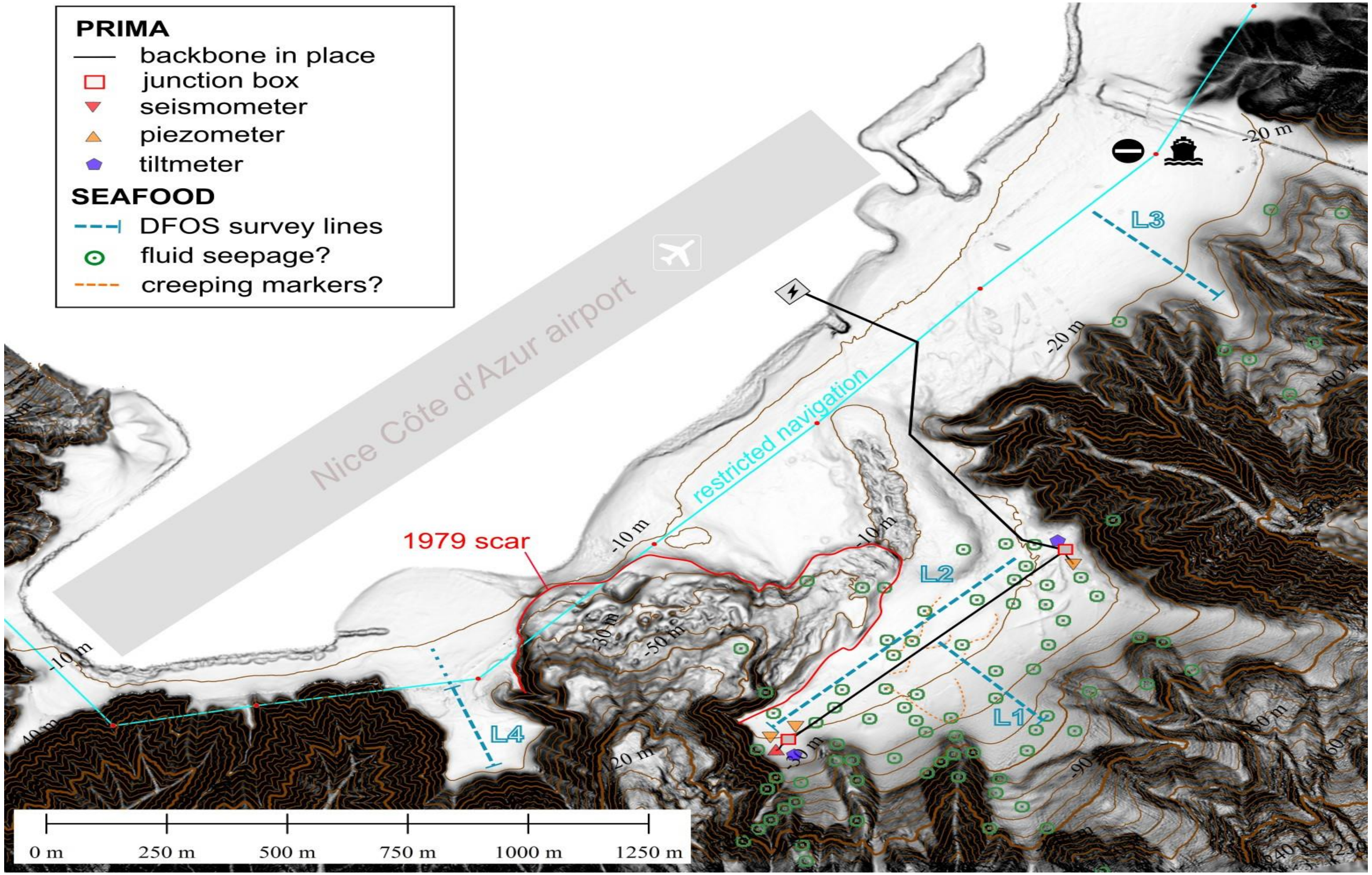
Aéroport de Nice : un site local avec de forts enjeux scientifiques et socio-économiques



Mai 2019 : déploiement de 4 lignes avec charrue Géoazur

Objectifs scientifiques

- Calibration vs instrumentation + std
- Stabilité pentes
- Sorties et circulations de fluides
- Tester imagerie passive et active

N’importe quelle fibre, mais pas n’importe quel câble

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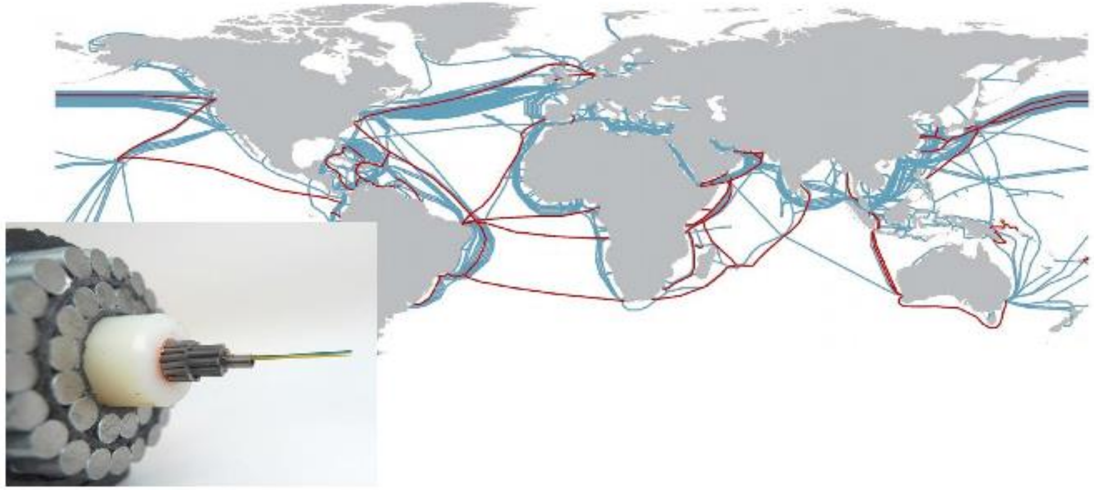
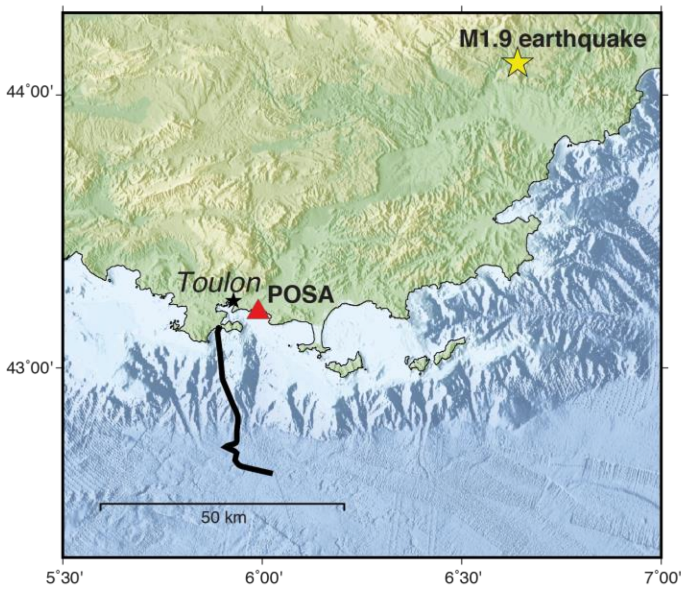
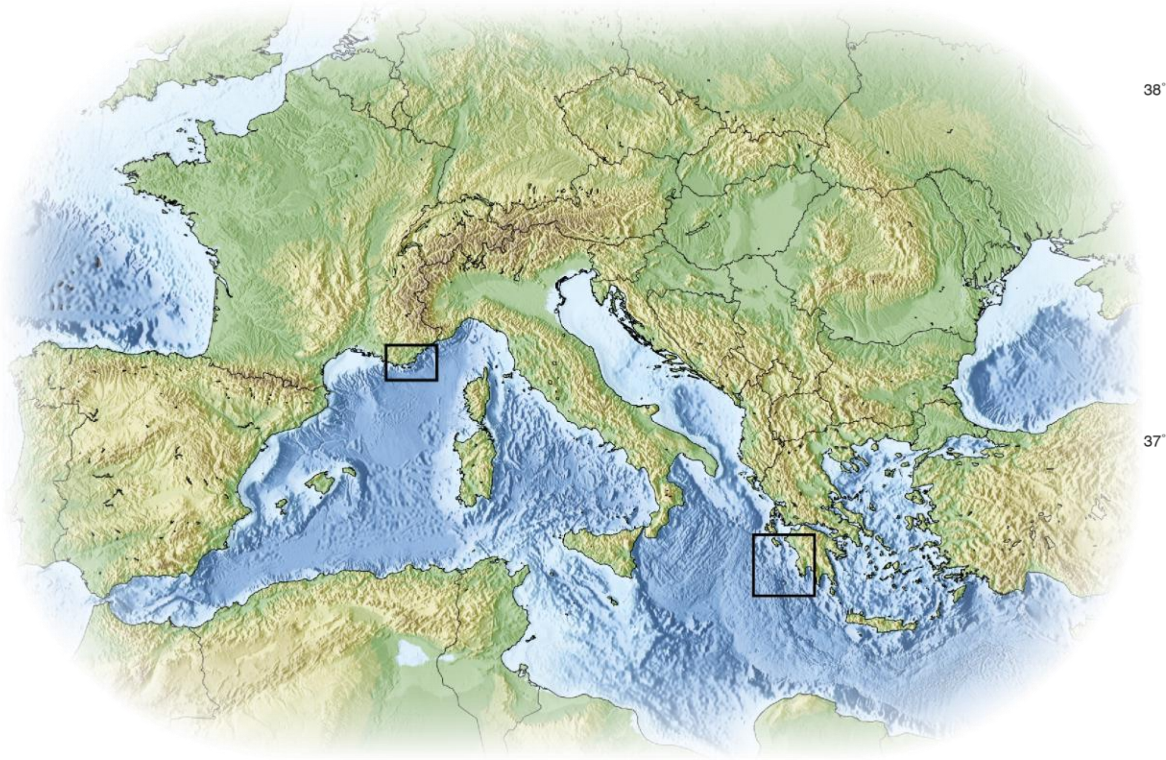
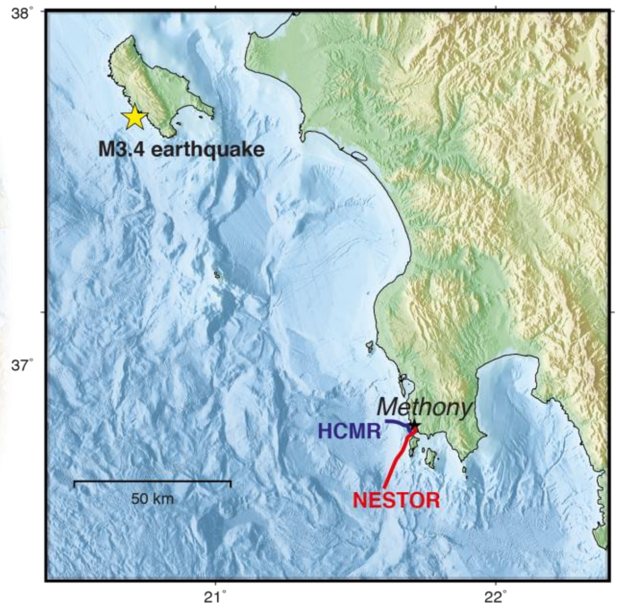


Tapissent la plupart des océans et zones côtières mais câbles particuliers et pas emplacement imposé

DAS experiments : 3 Telecom Cables EMSO– KM3NET and Nestor

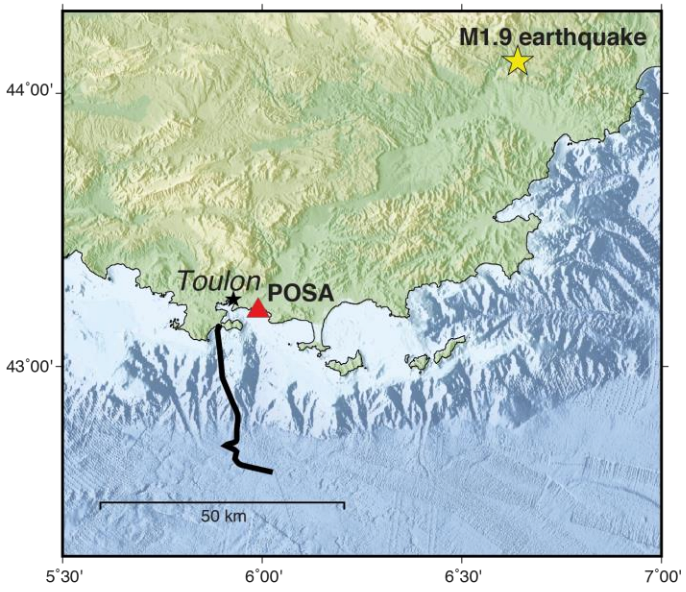




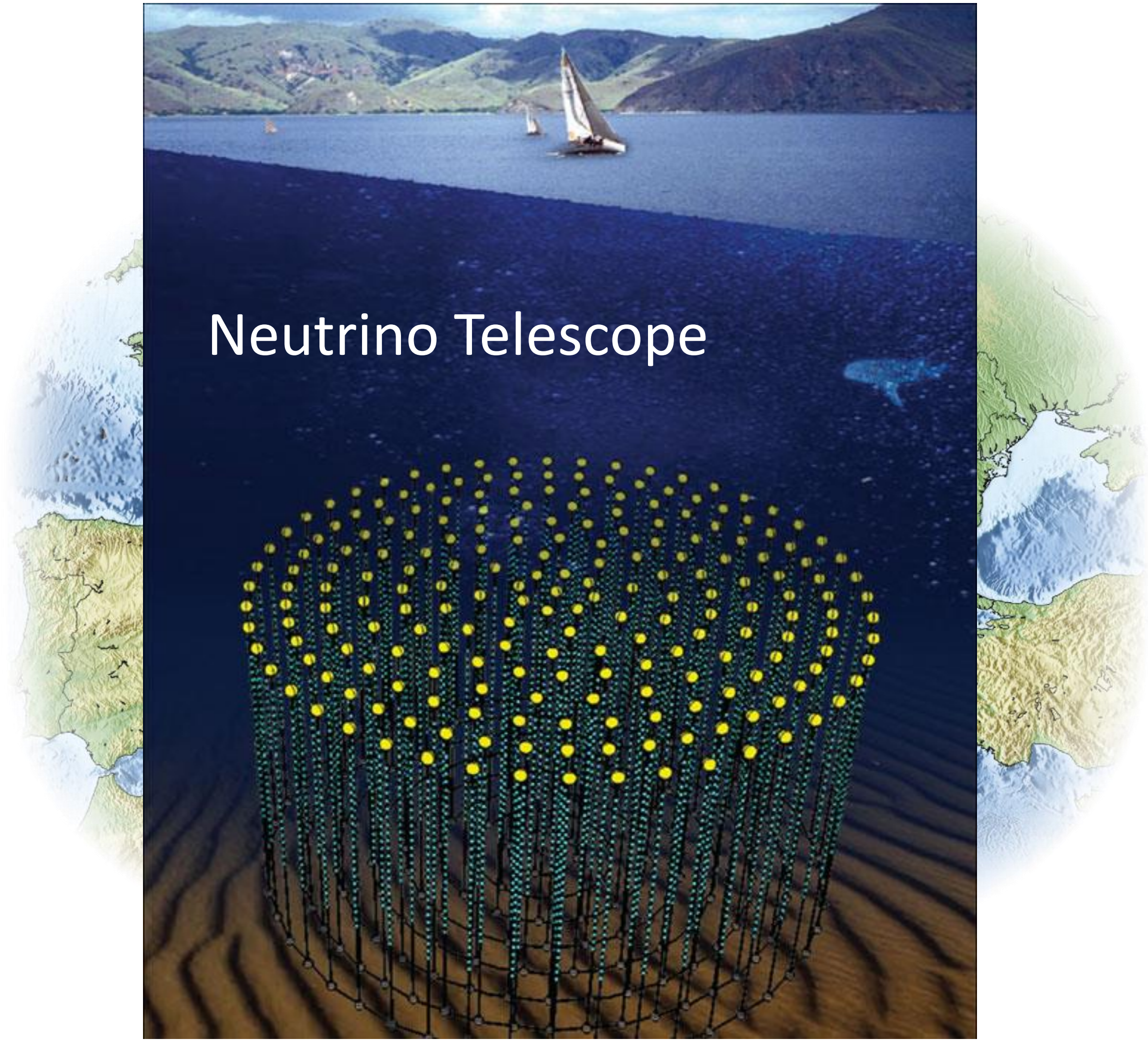


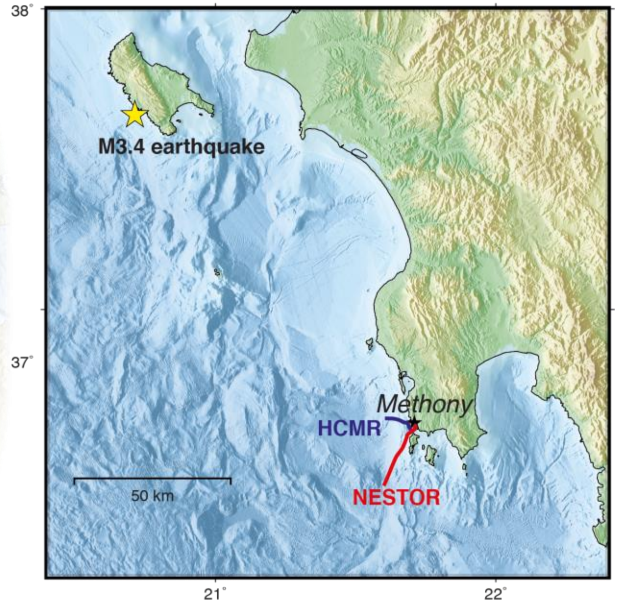
EMSO European Multidisciplinary Seafloor and Water Column Observatory

