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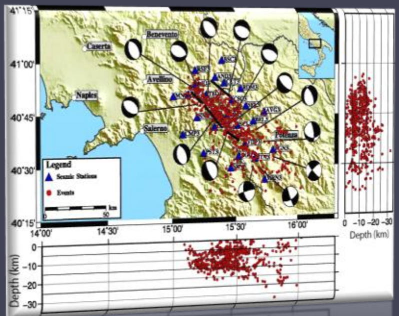

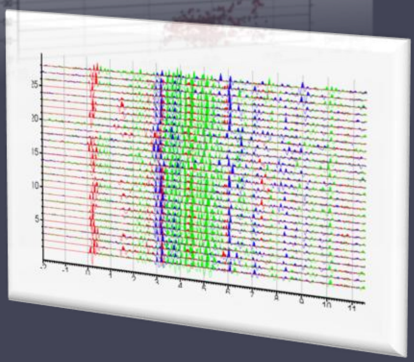

SCALING RELATIONSHIPS FOR EARTHQUAKE SOURCE PARAMETERS DOWN TO DECAMETRIC FRACTURE LENGTHS

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SM2.2

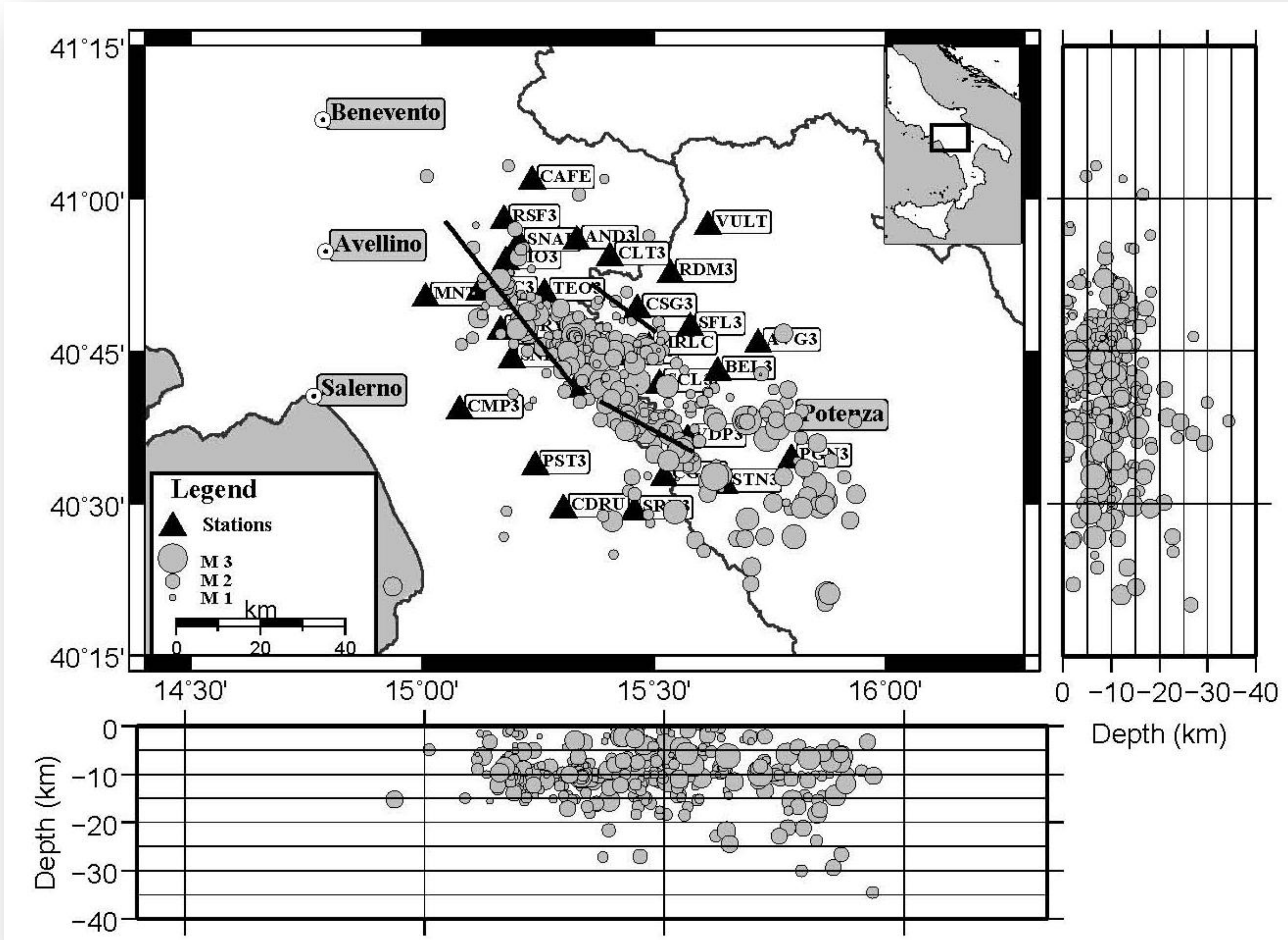
Earthquake source processes: source parameter scaling relations, and outstanding issues

What can we learn from microerthquakes occurring in active fault zones?

- A high density, high dynamic range seismic network to monitor and image the Irpinia active fault system: AMRA and INGV networks in southern Apennines.
- Microearthquake source parameters and scaling relationships : insights on small-scale rupture processes.
- Differences or similarities in the mechanical behavior of small and large earthquake ruptures: Understanding the role of active fault background micro-seismicity in the inter-seismic and the preparation phases of large earthquakes.

Present-day seismicity (Mw < 3.3)

The current low-magnitude seismicity occurs along the Apenninic belt, normal fault system 1980 earthquake fault system within the upper 20 km of the crust

