Probing Rupture Dynamics and Ground Motion Signatures from Induced and Natural Earthquakes

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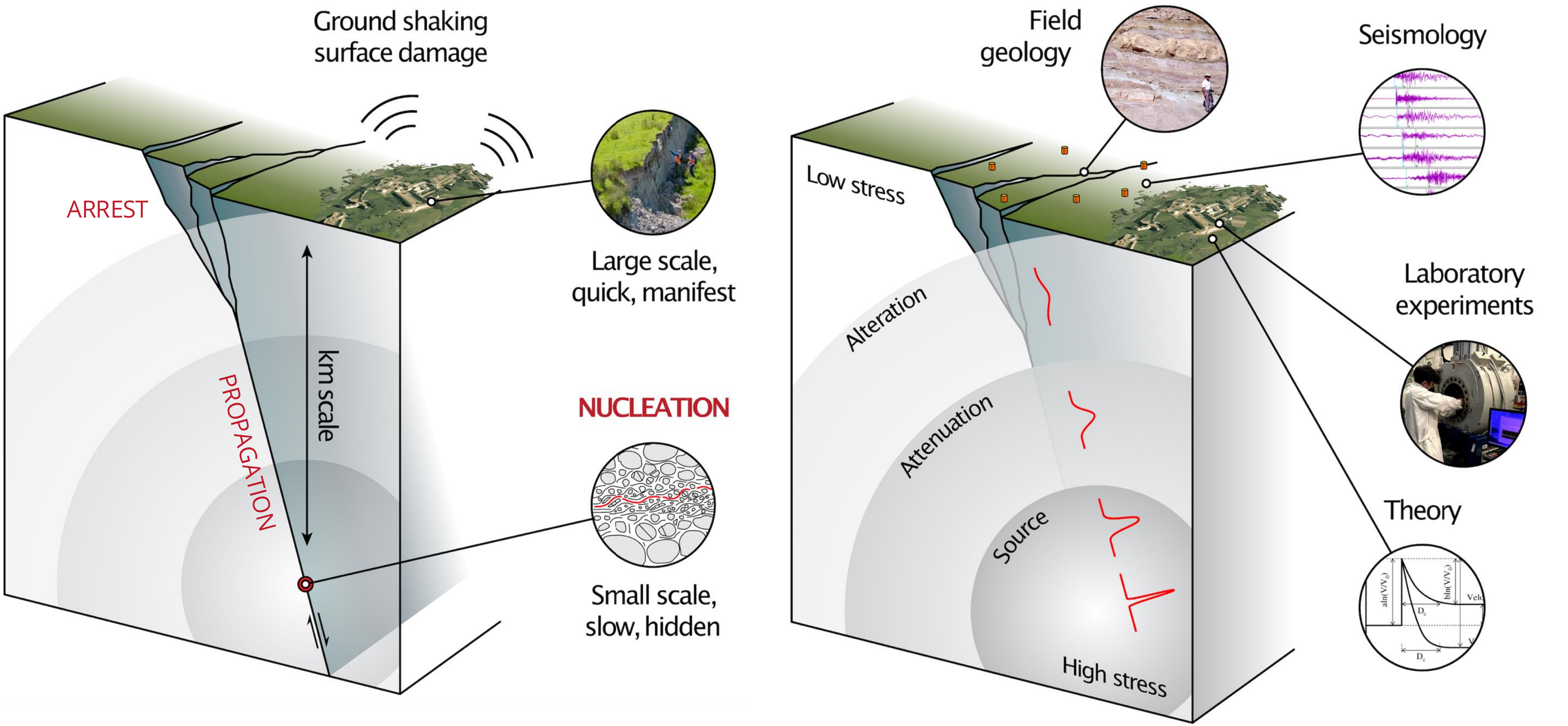
Earthquakes



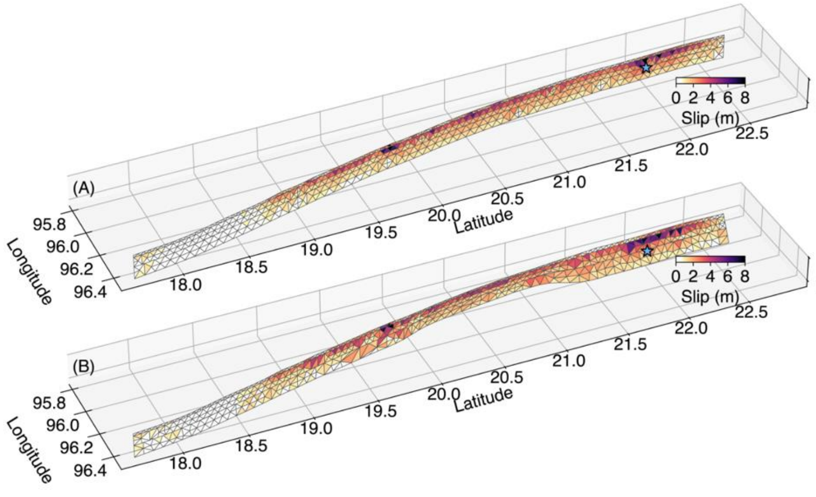
Earthquakes nucleate at a certain point in the crust, propagate along a fault surface, and eventually come to a stop. These coseismic rupture phases can be studied through recorded data in the near and far field, with modeling, and by reproducing the ruptures at laboratory scale.

Outlines

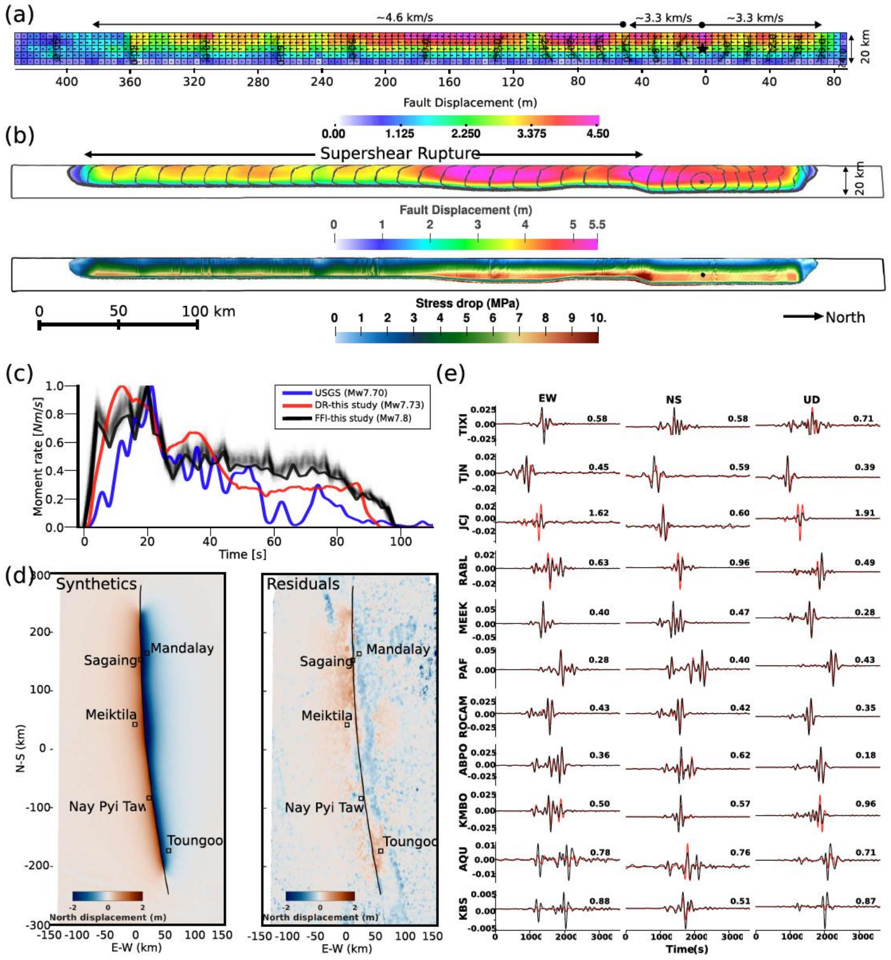
- Dynamic consistency of kinematic source models
- Modeling high-frequency radiation
- Induced micro-seismicity in underground natural laboratories

Dynamic consistency of kinematic source models

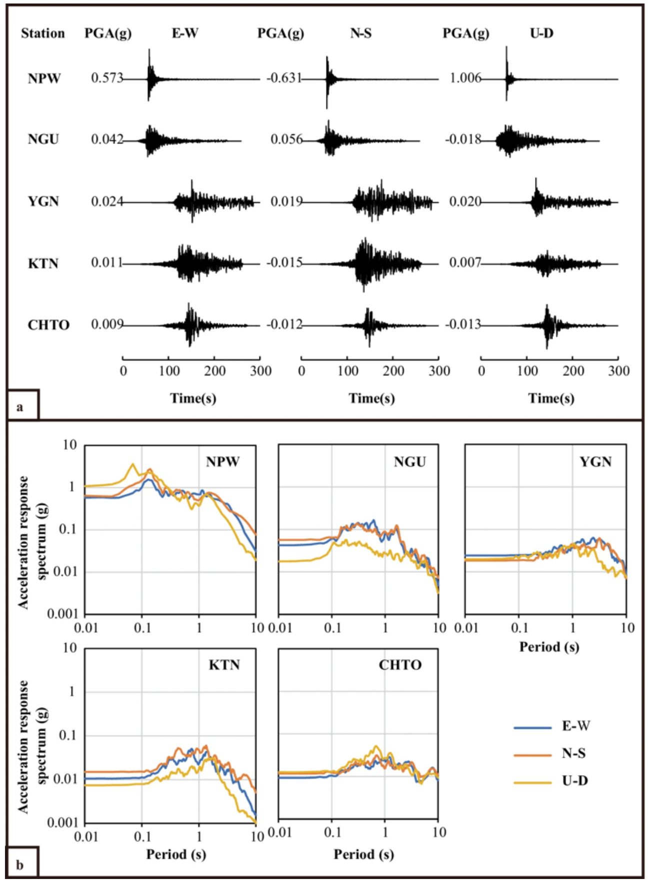
The 2025 M 7.7 Myanmar earthquake



Melgar et al 2025



Li et al 2025



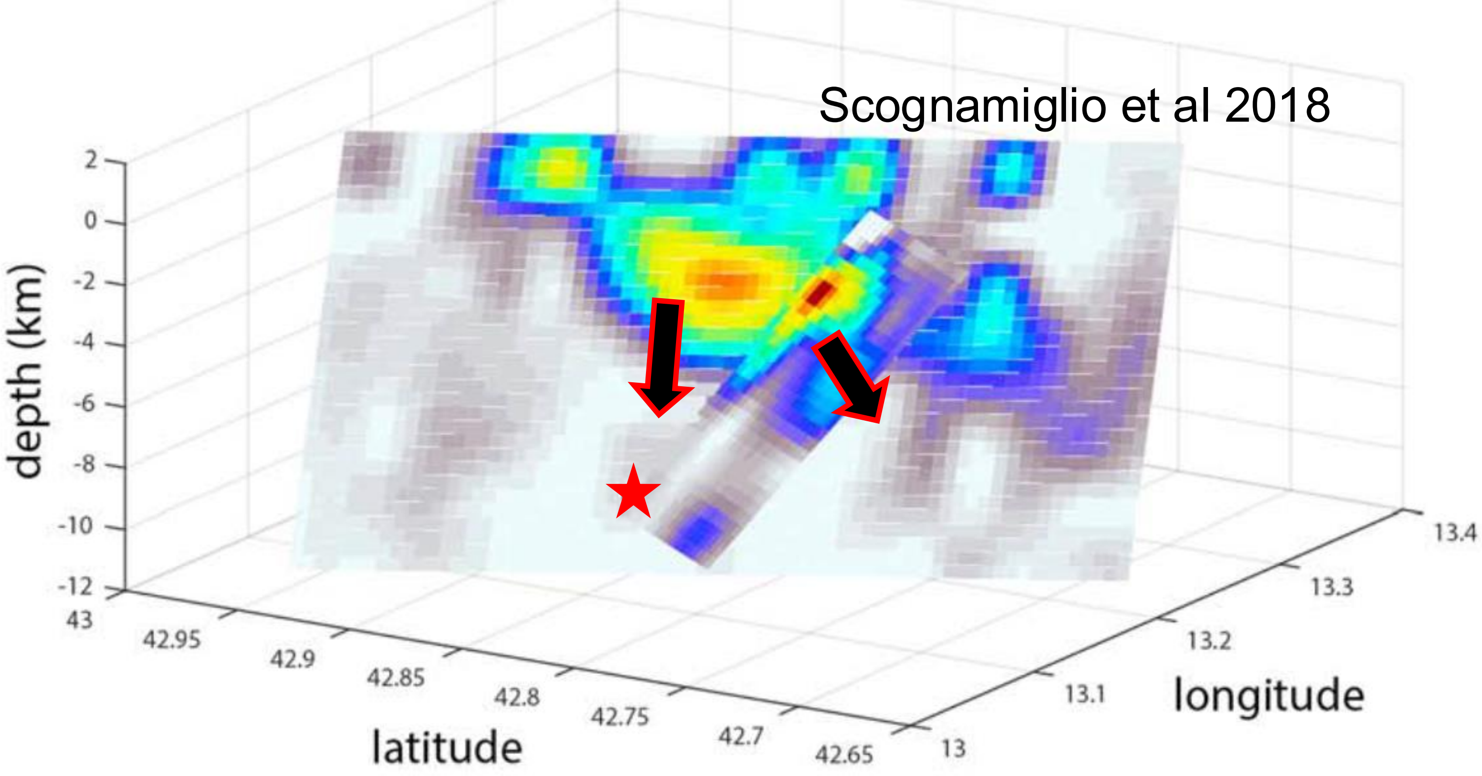
Xu et al 2025

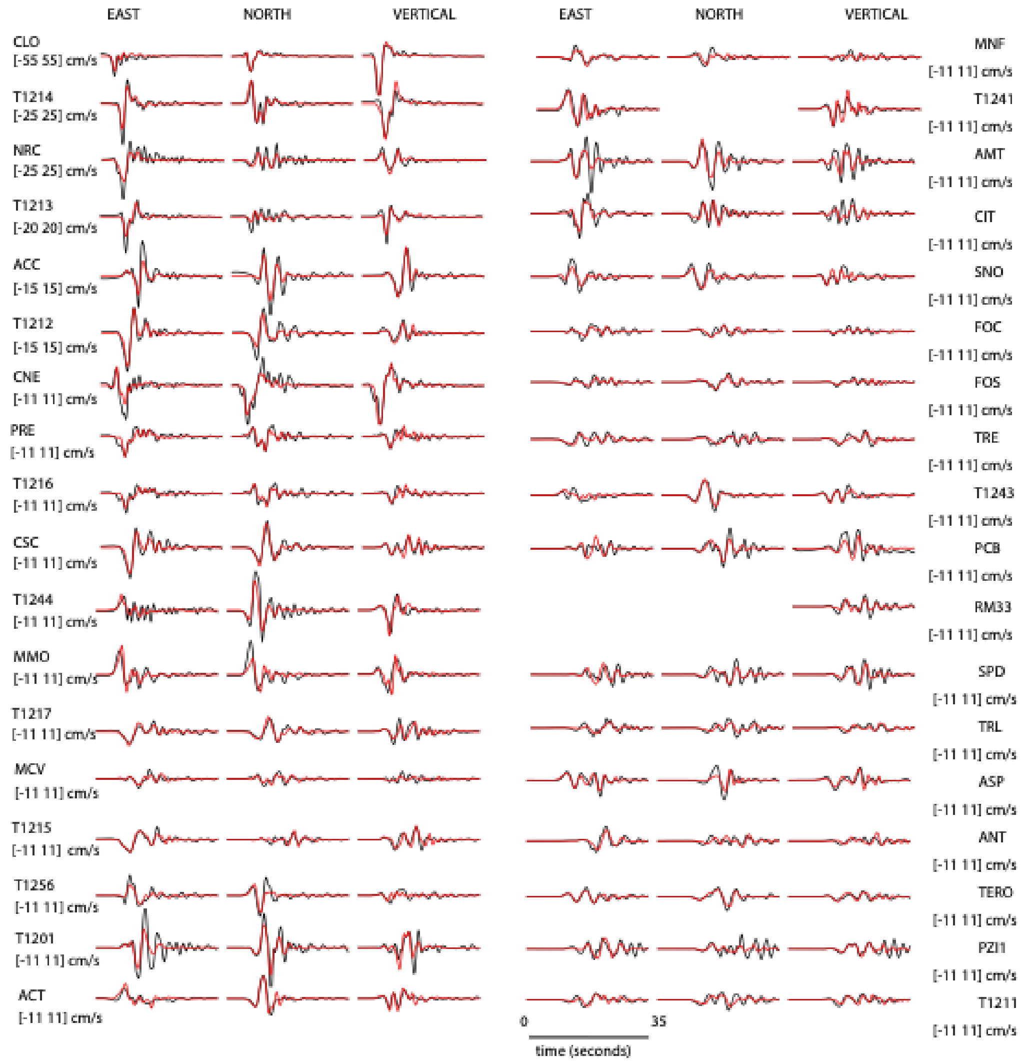
Are there dynamic conditions that explain a kinematic model? Is it possible to generate a dynamically consistent rupture that reproduces the distribution of parameters (slip, rupture times, rise time, source time function) of the kinematic model?

We can fit observations (seismic data, GNSS, InSAR) up to low frequencies (< 1 Hz), but the recordings extend to ~10–500 Hz. How can we constrain the higher frequencies?

➢ Dynamic consistency of kinematic source models

Kinematic model of the 2016 Mw 6.5 Central Italy Norcia event: this model suggests that two fault planes may have slipped simultaneously



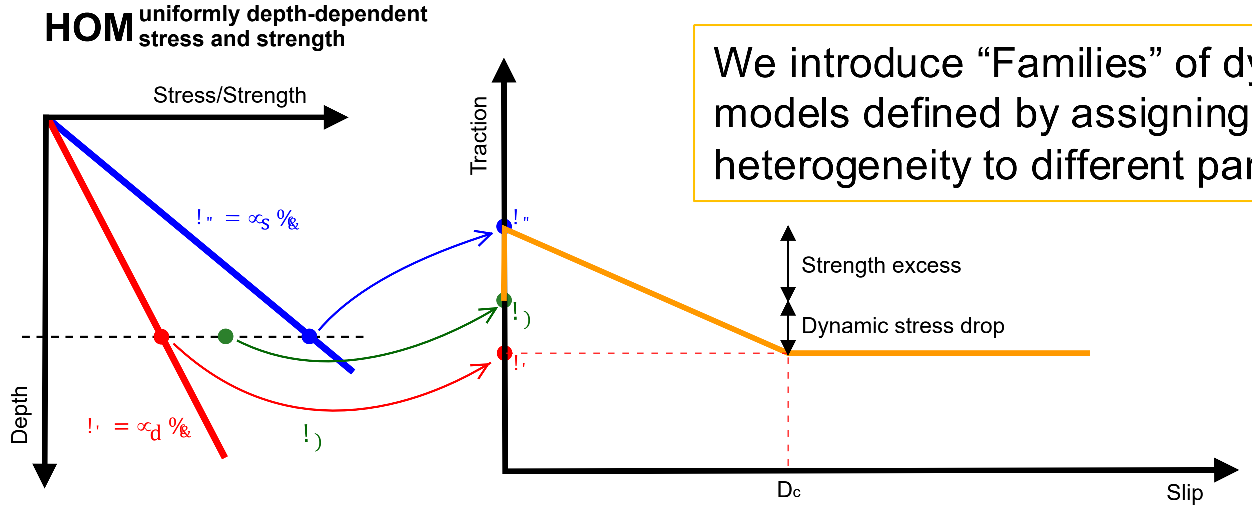


Key characteristics indicating possible dynamic incompatibility:

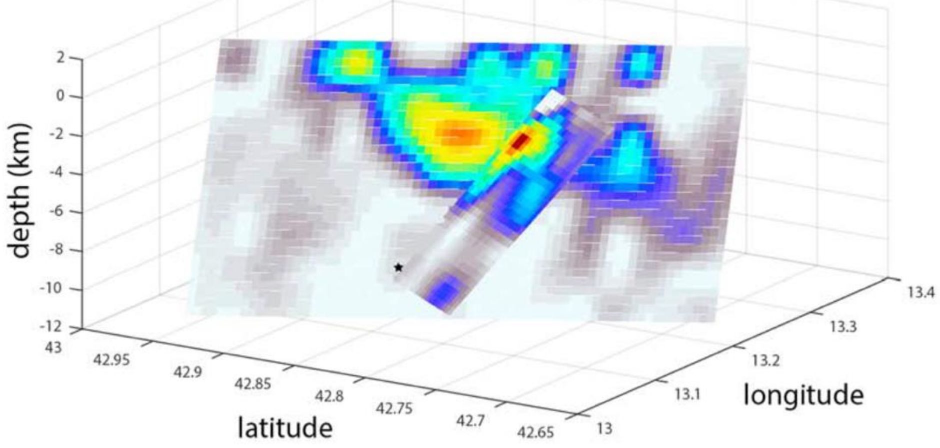
1) Nucleation in an area with almost zero slip (<=20cm)
2) High slip (~3m) patch few km away from the hypocenter
3) Activation of a misoriented secondary fault
4) Spatial heterogeneity in slip and rake.

