Spectral Corrections for Propagation and Site Effects: Implications for Stress Drop Estimation in the 2016 M_w 6.0 Amatrice Earthquake

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How Do Propagation and Site Effects Influence Stress Drop Estimates?

Goal: Understand why GMPEs suggest much higher stress drops (10-18 MPa) than published estimates (3-4 MPa).

Comparison of Two Spectral Corrections Methods for Propagation and Site Effects

➢ Gabrielli et al. (2025) – SG

Gabrielli S., Akinci A., Del Pezzo E. (2025). *Temporal and spatial variability of S-wave and coda attenuation in the Central Apennines, Italy*. Front. Earth Sci., 12:1487797, doi: 10.3389/feart.2024.1487797

- **Geometrical Spreading :** $G(R) = 1/R$

- **Propagation and Site Effect:** $A(f,R) = e^{-\pi f R / (\beta Q(f))} \cdot e^{-\pi k_{\mathrm{Site}} f} \cdot H_{\mathrm{STAZ,SG}}(f)$ with $Q(f) = Q_0 \cdot f^{n}$
  - $Q_0 = 80$
  - $n = 0.66$
  - $\beta = 3.5$ km/s
  - $k_{\mathrm{Site}} = 0.02$ (A), 0.03 (B), 0.04 (C), 0.05 (D)

➢ Calderoni & Abercrombie (2023) – GC

Calderoni G., Abercrombie R. E. (2023). *Investigating spectral estimates of stress drop for small to moderate earthquakes with heterogeneous slip distribution*. JGR: Solid Earth, 128, e2022JB025022, doi: 10.1029/2022JB025022

- **Geometrical Spreading :** $G(R) = 1/R$

- **Propagation and Site Effect:** $A(f,R) = e^{-\pi k_{\mathrm{TOT}} f} \cdot H_{\mathrm{STAZ,GC}}(f)$ with $k_{TOT} = \int \frac{1}{Q} ds$

k_{TOT}, the frequency-independent attenuation parameter (Anderson & Hough, 1984; Singh et al., 1982)
$H_{\mathrm{STAZ}}(f)$ is the site term (Calderoni et al., 2019)

SECURE

REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

GC: k_{TOT} versus distance

Due to the structure of equation (Singh et al. 1982; Anderson & Hough, 1984)

$$k_{TOT} = \int \frac{1}{Q}\, ds$$

The frequency-independent attenuation parameter, k_{TOT} tends to increase with source distance. However, the variability at similar distances can be large because of variations of Q in the uppermost layers at different stations.

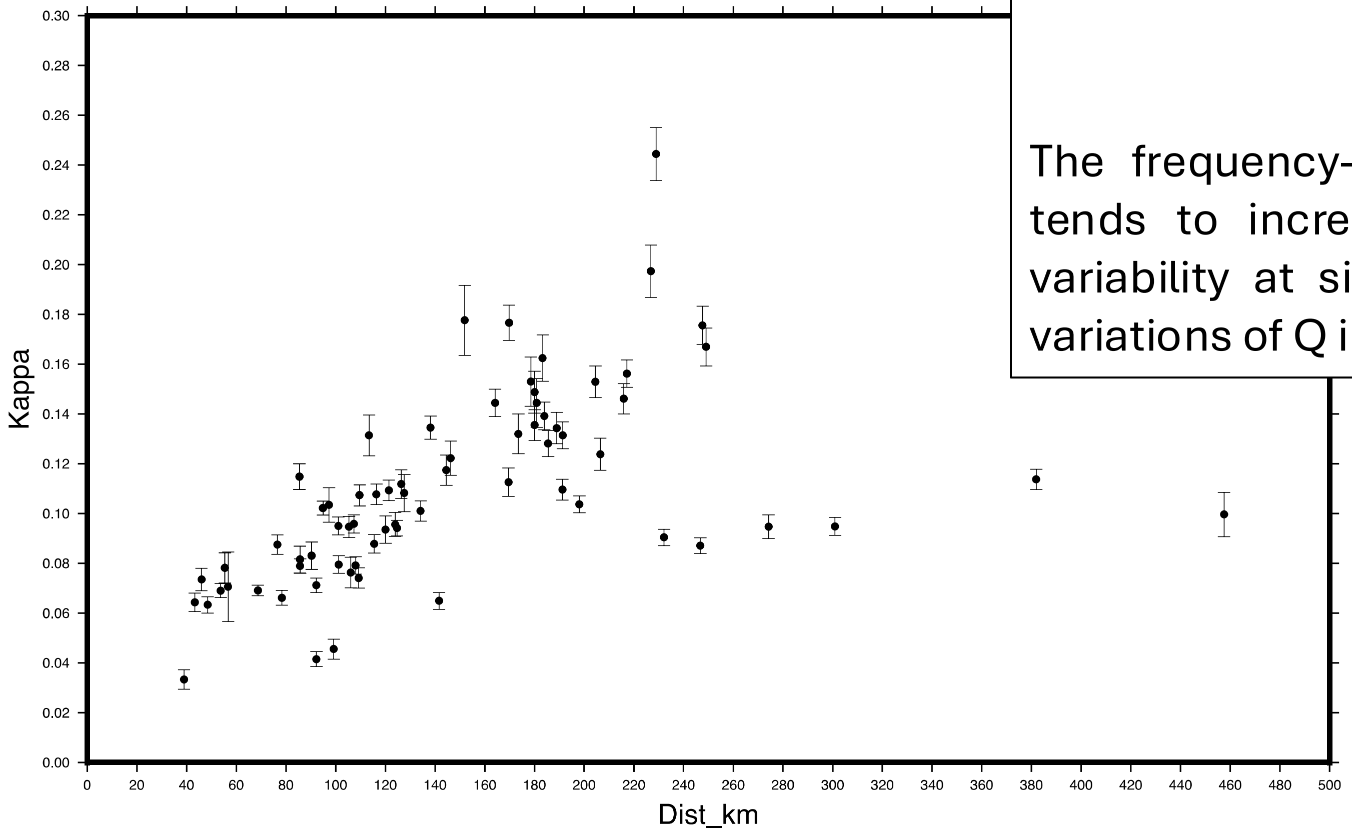
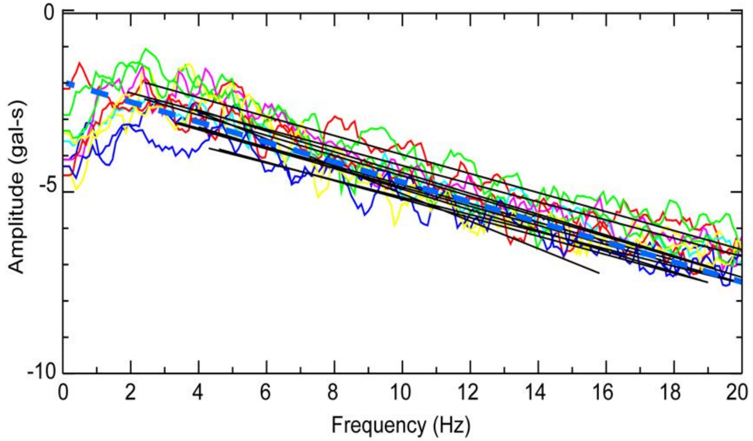


Fig. 1 k_{TOT} versus distance from the center of the AVN seismic sequence

Attenuation parameter κ_{TOT}



k_{TOT}, the frequency-independent attenuation parameter, characterizes the exponential decay of attenuation, calculated at each station (Anderson & Hough, 1984; Singh et al., 1982), $H_{STAZ}(f)$ is the site term (Calderoni et al., 2019)

SG: k_{Site}= 0.02 (A), 0.03 (B), 0.04 (C), 0.05 (D)

Comparison of propagation and site effects (R<120 km):

Models:

- **SG** (k_{Site} + Q(f) + H $_{STAZ,SG}$(f))
- **GC** (k_{TOT} + $H_{STAZ,GC}$(f))

Examples of corrected spectra using both approaches for each station and different values of:

- ✓ $k_{Site}, H_{STAZ,SG}(f)$
- ✓ $k_{TOT}, HST_{AZ,\ GC}(f)$

- k_{Site} = 0.02 (A), 0.03 (B), 0.04 (C), 0.05 (D)

