13th Munich Earth Skience School
Environmental Seismology

03 March 2023

Intrinsic attenuation and scattering

Why coda Q does not tell the full story

Using seismic envelopes to separate the effects of source, site and path

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@trichter on GitHub and in the ObsPy forum

rf

Framework for calculation of receiver functions

Deconvolution, moveout, piercing points, ...

obspyh5

Quick & dirty IO of waveforms preserving metadata, HDF5

ObsPy

A Python Framework for Seismology

yam

dv/v with stretching technique

CLI

configuration in JSON file

easy definition and house-keeping of different correlation and stretching schemes

cc shorter than 1d possible

obspycsv

Quick & dirty IO of earthquake catalogs to CSV format

read EVENTTXT

flatten ObsPy catalogs to NumPy arrays

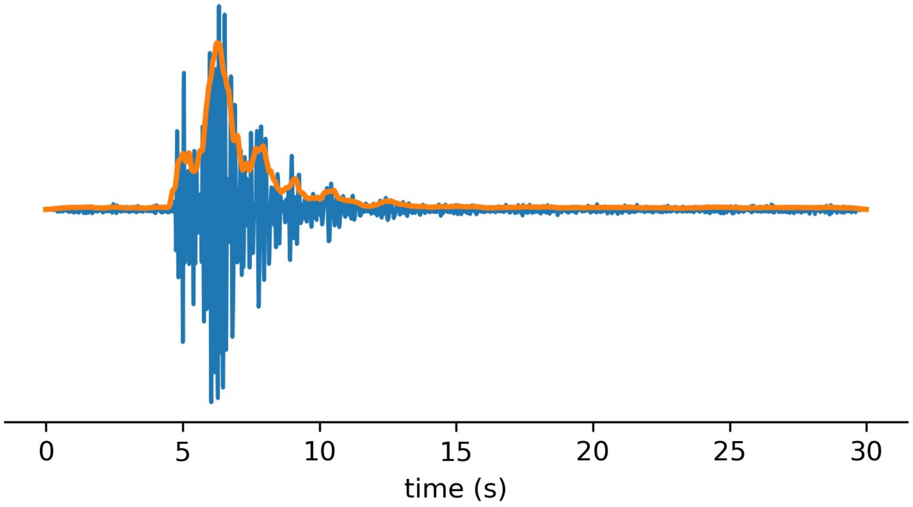
Qopen

Contents

Introduction

Envelope and radiative transfer

- Phase information in the coda cannot be modeled easily
- Only coda amplitude (resp. energy) is of interest
- Convert waveforms to envelopes (Hilbert transform)
- Transition of wave equation to equation of radiative transfer
- Opens field for Monte-Carlo particle simulations



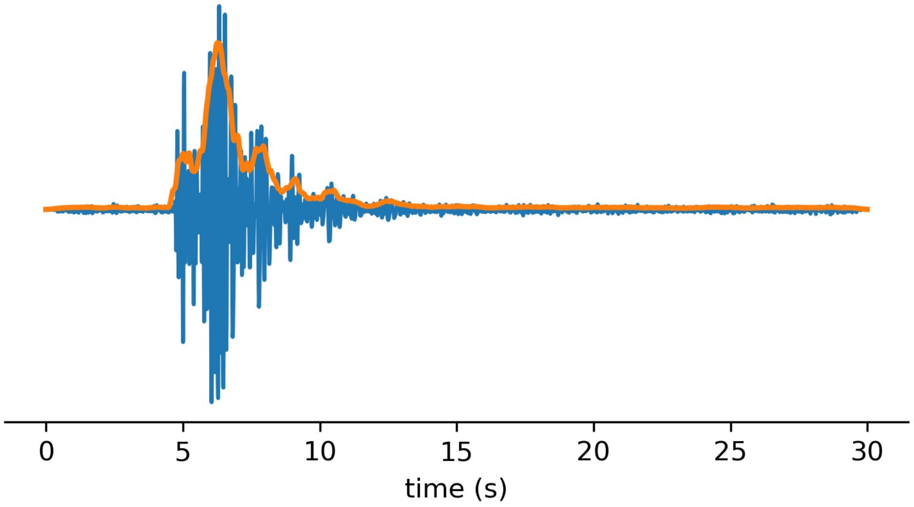
Intrinsic attenuation vs scattering, about Quality factors

Definition Quality factor

$$Q := 2\pi \frac{\text{total energy}}{\text{energy loss per cyclce}}$$

For direct wave:

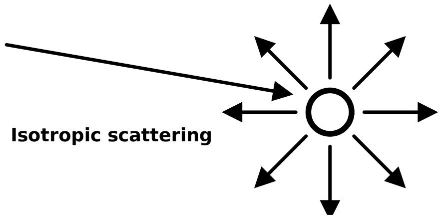
$$Q^{-1} = Q^{-1}_{\text{intr}} + Q^{-1}_{\text{scatt}}$$

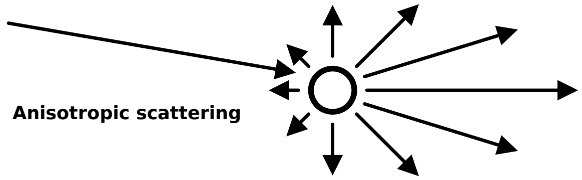


$$Q^{-1}_{\text{intr}} = \frac{v}{2\pi f l_{\text{a}}} \qquad Q^{-1}_{\text{scatt}} = \frac{v}{2\pi f l}$$

Isotropic vs nonisotropic scattering – transport mean free path

- Mean free path l_0: Length in which 63% of the wave energy is scattered, mean length between two scattering events
- Transport mean free path l^*: Length in which the propagation direction of 63% of the wave energy becomes independent from its original propagation direction—the wave "forgets" its initial direction due to scattering





$$l^* = l_0 \quad t^* = t_0$$

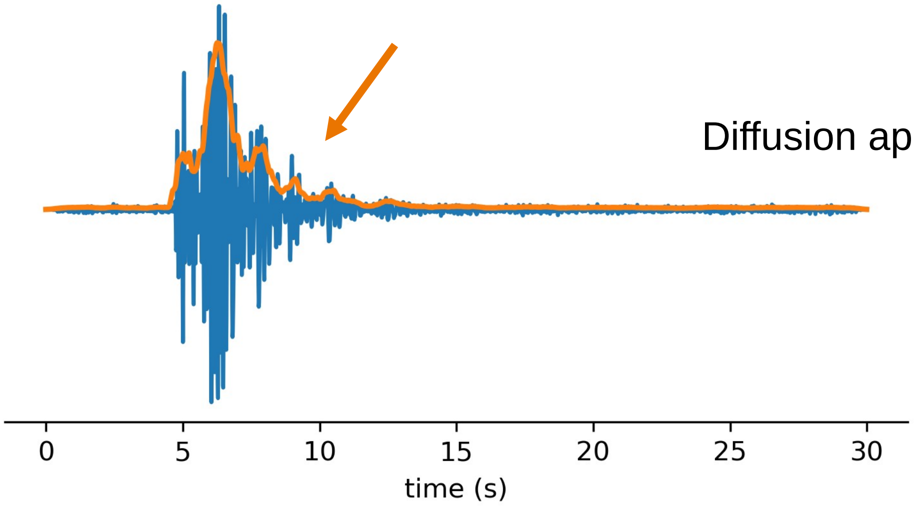
$$l^* > l_0 \quad t^* > t_0$$

$$t_0 = \frac{l_0}{v_s} \qquad t^* = \frac{l^*}{v_s}$$

What about coda Q?

Obviously coda Q is not simply the sum of intrinsic and scattering Q as for the direct wave.

The interpretation of coda Q depends on the scattering regime in the coda!



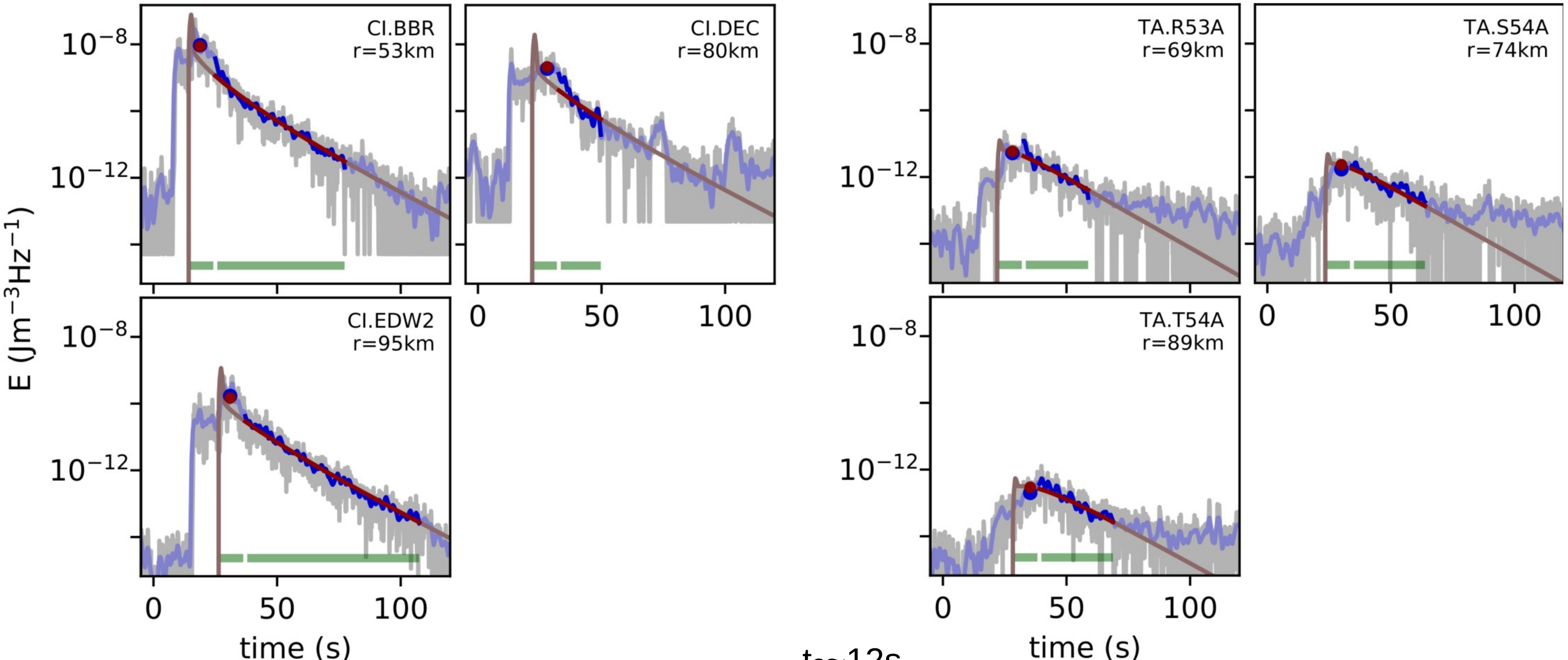
Single scattering approximation:

