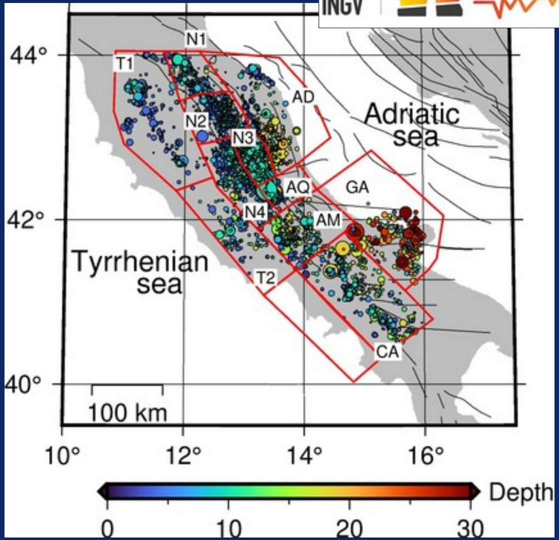


Bindi et al., 2024 (BSSA)

Bridging Spectral Decomposition and Ground-Motion Models: Results from SECURE and Perspectives

Dino Bindi & WP2, WP3

GFZ-Potsdam

Rome, 12 March 2026

GFZ Helmholtz Centre for Geosciences

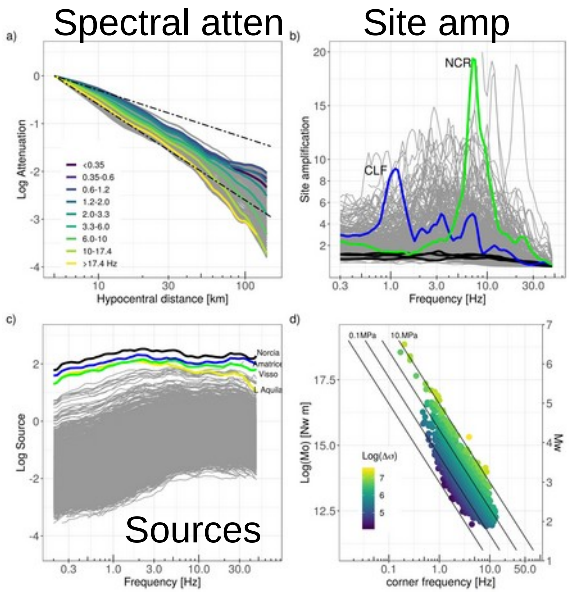
HELMHOLTZ

regional-Scale Earthquake ground motion prediCtions throUgh pyhsics-based and empiRical approachEs: a case study Central Italy

- WP1 Enhancements of Existing Crustal Velocity Models and Seismic Datasets
- WP2 Characterization of Earthquake Source and Seismic Wave Propagation in the Central Apennines
- WP3 Ground Motion Predictions using Innovative Approaches
- WP4 Testing the Performance of Ground Motion Models and Empirical Relationships

In the context of SECURE

WP2 – Physical ingredients

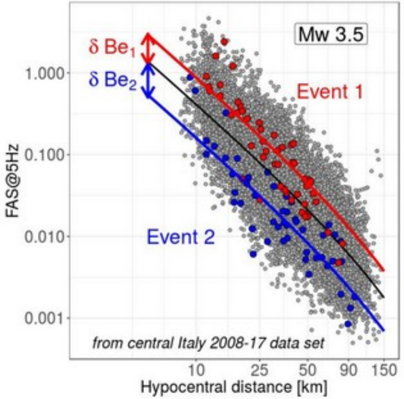


WP3 – Ground motion models

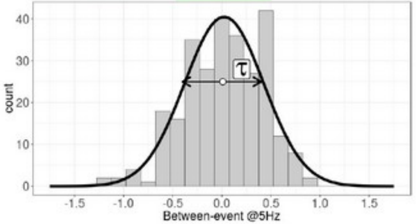
$$Log[FAS(f)] = Scaling(R) + Scaling(M) + \delta S2S + \delta Be + \epsilon$$

Station-term (δS2S)

Event-term (δBe)

