Investigation of the Ionian basin and Calabrian arc lithosphere.

"Potrebbe essere giusto o sbagliato: lo saprai solo se avrai sbagliato."

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Academic Year 2024/2025

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

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

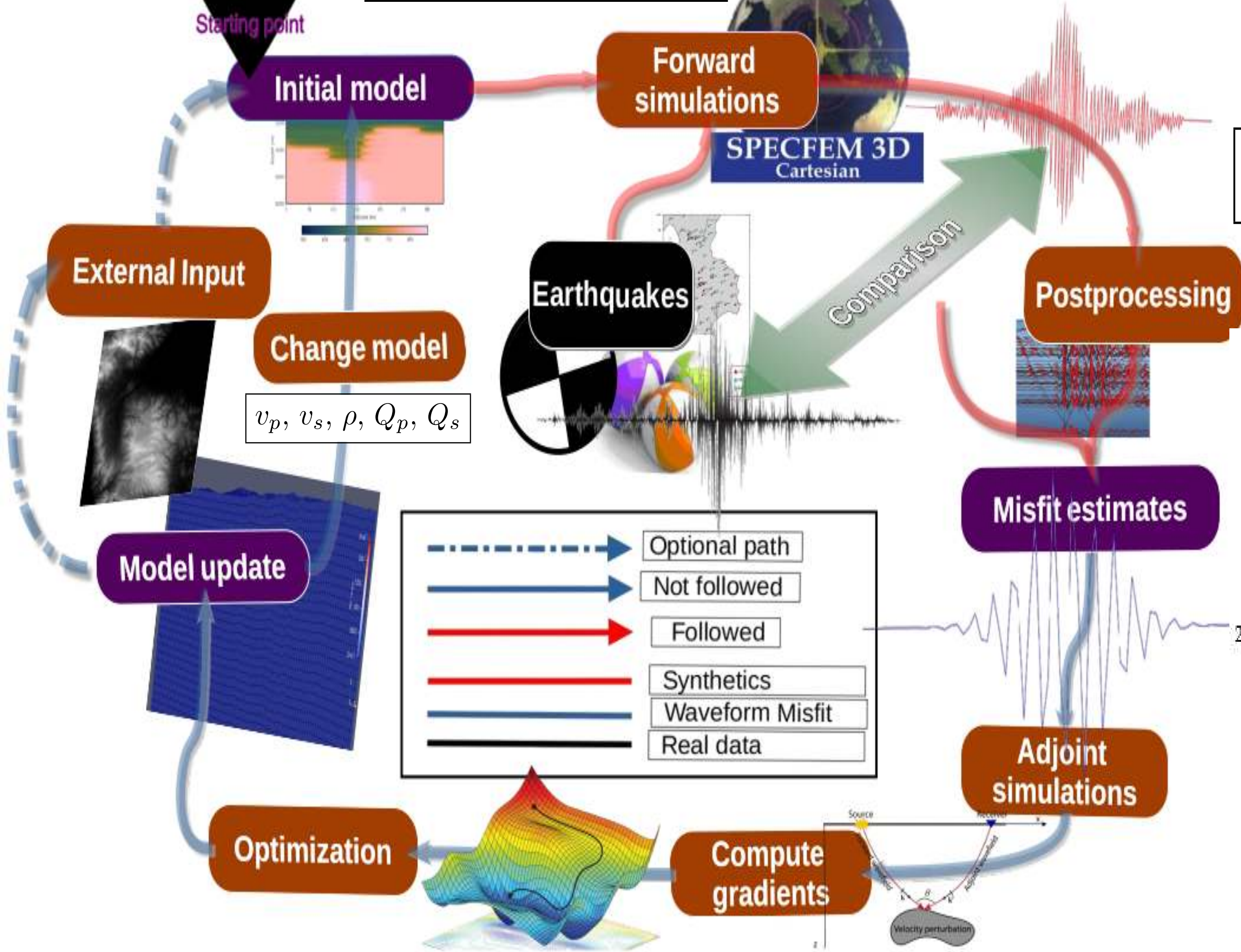
$$\rho(\mathbf{x})\ddot{\mathbf{u}} - \nabla\cdot\mathbf{T}(\mathbf{x},t) + \mathcal{V} = \mathbf{F}(\mathbf{x}_s,t)$$

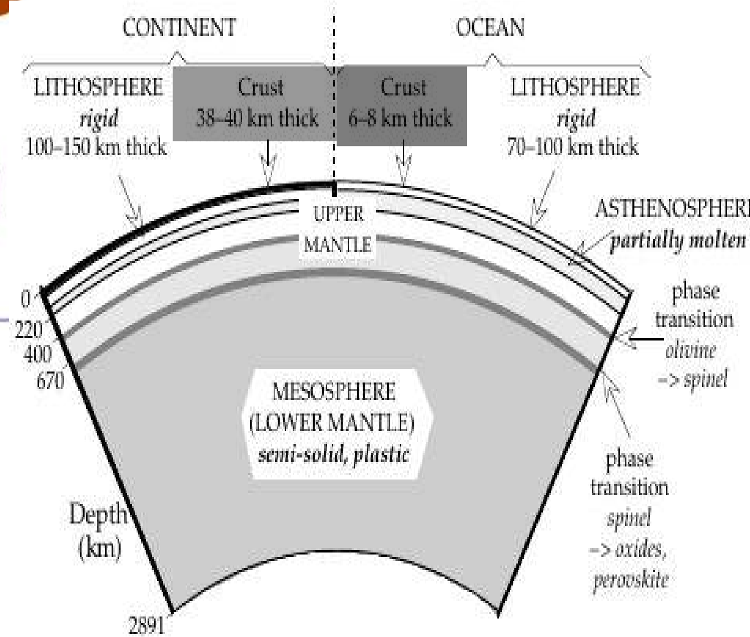
$$\hat{\mathbf{n}}\cdot\ \mathbf{T} = \mathbf{0}$$

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

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

$$\mathbf{u}(\mathbf{x},0) = \mathbf{0}\,,\quad \dot{\mathbf{u}}(\mathbf{x},0) = \mathbf{0}$$



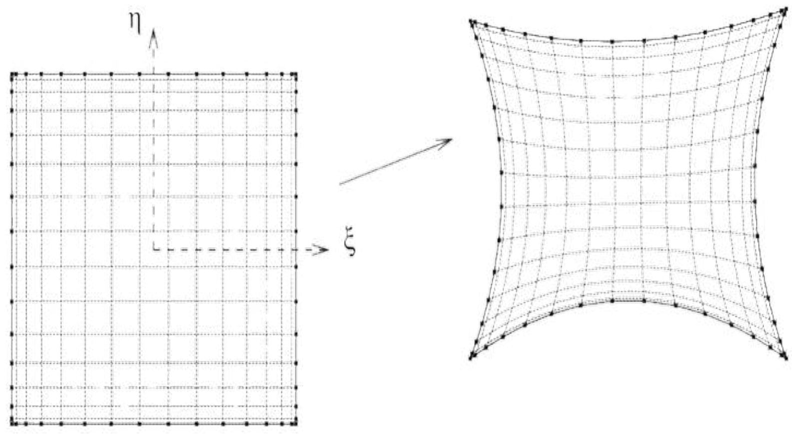


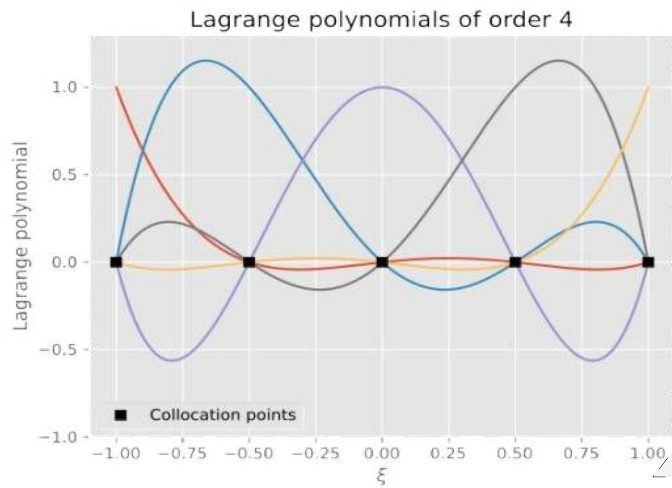
[1] Lowrie 2003

Spatial discretization[2] and weak formulation of the 3D wave equation.

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

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





GLL quadrature

Mass matrix is <u>fully diagonal.</u>

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

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

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

[2] Komatitsch1997

Time discretization: Newmark scheme.

Advantages

- Curved finite elements are mapped to unit cube, described by 8 or 27 control points.
- Efficient MPI parallelization.
- ASCII based, serial I/O, ADIOS I/O, HDF5, GPU compatible.

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

CMB matrix term.

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.

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

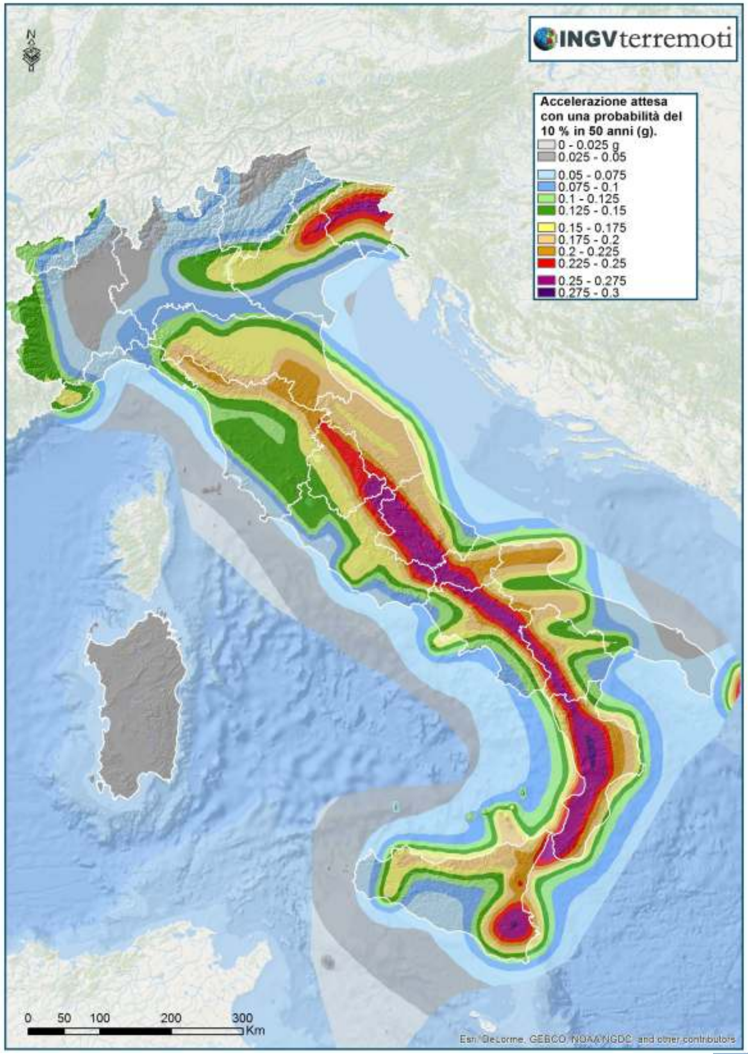
$$C = \Delta t \left(\frac{v_{s,min}}{h_{min}} \right).$$

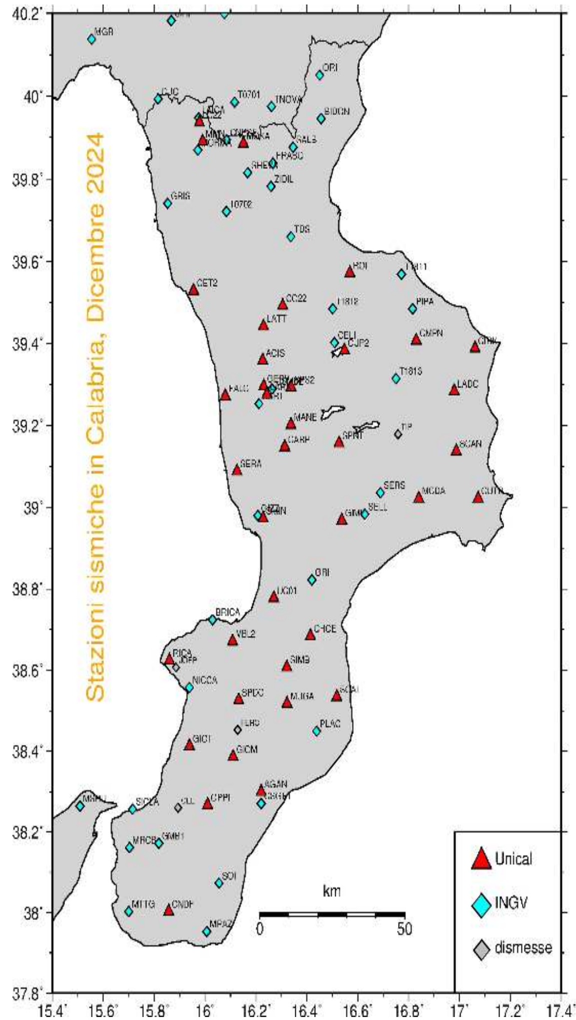
Benchmarks test (regional models)[3] C ~ 0.5.

