Multi-Method Source Parameters Estimation and Uncertainty Analysis for the 2016–2017 Amatrice–Visso–Norcia Seismic Sequence

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INGV

SECURE

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

Objective

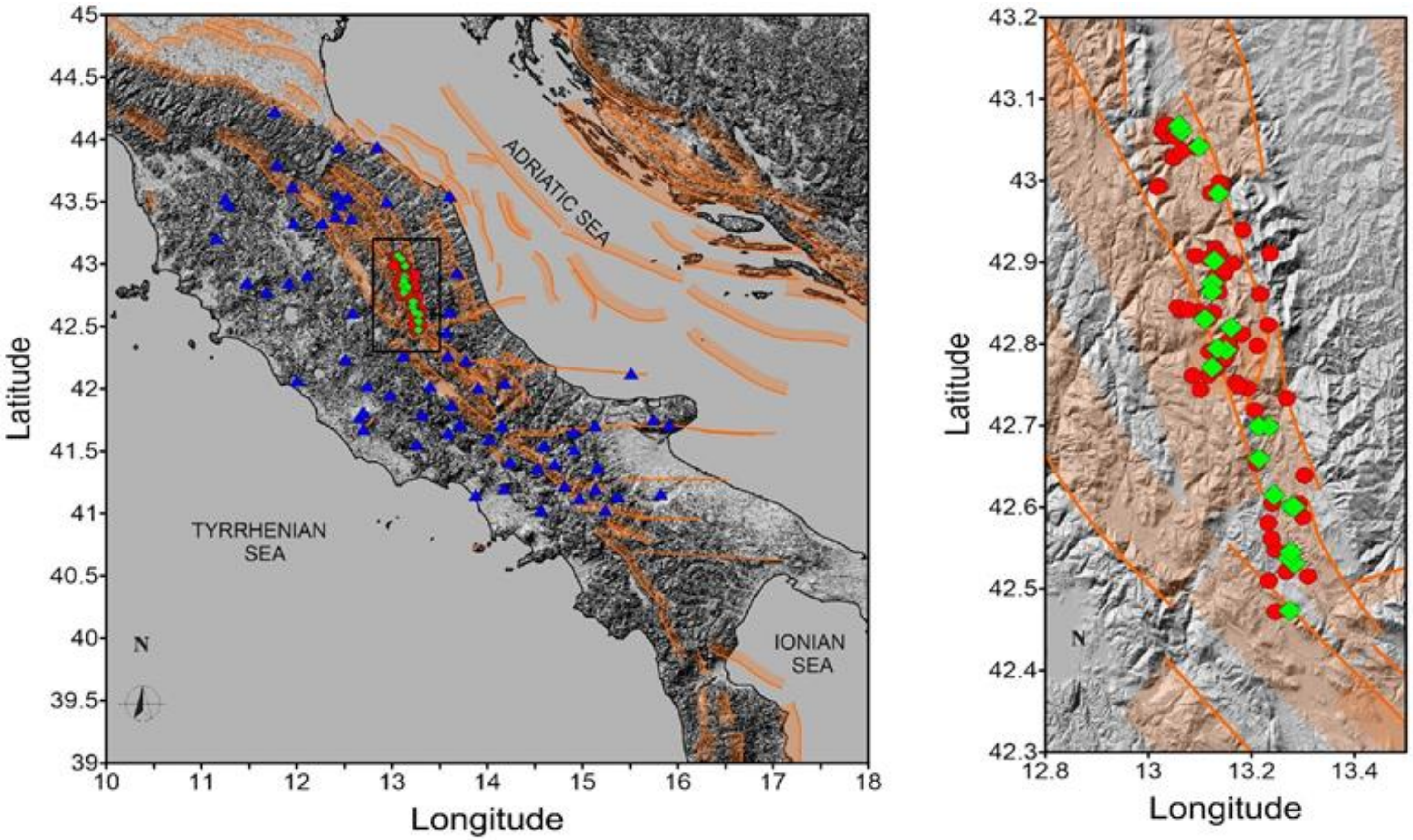
- Evaluate stress-drop consistency and epistemic uncertainty
- Compare five independent methods

Case study

- 2016–2017 Amatrice–Visso–Norcia sequence Central Italy

Dataset

- ~100 events common to several Methods (red+green)
- 22 events analyzed by all five Methods (green)



Methods

SP: Spectral Fitting (Calderoni et al., 2019 and Calderoni & Abercrombie, 2023) method isolates the source term by removing path and site effects from S-wave spectra and fitting a Brune model.

SR: Spectral Ratio method uses direct-waves amplitudes of co-located events with different magnitudes (Calderoni et al., 2013 and Calderoni & Abercrombie, 2023) to cancel common propagation and site effects.

GIT: Generalized inversion technique (Bindi et al., 2020; Morasca et al., 2022) jointly estimates source, attenuation, and site terms from large datasets of S-wave amplitude spectra.

CCT: Coda calibration technique (Mayeda et al., 2003; Morasca et al., 2022) uses stable coda waves, whose scattered nature averages out path heterogeneity, source radiation pattern, and directivity.

CERT: Coda envelope spectral ratios technique combines the stability of seismic coda waves with the empirical Green's function (EGF) approach to cancel out average path and site effects.

