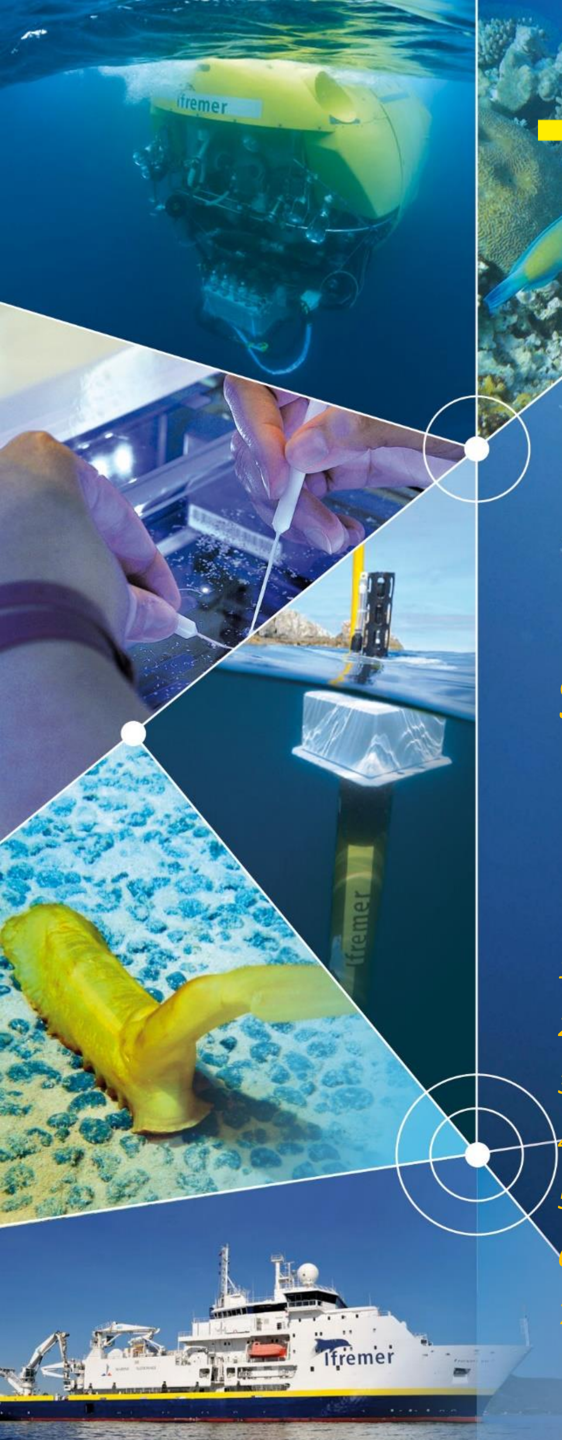

Marine techniques for geodetic modelling

S. Murphy[1]
P. Garreau[2], M. Palano[3], G. Cappelli[4], M. Arhant[5], M. Terzariol[1], L. Quetel[4], P. Jousset[6], G. Riccobene[7], G. Currenti[3], and M.-A. Gutscher[1]

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[2]*LOPS, Ifremer, Plouzané, France*
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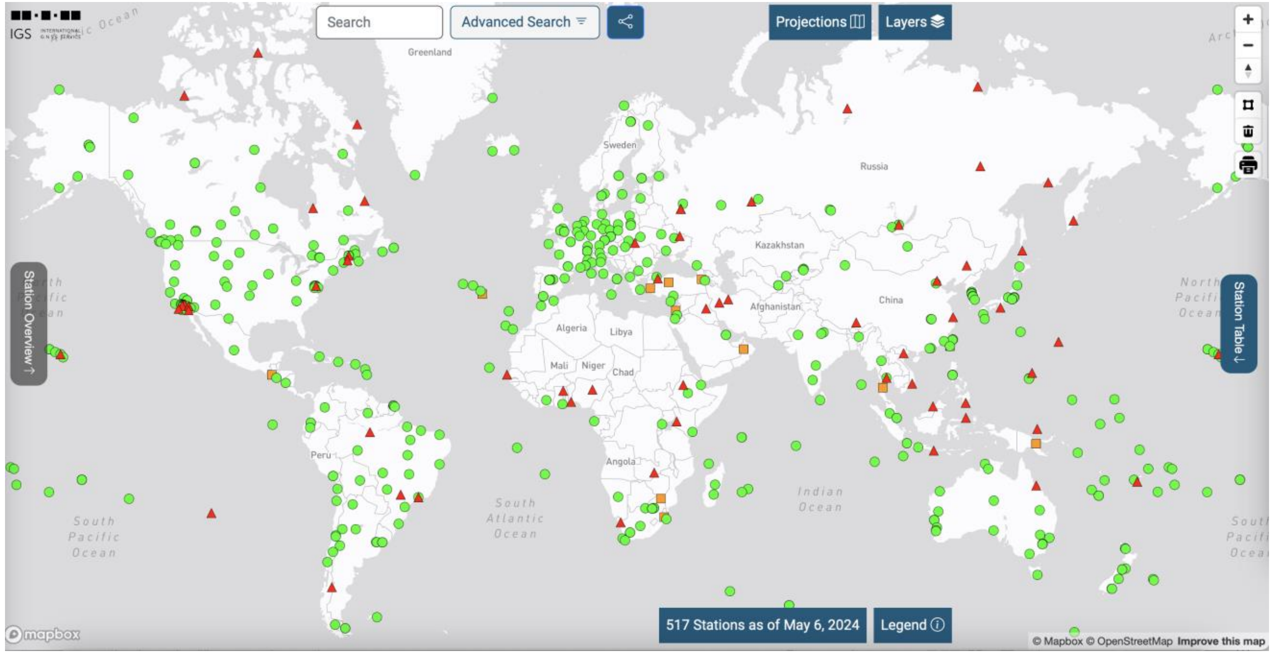
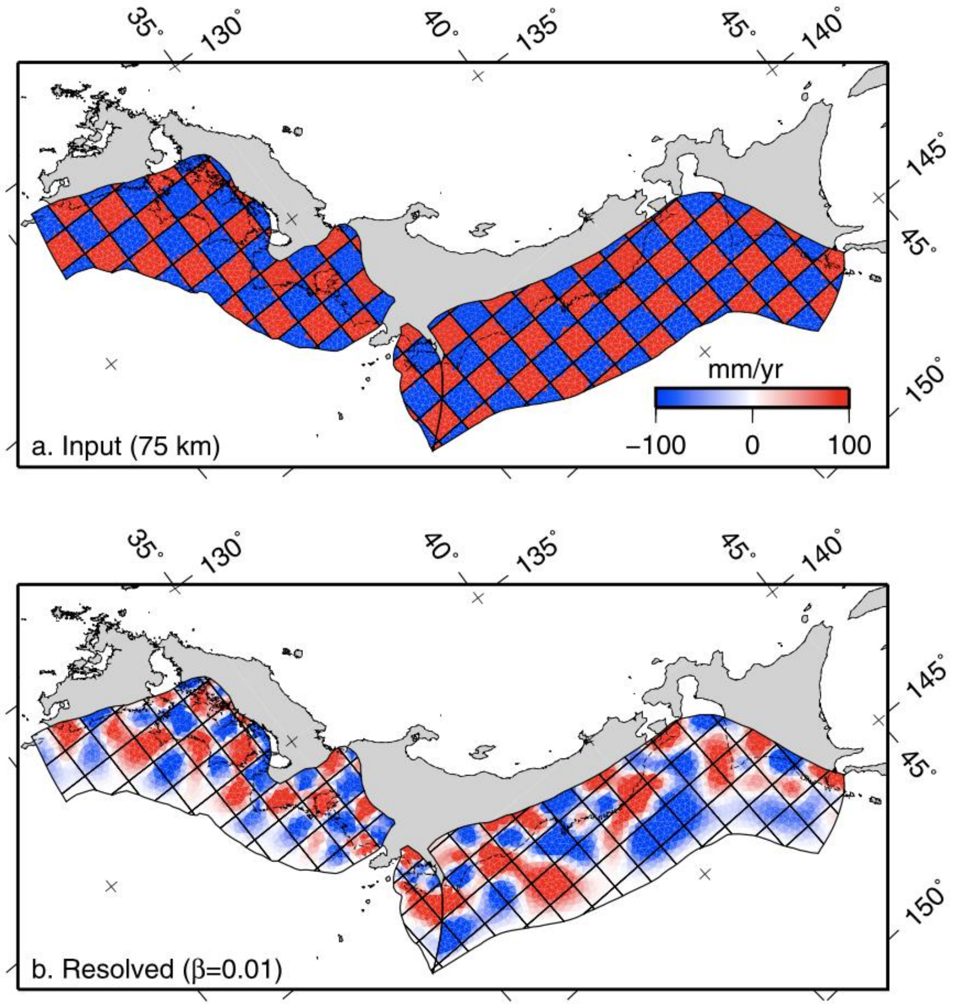
[4]*IDIL Fiber optics, Lanion, France*
[5]*SMASH, RDT, Ifremer*
[6]*Geo-Forschungs Zentrum, Potsdam, Germany*
[7]*INFN - LNS, Catania, Italy*

Motivation

Location of geodetic networks are mostly on land



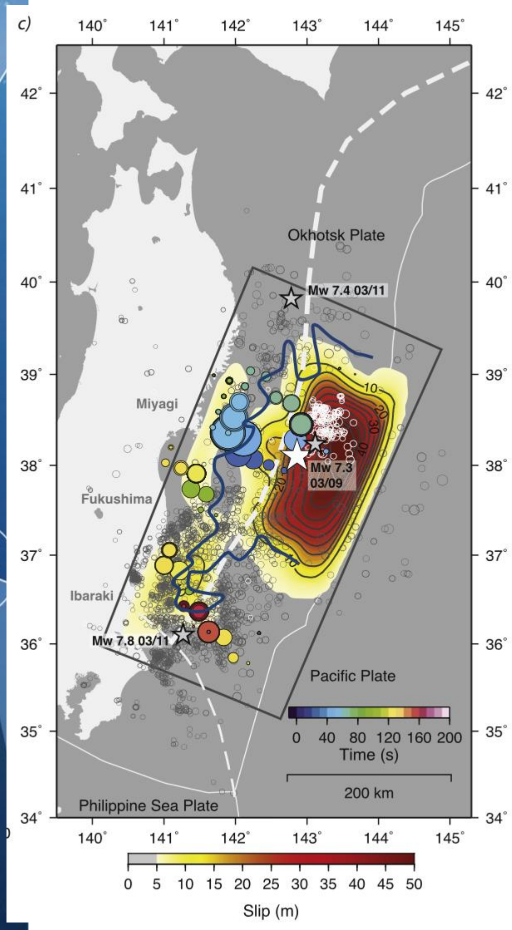
International GNSS Service



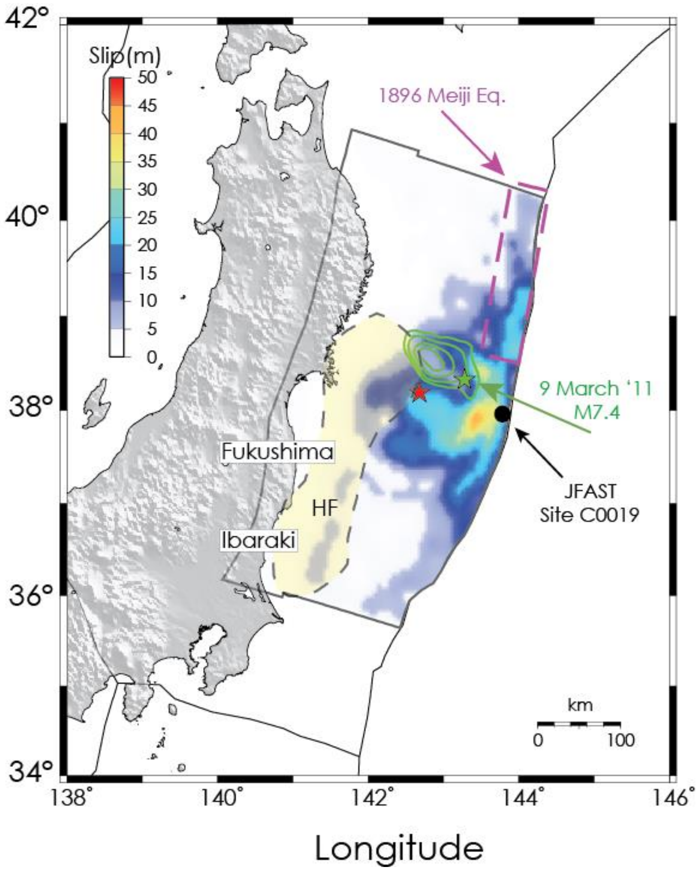
Loveless and Meade, JGR, 2010

Motivation

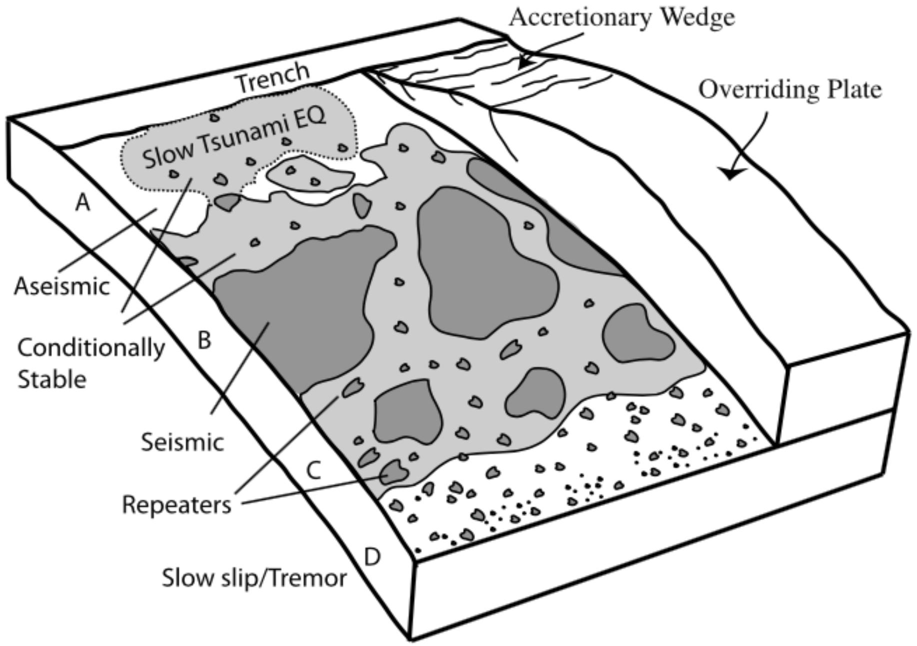
- Large amount of unexpected slip in trench for Tohoku earthquake
- Near surface slip is imporant for tsunami hazard



Satriano et al., 2014



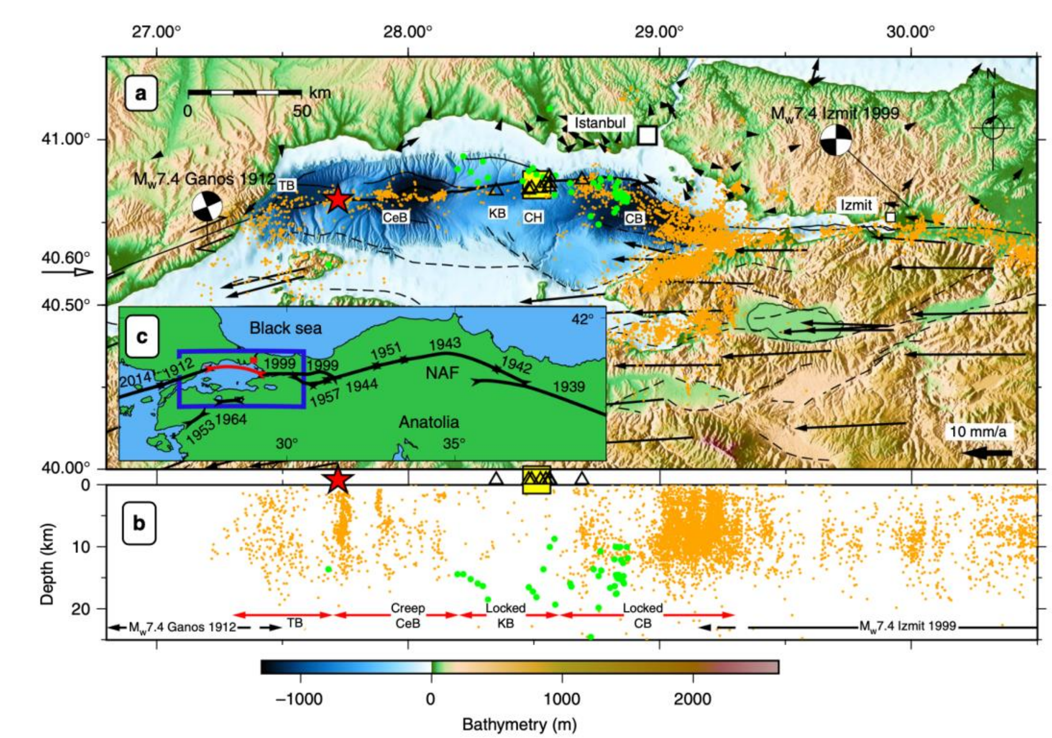
Romano et al., 2014



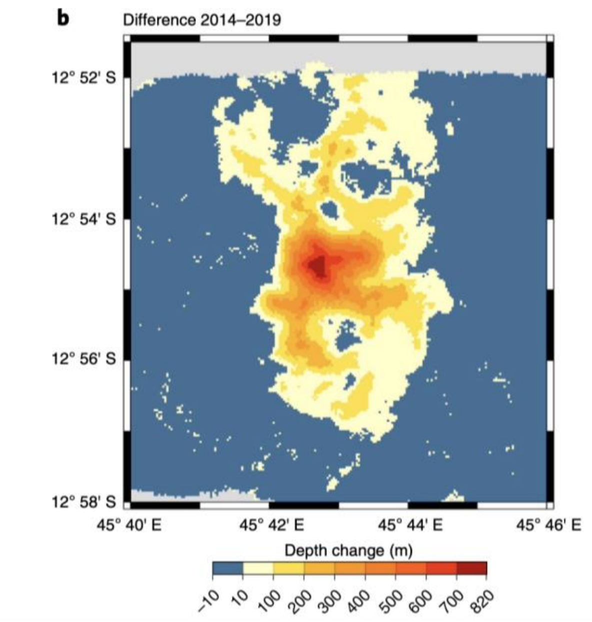
Lay et al., 2012

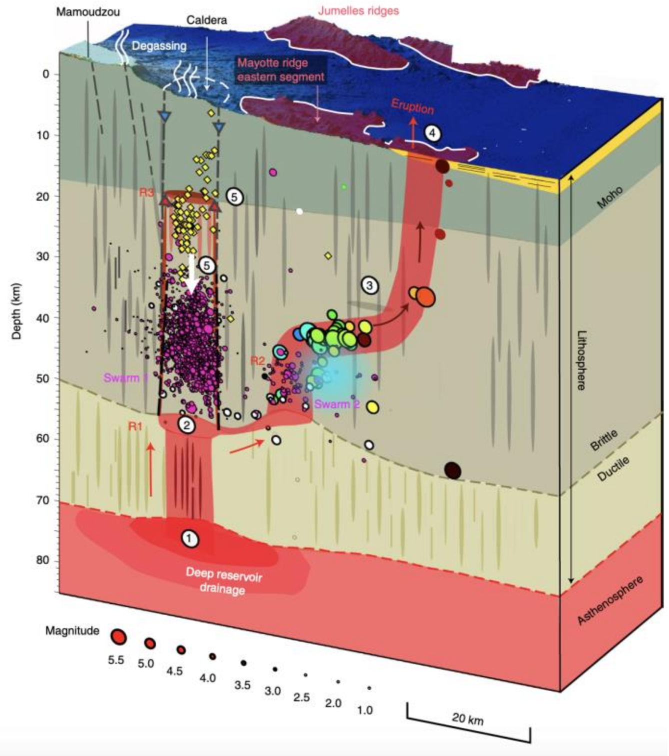
Motivation

- Need to identify locked and creeping patches on strike-slip faults
- Deformation on submarine volcanoes



Lange et al., 2019

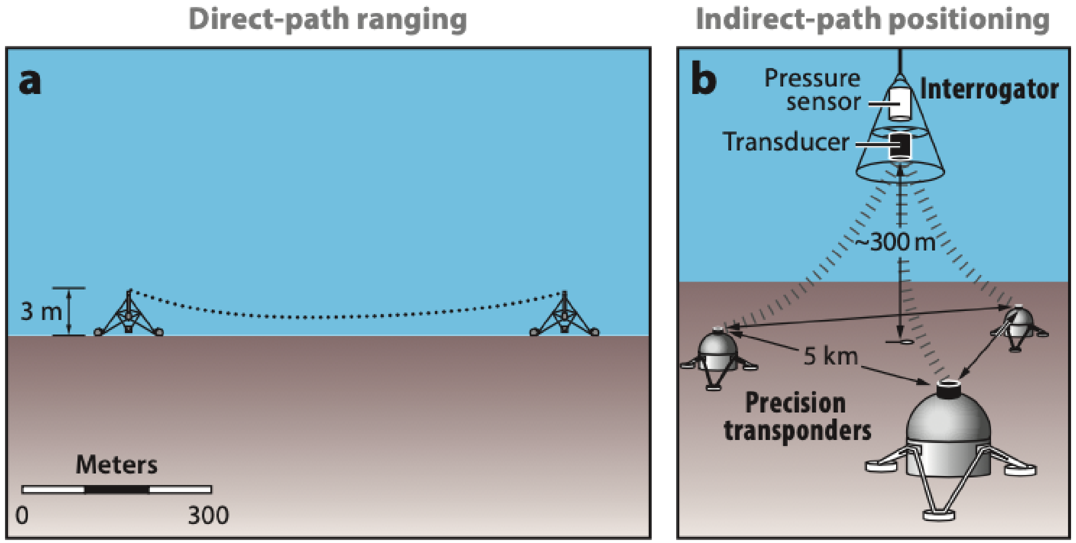




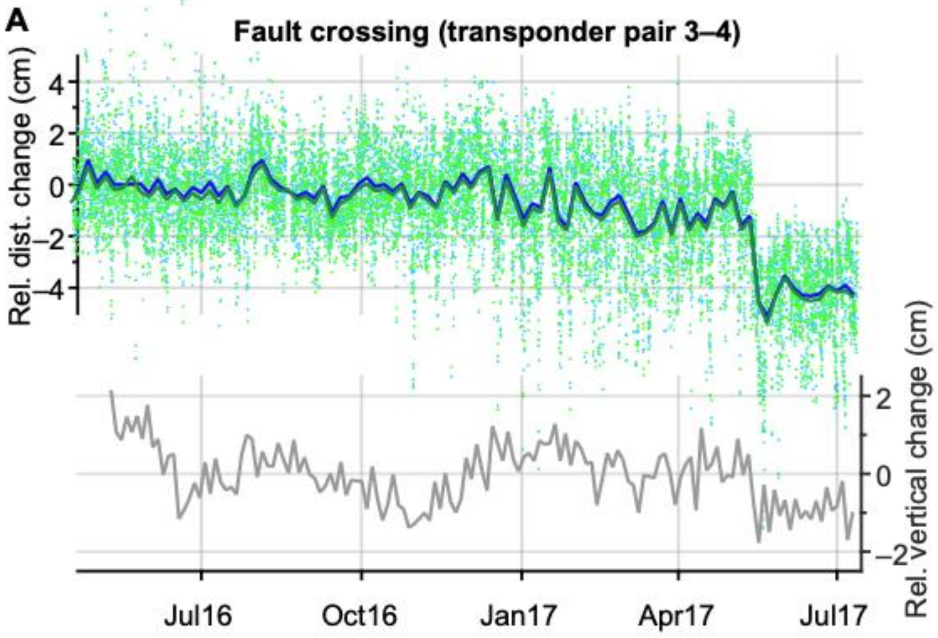
Feuillet et al., 2021

Marine Geodesy

- Path Ranging: recorded time of flight between transponders
- Direct-path has a range of ~1km, indirect 5km
- Need to know uncertainity in speed of sound in water
- Resolution on the order of 1.5cm (direct) and 1-2cm (indirect)



