Analisi dell'Impatto delle Variazioni di Attenuazione sul Moto del Suolo nell'Appennino Centrale

Mid-Term Meeting SECURE (Pianeta Dinamico Project 2023–25)

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Simona Gabrielli, Aybige Akinci,
Edoardo Del Pezzo

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ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

SECURE

Aim of the study

- It is fundamental to define the attenuation characteristics of the area and the relationship with the **ground motion models** to predict ground motion from hypothesized events
- Here, we performed **stochastic simulations** incorporating frequency-dependent **Q** values from **Gabrielli et al. (2025)** as input parameters for **strong-ground motion simulations**
- The aim is to explore the **effects** and **impact** of varying physical parameters, such as **attenuation**, its **frequency dependence,** and **stress drop,** on the simulations.
- These estimates are further compared with the ground motion prediction equations applicable to the region to determine how variations in attenuation, frequency dependence, and stress drop impact the simulations.

ttenuation of Seismic Wav

• Seismic attenuation describes the energy loss experienced by seismic waves as they propagate. It is controlled by the temperature, composition, melt content, fractures of the rocks through which the waves travel.

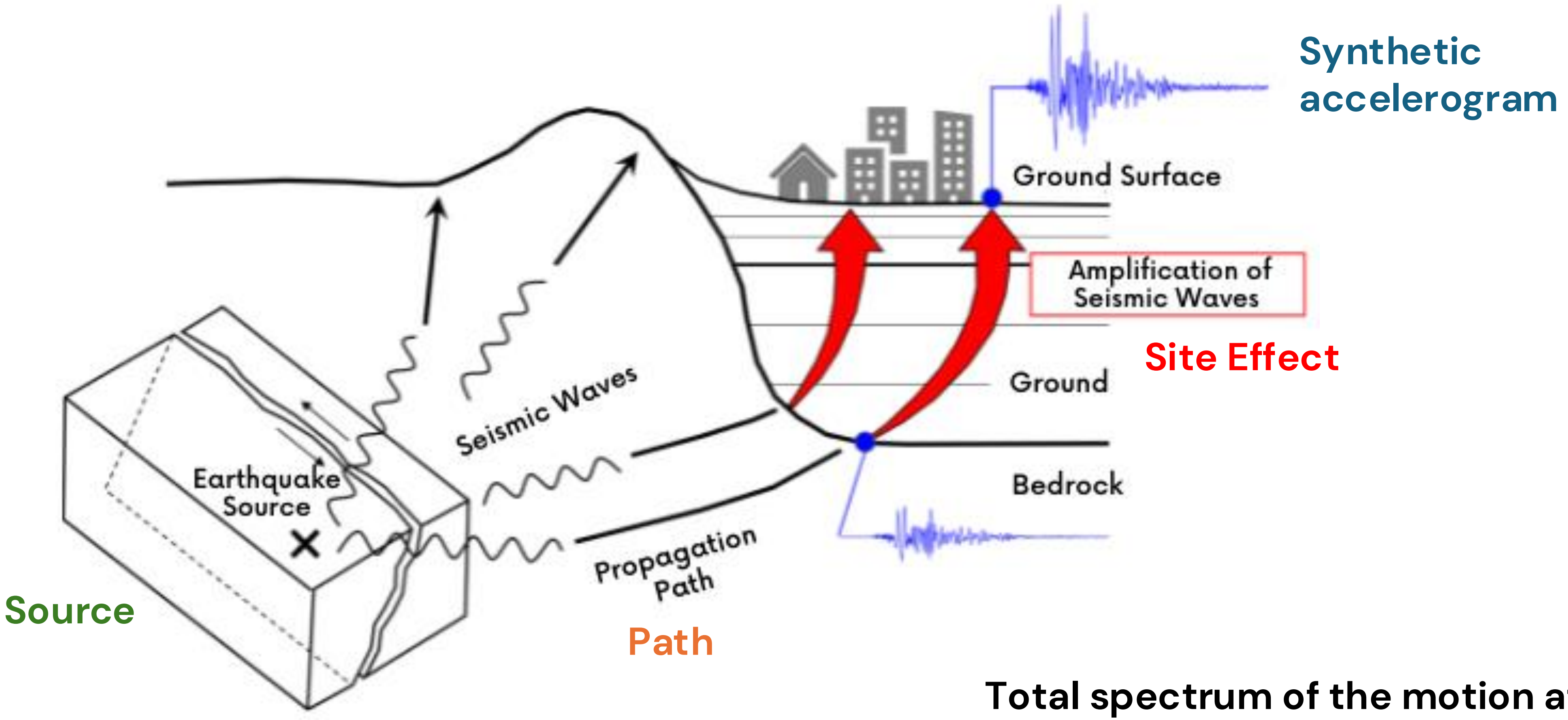
$$\frac{1}{Q(\omega)} = -\frac{\Delta E}{2\pi E} \quad \rightarrow \quad \frac{1}{Q(\omega)} = -\frac{\Delta A}{\pi A}$$

• The overall attenuation is given by:

$$Q_{tot}^{-1} = Q_i^{-1} + Q_{Sc}^{-1}$$

where Q and Q are intrinsic attenuation (absorption) and the scattering loss, inverse of the quality factor Qsc and Qi

ttenuation and Ground Motic



From Hiroyuki Miura, Hiroshima University

Total spectrum of the motion at site

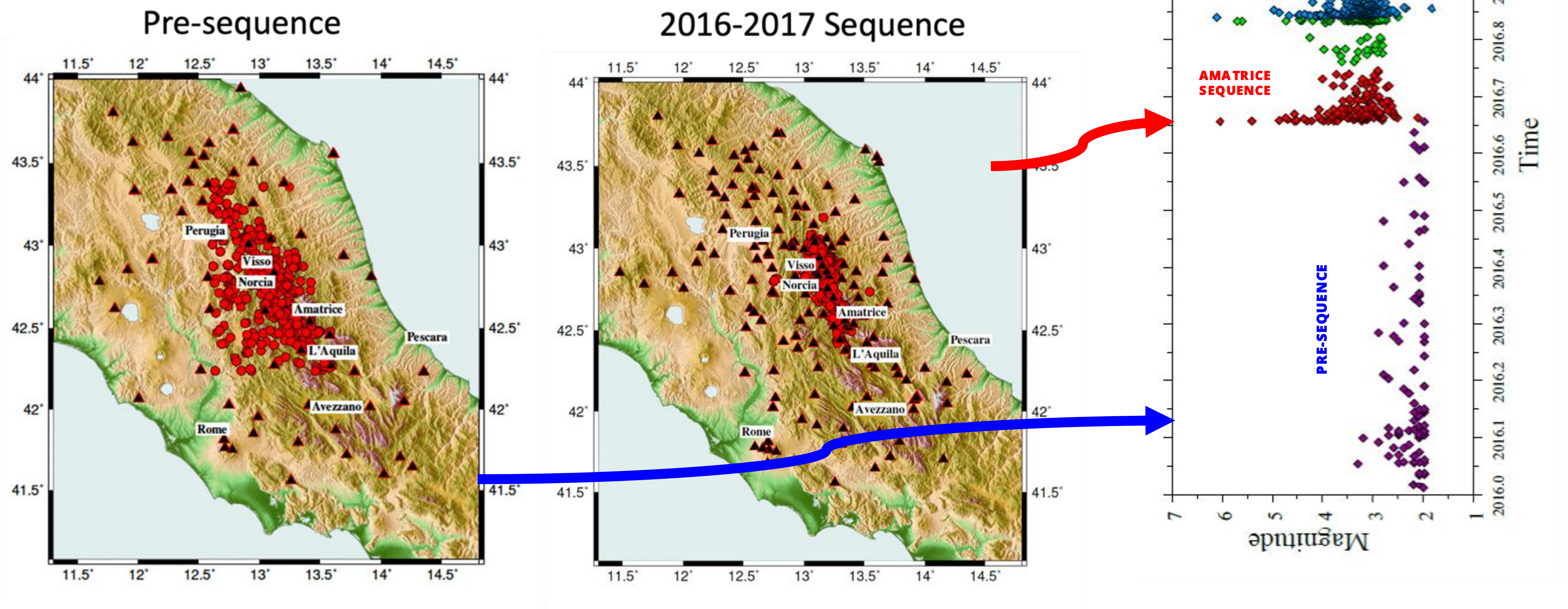
$$Y(M_O, R, f) = E(M_O, f)\underline{P(R, f)}G(f)I(f)$$

Boore (2003)

