Volcanic Seismic Earthquakes at Mount St. Helens Exhibit a Constant Seismically Radiated Energy per Unit Size.

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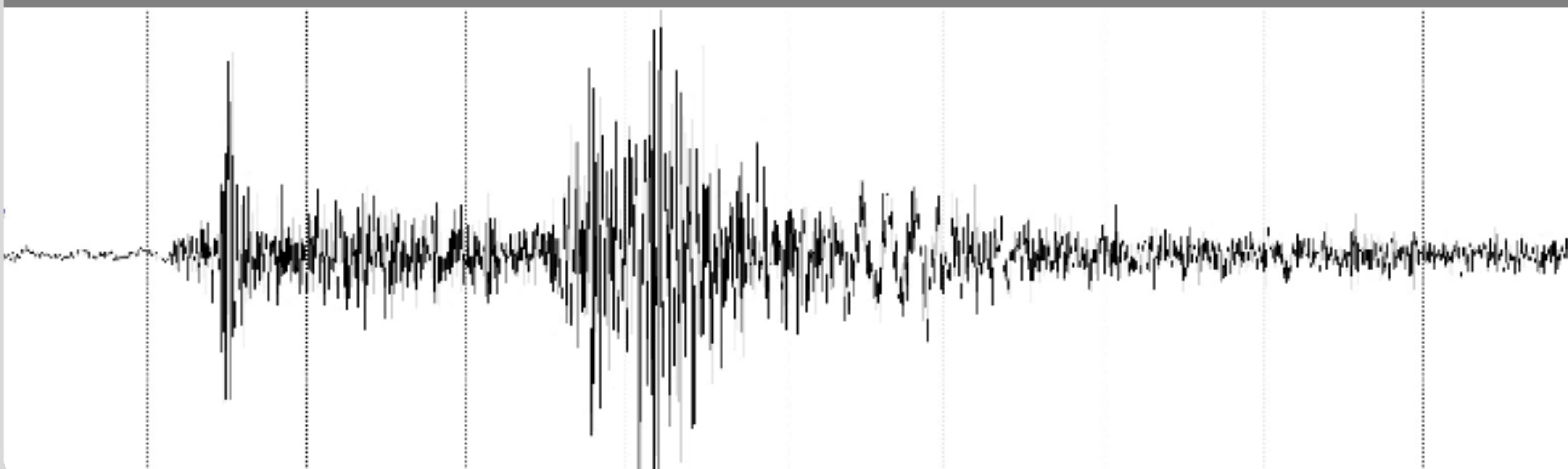

Question: What is the size/duration scaling of low-frequency volcanic seismic events?

Is the scaling similar to tectonic earthquakes?

- Observations from laboratory simulations of low-frequency volcanic seismic events
- Observations of low-frequency earthquakes observed at Mount St. Helens in September, 2006

Talk Outline

1. **Laboratory data**
   - Two rock deformation experiments
2. **Field data**
   - Temporary deployment (September 2006), 6073 earthquakes
3. **Methods: spectral ratio approach**
   - Cross correlation coefficients => 8 event families
   - Estimate $M_0 - f_c$ values, scaling
4. **Observations**
   - $M_0 - f_c$ scaling observations
   - Seismically radiated energy
5. **Conclusions**

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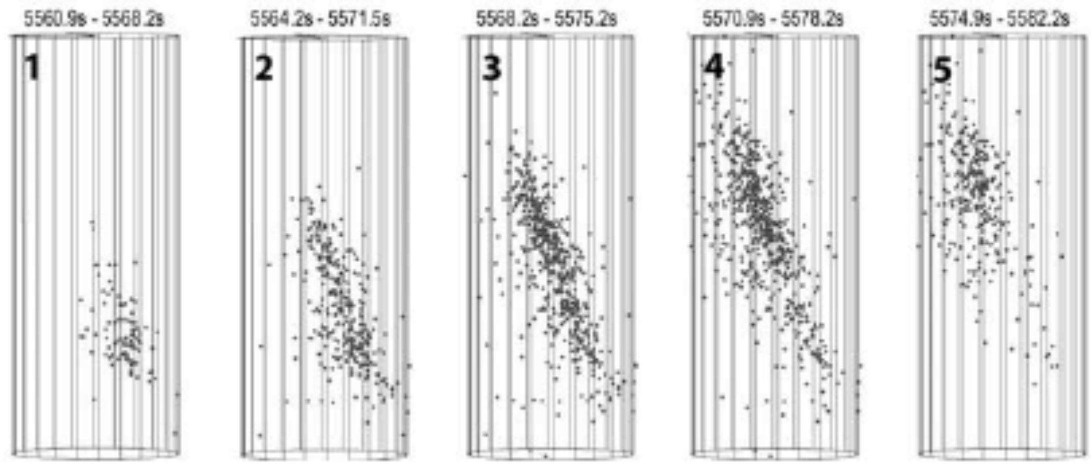
Laboratory data:
How is laboratory volcano seismicity simulated?
Rock deformation experiments