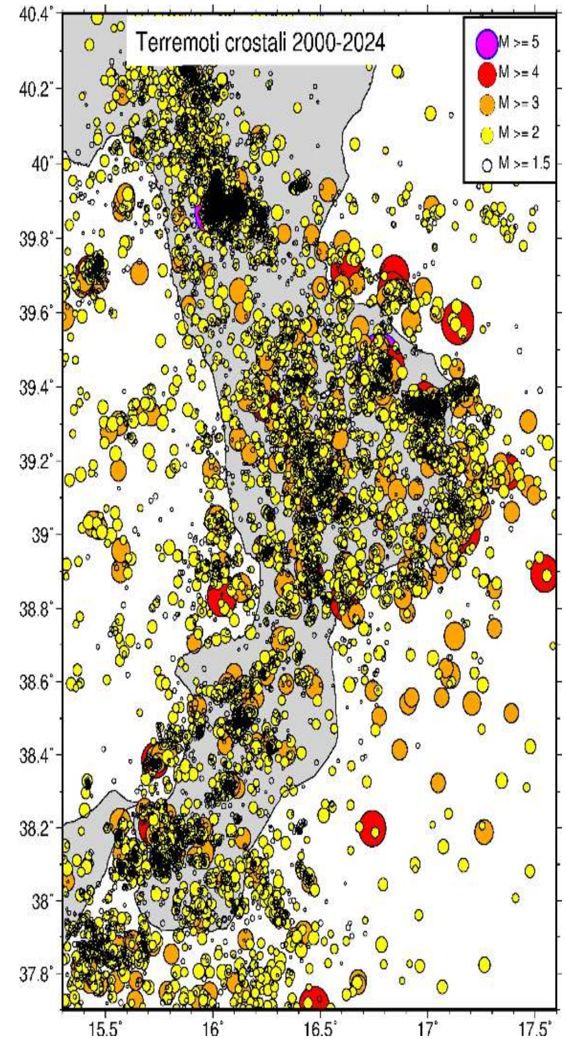
Frequency goal 0.3 Hz.

[3]Tromp et Modrak 2006

The importance of the lithospheric structure of the Calabrian arc and Ionian basin[4].

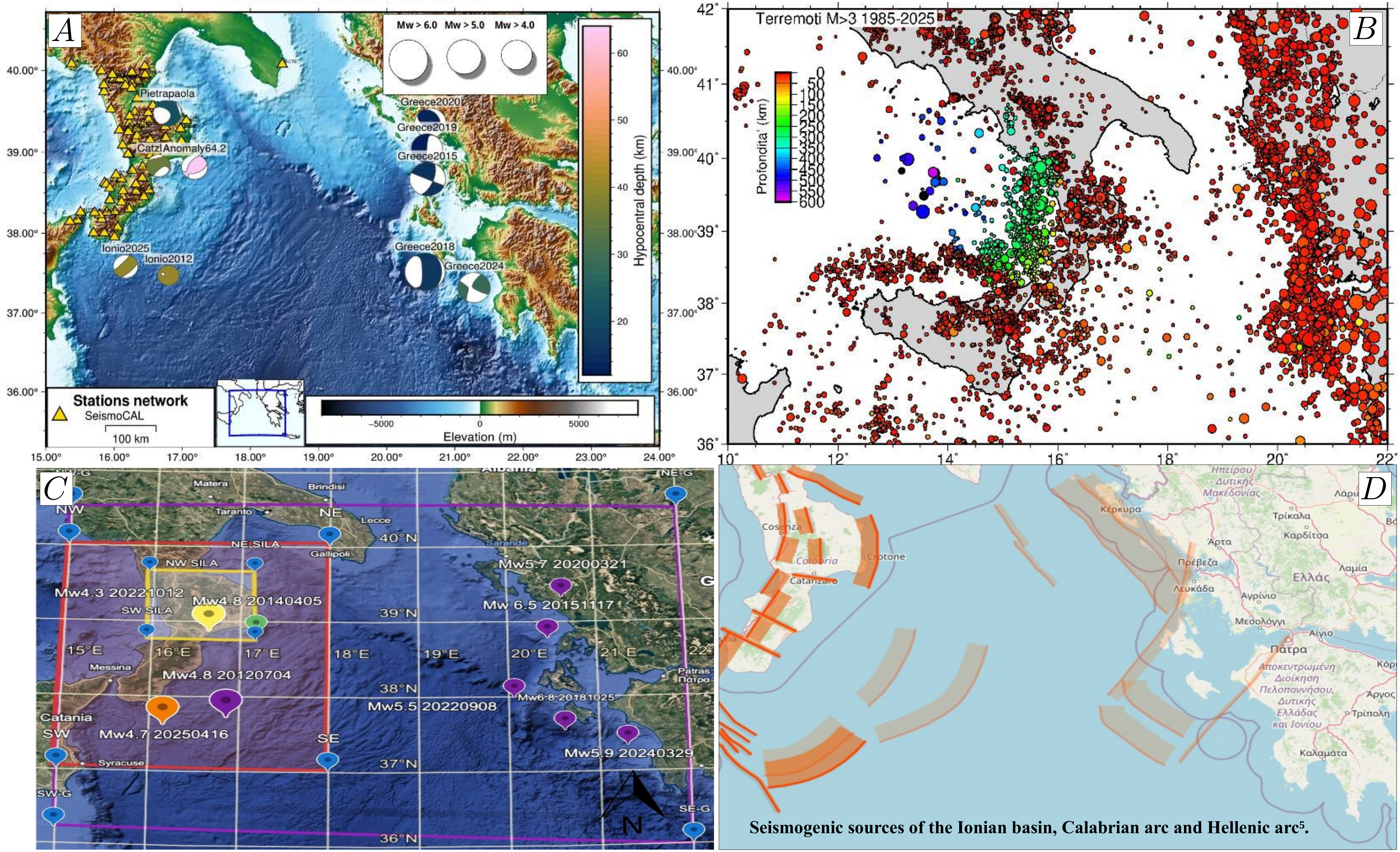






Università della Calabria
Rete Sismica

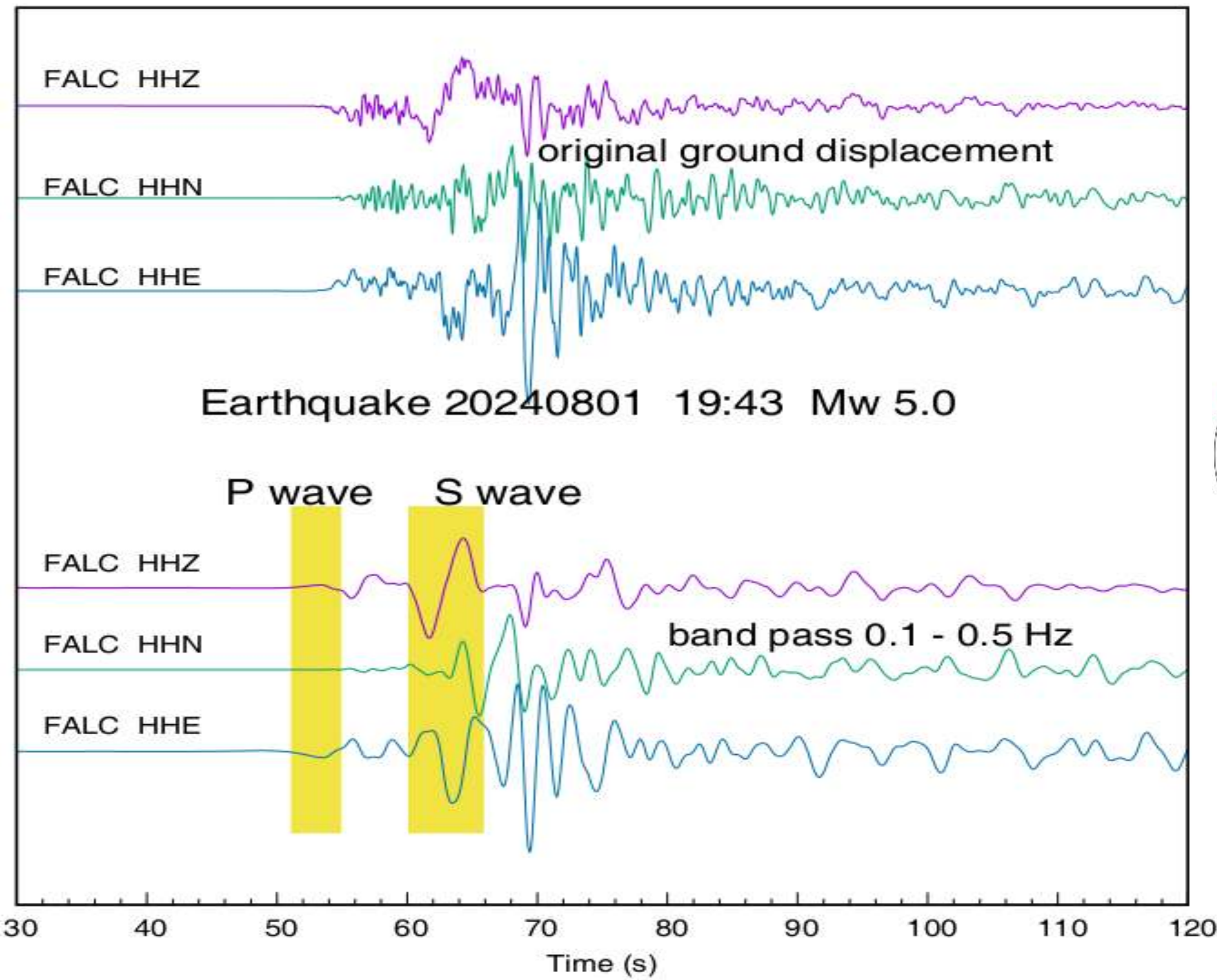
[4] http://doi.org/doi:10.7914/SN/IY



Seismogenic sources of the Ionian basin, Calabrian arc and Hellenic arc[5].

[5] INGV-DISS source

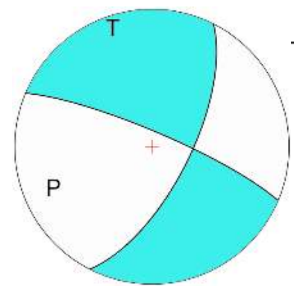
Observed seismograms contains contribution from the source and from the propagation of seismic waves throughout an highly heterogeneous medium.



MT components

20240801.194320.0

$$\begin{bmatrix} M_{rr} & M_{rt} & M_{rp} \\ M_{rt} & M_{tt} & M_{tp} \\ M_{rp} & M_{tp} & M_{pp} \end{bmatrix}$$



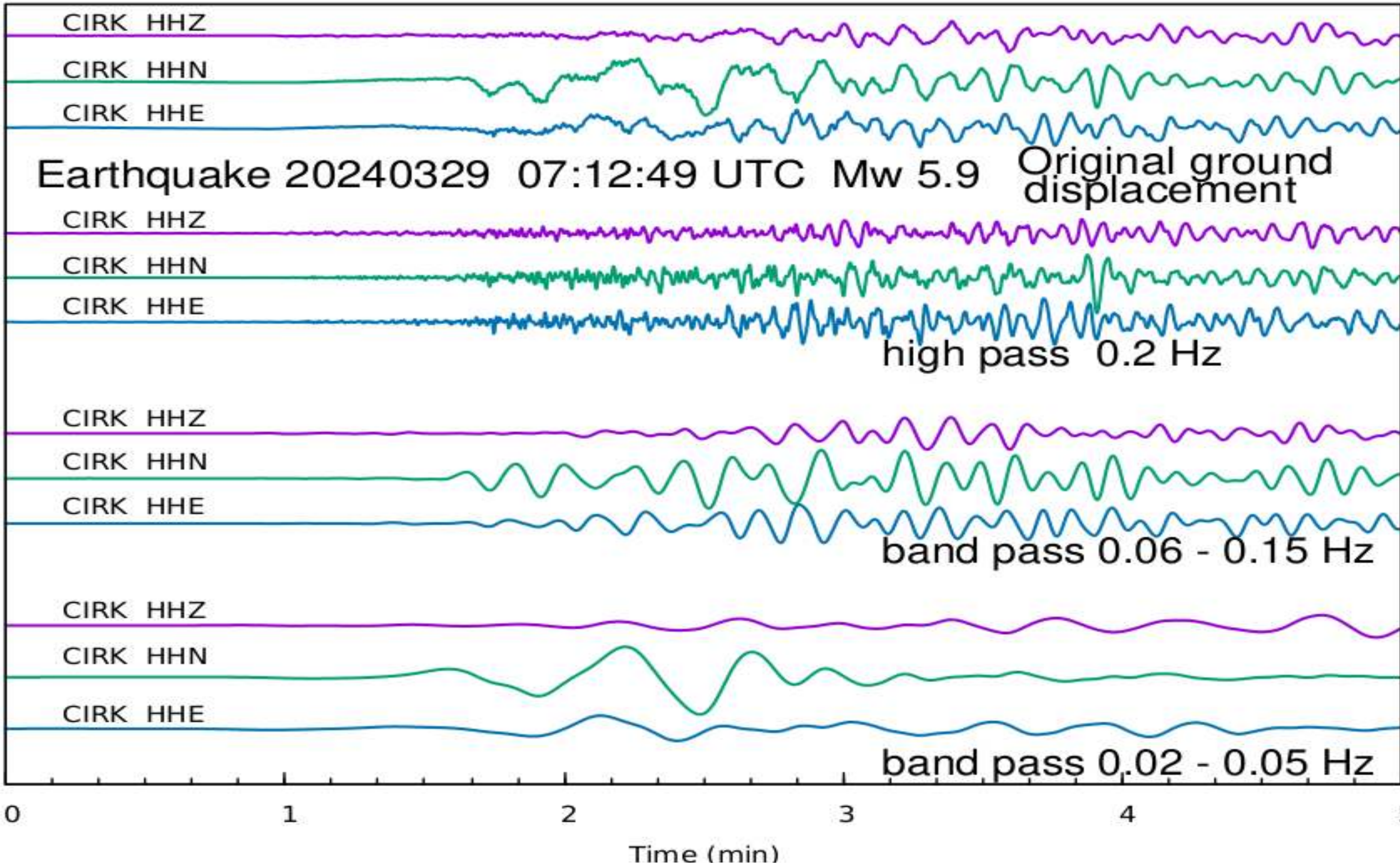
Values

in 10^{23} dyne cm

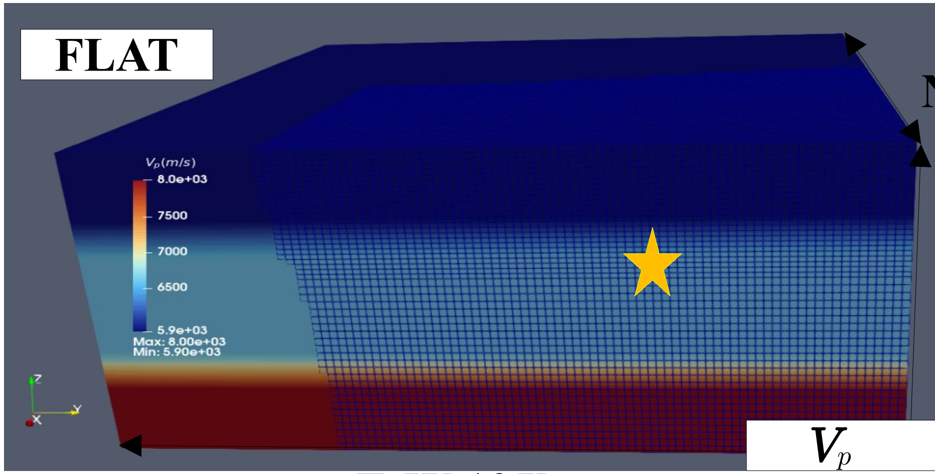
$$\begin{bmatrix} -1.91 & 2.170 & -3.840 \\ 2.170 & 4.04 & 2.410 \\ -3.840 & 2.410 & -2.13 \end{bmatrix}$$

EQ20240801 19:43:20 UTC
Mw5.0
M_0 = **5.62** $\cdot 10^{16}$ **N·m**
Lat 39.4°N
Long 16.75°E
26.3km deep
2kmSE PIPA.

