Exploring the Evolution and Source Properties of Injection-Induced Seismicity in Northern Oklahoma Using a Large-*n* Seismic Array

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Overview

- Historical Seismicity in Oklahoma
- LASSO array
- Spatio-temporal evolution of recorded seismicity
- Source properties

- Click on hyperlinks (✚➜) for further information
  - ✚ opens URL with supplementary information
  - ➜ jumps to page in document with further information like detailed methods
  - ← jumps back from method section

Historical Seismicity in Oklahoma

- 74 M3+ earthquakes 1980 - 2010
- 1816 M3+ earthquakes 2010 - 2016
- Associated with wastewater disposal operations ✚
- Installation of LASSO array ✚ 04/2016 - 05/2016

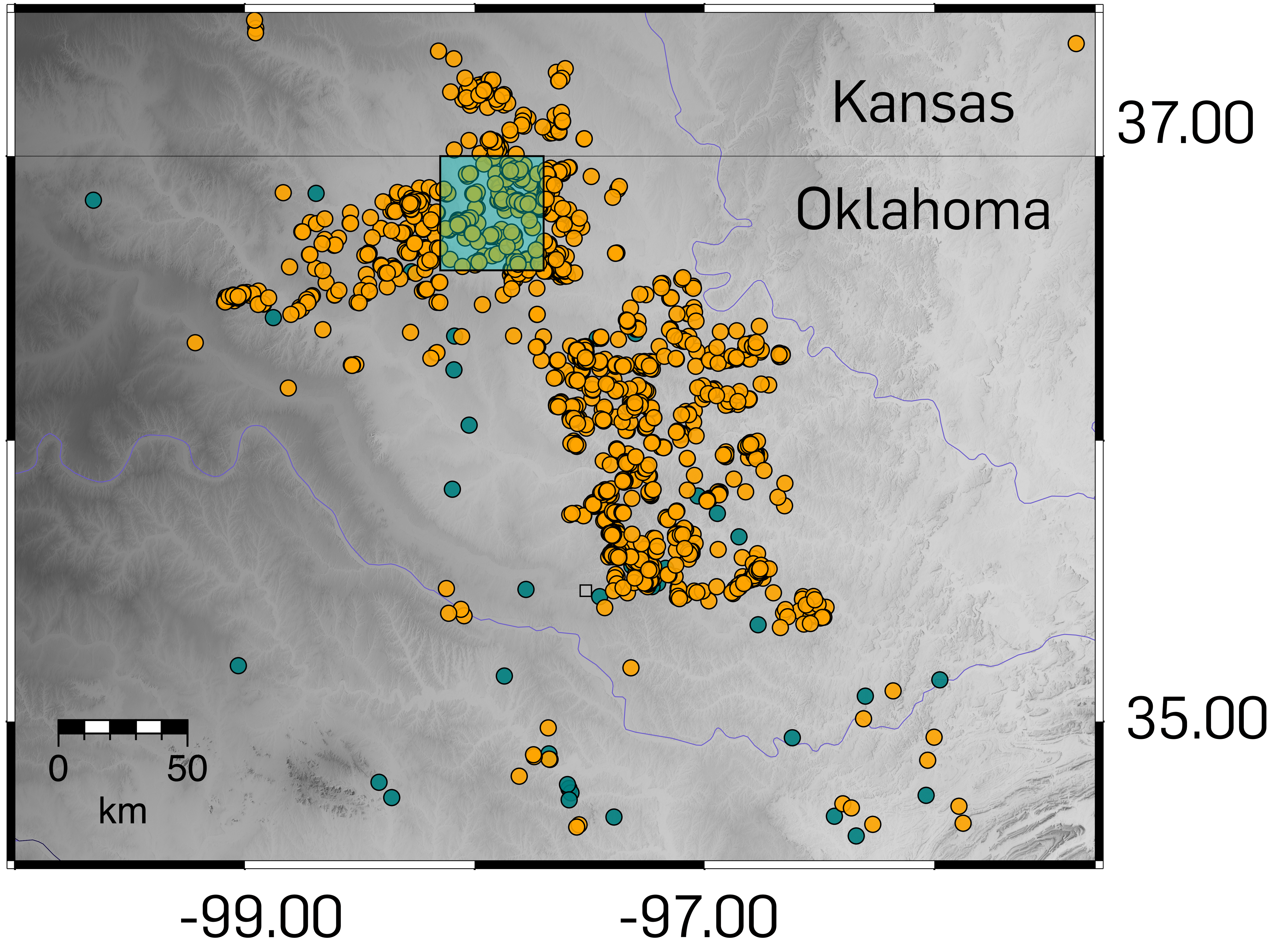


Figure 1: Location of the LASSO array. Teal / orange denote M3+ earthquakes from 1980 - 2010 and 2010 - 2016, respectively. Catalog from USGS ✚.

LASSO

- LArge-*n* Seismic Survey in Oklahoma (LASSO)
- >1800 stations (vertical, 500 Hz) for ~1 month (04/2016 - 05/2016)
- Area of wastewater disposal
- >1800 earthquakes detected
- Mix of strike-slip and normal faulting

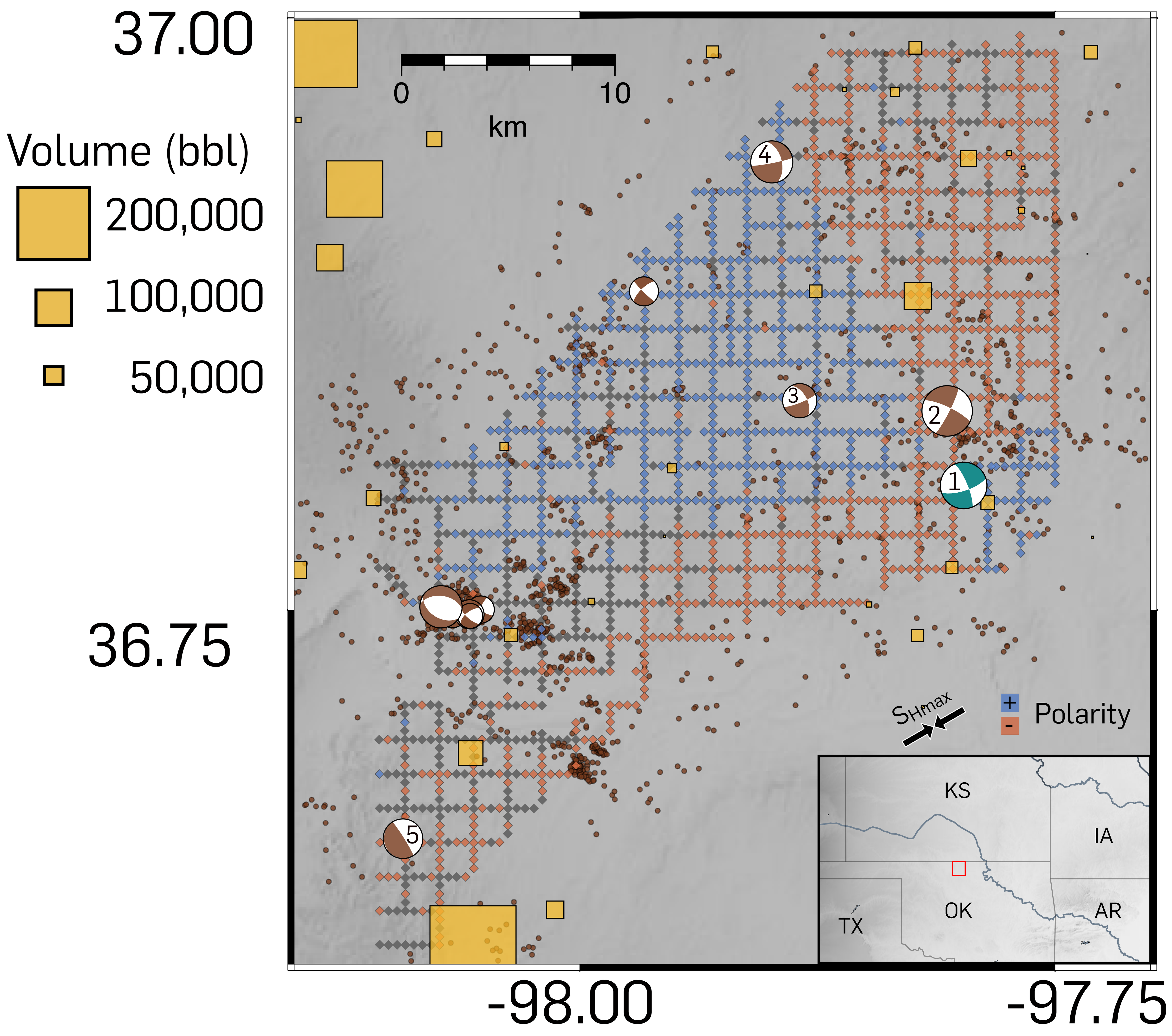


Figure 2: Overview of the LASSO array. Diamonds denote deployed stations, brown circles the detected seismicity, and rectangles show the location of the injection wells scaled according to cumulative injection volume during the deployment. Stations (nodes) are color coded according to the P-wave polarity (blue - positive, red - negative, grey - undefined) of the teal colored focal mechanism. Numbered earthquakes are referred to below.

