Investigation of the Ionian basin and Calabrian arc lithosphere

"Potrebbe essere giusto o sbagliato. Lo saprai solo se avrai sbagliato."

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In collaboration with the Seismology research group at the University of Münster for a three months Erasmus traineeship (April-June)

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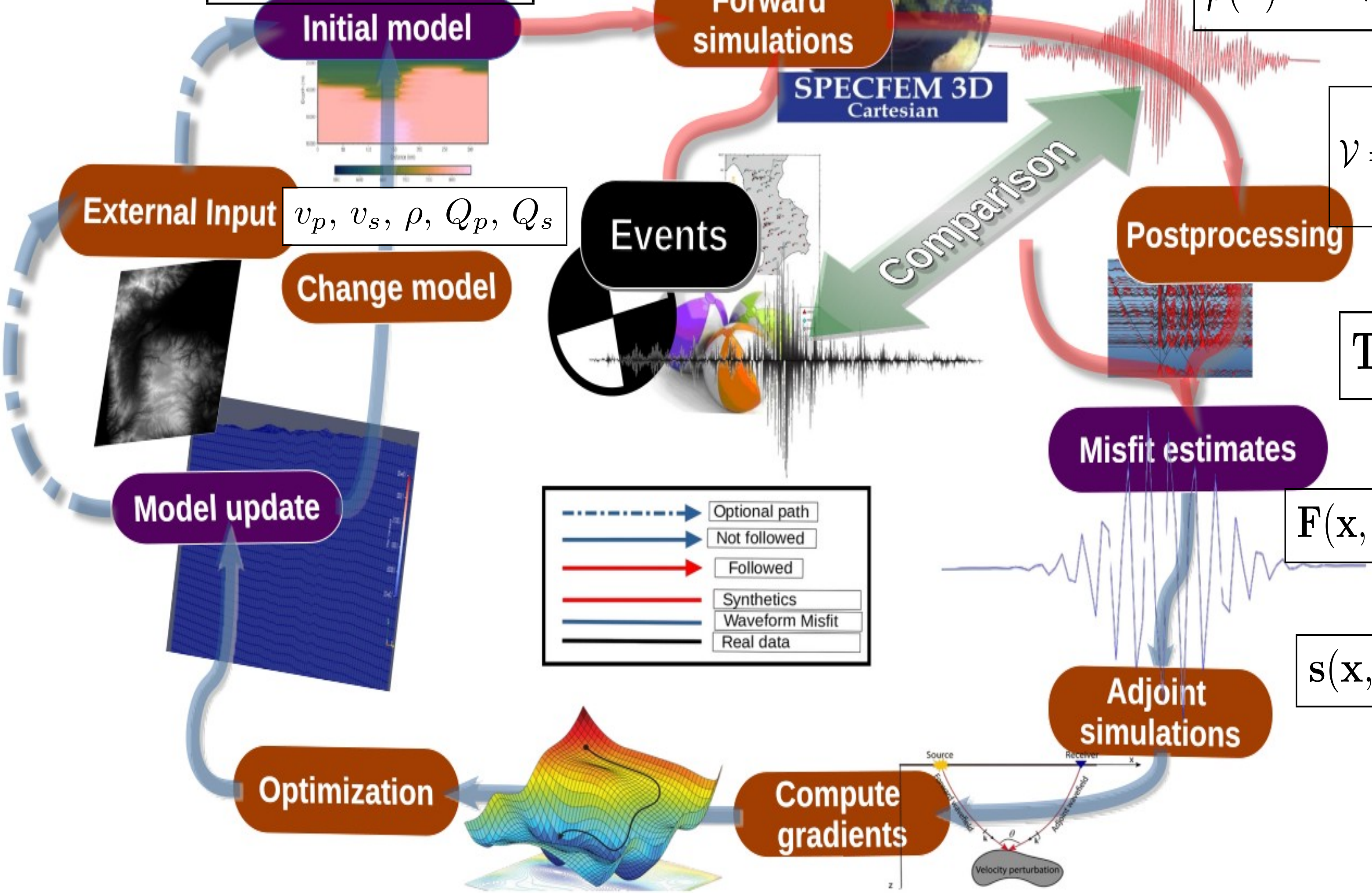
SPECFEM 3D Cartesian

DIPARTIMENTO DI FISICA

Academic Year 2024/2025

SEM (Spectral-Element Method) and Full Waveform Inversion overview

$$G(m) = d$$



$$\rho(\mathbf{x})\ddot{\mathbf{u}} - \nabla \cdot \mathbf{T}(\mathbf{x},t) + \mathcal{V} = \mathbf{F}(\mathbf{x}_s,t)$$

$$\mathcal{V} = \begin{cases} \mathbf{0} & \text{elastic ,} \\ 2\rho\zeta\dot{\mathbf{u}} + \rho\zeta^2\mathbf{u} & \text{viscoelastic.} \end{cases}$$

$$\mathbf{T}(\mathbf{x},t) = \mathbf{C}(\mathbf{x}) : \nabla\mathbf{u}(\mathbf{x},t)\,,$$

$$\mathbf{F}(\mathbf{x},t) = -\mathcal{S}(t)\,\mathbf{M}\cdot\nabla\delta(\mathbf{x}-\mathbf{x}_s)$$

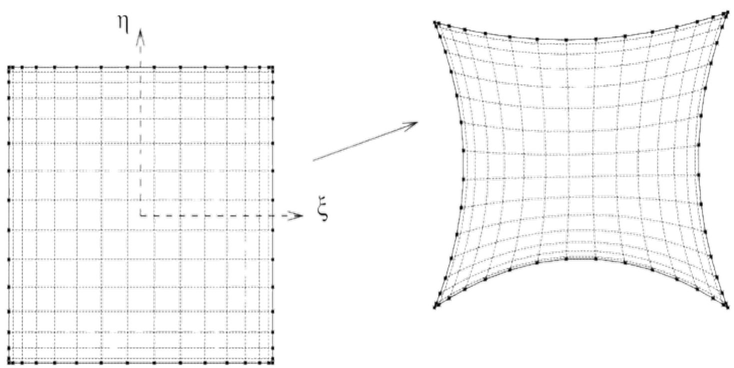
$$\mathbf{s}(\mathbf{x},0) = \mathbf{0}\,, \quad \partial_t\mathbf{s}(\mathbf{x},0) = \mathbf{0}$$

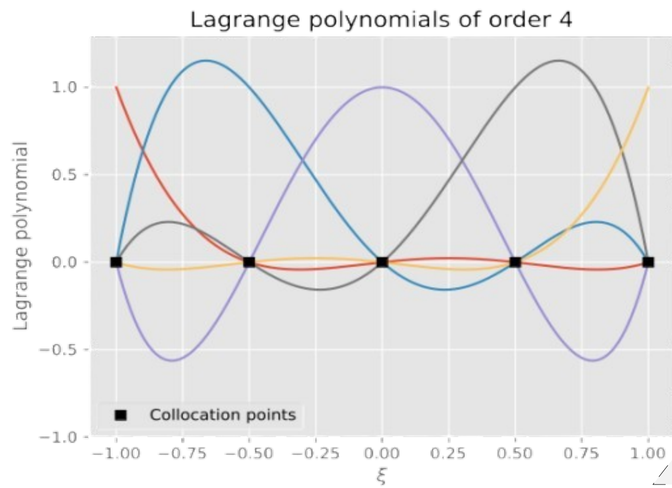
$$\hat{\mathbf{n}}\cdot\ \mathbf{T} = \mathbf{0}$$

Goal: finding the displacement field **u** s.t. ∀ test function **w** this equation is satisfied.

$$\int_\Omega [\mathbf{w}\cdot\mathbf{T} - \mathbf{w}\cdot\mathbf{C}:\nabla\mathbf{u}]\mathrm{d}^3\mathbf{x} = \int_\Omega \mathbf{M}:\nabla\mathbf{w}(\mathbf{x_s})\mathcal{S}(t)\mathrm{d}^3\mathbf{x}$$

Spatial discretization[2]





GLL quadrature

Mass matrix is fully diagonal

$$u(\mathbf{x}(\xi,\eta,\zeta)) \approx \sum_{i,j,k=0}^{N_i N_j, N_k} u_i(\xi)\ell_j(\eta)\ell_k(\zeta).$$

$$\ddot{\mathbf{u}}(t) = \mathcal{M}^{-1}\ [\mathcal{F}(t) - \mathcal{K}\,\mathbf{u}(t)]$$

Meshing strictly with conforming/non conforming hexahedral elements!
Major discontinuities practically feasible though.

[2] Komatitsch1997

Time discretization: Newmark scheme

Advantages:

- Conservative (angular momenta, momentum etc.),
- Curved finite elements are mapped to unit cube, described by 8 control points,
- Efficient MPI parallelization,
- ASCII based, serial I/O, ADIOS I/O, HDF5, GPU compatible.

$$
\begin{aligned}
\mathbf{u}_{n+1} &= \mathbf{u}_n + \Delta t\,\mathbf{v}_n + \frac{\Delta t^2}{2}\mathbf{a}_n \\
\mathbf{v}_{n+1/2} &= \mathbf{v}_n + \frac{\Delta t}{2}\mathbf{a}_n \\
\mathbf{a}_{n+1} &= \mathbf{M}^{-1}\left(\mathbf{F}_{n+1} - \mathbf{C}\mathbf{v}_{n+1/2} - \mathbf{K}\mathbf{u}_{n+1}\right) \\
\mathbf{v}_{n+1} &= \mathbf{v}_{n+1/2} + \frac{\Delta t}{2}\mathbf{a}_{n+1}
\end{aligned}
$$

[3] Tromp et Modrak2006

Disadvantages:

- The finer the mesh the stricter the timestep upper value!
- Ill-shaped elements increase the solving time or make it computationally infeasible.
- <u>No stability studies</u> up until now for unstructured heterogeneous medium.

Rule of thumb N ~ 5 in “hero runs”

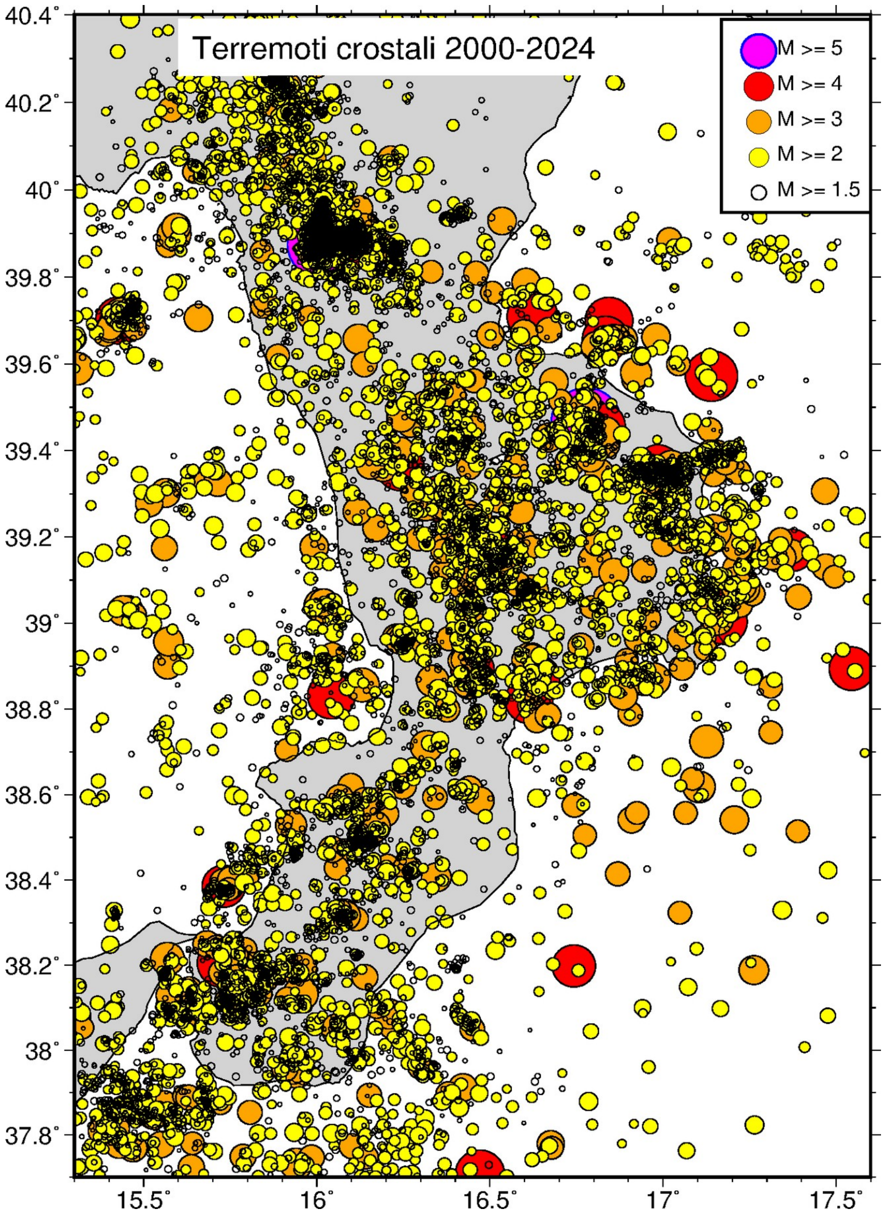
$$\Delta t \leq C \frac{\min_{\Omega_i \in \mathbf{\Omega}} h}{\max_{\in m} v}$$

$$h = \frac{N_{GLL}\, V_{S,min}}{5\, f_{max}}$$

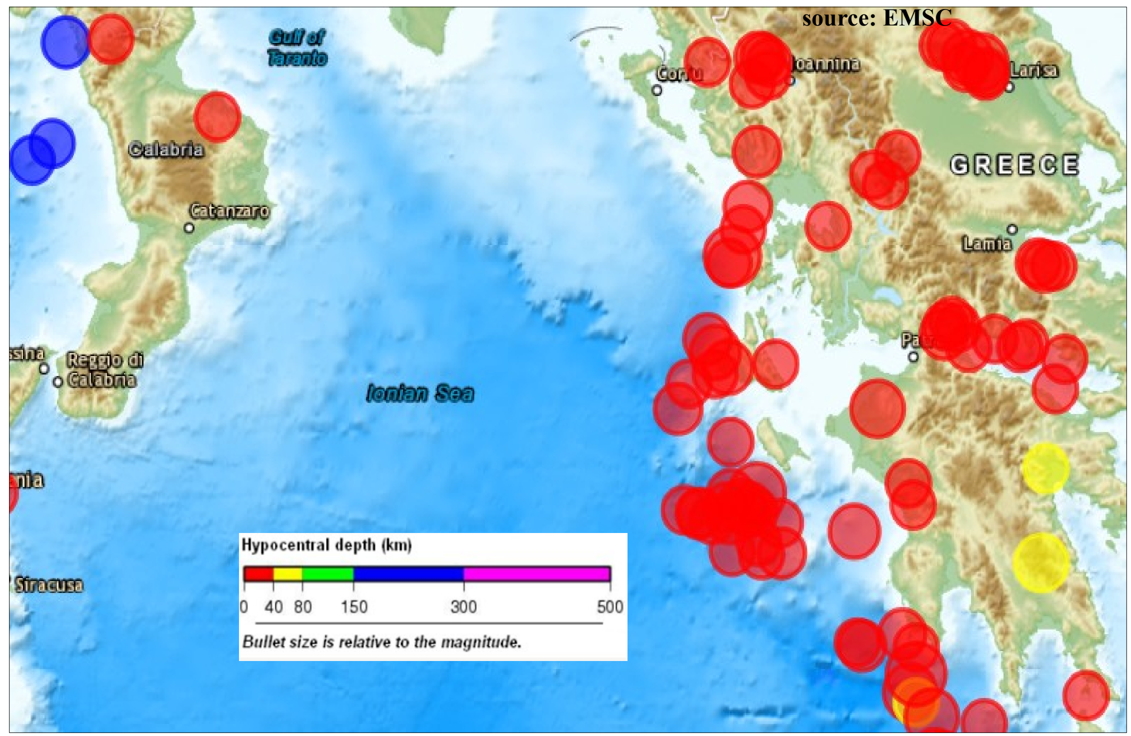
Benchmarks test (regional models)³ C ~ 0.5

Freq. goal: 0.3 Hz

Why it's important to study the lithospheric structure of the Calabrian arc and Ionian basin.