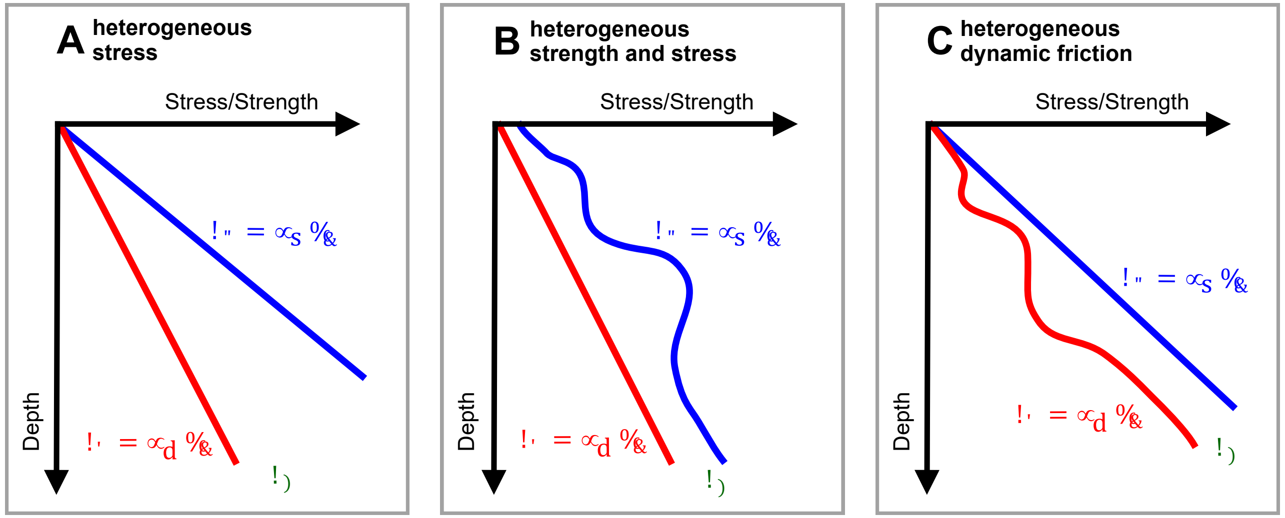
Dynamic consistency of kinematic source models: Families of dynamic models

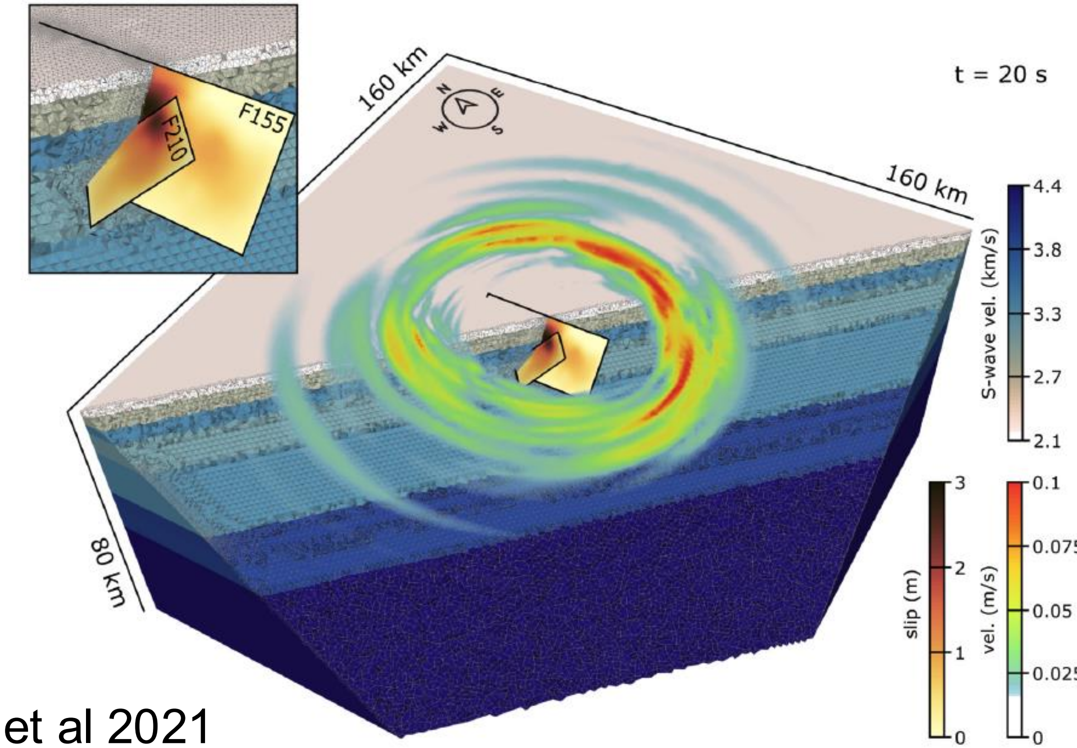
To validate the mechanical viability of the kinematic rupture model proposed for the Mw 6.5, 30 October 2016 Norcia earthquake (Scognamiglio et al 2018).



We introduce "Families" of dynamic models defined by assigning heterogeneity to different parameters.





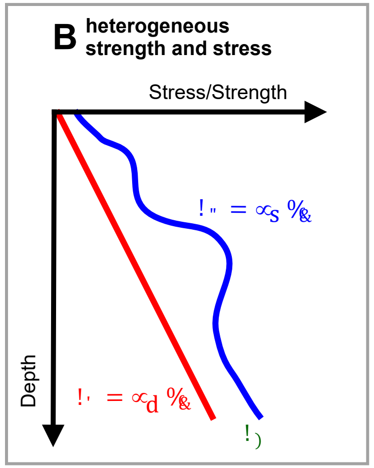


Tinti et al 2021

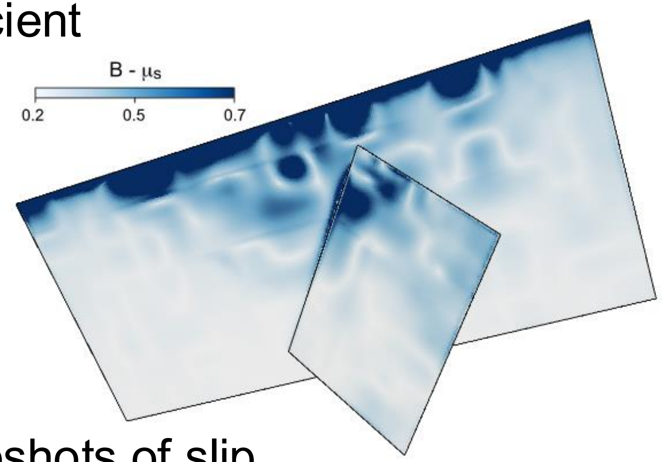
…toward physics-based ground-motion simulations

Families of dynamic models

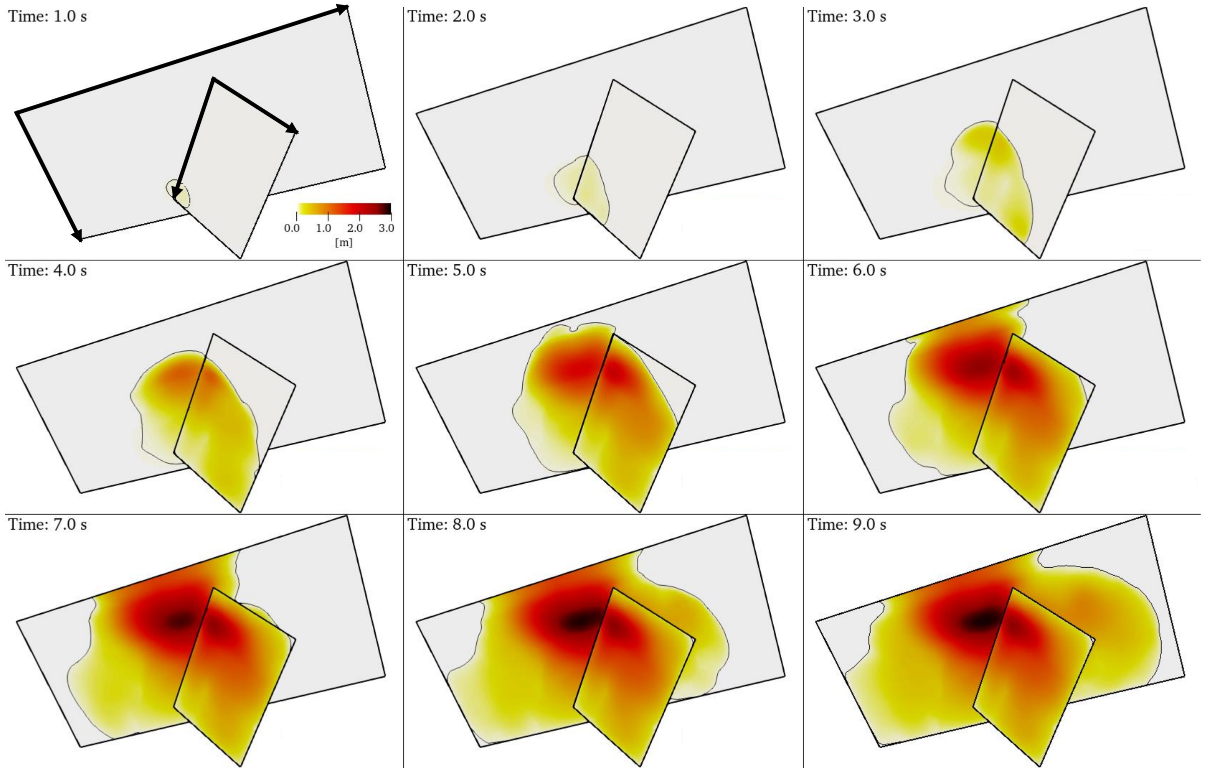
Tinti et al 2021



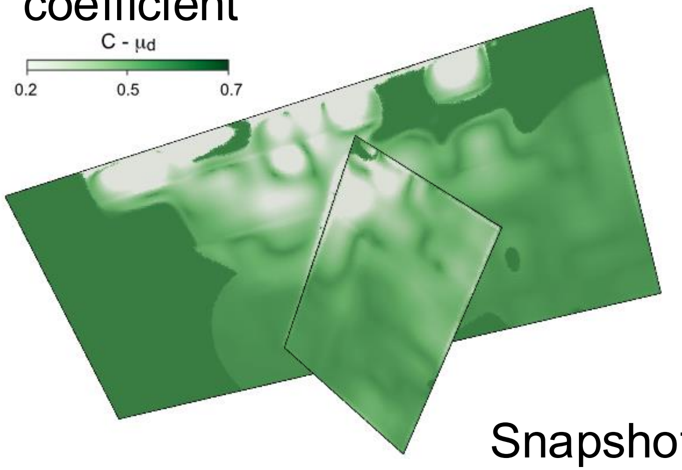
Heterogeneous Static friction coefficient

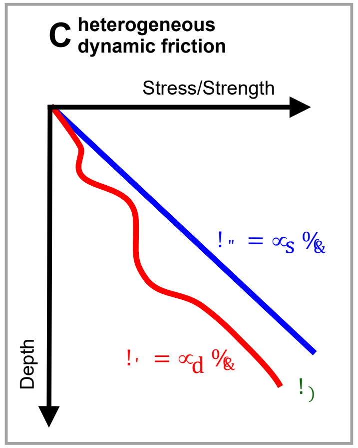


Snapshots of slip

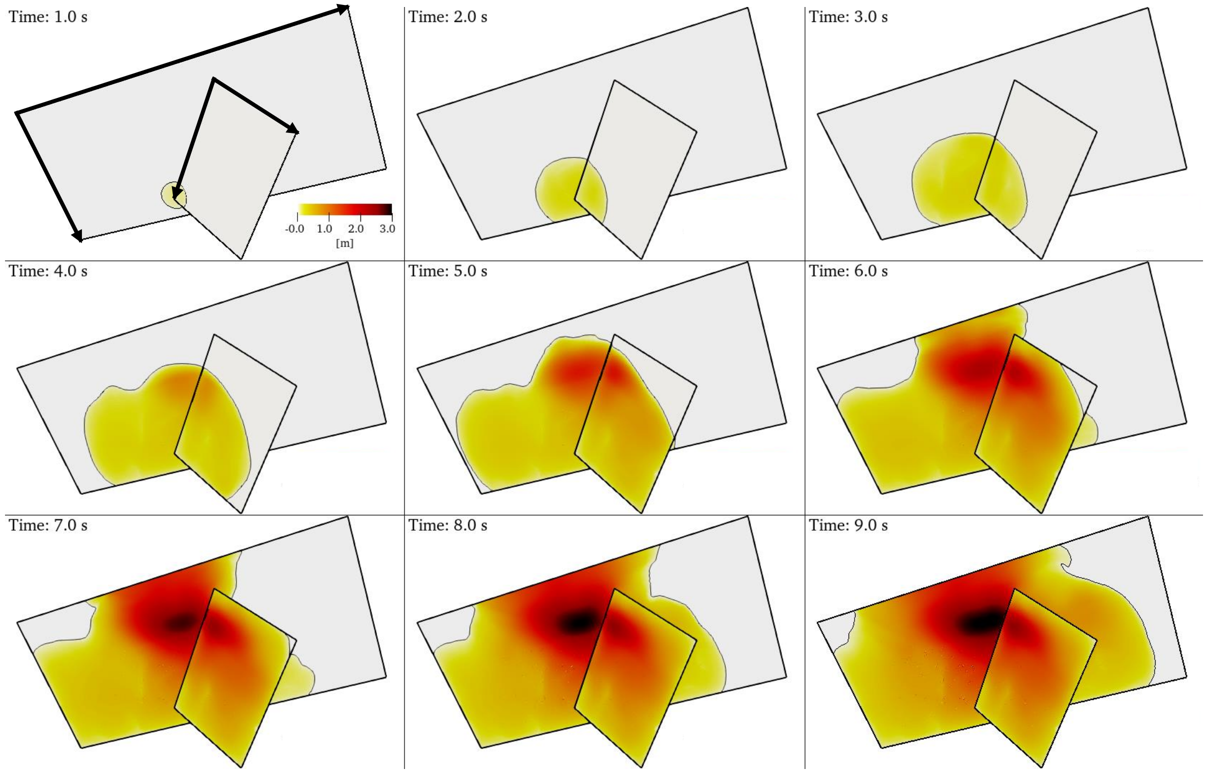


Heterogeneous Dynamic friction coefficient



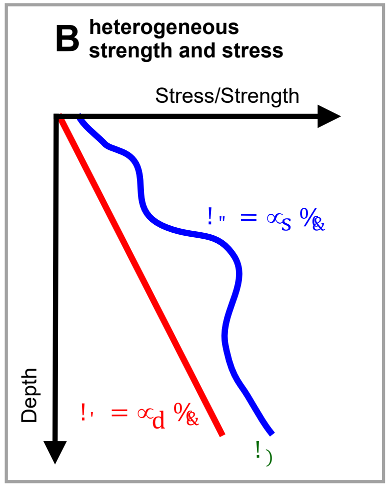


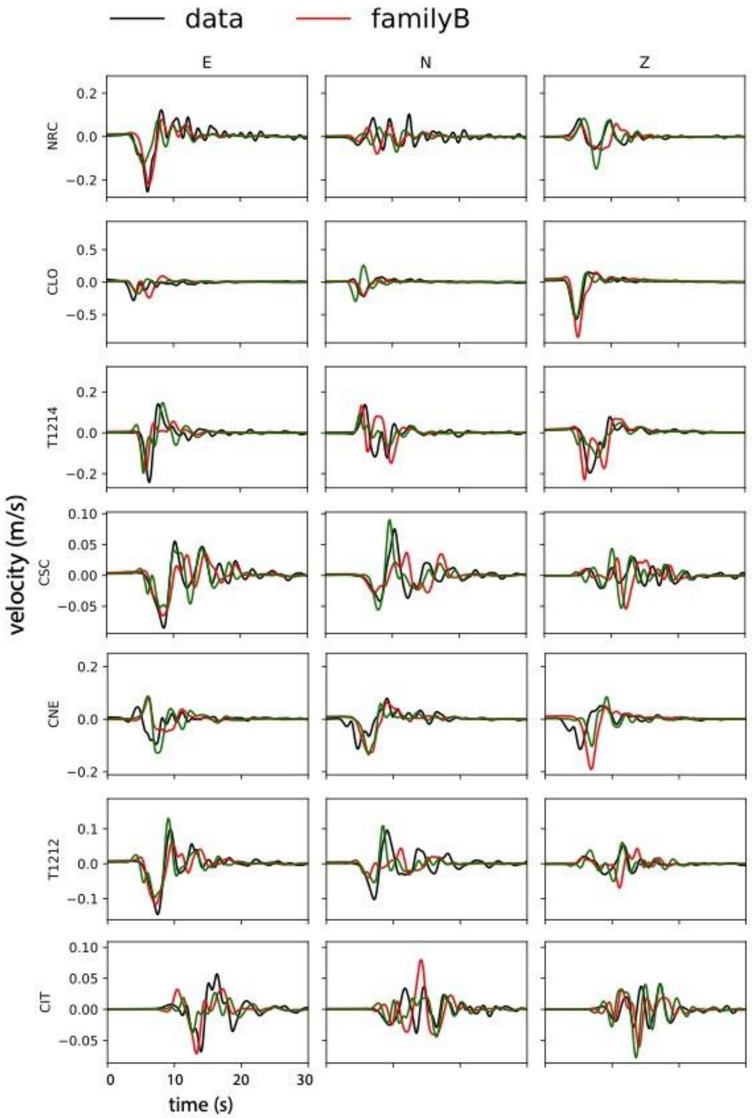
Snapshots of slip

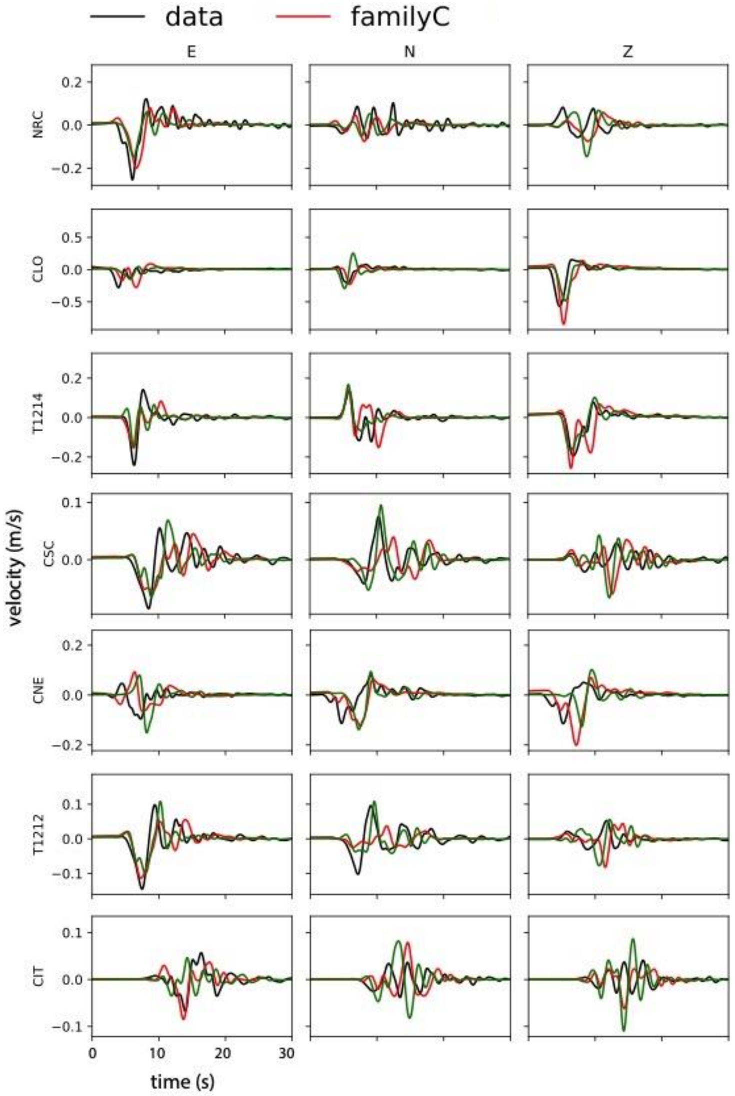


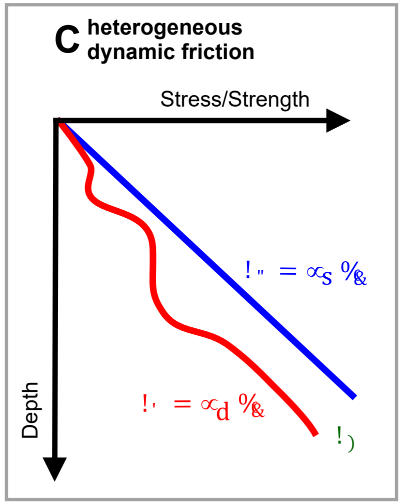
Families of dynamic models: waveforms fit

The models from the two different families show a satisfactory fit to the observed waveforms (in the frequency range 0.02–0.5 Hz) at the closest stations, even though we are not inverting any seismic data.