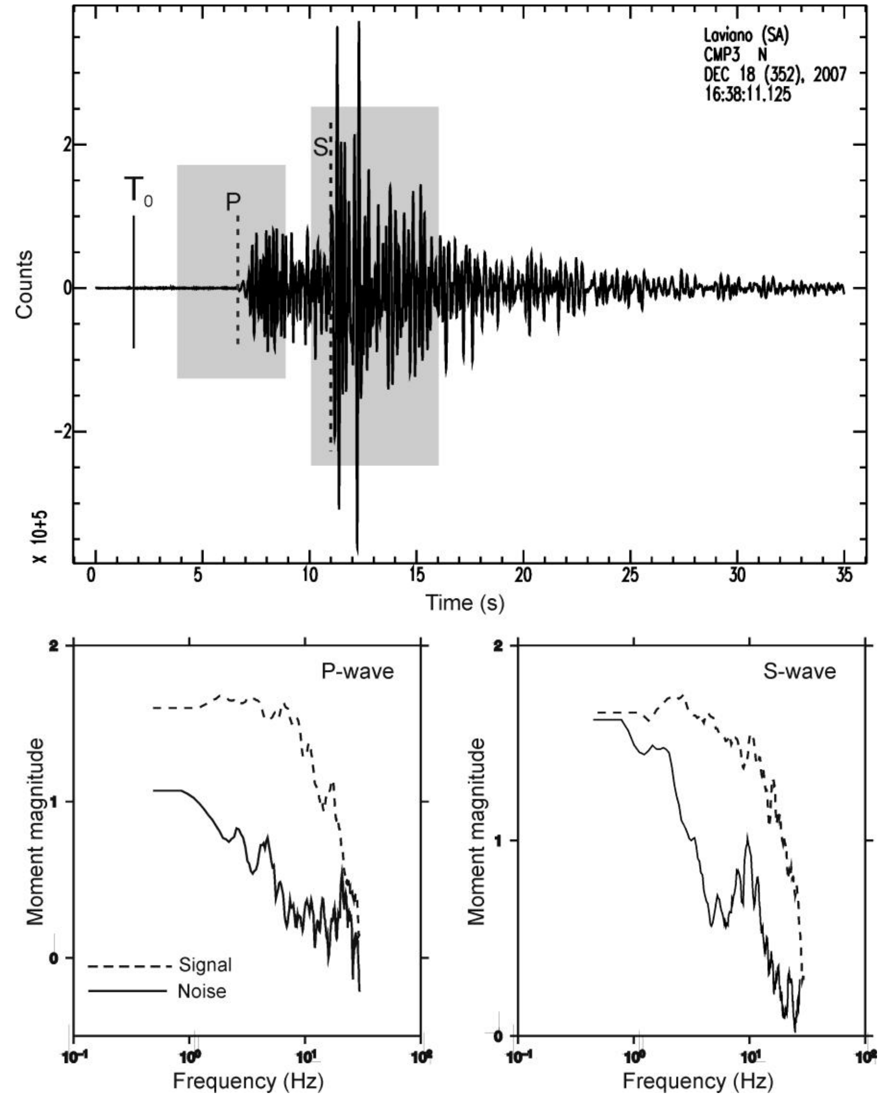


Isnet Catalogue (2007-2010)

Waveforms & Spectra

Example of a seismogram relative to a M 2.9 earthquake. Grey shaded areas identify the used time-windows for P- and S-wave. (Lower panels) *P- and S-wave*

Displacement spectra converted in moment magnitude compared with the spectrum of noise.



Theory 1/2

Displacement spectrum

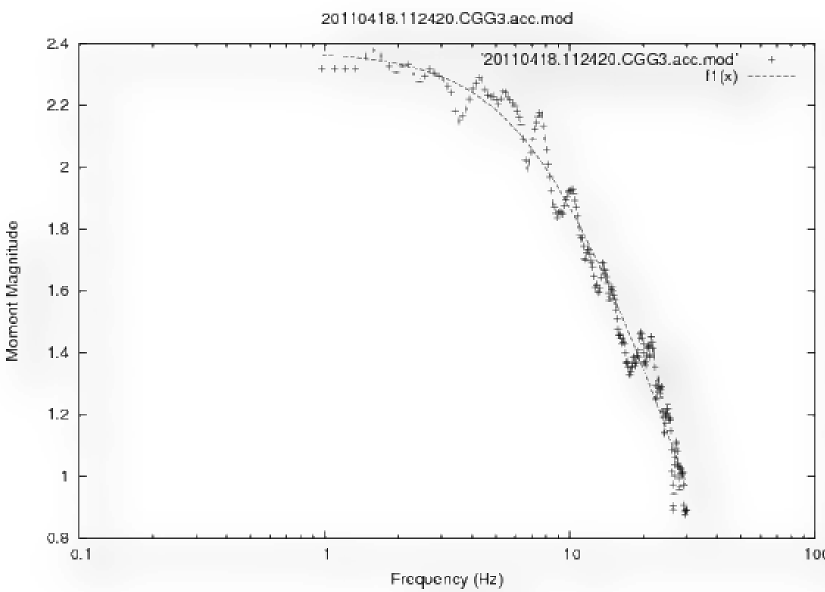
$$U(\omega) = S_o(\omega)Q(\omega)R(\omega)$$

source

$$S_o(\omega) = C_s \frac{\Omega_o}{1+(\frac{\omega}{\omega_c})^2} \qquad C_s' = \frac{R^c_{\theta\varphi}F_S}{4\pi\rho_h^{1/2}\rho_o^{1/2}c_h^{5/2}c_o^{1/2}R'} \qquad R' = \sqrt{\frac{\rho_o c_o}{\rho_h c_h}}R$$

Path attenuation

$$Q(\omega) = e^{-\omega t_c^*} \qquad t_c^*(\omega) = \frac{T_c}{Q_o\omega^n}$$



Site transfer

$$R_j(\omega) = \frac{1}{N_j}\sum_{i=1}^{N_j}\frac{U_{ij}(\omega)}{S_{oi}(\omega)Q_{ij}(\omega)}$$

Spectral parameters: LF level, corner freq, squared velocity integral

Source Parameters:Seismic moment, source radius, static stress drop, radiated energy, apparent stress

Theory 2/2

Radiated energy (Boatwright,1980)

$$E_S = \left(\frac{R}{R^c_{\vartheta\phi}}\right)^2 \frac{\rho c}{e_c(\theta,\phi)} I_c$$

Integral of squared velocity

$$I_c = \int_0^\infty \dot{u}^2 dt = \frac{1}{\pi}\int_0^\infty \omega^2 \left|U(\omega)\right|^2 d\omega$$

Correction for bandwidth limitation (Ide & Beroza, 2001)

$$E^{corr} = \frac{2}{\pi}\frac{E^{obs}}{F(\omega_M,\omega_c)}$$

$$F(\omega_M,\omega_c) = \frac{\left(-\frac{\omega_M}{\omega_c}\right)}{1+\left(\frac{\omega_M}{\omega_c}\right)} + arctg\left(\frac{\omega_M}{\omega_c}\right)$$

Apparent stress (Wyss,1970)

