Engineering and Physical Sciences Research Council

Insights into the downhole array spectra of seismicity induced by hydraulic-fracturing

Adam Klinger and Max Werner
University of Bristol

e-mail: ak13671@bristol.ac.uk

Introduction

Motivation:

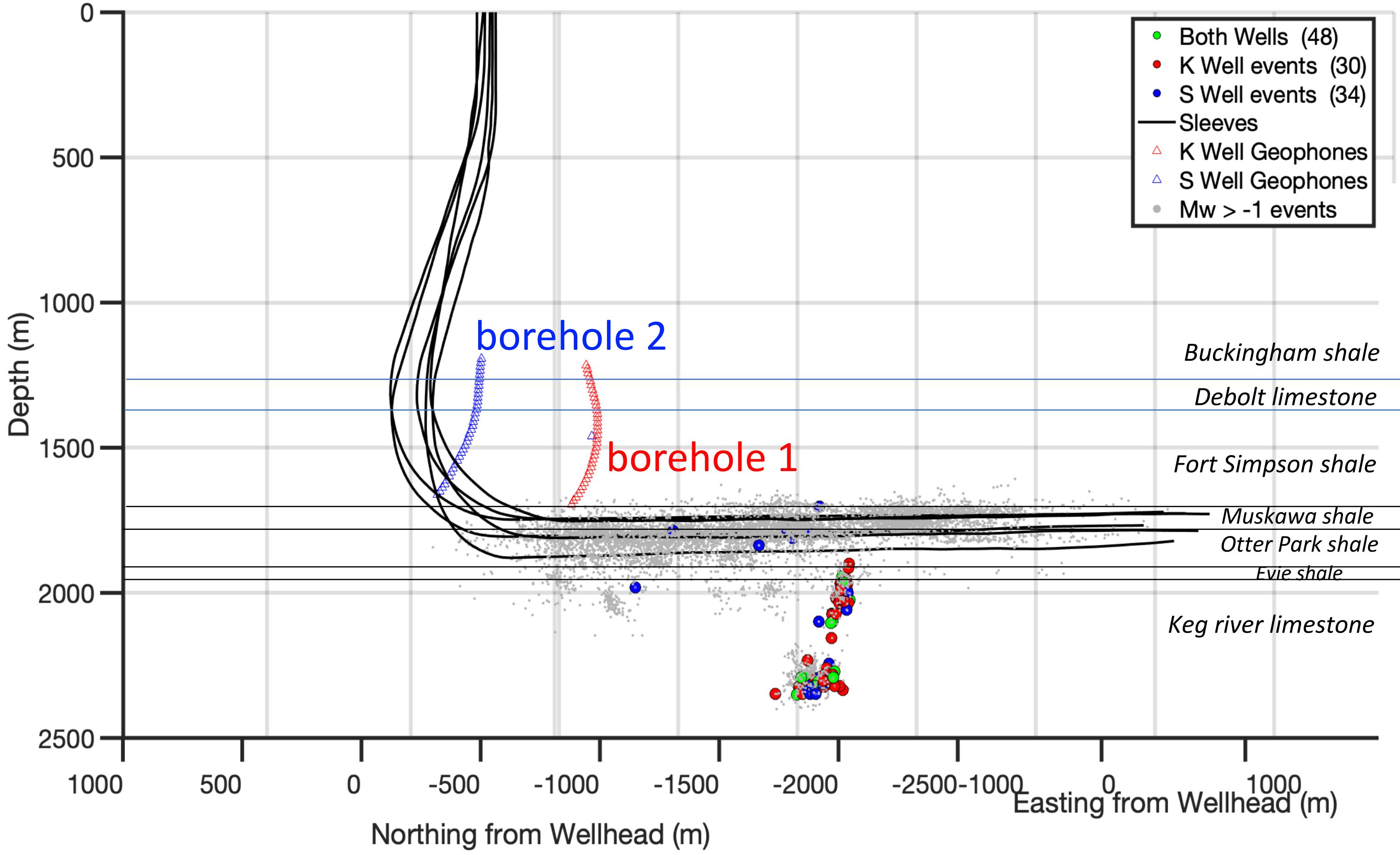
- During large-scale fluid injection, the underlying physical mechanisms causing fault reactivation are not yet well established.
- In enhanced geothermal projects multiple studies have shown a connection between stress drops and distance from the point of fluid injection, which is thought to be caused by a reduction of normal stresses (Goertz-Allmann et al., 2011, Kwiatek et al., 2014, Lengline et al., 2014). However, it is still unclear how ubiquitous this is across datasets and geological setting.
- Stress drops are most sensitive to the corner frequency (f_c), which can be determined from far-field radiation.
- Borehole arrays increase SNR and reduce surface scattering effects compared to surface stations, however, high frequency resonances can compromise the resolution of f_c.