Modeling real seismograms in time domain is challenging.



No topography Sila region test – three homogeneous layers model.

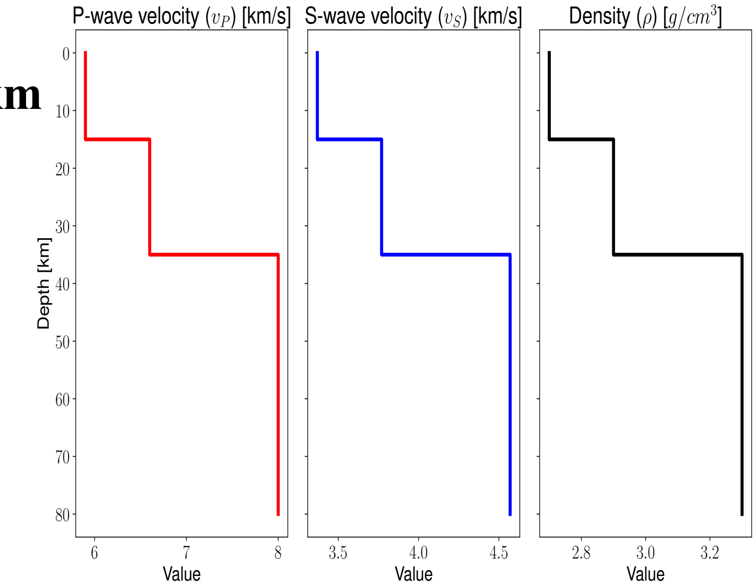


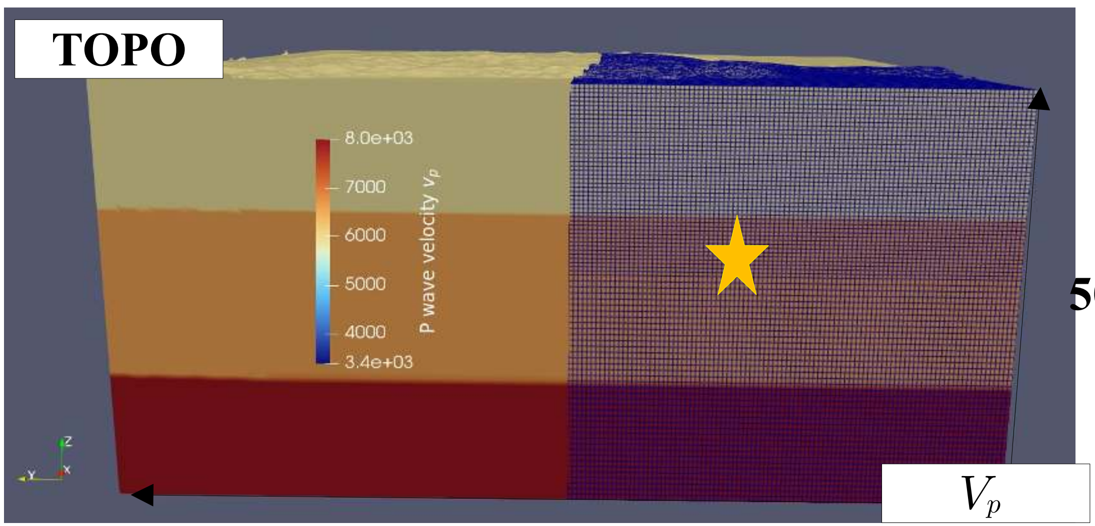
N-S 101km

50 km

E-W 105km

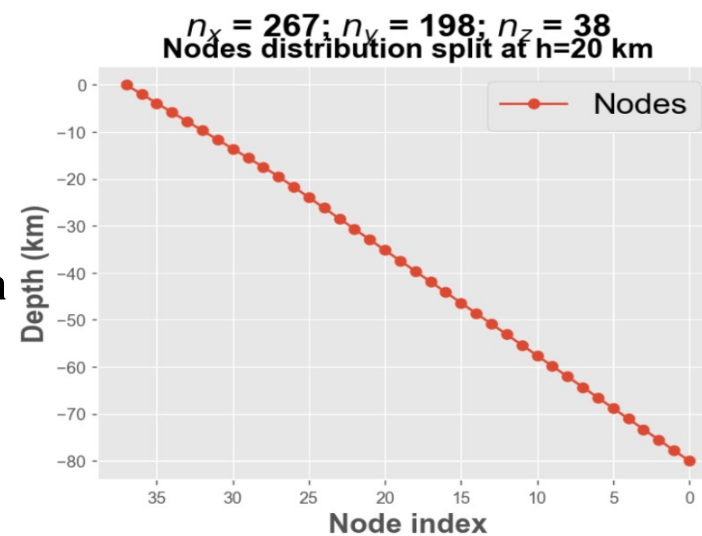
Total number of elements 530k. Spacing ~ 1.5km.



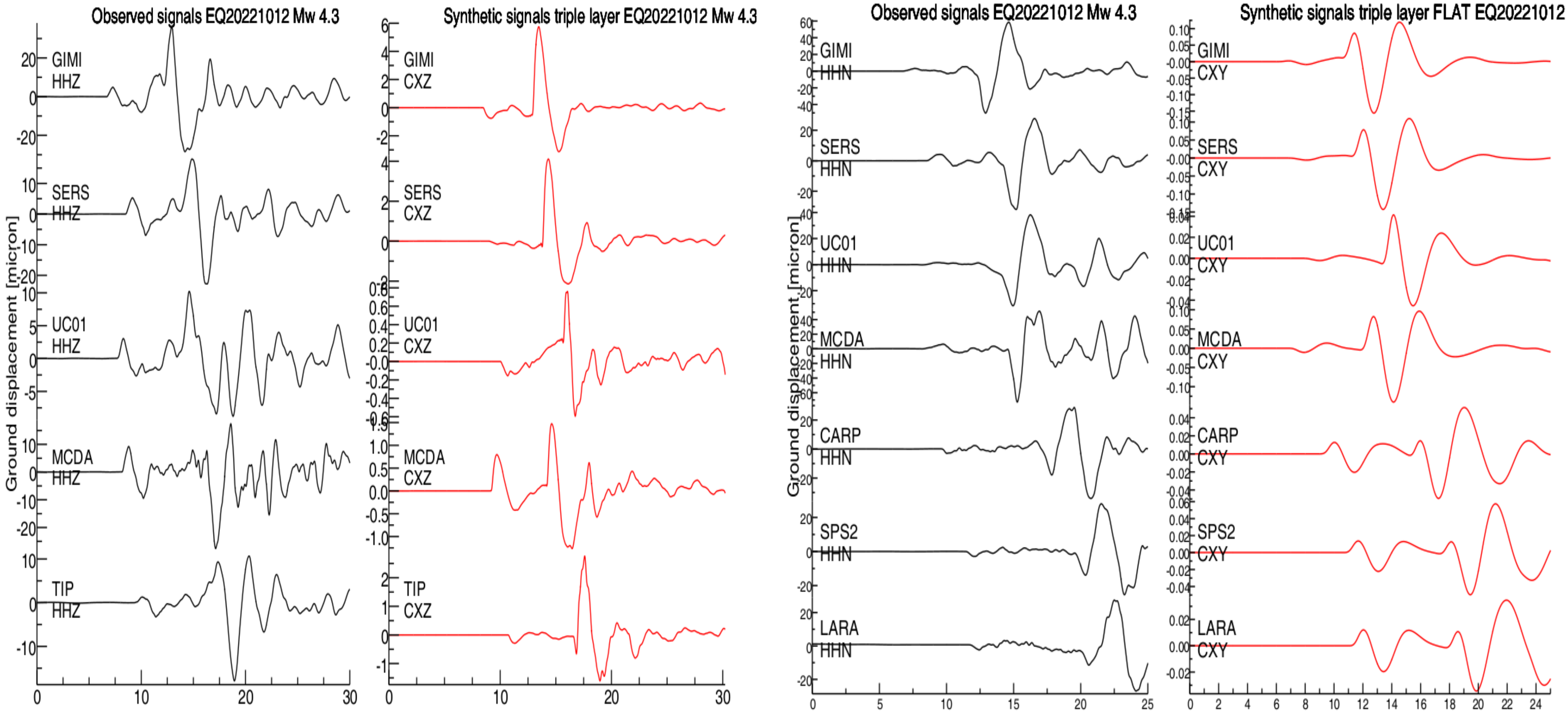


50 km

N-S 105km



Comparison of real data and synthetics with and without topography.



c 0.01 - 0.2

TOPO

c 0.04 - 0.3

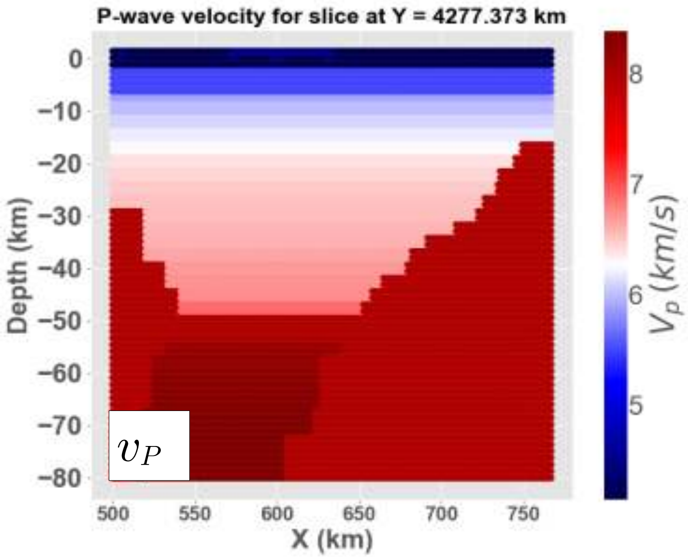
FLAT

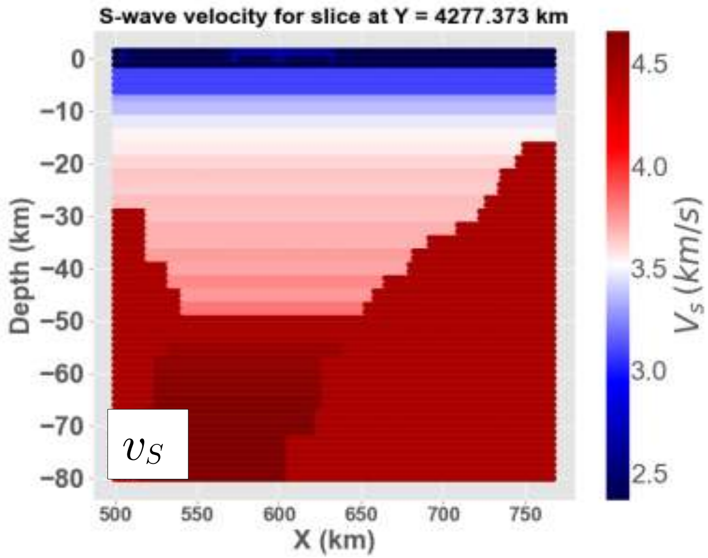
Synthetics

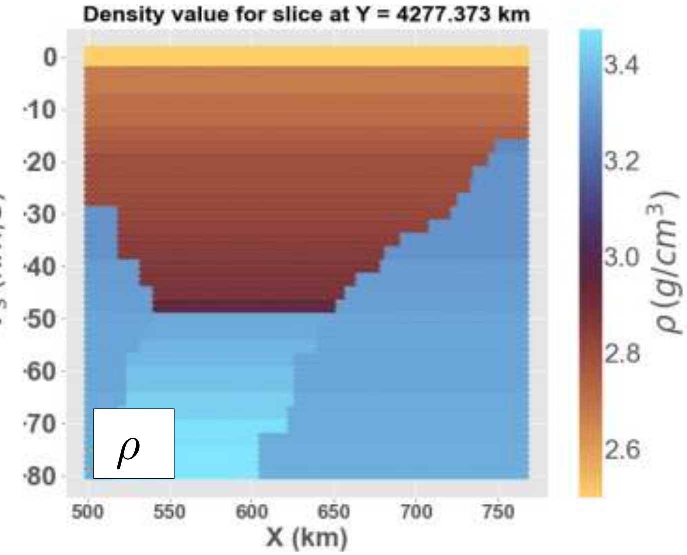
Observed

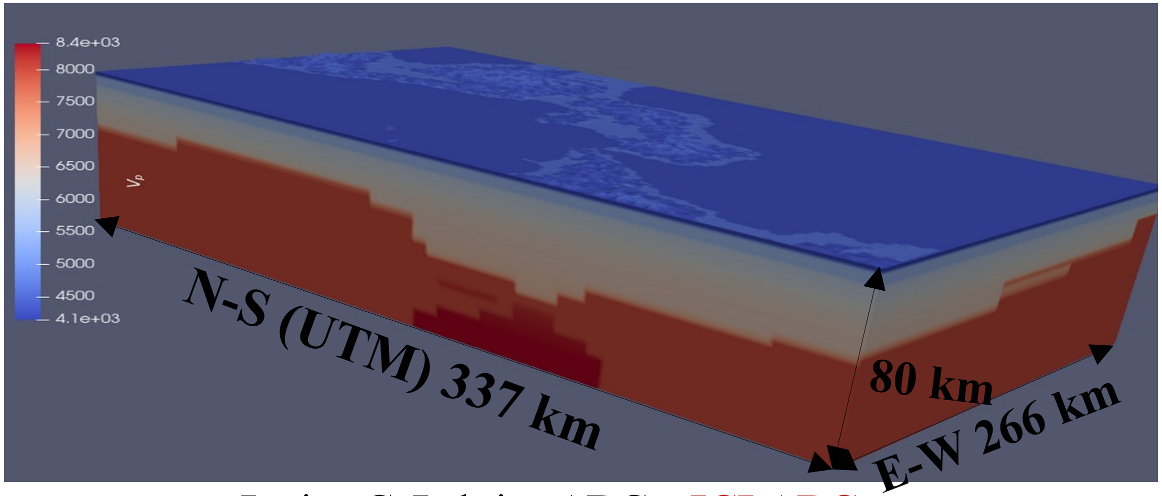
20221012 Mw4.3
(38.83°N,16.65°E) D35km 7kmSE CZ.