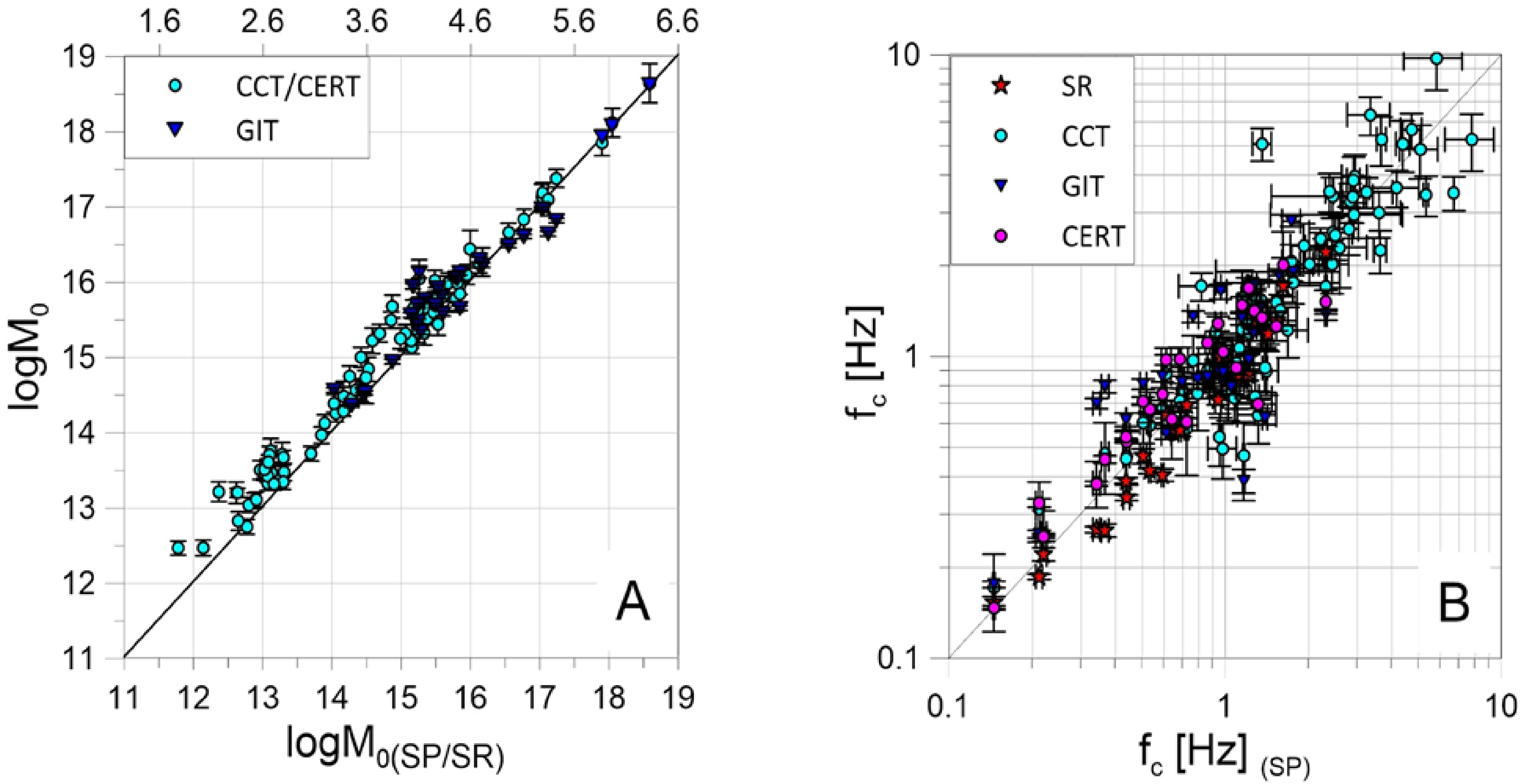
Dataset Overview by Method

Method	Main reference	Central Italy events in original publication	Central Italy events added for this study	Magnitude range (targets)	Wave type / window	Stations / network	SNR criteria	frequency band	Distance Range
SP (spectral analysis)	Calderoni & Abercrombie (2023)	30 largest events of 2016–2017 CI sequence (Mw > 3.5)	65 events	Mw ≈ 1.8–6.33	S-wave windows including 95% of cumulative squared horizontal velocity above noise; 10–30 s, with 10% of window starting before S arrival	INGV-Italian national seismic network; mostly 24-bit broadband 40 s Nanometrics Trillium	SNR > 3	0.05-10Hz	7-117 km
SR (direct-wave spectral ratios)	Calderoni & Abercrombie (2023)	30 target events (same as SP) + 42 EGF events	-	Targets: Mw > 3.5; EGFs: 2.2 ≤ ML ≤ 4.05; ΔM = 0.79–3.09	Fixed 10 s windows, starting 1 s before S arrival, for both targets and EGFs	INGV-Italian national seismic network; mostly 24-bit broadband 40 s Nanometrics Trillium	SNR > 3 for both target and EGF	0.05-10Hz	co-located events within 3 km from the target event
CCT (coda calibration)	Morasca et al. (2022)	calibration data: 39 moderate-to-large events (3.5 < Mw < 6.33) + validation data 247 events (Mw ≈ 1.7–5.0)	66 events	Mw ≈ 1.7–6.33	Coda envelopes in 17 narrow bands (0.03–25 Hz) from horizontal components	14 well-distributed stations from INGV network (100–200 sps; velocimeters + accelerometers)	frequency dependent SNR	0.03-25Hz (where possible)	5-200 km (for calibration model)
CERT (coda-wave spectral ratios)	Mayeda et al. (2007) (methodological reference)	not applied in Central Italy	27 target events + 36 EGFs events	Targets: Mw > 3.5; EGFs: 2.2 ≤ ML ≤ 5.3; ΔM = 0.79–3.3	Coda envelopes in 17 narrow bands (0.03–25 Hz) from horizontal components	14 well-distributed stations from INGV network (100–200 sps; velocimeters + accelerometers)	frequency dependent SNR	0.03-25Hz (where possible)	co-located events within 15 km from the target event
GIT (generalized inversion technique)	Morasca et al. (2022)	calibration: 4946 earthquakes (Mw ≈ 1.5-6.3) + validation data 247 events (Mw ≈ 1.7–5.0)	66 events	Mw ≈ 1.7–6.33	S-wave windows on horizontal components starting 0.1 s before S-arrival, ending at distance-dependent energy percentages (≥4 s)	624 stations from INGV network and RAN-Italian strong motion network	frequency dependent SNR	0.2-47.2Hz (where possible)	5-150 km (for calibration model)

