Microearthquake stress drop and attenuation from borehole DAS at Cape Modern

1/20/2026 SCEC Stress Drop Validation Workshop

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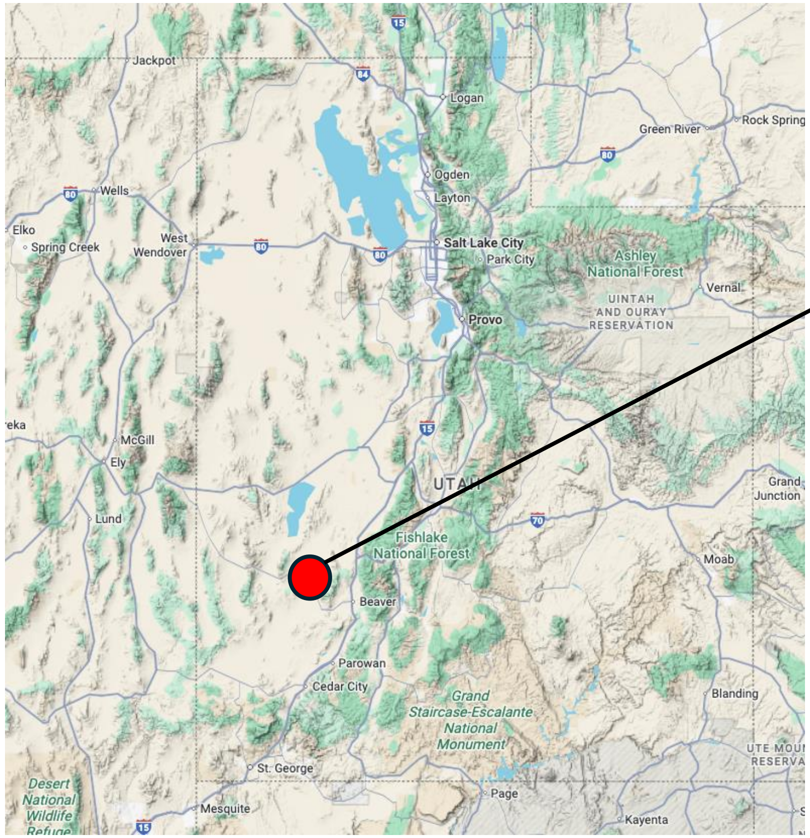
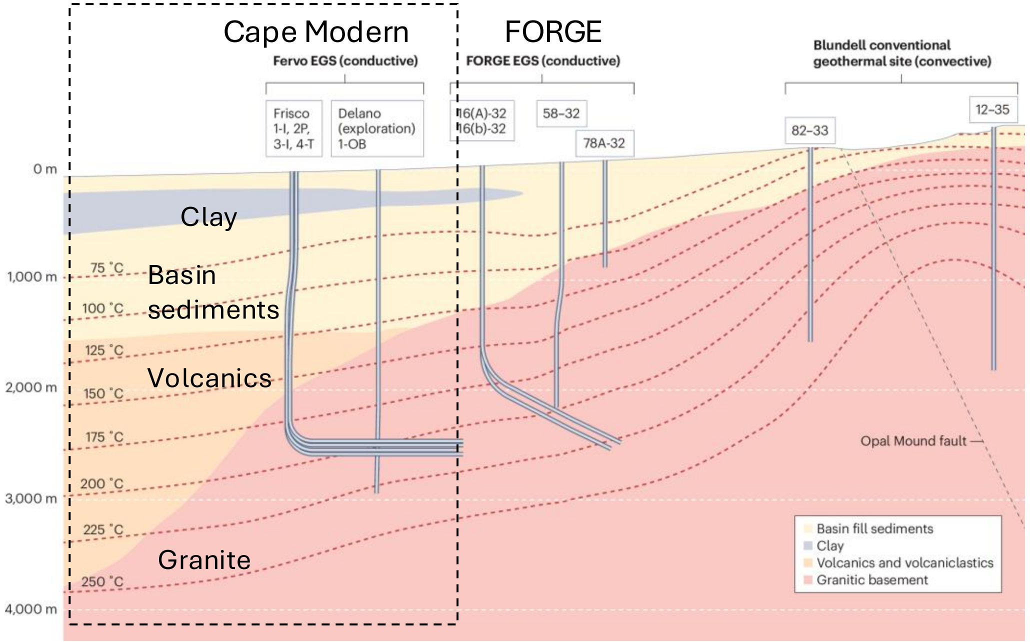
Cape Modern geothermal field in Utah

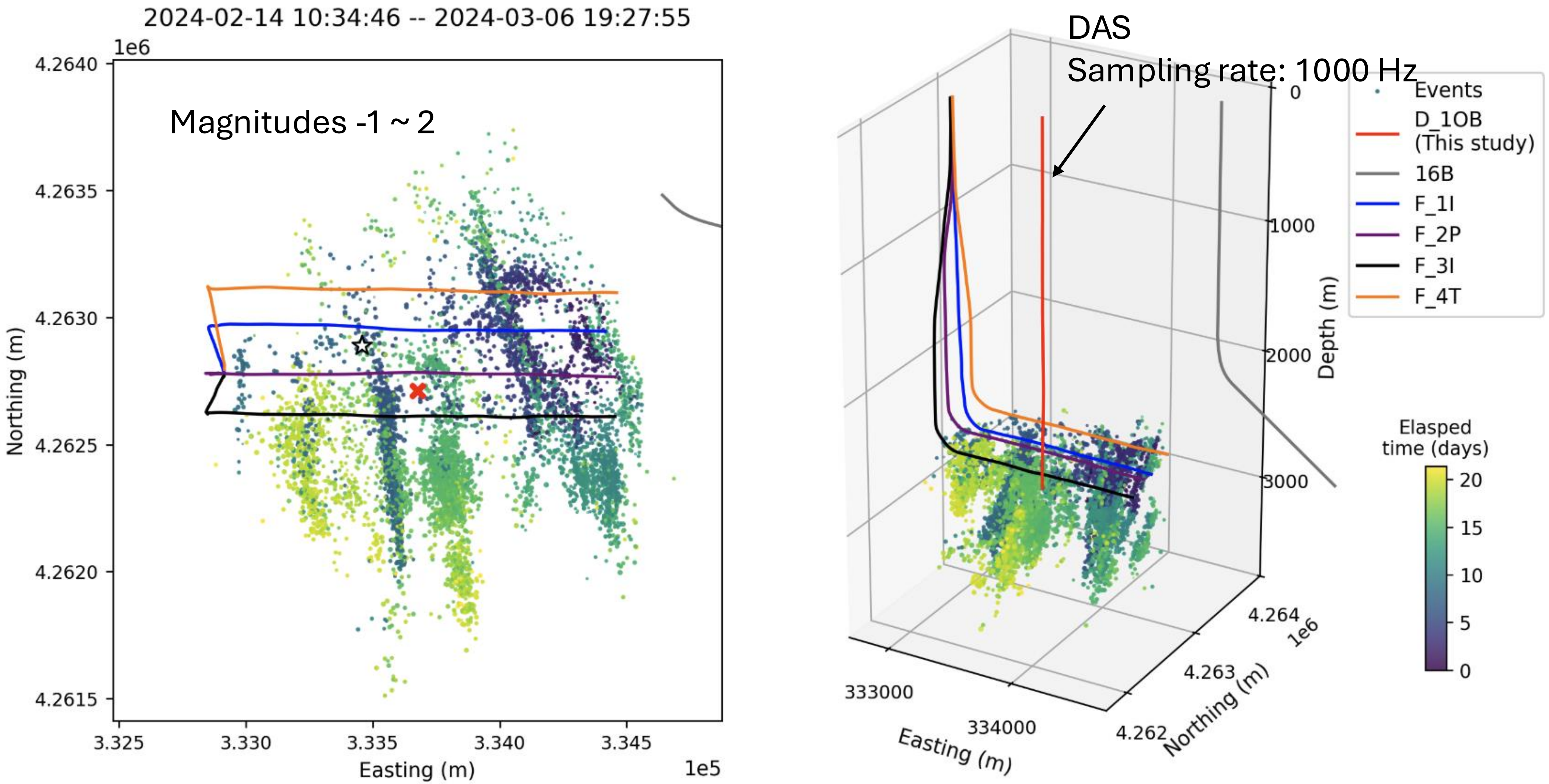
Enhanced Geothermal System (EGS)





Horne et al. (2025)