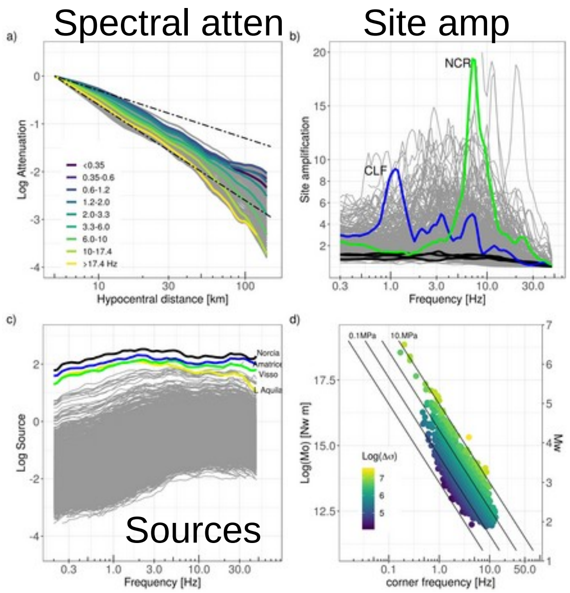


$$\sigma^2 = \tau^2 + \phi_{S2S}^2 + \phi_0^2$$

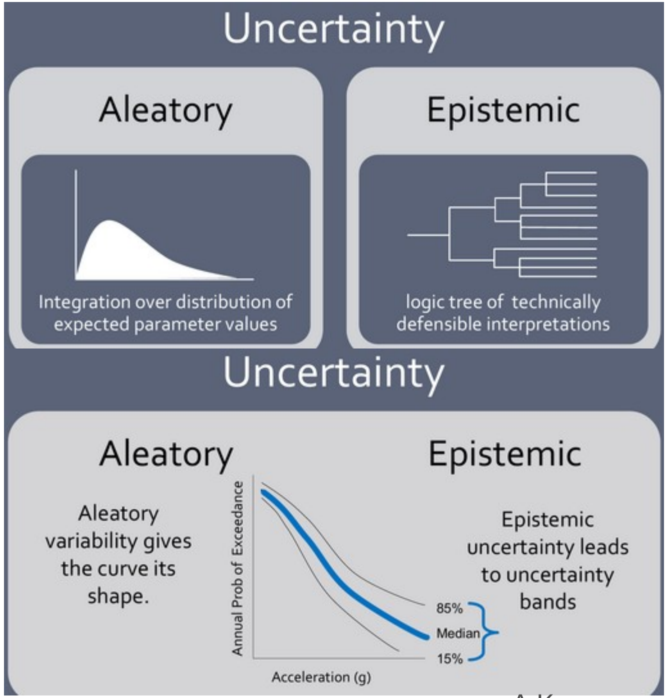


Why we need to decompose

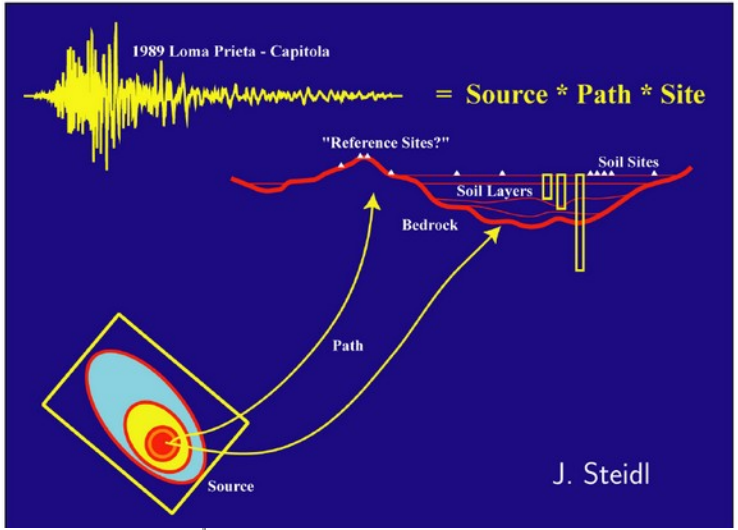
WP2 – Physical ingredients

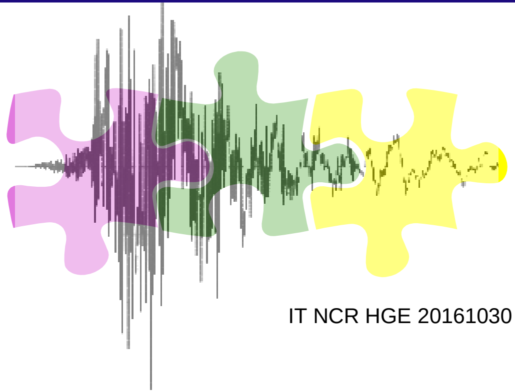


$$Log[FAS(f)] = Scaling(R) + Scaling(M) + \delta S2S + \delta Be + \epsilon$$

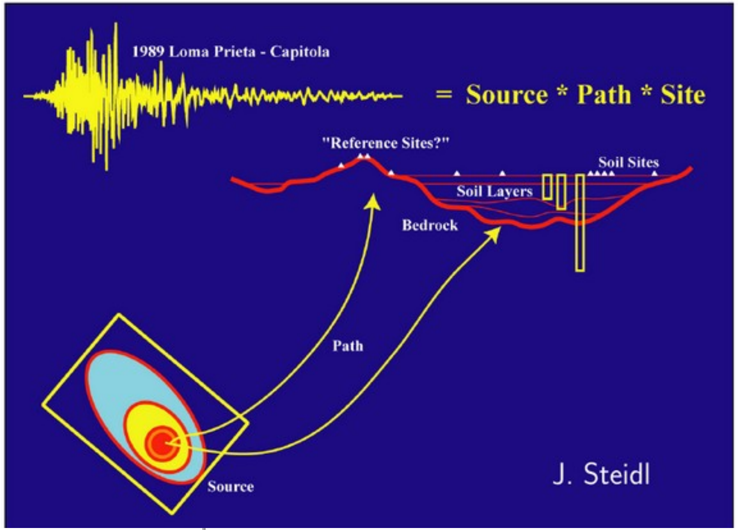


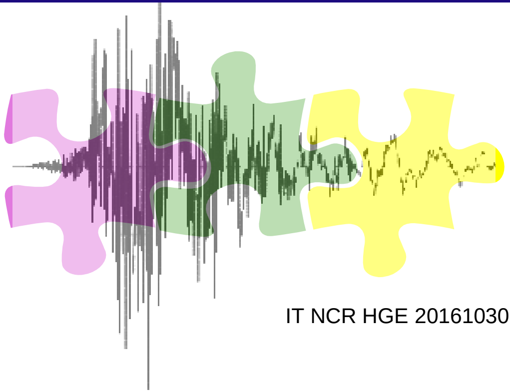
A.Kammerer



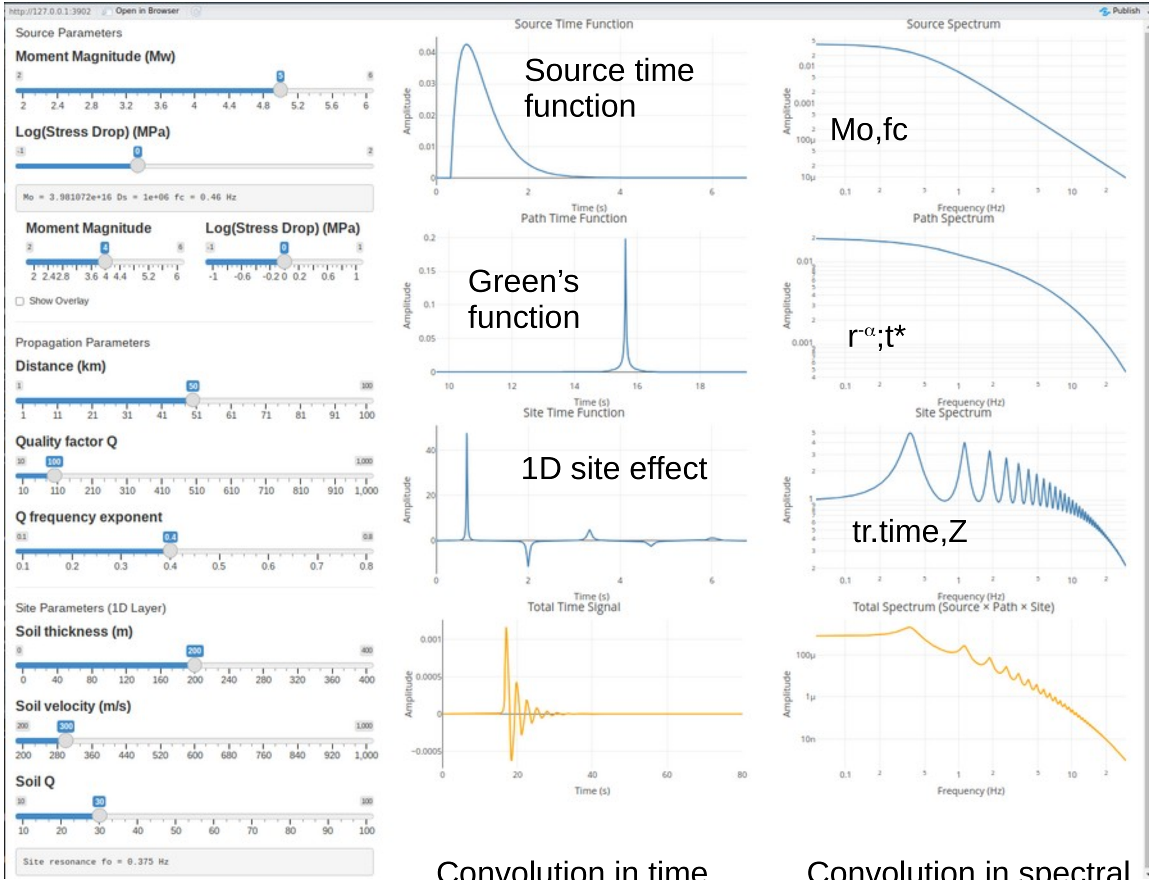


IT NCR HGE 20161030 esm-db.eu





IT NCR HGE 20161030 esm-db.eu



Convolution in time domain

Convolution in spectral domain

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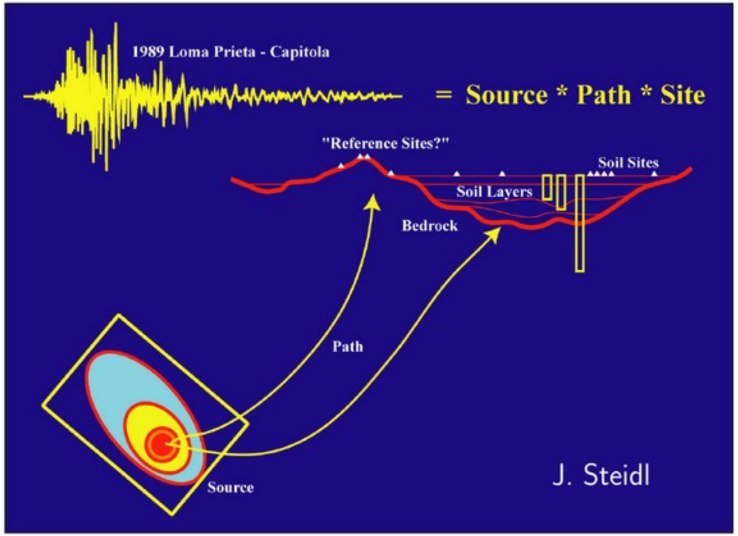
Spectral decomposition GIT & SECURE WP2



$$FAS(f) = S(f)\,P(f)\,G(f)$$

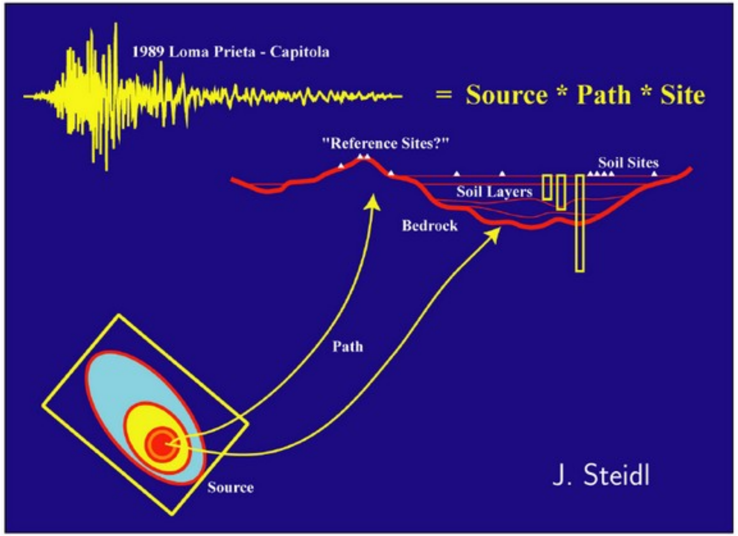
Source — Propagation — Site

$$\log_{10}FAS_{ij}(f) = \sum_{k=1}^{Nev}\delta_{ik}\log_{10}S_k(f) + a_n\log_{10}P_n(f) + a_{n+1}\log_{10}P_{n+1}(f) + \sum_{k=1}^{Nst}\delta_{jk}\log_{10}Z_k(f)$$

where $a_n = (R_{n+1} - R_{ij})/(R_{n+1} - R_n))$

$$a_{n+1} = 1 - a_n \quad R_n \le R_{ij} < R_{n+1}$$

Spectral decomposition GIT & SECURE WP2



$$FAS(f) = S(f)\ P(f)\ G(f)$$

Source

Site

Propagation

$$\log_{10} FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} \log_{10} S_k(f) +$$

$$+ a_n \log_{10} P_n(f) + a_{n+1} \log_{10} P_{n+1}(f) +$$

$$+ \sum_{k=1}^{Nst} \delta_{jk} \log_{10} Z_k(f)$$

where $a_n = (R_{n+1} - R_{ij})/(R_{n+1} - R_n))$

$a_{n+1} = 1 - a_n \quad R_n \leq R_{ij} < R_{n+1}$

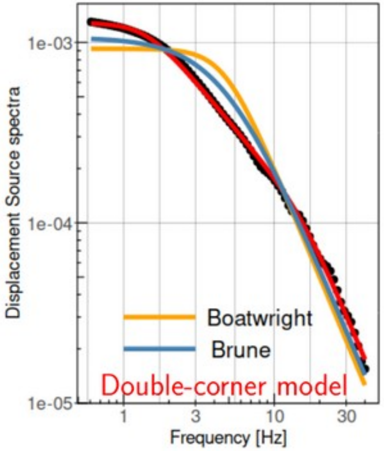
15:10 WP2 Calderoni G. *Multi-Method Stress Drop Estimation and Uncertainty Analysis for the 2016–2017 Amatrice–Visso–Norcia Seismic Sequence.*