Differences among the datasets (number of events, stations, wave types, frequency and distance ranges) mainly reflect the **specific data requirements and selection criteria of each technique.**

Seismic Moment and Corner Frequency

~100 events



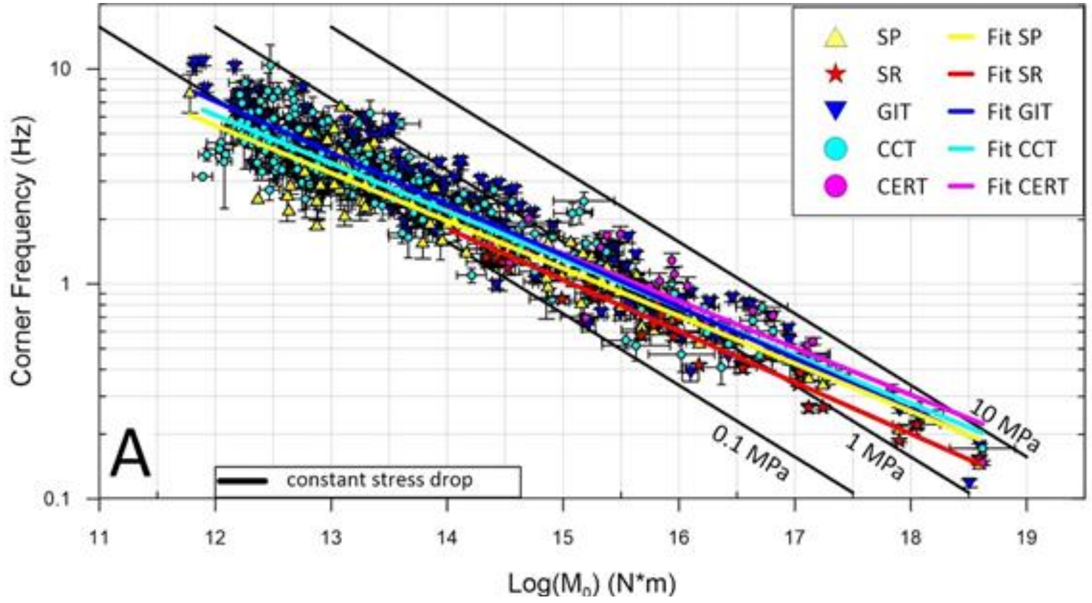
For a fixed M_0, the Brune model predicts $\Delta\sigma \propto fc^3$.

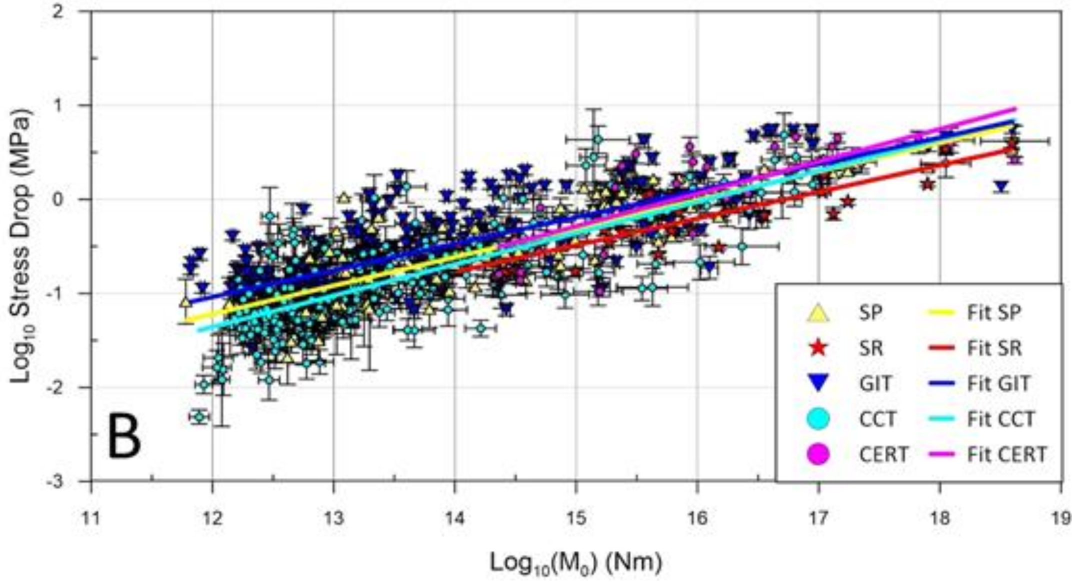
- This means that **small differences in corner frequency can produce large differences in stress-drop estimates**.
- However, we do **not observe systematic departures from the 1:1 trend** among the fc estimates obtained with the different methods.
- Therefore, the **underlying source scaling relations appear consistent across methods**, although absolute stress-drop values may differ.

Source Scaling

- ~100 events for SP
- ~ 30 events for SR, CERT
- ~100 events + Morasca et al. (2022) events for GIT, CCT

- **A departure from self-similar scaling is observed consistently across all methods.**
- The agreement among methods suggests that this behavior **reflects a genuine property of the AVN seismic sequence**.
- Nevertheless, **some methodological bias cannot be completely excluded**.