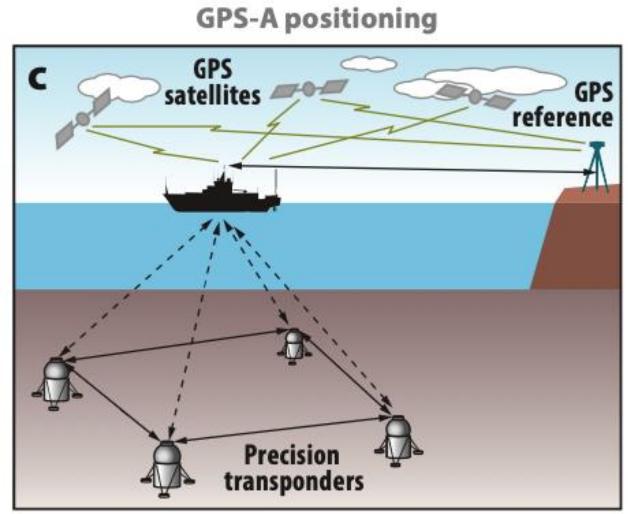
Burgmann and Chadwell 2014



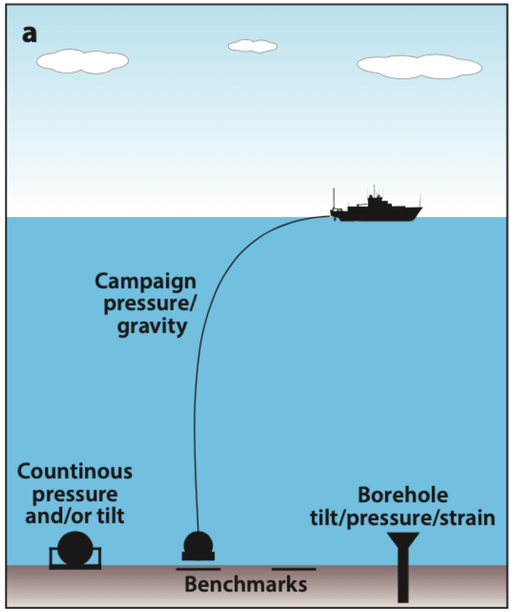
Urlaub et al., Sci Adv, 2018

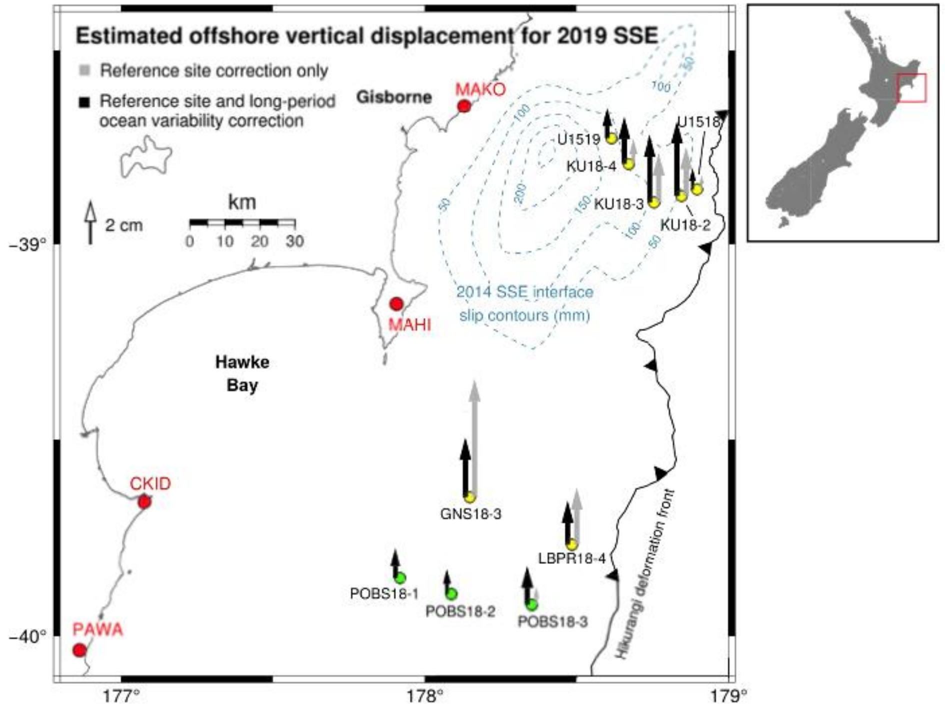
Marine Geodesy

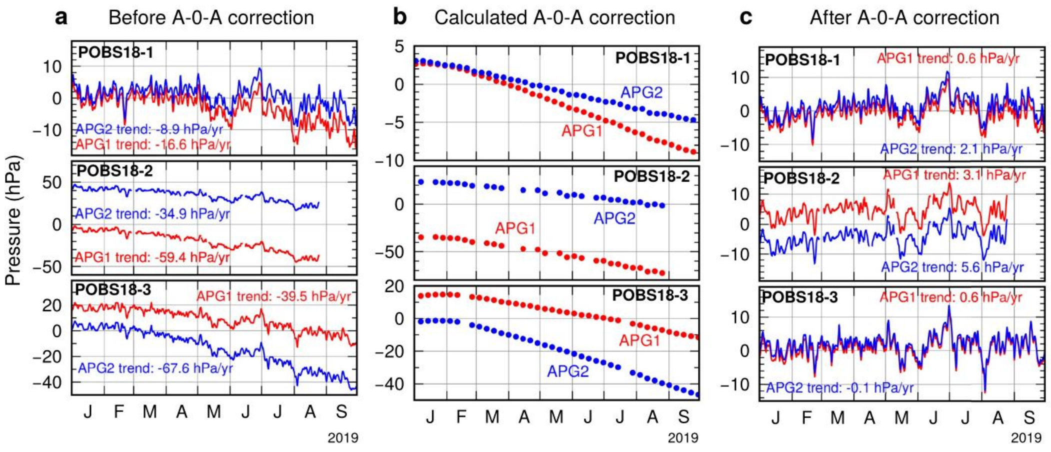
- GPS-A networks : acoustic ranging connects seafloor transponders to sea surface GPS
- Pressure sensors: change in water column height implies change in vertical displacement



Burgmann and Chadwell 2014



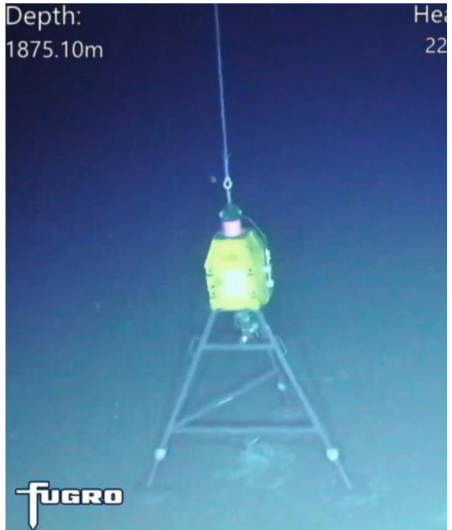


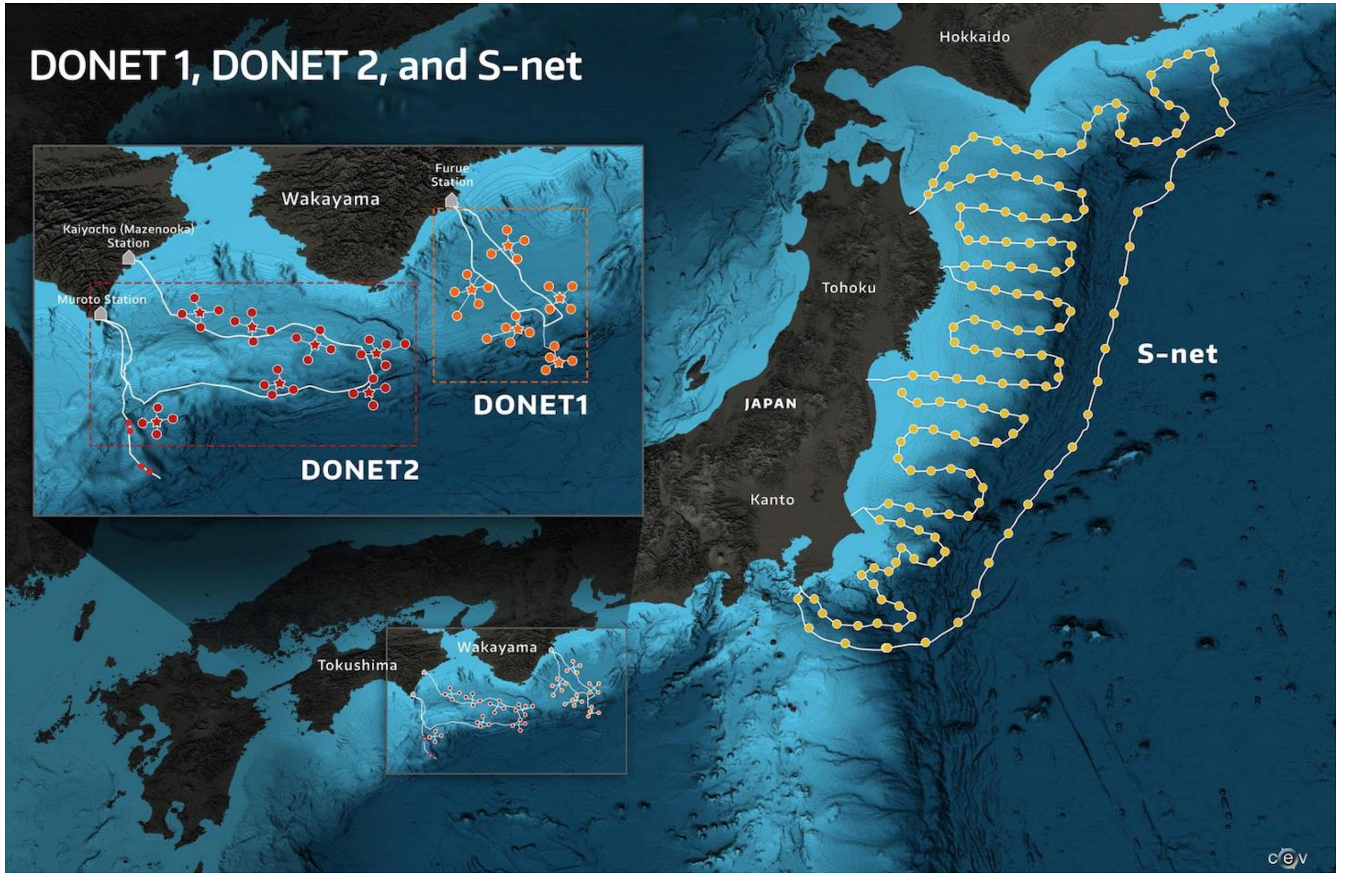


Woods et al., 2022

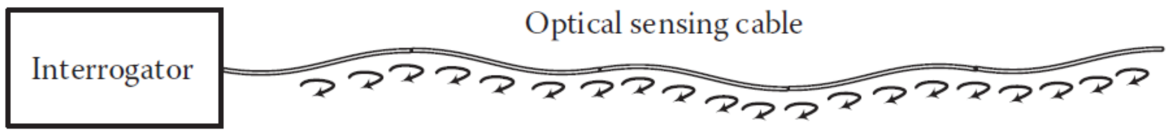
Deployment

- Temporary deployments require multiple sea campagins
- Permanent cabled networks are expensive

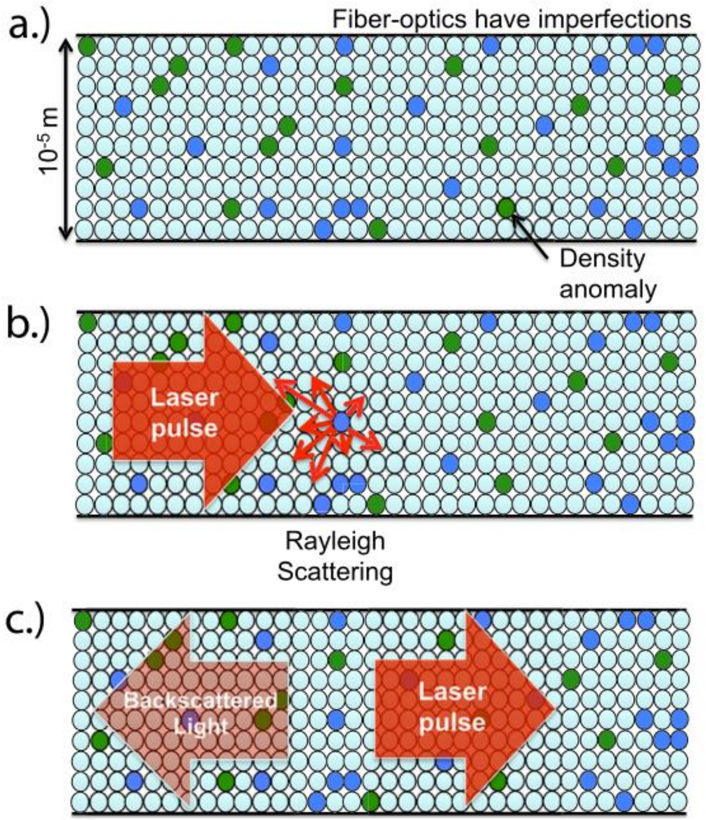




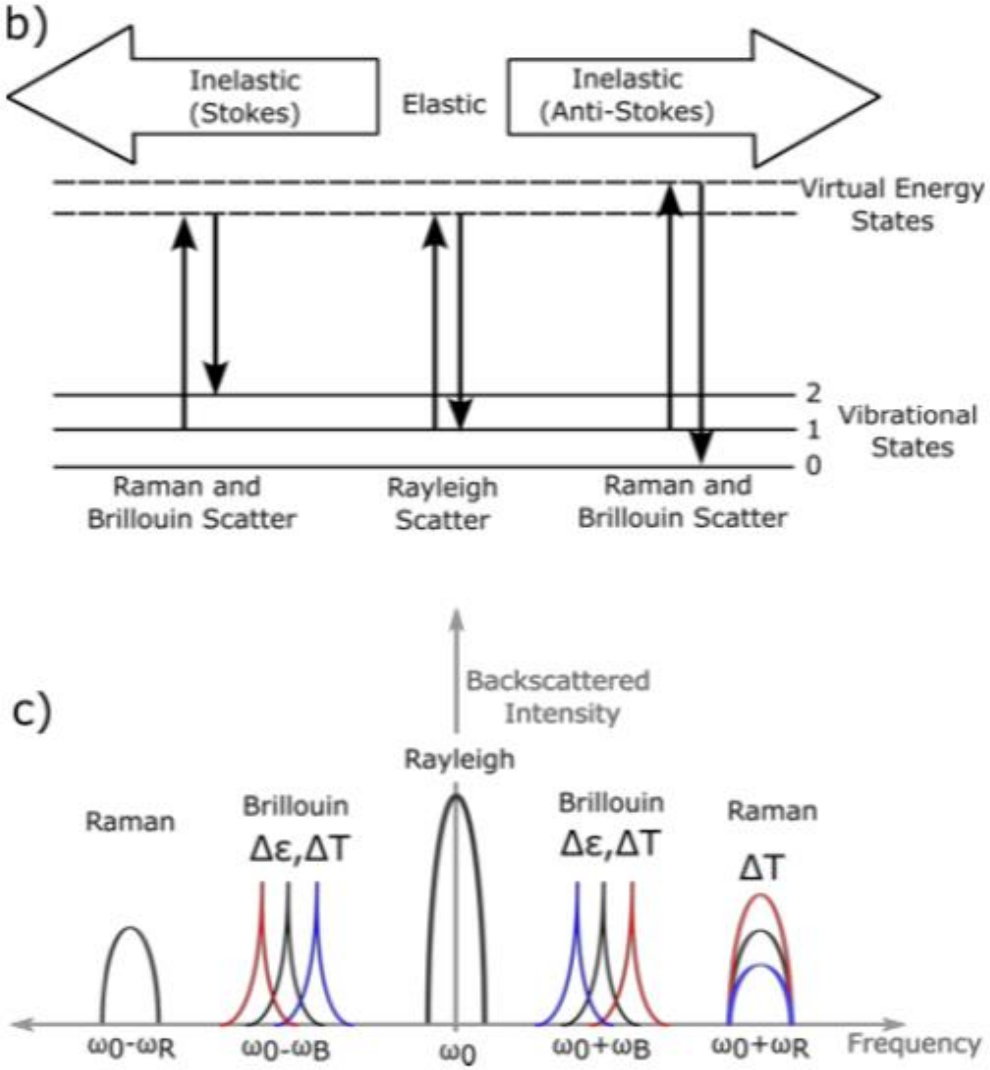
Distributed Strain Sensing



Hartog et al., 2017



Lindsey et al., 2020



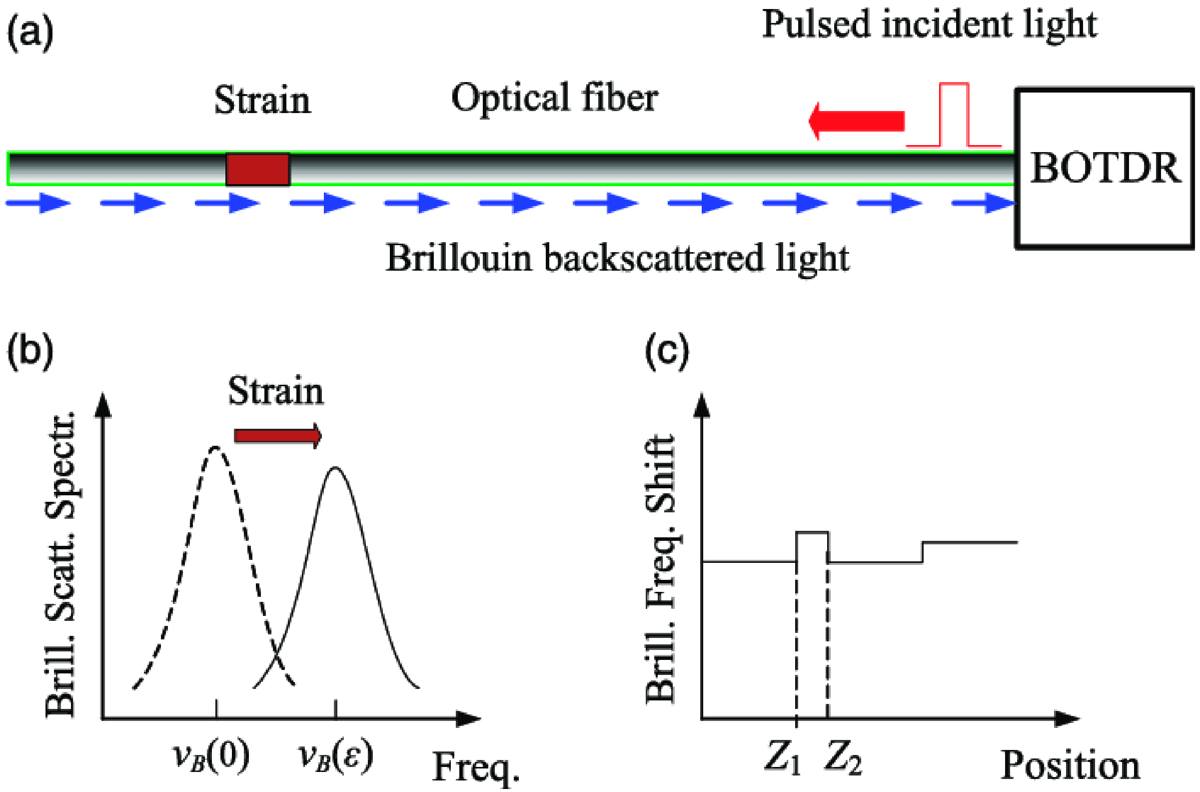
Jousset et al., 2024

BOTDR : Brillouin scatter

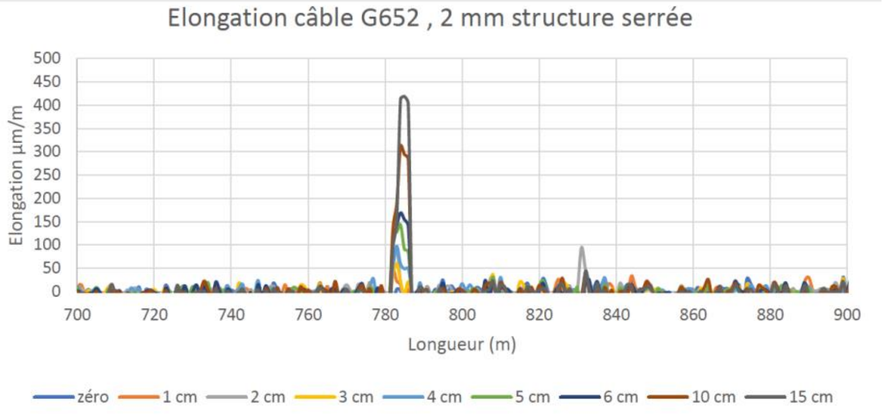
DTS (Distributed Temperature Sensing) / DSS (Distributed Strain Sensing) :

- measures long-term strain and temperature variation with spatial sampling from 1 m to several tens of metres
- at a sampling rate of +10 min with an accuracy of 0.1°C / 20 mε

$$\Delta\nu = \Delta\epsilon\, C^{\nu\epsilon} + \Delta T\, C^{\nu T}$$



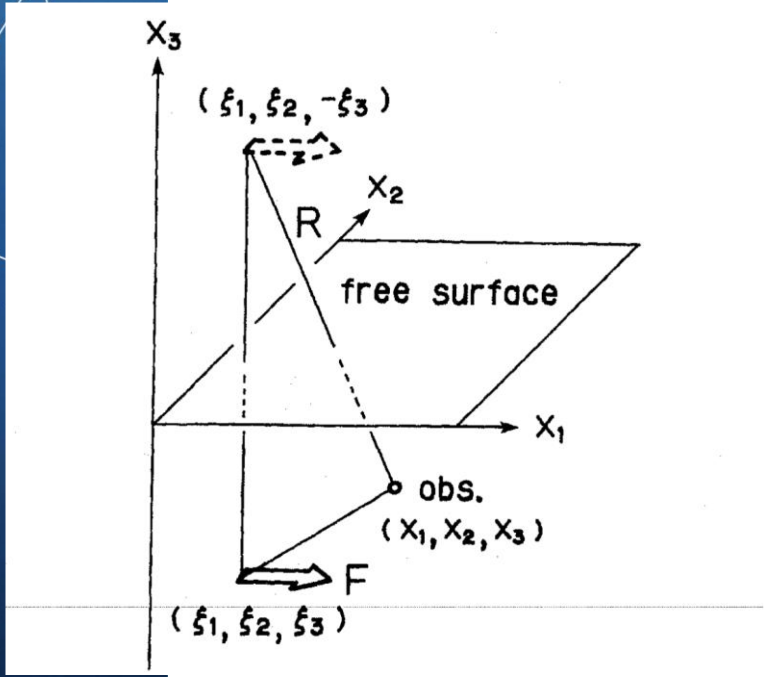
Feng et al., 2014



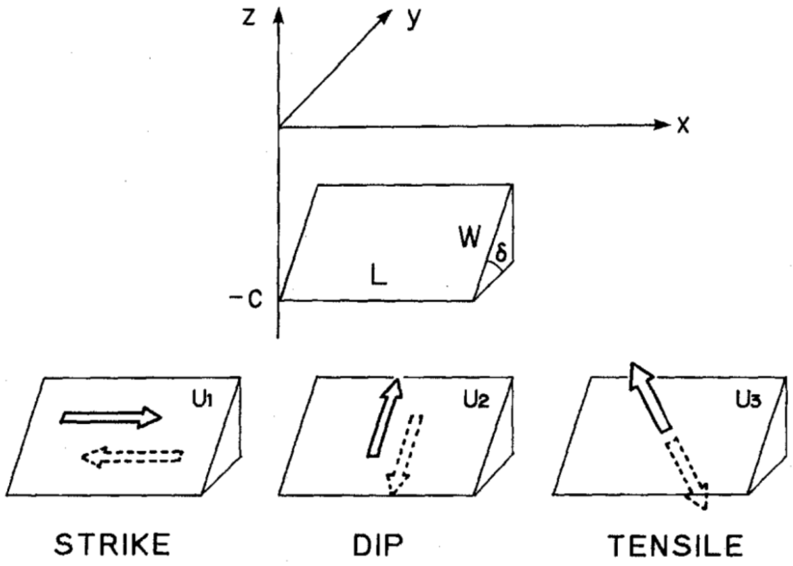
Acquisition entre 700 et 900 m

Geodetic Modelling

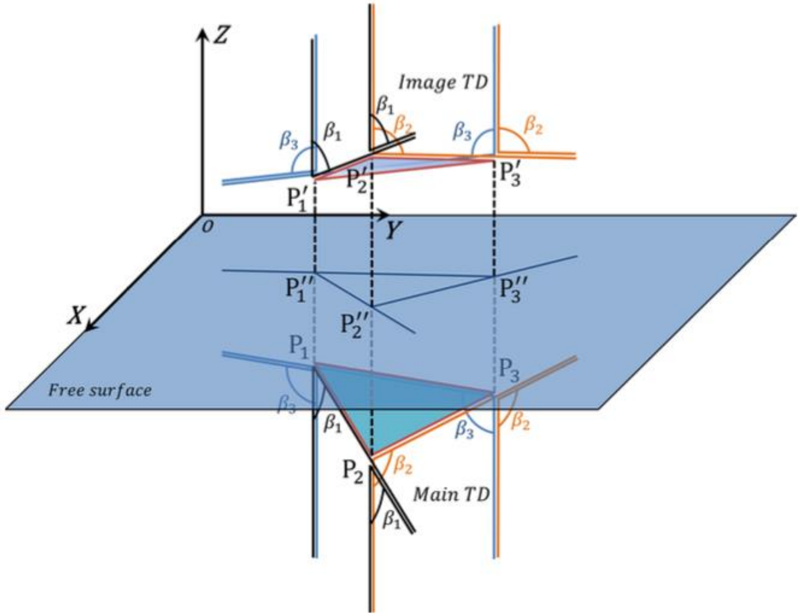
- Analytical solutions for dislocations
- Uniform slip at a point, across a rectange or triangle
- Method of images used to reproduce the earth's surface
- Provides rapid calculation of static displacement, strain and stress



Okada, 1992



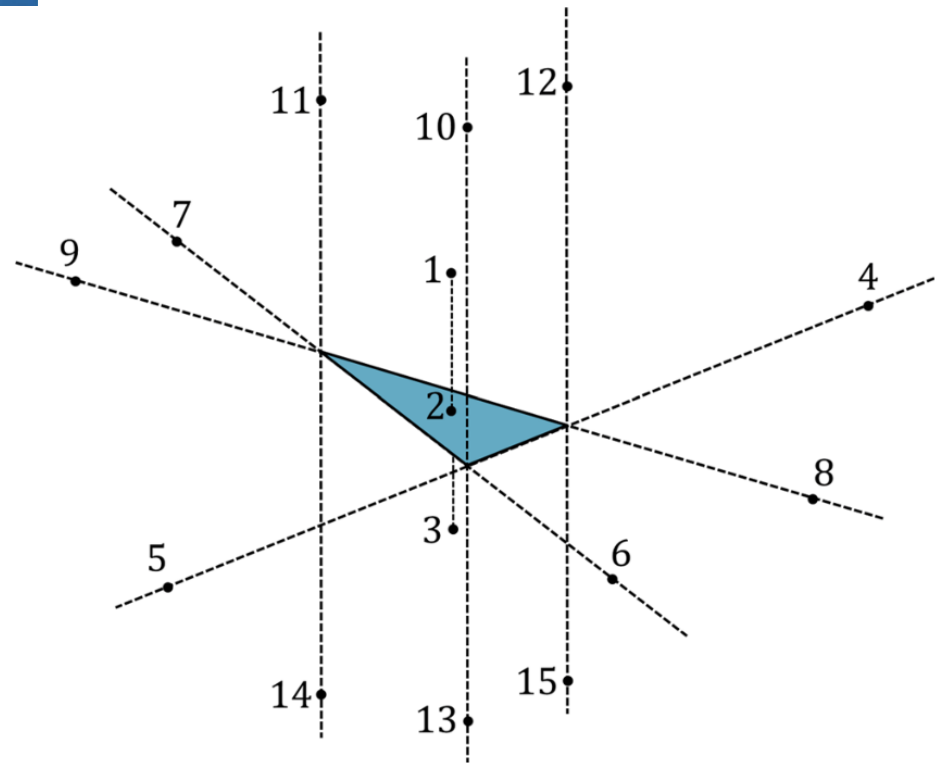
Okada, 1992



Nikkhoo and Walter, 2015

Geodetic Modelling

- Use the Nikkho and Walter’s scheme as it removes a number of singularities and numerical instablities
- Singularities still exist on edge of triangles by definition