Spatio-temporal Evolution of Seismicity

- Earthquakes mostly deeper than injection depths
- The majority of earthquakes occur in the basement

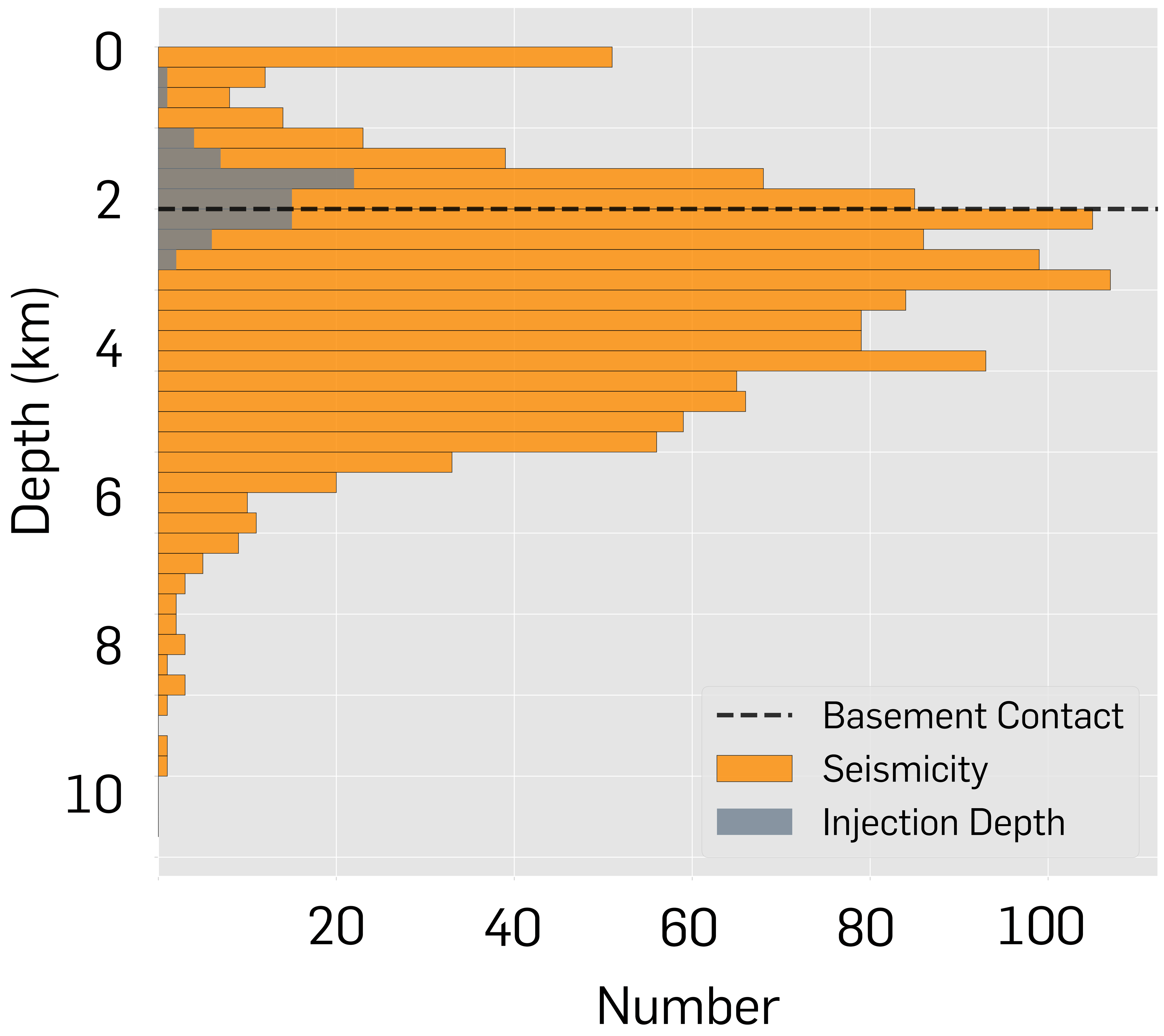


Figure 3: Base of injection wells and earthquake occurence with depth in 0.25 km bins. The basement contact varies in this area and is only approximated here.

Spatio-temporal Evolution of Seismicity

- Development of local magnitude
  - Decay of peak ground displacement amplitude (A) with distance (R) of Wood-Anderson Seismometer +
- Ml = log A + x0 • log r + x1 • r + x2

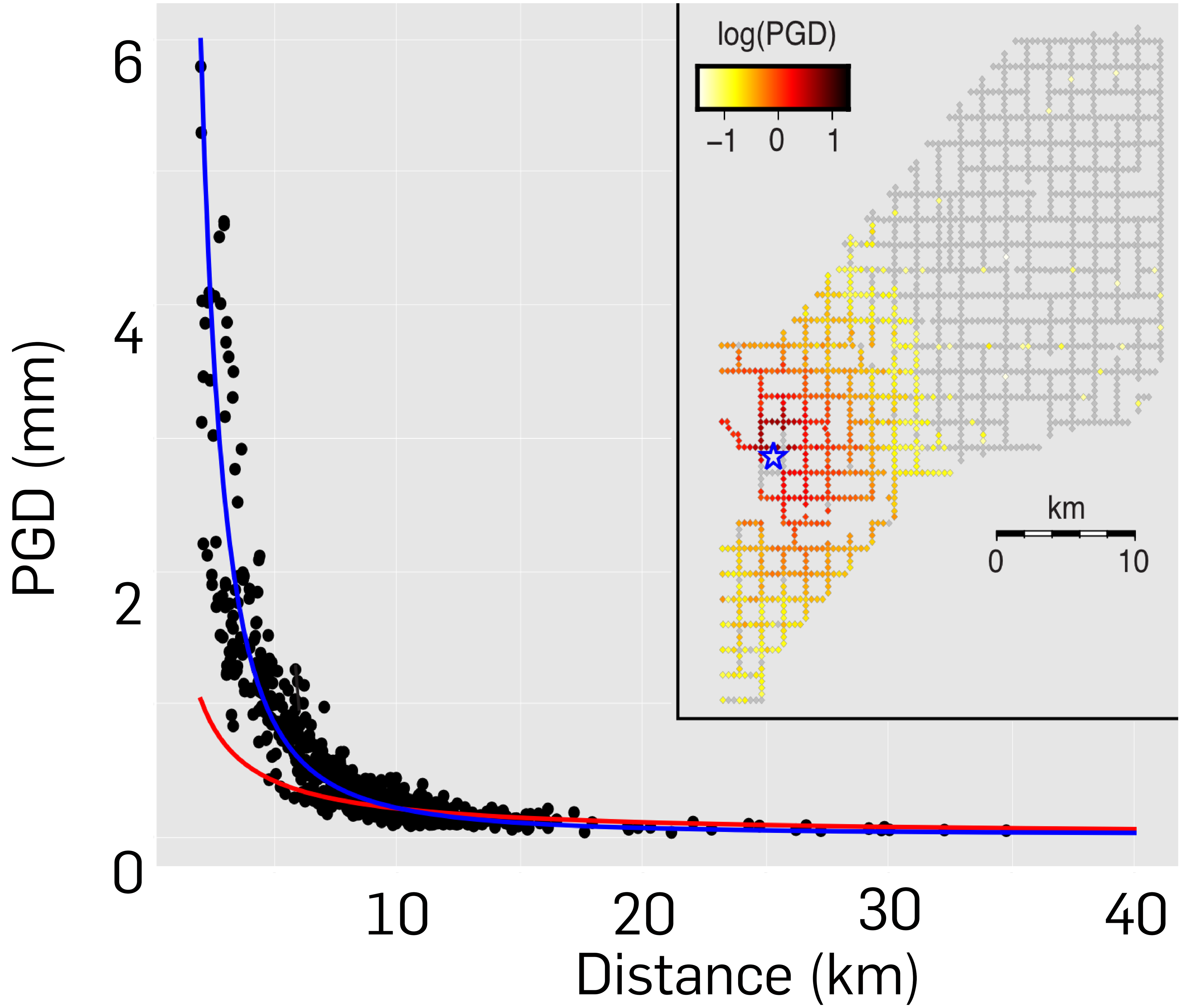


Figure 4: Wood-Anderson peak ground displacements (PGD) vs. distance on LASSO stations with fits to OGS equation (red line) and equation derived in this study (blue line) for an M_l 1.54 earthquake. Inset shows the spatial distribution of stations and their amplitudes. Gray stations do not contribute to the estimate. Blue star shows the earthquake location.