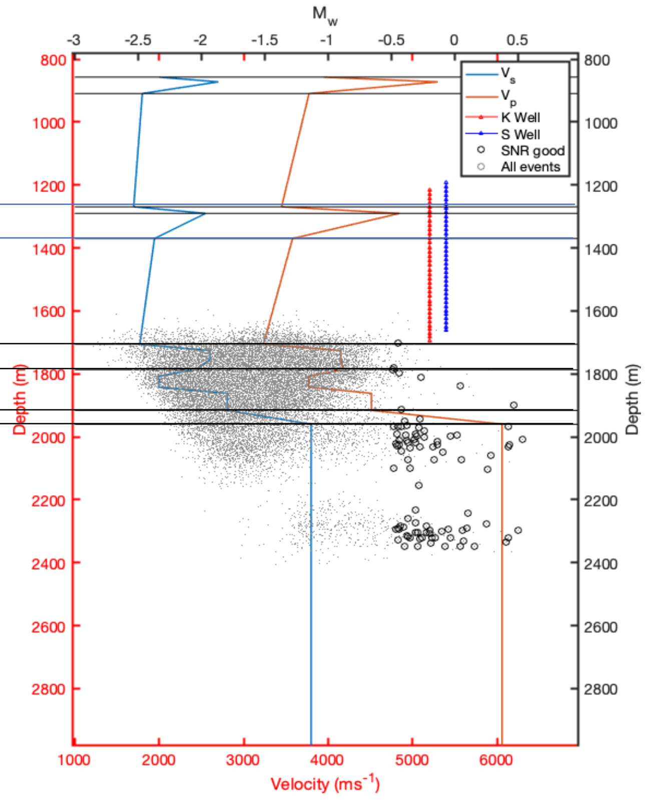
Scientific questions:

1. Can we obtain robust estimates of f_c form micro-seismicity recorded along a borehole array?
2. Do we see systematic variation in f_c along a borehole array?
3. Do some stations show more reliable estimates of f_c?
4. What are the most likely causes for perturbances to high frequency source parameters?

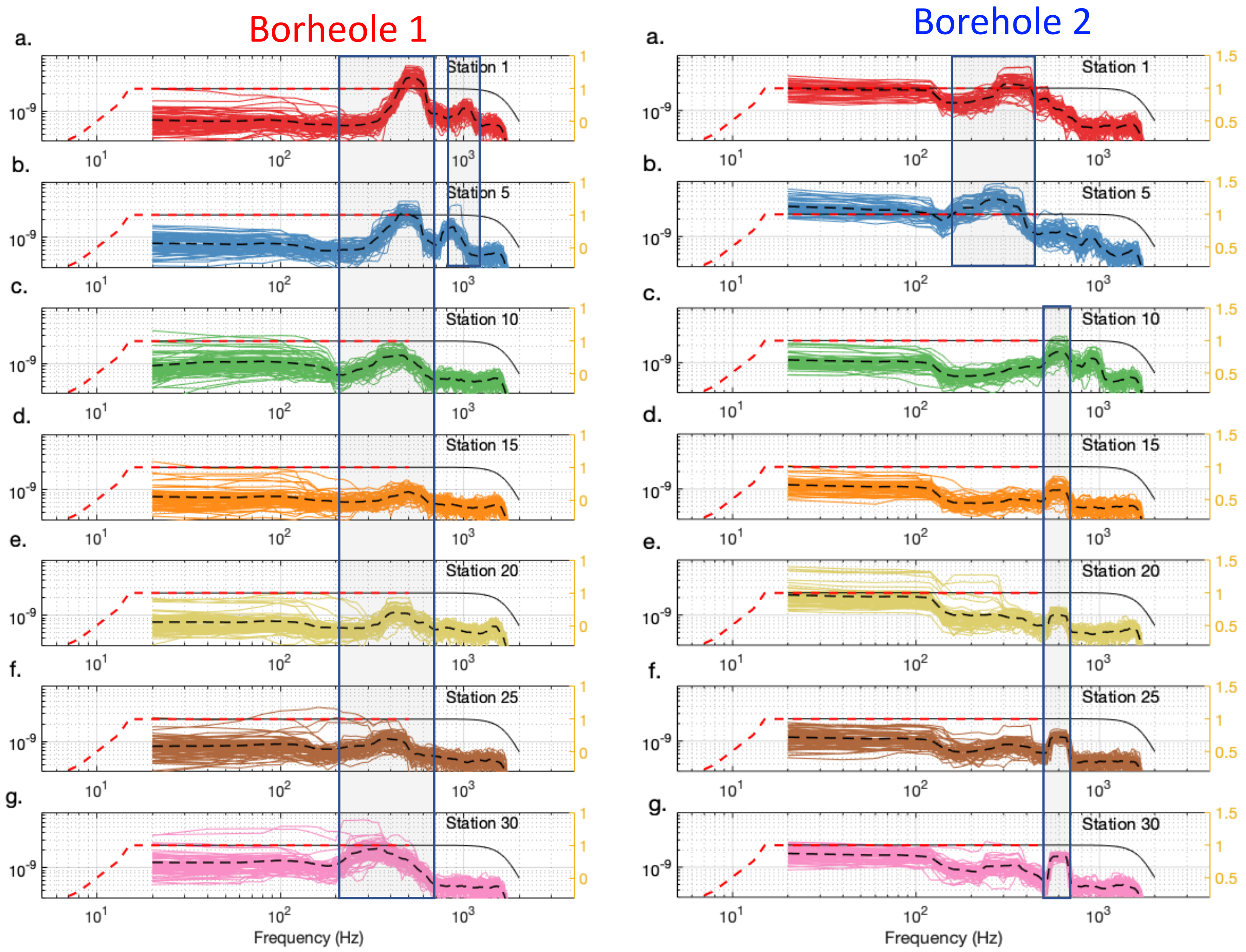
Dataset – Horn River (BC)