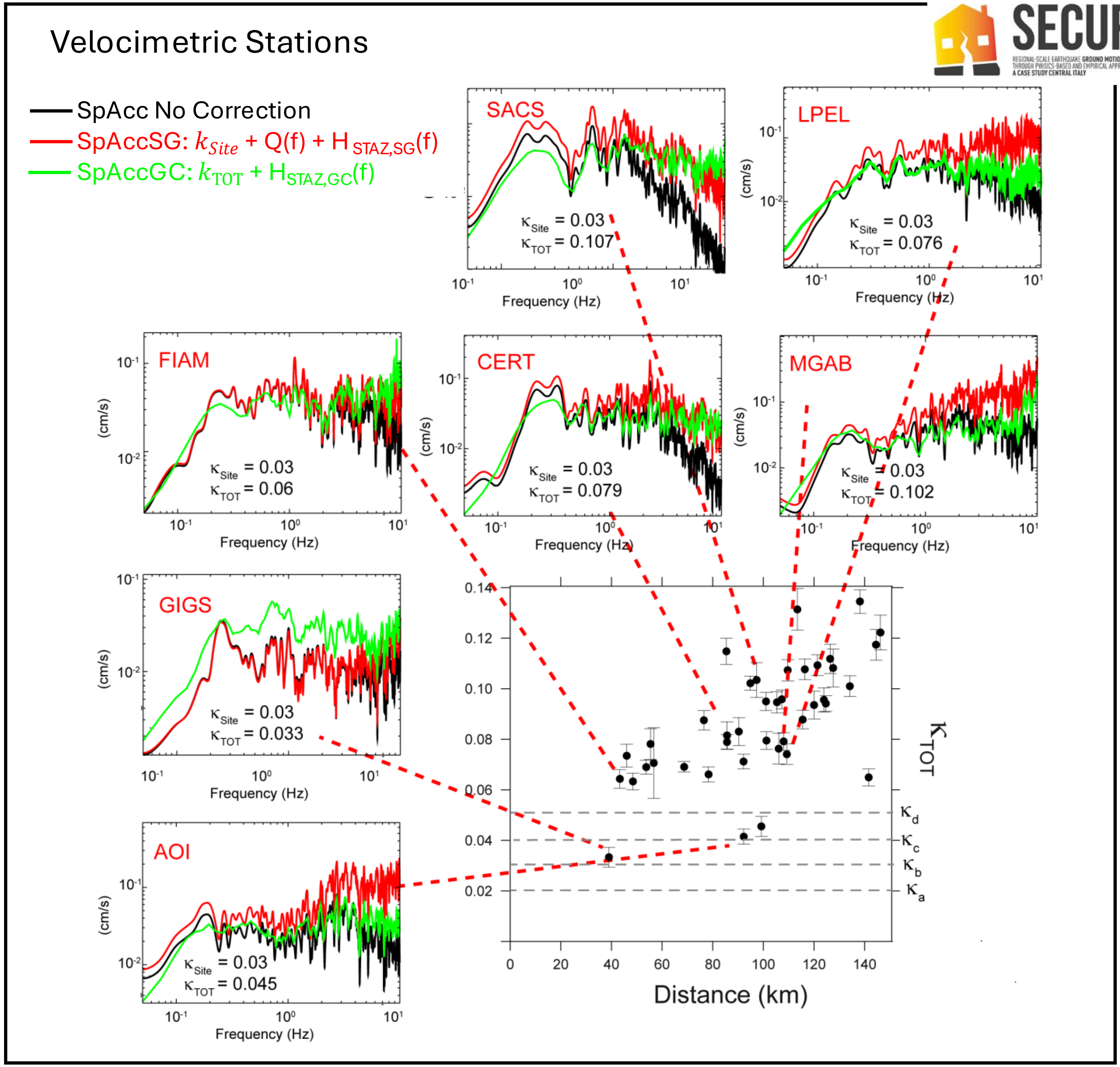
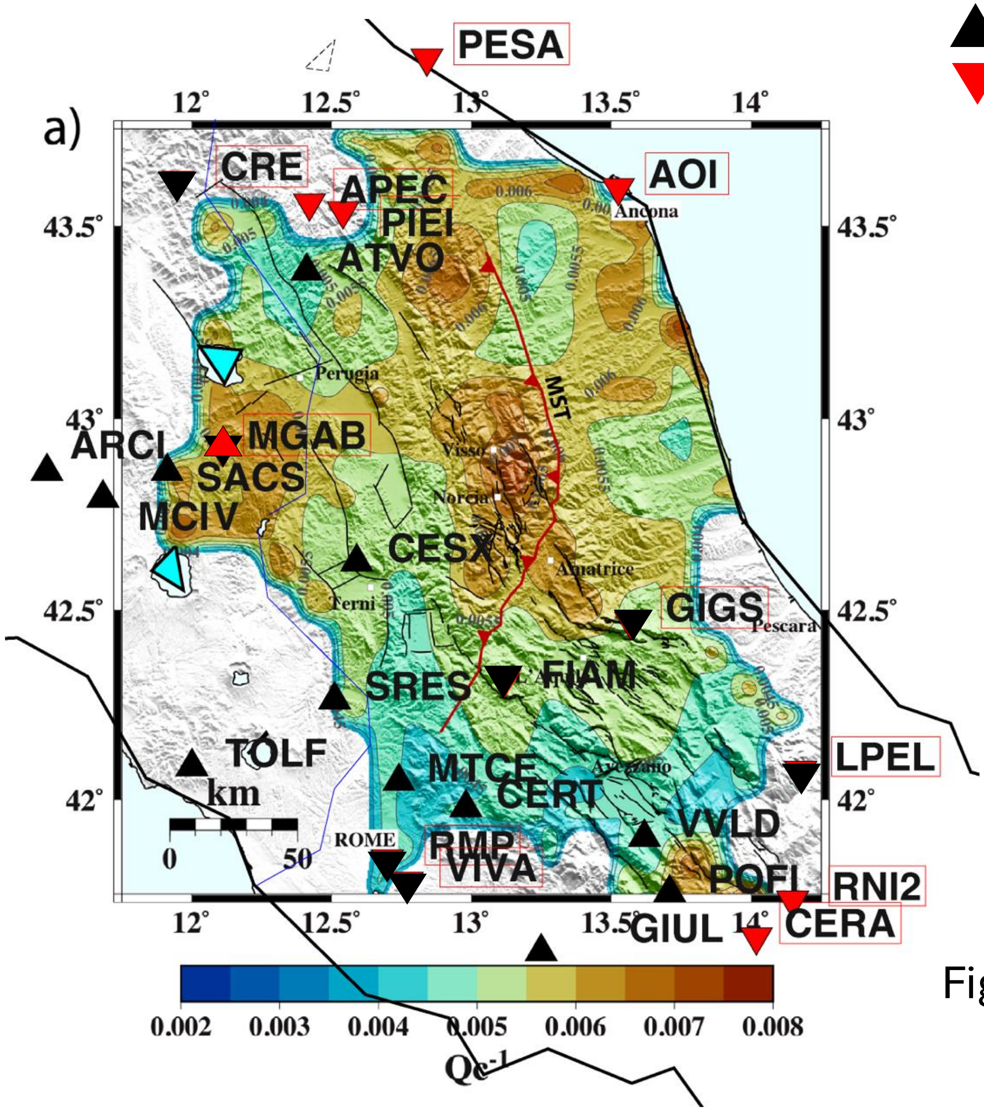


Fig. 2 Comparison of the Acceleration Spectra

Comparison of propagation and site effects (R<120 km):



▲ **High-Frequency Compensation (HFC)**

▼ **High-Frequency No Compensation (NFNC)**

- Out of the 18 **Staz HFC** stations, 12 are located within the area examined by Gabrielli et al., 2025.
- Out of the 7 **HFNC** stations, only 2 are within the examined area.