#	X	Y	Z	u (This paper)	u' (Meade 2007)	ϵ_{XX} (This paper)	ϵ'_{XX} (Meade 2007)
1	−1/3	−1/3	−3	0.0352311877319734	0.0352311877319732	0.0481047005255181	0.0481047005255181
2	−1/3	−1/3	−14/3	−0.509465745232405	−0.509465745232405	−0.244188978214975	−0.244188978214977
3	−1/3	−1/3	−6	−0.0450664903903138	−0.0450664903903139	0.0546831404832553	0.0546831404832554
4	7	−1	−5	−0.00230579292792908	NaN	0.000829157341339727	NaN
5	−7	−1	−5	0.00401472894583963	0.00401472894583941	0.00114439668841158	NaN
6	−1	−3	−6	0.00483219740842196	NaN	−0.00386292388925956	NaN
7	−1	3	−3	0.00261498816660580	0.00261498816660530	−0.00243788640223540	NaN
8	3	−3	−6	−0.00498017723062124	0.0498371783469113	0.000706397690338731	142952905402461
9	−3	3	−3	0.00469791958297159	0.00469791958297180	0.000211254167350266	0.00431126958717604
10	−1	−1	−1	0.00147786823004841	0.00147786823004838	0.00650800501584133	NaN
11	−1	1	−1	0.00374844575688324	0.447846746319388	0.000922452413344460	NaN
12	1	−1	−1	0.0166558386729541	−0.427442461889551	0.00441202690885827	NaN
13	−1	−1	−8	−0.00656347406353817	NaN	0.00330232019558791	NaN
14	−1	1	−8	−0.0105680479573571	NaN	0.00876398663844928	NaN
15	1	−1	−8	−0.00213929091658054	NaN	−0.000914111766849476	NaN

Nikkhoo and Walter, 2015

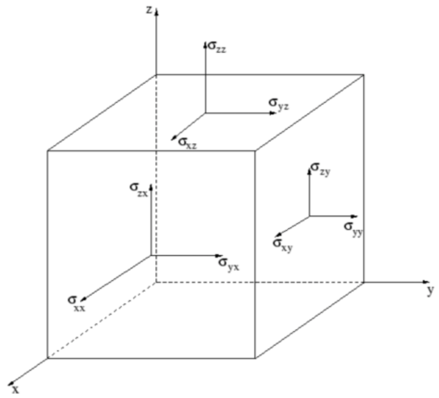
Geodetic Modelling

- Caculate strain tensor in model

$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$$

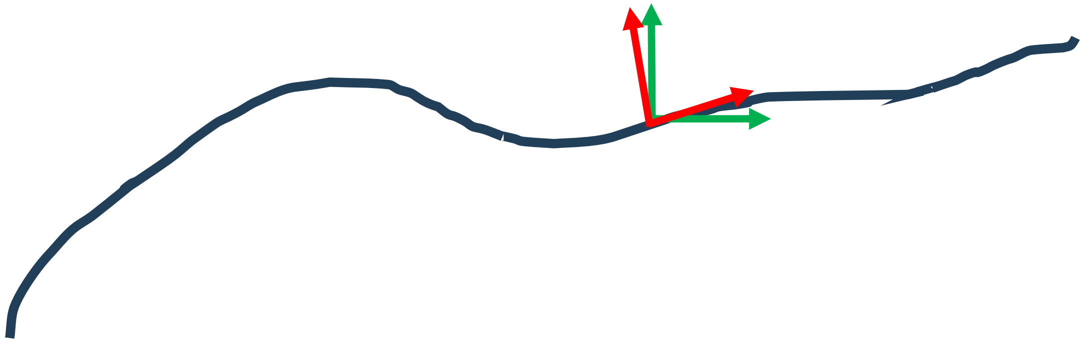
- Cable measures strain longitudially

$$\epsilon_{ij} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}$$



- Rotation for a 2nd Rank Tensor

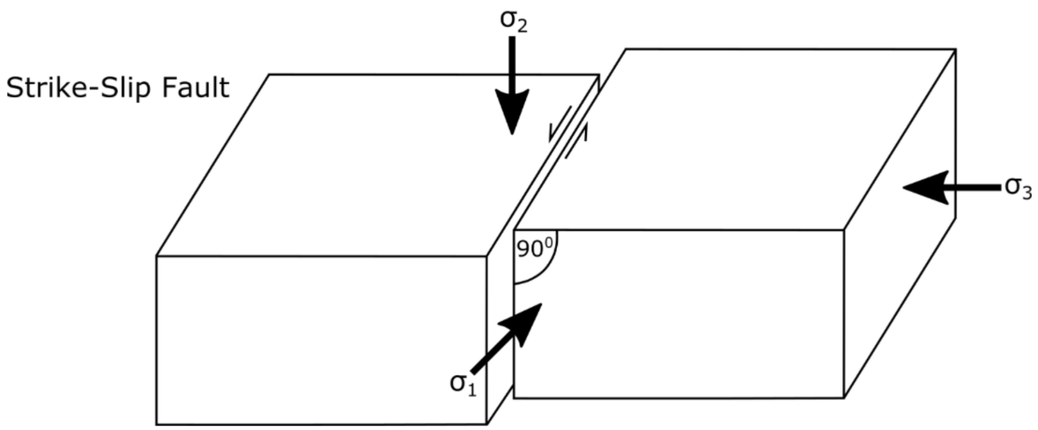
$$\epsilon'_{ij} = R_z(\theta)\,\epsilon_{ij}\,R_z(\theta)^T$$

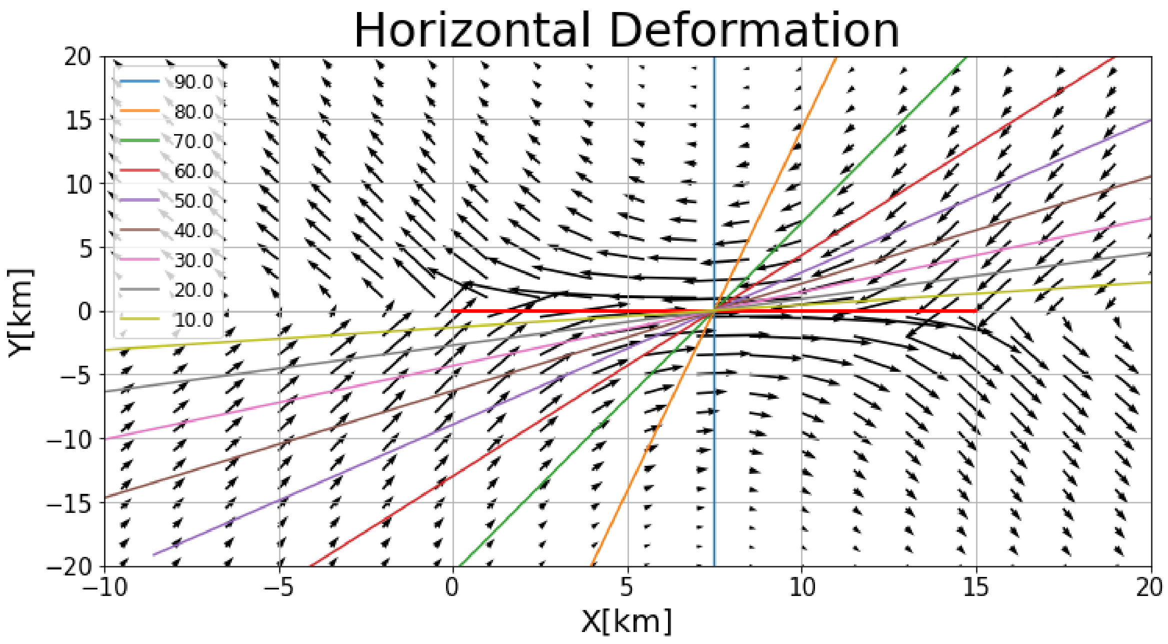


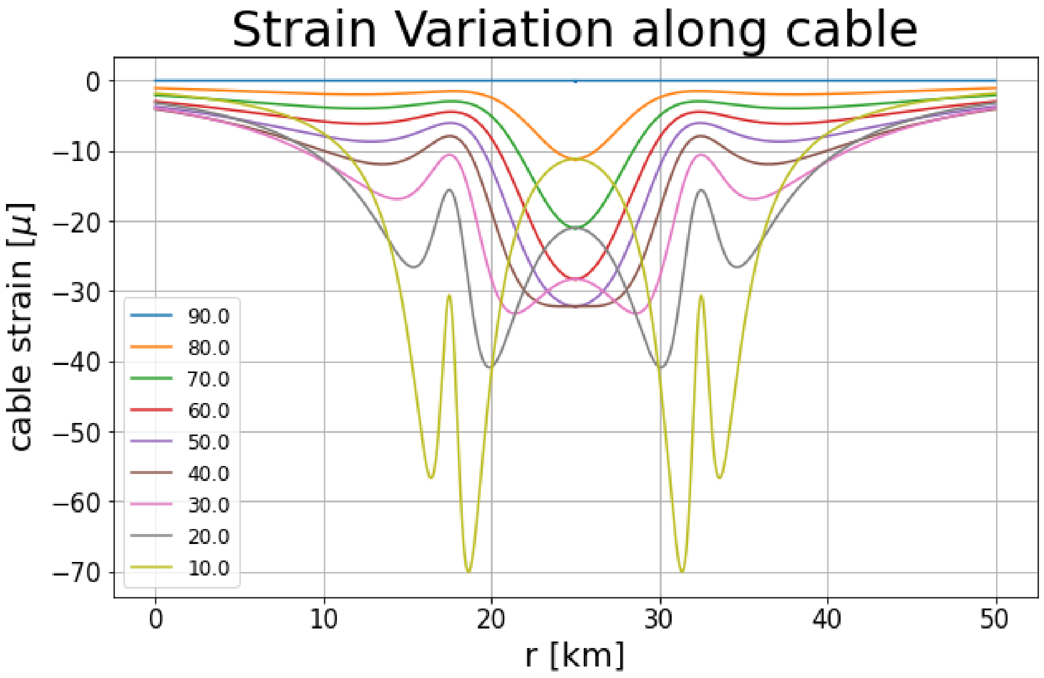
$$\epsilon_{rr} = \epsilon'_{xx}$$

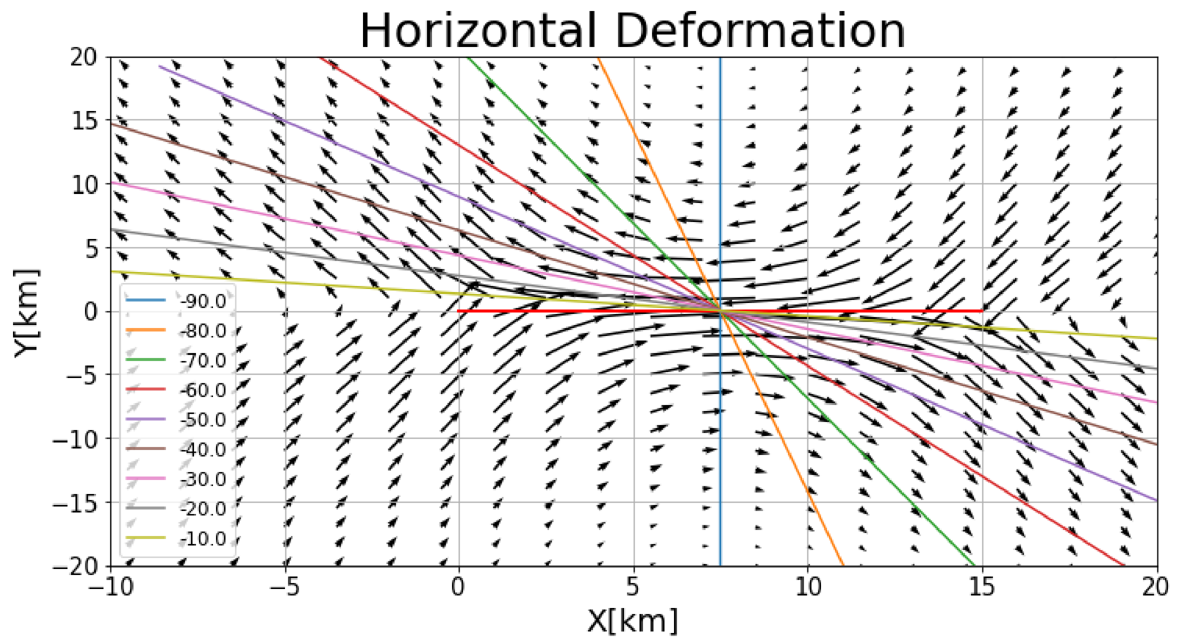
Cable response

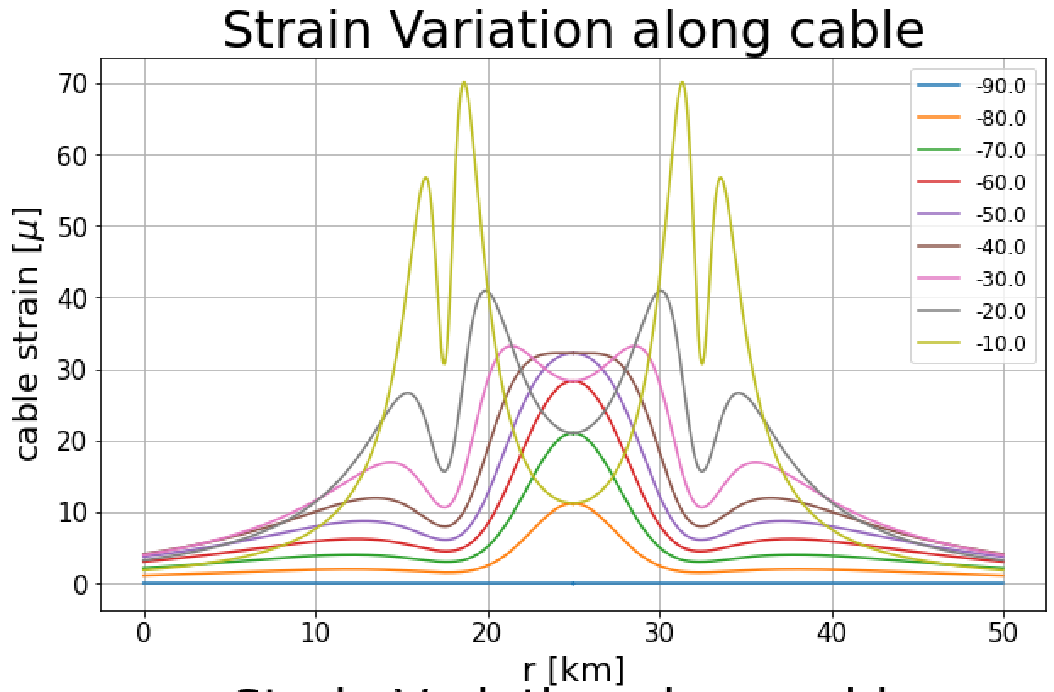
- Model a left lateral strike-slip
- Dip : 90°
- 15km x 15km fault, 1m uniform slip
- Similar to M6.5
- Cable orientations are in relation to fault

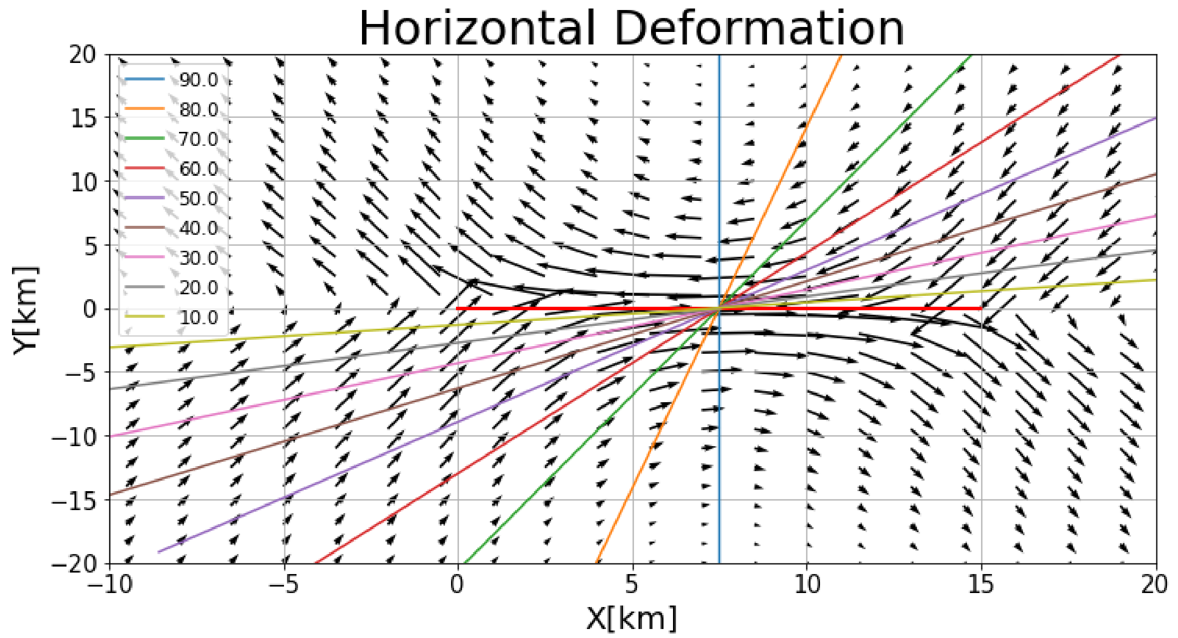


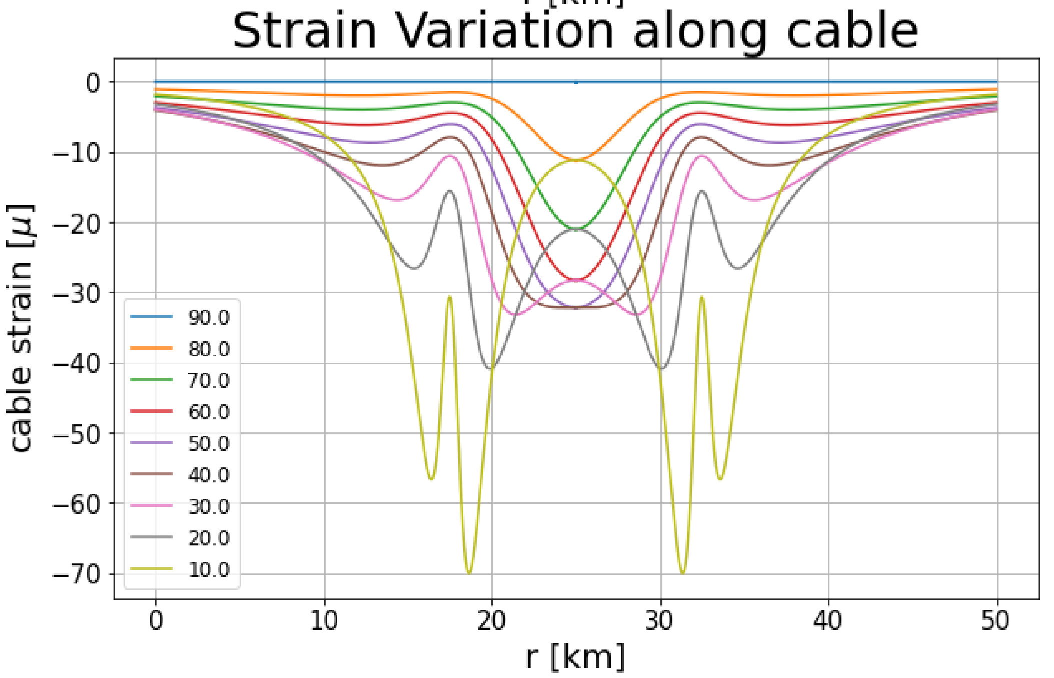





Horizontal Deformation
Y[km]
X[km]
20
15
10
5
0
−5
−10
−15
−20
−10
−5
0
5
10
15
20
-90.0
-80.0
-70.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0

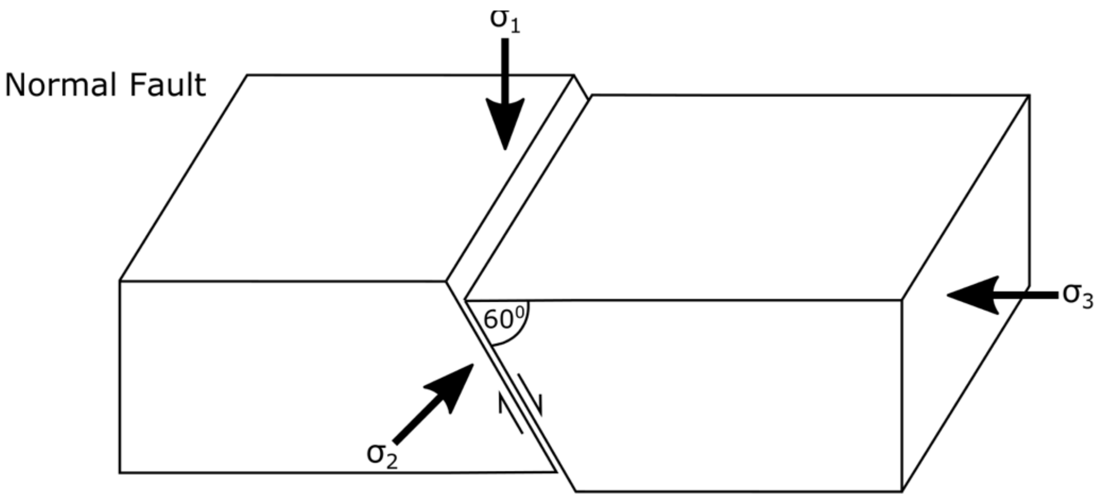

Strain Variation along cable
cable strain [μ]
r [km]
70
60
50
40
30
20
10
0
0
10
20
30
40
50
-90.0
-80.0
-70.0
-60.0
-50.0
-40.0
-30.0
-20.0
-10.0

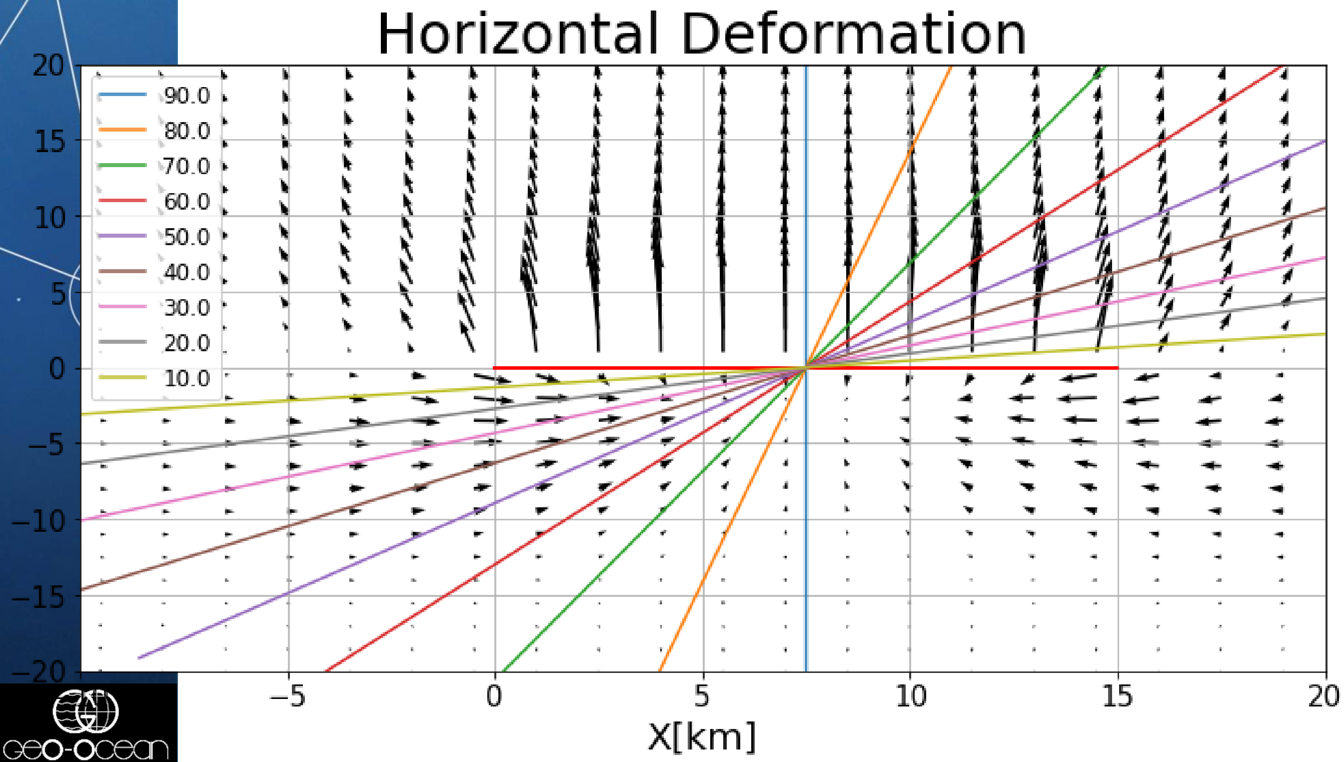

Horizontal Deformation
Y[km]
X[km]
20
15
10
5
0
−5
−10
−15
−20
−10
−5
0
5
10
15
20
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0