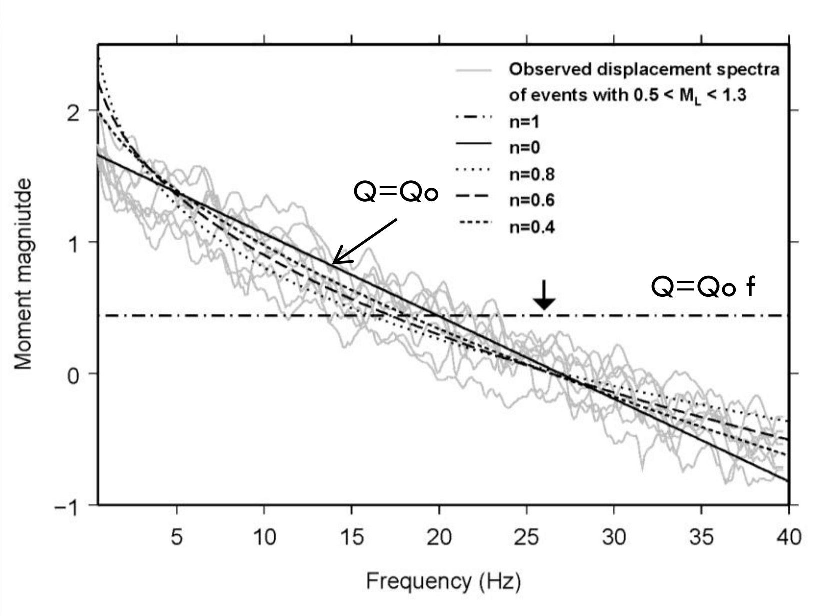
$$\tau_a = \mu\frac{E_S}{M_0}$$

Multi-step inversion of displacement spectra

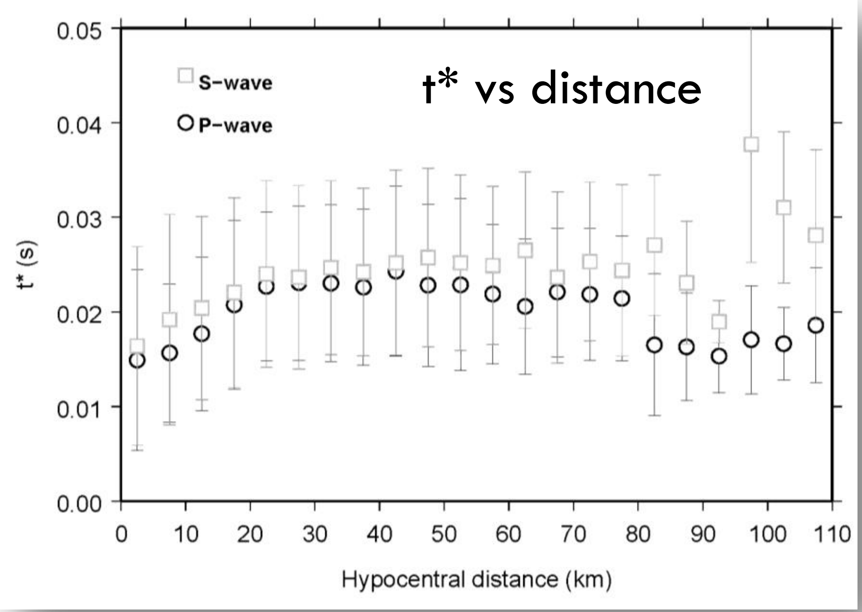
Step	Procedure	Comment
1	Ωo, fc and source-receiver t*=T/Q from non-linear inversion of displacement spectra	omega-square model, 3-parameter inversion.
2	Determine t* by fixing the event <Ωo> and <fc>	Analysis of t* vs distance → t*(R) model
3	Determine P- and S-site response functions	Averages of station spectra, each of them is corrected by best-fit source/attenuation models
4	Correct original spectra for P-and S- average site responses	Remove constant and frequency dependent site amplification/attenuation factors
5	Ωo, fc are newly determined by the inversion of site/attenuation corrected displacement spectra	Correction for site/attenuation functions provides with more robust and accurate estimates of

Correction for path attenuation and …

The constant-Q attenuation model is tested (and preferred) against Q(f)



The attenuation parameter t* (travel-time/Q) vs distance

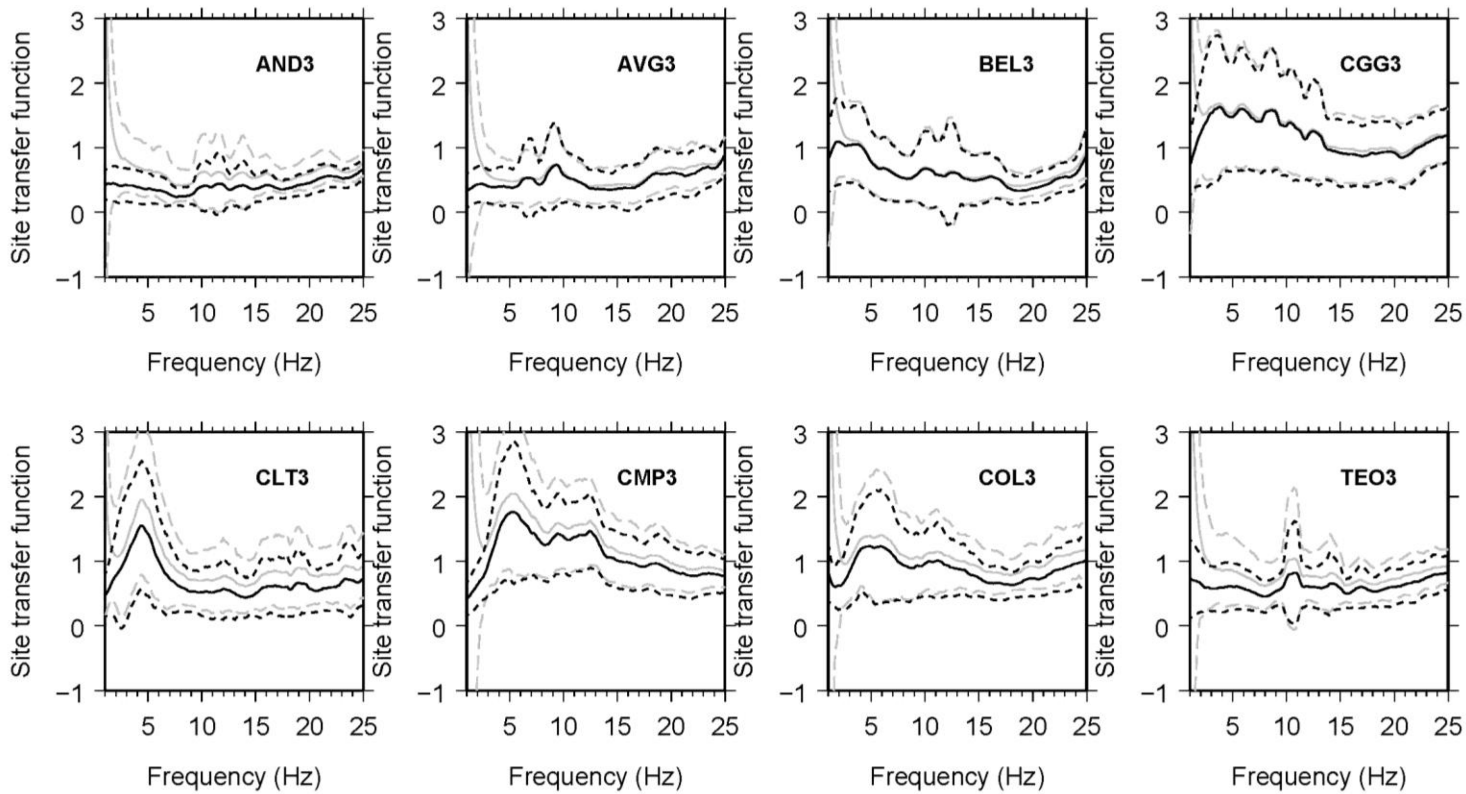


The estimates of the attenuation parameter from μ-eqk spectra provides with an attenuation model :

