



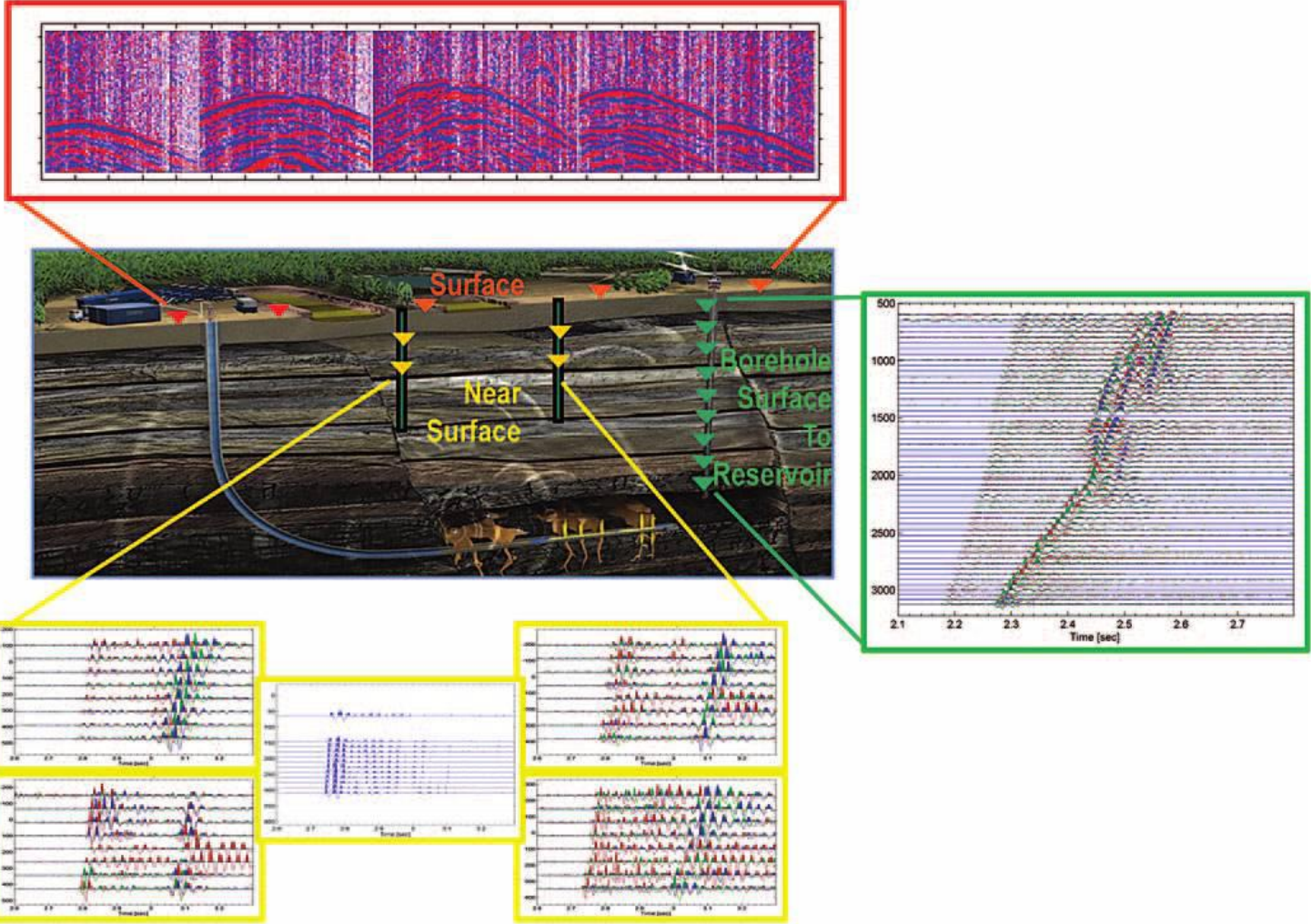
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# Attenuation from (direct) waves of (micro-)seismic Events

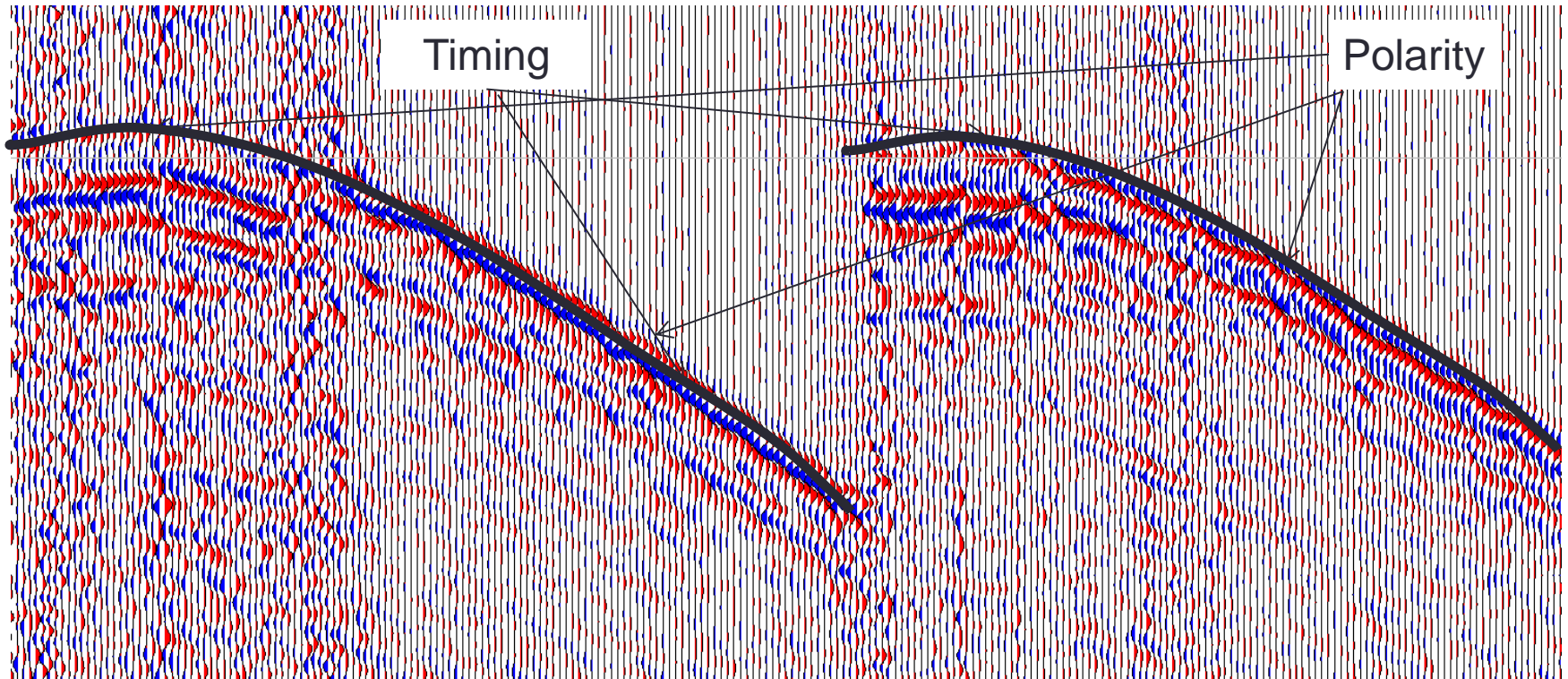
Leo Eisner, Seismik s.r.o.

- **Motivation:**
  - ▶ Microseismic monitoring: downhole and surface
  - ▶ Downhole and surface monitoring – frequency content
  - ▶ Source mechanism inversion from downhole arrays & attenuation
- **Methodology – theory**
- **Case studies**
  - ▶ Benchmarking with spectral ratios
  - ▶ data issues
- **Validity and limitations**
  - ▶ Corner frequency
  - ▶ Multipathing

# Microseismic monitoring – what is downhole and surface



Maxwell et al, TLE, 2012

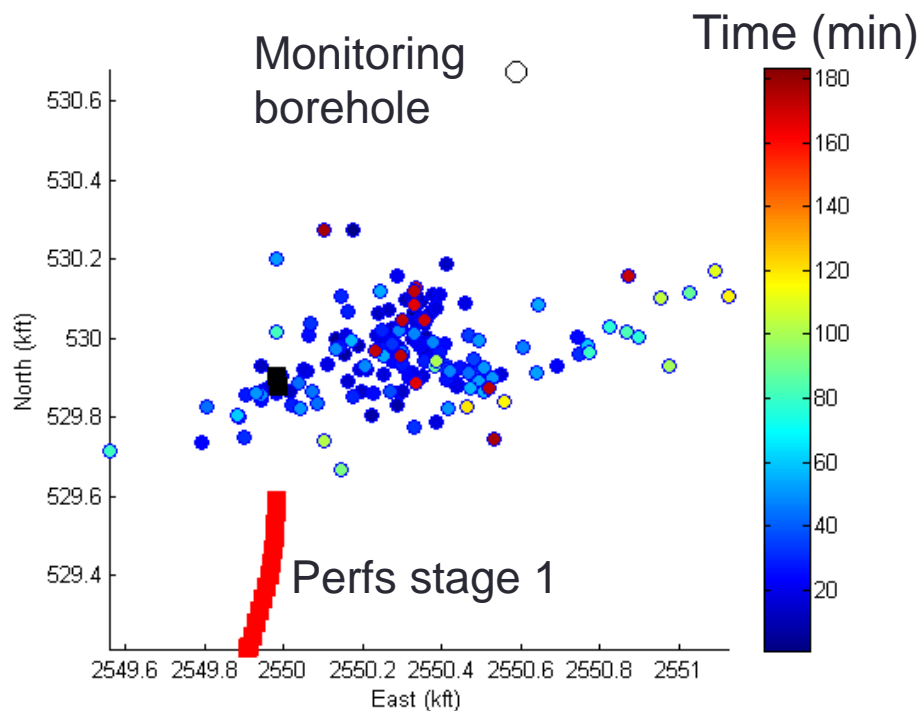


Timing of the first arrivals (i.e. moveout) constrains a location of the microseismic events. Traditionally, only timing – arrival times of the first breaks are used.

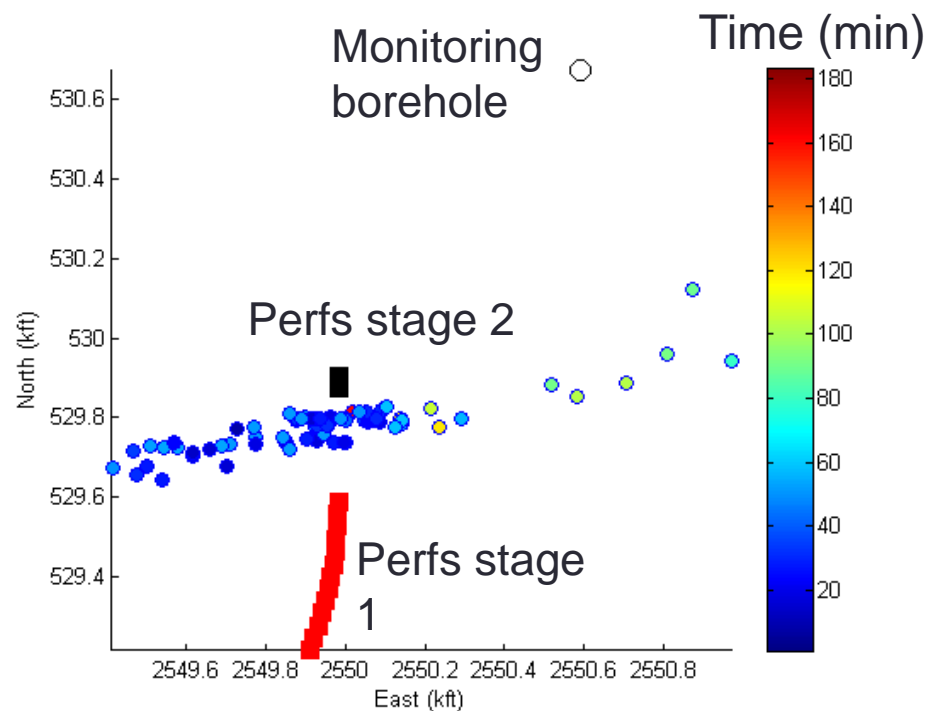
Phase (i.e. polarity) provides an additional information. Polarity of first arrivals is changing and these polarity changes carry information about the source mechanism, in addition to the location.