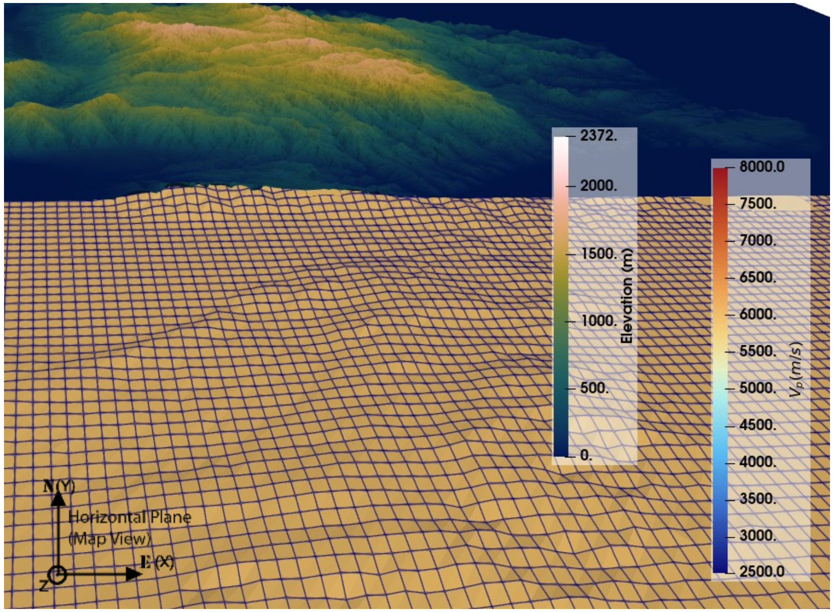
Simulations throughout the Calabrian arc - ICLARC 3D model.









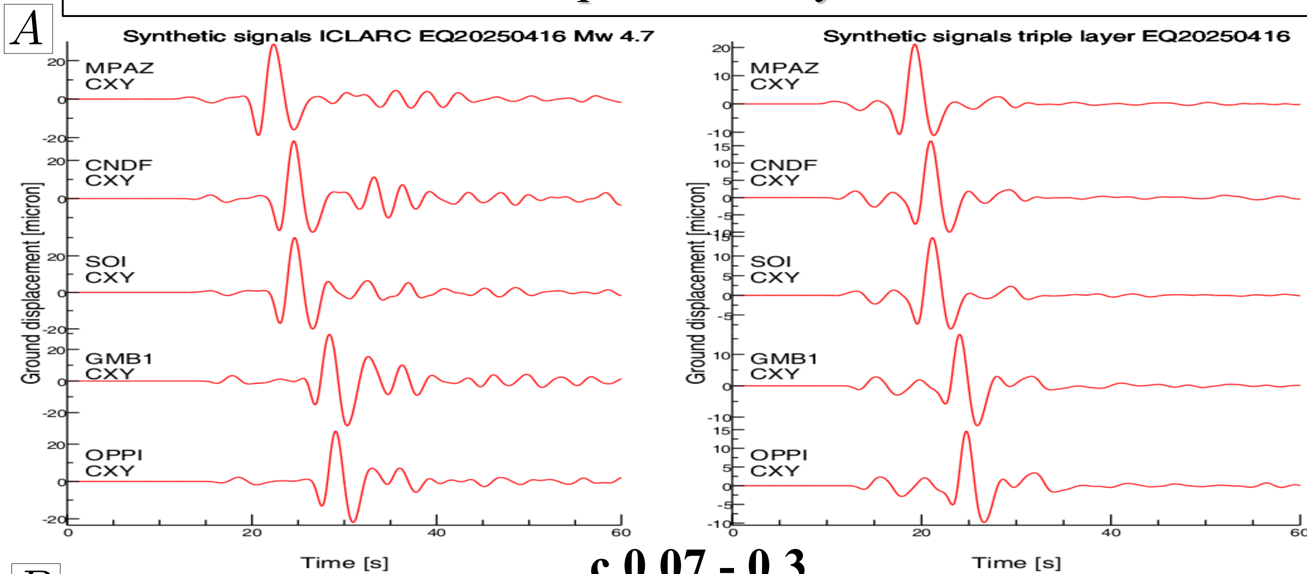


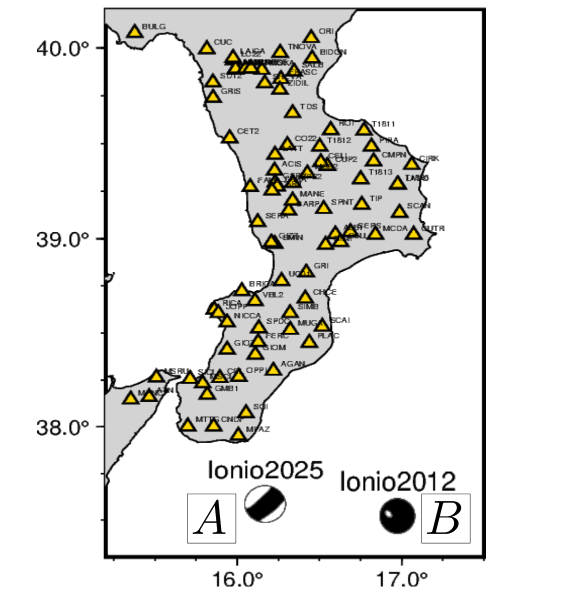
Ionian **C**a**L**abrian **ARC** – **ICLARC**.

Total number of elements 2.49 million.

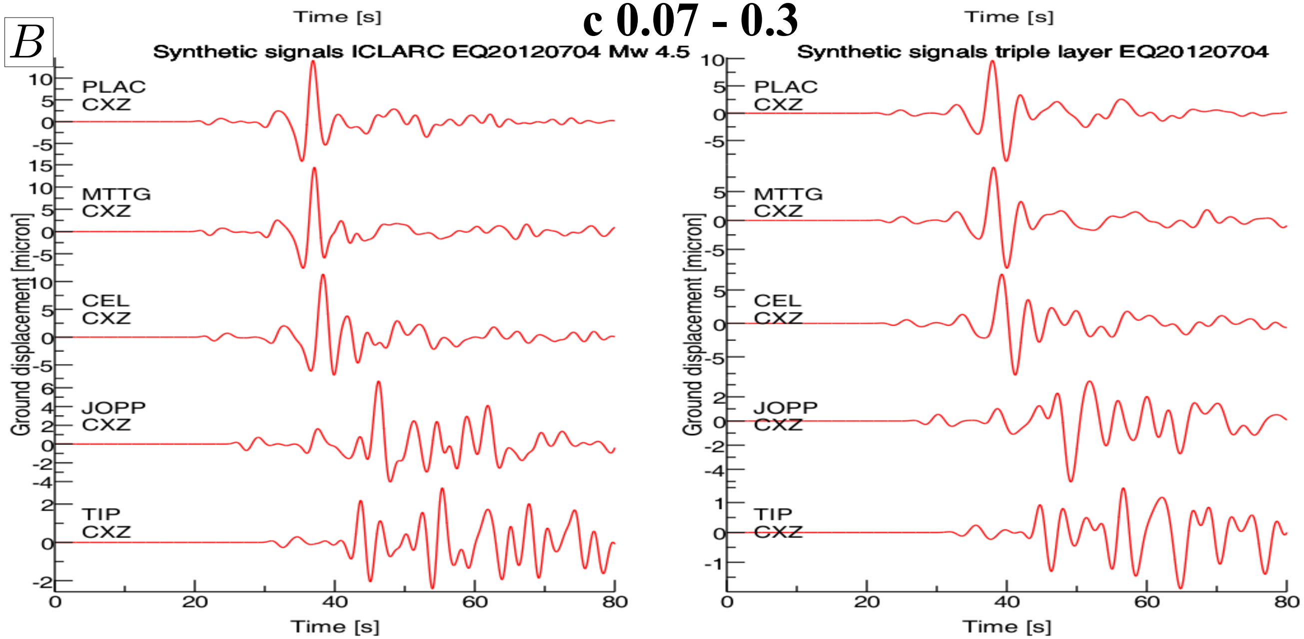
Element's spacing ~ 1.7 km. Nodes split at 20km.

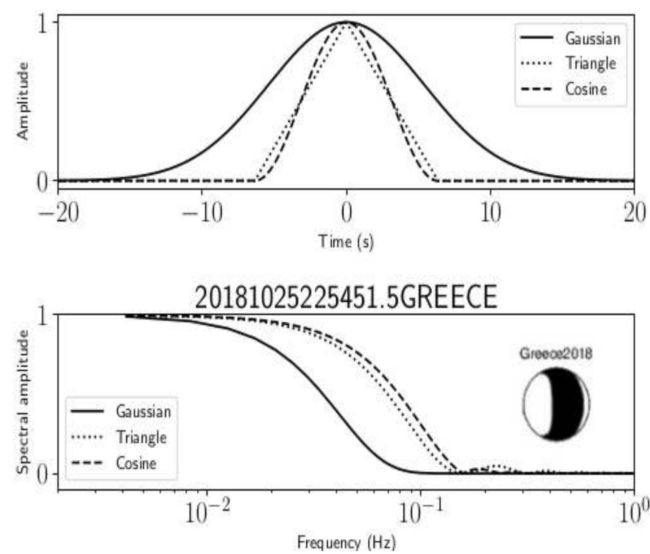
Comparison of synthetics - ICLARC vs 1D model.