- Frequency-independent Q
- Distance-dependent t* , similar trend for P- and S-waves

… site effects

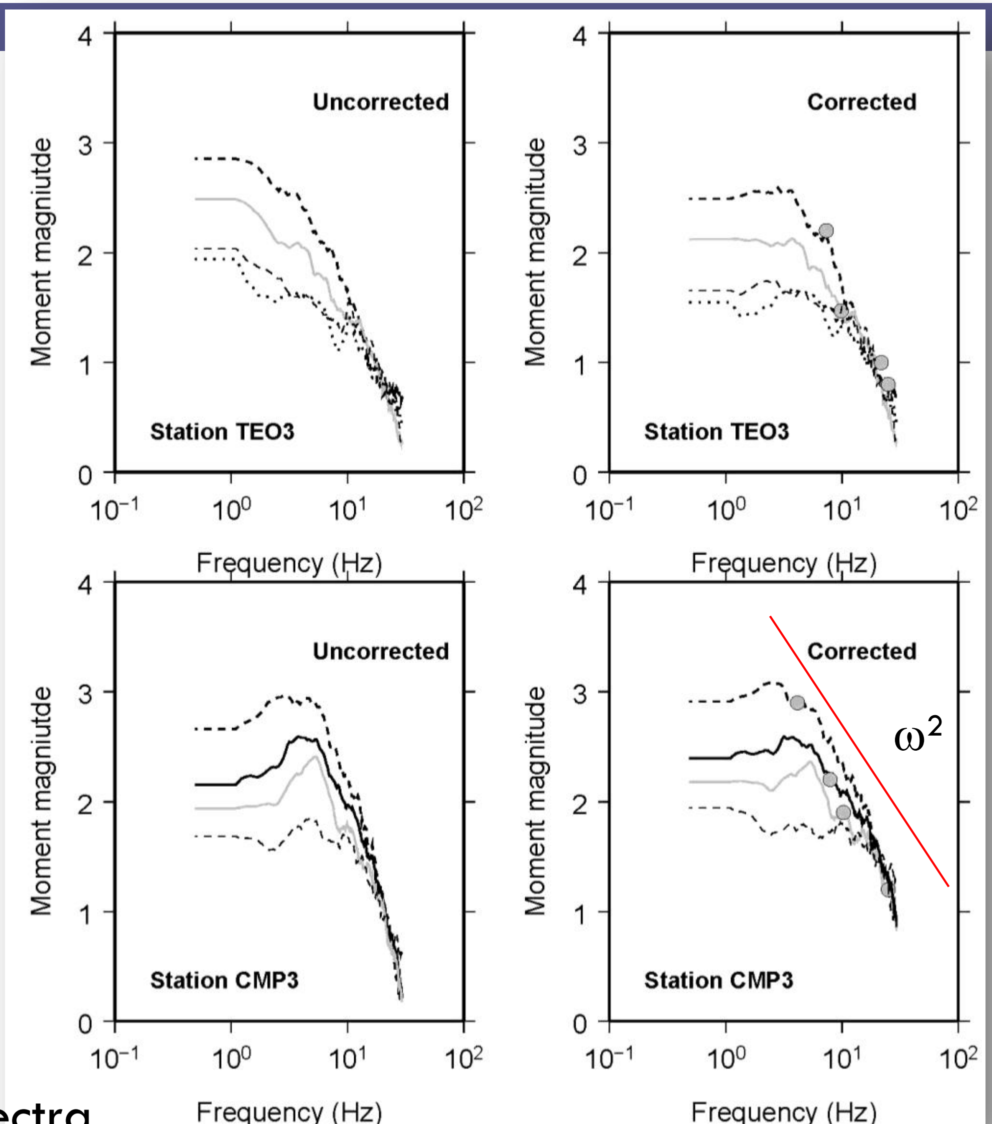
P- and S site functions are inferred from an iterative procedure where the station spectra are averaged over the recorded events after correction for the source and attenuation functions



S-site response functions from ground acceleration and velocity records

Spectral shapes

After correction for travel path attenuation and site response functions the displacement spectra show an omega-square, high frequency falloff, and a self-similar moment-frequency scaling down to about 20 Hz.