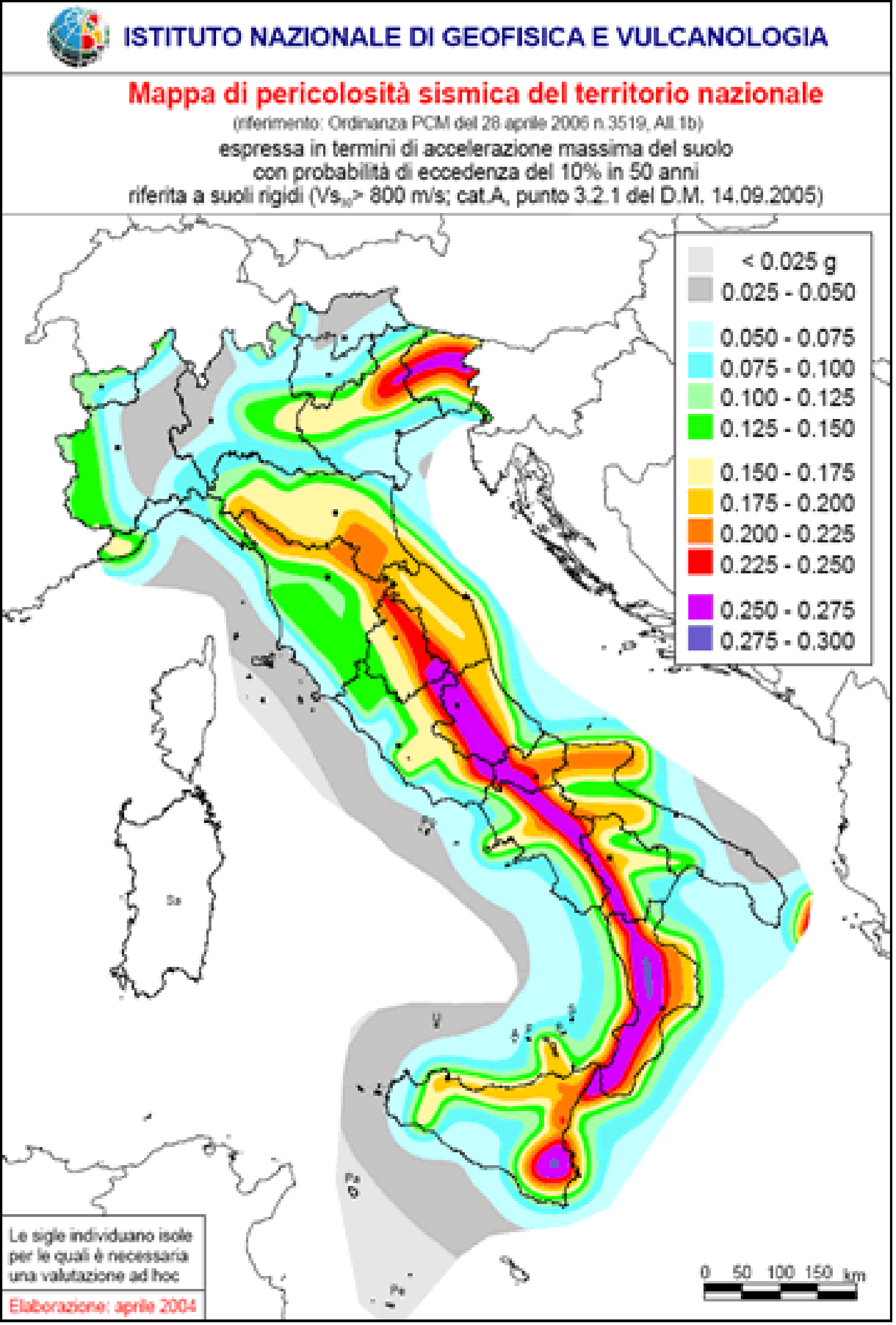
Mw > 4 earthquakes recorded in the last year.

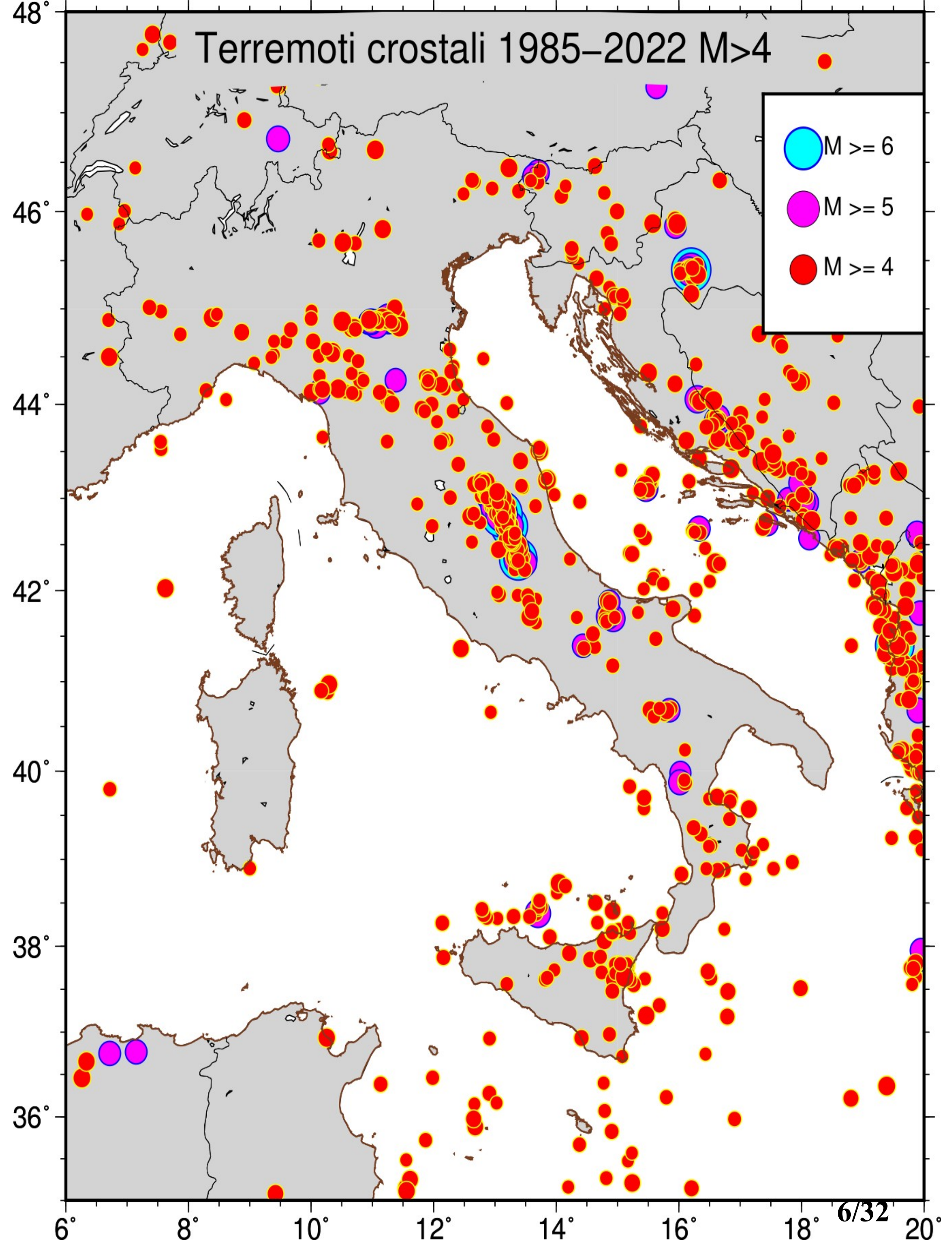


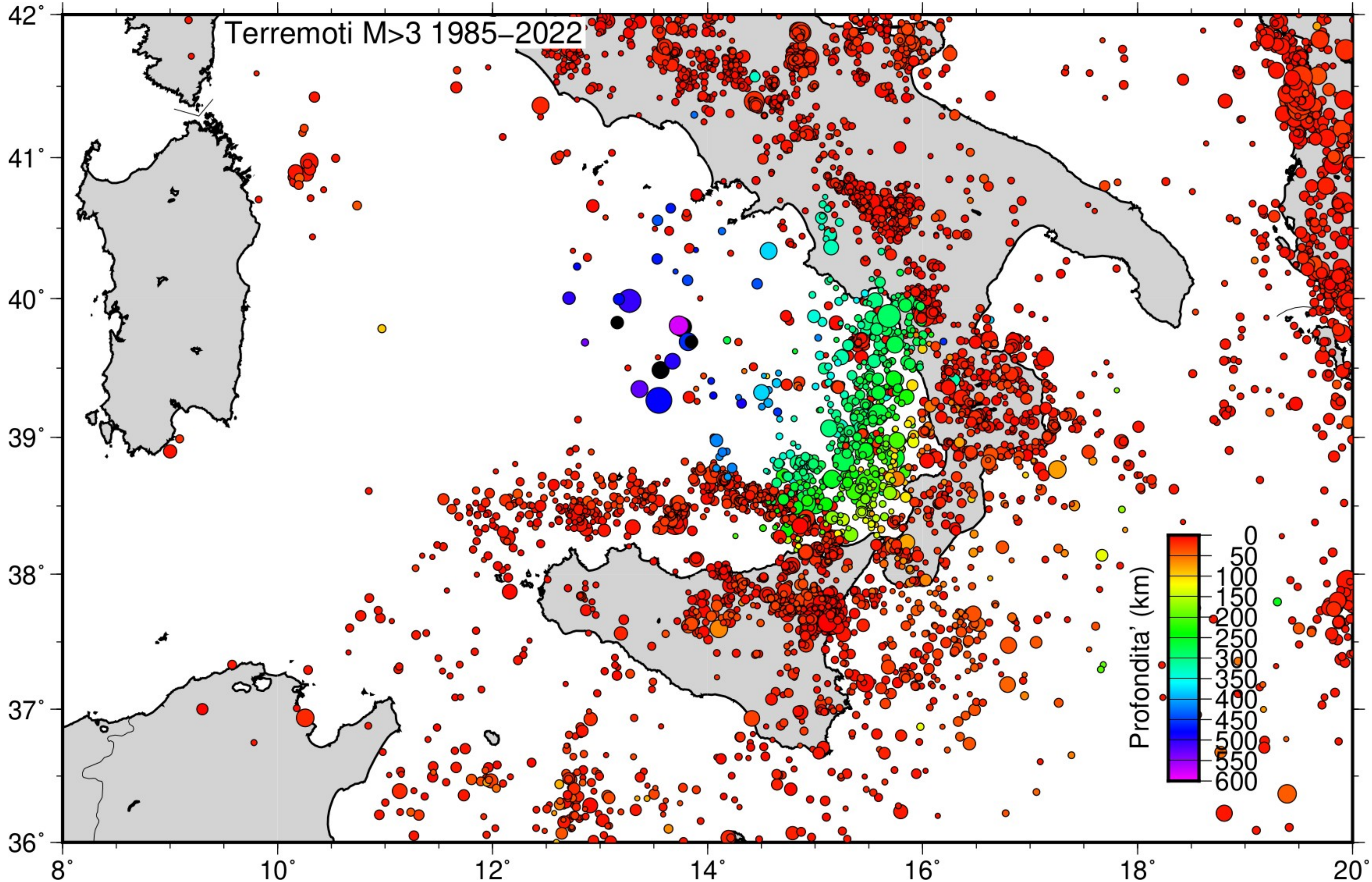
Still a debate on what lies in that region in terms of sediments and material properties.

See:

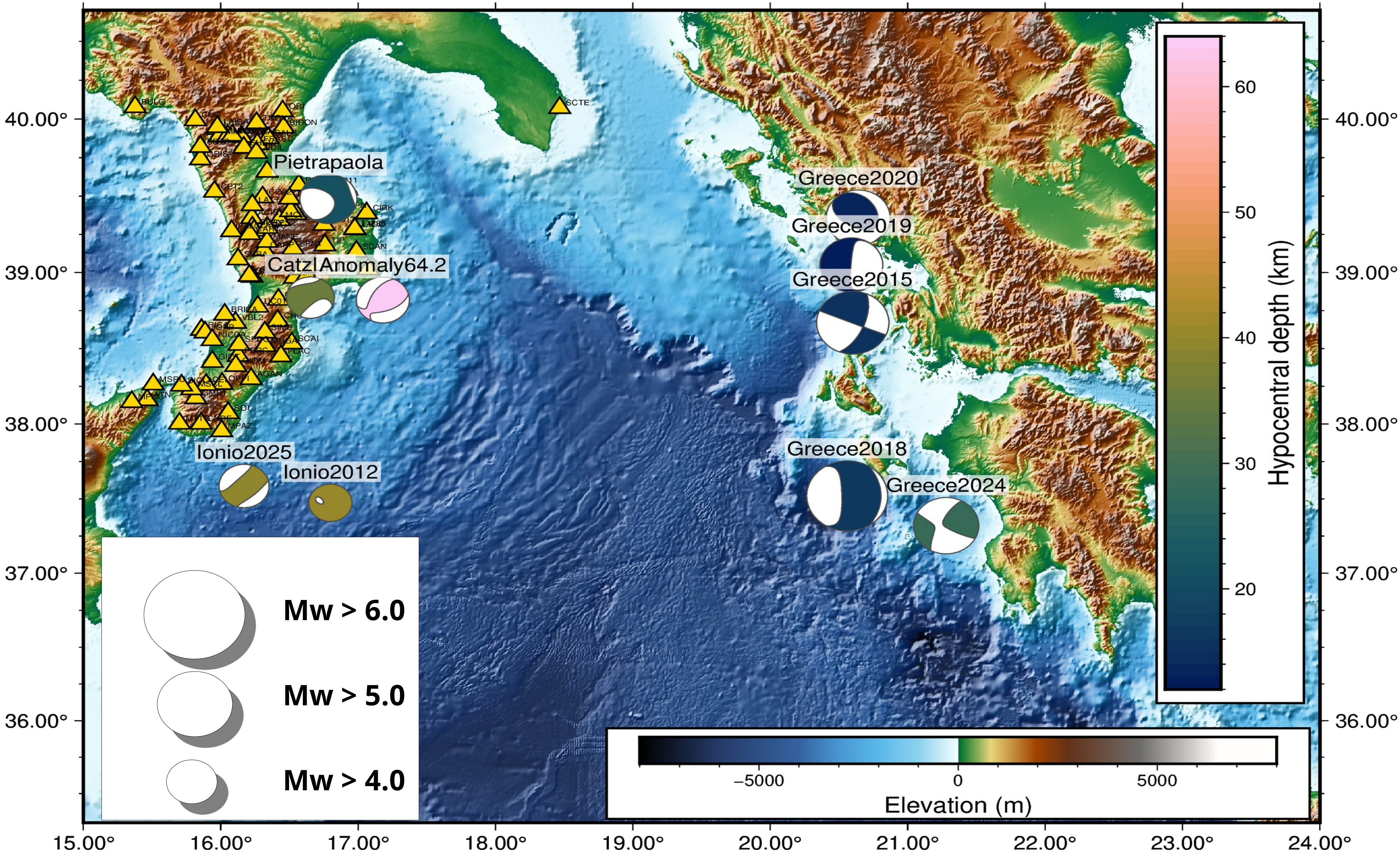
Dannowski_etal_2019 ; El_Sharkawy_etal_2021


ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA
Mappa di pericolosità sismica del territorio nazionale
(riferimento: Ordinanza PCM del 28 aprile 2006 n.3519, All.1b)
espressa in termini di accelerazione massima del suolo
con probabilità di eccedenza del 10% in 50 anni
riferita a suoli rigidi (Vs30 > 800 m/s; cat.A, punto 3.2.1 del D.M. 14.09.2005)
< 0.025 g
0.025 - 0.050
0.050 - 0.075
0.075 - 0.100
0.100 - 0.125
0.125 - 0.150
0.150 - 0.175
0.175 - 0.200
0.200 - 0.225
0.225 - 0.250
0.250 - 0.275
0.275 - 0.300
Le sigle individuano isole
per le quali è necessaria
una valutazione ad hoc
Elaborazione: aprile 2004
0 50 100 150 km

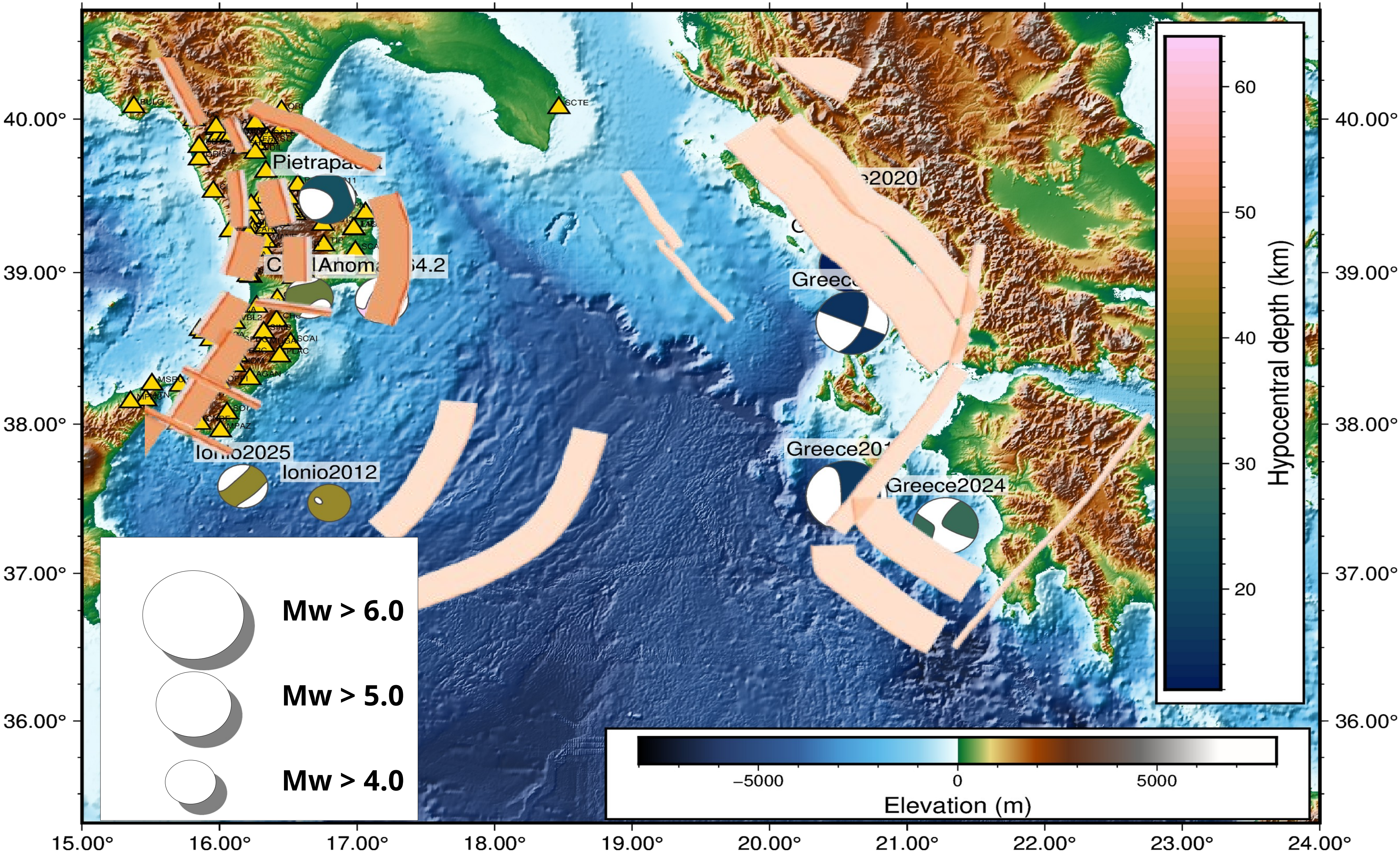

Terremoti crostali 1985–2022 M>4
M >= 6
M >= 5
M >= 4
48°
46°
44°
42°
40°
38°
36°
6°
8°
10°
12°
14°
16°
18°
20°