Microearthquakes induced by stimulation

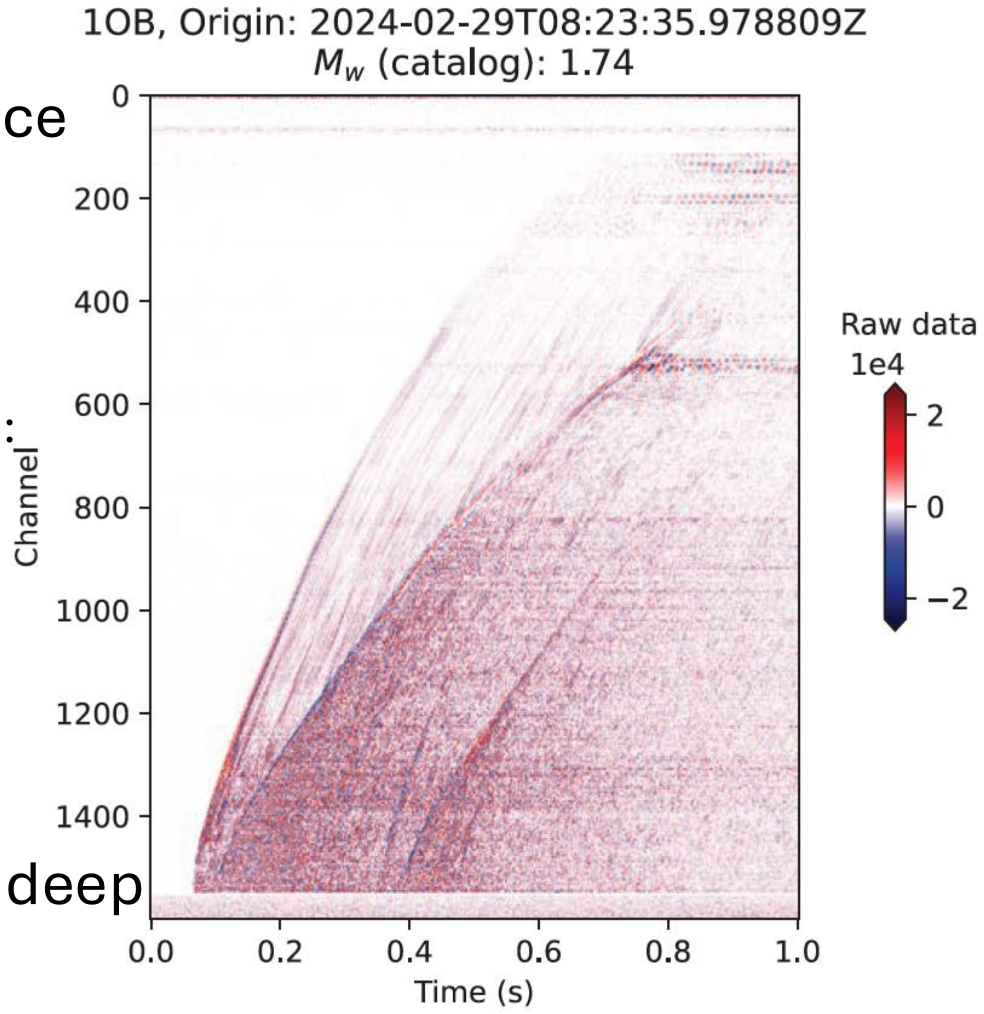


An event captured by the vertical cable

Surface

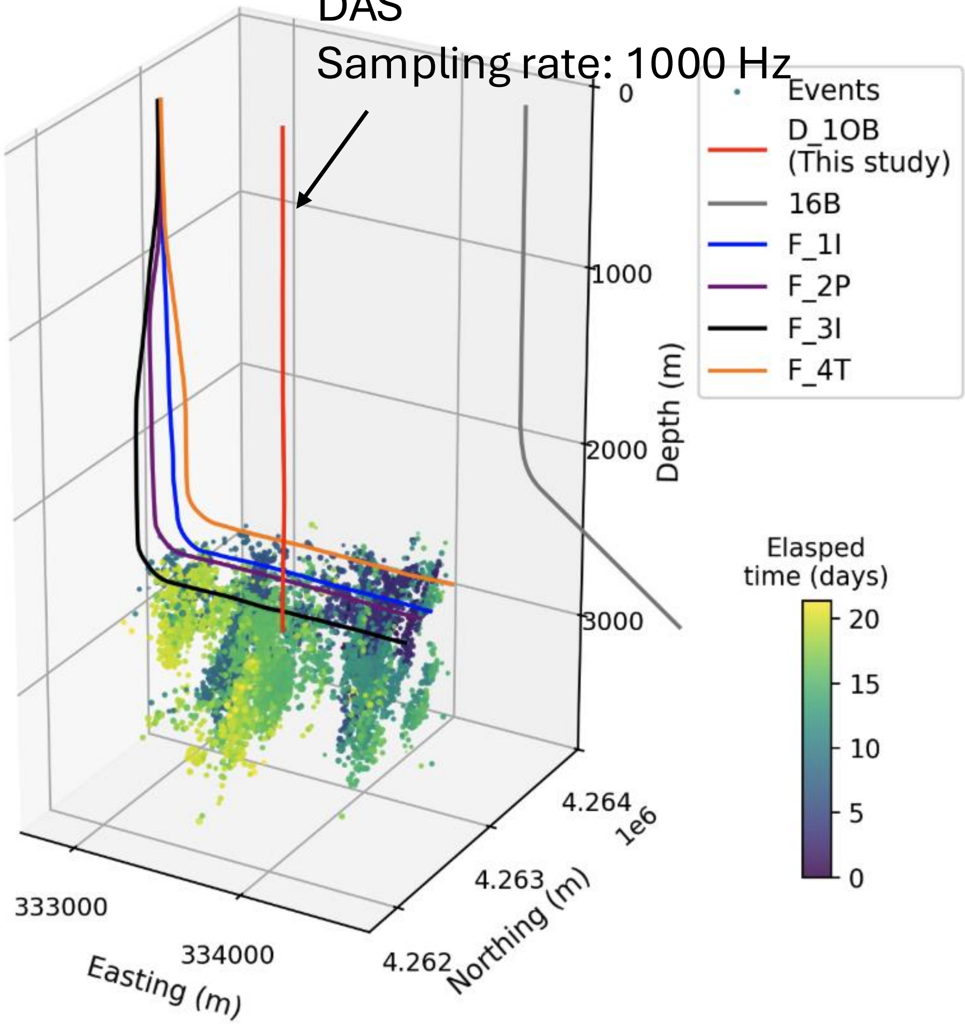
Channel separation: 2m

~3 km deep

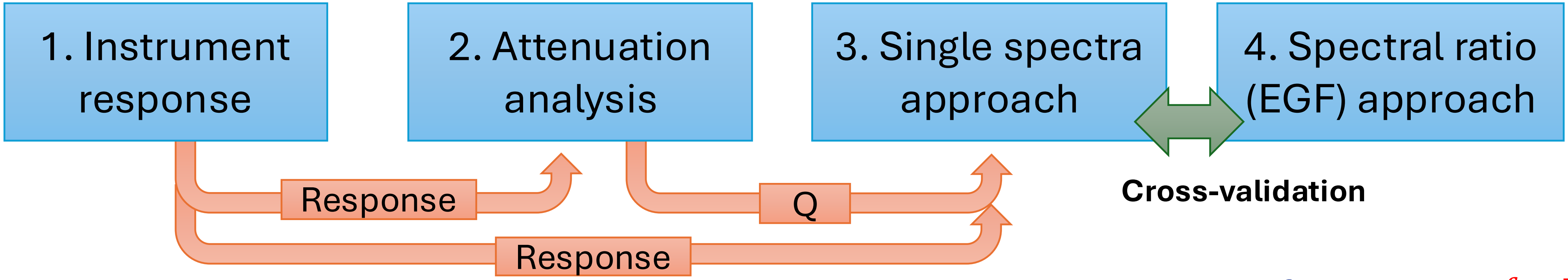


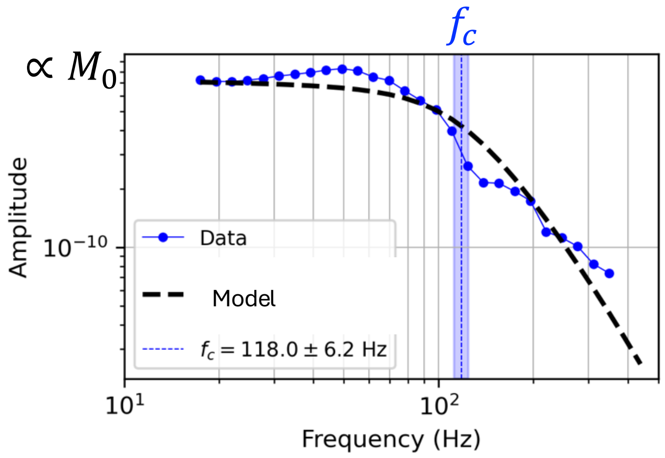
DAS

Sampling rate: 1000 Hz

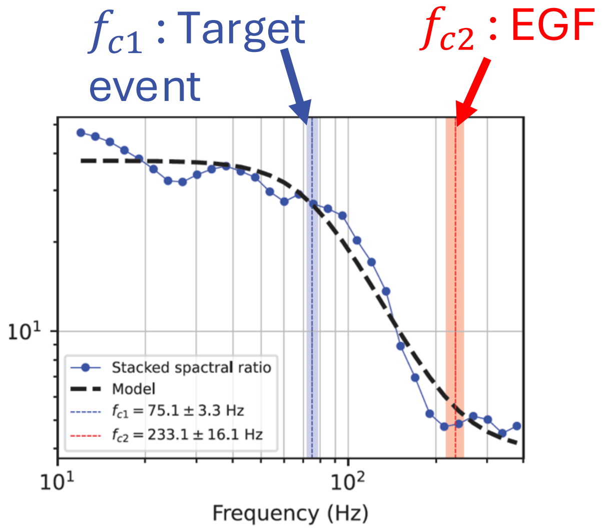


The workflow for source parameter estimation





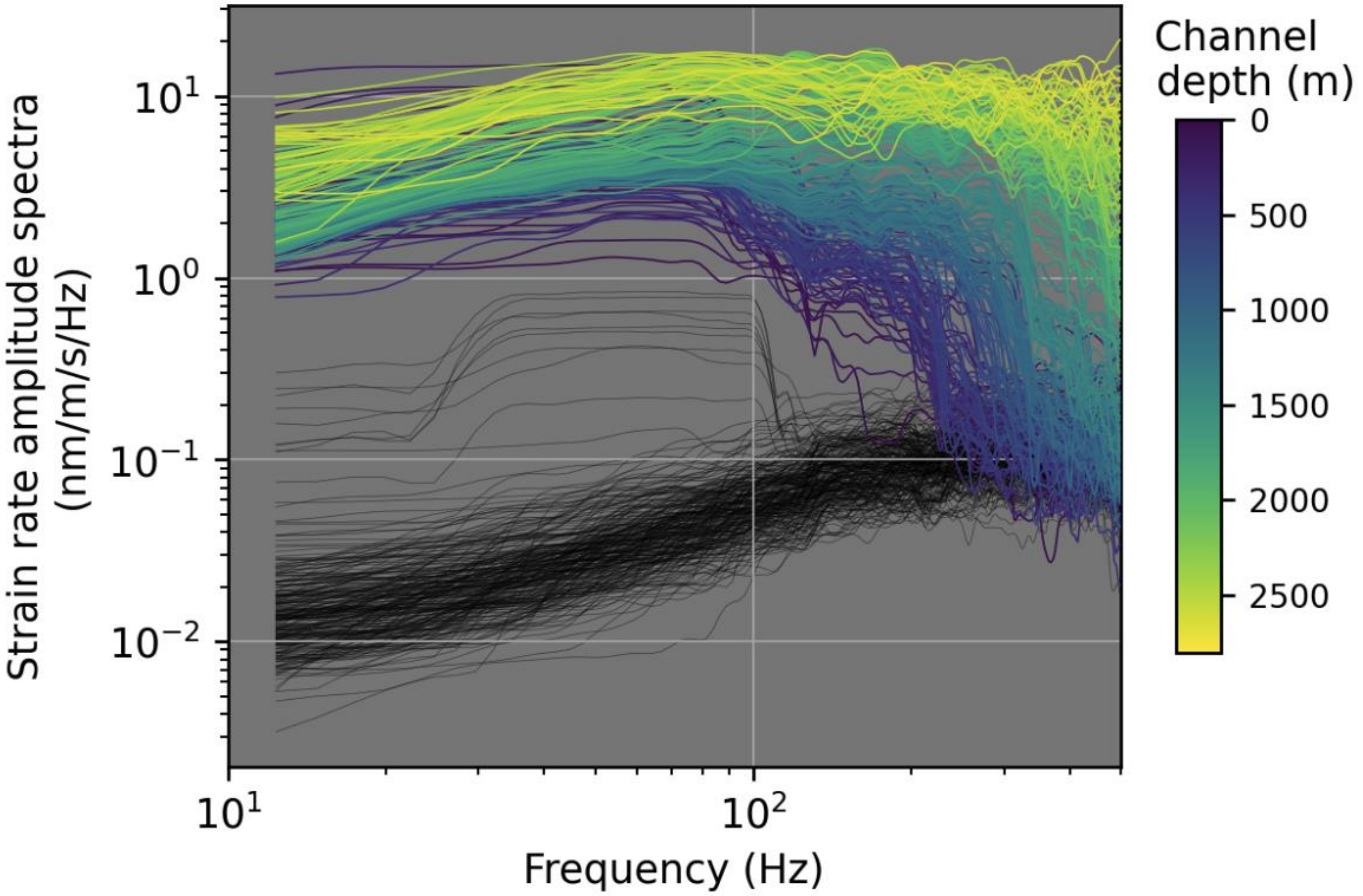
(e.g., Brune, 1970)



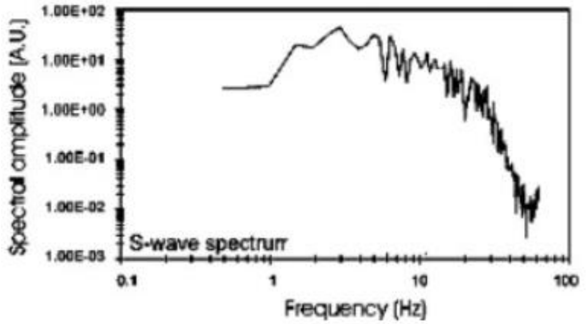
(e.g., Abercrombie, 2014, 2015)

Decomposing the P-wave spectra of DAS

(Proportional to acceleration)

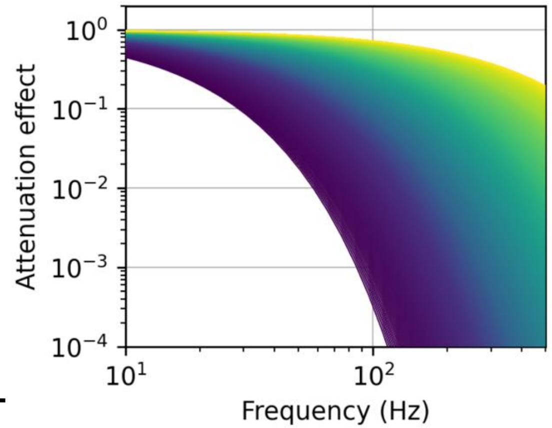


1. Source spectra



$$\frac{\Omega_0}{\left|1+\left(\frac{f}{f_c}\right)^{\gamma n}\right|^{\frac{1}{\gamma}}}$$