Five acoustic emission (AE) event location time windows



- Two rock deformation experiments: stiff, servo-controlled triaxial testing machine at UCL
  - under dry conditions (gas saturated)
  - under water saturated conditions
  - constant axial strain rate: $5 \times 10^{-6}\ s^{-1}$
  - 10 PZT sensors arrayed on sample

- Rock sample: Etna basalt
  - porphyritic alkali lava-flow basalt
  - 3.8% porosity, ρ = 2860 kg/m^3
  - 40 mm diameter, 100 mm length
  - P-wave velocity: 3250 m/s

Laboratory data: **What types of seismic signals are produced?**

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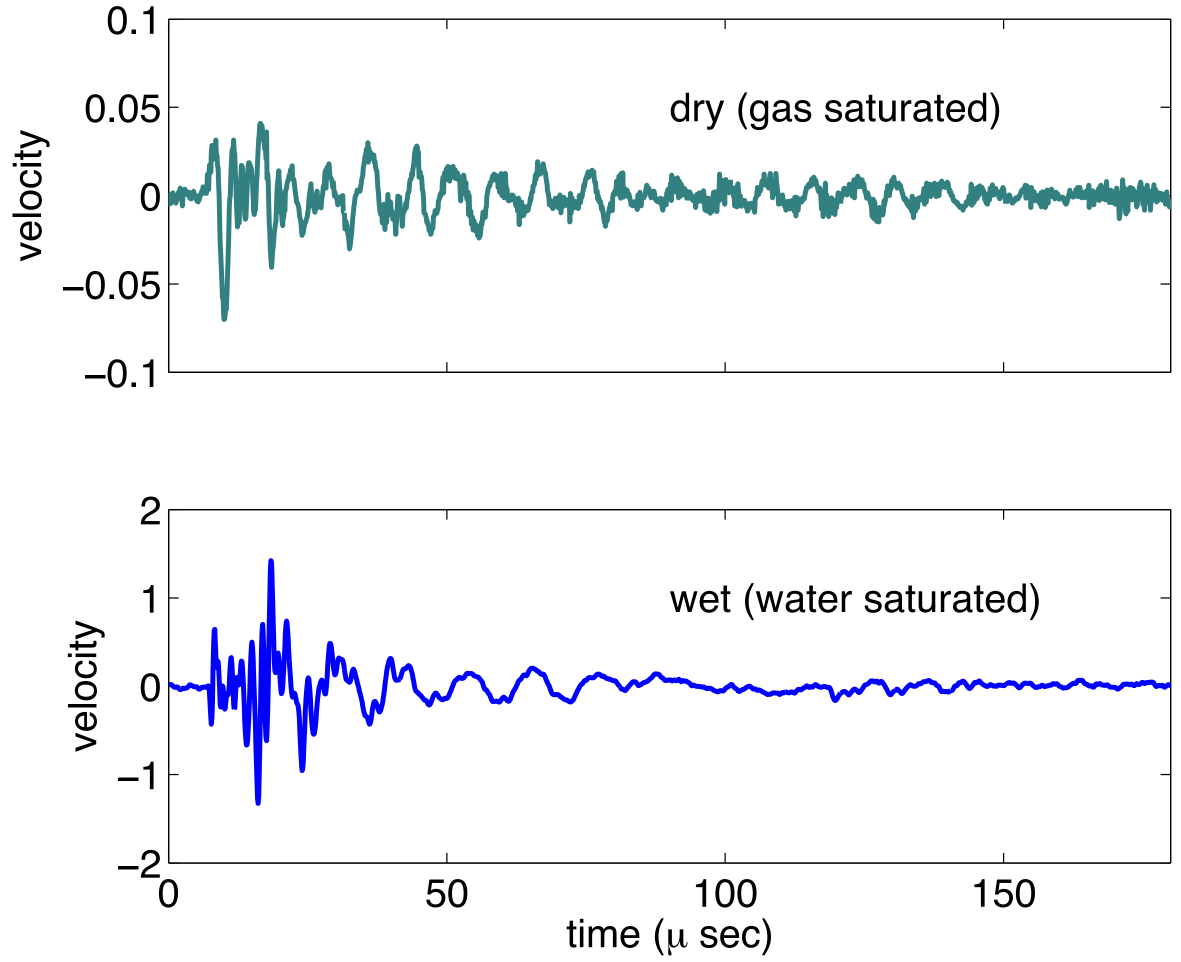
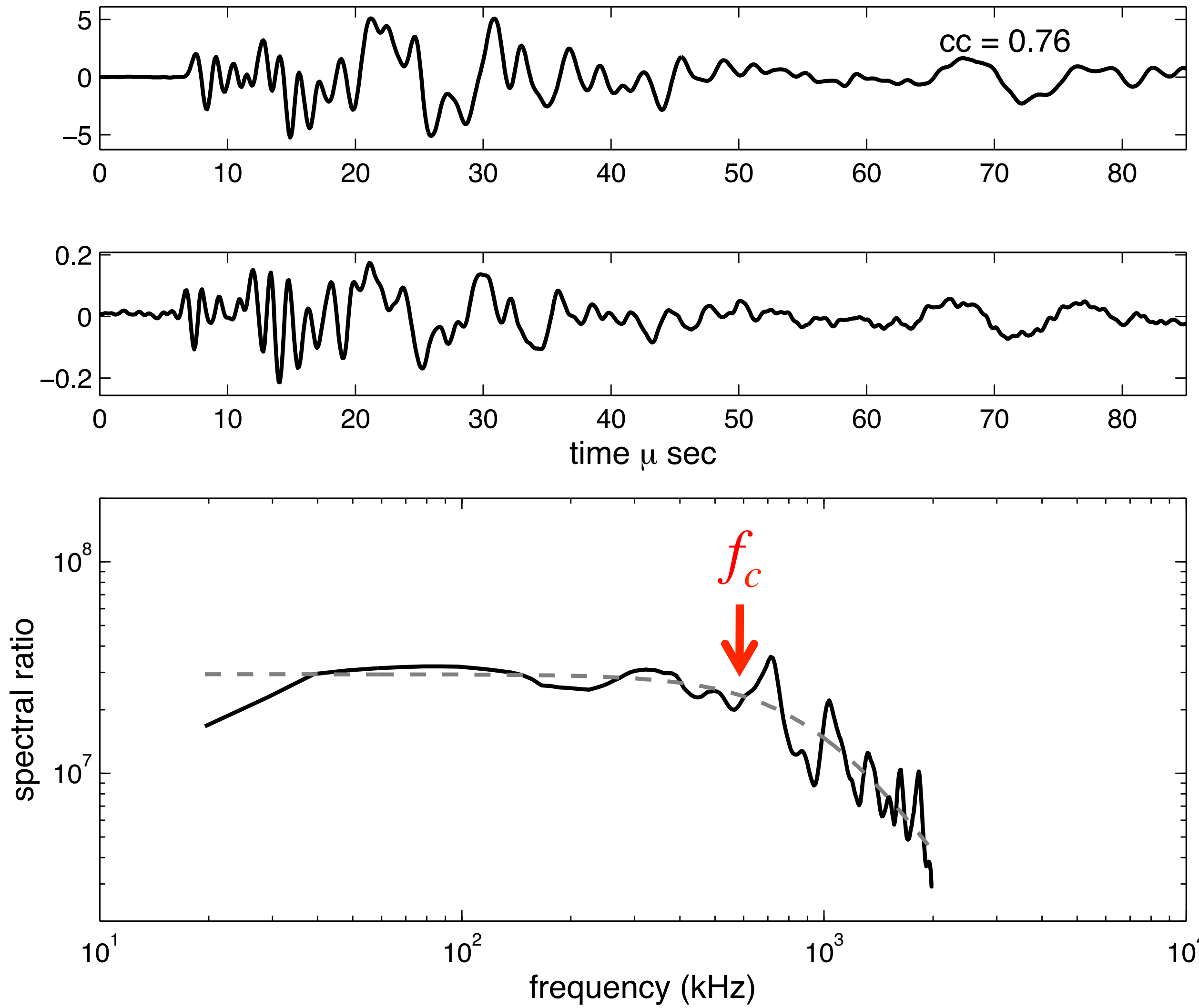
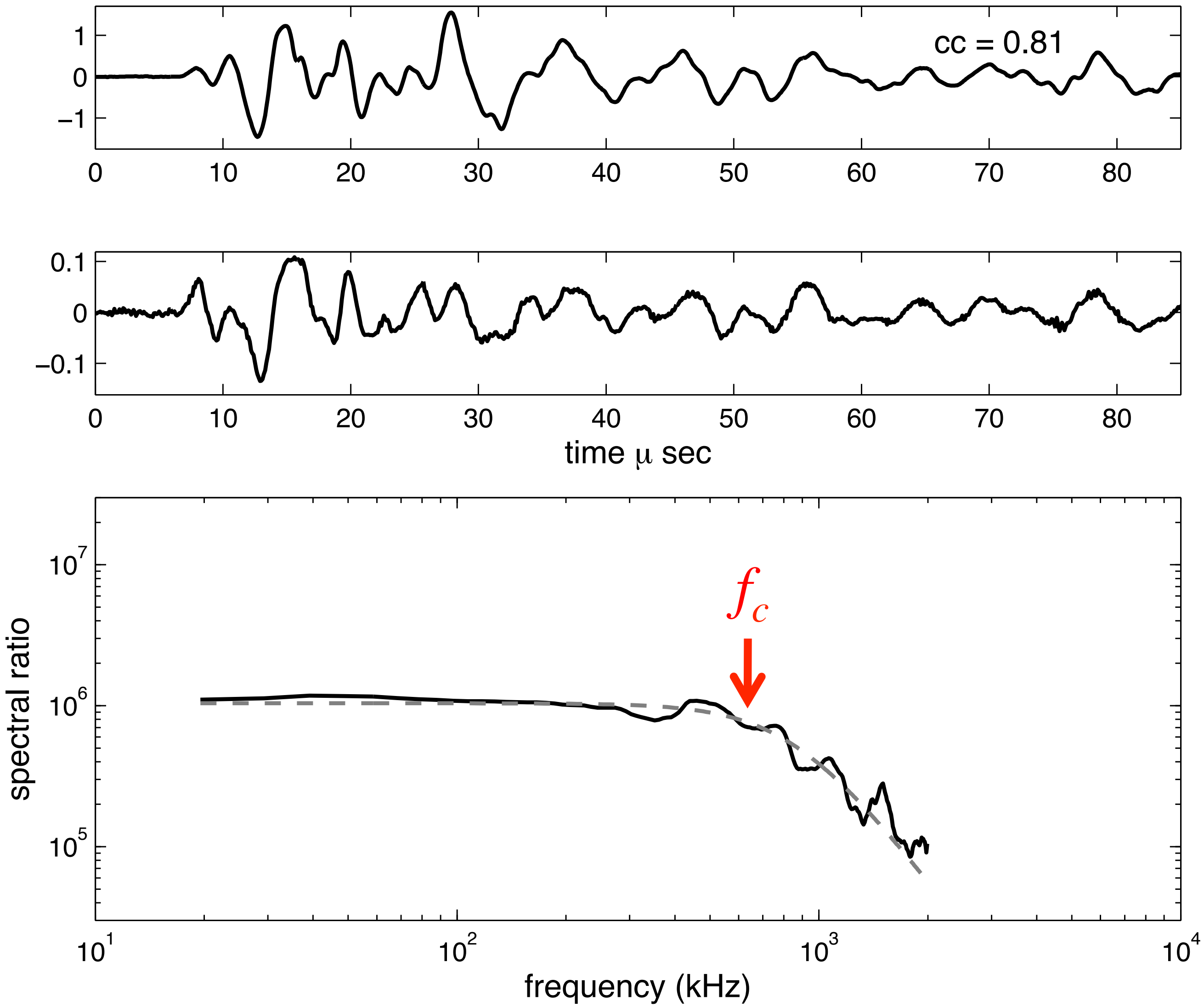