Terremoti M>3 1985–2022
Profondita' (km)
0
50
100
150
200
250
300
350
400
450
500
550
600
42°
41°
40°
39°
38°
37°
36°
8°
10°
12°
14°
16°
18°
20°

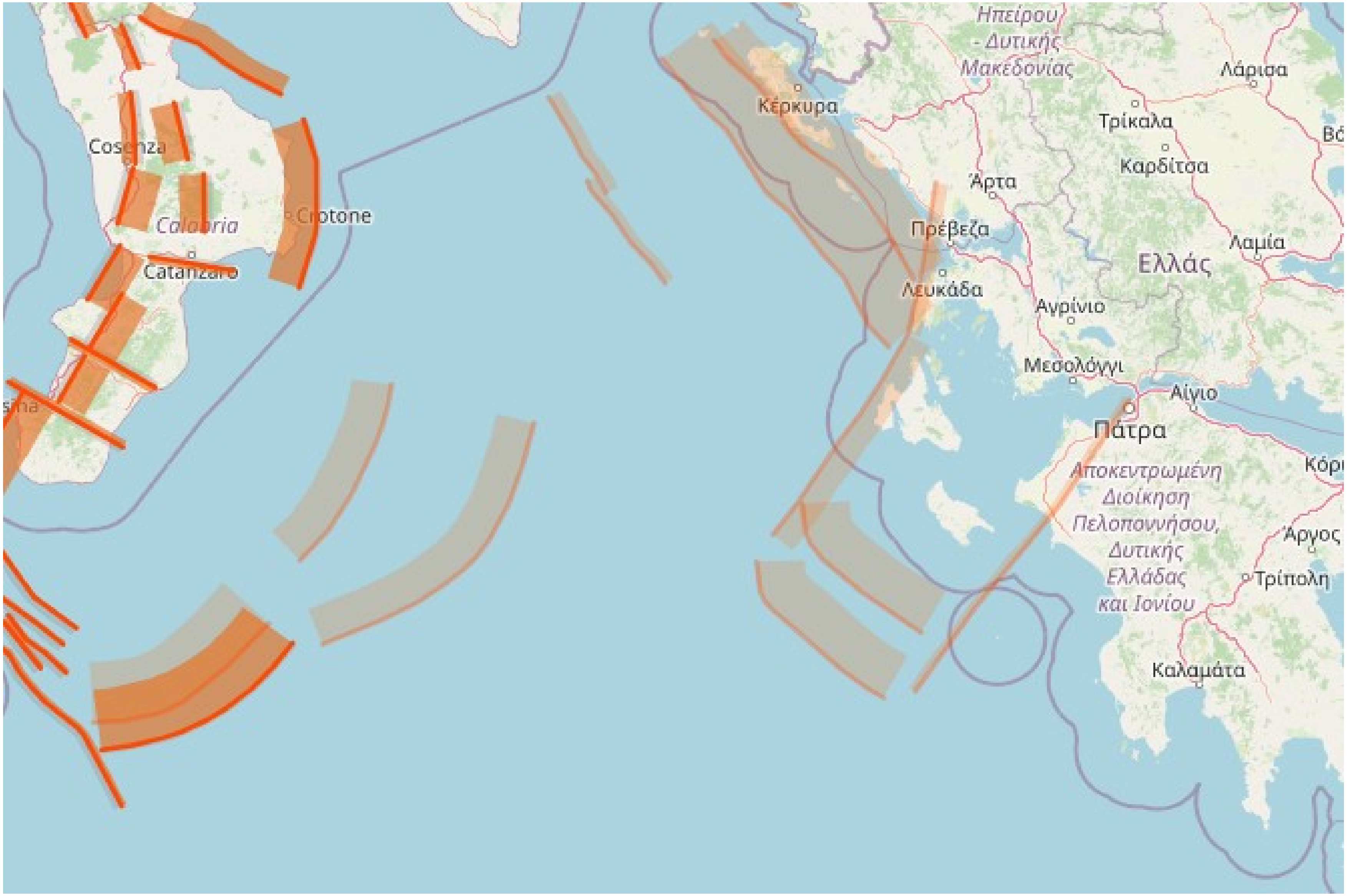
Events used in all runs



Events used in all runs



Seismogenic sources of the Ionian basin arc – INGV source



Università della Calabria
Rete Sismica

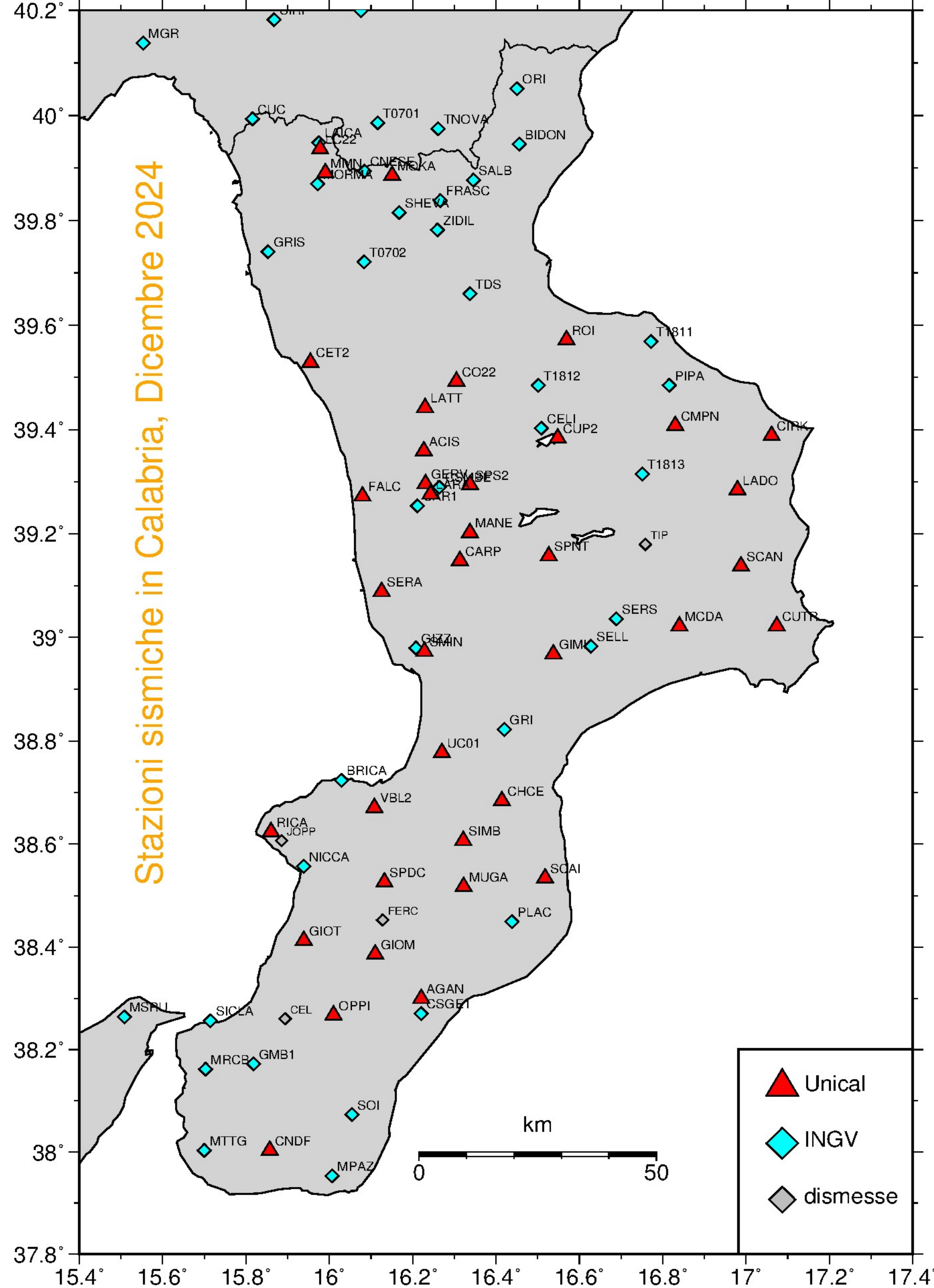
SEISMOCAL

Seismographs network

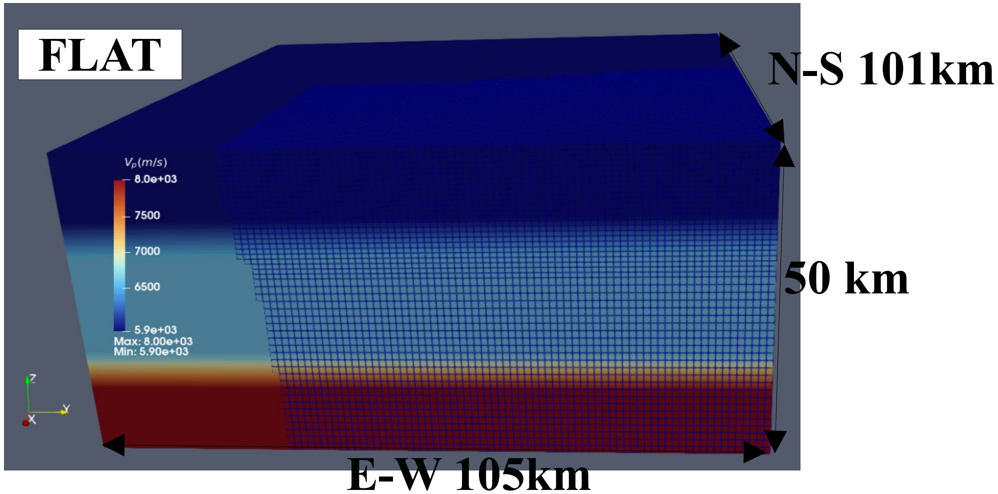
The website www.sismocal.org provides information on the technical and scientific activities carried out in the Seismology Laboratory of the University of Calabria.

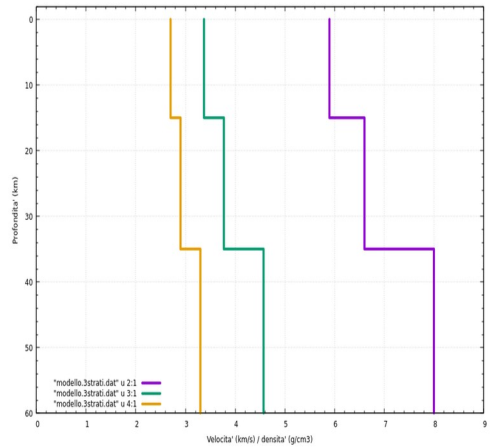
The purpose of the Laboratory, achieved through the analysis of data provided by the Unical Seismic Network (doi:10.7914/SN/IY, http://doi.org/doi:10.7914/SN/IY), is the monitoring of earthquakes that occur in Calabria and surrounding areas.

The available catalog online starts from 1-5-2013 till now.



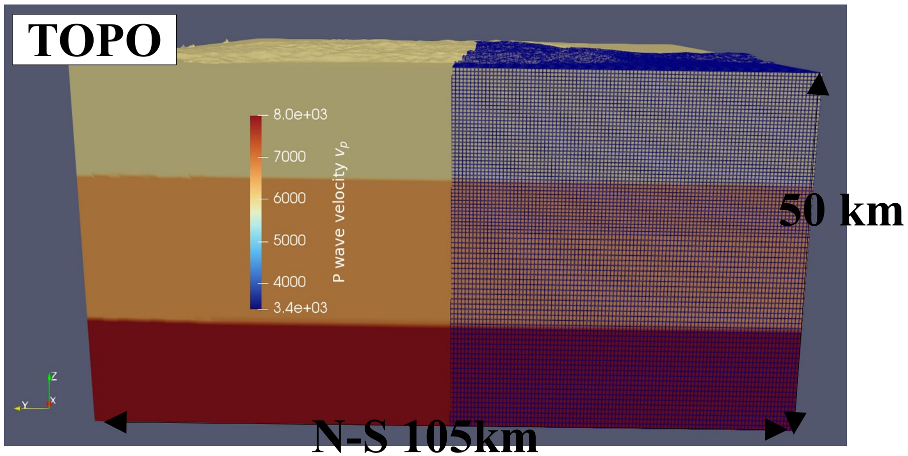
No topography Sila region test – homogeneous purely isotropic triple layer model

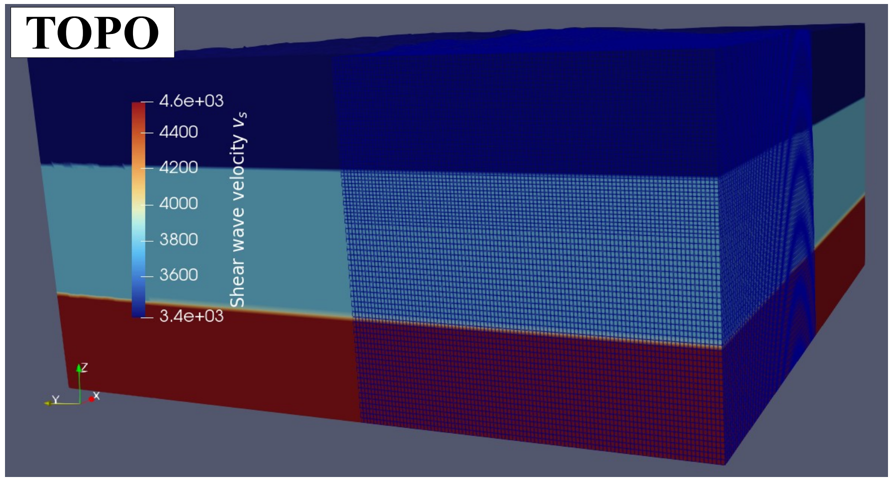




Total number of elements 530k,
NX NY NZ 105 101 50 spacing ~ 1.5km
lowering nodes at 20km

With topography NX NY increased both to 150

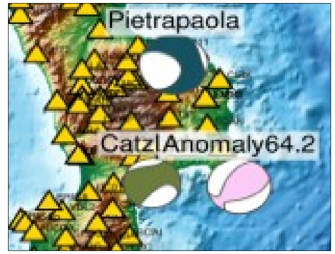




Synthetics vs real data

bp c 0.1 0.3 n 2 p 1
colvolve cos09.sac

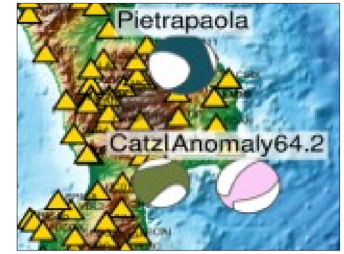
20221012
Mw4.3
(38.83,16.65)
35km
7kmSE CZ

