# Towards a regionalized spectral model for Italy

## - a source-attenuation tale -

D. Bindi (GFZ),
D. Spallarossa (Uni-Genova), M. Picozzi (OGS), A. Oth (ECGS),
K. Mayeda (AFTAC), G. Tarchini (Uni-Genova), S. Parolai (Uni-Trieste),
P. Morasca (INGV), G. Lanzano (INGV), S. Sgobba (INGV), F. Pacor (INGV), ...

# Outline

- Perform spectral decomposition (GIT) to interpret partially- or fully-NE residuals:

  Example 1 – $\Delta\sigma$ .vs. $\delta B_e$

  Example 2 – $\tau$ .vs. source parameter selection

  Example 3 – $\delta$*P2P* .vs. spatial distribution of Q-residuals

- Not a single GIT solution:
  - the GIT design matrix is not full rank: non-uniqueness of the solution
  - data geometry and correlation
  - impact of model assumptions (SCEC $\Delta\sigma$-benchmark)

- GIT for central and southern Italy using regional attenuation models

- A 2D grid approach to GIT:

  Example 1 – Depth distribution of $\Delta\sigma$ for Ridgecrest

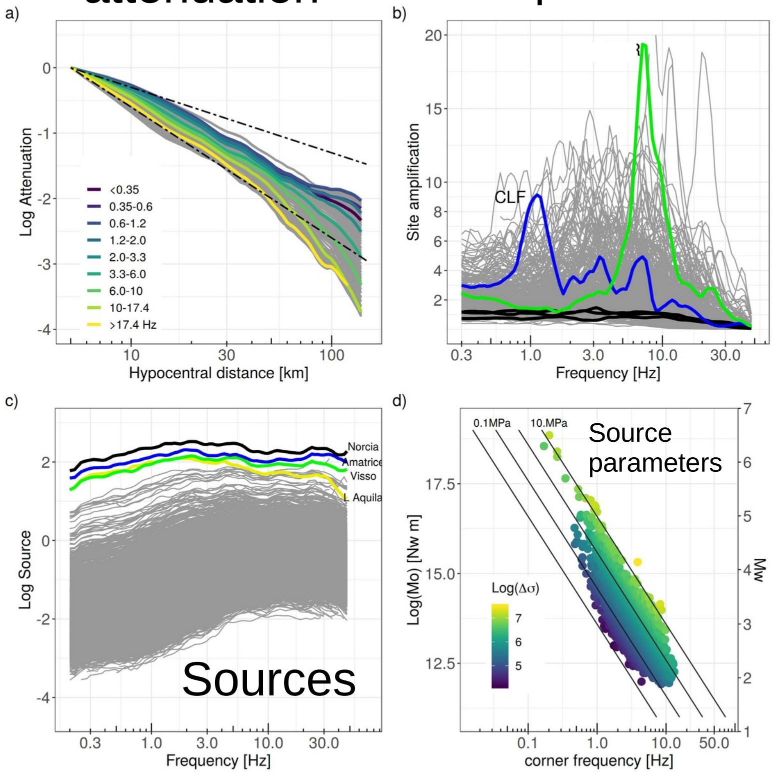
  Example 2 – Ongoing attempts for Italy (ITACAext flatfile)

# Seismological models for source, propagation and site effects GIT approach

**SECURE WP2**

Spectral attenuation

Site amplifications



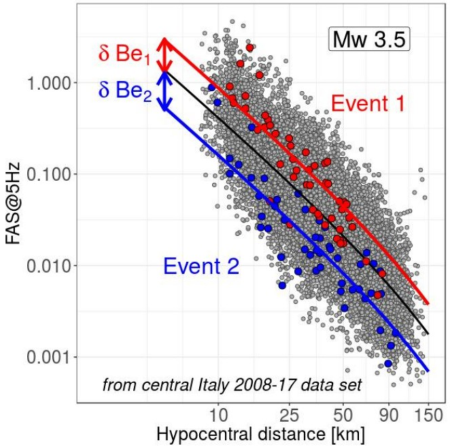

# Ground Motion Prediction Models (median and variability)

**SECURE WP3**

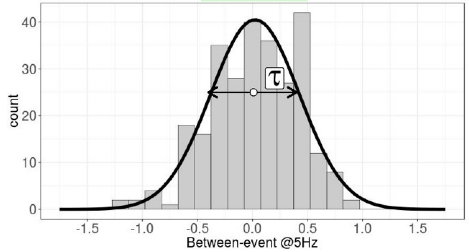
$$Log[FAS(f)] = Scaling(R) + Scaling(M) + \delta S2S + \delta Be + \epsilon$$

Station-term

Event-term




$$\sigma^2 = \tau^2 + \phi_{S2S}^2 + \phi_0^2$$



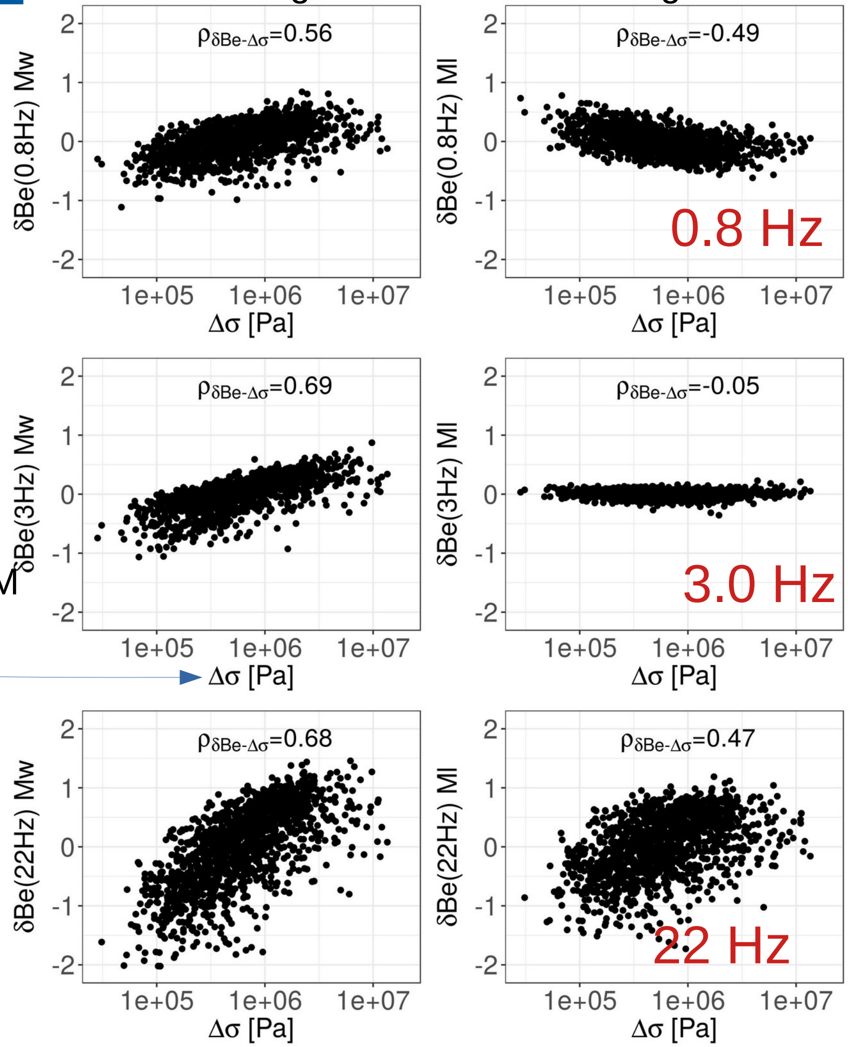

Self-similar median model ($M_0$ controlled)

→ *GIT - GMPM residuals* comparison

GFZ Helmholtz Centre for Geosciences

# Example 1

Moment magnitude  Local magnitude



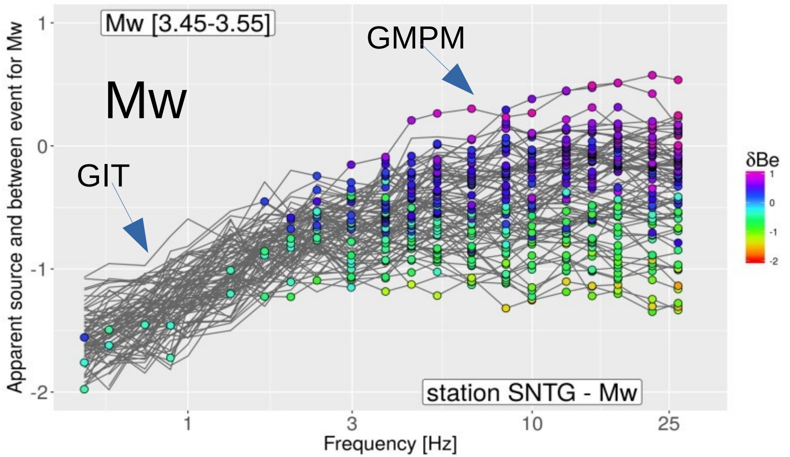

GMPM

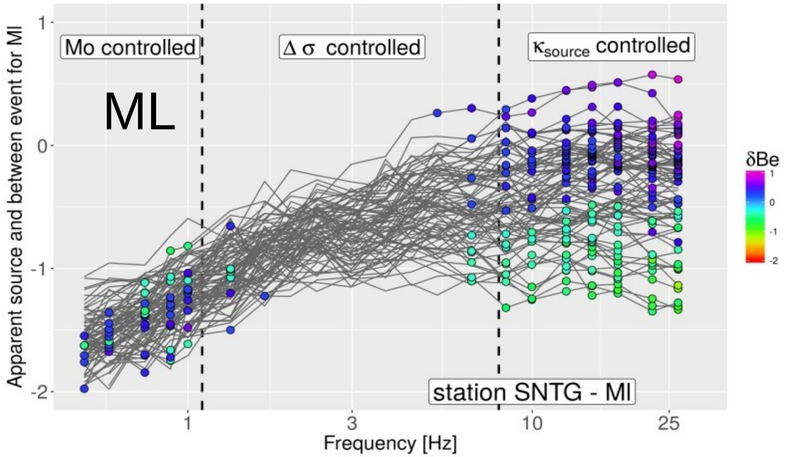
GIT

## Apparent source spectra

(i.e., recorded spectra corrected for attenuation and site effects)

Circles correspond to $|\delta B_e|>0.2$

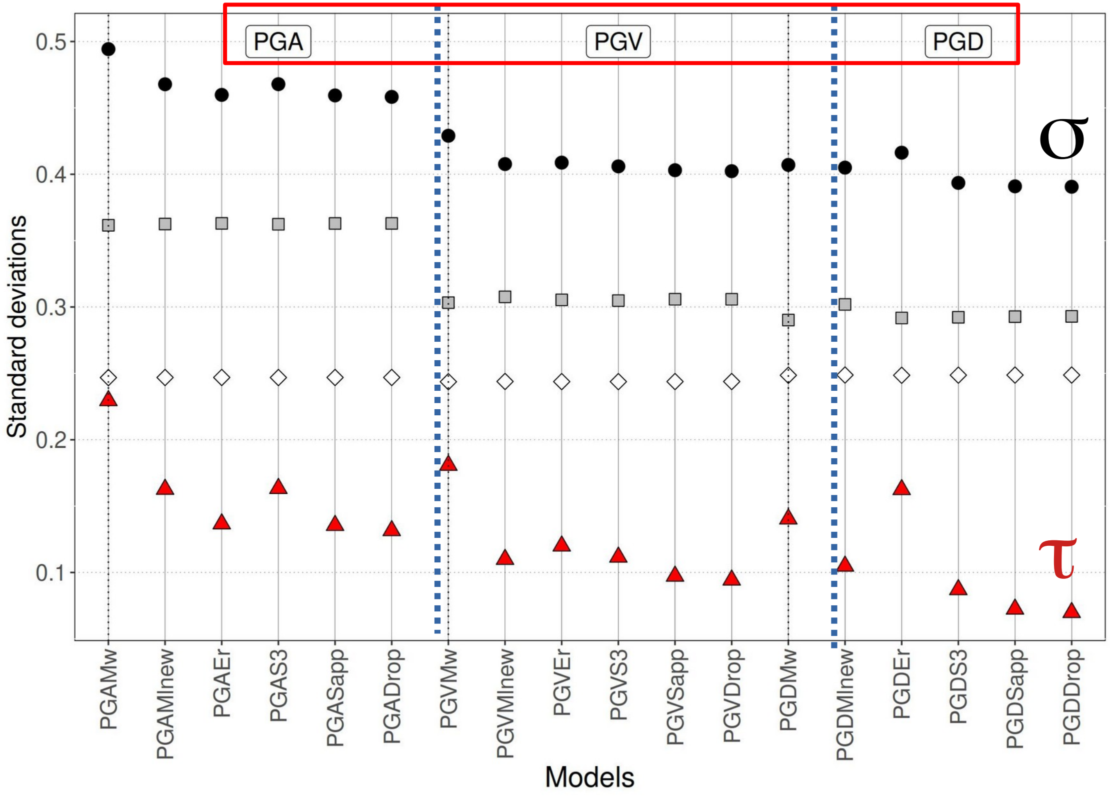


# Example 2

*Partially non-ergodic GMPM*

$$log(PGx) = c_0 + F_{D1} + F_{D2} + F_M + \boxed{\delta B_e} + \delta S2S + \epsilon$$