Dataset

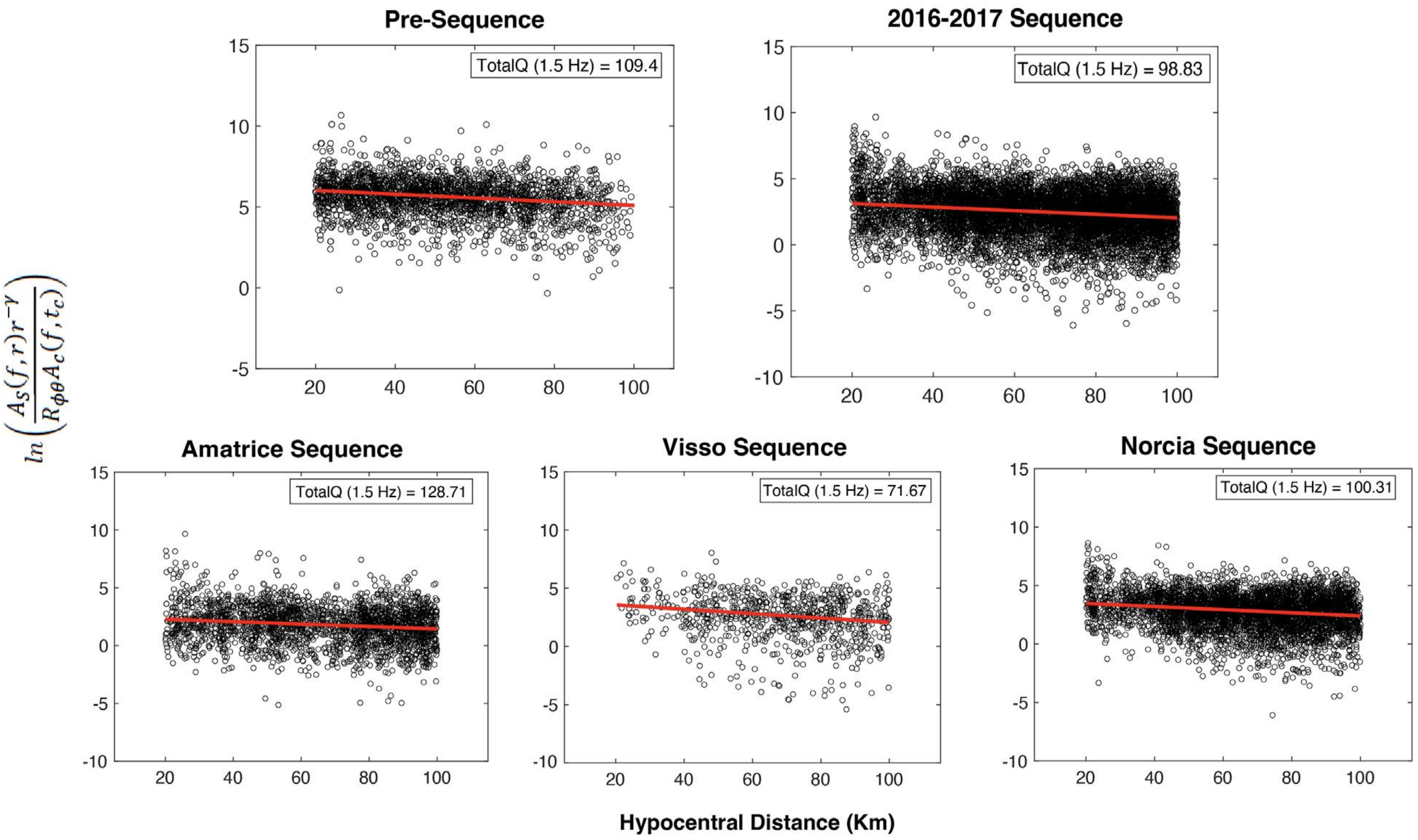
- Study focused on the sequence of large earthquakes occurred in the Central Apennines in 6–7 months during **2016–2017** (Amatrice Mw 6.0 - Visso Mw 5.9 – Norcia Mw 6.5)

- The sequence dataset was **sub-divided** into three separate sequences following the mainshock of Amatrice, Visso and Norcia



Coda normalization – Attenuation of Qs – Temporal Variation

We evaluate the **temporal variation of Q** for the pre-sequence, the 2016-2017 sequence, and the three sub-sequences.



	Gabrielli et al., 2025
Pre-Sequence	$93\ f^{0.58}$
2016-2017 Sequence	$80\ f^{0.66}$
Amatrice Sequence	$98\ f^{0.56}$
Visso Sequence	$58\ f^{0.8}$
Norcia Sequence	$74\ f^{0.7}$

Coda normalization – Attenuation of Qs – Temporal Variation

We evaluated the **temporal variation of Q** for the pre-sequence, the 2016-2017 sequence, and the three sub-sequences of Amatrice, Visso, and Norcia (AVN).

The variation of Q is opposite to the frequency dependence change, as seen also in previous studies (Akinci et al., 2022)

	Gabrielli et al., 2025
Pre-Sequence	$93\ f^{0.58}$
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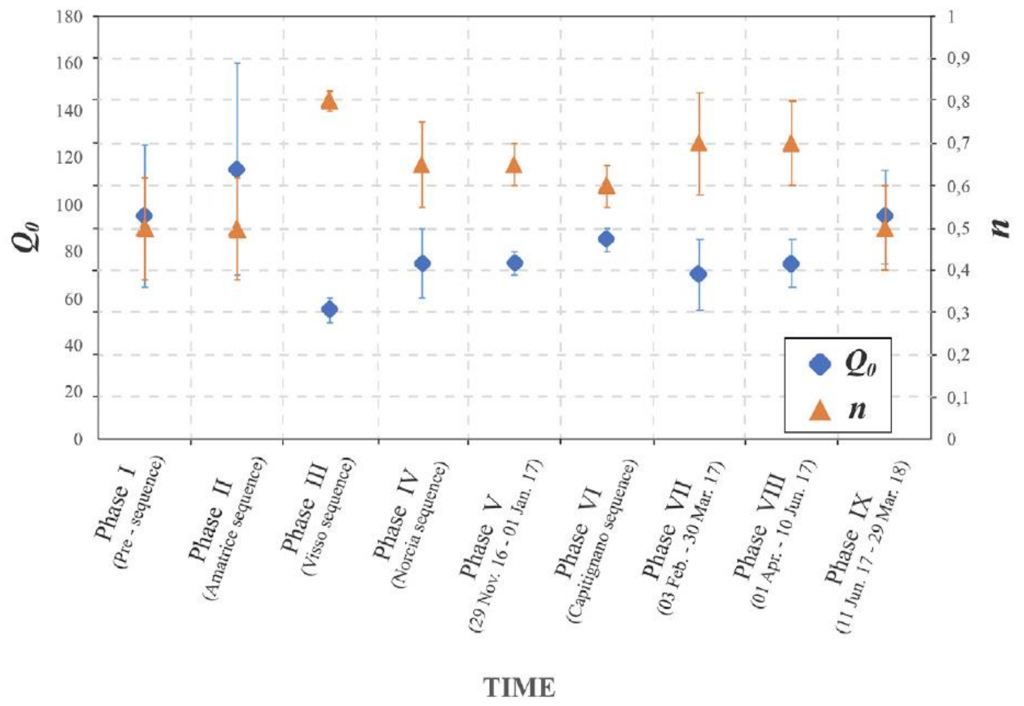
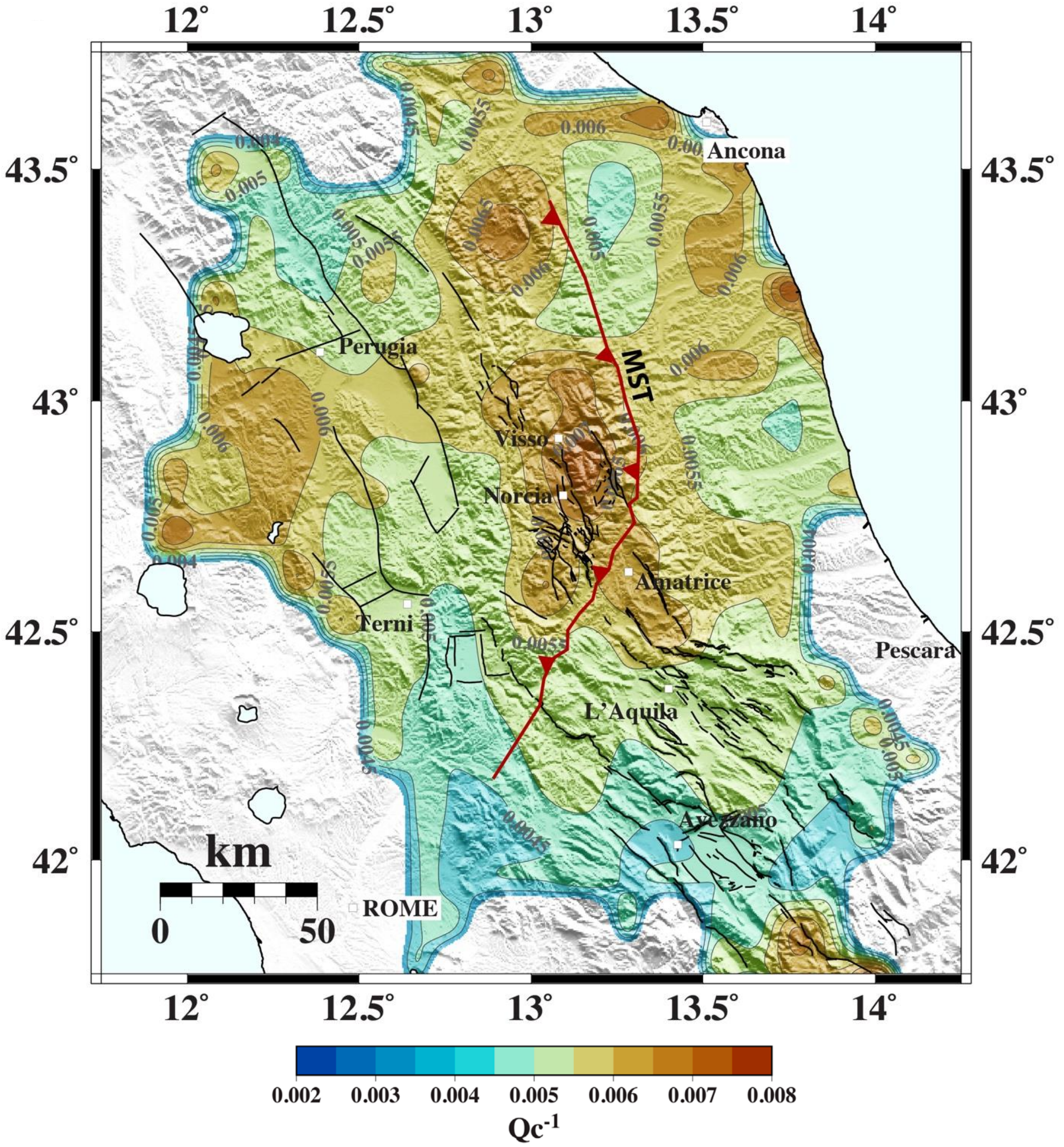