$$Q_{\mathrm{coda}}^{-1} = Q_{\mathrm{intr}}^{-1} + Q_{\mathrm{scatt}}^{-1}$$

Diffusion approximation:

$$Q_{\mathrm{coda}}^{-1} = Q_{\mathrm{intr}}^{-1}$$

Scattering regime in the coda – transport mean free time



ta~12s

t*~40s => single and multiple scattering

$$Q_{\mathrm{coda}}^{-1} = Q_{\mathrm{intr}}^{-1} + Q_{\mathrm{scatt}}^{-1} \ ?$$

t*~7s => diffusion approximation valid

$$Q_{\mathrm{coda}}^{-1} = Q_{\mathrm{intr}}^{-1}$$

=> scattering regime can be determined with the shape of the envelope

Motivation

Kernels for tomography of coda Q and dv/v observations

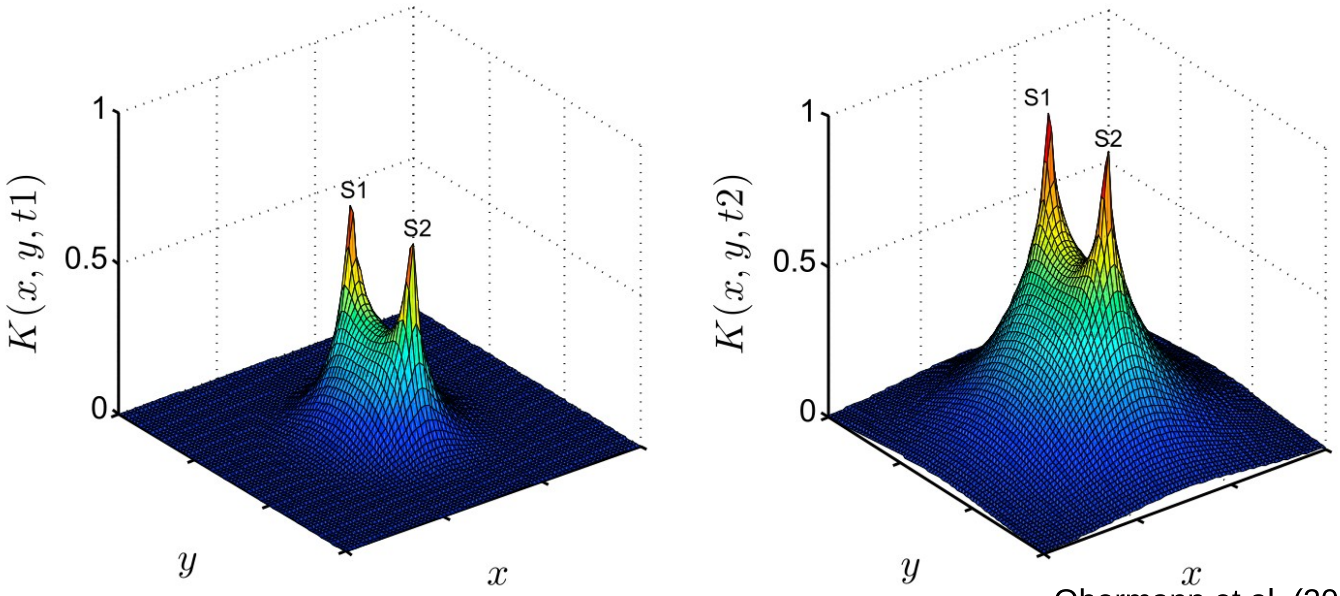
Observations of relative velocity change (dv/v) often use the coda

Coda Q can be determined for each station-earthquake pair (similar to first arrivals) and is therefore predestined for tomography.

=> Need for travel time kernel of the coda

=> Estimate of transport mean free path can confine the shape of the kernel

(and check validity of assumptions leading to kernel estimate)

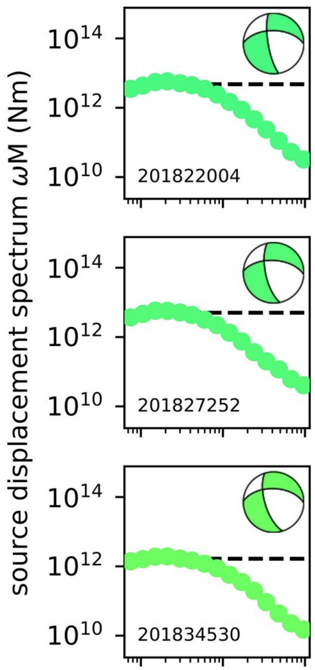


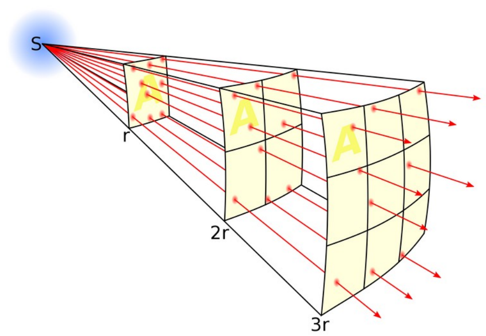
Obermann et al. (2014)

Source, Site, Path

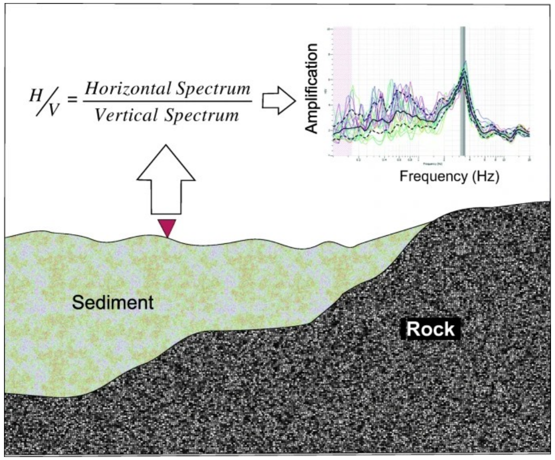
Seismogram is convolution of

source function x propagation filter x site response





- Geometrical spreading
- Attenuation
- Scattering
- Reflections, conversions, ...



Yilmaz al. 2021

- H/V
- Vs30
- kappa

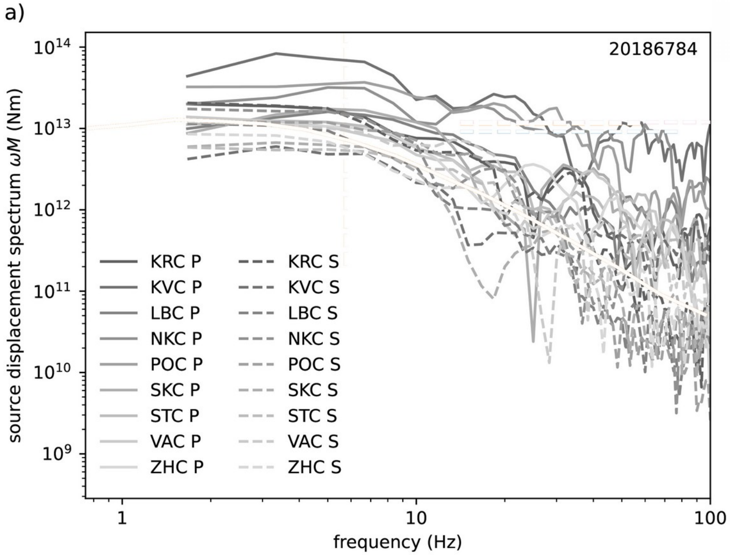
- Moment tensor
- Moment rate function / source displacement spectrum
- Slip distribution

Conventional method to calculate source spectrum

- Take spectra of waveforms around onset
- Correct for geometrical spreading and radiation pattern
- Optimize seismic moment M0, corner freq fc and attenuation Q

$$\Omega(f) = \frac{\Omega_0 e^{-(\pi f t / Q)}}{\left[1 + (f / f_c)^{\gamma n}\right]^{1/\gamma}}$$

Abercrombie 1995



- Tradeoff between Q and fc
- Q can be a function of frequency

Spectrum can be used to calculate stress drop.

