Source parameter estimation using the Coda Calibration Tool in the Yellow Sea and Korean Peninsula region (2.2 < Mw < 5.5)

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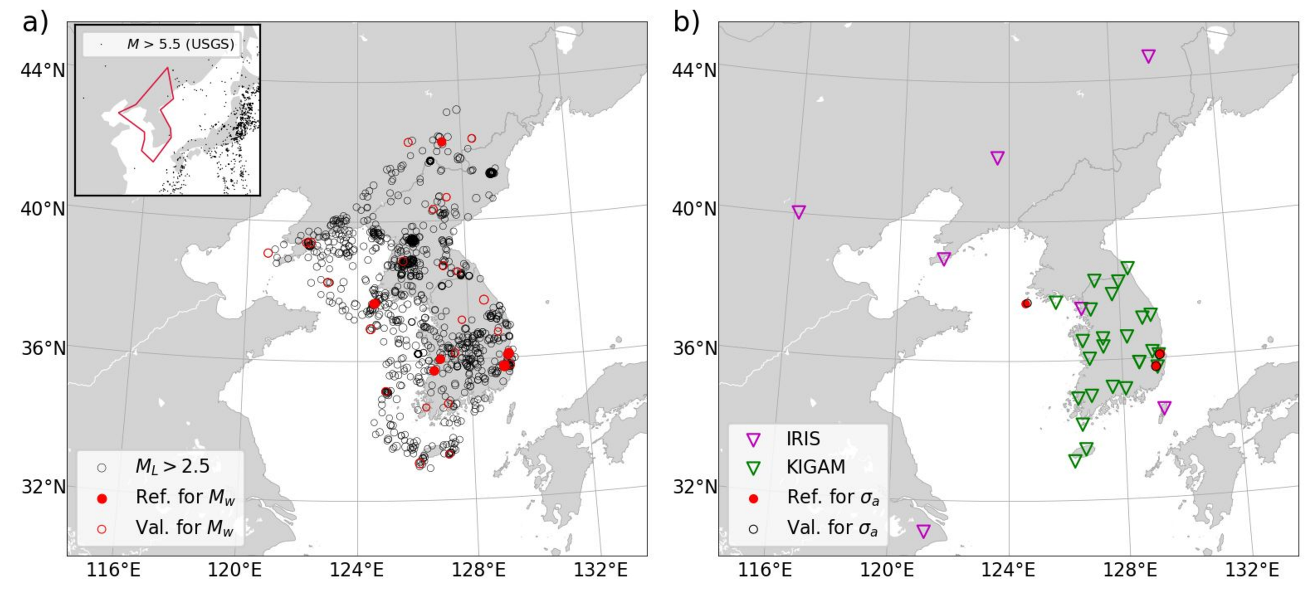
Abstract