Akinci et al., 2022

Coda normalization – Attenuation of Qs – Spatial Variation

We evaluate the **spatial** and **temporal** variation of **Qc**

There is a **variation** during the sequences in the **spatial distribution** of the attenuation, with **high attenuation** anomalies (low Q – high Qc^{-1}) in the Central Apennines Area



Stochastic Simulation of Time

Y(M₀,R,f) = **E(M₀,f)** × **P(R,f)** × **S(f)** × **I(f)**

TARGET FOURIER AMPLITUDE SPECTRUM

Earthquake source

Propagation path

Site response

Instrument, ground motion, empirical filter

$C \times M_0 \times S(M_0, f)$

$\boxed{\text{G(R) and inelastic Attenuation}}$

$A(f) \times D(f)$

$$C = \frac{\langle R_{\theta\varphi} \rangle VF}{4\pi\rho_s \beta_s^3 R_0}$$

$$S(f) = \frac{4\pi^2 f^2}{1 + \frac{f^2}{f_0^2}}$$

$$P(f) = \frac{e^{-\frac{\pi R f}{Q(f)\beta}}}{R}$$

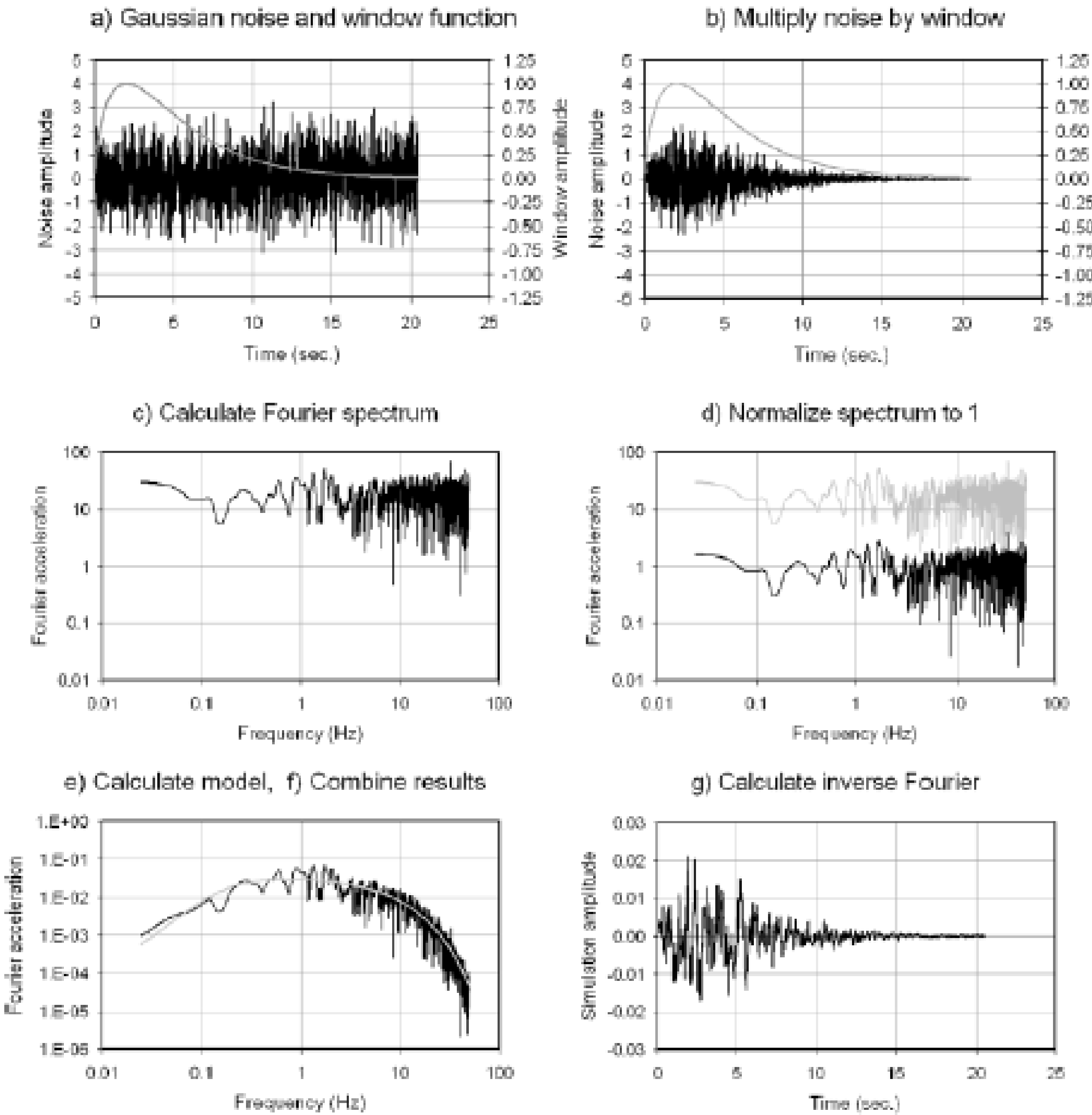
and

$$Q(f) = Q_0 f^{\eta}$$

$$D(f) = \sqrt{\frac{1}{1 + \left(\frac{f}{f_{max}}\right)^8}}$$

or

$$D(f) = \exp(-\pi \kappa_0 f)$$

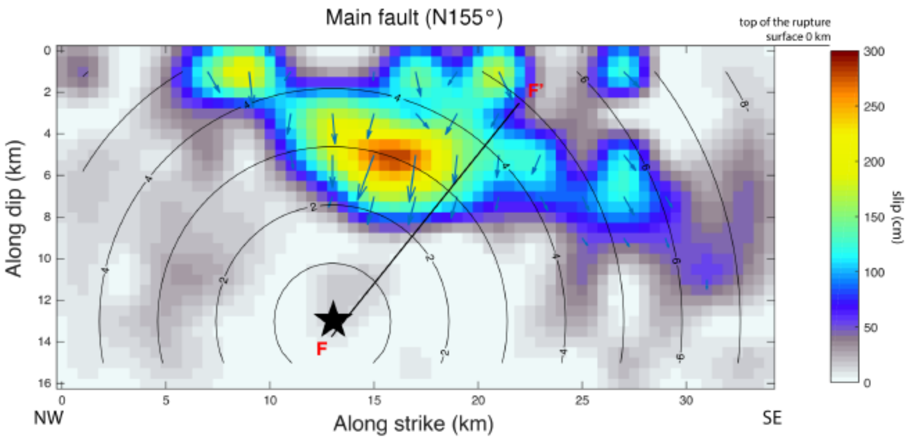


From SCEC BBP EXSIM Documentation

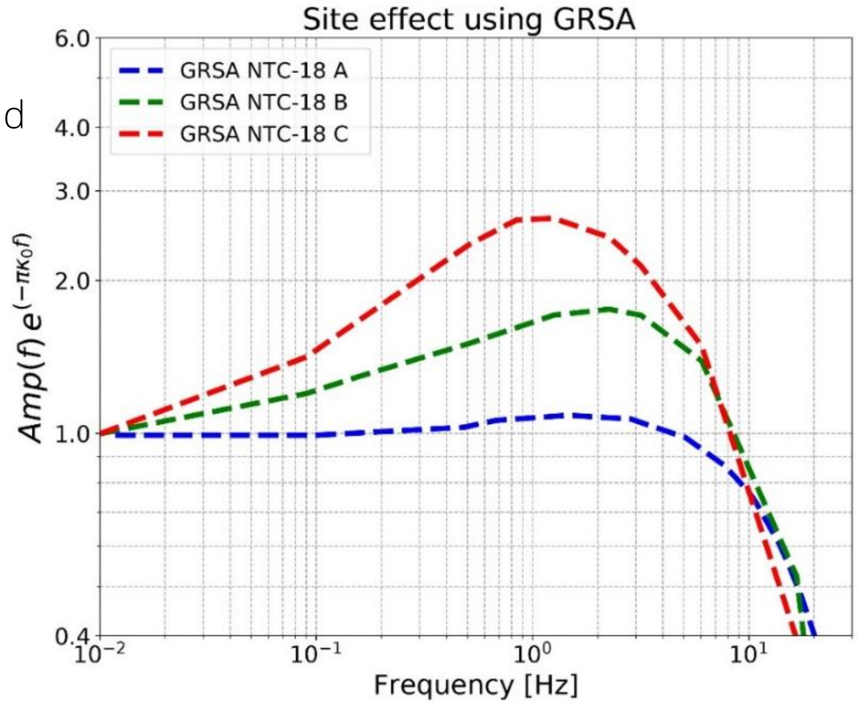
(Motazedian and Atkinson, 2005)