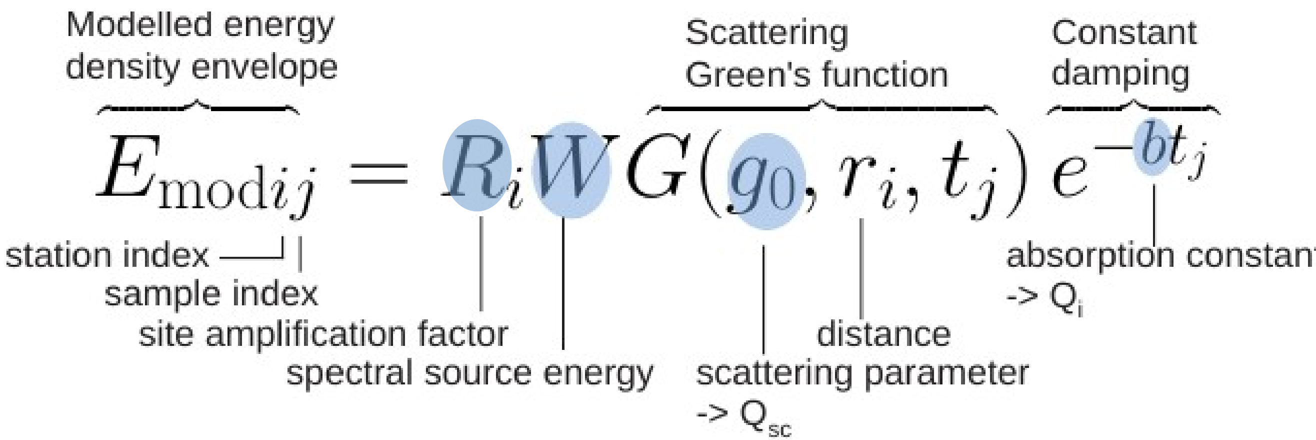
Self-similarity of differently sized earthquakes?

Qopen method

Separation of intrinsic and scattering
Q by envel***ope*** inversio***n***

Idea: Intrinsic attenuation and scattering strength can be separated and quantified with the temporal and spatial shape of the envelope!

Qopen method for shear waves



- G accounts for geometrical spreading and scattering => here G is analytic
- Compare with observed envelopes of S wave + coda
- Invert for Ri, W, g0 and b (optimization in g0 + least squares log fit)
- Repeat the steps for all frequency bands
- Repeat with different earthquakes

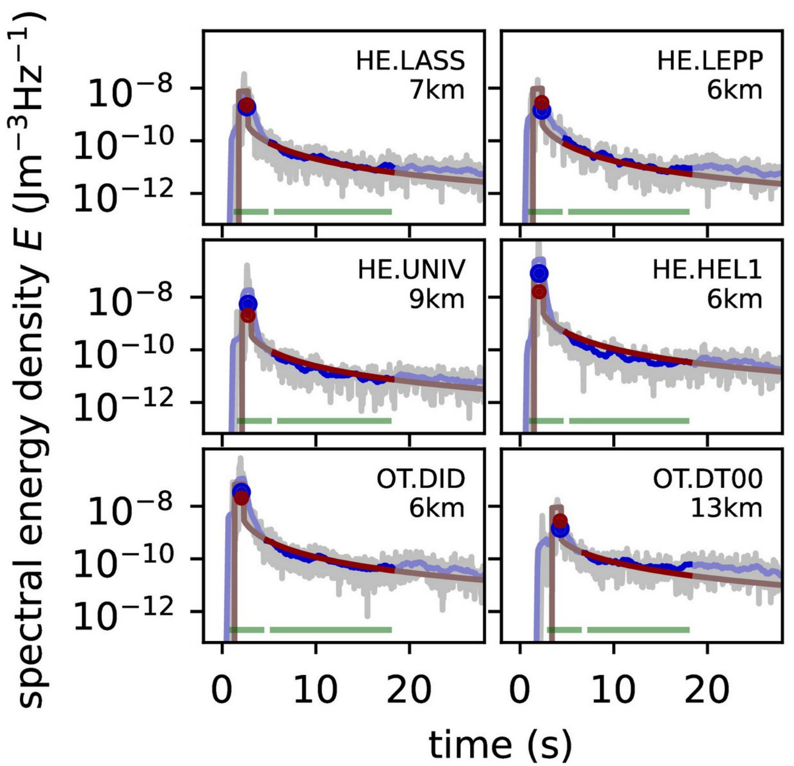
- Assumptions:
  - homogeneous half space
  - point source (small EQ)
  - moment tensor ignored

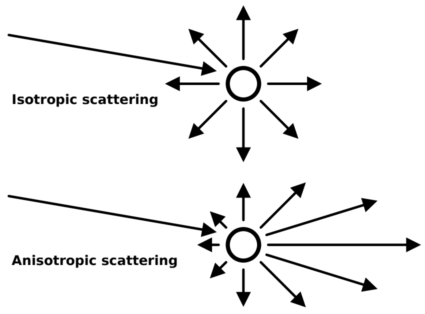
Sens-Schönfelder & Wegler 2006, Eulenfeld & Wegler 2016

Imprint of anisotropic scattering

- Qopen assumes isotropic scattering, this is often a bad assumption
- In an anisotropic scattering environment the scattering strength estimated with Qopen relates to the transport mean free path (Gaebler et al. 2015)
- Model cannot predict correct envelope directly after the S body wave

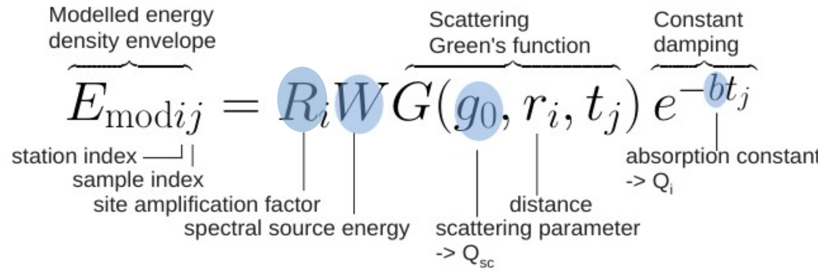
  => In the inversion the envelope inside the direct wave window needs to be averaged