Spatio-temporal Evolution of Seismicity

- Development of local magnitude
  - 1156 earthquakes with M_l
  - b-value ~1
  - Magnitude of completeness Mc ~1

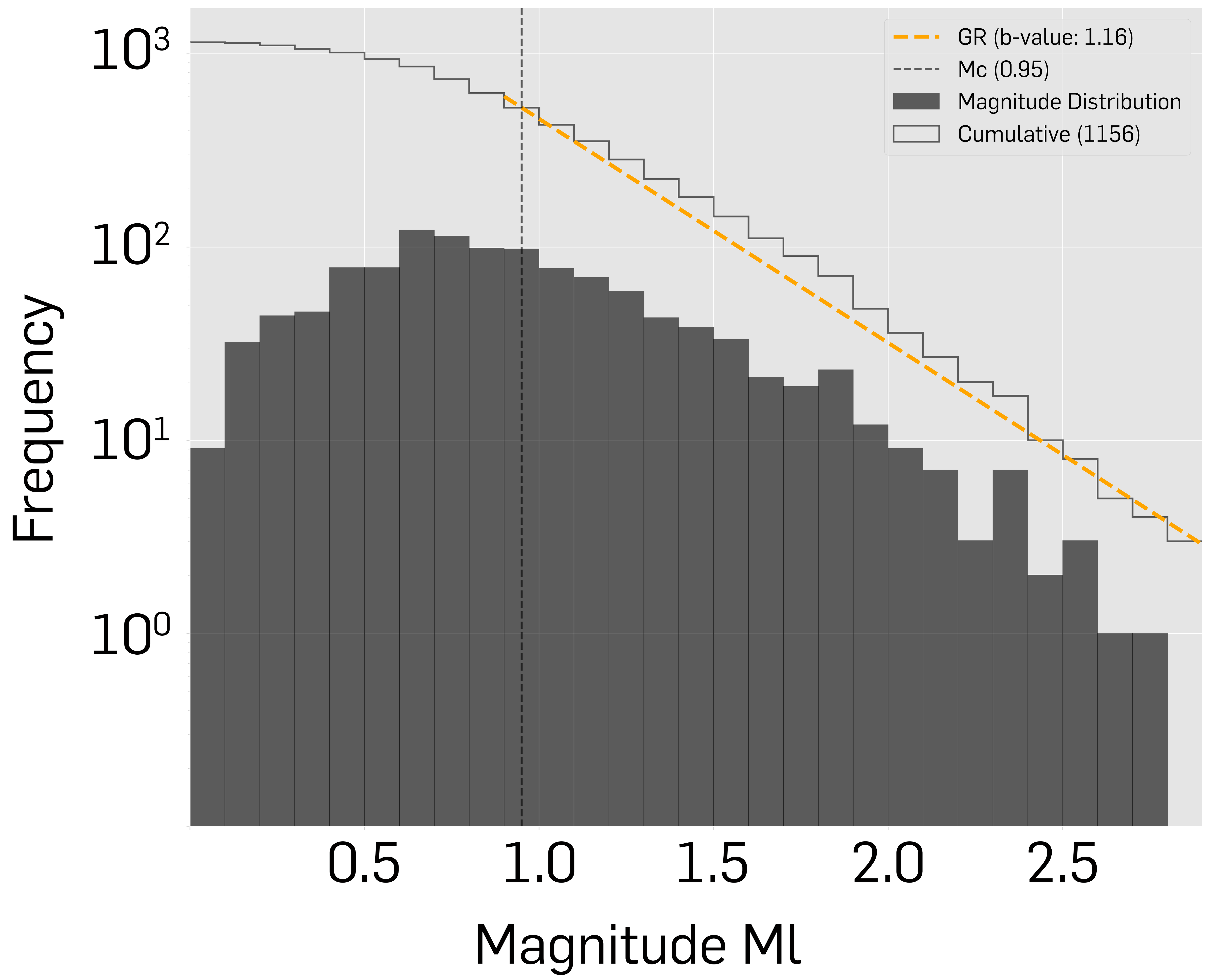


Figure 5: Magnitude frequency distribution, magnitude of completeness Mc, and b-value for the sequence.

Spatio-temporal Evolution of Seismicity

- Clustering using nearest-neighbor method +
  - Small rescaled times suggest that background events occur close in time but are widely spaced

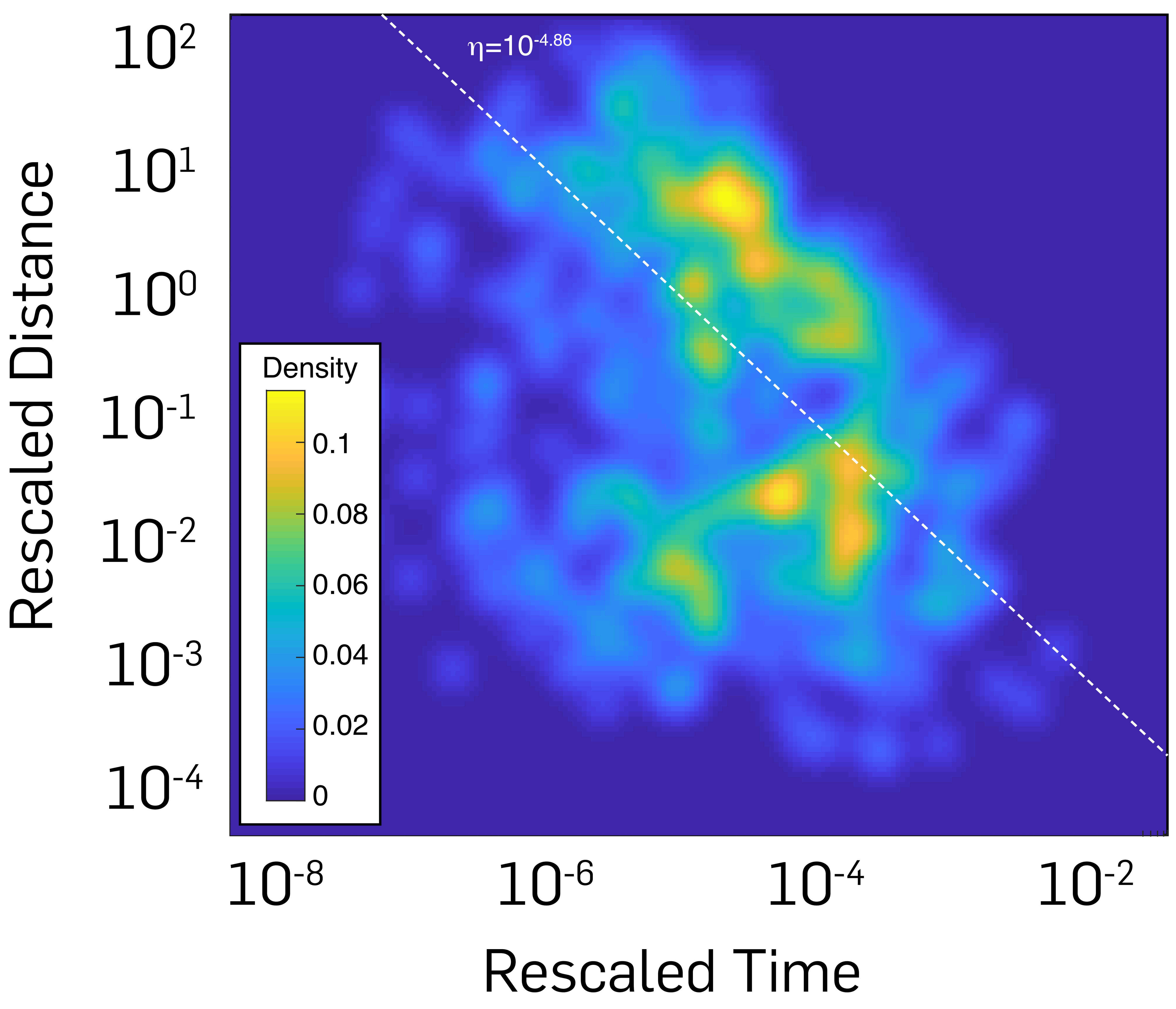


Figure 6: Clustering style of the seismicity in the LASSO array. (A) Joint 2-D distribution of the rescaled time and rescaled distance to the parent event. The diagonal dotted white line corresponds to the best fit η that divides independent and clustered events.

Spatio-temporal Evolution of Seismicity

- Clustering using nearest-neighbor method +
  - Single-event clusters dominate
  - Background events likely driven by stress changes induced from saltwater disposal
  - Clusters are small in size (only 4 clusters with > 10 events)