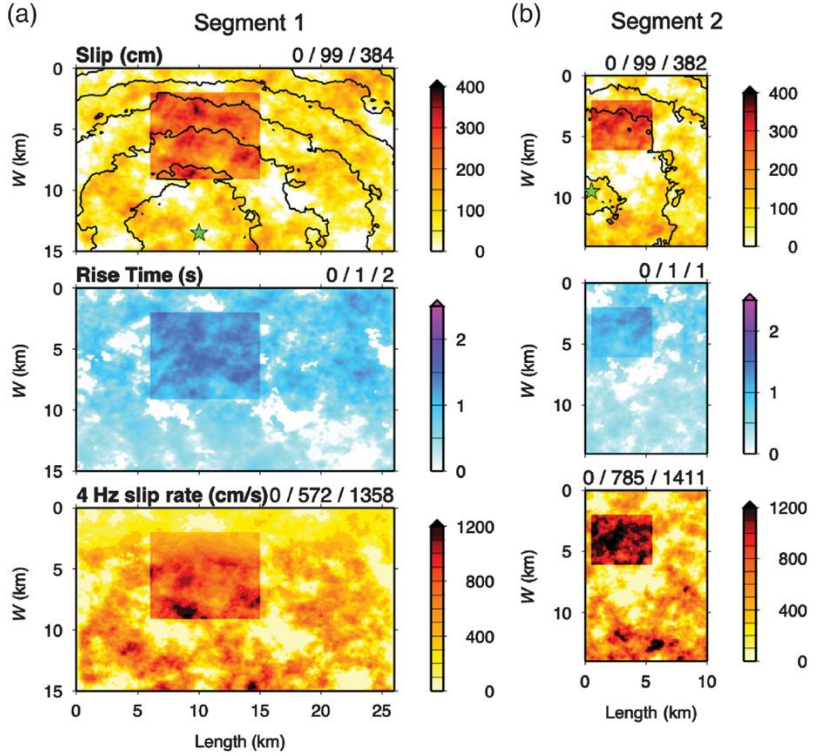


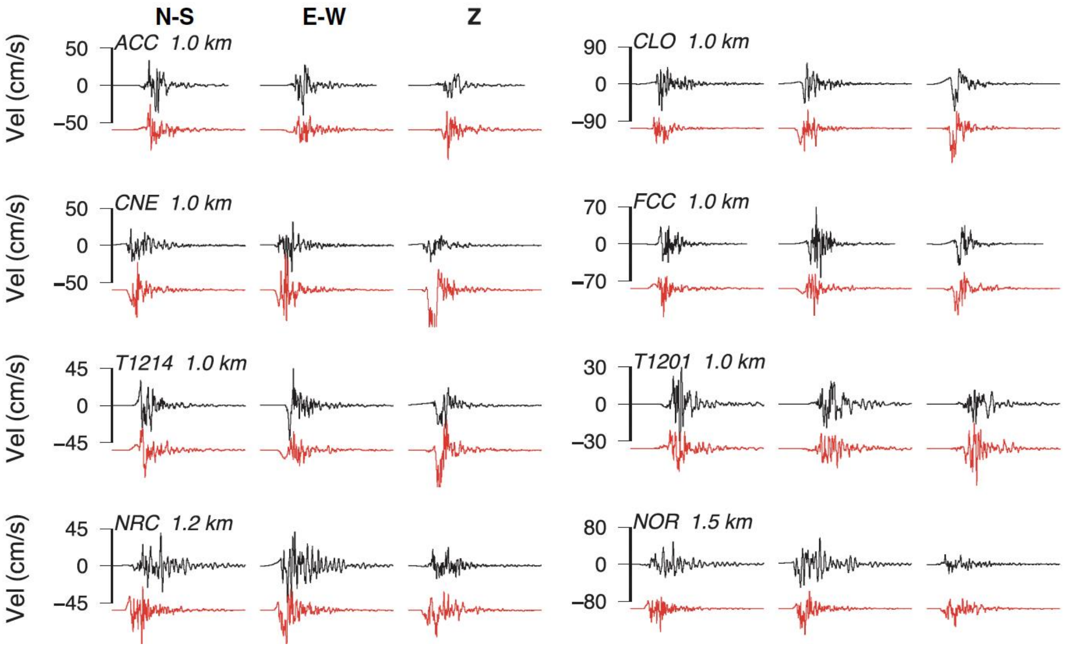


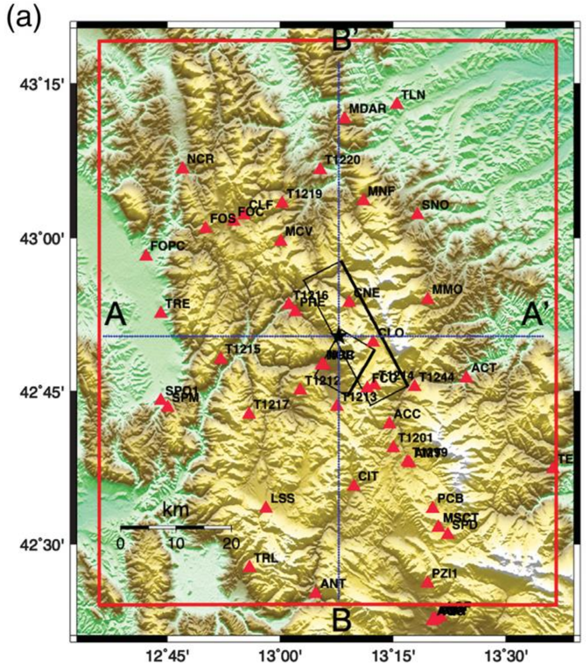


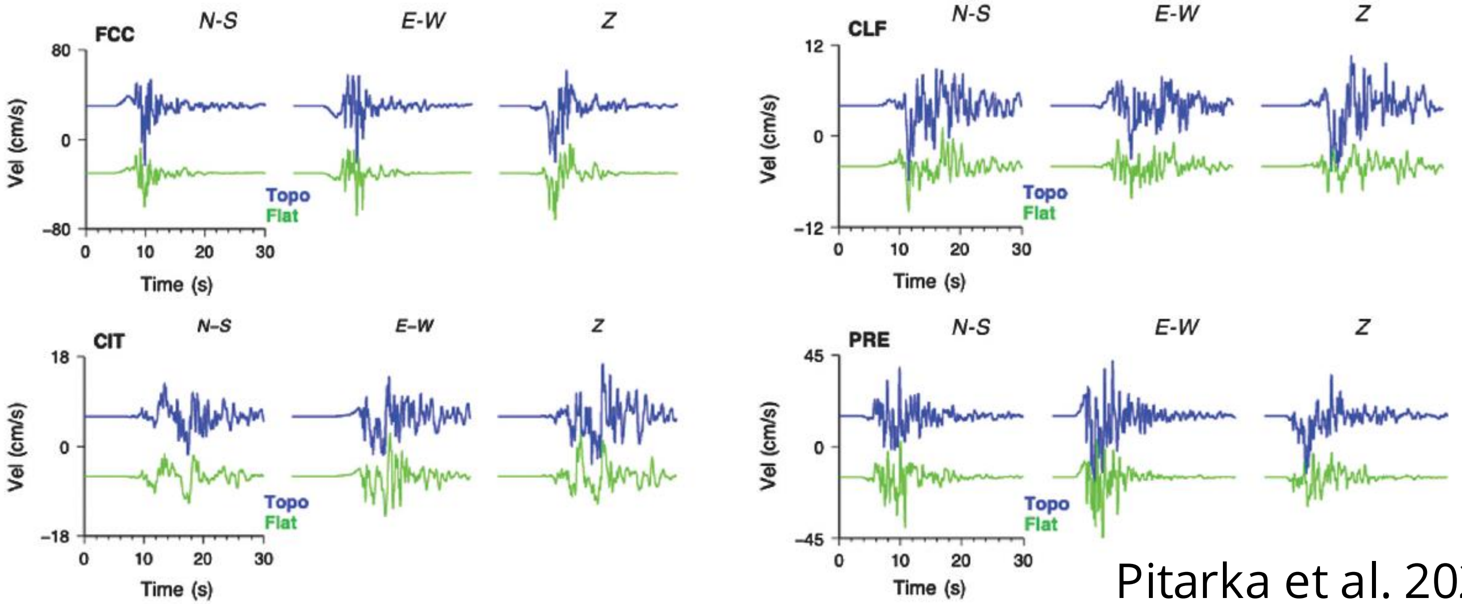
Tinti et al 2021

Literature: Rupture models and high-frequency radiation scenarios









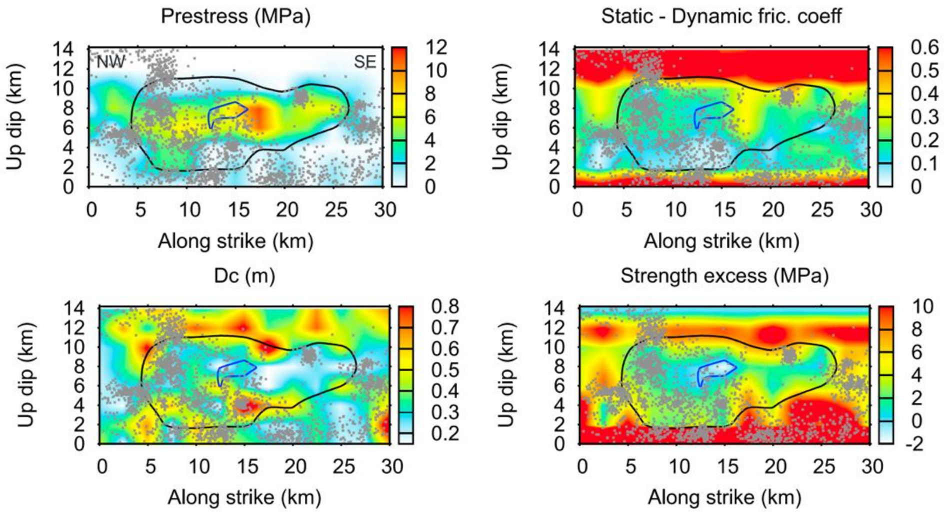
In Pitarka et al 2022, the Mw 6.5 Norcia earthquake was used to generate broadband simulations up to 3–5 Hz, by adding a stochastic high-frequency component to the kinematic model. The results highlight the important role of topography in shaping high-frequency ground motion, while no specific phase of the rupture was identified as the dominant source of the highest frequencies.

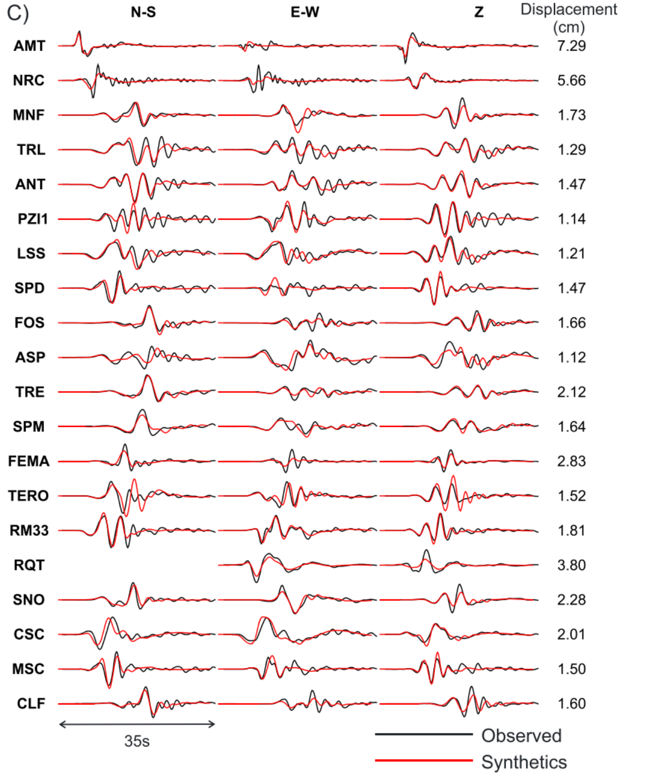
Pitarka et al. 2022

Literature: Dynamic inversion modeling and high-frequency radiation

Dynamic inversion models are recently emerging. The 2016 Mw 6.1 Amatrice event, Central Italy retrieved for frequencies 0.02-0.5 Hz.

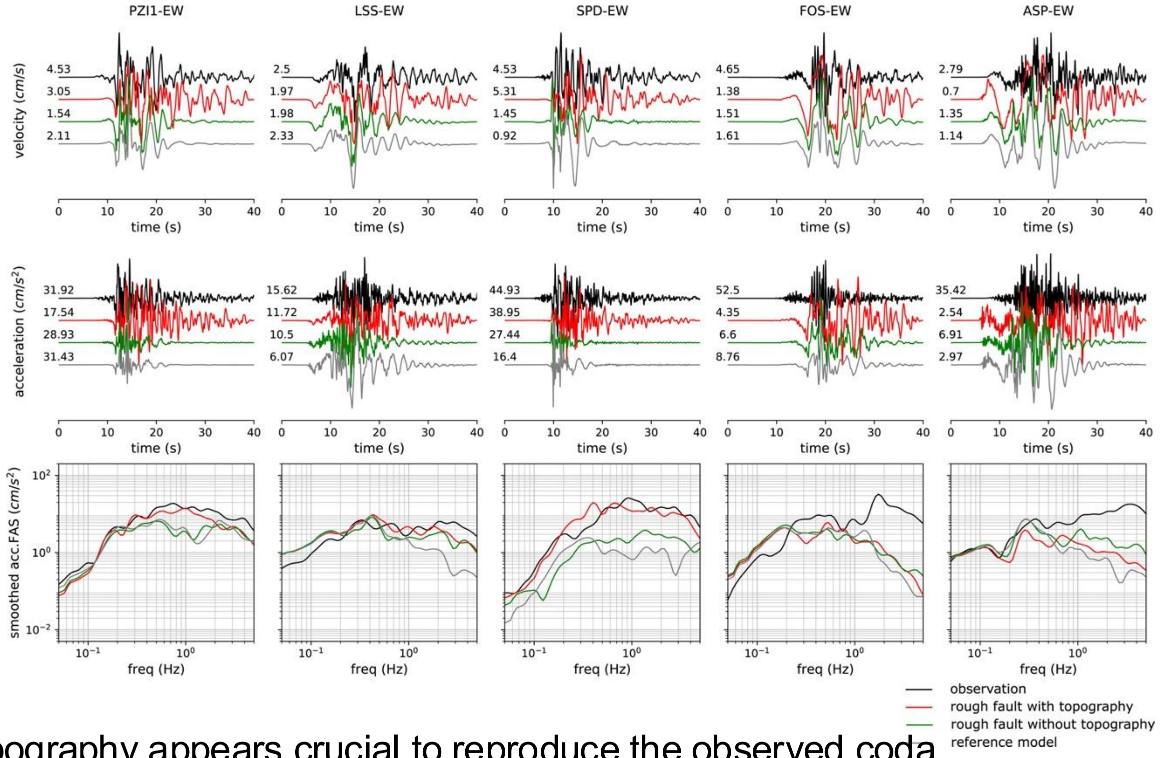
Gallovic et al. 2022

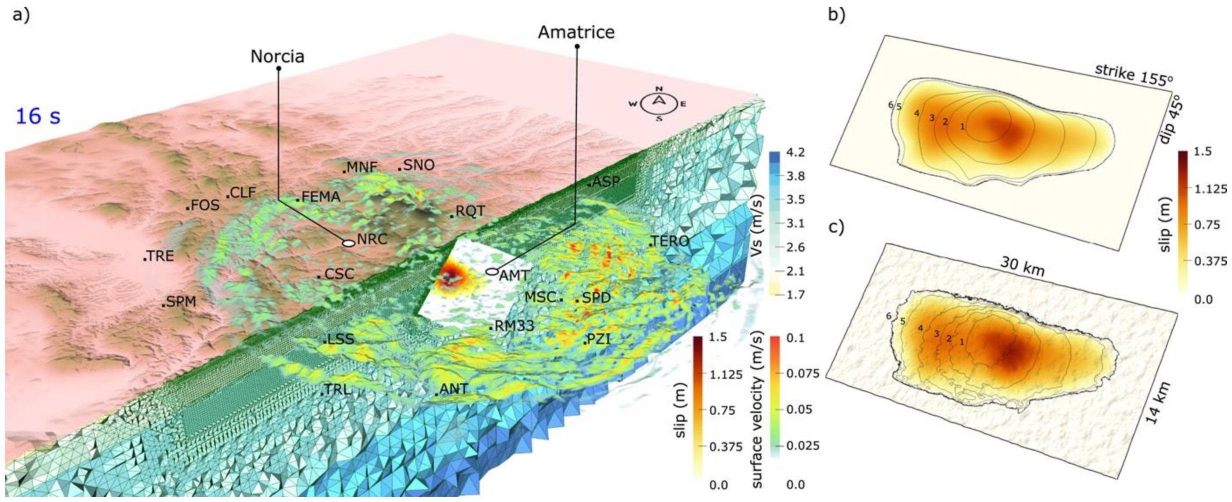




Forward dynamic modelling of the 2016 Mw 6.1 Amatrice event, Central Italy. for frequencies up to 5 Hz with fractal fault roughness, frictional heterogeneities, viscoelastic attenuation, and topography.

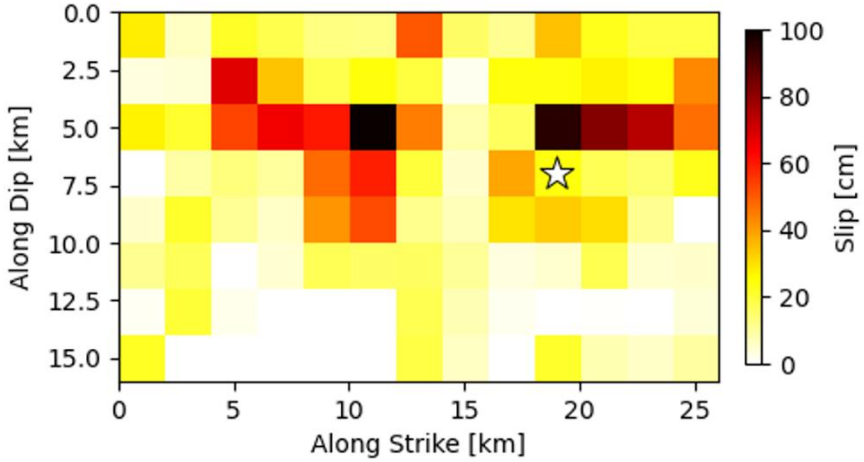
Taufiqurrahman et al. 2022





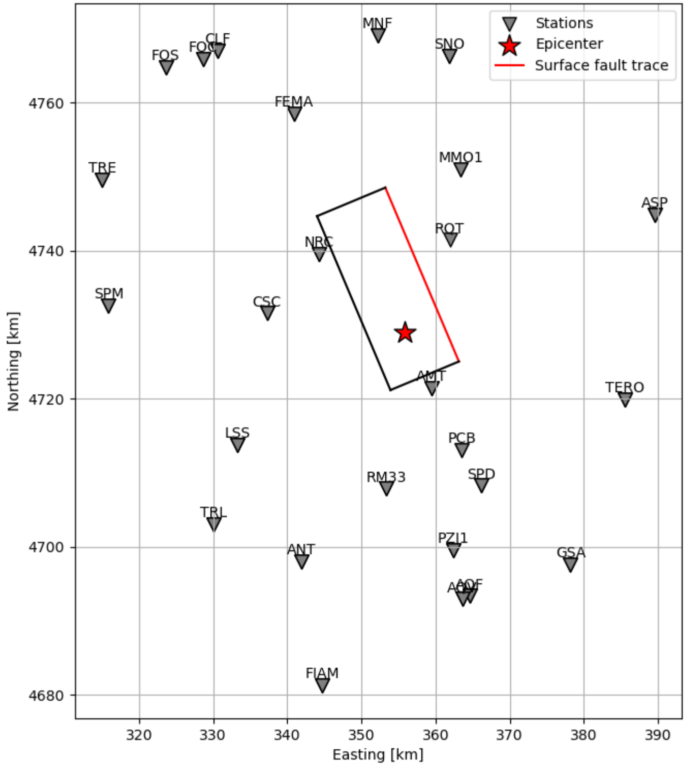
topography appears crucial to reproduce the observed coda

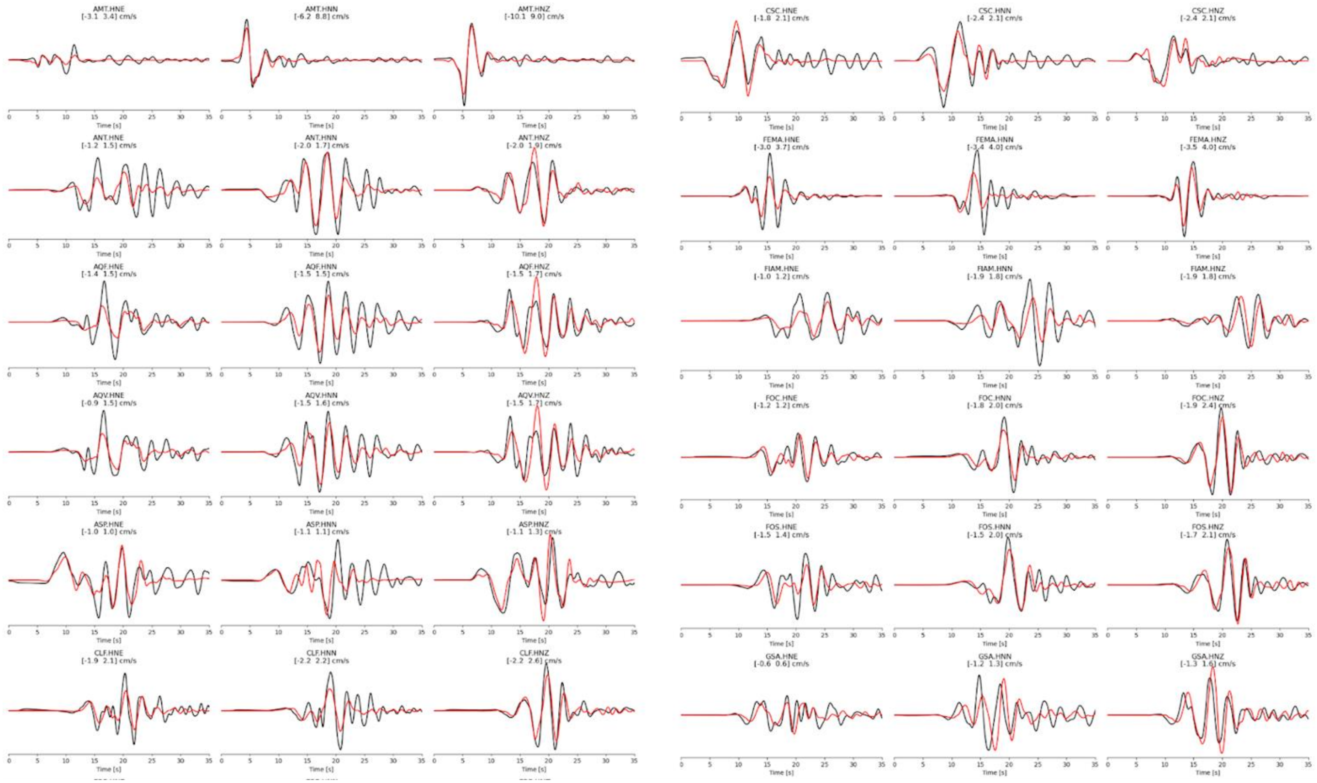
Modeling high-frequency radiation: the 2016 Mw 6.1 Amatrice event



Kinematic model of the 2016 Mw 6.1 Amatrice earthquake from strong-motion data (≤ 0.5 Hz) with multi window approach.