Source scaling controlled by different source parameters

$$F_M = b_1(\mathbf{M} - 3)$$

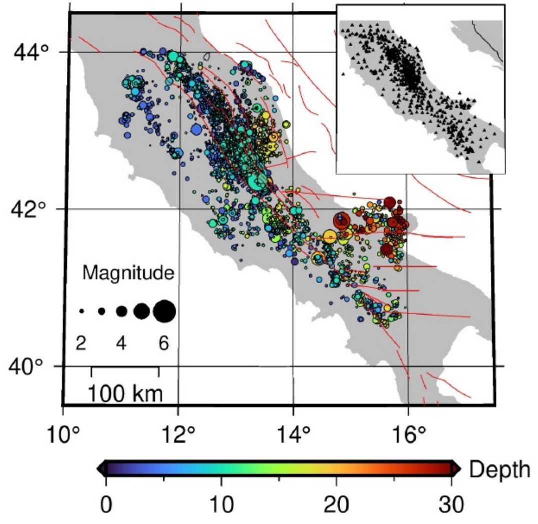
$$F_M = b_2(Ml - 3)$$

$$F_M = b_3(\mathbf{M} - 3) + b_4(log(\Delta\sigma) - \overline{log(\Delta\sigma)})$$

$$F_M = b_5(\mathbf{M} - 3) + b_6(log(\sigma_a) - \overline{log(\sigma_a)})$$

$$F_M = b_7(log(E_r) - 6)$$

$$F_M = b_8(S_3 + 1.5)$$

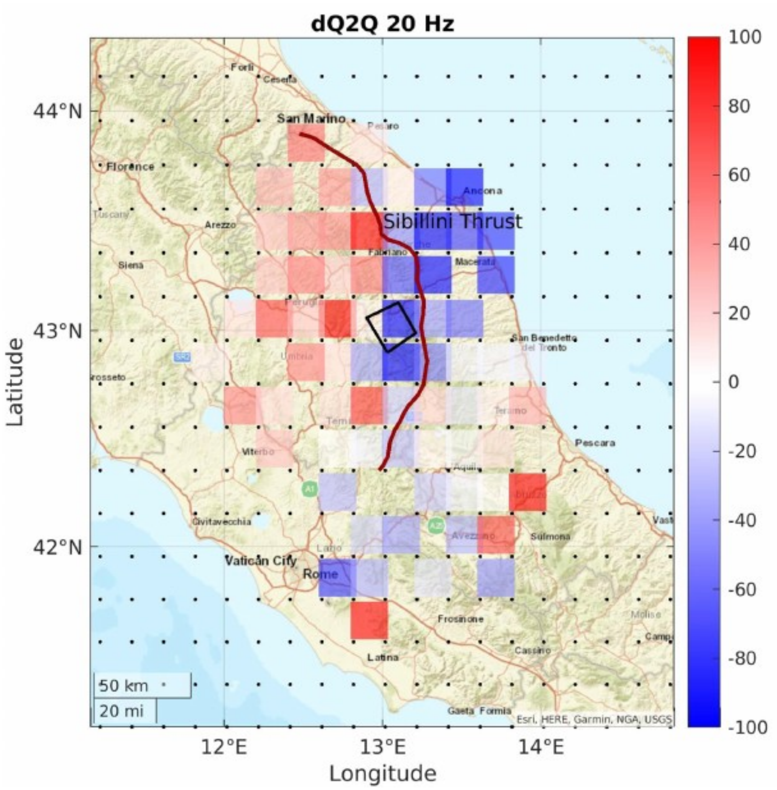



Bindi et al., BSSA, in revision

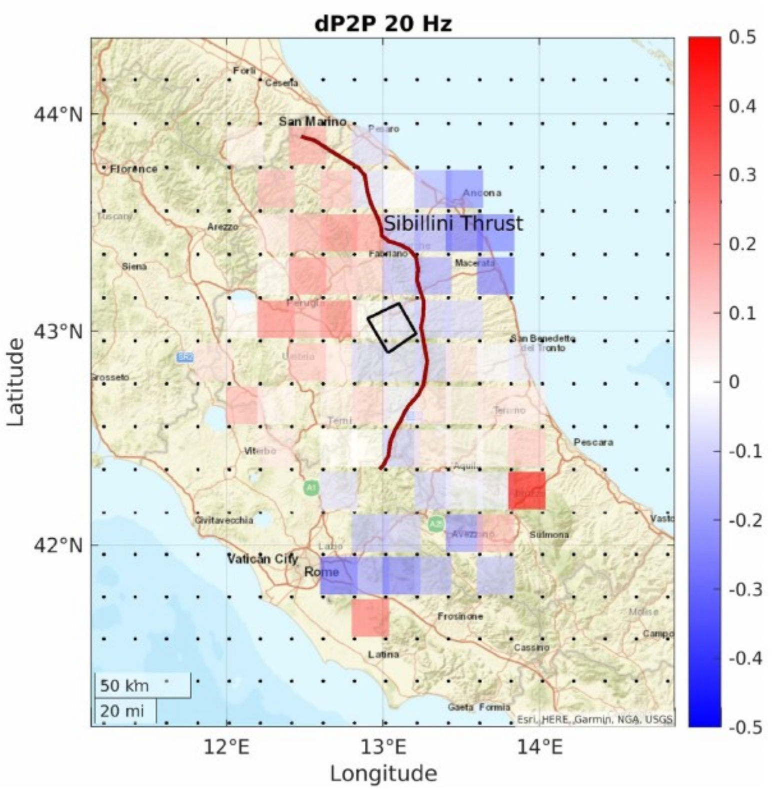
GFZ Helmholtz Centre for Geosciences

# Example 3

Residual δQs map from GIT




Non-ergodic GMM term δP2P



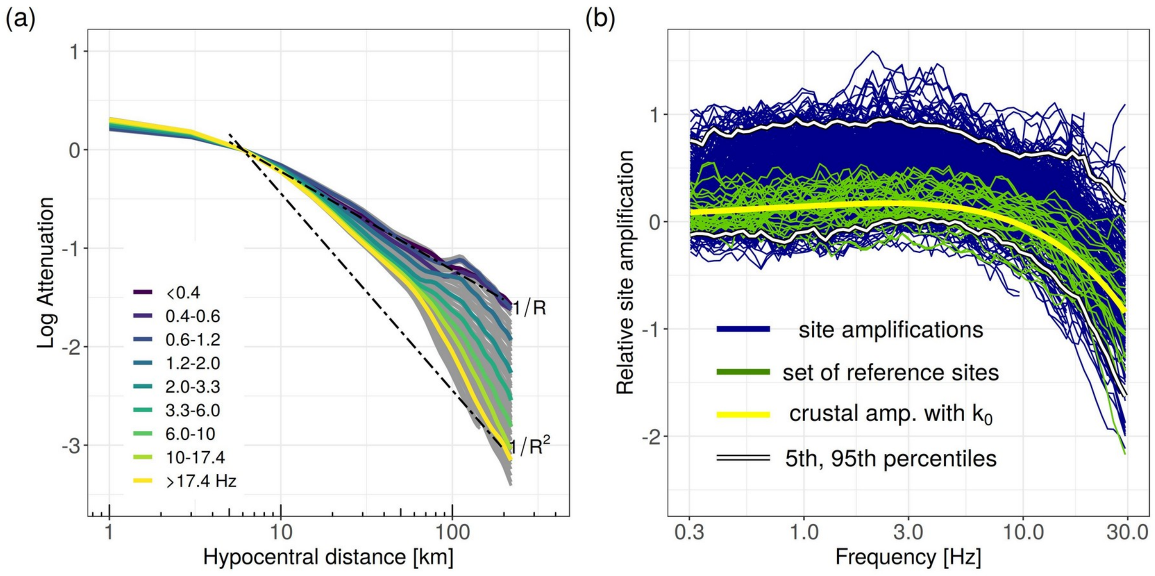

Morasca et al (2022)

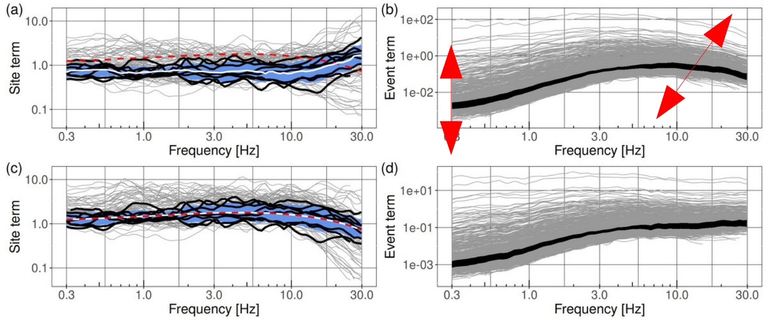
GFZ Helmholtz Centre for Geosciences

# Not a single GIT solution

*waveform(t) = [Source*Propagation*Site] (t)*
*FAS(f) = Source(f)Propagation(f)Site(f)*

1. Matrix of coefficients is not full rank: - by model design, the solution cannot be unique;
- constraints are needed [a-priori assumptions]

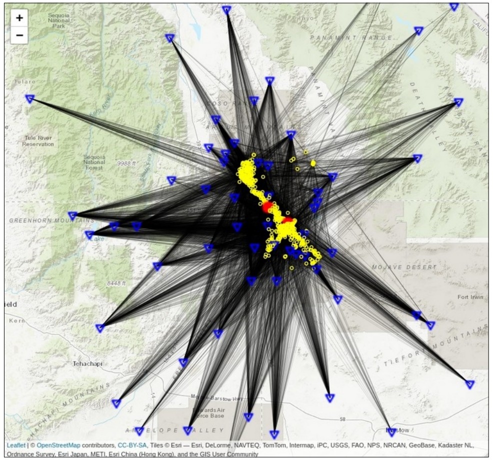


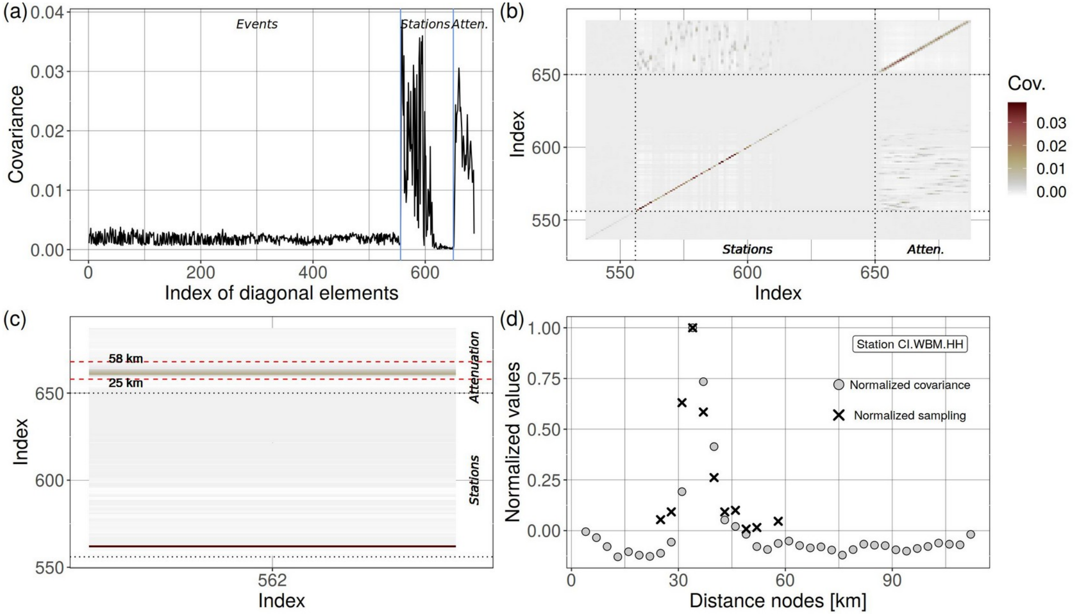



# Not a single GIT solution

| | |
|---|---|
| *waveform(t)* | *= [Source*Propagation*Site] (t)* |
| *FAS(f)* | *= Source(f)Propagation(f)Site(f)* |

1. Matrix of coefficients is not full rank
2. Correlation between different terms: - depends on the geometry (events and station selection)