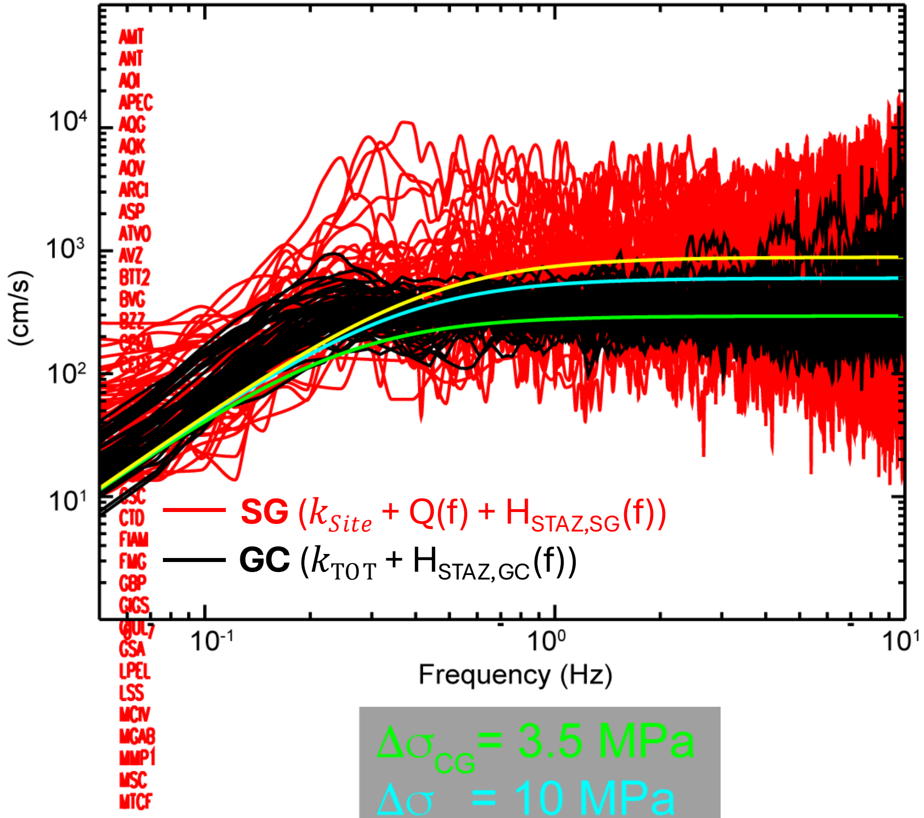
Fig. 3 Redraw Fig. 8 from Gabrielli et al., (2025)

Velocimetric Stations

N	HFC	HFNC
1	ARCI	APEC
2	ATVO	CERA
3	CERT	MGAB
4	CESX	PESA
5	GIUL	PIEI
6	MCIV	RNI2
7	MTCE	AOI
8	POFI	
9	SACS	
10	SRES	
11	TOLF	
12	VVLD	
13	CRE	
14	GIGS	
15	LPEL	
16	RMP	
17	VIVA	
18	FIAM	

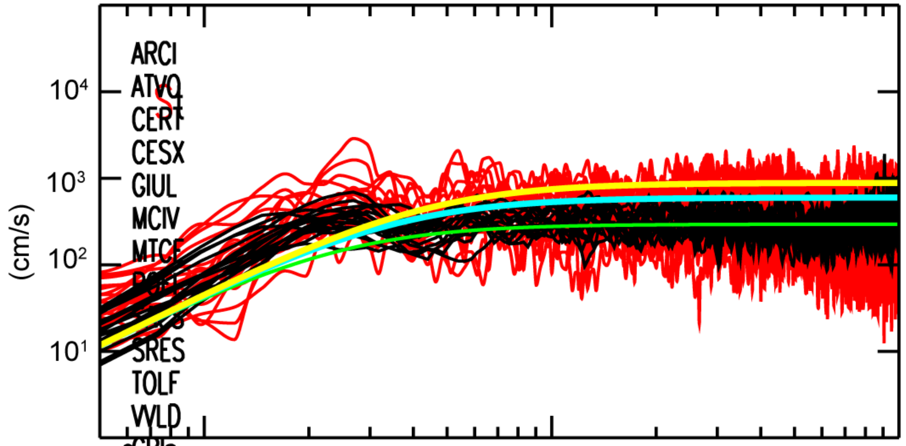
Comparison of the Acceleration Spectra: SG vs GC

Velocimetric Stations



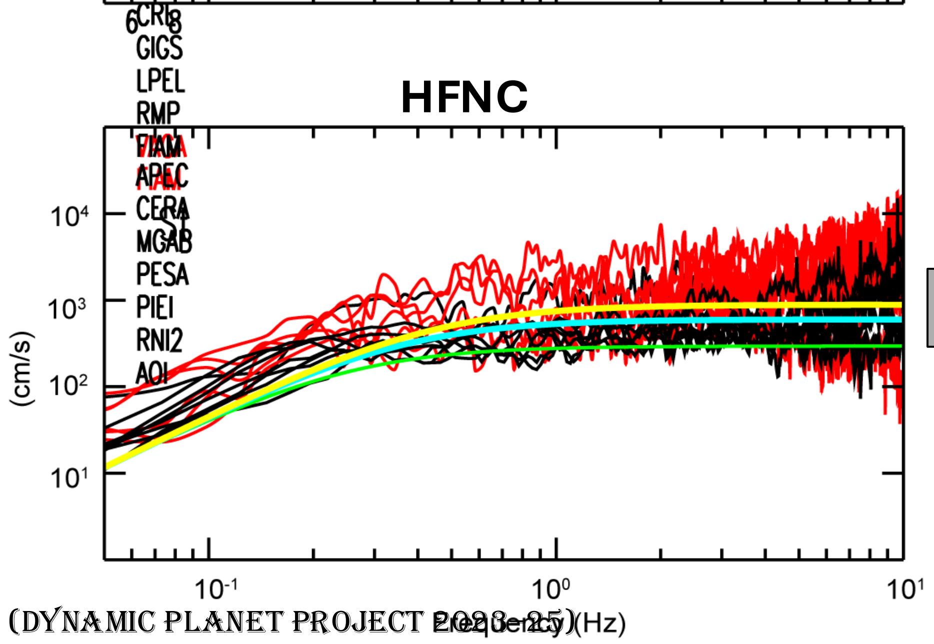
$\Delta\sigma_{CG}$= 3.5 MPa
$\Delta\sigma$ = 10 MPa
$\Delta\sigma$ = 18 MPa

HFC



$\Delta\sigma$= 3.5 MPa

HFNC



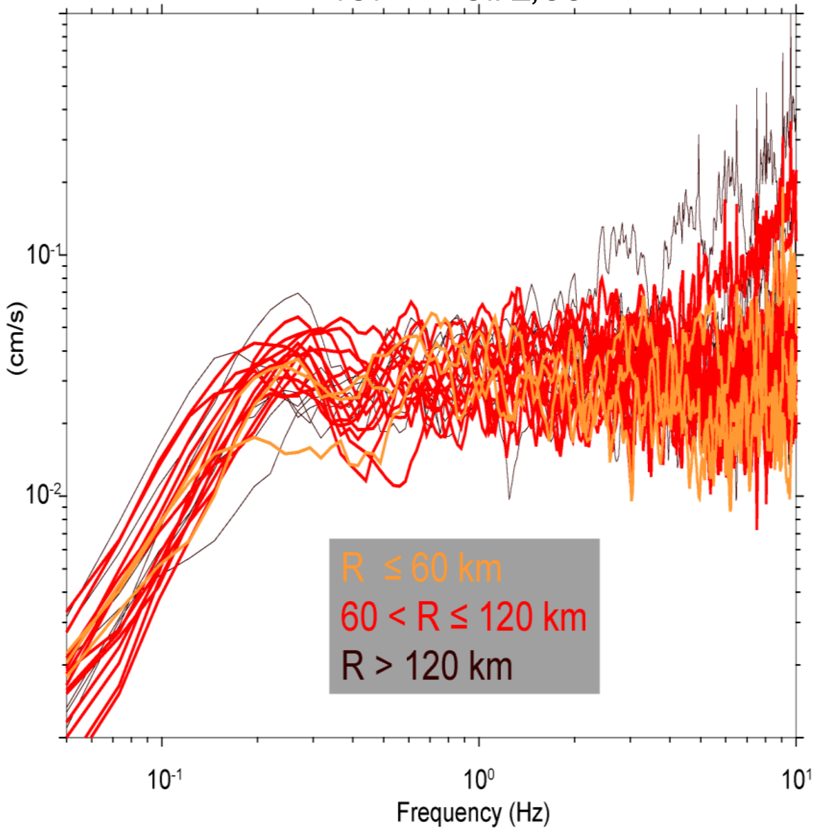
$\Delta\sigma$= 18 MPa

HFC: High-Frequency Compensation
HFNC: High-Frequency No Compensation (NFNC)