Stochastic Wave Modeling – Input parameters

Fault plane model for the simulation from Scognamiglio et al. (2018)



Generic Site Amplification used in the simulation



This stochastic methodology simulates the strong-ground motion at high frequencies (HF)

Parameter	**Value of Function**	**Reference**
Hypocenter	Latitude = 42.84° ; Longitude = 13.11°; Depth = 9.52 km	INGV
Rupture model	Strike; Dip; N° of subfaults: 155°; 47°, 354	Scognamiglio et al., (2018)
Rupture Time	According Rupture model	Scognamiglio et al., (2018)
Magnitude	Mw6.5	INGV
Stress Drop	20 Mpa	Akinci et al., (2022)
Geometrical Spreading $G(R_{ijm})$	$R^{-1.1}$ if R < 40 km; $R^{-0.5}$ if R > 40 km	Akinci et al. (2022)
Quality Factor	Values of this study: **Qs(f) = 93 f^ 0.58 Pre Seq** **Qs(f) = 80 f^ 0.66 Seq** **Qs(f) = 98 f^ 0.56 Amatrice** **Qs(f) = 58 f^ 0.8 Visso** **Qs(f) = 74 f^ 0.7 Norcia**	This study
Kappa κ_0	0.025 s site A 0.035 s site B 0.040 s site C	Joyner & Boore (1981)
Site Amplification	Generic amplification	NTC-08

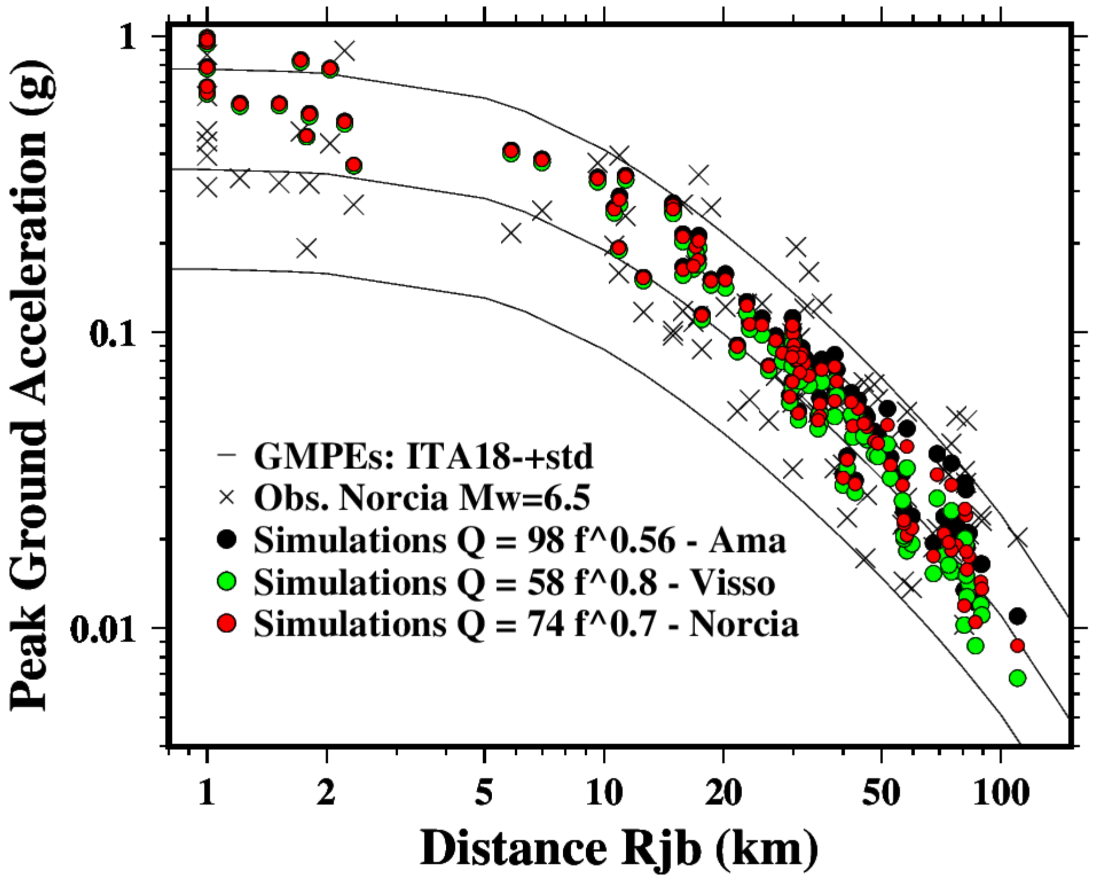
PGA Simulatio

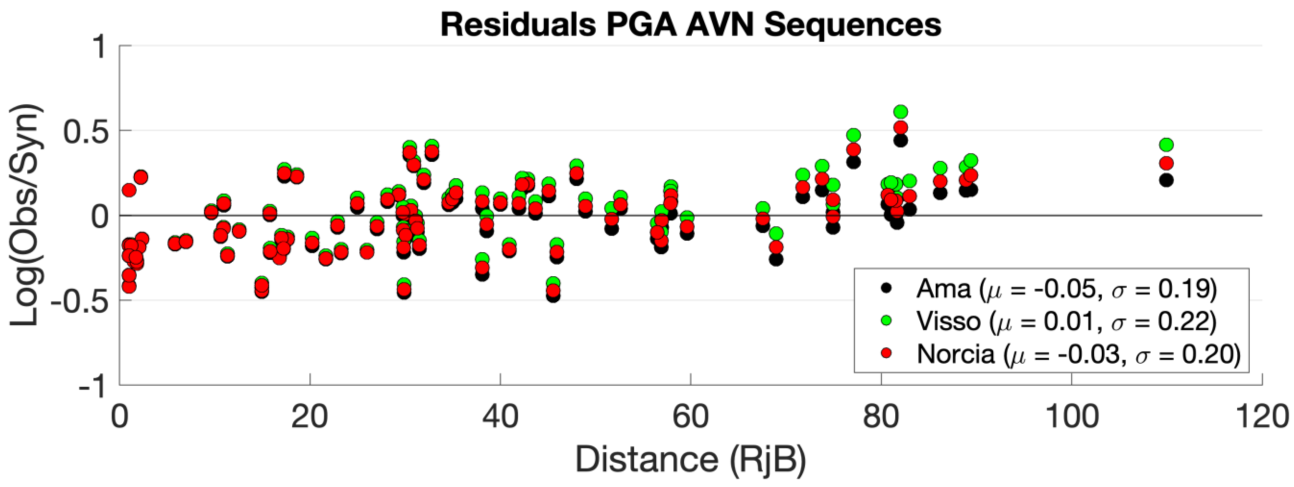
Simulation of GM changing the value of Qo(f)^n for the three subsequences of AVN.

Q (f) = Qo(f)^n strongly vary over time, both in amplitude and in frequency dependence

Even changing the values of Q, the results are in the same range (and in
±1 sd of the GMMs) and do not present high variations, if not at higher Rjb.

This is also visible in the residuals between observed accelerations and simulated