- Multi-stage, multi-well, hydraulic stimulation of 3 tight shale formations.
- 90,000 + events recorded
- We select **78 candidate events (- 0.5 < M_w < 0.5).**





Pre-event noise (Z component)



We observe clear notches pre-event noise displacement spectra from all 78 spectra at both borehole arrays.

Borehole 1:

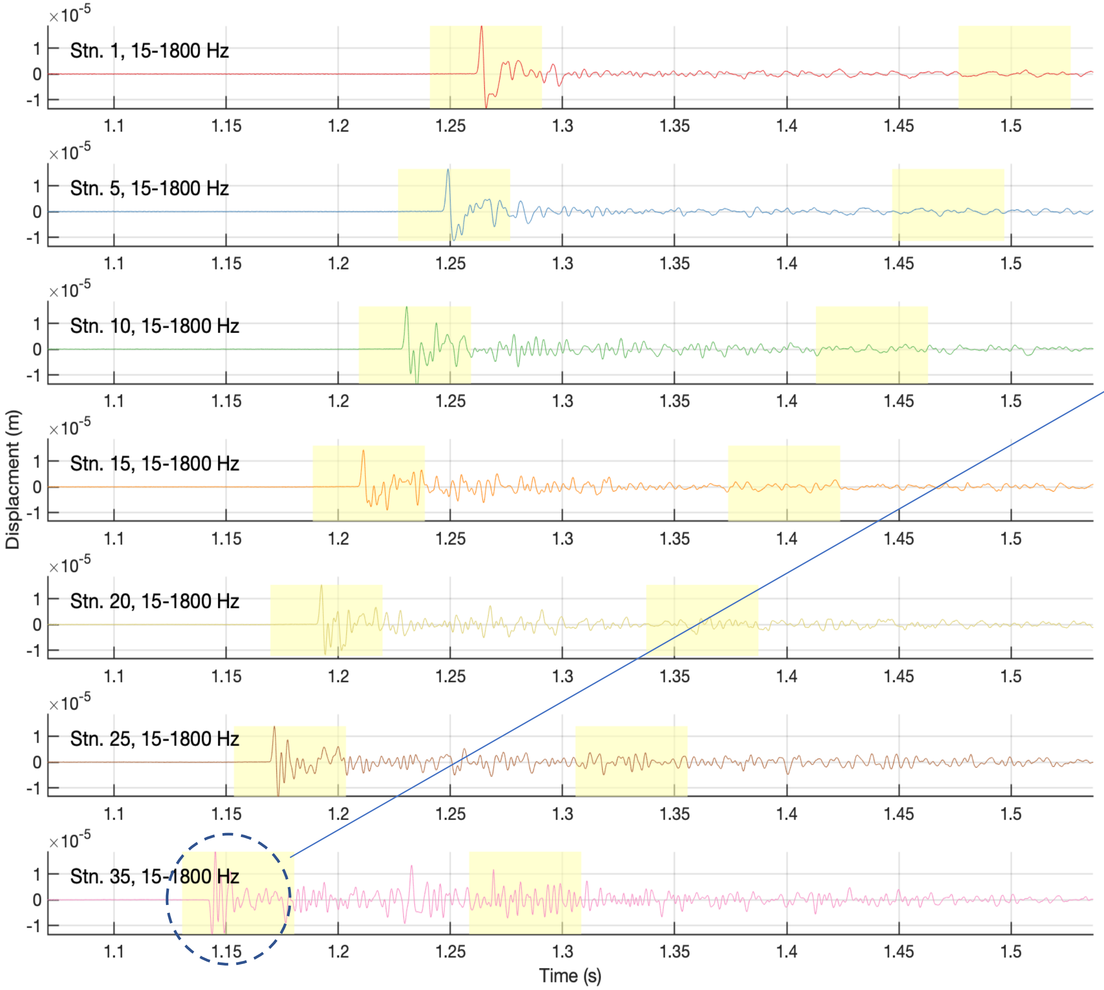
- At Well 1 the strongest resonances are at the shallowest stations (Stations 1-5) at around **300-500 Hz** and a **peak at 500 Hz**. Multiples can be seen at 1000 Hz.
- The **deepest stations** (stations 25-30) show a broader notch at around 200-500 Hz with a **peak at around 350 Hz.**