DAS experiments : 3 Telecom Cables EMSO– KM3NET and Nestor



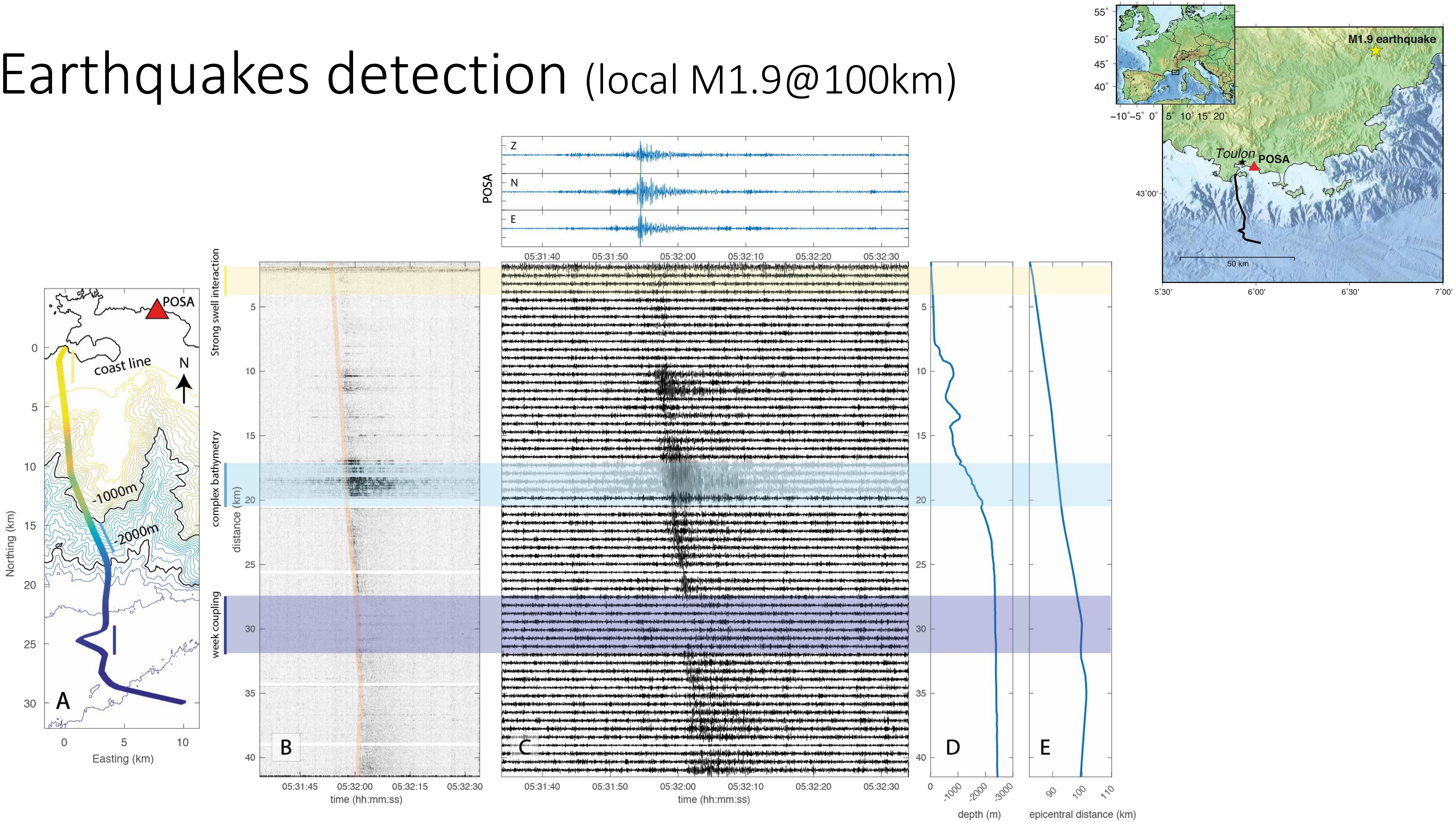
MEUST/KM3NET



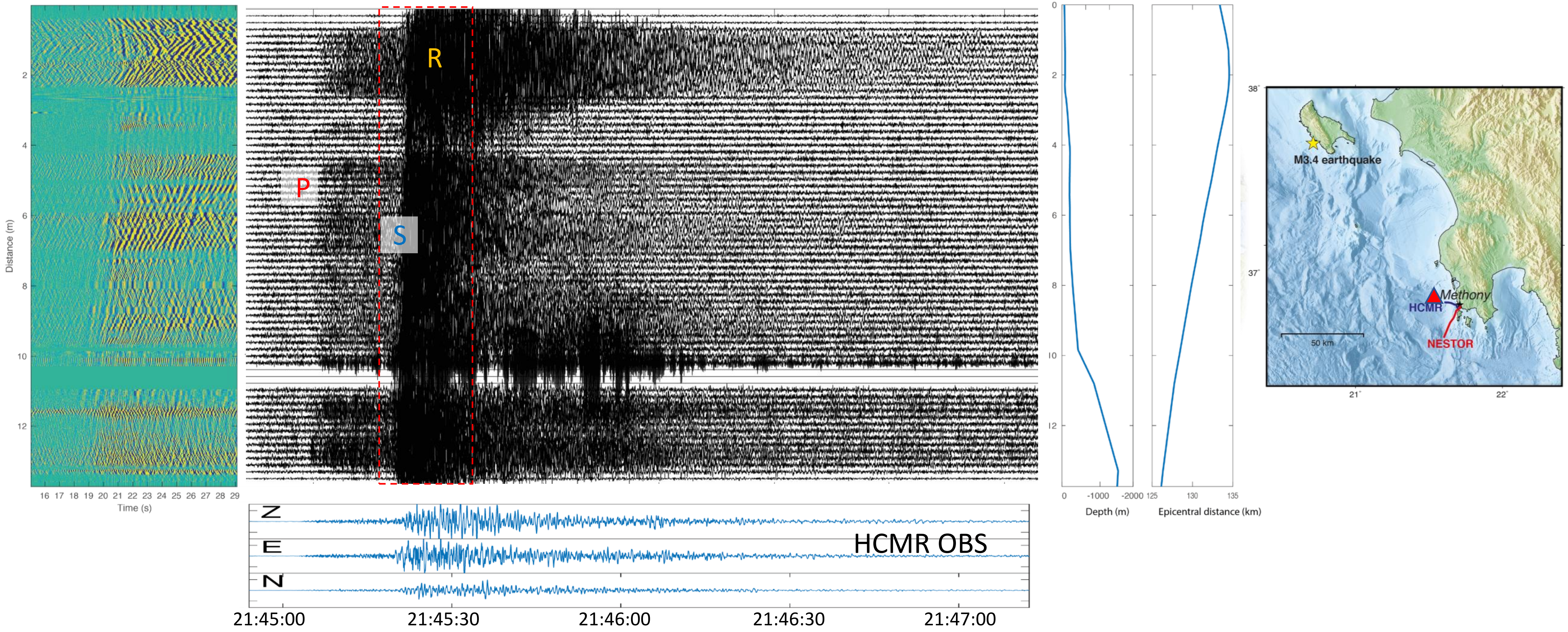


NESTOR project

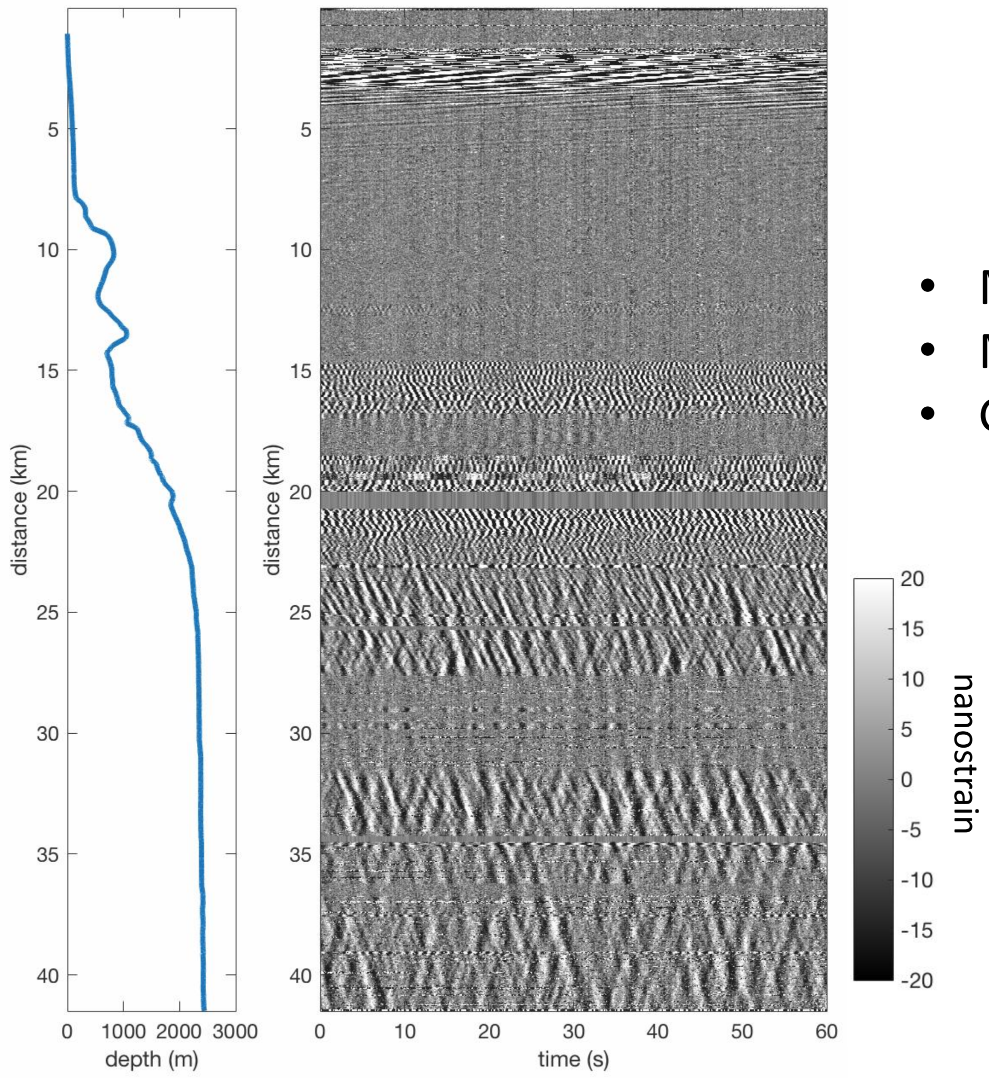
Earthquakes detection (local M1.9@100km)



Earthquakes detection (regional M4.3 in Greece)

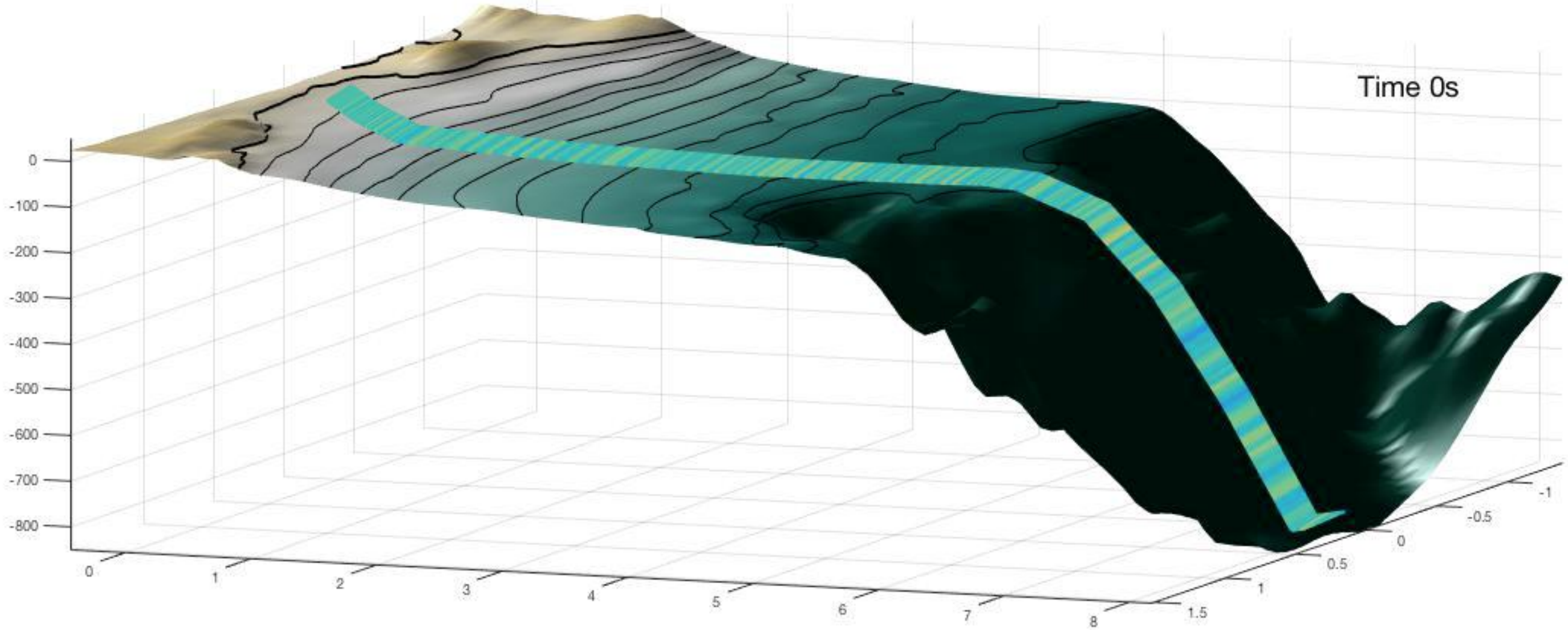


Ocean solid-Earth interactions

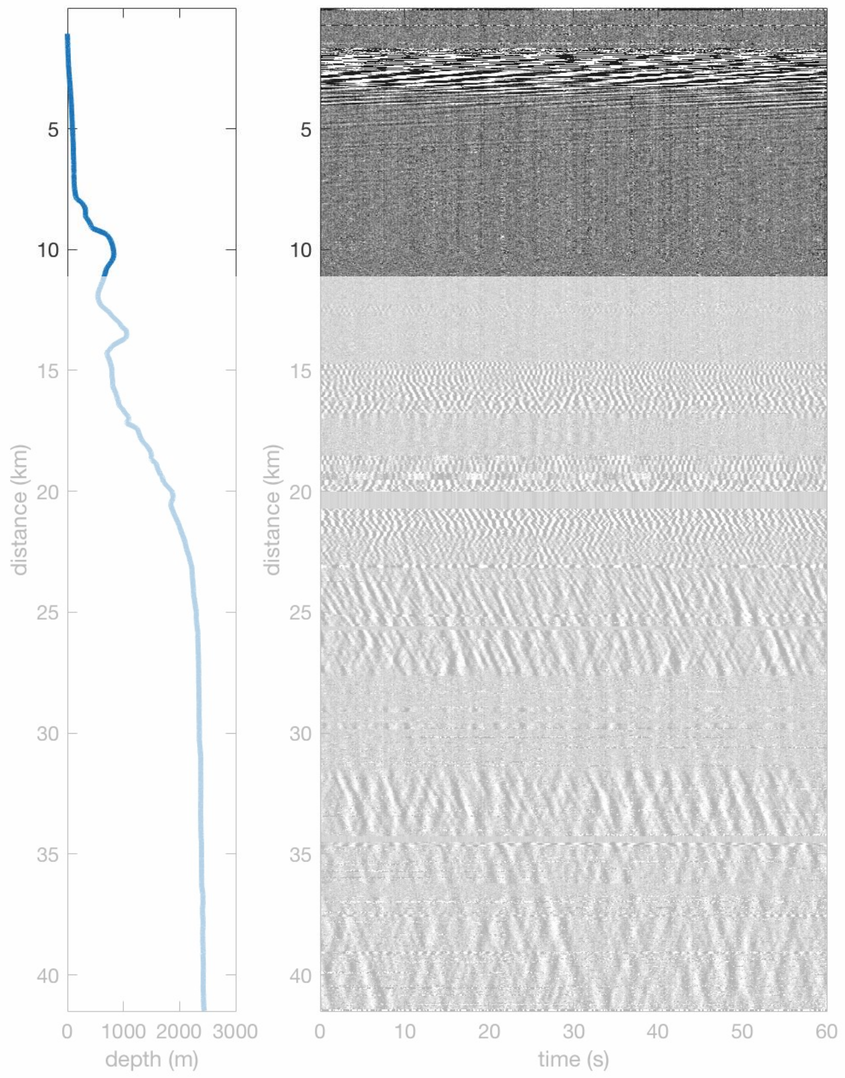


- Monitoring the evolution of different types of waves
- Multi-scale observation (m-km) of the wave-bathymmetry interaction
- Generation of microseismic noise