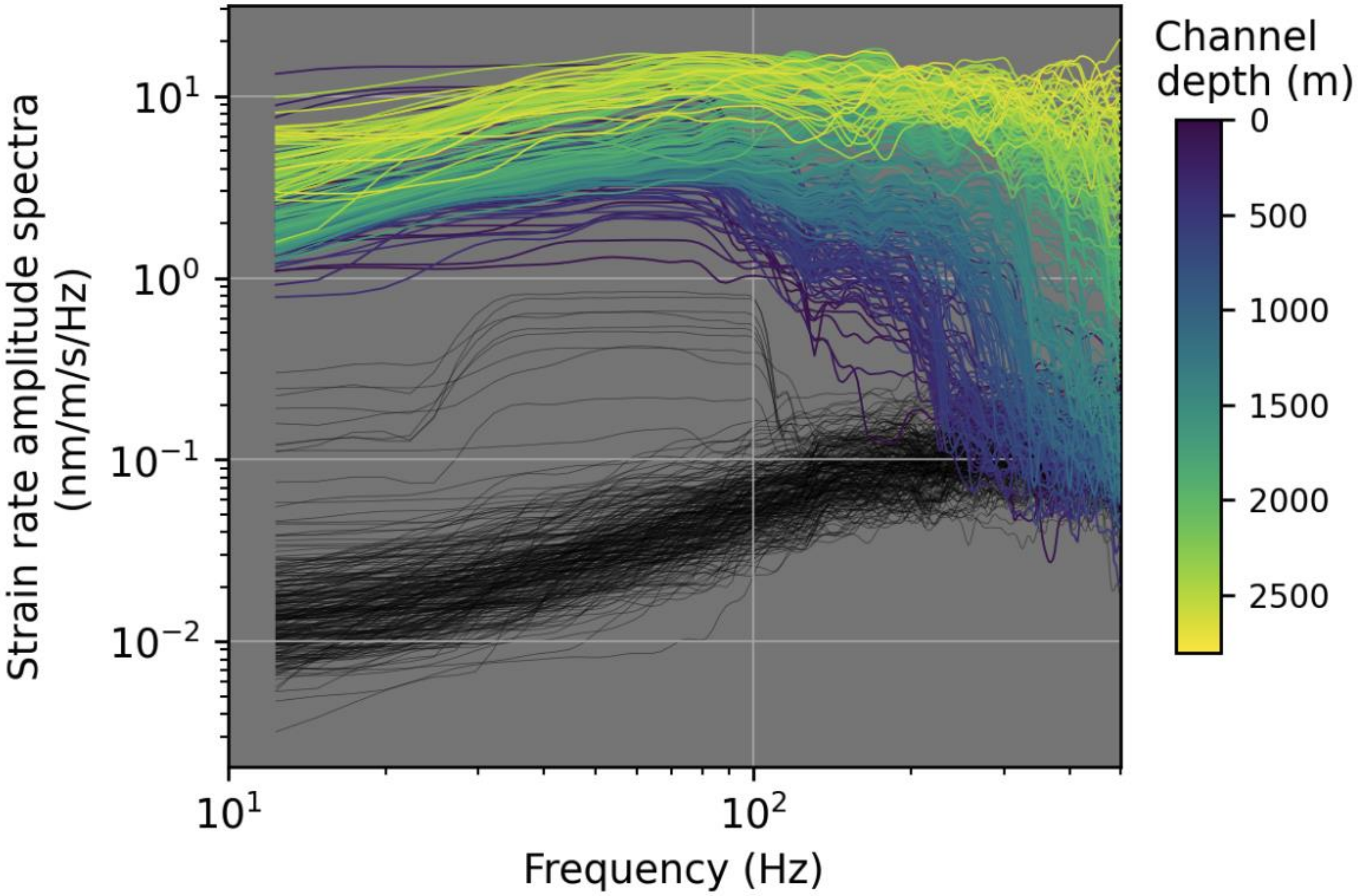
2. Attenuation



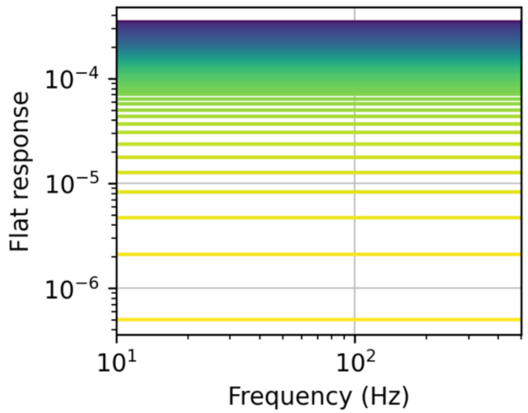
$$e^{-\pi f \kappa}$$

Decomposing the P-wave spectra of DAS

(Proportional to acceleration)



3. Sensitivity to incident angles



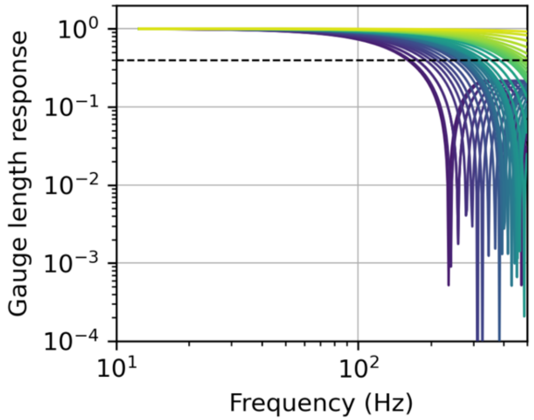
P waves

$$v \cdot cos^2\theta$$

S waves

$$v \cdot cos\theta sin\,\theta$$

4. Gauge length effect

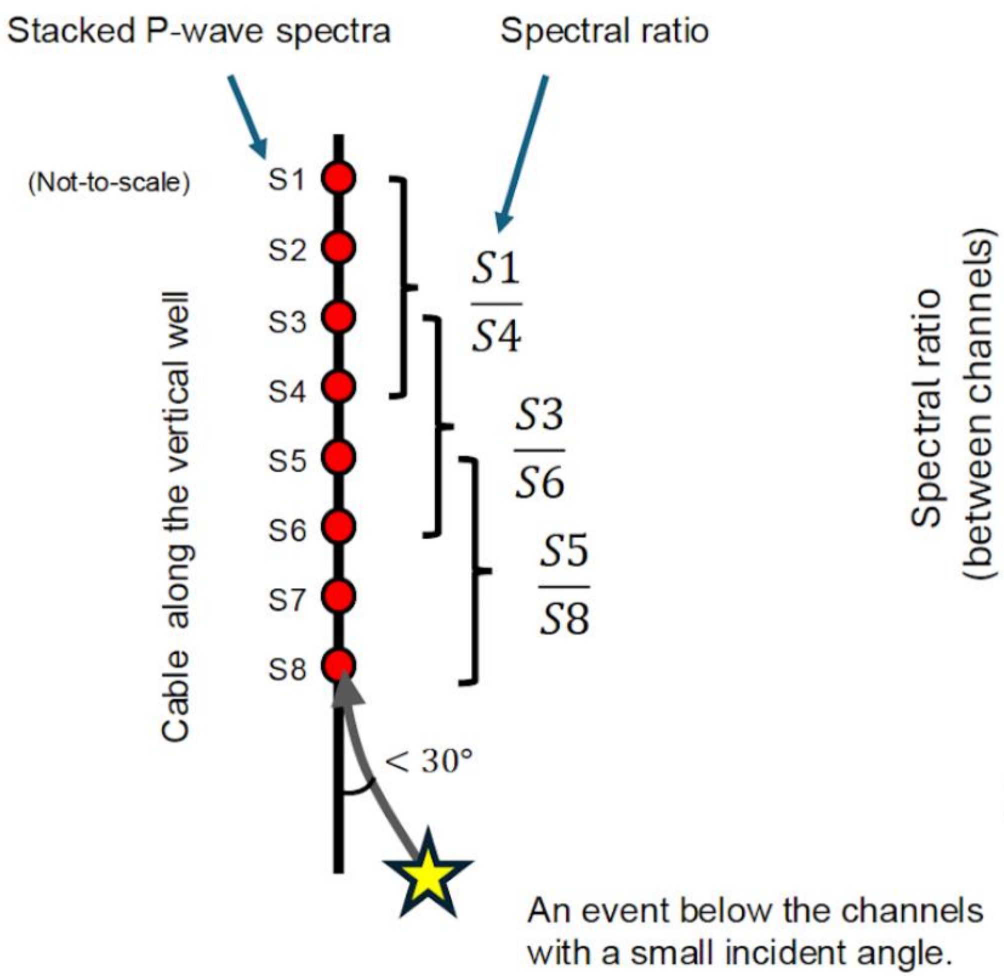


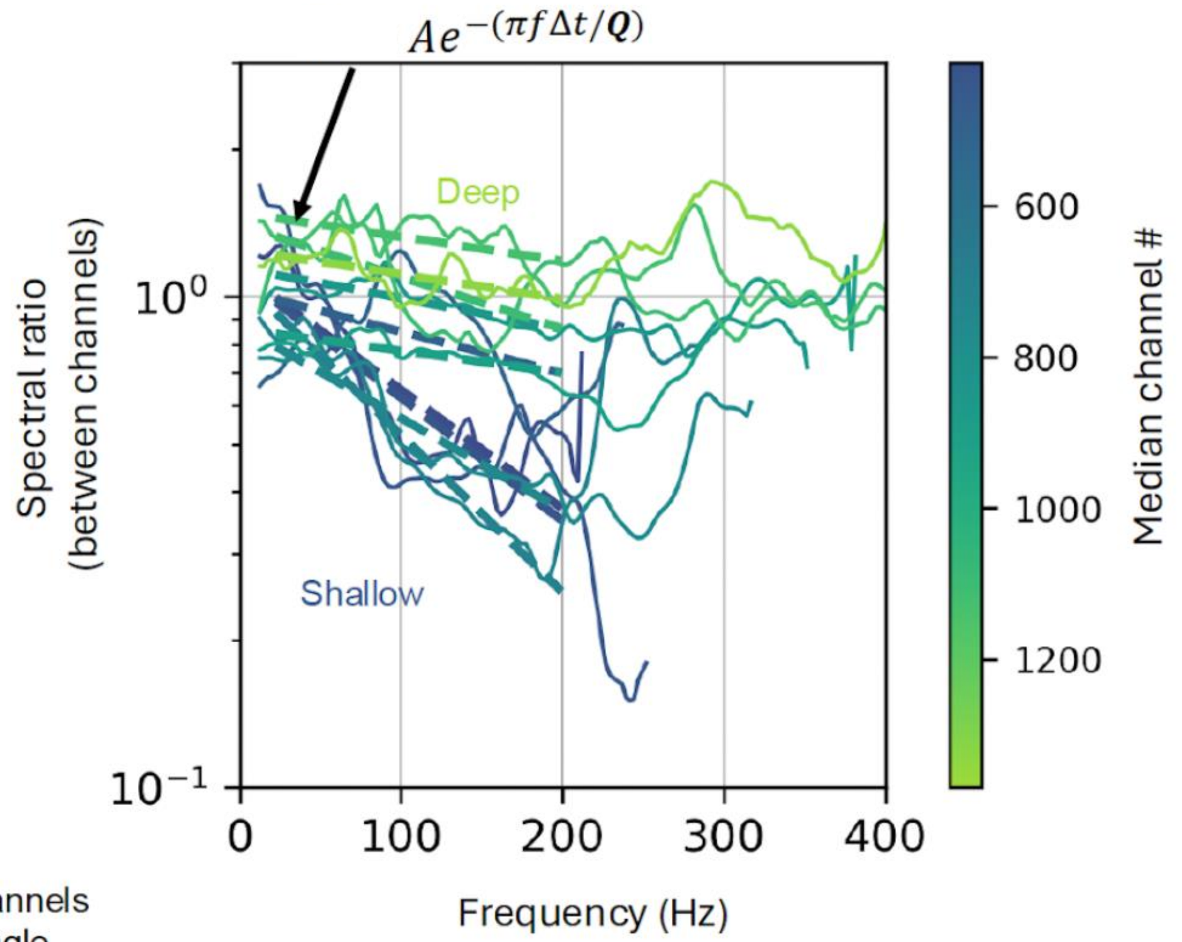
$$sinc(\frac{\pi f L}{v \cdot cos\theta})$$

L : Gauge length (10 m)