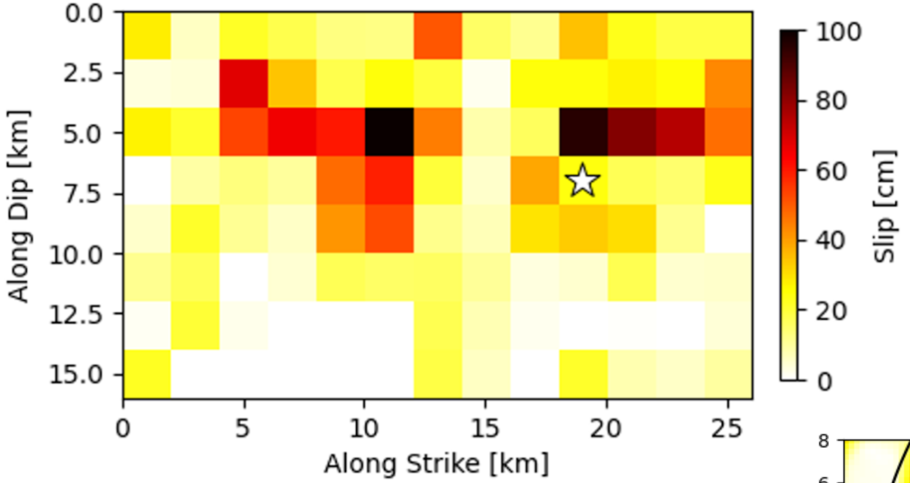
Tinti et al 2016, Locchi et al 2025



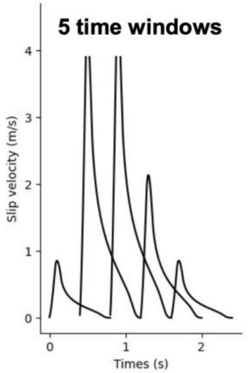


What if we extrapolate the waveforms up to 5 Hz? Extending these models to higher frequencies remains a major challenge.

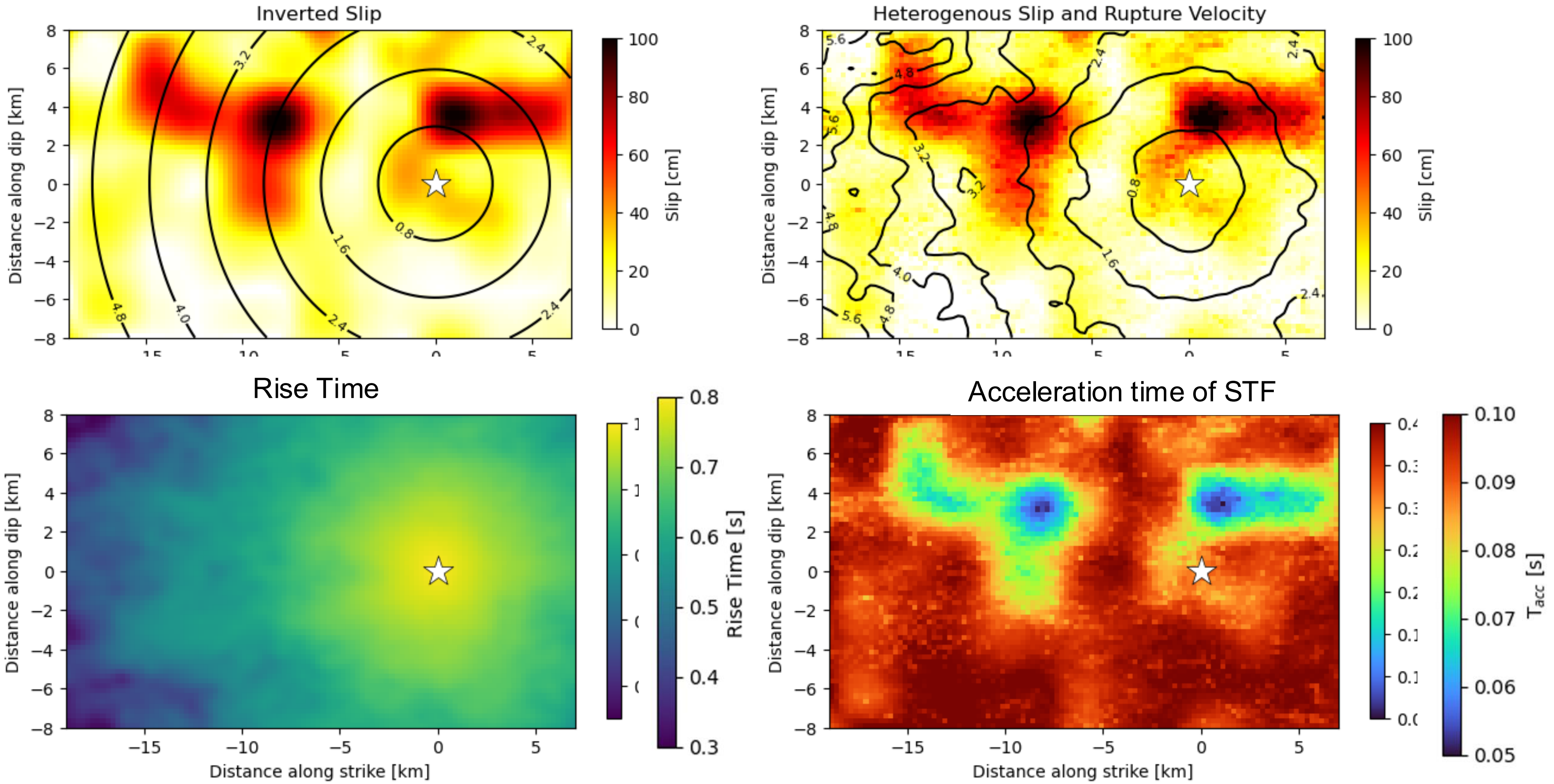
Modeling high-frequency radiation: the 2016 Mw 6.1 Amatrice event



Original model
with subfaults of 2 x 2 km^2.



Refined model with subfaults of 0.25 x 0.25 km^2.



High-frequency radiation is introduced in the model through the spatial variability of slip, rupture front, rise time, and acceleration time of the source time function.

Heterogeneities are added on top of the original model, preserving its integrity while introducing variability with physical meaning from a dynamic perspective.

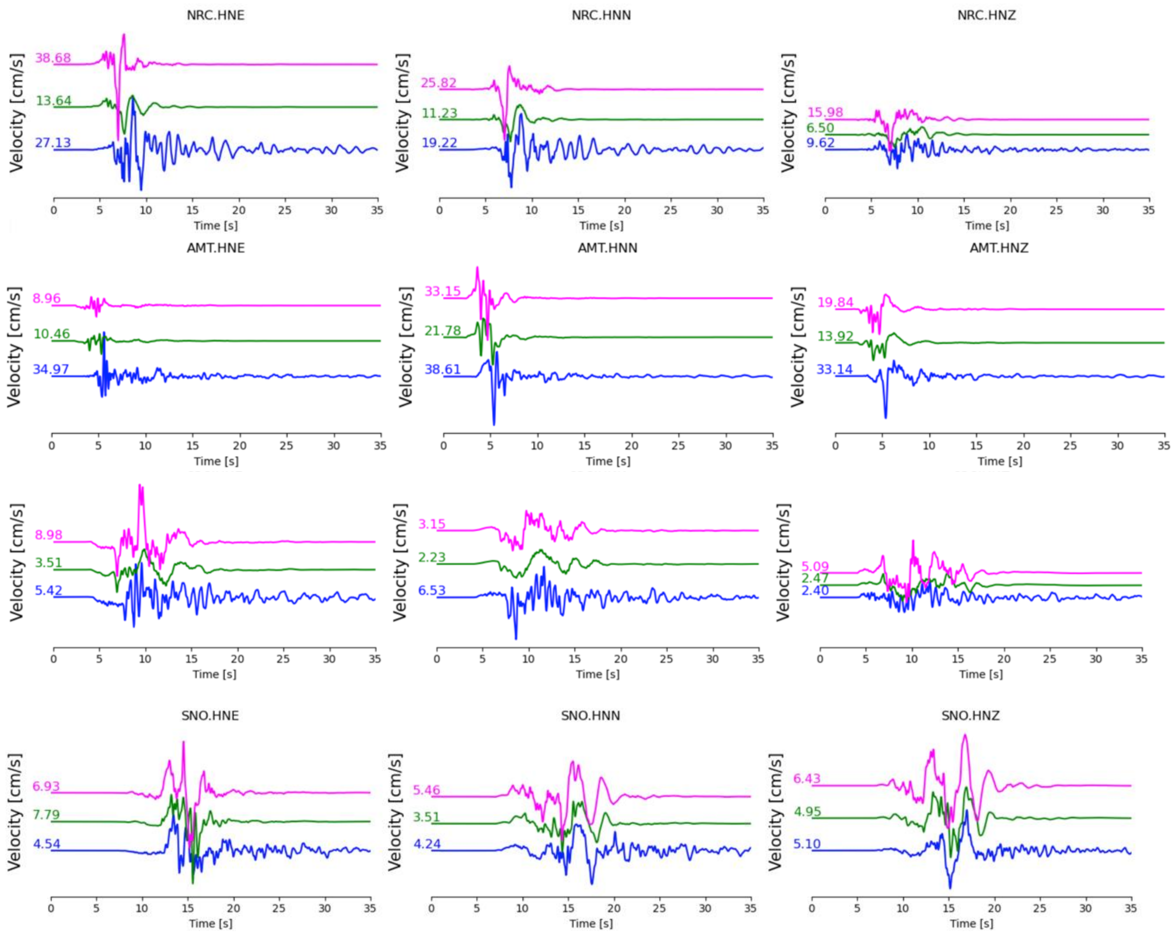
We omit heterogeneities related to site effects, velocity structure, and topography.

PGV can be either enhanced or smoothed by these short wavelengths.

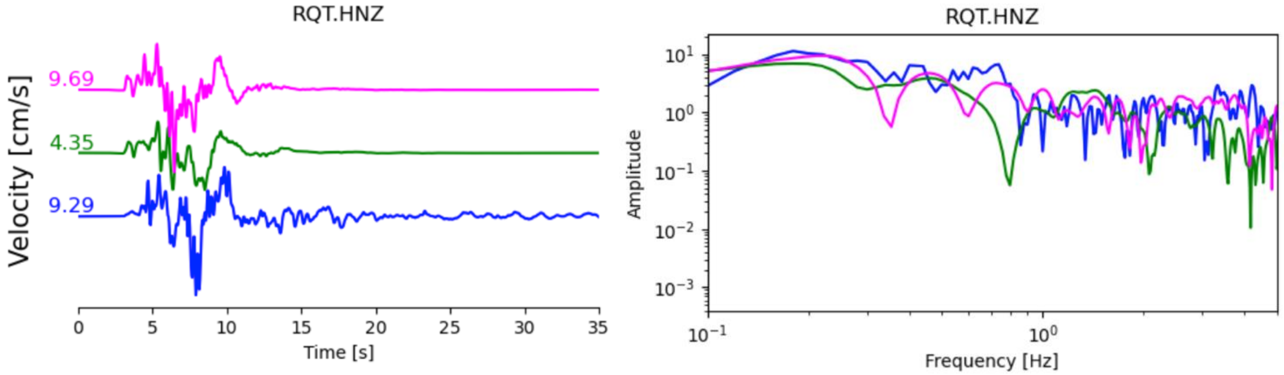
Locchi et al 2025

Modelling natural earthquakes: the 2016 Mw 6.1 Amatrice event

Frequency up to 5Hz.



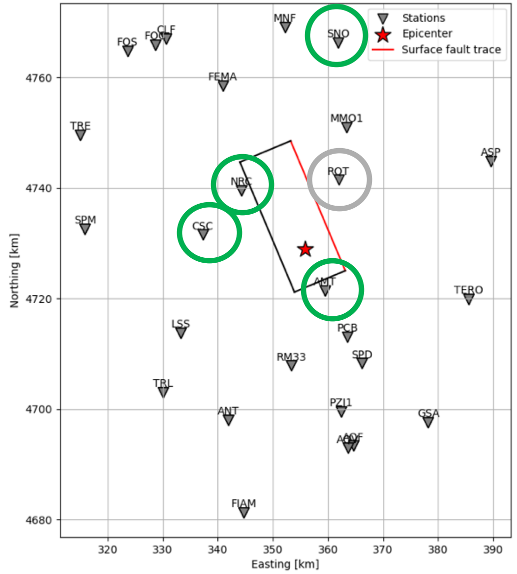
RQT is a station with site classified as A class.



Data

Interpolated original model

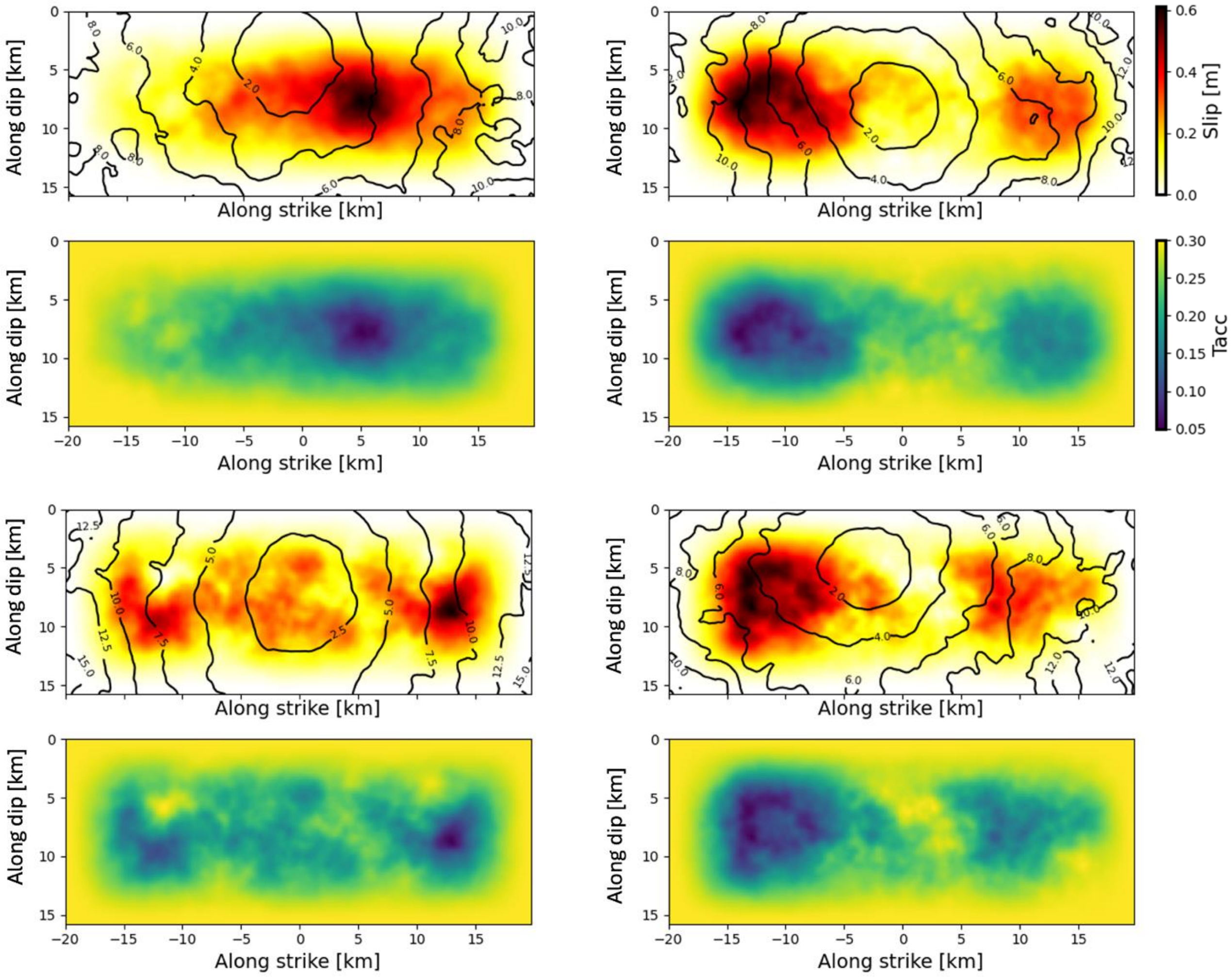
High-frequency model

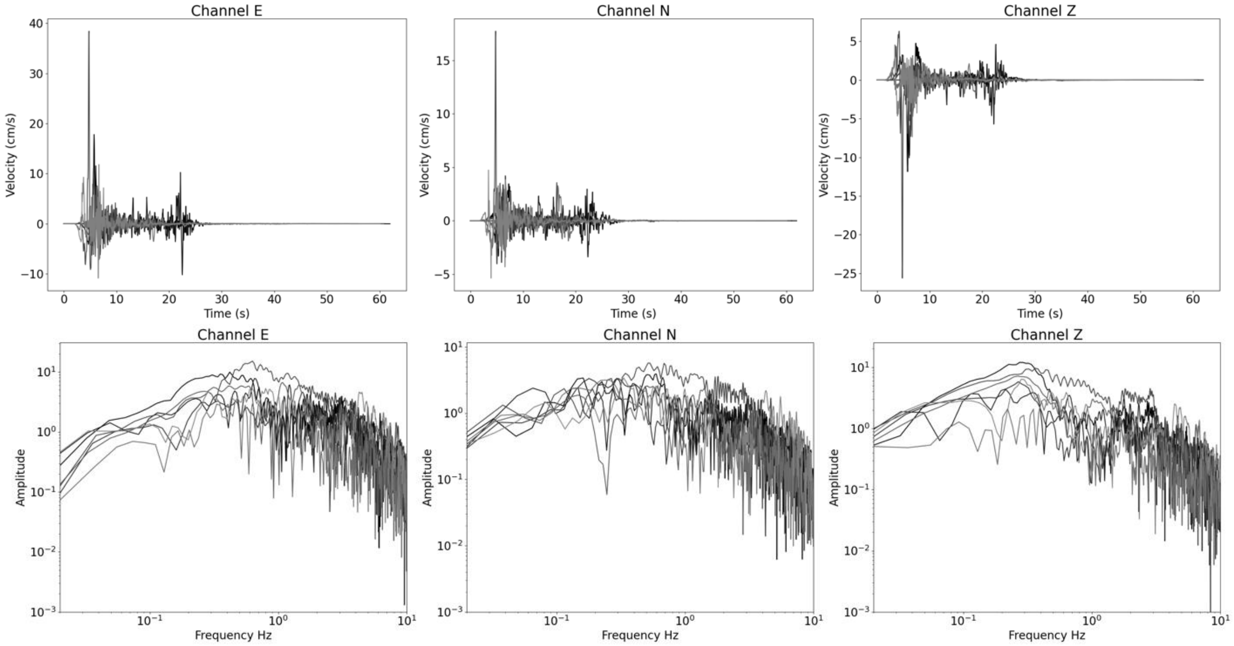


Comparison of synthetics from the simply interpolated original model, synthetics with added short-wavelength heterogeneities at the source, and real recordings (up to 5 Hz) at near-fault stations.

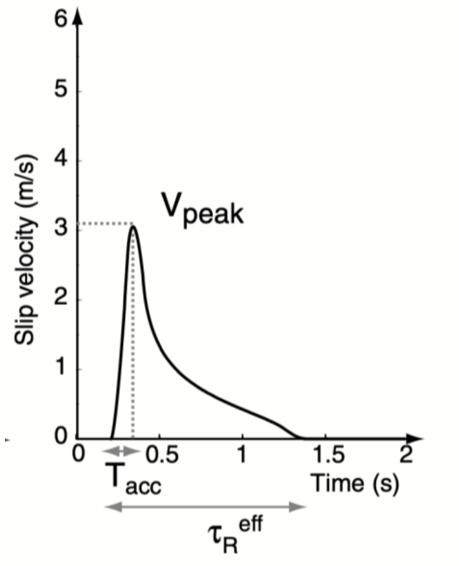
Locchi et al 2025

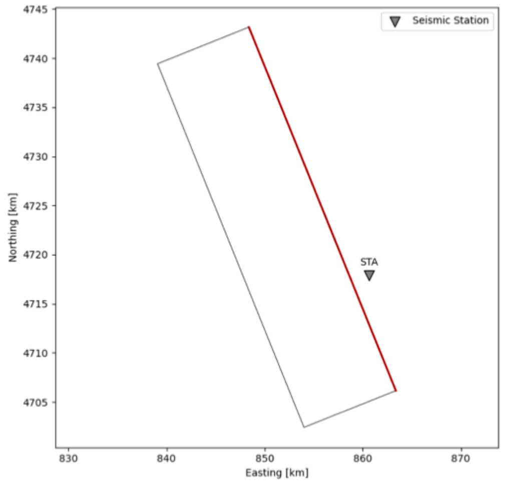
Modelling natural earthquakes: scenarios at high frequency





Physics-based scenarios at a station 2 km from the fault: varying nucleation, rupture-time distribution, slip, positive acceleration duration (Yoffe STF) — all heterogeneously distributed along the fault plane.