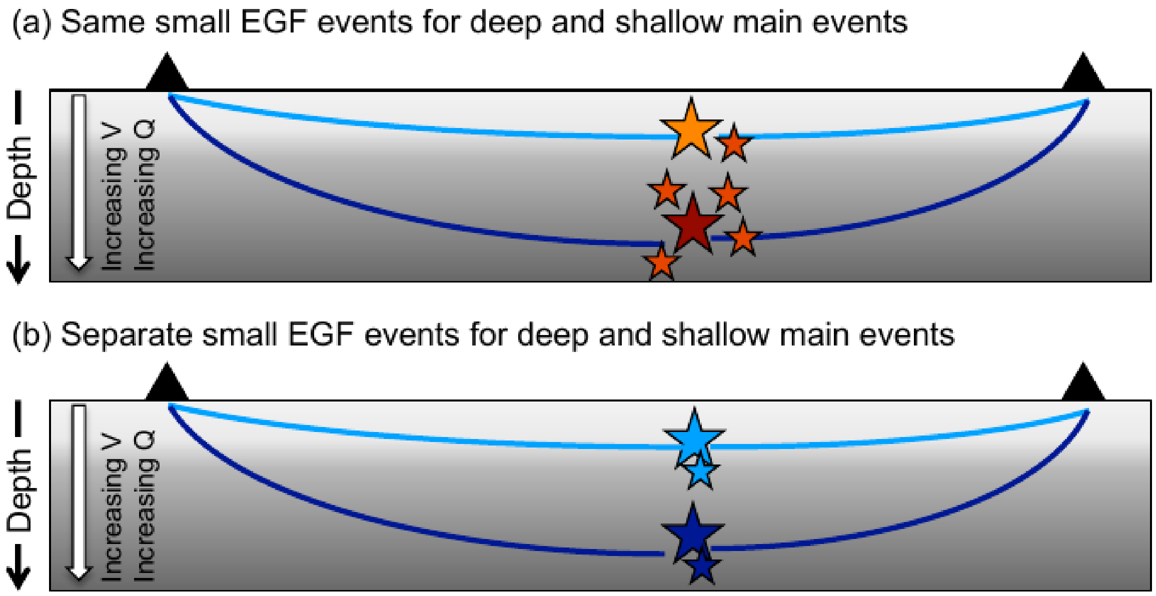

Bindi et al (2023a,b) SRL

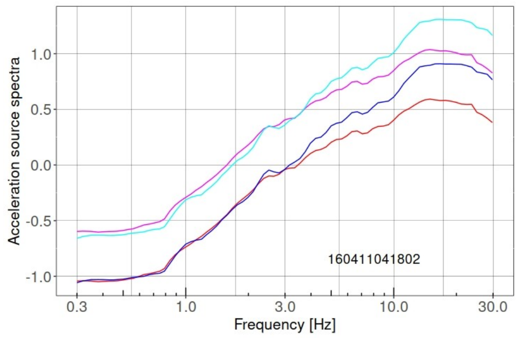
GFZ Helmholtz Centre for Geosciences

# Not a single GIT solution

*waveform(t) = [Source*Propagation*Site] (t)*
*FAS(f) = Source(f)Propagation(f)Site(f)*

1. Matrix of coefficients is not full rank
2. Correlation between different terms
3. Model assumptions on attenuation : depth-dependent attenuation and source trade-off

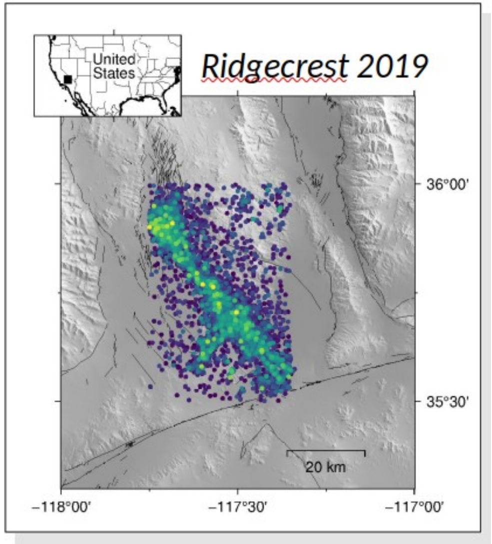


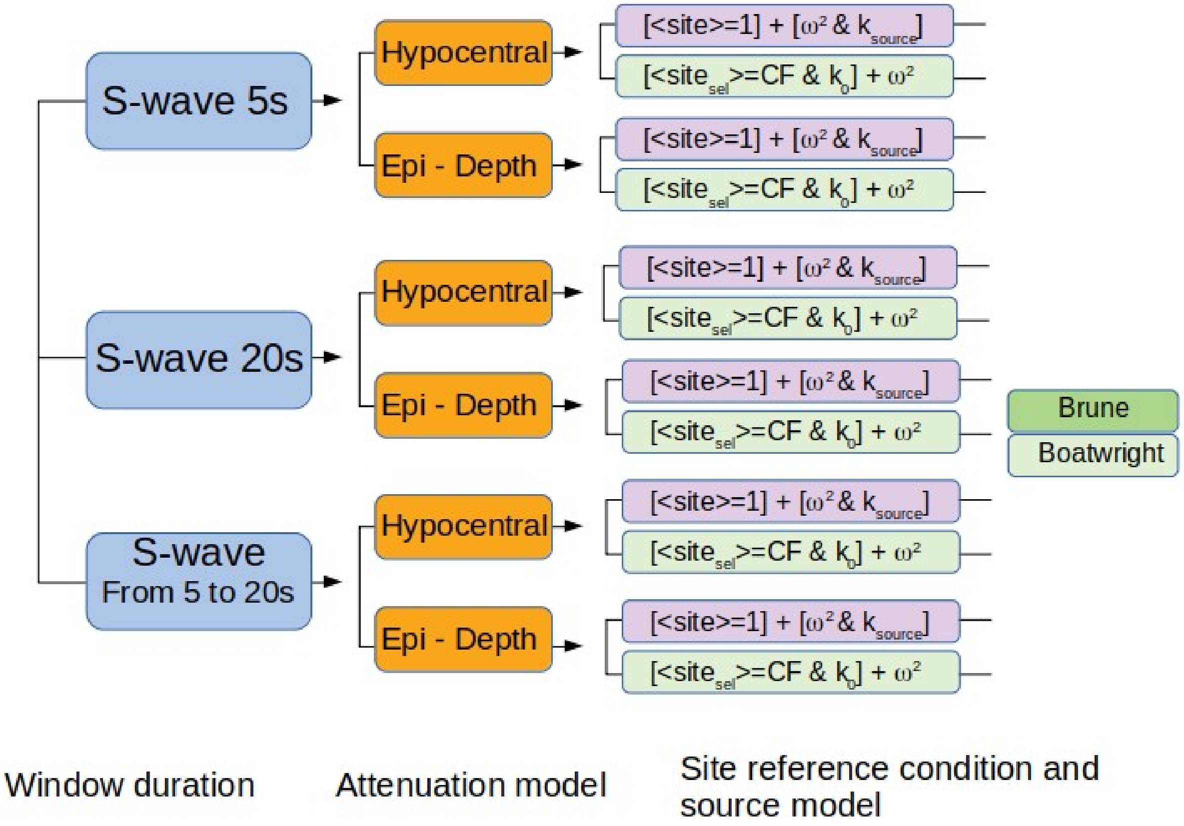

Abercrombie et al. (2021, JGR)

GFZ Helmholtz Centre for Geosciences

# Ridgecrest Benchmark

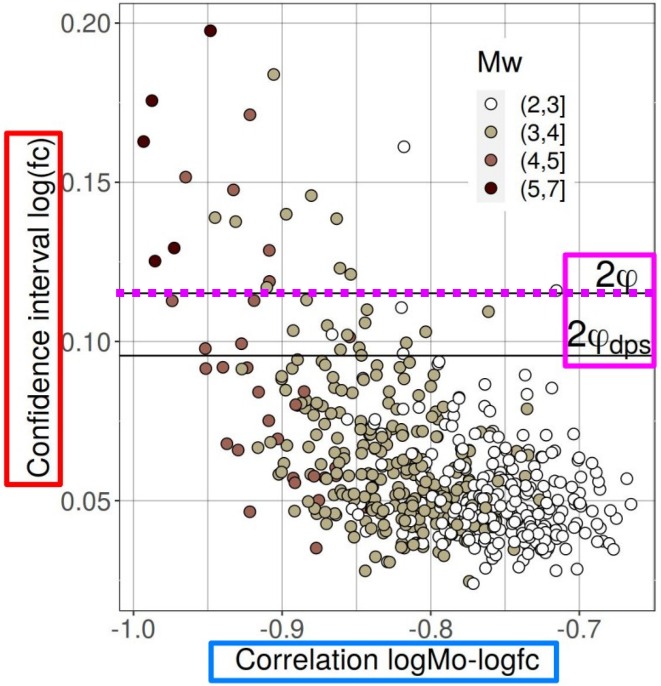



**Benchmark data set**
[from Trugman, 2020]




Bindi et al (2023a,b) SRL

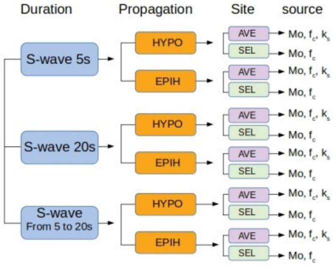
# Ridgecrest benchmark




## Mixed-effects regression

$$\phi_{\mathrm{dps}} = \sqrt{\phi^2_{\mathrm{duration}} + \phi^2_{\mathrm{propagation}} + \phi^2_{\mathrm{site}}},$$

$$\phi = \sqrt{\phi^2_{\mathrm{dps}} + \phi^2_0},$$

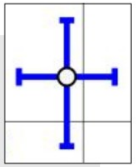



Within-event variability
"epistemic" uncertainty

## Confidence intervals

```
> sigma(model)
[1] 0.04231737
> vcov(model)
              LMo            fc
LMo  0.0000486878 -0.0007384827
fc  -0.0007384827  0.0228986235
```

Covariance matrix



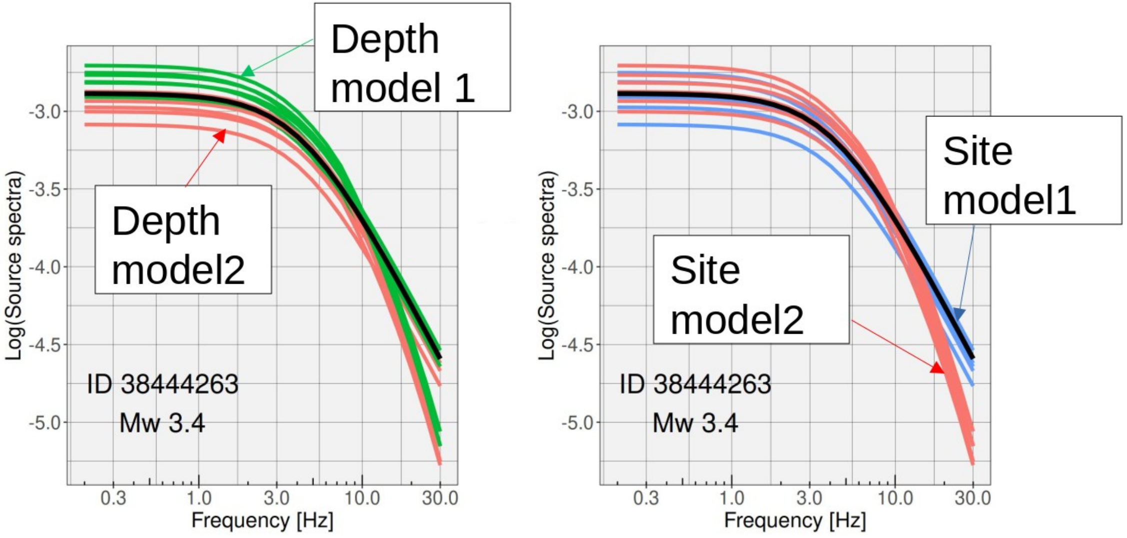
"aleatory" uncertainty

"Epistemic" (model) uncertainty larger than aleatory (statistical) one for most of the earthquakes

Bindi et al (2023a,b) SRL

# Ridgecrest benchmark

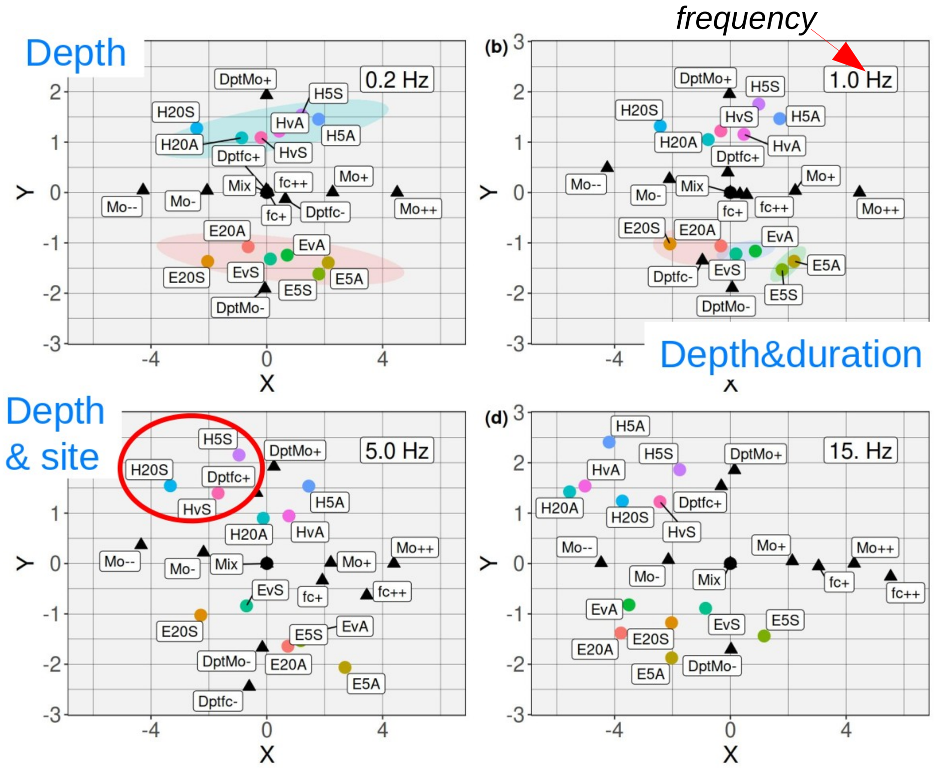
*Source spectra of one specific event for the 12 logic-tree branches, color-coded with different model assumptions*