We use the spectral characteristics of the low-frequency earthquakes to calculate the size-duration scaling

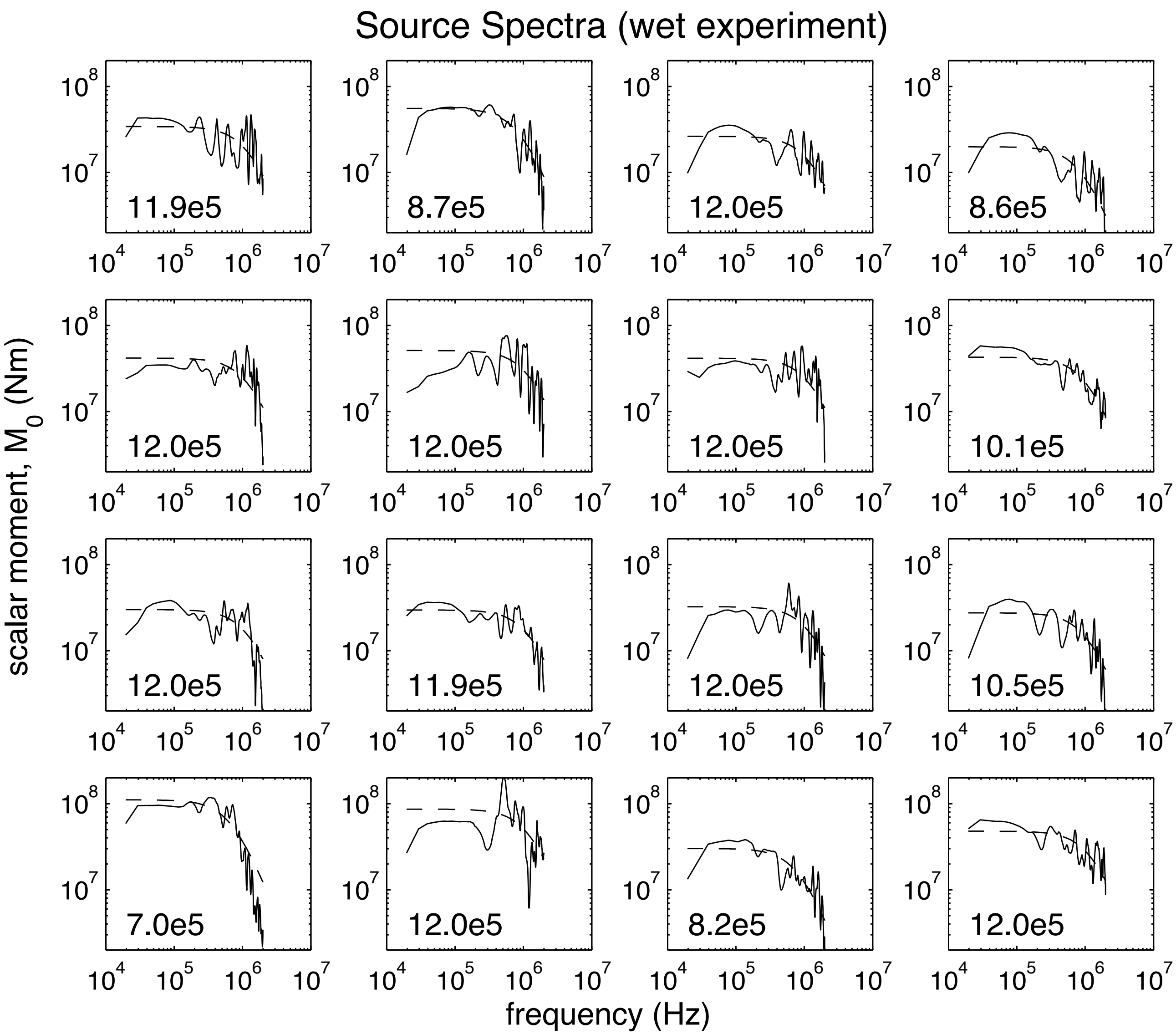
Methods: Empirical Green's Function
wet experiment