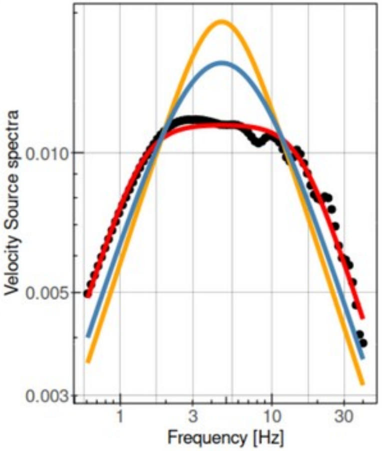
Spectral decomposition GIT & SECURE

$$S_k(f) = [s_1, s_2, \cdots, s_{Nfre}]$$

$$FAS(f) = S(f)\,P(f)\,G(f)$$

Source Propagation Site





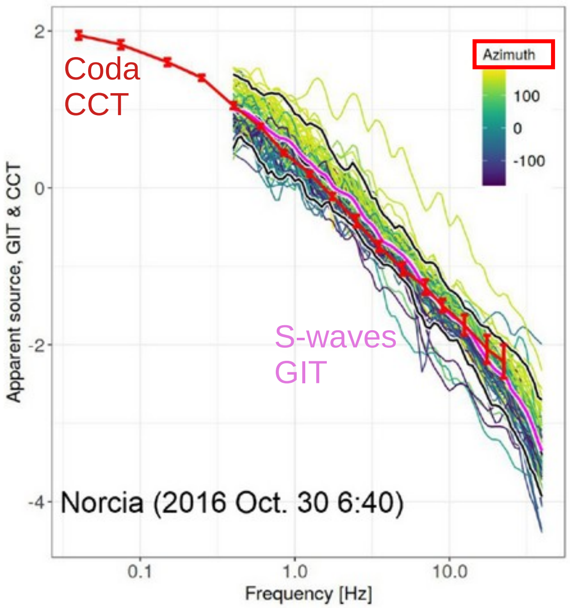
$$log_{10}FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} log_{10}S_k(f) +$$

$$+ a_n log_{10}P_n(f) + a_{n+1} log_{10}P_{n+1}(f) +$$

$$+ \sum_{k=1}^{Nst} \delta_{jk} log_{10}Z_k(f)$$

Spectral decomposition GIT & SECURE

S_{kj}={ [s_{1j},..$s_{Nfre,j}$]$_{j=1,Nsta}$ }



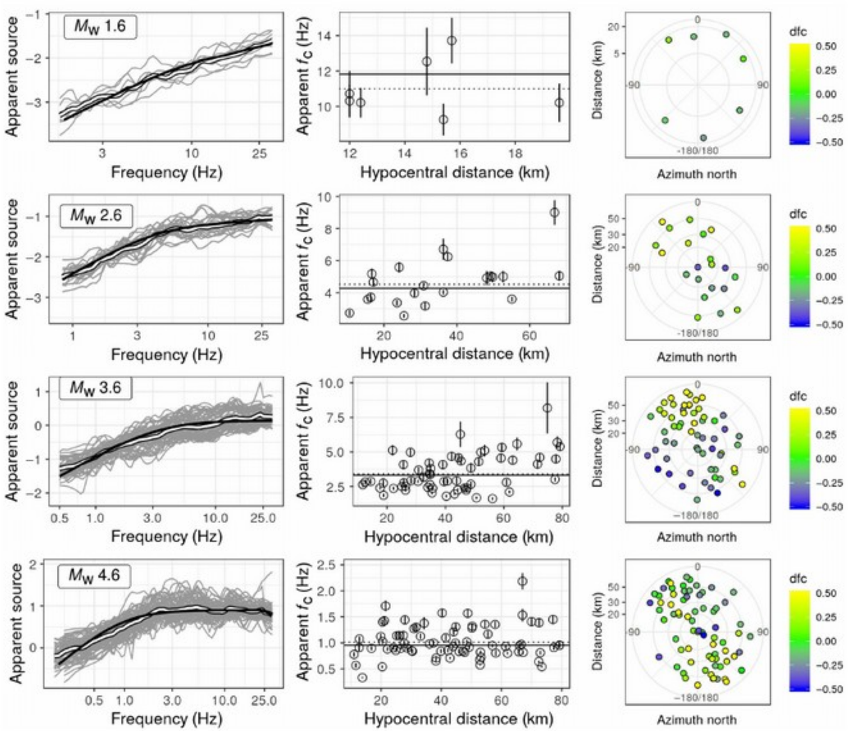
$$FAS(f) = S(f)\ P(f)\ G(f)$$

Source Propagation Site

$$log_{10}FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} log_{10} S_k(f) +$$
$$+ a_n log_{10} P_n(f) + a_{n+1} log_{10} P_{n+1}(f) +$$
$$+ \sum_{k=1}^{Nst} \delta_{jk} log_{10} Z_k(f)$$

Morasca et al. 2022 GJI

Spectral decomposition GIT & SECURE



$$FAS(f) = S(f)\ P(f)\ G(f)$$

Source Site
Propagation

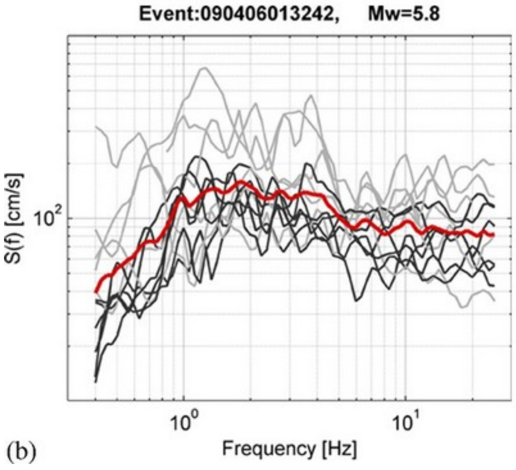
$$log_{10}FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} log_{10}S_k(f) +$$

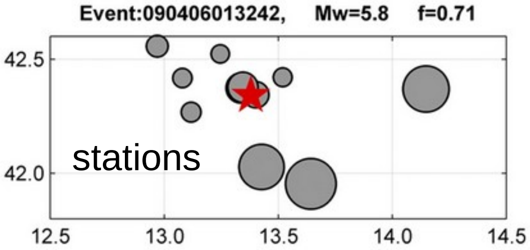
$$+ a_n log_{10}P_n(f) + a_{n+1} log_{10}P_{n+1}(f) +$$

$$+ \sum_{k=1}^{Nst} \delta_{jk} log_{10}Z_k(f)$$

Bindi et al. 2020, BSSA

Spectral decomposition GIT & SECURE





$$FAS(f) = S(f)\,P(f)\,G(f)$$

Source Propagation Site

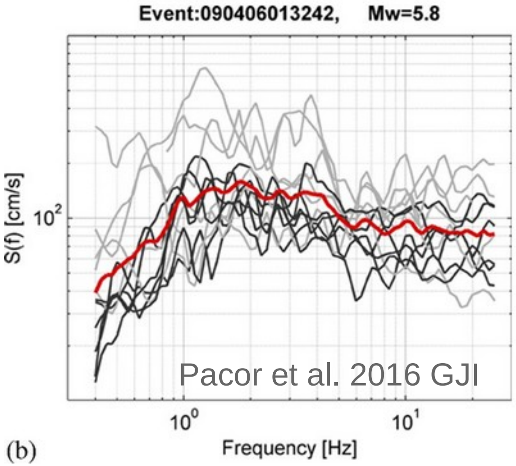
$$\log_{10} FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} \log_{10} S_k(f) +$$

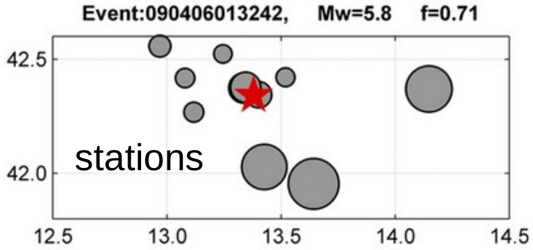
$$+ a_n \log_{10} P_n(f) + a_{n+1} \log_{10} P_{n+1}(f) +$$

$$+ \sum_{k=1}^{Nst} \delta_{jk} \log_{10} Z_k(f)$$

Pacor et al. 2016 GJI

Spectral decomposition GIT & SECURE





$$FAS(f) = S(f)\,P(f)\,G(f)$$

Source, Propagation, Site

$$log_{10}FAS_{ij}(f) = \sum_{k=1}^{Nev} \delta_{ik} log_{10} S_k(f) +$$

$$+ a_n log_{10} P_n(f) + a_{n+1} log_{10} P_{n+1}(f) +$$

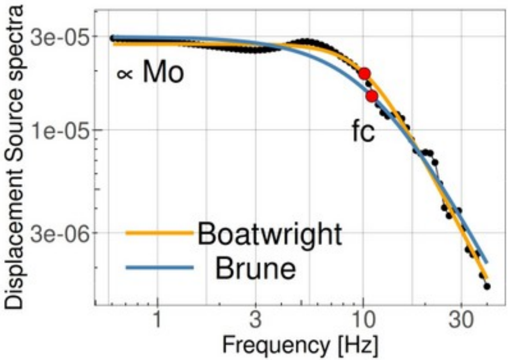
15:25 WP2 Cirella, A., *Linking Stress Drop and Slip Heterogeneity to Assess Source Rupture Directivity for Earthquakes in Central Italy.*
15:55 WP2 Colavitti, L. *Data-Driven Empirical Modeling of Source Directivity Effects in a Ground Motion Model for Central Italy*