Low-frequencies

High-frequencies

*Sammon's maps for the 12 logic-tree branches and different frequencies*

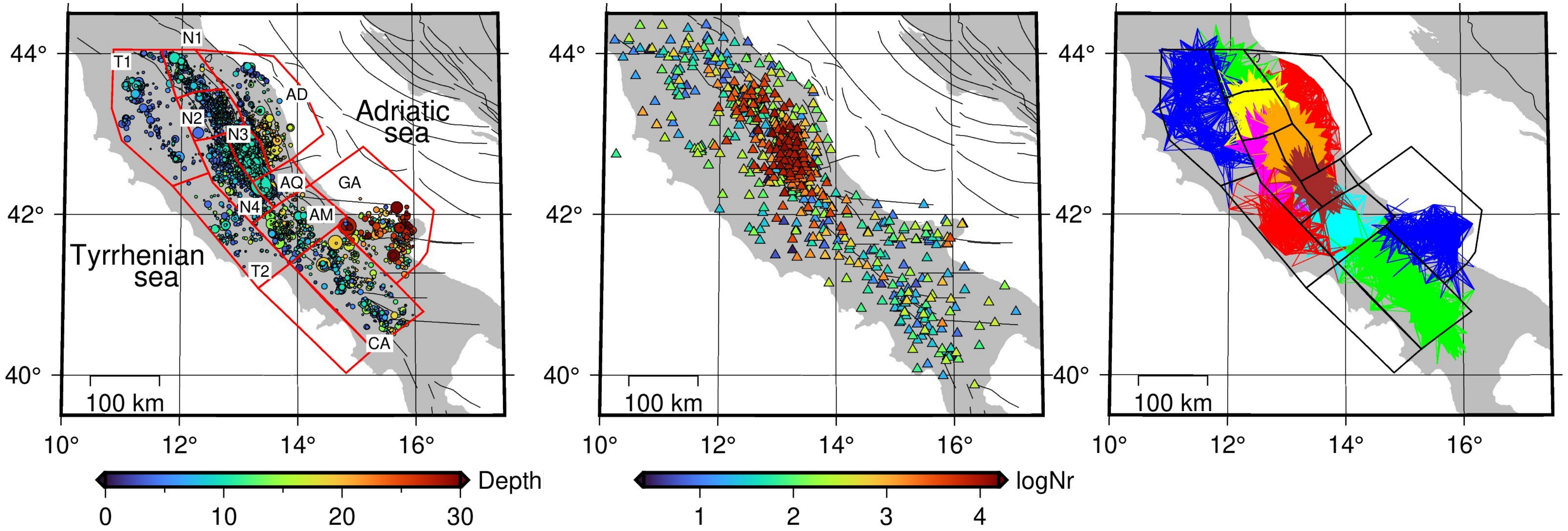



## Different model assumptions control the source variability over different frequency bands

Bindi et al (2023a,b) SRL

GFZ Helmholtz Centre for Geosciences

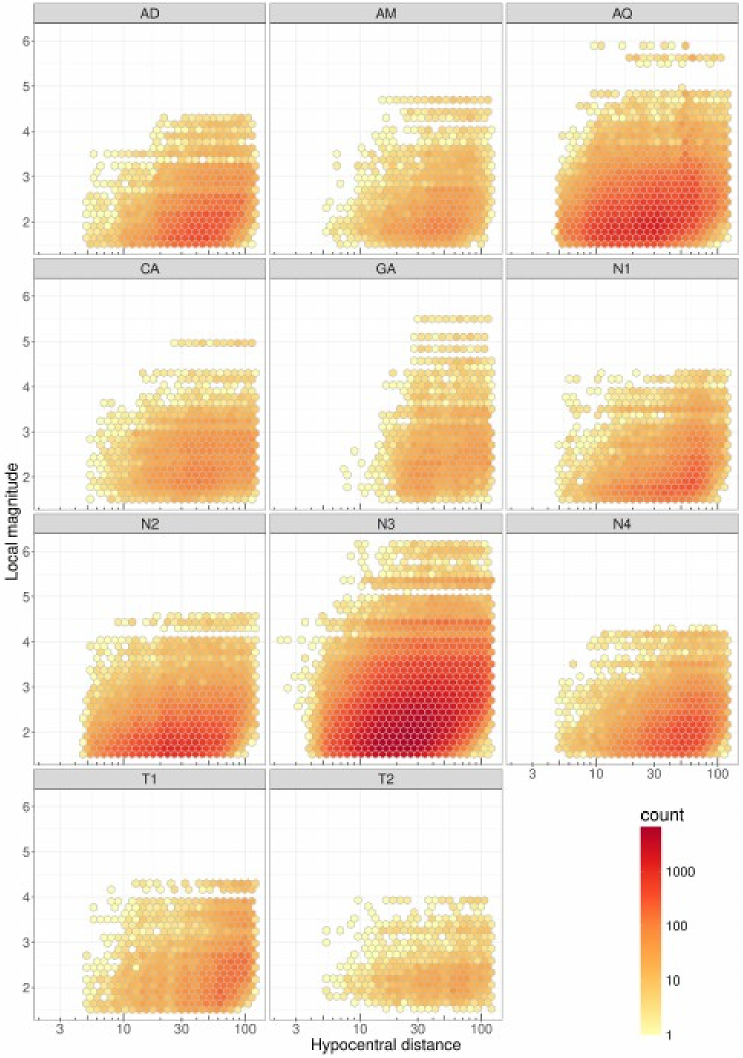
# GIT spectral model for Central-Southern Italy




28943 earthquakes, ~1000 sensors, 901,228 amplitudes at 3 Hz

Bindi et al (2024) BSSA

GFZ Helmholtz Centre for Geosciences



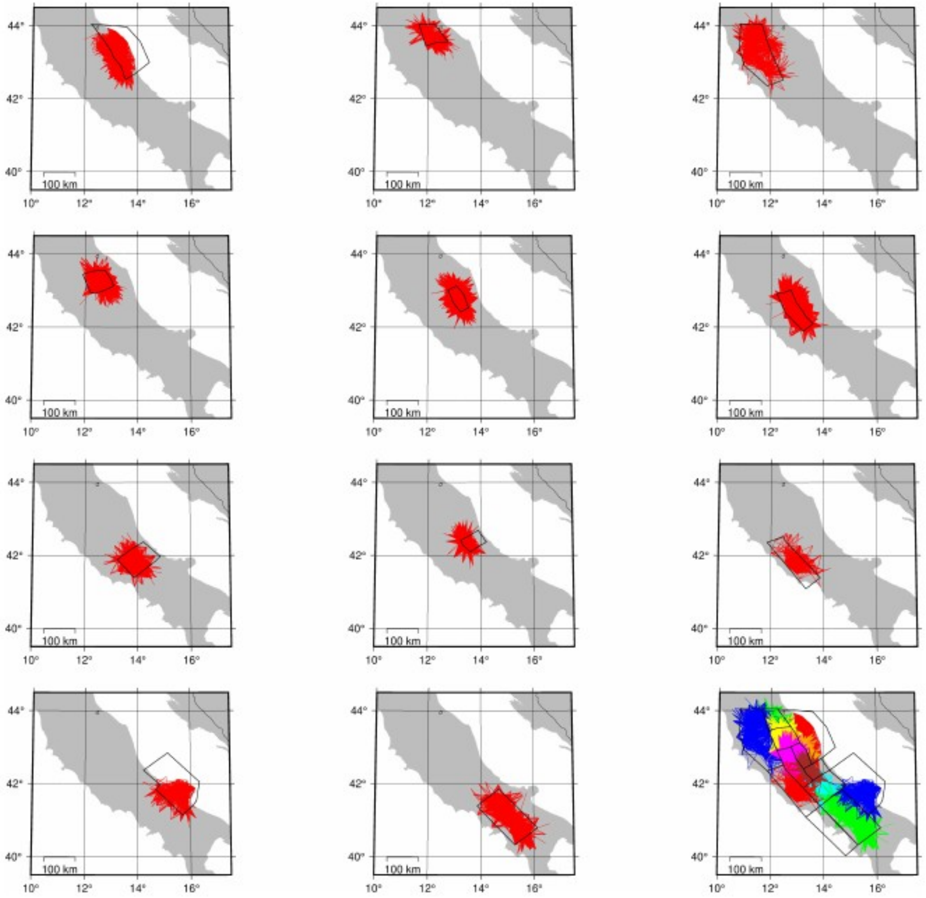
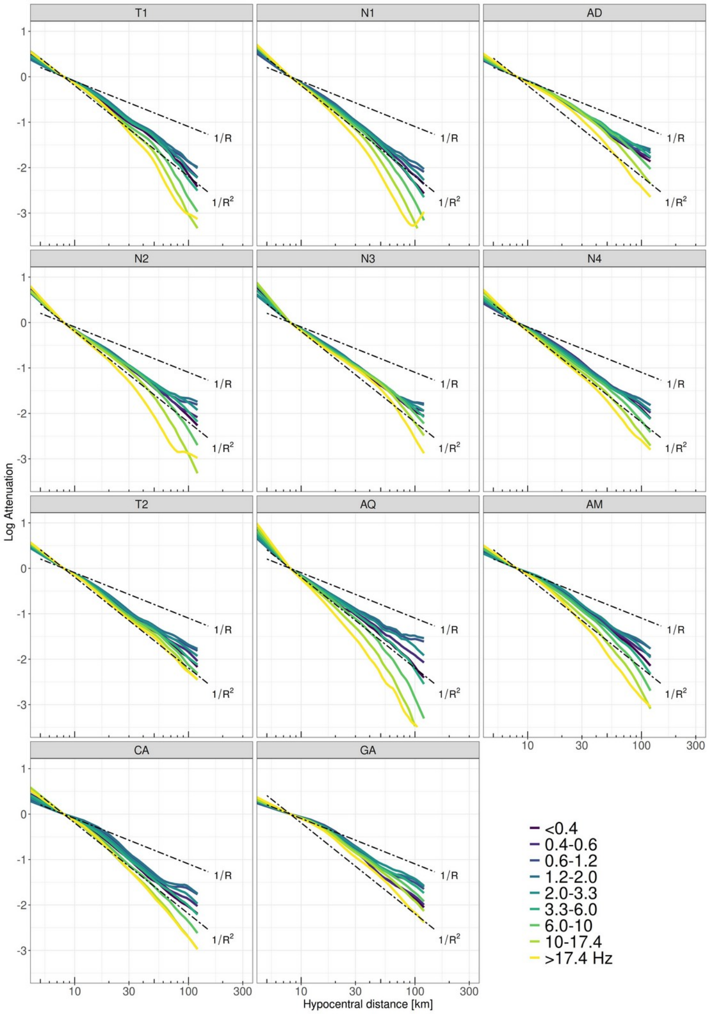
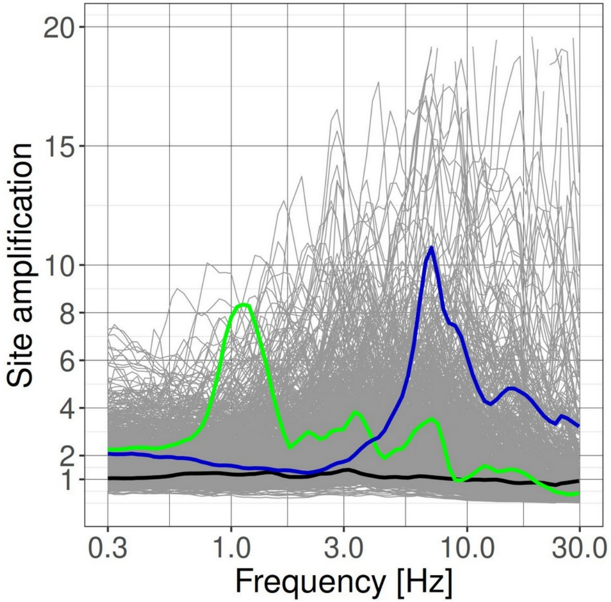
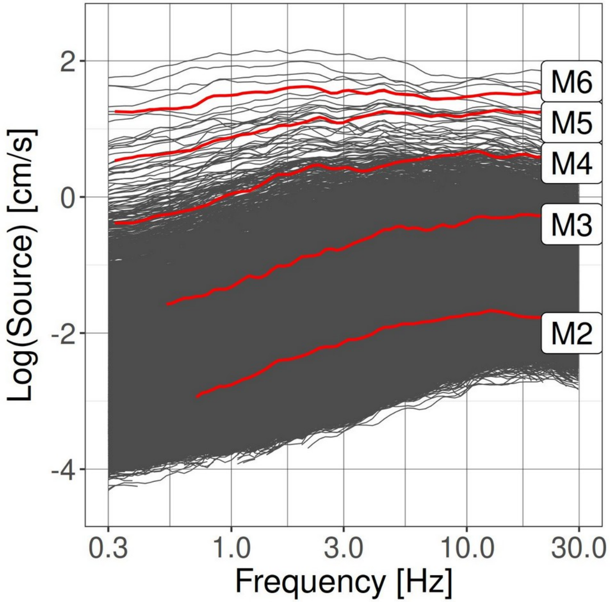




Figure S8: Source to station path coverage for each polygon of Figure 1, used to separate the source and site terms (the maximum hypocentral distance is limited to 60 km).