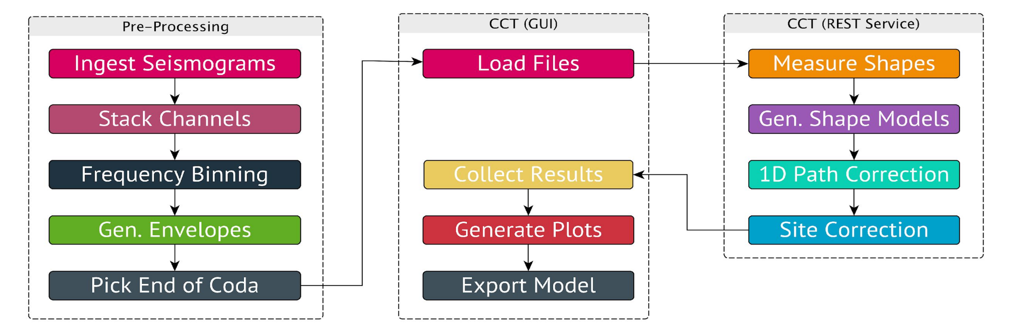
Estimating moment magnitude (Mw) and source spectra is critical for seismic hazard assessment and understanding earthquake physics, but stable results are often hindered by path and site effects, simplified assumptions, and limited bandwidth. We apply the Coda Calibration Tool (CCT) to 1,266 seismic events with ML ≥ 2.45 that occurred in the Yellow Sea and Korean Peninsula (YSKP) region over the past 30 years. The CCT, which leverages the empirical relationship between coda envelope characteristics and path/site effects, enables the estimation of source parameters from the resulting moment-rate spectra. We use broadband 20 sps data from 28 local and 7 regional stations to construct coda envelopes and employ apparent stress estimates from four Mw 4.9+ events, including the 2016 Gyeongju and 2017 Pohang mainshocks, to obtain stable site corrections in the 1-5 Hz range as reference events. The CCT results include 1,066 Mw estimates, with the smallest being Mw 2.2, which we compare to Mw from time-domain moment inversion and to catalogued ML values. We present a source scaling relationship using apparent stress, Mw, and corner frequency, and examine the spatial distribution of apparent stress. We also describe distinct spectral characteristics of man-made events, including mine collapses and nuclear tests, and confirm that the CCT's distance-based path correction assumption and its energy-based source parameter estimation work well for the YSKP region.

Dataset: M_L ≥ 2.5 Seismic Events in the YSKP (1996-2025)



- 1,277 seismic events (M_L ≥ 2.5, 1996-2025) from the KIGAM catalog
- Broadband waveforms from 28 KIGAM and 7 IRIS stations, including 4 arrays near the DMZ
- East and north components of velocity, -350 s to +1150 s relative to origin time
- Envelopes, computed with the *"Tool > Create Envelopes"* function in the Coda Calibration Tool

Method: Coda Calibration Tool (CCT)



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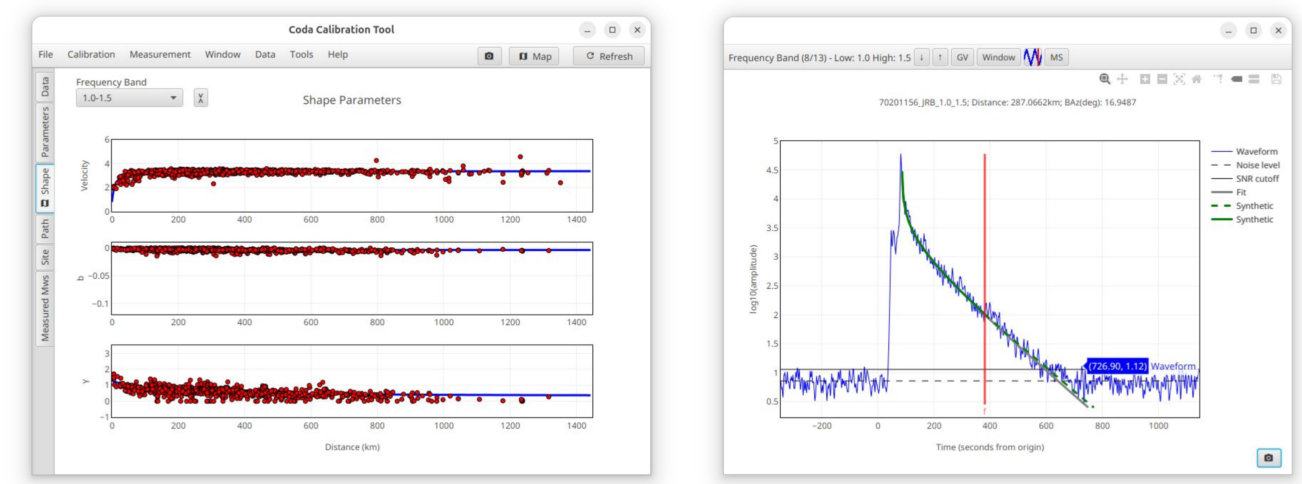
CCT on GitHub

- **Coda Calibration Tool (CCT; Barno, 2017):** Java-based implementation with a graphical interface, providing a consistent workflow from coda envelope construction to source parameter estimation.
- **Stable:** Coda waves are less sensitive to rupture directivity, providing a robust basis for empirical calibration (Mayeda & Walter, 1996).
- **Transportable:** Path and site effects are calibrated with reference events and then applied to other events (Mayeda et al., 2003; Morasca et al., 2005).