# Downhole-surface comparison

**DOWNHOLE** locations (170 events)



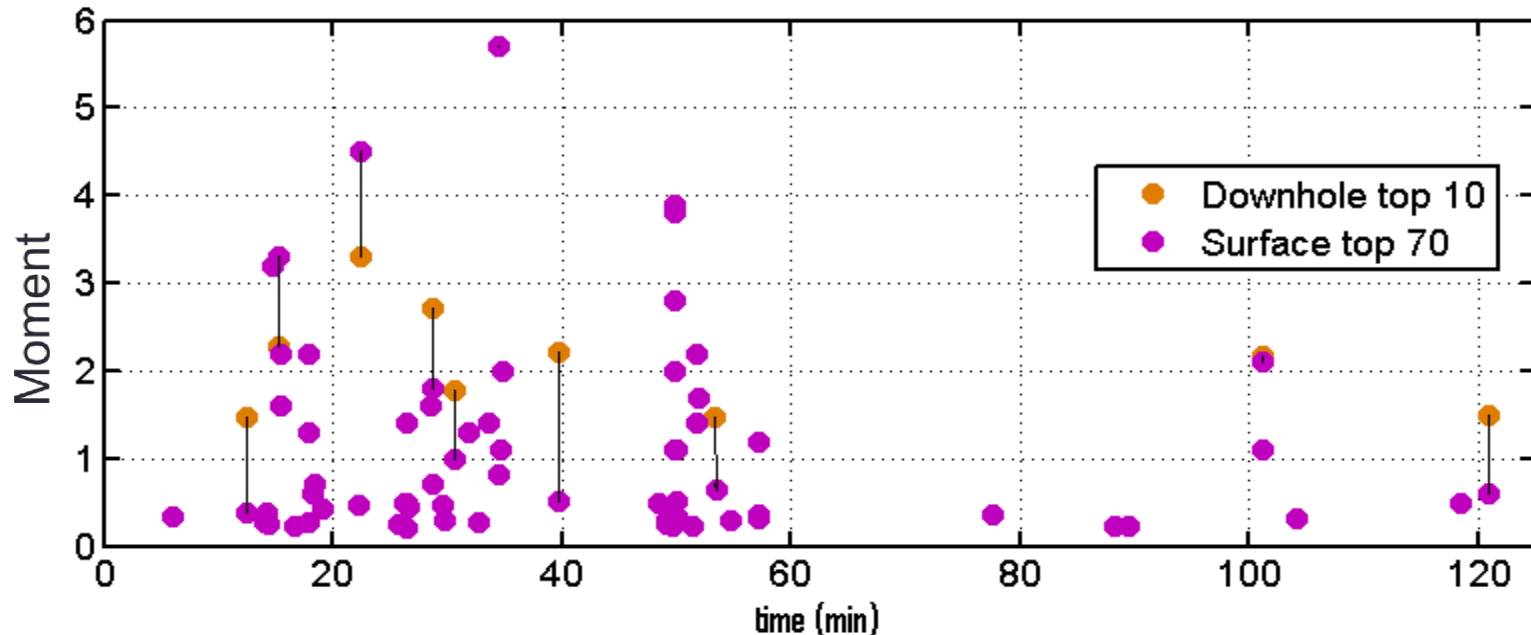
**SURFACE** locations (70 events)



Two map views reveal somewhat different view of the same fracture:

1. Shift (300 ft west, 100 ft south)
2. Scatter (fracture width or location error?)
3. Complexity (2 frags or one simple frac?)

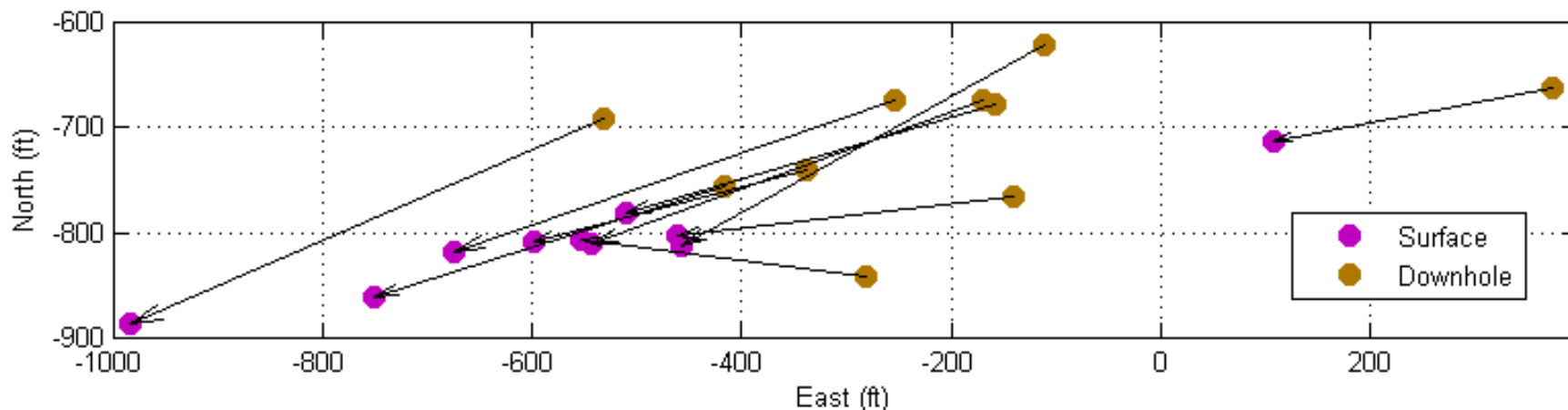
# Downhole-surface comparison - timing



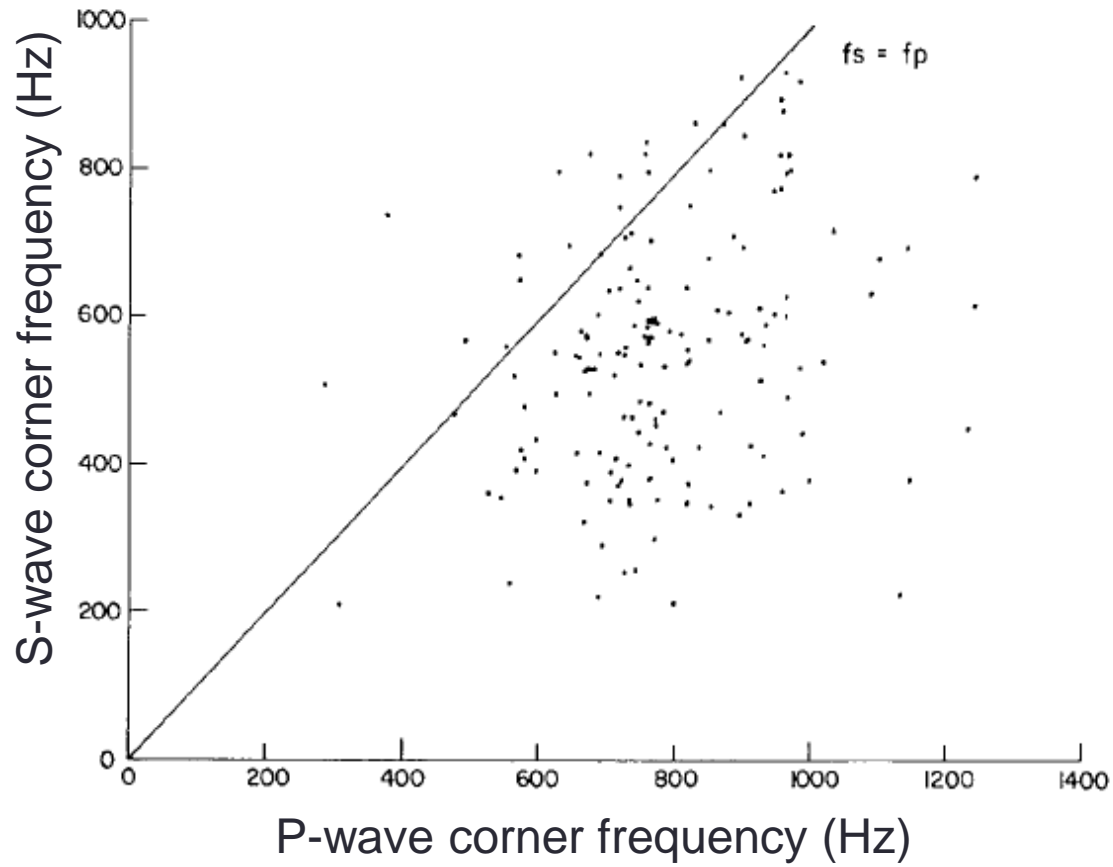
Every downhole event in top 10 events by magnitude has a corresponding event found by the surface event found within 0.5.

Likelihood that this match between the surface and downhole origin times is random is less than  $10^{-18}$ . This is NOT a coincidence!