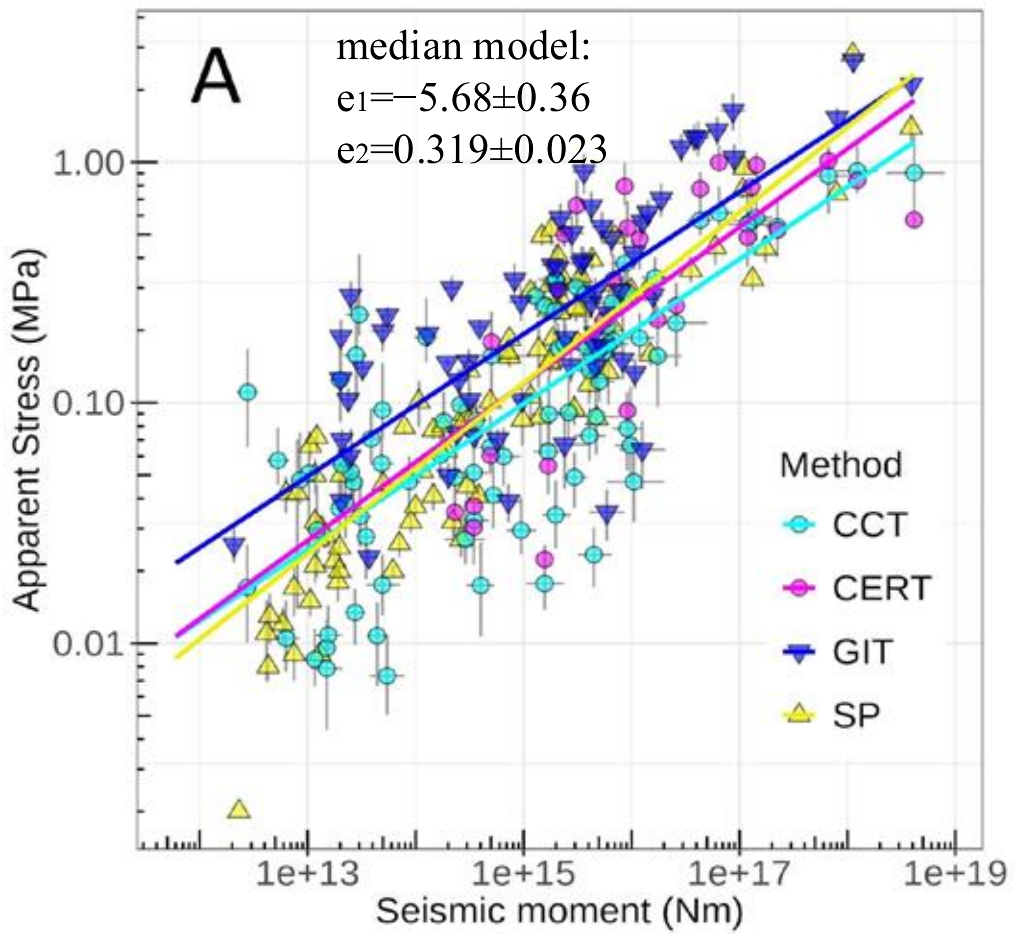
Amatrice-Visso-Norcia 2016-2017 log10(f_c) vs log10(M_0)				
Method	**Slope**	**err**	**CC**	**N**
SR	-0.239	± 0.176	97%	28
SP	-0.222	± 0.111	95%	97
CCT	-0.224	±0.064	94%	286
GIT	-0.239	±0.064	95%	284
CERT	-0.219	± 0.331	90%	27

Amatrice-Visso-Norcia 2016-2017 log10(StressDrop) vs log10(M_0)				
Method	**Slope**	**err**	**CC**	**N**
SR	0.284	± 0.528	85%	28
SP	0.303	± 0.310	84%	97
CCT	0.332	± 0.194	82%	286
GIT	0.283	± 0.193	78%	284
CERT	0.345	± 0.994	74%	27