Borehole 2:

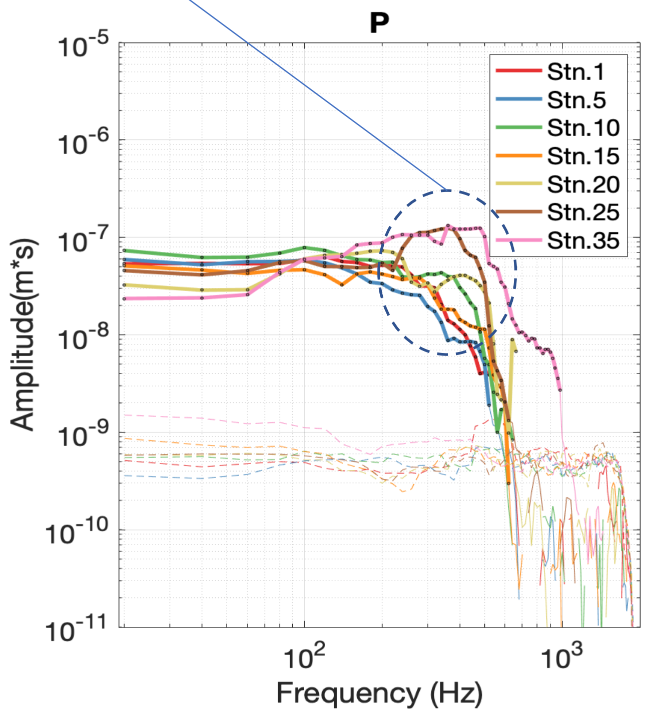
- **Broad notches** at around **150-400 Hz at** shallowest stations
- **Narrow notch at 500 Hz** and is consistent from stations 10-35

- Noise source is **observable in the continuous time series and strongest on the Z-component**: Likely caused spurious frequencies in the instrument.

Spectral analysis (far-field)