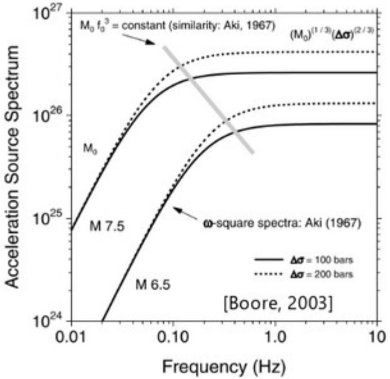
10:30 – Keynote Lecture, Gallovič, F., (Charles University in Prague, Czech Republic), *Constraining kinematic and dynamic rupture models for broadband strong-motion simulations.*

WP2 Physical ingredients / WP3 Ground motion models

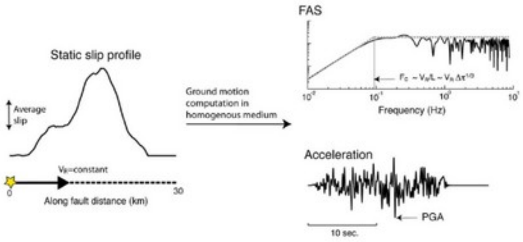
Stress drop

GMMs are based on self-similar source scaling





[Boore, 2003]



[Causse &Song, 2015]

Models

$$FAS_D(f) = \Gamma \frac{M_o}{\left[1+\left(\frac{f}{f_c}\right)^{\gamma n}\right]^{\frac{1}{\gamma}}}$$

n=2

γ=1 Brune [1970]

γ=2 Boatwright [1980]

Definition of stress drop Δσ

$$\Delta\sigma = \frac{7}{16}\left(\frac{\bar{f}_c}{k\beta}\right)^3 M_o$$

- Circular crack model with uniform Δσ [Eshelby, 1957]
- κ depends on the rupture model

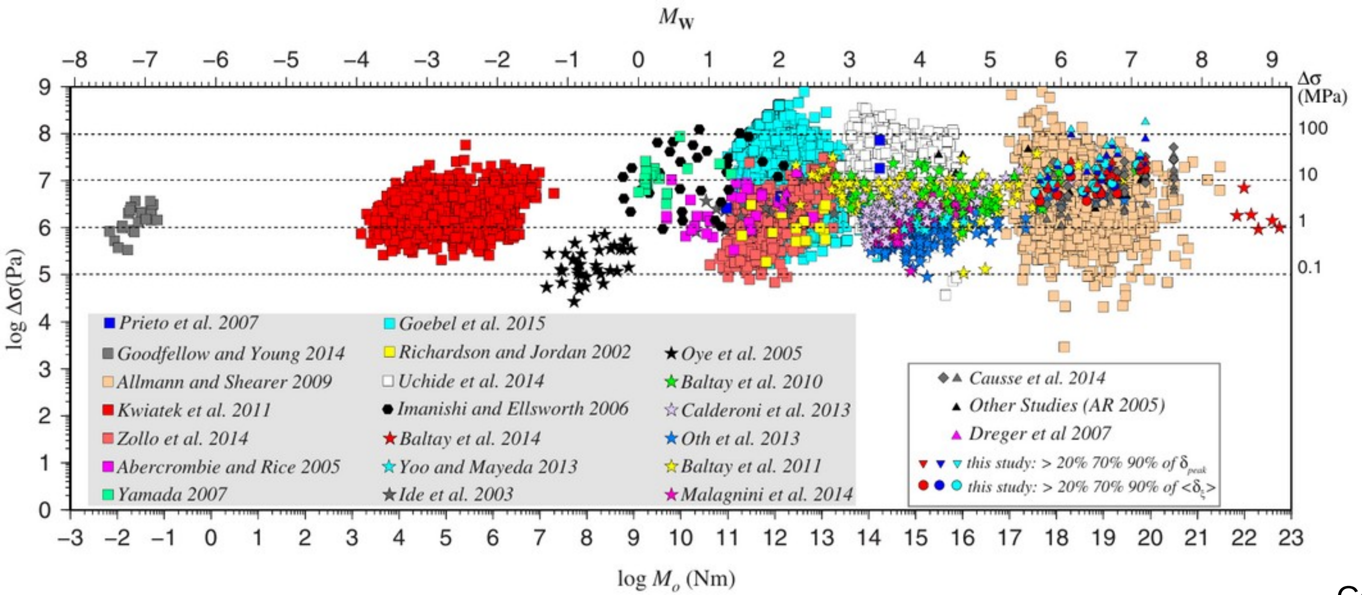
Stochastic simulations

log(PGA) ~ 0.31M + 0.8 log(Δσ)

[Hanks & McGuire, 1981; Boore, 2003]

Stress drop variability

Aggregation bias;
Between-groups confounding



Cocco et al. 2016

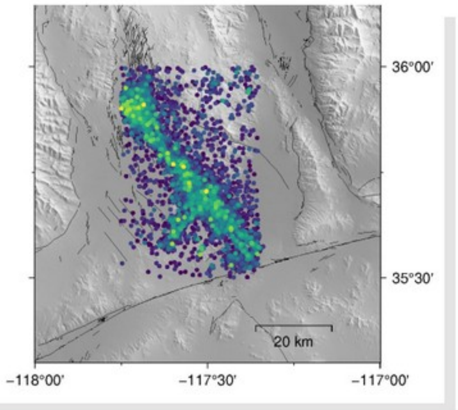
Pooled data set of results
(between-studies)

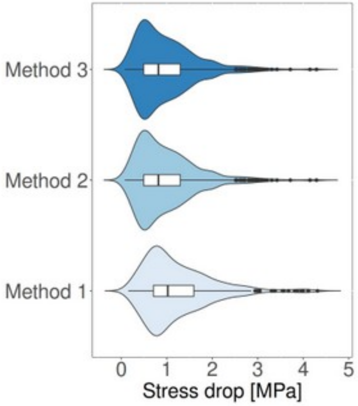
- Large Δσ variability (~3 orders)
- No clear trend

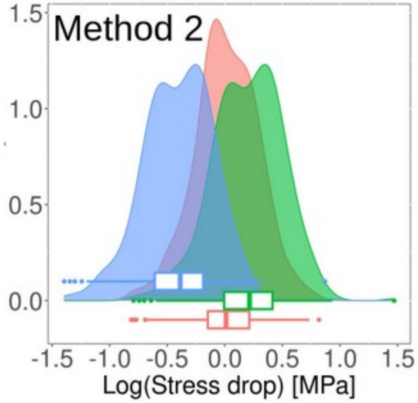
Individual data set
(within-study)

- Large Δσ variability (>2 orders)
- Some data sets show a trend

Stress drop variability SCEC stress drop benchmarch [Ridgecrest]







Data set: Ridgecrest 2019
From Trugman, 2020

Nev = 556
Nst=67
Nrec=
M in[2.5,7.1]
R: 5-112km

Between-Methods variability

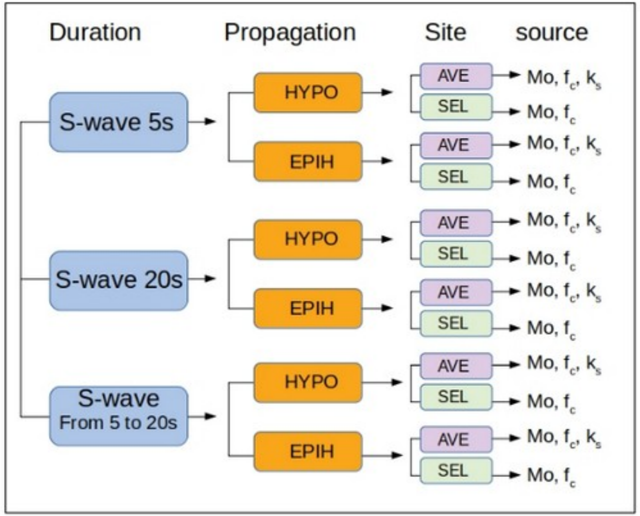
The participants applied different methods such as spectral decomposition, Spectral ratios, coda-analysis, time deconvolution, finite-fault kinematic approaches, etc

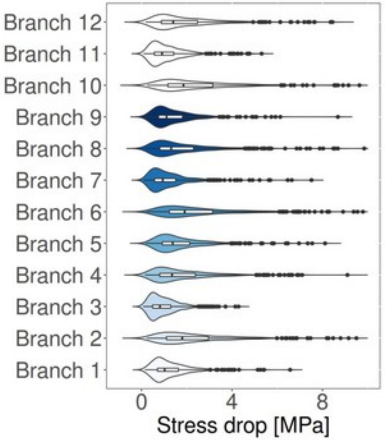
Within-method variability

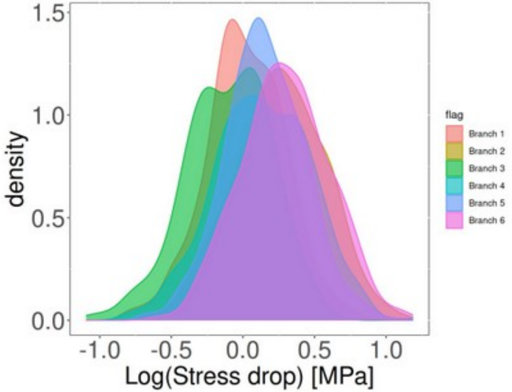
Considered method: GIT

Investigated alternative choices for different model components

Stress drop variability SCEC stress drop benchmarch [Ridgecrest]