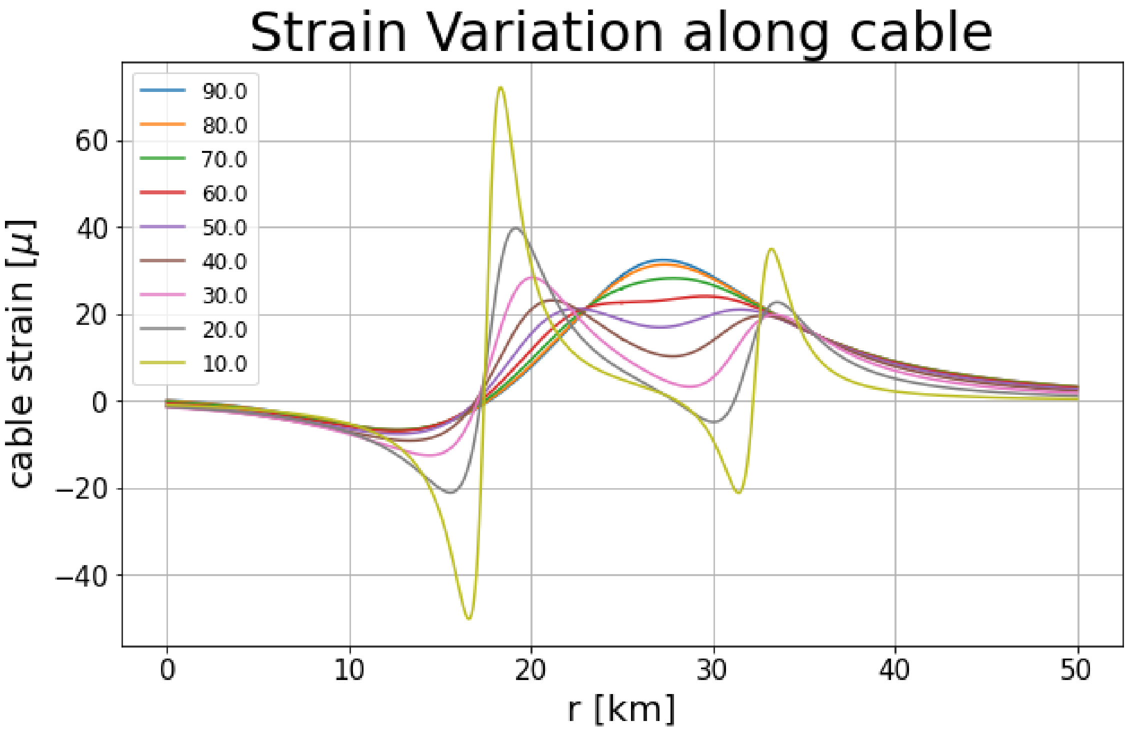

Strain Variation along cable
cable strain [μ]
r [km]
0
−10
−20
−30
−40
−50
−60
−70
0
10
20
30
40
50
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0

Cable response

- Normal fault
- Dip: 60°
- 15km x 15km fault , 1m slip
- Similar to M6.5

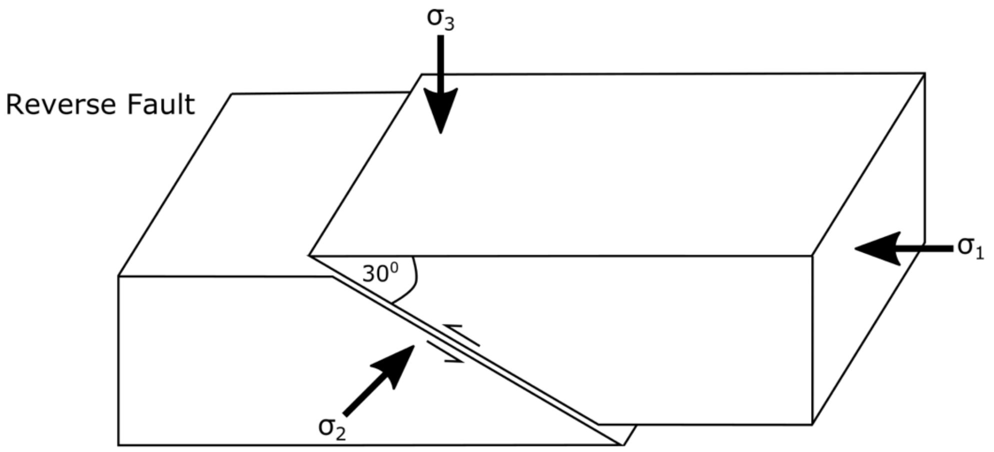


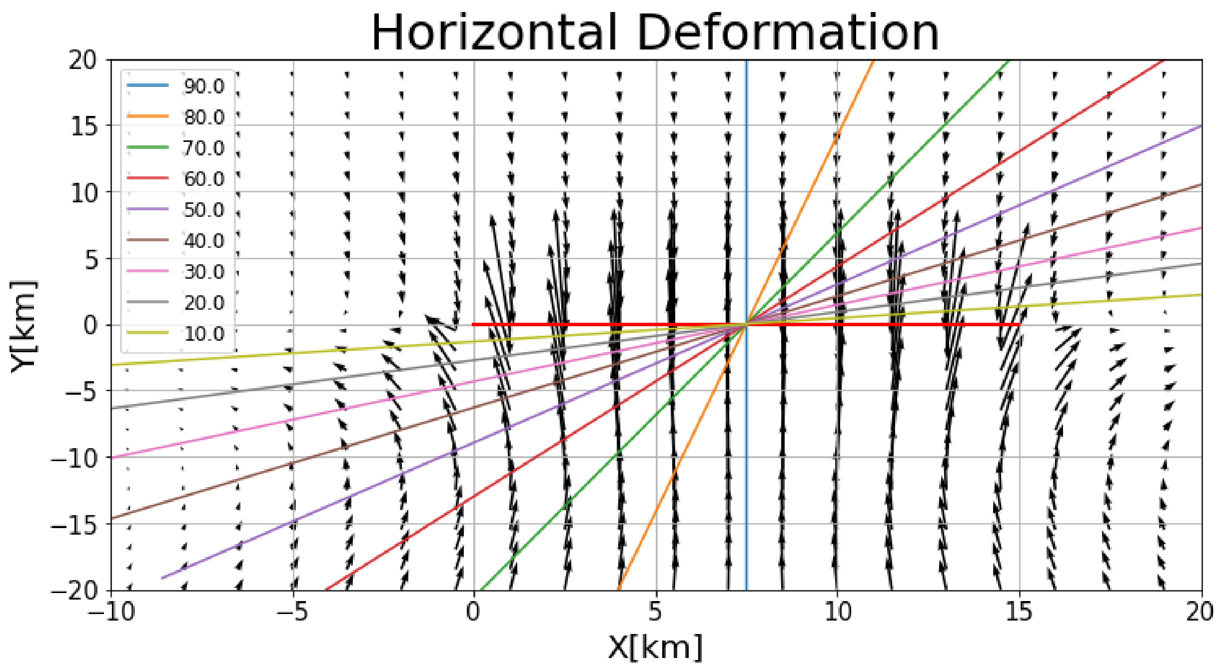


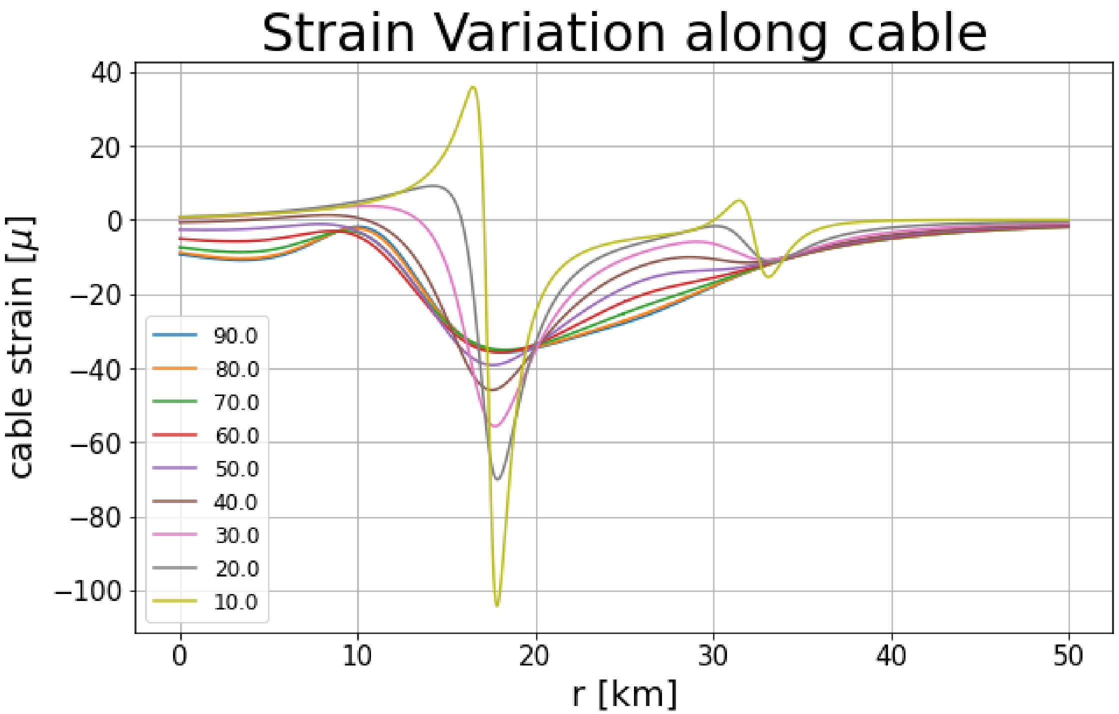


Cable response

- Thrust fault
- Dip: 30°
- 15km x 15km fault , 1m slip
- Similar to M6.5

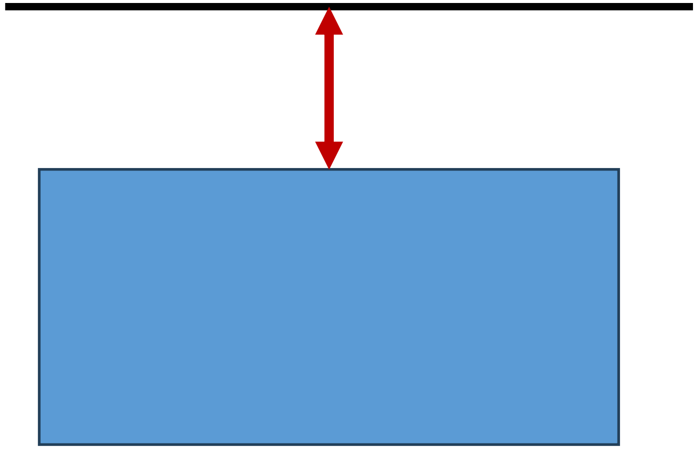


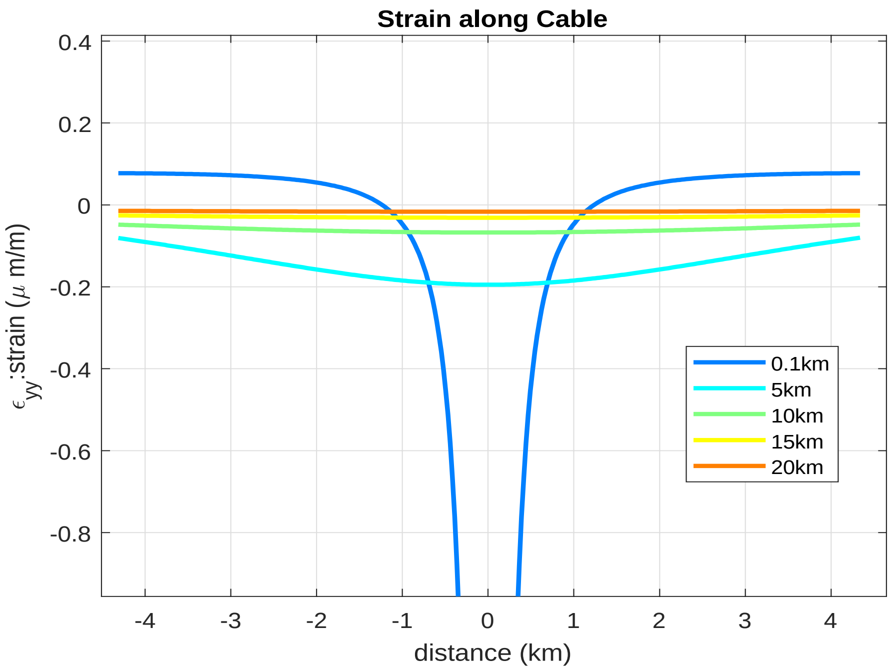


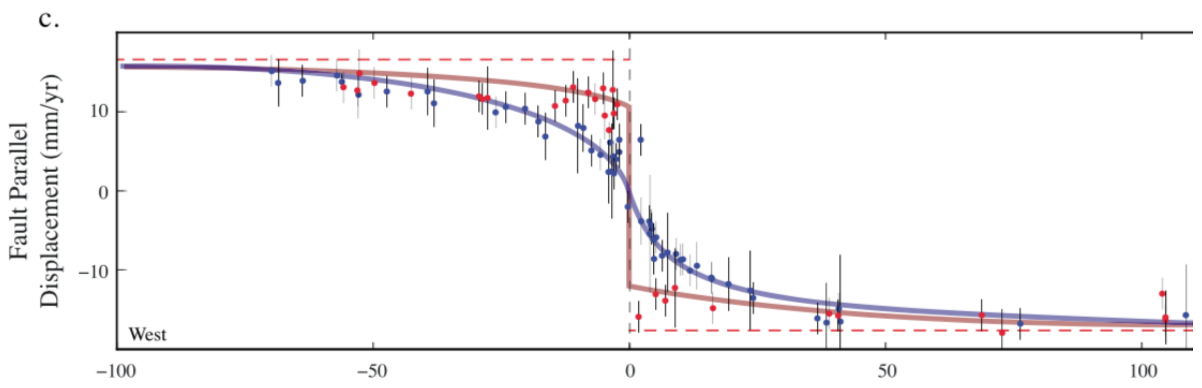


Cable response: depth

- Model a left lateral strike-slip
- Length: 20km Width : 5km, Slip : 1cm
- Dip : 90°
- Cable orientation at 60 ° to fault trace
- Fault buried at 0.1m, 5km, 10km, 15km, 20km





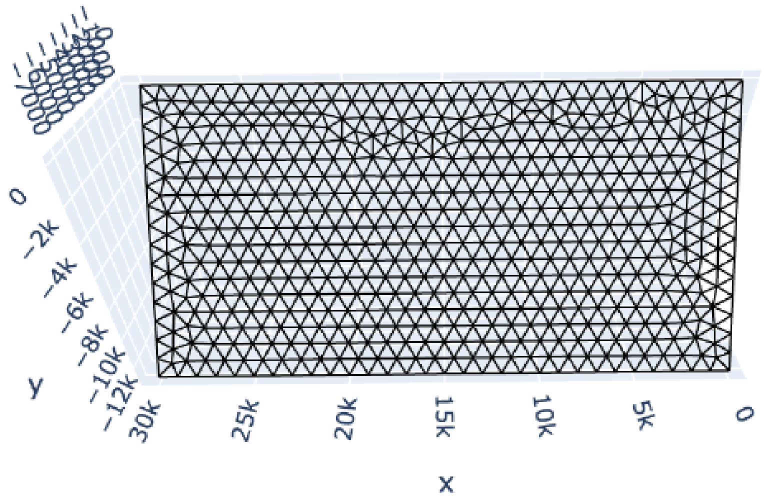


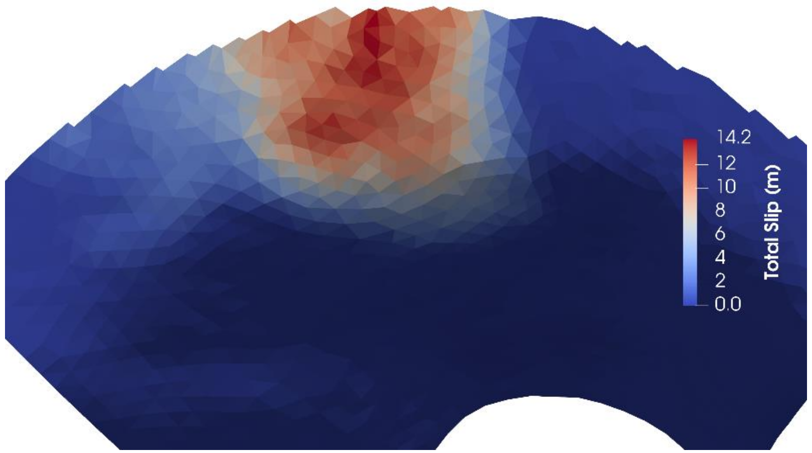
Jolivet et al., GRL, 2015

What can we observe of the fault?

$$\mathbf{d} = \mathbf{G}\,\mathbf{m}$$

$$\begin{bmatrix} d_1 \\ . \\ . \\ . \\ d_m \end{bmatrix} = \begin{bmatrix} g_{11} & \dots & \dots & g_{1n} \\ g_{21} & & & \\ . & & & \\ . & & & \\ g_{m1} & \dots & \dots. & g_{mn} \end{bmatrix} \begin{bmatrix} m_1 \\ . \\ . \\ . \\ m_n \end{bmatrix}$$





Resolution Matrices

What we have: $\mathbf{d} = \mathbf{G}\mathbf{m}_{\mathbf{true}}$

Inverse solution: $\mathbf{m}_{\mathbf{G}} = \mathbf{G}^{\mathbf{G}}\mathbf{d}$

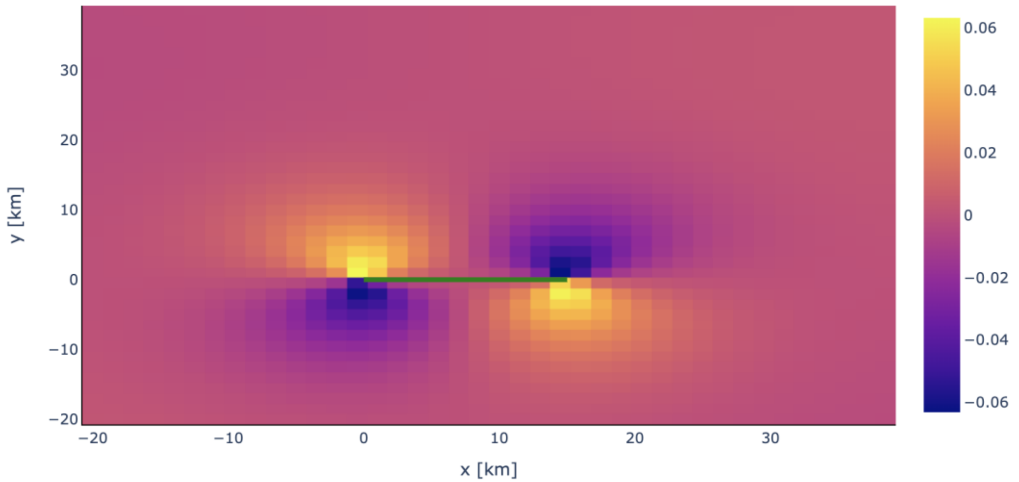
$$\left.\begin{array}{l} \mathbf{d} = \mathbf{G}\mathbf{m}_{\mathbf{true}} \\ \mathbf{m}_{\mathbf{G}} = \mathbf{G}^{\mathbf{G}}\mathbf{d} \end{array}\right\} \quad \mathbf{m}_{\mathbf{G}} = \mathbf{G}^{\mathbf{G}}\,\mathbf{G}\,\mathbf{m}_{\mathbf{true}}$$

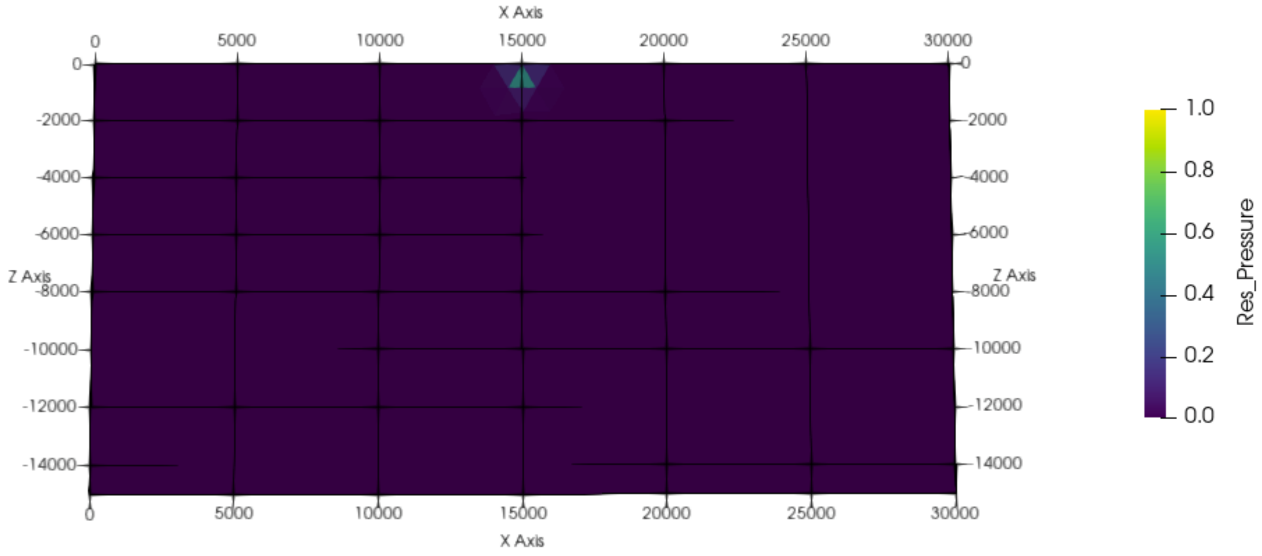
The Model Resolution Matrices: $\mathbf{R}_{\mathbf{m}} = \mathbf{G}^{\mathbf{G}}\mathbf{G}$

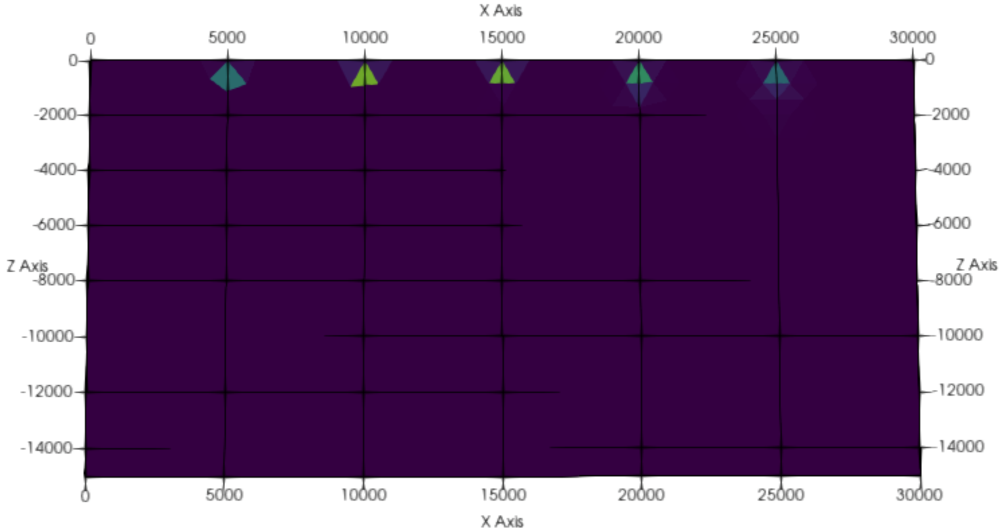
We want $\mathbf{m}_{\mathbf{G}} = \mathbf{m}_{\mathbf{true}}$ $\Rightarrow$ $\mathbf{R}_{\mathbf{m}} = \mathbb{I}$

What might ranging/pressure sensors detect

- Strike-slip fault with 90° dip
  - Fault size: 30km x 15km
  - Element size: 1km
- Ranging proxy
  - change in distance between two points
  - located at: 500m either side of fault trace
- Pressure proxy
  - vertical displacement at surface
  - located at: 50m, 100m, 250m, 500m from fault trace

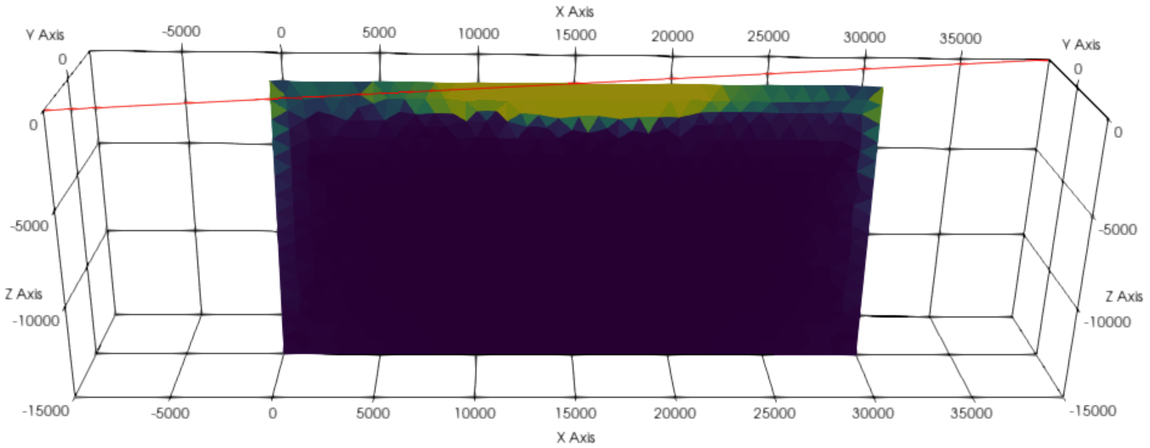


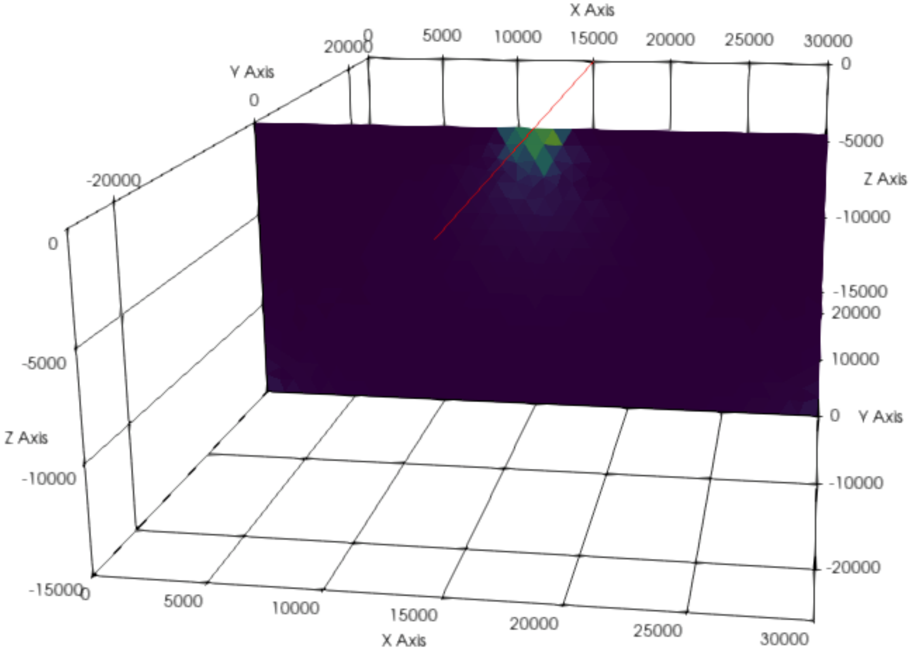


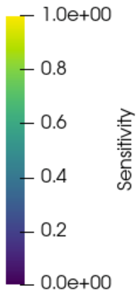


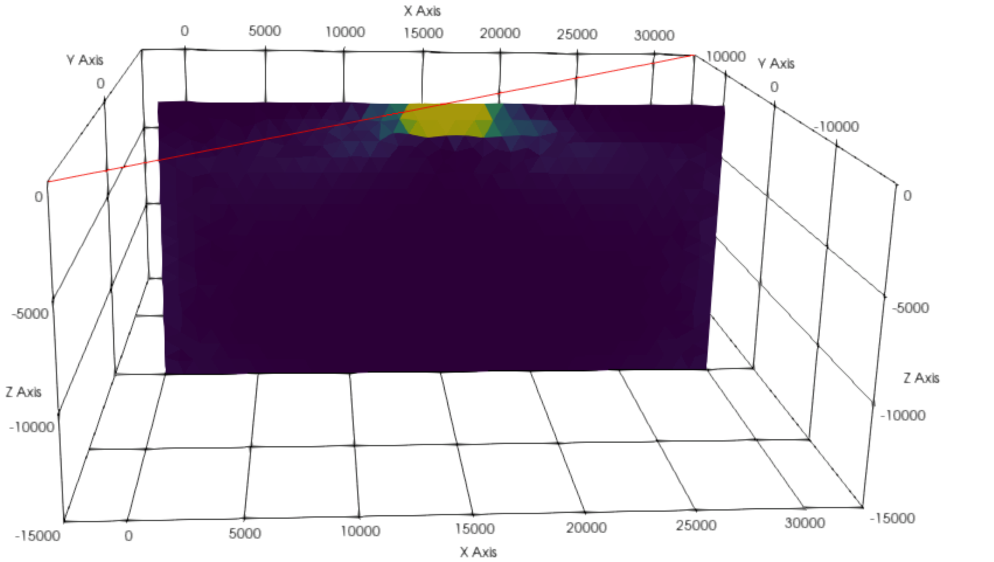
What can the cable see?