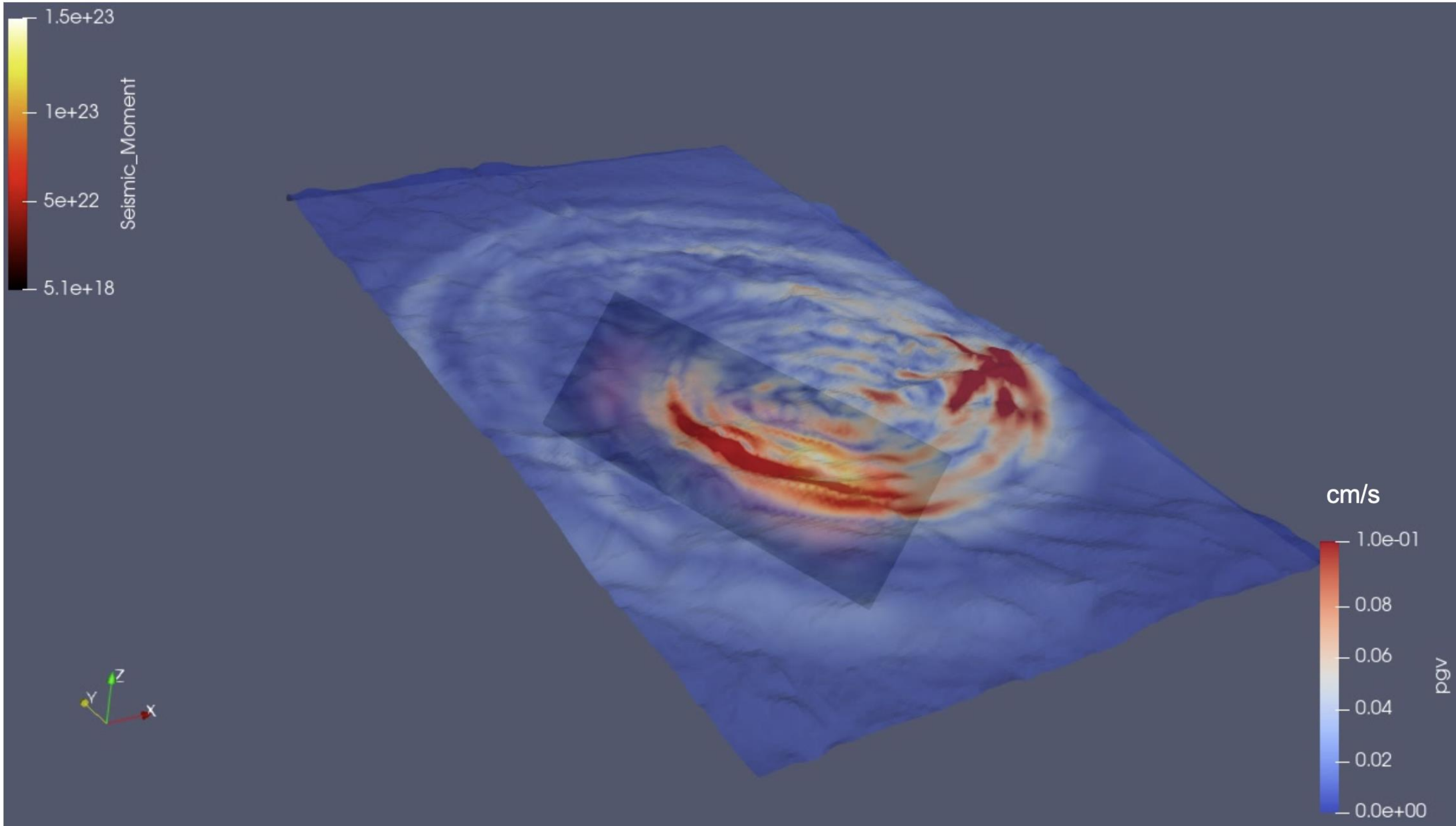


Locchi et al 2025

Modelling natural earthquakes: scenarios at high frequency

Physics-based scenarios with local topography modeled with SPECFEM (Locchi et)

Broadband ground-motion simulations with high-performance computing are now possible, and scenarios developed by many researchers worldwide could be shared and tested on different local topography, structural models, and site conditions.



Induced micro-seismicity in underground natural laboratories

- Can we further improve our understanding of seismic processes by moving closer to the fault?

- We have seen that long wavelengths can be explained by dynamic consistency, whereas short wavelengths can be attributed to fault roughness, stress heterogeneity, or topographic effects.

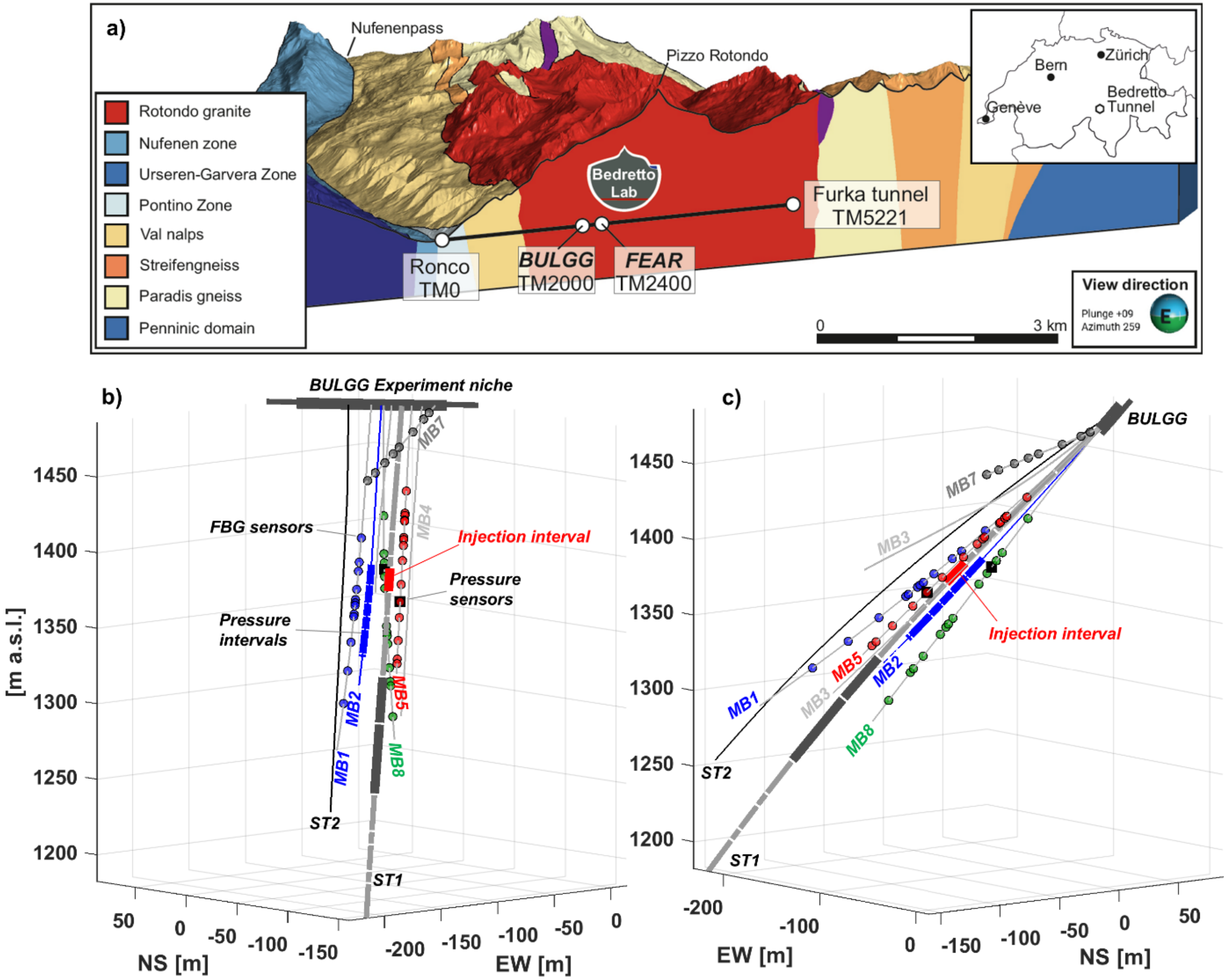
- Thanks to the FEAR ERC project, we have turned our attention to smaller, fluid-induced events. In the recently developed near-fault observatories, we can obtain high-resolution recordings close to the fault and better constrain the rupture process. The project aims to induce a Mw ~1 earthquake and study its characteristics at small scale, taking advantage of this unprecedented resolution.

FEAR

Fault Activation and Earthquake Rupture

Induced micro-seismicity in underground natural laboratories

We are currently building the FEAR experimental testbed: boreholes hundreds of meters long were drilled from the tunnel and instrumented with arrays of acoustic emission sensors, geophones, strainmeters...

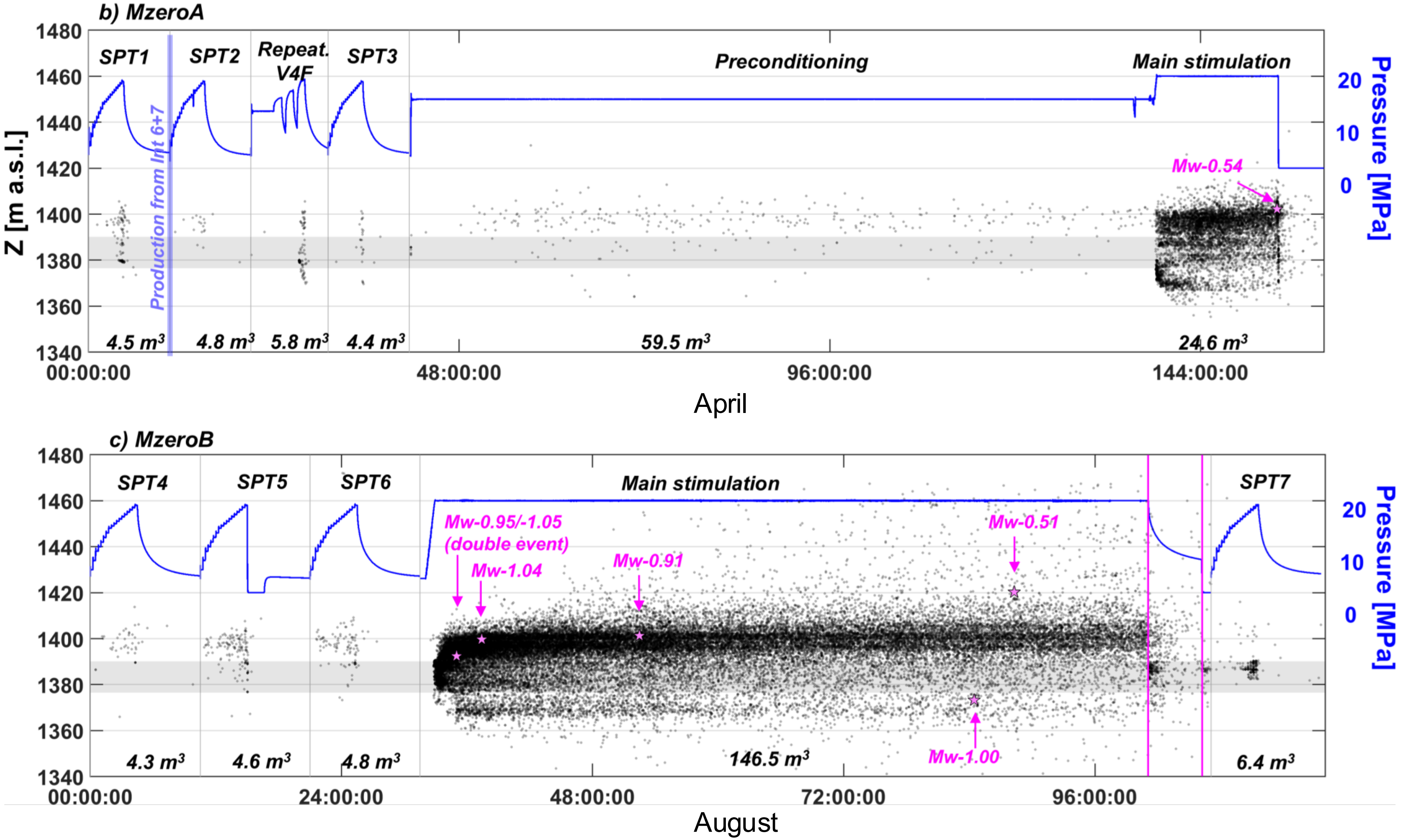


FEAR

Fault Activation and Earthquake Rupture

The 2024 experiments in the Bedretto underground natural laboratories

We conducted several experiments in 2024 in a nearby area, since this laboratory has been active since 2022. We used the existing infrastructure of the Geothermal Testbed and attempted to trigger Mw ~0.0 quakes.



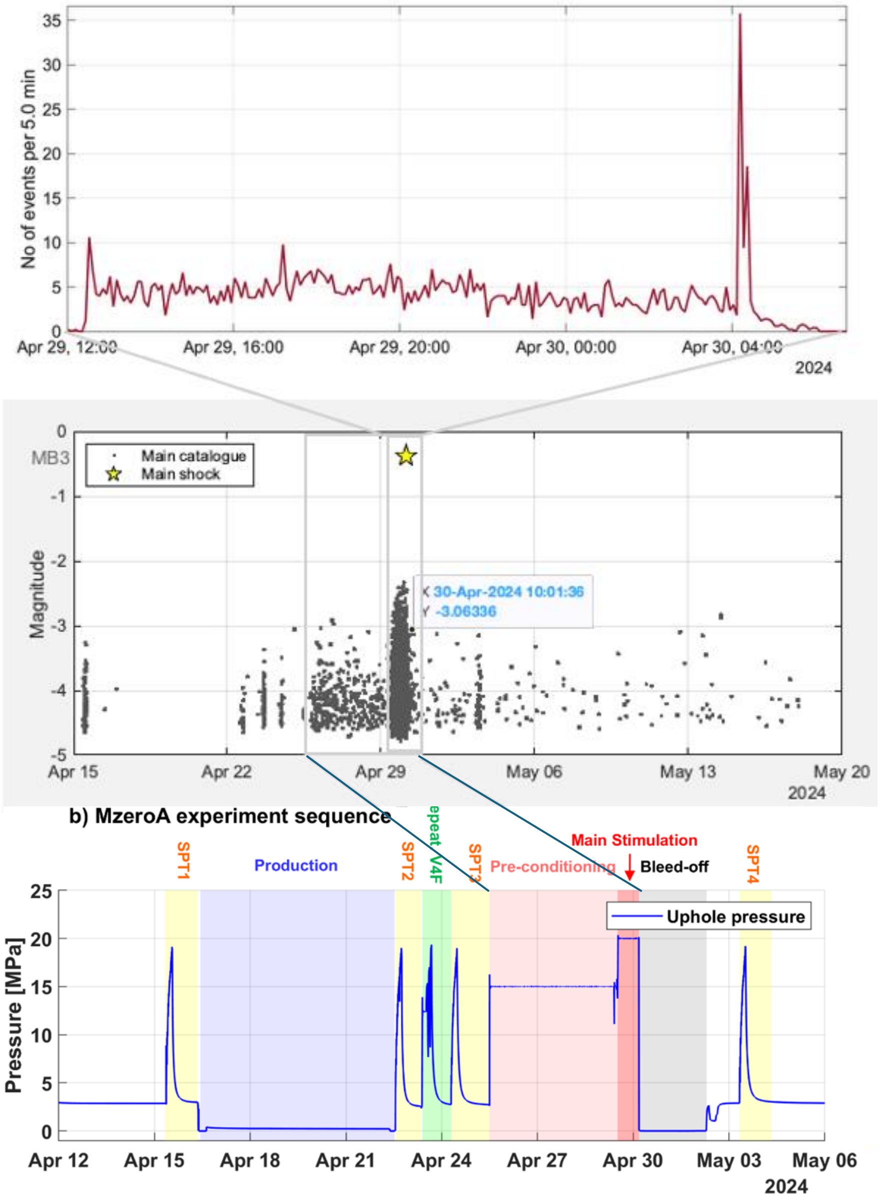
20 MPa stimulation for 16 hours

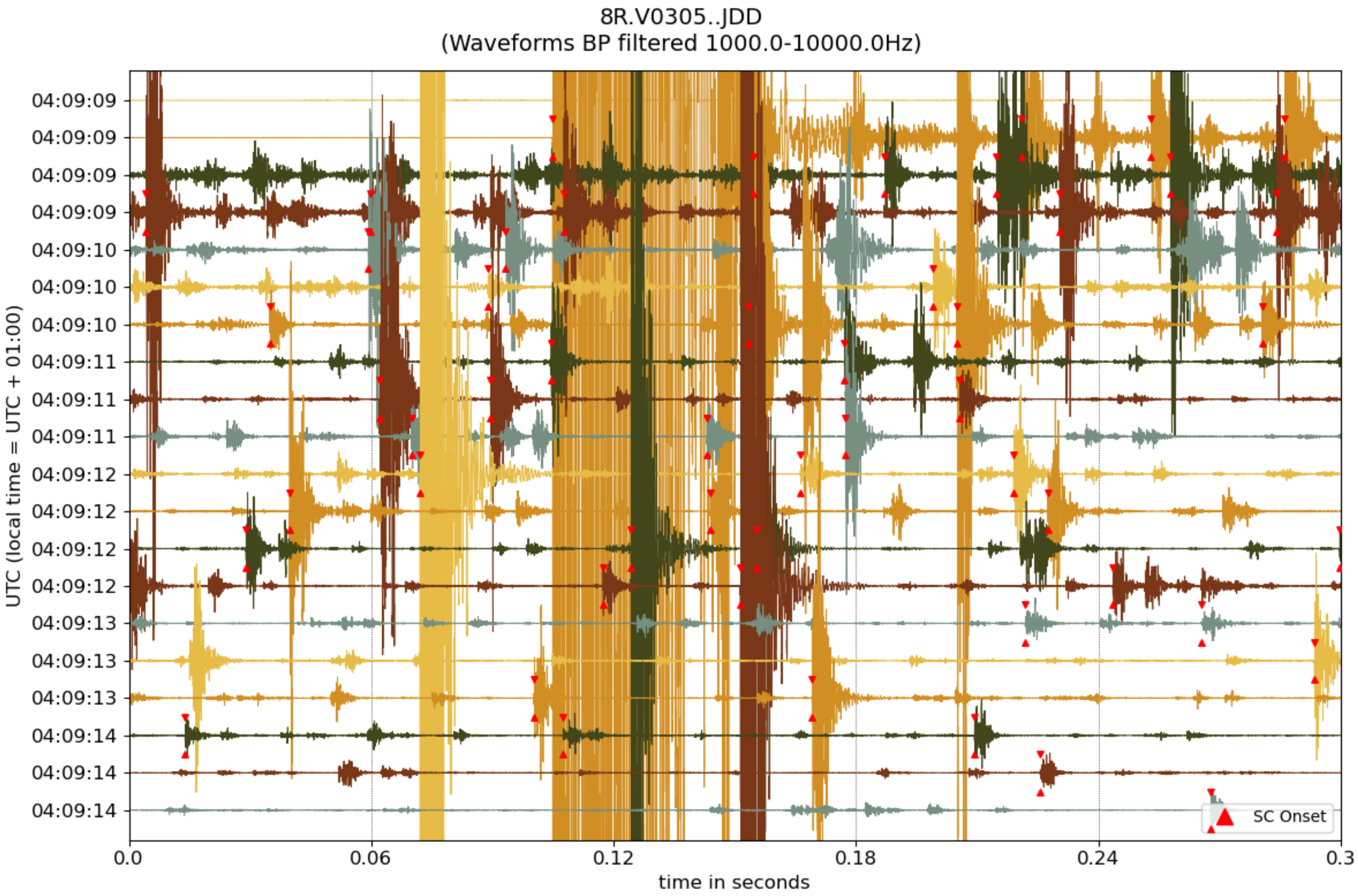
20 MPa stimulation for a total of 70 hours

Gishig et al 2025

The 2024 experiments in the Bedretto underground natural laboratories

The seismisity rate preceeding the mainshock to not change in the hours before the event