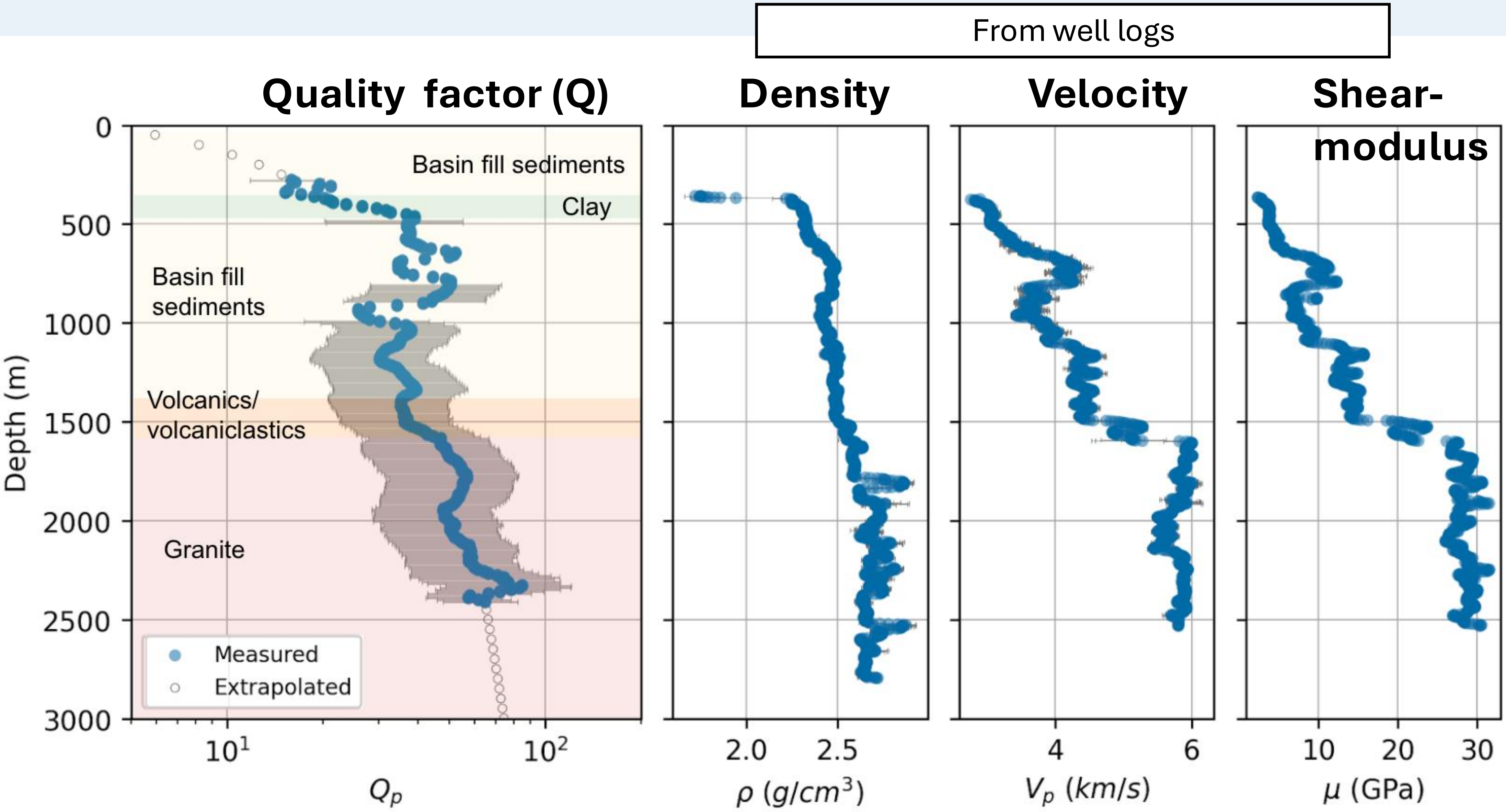
Bakku (2015)

Estimate attenuation using spectral ratio (along-depth)

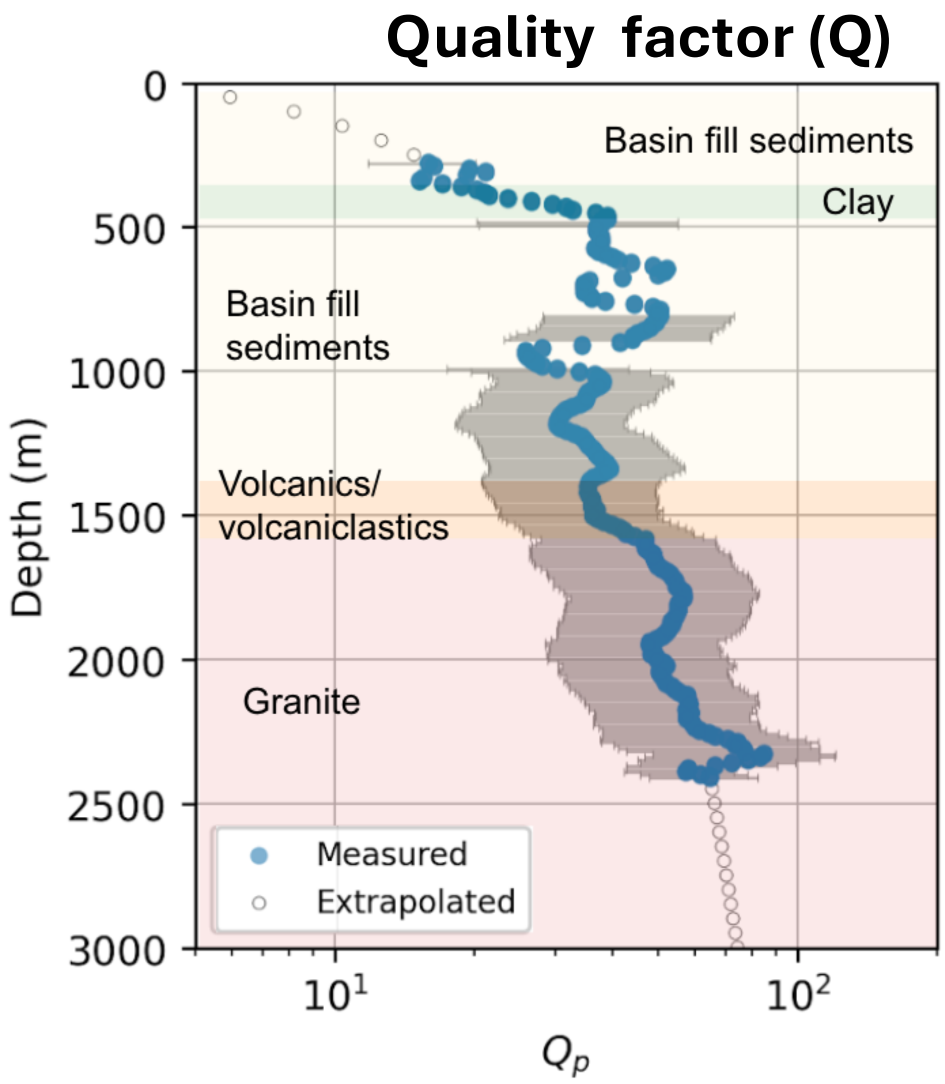


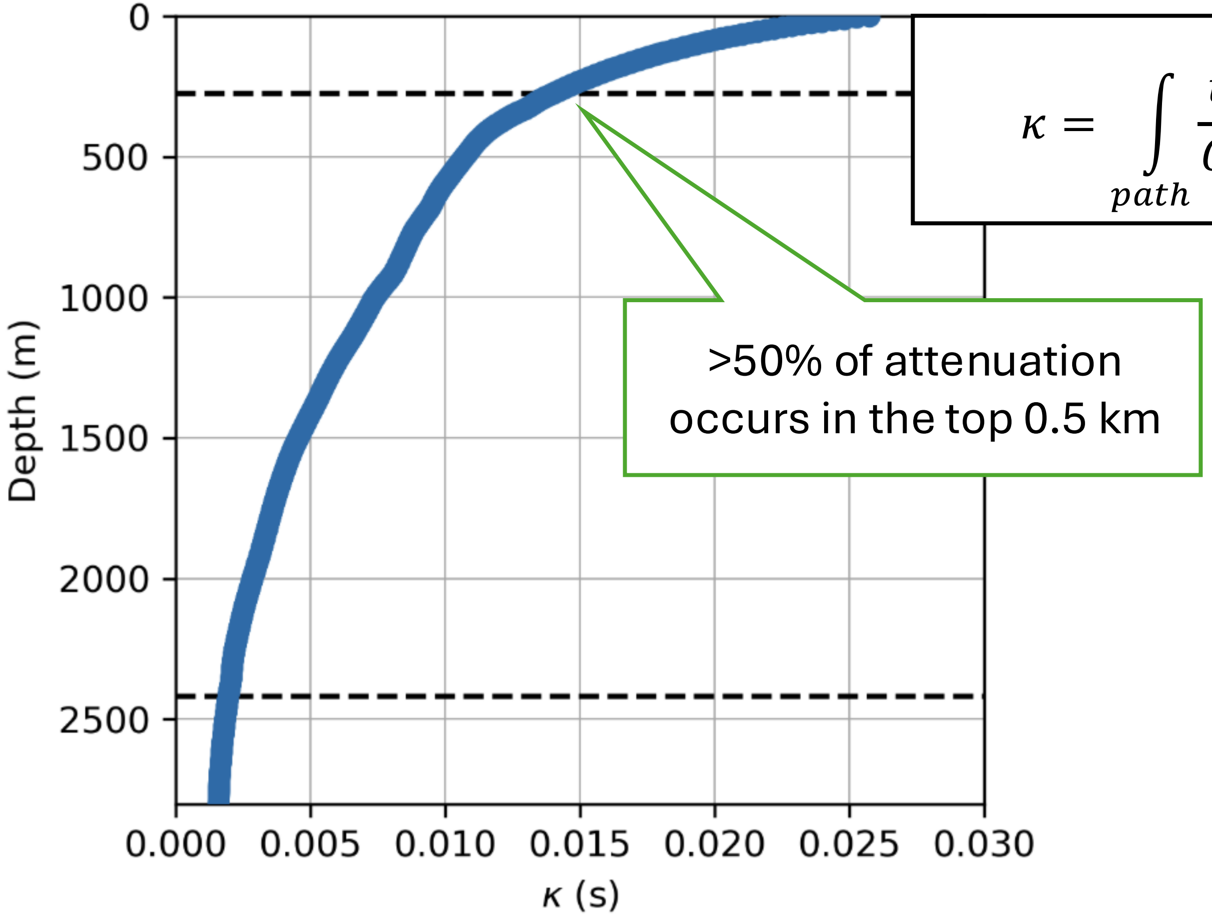


Q profile on the top 2.5 km



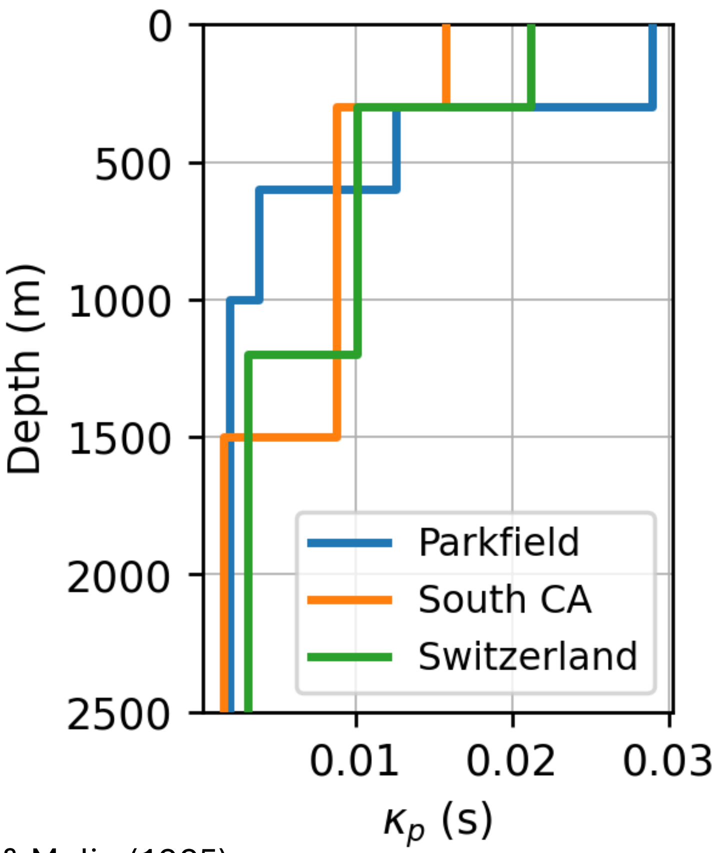
Accumulated attenuation (Kappa) for an event at the well bottom