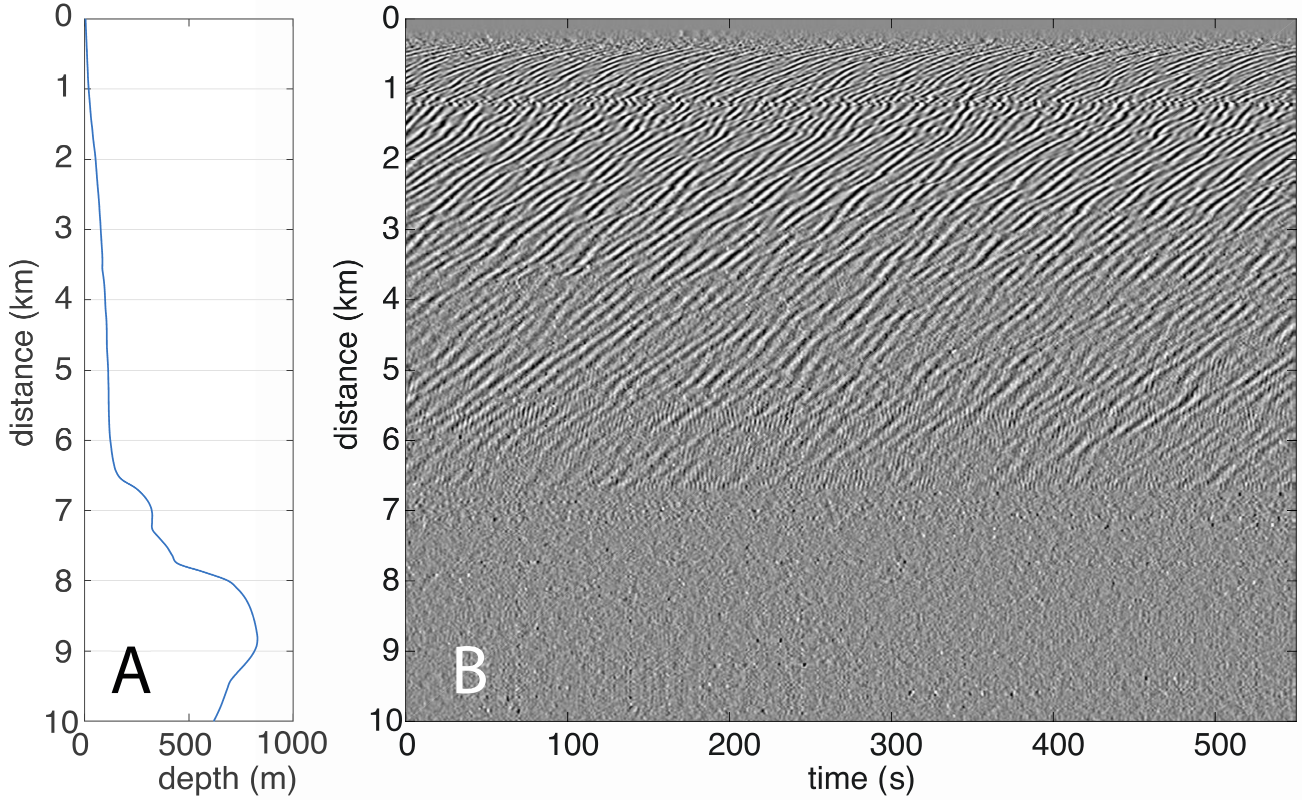
Gravity waves and primary microseism peak



Gravity waves and primary microseism peak

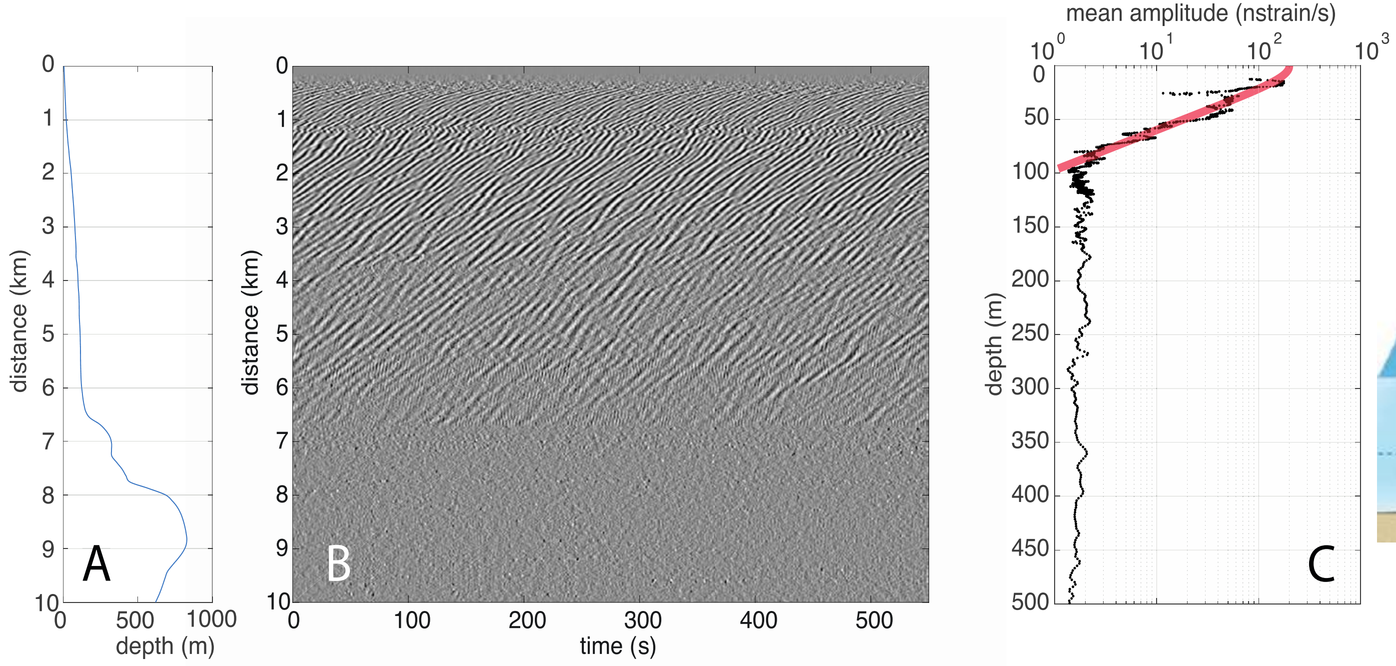


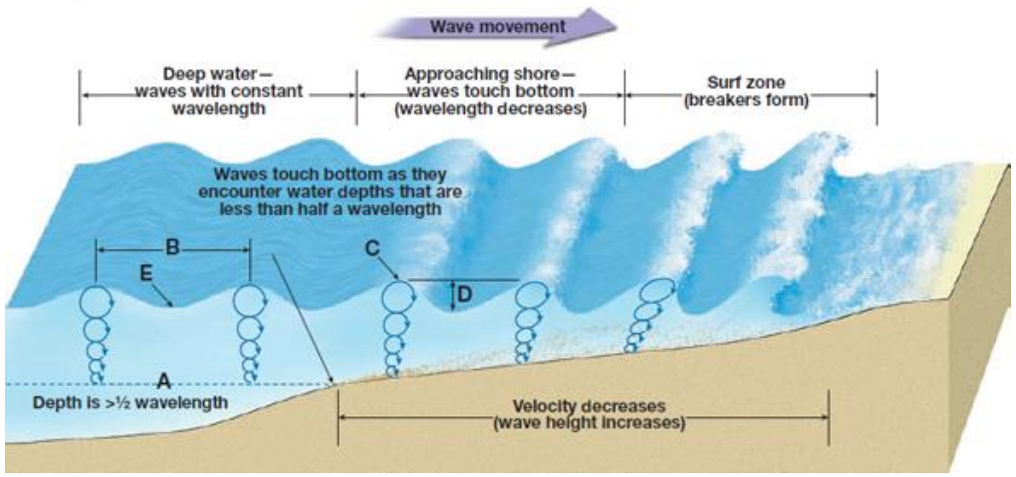
Depth < 100m



Gravity waves and primary microseism peak

Periodic oscillations 0.1 - 0.25 Hz, which propagate landward with **increasing amplitude**

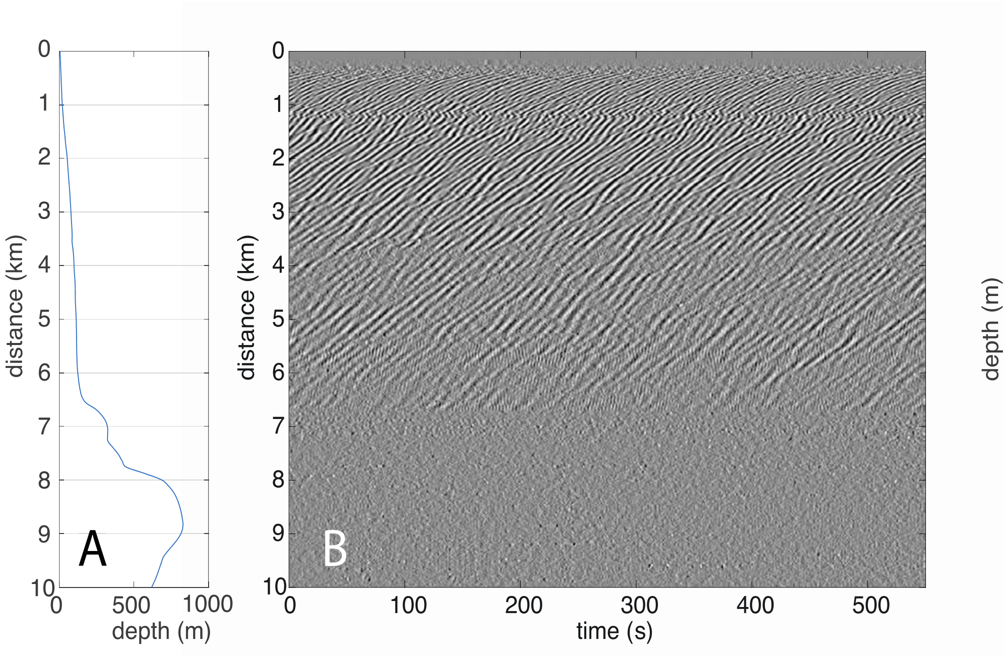


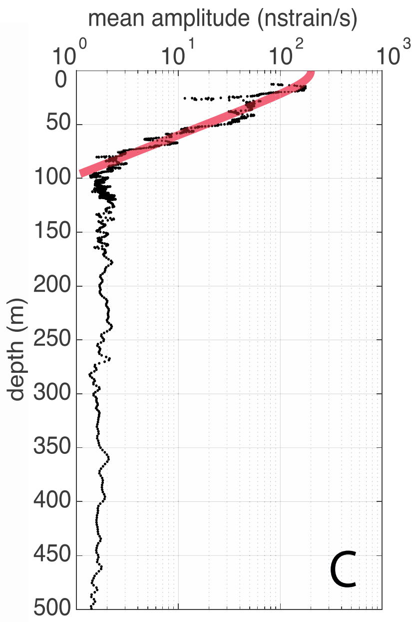


$$\frac{P_d(h)}{P_{d0}} = \frac{1}{\cosh\,(k.h)}$$

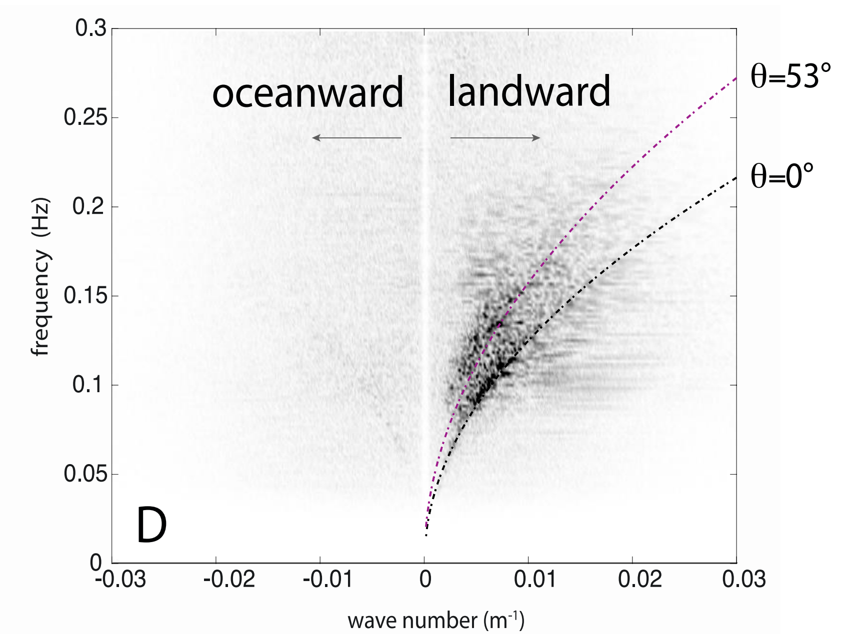
Gravity waves and primary microseism peak

Periodic oscillations 0.1 - 0.25 Hz, which propagate landward with **decreasing velocity**