Estimation of site response and source spectra

$$E_{\text{mod}ij} = R_i W G(g_0, r_i, t_j)\, e^{-b t_j}$$

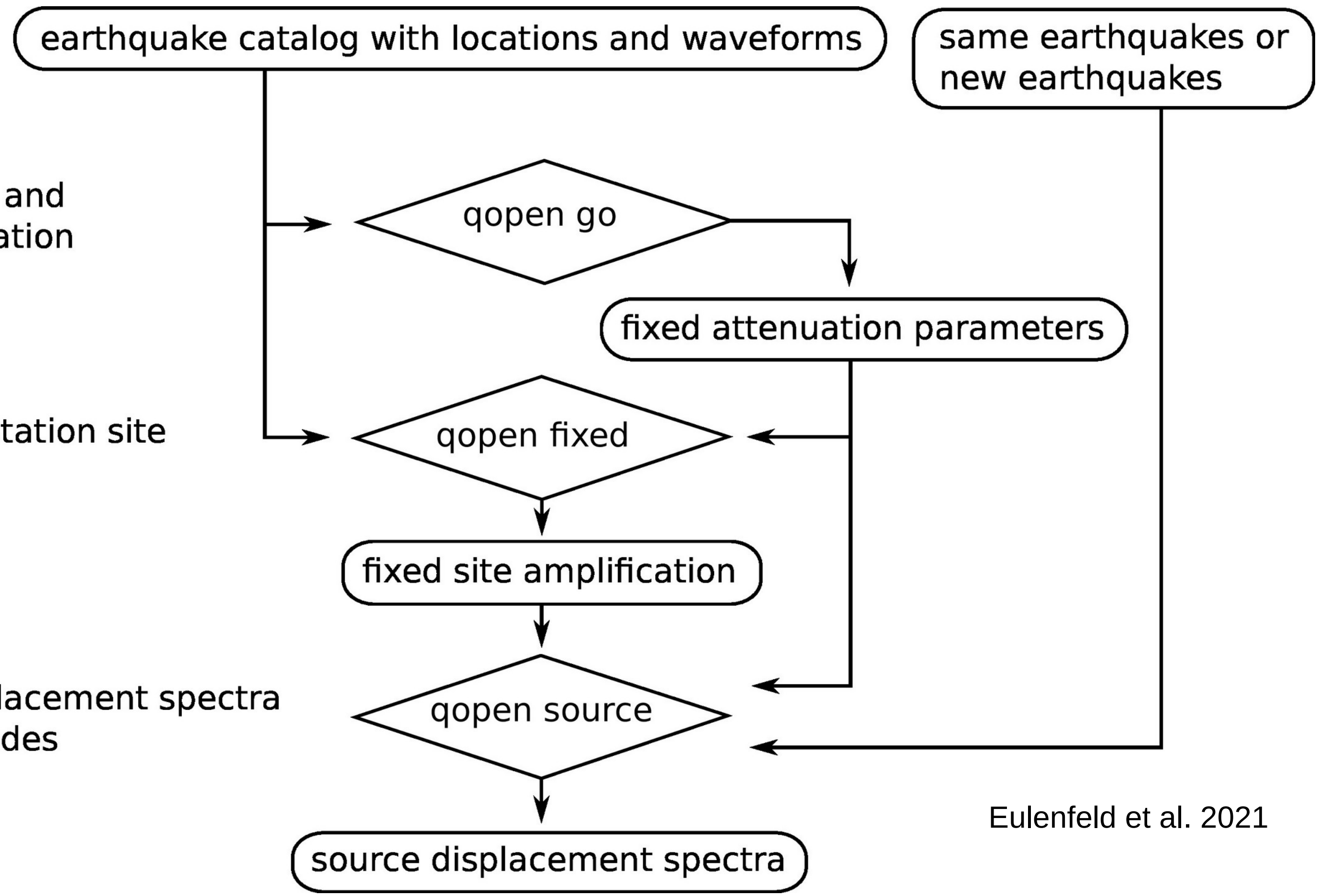


Setup

Estimate intrinsic and scattering attenuation

Refine and align station site amplification

Calculate source displacement spectra and moment magnitudes



Eulenfeld et al. 2021

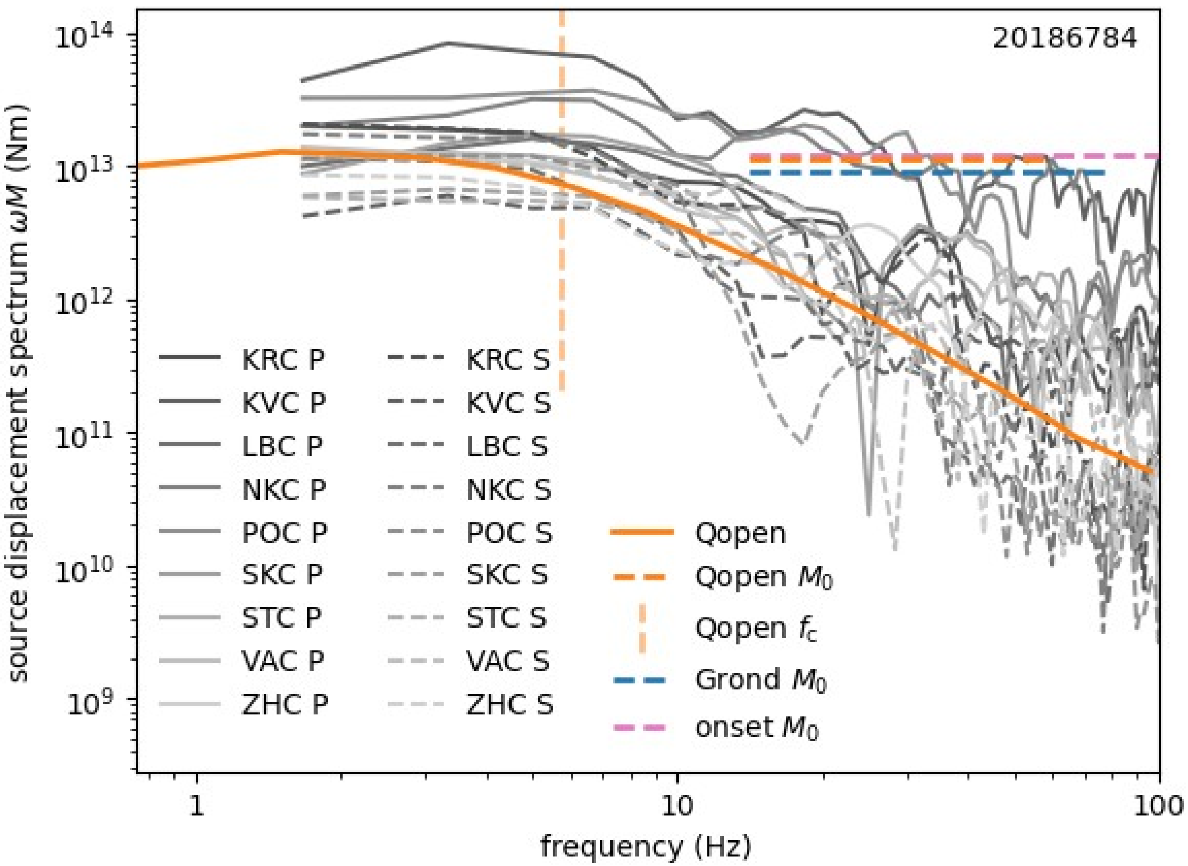
Source spectra and seismic moments

Qopen inversion
vs Grond moment tensor inversion
vs spectra from Fourier transform
of body waves

Abercrombie 1995

$$\omega M(f) = M_0 \left(1+\left(\frac{f}{f_c}\right)^{\gamma n}\right)^{-\frac{1}{\gamma}}$$

- $\omega M(f)$: source displacement spectrum
- M_0: seismic moment
- f_c: corner frequency
- γ: corner sharpness
- n: high freqcuency fall-off (2 for omega-square model)