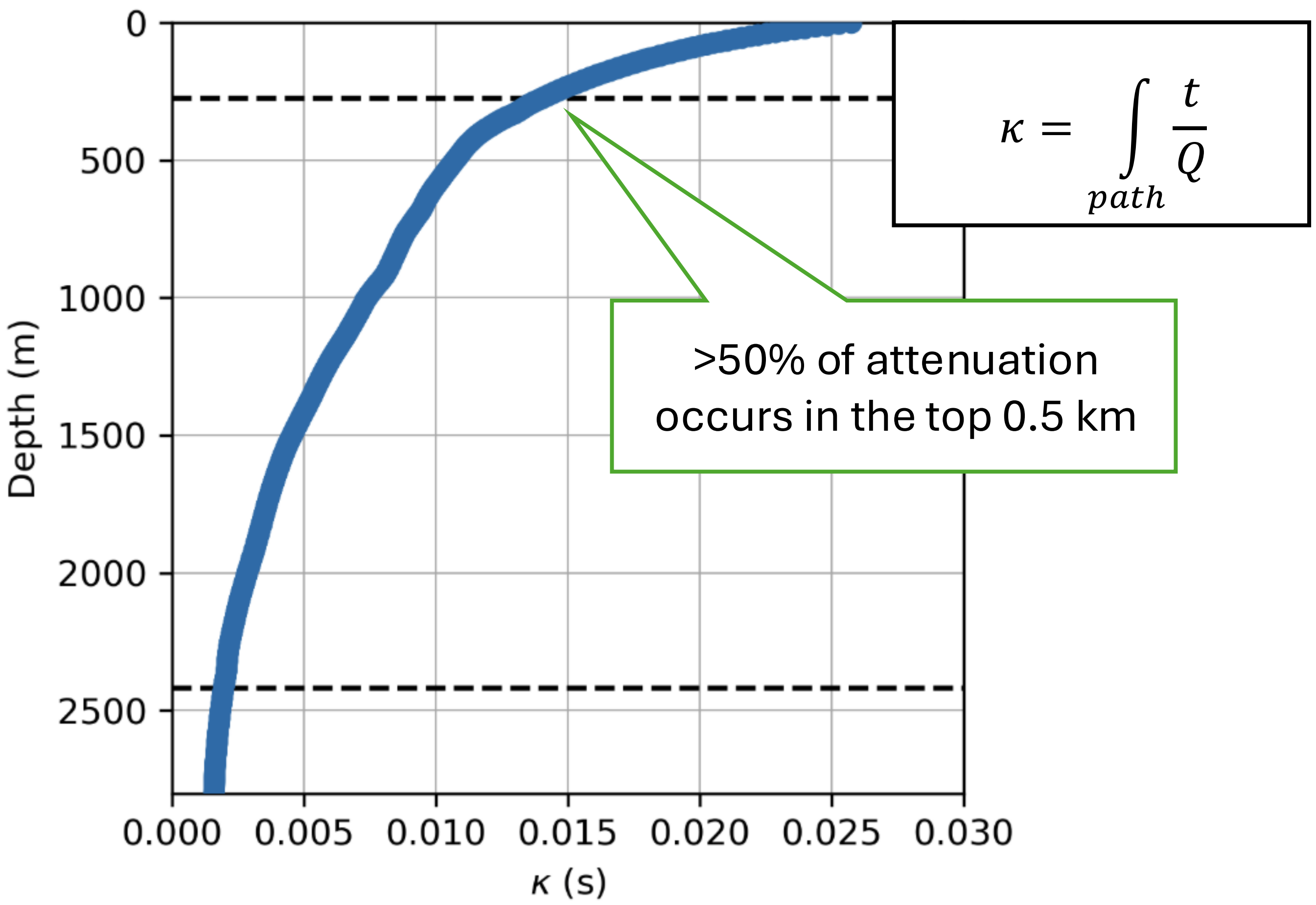




$$\kappa = \int_{path} \frac{t}{Q}$$

Kappa agree with other attenuation studies

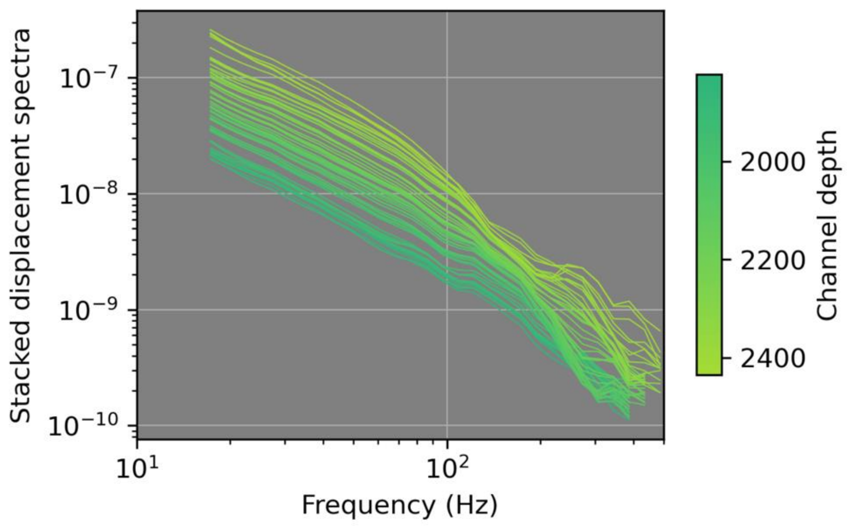


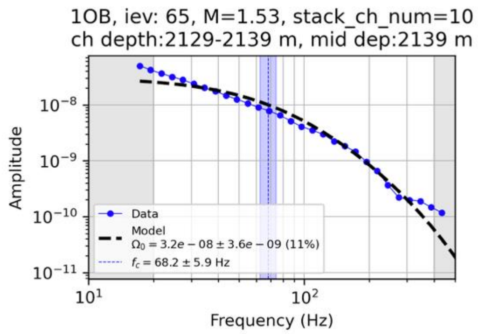


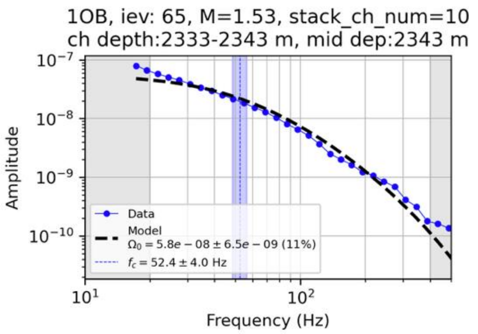
Jongmans & Malin (1995)
Abercrombie (1998)
Bethmann et al. (2012)

Single spectra fitting for source parameters

Stack channels every 20 m







Brune's model

$$\Omega_r = \frac{\Omega_0}{\left|1+\left(\frac{f}{f_c}\right)^{\gamma n}\right|^{\frac{1}{\gamma}}} \cdot e^{-\pi f \kappa}$$

$\gamma = 1$: Brune's model
$n = 2$: High-f fall-off rate

$$\kappa = \int_{path} \frac{t}{Q}$$

Source radius

$$a = \frac{k\beta}{f_c}$$

β: Source Vs (from 1D model)
k=0.38: (Kaneko and Shearer,2014)

Seismic moment

$$M_0 = \frac{4\pi\rho c^3 R\Omega_0}{U_{\phi\theta}}$$

$\rho = 2790$: Density
c : Source Vs (from 1D model)
R: Hypocentral distance
$U_{\phi\theta} = 0.52$: For P wave average radiation pattern (Madariaga, 1976)

Spectral stress drop

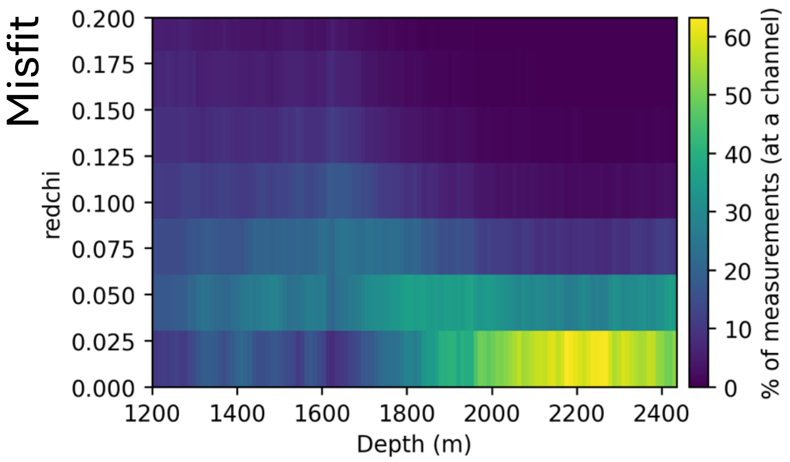
$$\Delta\sigma = \frac{7}{16}\frac{M_0}{a^3}$$

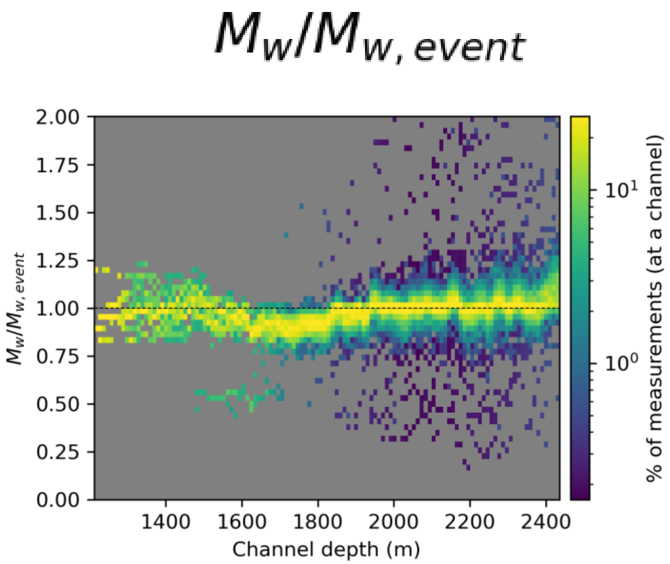
Quality Control

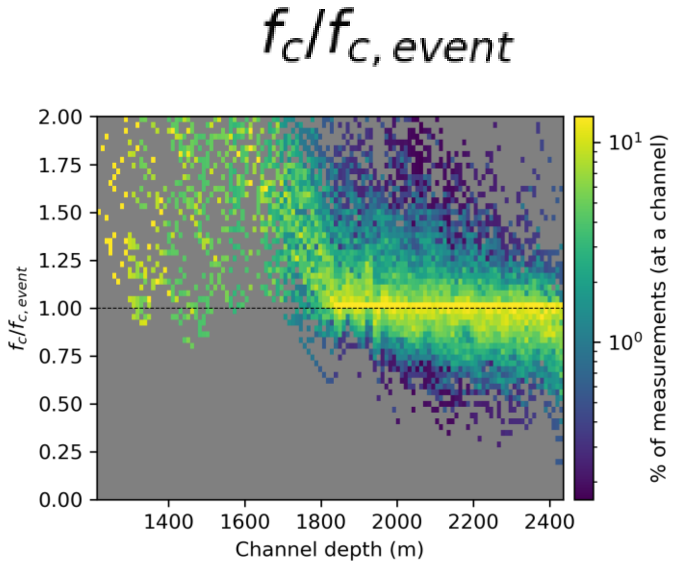
- Spectral point-wise SNR>3
- 1.2 fmin <fc<0.8 fmax
- Reduced chi-square (misfit) <0.02
- Uncertainty < 50% (std/result)
- Incident angle < 45 deg
- Good cable (dep 2.0~2.4 km)

(Brune 1970; Madariaga 1976; Eshelby 1957)