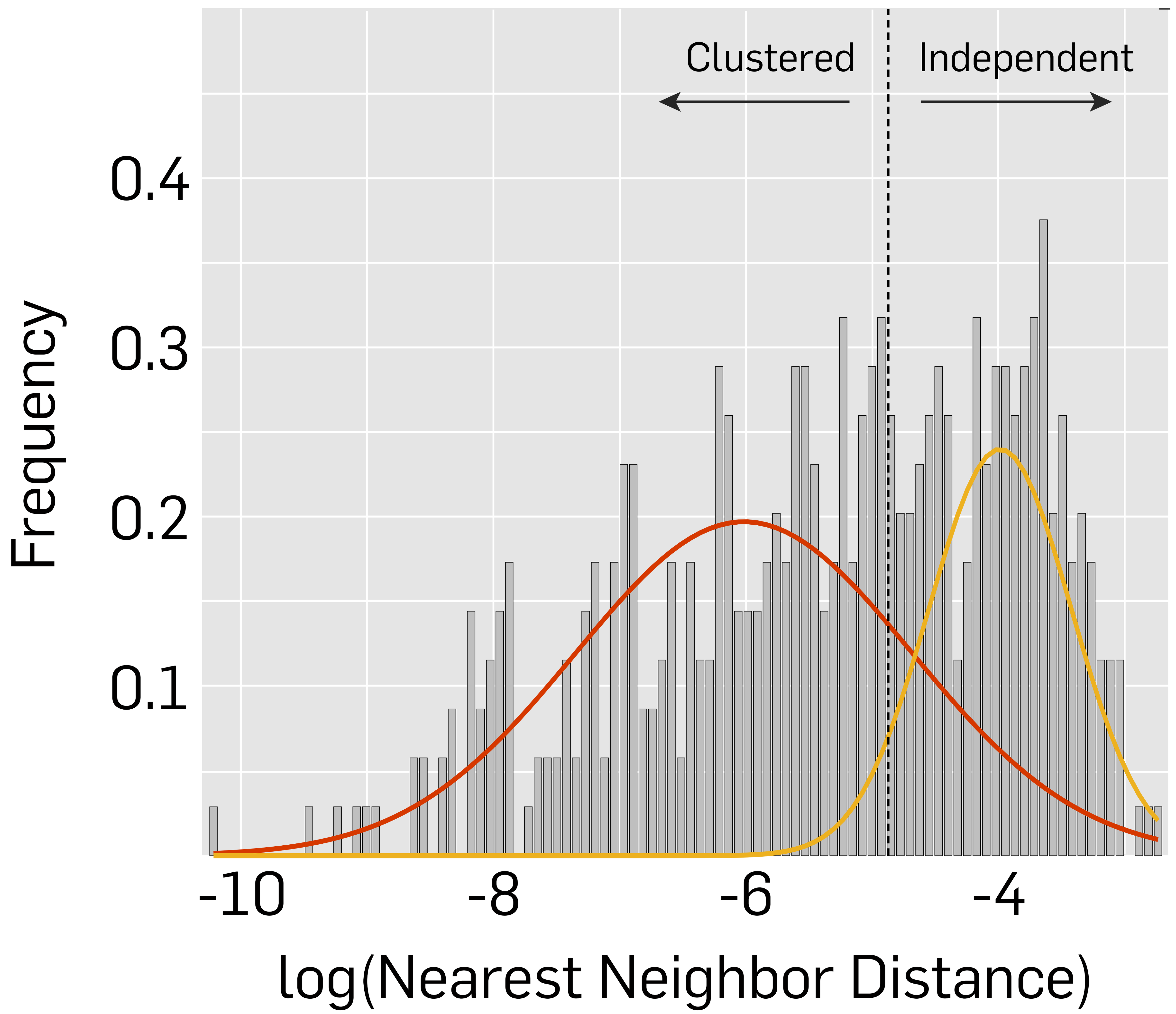


Figure 7: Histogram of nearest neighbor distances with curves showing the fit to the distribution of clustered (red) and independent (orange) events. The dotted black line corresponds to the best fit η.

Source Properties - Single Spectra

- Single Spectrum Fitting
  - Estimate corner frequency f_c and seismic moment M_0 from P-wave spectra
  - Fit Boatwright + spectrum to multi-taper spectral estimate +
  - Delete-one jackknife mean (at least 20 station estimates) to get an event estimate +
  - Azimuthal dependency of parameters f_c and M_0

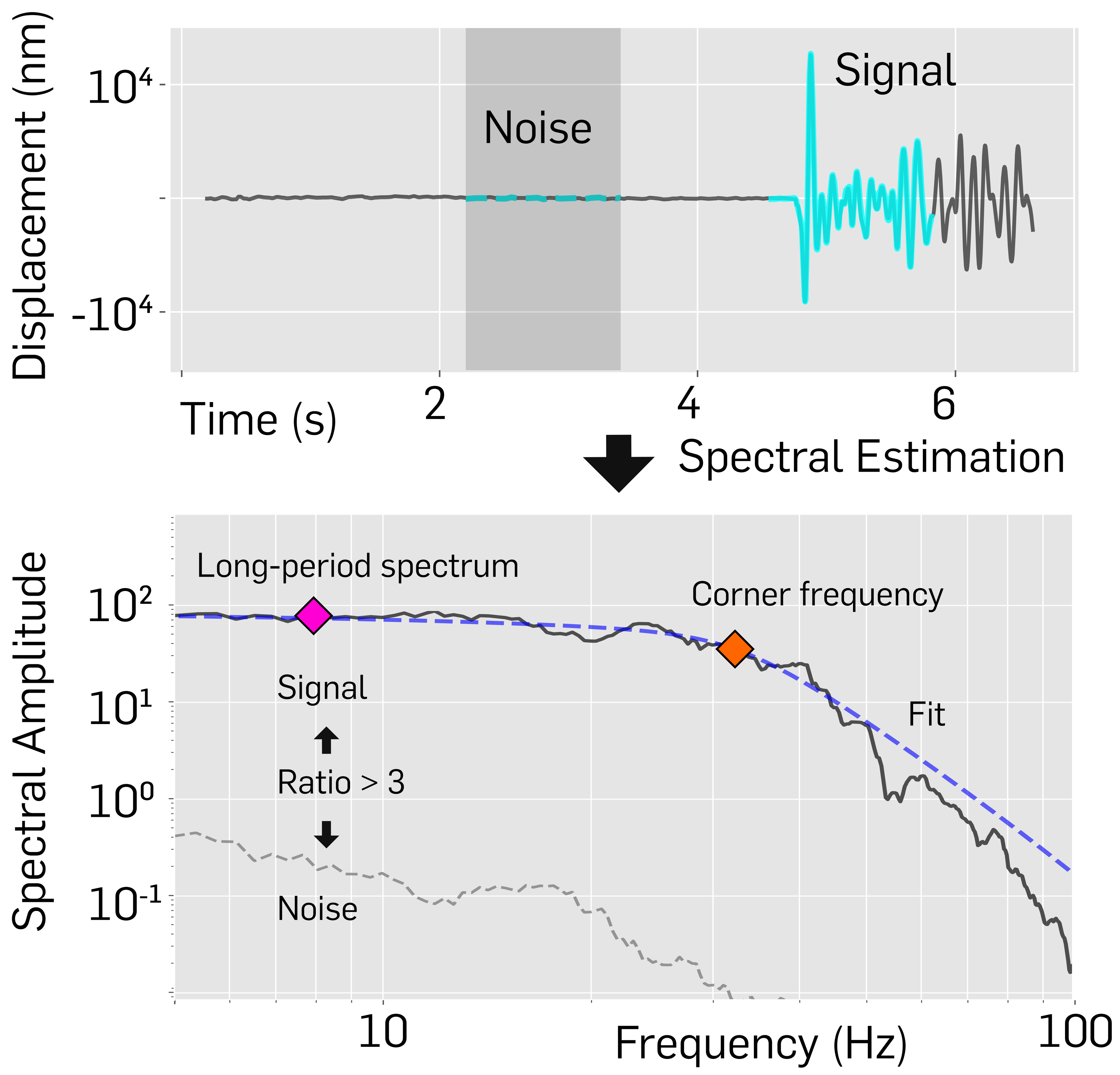
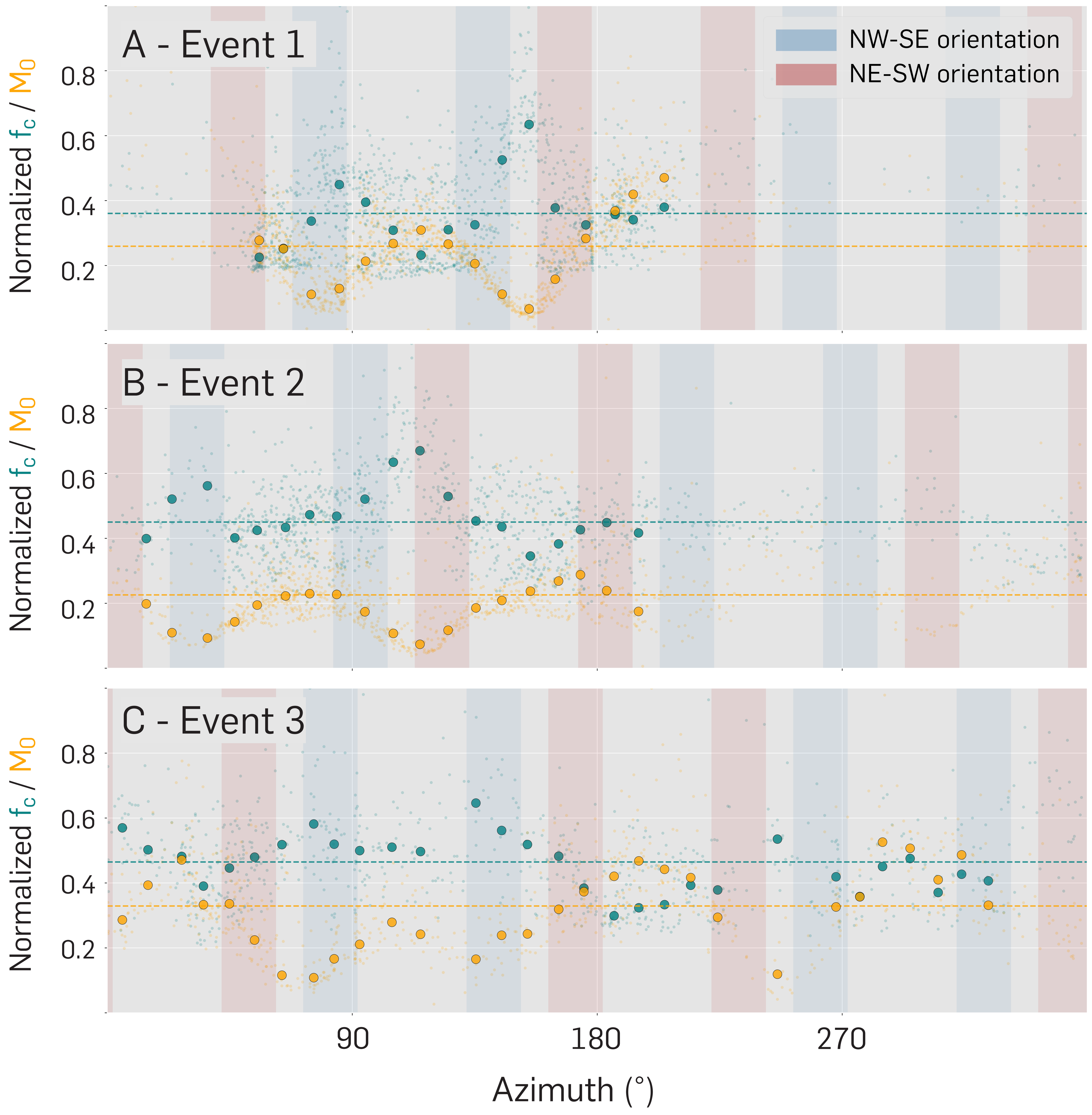