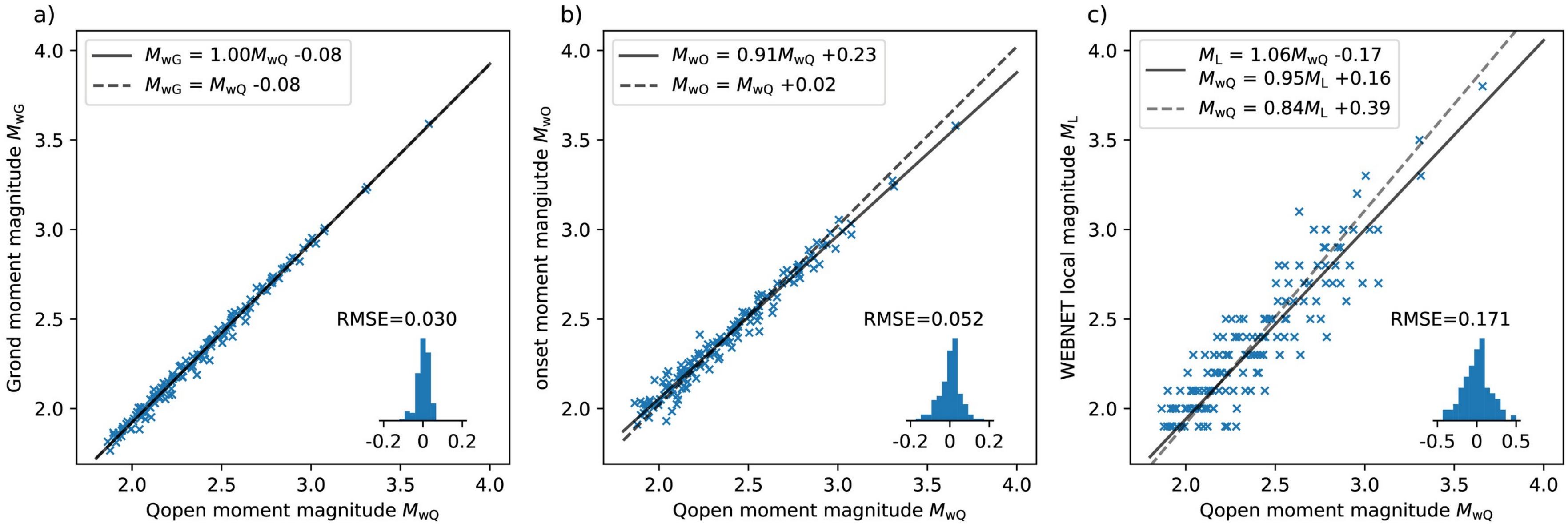
Eulenfeld et al. 2021

Czech 2018 EQ swarm – moment magnitudes

Qopen inversion

vs Grond moment tensor inversion

vs spectra from Fourier transform of body waves



=> Robust estimation of moment magnitudes for small earthquakes

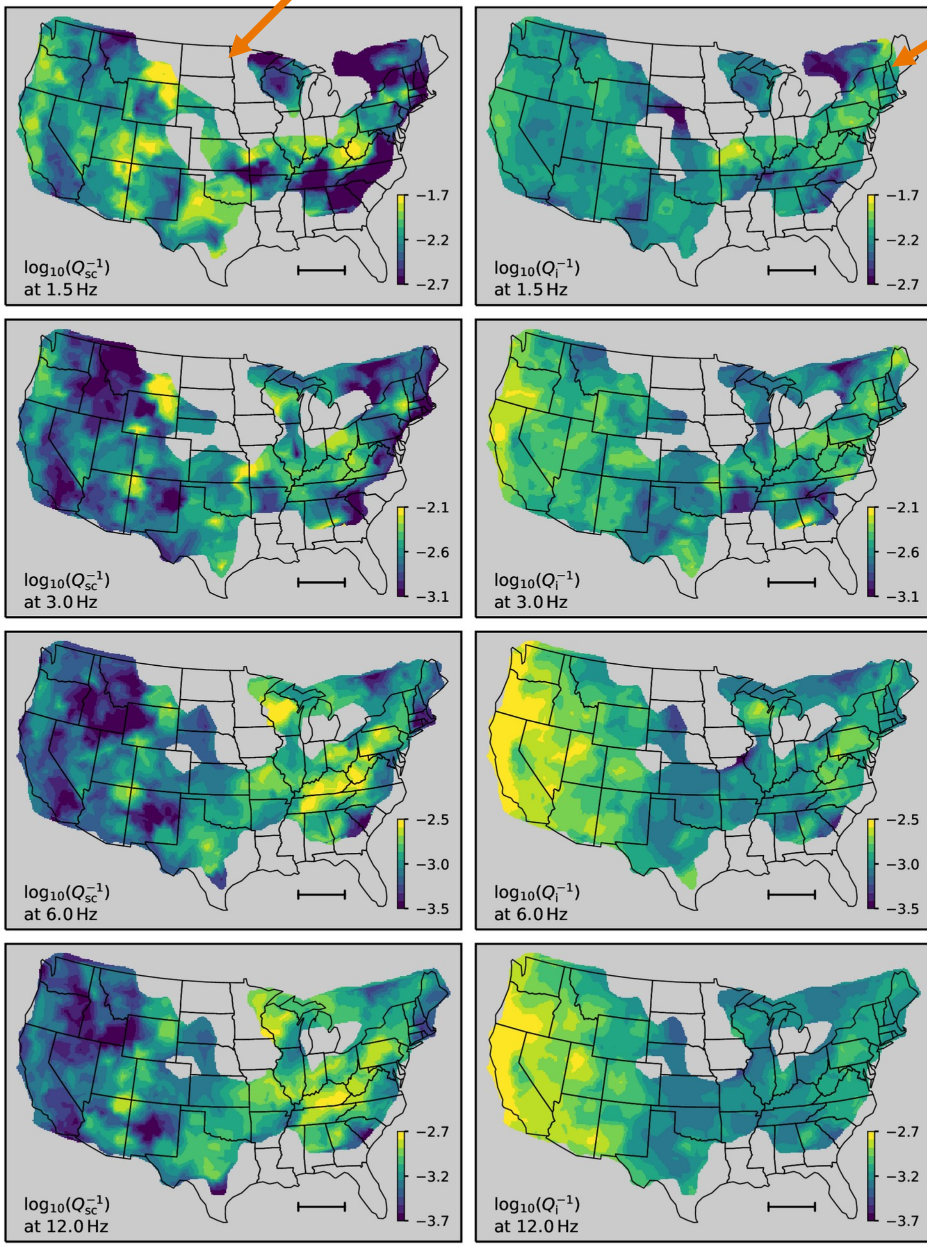
=> Can be used in high scattering environments with a lack of impulsive onsets

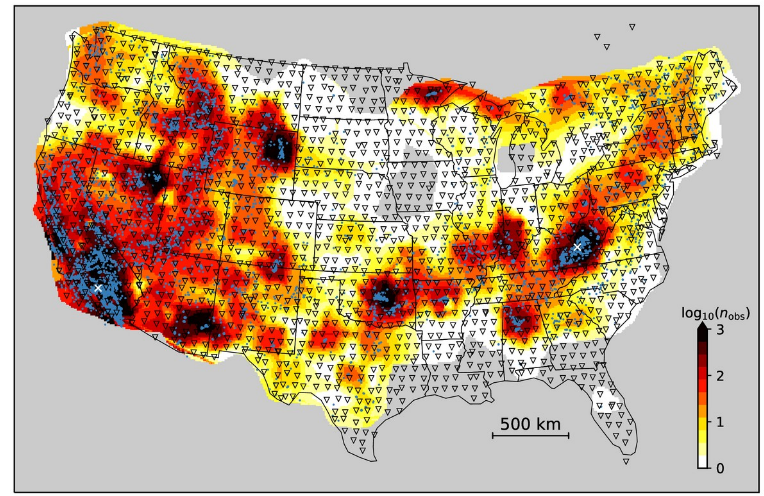
Code available at github.com/trichter/qopen

Eulenfeld et al. 2021

Applications

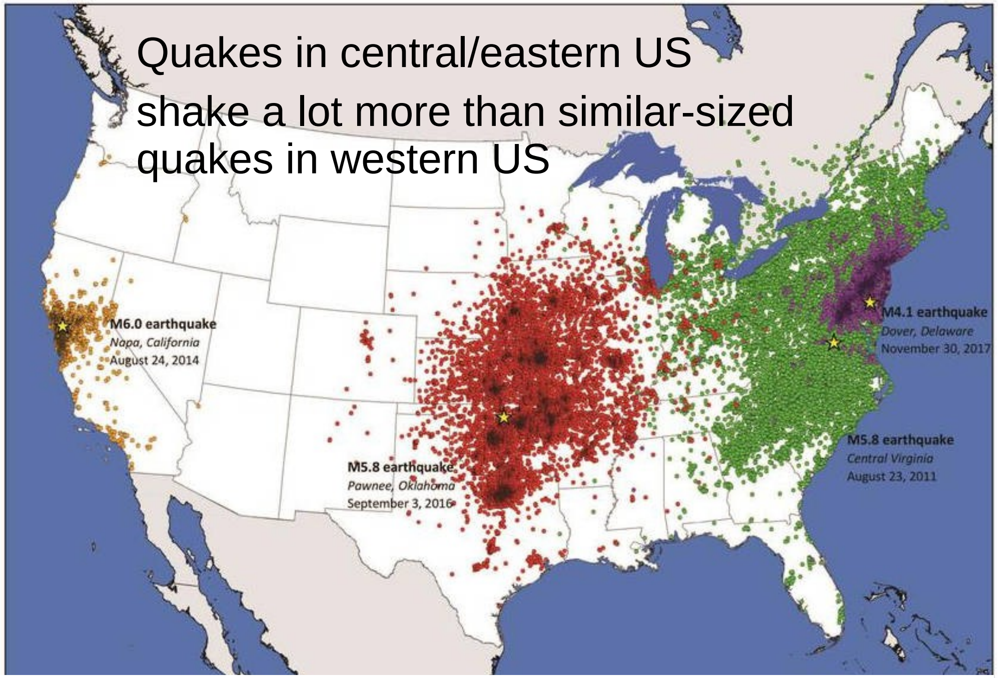
USArray – scattering strength (left) versus intrinsic attenuation (right)