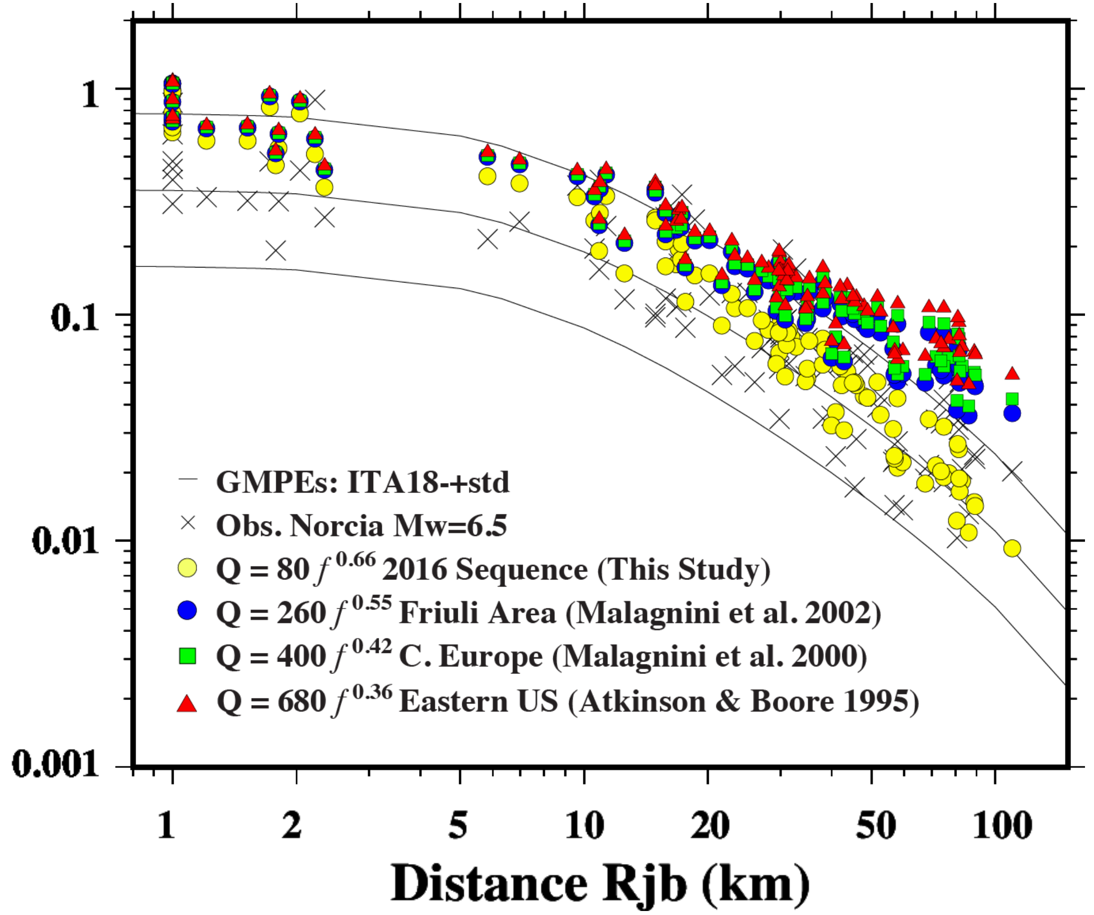


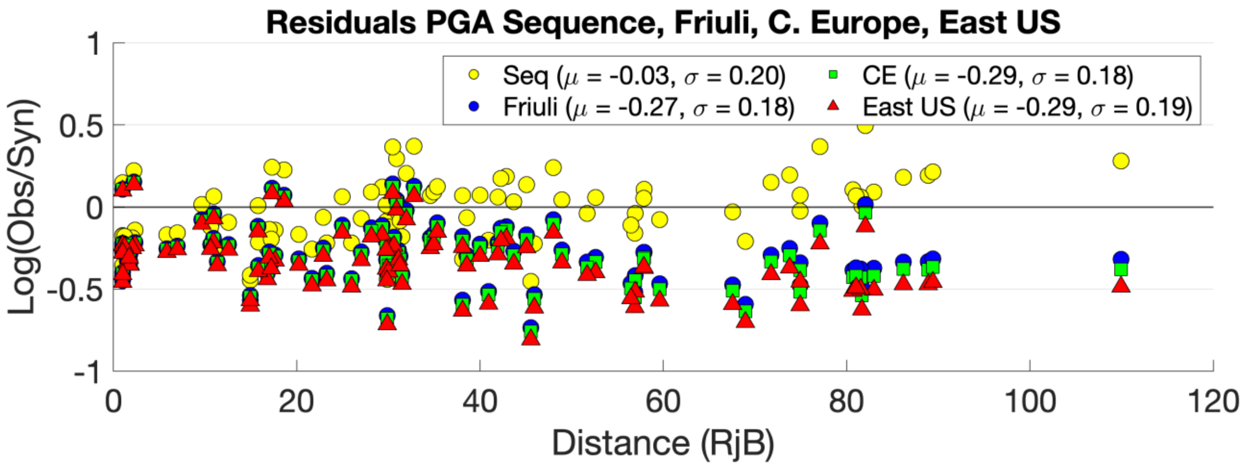
PGA Simulatic

Comparison between different geological regions with different Qo(f)^n (**Friuli**, Central Europe, and Eastern US).

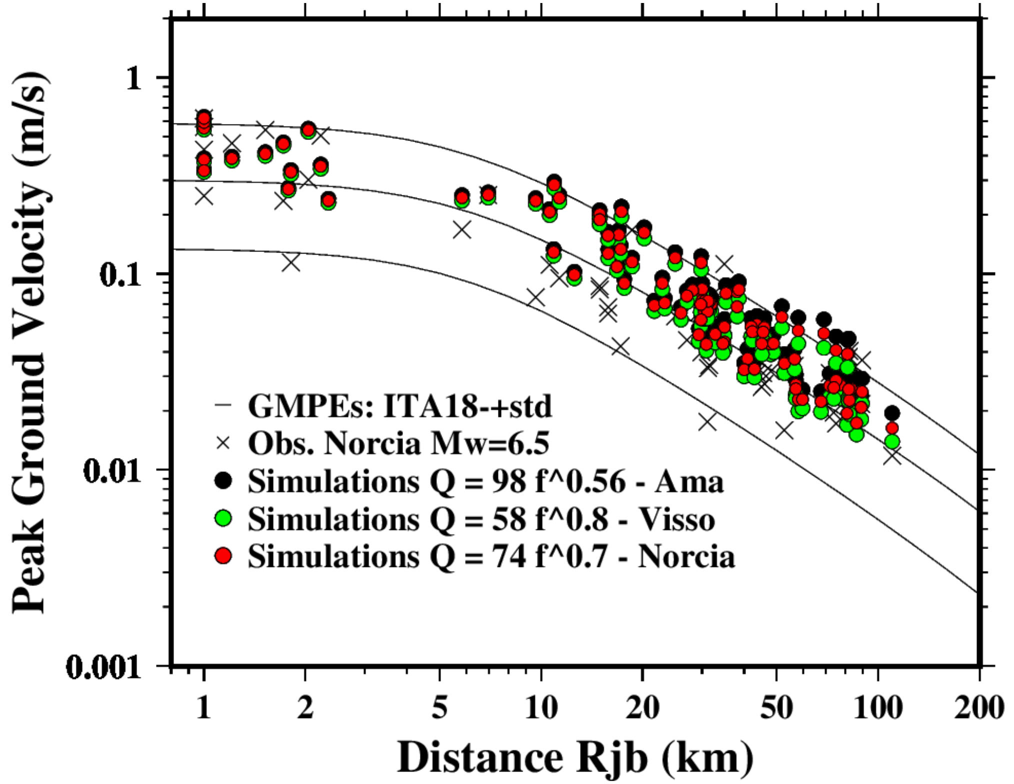
The use of different Q, even if with events of similar magnitude (e.g., Friuli mainshock), shows a clear different trend in the GM predictions

This is also visible with the residuals, with an overestimation when using attenuation values of different geological areas