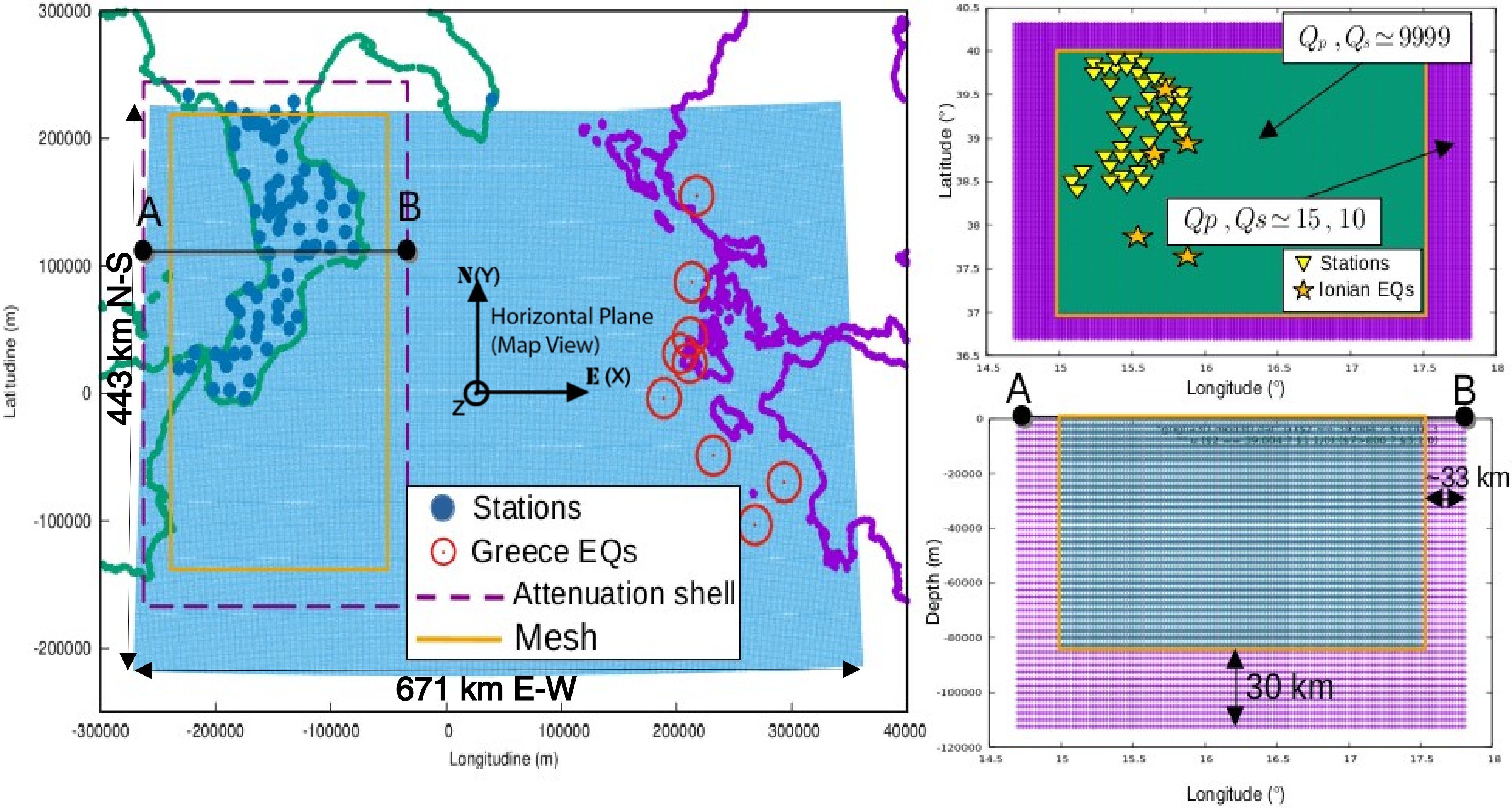
c 0.07 - 0.3





Synthetics

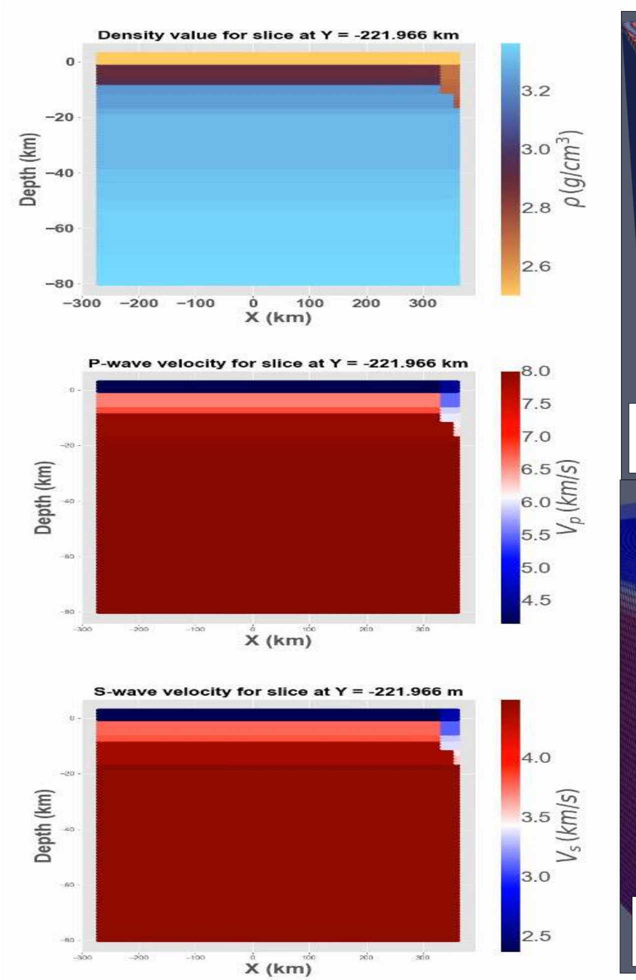
Depth section of the shell attenuation layer - ICLERC & ICLARC.

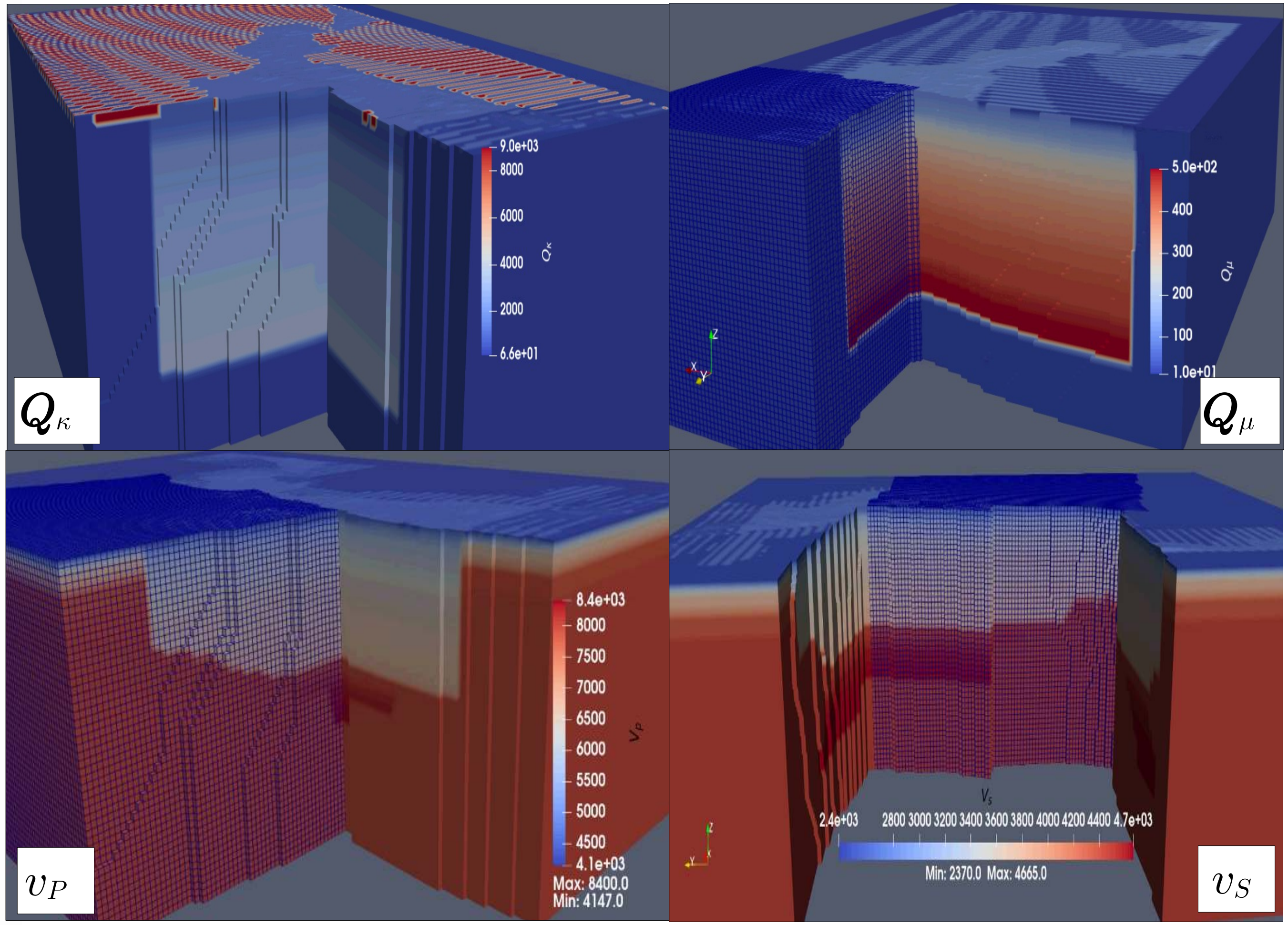


Ionian CaLabrian Ellenic aRC – ICLERC model. From 80 km up to the bottom follows the AK135 model.

Total number of elements 6.1 million. Elements spacing ~ 2.2 km.

Reflected phases and anelastic attenuating layer for 3D model.



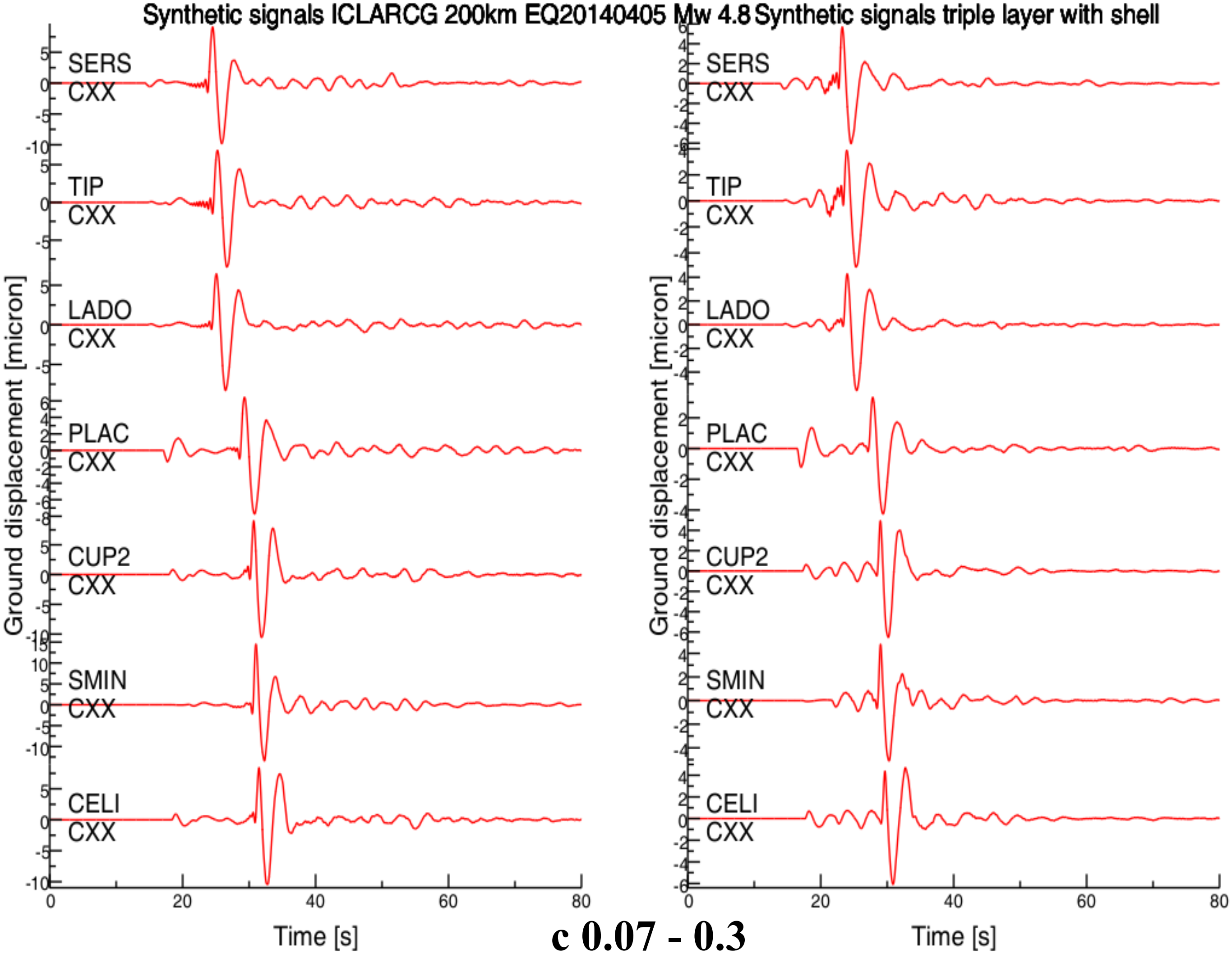


$$Q_P^{-1} = \left(1 - \frac{v_S^2}{v_P^2}\right) Q_\kappa^{-1} + \frac{v_S^2}{v_P^2} Q_\mu^{-1},$$

$$Q_S^{-1} = Q_\mu^{-1}.$$

The binary, which interpolates on the GLL nodes, does the conversion internally from Q_P,Q_S (.xyz file) to Q_κ,Q_μ (shown in Figure).

Comparison of synthetics - ICLARC with shell vs 1D model with shell.

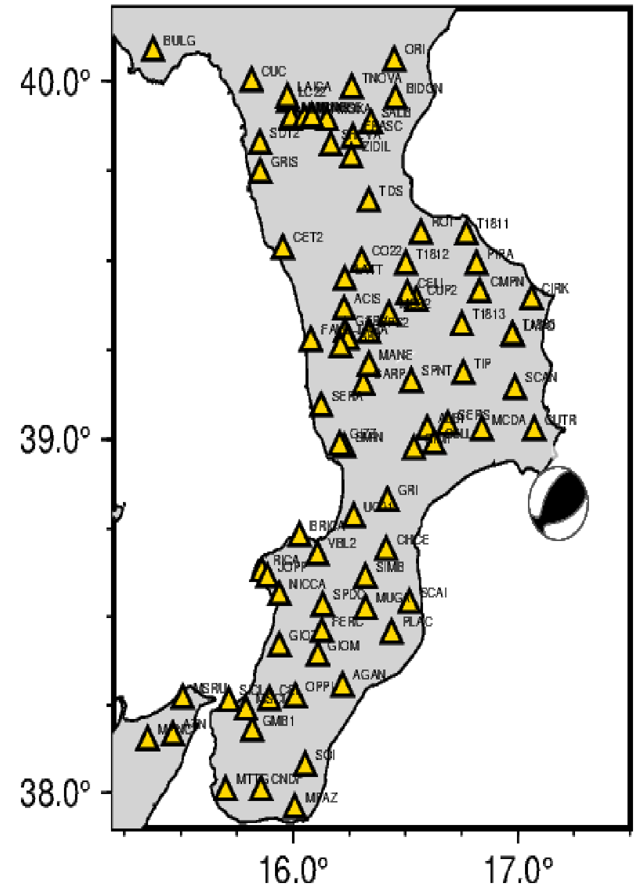


c 0.07 - 0.3

Synthetics

EQ20140405 Mw4.8 D64km

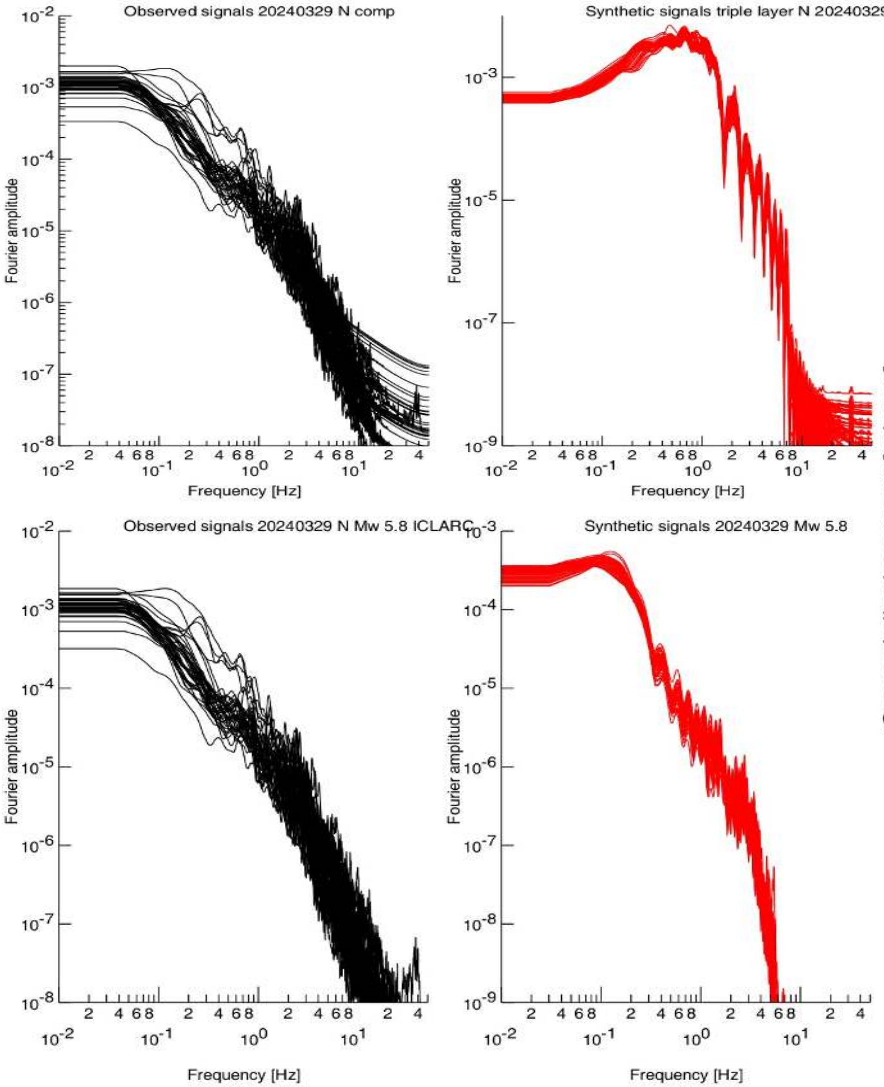
(38.82°N,17.18°E) 35kmS-CUTR.