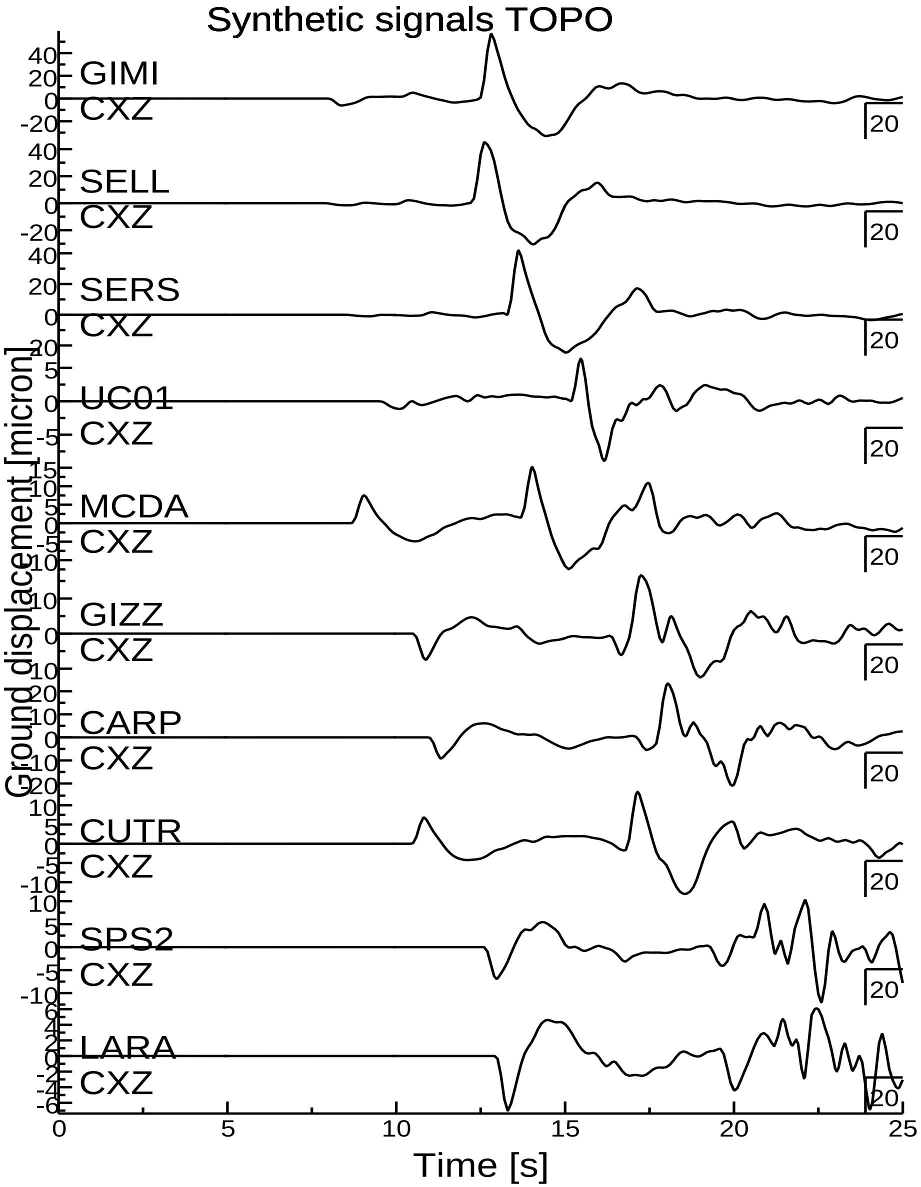


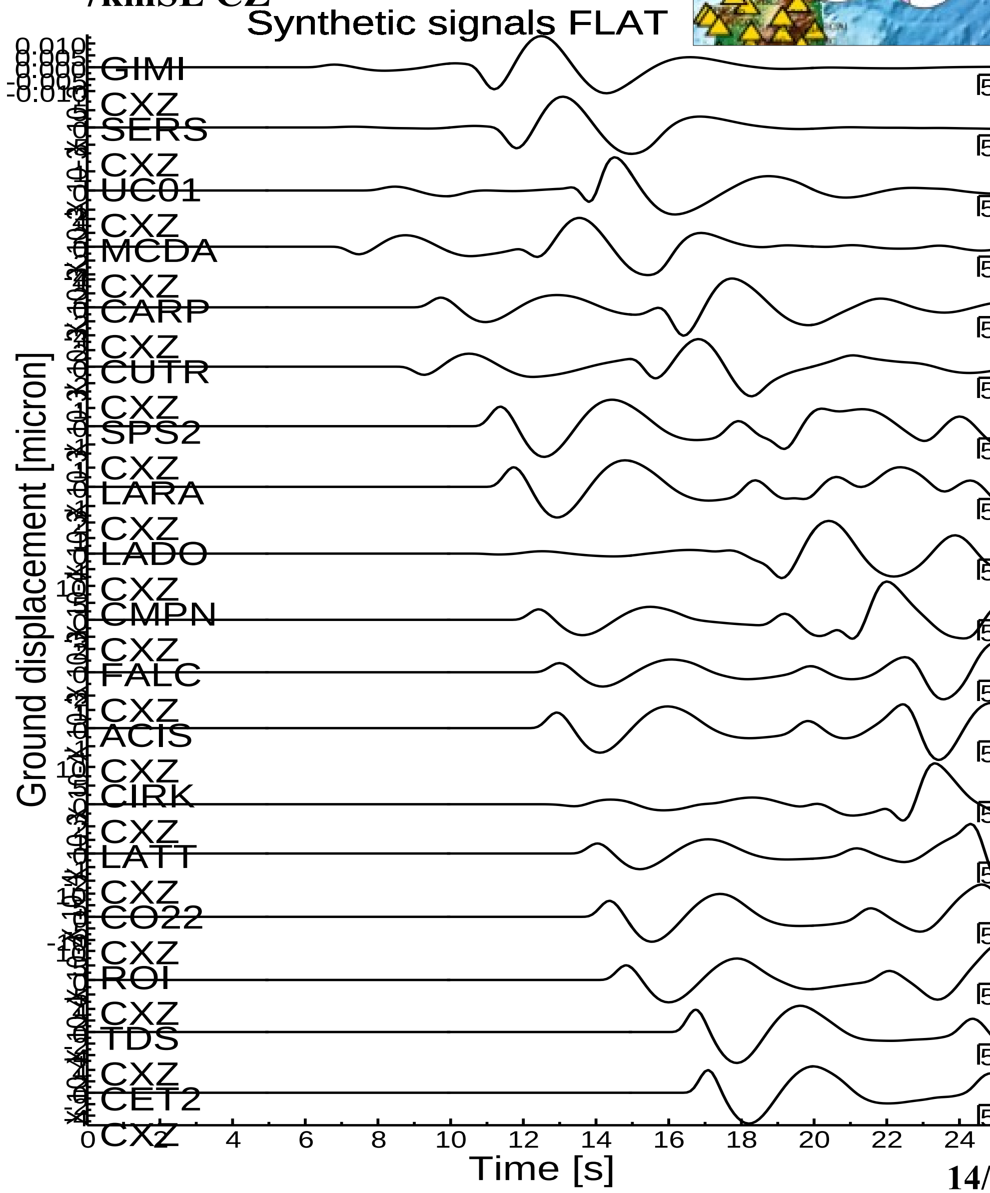
Synthetics vs real data

bp c 0.1 0.3 n 3 p 1
colvolve cos2.sac

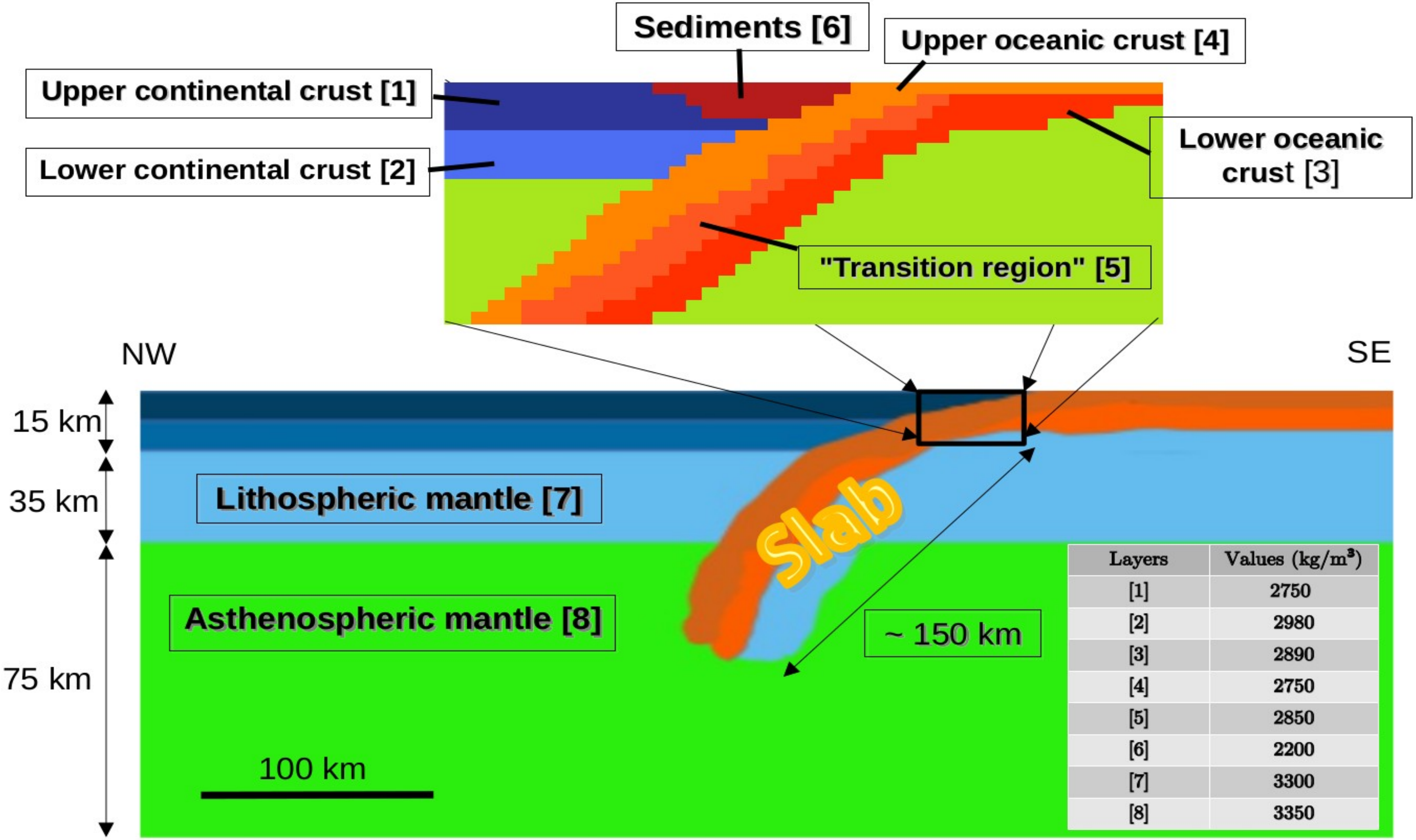
20221012
Mw4.3
(38.83,16.65)
35km
7kmSE CZ



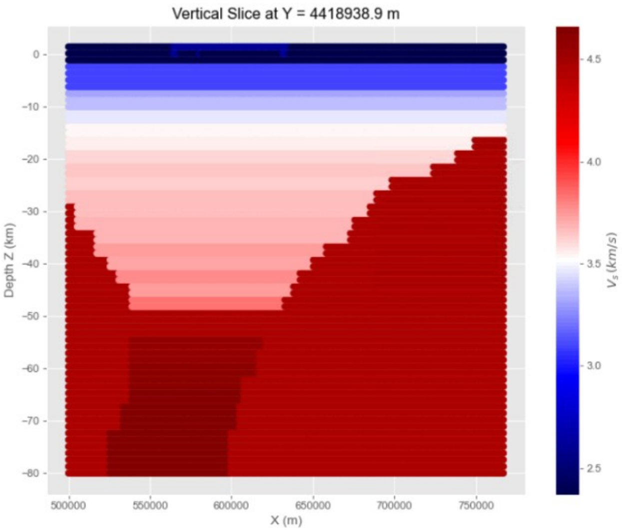


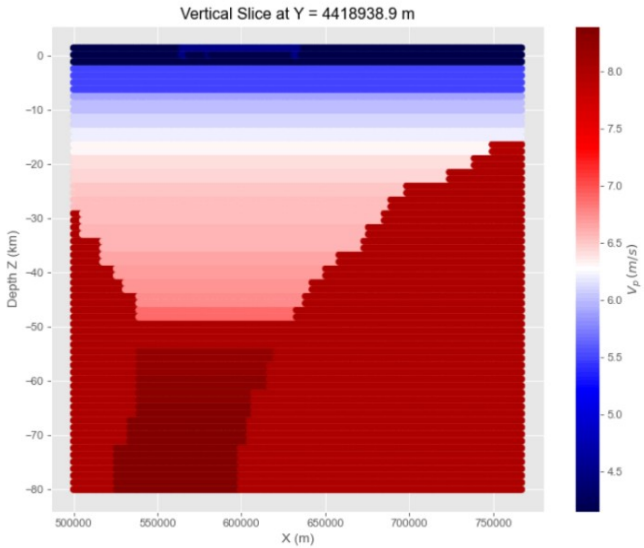


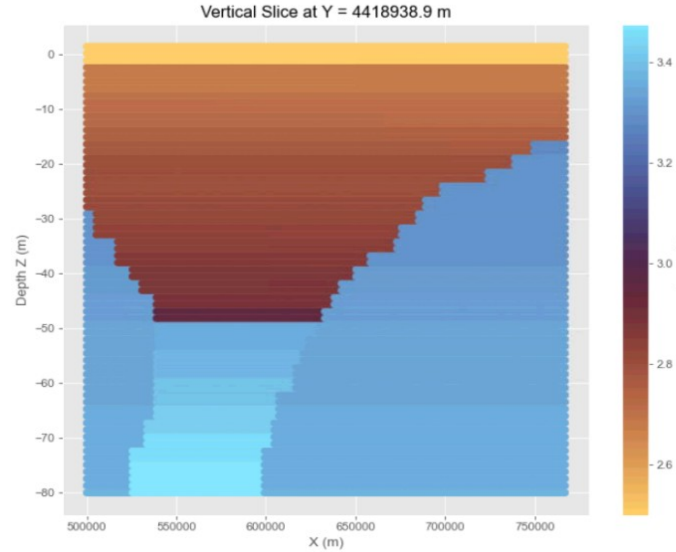
Discretization of slab subduction zone in regional model

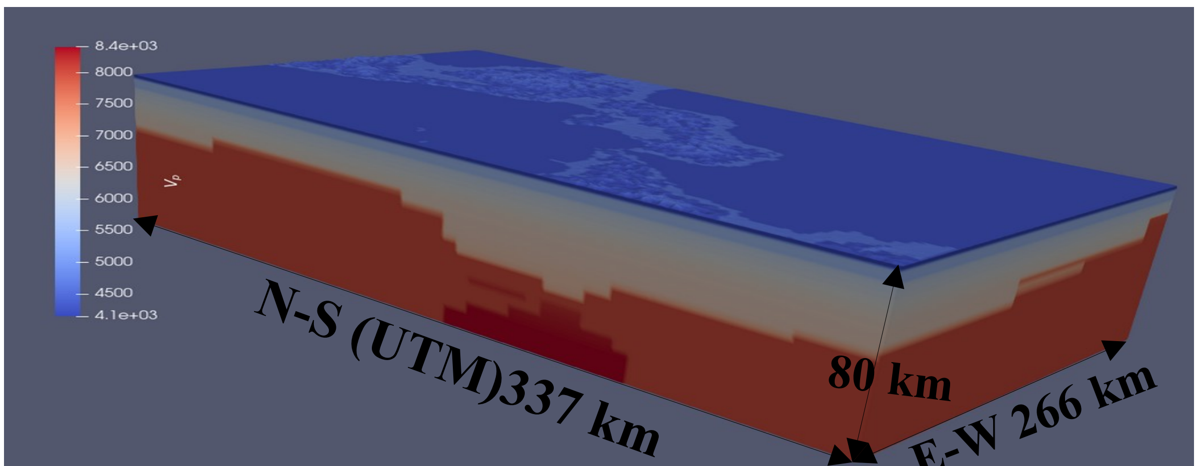


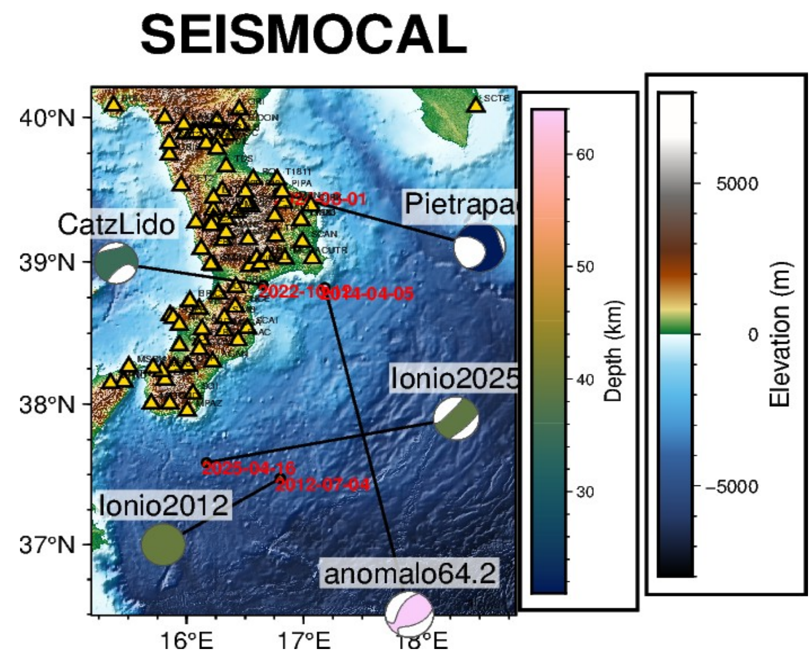
Layers	Values (kg/m^3)
[1]	2750
[2]	2980
[3]	2890
[4]	2750
[5]	2850
[6]	2200
[7]	3300
[8]	3350





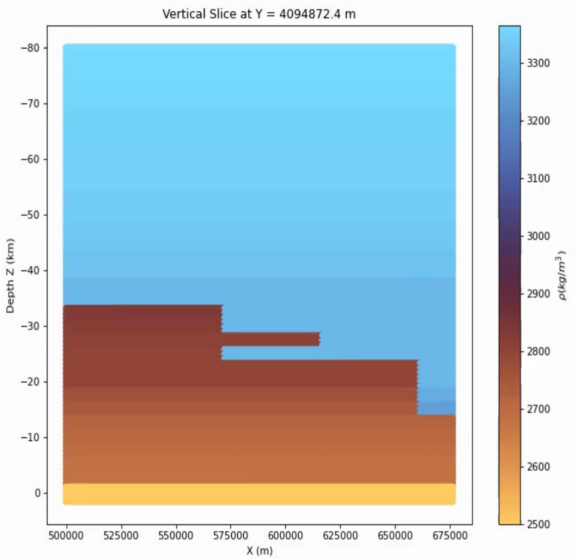


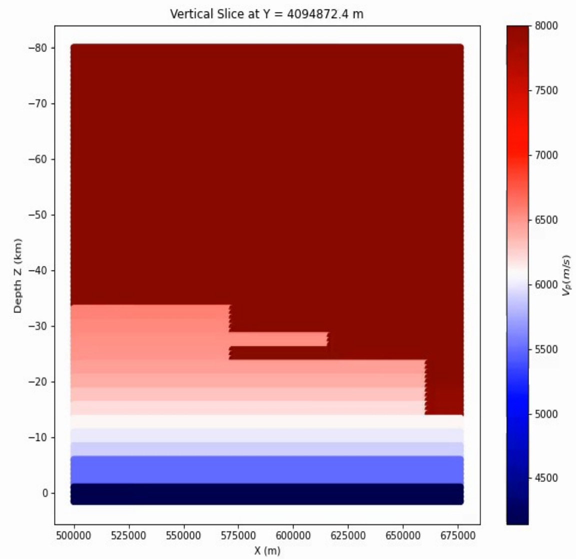


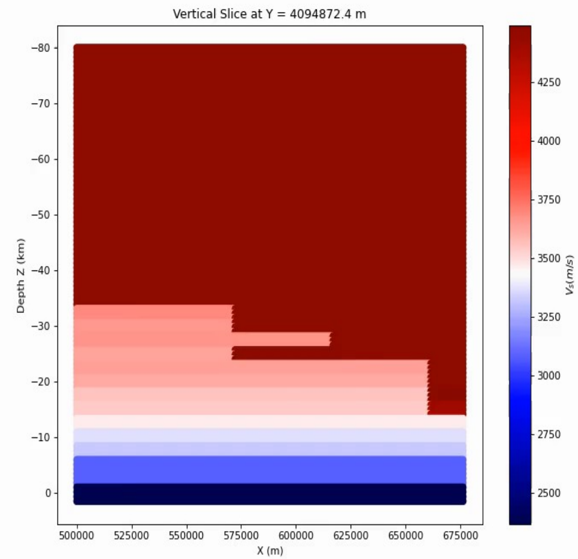


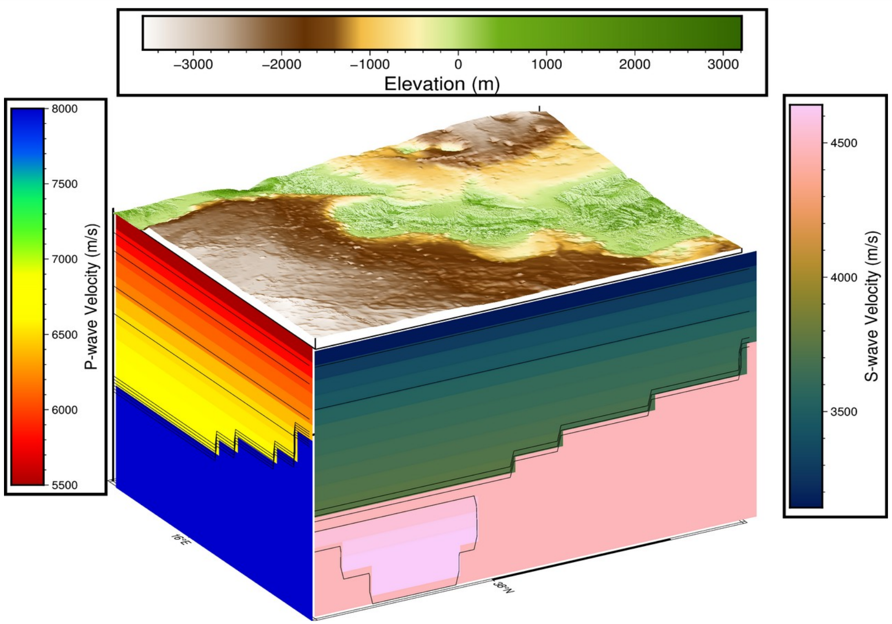
Total number of elements 2.6 million,
NX NY NZ 200 200 65 spacing ~ 1.5km