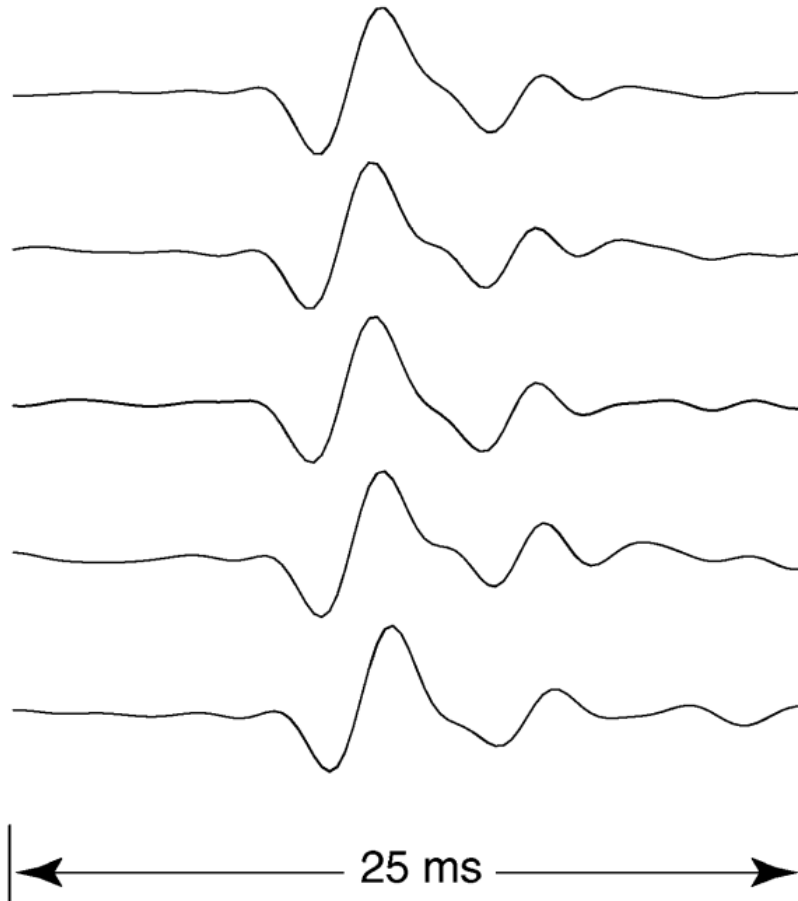
# Downhole-Surface Locations map view



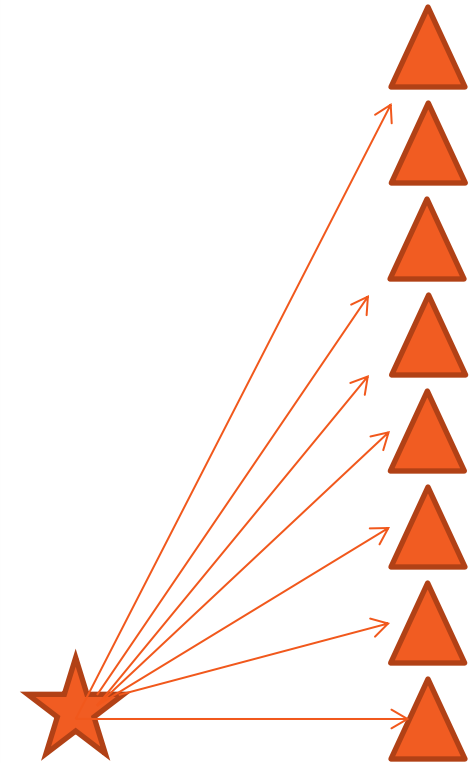
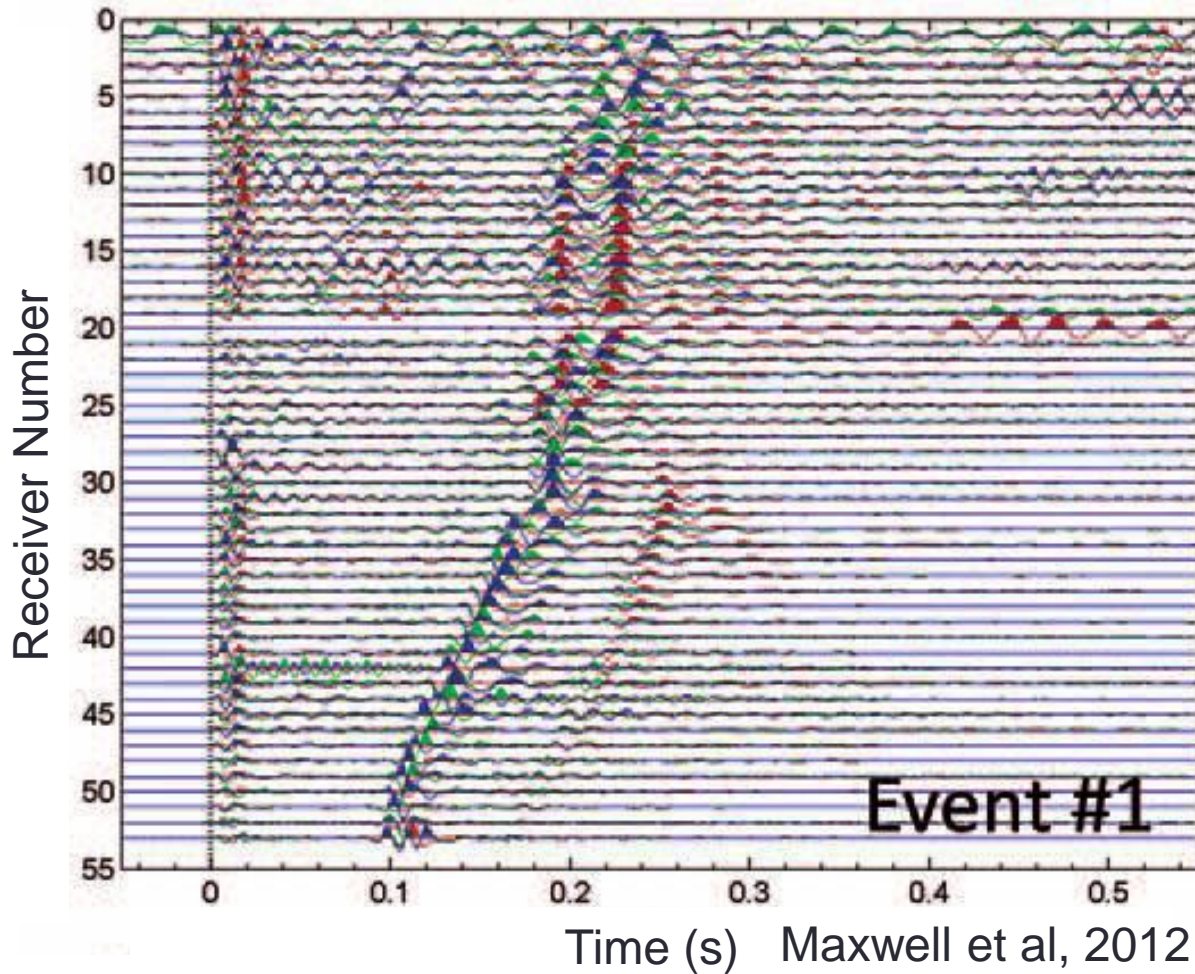
Note that corresponding locations appear to be relatively close - by 300 ft to the east and 100 ft south – this confirms a correct match between events. The surface location is not likely to be shifted, so shifted are most likely the downhole locations.



Pearson, C, JGR 1981



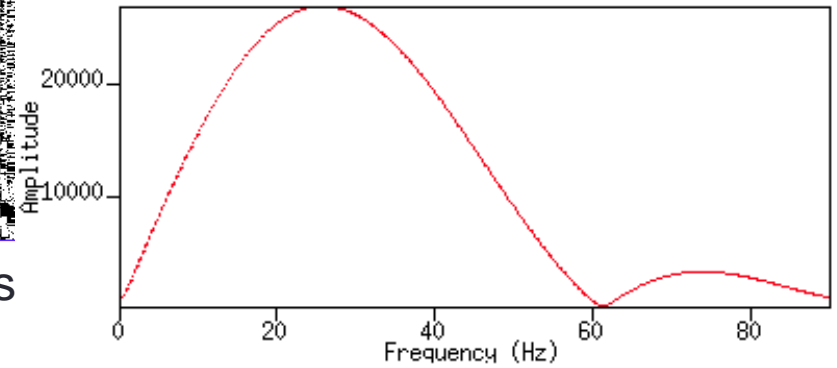
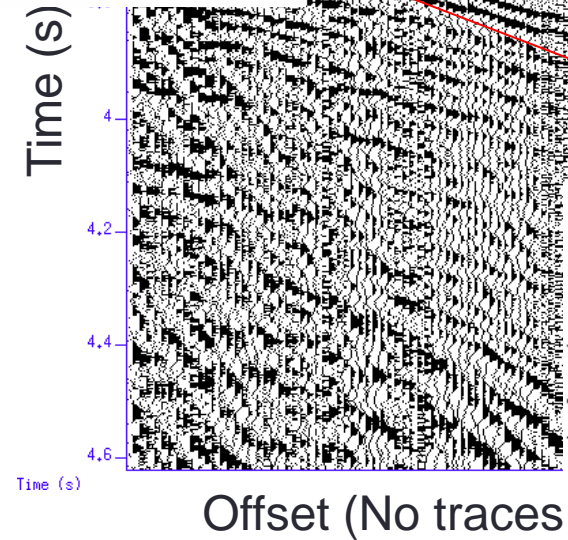
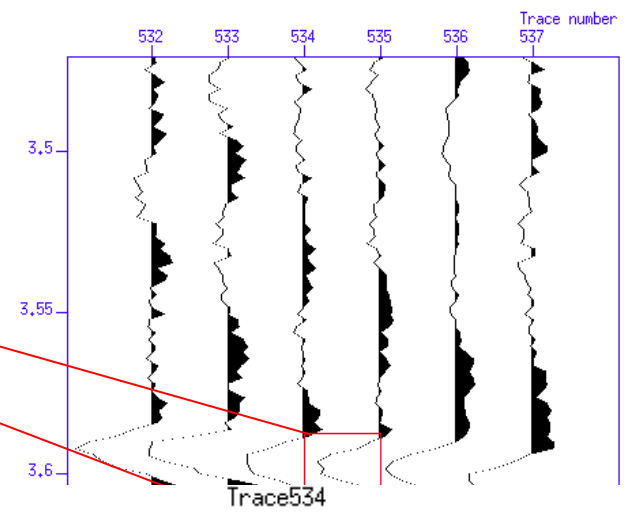
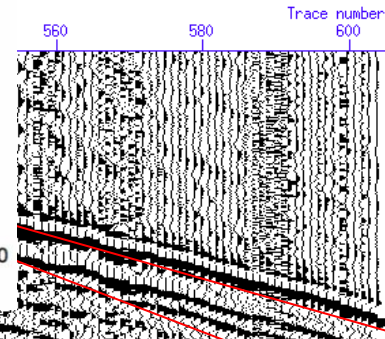
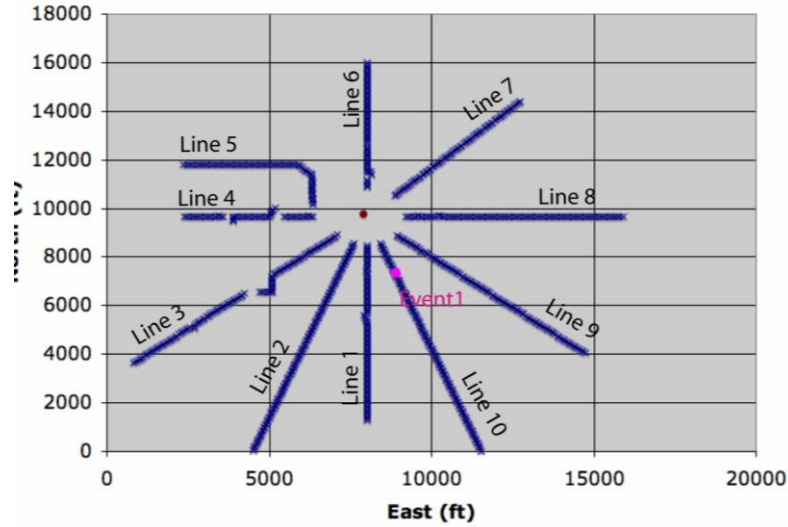
Signal duration  $\sim 5$  ms ( $\sim 200$  Hz)



Note the widening of signal from 100 Hz @ Rec 52 to 50 Hz @ rec 2

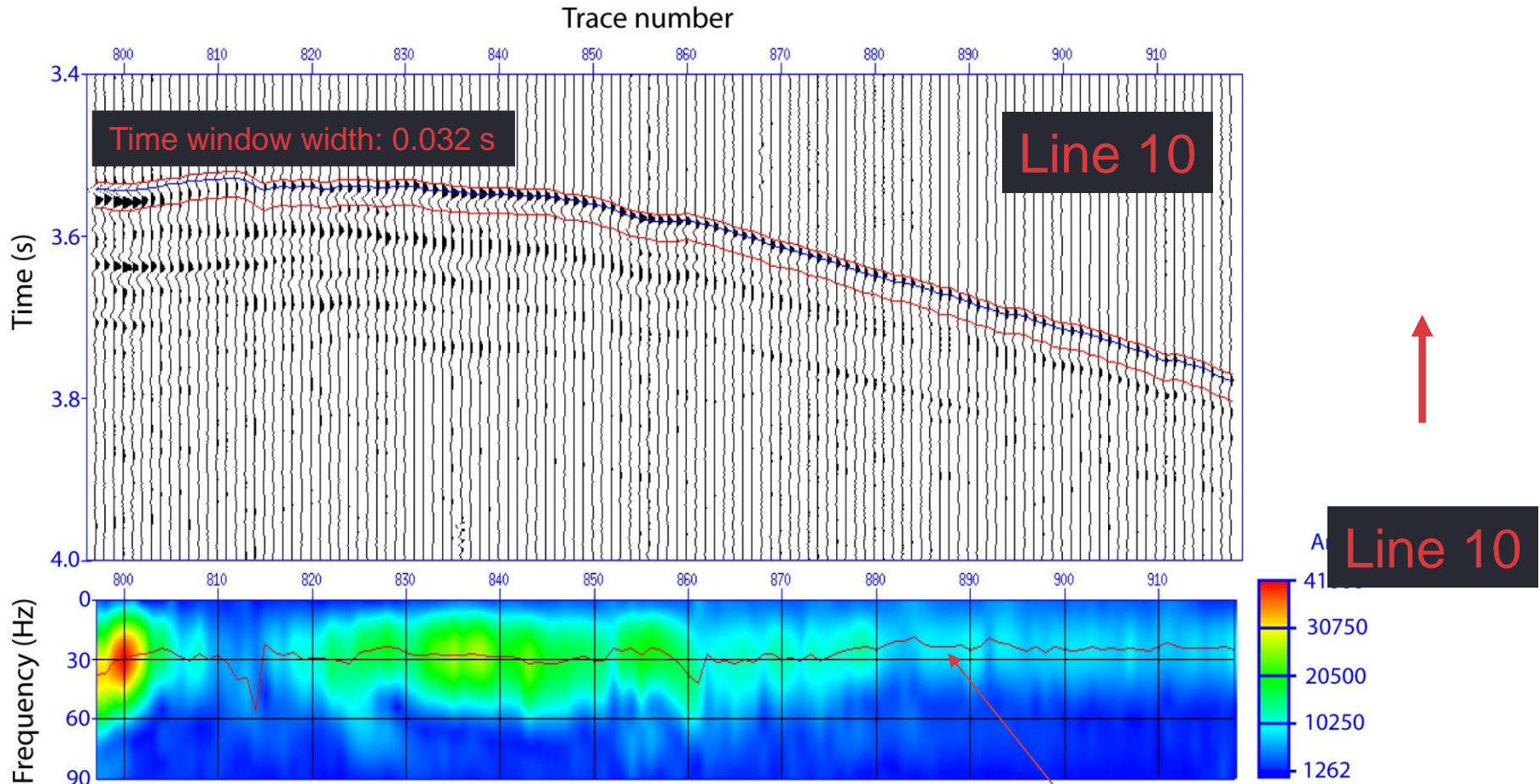
# Surface monitoring: sedimentary basins

Location map



# Surface monitoring: sedimentary basins

Data from line 10 (1C). Raw data

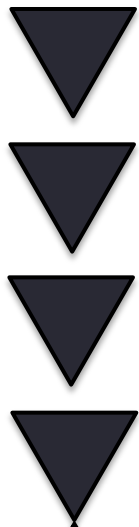


Red line: frequency peak of the spectrum for each seismic trace

Coherent arrival shows higher frequency content at near offsets (earliest arrivals).  
Peak frequency decreases with increasing offset.