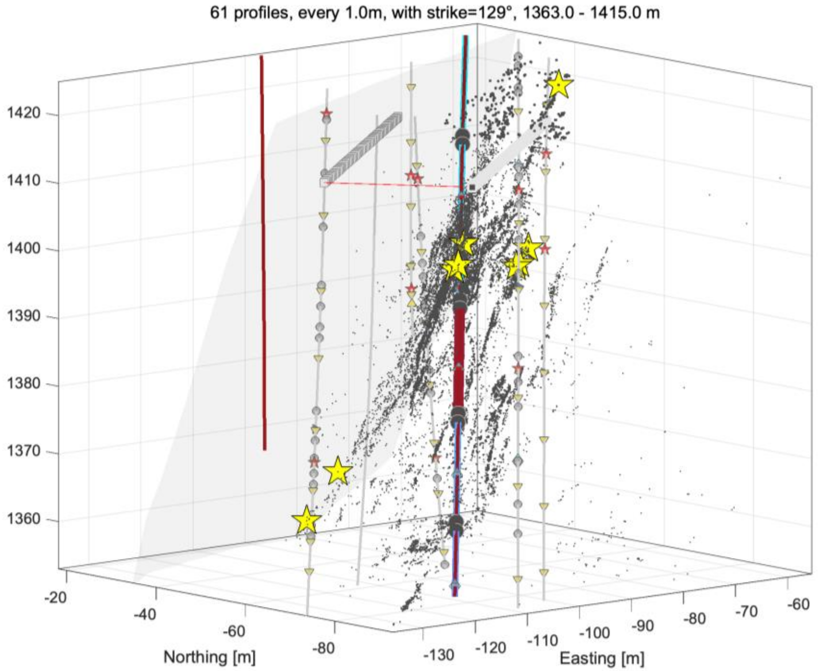




Gishig et al 2025   Meier et al 2025

FEAR
Fault Activation and Earthquake Rupture

Source parameters from spectral inversion



Meier et al 2025

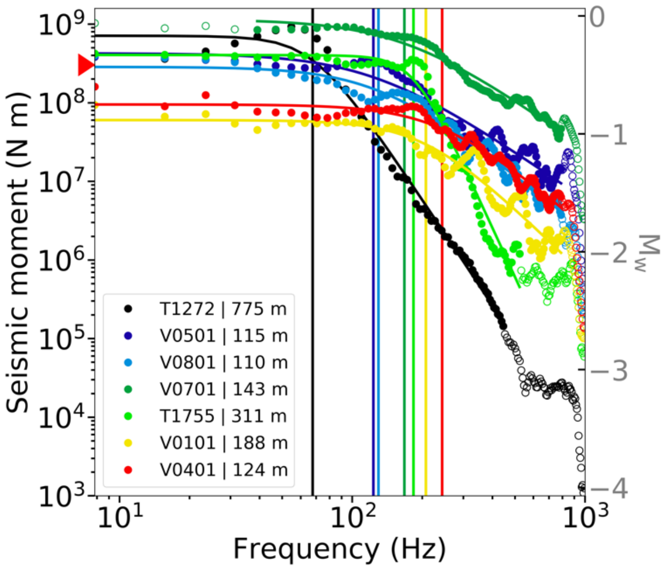
$\mathbf{M_w = -0.54 \pm 0.14}$

$\mathbf{f_C = 160 \pm 20\ Hz}$

ASSUMING for M_W estimation

V_S = 3030 m/s	S-wave velocity
ρ = 2620 g/cm^3	Density
FS = 1	Free-surface coefficient
R_S = 0.63	Radiation coefficient

Supino et al 2025



ONLY STATIONS WITH ~OMEGA-2 DECAY | V0*

$$r = \frac{k}{f_C}$$ with $k = k(v_R)$

SOURCE RADIUS — SOURCE MODEL and PHASE — RUPTURE VELOCITY

$$\Delta\sigma \propto \frac{M_0}{r^3}$$

STRESS DROP

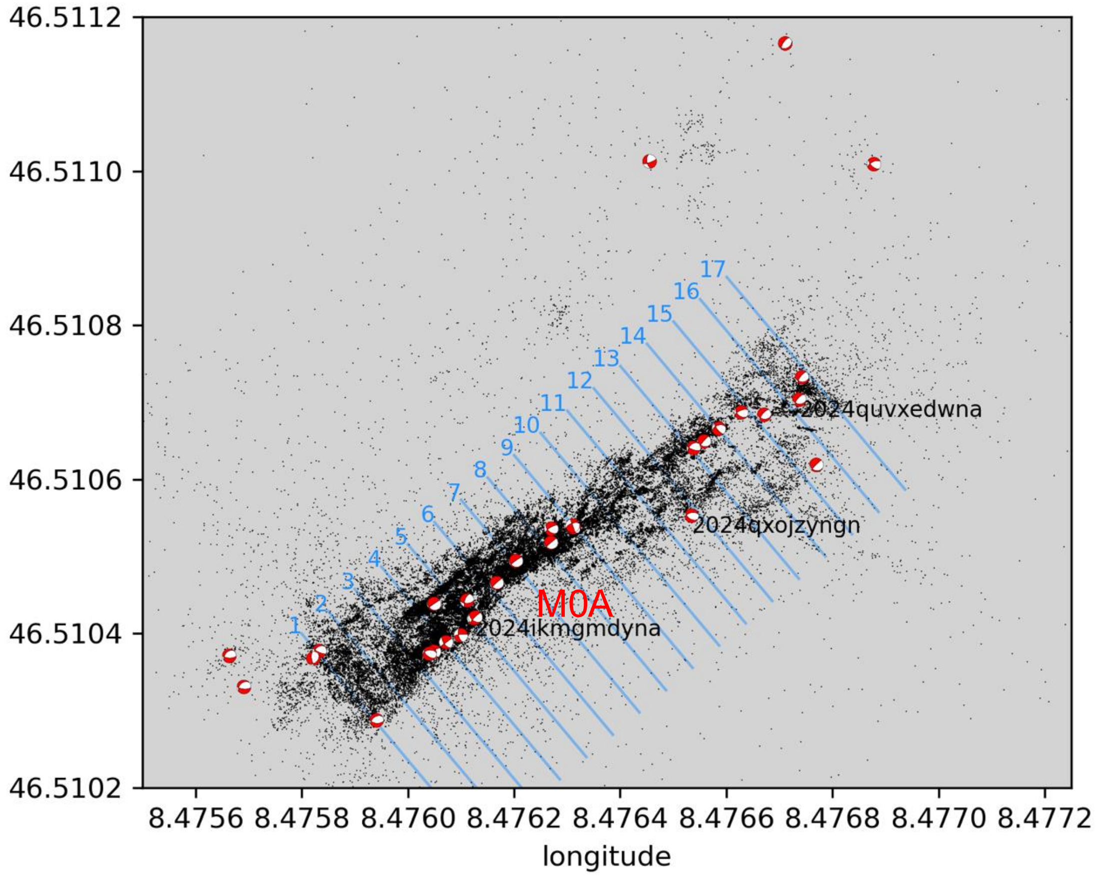
ASSUMING
Brune (1970) circular source model | **k = 0.37**

$$\Delta\sigma = 0.25 \pm 0.15\ MPa$$
$$r = 7.0 \pm 0.9\ m$$

ASSUMING
V_R = 0.9 V_S and Kaneko and Shearer (2014) circular source model | **k = 0.26**

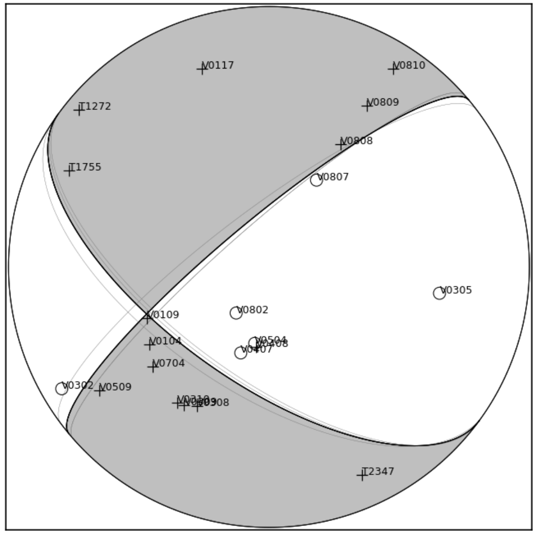
$$\Delta\sigma = 0.72 \pm 0.44\ MPa$$
$$r = 4.9 \pm 0.6\ m$$

The 2024 experiments in the Bedretto underground natural laboratories

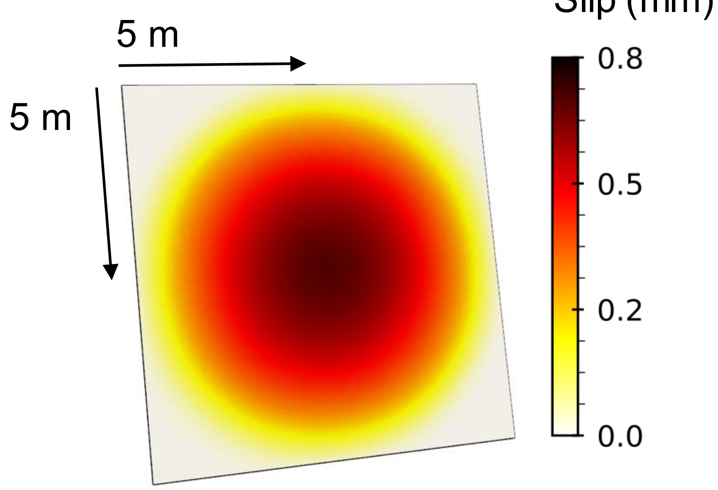


Focal mechanism inferred from polarities of AE sensors and geophones

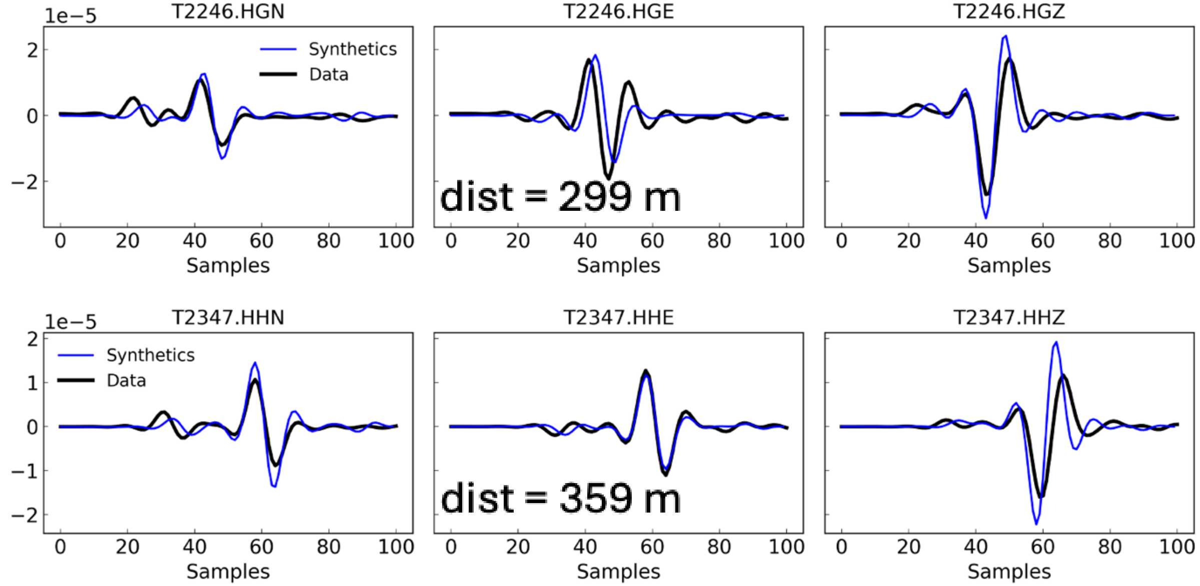
M0A



Strike, dip, rake= (230,73, -138)



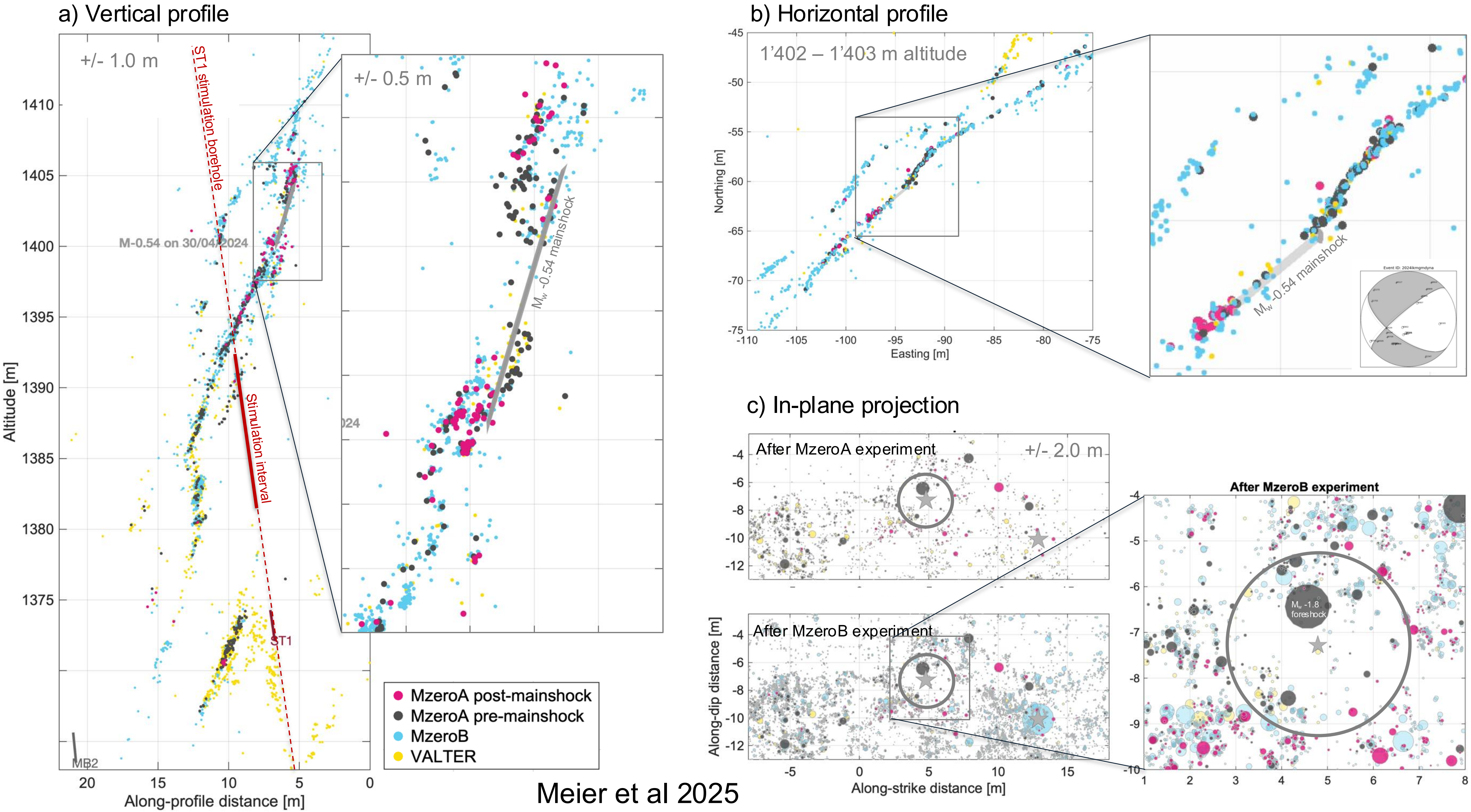
Frequencies up to 50 Hz



FEAR
Fault Activation and Earthquake Rupture

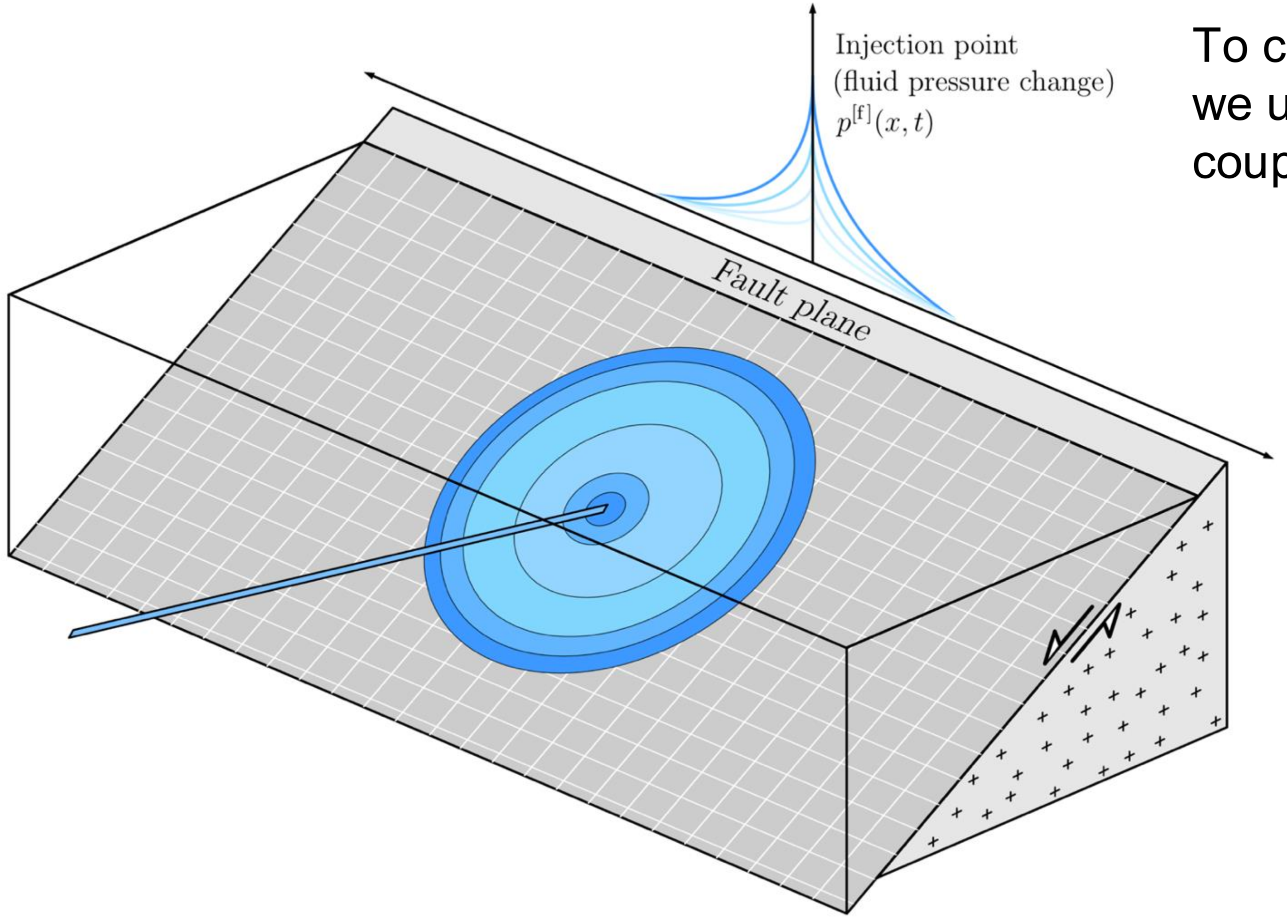
(Poggiali and Mosconi analyses)

The 2024 experiments in the Bedretto underground natural laboratories

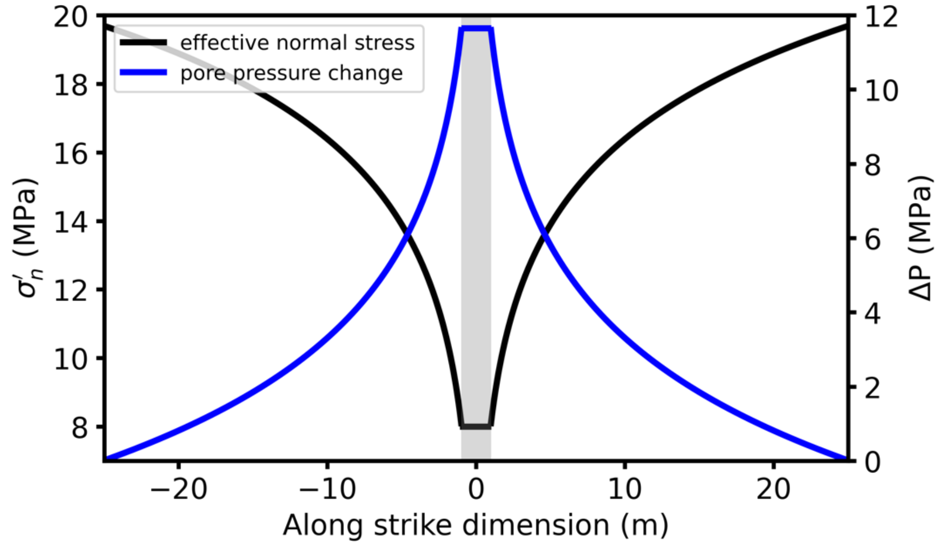


Meier et al 2025

Dynamic modeling of induced earthquakes



To create realistic pressure conditions in the fault zone, we use the TOUGH3-FLAC3D software, which allows coupled fluid-flow and geomechanical simulations.