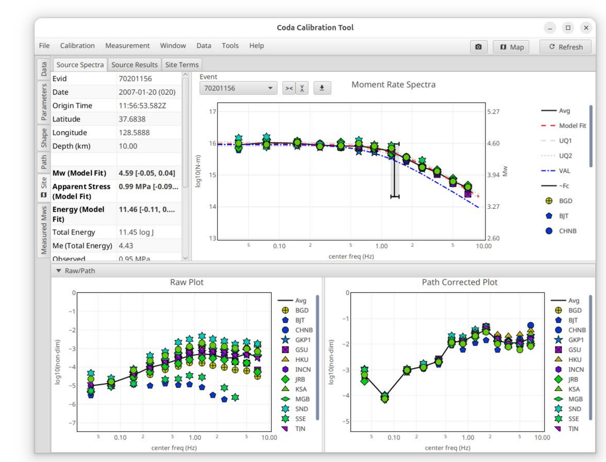
b(r): Controls the overall exponential decay rate (how fast the coda amplitude decays). Larger b(r) → faster, steeper decay. Mainly reflects intrinsic absorption, distance-adjusted (*b* in Q^{-1}_i)?

γ(r): Controls the initial curvature after the S-wave (how sharply the coda drops at onset). Larger γ(r) → sharper early bend. Mainly reflects scattering/diffusion, with some absorption influence (g^* in Q^{-1}_{sc}, partly *b* in Q^{-1}_i)?

Path correction, *b(r), γ(r)*
→ distance effects removed, dimensionless amplitudes

Site-transfer terms
using spectra from ref. Mw and coda-based σ_a (two from Chai et al., 2020 + one derived)