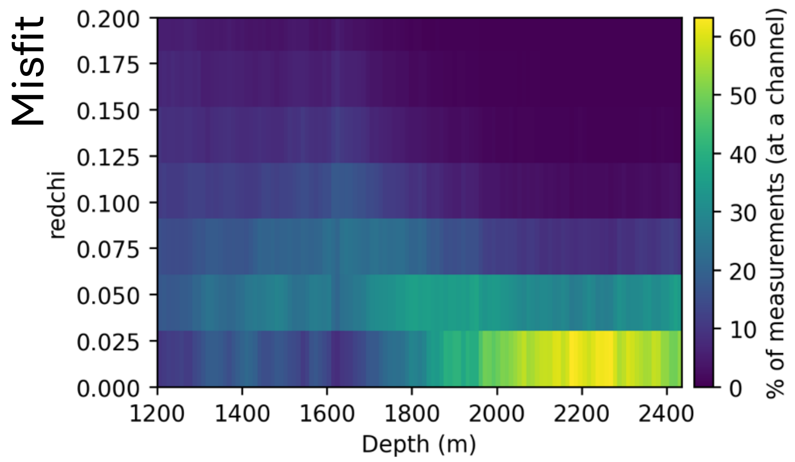
Which DAS channel to use matters

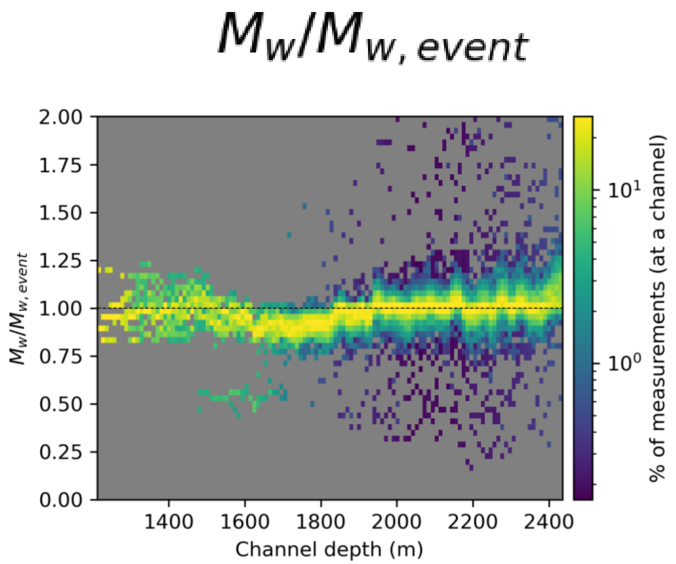


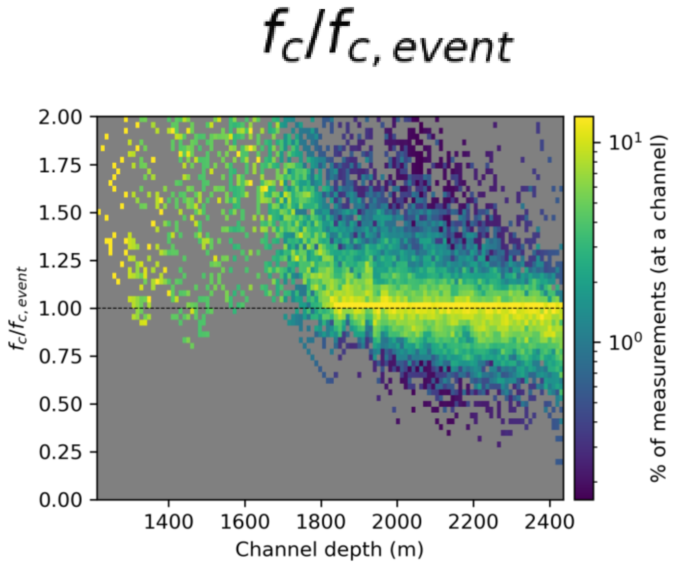


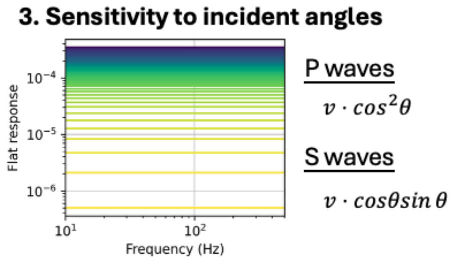


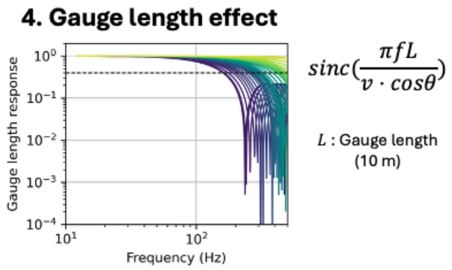
Which DAS channel to use matters







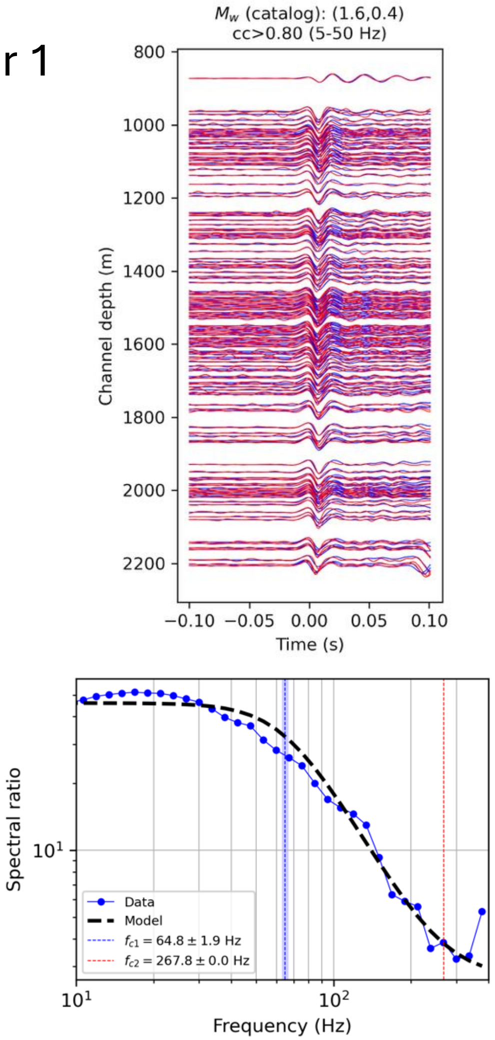




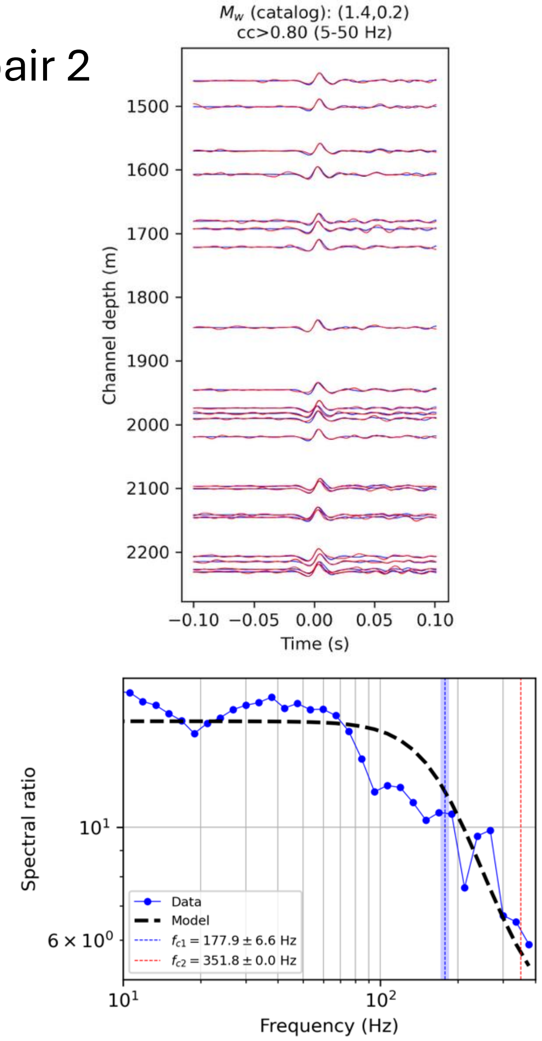
Uncertainty in incident angel can cause systematic bias in response removal
Possibly cause trade–offs with source parameters.

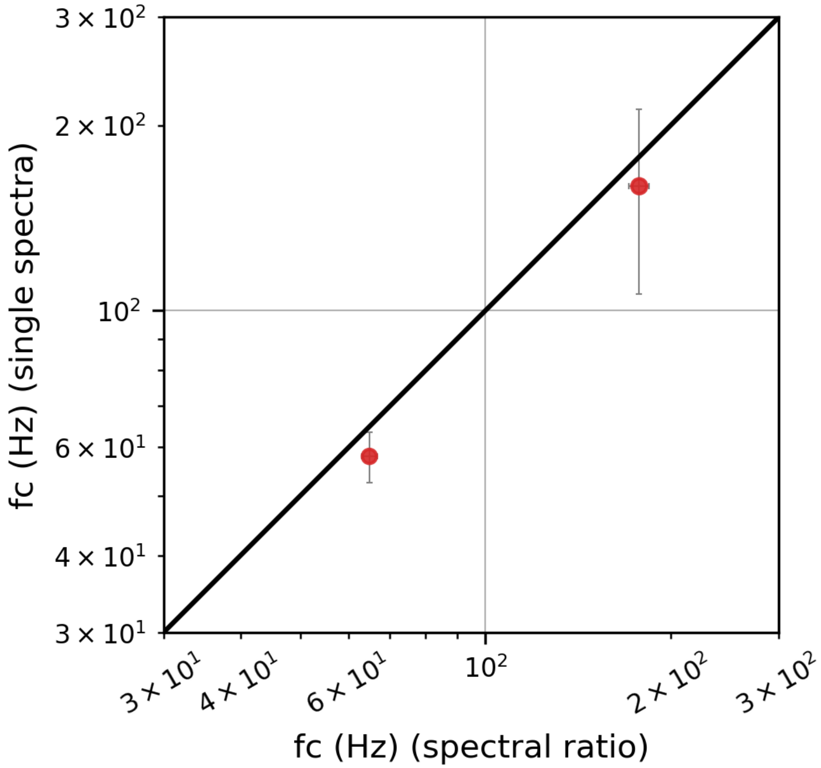
Compare fc estimated using single spectra and the EGF approach

Event pair 1



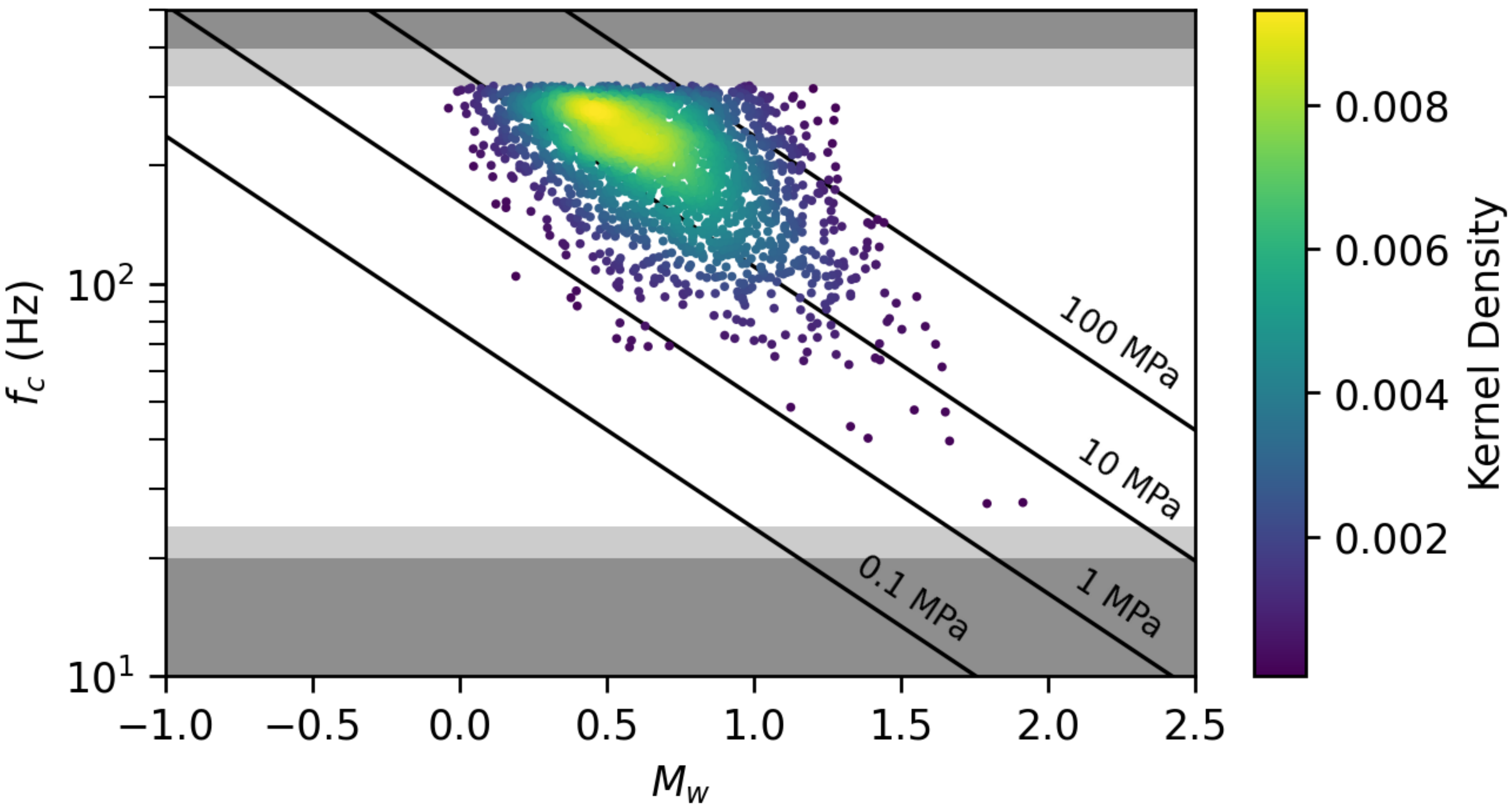
Event pair 2





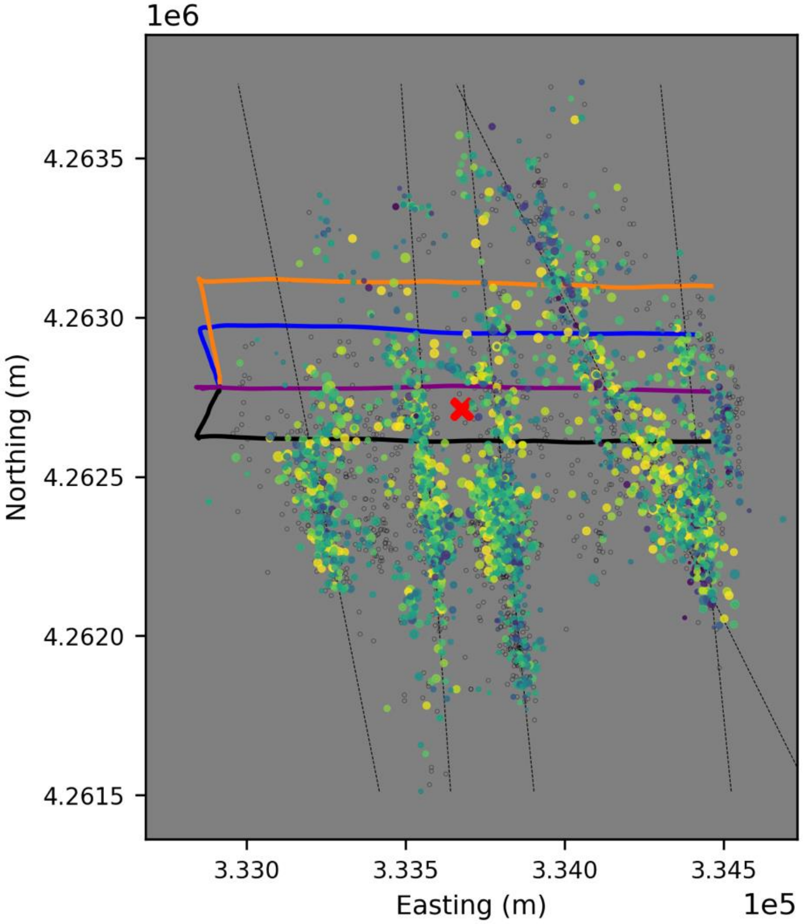
No evidence that the stress drop is magnitude dependent