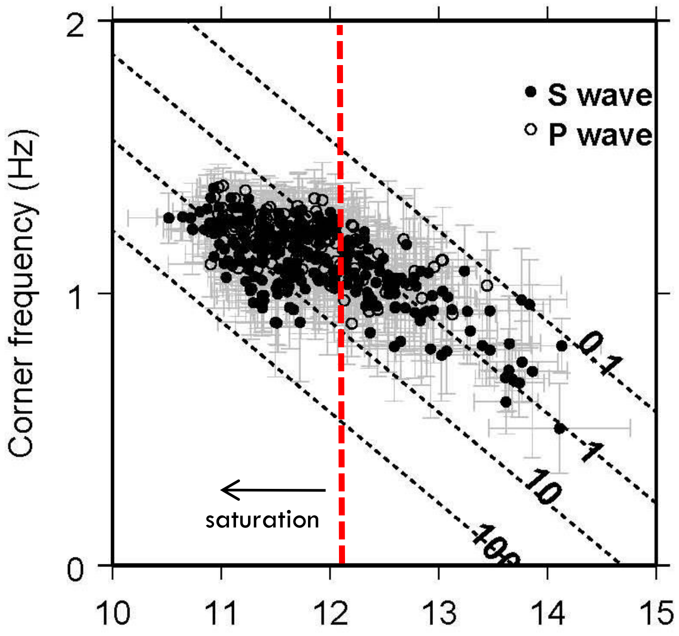


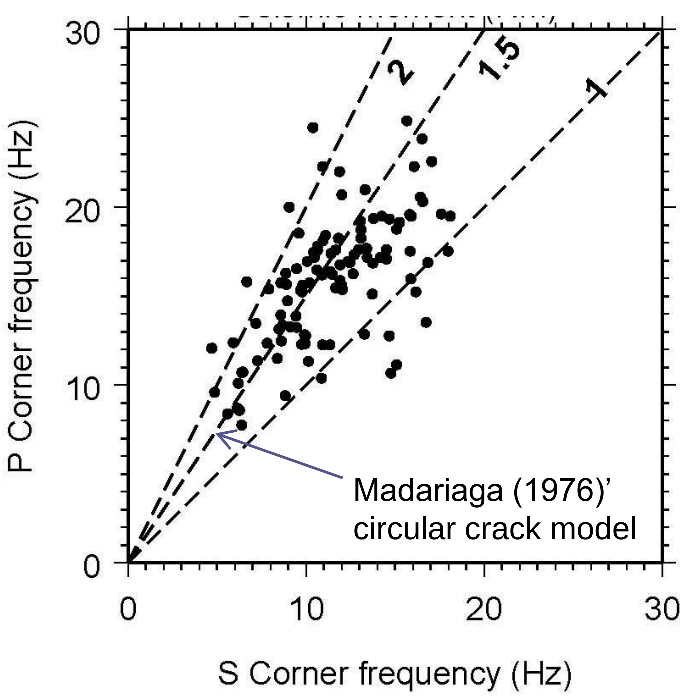
S-wave displacement spectra

P- and S-wave corner frequencies

Near-constant stress drop scaling, down to Mo about 10^{12} Nm . A saturation of corner frequencies is observed at smaller seismic moments

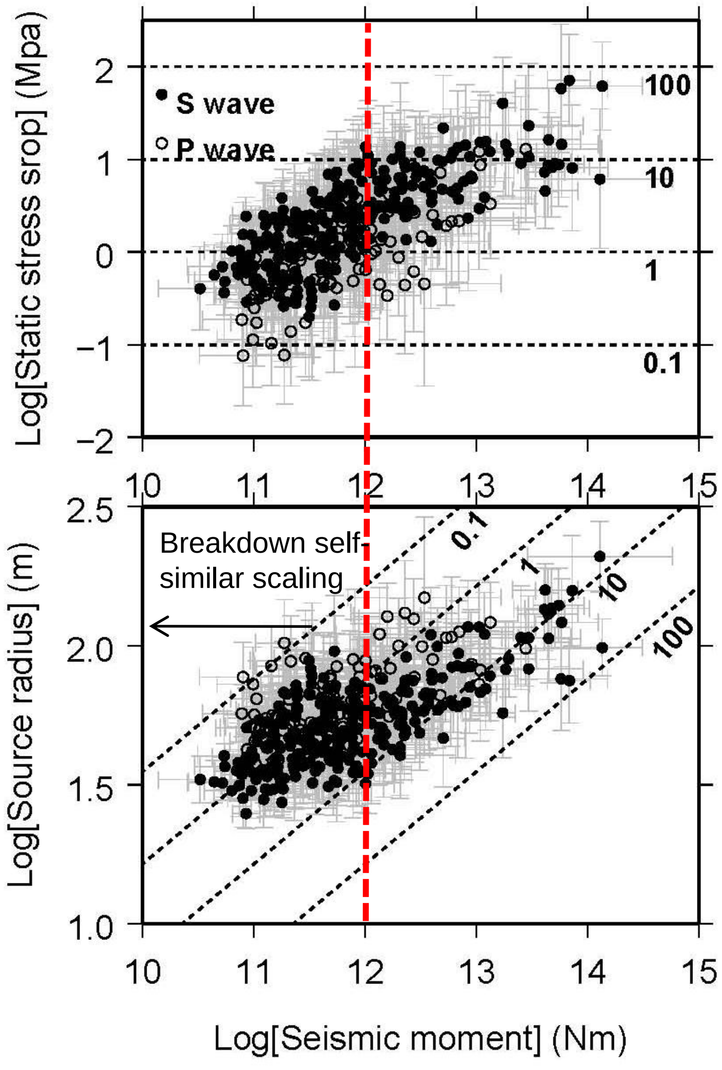
The average ratio between P- and S-corner frequencies is consistent with theoretical models of circular crack rupture.





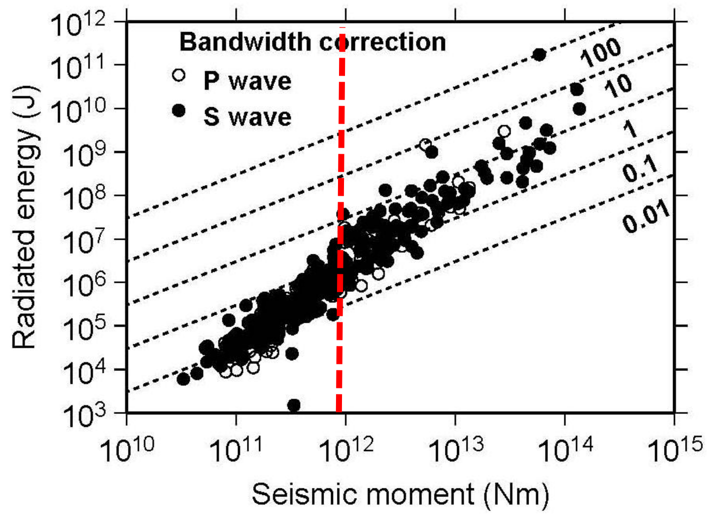
Source Radius & Static Stress Drop

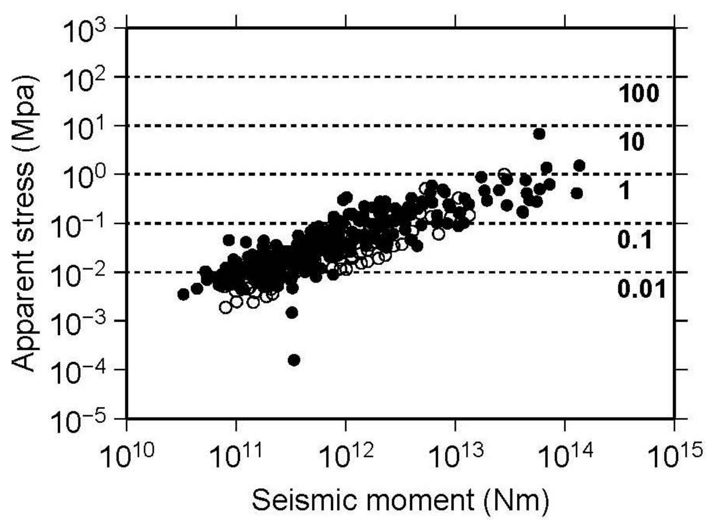
A breakdown in the constant stress drop scaling is observed for Mo < 10^{12} Nm (Mw 2), caused by the corner frequency saturation effect. Minimum source dimensions of several tens of meters are measured. Above Mo 10^{12} Nm an average static stress drop of 10 MPa is observed, (corresponding to a Brune value 4.5 times smaller)