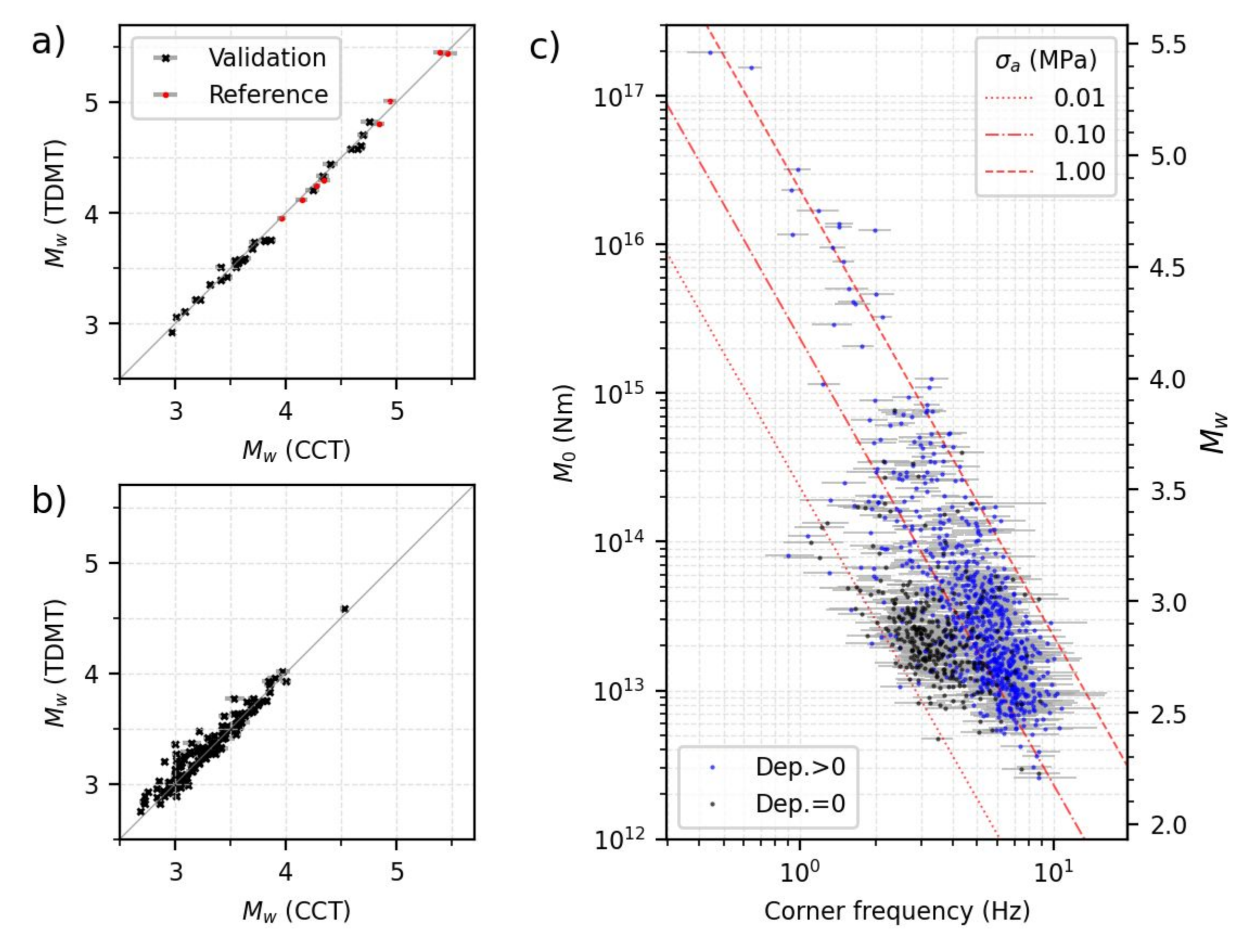
Moment-rate spectra
from the dimensionless, distance-corrected amp. scaled by site-transfer terms