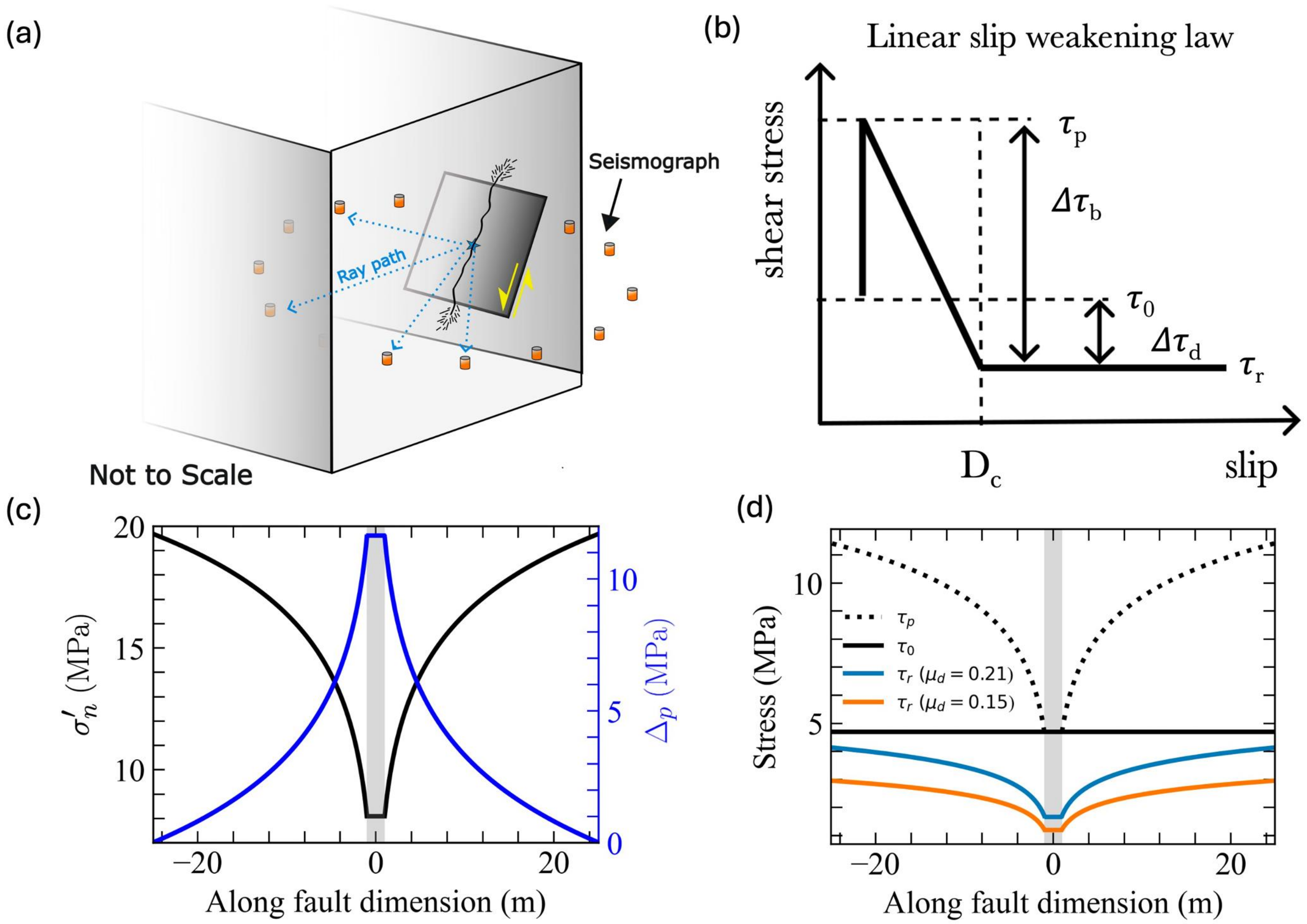


We simulate constant-rate fluid injection with different permeabilities on the fault and in the surrounding volume, allowing fluids to propagate along the fault. The simulation is stopped just before earthquake nucleation, and the resulting pressure profile is used as the initial condition for the dynamic rupture model.

Dynamic modeling of induced earthquakes

Physics-based dynamic rupture modeling framework to investigate induced earthquakes.

Seis Sol



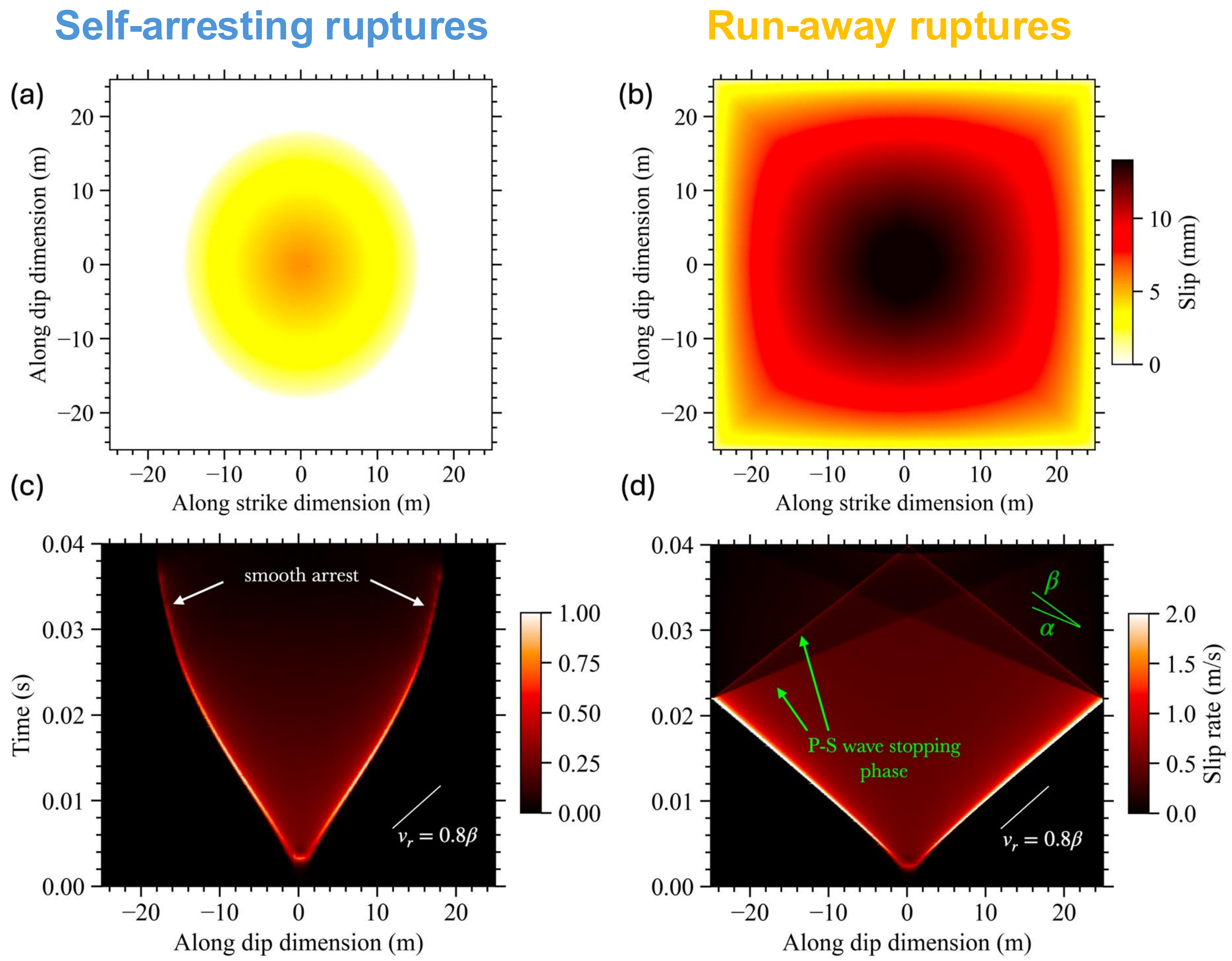
Mosconi et al (2025)

Dynamic modeling of induced earthquakes

Evolution of dynamic rupture models.

(a–b) Final slip distribution for **self-arresting** and **run-away ruptures.**

(c–d) Temporal evolution of points along the fault dip for the two models. Colormap shows slip velocity.

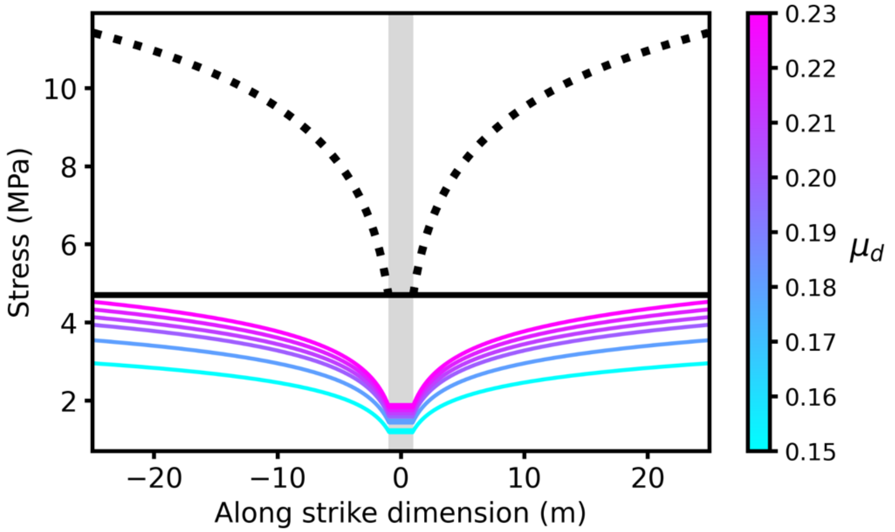


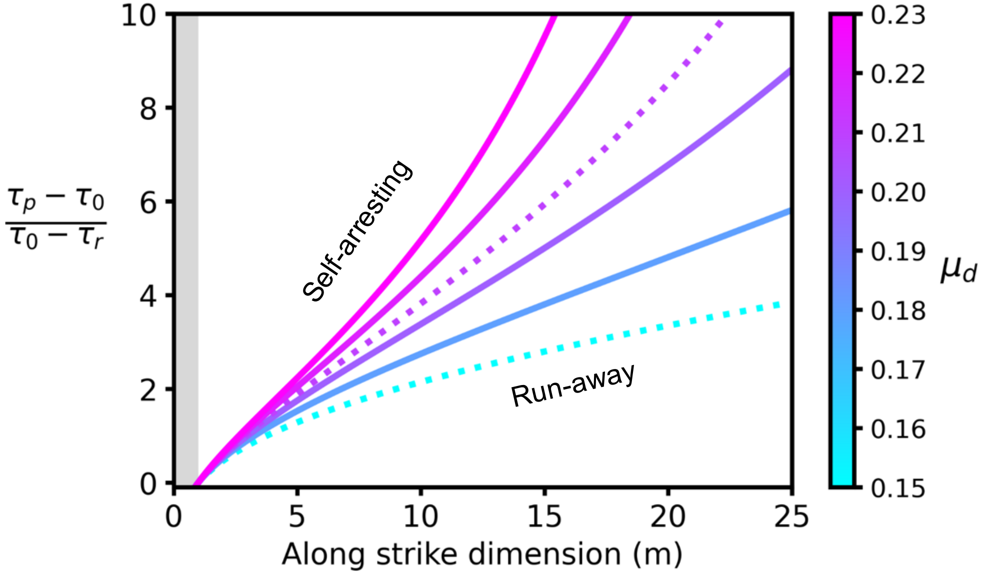
Mosconi et al (2025)

Dynamic modeling of induced earthquakes

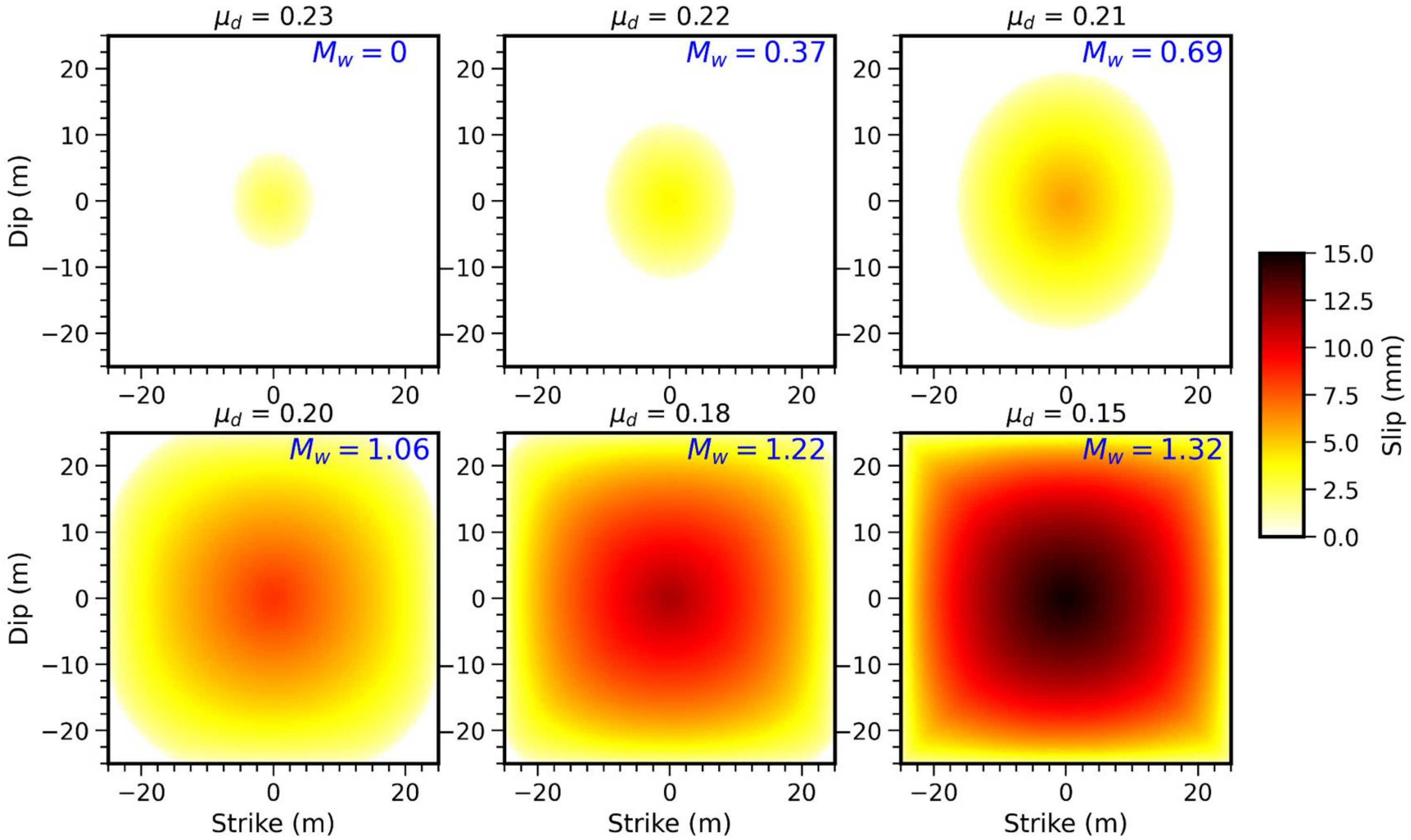
Varying the **dynamic friction coefficient** leads to different rupture dimensions

Mosconi et al (2025)





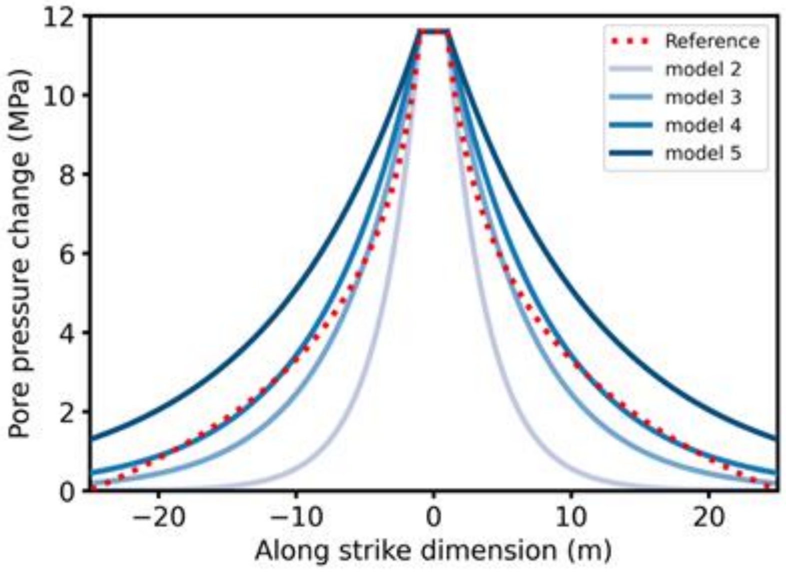
The transition from self-arresting to run-away earthquake appears gradually

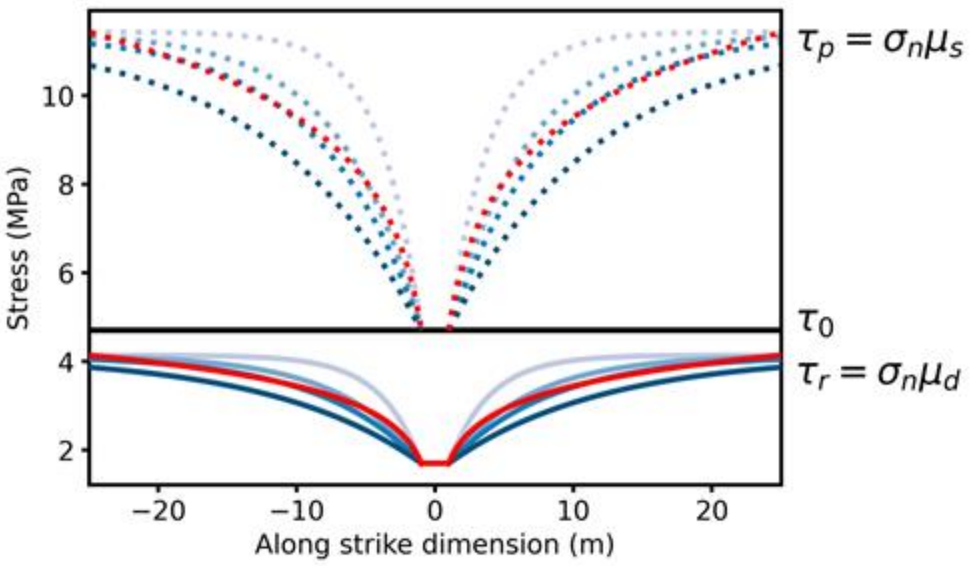


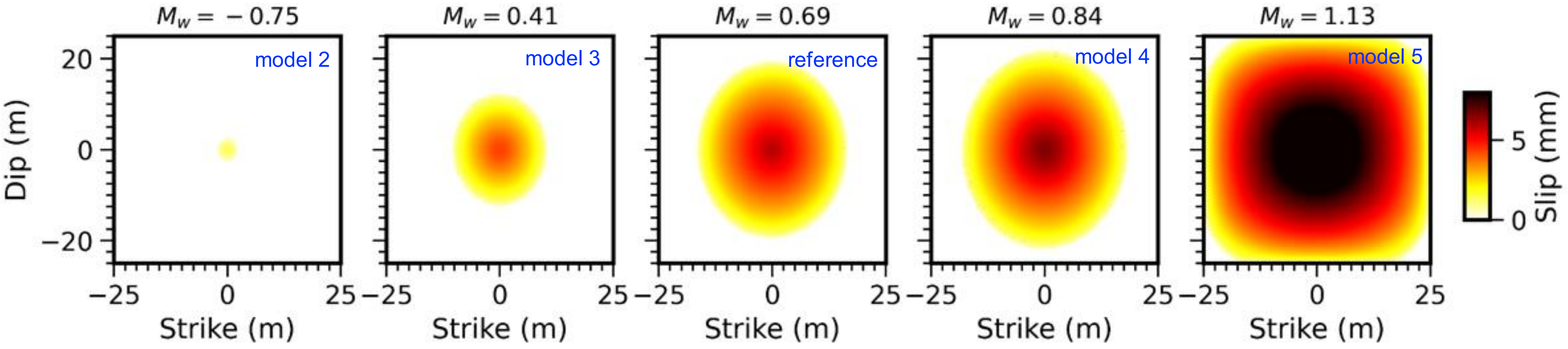
Dynamic modeling of induced earthquakes

Mosconi et al (2025)

Varying the **pore pressure profile** leads to different rupture dimensions

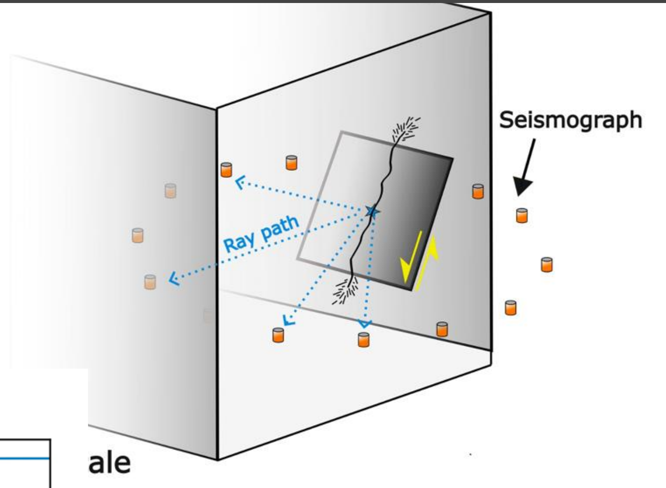


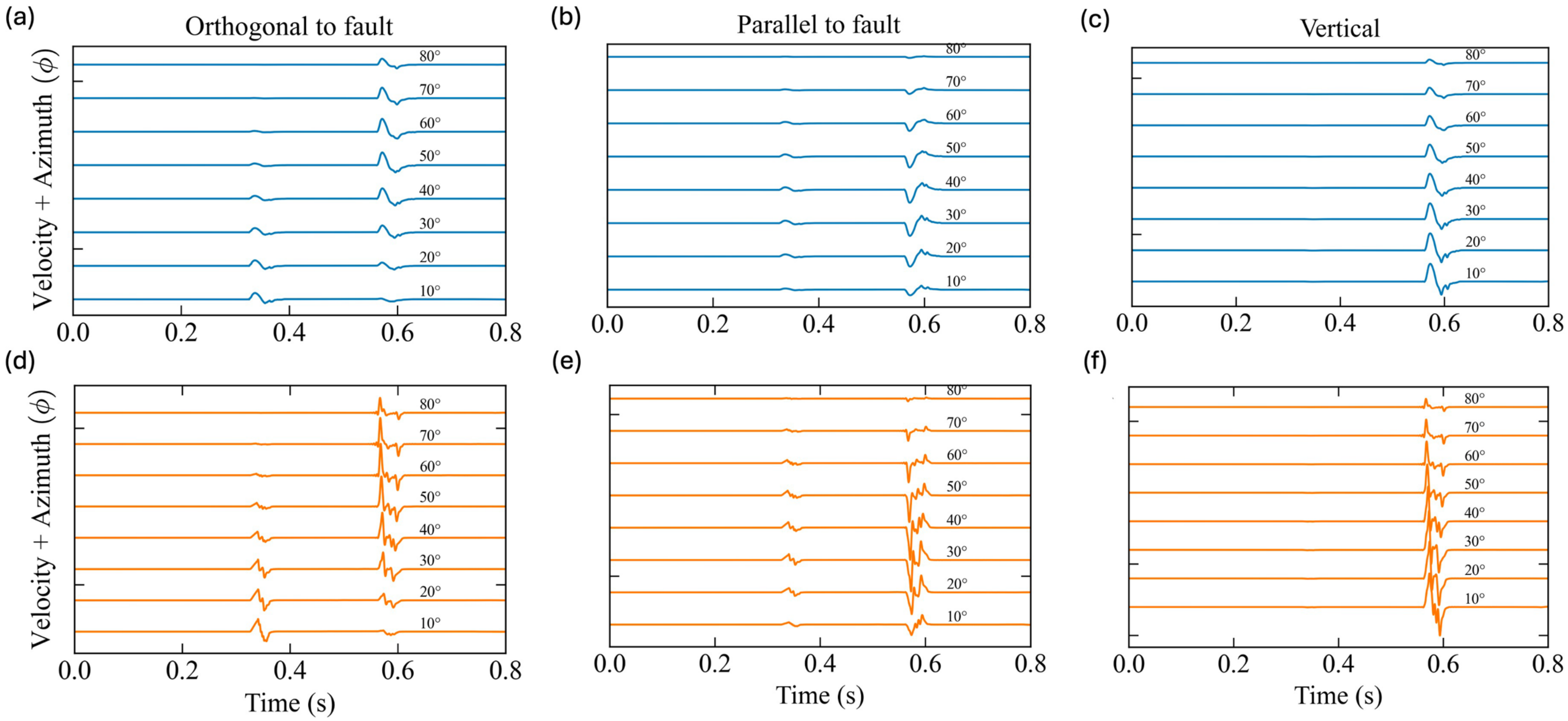




Self arresting versus run-away radiation

Waveforms for the self-arresting and run-away rupture scenario for receivers with 90◦ take of angle.