- Strike-slip fault with 90° dip
    - Fault size: 30km x 15km
    - Element size: 1km
- Cable: sample every 5m
- Cable orientations with respect to fault trace: 90°, 45°, 10°







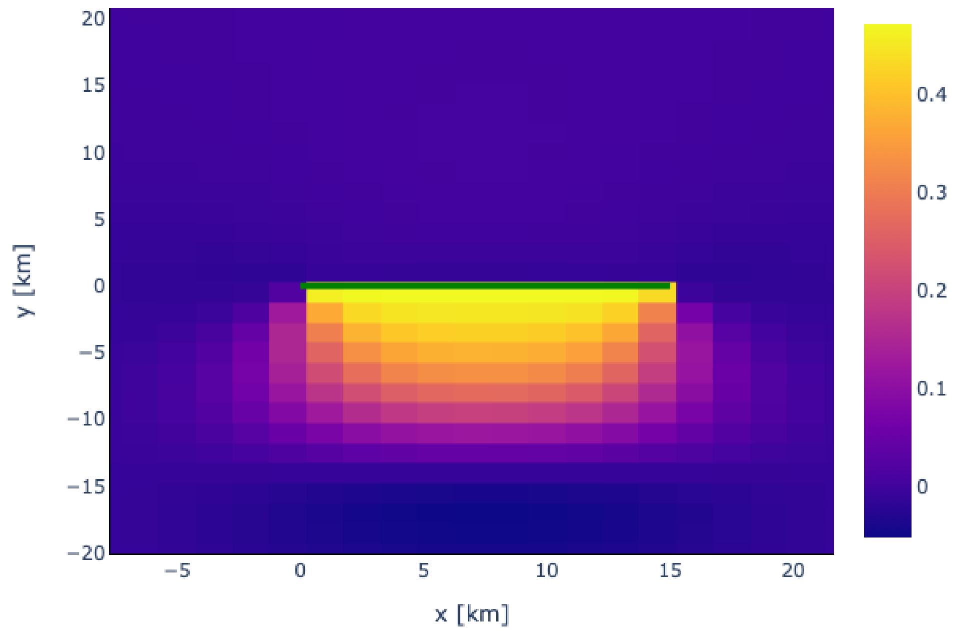


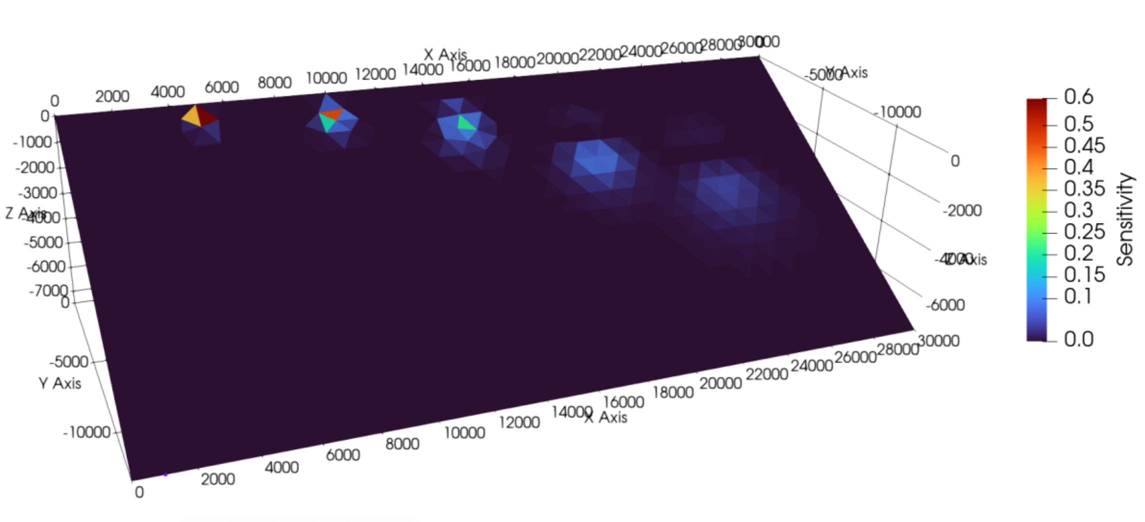
Thrust fault

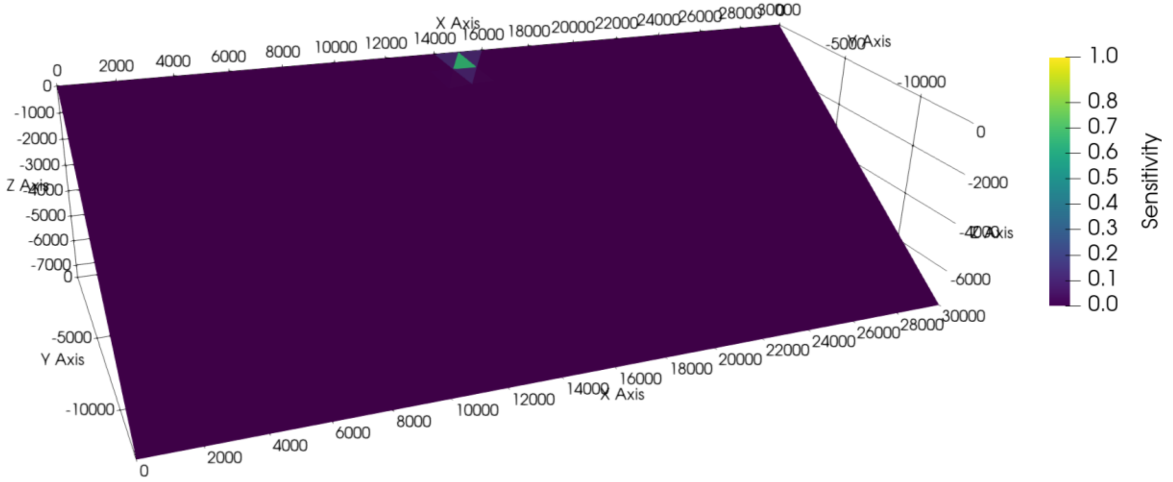
- Thrust fault with 30° dip
  - Length: 30km Width: 15km
  - Cells size: 1km

- Pressure stations at distances from fault trace 500m, 1km, 2km, 4km, 6km

- Ranging position: located at: 500m either side of fault trace



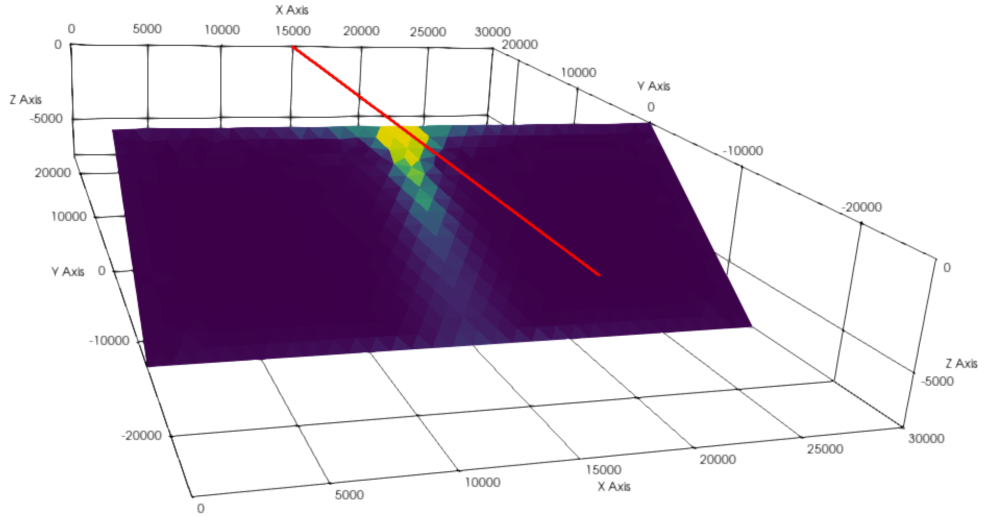


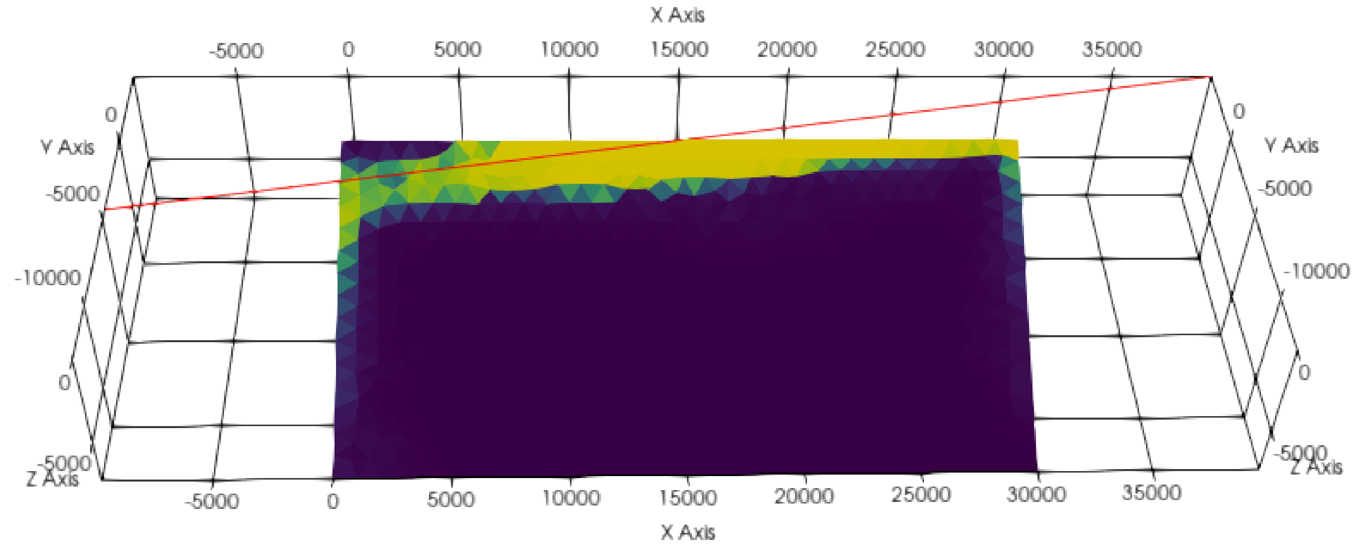


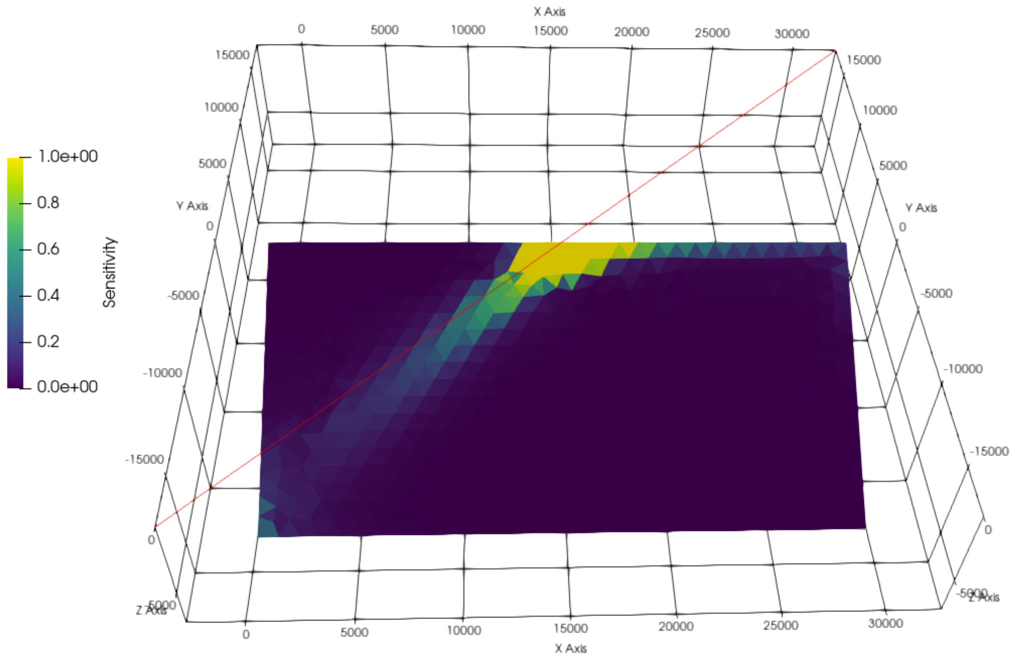
What can the cable see?

- Thrust fault with 30° dip
  - Length: 30km Width: 15km
  - Cells size: 1km

- Cable orientations with respect to fault trace: 90°, 45°, 10°





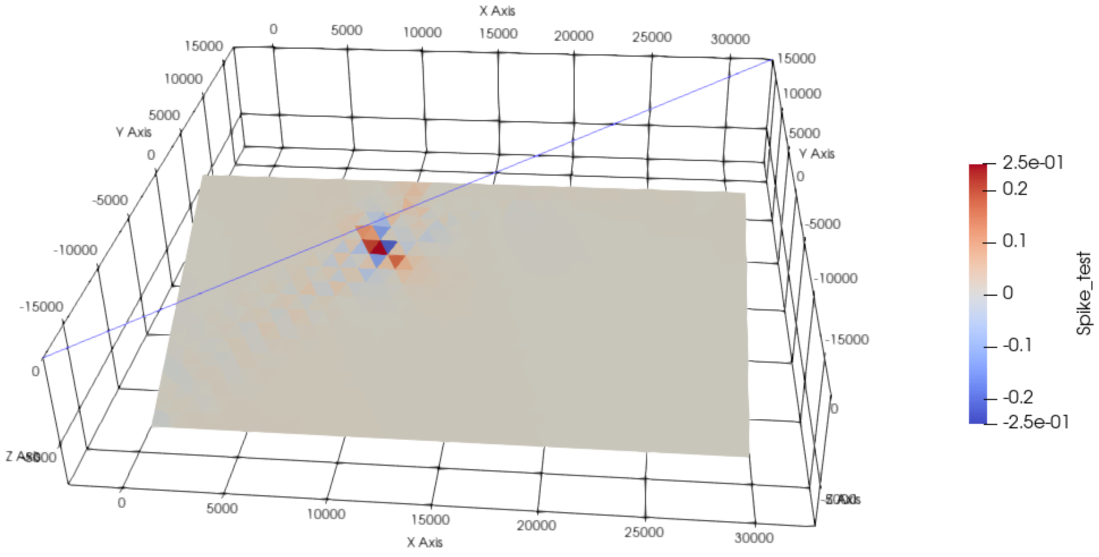


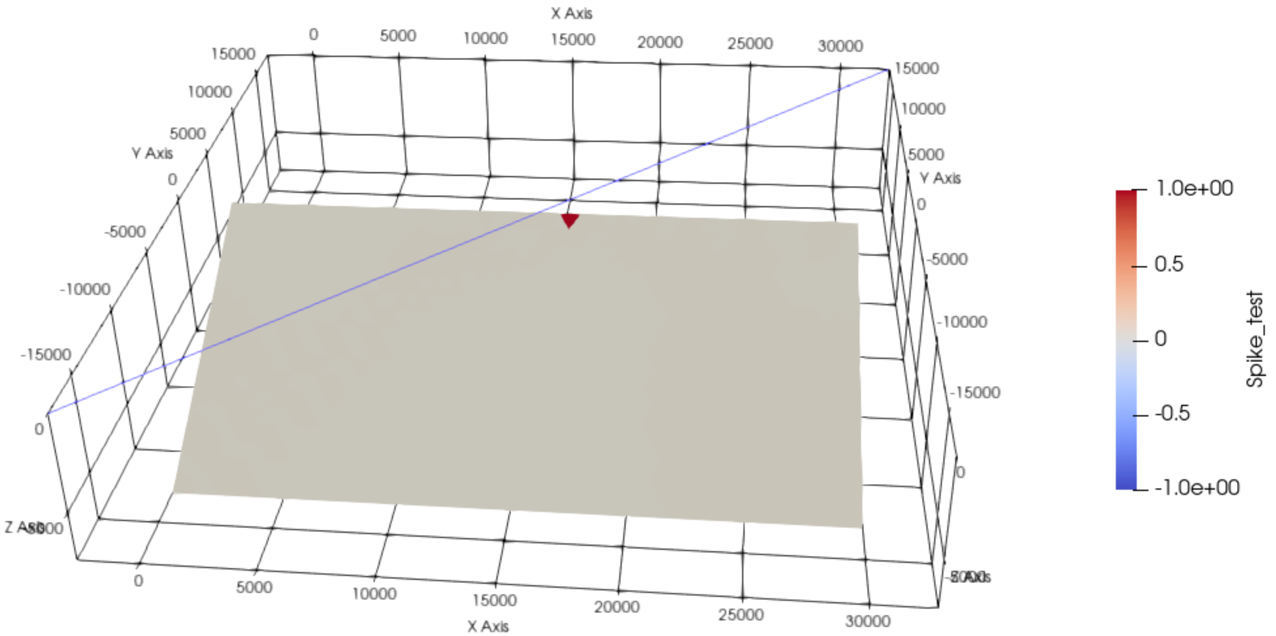
Spike Tests $\mathbf{m}_{\text{spike}} = \mathbf{R}_{\mathbf{m}}\mathbf{m}_1$

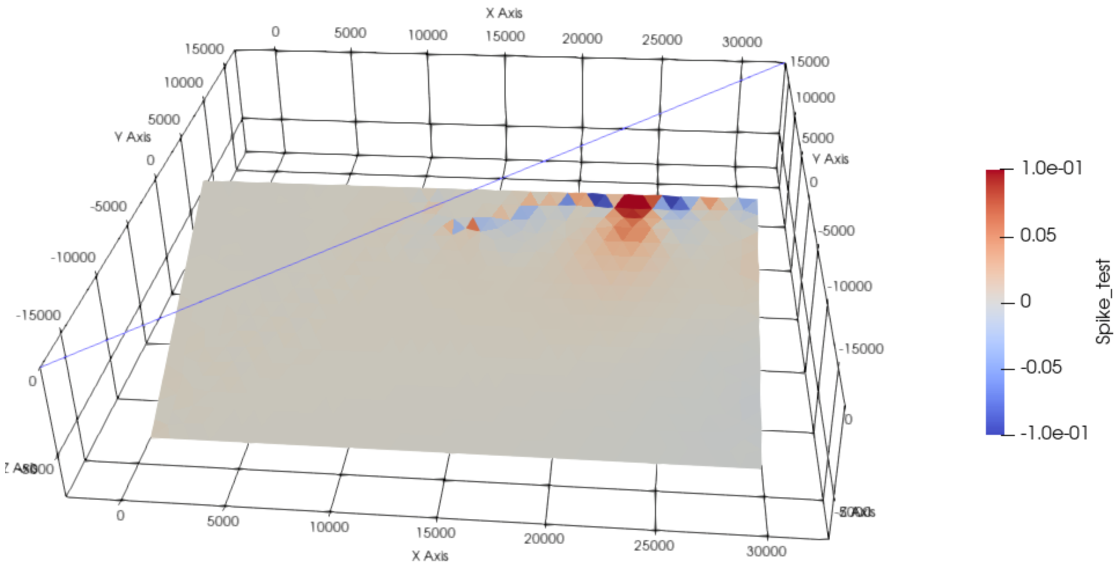
Thrust fault with 30° dip

Cable orientations : 45°

Active single cells on the fault

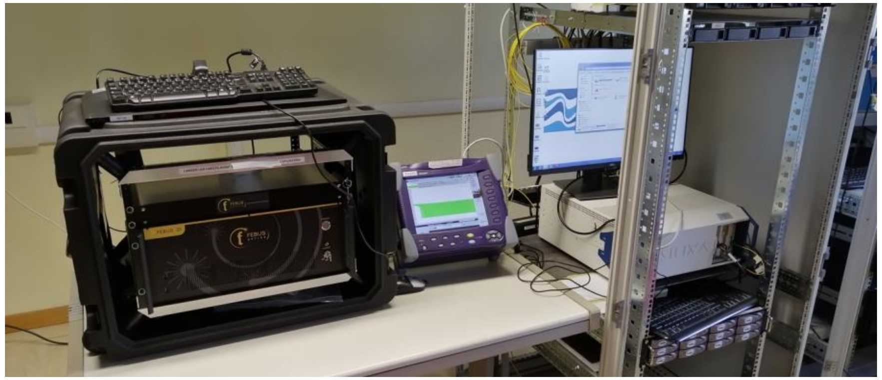


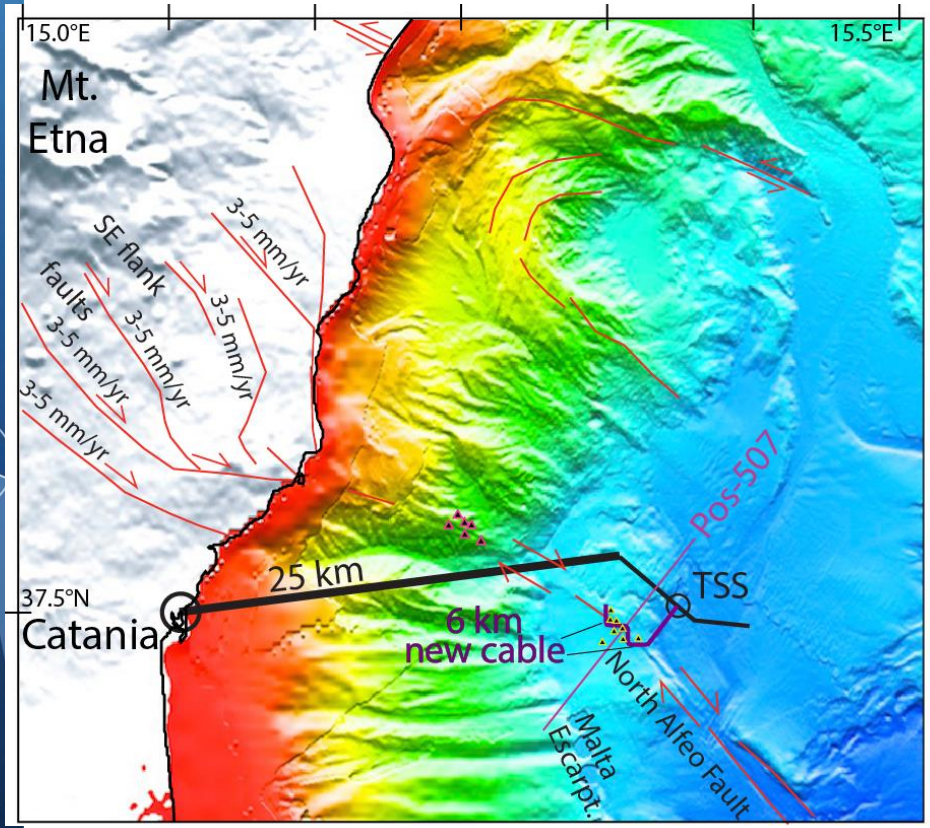


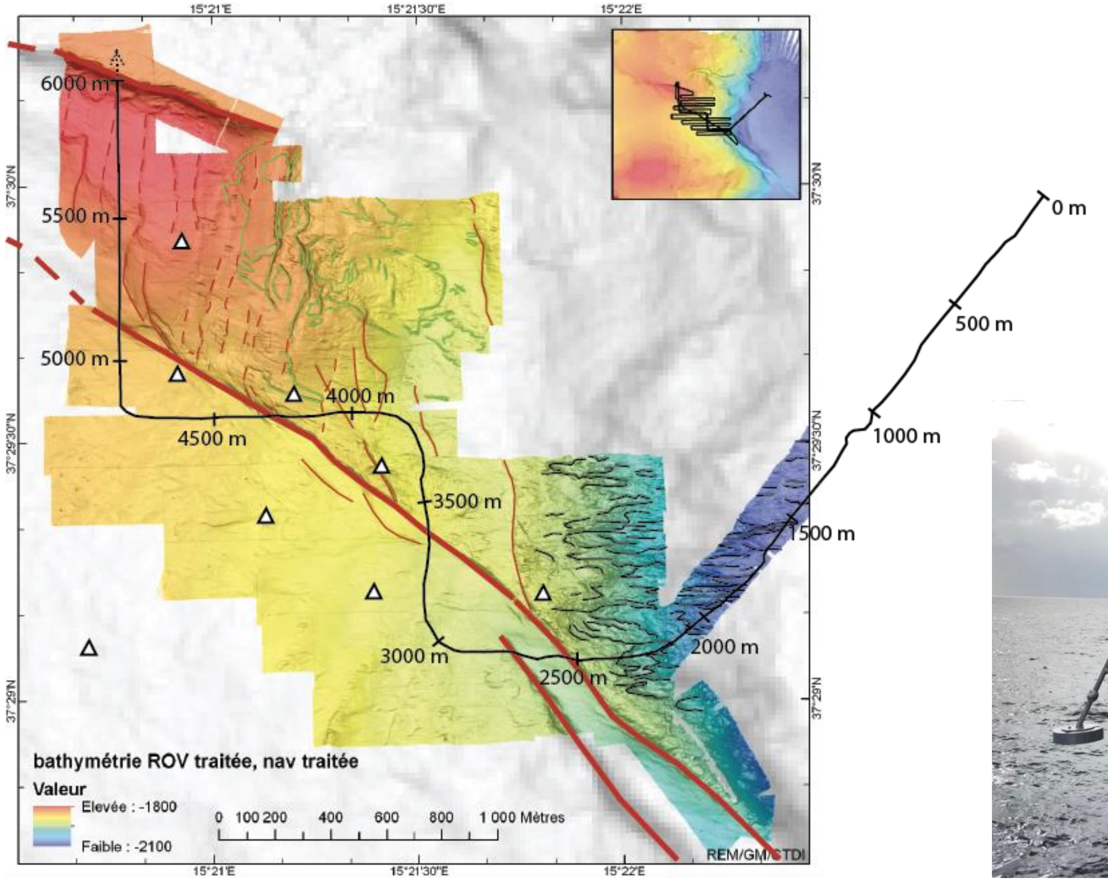


FOCUS Project

- Measuring strain along METOC cable since May 2020
- Focus X1 (2020) :
    - layed custom cable with looped fibres
    - deployed geodetic ranging stations