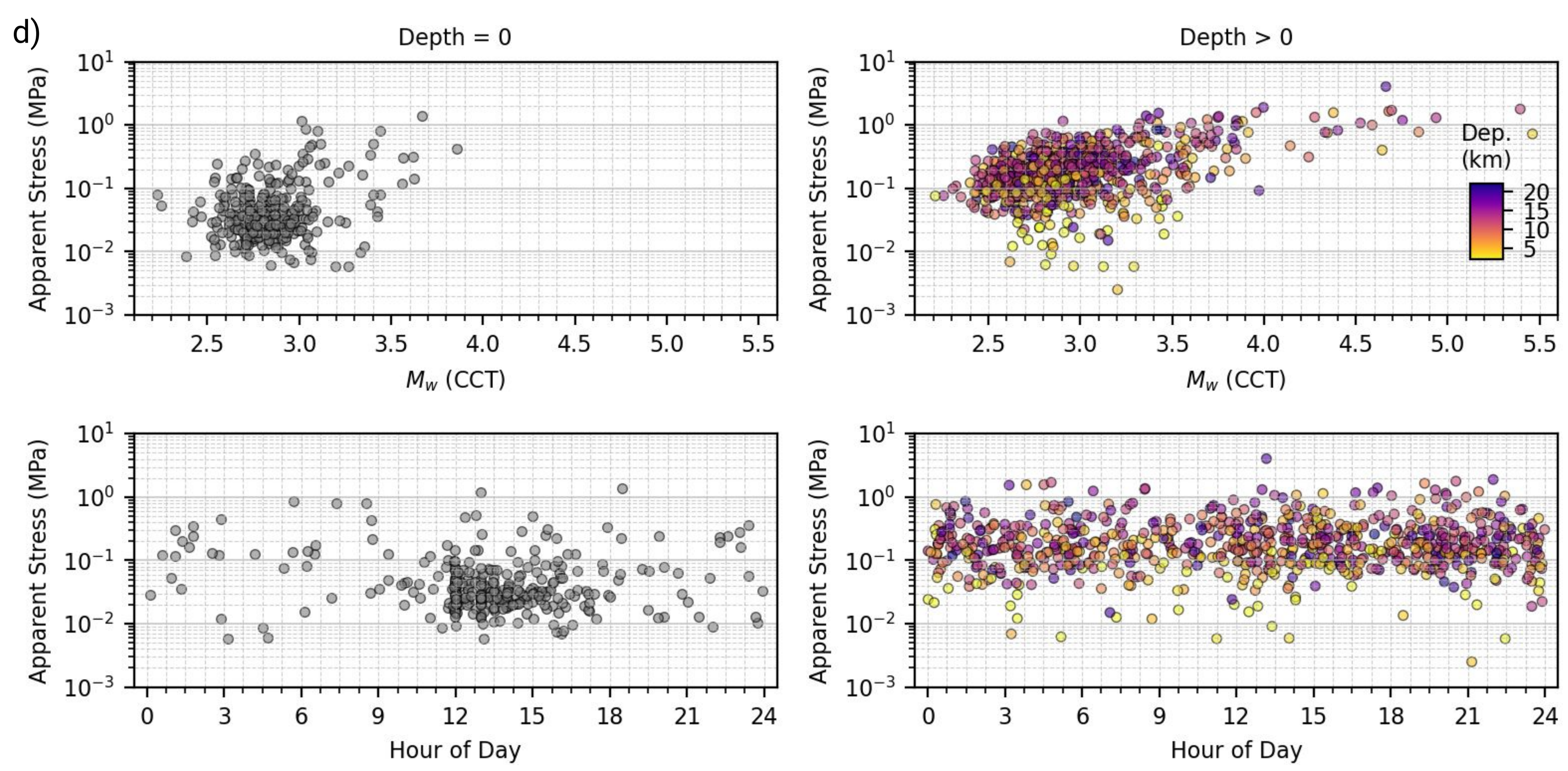


Results: CCT's Path Correction Effective in the YSKP

1,266 M_L ≥ 2.5 events analyzed with CCT → **1,066** source parameter estimates (M_w, f_c, E_r, M_0, σ_a).
Among them, 174 events with independent M_w (TDMT; Dreger, 2003) were compared with Mw (CCT):