Figure 8: The spectrum is estimated from a 1 second long (starting 0.2 before the P-wave arrival) window. The noise window is placed 2 seconds before the P-wave arrival and the Signal-to-Noise-Ratio (SNR) between 5 - 100 Hz has to be larger than 3 . Blue line shows fit to the spectrum.

Single Spectra - Azimuthal Dependency

- Azimuthal dependency of parameters f_c and M_0 (see also ➜)
- NW - SE focal plane orientation fits quite well with predictions of Madariaga (1976) ✚

Figure 9: Corner frequency (teal) and moment magnitude (orange) with azimuth (Event 1,2,3 from top to bottom). Small points denote each station estimate, dashed-lines the mean, and larger dots denote the mean in every 10° degree bin in the same color (minimum of 15 samples in each bin to be plotted). Blue and red colored areas illustrate azimuth ranges with an expected elevation of corner frequency after Madariaga (1976) ✚ for the two differernt possible fault planes.



Single Spectra - Sample Size

- >100% deviation of stress drop estimates by using only a small number of stations (<10)
- Number of stations should be taken under consideration for a stress drop error estimation
- Could be significantly reduced by requiring a maximum azimuthal gap of stations

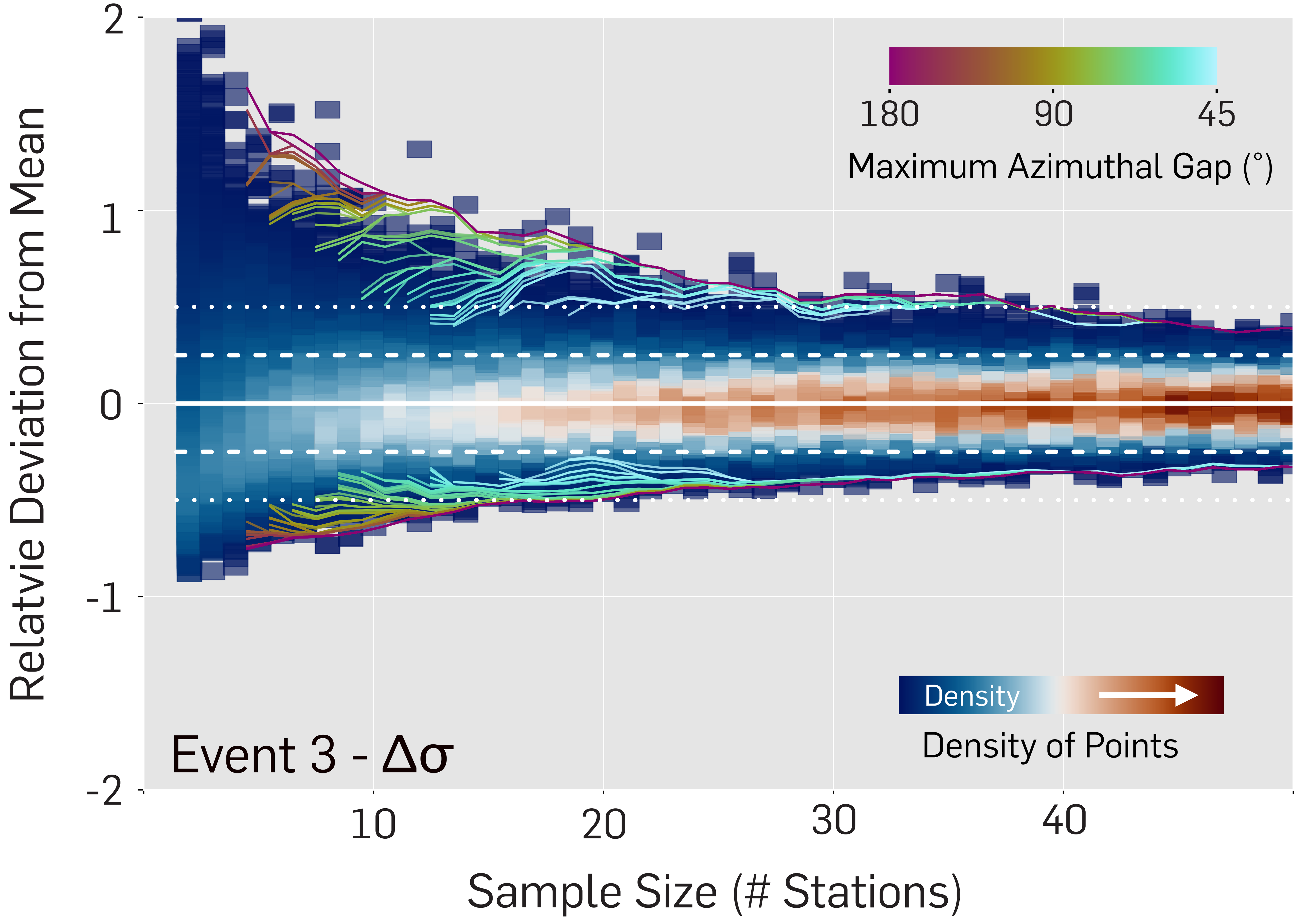


Figure 10: Deviation of the stress drop estimates for Event 3 using different random sample sizes (1000 iterations per sample size) as a fraction of the mean using all stations. The red/blue color bar represents the density of points around a given estimate, where the deviation as a fraction of the mean estimate is shown on the y-axis. The solid line shows the jackknife mean using all available station estimates, and the dashed/dotted lines show isolines of 25%/50% deviation, respectively. Colored lines corresponding to the colorbar on the top illustrate the maximum and minimum deviation for a specific sample size by requiring a maximum azimuthal gap of the subset of stations as a rolling mean over four samples.

Source Properties - Spectral Ratio

- Spectral Ratio Fitting
  - eGf spectral ratios to get refined corner frequencies ✚
  - Assume co-location of events mean cross-correlation >0.8 at 50 closest stations
  - Stack individual station ratios (at least 10) and fit with spectral model
  - Visually inspected spectral ratio fits