# Central-Southern Italy: regional attenuation models



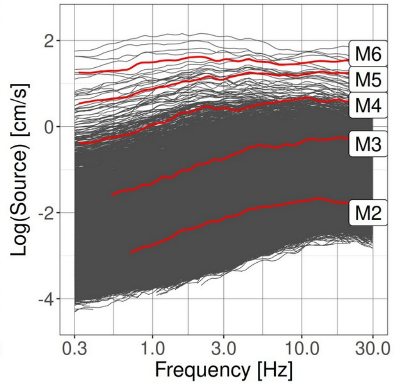



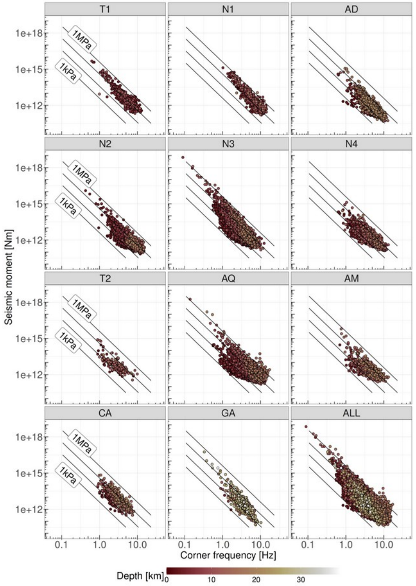




Bindi et al (2024) BSSA

GFZ Helmholtz Centre for Geosciences

# Source parameters




$$S(f) = \frac{\Omega^0}{[1 + (f/f_c)^2]},$$

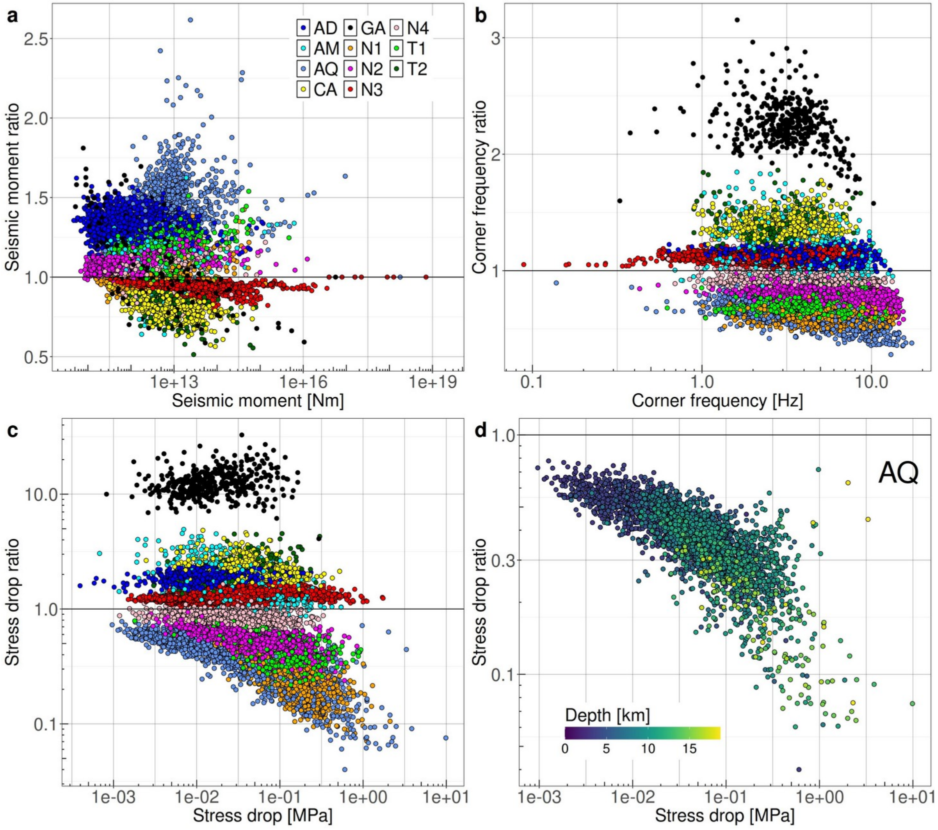
$$\Omega^0 = \frac{R^{\theta\phi} F V}{4\pi\rho\beta^3} \frac{M_0}{r_{\mathrm{ref}}},$$

$$r = \frac{k\beta}{f_c},$$

$$\Delta\sigma = \frac{7}{16} \frac{M_0}{r^3},$$

requiring that $M_w$ on average matches the INGV catalog in the magnitude range 3–5. By anchoring $M_w$ to the INGV catalog, we remove possible biases introduced either by the average reference site amplification due to the trade-off between source and site terms, and by the values assumed for different constants in equation (3). The second constraint is to fix individual $M_w$ above 5 to the INGV values. This