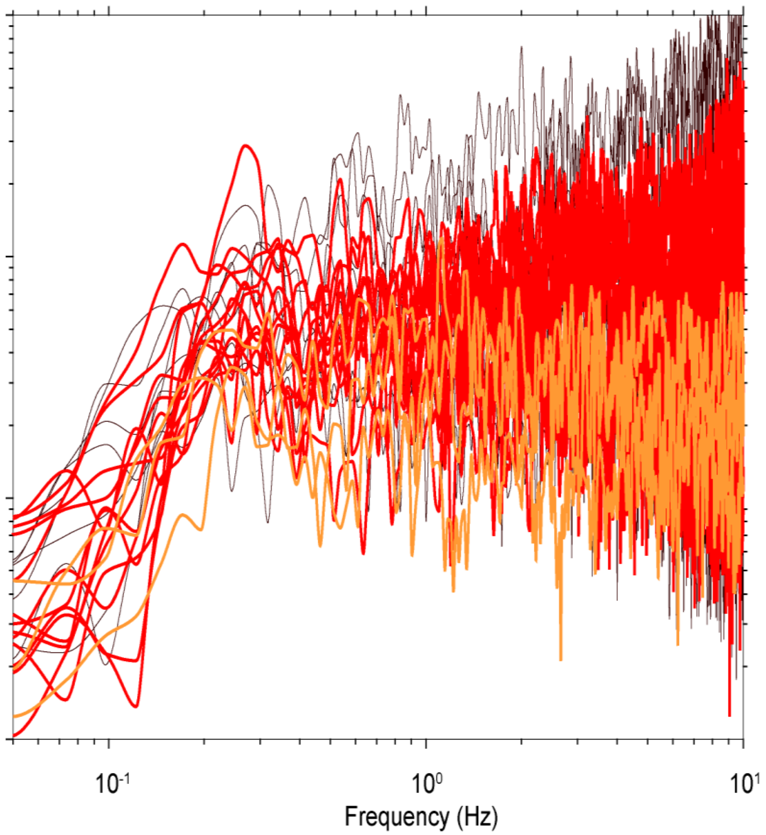
Dependence of the Correction (Propagation + Site) on Distance

Velocimetric Stations

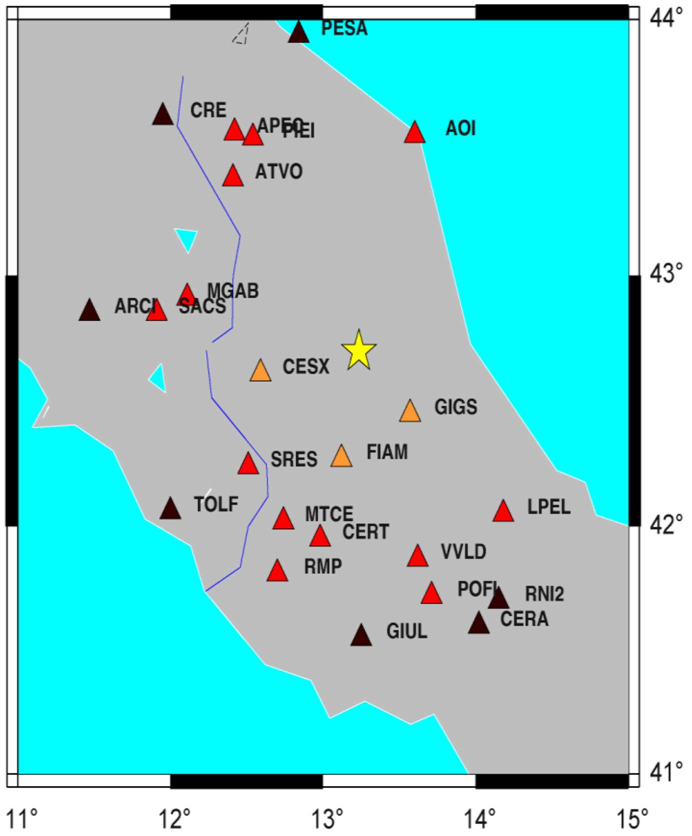
GC (k_{TOT} + $H_{STAZ,GC}$(f))



SG (k_{Site} + Q(f) + $H_{STAZ,SG}$(f))



Velocimetric Stations



Effect of Propagation and Site Corrections on Stress Drop Estimates ($\Delta\sigma_{SP}$)

Methodological ***Overview***

In Calderoni & Abercrombie (2023) is described the method used to estimate the Brune stress drop thought the spectral fitting ($\Delta\sigma_{SP}$):

- $\Delta\sigma_{SP}$ is determined assuming a straightforward circular source model (e.g., Brune, 1970; Madariaga, 1976).
- The amplitude spectrum of the ground motion at distance R from the source (V(f,R)) is the convolution of source ($\Omega_0(f)$), propagation along the path (A(f,R)), site effect (H(f)), and the instrument response (I(f)):

$$\Omega_0(f) = 2\pi f \cdot A(f,R) \cdot H_{STAZ,GC}(f) \cdot I(f)$$

$$\Omega_0(f) = \frac{F_S R_{\vartheta,\varphi}}{4\pi\rho\beta^3} \frac{M_0}{1+\left({}^{f}/_{f_0}\right)^2}$$

$$A(f,R) = 1/R\ e^{-\pi\kappa_{TOT} f}$$

$$\begin{cases} \Delta\sigma_{SP} = \dfrac{7}{16}\dfrac{M_0}{r^3} \\ r = \dfrac{0.3723\ \beta}{f_0} \end{cases}$$

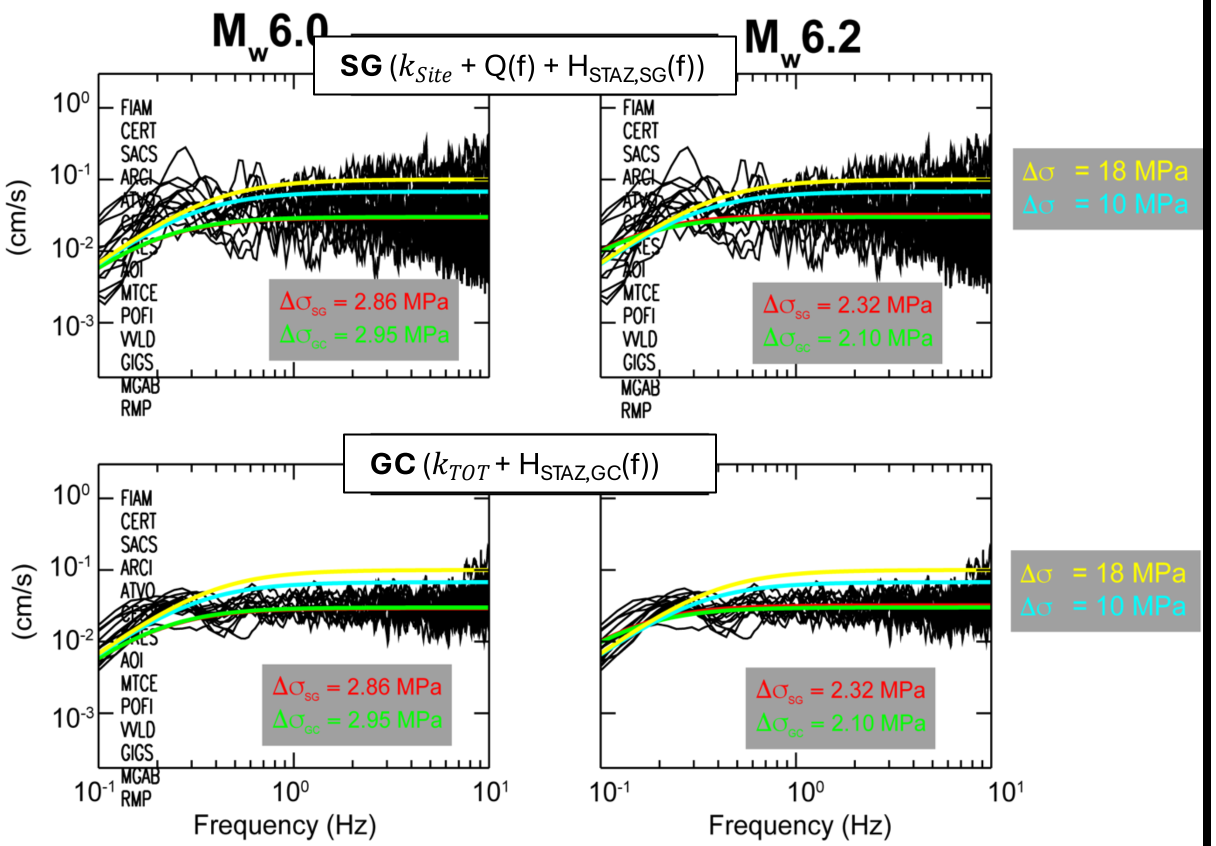
- A(f,R) is estimated (Anderson and Hough,1984; Calderoni et al. 2013) from the combined effect of the geometric spreading (1/R) and the crustal attenuation parameterized by the frequency-independent attenuation parameter, κ.