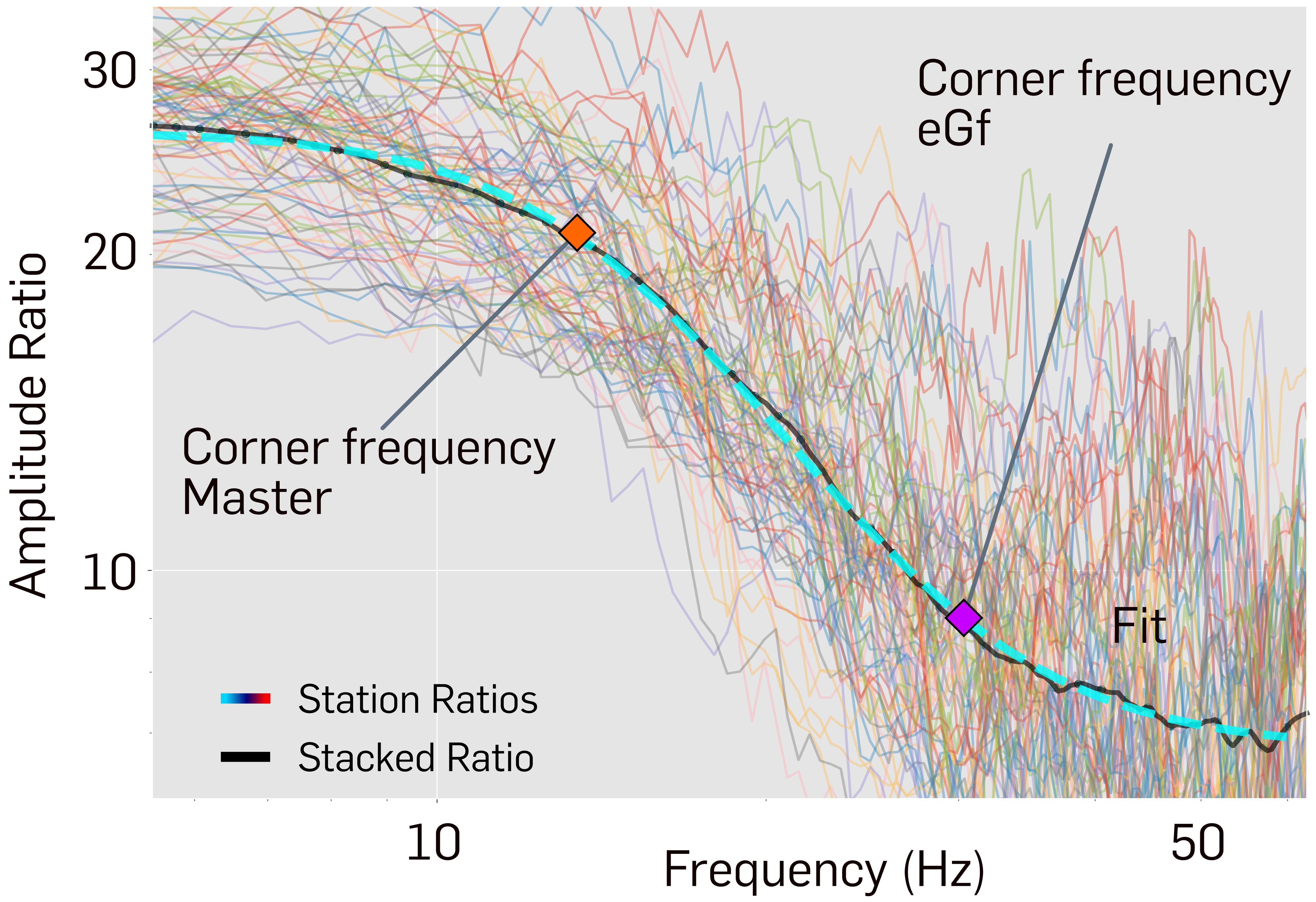


Figure 11: Example of spectral ratio for a M_L 2.08 master and M_L 1.39 eGf event (103 station ratios). Events have a mean cross-correlation of 0.83 at the 50 closest stations with overlapping picks. The same window lengths as for the single spectra estimates are used. Cyan colored dashed line shows fit to the stacked ratio (black line). Colored lines show individual station ratios.

Spectral ratio - Sample Size

- Variations >15 Hz by using a few stations (<10)
- Brune-type and Boatwright-type spectral model in the same study region

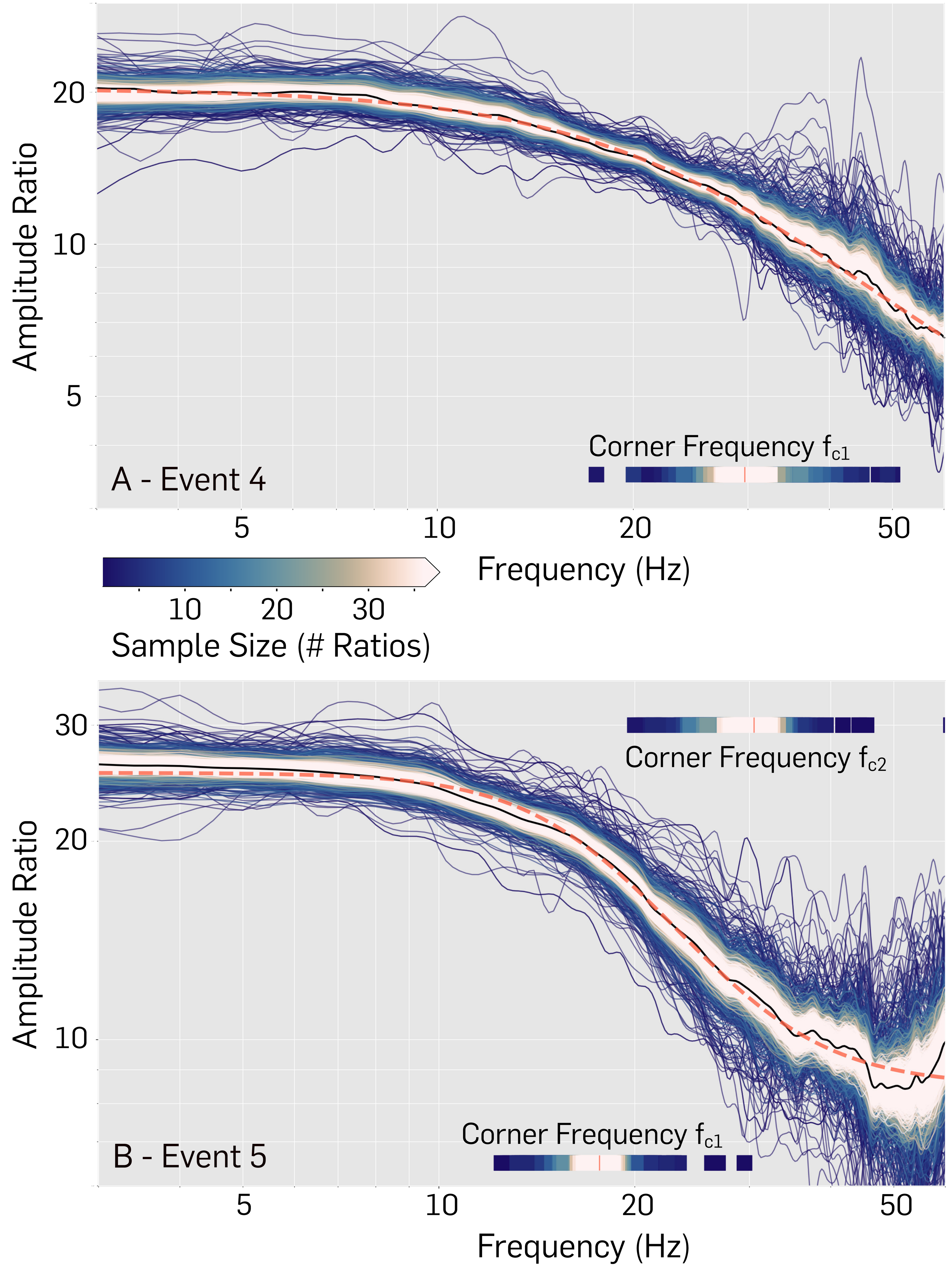


Figure 12: Corner frequency estimates from the stacked spectral ratios of two representative events using random subsets of station ratios (50 iterations per sample size; Event 4 - top, Event 5 - bottom). Black lines denote the stacked spectral ratio using all available stations, and the red lines the Brune (Top) or Boatwright (Bottom) model fit with $n = 2$. Spectra are colored by sample size, with the color bar shown between the panels. The rectangles at the upper (bottom plot) and lower (top and bottom plot) right side of the plots show he range of corner frequency estimates (f_{c1} - main event, f_{c2} - eGf event) across the range of sample sizes. These rectangles use the same color scheme as the stacked ratios (red vertical line denotes the corner frequency estimation from the given model). The f_{c2} of Event 4 could not be resolved due to frequency bandwidth limitations.

Source Properties - Stress Drop

- Stress drops range from 0.5 - 80 MPa
- No obvious scaling of stress drop with magnitude by considering frequency bandwidth limit (~3 • fc ➜) (see also ➜)
- Possible self-similar stress drop scaling for induced events?
- Observable range of stress drop is extended due to the higher sample rate and number of stations