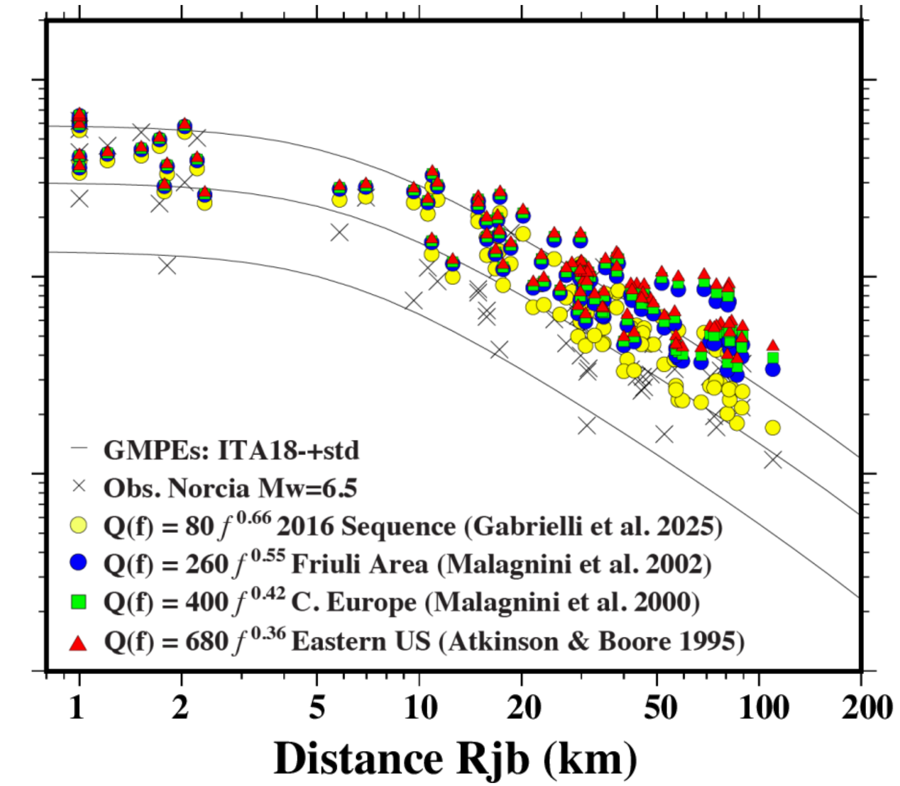


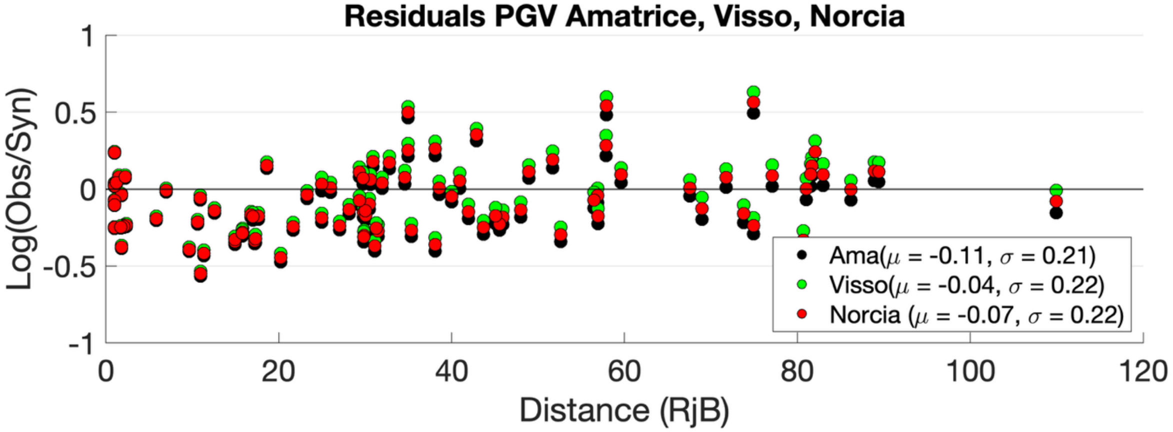
PGV Simulatio

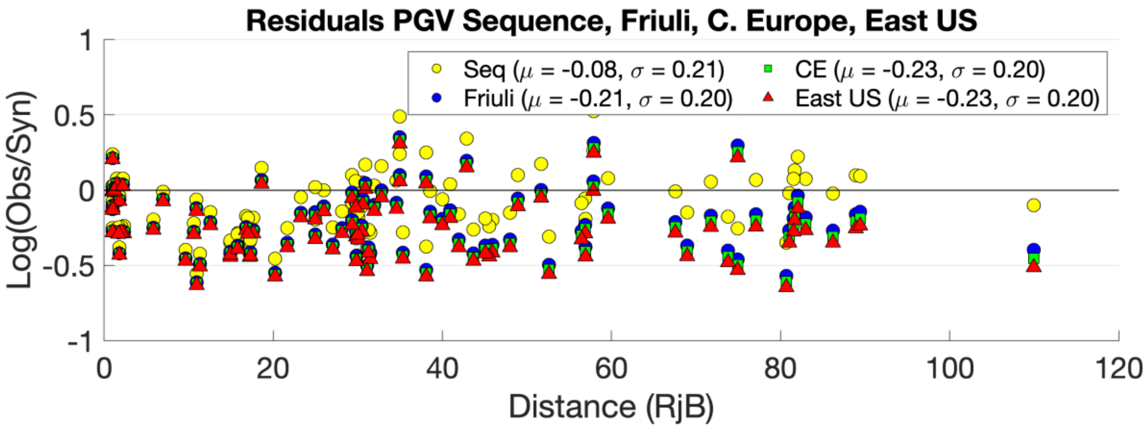


Simulation of GM (PGV) changing the value of Qo(f)^n

As for the PGA, we see larger differences at higher Rjb

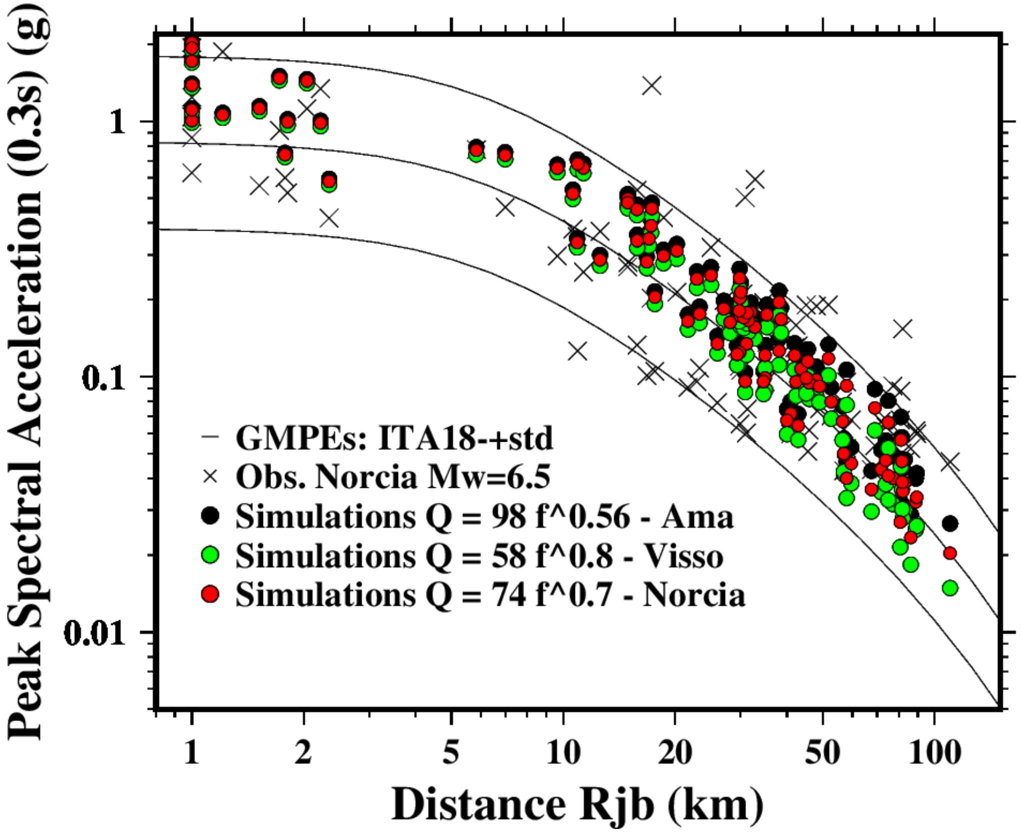


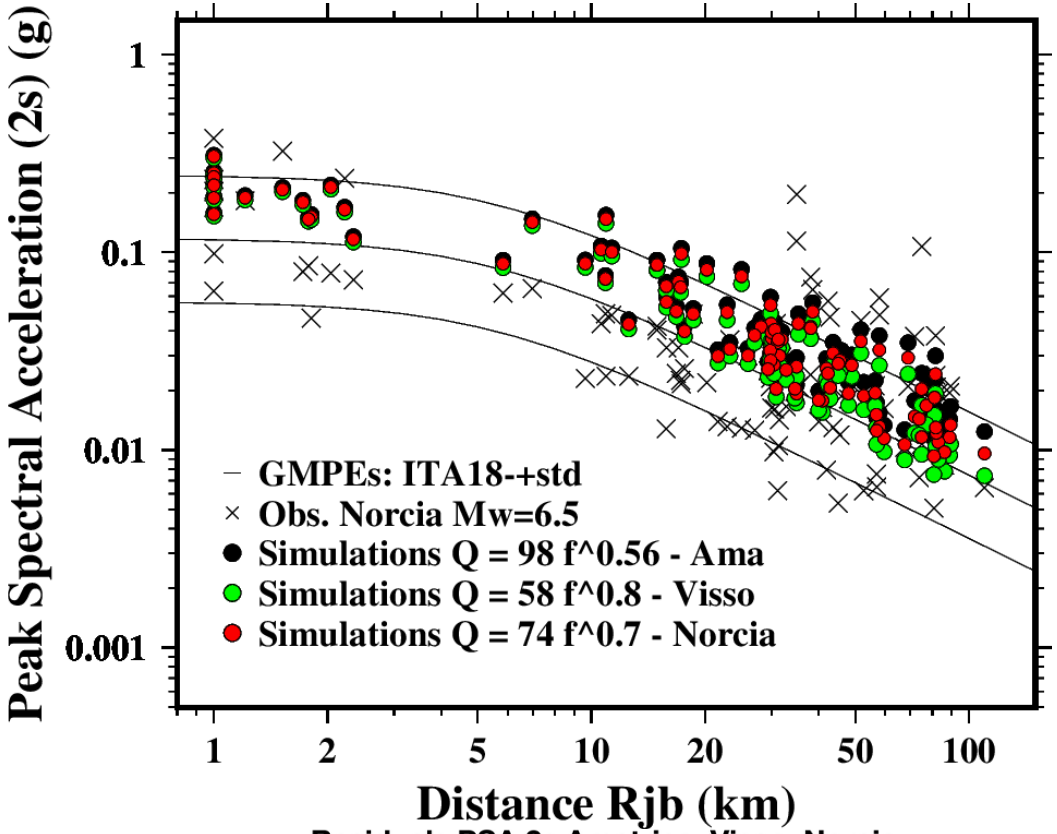


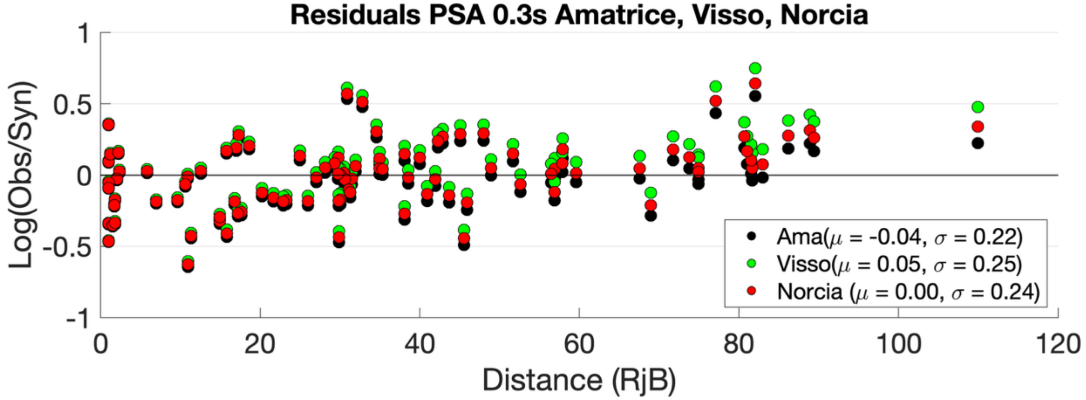


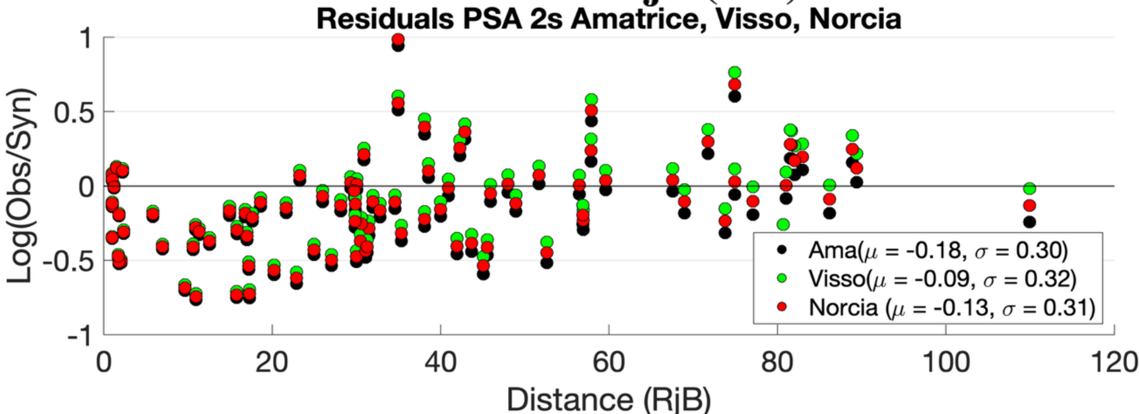
PSAs Simulati