Ratio no regional/regional attenuation



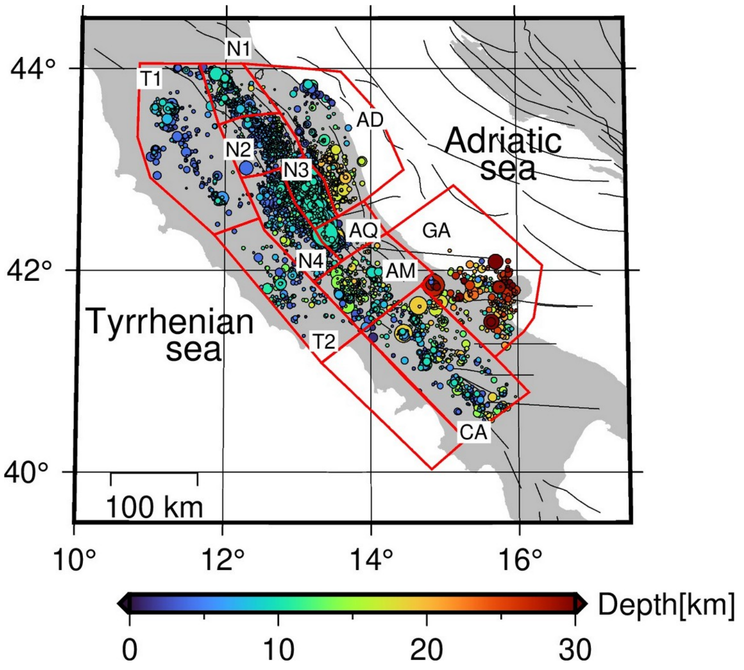

Bindi et al (2024) BSSA

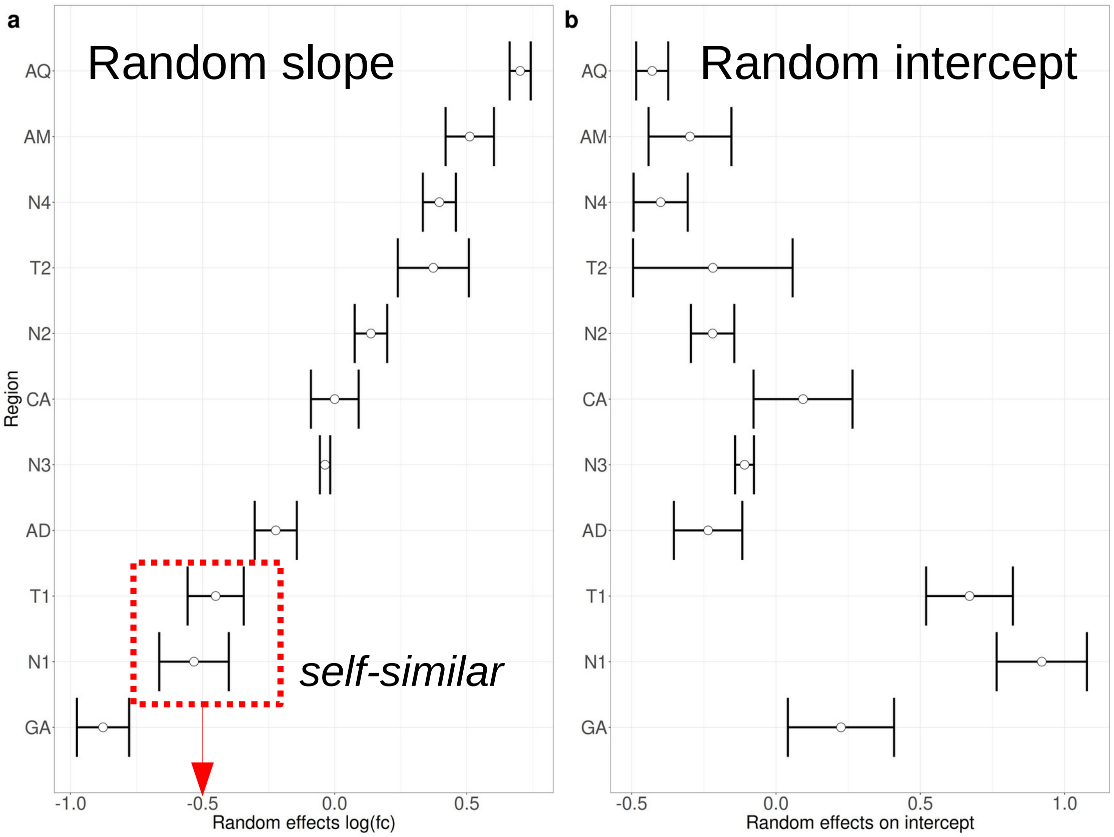
GFZ Helmholtz Centre for Geosciences

# Region-dependent $M_0$-$f_c$ scaling

$$\log(M_0)=a_2+b_2\log(f_c)+\delta a_2^{ROI}+\delta b_2^{ROI}$$

$$a_2 = 13.92 \pm 0.13 \quad \text{and} \quad b_2 = -2.50 \pm 0.14.$$



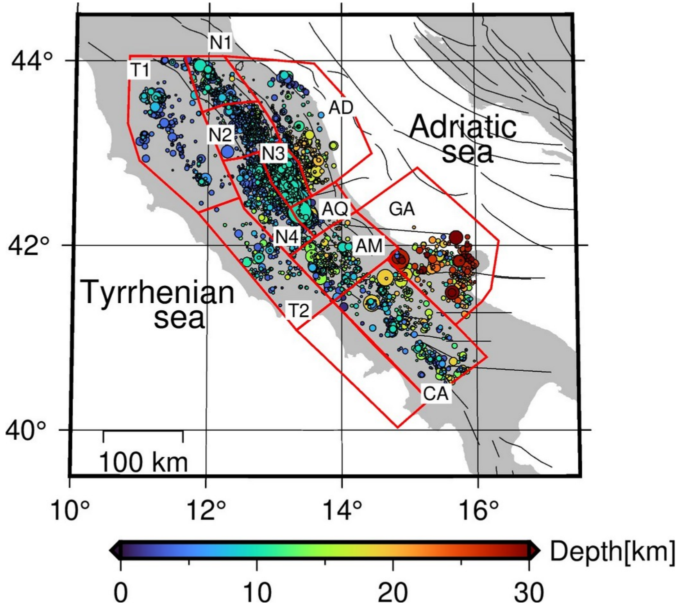



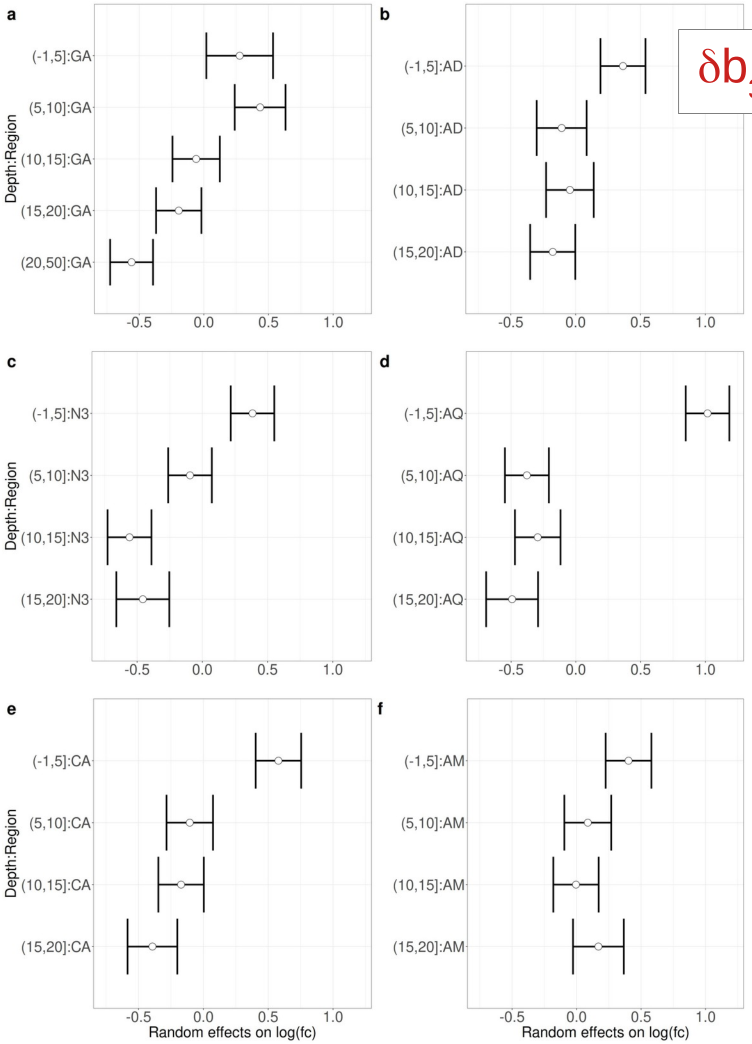

Bindi et al (2024) BSSA

GFZ Helmholtz Centre for Geosciences

# Region and depth dependent Mo-fc scaling

$$\log(M_0)=a_3+ b_3\log(f_c)+ \delta a_3^{ROI/DEPTH} + \delta b_3^{ROI/DEPTH}$$

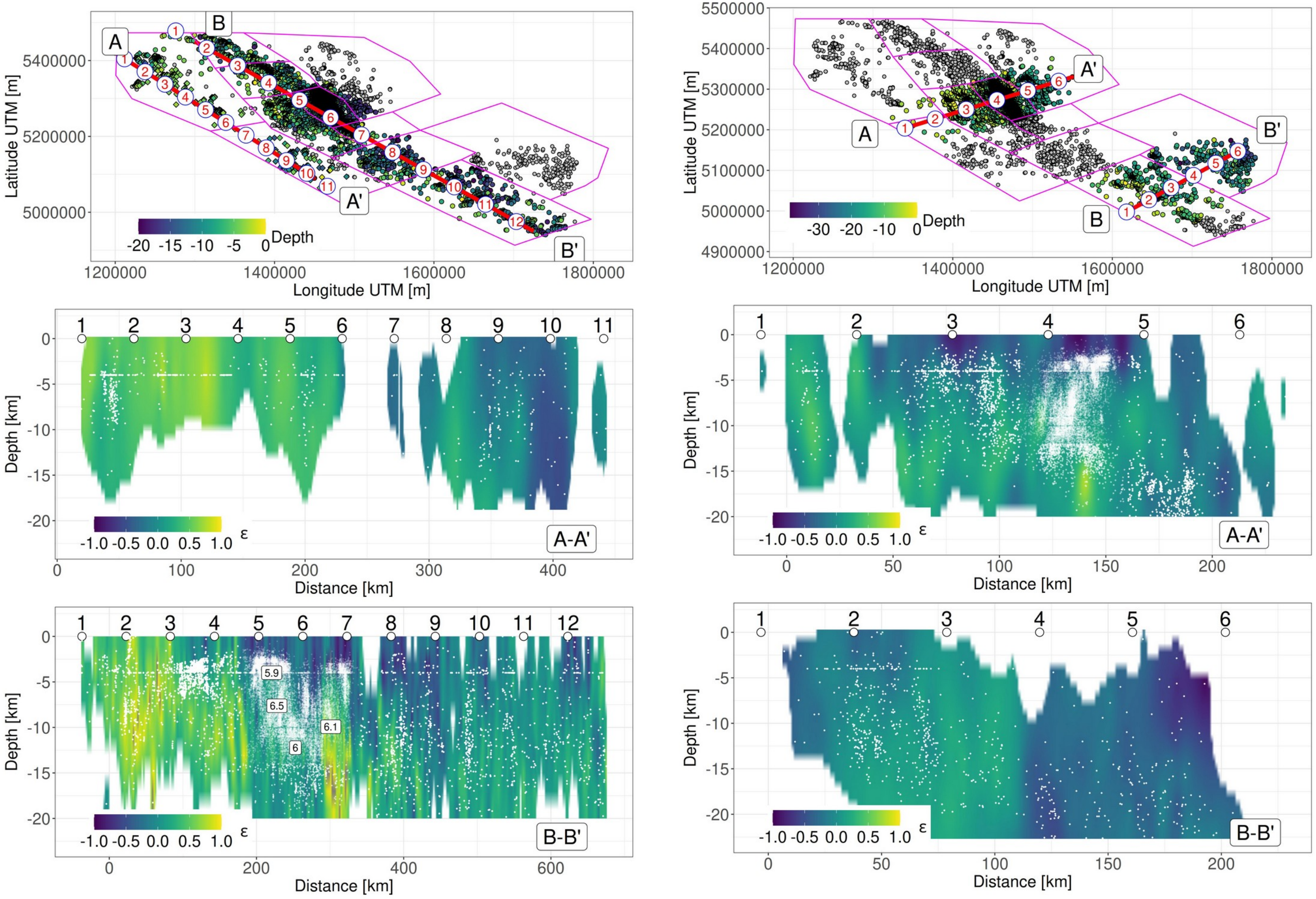



$\delta b_3^{ROI/DEPTH}$

Bindi et al (2024) BSSA

# Stress drop-seismic moment residuals




$$\log(\Delta\sigma)=c_1+c_2\log(M_o)+\varepsilon$$

Scaling and Depth Variability of Source Parameters in Central and Southern Italy Using Regional Attenuation Models


Dino Bindi[*1], Daniele Spallarossa[2], Matteo Picozzi[3], and Gabriele Tarchini[2]


Bindi et al (2024) BSSA

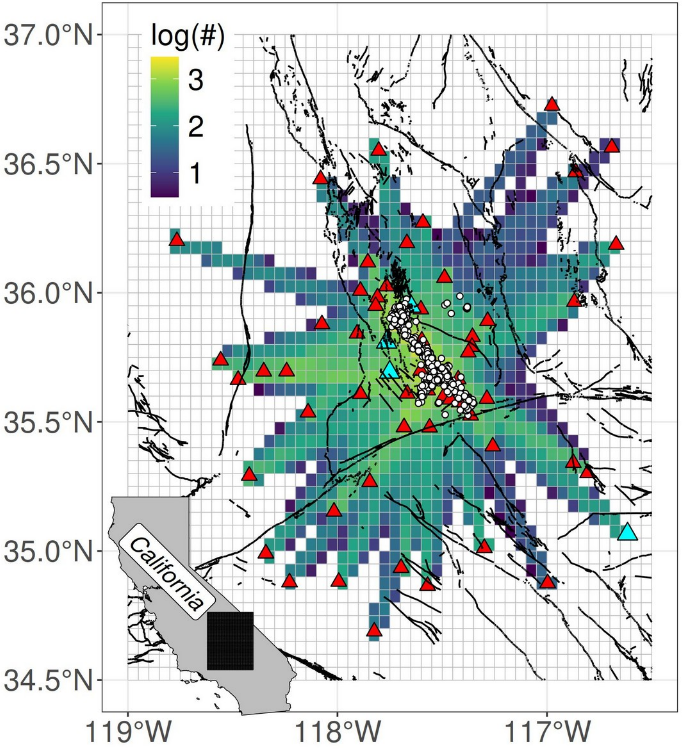
# Ridgecrest – a 2D grid approach for the attenuation

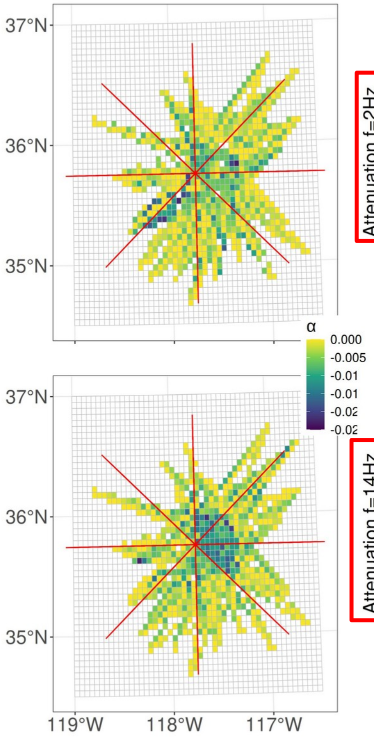

Non-peer reviewed **Research Article** submitted to SEISMICA

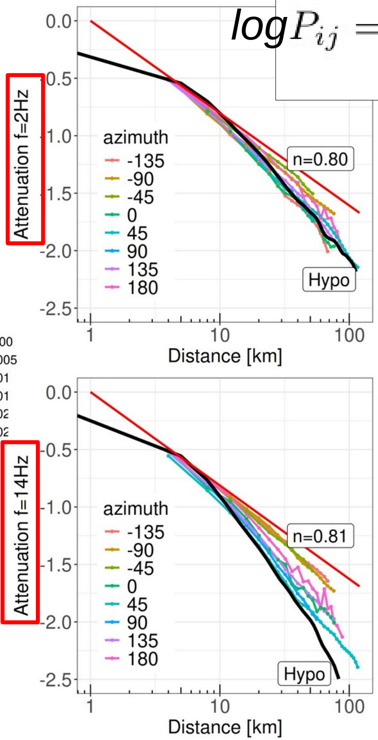
**Impact of Seismic Attenuation Corrections on Source Parameter Estimation**

Dino Bindi * [1], Matteo Picozzi [2], Adrien Oth [3], Daniele Spallarossa [4]