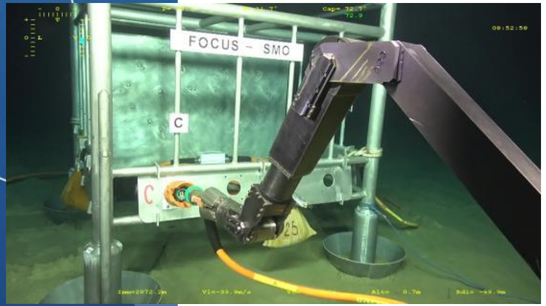


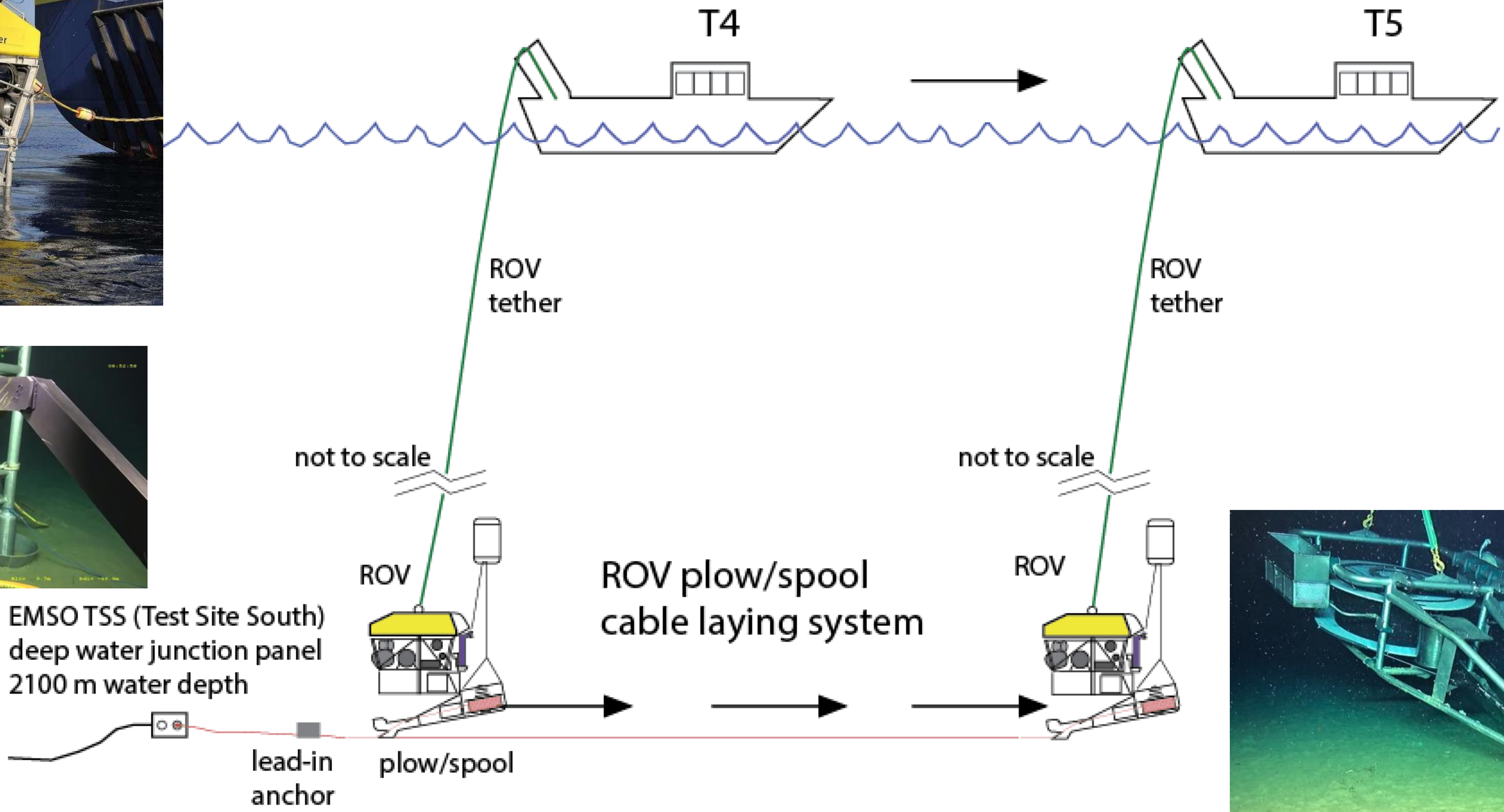


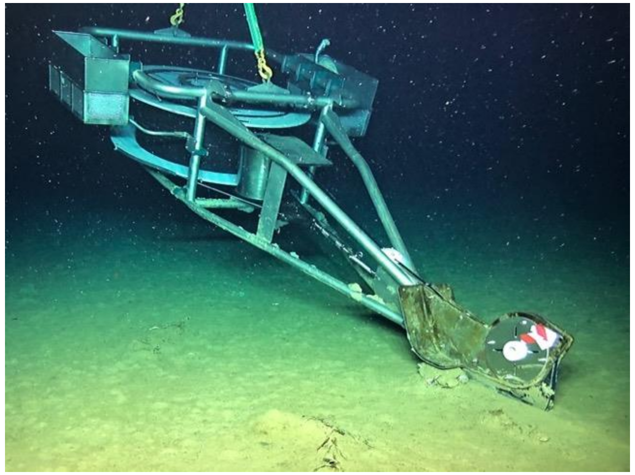


FocusX1 marine expedition: deployment 6-km-long cable

ROV cable laying system (plow/spool) → 8-10 mm cable (20cm burial)