- The site term $H_{STAZ}(f)$ is estimated by computing an average curve $H_{STAZ}(f)$ for each station, obtained by:
  - Calculating the average spectral amplitude of each event.
  - Determining the difference between the mean spectrum of the events and the estimated spectrum at each station.
  - Averaging the differences calculated across all seismic events considered in the study.

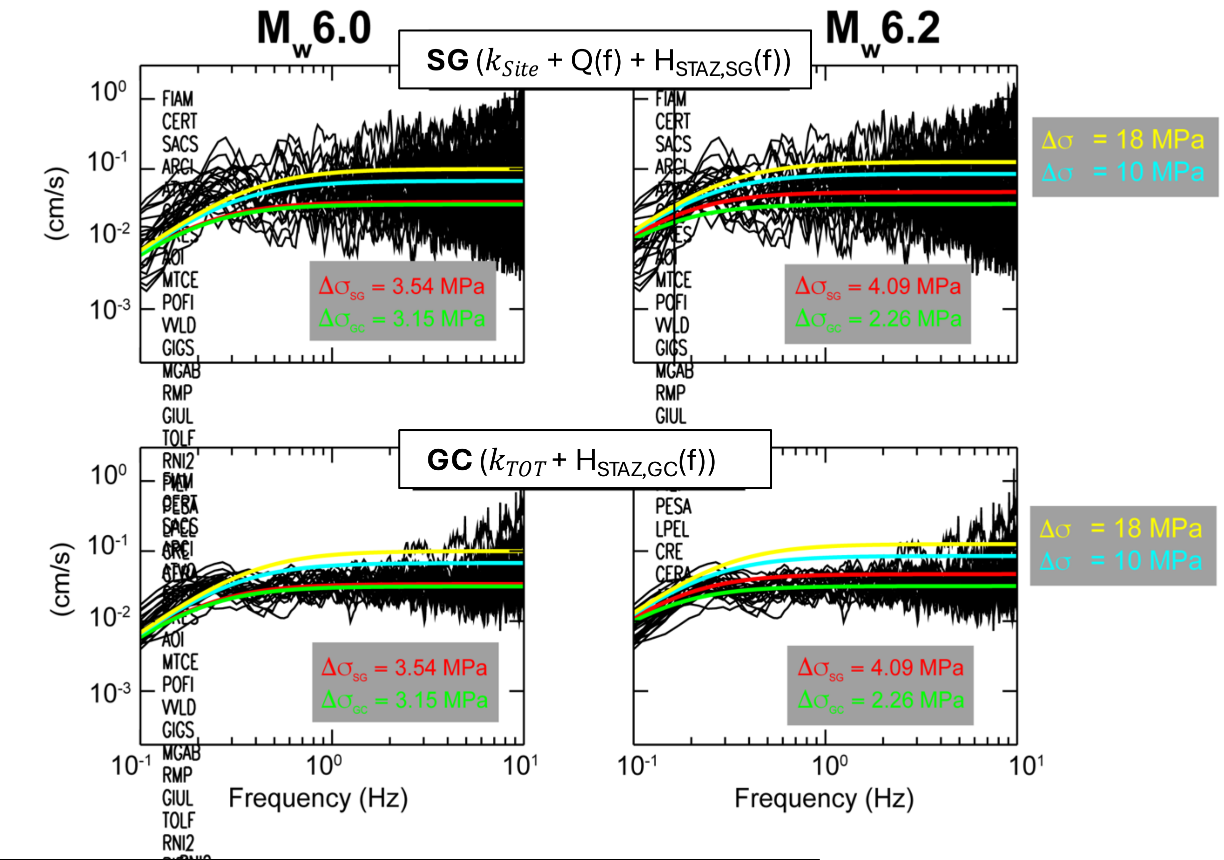
Effect of Propagation and Site Corrections on Stress Drop Estimates ($\Delta\sigma_{SP}$)

$\Delta\sigma_{SP}$ estimated from **SG**- and **GC**-corrected spectra, using **Velocimetric Stations** within Gabrielli et al. (2025) area and R <120 km, assuming M_w6.0 (INGV) and M_w 6.2 (USGS, GFZ).

Selected Stations within the Gabrielli et al. (2025) Area



Selected Stations within R < 120 km

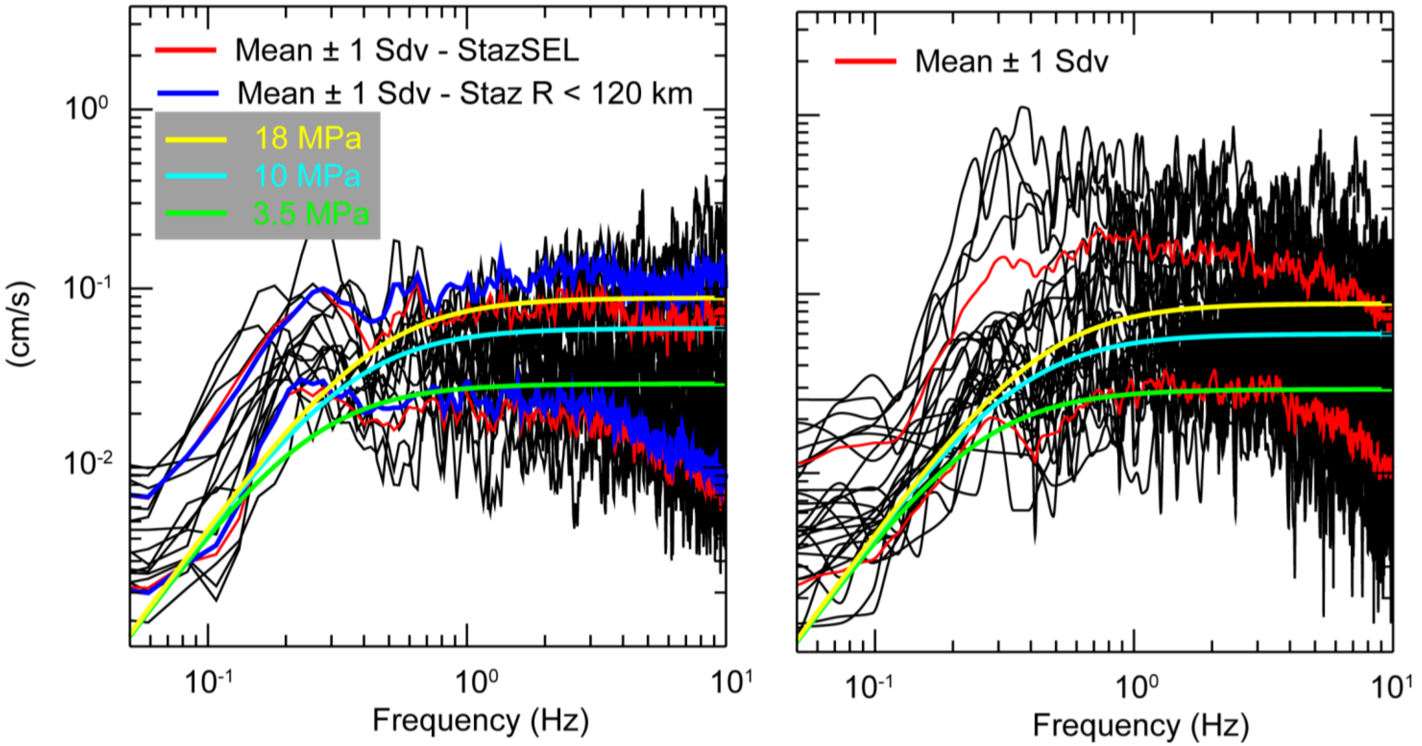


$\Delta\sigma_{SP}$ ~4 MPa for an Mw 6.2 event (R ≤120 km), well below the ~10-18 MPa required by GMPEs.