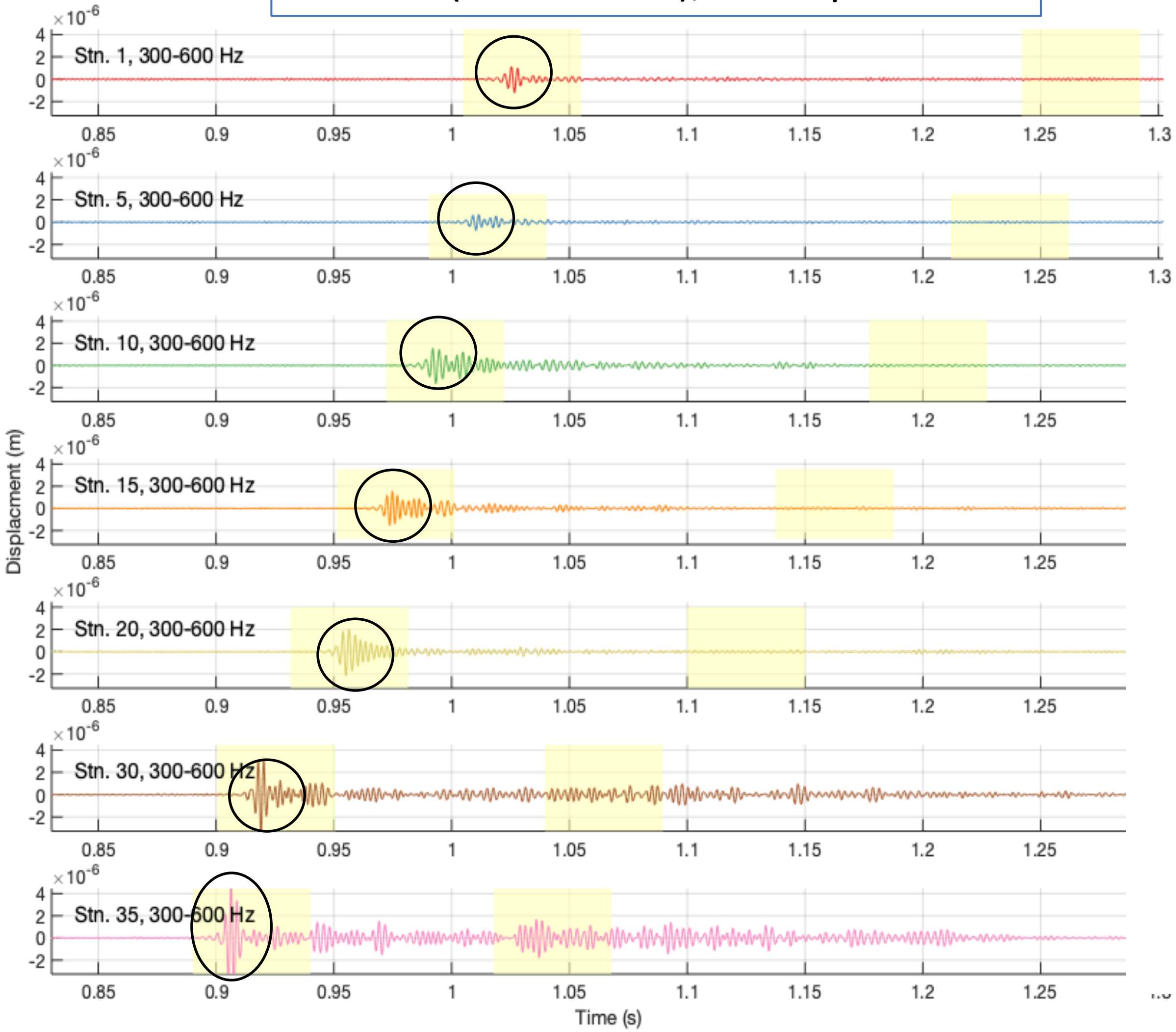


- We observe **bumps in the spectra** towards deeper stations.
- The bump does not correlate with a noise increase.
- What is causing this?