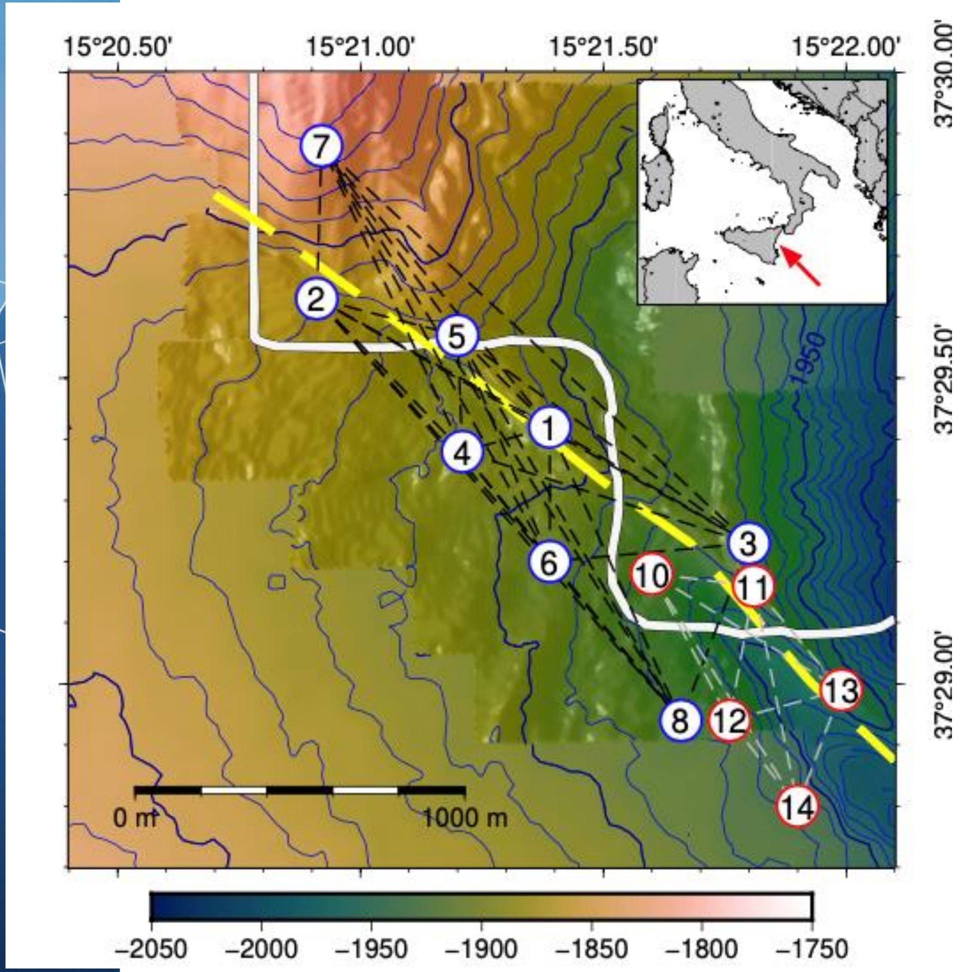




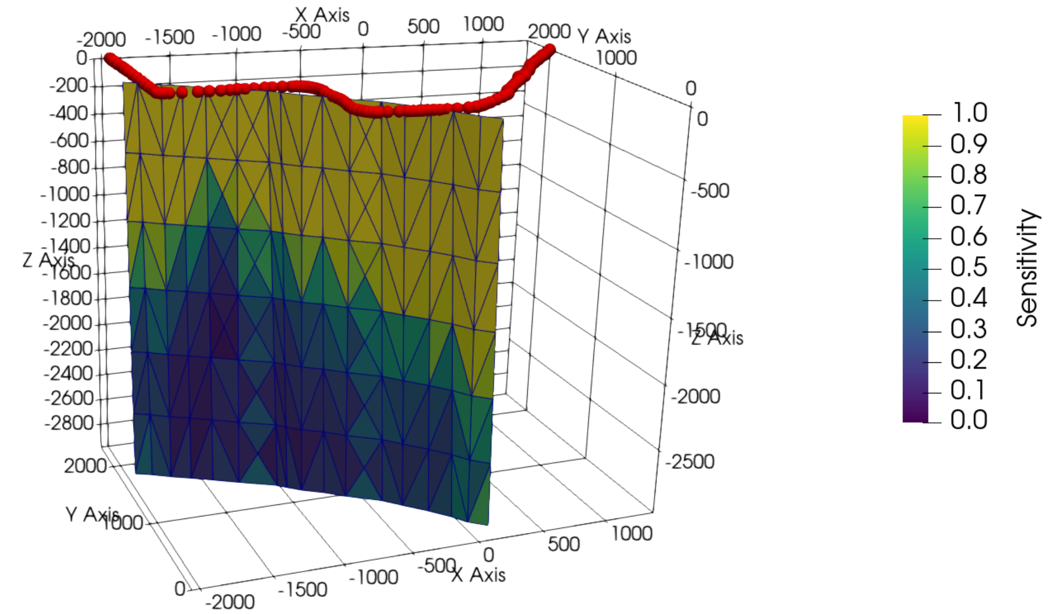


Modelled Resolution

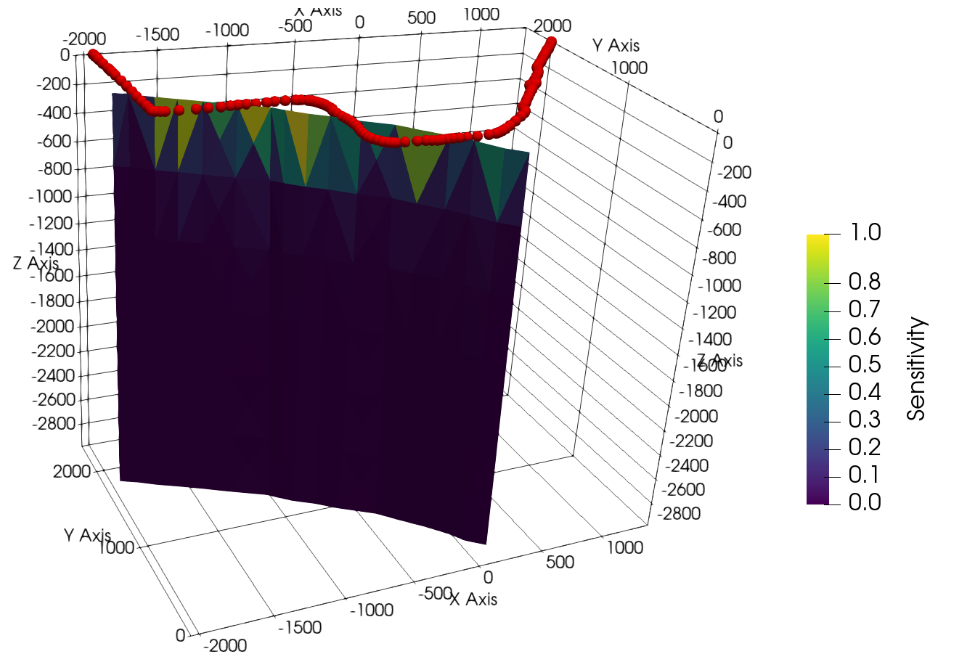
500m cell size used



Resolution from Cable

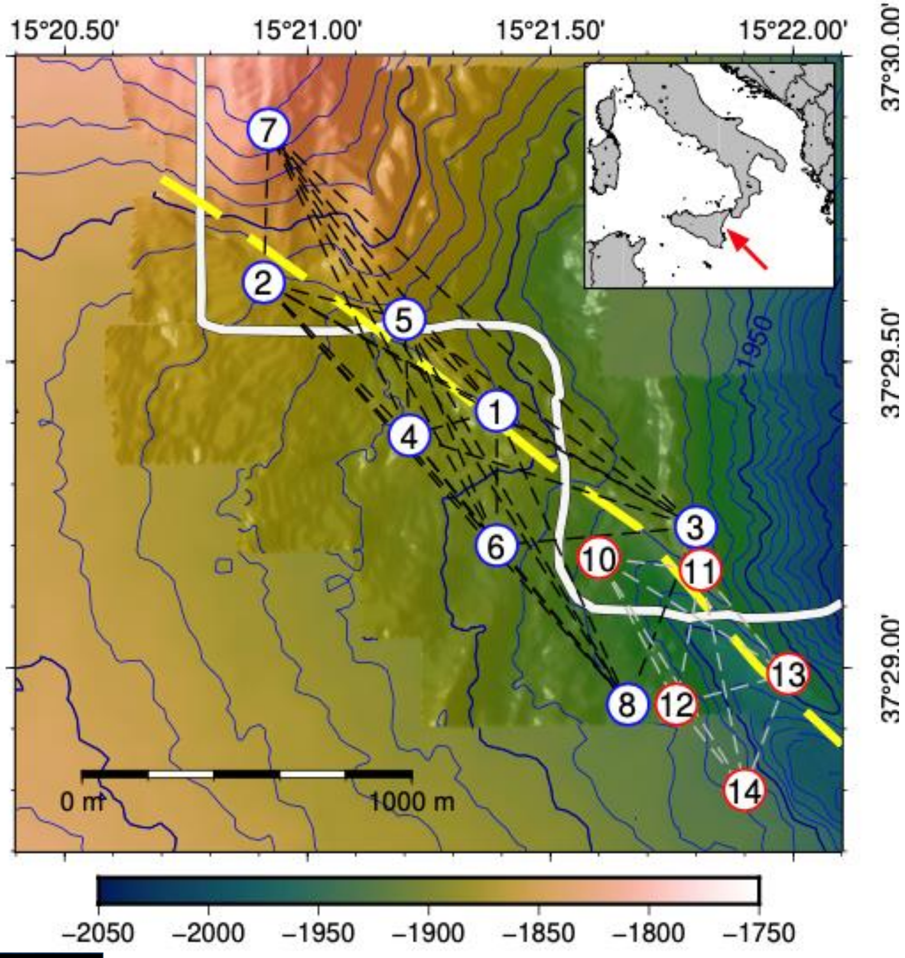


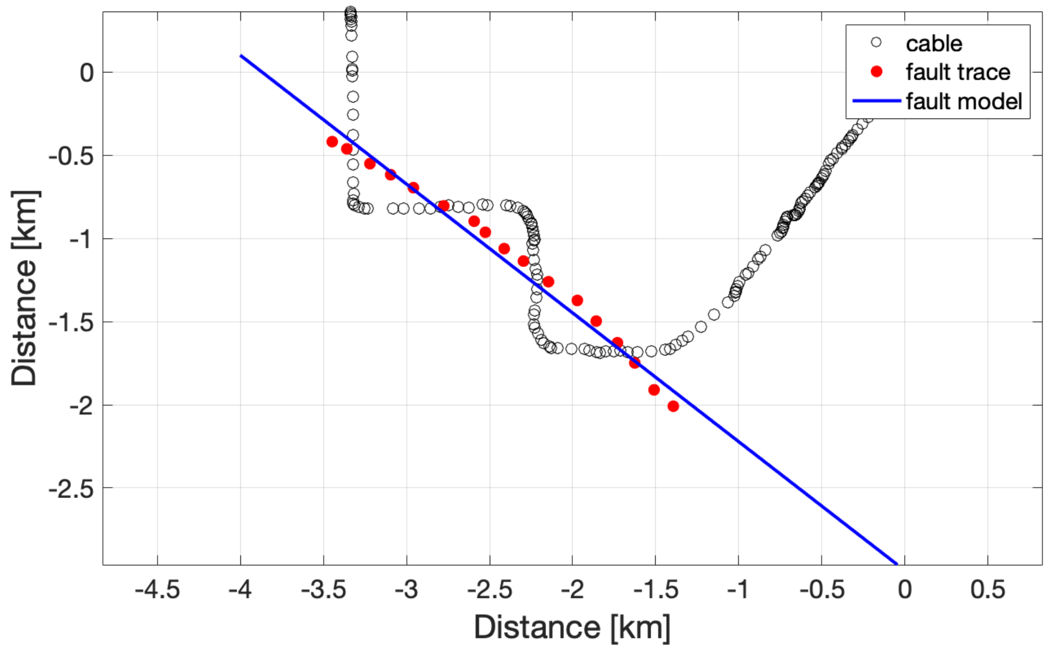
Resolution from Ranging

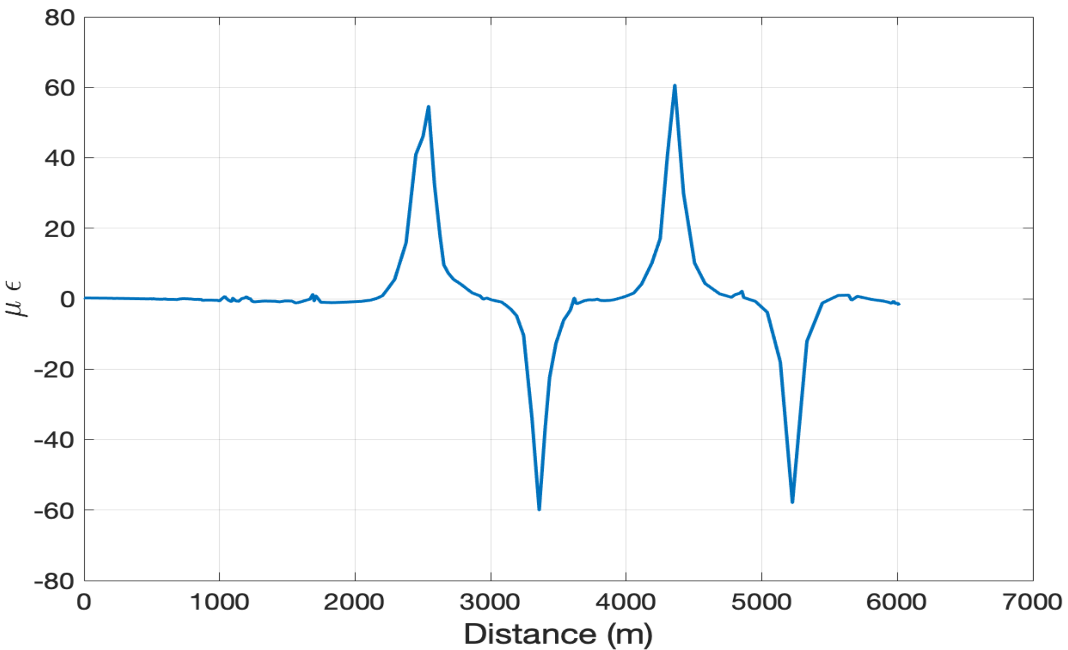


Modelled : Slip

- Predicted strain due to 4cm of dextral slip on 5km x 5km fault



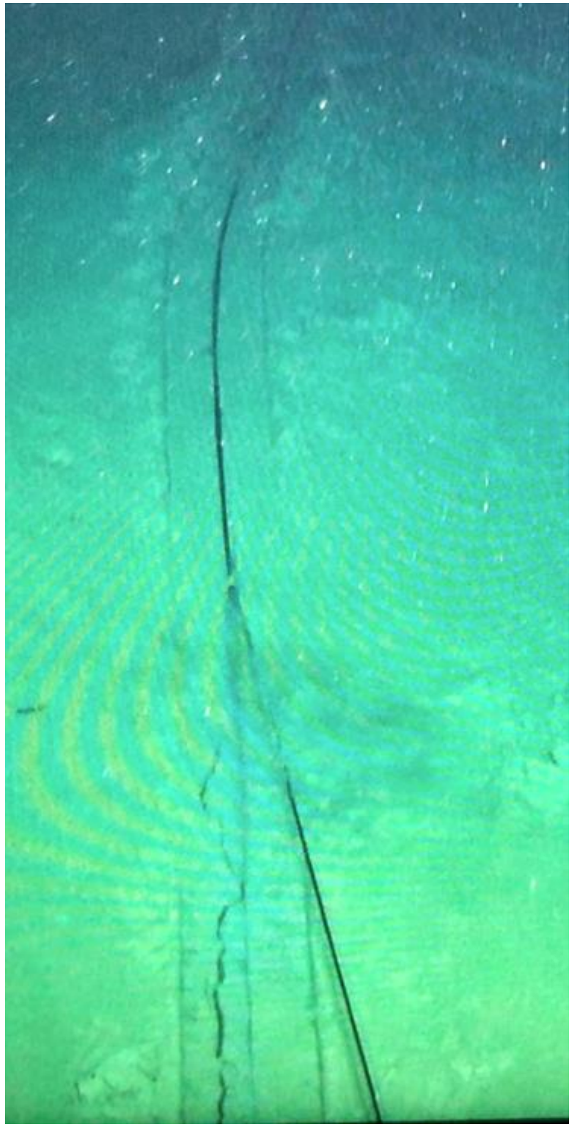




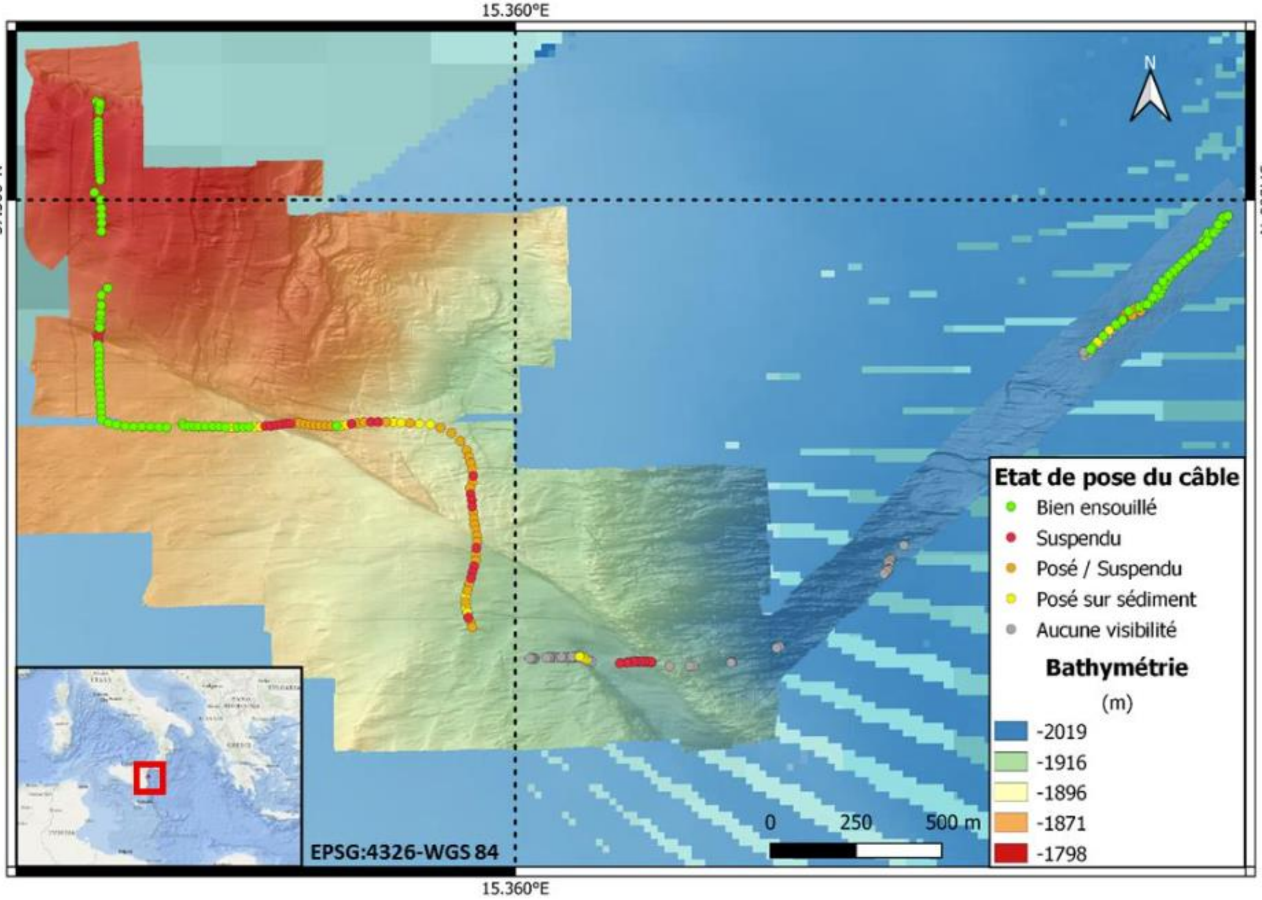
Coupling of cable: check your work

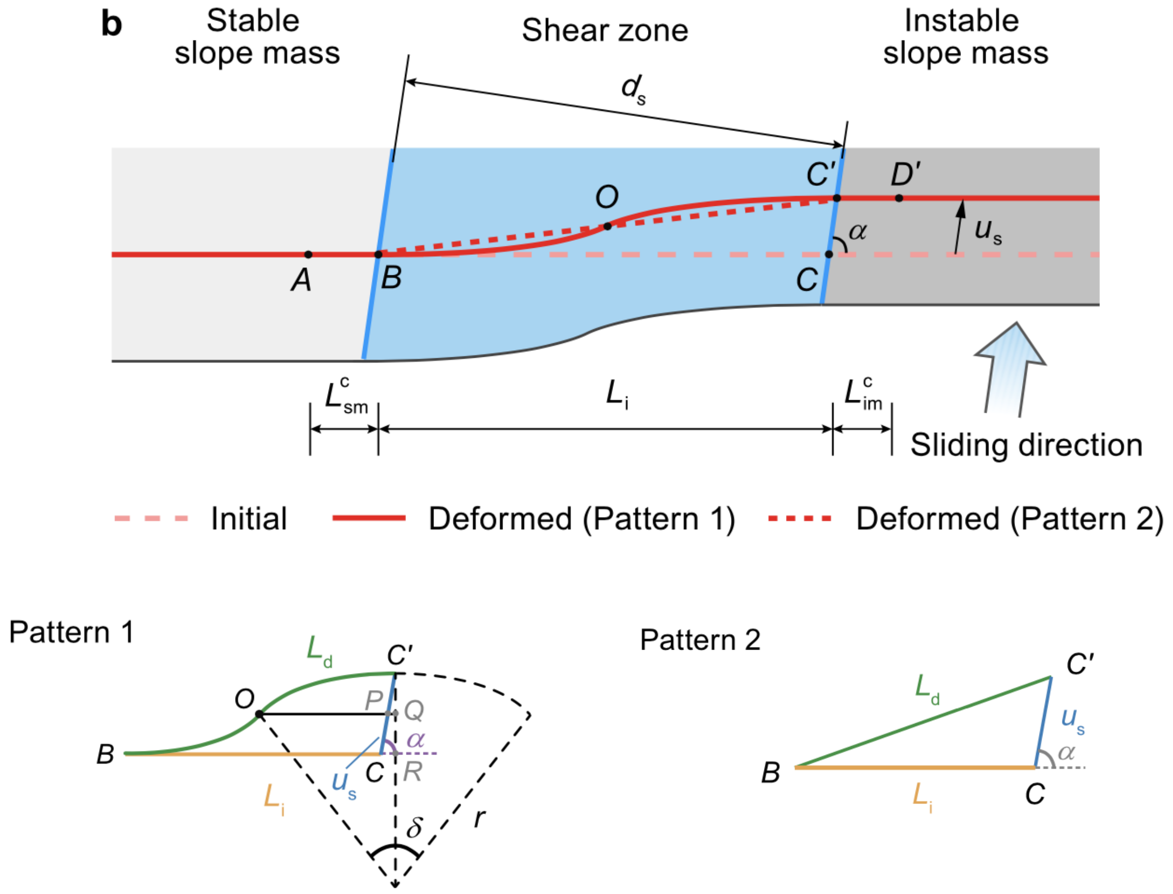
The dream

The reality (in places)



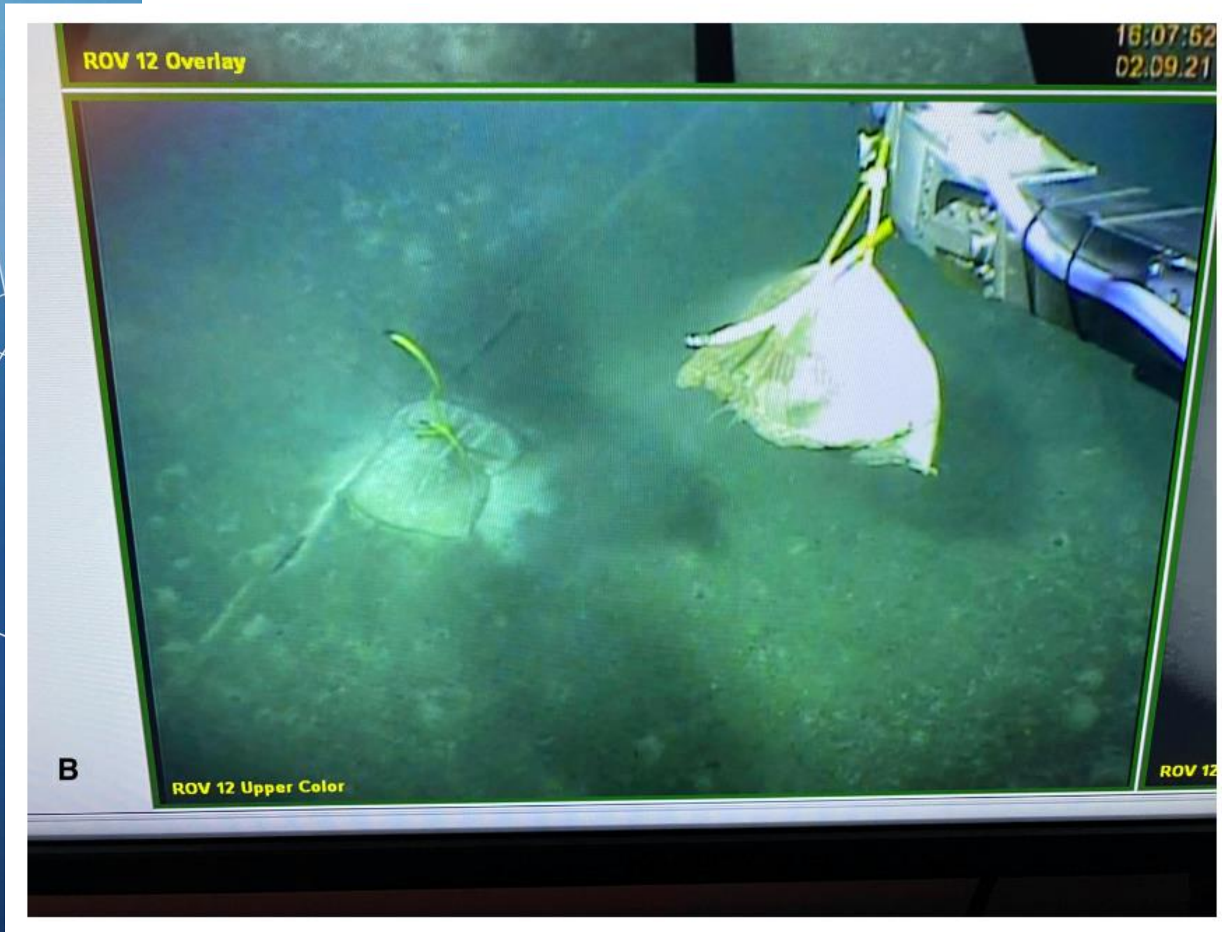
Coupling of cable

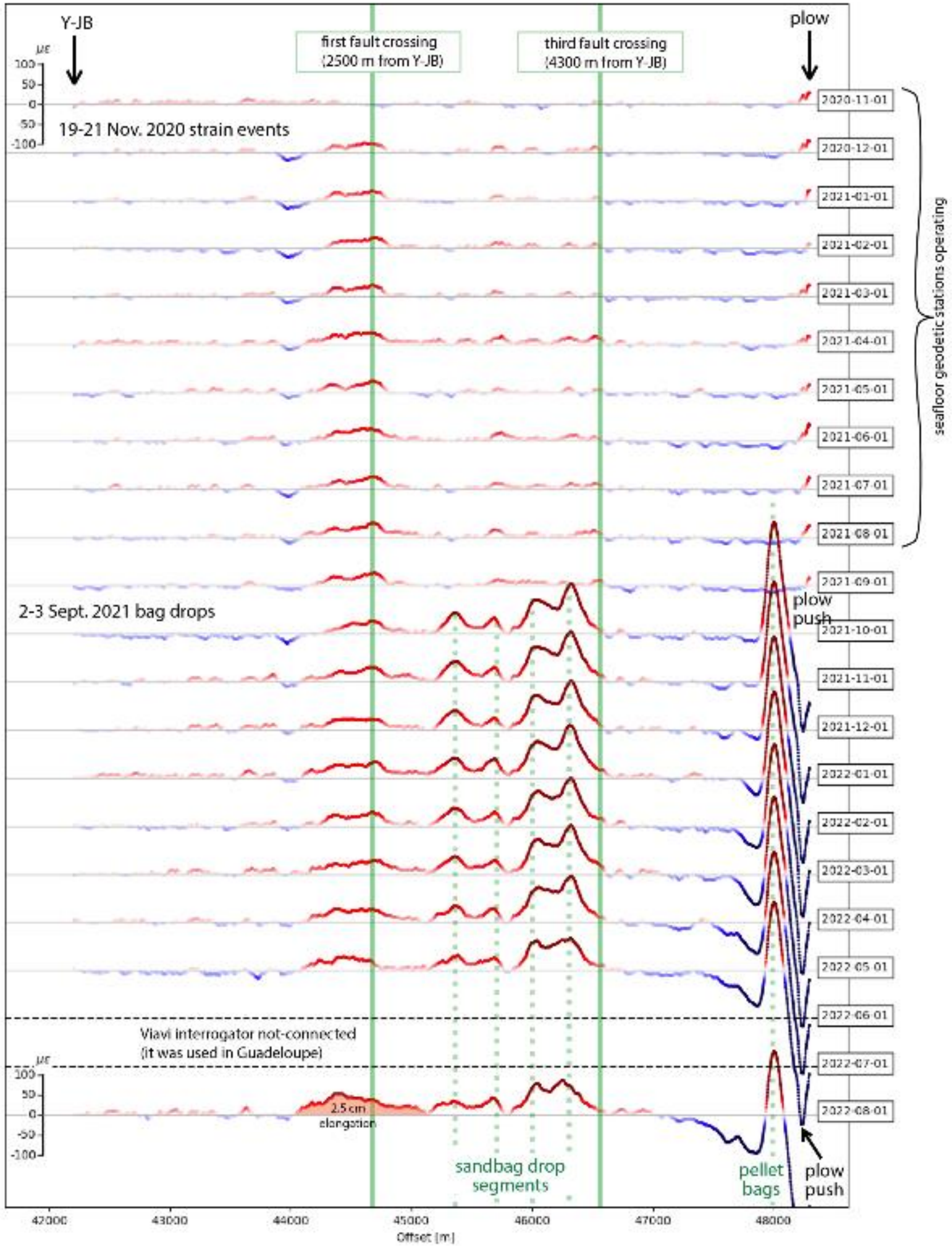




Zhang et al., 2018

Coupling of cable

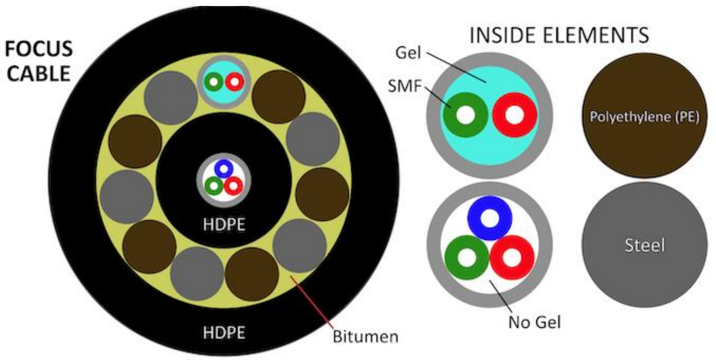


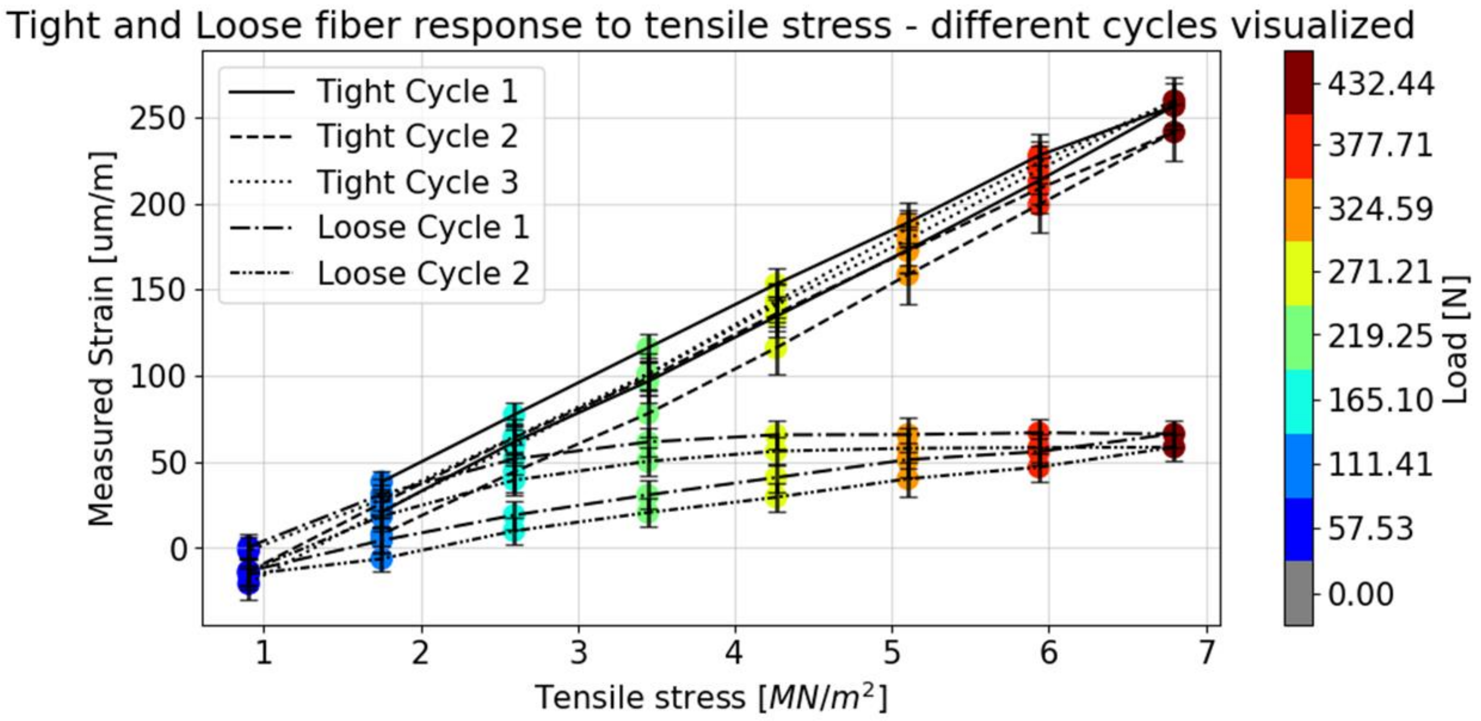


Gutscher et al., 2023

Issues: Cable response

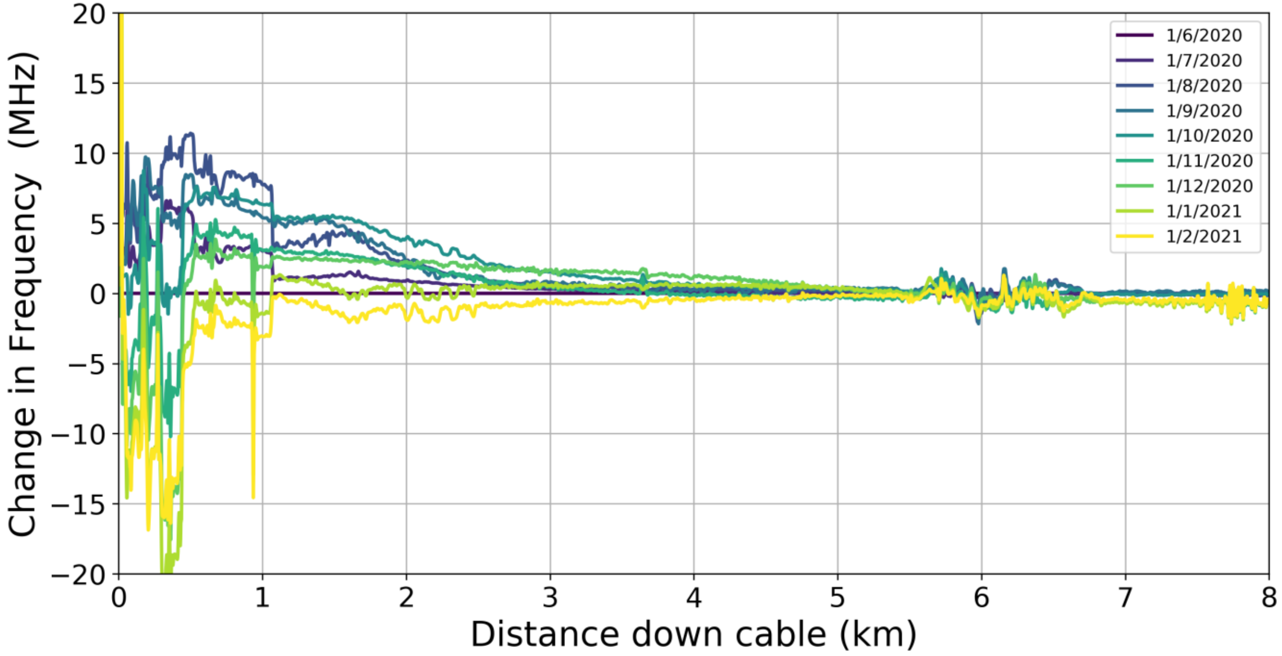
- Tests at SMASH Lab in Ifremer using Luna interrogator

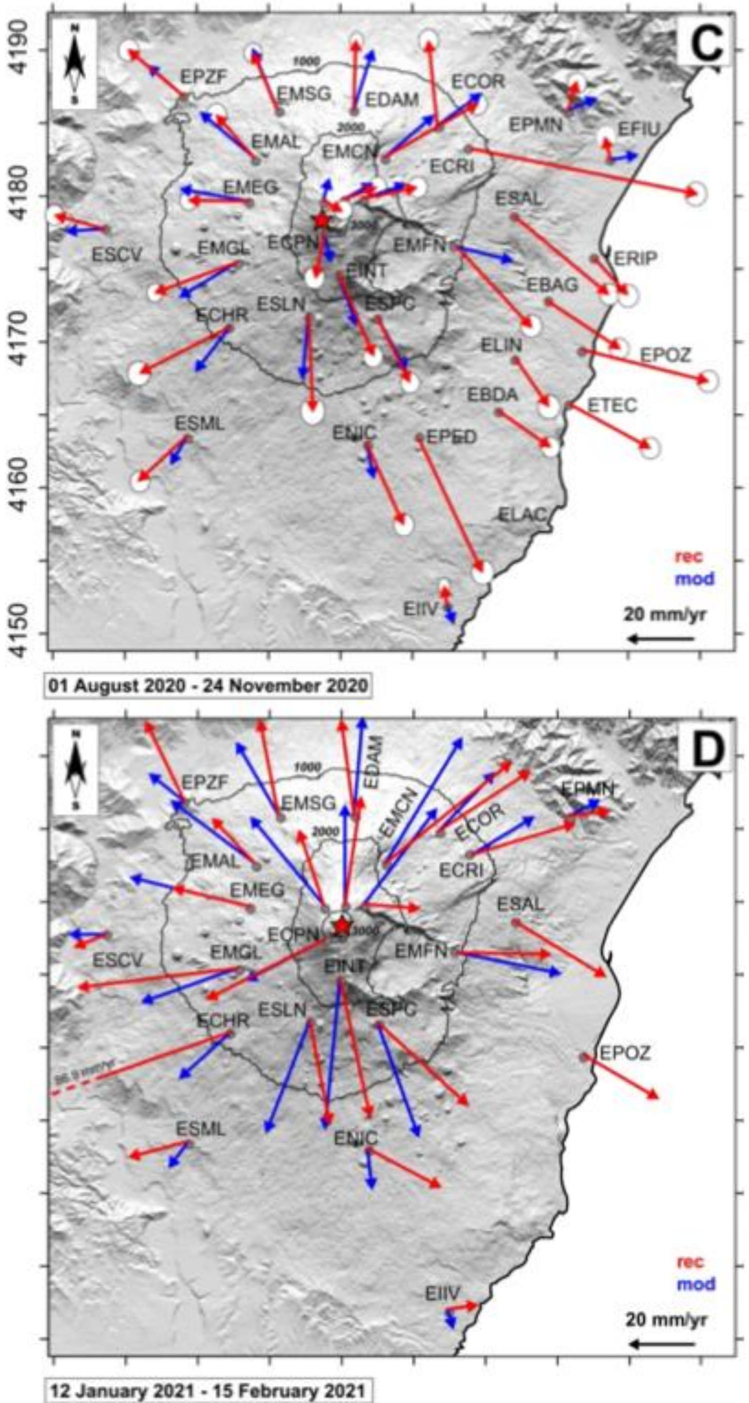




Near Shore cable signal

- Large surface deformation observed on land due to inflation and deflation of Etna during 2020-2021
- Raw BOTDR data shows similar large scale variation along the cable during same period.