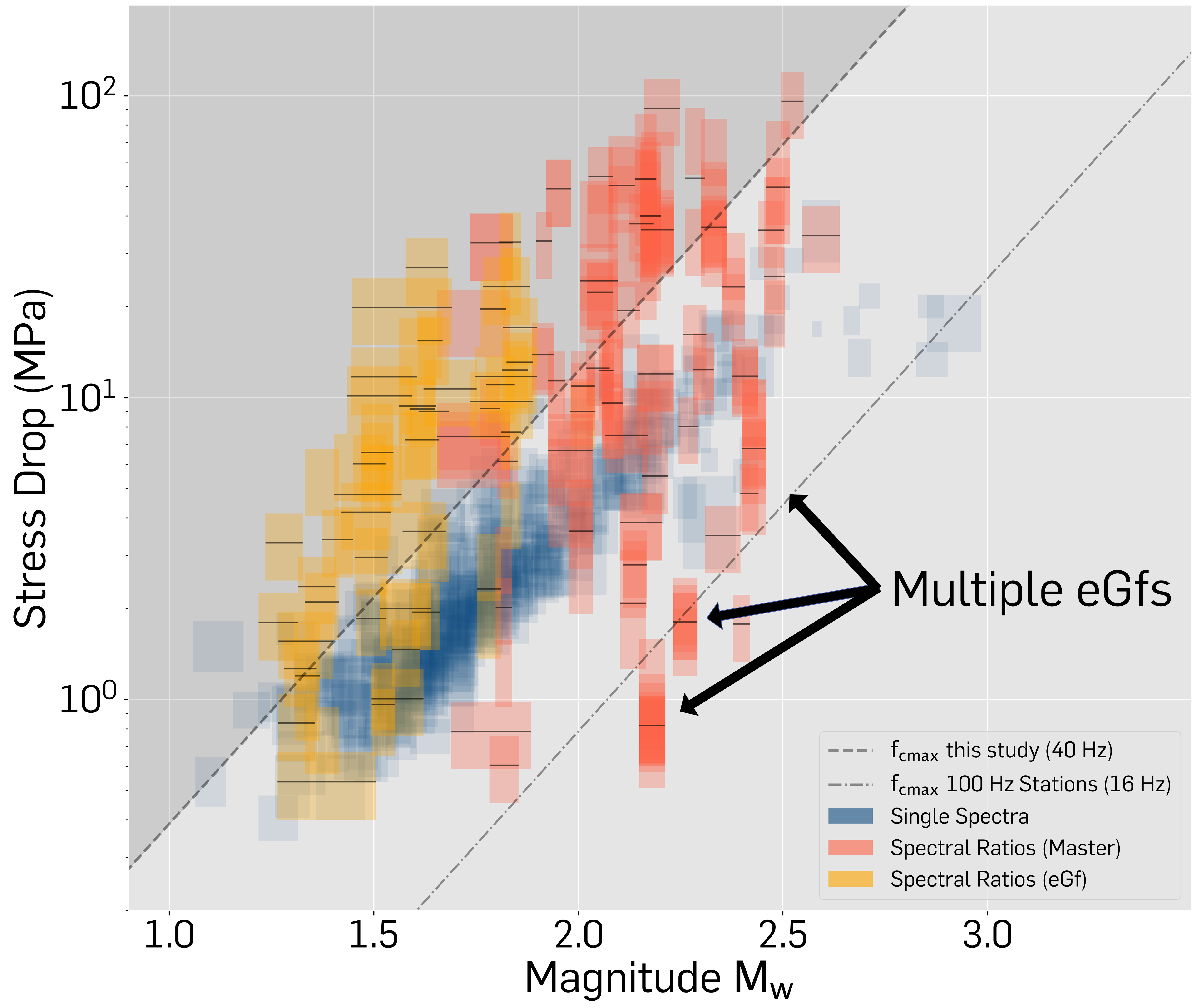


Figure 13: Stress drop vs. moment magnitude. Each estimation defines a rectangle dependent on the assumed error. M_W and stress drop (single spectra) errors are taken from delete-one jackknife mean (at least 20 stations). The stress drop error of the spectral ratios is assumed to be 25% and the black horizontal lines show the stress drop of spectral ratios (median for multiple estimates).

Conclusions

- LASSO array provides unique insight into induced seismicity
- Most earthquakes deeper than injection with b-value around 1
- Minimal clustering observed for induced events, but most events are independent
- LASSO reveals azimuthal dependency of single spectra estimates matching with theoretical considerations

- Large errors of spectral estimates should be expected by using a small (<10) number of stations
- Wide range of stress drops (0.5 - 80 MPa) for small earthquakes (M < 3)
- Possible self-similar scaling for induced events?

Methods - Picking

- P-wave arrival picks and polarities from a Kurtosis picker (PhasePApy)
- HASH was used to calculate focal mechanism solutions from the polarities

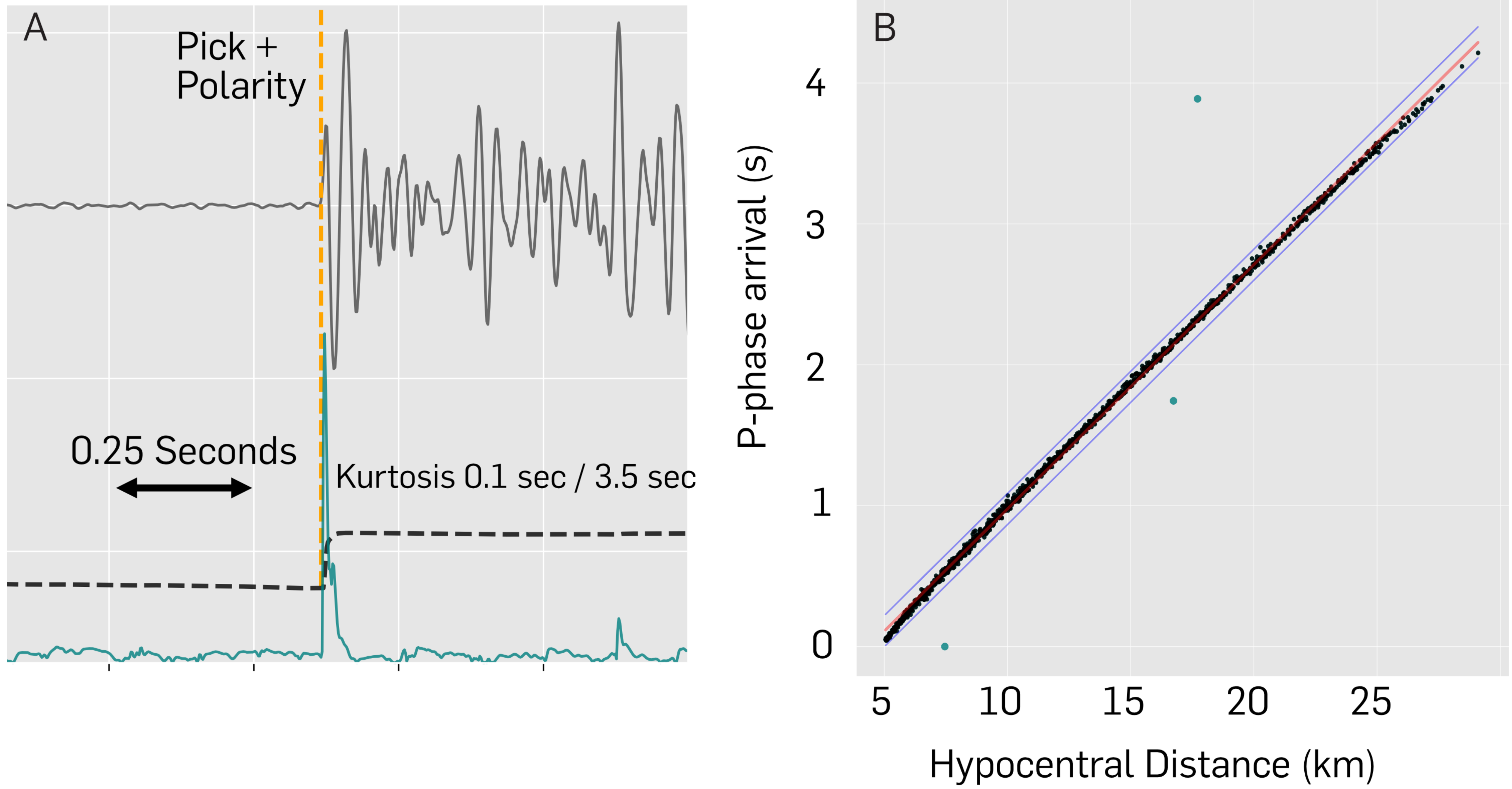
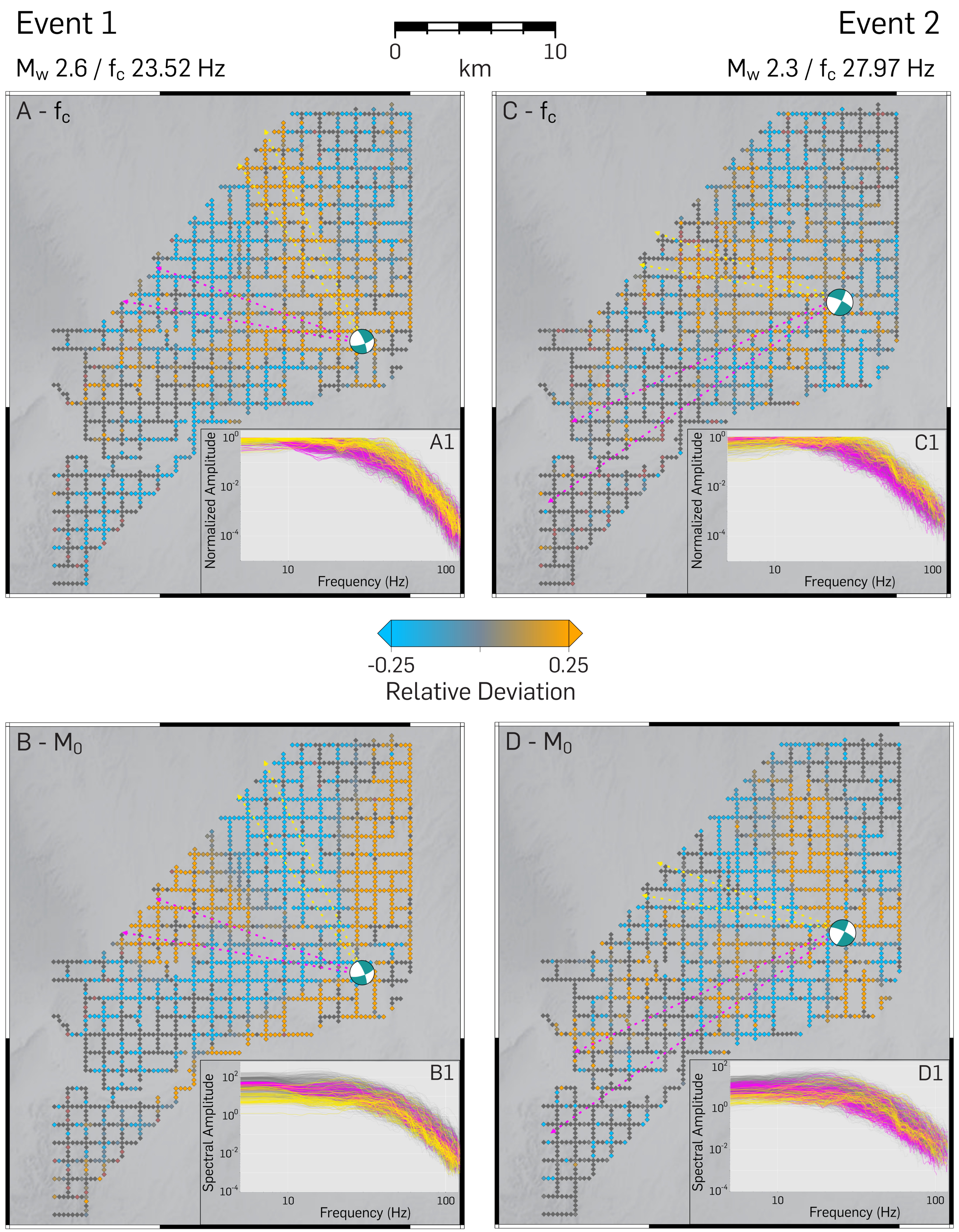