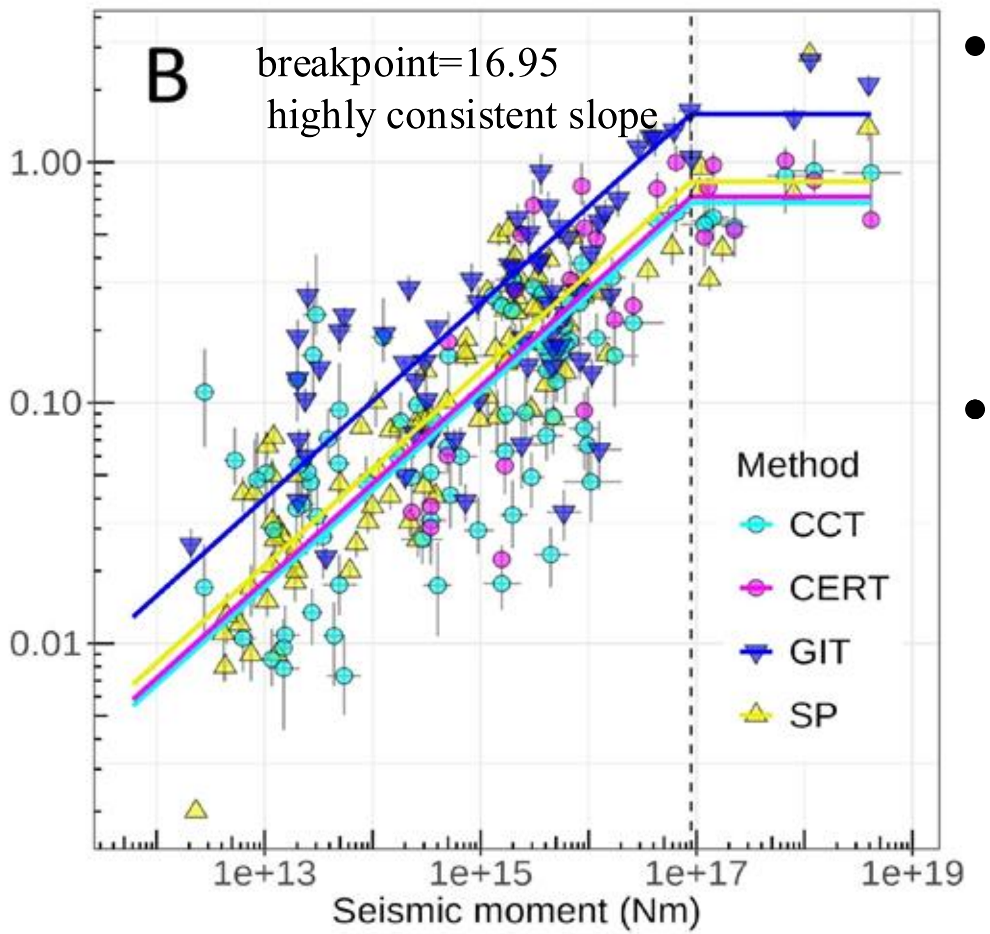
Apparent Stress

~100 events

best-fitting mixed-effects model



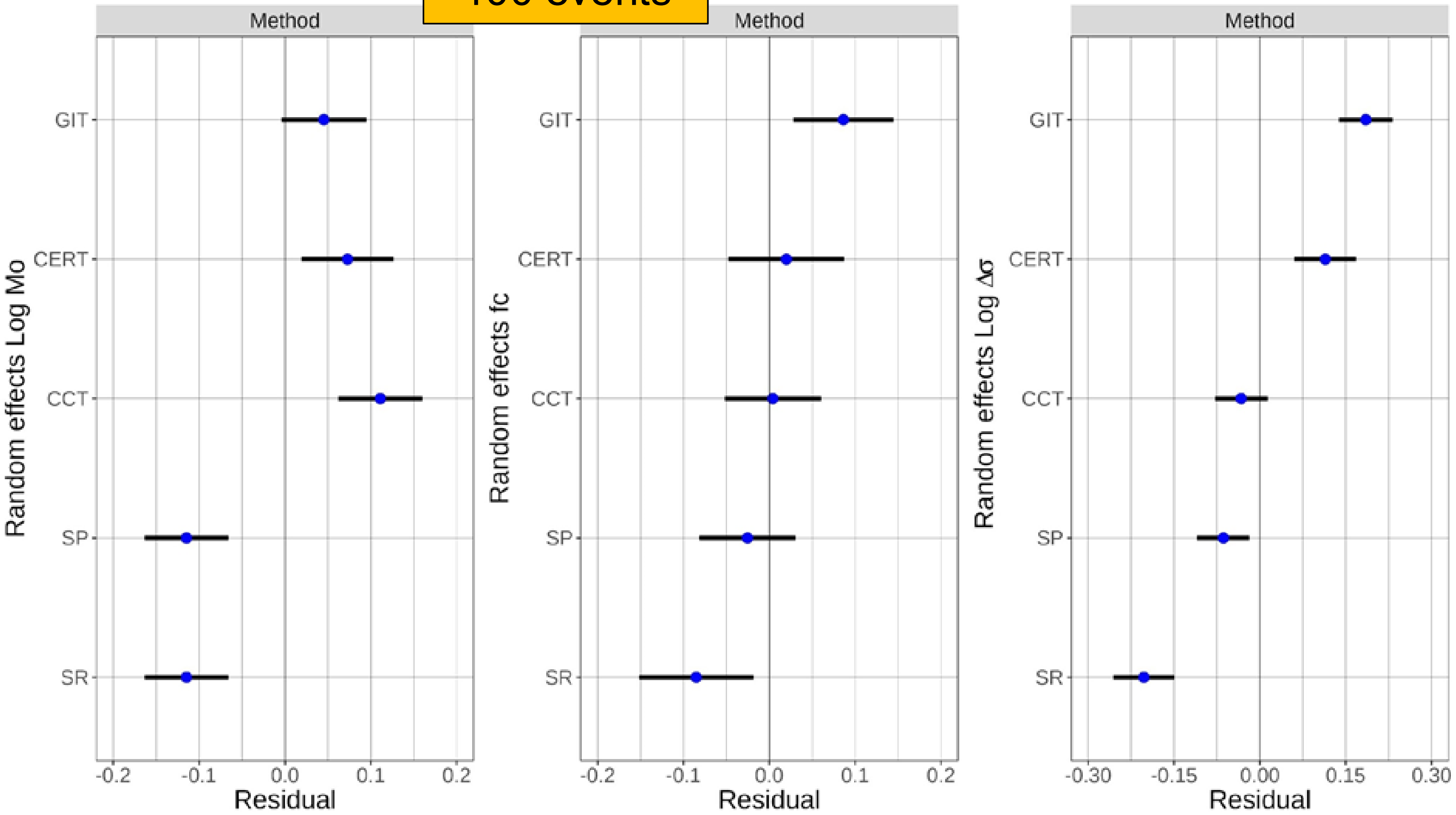
mixed-effects regression using a piecewise linear model



- The segmented model provides a better fit but is **not statistically justified.**
- However, it may still be useful for applications involving **mild extrapolation toward larger magnitudes**.

Variability across methods

~100 events



- To quantify inter-method variability, is used a **mixed-effects regression model**.
- The analysis includes about **100 events** and models variability in M_0, fc, and $\Delta\sigma$.
- The five methods are treated as **grouping factors**, allowing us to estimate method-dependent random effects.
- The resulting standard deviation of method effects is **0.11 for log M_0**, **0.09 for fc**, and **0.16 for log $\Delta\sigma$**.

Methods are internally consistent, and most residual variability appears to be event-specific rather than method-dependent.