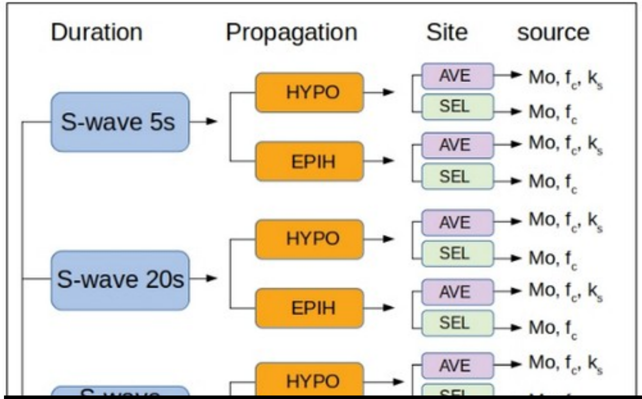


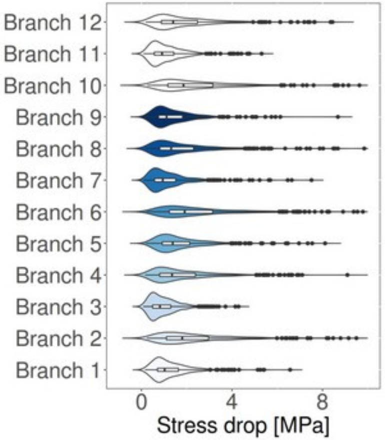
Statistics for the whole population

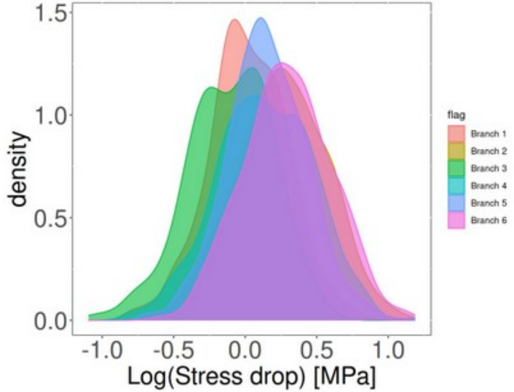
```
> quantile((df$drop_vs_3D),probs = c(0.025,0.5,0.975))
      2.5%       50%     97.5%
0.2806694 1.2339084 5.1477031
> quantile(log10(df$drop_vs_3D),probs = c(0.025,0.5,0.975))
       2.5%         50%        97.5%
-0.55180653  0.09128291  0.71161279
```

MPa

Stress drop variability SCEC stress drop benchmarch [Ridgecrest]








```
> sort(result$p50)
        50%         50%         50%         50%         50%         50%         50%         50%         50%         50% 
-0.08681238 -0.04017378 -0.02551702  0.01075241  0.04658297  0.11905079  0.13125700  0.14099140  0.14693779  0.25583089 
        50%         50% 
 0.26902009  0.28135963
> 0.28+0.087
[1] 0.367
```

$\log_{10}\Delta\sigma$

(2.3)

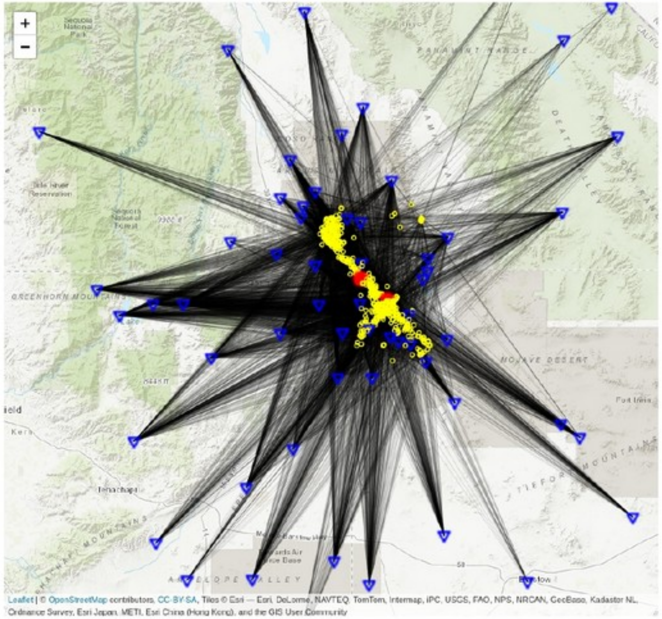
Our companions along the GIT journey

$$FAS(f) = S(f)\,P(f)\,G(f)$$

- **Non-Uniqueness of the solution**
- Attenuation-source interplay
  - Regional attenuation: polygons, cell-grid
  - Depth dependency

Spectral decomposition GIT – non uniqueness

Ridgecrest M7.1, 2016



Singular value decomposition

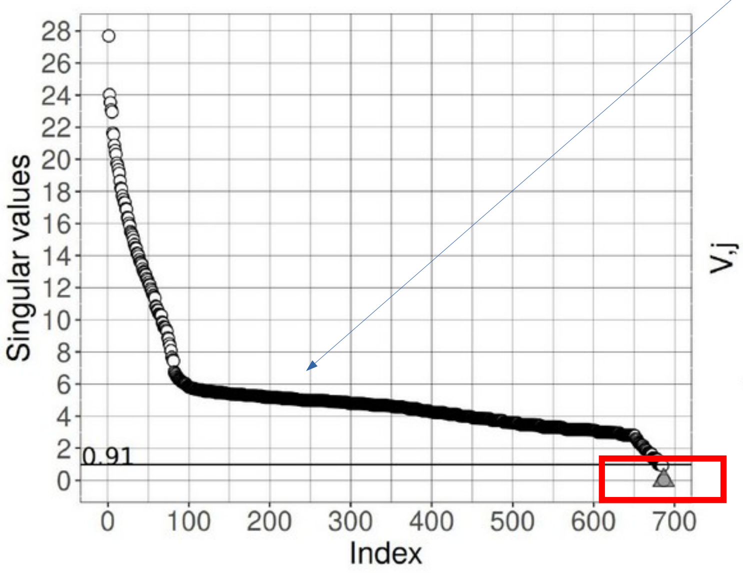
$$\text{SVD:}\quad G = U\,\Lambda\,V^T$$

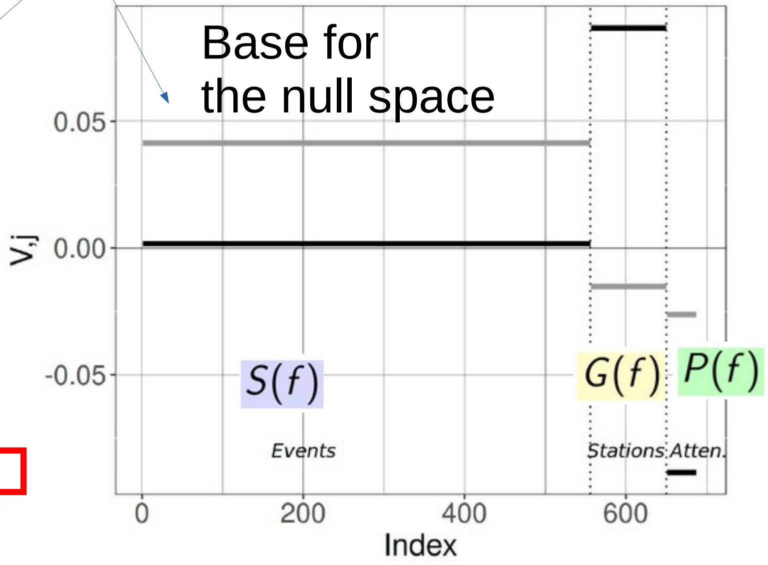
- Λ singular value matrix
- columns of V associated to $\lambda = 0$