Single-spectra fitting results

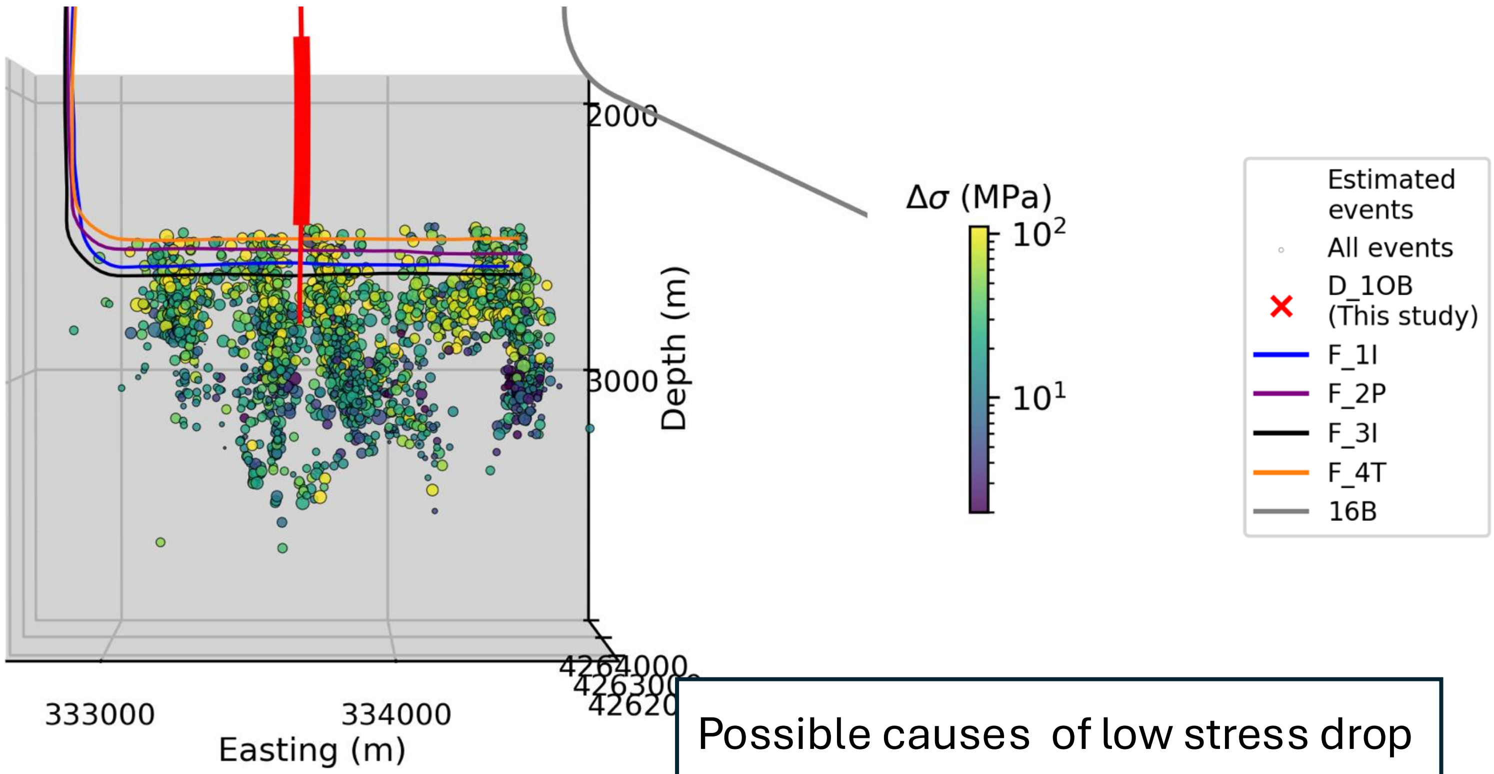


- Median: 36.7 MPa
- A higher sampling rate (> 1000 Hz) is required to characterize smaller (Mw < 0) events.

Mapping stress drops



Single-spectra fitting results

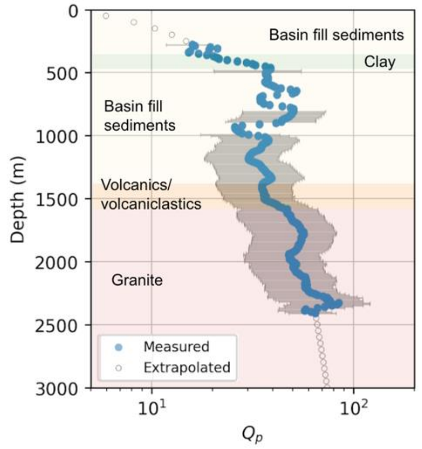


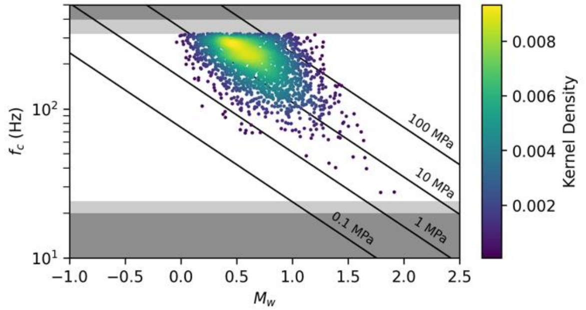
Possible causes of low stress drop zones:

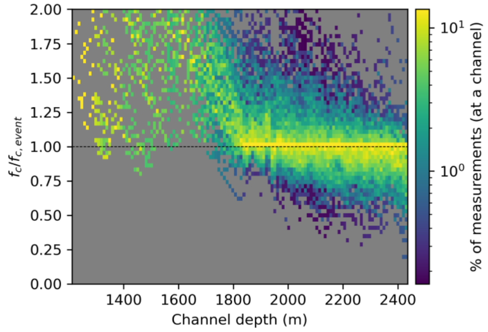
- Higher attenuation?
- Lower rupture velocity?
- Weaker rock (higher temp?)

Summary

- We estimate Q in the top 2.5 km in Utah.
  - Low Q in the top 0.5 km agrees with Parkfield, South CA (Cajon Pass), and Switzerland.
- We estimate spectral stress drop using single-spectra fitting for 0 < Mw < 2.
  - No obvious deviation of constant stress drop
- DAS response removal can be another source of systematic bias.







Chang, H., Nakata, N., Abercrombie, R. E., Dadi, S. & Titov, T. (in prep.). Characterizing shallow attenuation and microearthquake source parameters using downhole DAS array at the Cape Modern geothermal field.

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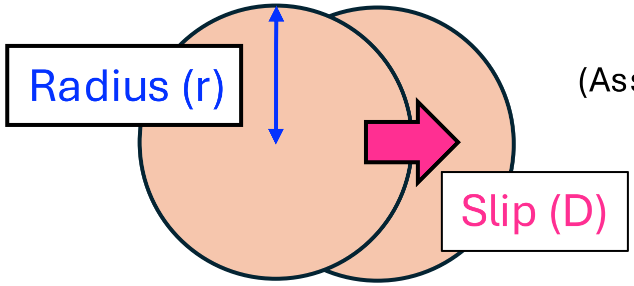
Source radius and slip

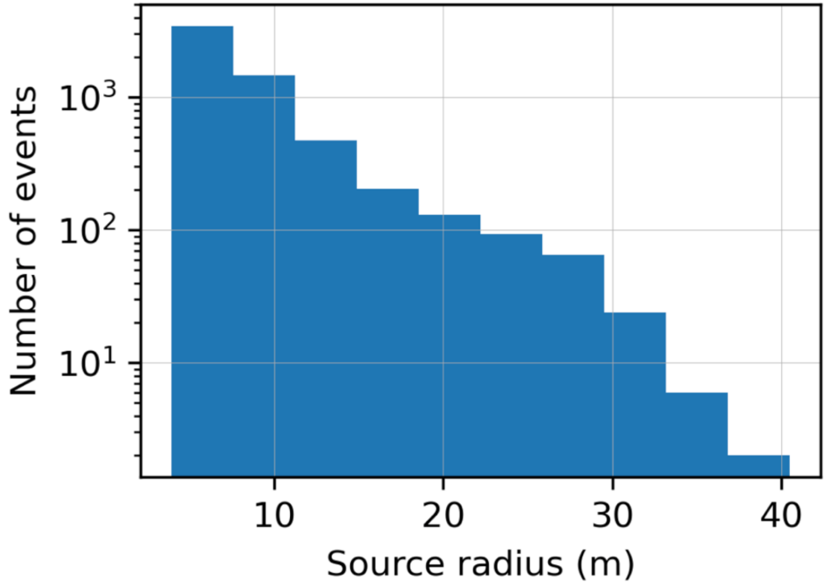


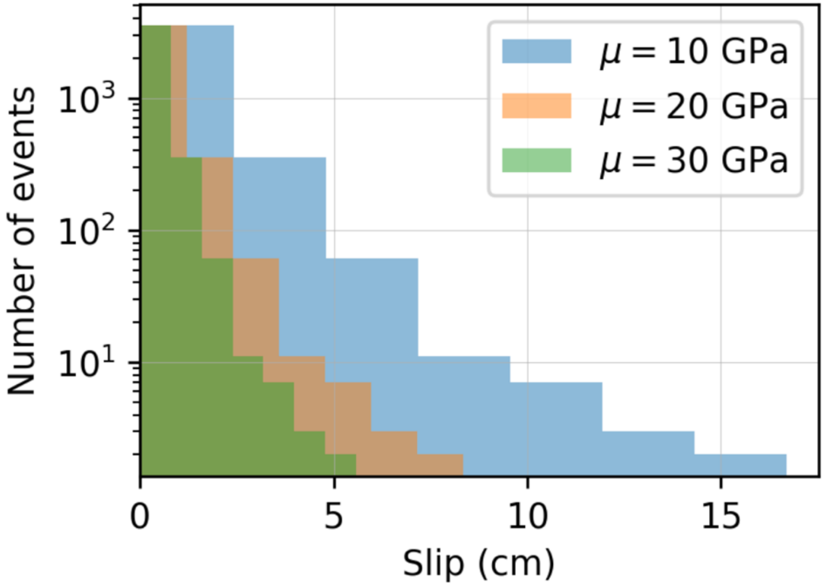
(Assuming double-coupled)