PSA simulations at 0.3s and 2s show **higher decay** during **Visso** with higher attenuation at higher Rjb at 0.3s rather than 2s (lower frequency)





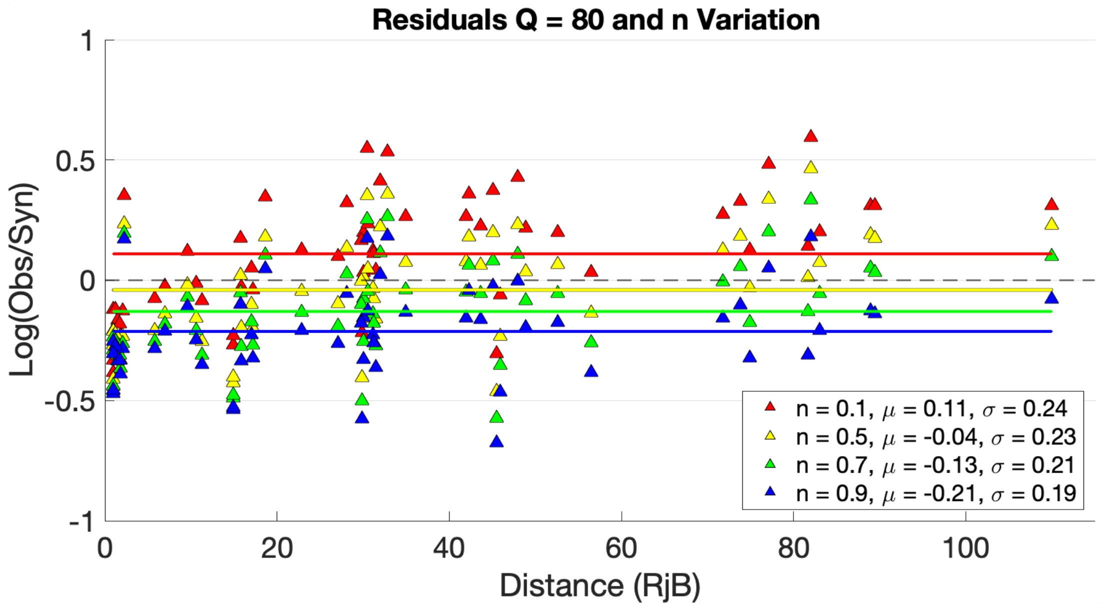


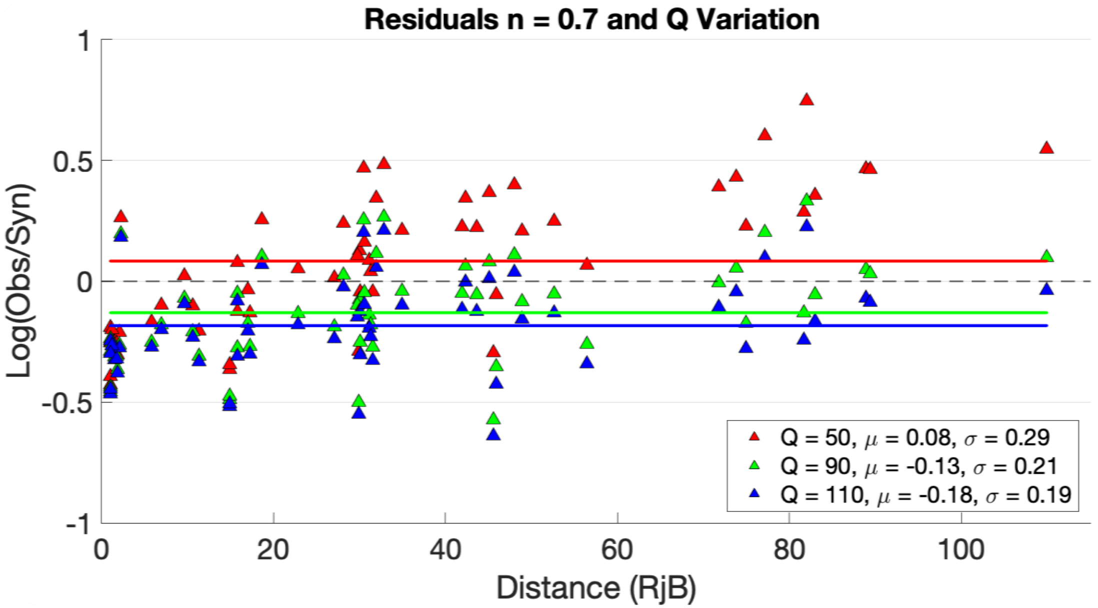


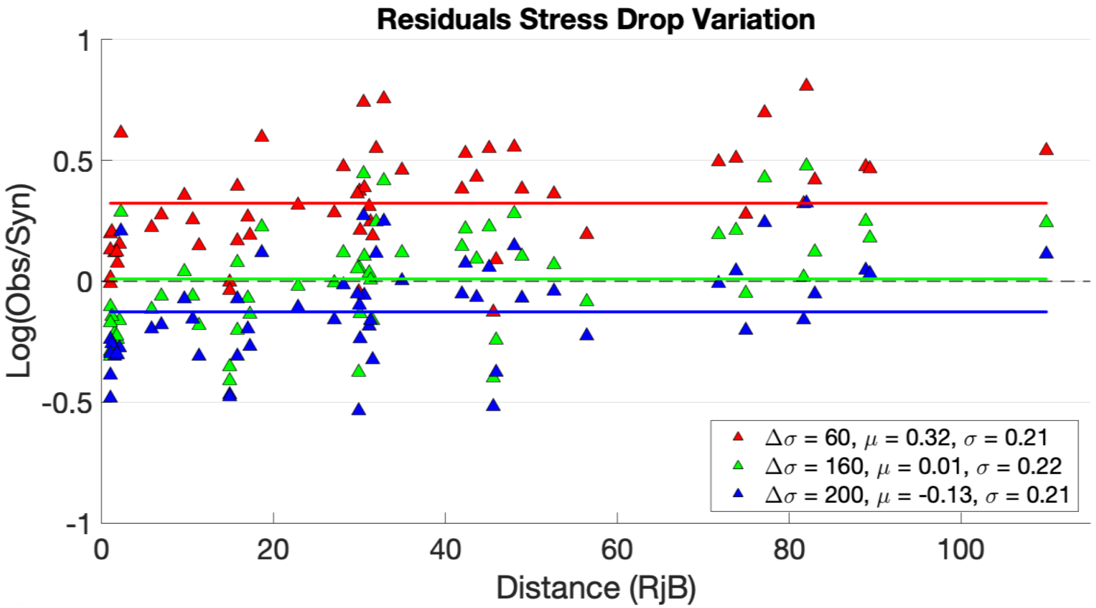
Q, n and Δσ

We performed the simulations by fixing each time the values of Q, n, and Δσ and changing the other parameters.

Our best approximation (lower residuals) varies around 200 bar for the Δσ, around 90 for the Q, and 0.7 for the n.