$$FAS(f) = S(f)\,P(f)\,G(f)$$

Spectral decomposition GIT – non uniqueness

SVD: $G = U \Lambda V^T$



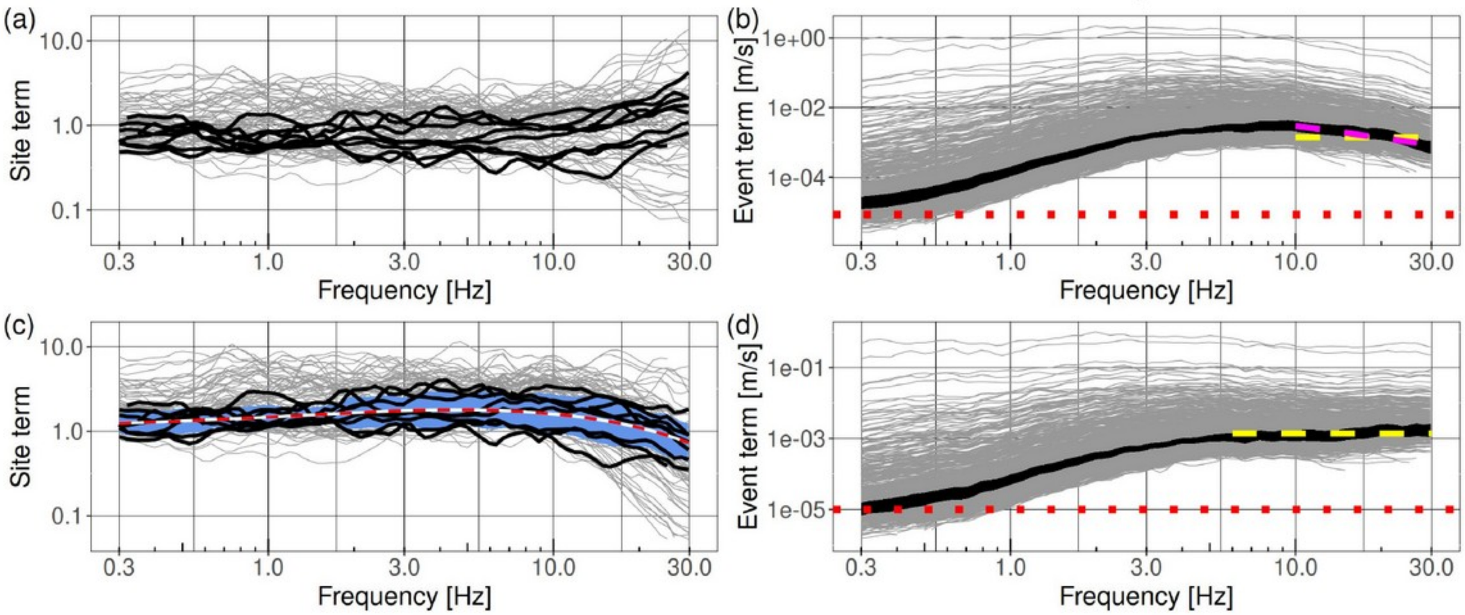


$$FAS(f) = S(f)\,P(f)\,G(f)$$

Bindi et al. 2023, SRL

Spectral decomposition GIT – non uniqueness

Impact of site constraint on source spectra



Bindi et al. 2023, SRL

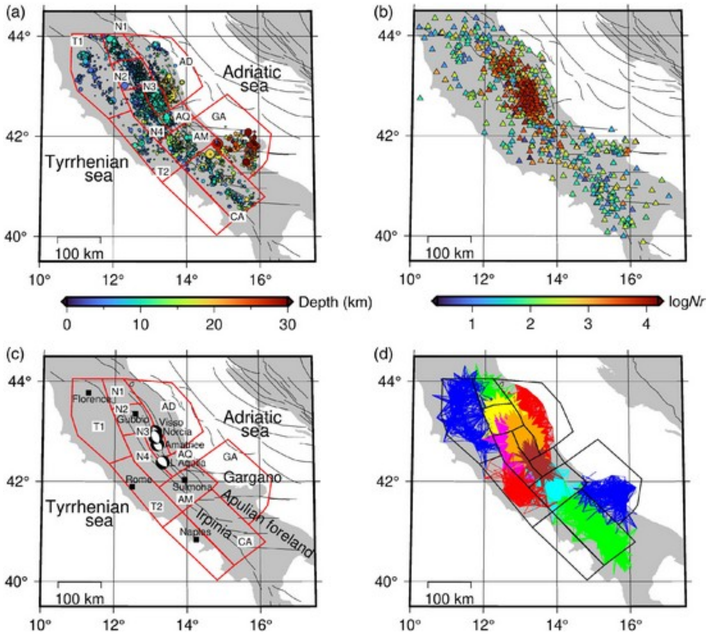
Our companions along the GIT journey

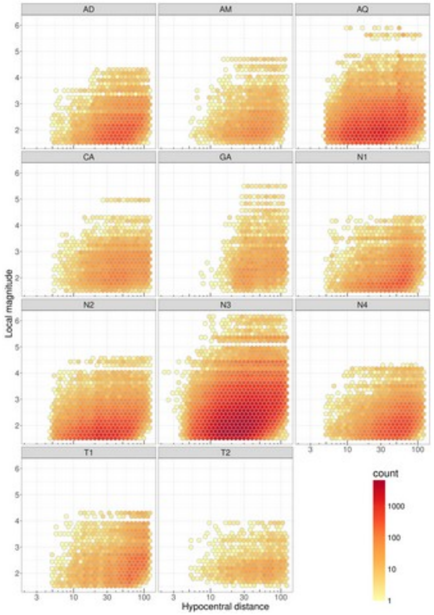
$$FAS(f) = S(f)\,P(f)\,G(f)$$

- Non-Uniqueness of the solution
- **Attenuation-source interplay**
  - **Regional attenuation: polygons, cell-grid**
  - Depth dependency

15:40 WP2 Gabrielli, S., *Spectral Corrections for Propagation and Site Effects: Implications for Stress Drop Estimation in the 2016 Mw 6.0 Amatrice Earthquake.*

Example regional attenuation





Bindi et al. 2024, BSSA
SECURE

Source regional models are useful for:

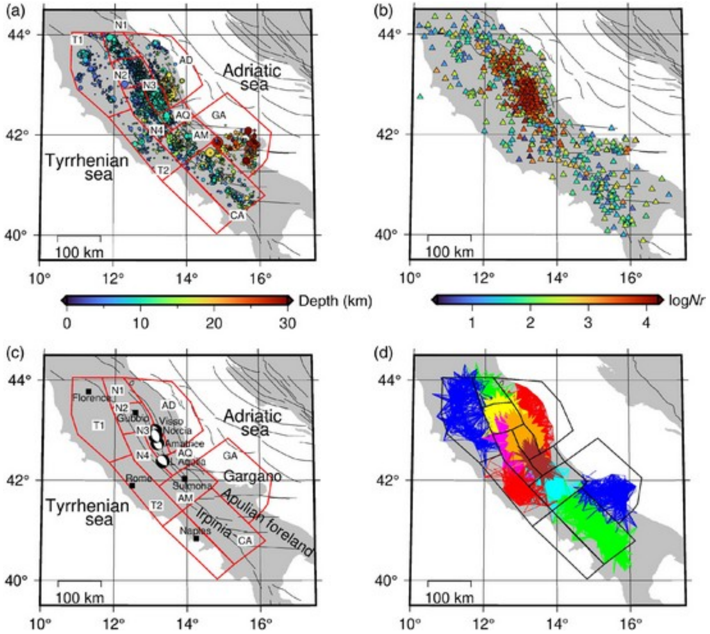
- capturing fault-system related differences in source behavior

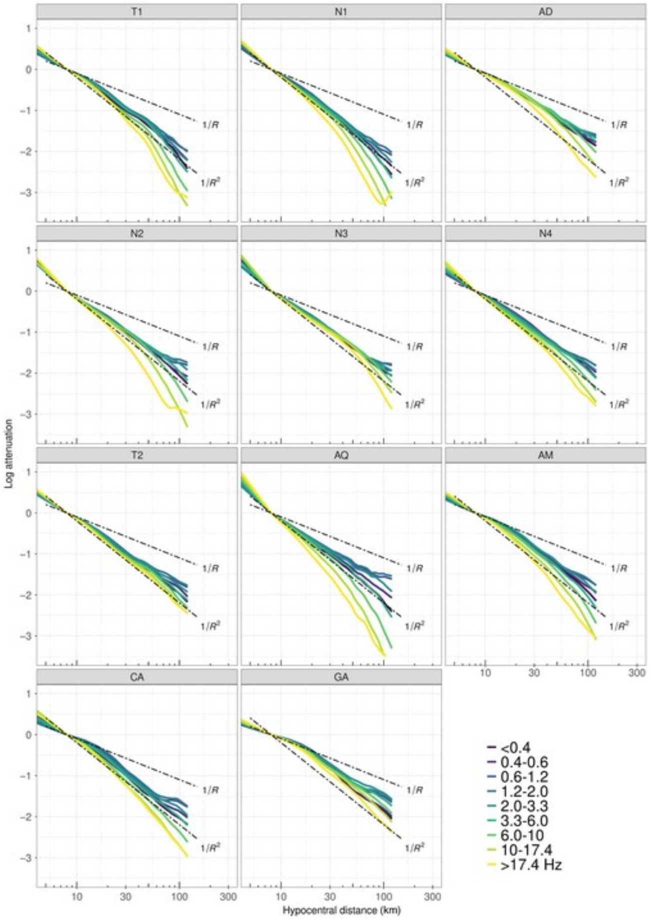
- analysis of δL2L/δBe residuals

- support development of magnitude conversions (e.g., T Allen, ongoing effort in Australia)