$$log(FAS_{ij}(f)) = logS_i(f) + logP_{ij}(f) + logZ_j(f)$$



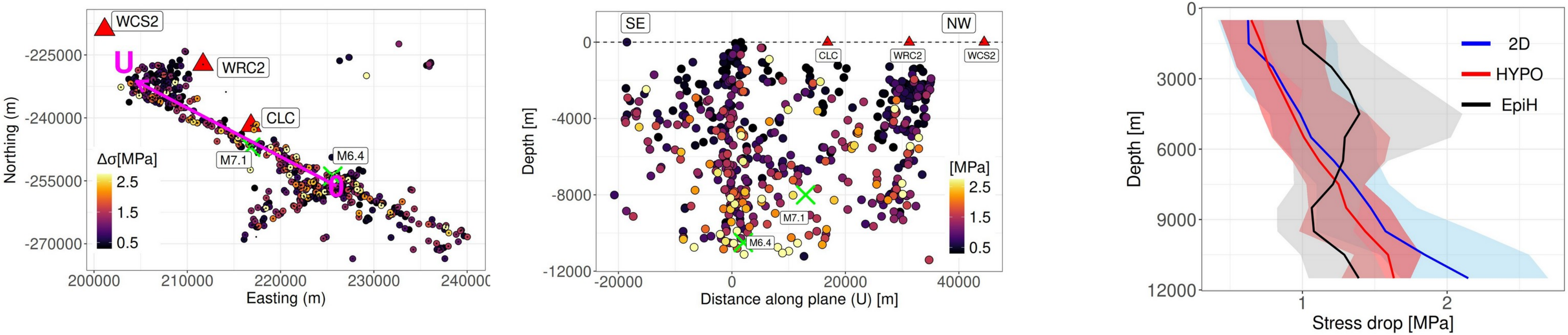



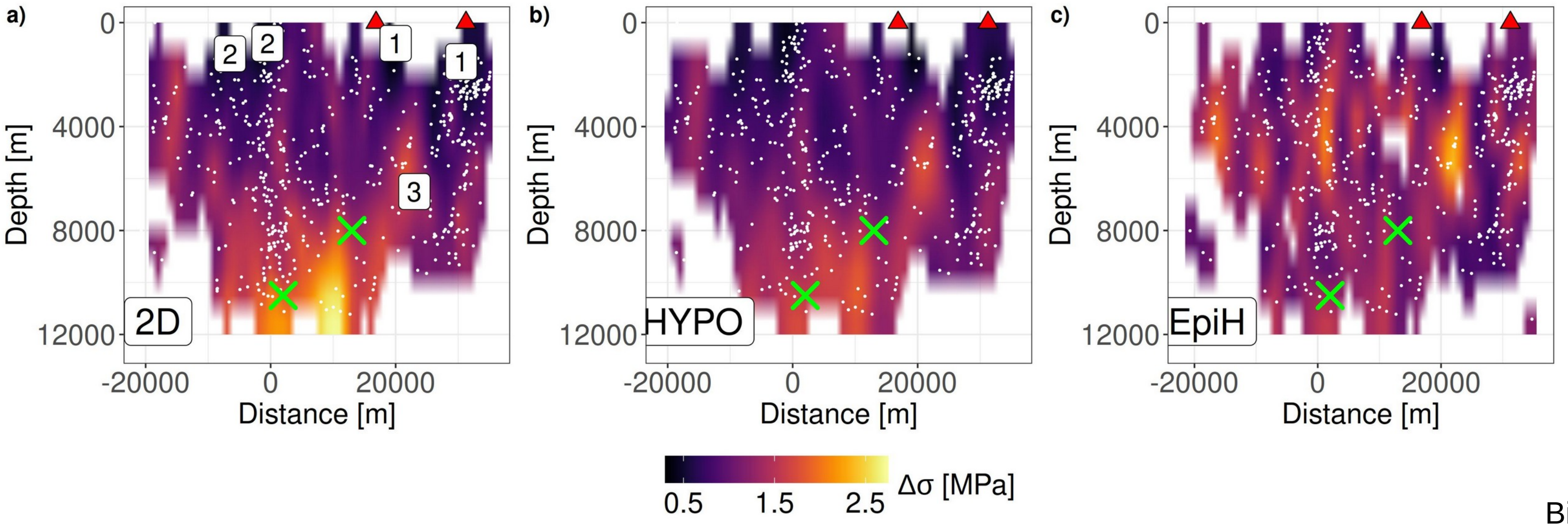

$$logP_{ij} = -n\, log(R_{ij}) + \sum_k \alpha_k\, d_{ijk}$$

Geometrical spreading

Absorption coefficients

Helmholtz Centre for Geosciences

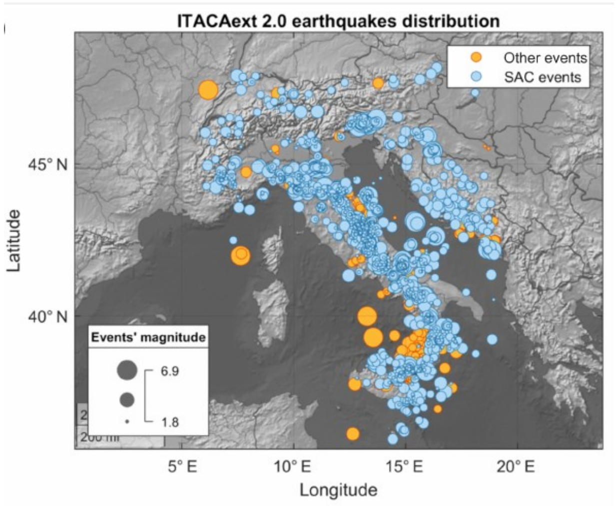


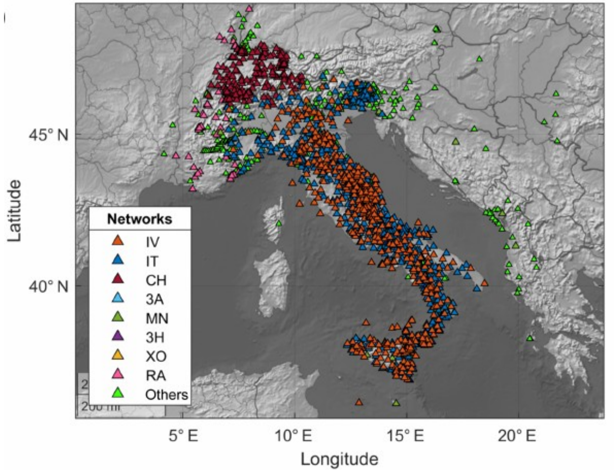



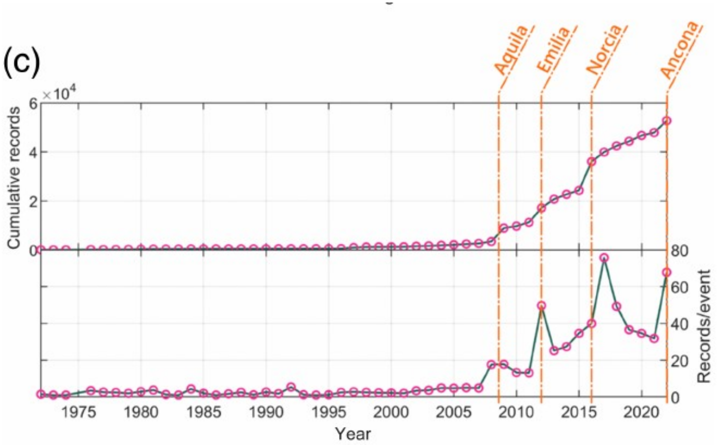

Bindi et al (2025)
in revision

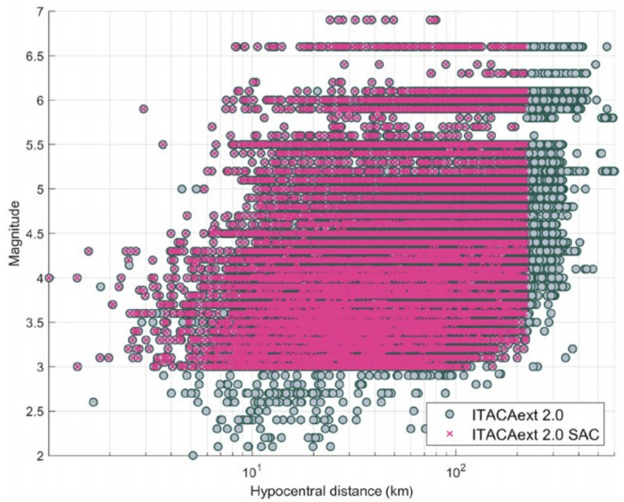
J. Zhang, X. Chen, and R. E. Abercrombie (2022). Spatiotemporal variability of earthquake source parameters at Parkfield, California, and their relationship with the 2004 M6 earthquake. JGR: SE, doi: 10.1029/2021JB022851.

# Ongoing analysis with ITACAext




**ITACAext 2.0: A High-Quality Parametric Table of Strong-to-Weak Motion Recordings for Seismological and Engineering Research in Italy**

Giovanni Lanzano*[1], Lorenzo Vitrano[1], Dino Bindi[2], Chiara Felicetta[1], Sara Sgobba[1], Lucia Luzi[1], and Francesca Pacor[1]

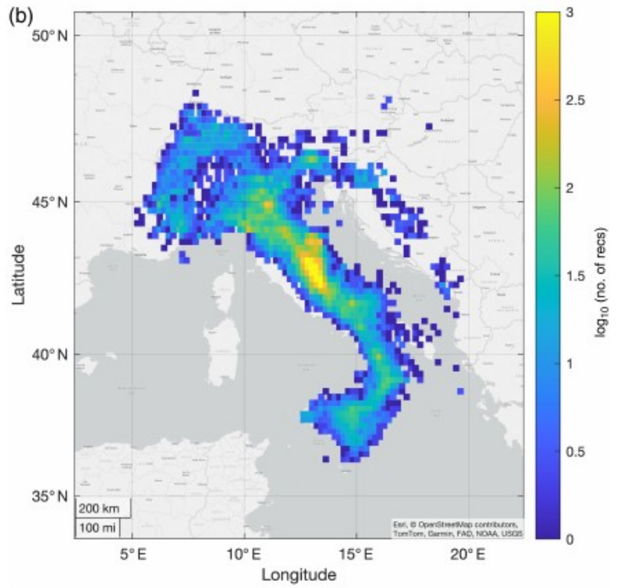
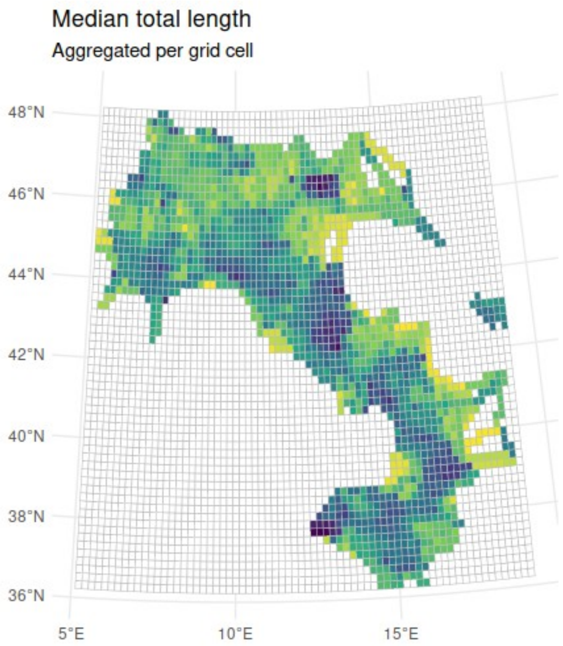


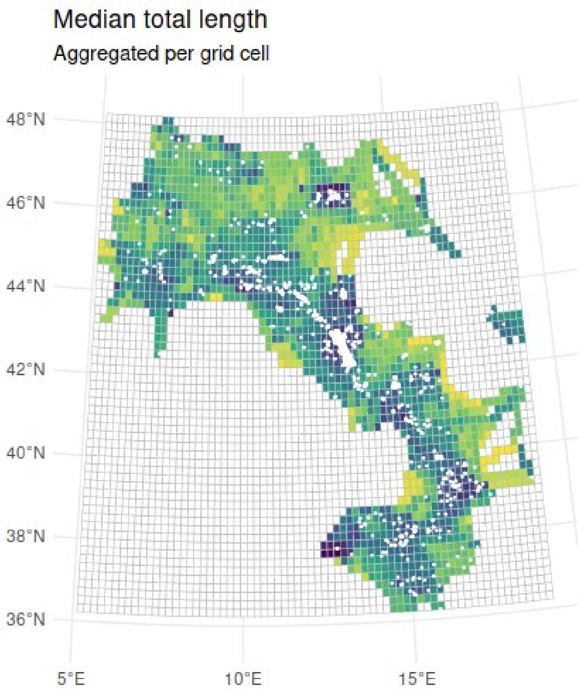

**Figure 9.** Path coverage of ITACAext_sac. (a) Source to site paths; (b) source to site middle point paths density measured considering a 0.2° × 0.2° grid. The color version of this figure is available