Methods: Empirical Greens function
dry experiment

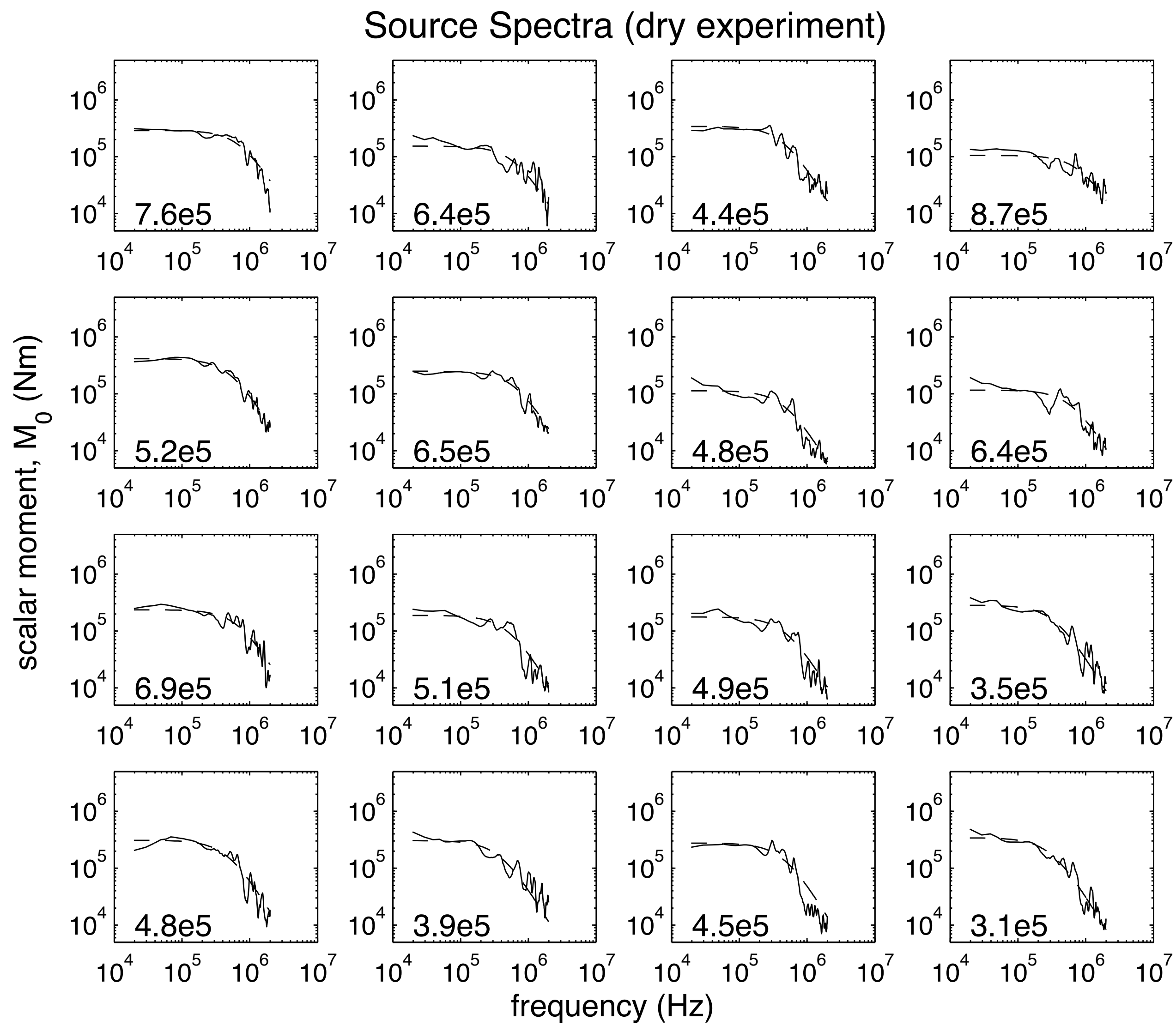


Observations: **Source spectra (wet experiment)**



Examples of source spectra with a sum of squared residuals (SSR) < 10% of sum of squared model values (SSM)

Observations: **Source spectra (dry experiment)**



Examples of source spectra with a sum of squared residuals (SSR) < 5% of sum of squared model values (SSM)

How do M_0 and f_c to scale for earthquakes?