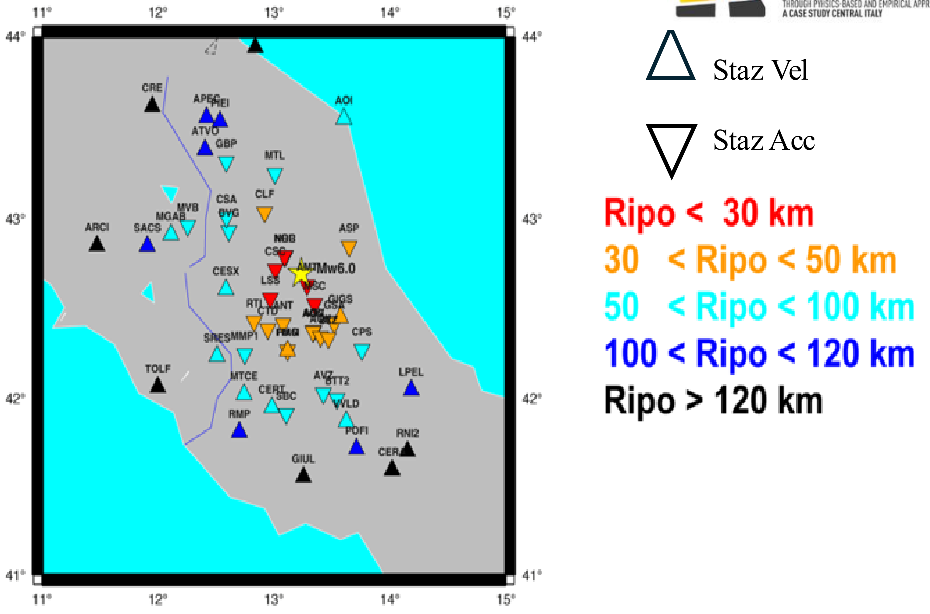
What controls the spectral fit at $\Delta\sigma \sim 10$ MPa: Sensor type (Acc vs. Vel) or source–receiver distance?

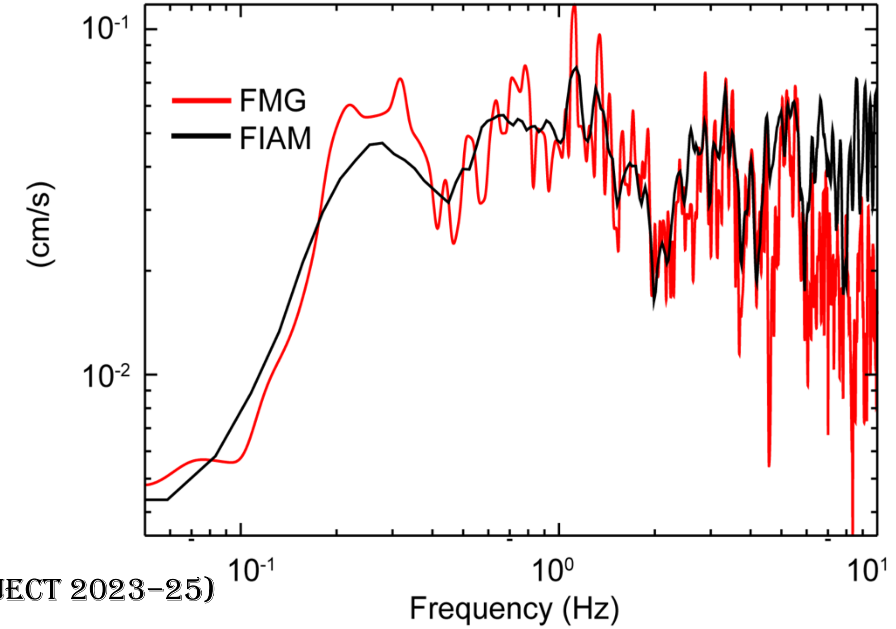
SG $(k_{Site} + Q(f) + H_{STAZ,SG}(f))$

Velocimetric Stations | Accelerometric Stations



Acc & Vel Stations

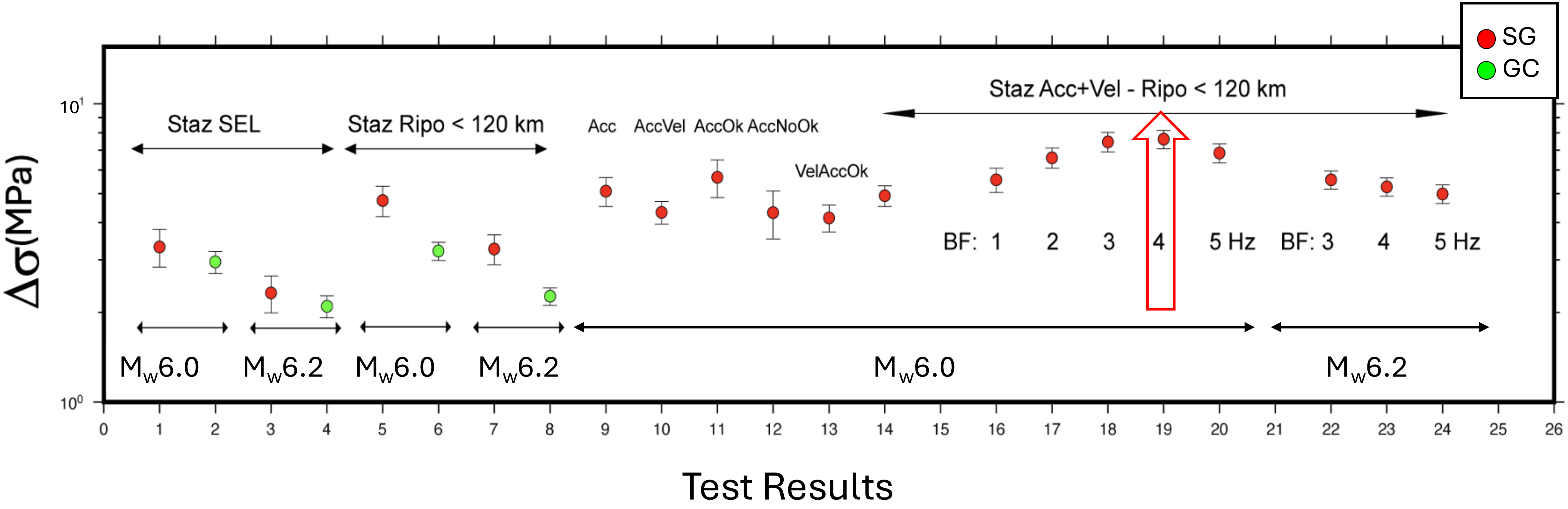




- ➢ Distance is the key factor.
- ➢ Spectral fit is primarily controlled by source–receiver proximity.

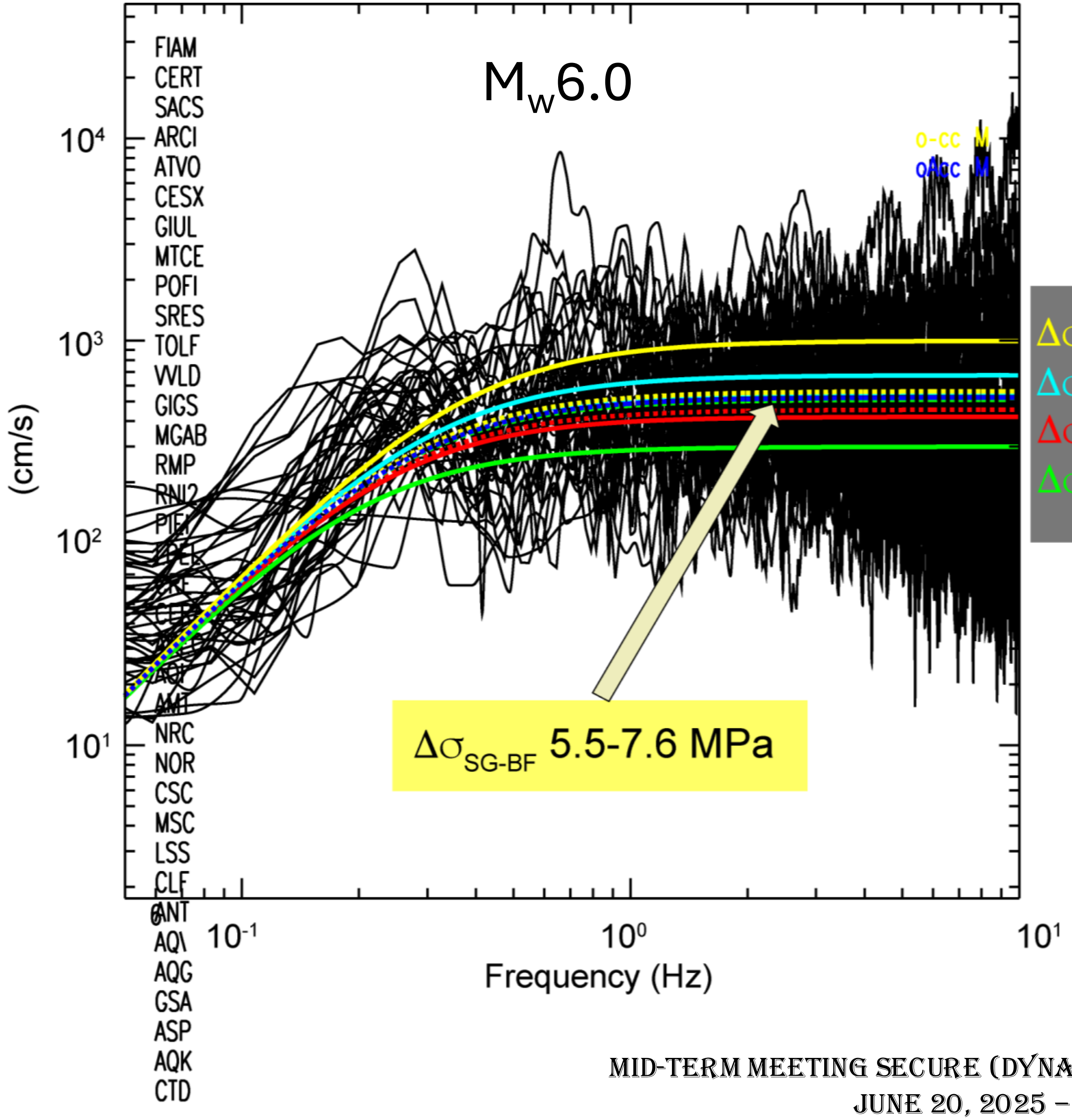
$\Delta\sigma_{SP}$ estimation from **SG**-corrected spectra