- prepare the set-up for numerical simulations

Example regional attenuation

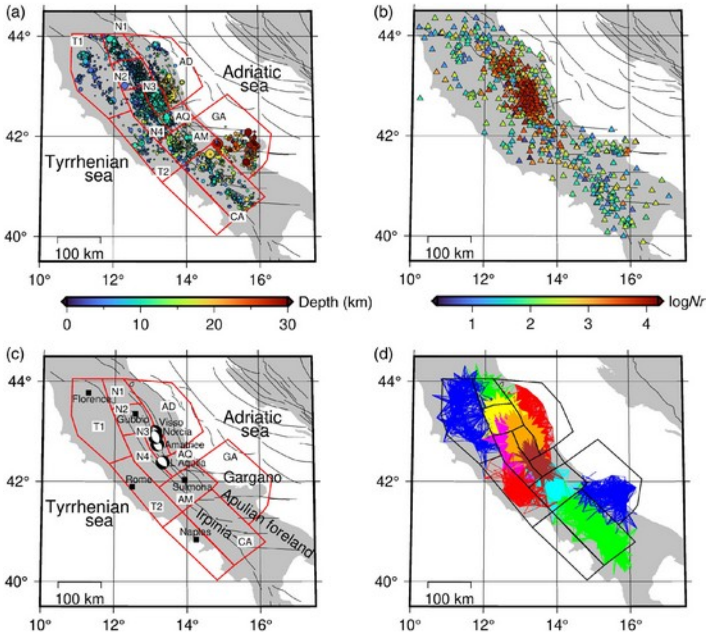


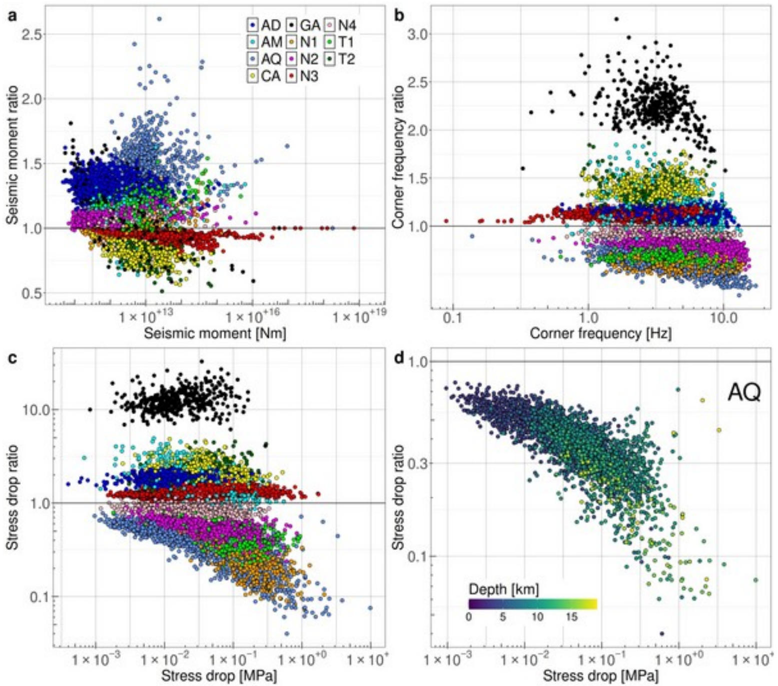


Bindi et al. 2024, BSSA
SECURE

Impact of regional attenuation

RATIO single model/multiple models



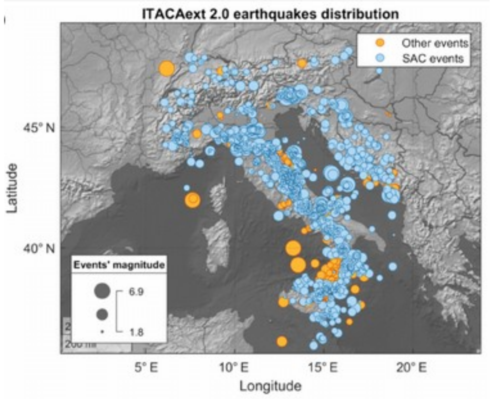


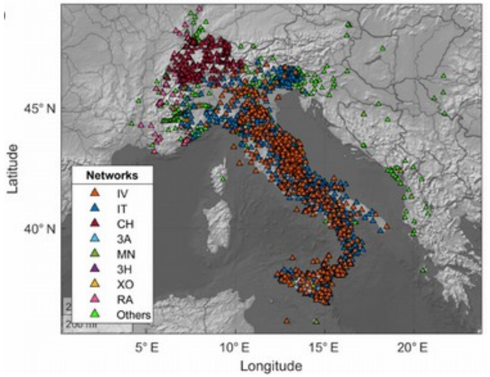
Bindi et al. 2024, BSSA
SECURE

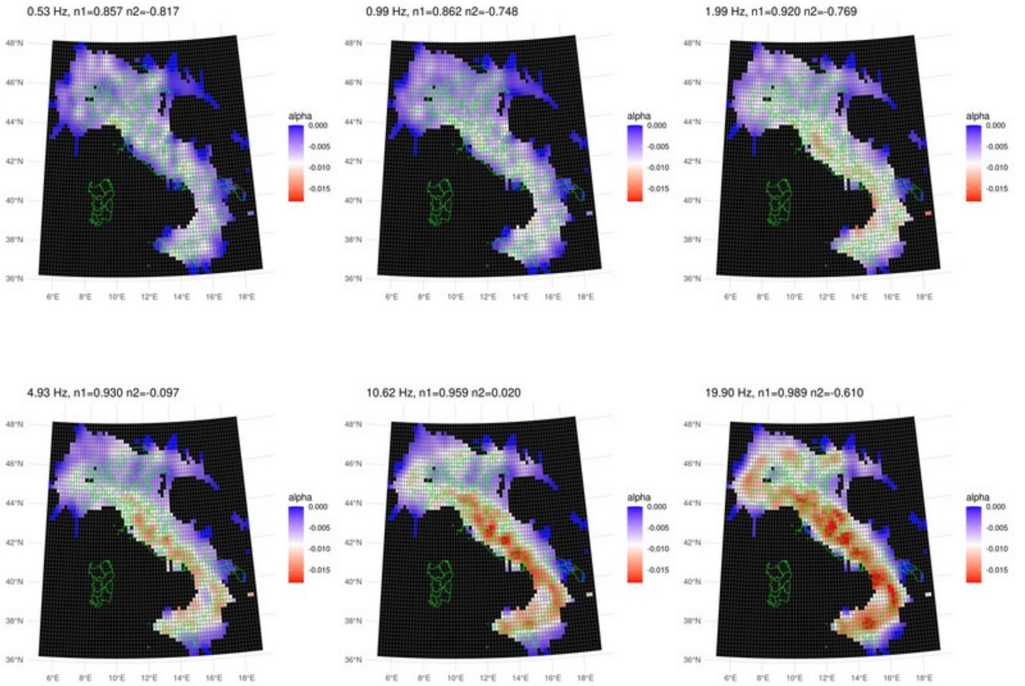
SECURE ITACA-extended

$$log(Path_{ij}(f)) = logG(R_{ij}; f) + \sum_{k}^{N_c} \lambda_{ijk}\alpha_k(f)$$

$$\begin{bmatrix} \mathbf{A} \\ \lambda\mathbf{L} \end{bmatrix} \mathbf{m} = \begin{bmatrix} \mathbf{d} \\ \mathbf{0} \end{bmatrix}$$



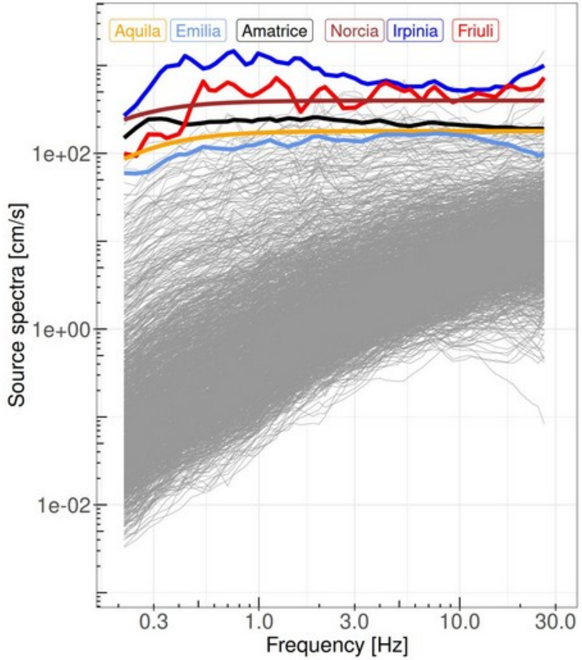


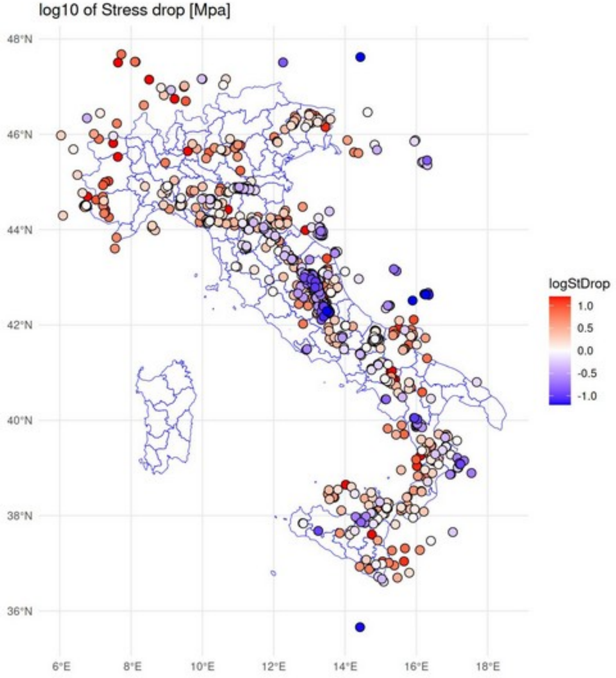


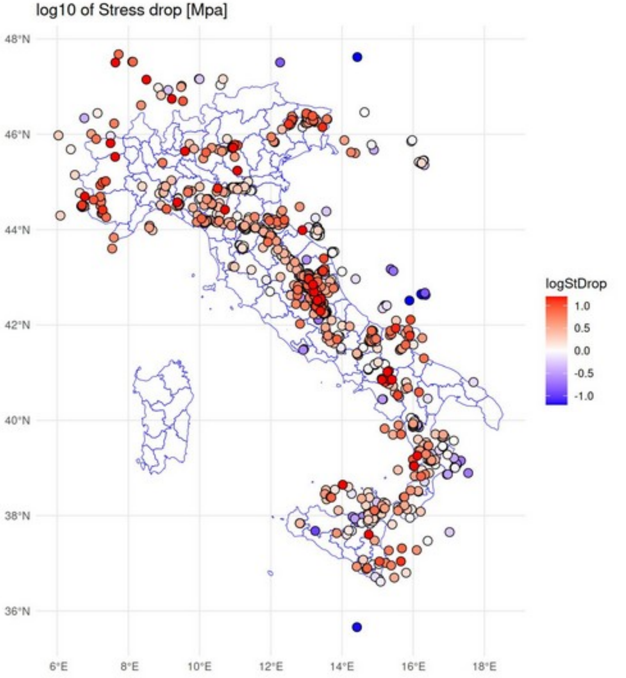
SECURE ITACA-extended

$$log(Path_{ij}(f)) = logG(R_{ij}; f) + \sum_{k}^{N_c} \lambda_{ijk}\alpha_k(f)$$

$$\begin{bmatrix} \mathbf{A} \\ \lambda\mathbf{L} \end{bmatrix} \mathbf{m} = \begin{bmatrix} \mathbf{d} \\ \mathbf{0} \end{bmatrix}$$