# Source mechanisms - motivation

12 geophones



10 m (32 ft)

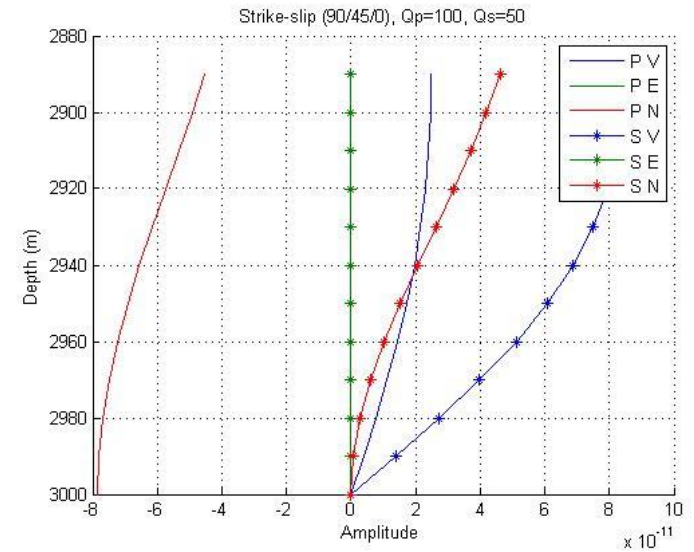
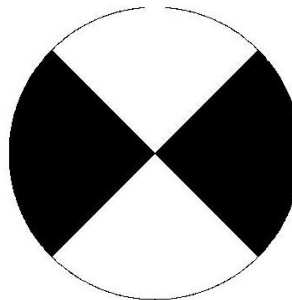
200 m (~656 ft)



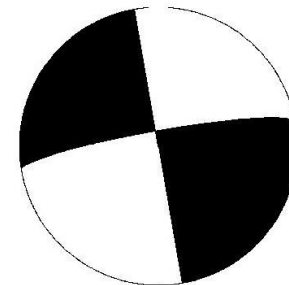
Dip:  $90^\circ$   
Strike:  $45^\circ$   
Rake:  $0^\circ$

Synthetic dataset

Input  
( $Q_p=100$   $Q_s=50$ )

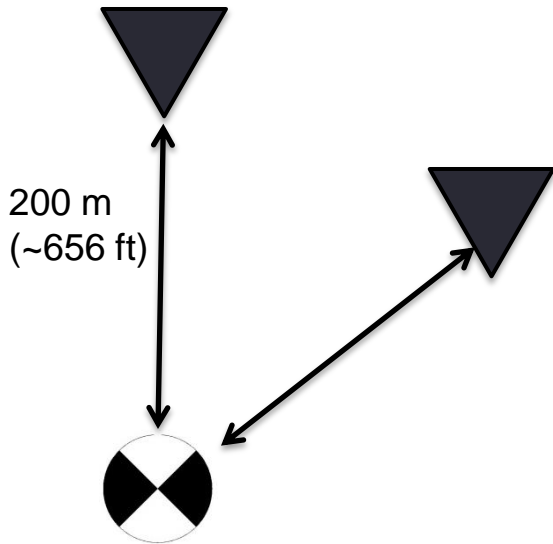


Inversion result  
(no Q:  $Q_p=1000$ ,  $Q_s=1000$ ):



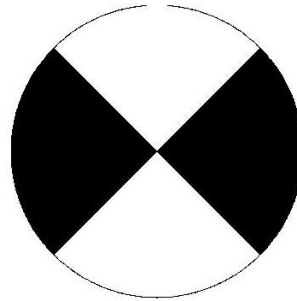
Dip:  $90^\circ$   
Strike:  $165^\circ$   
Rake:  $170^\circ$

Map view

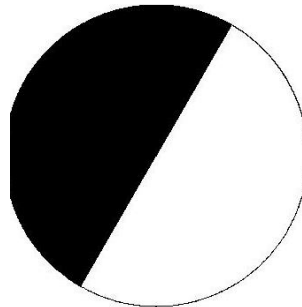


Assuming 100 Hz data

Input  
( $Q_p=100$   $Q_s=50$ )

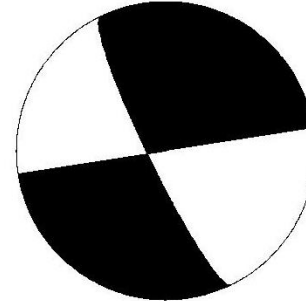


Dip:  $90^\circ$   
Strike:  $45^\circ$   
Rake:  $0^\circ$

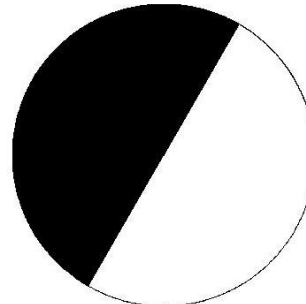


Dip:  $90^\circ$   
Strike:  $30^\circ$   
Rake:  $90^\circ$

Inversion result  
(no Q:  $Q_p=1000$ ,  $Q_s=1000$ ):

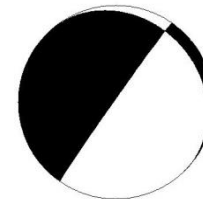


Dip:  $81^\circ$   
Strike:  $147^\circ$   
Rake:  $160^\circ$



Dip:  $90^\circ$   
Strike:  $30^\circ$   
Rake:  $90^\circ$

Single Well inversion



Dip:  $88^\circ$   
Strike:  $45^\circ$   
Rake:  $80^\circ$

# Theory - methodology

Observations =

Source function \*

Propagation effects \*

Receiver Response



This study

Earthquakes cause DC offset – their signal contains 0 Hz frequency at amplitude of particle displacement:



The upper part of the frequency spectra is limited by:

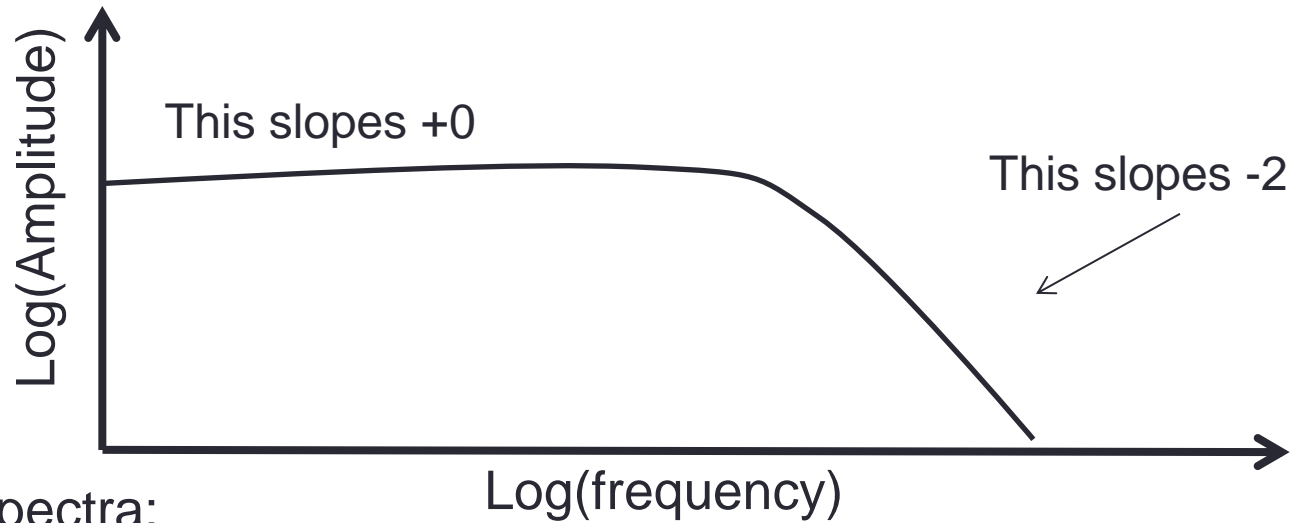
1. Rise time
2. Rupture time



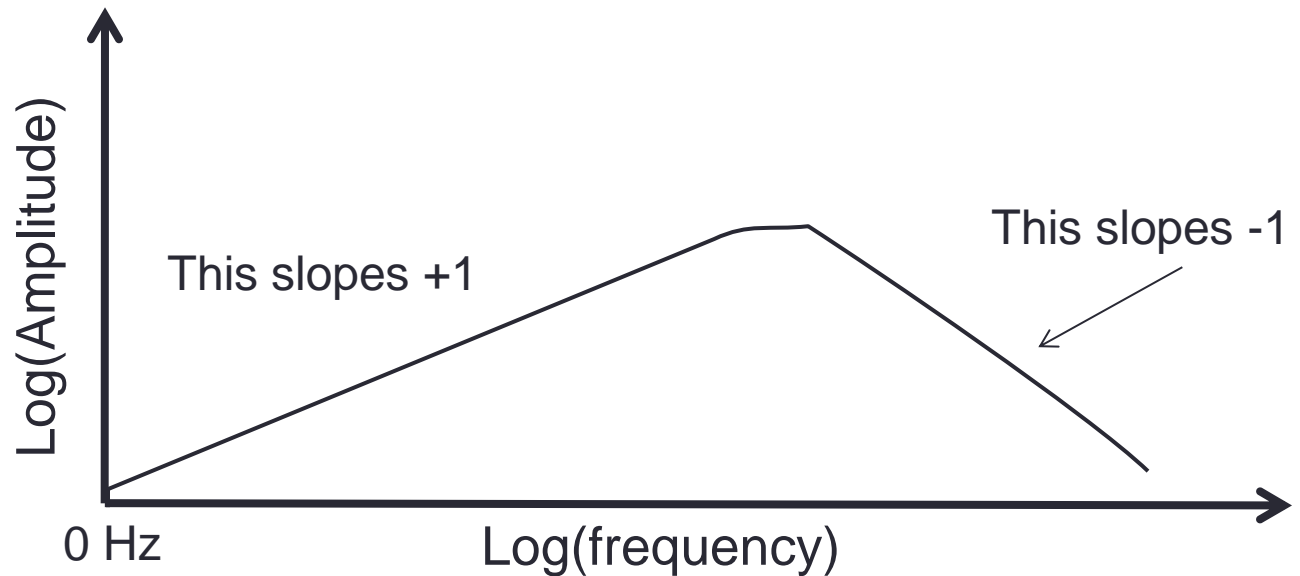
Corner frequency

# Source spectra

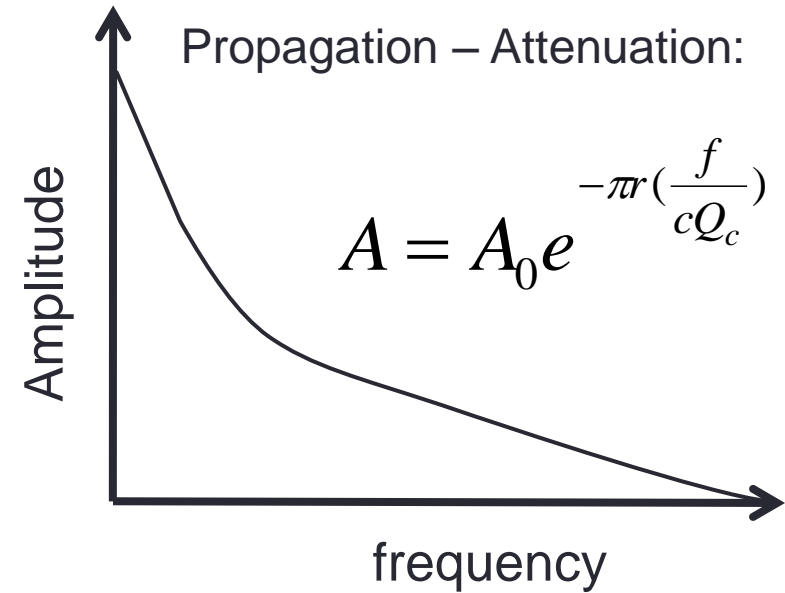
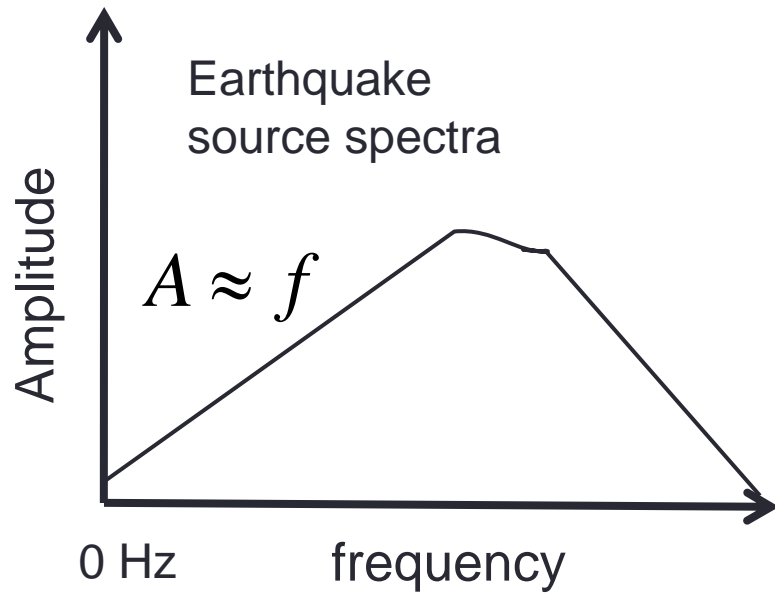
Particle displacement spectra:



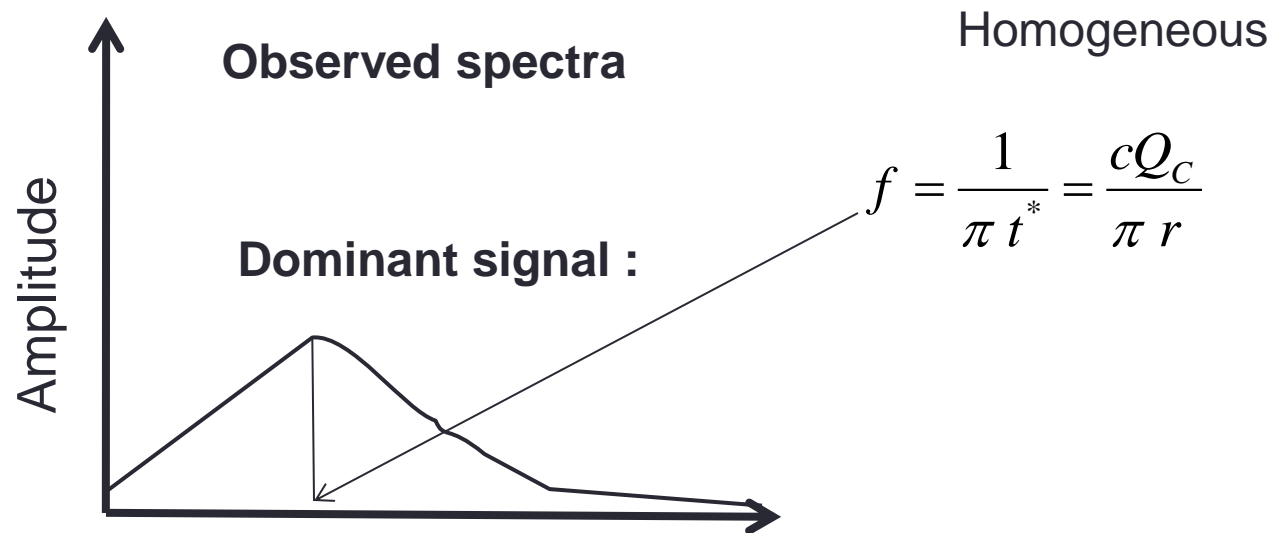
Particle velocity spectra:



# Source and propagation



$f$  ...is frequency  
 $r$ ... is distance  
 $c$ ... is velocity  
 $Q_c$ ... is attenuation coef.  
 $t^*$  ... is attenuation normalized time



For  $f < f_c$

$$A(f) \approx A_0 f e^{-\pi f t^*} \stackrel{\text{hom}}{=} e^{-\pi r \left(\frac{f}{c Q_c}\right)}$$

$$0 = e^{-\pi f t^*} - f \pi t^* e^{-\pi f t^*}$$

$$f_{peak} = \frac{1}{\pi t^*} \stackrel{\text{hom}}{=} \frac{c Q_c}{\pi r}$$

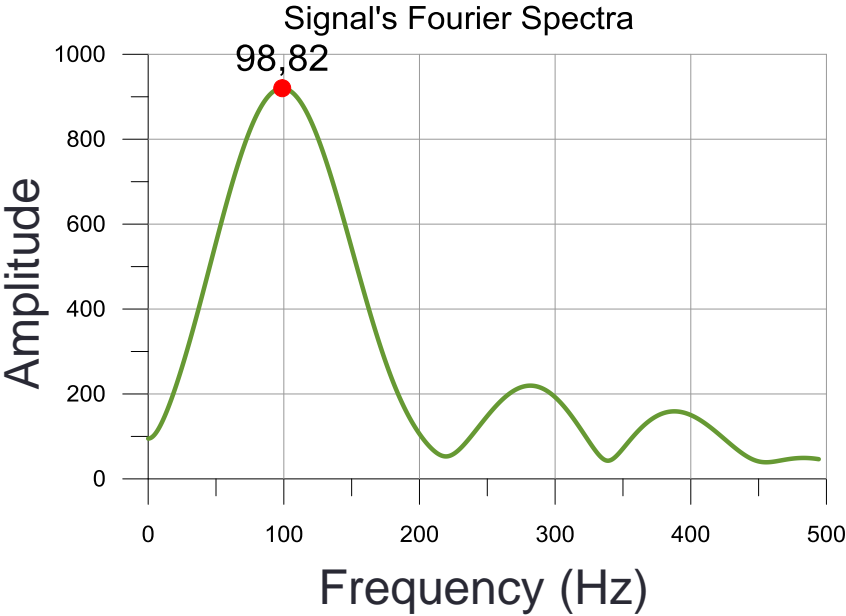
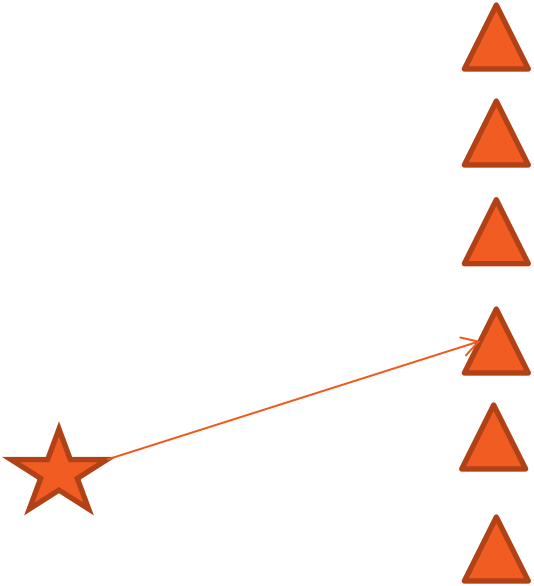
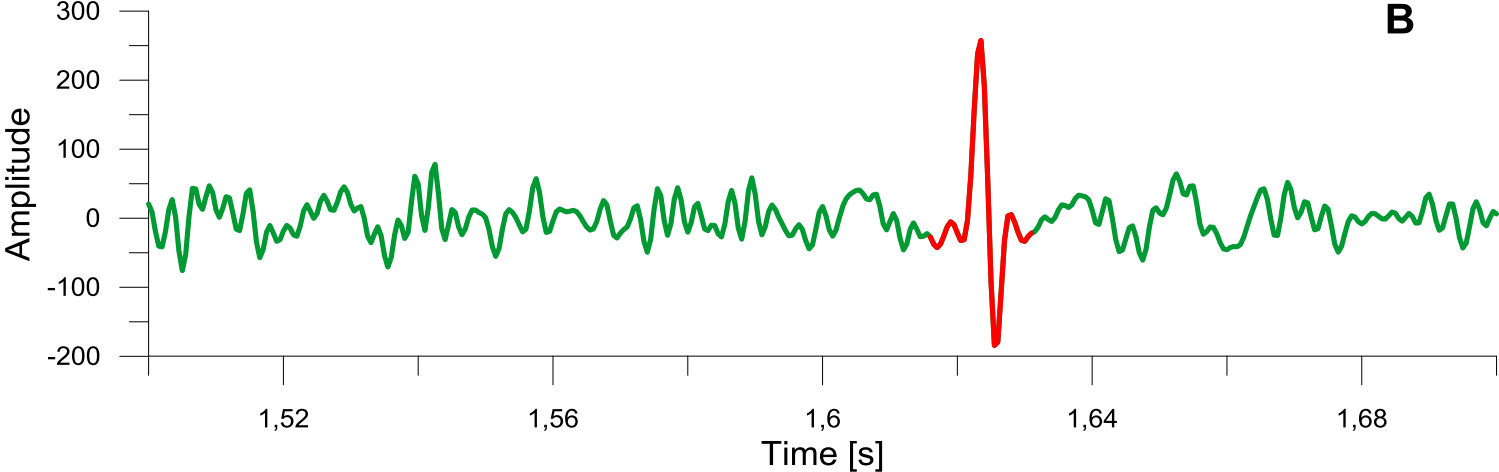
The peak frequency of a seismogram is the frequency corresponding to the maximum amplitude in Fourier spectra of the particle velocity.