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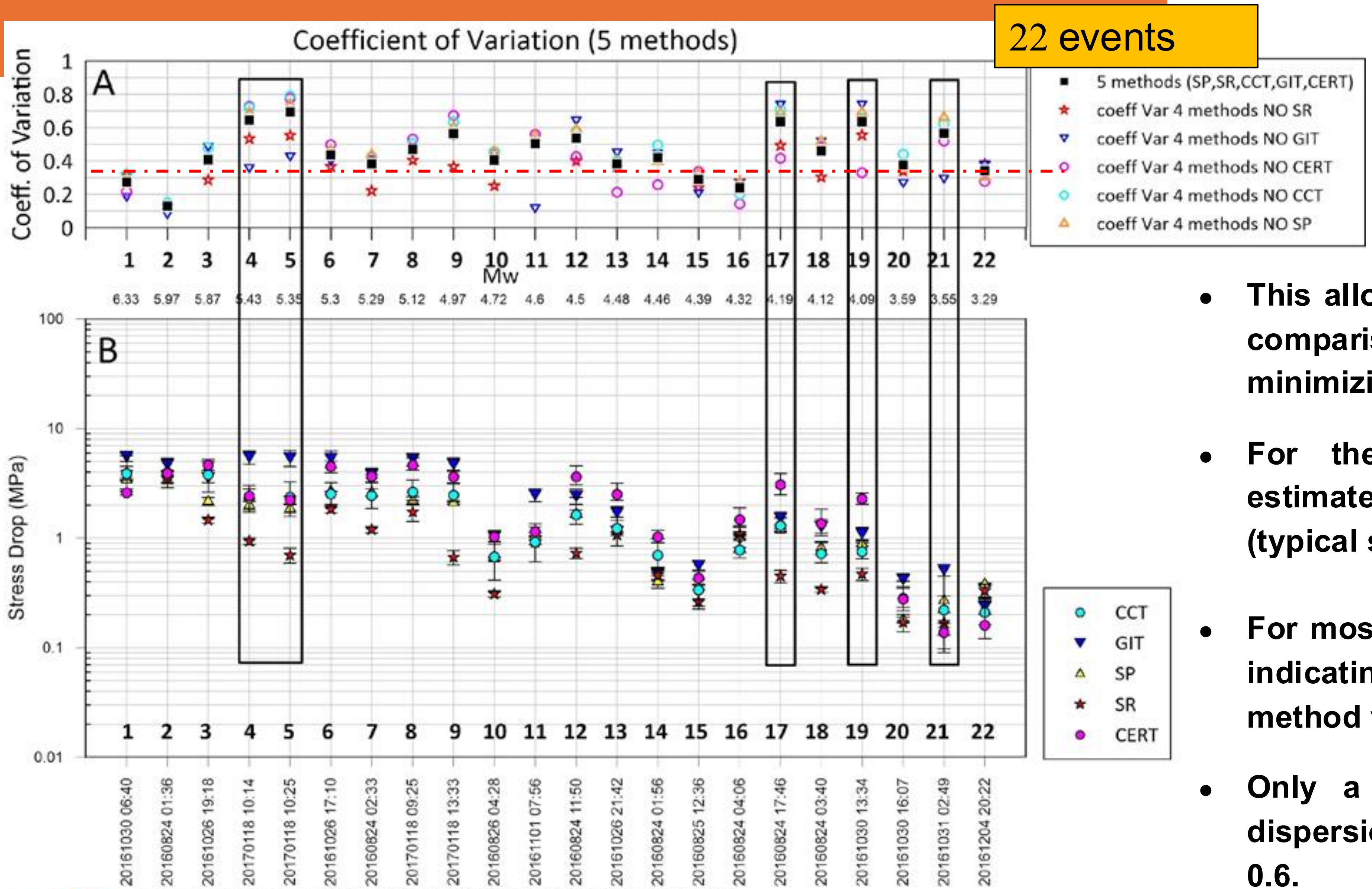
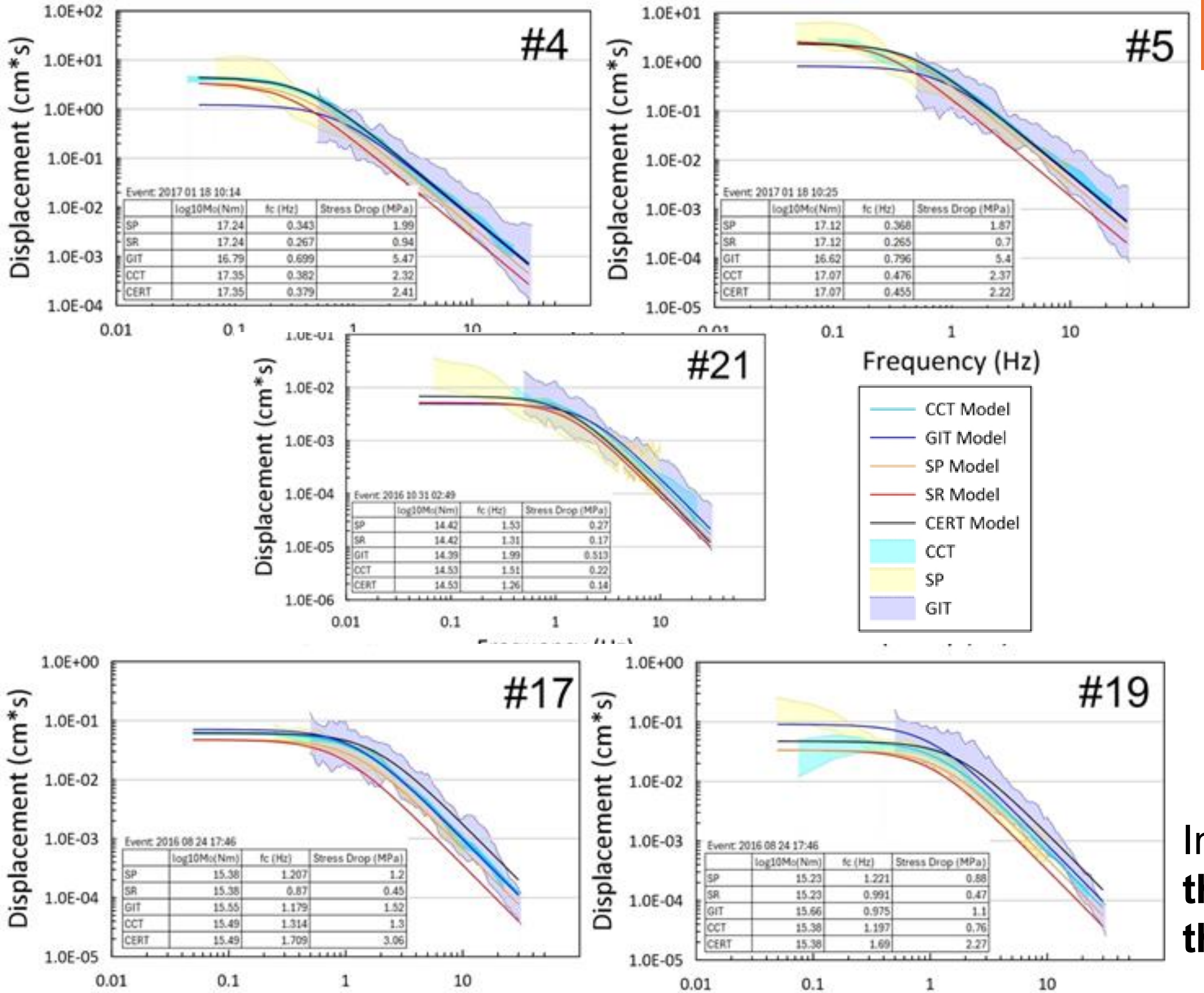
Core subset of 22 common events