Model section at different longitude (UTM shown)



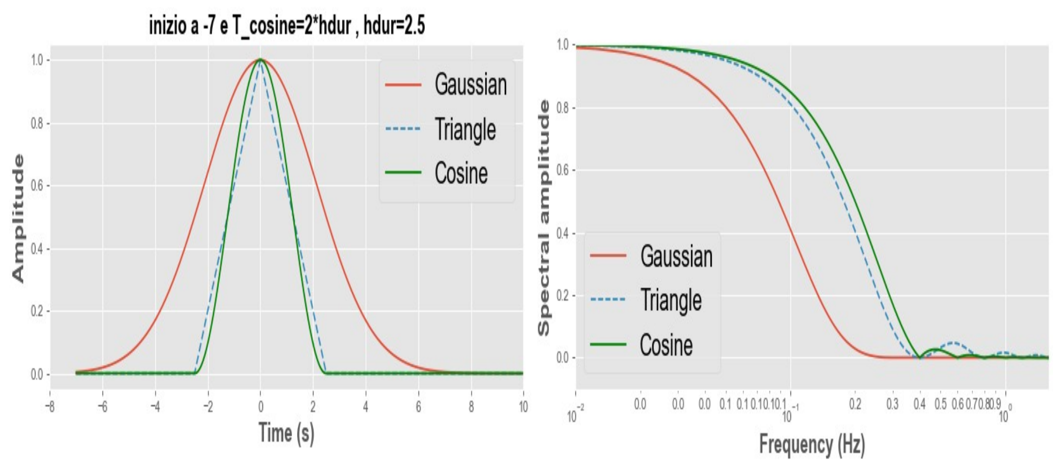






$$\lambda_{min} = \frac{v_{sMIN}}{f_{MAX}} = 8348m$$

$$T_{min} = 3.29\, s$$



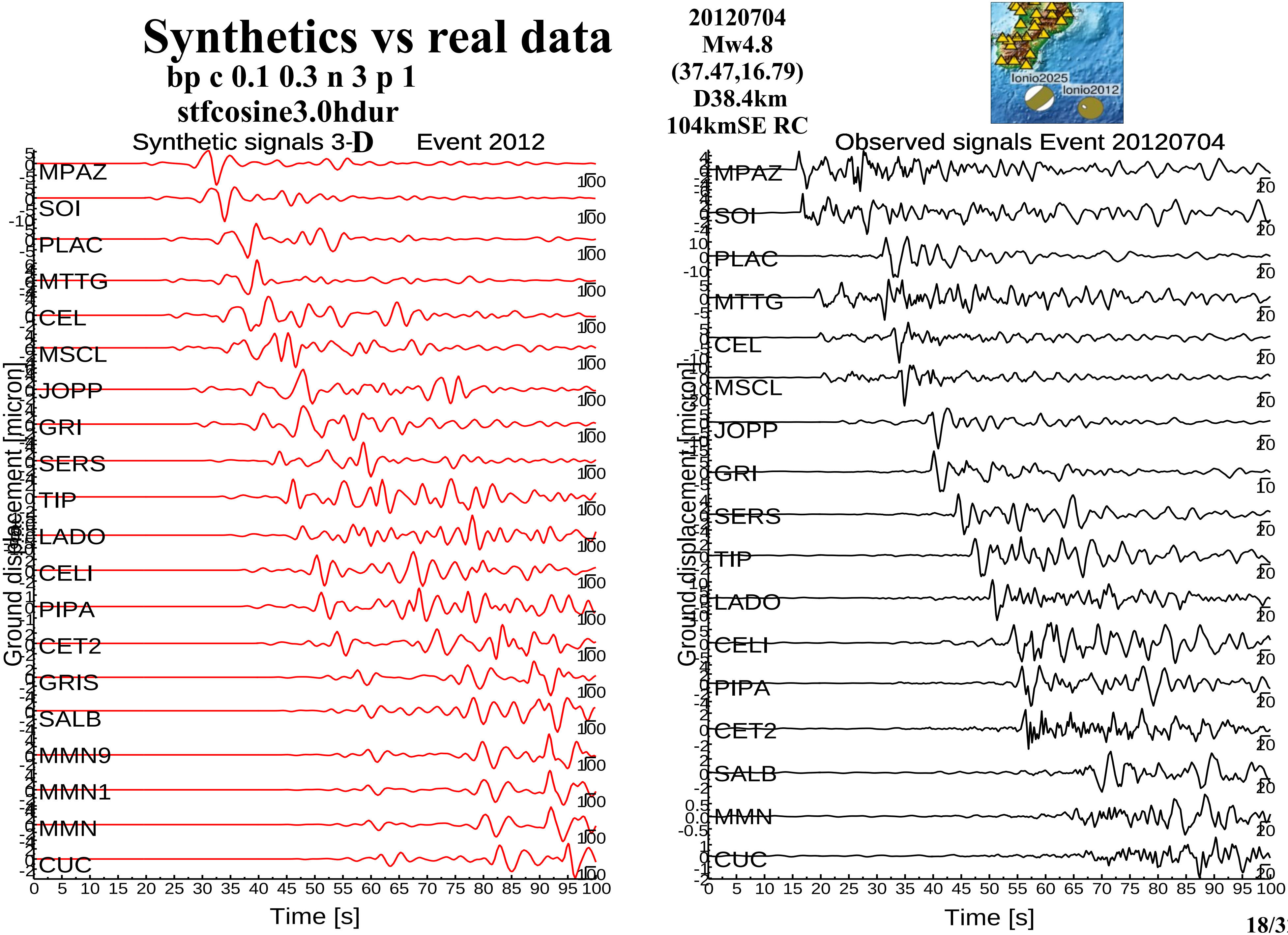
Ionian CaLabrian ARC - ICLARC

Synthetics vs real data

bp c 0.1 0.3 n 3 p 1

stfcosine3.0hdur

20120704
Mw4.8
(37.47,16.79)
D38.4km
104kmSE RC

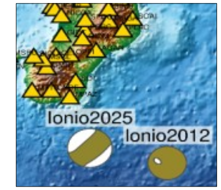


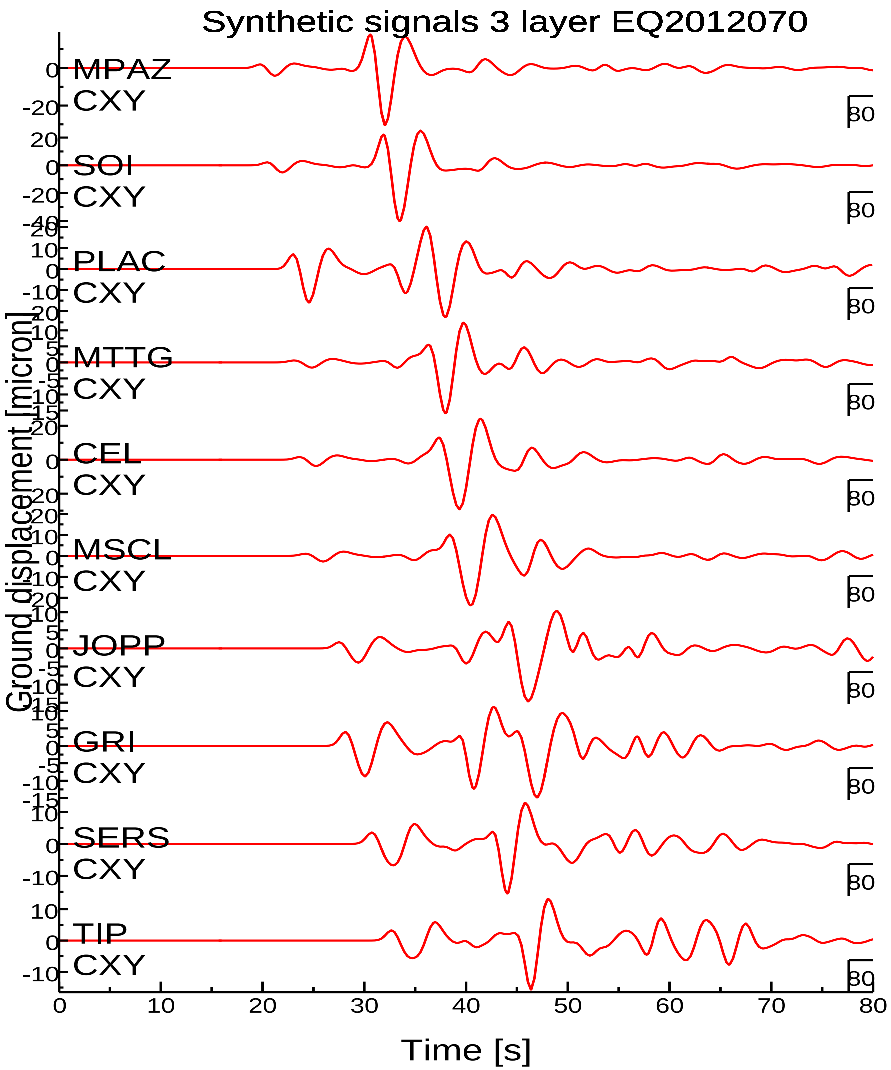
Synthetics vs real data

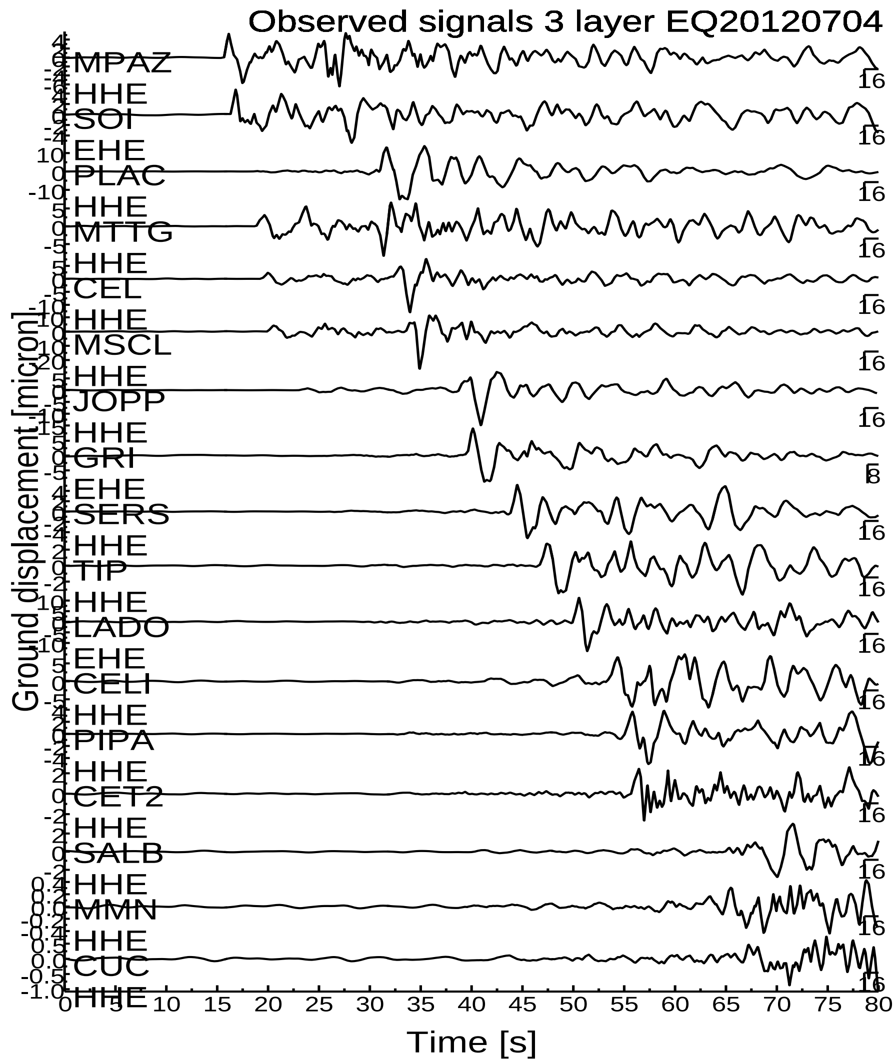
bp c 0.1 0.3 n 2 p 1

stf_cosine0.9hdur

20120704	20250416
Mw4.8	Mw4.7
(37.47,16.79)	(37.58,16.17)
D38.4km	D39km
104kmSE-RC	100kmS-RC