Figure 14: Overview of picking procedure. A) The kurtosis (0.1 second short and 3.5 second long window) of a representative example waveform is shown in teal along with the threshold (8σ) as the black dashed line. The orange vertical dashed line denotes the time of the automatic pick. B) The arrival times at all stations for which picks were determined are plotted against the distance as dots. The red line denotes the linear fit, and blue lines the lower and upper threshold (0.15 deviation). Teal picks are removed.

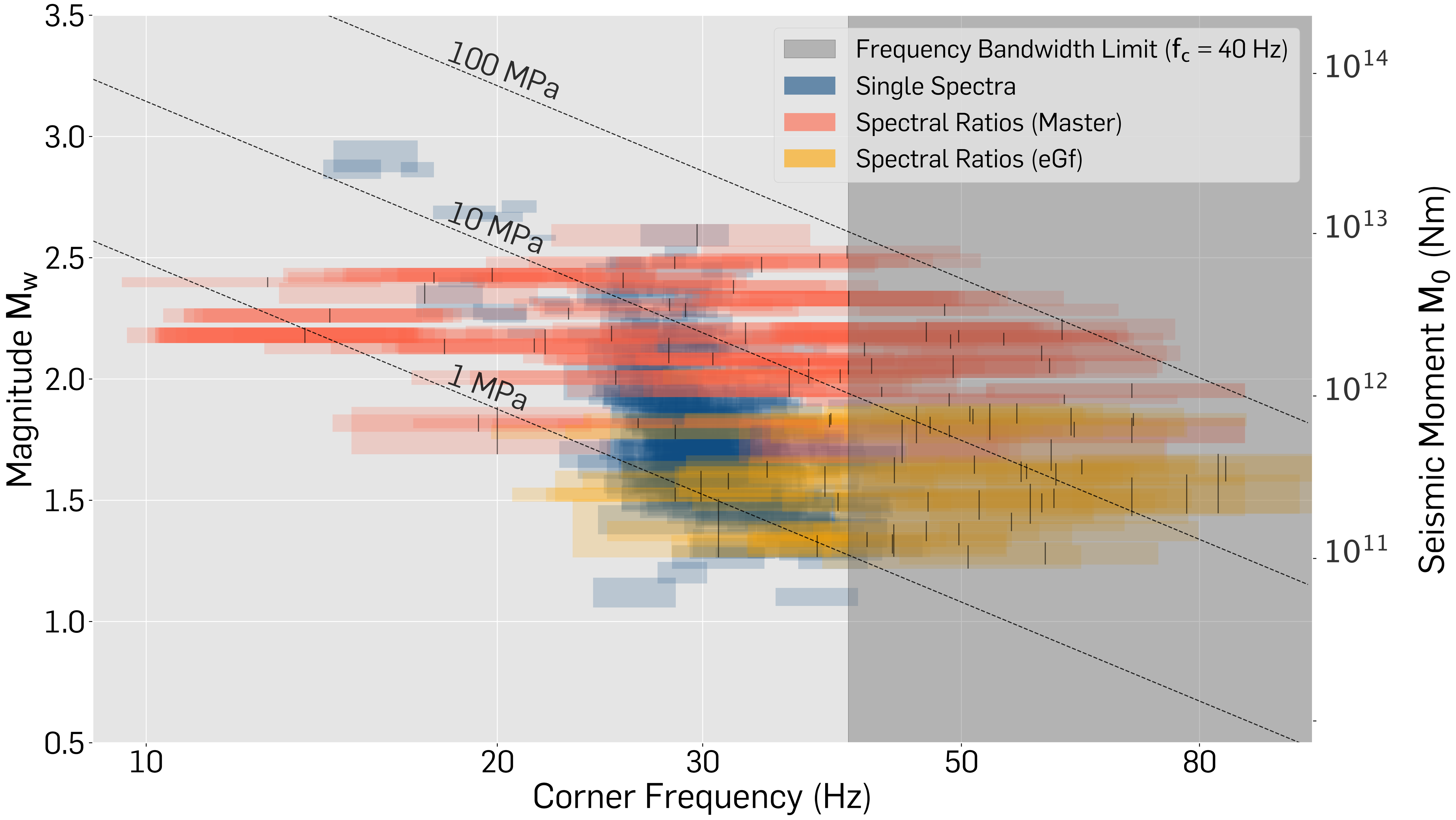
Single Spectra - Azimuthal Dependency

Figure 15: Single spectrum estimates from individual stations fits for Event 1 and 2. Symbols and map region are the same as in Figure 1. A and C show the relative deviation (blue - negative, orange - positive) of individual station measurements from the mean corner frequency; the mean is estimated from the jackknife mean using all stations (red nodes indicate SNR criteria not satisfied, grey indicate no pick). B and D, same as A and C except showing the relative deviation from mean moment magnitude. Insets show the multi-taper spectral estimates (original - A, C; normalized - B, D) at individual stations satisfying SNR criteria; most spectra are shown in grey and subsets of stations near the minimum (nodal plane) and maximum radiation directions plane are shown in yellow and magenta, respectively (map locations of these areas are shown in the main subplots). Spectra shown in the insets of A and C are normalized to the largest spectral amplitude to demonstrate the difference in the corner frequencies. Spectra shown in the insets of B and D demonstrate differences in the long-period spectra (and subsequent moment magnitude) recorded at individual stations.



Seismic Moment vs. Corner Frequency

Figure 16: Corner frequency vs. moment magnitude for all available events. Blue rectangles show estimates from single spectra. The dimension of a single rectangle are defined by the 95% jackknife confidence interval for fc and M0. The spectral ratio estimates (f_{c1} - red, f_{c2} - yellow) are manually reviewed and have a fixed error of 25%. The error of M_W is taken from the single spectra estimate. As a master event could have multiple eGfs, rectangles could overlap and increase the opacity of the area, which could be seen as more robust estimates. The dashed lines denote isolines for stress drop for a shear-wave velocity of 3600 km/s corresponding to a depth range between 2 - 8 km, in which the majority of the events are located (Figure 3).



Acknowledgments

- Data collected by the Large-n Seismic Survey in Oklahoma (LASSO) experiment are archived at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center under network code 2A in PH5 format and can be accessed at: http://ds.iris.edu/mda/2A/?starttime=2016-04-11T13:20:06&endtime=2016-05-24T15:41:19 (last accessed March 2020).
- The open-source Python package Obspy 1.0.1 was used for data processing available at: https://github.com/obspy/obspy (last accessed March 2020).
- Several figures were created using GMT 6 available at: https://docs.generic-mapping-tools.org/latest/ (last accessed March 2020).
- The other figures were created using Matplotlib 3.1.3 available at: https://matplotlib.org/ (last accessed March 2020).
- Some of the colormaps used in the plots contained in this presentation are available at: http://doi.org/10.5281/zenodo.1243862 (last accessed March 2020).
- Polarities and picks were determined using PhasePApy available at https://github.com/austinholland/PhasePApy (last accessed March 2020).
- Focal mechanisms were determined using HASH1.2 available at https://earthquake.usgs.gov/research/software/#HASH (last accessed March 2020).
- This project is partially funded by Ruhr University Bochum (RUB) new faculty startup funds, and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) project number 428868223.