- **This allows a direct event-by-event comparison of Δσ estimates while minimizing dataset selection bias**
- **For the AVN mainshocks, the estimated Δσ about 1.5 and 4.4 MPa (typical seismological range).**
- **For most events, CV is around 0.4, indicating relatively low inter-method variability.**
- **Only a few events show larger dispersion, with CV values above 0.6.**

Source spectra of events with higher coefficient of variation: CV ≳ 0.6



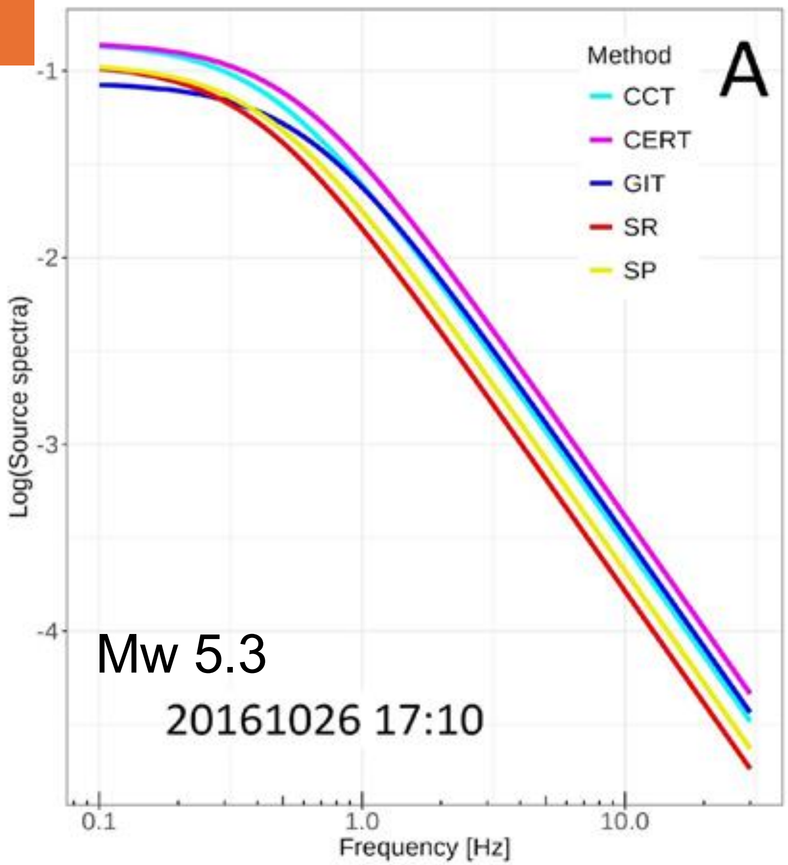
- For events **#4, #5, and #21**, the variability decreases when the **GIT method** is excluded.
- For events **#4, #5:** This happens because GIT uses **fixed M_w values for large events**, which introduces a stronger M_0–fc trade-off and may lead to **overestimation of $\Delta\sigma$**
- For event **#21:** Bandwidth starting at 0.5 Hz caused underestimated M_0, overestimated fc, and consequently higher $\Delta\sigma$.
- For events **#17 and #19**, the variability is mainly driven by **CERT, and partly by SR**.

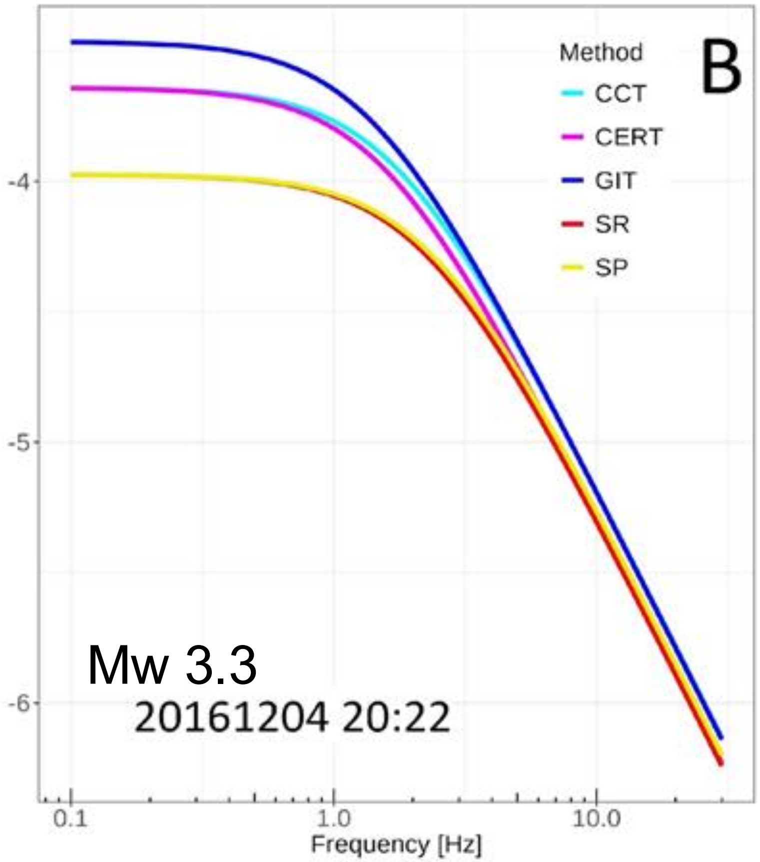
In these cases, the difficulty comes from **identifying the slope change in the high-frequency part of the spectral ratio**.