M_0 - f_c relation for a double-couple:

Seismic moment of a 2-D fault:

consider $M_0 = \mu A \overline{D}$,

$$\Delta\sigma \propto \mu \overline{D} / a$$

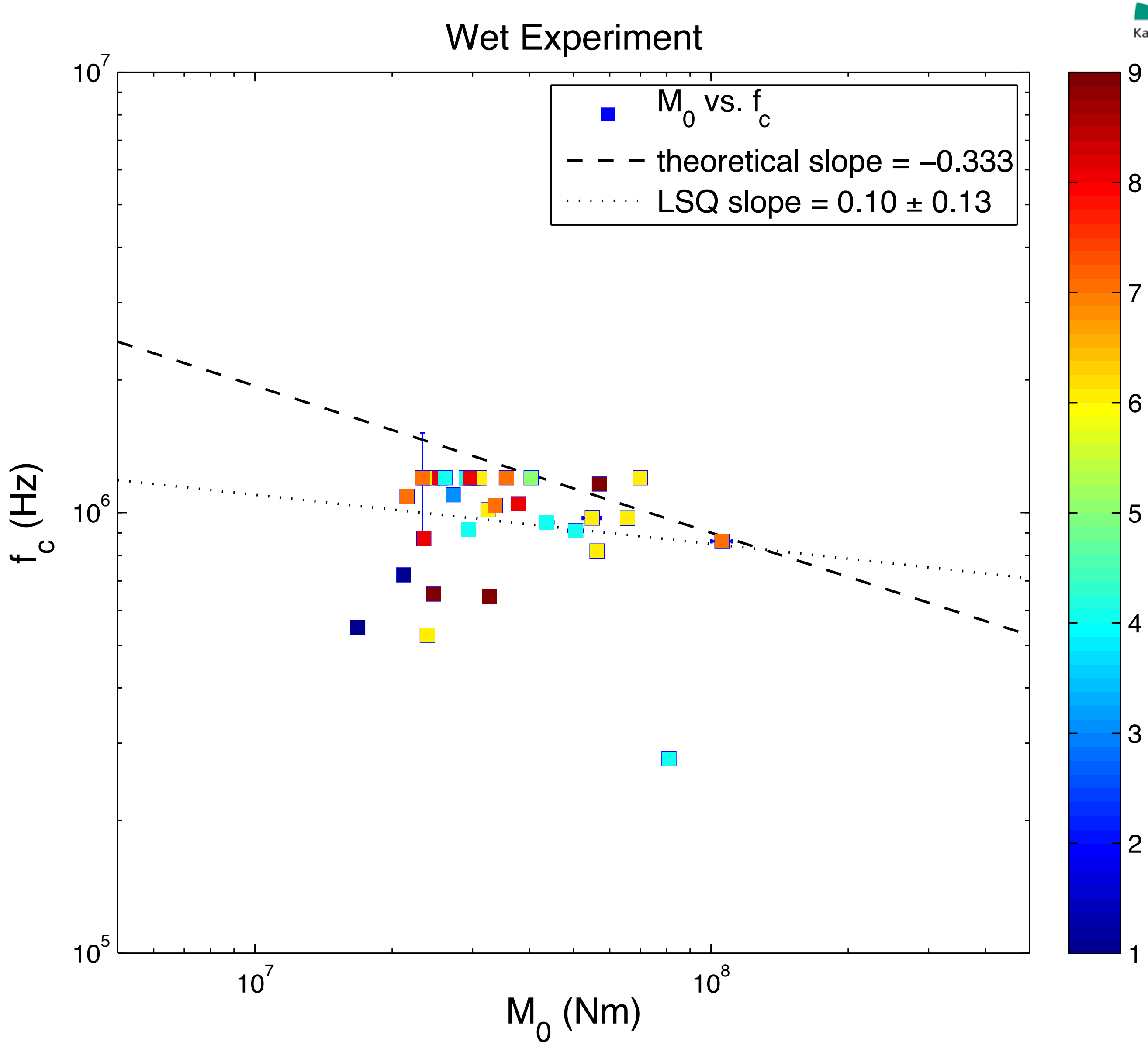
Radius in terms of corner frequency, f_c