# Case studies

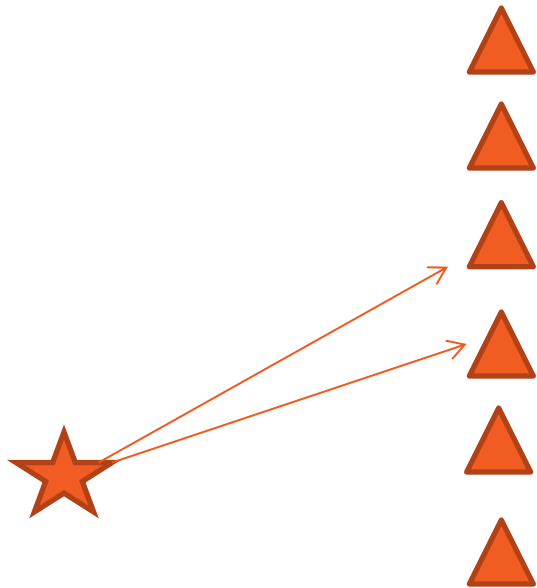
Assuming  $Q_p = Q_s = 50$

Distance [meters]	P-waves [Hz]	S-waves [Hz]
100	800	400
300	267	133
2000	40	20
4000	20	10

# Benchmarking : downhole dataset with spectral ratio



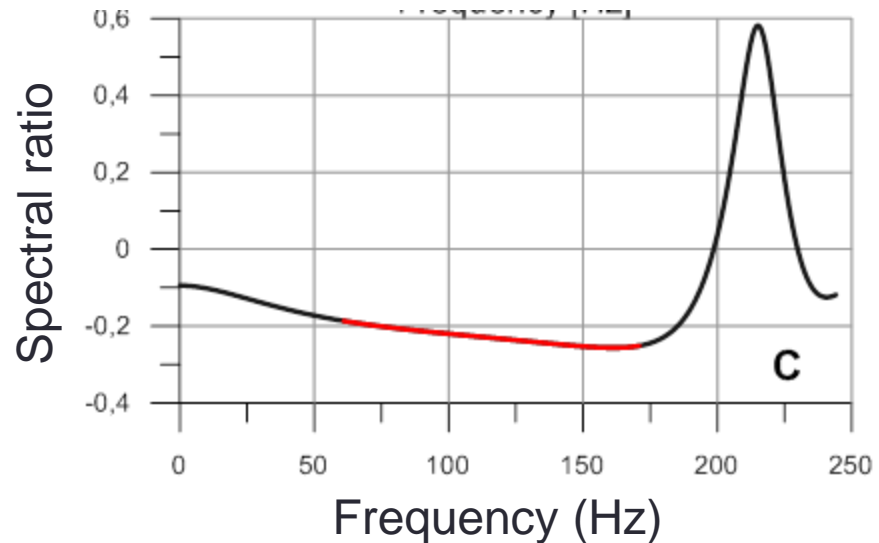
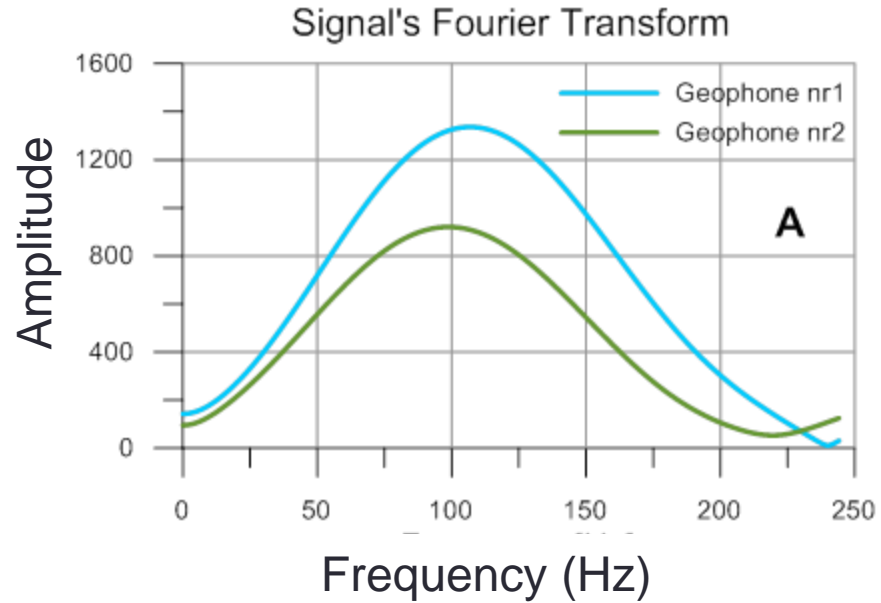
# Spectral ratio – benchmark methodology



Spectral ratio is not dependent on source radiation.

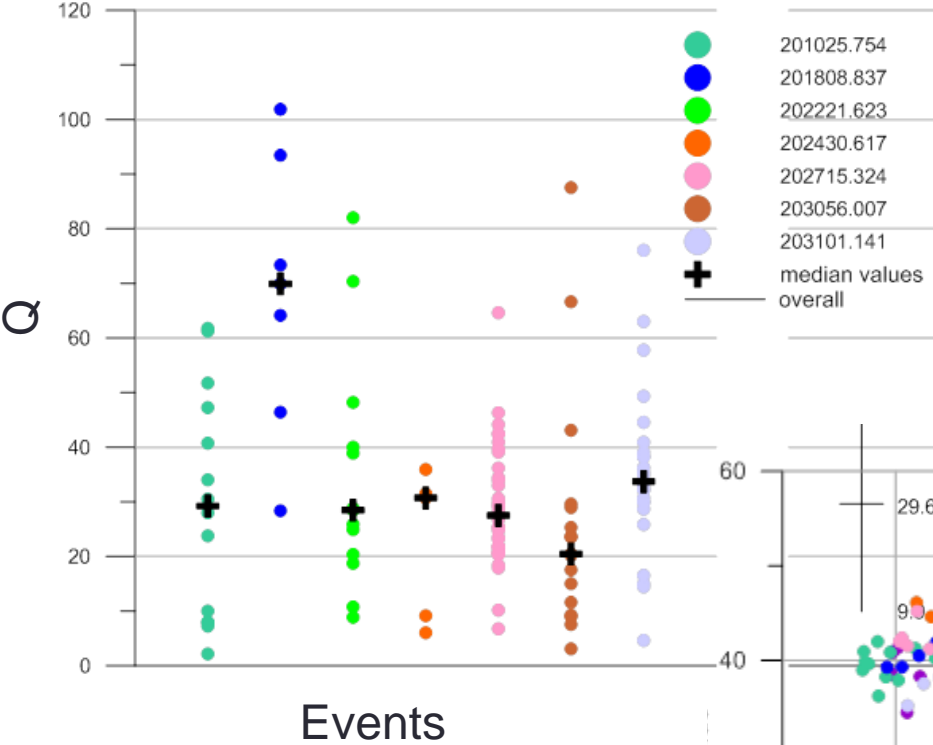


Hence it is not limited by the corner frequency assumption.

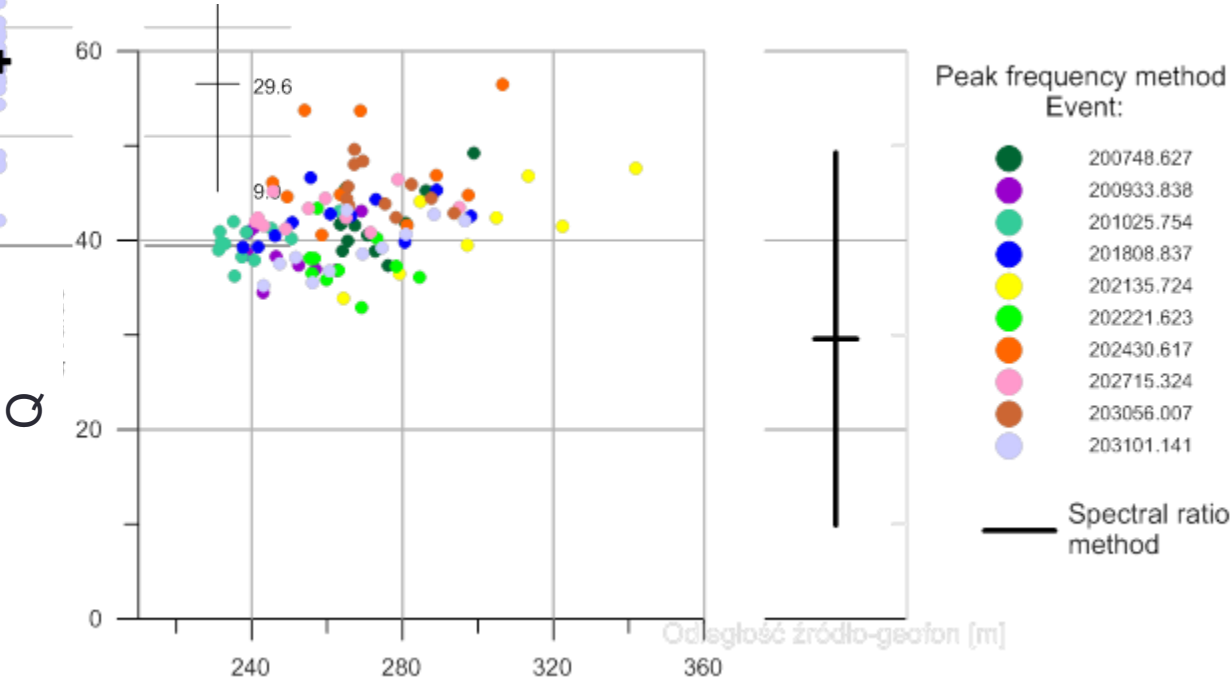


# Benchmark: spectral ratio vs peak frequency

### Spectral ratio – P-waves



### Peak frequency – P-waves

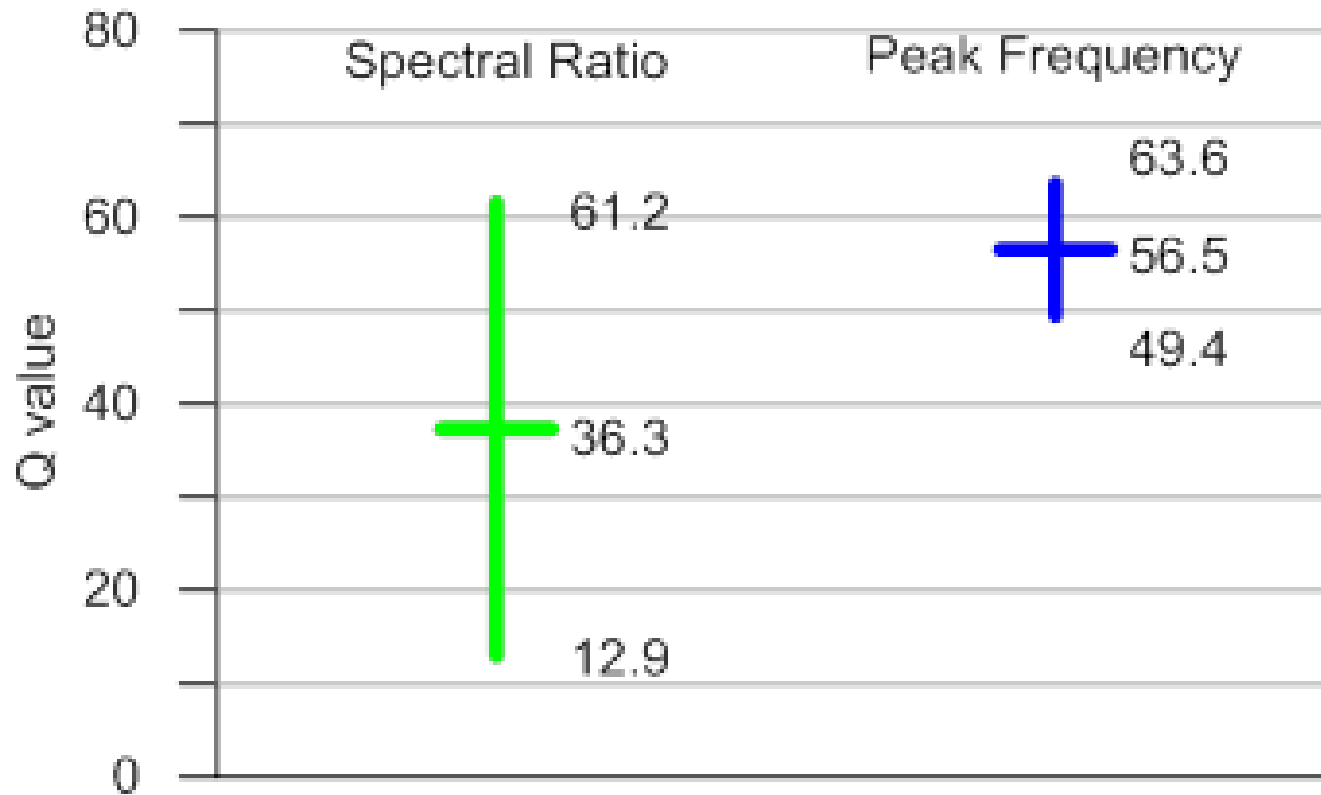


Distance (m)