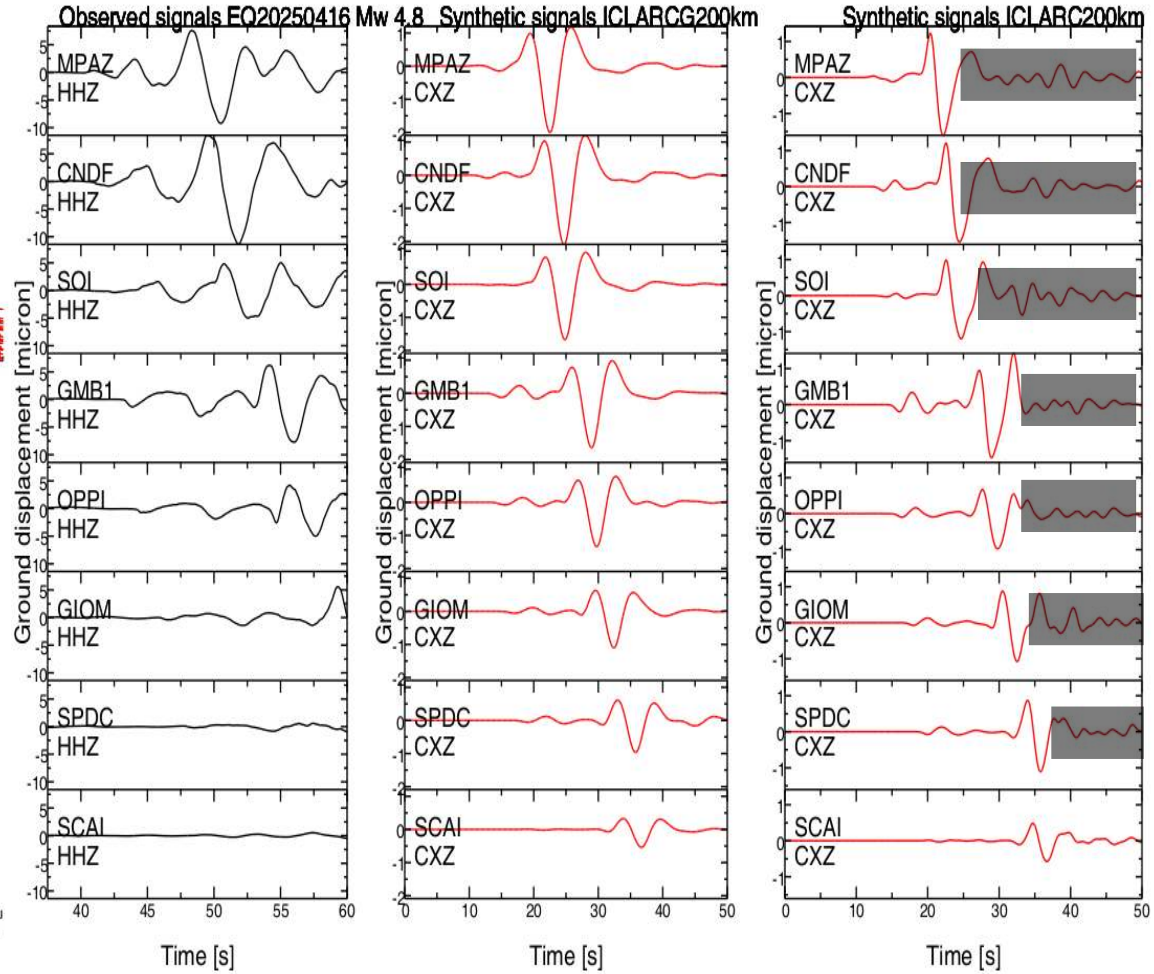
Synthetic spectra and comparison of signals with and without the shell.

EQ20240329 Mw5.8 (37.32°N,21.31°E) D35km.

Synthetics   Observed



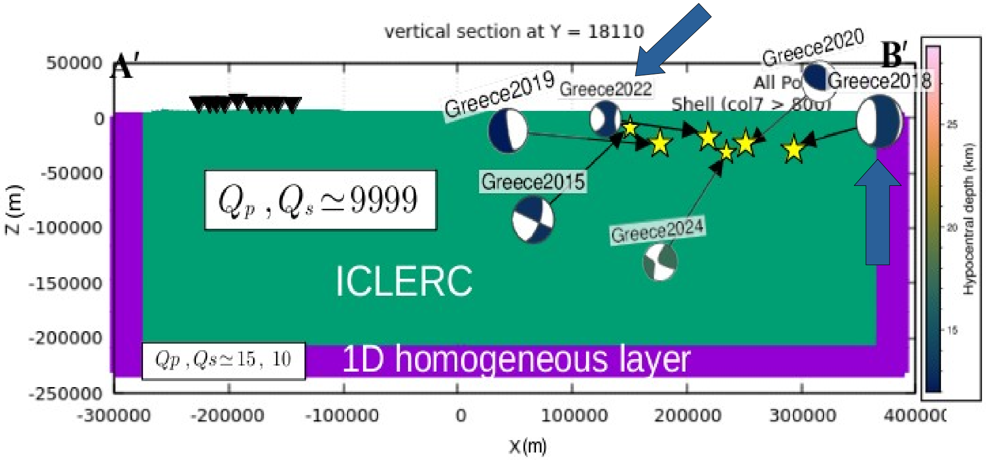
EQ20250416 Mw4.7 (37.58°N,16.17°E) D39km.

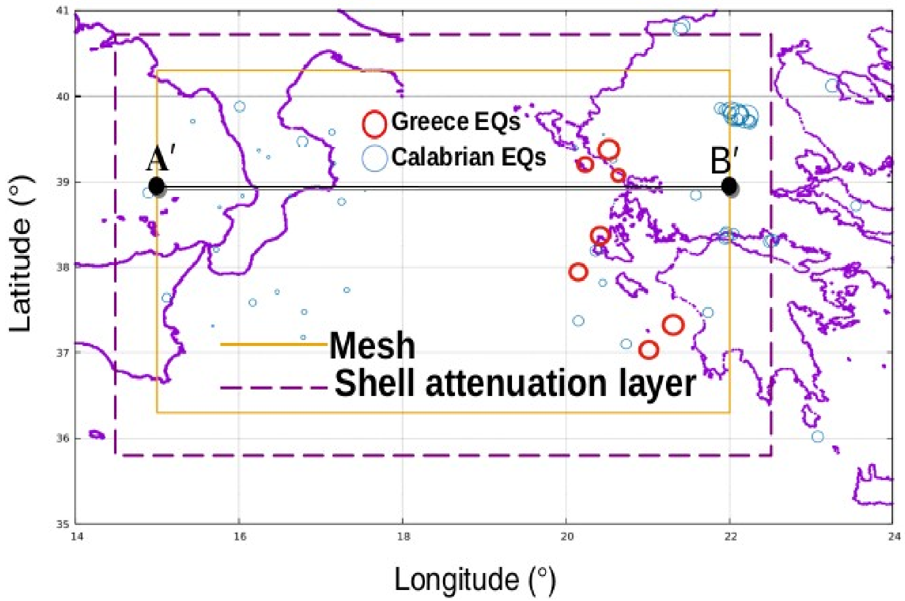


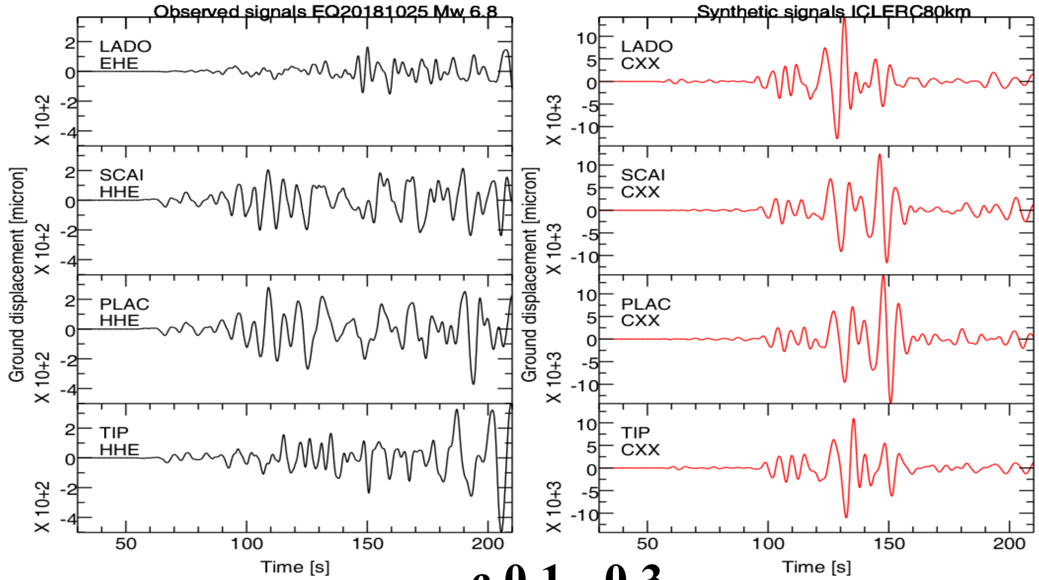
c 0.07 - 0.22

The shell works. However further simulations must be done, perhaps with a Q gradient.

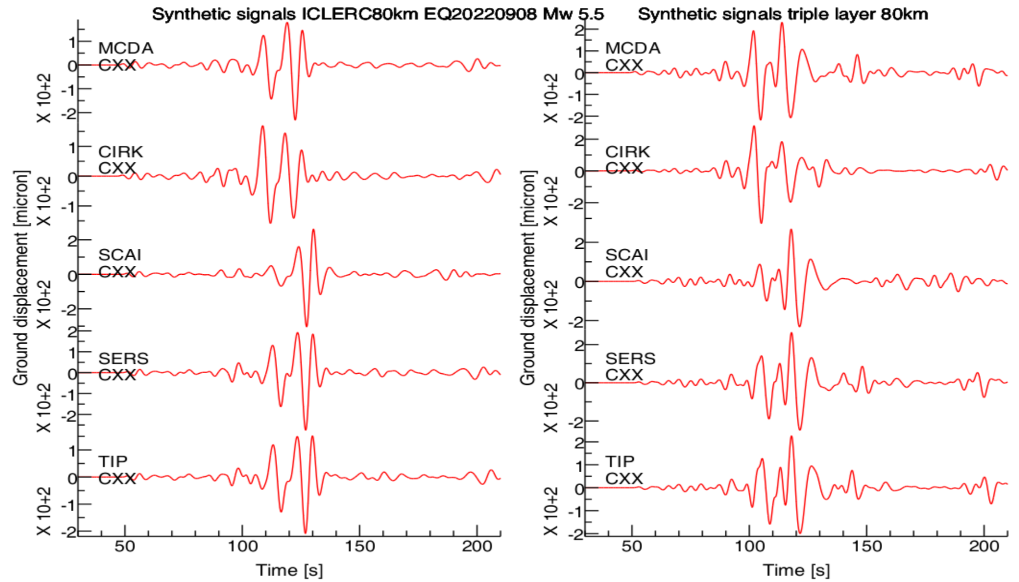
Greece earthquakes - EQ20181025 & EQ20220908 (no shell layer).