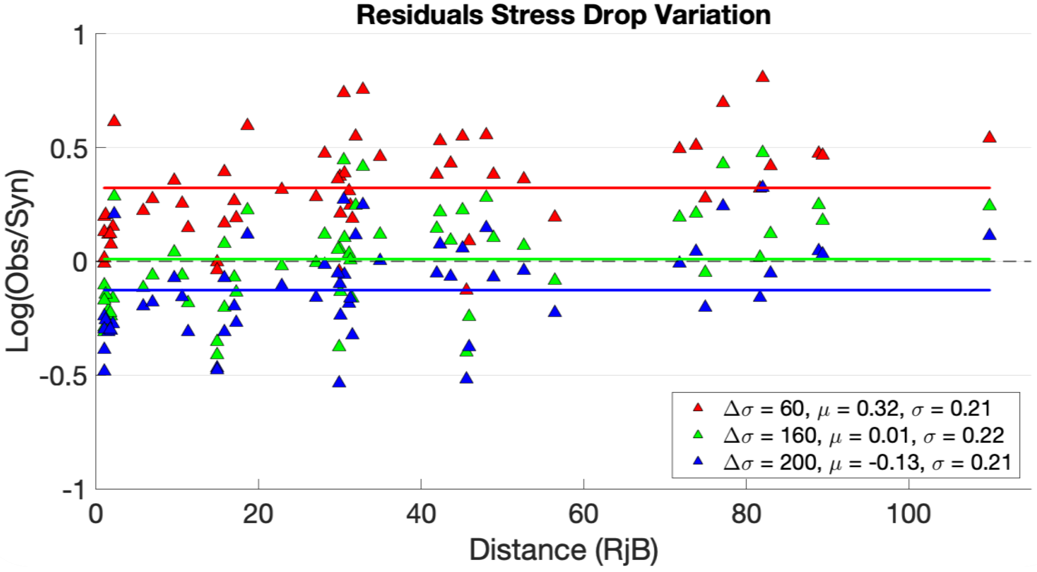


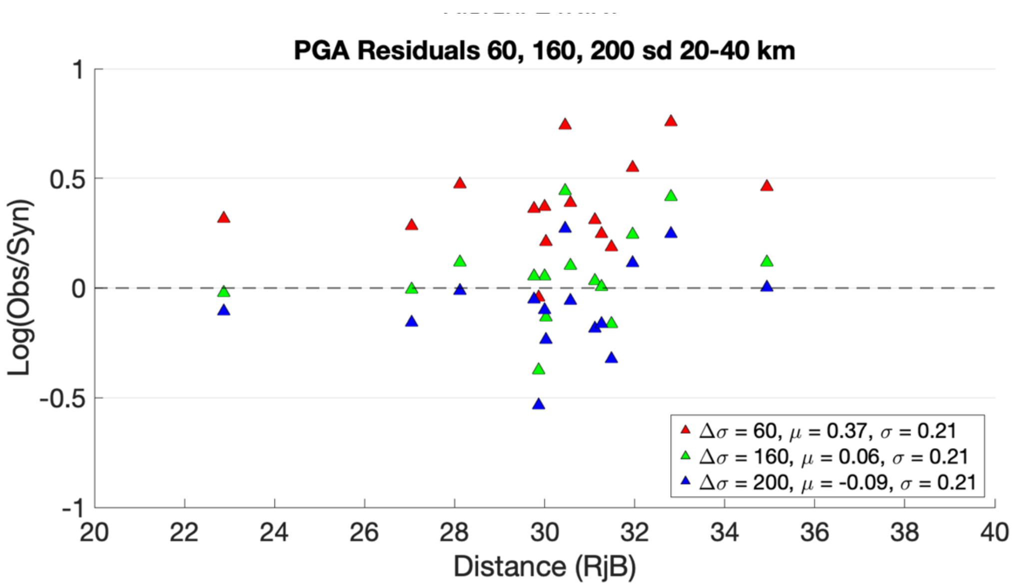


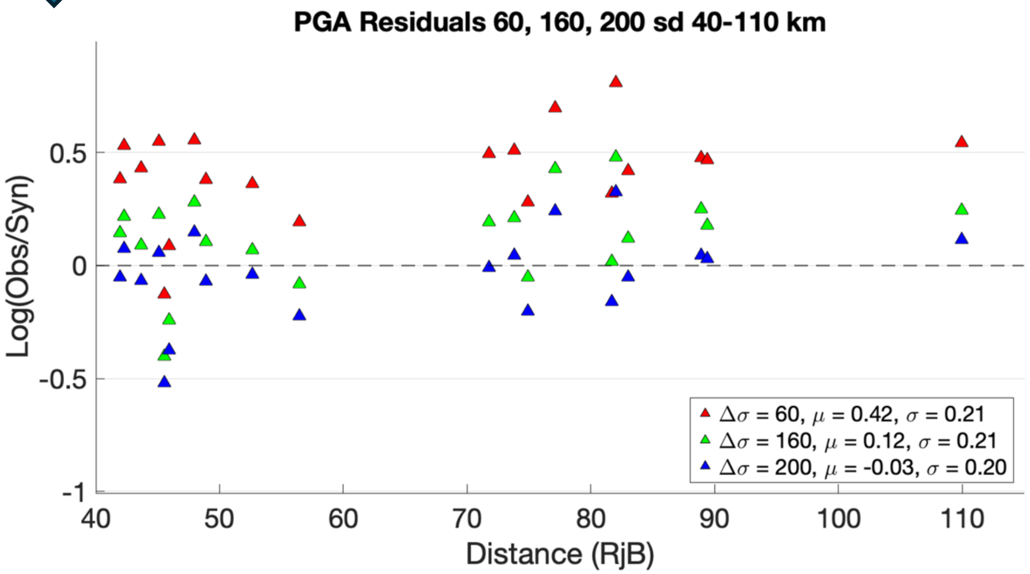


Q, n and Δσ

We checked the best values (mean and standard deviation) for different Rjb intervals



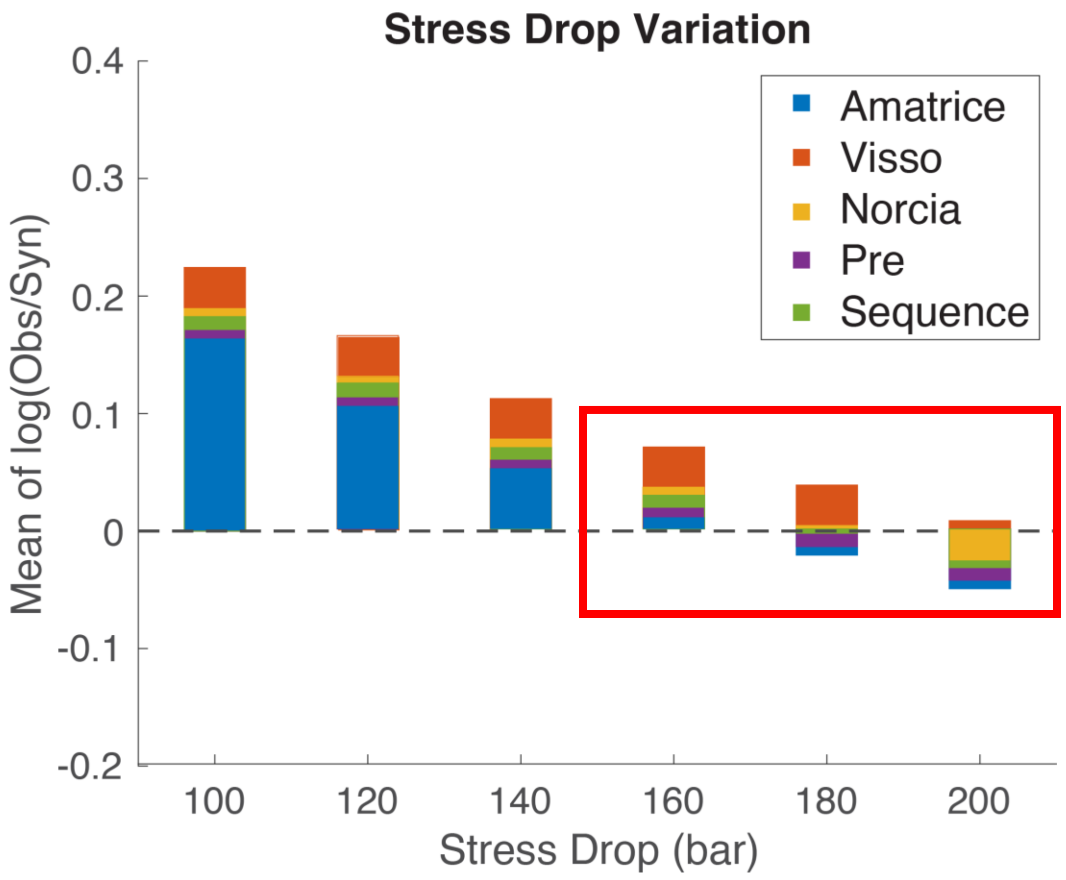




Q, n and Δσ

We simulated the ground motion using the ***$Q_0 f^n$*** values of each sequence from Gabrielli et al. (2025) and changing the **Δσ stress drop parameter**. Our best approximation (lower residuals) varies between **160 and 200 bar**

	140 bar	160 bar	180 bar	200 bar
Pre-Seq.	0.059	0.017	-0.015	-0.044
Sequence	0.070	0.029	-0.004	-0.033
Amatrice	0.052	0.010	-0.022	-0.051
Visso	0.111	0.070	0.037	0.007
Norcia	0.077	0.035	0.003	-0.027



Those values **agree** with the ones found by Akinci et al. (2022)(**160 – 200 bar**) and Malagnini & Munafò (2018) (> 200 bar for Mw≥5.5), **but** they are **higher** than those one of Morasca et al. (2022) of 1-100 bar and of Calderoni & Abercrombie (2023) of max 60 bar.

Conclusion

- Q is decreasing during the sequence, particularly during the Visso phase – probably related to fluid distribution during the sequence
- The **comparison** of the stochastic simulation of the **PGA, PGV** and **PSAs** of the Norcia mainshock, using the Q of the AVN sequence shows a **general agreement** even with fluctuations in the Q(f) and n parameter, with some variations at higher Rjb
- The use of Q(f) from other geological areas shows a stronger impact on the PGA and PGV absolute values, showing the impact of the Q(f) and its frequency dependence n on the peak ground simulation.


Thank you!