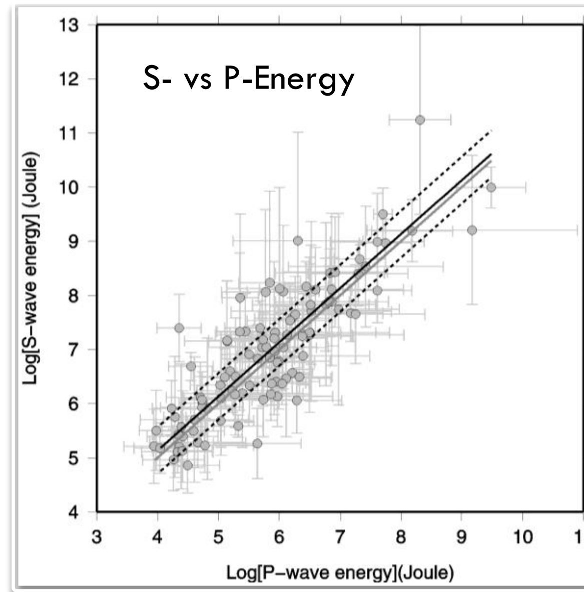


Seismic Energy & Apparent Stress

Radiated seismic energy also shows a breakdown in the constant stress-drop scaling even after correction for the limited frequency bandwidth. Below Mo~10^{12} Nm, apparent stress decreases with moment following the scaling relation $\tau_a \propto$ Mo.





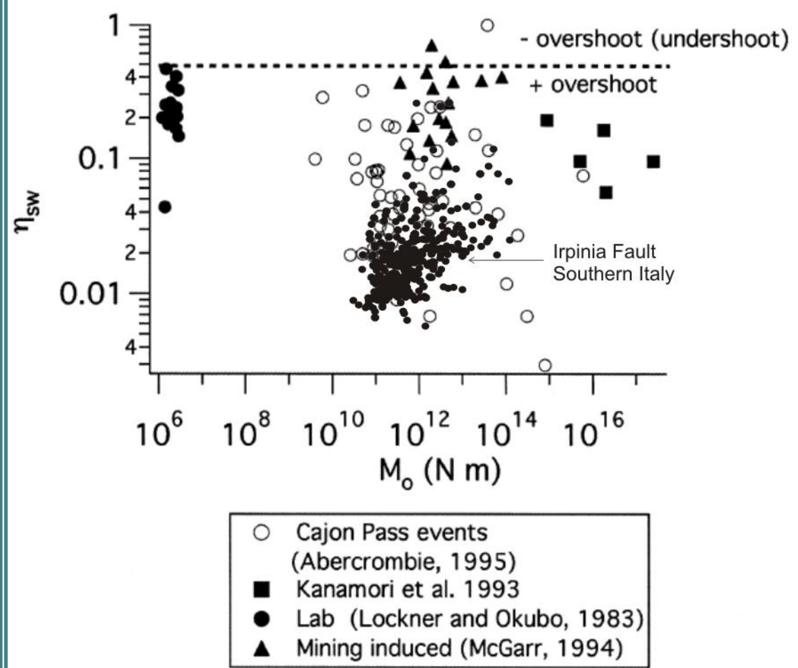


The average S-to-P energy ratio, q≈13, is consistent with the theoretical value, (q=10.1), given the observed corner frequency ratio.

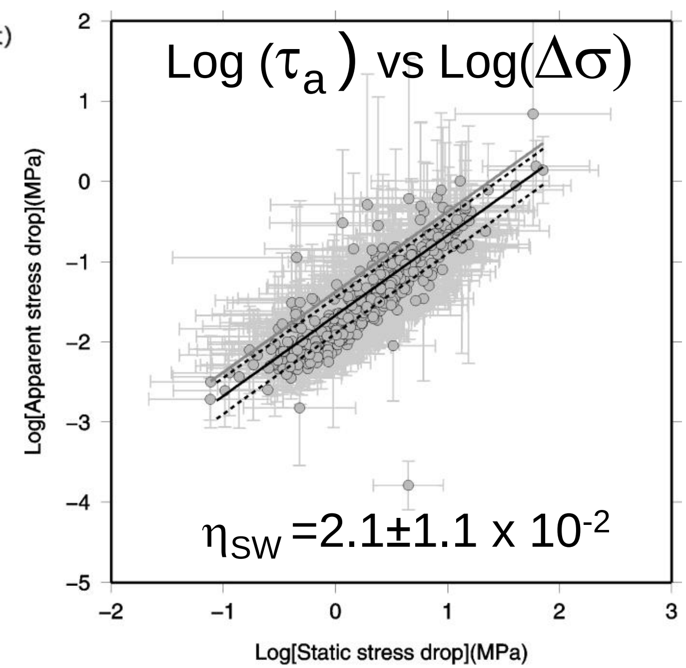
Savage-Wood seismic efficiency

The Savage-Wood seismic efficiency is very low (10 times smaller than for lab data), implying that radiated energy is only a small fraction of the whole available energy. It remains constant over about 4 orders of magnitude.