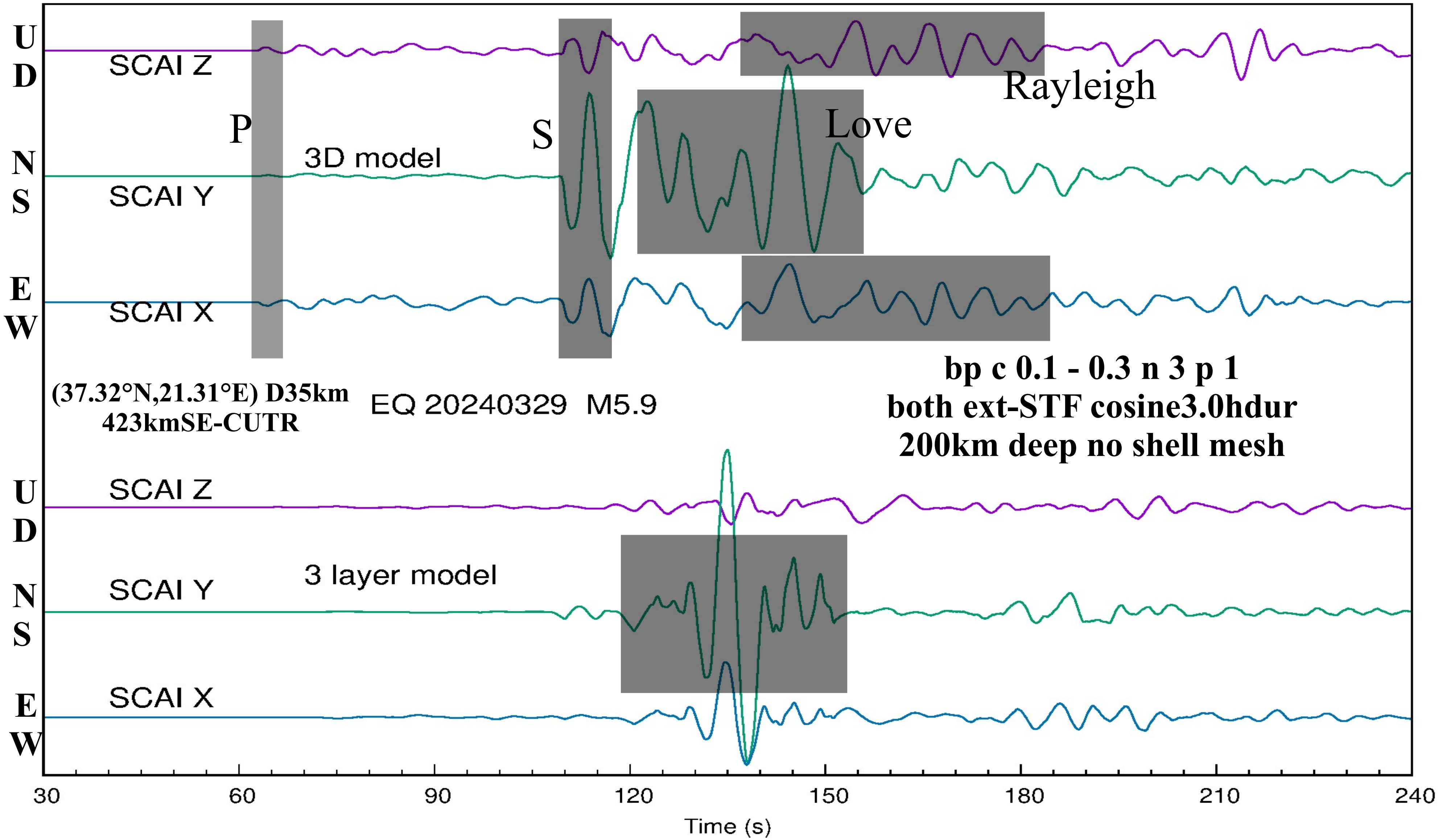
c 0.1 - 0.3



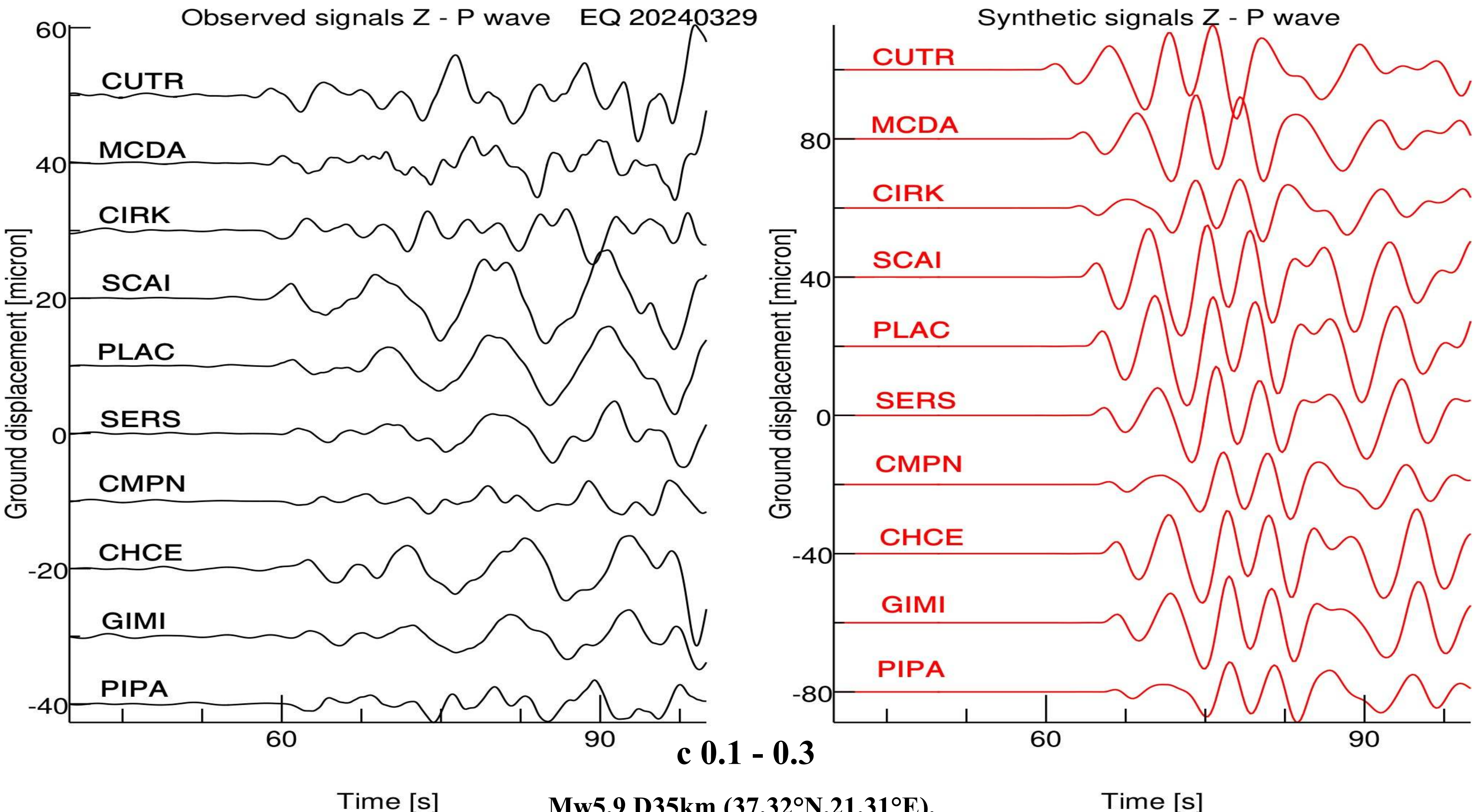
Synthetics

Observed

Synthetics from **ICLERC** 3D model with respect to triple layer model.



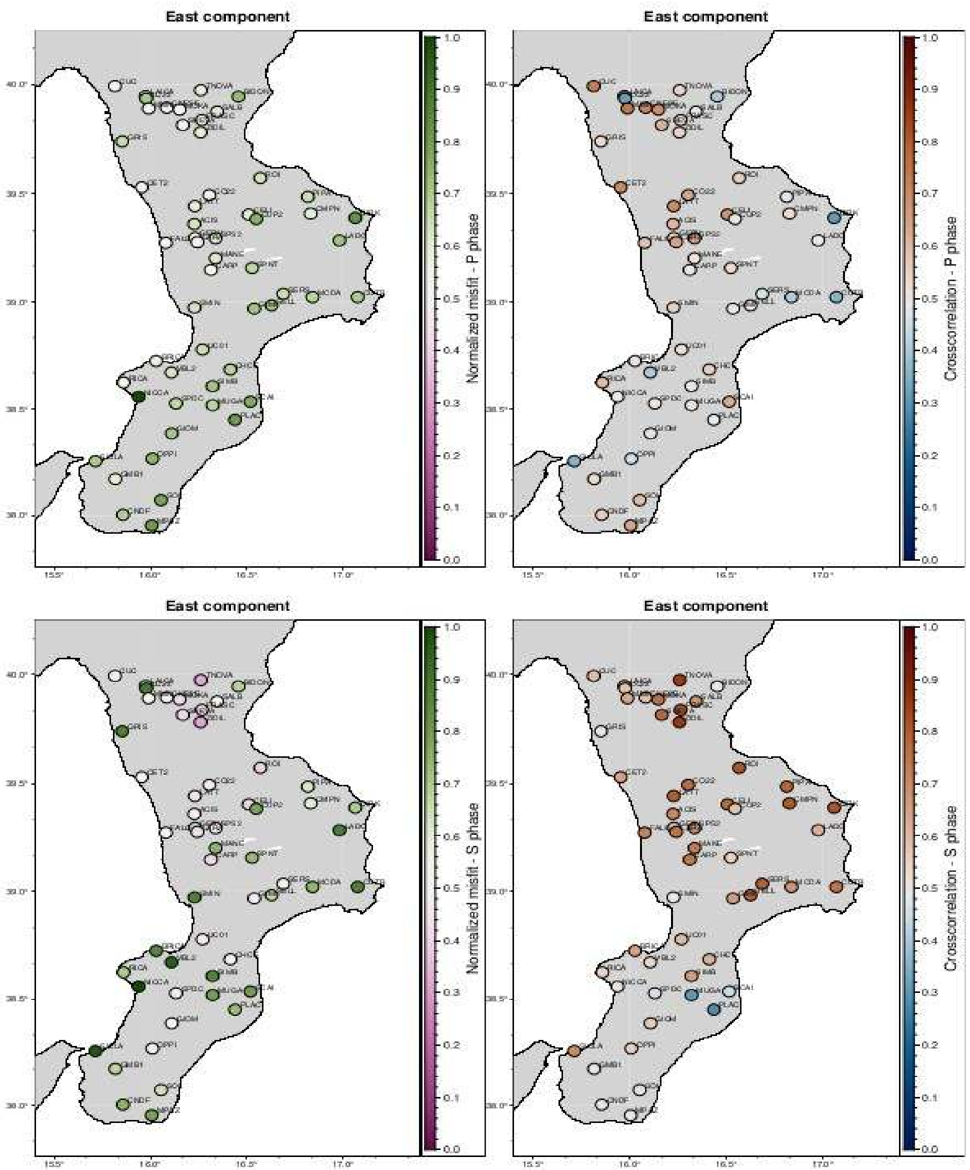
Synthetics vs real data - ICLERC (no shell).

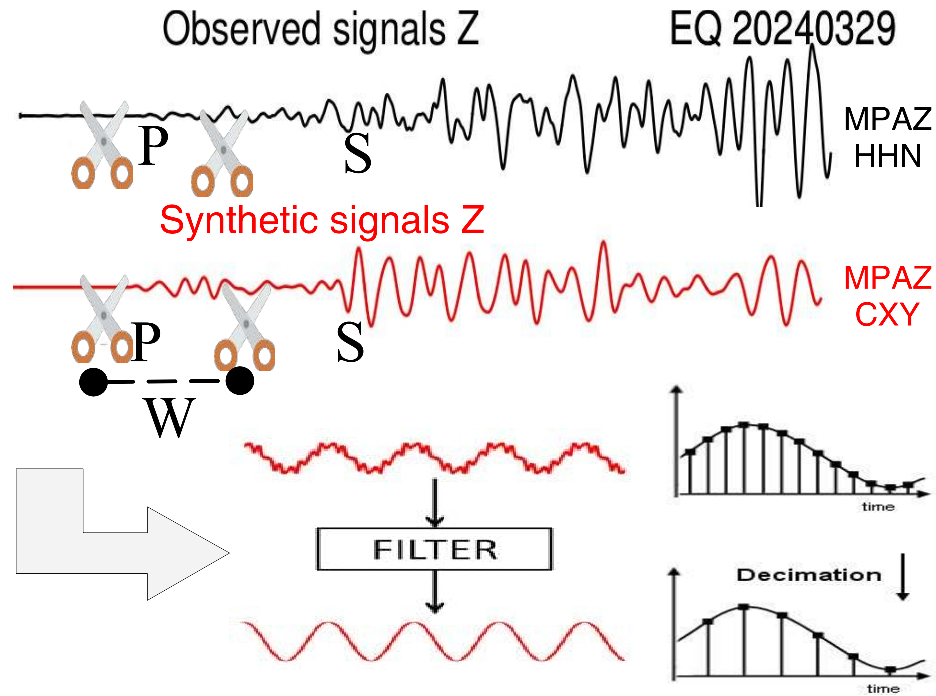


c 0.1 - 0.3

Mw5.9 D35km (37.32°N,21.31°E).

Misfit metrics computation - **ICLERC** EQ20240329 [0.07 - 0.12 / 0.012 - 0.03] Hz [30 / 30] s.





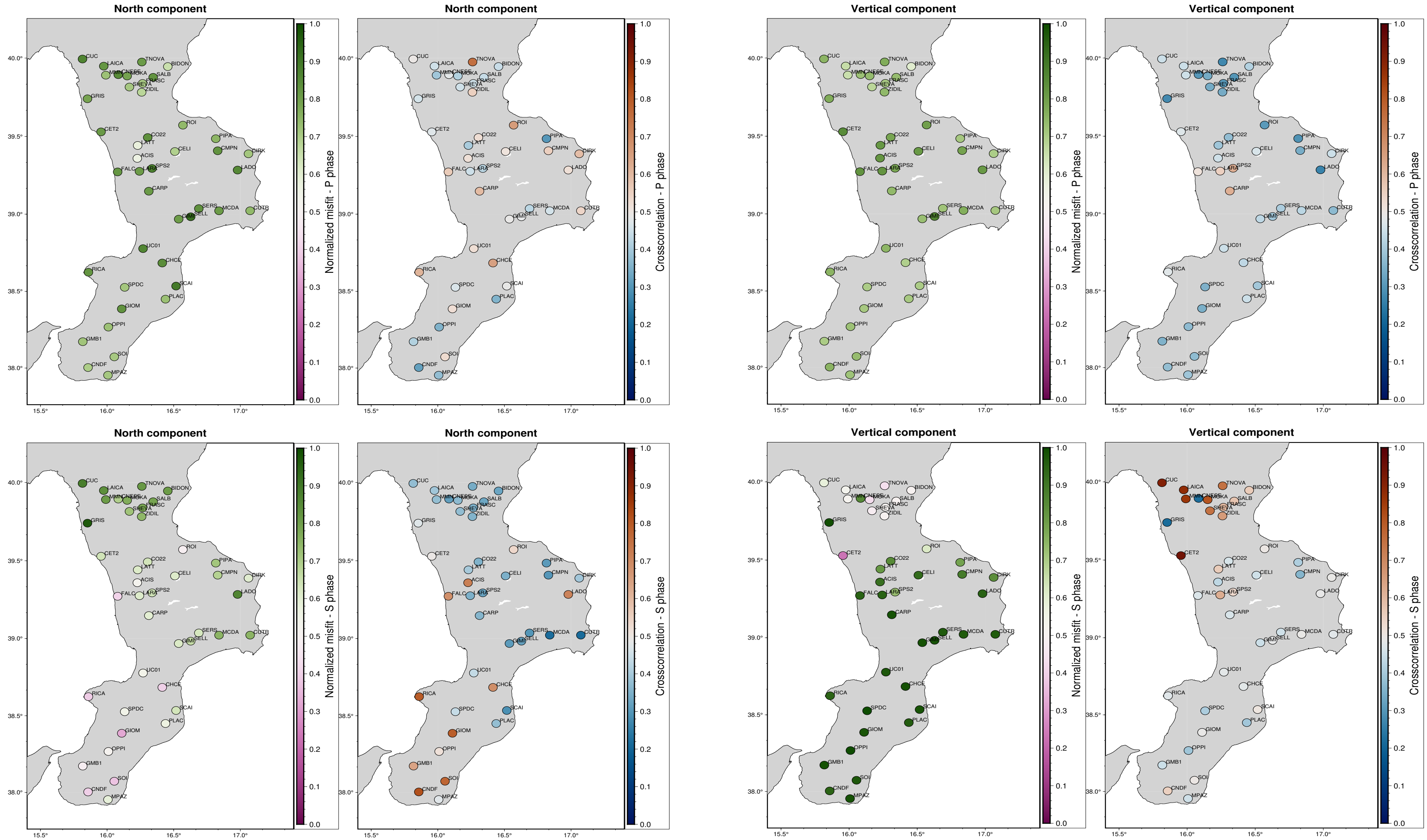
$$\chi(m) = \frac{1}{2}\sum_{i=1}^{N_r} \frac{\sqrt{\int_W [d_i(t) - s_i(t)]^2 dt}}{\sqrt{\int_W d_i(t)^2 dt} + \sqrt{\int_W s_i(t)^2 dt}}$$