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

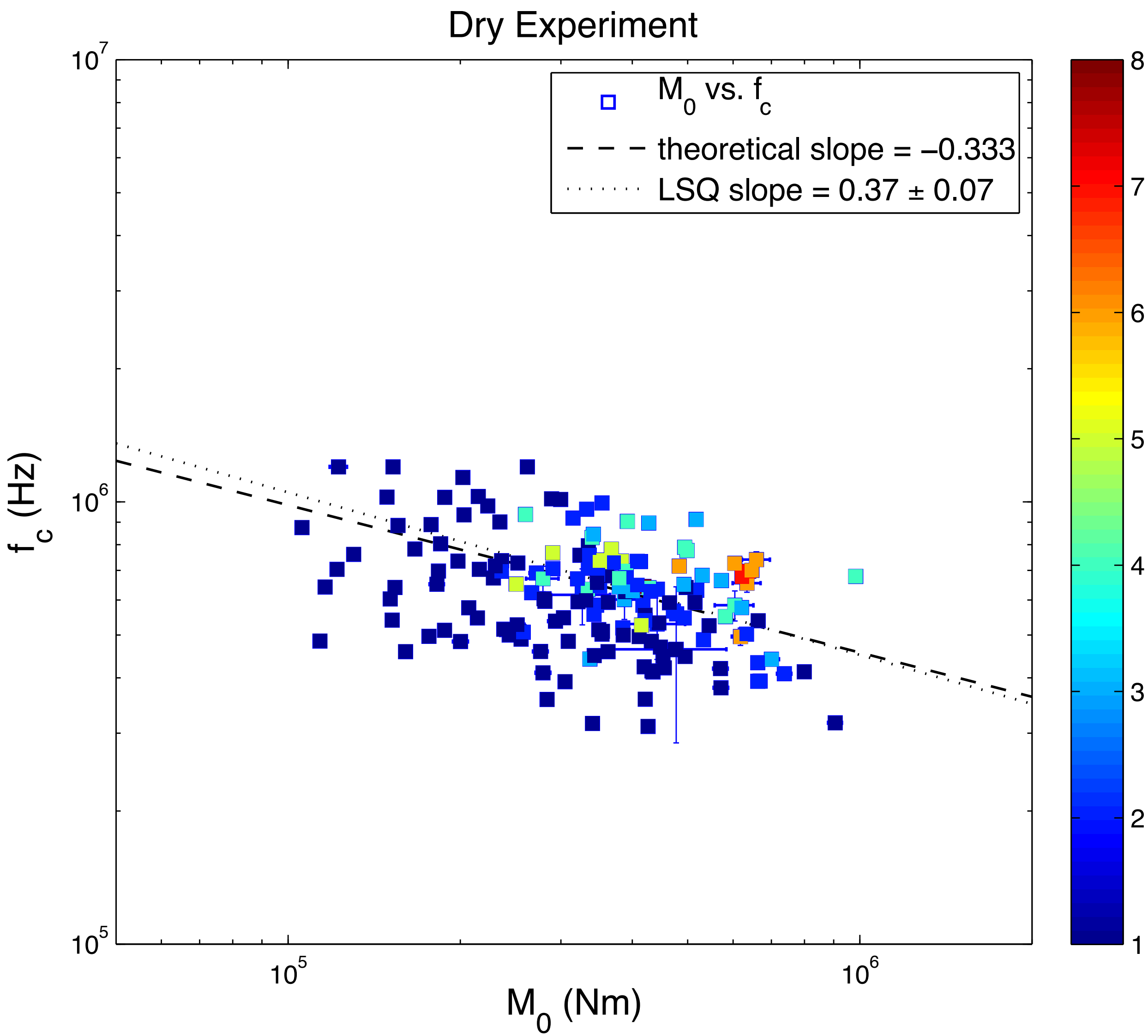
$$a = 0.315\beta / f_c$$

$$\boxed{M_0 \propto f_c^{-3}}$$

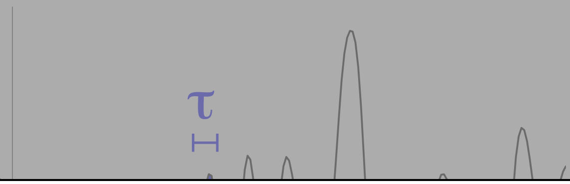
Observations: $M_0 - f_c$ scaling (wet experiment)



Observations: $M_0 - f_c$ scaling (dry experiment)