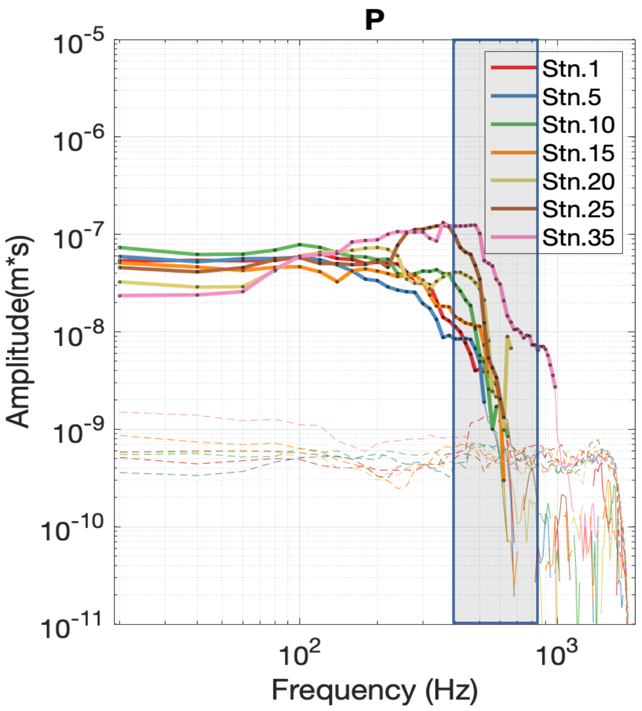


Instrument resonances

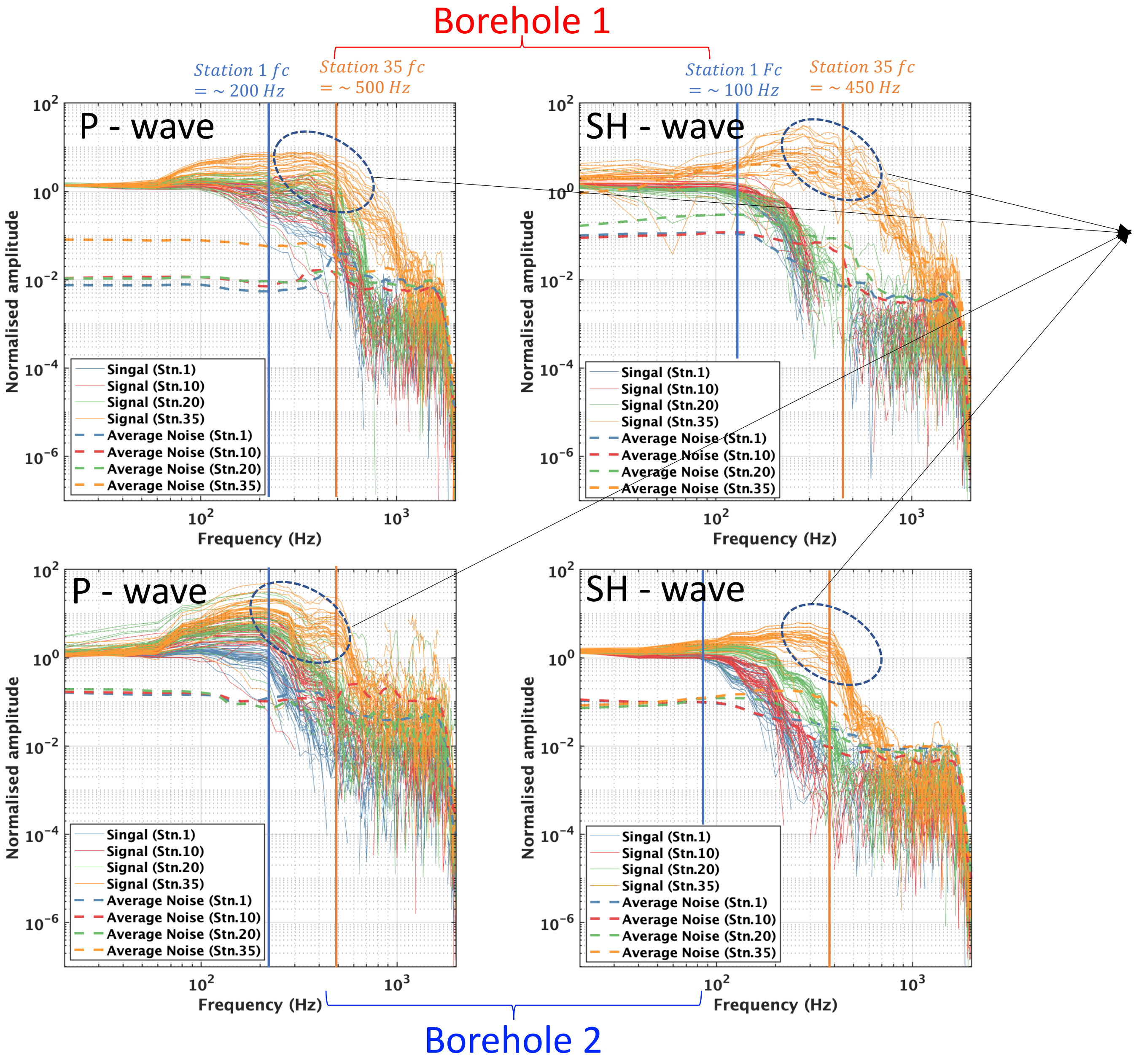
Filtered (300-600 Hz), Z component



- High frequency resonances (300-600 Hz) occur after the first initial particle motion and systematically increase in amplitude towards deeper stations.
- These are likely causing the bumps in the displacement spectra.
- **Is this seen across all events?**