- Multiple tests (1-25) are performed to estimate $\Delta\sigma_{SP}$ under different conditions, including variations in magnitude, frequency range, and station type.



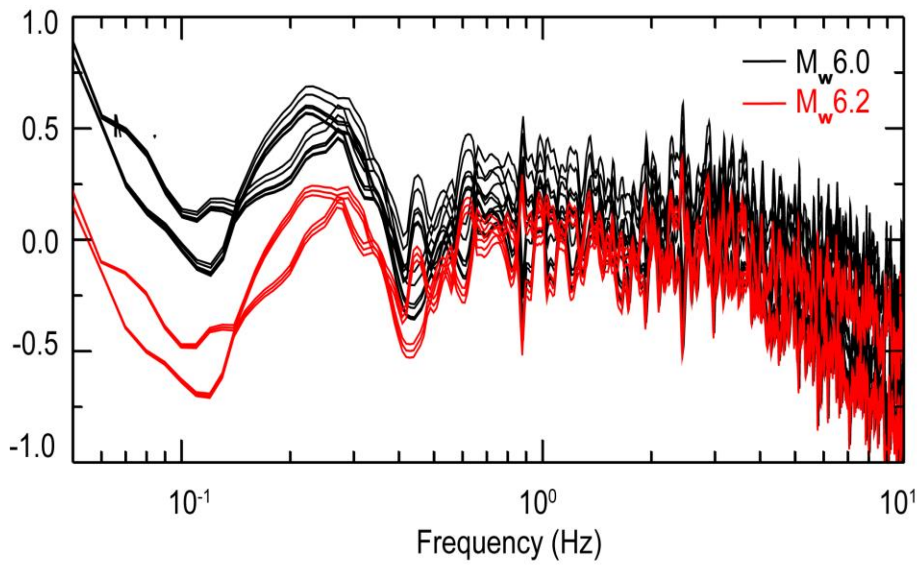
Maximun value: $\Delta\sigma_{SP}$ = 7.6 MPa from SG-corrected spectra considering frequencies up to 4 Hz

$\Delta\sigma_{SP}$: **SG**-corrected spectra using: Acc-Vel stations (R < 120 km)



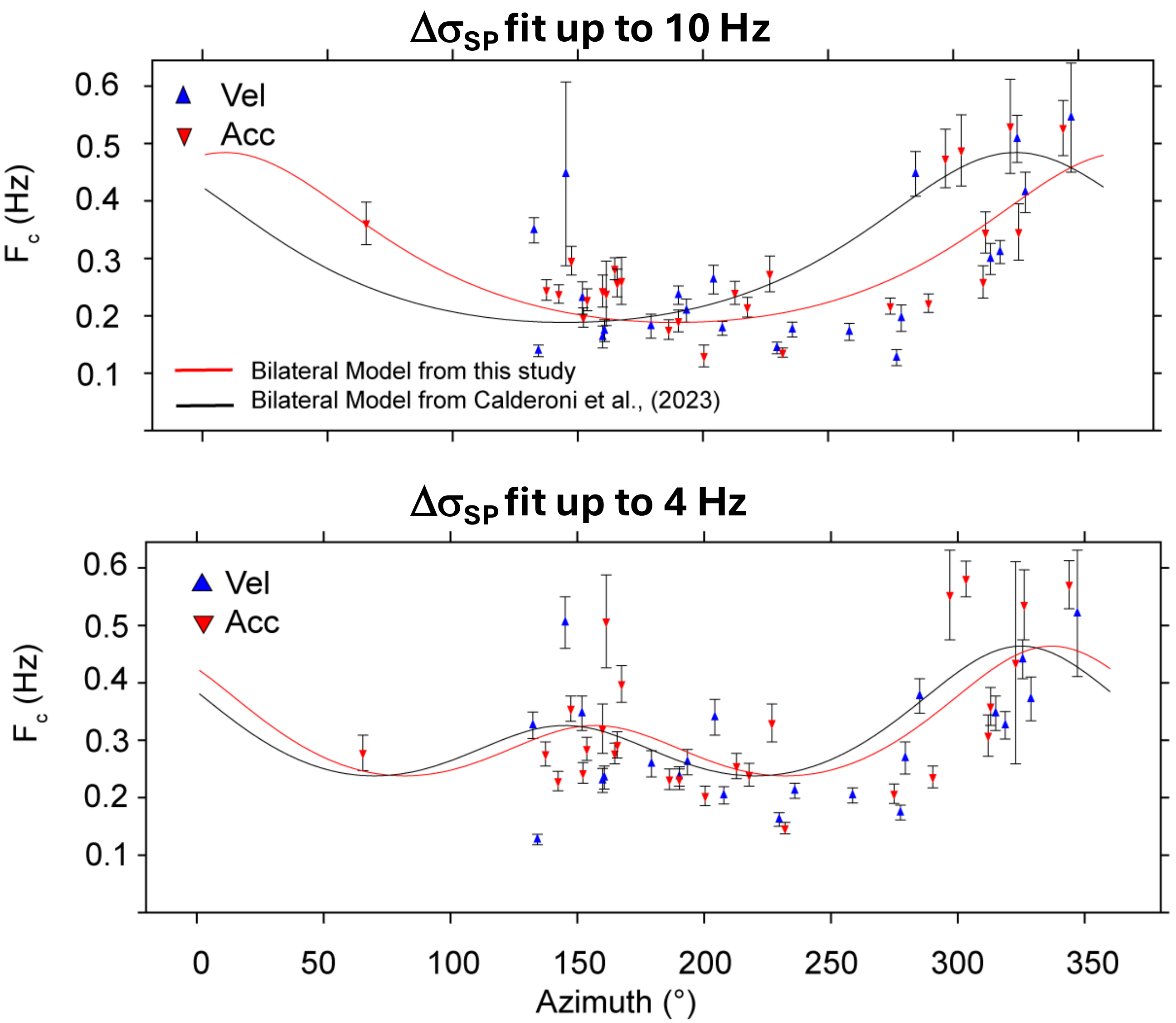
$\Delta\sigma$ 18 MPa
$\Delta\sigma$ 10 MPa
$\Delta\sigma_{SG}$ 4.3 MPa
$\Delta\sigma_{GC}$ 3.5 MPa

GOF Test



To obtain a $\Delta\sigma_{SP}$ value closer to 10 MPa, the spectral fit must be performed up to 4 Hz

F_c from $\Delta\sigma_{SP}$: **SG**-corrected spectra using Acc–Vel stations (R < 120 km)



F_c derived from relations between corner frequency and stress drop (Keilis-Borok, 1959; Eshelby, 1957)

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r} \qquad r = \frac{0.3724\,\beta}{f_0}$$

F_c were inverted across stations using a bilateral rupture model (Ben-Menahem, 1961).