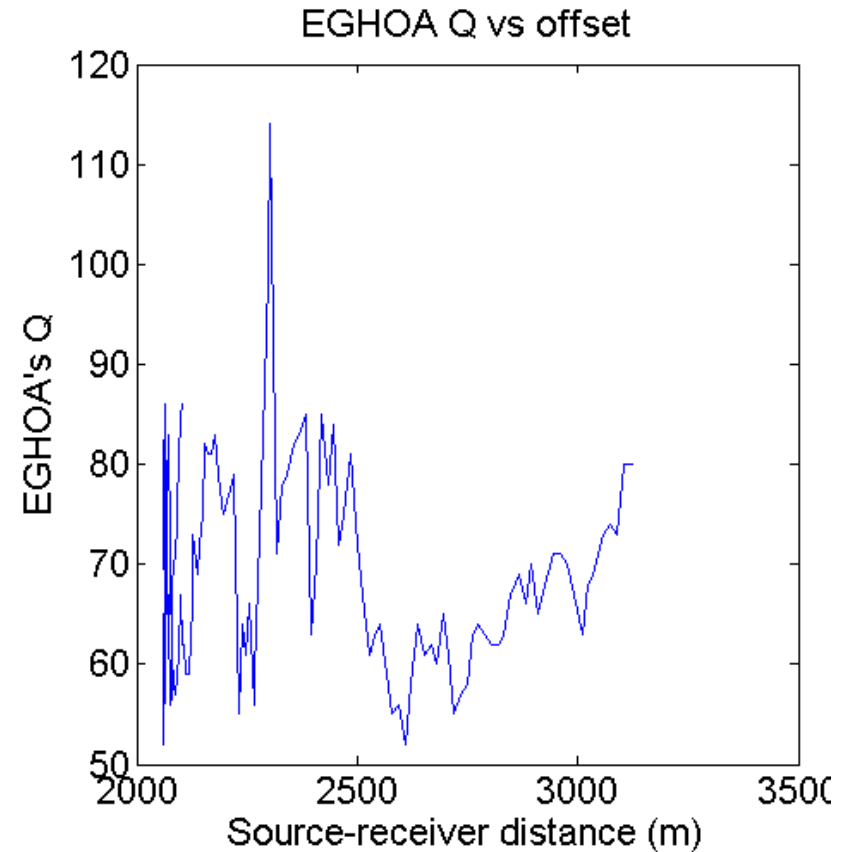
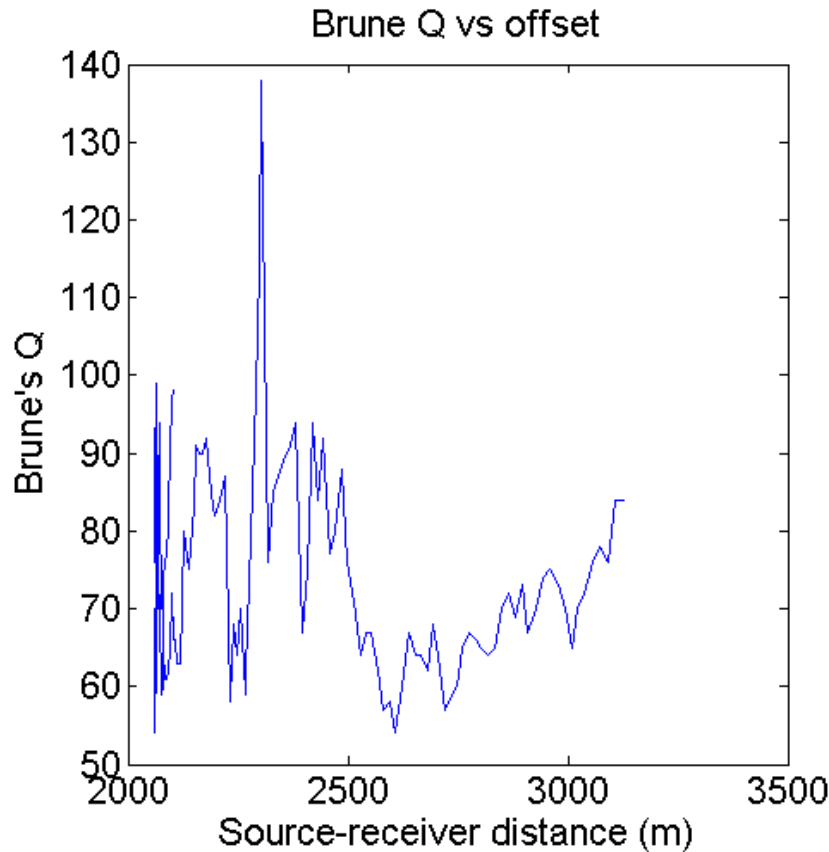
Odsleděcí zdrojlo-geofon [m]

## S-waves

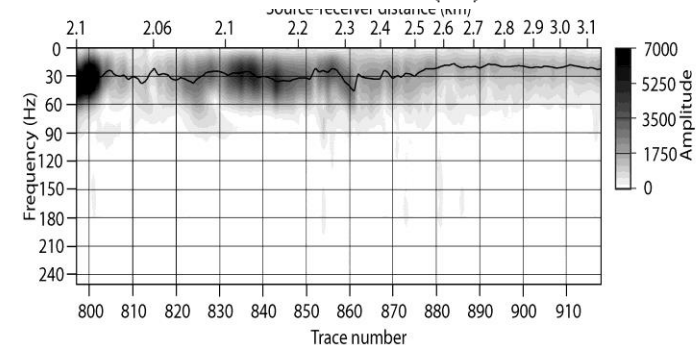
### Peak frequency & spectral ratio comparison



# To Brune or not to Brune

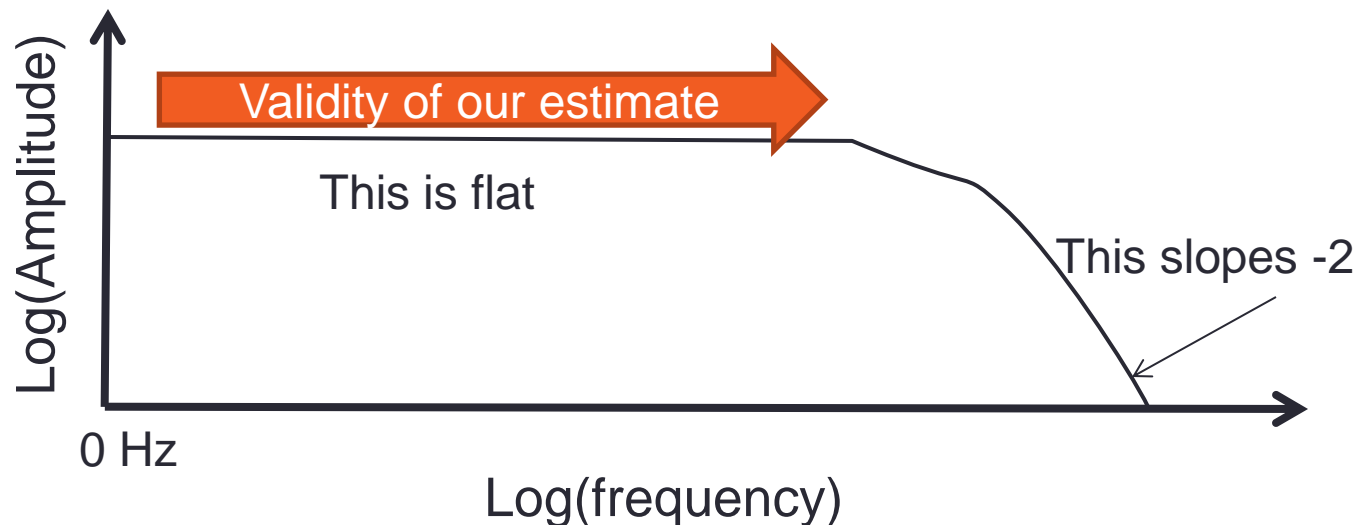


$$Q_c \stackrel{\text{hom}}{=} \frac{\pi r f_{peak}}{c}$$



## Limitations – corner frequency

# Corner frequency

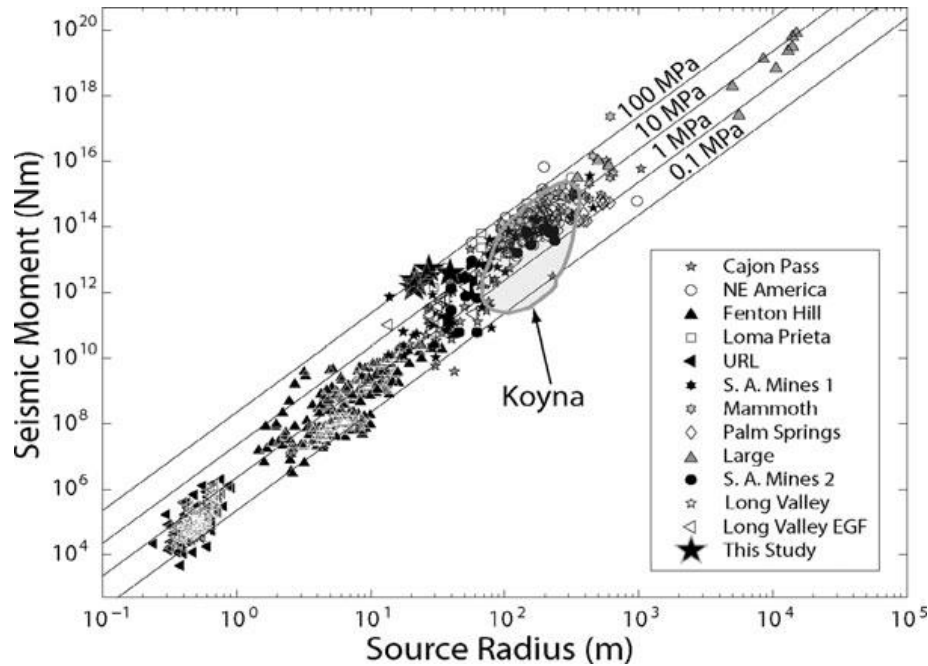


$$f_c = \frac{1}{2\pi} C_s V_s \sqrt[3]{\frac{16 \Delta\sigma}{7 M_0}}$$

where  $\Delta\sigma$  is stress drop,  $V_s$  is S-wave velocity and  $C_s$  is a constant varying from 1.53 to 1.85 for rupture speed to S-wave speed ratios from 0.5 to 0.9, respectively.