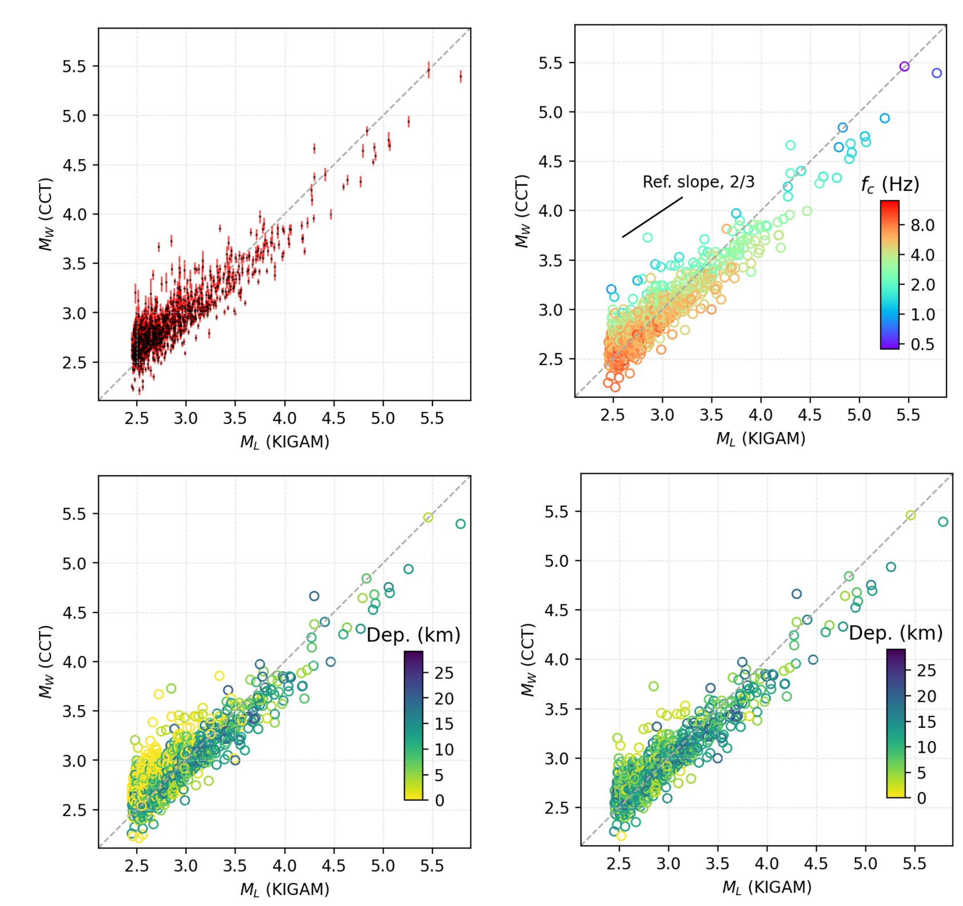
(a) 36 calibration events (8 ref + 28 val) → stable parameters.
(b) 138 additional TDMT events → M_w(CCT) vs. M_w(TDMT) matches well.
(c) Final results: f_c, M_0, and σ_a for 1,066 events.
(d) Depth > 0 km events: **σ_a increases with M_w**; no clear depth dependence when μ is constant.





M_L-M_w relationship: Previous studies often assumed a linear scaling (Sheen et al., 2018), though Shelly et al. (2021) noted its limitations and potential bias.

- Our results follow the curved trend predicted by theory: ~2/3 slope (→ ~1:1 near 2-4 Hz) → saturation
- This confirms the reliability of CCT-based Mw estimates (2.2–5.5).