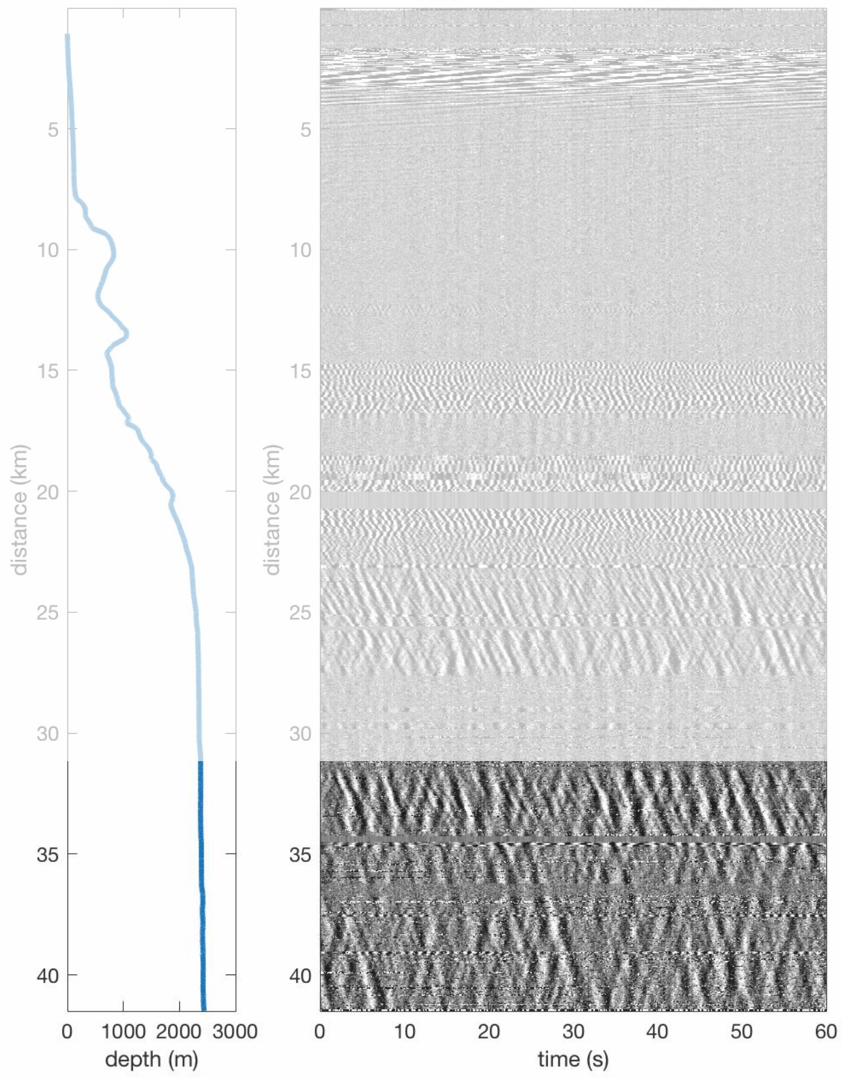


$$\frac{P_d(h)}{P_{d0}} = \frac{1}{\cosh(k.h)}$$

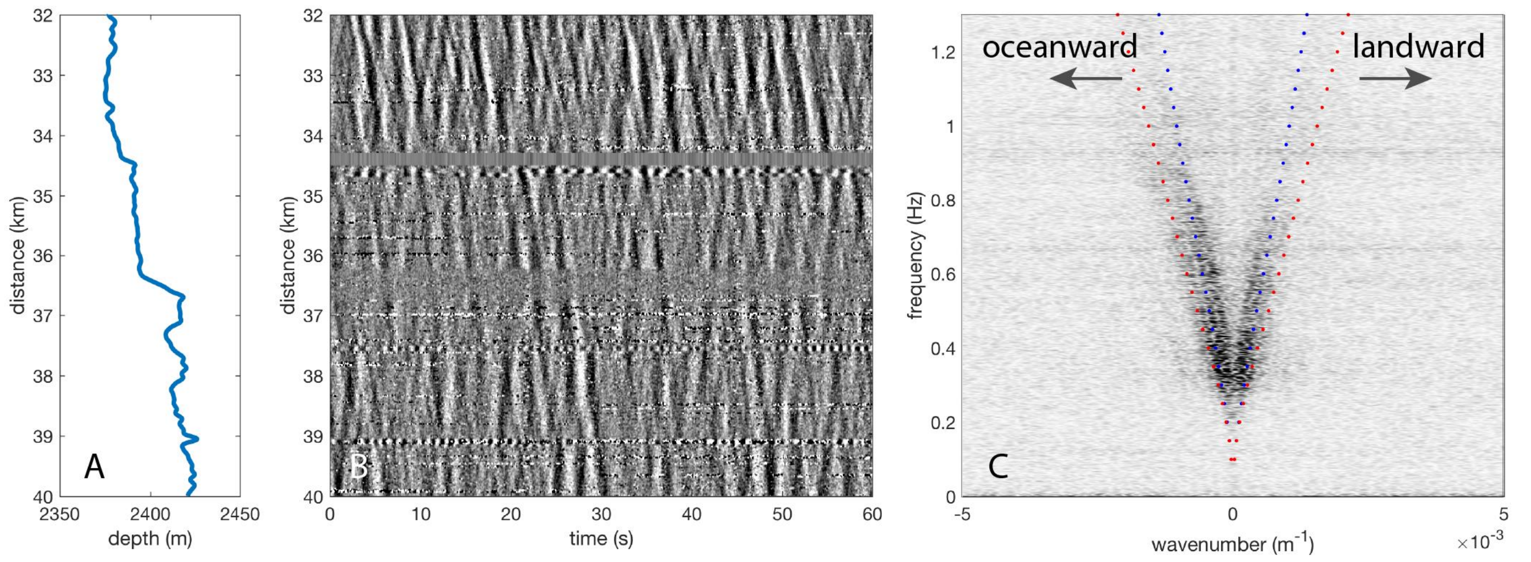


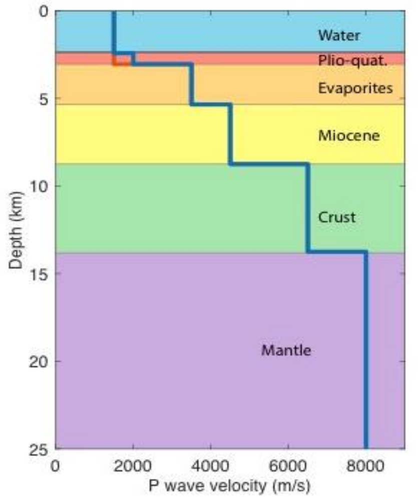
$$\omega = \sqrt{g.k.tanh(k.h)}$$

Nonlinear interaction - secondary microseism peak

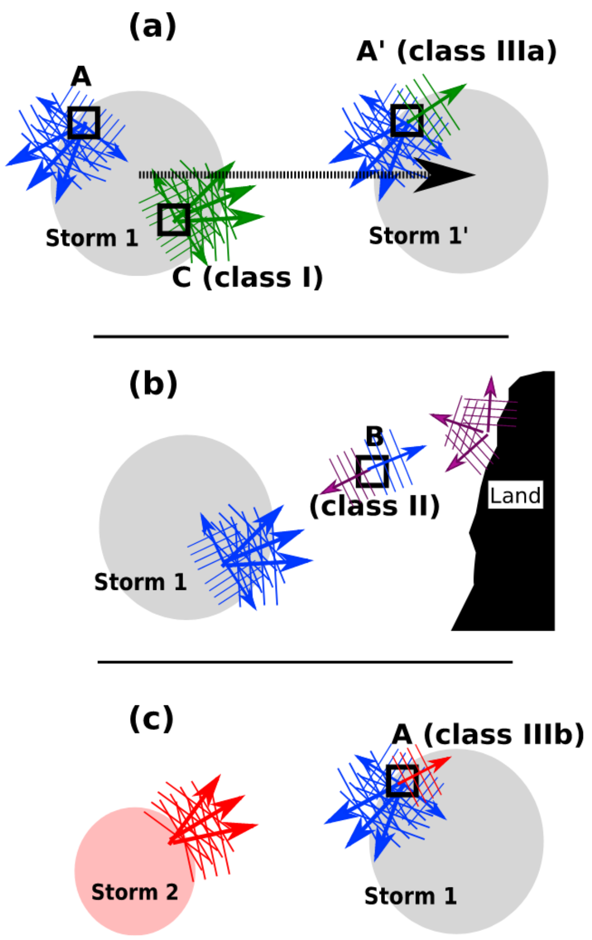


Depth = 2400m



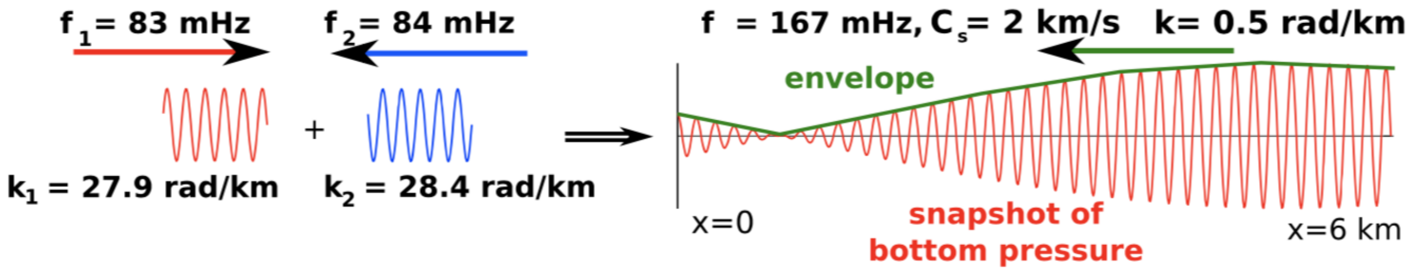


Nonlinear interaction - secondary microseism



Ardhuin 2011

Longuet-Higgins (1950) showed that the unattenuated second-order pressure term in a standing wave pattern, was capable of generating microseisms.



Gualtieri et al. 2014

Conclusion and perspective

- **Dense spatial and temporal sampling** of seismo-acoustic signals, in the oceans and along their margins

  Better detection and localization of small magnitude offshore events (EQ, LP, tremors)

  High resolution crustal imaging and monitoring

Conclusion and perspective

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- DAS and offshore **acoustic and elastic waves** : earthquake, ocean surface gravity wave and microseismic noise

  Applied to other acoustic signals (mammals or marine traffic)

Conclusion and perspective

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  High resolution crustal imaging and monitoring

- DAS and offshore **acoustic and elastic waves** : earthquake, ocean surface gravity wave and microseismic noise

  Applied to other acoustic signals (mammals or marine traffic)

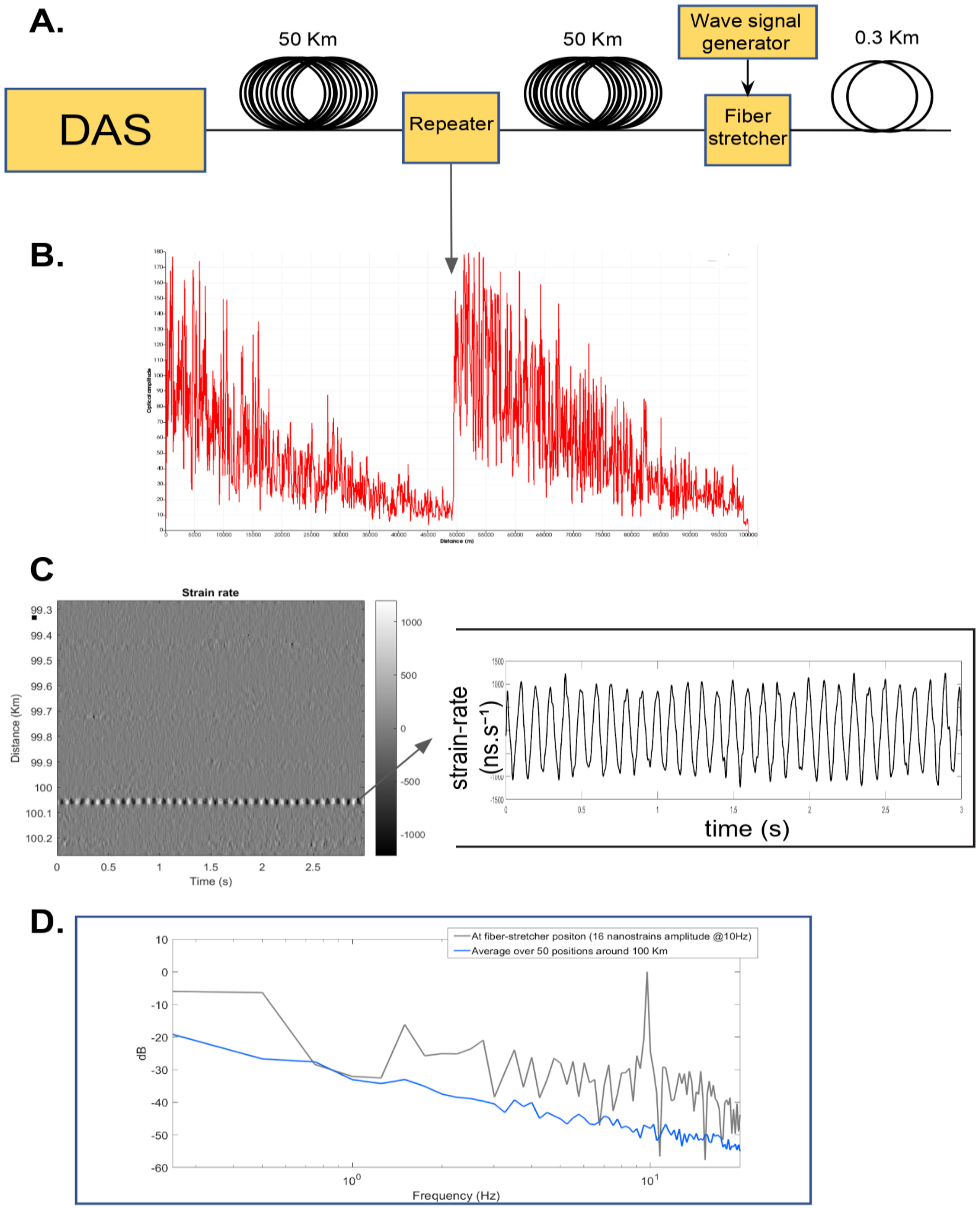
- **Standard range of DAS systems is about 50 km on a standard optical fiber**. This range already opens the ways to many applications, such as the monitoring of active and passive margins, thus encompassing most marine and geologic processes (e.g. subduction earthquakes, landslides, coastal erosion processes).

Conclusion and perspective

Bidirectional amplifier

- Standard range of DAS systems is about 50 km on a standard optical fiber
- Most existing cables were installed in the mid-2000’s and will have to be replaced in the next decade

FEBUS OPTICS
Distributed Optical Fiber Sensing



Conclusion and perspective

- **Dense spatial and temporal sampling** of seismo-acoustic signals, in the oceans and along their margins

  Better detection and localization of small magnitude offshore events (EQ, LP, tremors)

  High resolution crustal imaging and monitoring

- DAS and offshore **acoustic and elastic waves** : earthquake, ocean surface gravity wave and microseismic noise

  Applied to other acoustic signals (mammals or marine traffic)

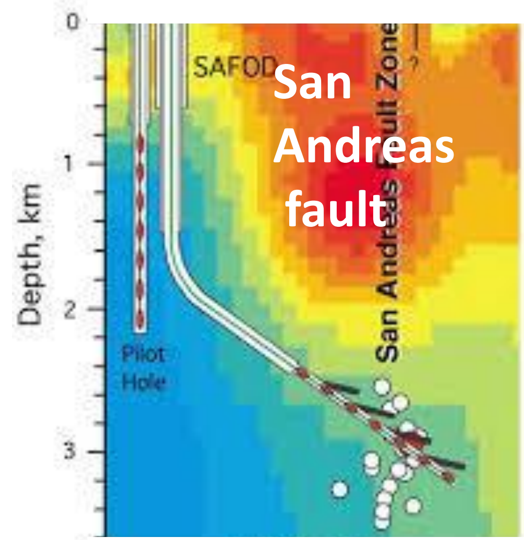
- **Standard range of DAS systems is about 50 km on a standard optical fiber**.

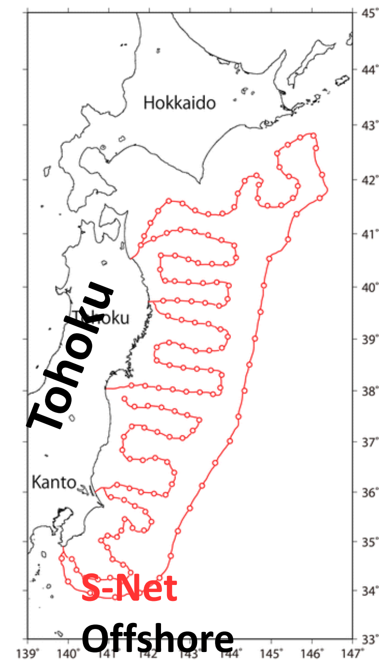
Sladen, A., Rivet, D., Ampuero, J., De Barros, L., Hello, Y., Calbris, G., & Lamare, P. (2019, June 7). Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables. https://doi.org/10.31223/osf.io/ekrfy review Nature - Communication

Instrumentation optique de haute résolution en extrémité de fibre longue pour monitoring géophysique en temps réel en environnement difficile

Pascal BERNARD, IPGP
Guy PLANTIER, ESEO-Angers

IPGP/OVSG : P. Bernard, C. Brunet, R. Moretti, S. Deroussi,
A. Peltier, M. Assaoui, R. Daniel ...
ESEO : G. Plantier, M. Feuilloy, R. Feron,
Ph. Ménard, A. Source, G. Savaton

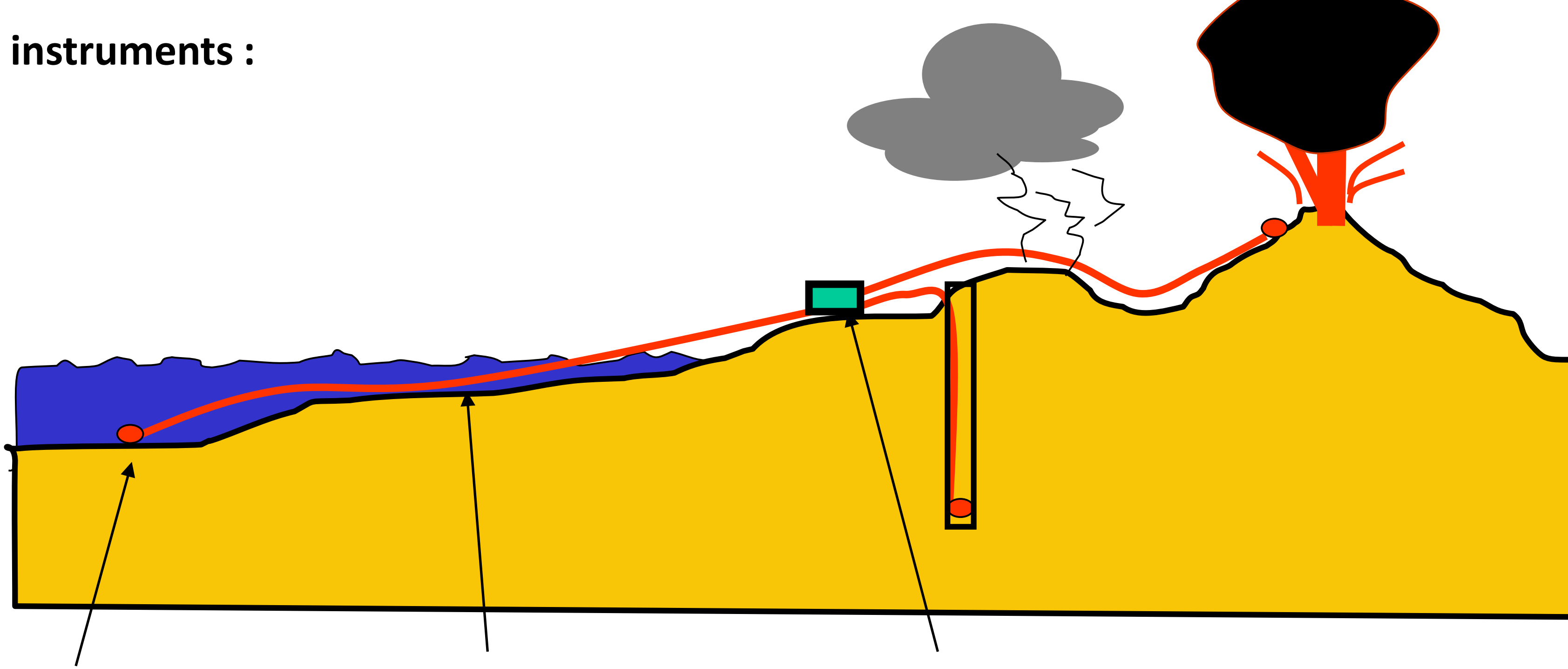




Offshore Observatory Japan

volcanoes, deep boreholes, far offshore, large landslides…
→ difficult or dangerous access, expensive repairs,
high temperature, lightning strikes, ...