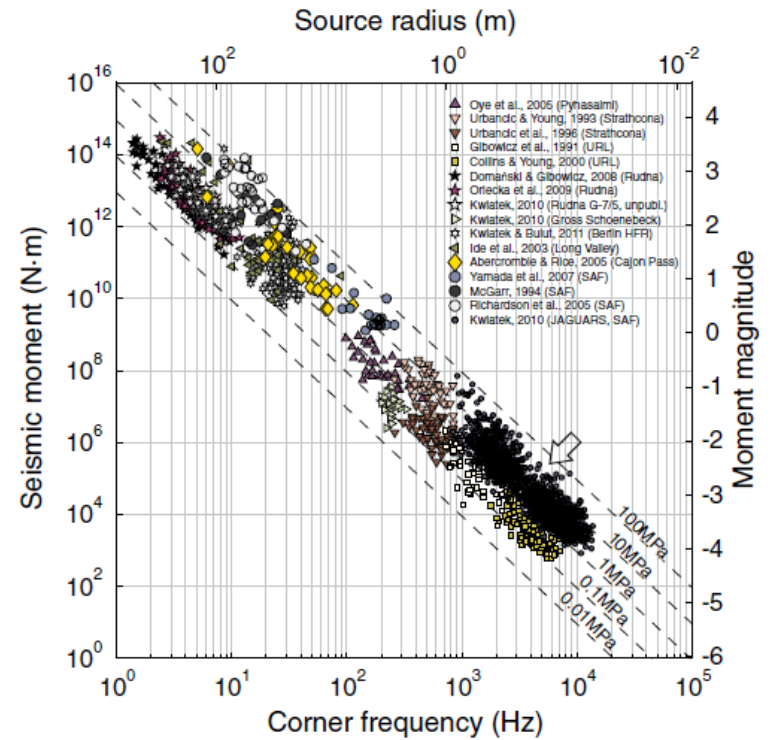
# Moment, stress drop and radius

Mostly fluid

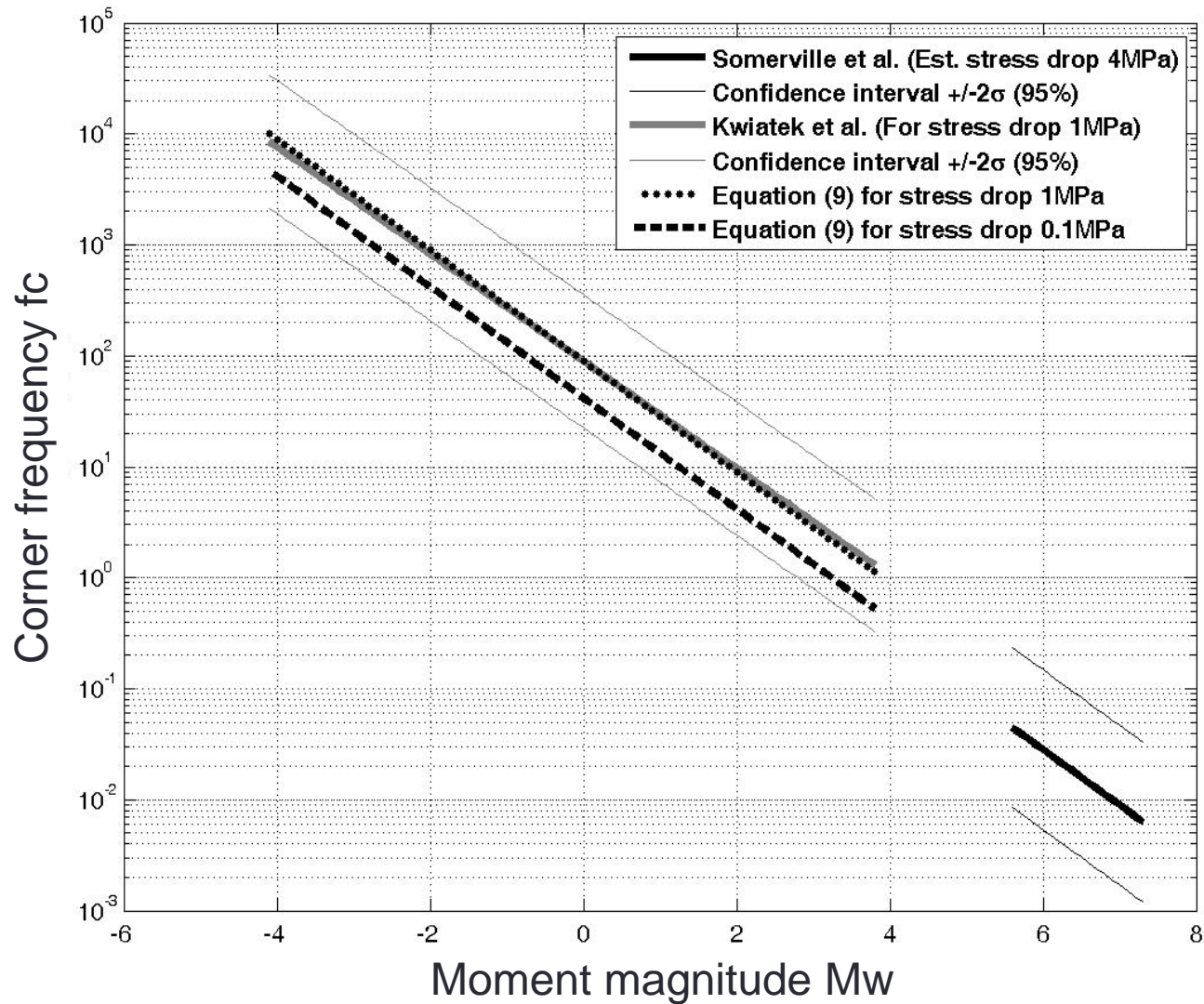


J. Tomic, et al. 2009, Geophys. J. Int.

Mining



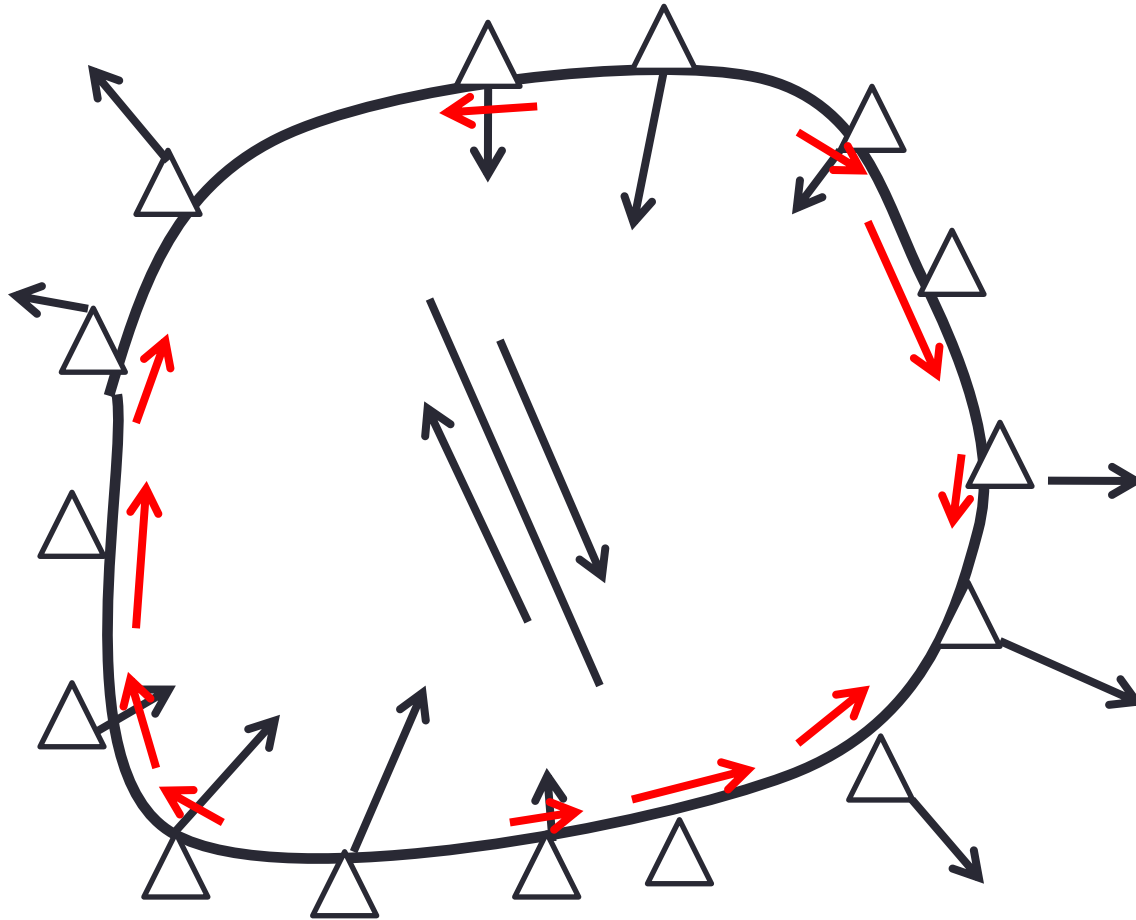
Kwiatek, et al. 2011, BSSA



- ▶ Peak frequencies in observed microseismic data is determined by attenuation, not the corner frequencies
- ▶ Frequency content of microseismic events observed from surface and downhole arrays can be explained by attenuation
- ▶ Peak frequency provides realistic estimates of effective Q, Q of 50-100 explain observed data
- ▶ Peak frequency Q inversion is consistent with spectral ratio method and provides less scattered estimate of Q

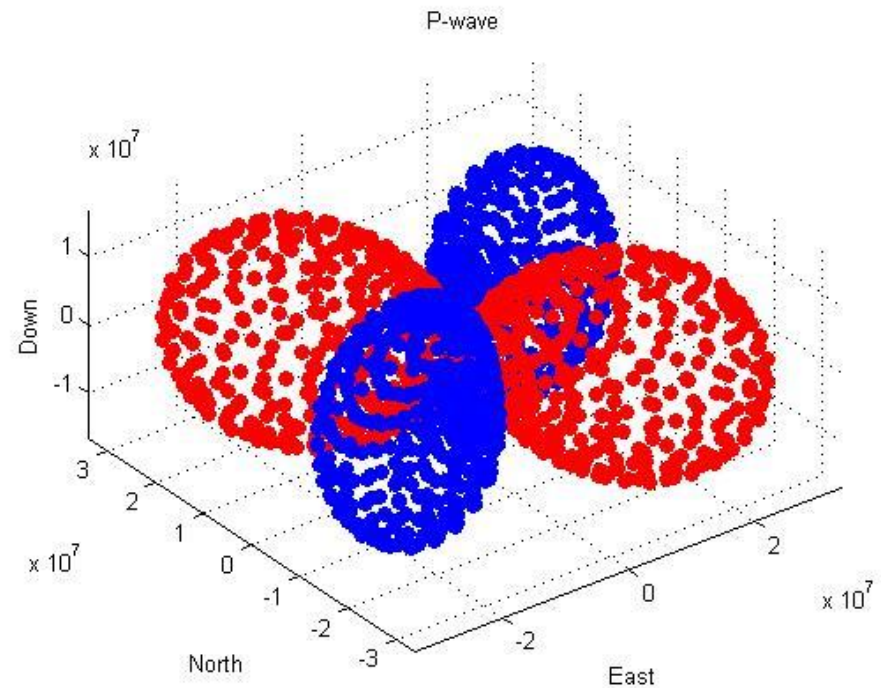
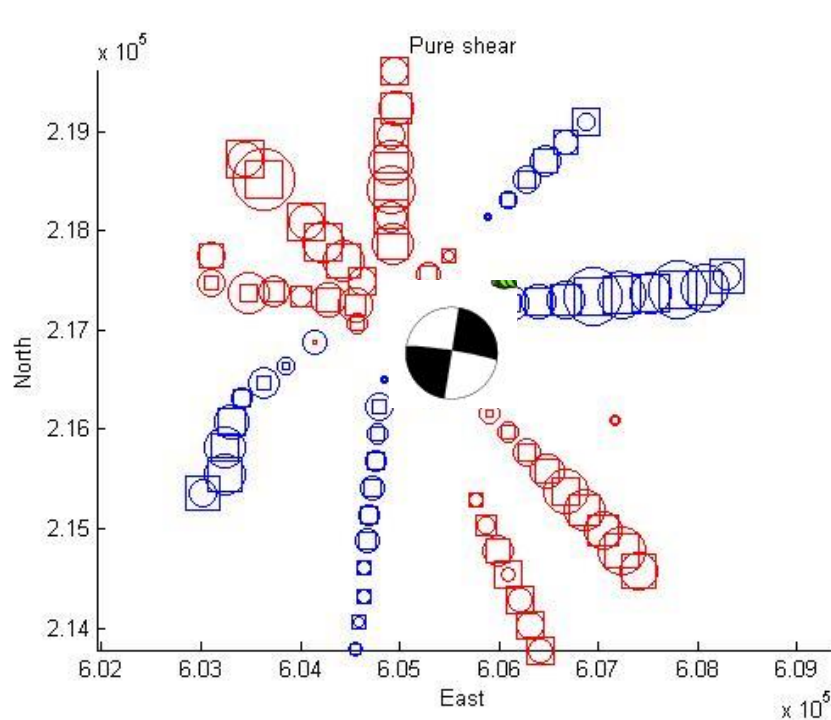
$$f_{peak} = \frac{1}{\pi t^*} \stackrel{\text{hom}}{=} \frac{cQ_c}{\pi r}$$

- Thank you for your attention
- Ivo Oprsal, Davide Gei, Miroslav Hallo, Milosz Wcislo



# Typical strike-slip event at surface

Inverted: Pure Shear (90/190/-5)



Blue and red colors represent a positive and a negative first motion. Circles are the data and squares are synthetics prediction by a source mechanism.