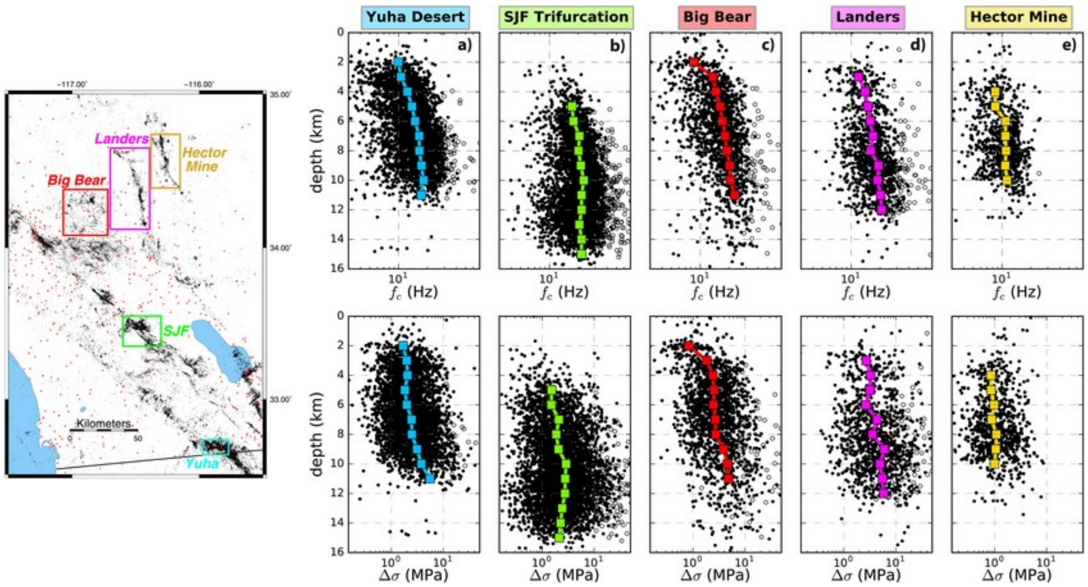


Our companions along the GIT journey

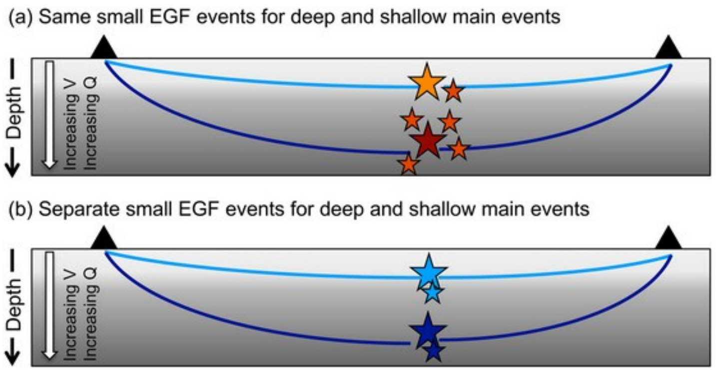
$$FAS(f) = S(f)\, P(f)\, G(f)$$

- Non-Uniqueness of the solution
- Attenuation-source interplay
  - Regional attenuation: polygons, cell-grid
  - **Depth dependency**

The depth-dependency issue



Trugman and Shearer 2017
http://dx.doi.org/10.1002/2017JB013971



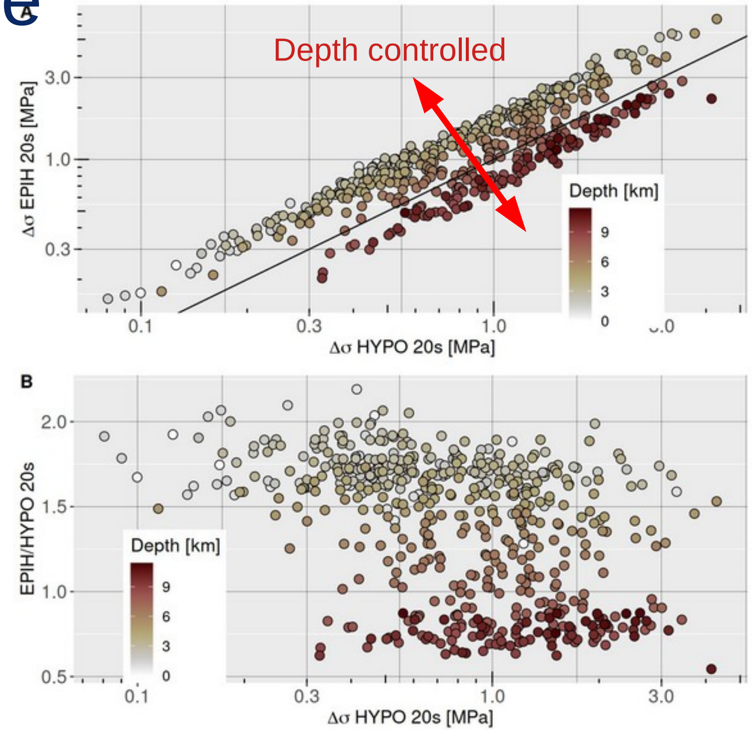
Does Earthquake Stress Drop Increase With Depth in the Crust?

Rachel E. Abercrombie, Daniel T. Trugman, Peter M. Shearer, Xiaowei Chen, Jiewen Zhang, Colin N. Pennington, Jeanne L. Hardebeck, Thomas H. W. Goebel, Christine J. Ruhl

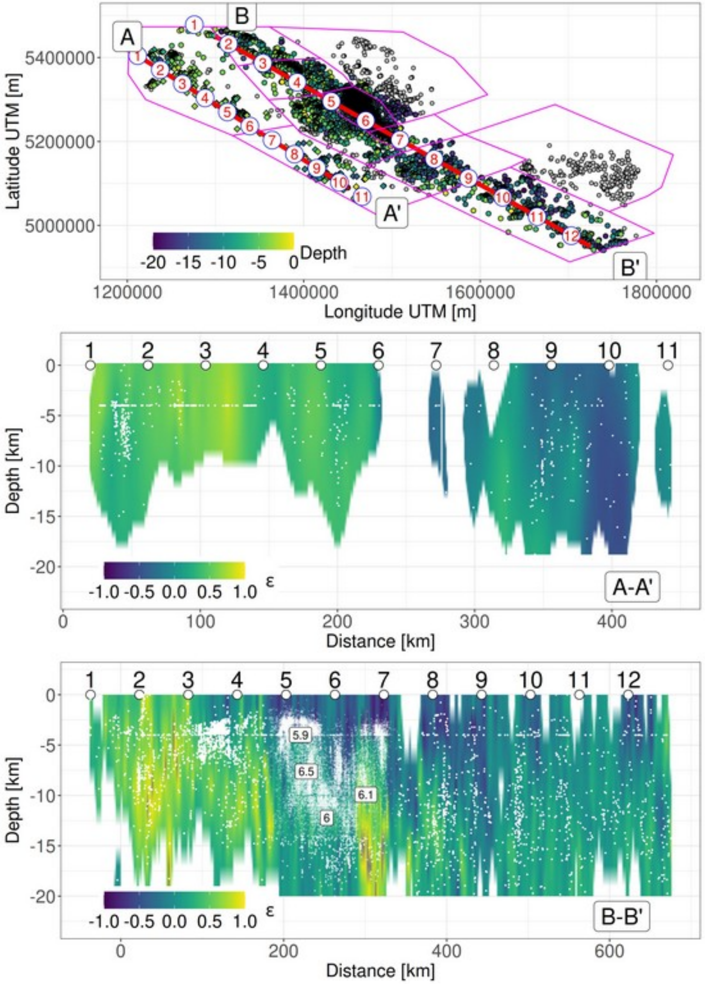
First published: 16 September 2021 | https://doi.org/10.1029/2021JB022314 |

Depth issue

Depth dependent / Depth independent



Bindi et al. 2023, SRL



Bindi et al. 2024, BSSA SECURE

SECURE - Farewell

Ground-motion models describe variability statistically. Spectral decomposition allows us to give that variability a physical meaning.

In SECURE, we applied this idea at regional scale in Central Italy.

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In SECURE, we applied this idea at regional scale in Central Italy.

Thank you, SECURE community, for the nice journey we took together.

Alla prossima !!! Dino