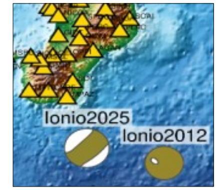


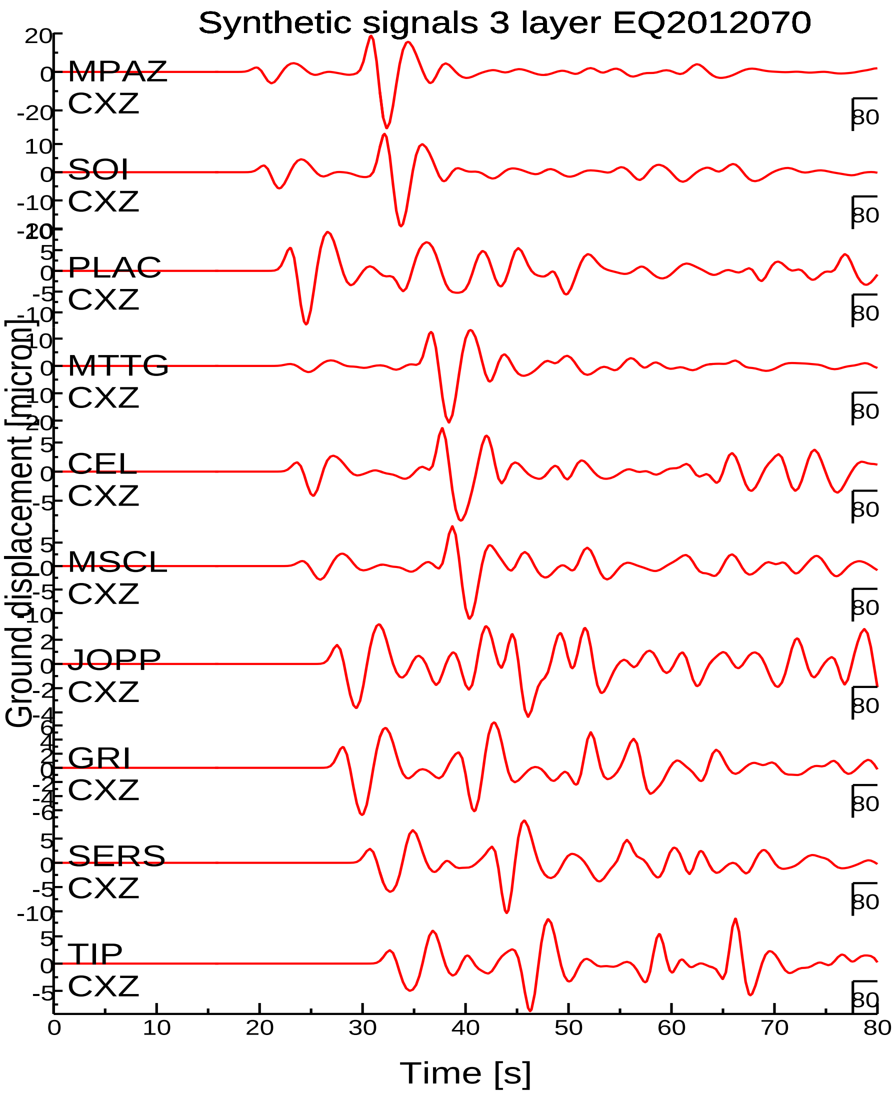
Synthetics vs real data

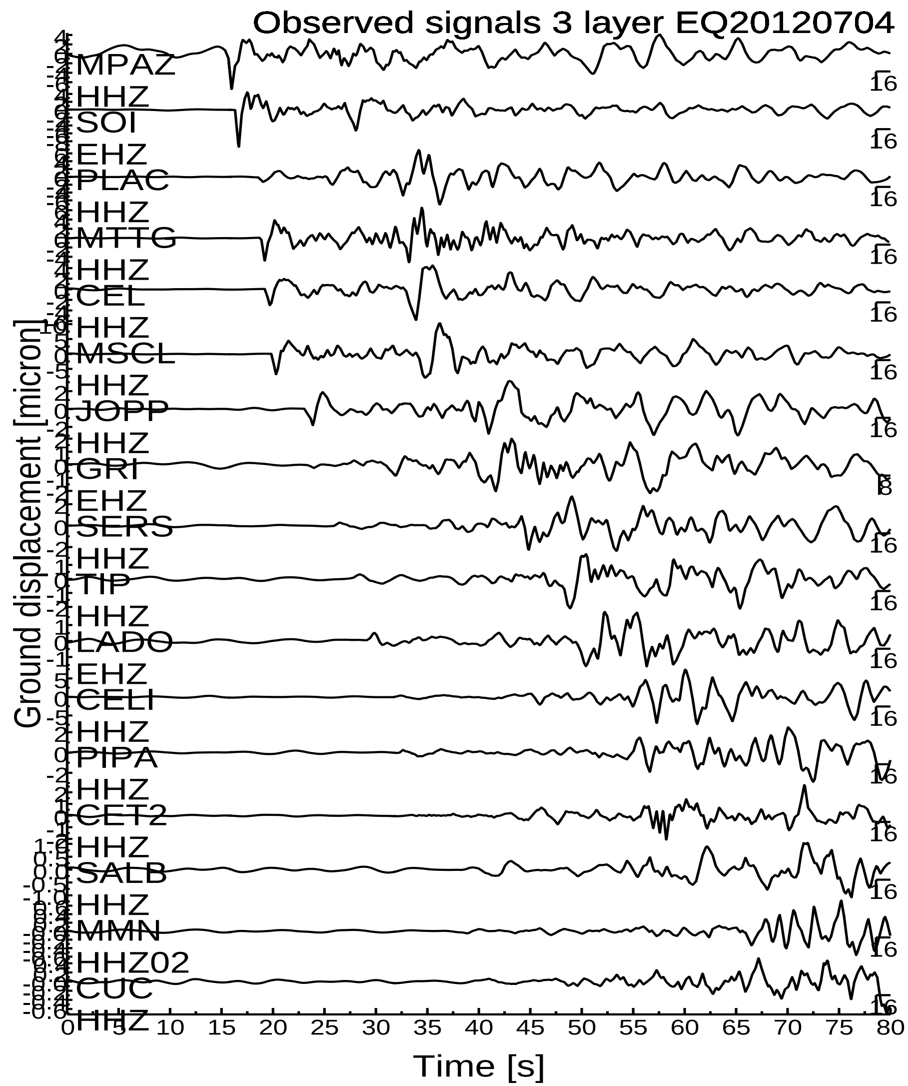
bp c 0.1 0.3 n 3 p 1

stf_cosine3.0hdur

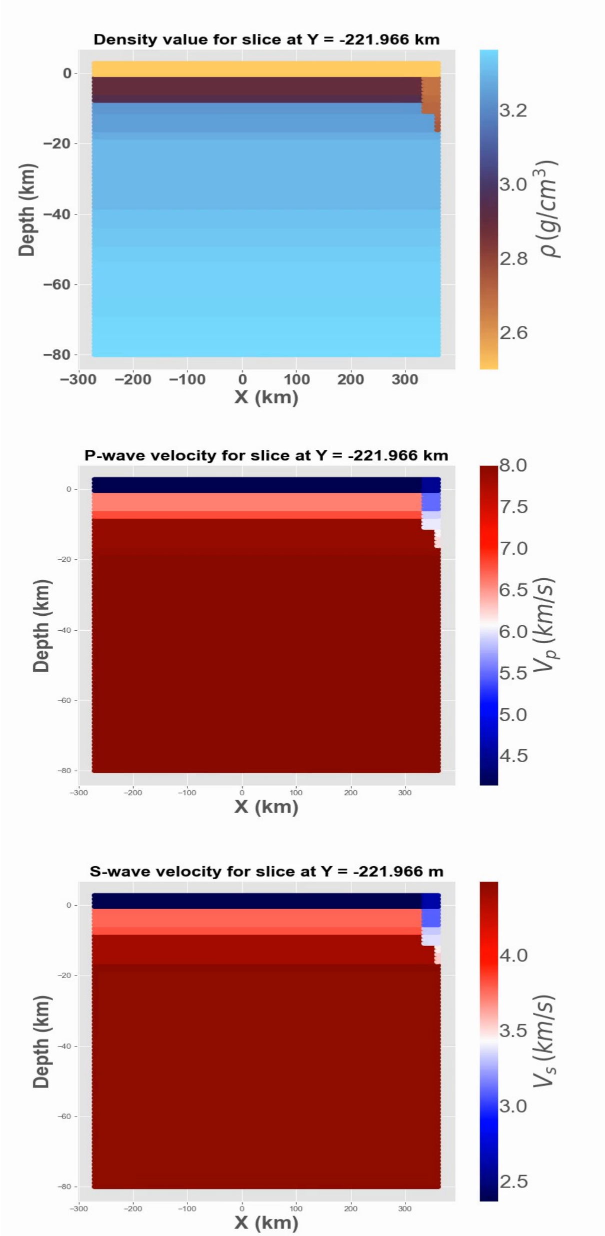
20120704
Mw4.8
(37.47,16.79)
D38.4km
104kmSE-RC

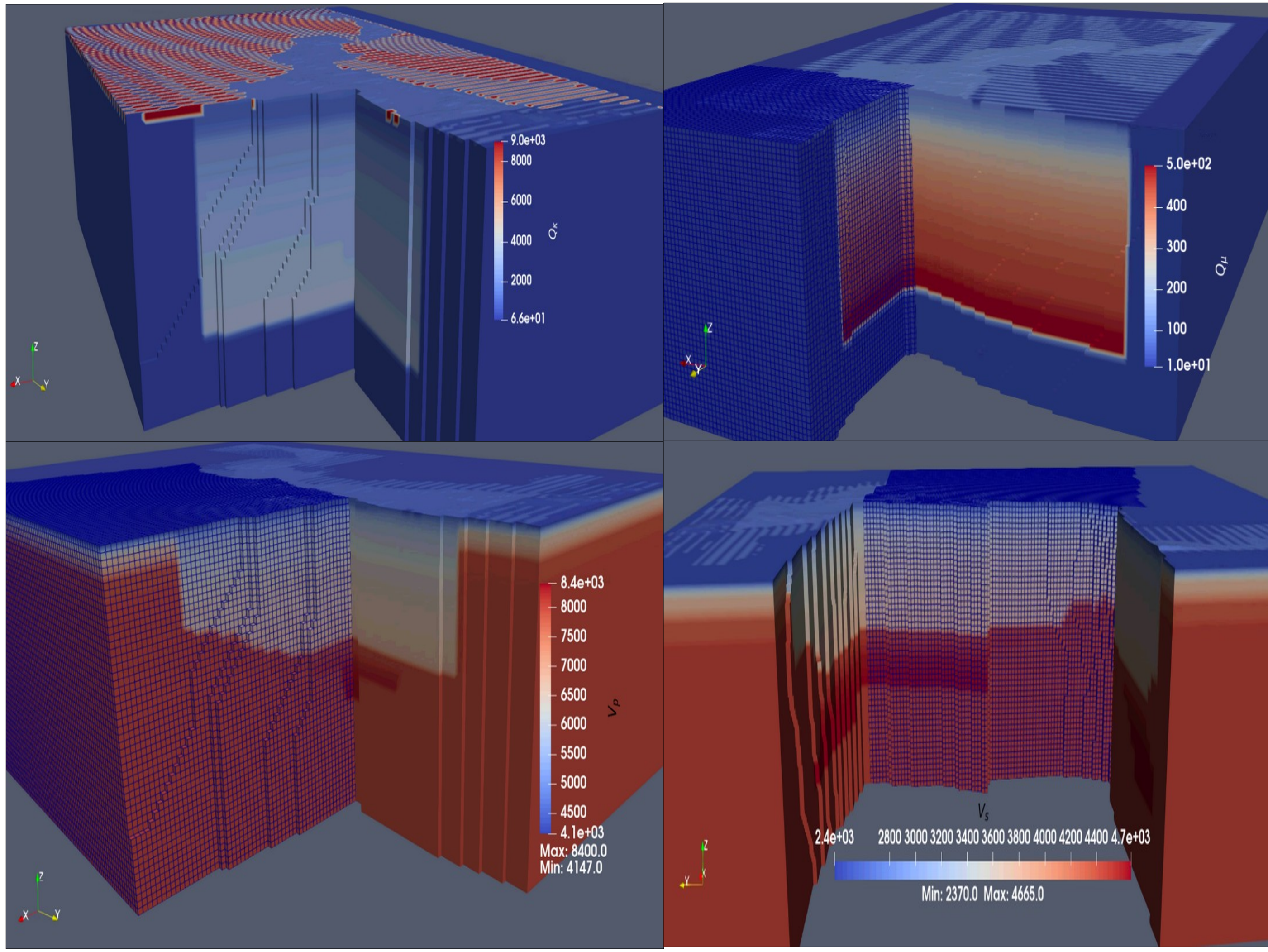






Reflected phases and shell attenuation layer for anelastic isotropic model



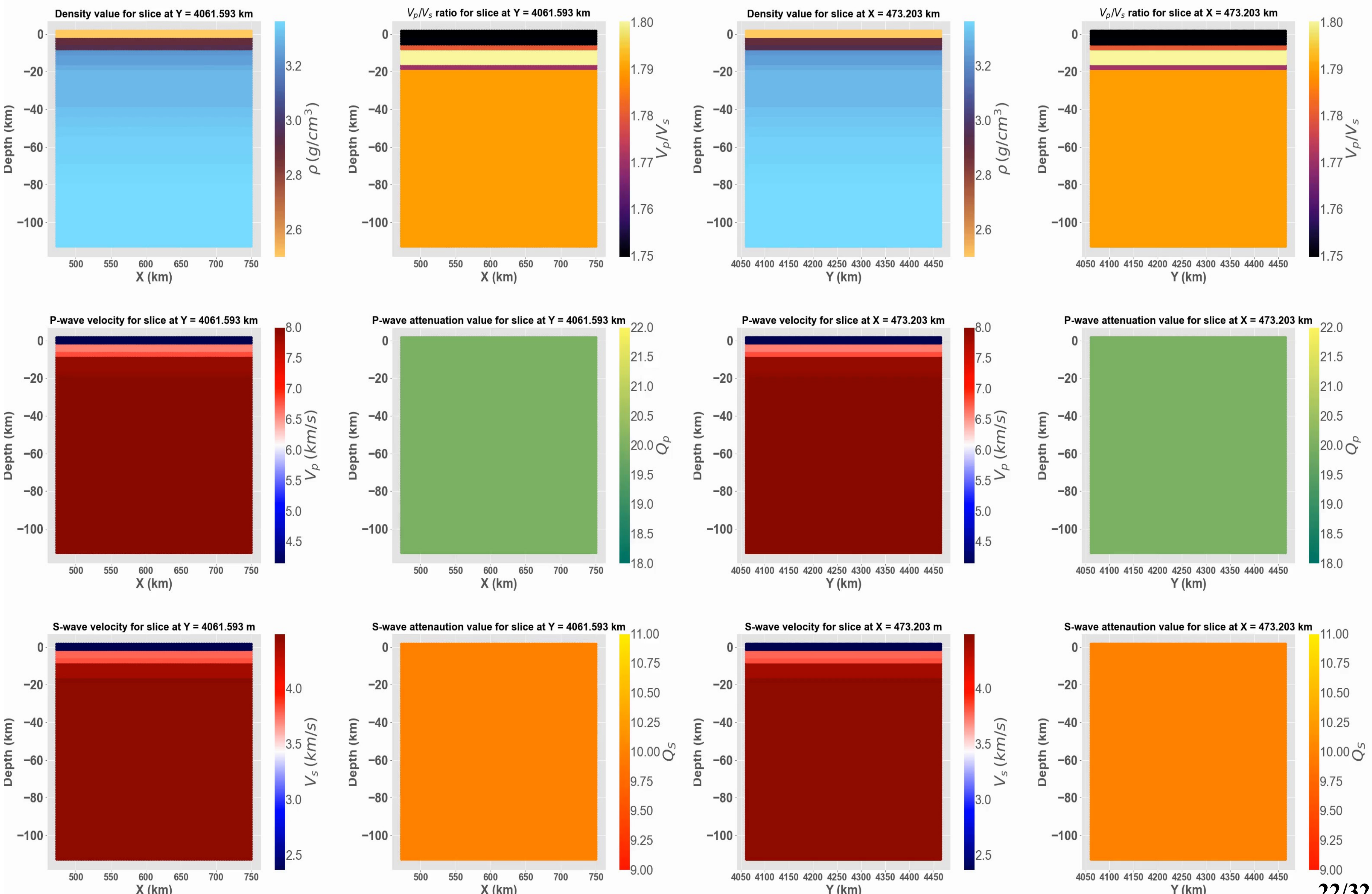


$$Q_p^{-1} = \left(1 - \frac{c_s^2}{c_p^2}\right) Q_k^{-1} + \left(\frac{c_s^2}{c_p^2}\right) Q_\mu^{-1}$$

$$Q_s^{-1} = Q_\mu^{-1}$$

The binary which interpolates on the GLL nodes does the conversion internally from Qp,Qs(.xyz file) to Q_κ,Q_μ(shown)

ICLARC 3D model + attenuation "shell" for Ionian mesh (anelastic isotropic)