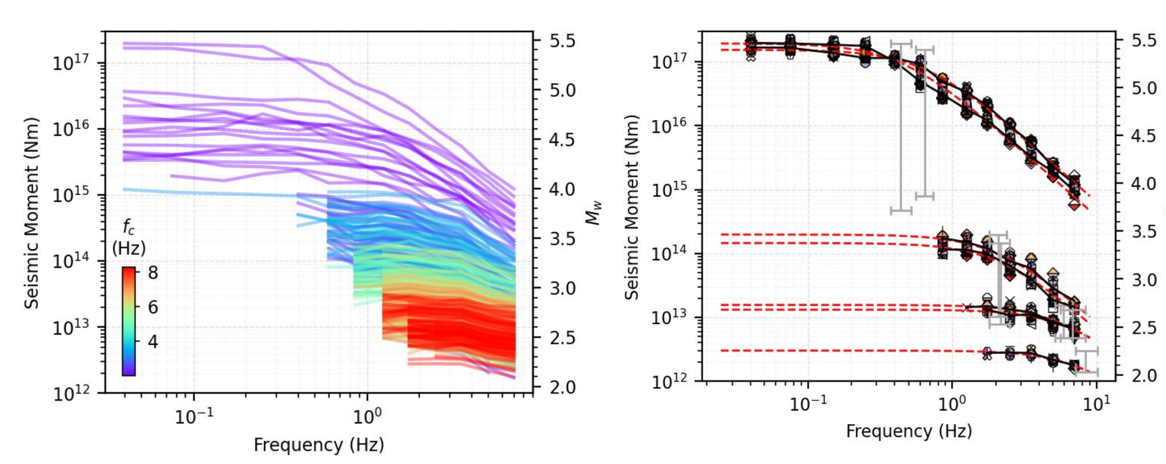


Left column: all events
Right column: Dep. > 0

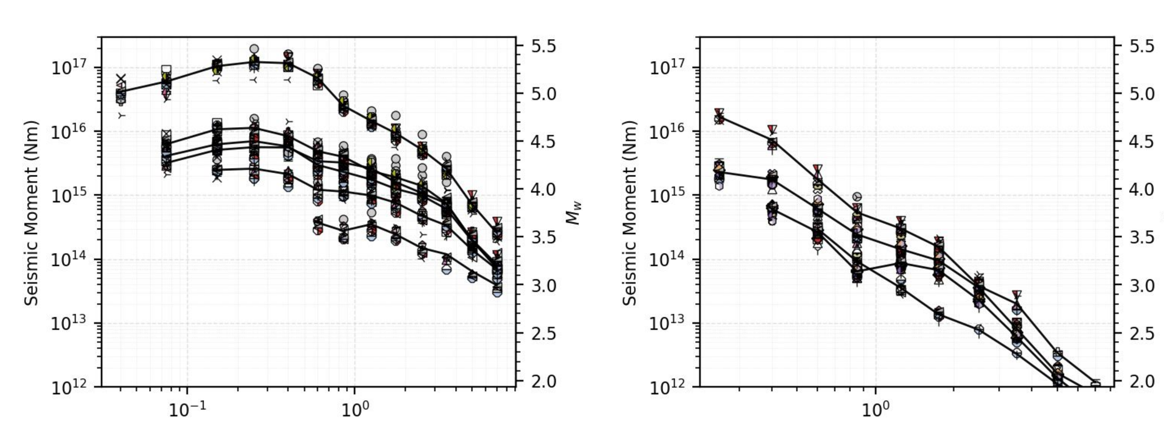
Discussion: Spectral Features and σ_a Regional Variation

For the 751 events with Depth > 0 km,

- **Largest events (Mw 5.4 Gyeongju, Mw 5.5 Pohang)**: different f_c estimates
- **Small events:** stable spectra across stations, even with ~30% energy ratio