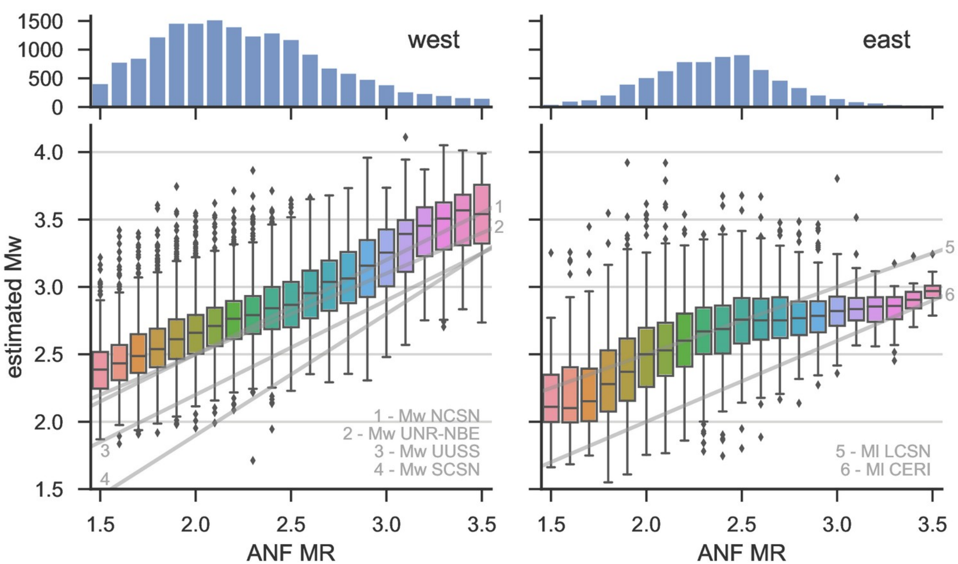


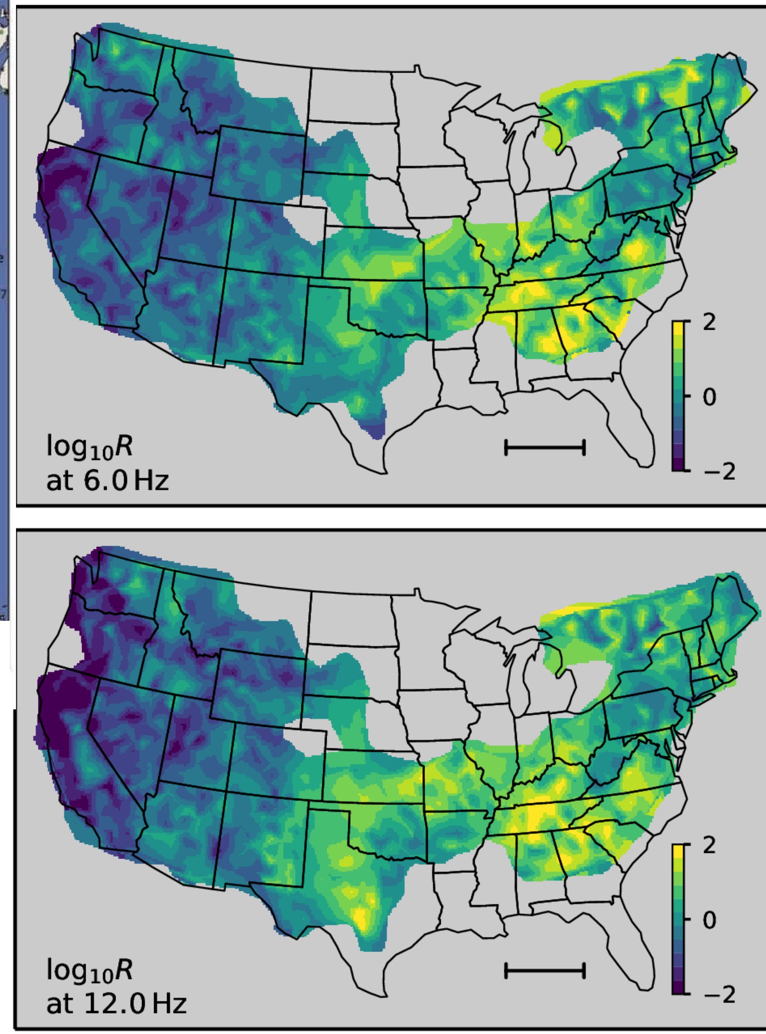


Eulenfeld & Wegler 2017

Application USArray – high freq site amplification, magnitudes



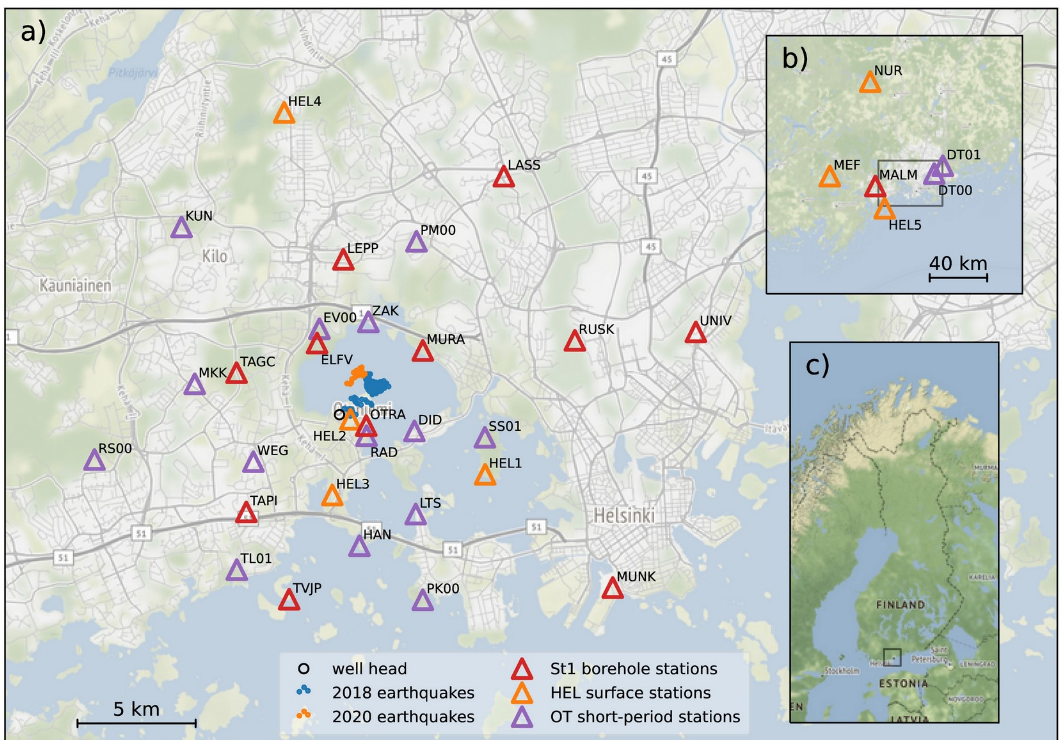


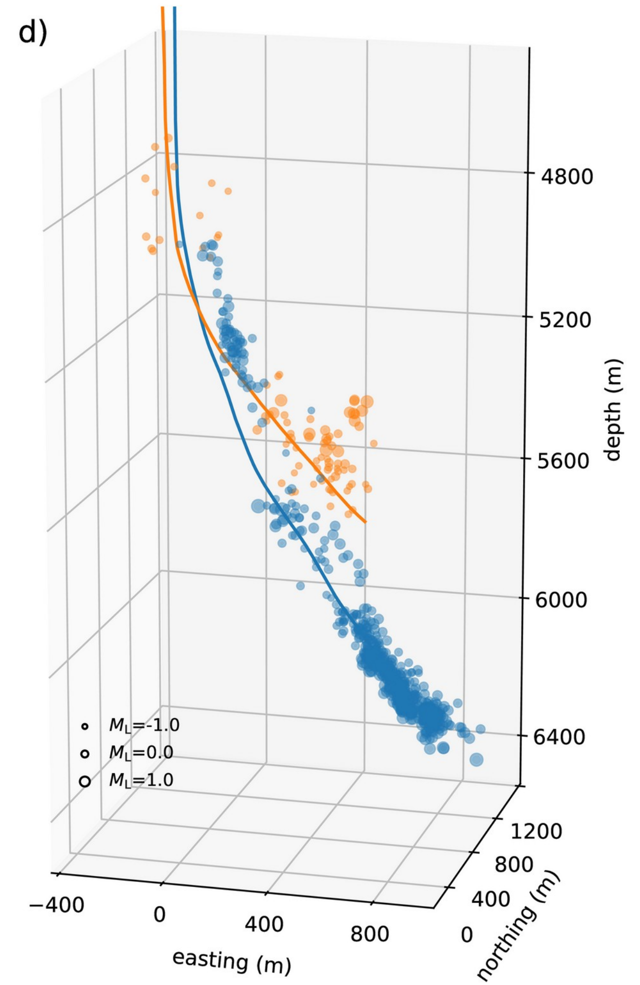


Eulenfeld & Wegler 2017

Helsinki 2018 and 2020 stimulation

- 2018 stimulation induced ~450 earthquakes (blue) with 0<=ML<=1.8,
  90 MPa peak well-head pressure,
  18 000 m3 volume
- 2020 stimulation induced ~25 earthquakes (orange) with 0<=ML<=1.8
  70 MPa, 2 900 m3 volume