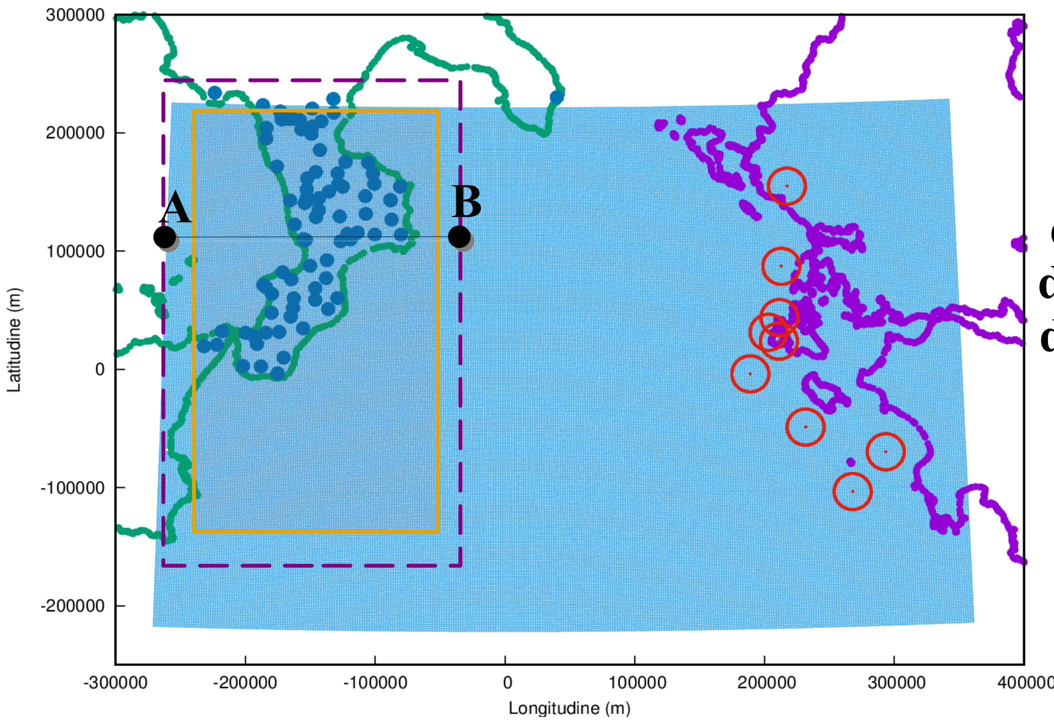


Synthetics vs real data

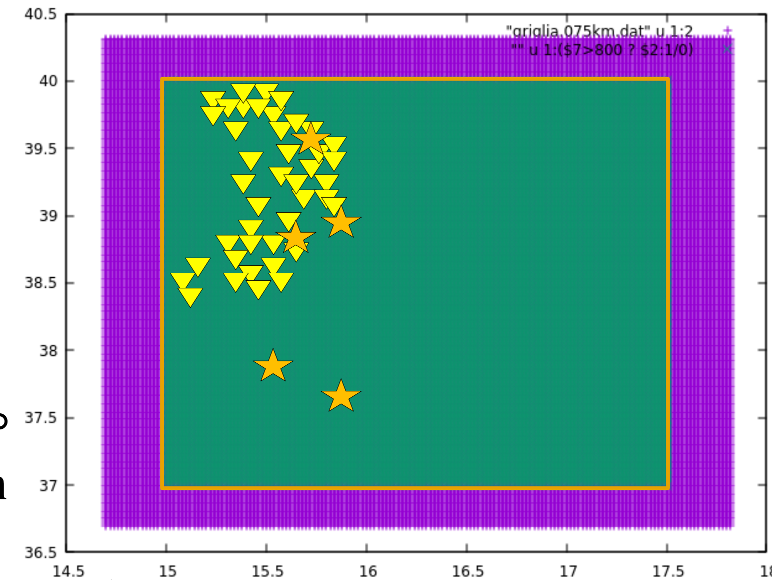
2012 guscio vs real

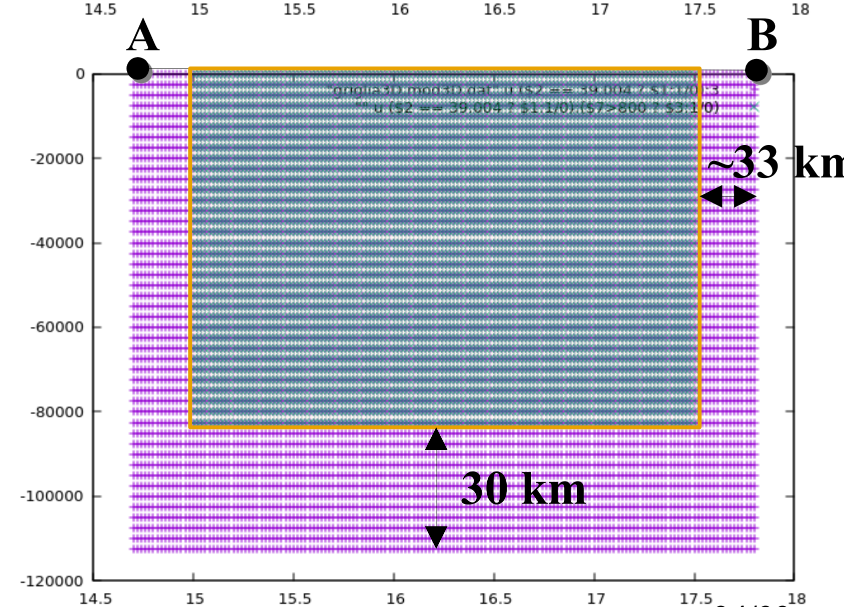
2025 guscio vs real

Depth section of the shell attenuation layer – ICLERC & ICLARC



dx=0.02°
dy=0.016°
dz=2.5km



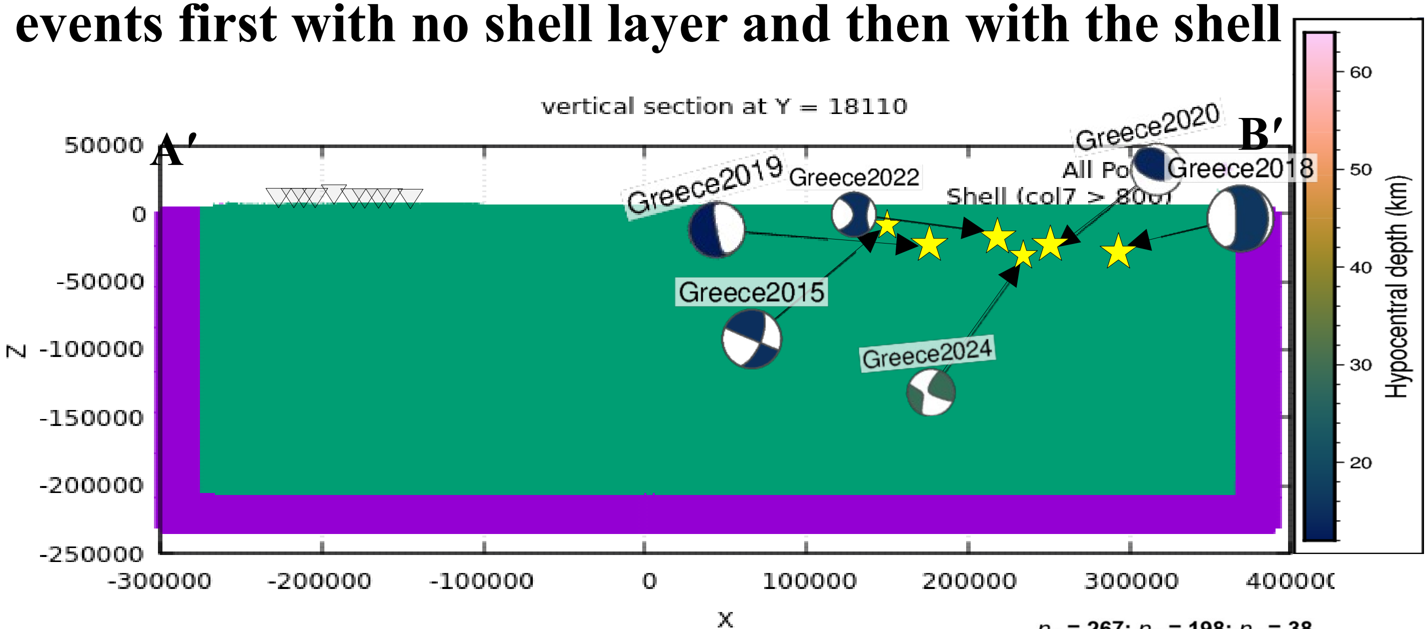


Degrees converted through Lambert projection

Ionian CaLabrian Ellenic aRC - ICLERC

Model up to 200km, 30km deep shell

Greece events first with no shell layer and then with the shell

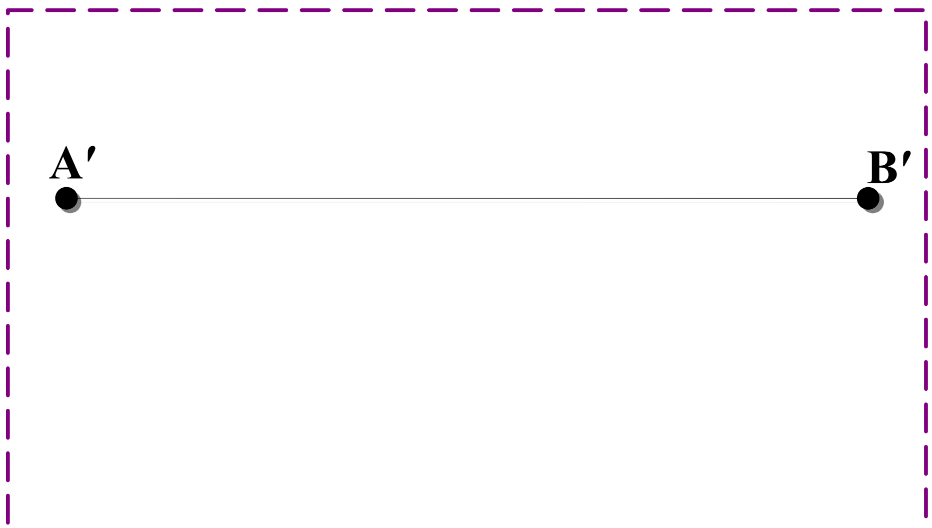


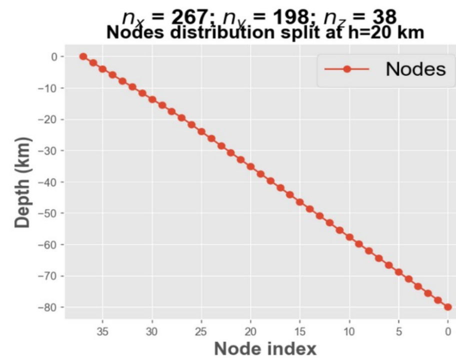
$$\lambda_{min} = \frac{v_{sMIN}}{f_{MAX}} = 6322m$$

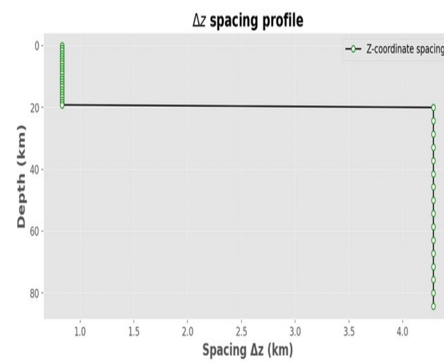
$$T_{min} = 1.28\,s$$

Mesh

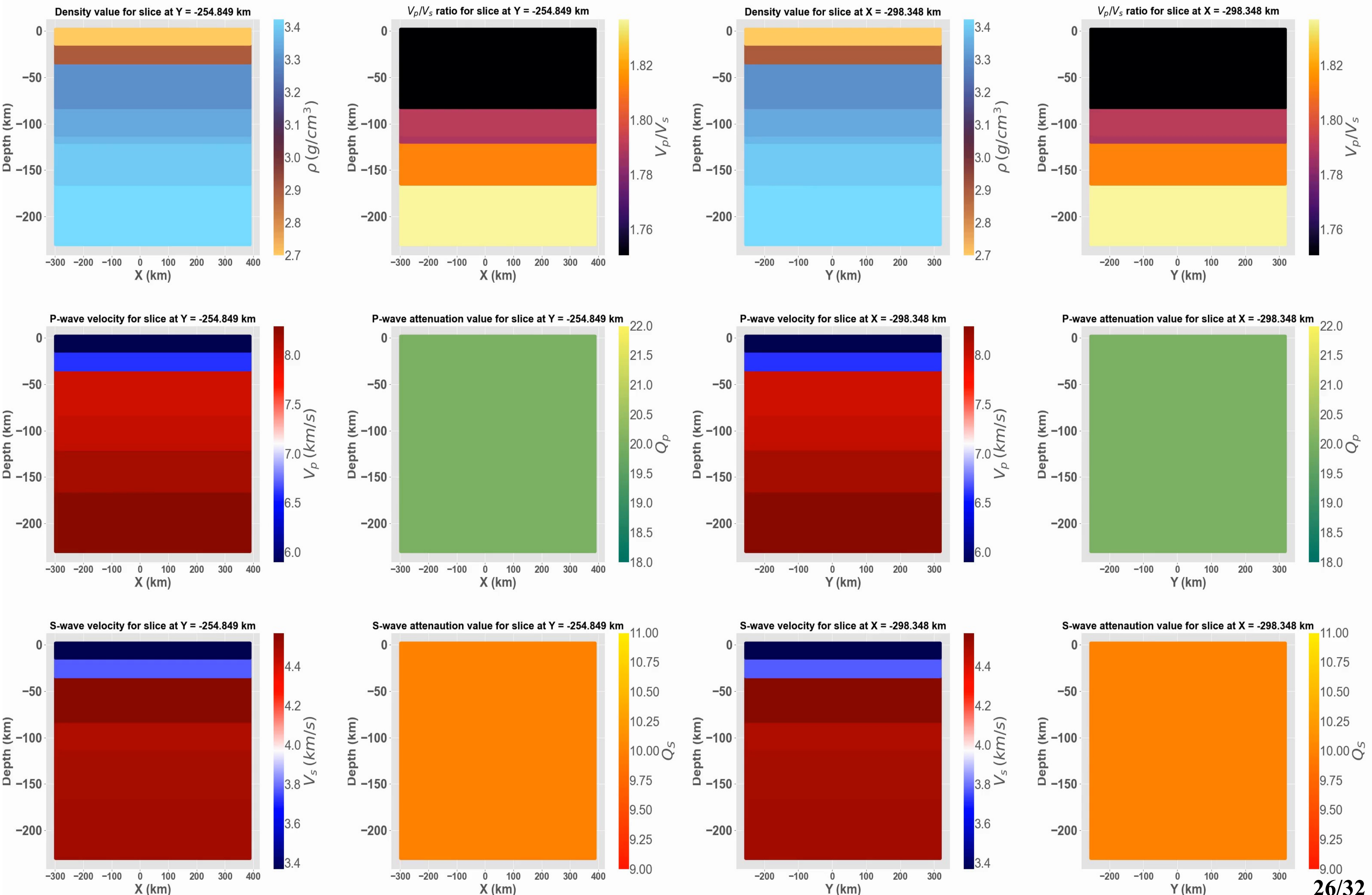
Shell attenuation layer







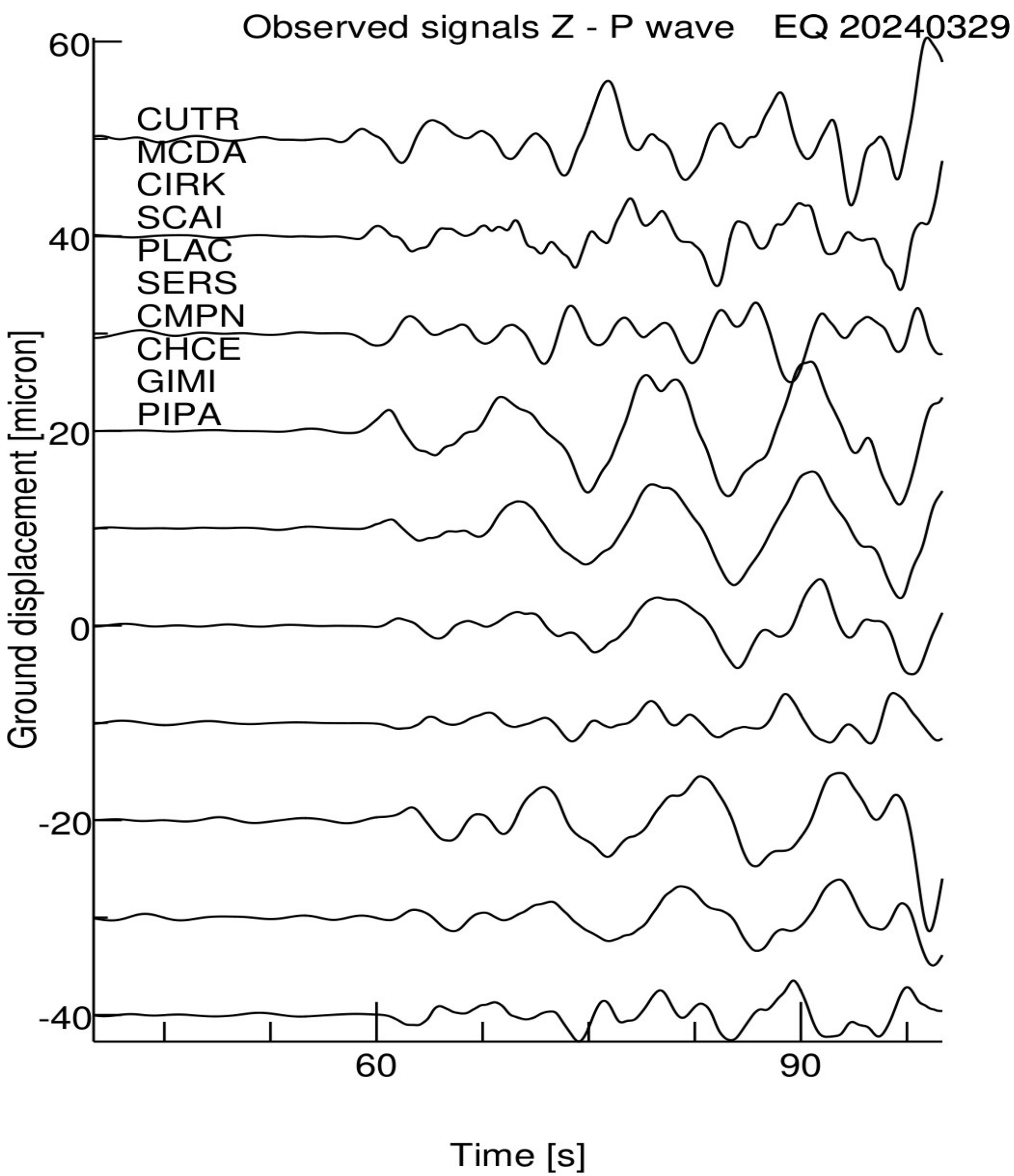
Homogeneous triple layer+ak135 from 82.5km for Ionian mesh + shell (purely isotropic)