Optical instruments :



SENSOR :

Opto-mechanical,

no electronics

LONG OPTICAL FIBER

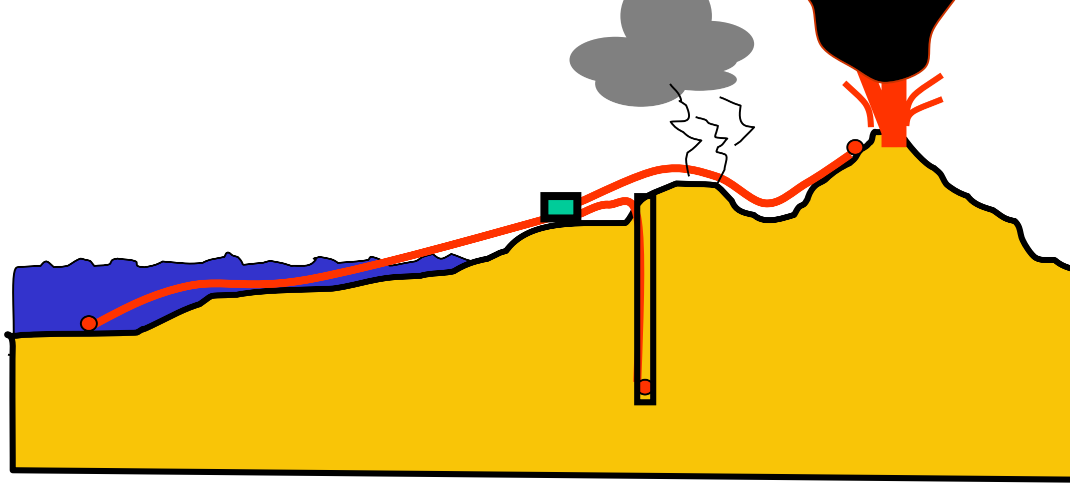
up to 50 km

CONTROL/ACQUISITION :

Remote installation

for natural hazard monitoring in harsh environment:
far offshore, deep borehole, mountain/volcanoes,…

Optical instruments :



+ optical fiber tens of km long

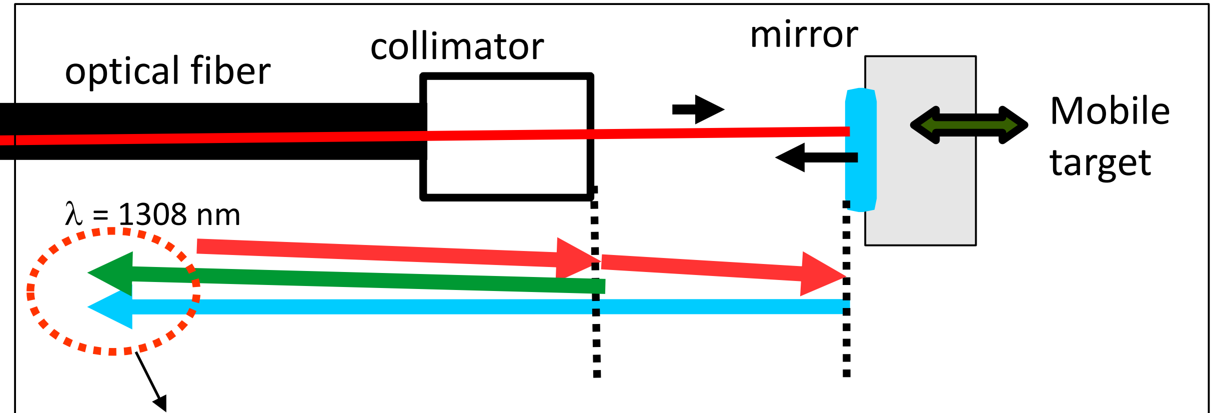
+ stability with time (no electronic drift at the sensor)

+ fiber and sensor unsensitive to EM perturbations (lightning, telluric currents, industrial environment, high voltage power lines…)

+ sensor less sensitive to high temperature (no electronic component) nor very low temperature

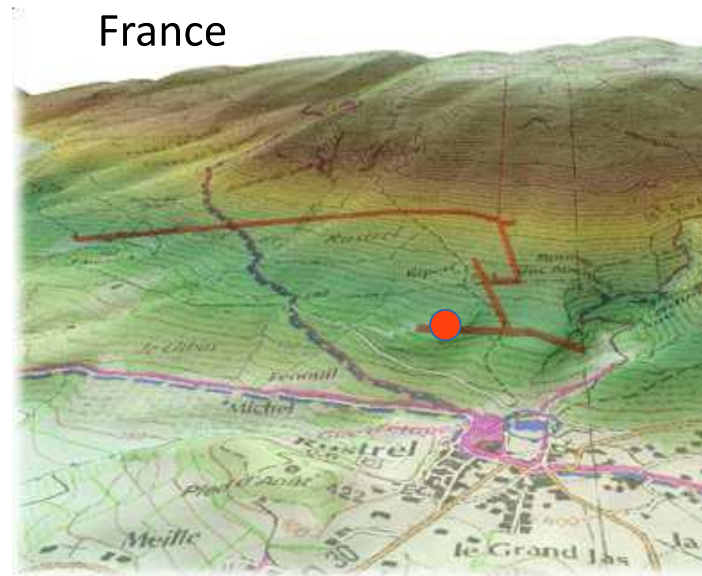
+ sensor simple, small, and robust: no maintenance

+ laser interferometry allows for very high resolution



Fabry-Pérot interferometry:
Interference of the 2 reflected beams
→ high resolution of target displacement

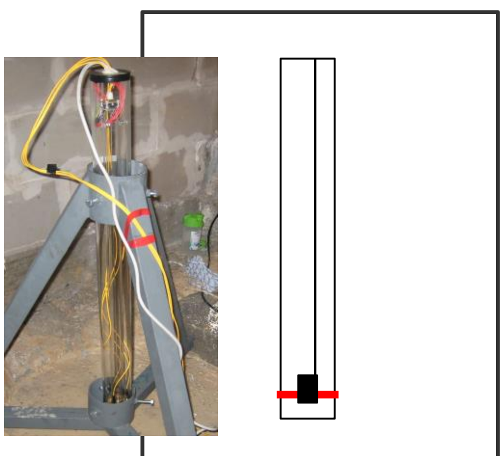
LSBB
Underground Laboratory,
France



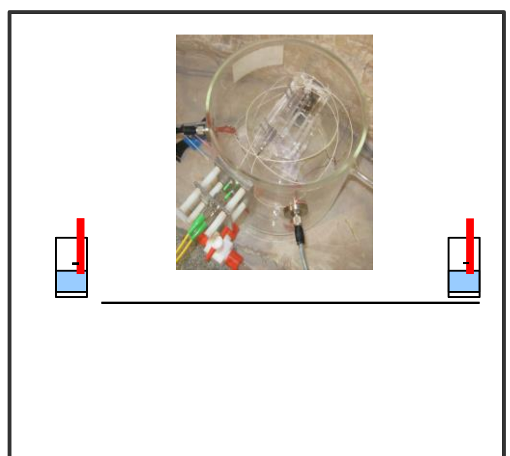
project « LINES » 2009-2012

GMontpellier
IPGP
ESEO-Angers
LOSE-Toulouse
LSBB

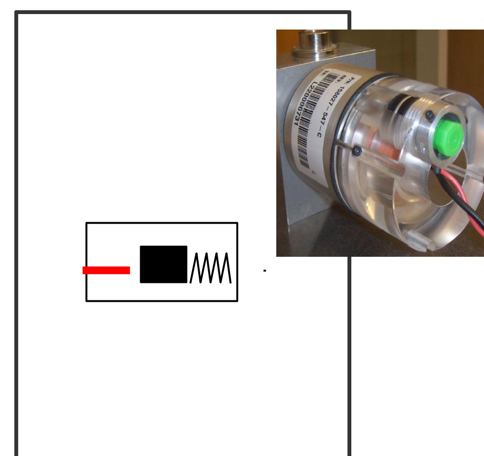
Borehole
Tiltmeter 1 m



Long base
Hydrostatic tiltmeter
150 m

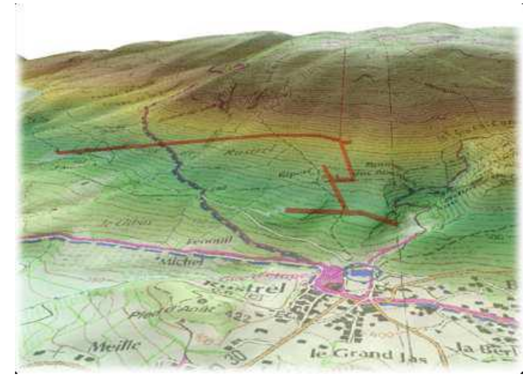


Geophone 2 Hz

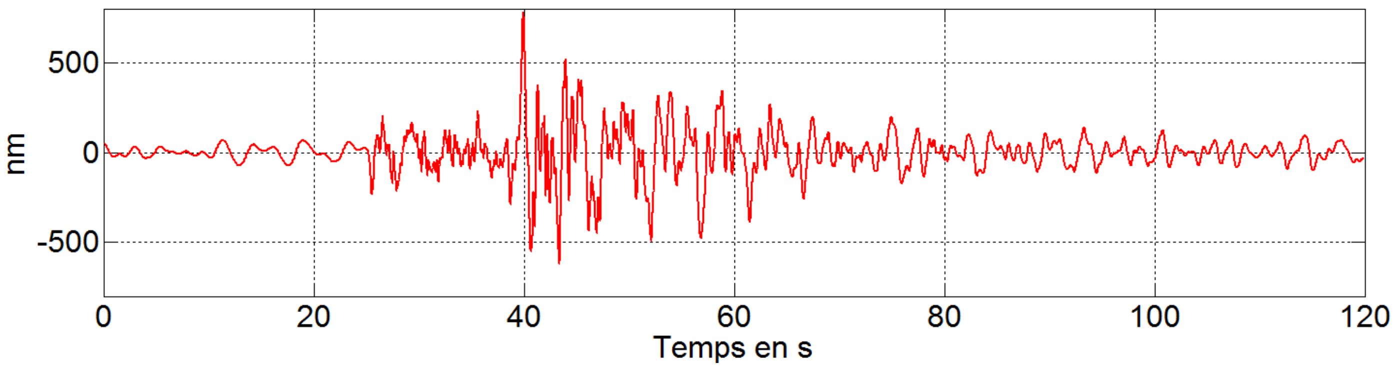


Test of the optical seismometer
2 Hz geophone, 1 component
3 km optic fiber

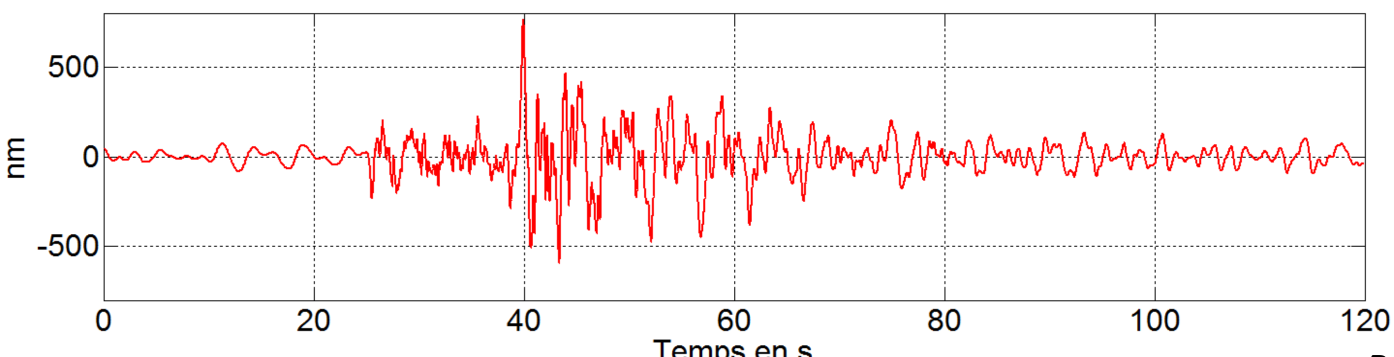
Rustrel, LSSB Laboratory,
Southern France
2009-2012



earthquake M=4, d=100 km - 0.1-20 Hz



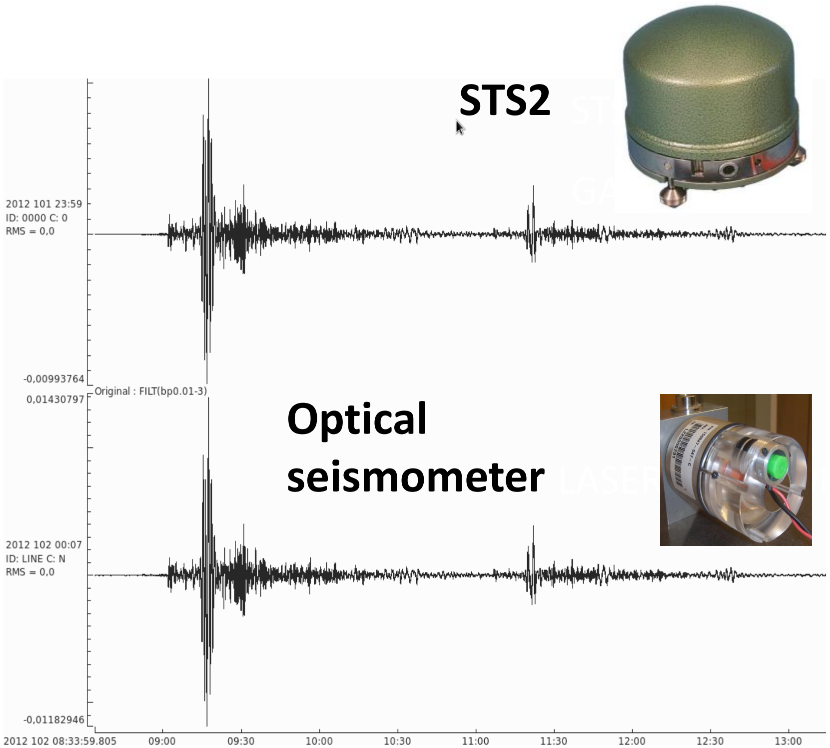
STS2



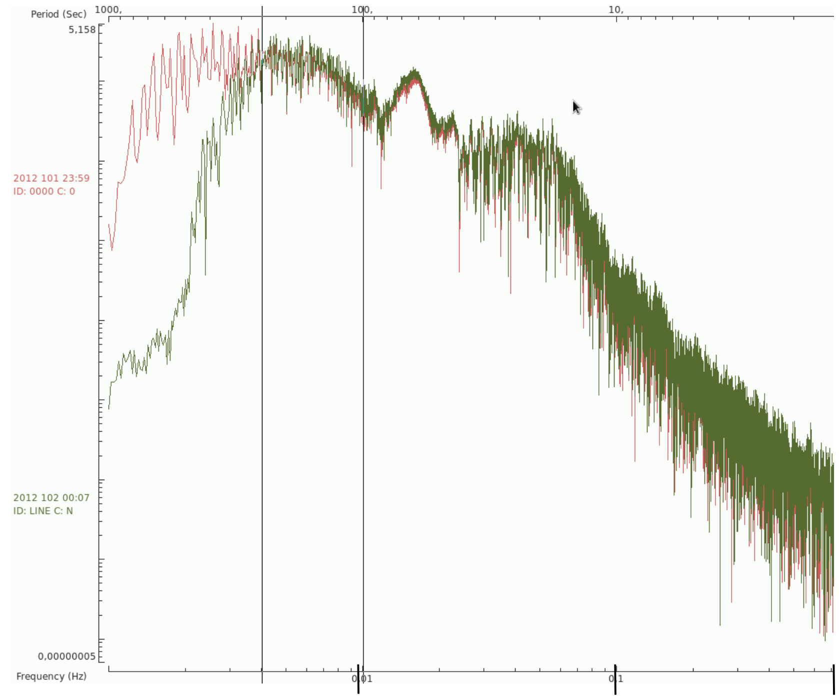
Optical seismometer

Bernard et al., SRL, 2019

N displacement (m) for the **2012 Sumatra M=8.7 earthquake at LSBB**



4 hours



0.01 0.1 1 Hz

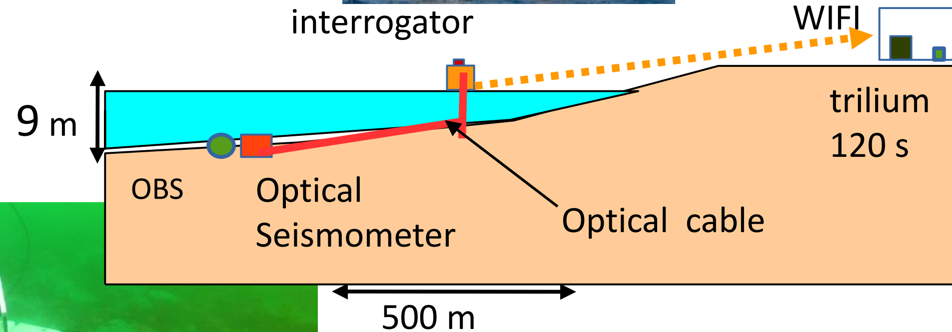
Long period surface waves

250 s
with a 2 Hz geophone !