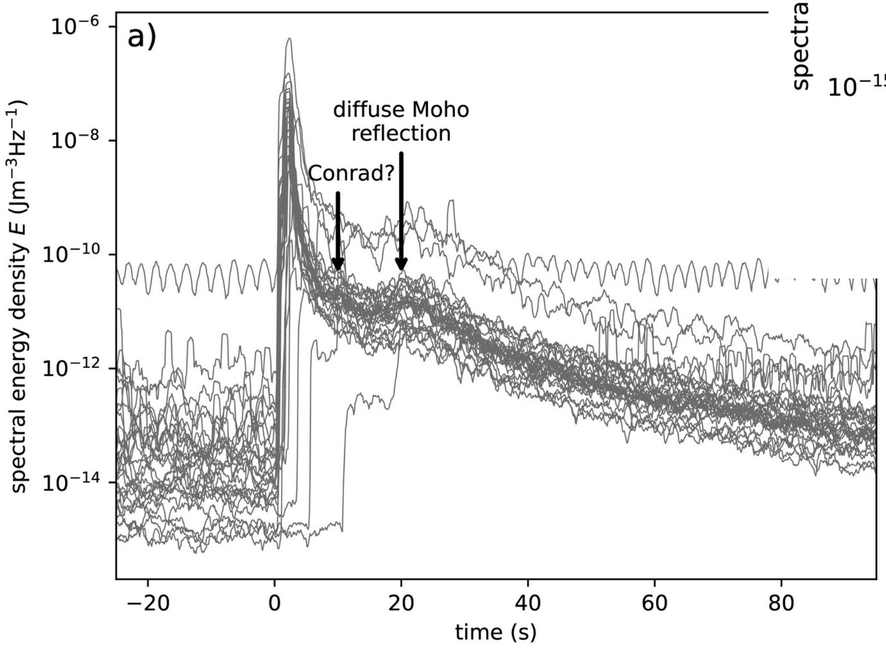


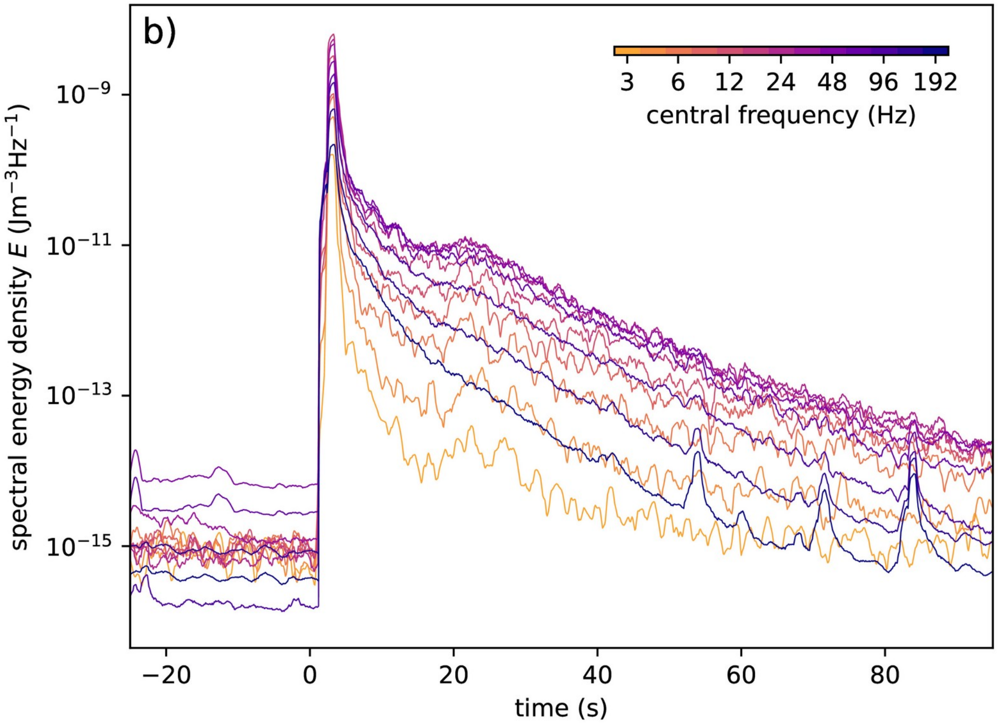


Eulenfeld et al. 2023

Helsinki 2018 stimulation – example envelopes for 1 event

All stations 8 Hz – 16 Hz

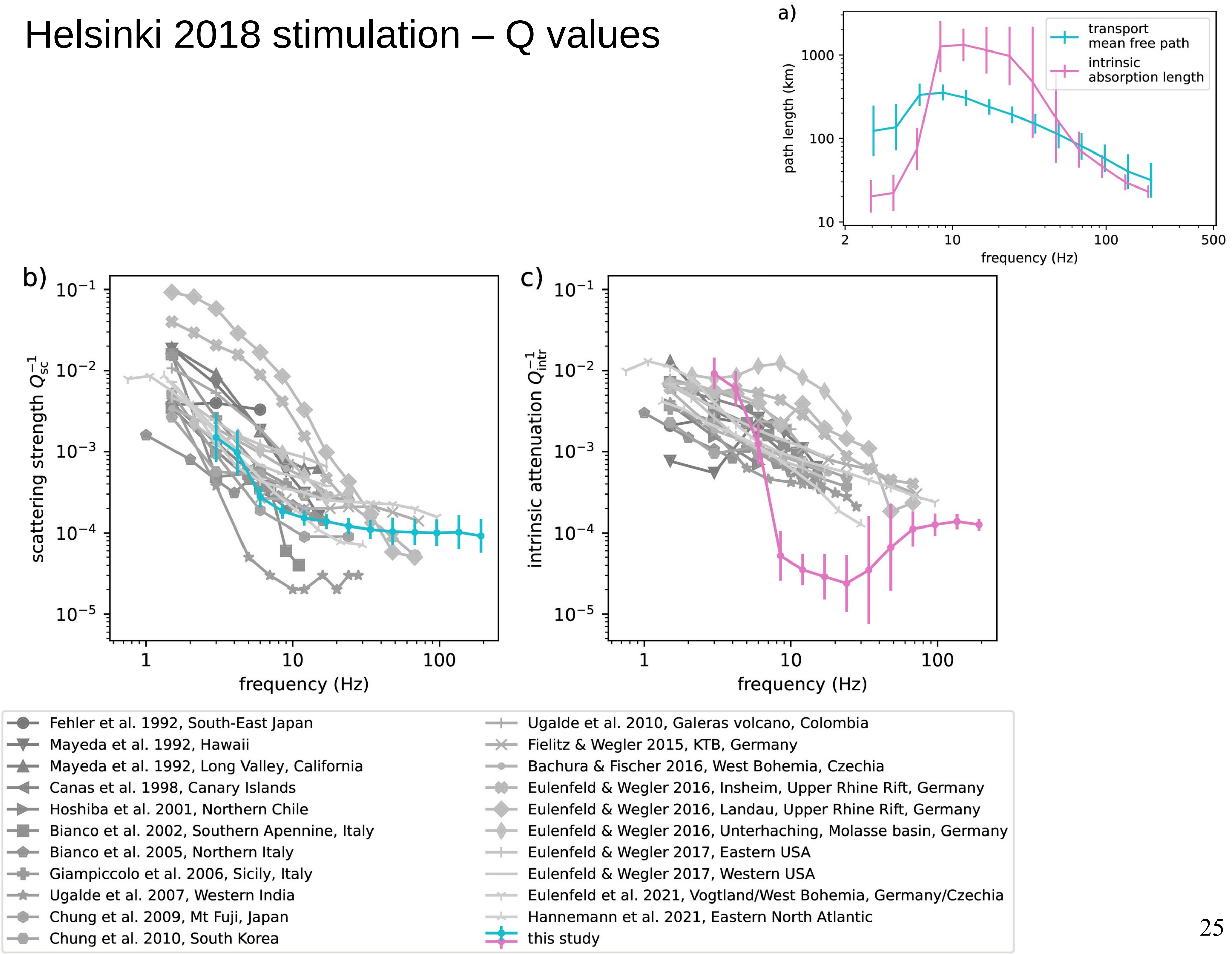




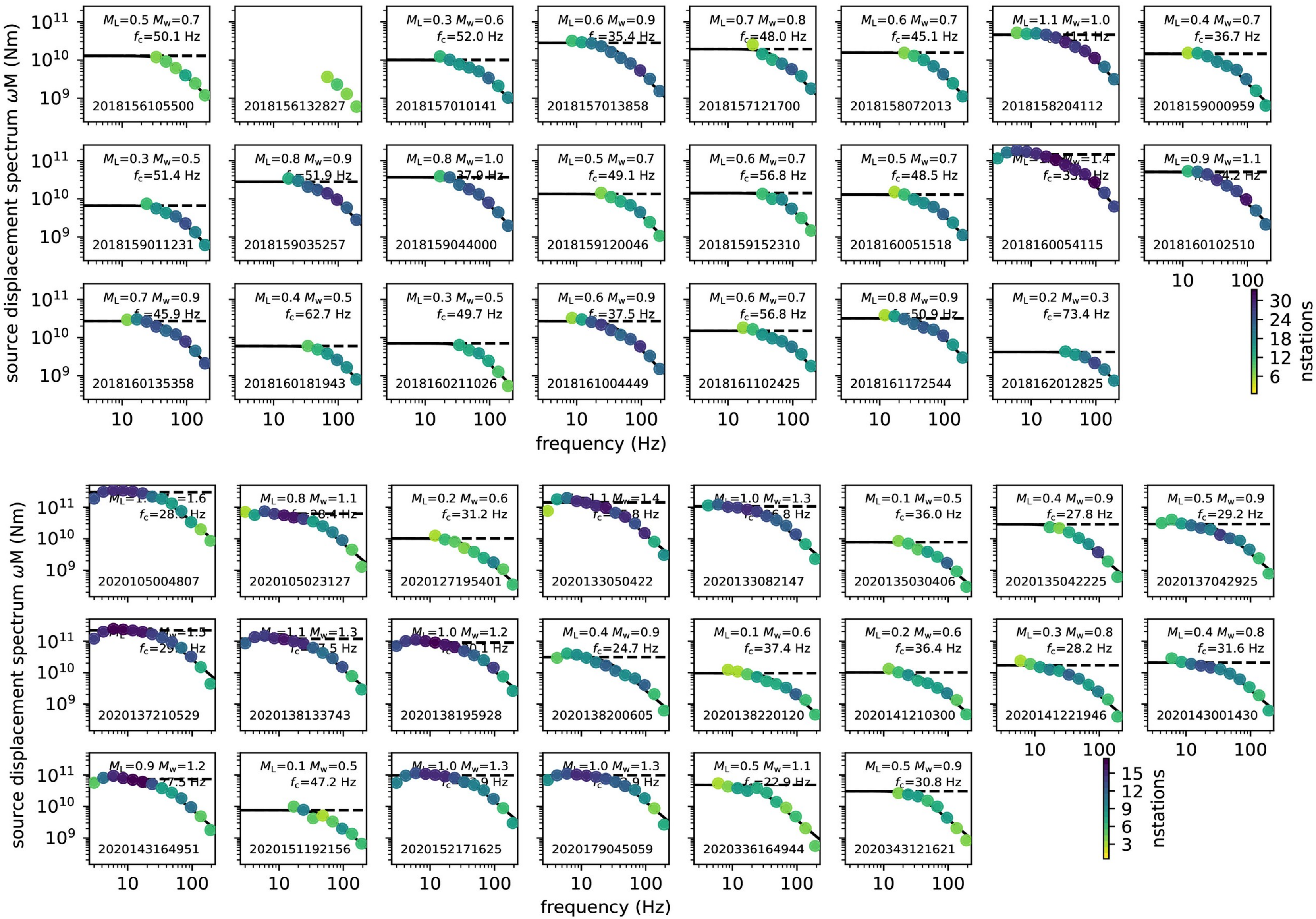
Single station,
different frequency bands