GFZ Helmholtz Centre for Geosciences

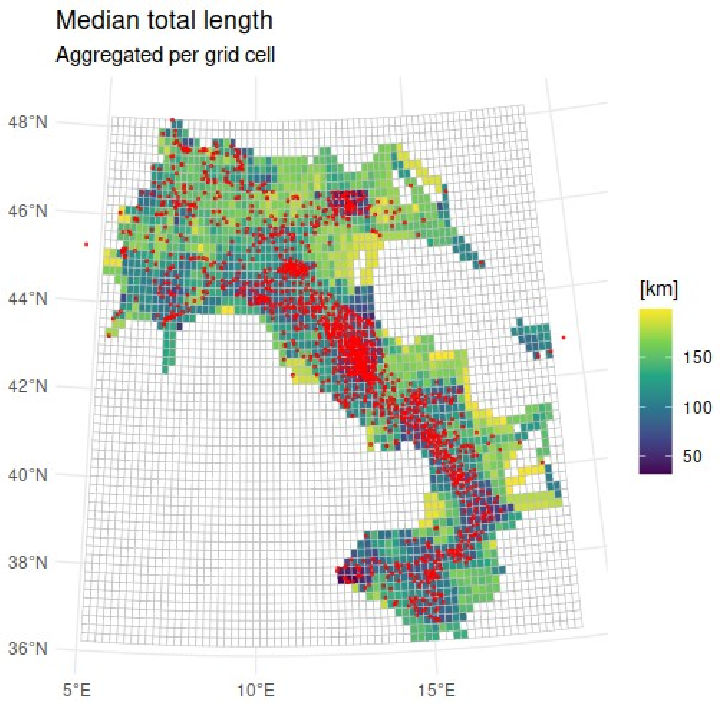
# Ongoing analysis with ITACAext




Max 200km



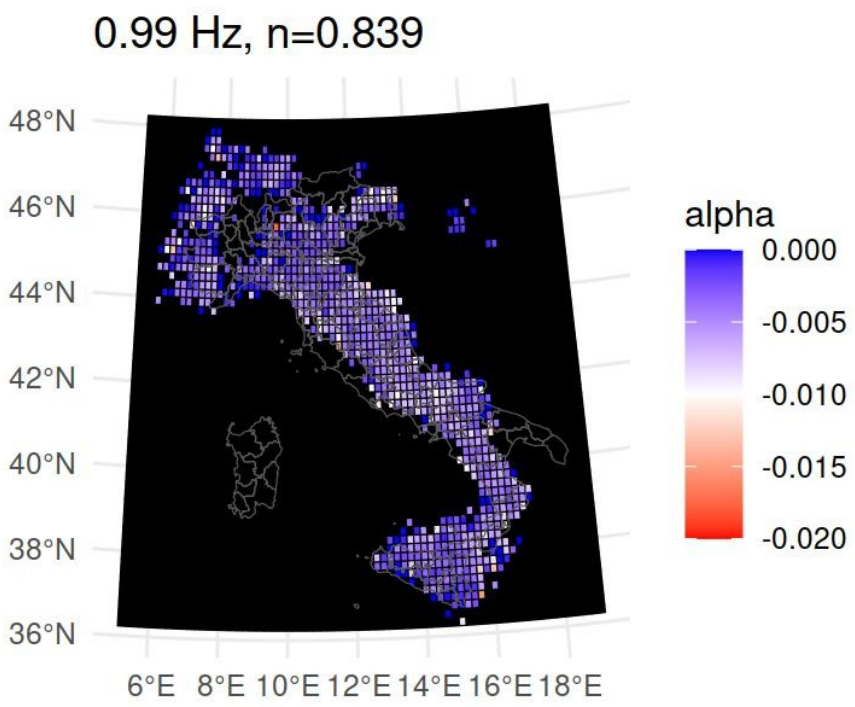

with events

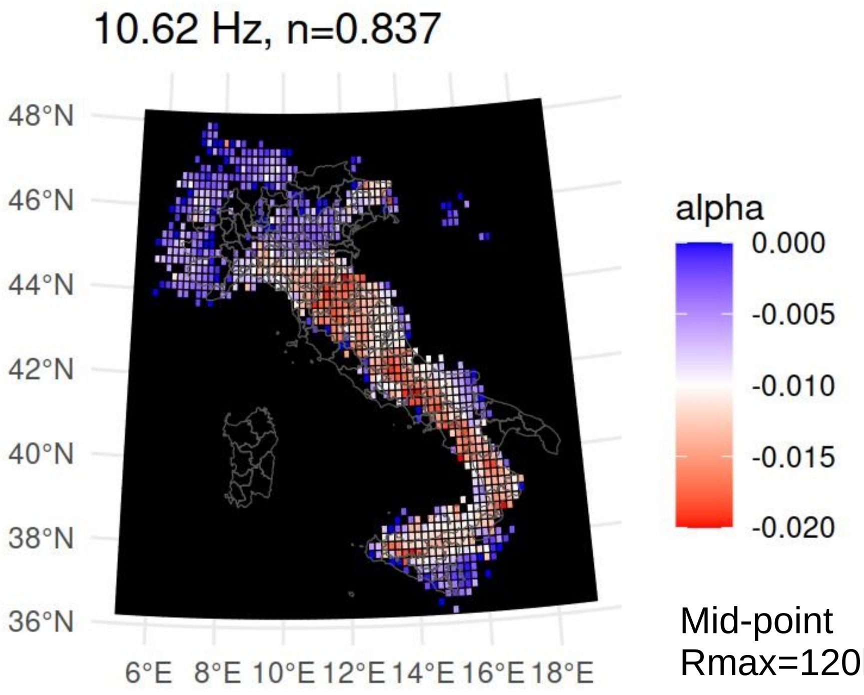



with stations

GFZ Helmholtz Centre for Geosciences

# Ongoing analysis with ITACAext … work in progress!!

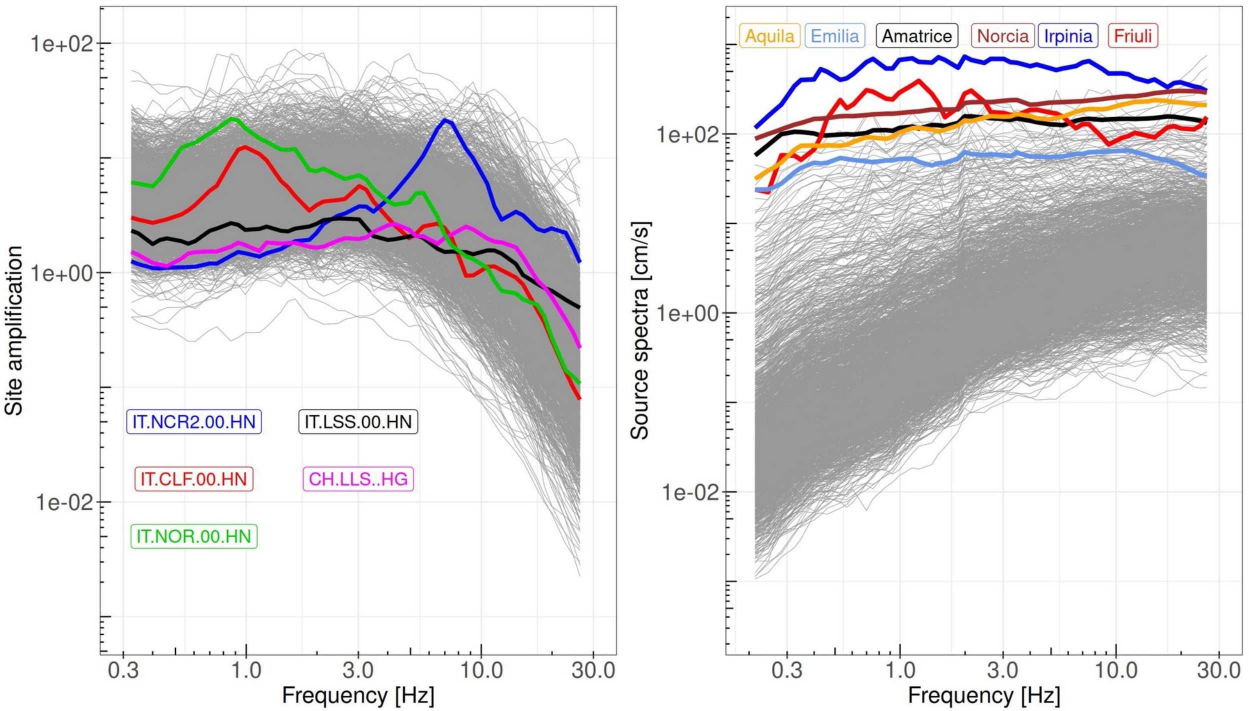



Mid-point
Rmax=120km

Results about the **2D absorption coefficients** at 0.99 and 10.62 Hz
n is the geometrical spreading exponents (values depend on max distance)

# Ongoing analysis with ITACAext … work in progress!!



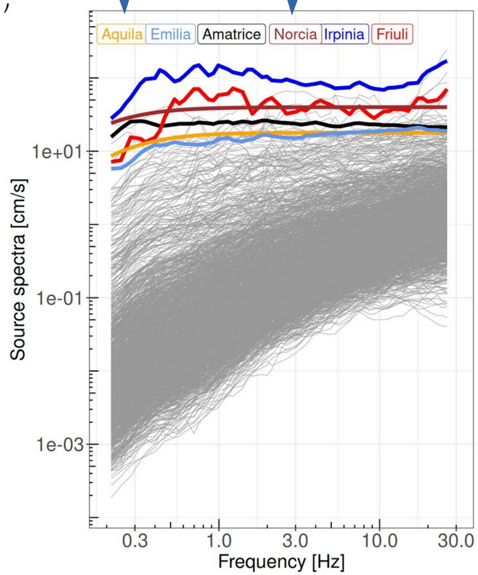

Preliminary results about source spectra obtained the 2D attenuation model and constrained site amplifications.

GFZ Helmholtz Centre for Geosciences

# Outlook (ITACAext)

- **Apply GIT with constrained source spectra**

Constrained to be Brune-like with parameters from Morasca et al (2023)




GFZ Helmholtz Centre for Geosciences

# Outlook (ITACAext)

- Apply GIT with constrained source spectra

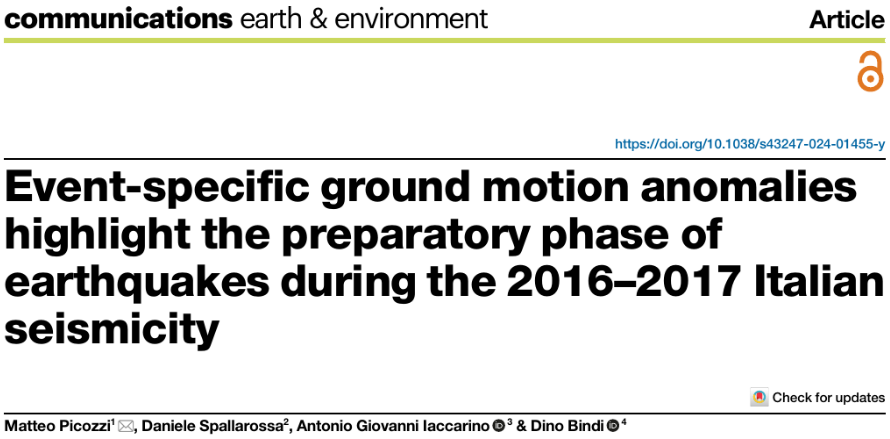
- **Apply GIT with site term constrained using δS2S(FAS) from non-ergodic GMM**

# Outlook (ITACAext)

- Apply GIT with constrained source spectra

- Apply GIT with site term constrained using δS2S(FAS) from ne-GMM

- **Investigate the temporal variability of the GIT results and compare with the temporal (and spatial) variability of the ne-GMM residuals**

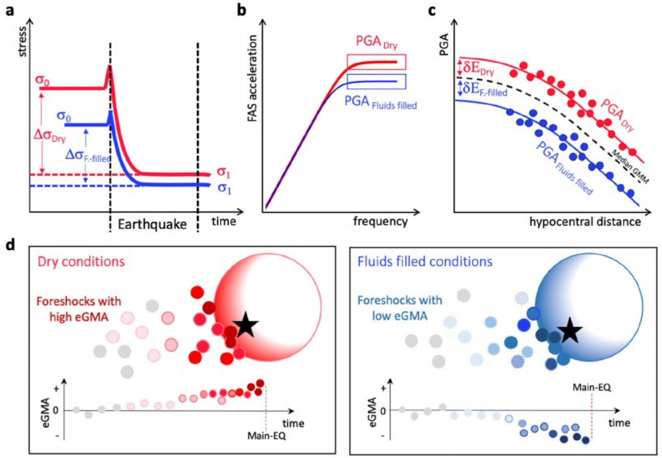

**communications** earth & environment — Article

https://doi.org/10.1038/s43247-024-01455-y

**Event-specific ground motion anomalies highlight the preparatory phase of earthquakes during the 2016–2017 Italian seismicity**

Check for updates

Matteo Picozzi[1], Daniele Spallarossa[2], Antonio Giovanni Iaccarino[3] & Dino Bindi[4]



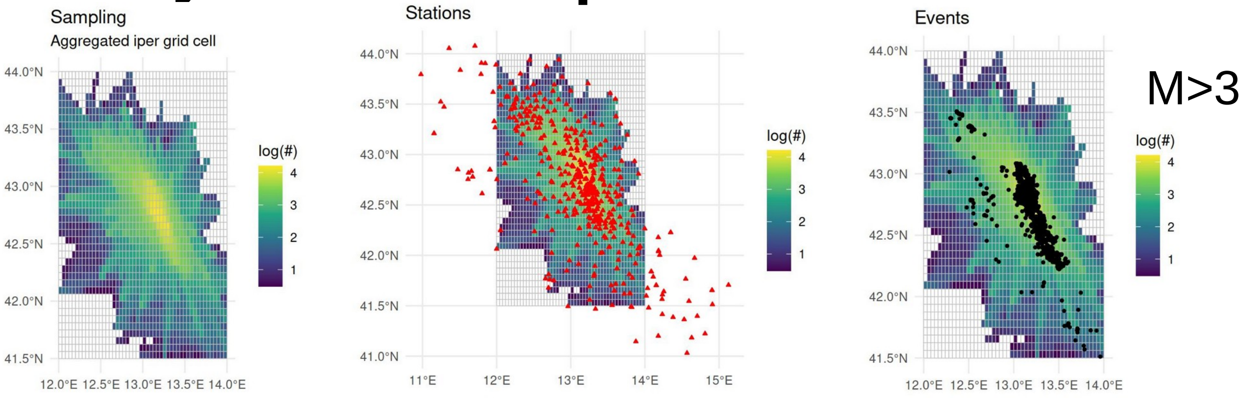
# Outlook

- Apply GIT with constrained source spectra

- Apply GIT with site term constrained using δS2S(FAS) from ne-GMM

- Investigate the temporal variability of the GIT results and compare with the temporal (and spatial) variability of the ne-GMM residuals

- **Repeat the analysis for the Spallarossa's central Italy data set (N3)**



# Outlook

- Apply GIT with constrained source spectra

- Apply GIT with site term constrained using $\delta$S2S(FAS) from ne-GMM

- Investigate the temporal variability of the GIT results and compare with the temporal (and spatial) variability of the ne-GMM residuals

- Repeat the analysis for the Spallarossa's central Italy data set (N3)

***Thank you for your attention !!!!***

Contact: dino.bindi@gfz.de
https://www.gfz.de/en/staff/dino.bindi/sec26