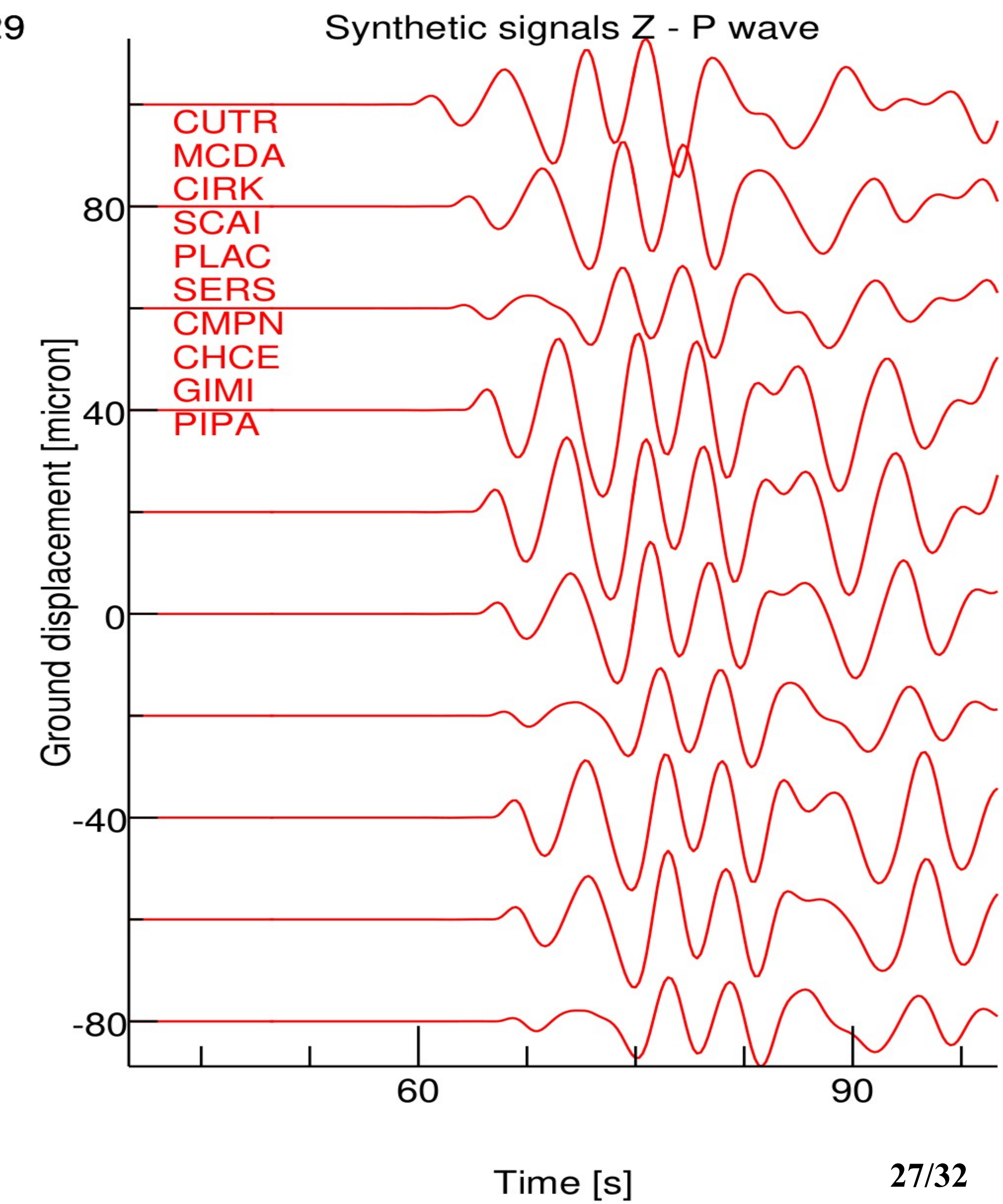


Synthetics vs real data

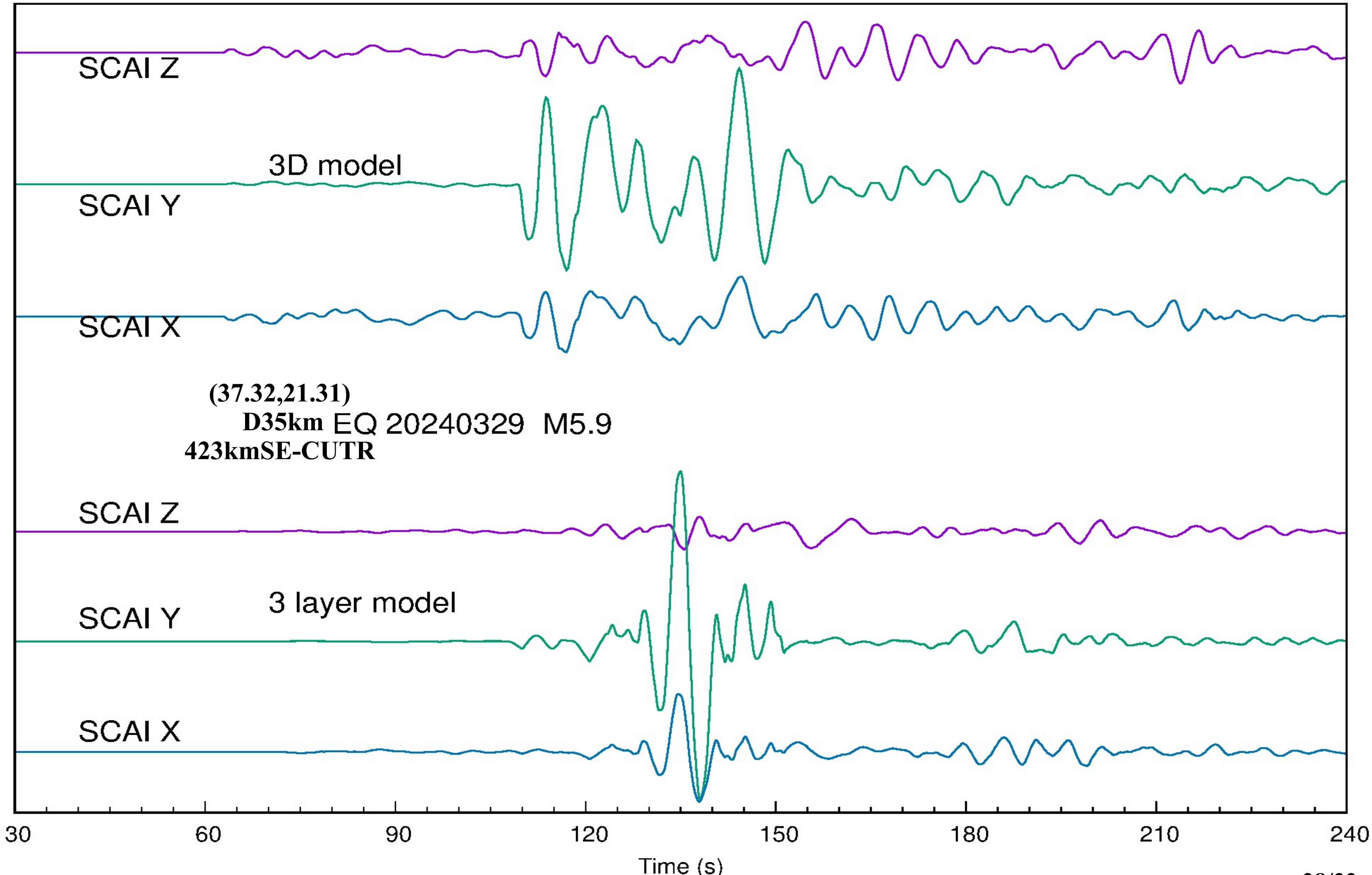
20240329
Mw5.9
(37.32,21.31)
35km
423kmSE-CUTR

bp c 0.1 0.3 n 3 p 1
stf_cosine3.0hdur

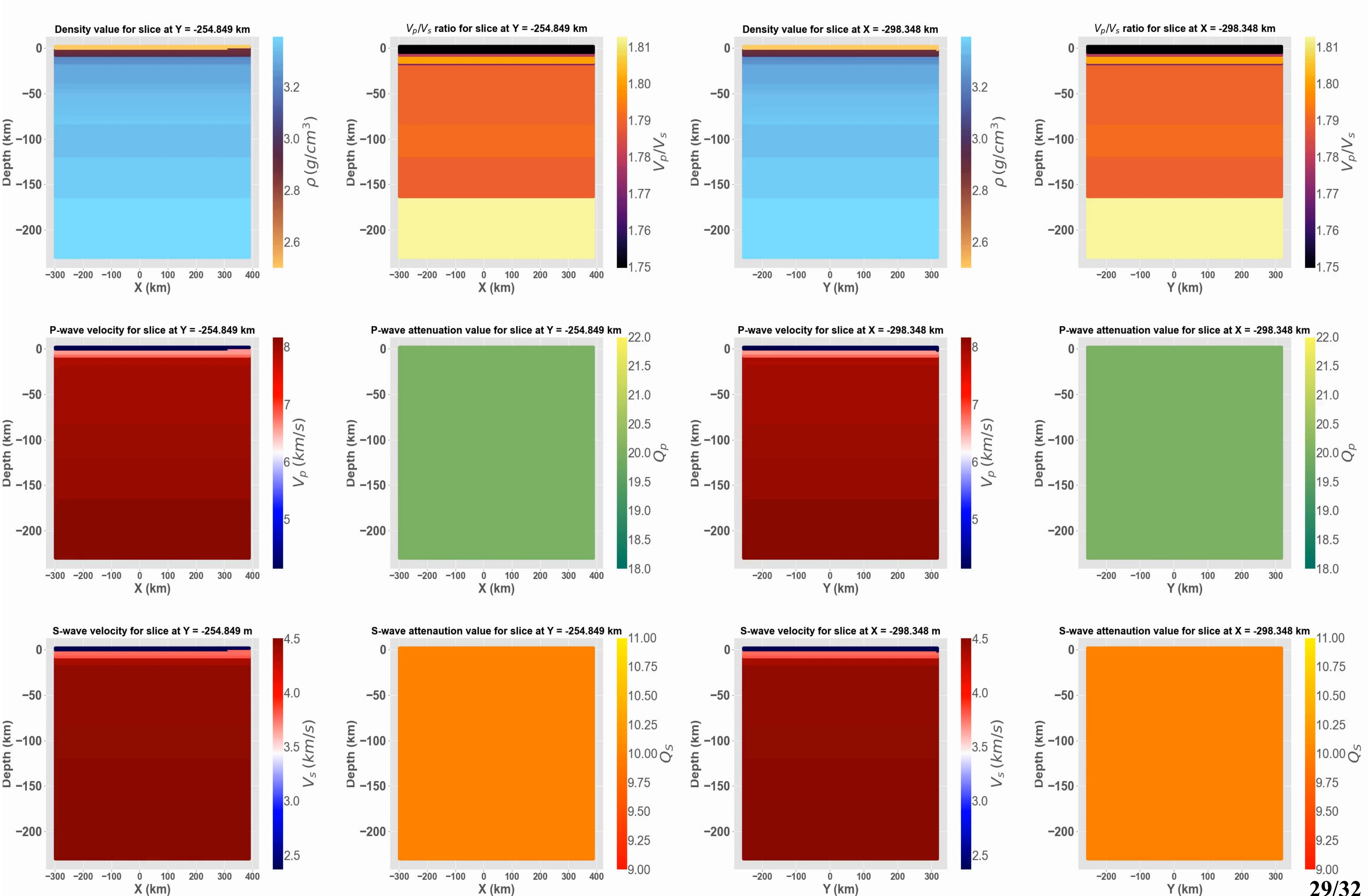




Synthetics from 3D model w.r.t. homogeneous triple layer



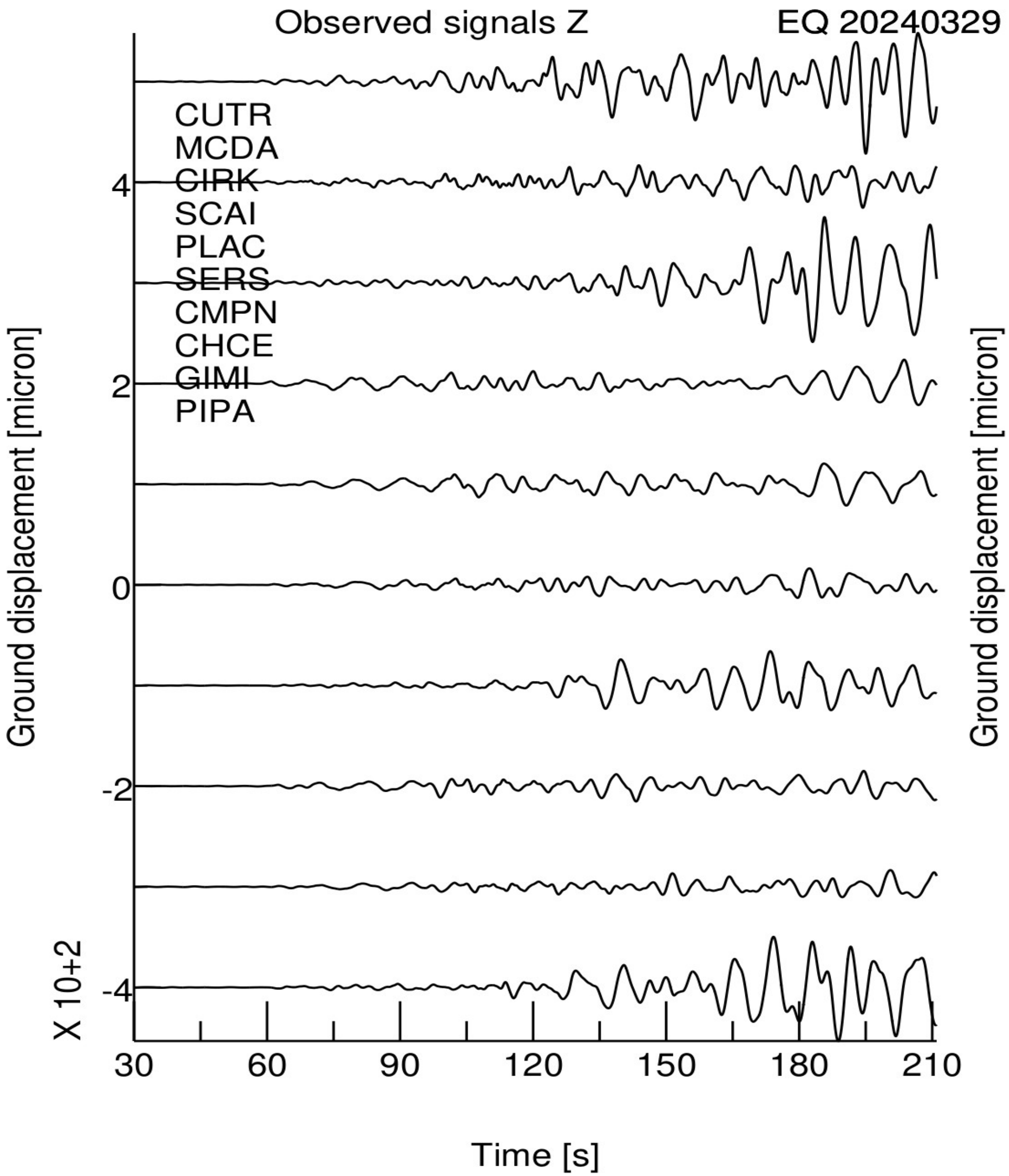
ICLERC 3D model for Ionian mesh + shell (purely isotropic)

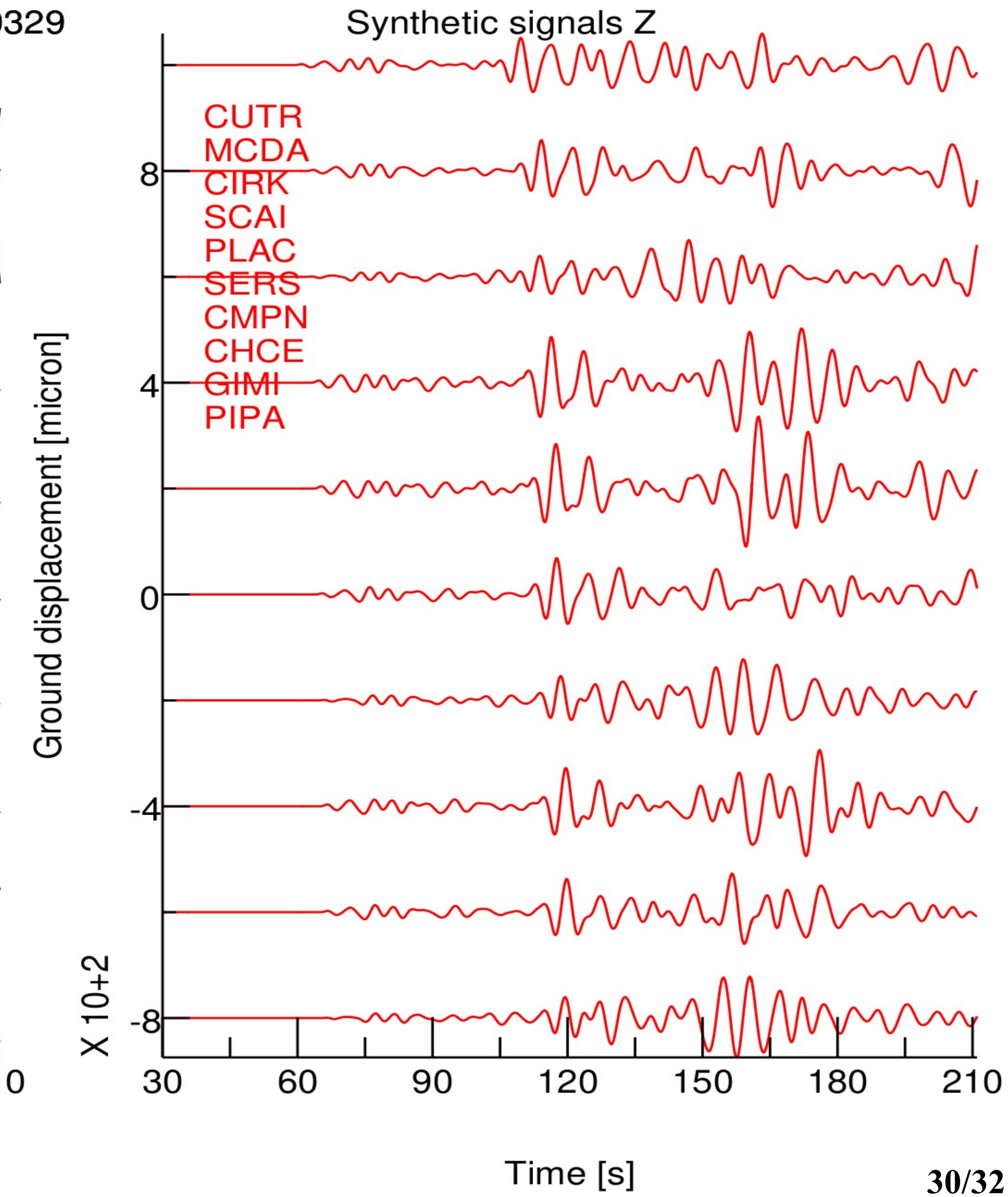


Synthetics vs real data

bp c 0.1 0.3 n 3 p 1

20240329
Mw5.9
(37.32,21.31)
35km
423kmSE-CUTR





Conclusions

Many questions still needs to be answered:

- **Why so many synthetics show such a <u>low amplitude</u> just by changing the STF?**
- **Selecting <u>attenuation</u> within the source code (not the model!) seems to have <u>no effect</u> on amplitude or even delays on the synthetics. Why?**
- **The discretization cannot be reduced further since the computation times with the ICLERC mesh took <u>32 hours</u> for 240s traces. [Wall-time 36:00h]**
- **Unwanted <u>reflected phases</u> are not completely deleted by means of the shell layer.**
- **What about the <u>ocean load</u>? One road to implement it is too overkill…**

Nonetheless both polarity and amplitudes as well as the period of surface waves seems to be resolved <u>really well</u> with our procedure.

Overall, this is still a <u>first small step</u> towards a more refined knowledge of the area. The uncertainties are many, but that's up to future researchers to deal it with.

We acknowledge the cluster Newton, ad the super-computing facility of the University of Calabria (Cosenza).
Most runs have been run on 4 nodes, 20 CPU each with 128GB RAM/node.

Thank you for your attention and for hosting me at the University of Münster.
This experience has been great. :)

Minimum period resolved

$$T_{max} = \frac{\text{avg\_distance}}{\text{v\_min}} \times \text{num\_points\_per\_wavelength}$$

5

Average distance between each element

$$\text{AVG\_DISTANCE} = \frac{\text{MAX\_ELEMENT\_SIZE}}{\text{NGLL} - 1}$$

NGLL=5

Time step suggested CFL condition
KOMATITSCH2005 CMAX=0.35
CMAX=0.5 Hom Nath Gharti

$$\text{DELTA\_T\_SUGGESTED} = \text{C\_MAX} \times \frac{\text{MIN\_GLL\_POINT\_DISTANCE}}{\text{VMAX}}$$

IN QUESTO CASO
Vs=3370
vp=8000

```
**********************************************

*** Xmin and Xmax of the model =     517071.938        722459.812
*** Ymin and Ymax of the model =     4094891.00        4430751.00
*** Zmin and Zmax of the model =    -83000.0000        2000.44995

*** Max GLL point distance =     2902.93750
*** Min GLL point distance =     11.8247070
*** Max/min ratio =     245.497620

*** Max element size =     8868.61328
*** Min element size =     68.4799805
*** Max/min ratio =     129.506653

*** Minimum period resolved =     3.28954482
*** Maximum suggested time step =     7.35000009E-04

*** for DT :     5.0000000000000001E-004
*** Max stability for wave velocities =    0.338274747

Elapsed time for checking mesh resolution in seconds =    0.12590262499999999
saving VTK files for Courant number and minimum period
```