η_{SW} = Apparent stress /Static Stress Drop



Redrawn from Beeler et al, 2003

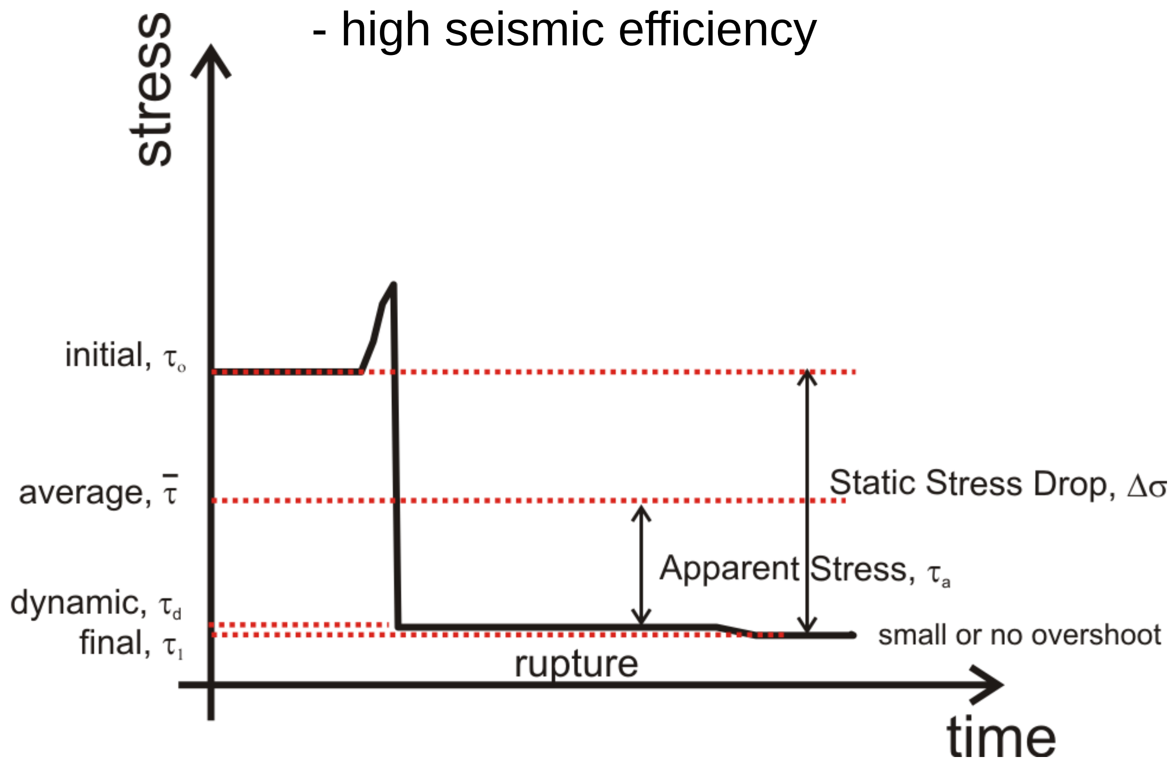


Fault lubrication or …

Fault lubrication driven by fluid pressurization at the fault zone, would produce a substantial decrease of dynamic friction with a consequent increase of the seismic efficiency, as measured by the ratio between apparent stress and static stress release.

Fault lubrication by fluid pressurization :

- decrease of shear strength
- increase of apparent stress
- high seismic efficiency

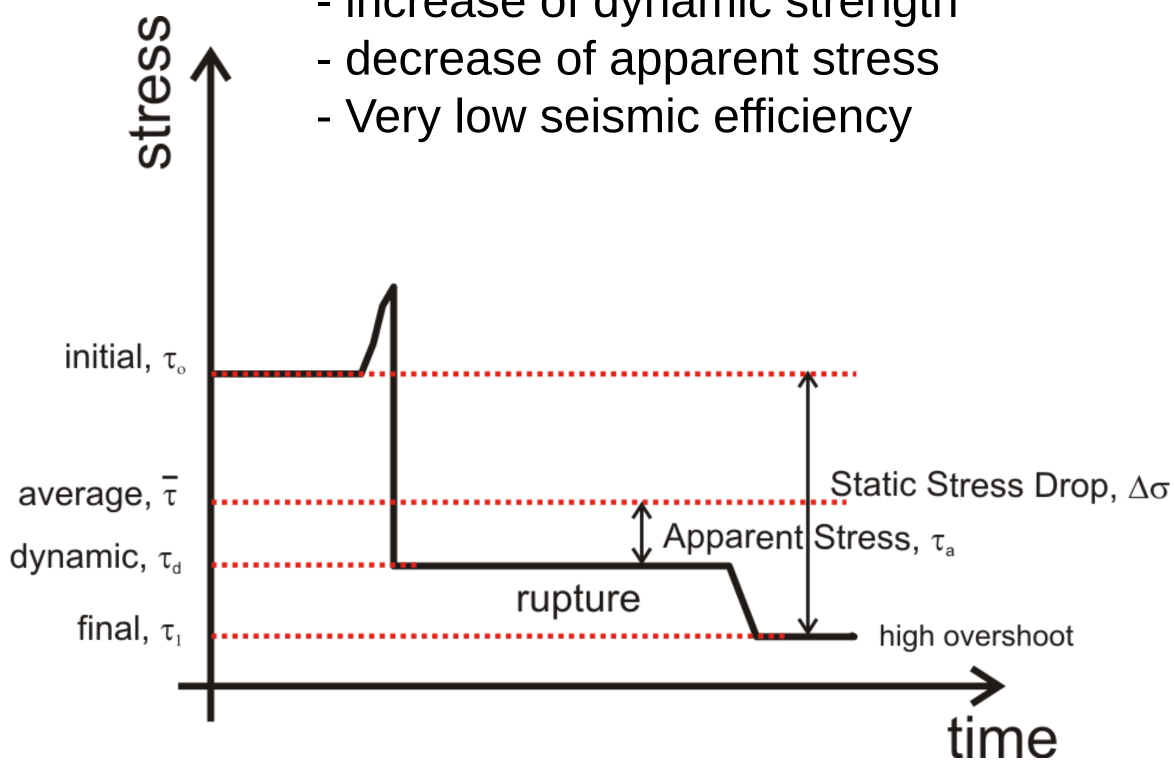


… dynamic stress overshoot ?

The occurrence of a dynamic stress overshoot is associated with the process of additional stress drop / fault slip driven by inertial forces acting on the moving fault blocks (Savage & Wood, 1971). This would result in a relatively low seismic efficiency as observed for Irpinia data.

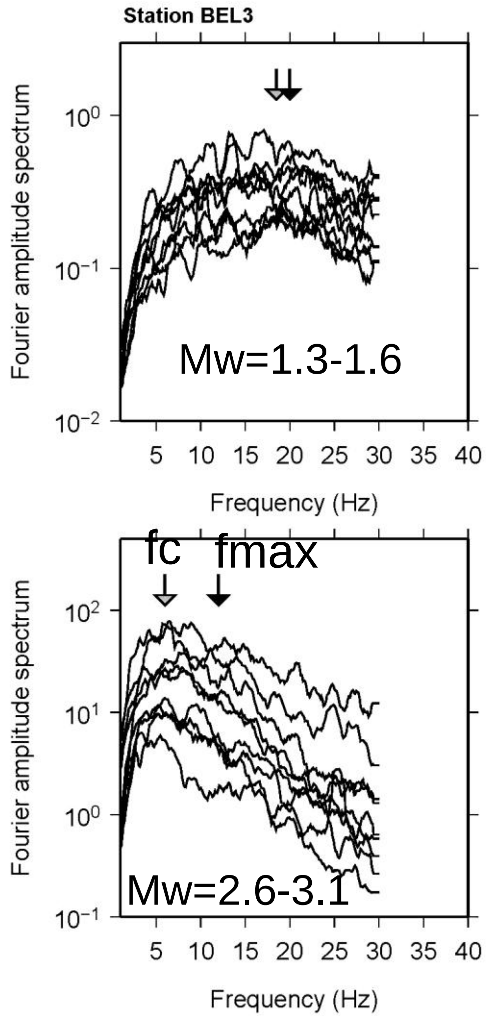
Dynamic stress overshoot as an effect of inertial forces during the rupture process:

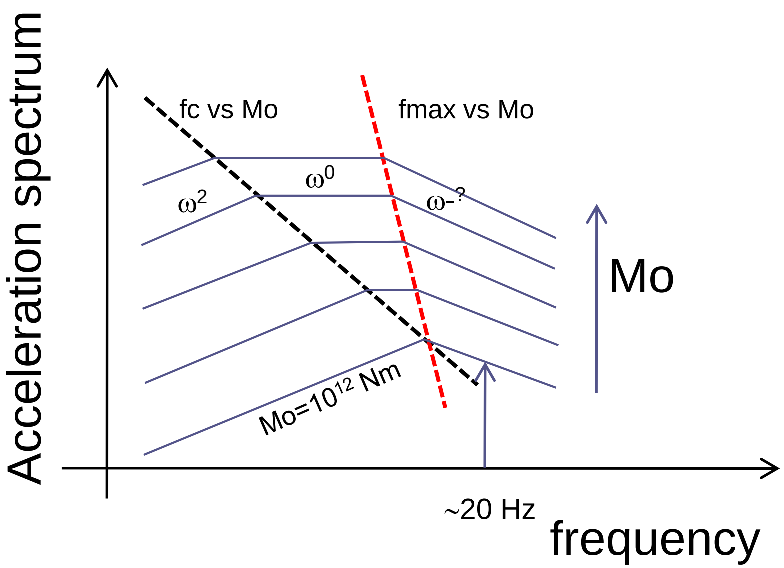
- increase of dynamic strength
- decrease of apparent stress
- Very low seismic efficiency



Is f_{max} a source effect?

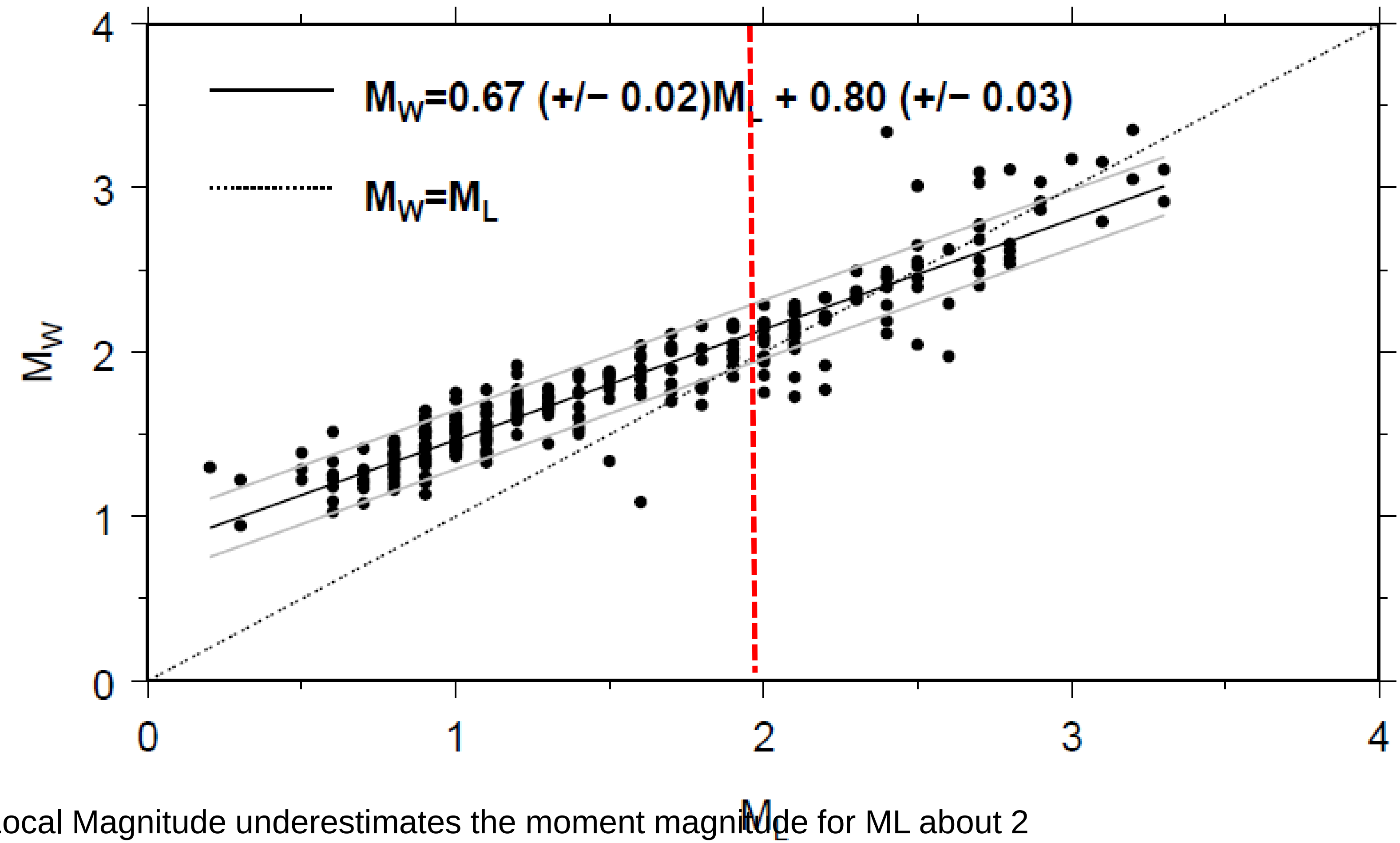
The evidence for the cut-off frequency f_{max} which decreases with magnitude suggests that it is a source related effect, e.g. the width of the fault cohesive zone. It depends on the earthquake size, being greater (~100 m) for the largest events of the sequence.





The corner frequency saturation at about 20 Hz can be explained as a low-pass filtering effect due to f_{max}

Magnitude: Moment vs Local



- ❑ Local Magnitude underestimates the moment magnitude for ML about 2
- ❑ This is due to violation of the constant stress drop scaling for Mw about 2
- ❑ Local Magnitude → peak displacement, high frequency, Moment Magnitude → Integral of displacement, low frequency

Conclusions

- **A nearly constant stress drop and apparent stress scaling** of P- and S-corner frequencies and seismic energies is observed down to a seismic moment value of about 10^{12} Nm, below which a breakdown in the earthquake self-similarity occurs.
- **The breakdown in self-similarity** is caused by a spectral cut-off frequency, fmax, which appears to be magnitude-dependent. We argue that a limiting source wavelength of 50-60 m is related to the lateral extension of the cohesive fault zone, whose width seems to depend on the earthquake size.
- **The ratio between apparent stress and static stress drop** (Savage-Wood seismic efficiency) is extremely low, indicating that radiated energy is a very small fraction of whole energy spent by friction and fracture development.
- **Our results imply that dynamic overshoot** could be the dominant mechanism controlling the seismic radiation from microearthquake ruptures along the Irpinia fault zone. The alternative hypothesis of a dominant weakening effect driven by fluid pressurization contrasts with the very low values of SW efficiency and the lack of evidence for its variation with seismic moment in the explored magnitude range.

credits

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or

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* The paper is under evaluation, check the exact references at the Journal website