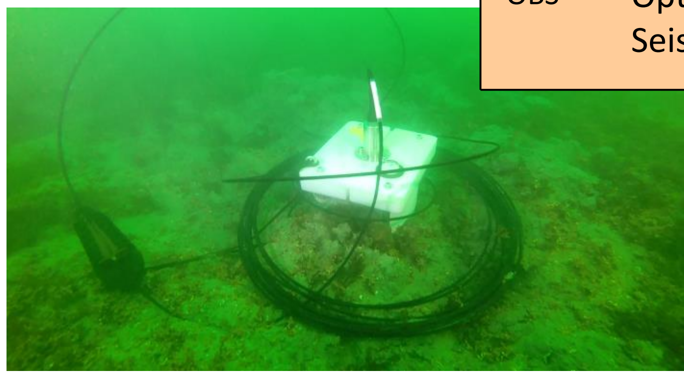
Test of Optical seismometer
Offshore
2 Hz, 3 component geophone

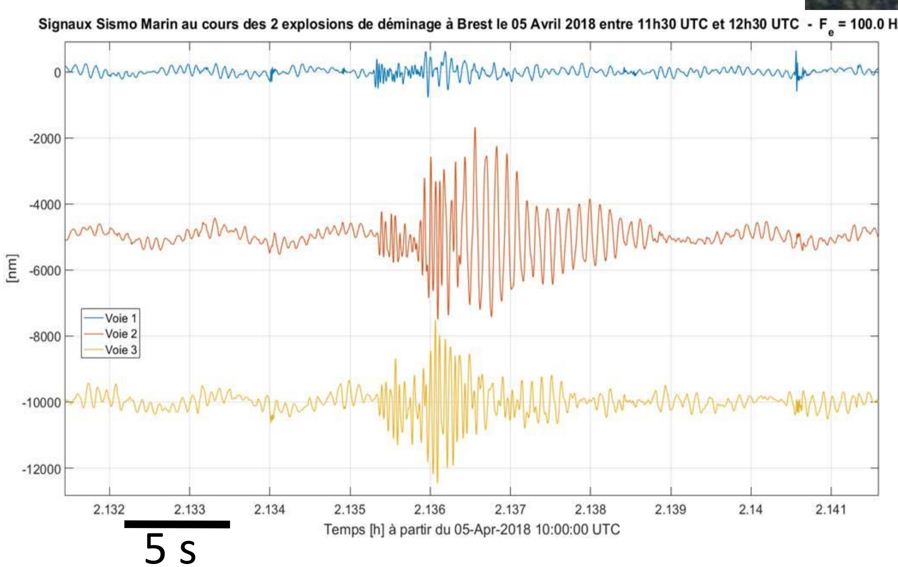
Lanveoc, Sea Test Base, Brittany,
March-November 2018
SATT-Ouest Valo

OUEST VALORISATION
Ressources d'innovation



IPGP design

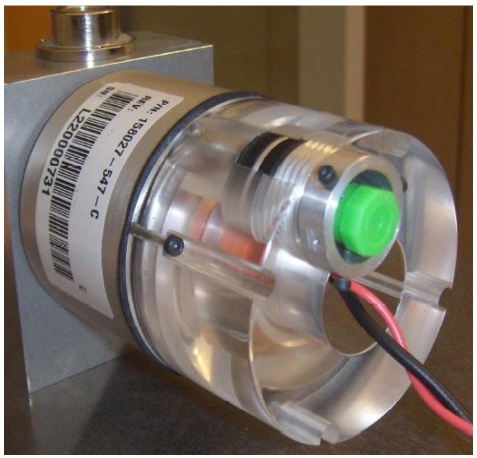




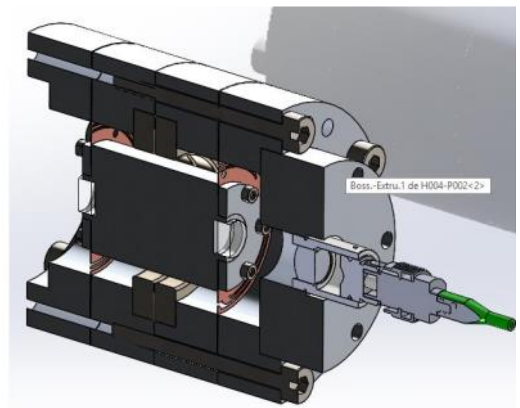
Mine clearing blast

Bernard et al., SRL, 2019

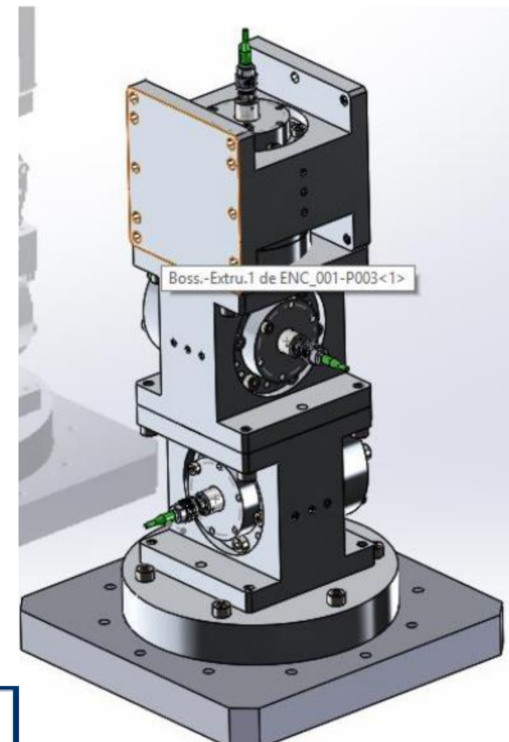
Sensor :
No levelling
→ omnidirectional
→ requires to shift the resonance from 2 Hz → 10 Hz



Customized
Sercel 2 Hz geophone



HIPERSIS ANR project:
seismometer 10 Hz



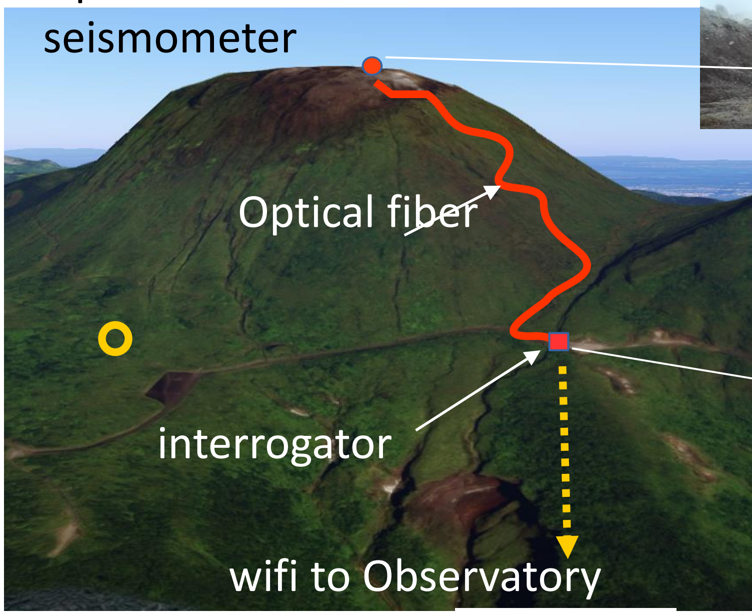
3 component

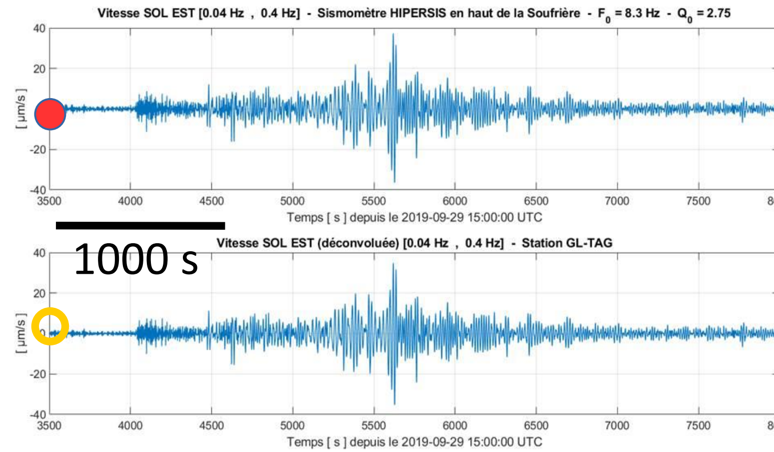
Optical seismometer
10 Hz, 3 comp, Fiber 1.75 km long
La Soufrière Volcano, Guadeloupe

since 21 September 2019

HIPERSIS

Optical seismometer

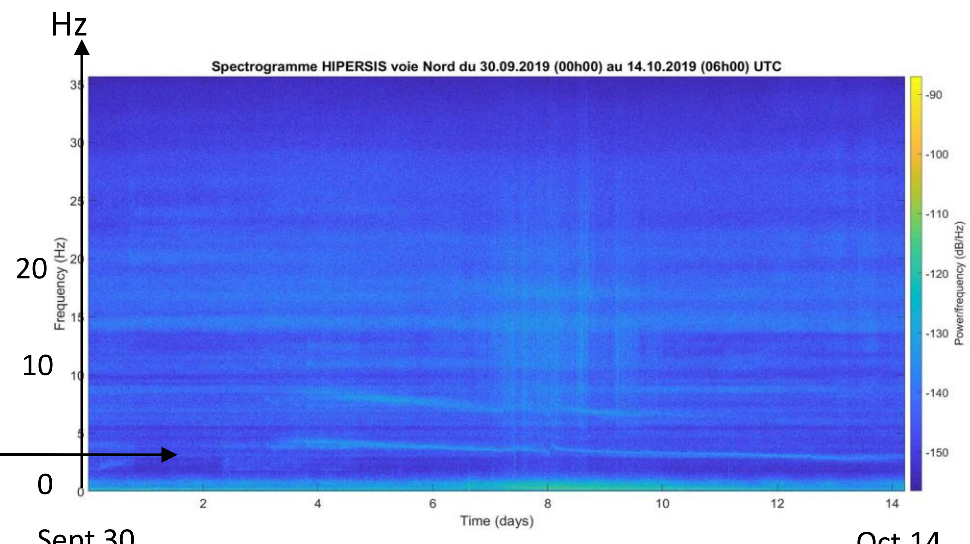




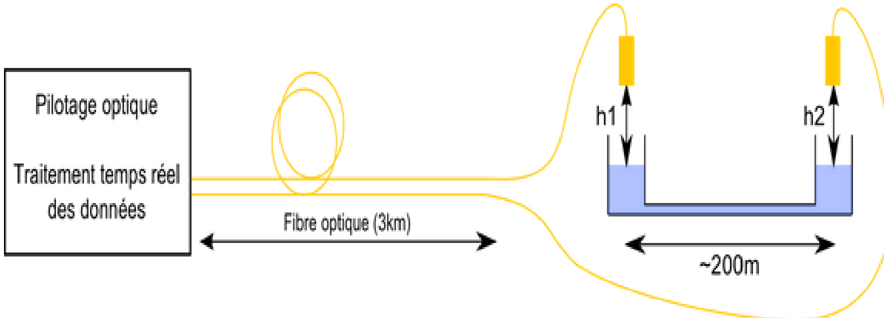
M=6.8, Chile 29th sept. 2019

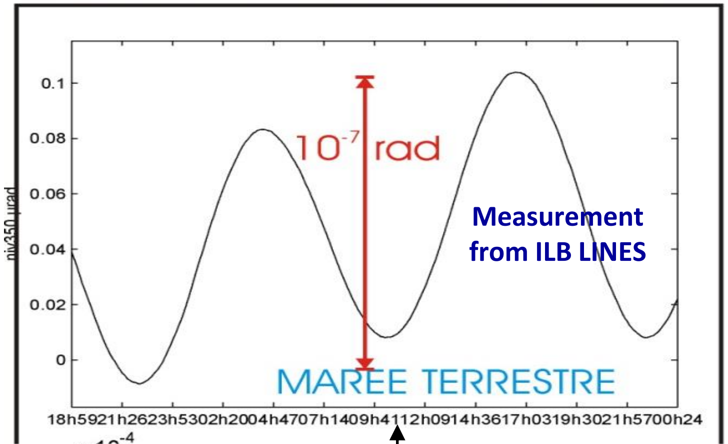
signal → period up to 30 s !

~ 3 to 4 Hz resonance

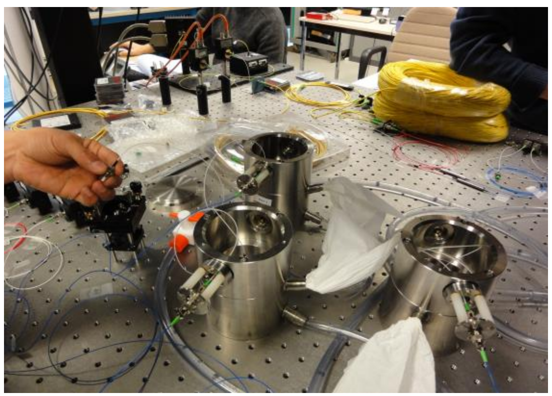


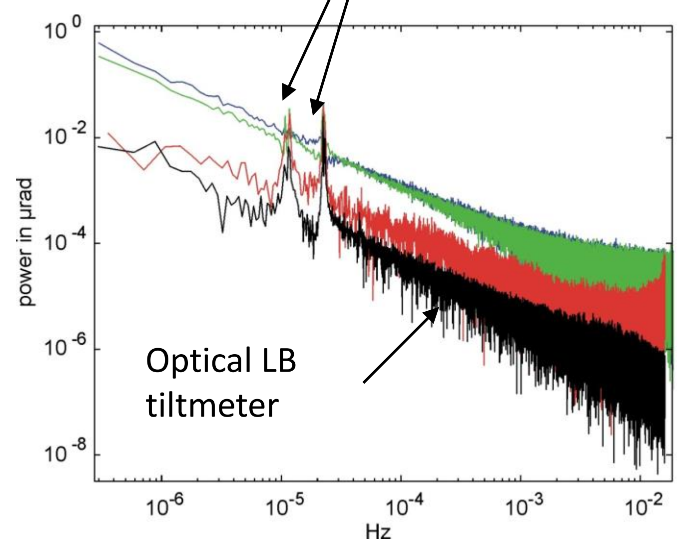
long base optical tiltmeter
ENS – F. Boudin

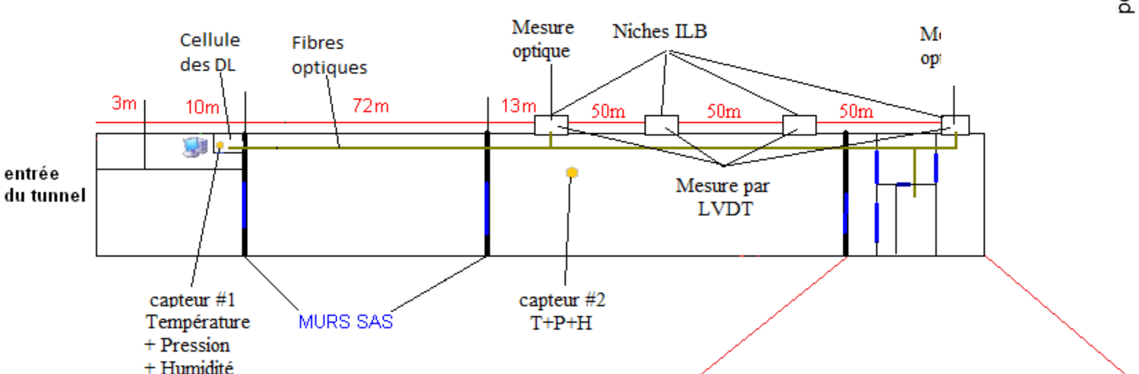




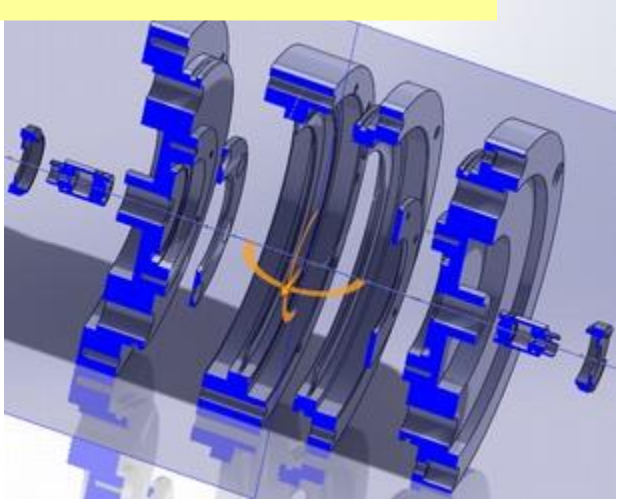
Earth tides





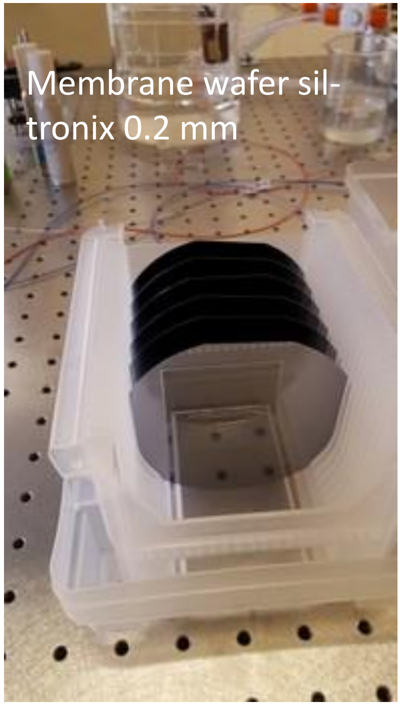


design du pressiomètre optique sous-marin

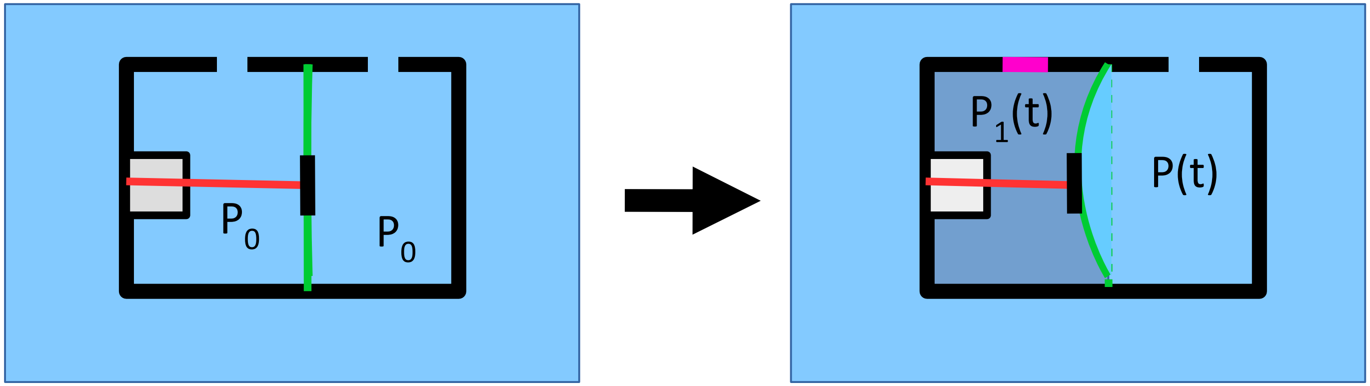


pression différentielle entre deux compartiments séparés par une membrane déformable