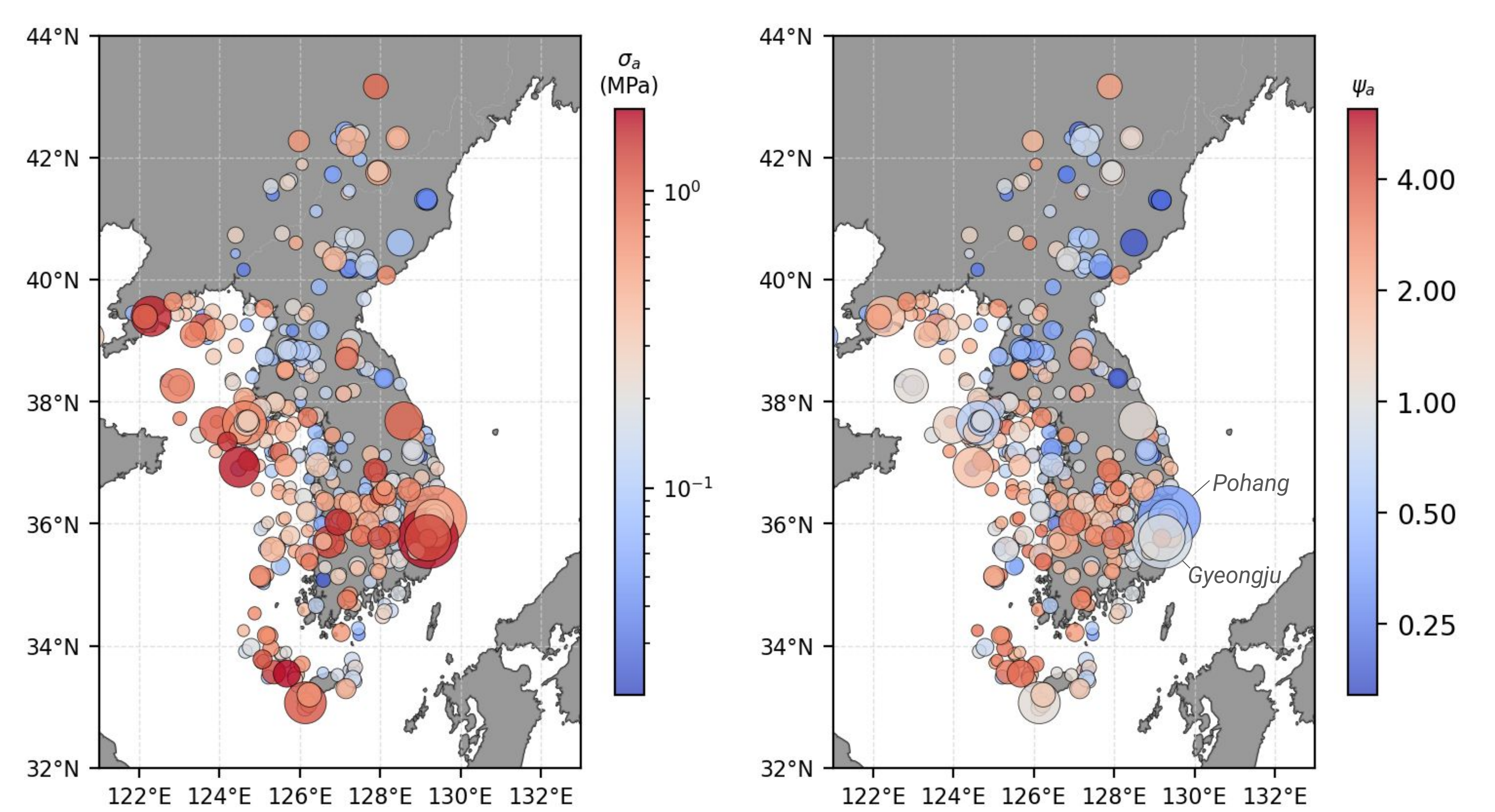
- Applied the obtained calibration parameters to: six DPRK nuclear tests; event 8 minutes after the 6th test; South Korean mining collapse events
- **DPRK tests (all six)**: spectra exhibit a distinctive fall-off pattern
- **Post-Test 6 event**: spectrum resembles mining collapse cases



Introducing ψ_a, normalized apparent stress (σ_a) with magnitude dependence removed *(left: σ_a, right: ψ_a)*

$$\psi_a = \frac{\sigma_a}{10^{aM_w+b}}, \quad \log_{10}\psi_a = \log_{10}\sigma_a - (aM_w + b)$$

- **Southeastern Korea:** among the two largest instrumental earthquakes, σ_a high but ψ_a (magnitude dependence removed) relatively low; and 2016 Gyeongju (Mw 5.4) < 2017 Pohang (Mw 5.5)
- **Central Korea / DPRK test site:** σ_a high vs. low, and ψ_a showed the same contrast



References: **Barno** J., 2017. LLNL/Coda-Calibration-Tool, U.S. DOE; **Chai** et al., 2020. Stress-Drop Scaling of the 2016 Gyeongju and 2017 Pohang Earthquake Sequences Using Coda-Based Methods, BSSA; **Mayeda** K., and Walter W. R., 1996. Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, JGR.; **Mayeda** K. et al., 2003. Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, BSSA; **Morasca** P. et al., 2005. Coda-derived source spectra, moment magnitudes and energy–moment scaling in the western Alps, GJI; **Sheen** et al., 2016. A Local Magnitude Scale for South Korea, BSSA; **Shelly** D. R. et al., 2021. A Big Problem for Small Earthquakes: Benchmarking Routine Magnitudes and Conversion Relationships with Coda Envelope-Derived in Southern Kansas and Northern Oklahoma, BSSA.