Sammon’s maps:

- Nonlinear dimensionality-reduction
- Projects spectral data into 2D space
- Preserves distances between spectra
- Reveals similarities among methods

Spectral consistency across methods for two representative events



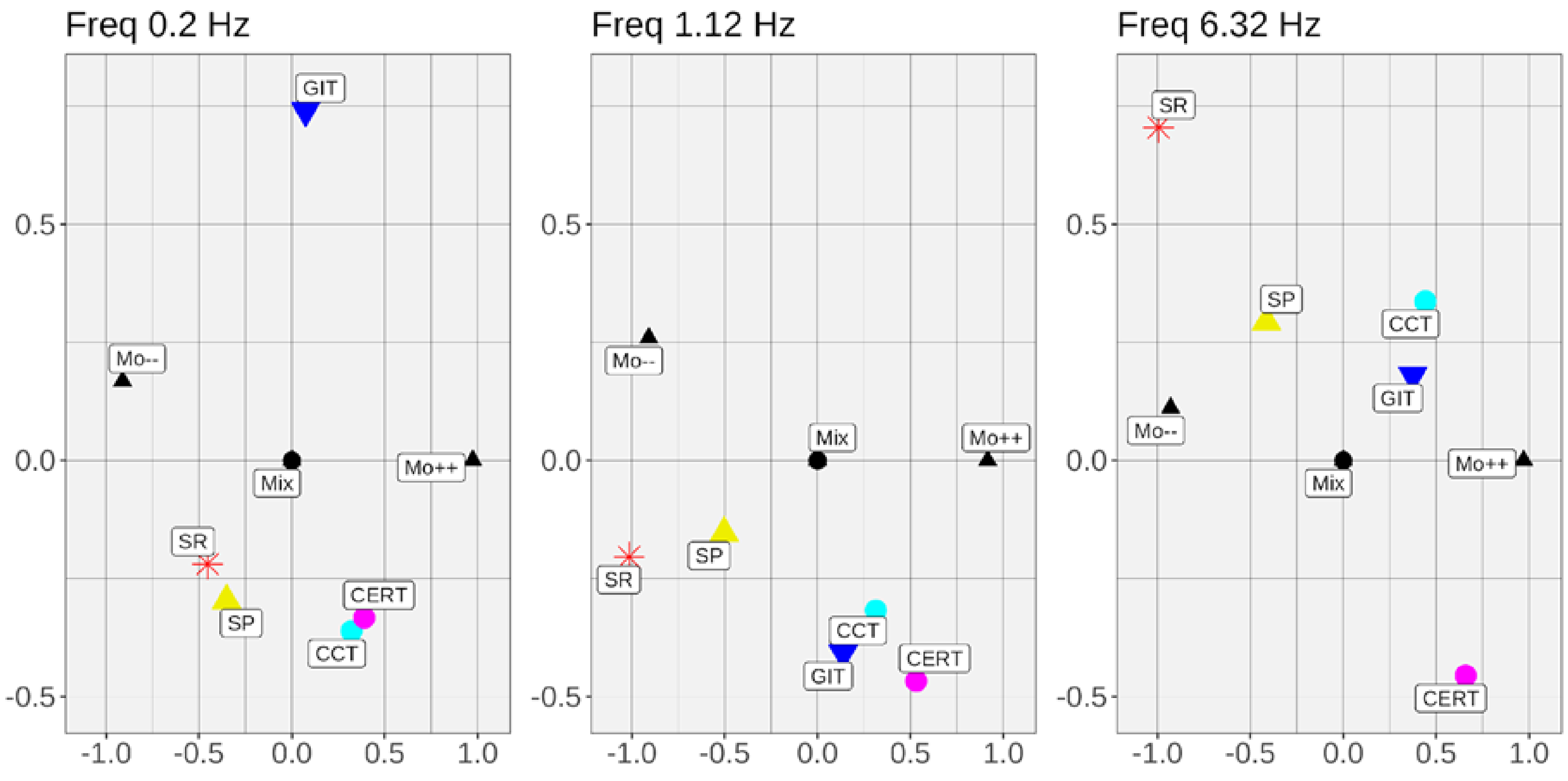


- **Mw5.3:** similar spectral trends across methods
- **M_w3.3:** larger variability in spectral slopes
- **$\Delta\sigma$:** ~2–5 MPa (M_w 5.3) vs ~0.2–0.4 MPa (M_w 3.3)
- **Key point:** evaluate **spectral shape and stress drop together**

Sammon's maps

22 events

We use Sammon's maps to visualize spectral similarity across methods and frequencies for all 22 events



- Each point represents a method, and the distance between points reflects **the similarity of the predicted spectra**.
- At low frequencies, **CERT and CCT cluster together**, reflecting similar seismic moments.
- Around the **corner-frequency range**, **CCT and GIT become closer**.
- At **high frequencies**, **CERT predicts the highest amplitudes**, while **SR the lowest**.

Conclusions

- Systematic comparison of 5 independent methods to estimate source parameters for the 2016–2017 AVN seismic sequence shows that multi-method integration improves the reliability and robustness of the results.
- Relationships between seismic moment (M_0), corner frequency (fc), stress drop and apparent stress are consistency across all methods
- All methods show common departure from self-similar scaling.
- Apparent Stress shows consistent magnitude-dependent trends and evidence of saturation at intermediate-to-large magnitudes.
- The mixed-effects regression (~100 events) analysis indicates:
  - Limited inter-method variability (≤ few tenths of log units).
  - Systematic biases are method-specific but quantifiable.
  - Most residual uncertainty is event-specific rather than method-dominated.
- Event-by-event comparison of 22 common events show low epistemic uncertainty (CV of $\Delta\sigma < 0.4$).
- Scaling trends and relative variations are robust and suitable for physics-based hazard models.

Thank you for your Attention!