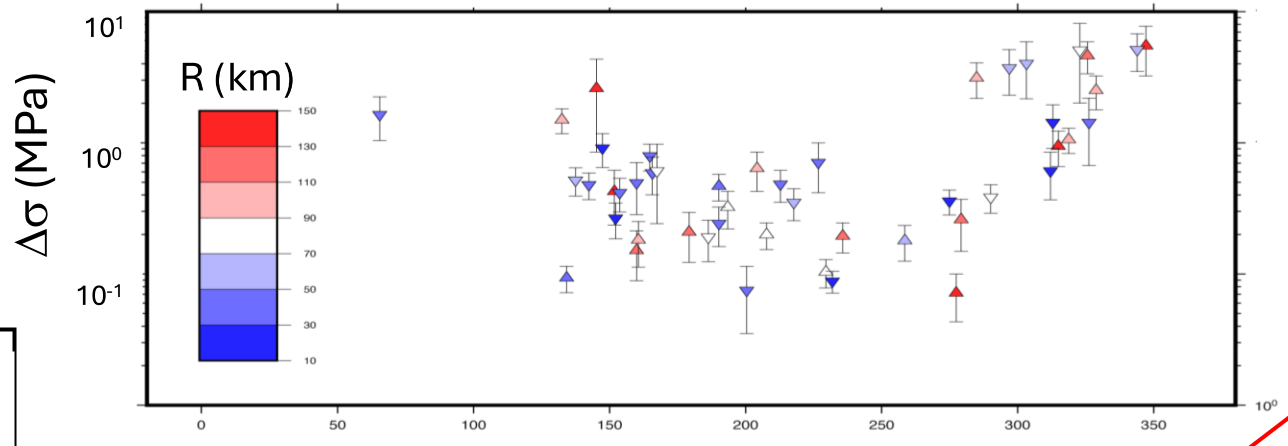
$$C_d = \left(\frac{k^2}{\left(1 - \frac{v_r}{\beta}\cos\vartheta\right)^2} + \frac{(1-k)^2}{\left(1 + \frac{v_r}{\beta}\cos\vartheta\right)^2} \right)^{1/2}$$

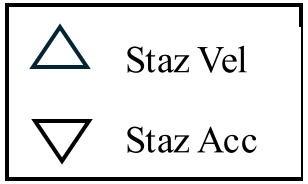
Bilateral rupture model fit improves notably with $\Delta\sigma_{SP}$ (F_c) estimates up to 4 Hz

$\Delta\sigma_{SP}$: **SG**-corrected spectra using Acc–Vel stations (R < 120 km)

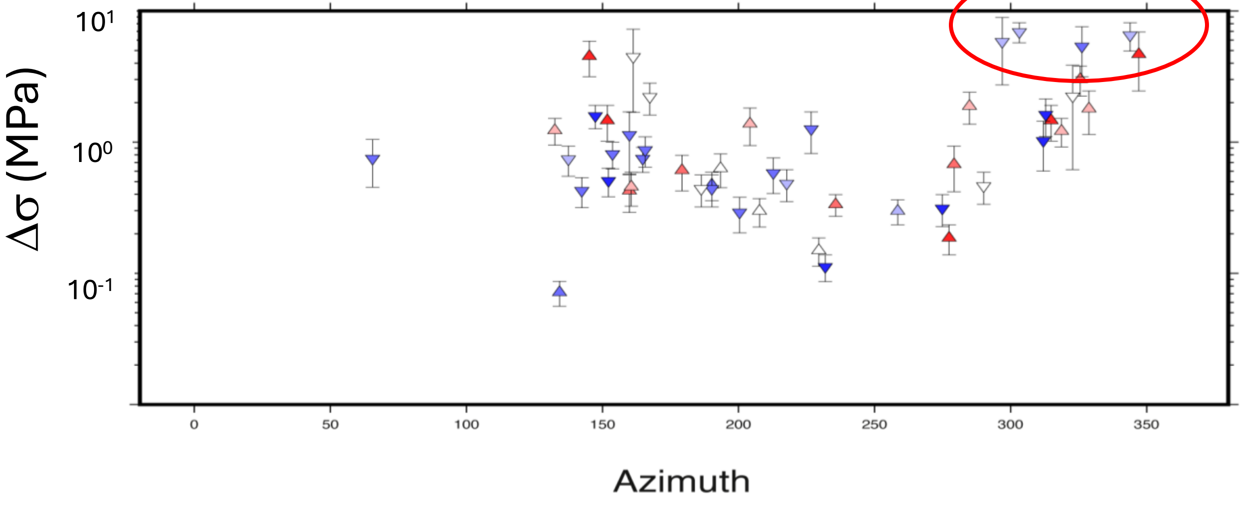
- Dependence of $\Delta\sigma_{SP}$ on Distance

$\Delta\sigma_{SP}$ fit up to 10 Hz





$\Delta\sigma_{SP}$ fit up to 4 Hz



Maximum $\Delta\sigma_{SP}$ values reached in the forward direction at the closest stations.

Conclusions

- The analysis highlights the impact of source–station distance and rupture characteristics on stress drop estimates

- Higher $\Delta\sigma$ values are observed at near-source stations

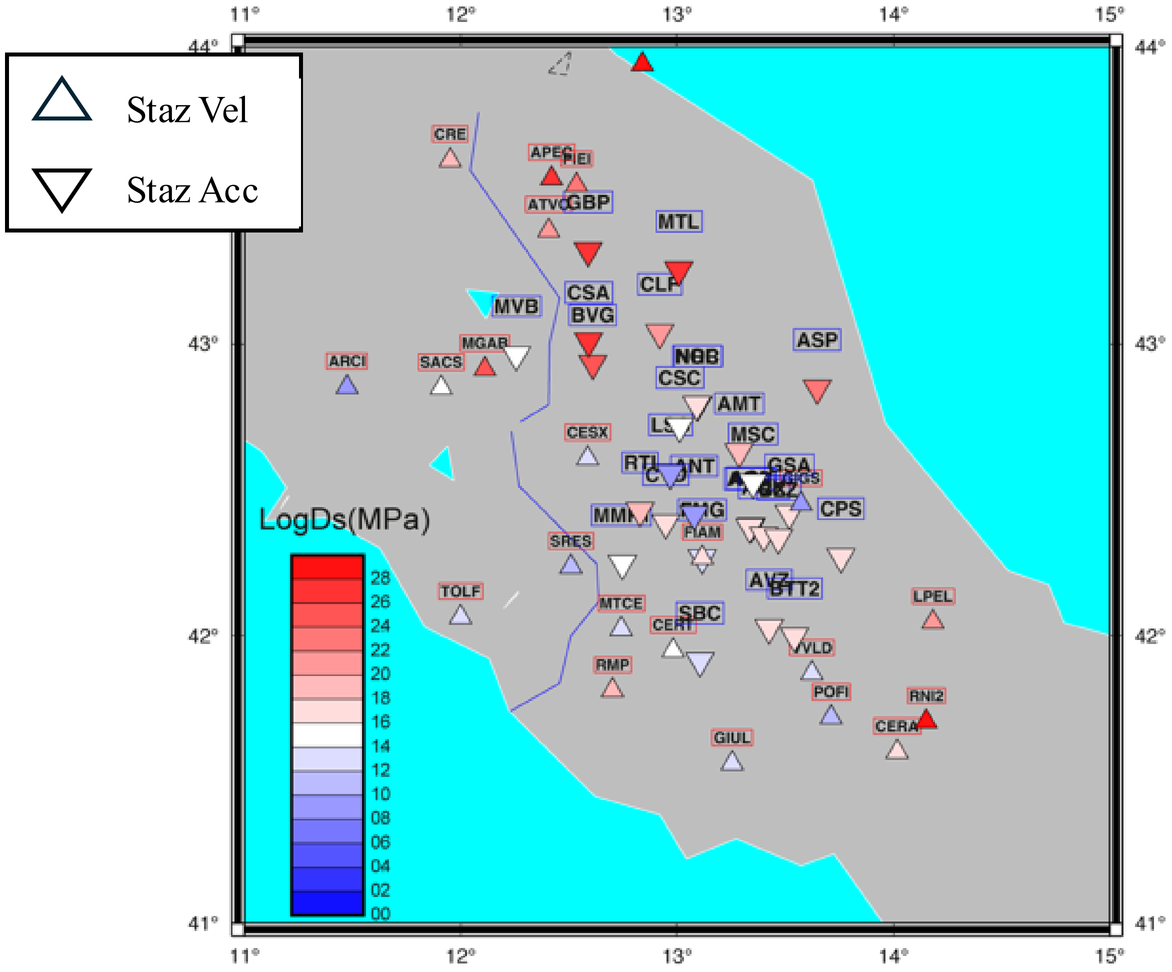
- This trend is likely driven by source directivity and rupture heterogeneity

Thank you for your Attention!

Spatial variation of $\Delta\sigma_{SP}$ from SG corrected spectra:
Staz Acc+Vel, Ripo < 120 km, and Color scale as a function of R

+ Freccia Dir
- Faglia
- (logDs-logDsSG)

Stima ΔσSP_SG fino a 10 Hz



Stima ΔσSP_SG fino a 4 Hz