Eulenfeld et al. 2023

Helsinki 2018 stimulation – Q values

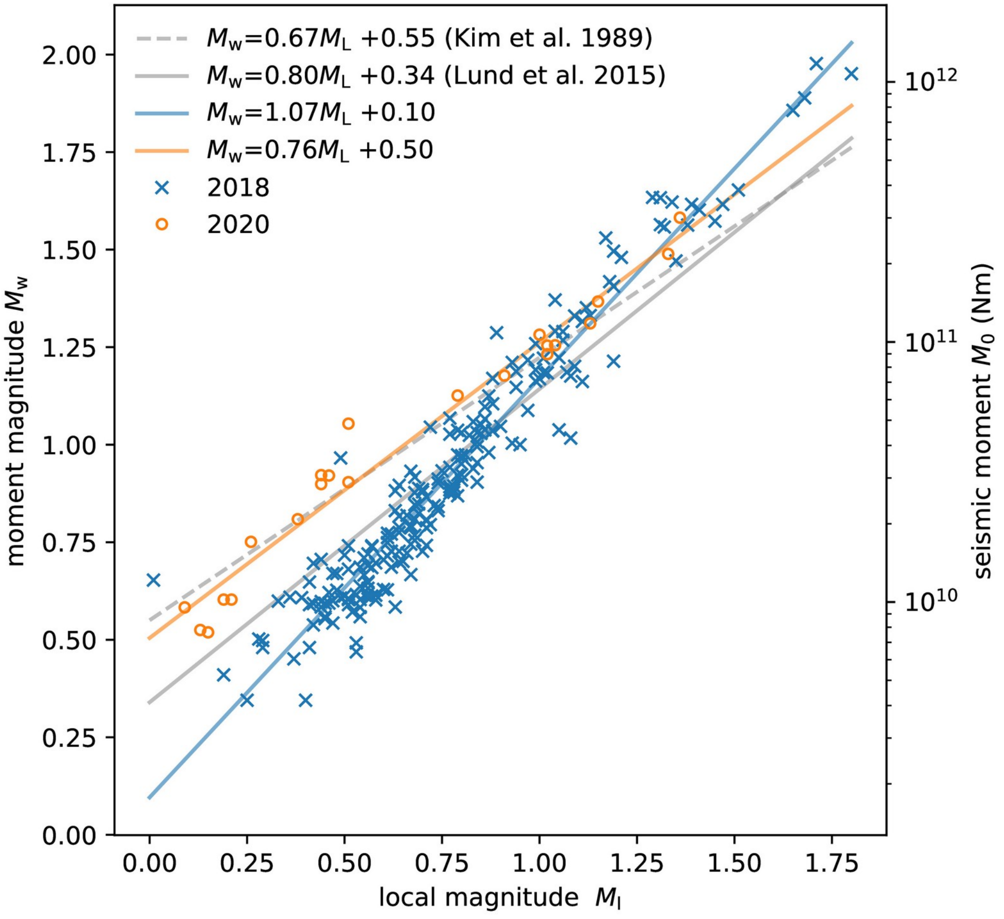


Helsinki 2018/2020 – source displacement spectra



Helsinki 2018/2020 – moment magnitudes

- Mw versus ML relationship for the two stimulations
- 2020 events have systematically smaller ML for same Mw compared to 2018 events

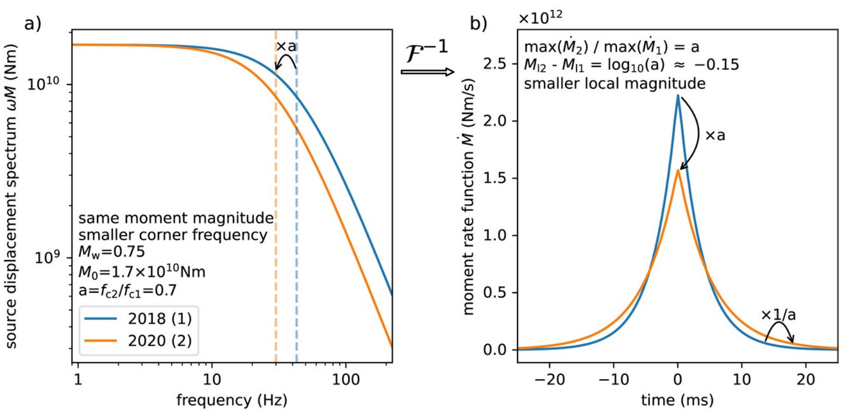


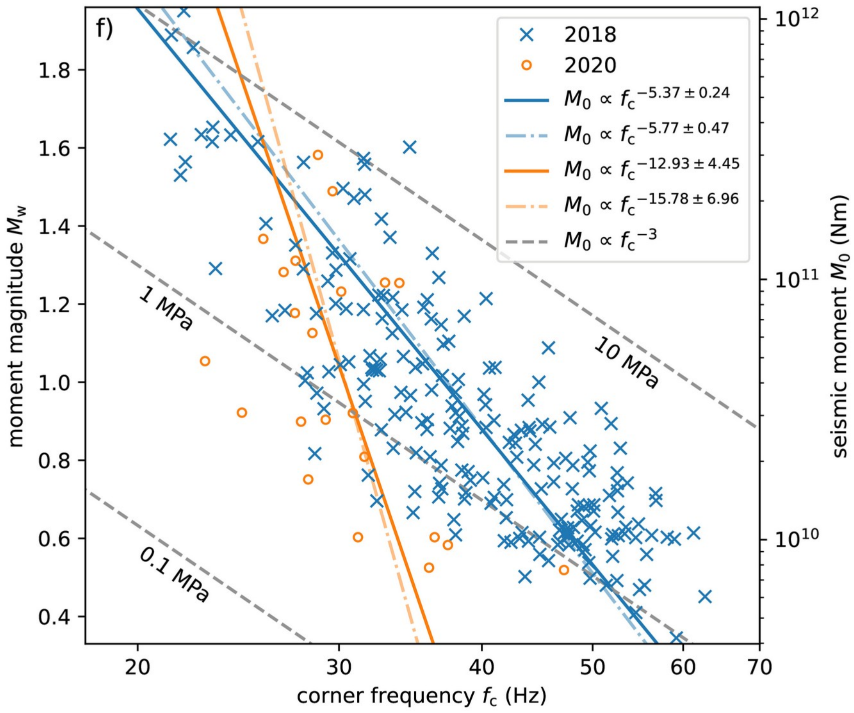
Eulenfeld et al. 2023

Helsinki 2018/2020 – source parameters

Eulenfeld et al. 2023

- Mw versus fc relationship for the two stimulations
- 2020 events have systematically smaller fc for same Mw compared to 2018 events
- Consistent with Mw-ML relationship





Summary

- Quickly estimate scattering and intrinsic attenuation parameters for your local data set
- Estimation of site responses (relative)
- Robust determination of moment magnitude and other source parameters

Thanks!

References

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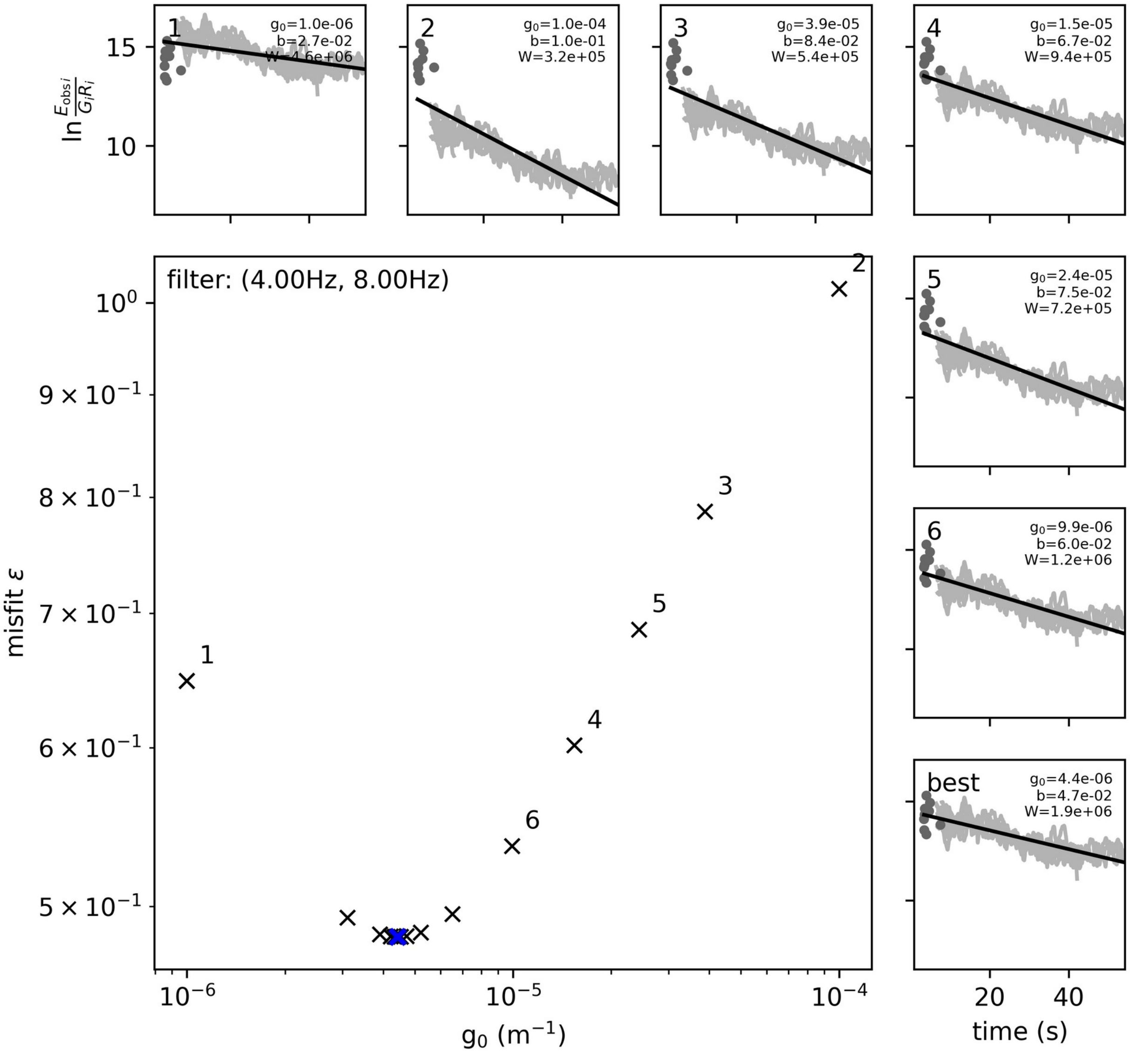
Qopen optimization



Eulenfeld & Wegler 2016

Helsinki 2018 stimulation – envelope fits example 16 – 32 Hz