$$r = \frac{k\beta}{f_c}$$

$k = 0.38$
β : Shear-wave velocity

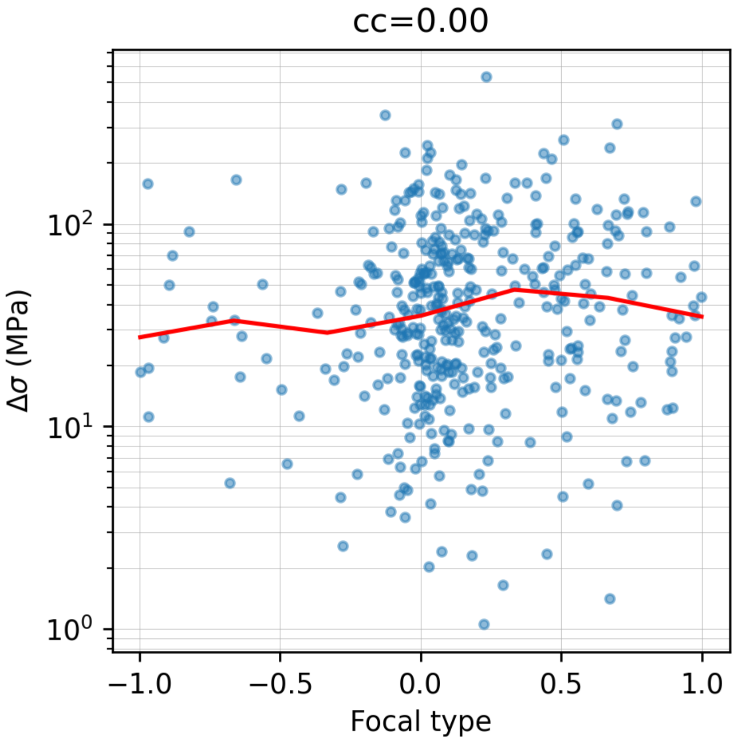
$$D = \frac{M_0}{\mu \pi r^2}$$



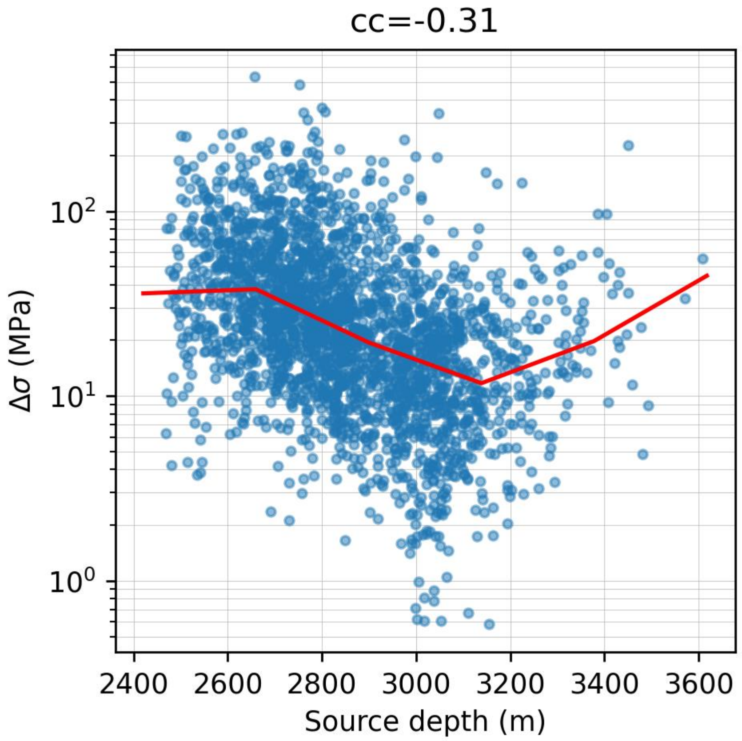


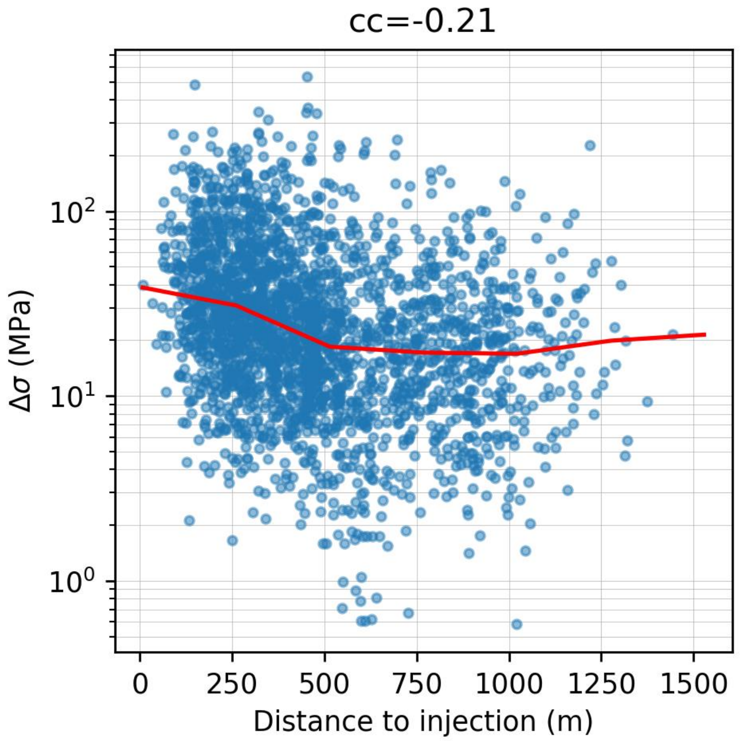
Assume different shear modulus (μ)

$\Delta\sigma$ vs focal mechanism, depth, injection distance



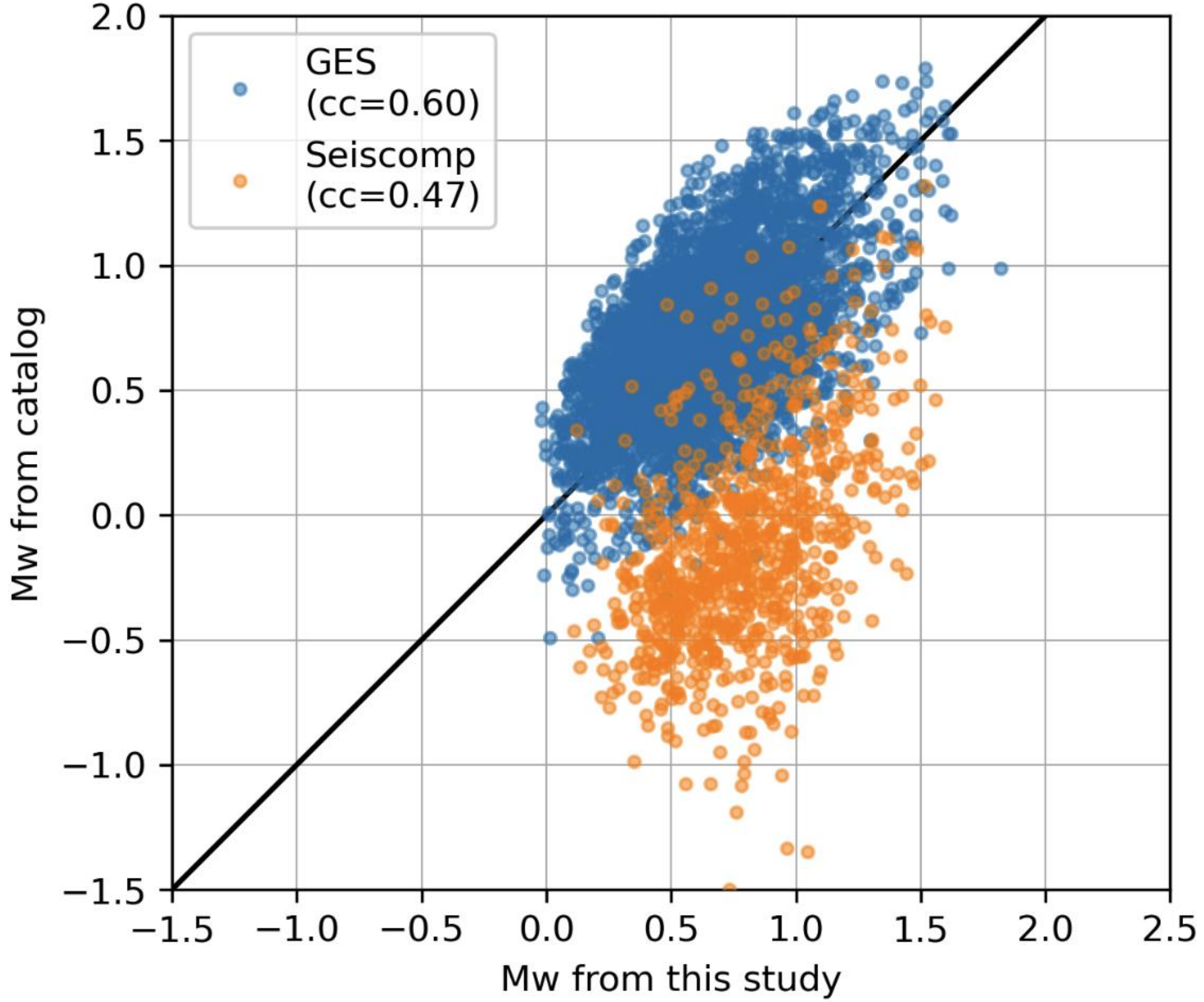
Normal Strike-slip Reverse



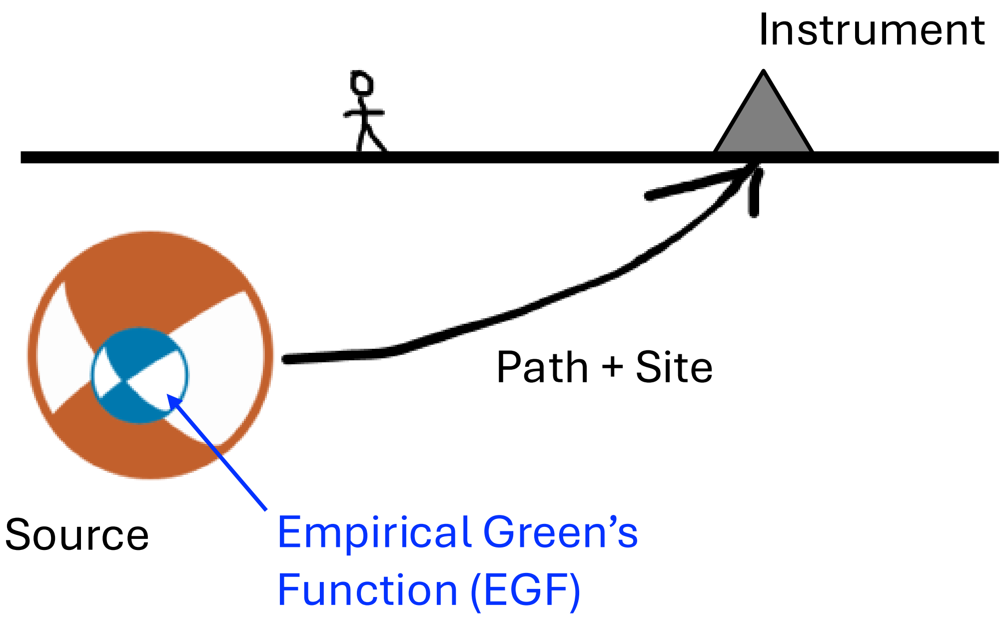


- Goertz-Allmann & Wiemer (2012) expected large distance, larger $\Delta\sigma$
- Opposite trend here because of $\Delta\sigma$-depth correlation

Comparison with Mw estimated by surface network

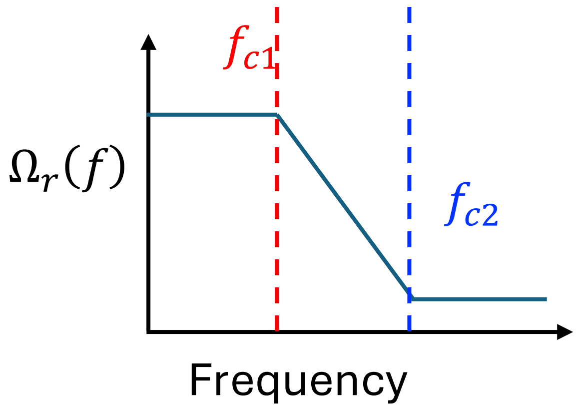


Spectral ratio (EGF) approach effectively avoids site-effect bias



$$\frac{U_1(f)}{U_2(f)} = \frac{Source_1(f)\ \cancel{Path(f)\ Site(f)\ Instrument(f)}}{Source_2(f)\ \cancel{Path(f)\ Site(f)\ Instrument(f)}}$$

$$\Omega_r(f) = \Omega_{0r}\left[\frac{1+\left(\frac{f}{f_{c1}}\right)^{\gamma n}}{1+\left(\frac{f}{f_{c2}}\right)^{\gamma n}}\right]^{1/\gamma}$$



However, an EGF can be difficult to find...

e.g., Need highly similar waveforms between target and EGF (cc>0.8)