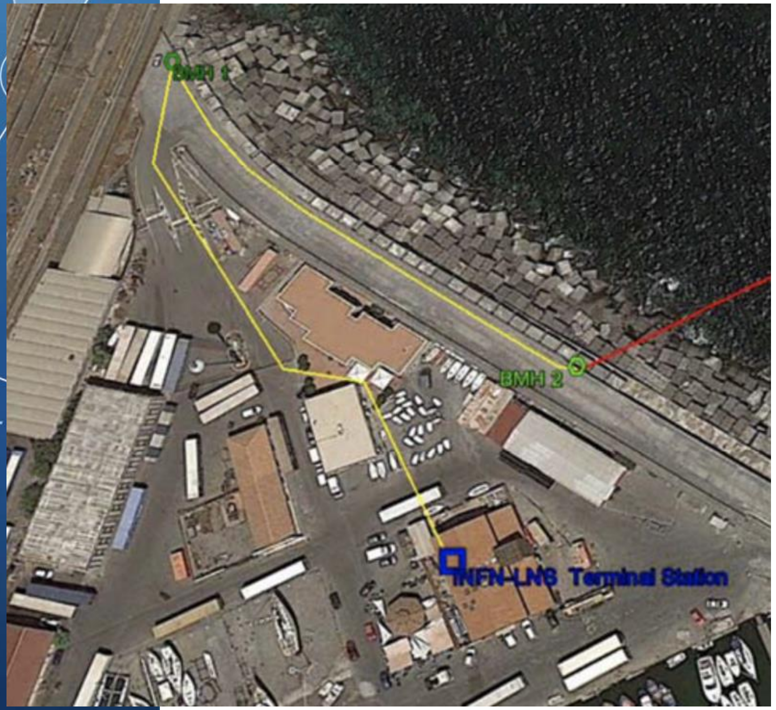


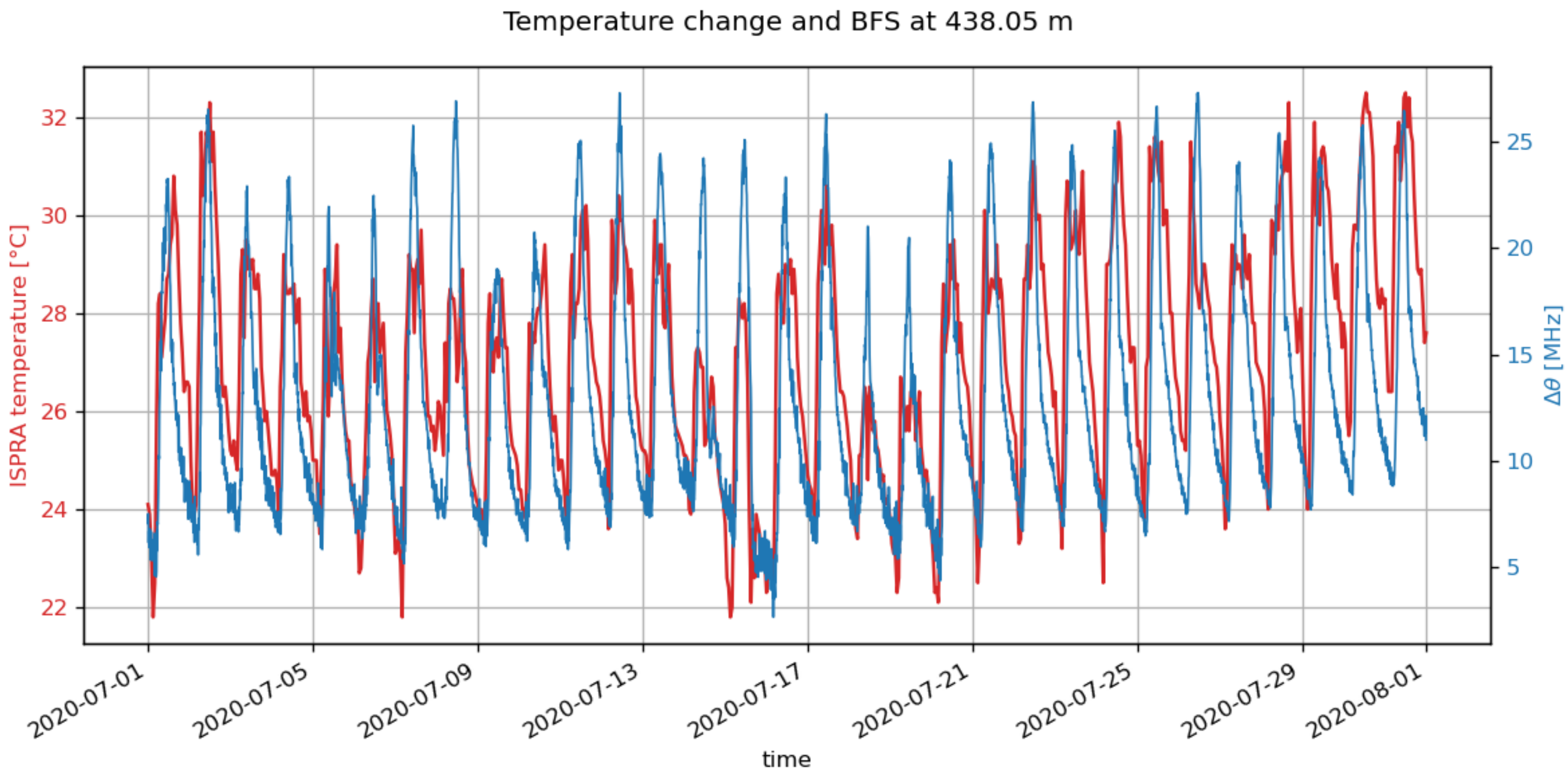
Bruno et al., 2022

Diurnal Temperature

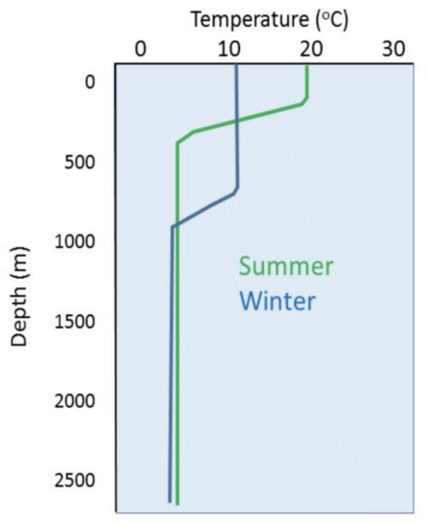
$$\Delta f = \Delta\epsilon\, C^{F\epsilon} + \Delta T\, C^{FT}$$

$$C^{F\epsilon} = 0.049\, MHz\,/\,\mu\varepsilon \qquad C^{FT} = 1.06\, MHz\,/\,°C$$

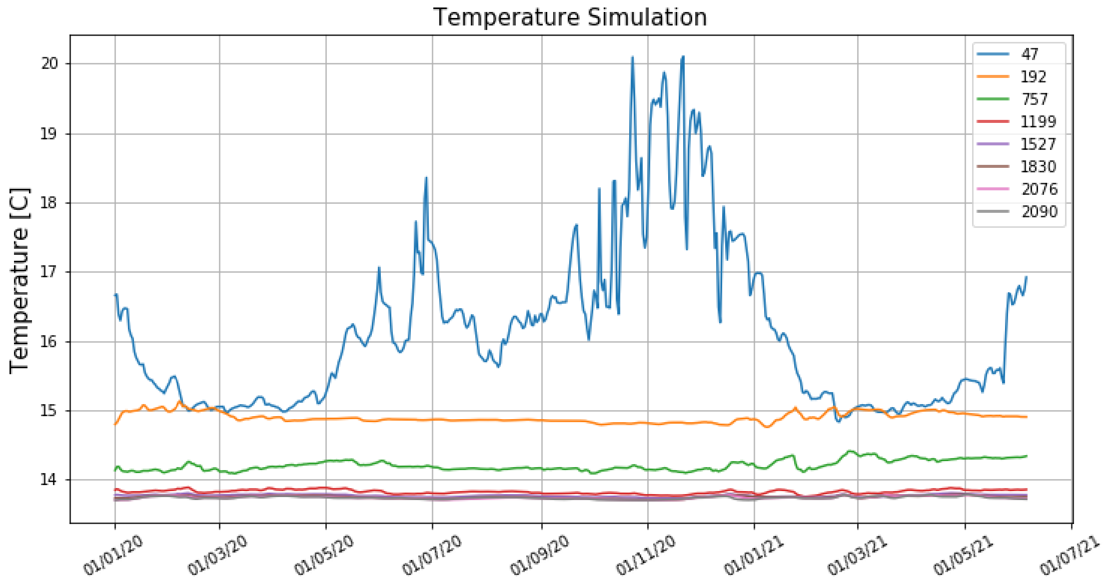


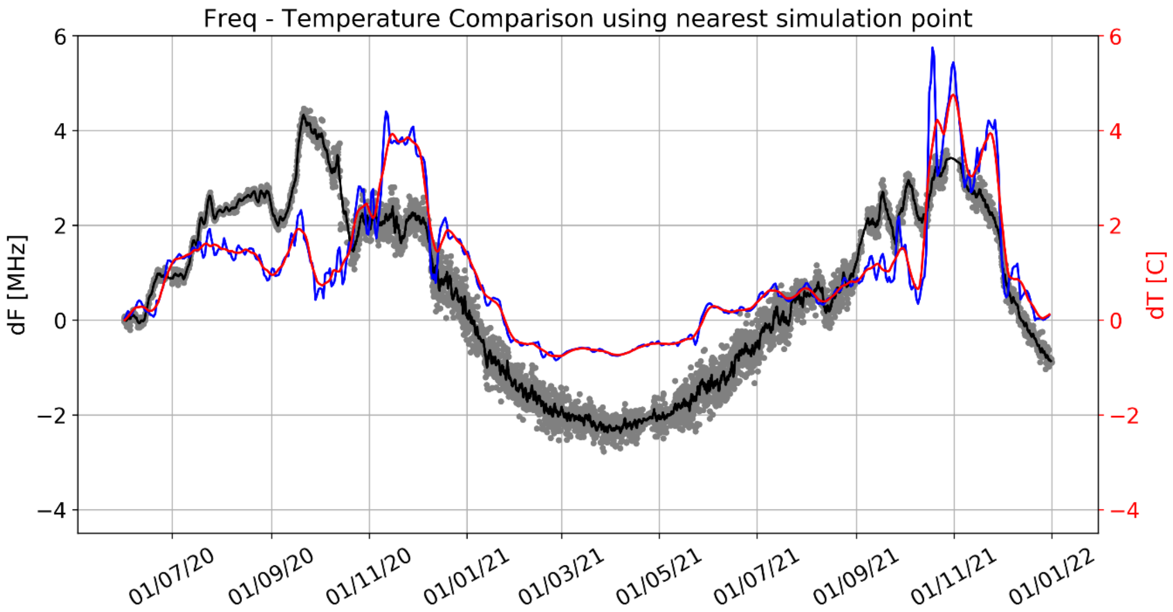


Issues: Seasonal Temperature



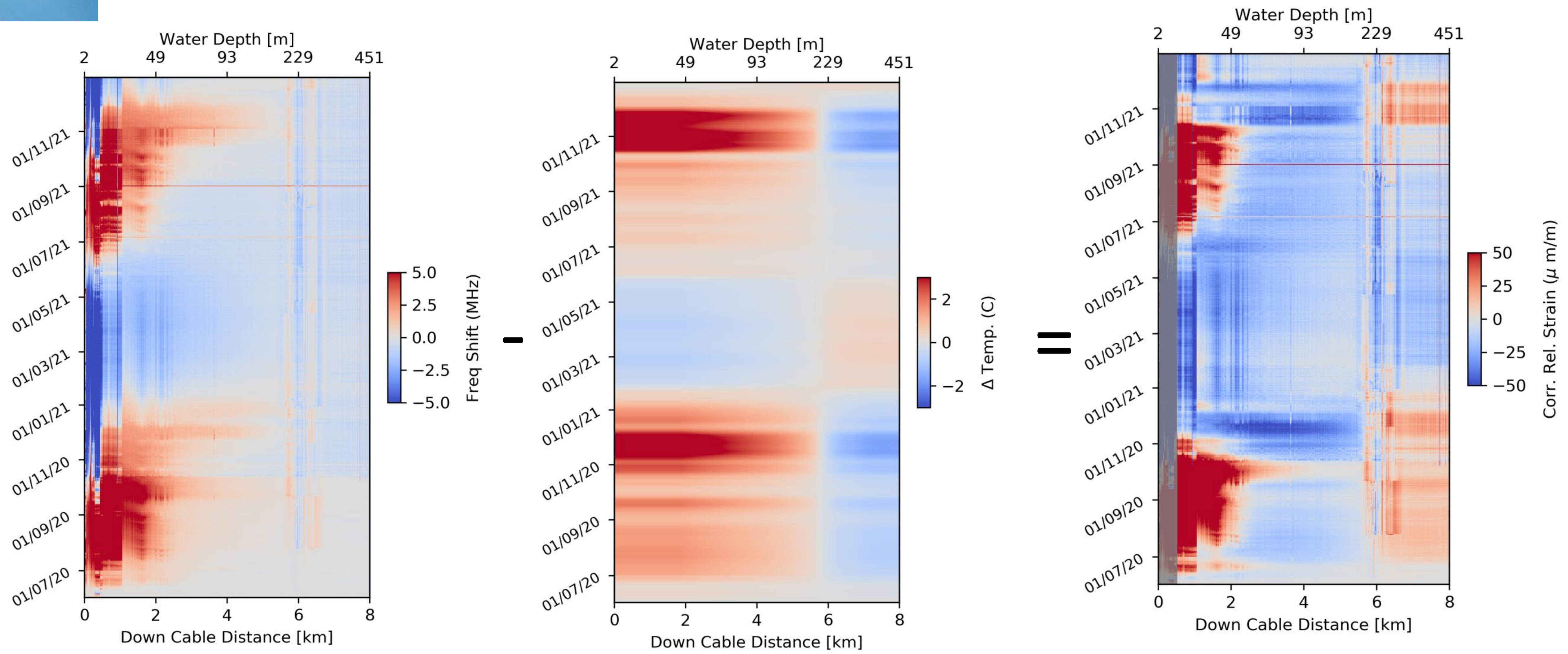
Temperature at seafloor is simulated using the CMEMS model which accounts for sea surface temperature, salinity, wind provided by CMCC. Different colours represent different water depths, legend in meters.





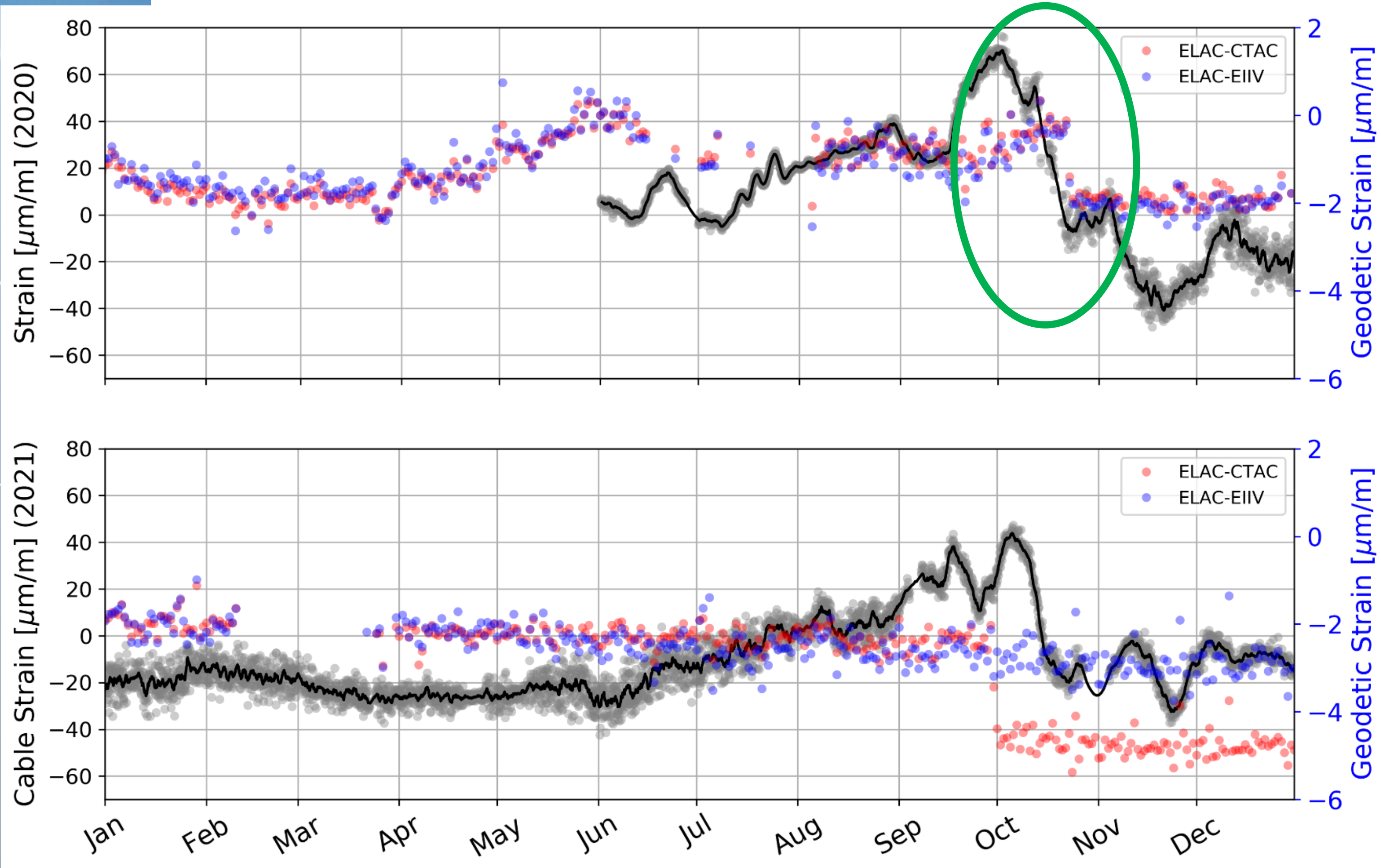
Issues: Temperature

$$\Delta\epsilon = \left(\Delta f - \Delta T\, C^{FT}\right)\frac{1}{C^{F\epsilon}}$$

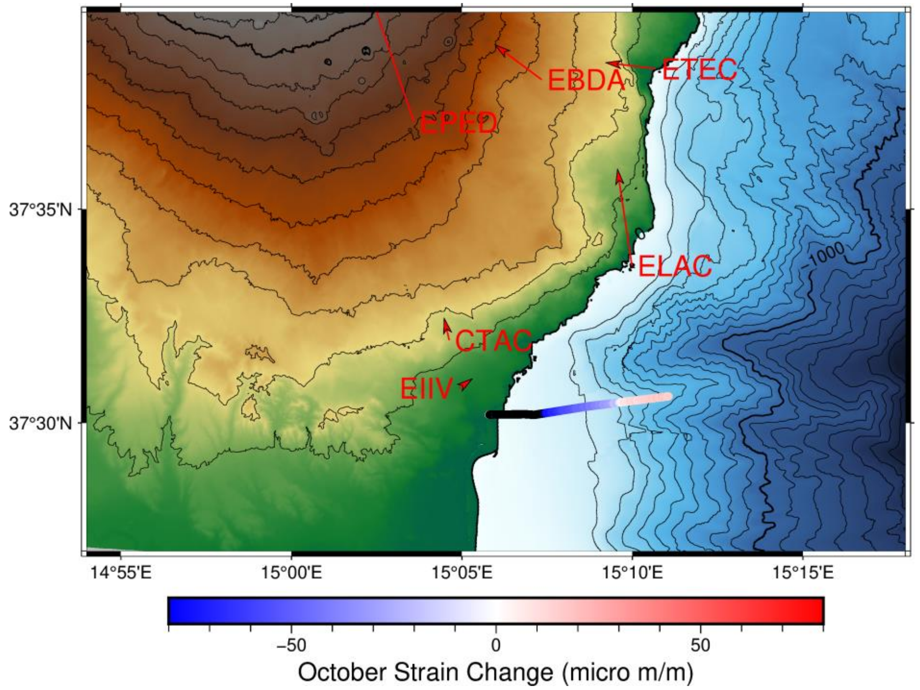


Near Shore cable signal

- Strain time series at 2km down the cable
- In October 2020 see drop in strain at similar time as GNSS stations observe event
- **BUT** cable sees same drop a year later implying seasonal temperature variation



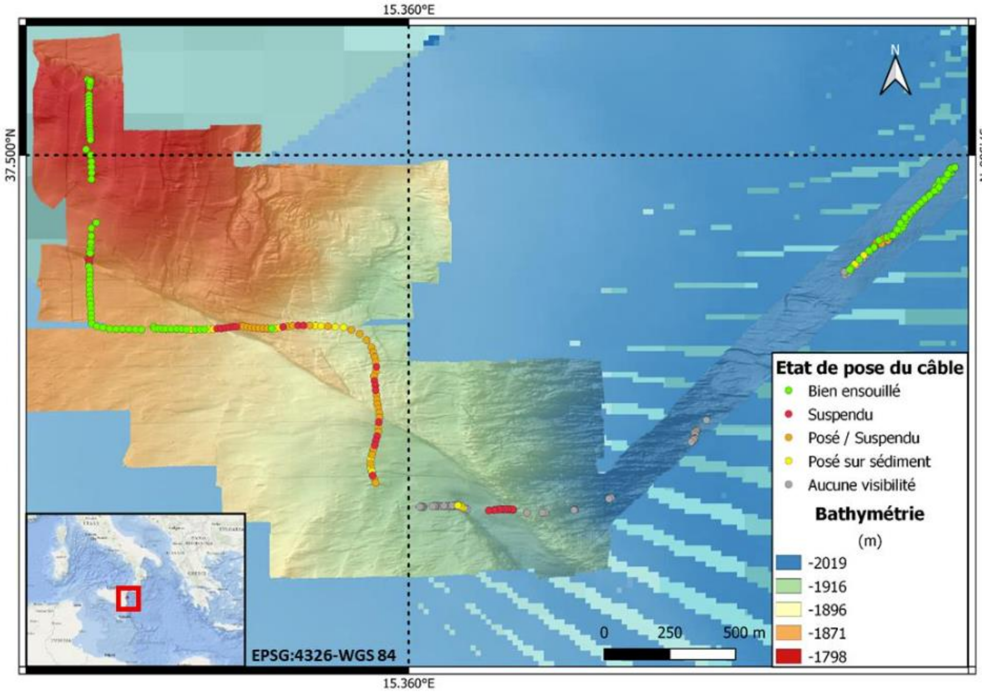
Difference in displacement : *15/10/20 – 15/11/20*

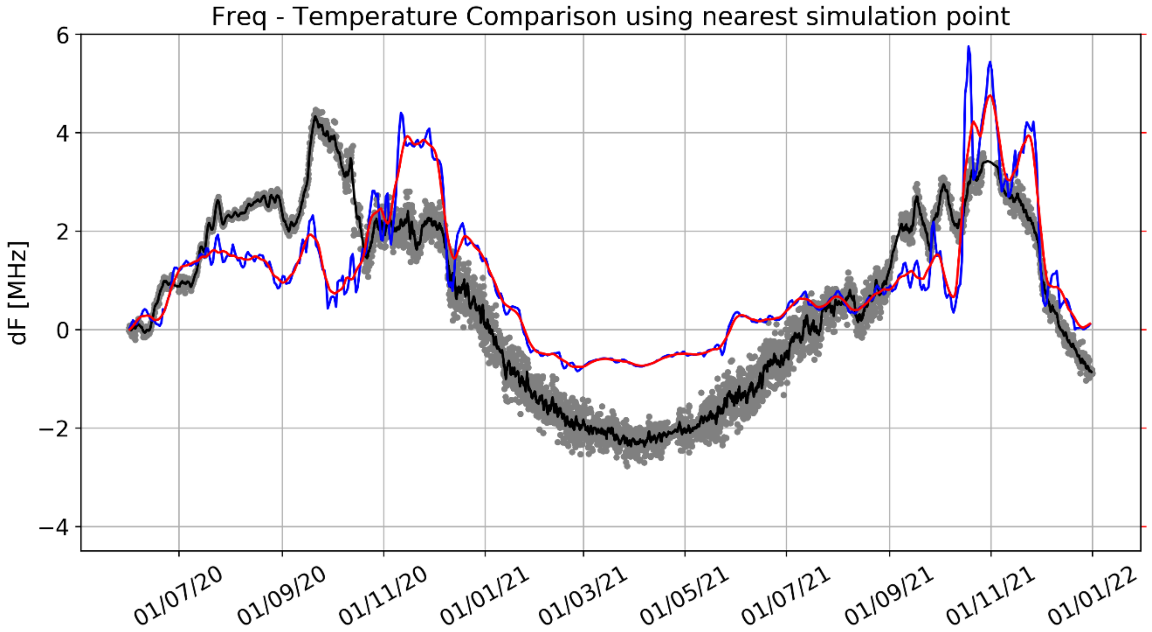


Conclusions

- Analytical modelling important tool in deployment design, particularly in understanding the response of non-standard instruments.

- Resolution matrices are useful in determing what can be observed of your model by the data given its geometry **but** they are dependent on the assumptions made



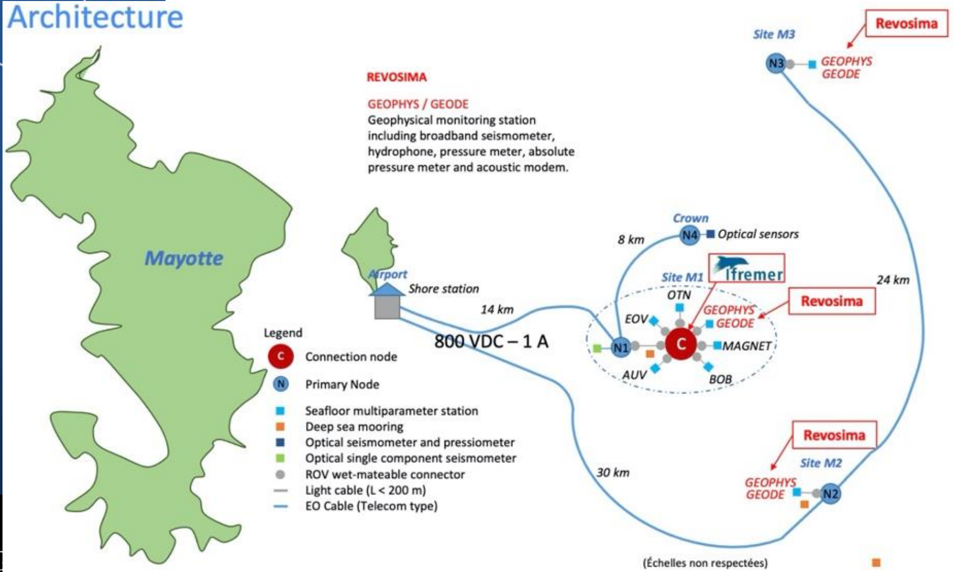


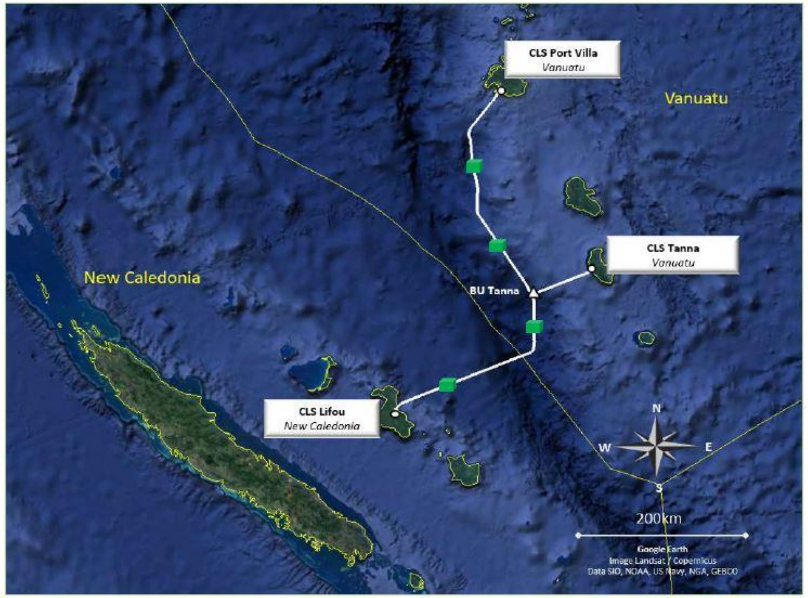
Conclusions

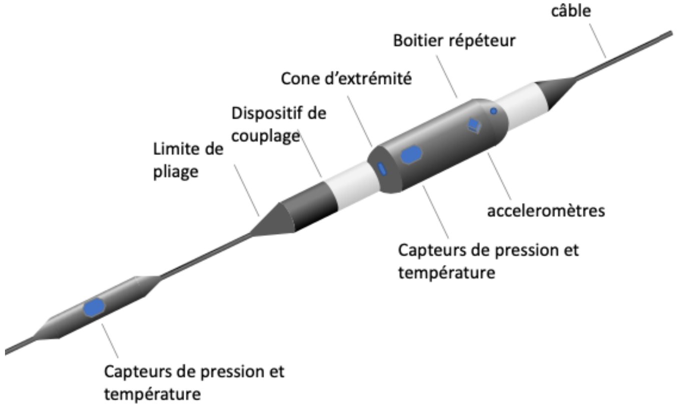
DSS is promising as it has the potential to provide high resolution data while piggy-backing on other infrastrucutre (e.g., New Caledonia – Vanuatu SMART cable, Mayotte)

Howerver there are still issues to be better understood:

- accounting for temperature variations (Ramen, combined in version using Brillouin)
- cable coupling with the seafloor
- understanding the effect of cable archeture on measurement








"That's all Folks!"