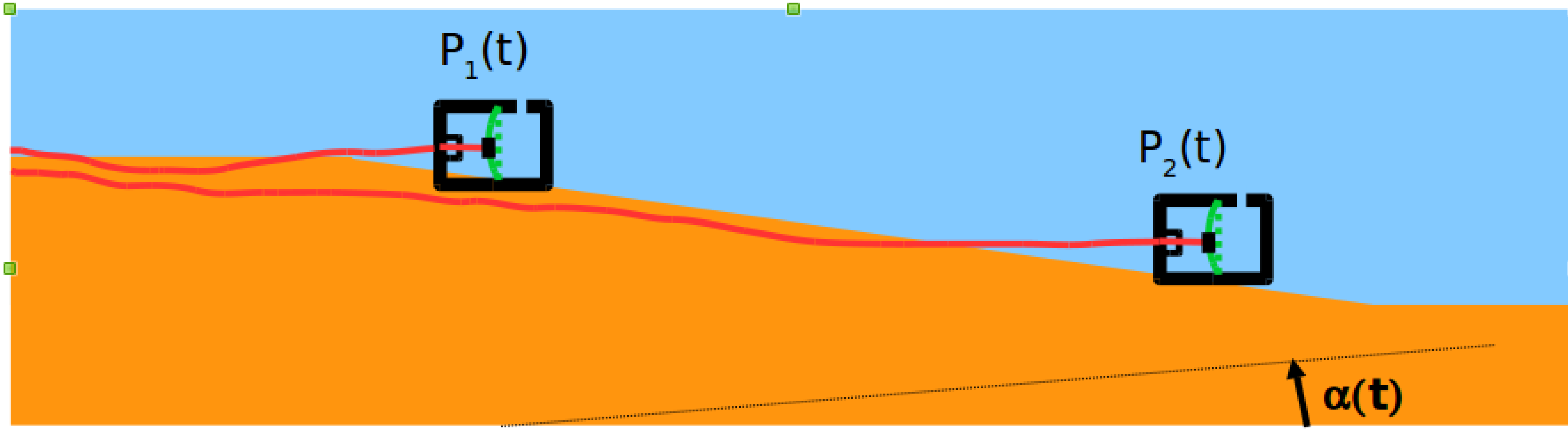
membranes en cours de test et de modélisation:
Sensibilité nominale :
d=1 μm pour 0.1 mm d'eau de ΔP
soit d=1 nm pour $\alpha=10^{-9}$ et L=100 m

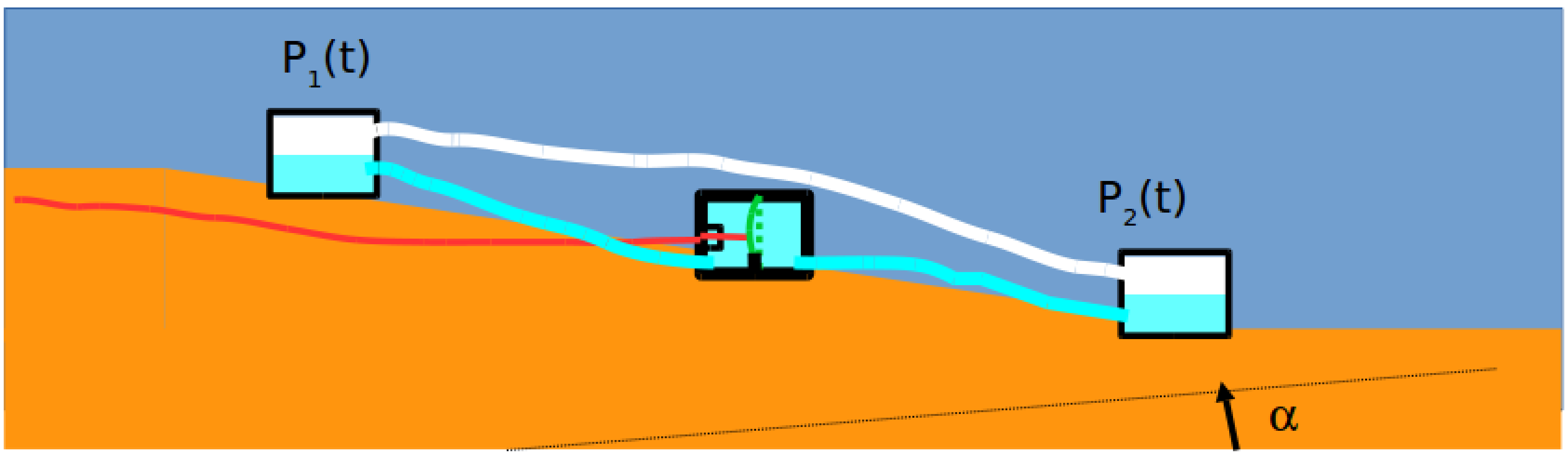


- problème de l'équilibrage après installation pour travailler en faible déformation de la membrane

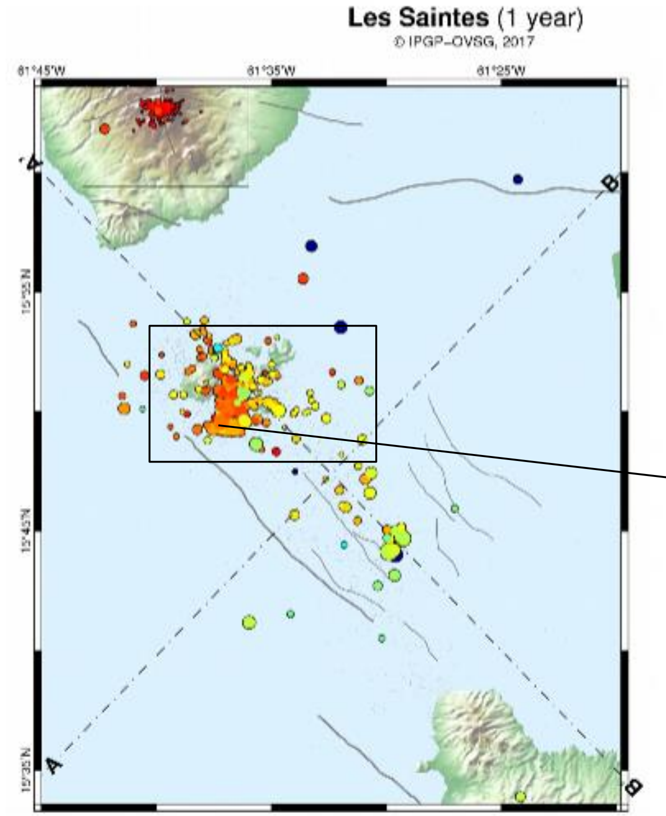


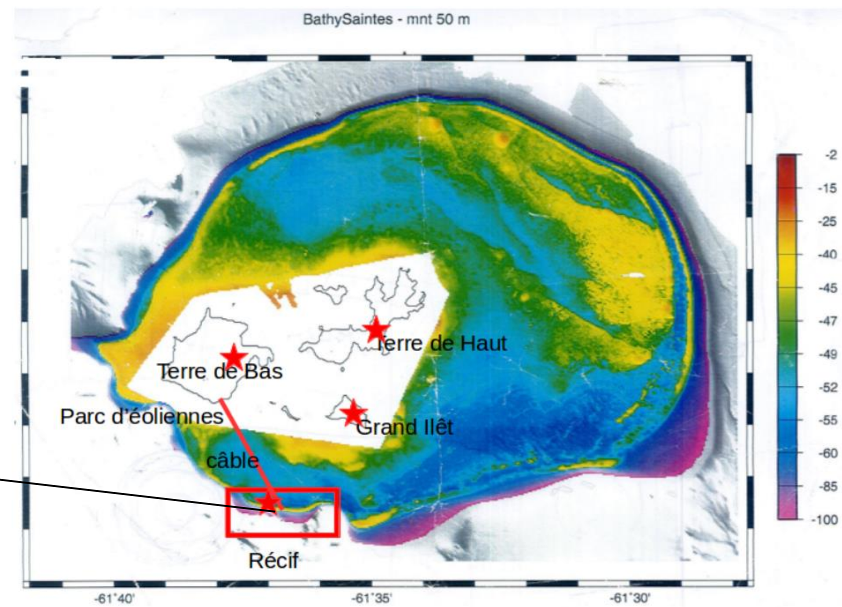
Design for ocean bottom installations

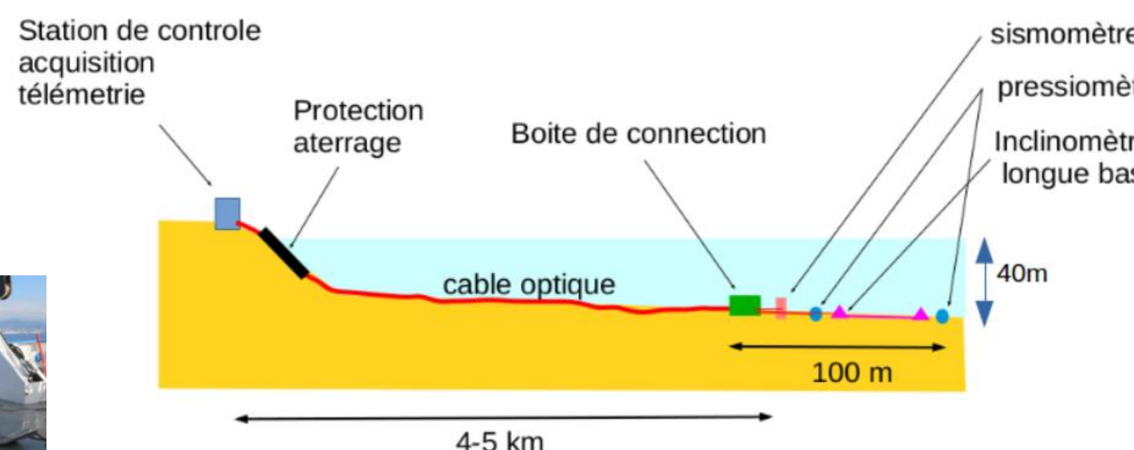




Microseismicity of Les Saintes islands - PREST interreg
offshore installation of
optical seismometer, pressiometer, and tiltmeter
June 2020







Plow GEOAZUR

Qualification in pilot sites prone to volcanic and seismic hazard

Volcano - 2020-2022

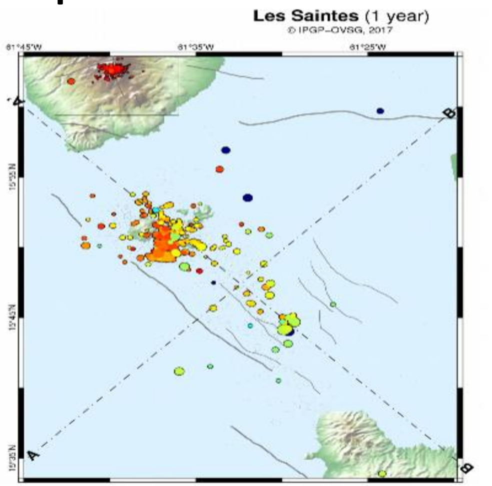
La Soufrière de Guadeloupe

seismometer antenna
strainmeter, titlmeter,
microphone, ...
.

Offshore seimicity- 2021-2022

Les Saintes, Guadeloupe

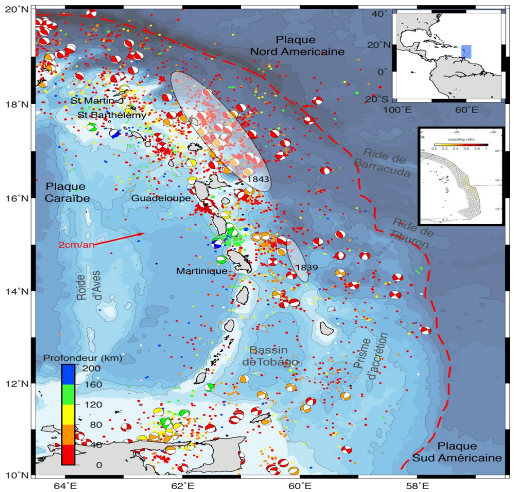
hydrophones
seismometer
antenna/DAS



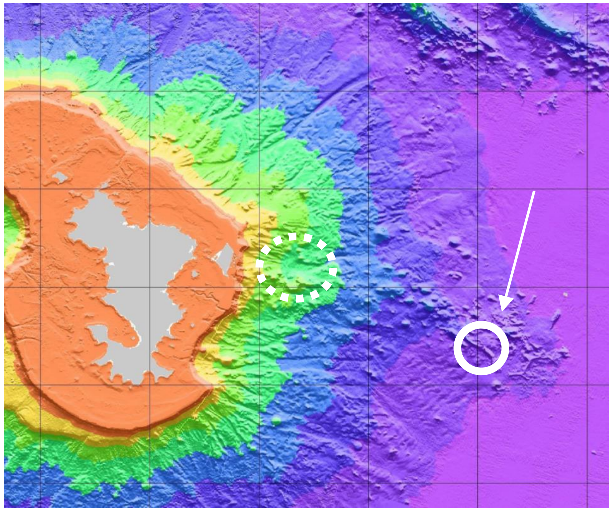
Far Offshore 2021+ coll. IFREMER

Lesser Antilles

Coupling & Mega-earthquakes



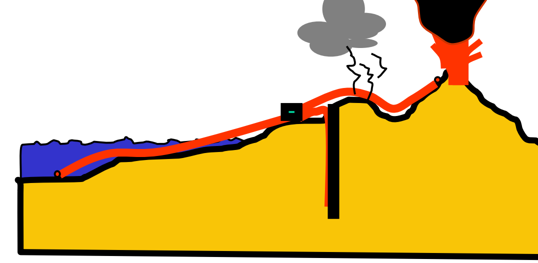
Mayotte :
New born
Submarine
Volcano



+   other earthquake and volcano targets : Japan, Chile, Italy, Greece, Turkey,...

CONCLUSION

Innovative optical Geophysical sensors



SENSOR

- no electronics
- no power need
- resistant high and low T
- unsensitive to EM

→ robust, no maintenance

OPTICAL CABLE

- 50 km - more?
- unsensitive to EM

INTERROGATOR

- resolution 0.03 nm
- 1.5 W / channel

HIGH RESOLUTION OPTICAL INSTRUMENTS

-seismometers (ESEO-IPGP)

Bernard et al., SRL, 2019

- borehole tiltmeter (GM)

- long base tiltmeter (ENS)

- pressiometer (ENS)

- strainmeter

- hydrophone

- microphone

- pressiometer, T

- geochemical sensors.

etc...

Antilles (IPGP Observatory):

- La Soufrière Volcano, Guadeloupe
- Les Saintes seismicity – offshore
- subduction far offshore (*IFREMER*)

Mayotte (IPGP Observatory) :

- new-born submarine volcano (2018) (*IFREMER*)

La Réunion Volcano (IPGP Observatory)

Other volcanic and seismic regions

(Italy, Japan, Chile, Greece, Antartic...)