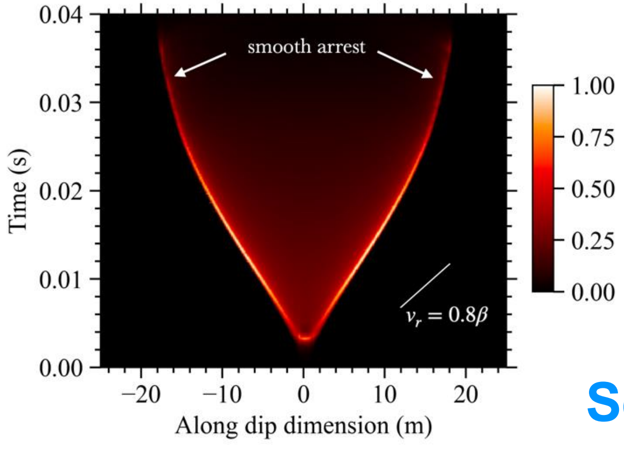
Self-arresting ruptures

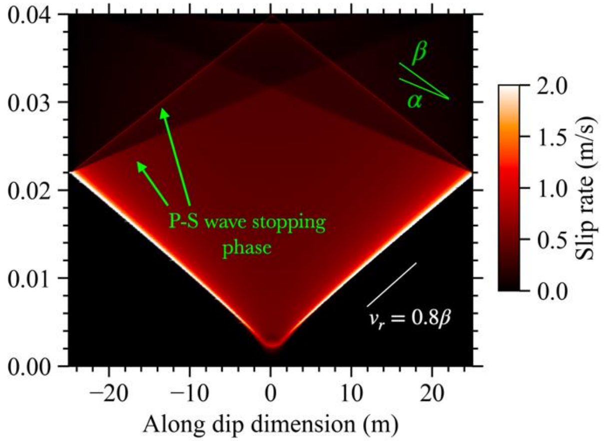
Run-away ruptures

Mosconi et al (2025)

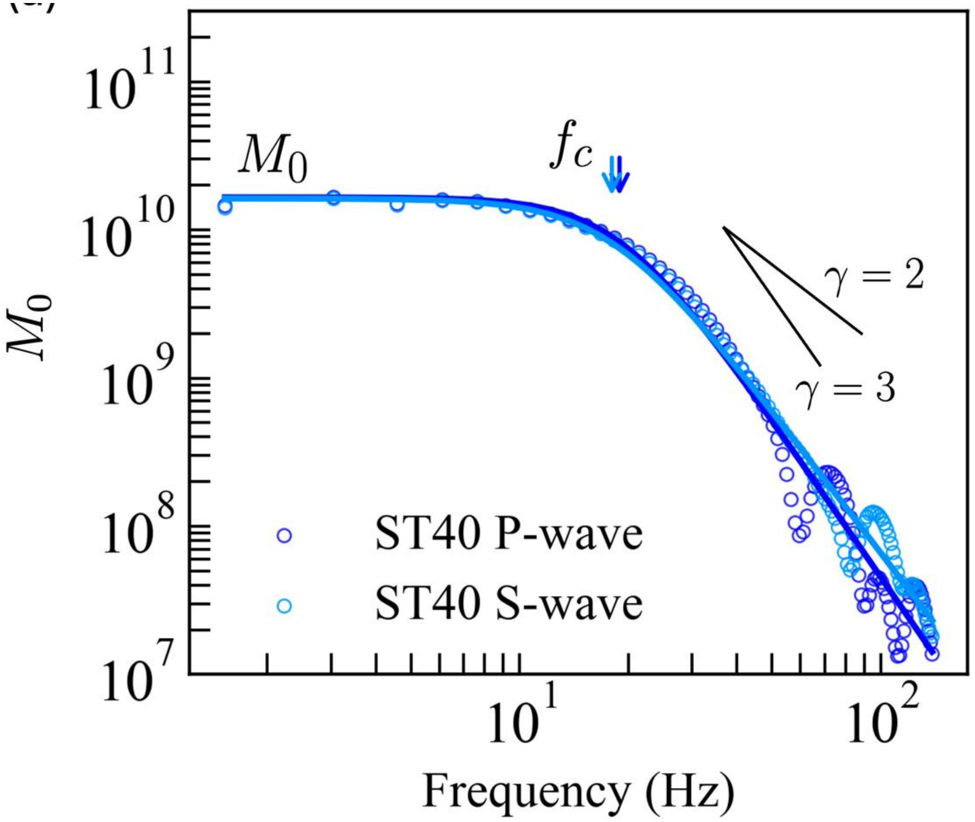
Self arresting versus run-away radiation

Mosconi et al (2025)

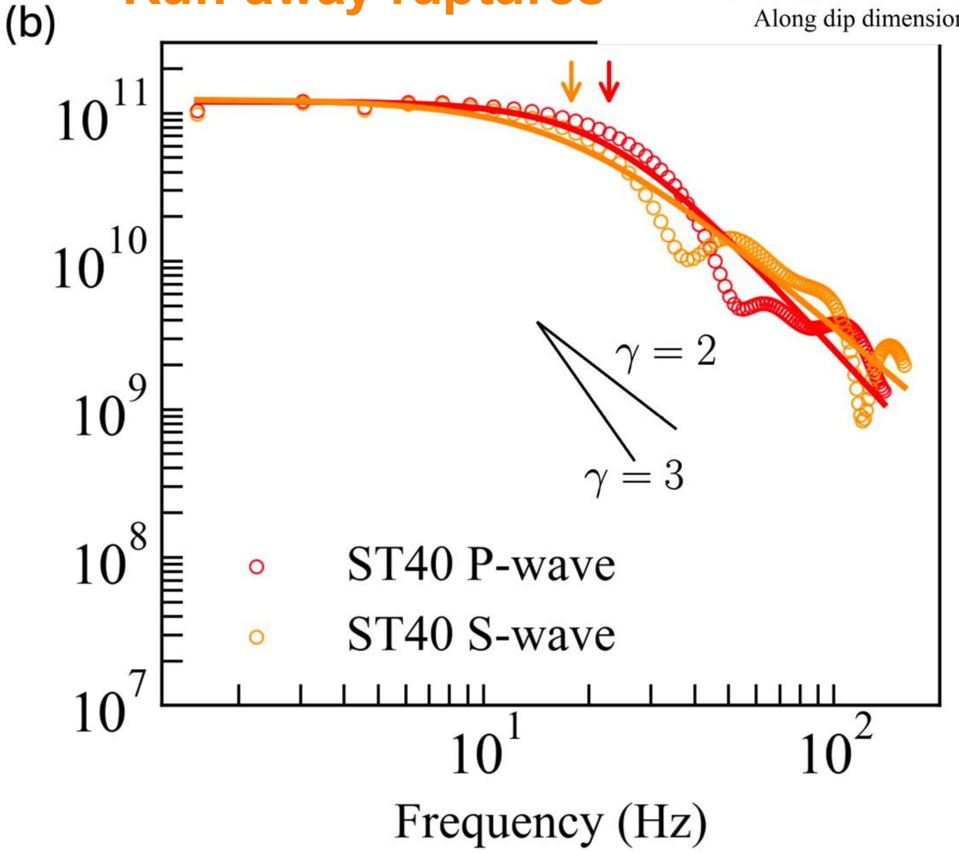




Self-arresting ruptures



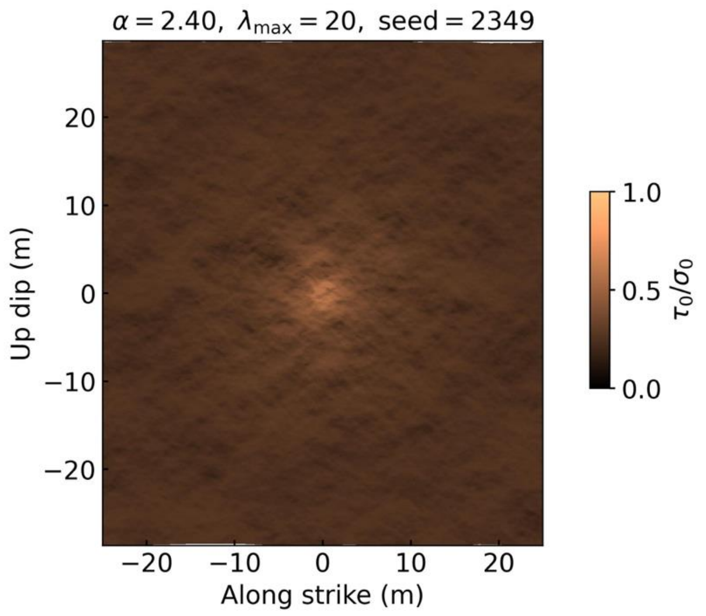
Run-away ruptures



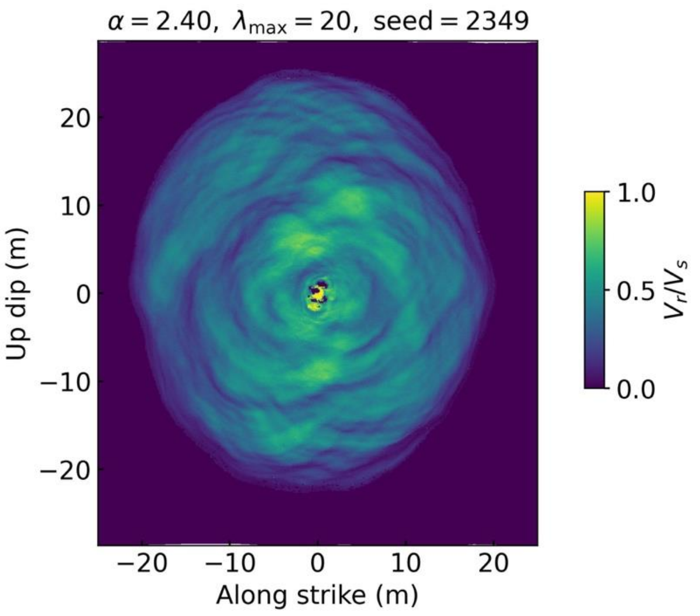
Spectrum of self-arresting and run-away rupture models at a station located at ϕ = 40◦ and 90◦ take-off angle

Preliminary results with geometrical roughness

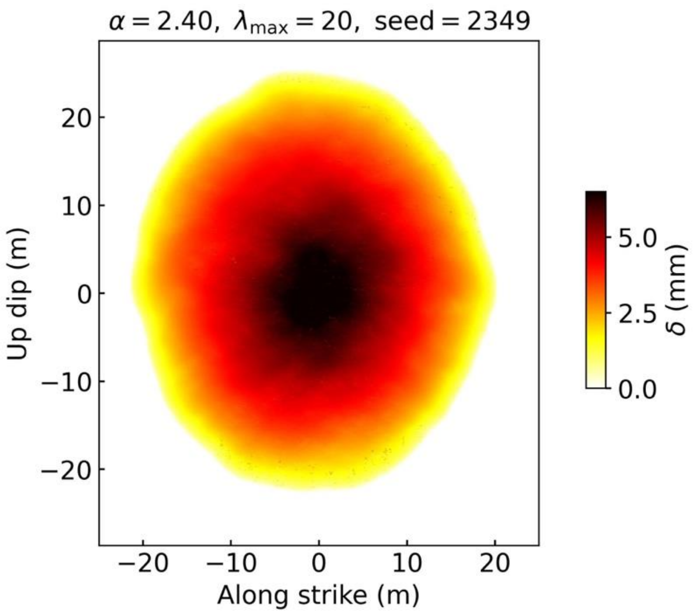
Initial stress / effective normal stress



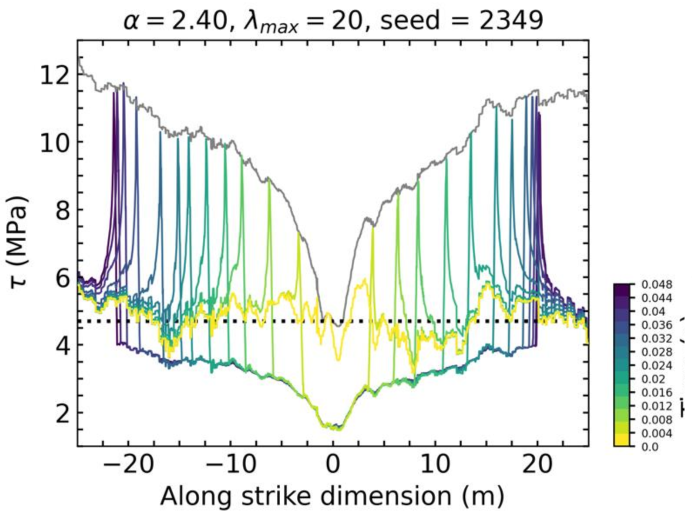
Rupture velocity

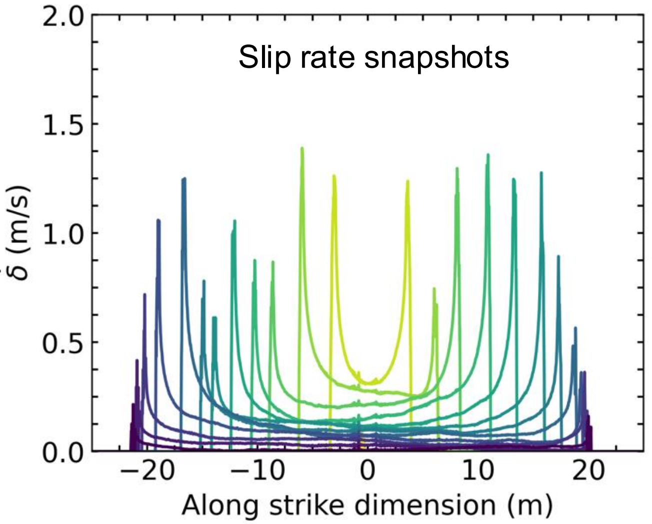


Slip distribution



After studying self-arresting events and their distinctive radiation compared to standard run-away ruptures, we turned to small-scale fault roughness to investigate both its impact on rupture dynamics and whether radiation effects can mask these characteristic signatures.





Mosconi et al (2025)

Final remarks

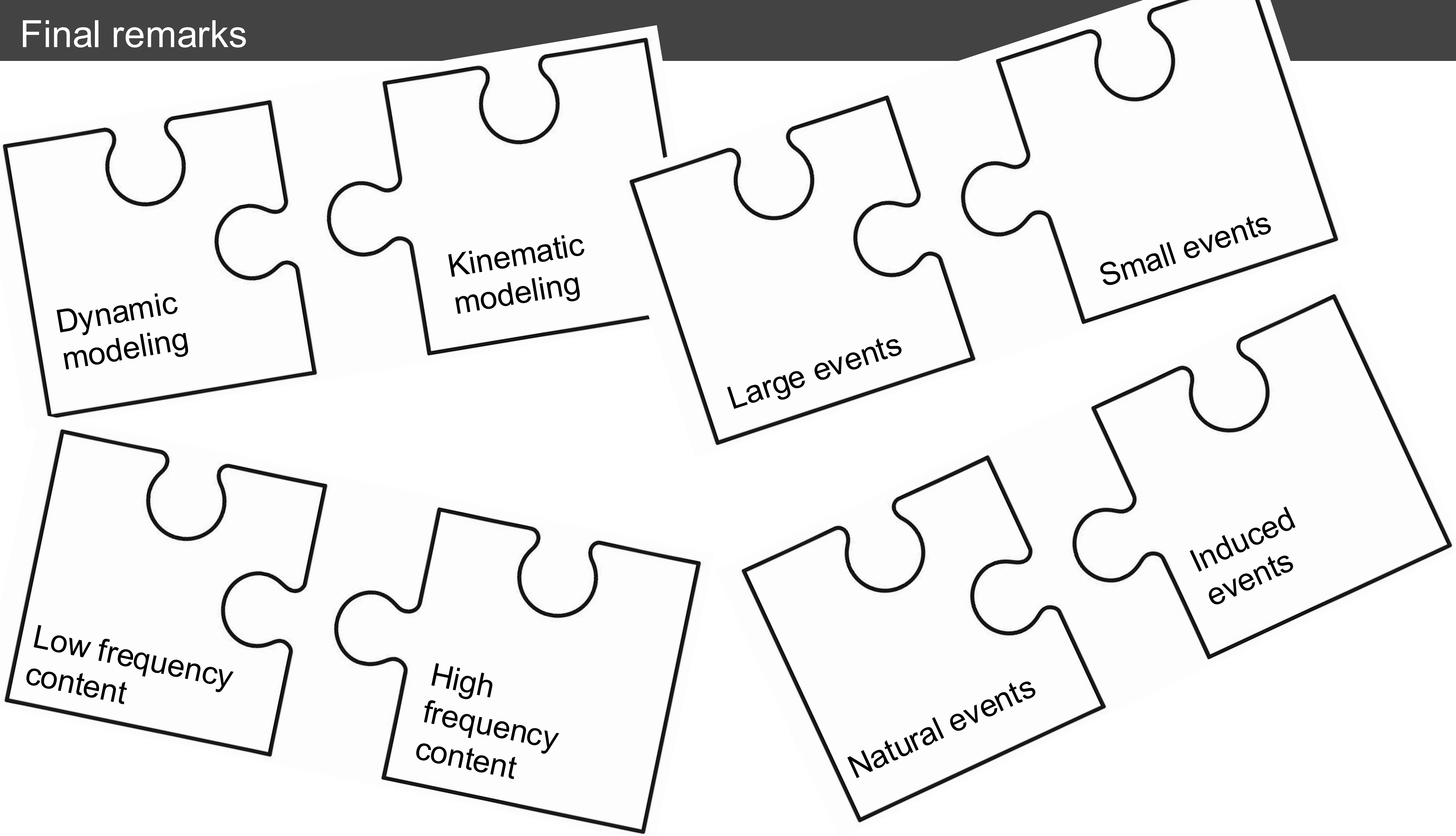
- Reproducing observed features of natural earthquakes and induced events underscore the importance of linking rupture physics to measurable ground motion characteristics across scales.

- Are small and large earthquakes characterized by the same physical processes? This remains an open question, whose solution requires understanding the complex interactions among the physical processes that jointly contribute to dynamic breakdown.

- Where do the high-frequency radiation come from ? Is it dominated by rupture front acceleration/deceleration, fault roughness, spatial heterogeneities in dynamic parameters, surface topography, or structural heterogeneities?

- Insights from laboratory-scale experiments, such as those conducted at the Bedretto Underground Laboratory — which aim to improve earthquake predictability, deepen our understanding of rupture physics and scaling laws, and advance safe geoenergy practices — may also inform future SCEC activities and statewide efforts.

Final remarks



2025 Statewide California Earthquake Center
SCEC ANNUAL MEETING

September 7-10, 2025
Hilton Palm Springs, California

Thanks

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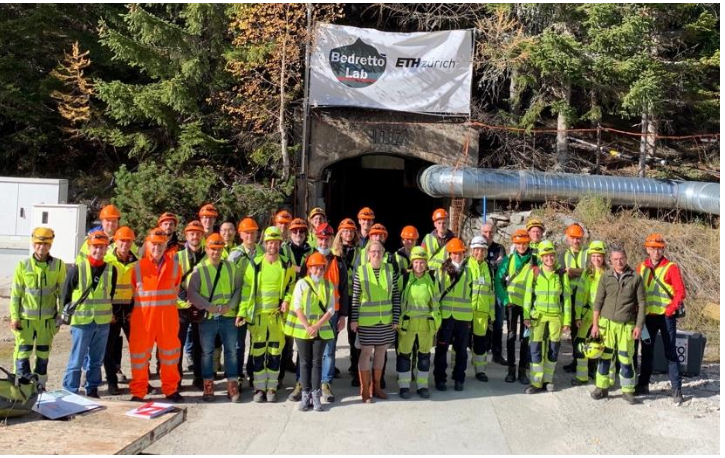
Fault Activation and Earthquake Rupture



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