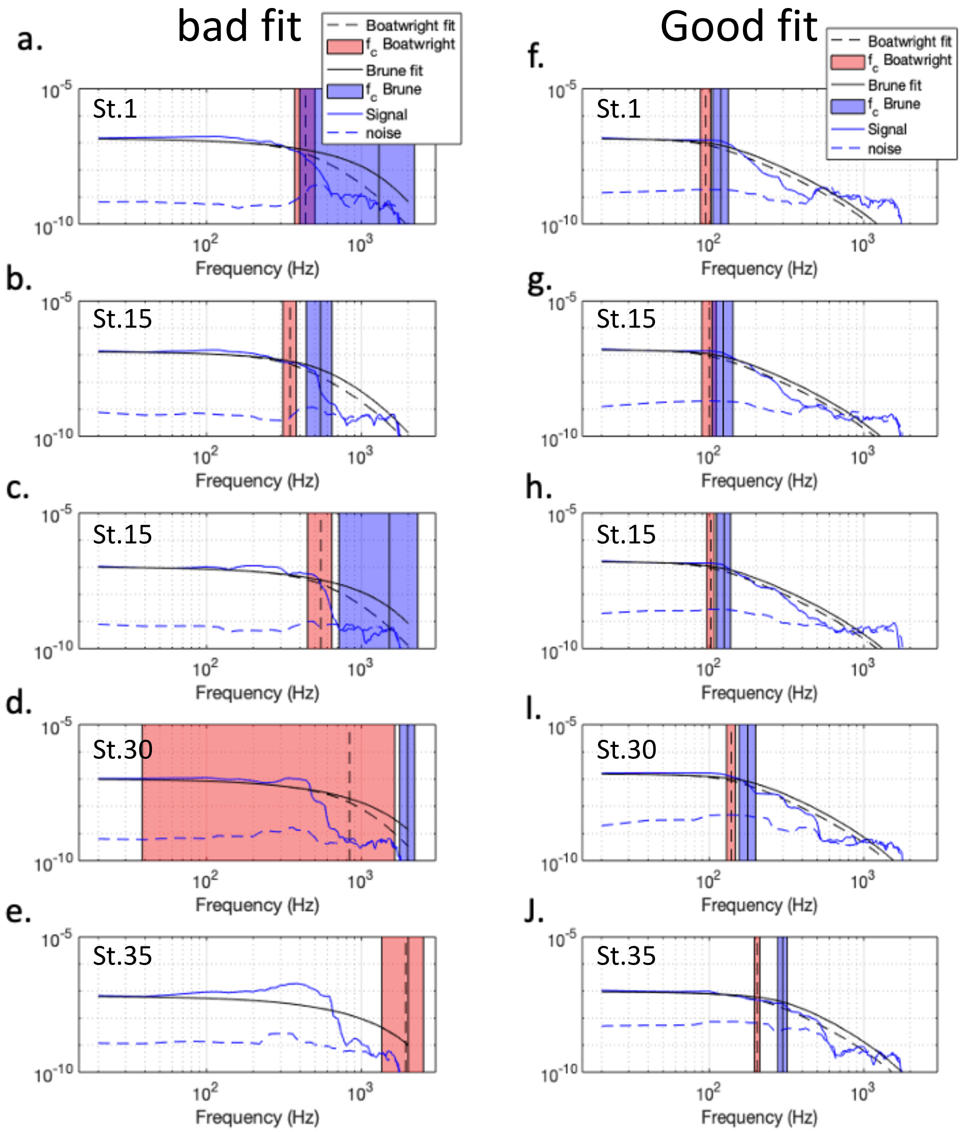


Spectral observations (far-field)



- All phase arrivals at **both boreholes show bumps in the spectra at the deepest stations**.
- We observe a systematic increase in corner frequency across all events.
- **Could this effect measurement of f_c?**

Inversion for f_c



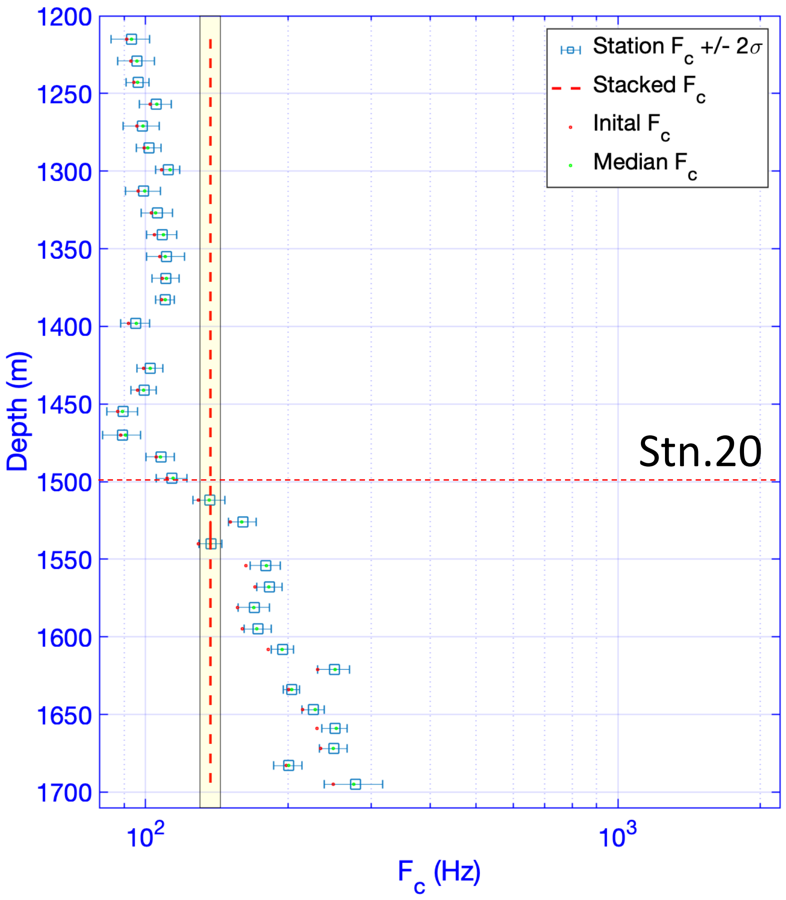
- We invert for f_c using the Boatwright and Brune source models:

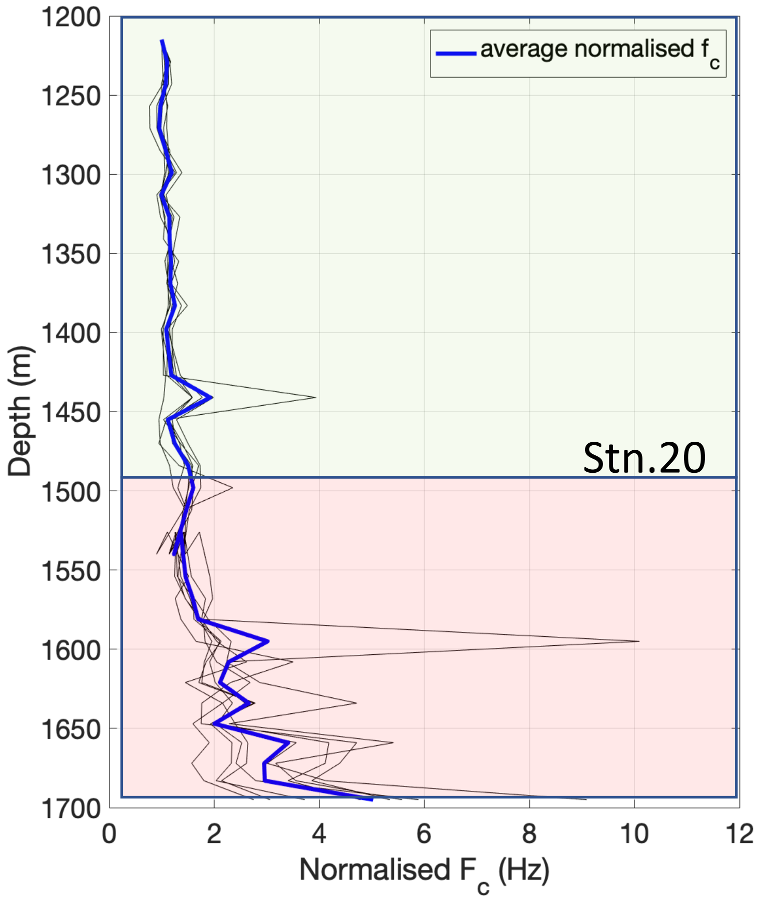
$$\Omega(f) = \frac{\Omega_o e^{-\pi f t/Q}}{\left[1 + \left(\frac{f}{f_c}\right)^n\right]^{1/y}} \qquad Brune: n = 2 \; y = 1 \qquad Boatwright: n = 4 \; y = 2$$

- We assume that Q = 1000 (Average from Canadian sedimentary basin) and calculate Ω_o from the spectra.
- We then:
  - Invert for $\boldsymbol{f_c}$ using a 1D parameter grid search in MATLAB
  - Calculate residuals between model and data
  - Create 30 new synthetic spectra by resampling residuals at each frequency point
  - Run 1D inversion for each new synthetic spectrum

Get 1050 $\boldsymbol{f_c}$ estimates for each event

f_c *vs* station depth





A robust inversion shows :

- ***f*$_c$'s that do not saturate** at the user defined bound (2000 Hz).
- Initial f_c that falls within the uncertainty of the f_c's from the synthetic spectra
- **8 out of 78 events show robust estimates of *f*$_c$.**
- We observe **relatively consistent *f*$_c$ up to station 20**, as seen from 8 events.
- Below this, f_c increases systematically with station depth.
- The deepest stations (stations 30-35) show f_c's that can exceed a factor of 4 compared to the shallower stations.
- This **variation in *f*$_c$ is unexpected** and is unlikely to be caused by directivity effects over a small azimuthal range.

Conclusions

Scientific questions:

1. Can we obtain robust estimates of f_c form micro-seismicity recorded along a borehole array?
2. Do we see systematic variation in f_c along a borehole array?
3. Do some stations show more reliable estimates of f_c ?
4. What are the most likely causes for perturbances to high frequency source parameters?

1. In most cases model inversion does not provide good fits to the spectra. We find only **8 out of 90,000 + events show robust f_c estimates when using 1D bootstrap inversion.**
2. Yes, deeper stations show an increase in the f_c across all phases and at both boreholes. This is likely caused by spurious frequencies in the instruments.
3. Shallower stations (1-20) show similar f_c 's , which are more reliable than deeper stations (21-35), as these show a systematic increase with depth.
4. We observe clear resonances in the 300-600 Hz frequency band after the arrival of the P-phases. **This is most likely caused by the resonance of spurious frequencies** which could be amplified after initial particle motion.

- Advice for operators:
  - Stacking f_c 's across all stations along a borehole array may not be an appropriate method for determining stress drops. Instead, a careful selection of stations may be required instead.