Marine Biology; oceanography

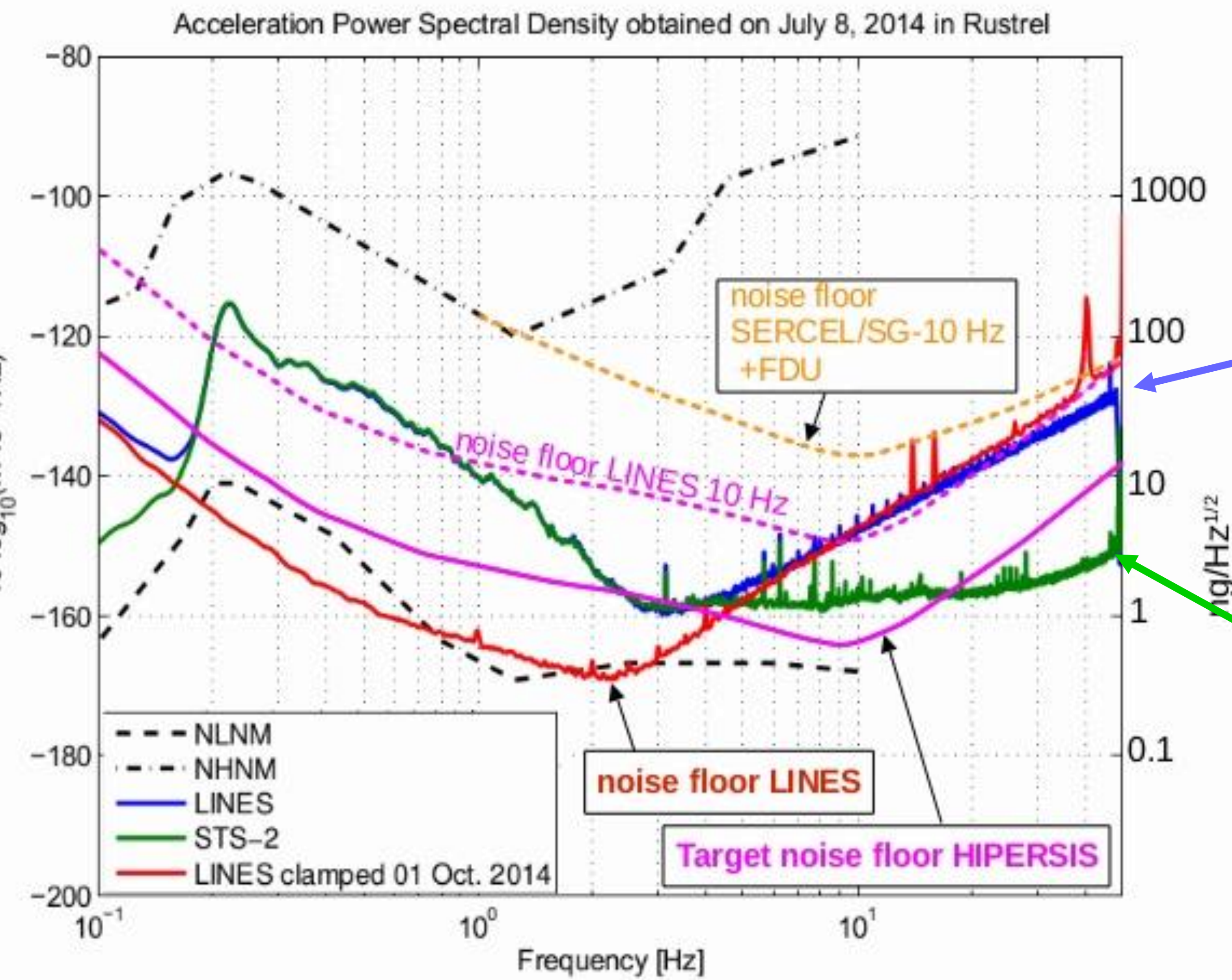
Marine mammals, physical parameters.

Geo-industries:

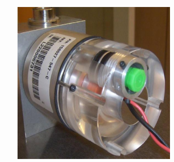
geothermy,mining (*INERIS*), oil/gas production, storage

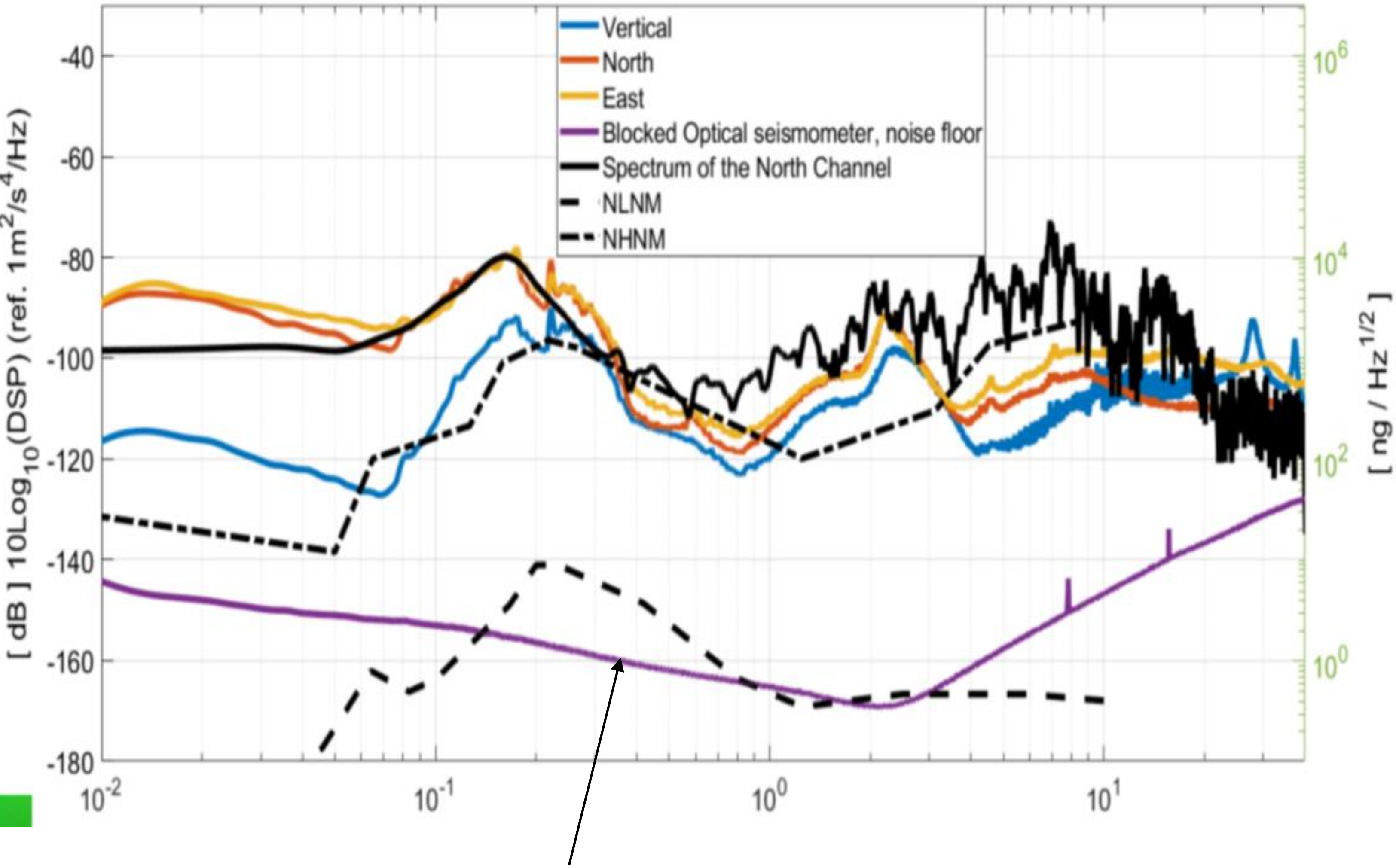
Building industry sector:

offshore wind farms, bridges,dams ...

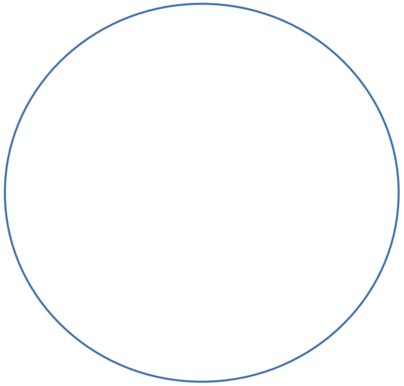


Acceleration Power Spectral Density obtained on July 8, 2014 in Rustrel
−80
−100
−120
−140
−160
−180
−200
1000
100
10
1
0.1
noise floor
SERCEL/SG-10 Hz
+FDU
noise floor LINES 10 Hz
noise floor LINES
Target noise floor HIPERSIS
NLNM
NHNM
LINES
STS−2
LINES clamped 01 Oct. 2014
10^-1
10^0
10^1
Frequency [Hz]

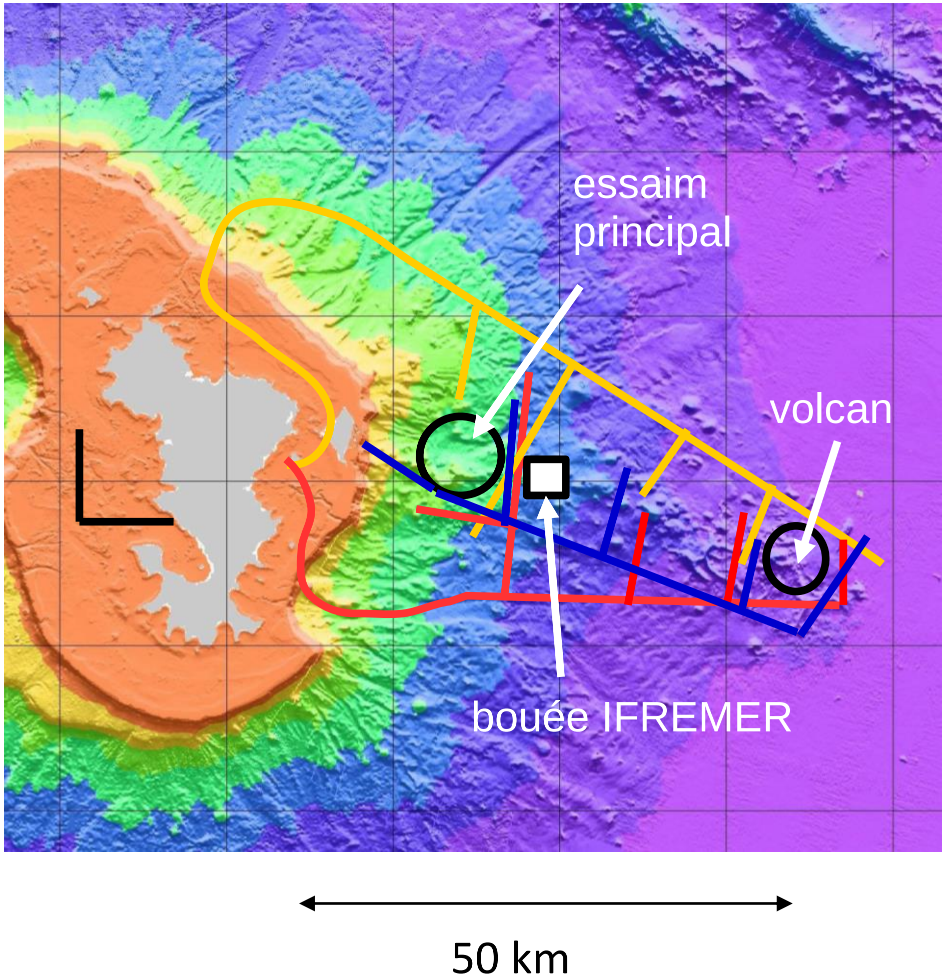




Noise floor of the optical interrogator



Elements de reflexion pour un Observatoire sous-marin temps-réel à Mayotte



- Cable sous-marin : 25 ke/km
  100-200 km
- Temps bateau cablier : 50 ke/jour
- Aterrage ?
- instrument : 50-200 ke par sites

Cablage instruments fond de mer

4 possibilités:
1. Aterrage :
- telecom nord
- telecom sud
- telecom petite terre ?

2. Bouée IFREMER

Capteurs : association
→ électriques (commerciaux)
→ optiques
- sismomètres
- extensomètres
- inclinomètres
- hydrophones
- pressiomètres
- chimie ? …

+ système DAS (sur aterrage)

Sur la bouée :
Capteurs optiques pour longues distances

LOFHIG

Generic work on the opto-electronic system

-Real time algorithm adaptative deconvolution (linear), AI (non linear correction)
-New optical architecture and modulation for long distances > 50 km
-Design custom system for merging DAS techniques and our optical arrays

Improving the optical seismometer of HIPERSIS

- miniaturization for deep borehole applications
- long period seismometer
- strong motion accelerometer

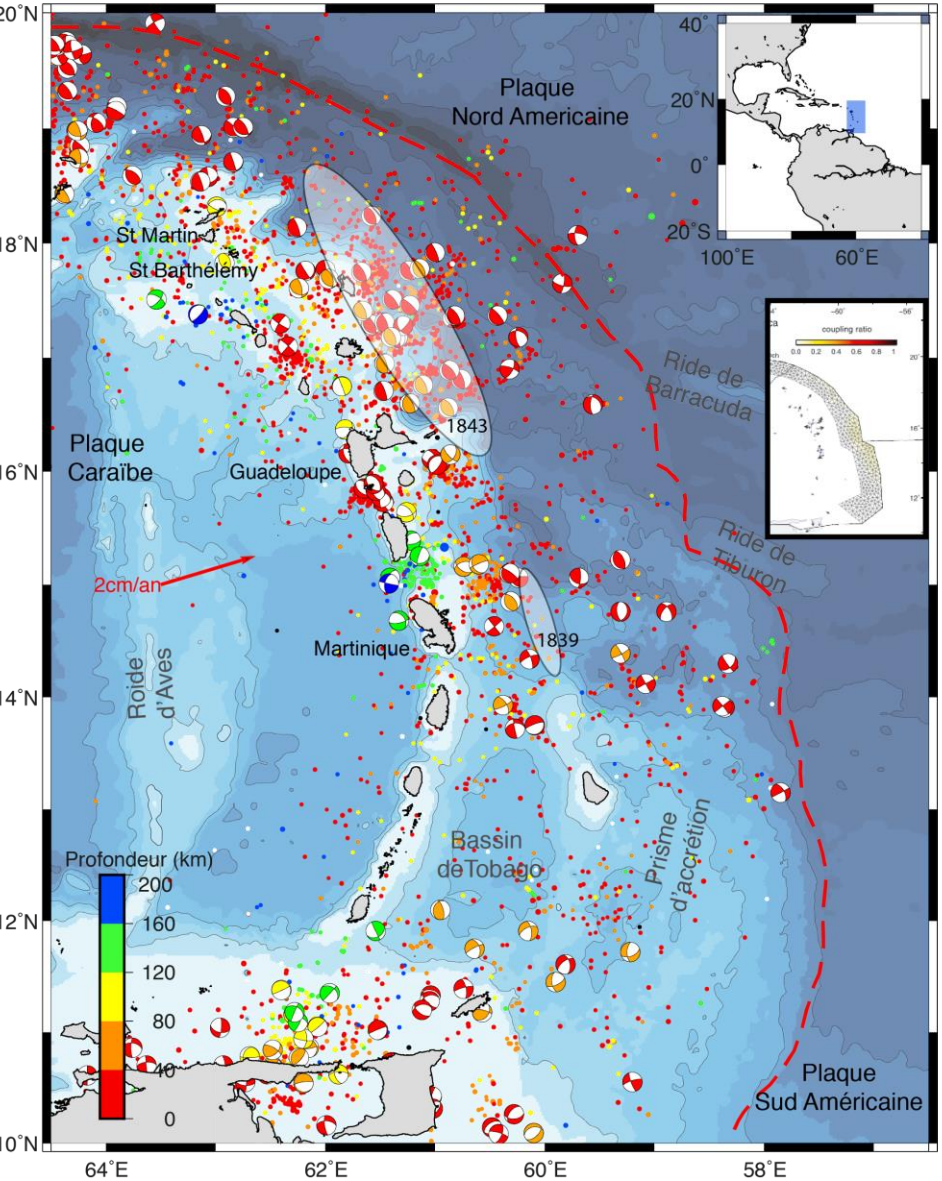
Design and construction of new sensors - TRL 3 to 6

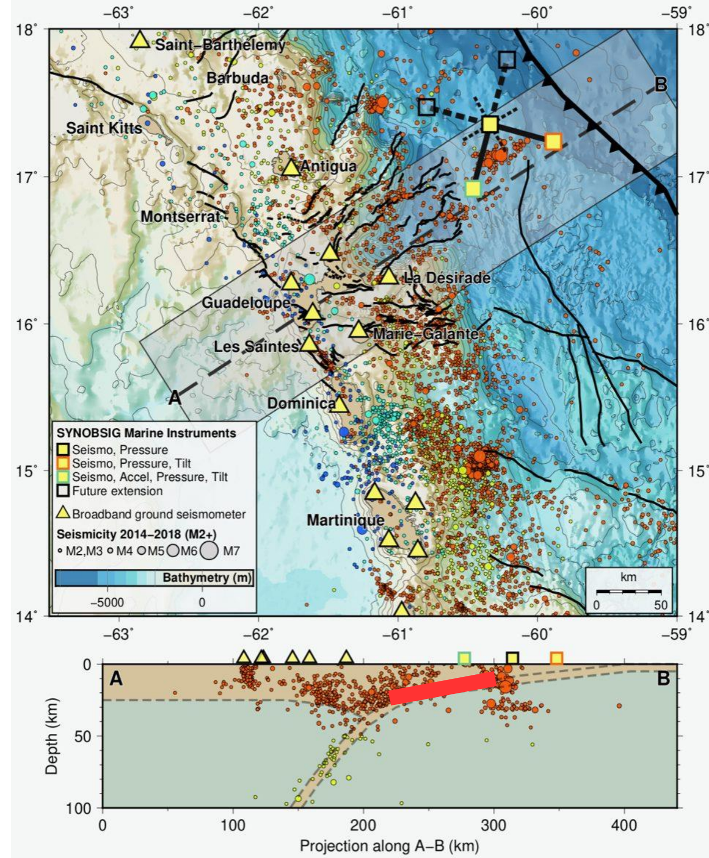
-Hydrophones
-Strainmeters
-Tiltmeters
- Pressiometers
-Gradio-gravimeters
-Geochemistry, ...
...etc...

Intellectual Property – Possible patents

ESEO, IPGP, ENS
SATT-Ouest, Valorisation CNRS, Valorisation CNRS

Future optical instrumentation offshore ?





Offshore Seismological targets in Caribbean:

- with **landing cables**
  5 km → 50 km →?200 km

- with **cable on buoys**
  IPGP-ESEO-IFREMER

IPGP

- Concept and design of new instruments
- Comparison with commercial instruments
- Installation in pilot sites
- Integration to observatories for real time monitoring
- Data analysis and interpretation
- Modeling of dynamic processes

ESEO

- seismometers : self-calibration systems
- opto-electronics, laser Diode, (P, T), long distance
- fusion of DAS with the optical seismometer
- digital and analog hardwares (DSP, FPGA)
- embedded artificial intelligence

ENS :

- construction of tiltmeters and gravimeters