Normalized L2 norm

$$\mathcal{NCC}(\tau) = \sum_{i=1}^{N_r} \frac{\int_W [d_i(t)\, s_i(t+\tau)]\, dt}{\sqrt{\int_W d_i(t)^2 dt}\sqrt{\int_W s_i(t)^2 dt}}$$

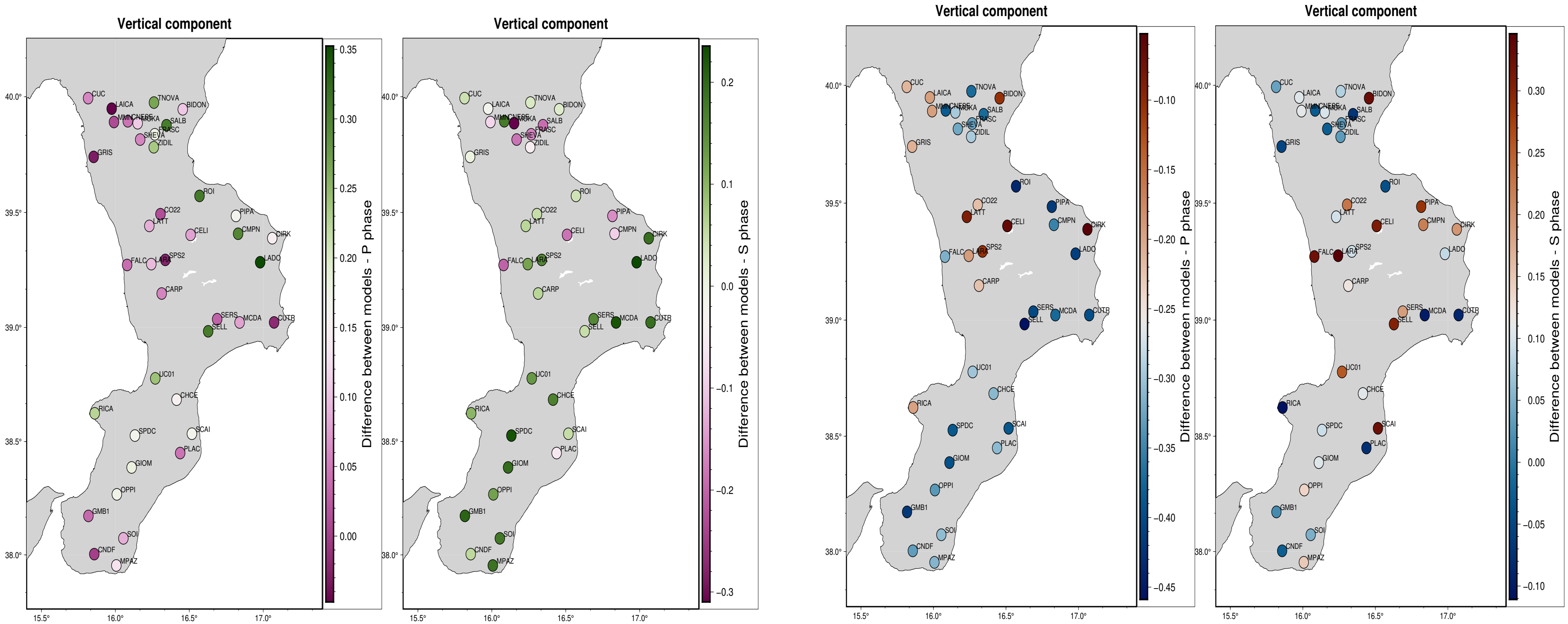
Normalized Cross Correlation

Misfit metrics computation - **ICLERC** EQ20240329 [0.07 - 0.12 / 0.012 - 0.03] Hz [40 / 40] s.



- **Widening the time window for metric computation improves both L2 norm and cross-correlation performance.**

Misfit metrics computation – **ICLERC** vs 1D model EQ20240329 [0.07 - 0.22 / 0.02 - 0.10] Hz [30 / 35] s.



- **NCC gives better results between the two metrics, by looking at Z component synthetics.**
- **This was confirmed by looking at polarity and shape for the P wave arrivals.**
- **Towards Vibo Valentia and the Aspromonte region the L2 differences increase with encouraging results.**

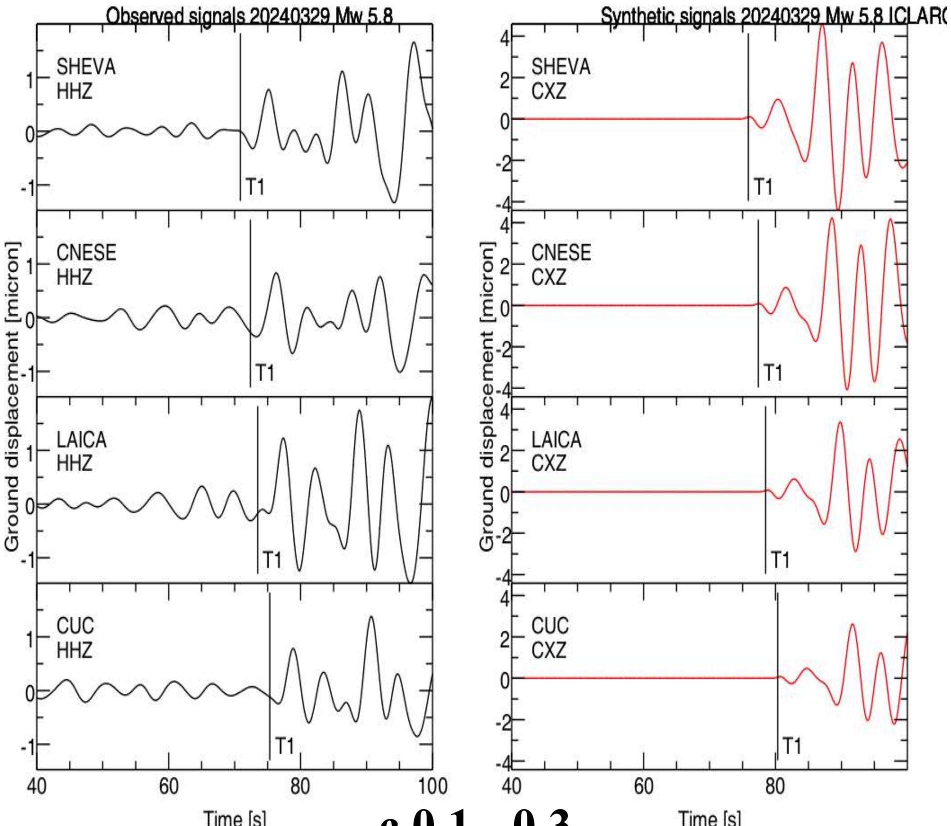
Goal

$\delta\chi < 0$

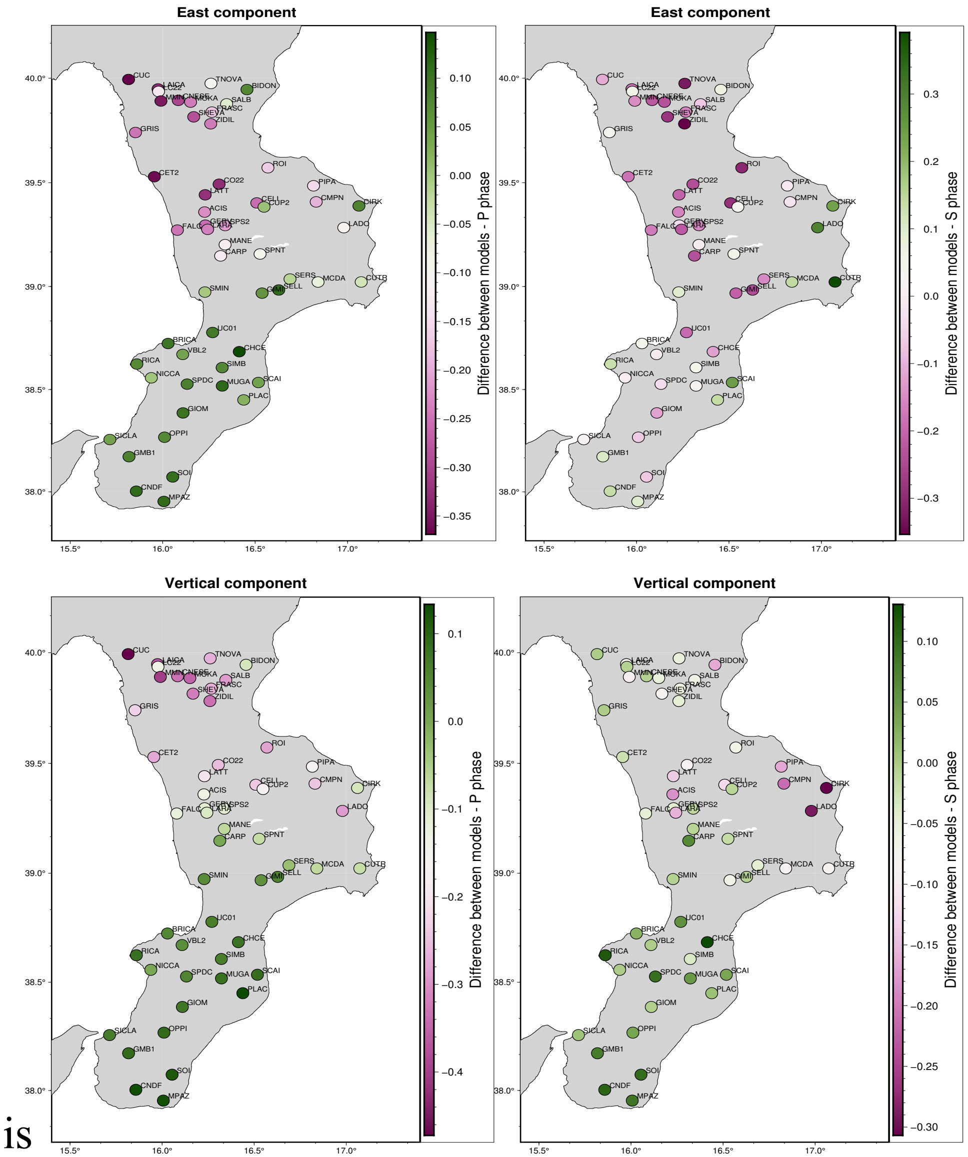
$\delta\mathcal{NCC} > 0.$

Misfit metrics computation – EQ20240329 [0.07 - 0.22 / 0.02 - 0.10] Hz [30 / 35] s.

Changing the STF type to a Dirac delta one improves significantly the results.



c 0.1 - 0.3



Phase arrival times are consistent between synthetic and observed signals.
However the frequency content of synthetic signals is narrower than observed recordings.

Preliminary conclusions and final remarks.

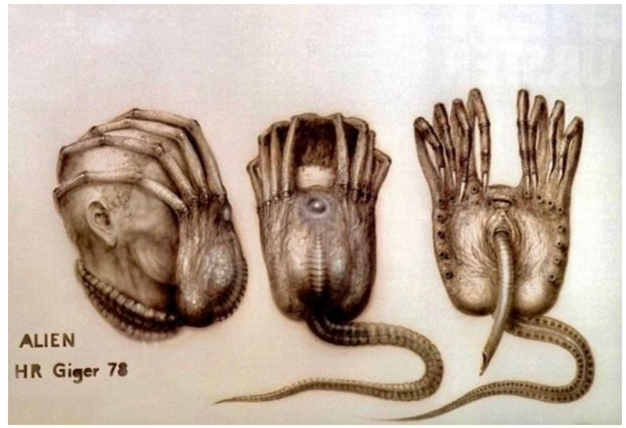
- **Most synthetics show a satisfactory agreement about wave polarity and amplitude compared to real data.**

- **Undesired phases reflected at mesh boundaries are attenuated but not completely removed by the shell layer.**

- **Used misfit metrics confirm that preliminary 3D model (ICLARC/ICLERC) is better than the triple layer model.**
- **Achieving precise 3D model of the Ionian basin requires a lot more observations, possibly even at the Sea bottom, likely feasible in future decades.**

Overall, this is still a first small step towards a more refined knowledge of the area.

The uncertainties are many, but that's up to future researchers to deal it with. (https://github.com/ionianbasin/)



I acknowledge Newton cluster, and the super-computing facility of the University of Calabria (Cosenza), *Mecenate* at Sismolab and the Seismology group for hosting me at the University of Münster.

Thank you for your attention.