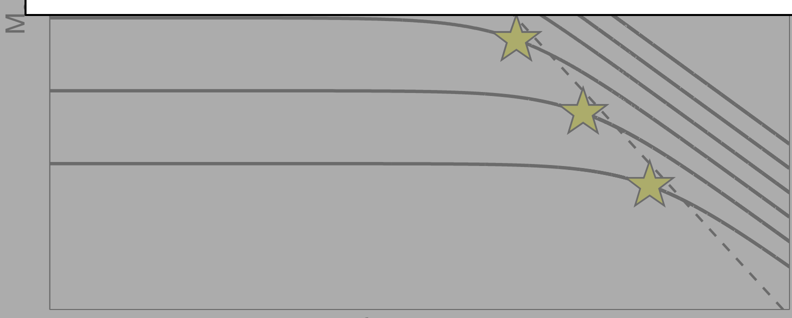


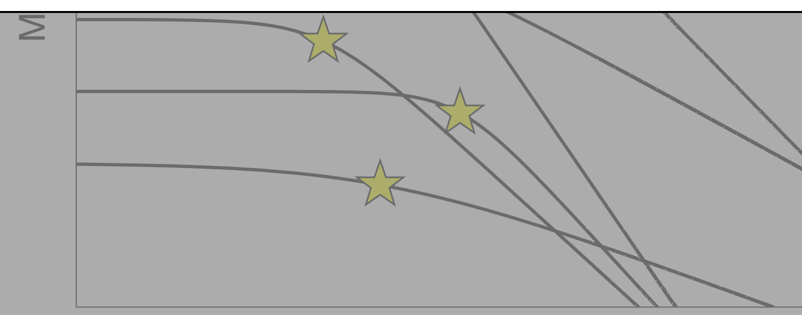
Implications



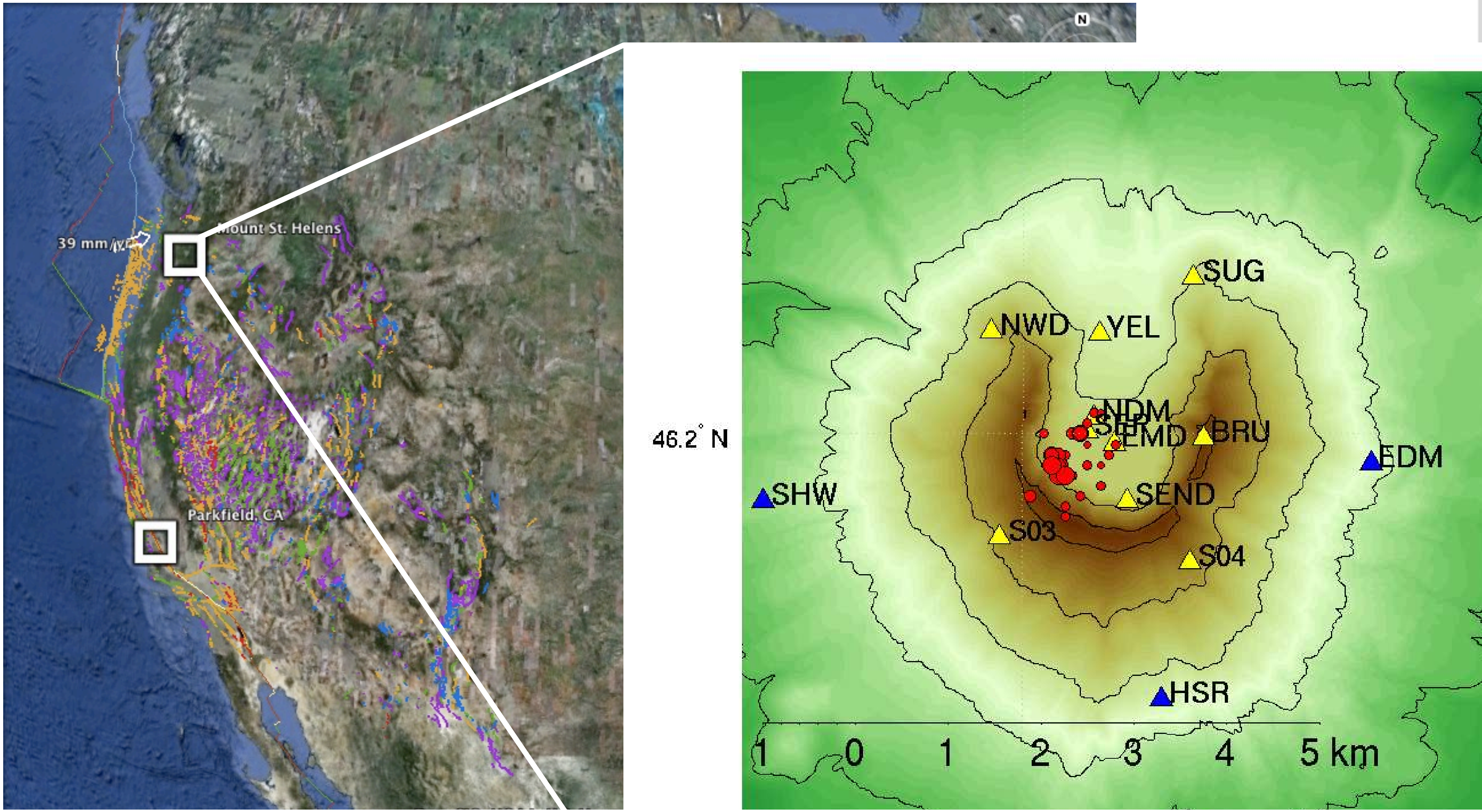
M_0 (size) ~ amplitude $f_c \sim \tau$

For wet experiment, amplitude likely dependent on driving fluid pressure difference. Size-duration scaling should deviate from brittle-failure scaling.





Field data: temporary broadband deployment from 09/04 – 09/09/2006

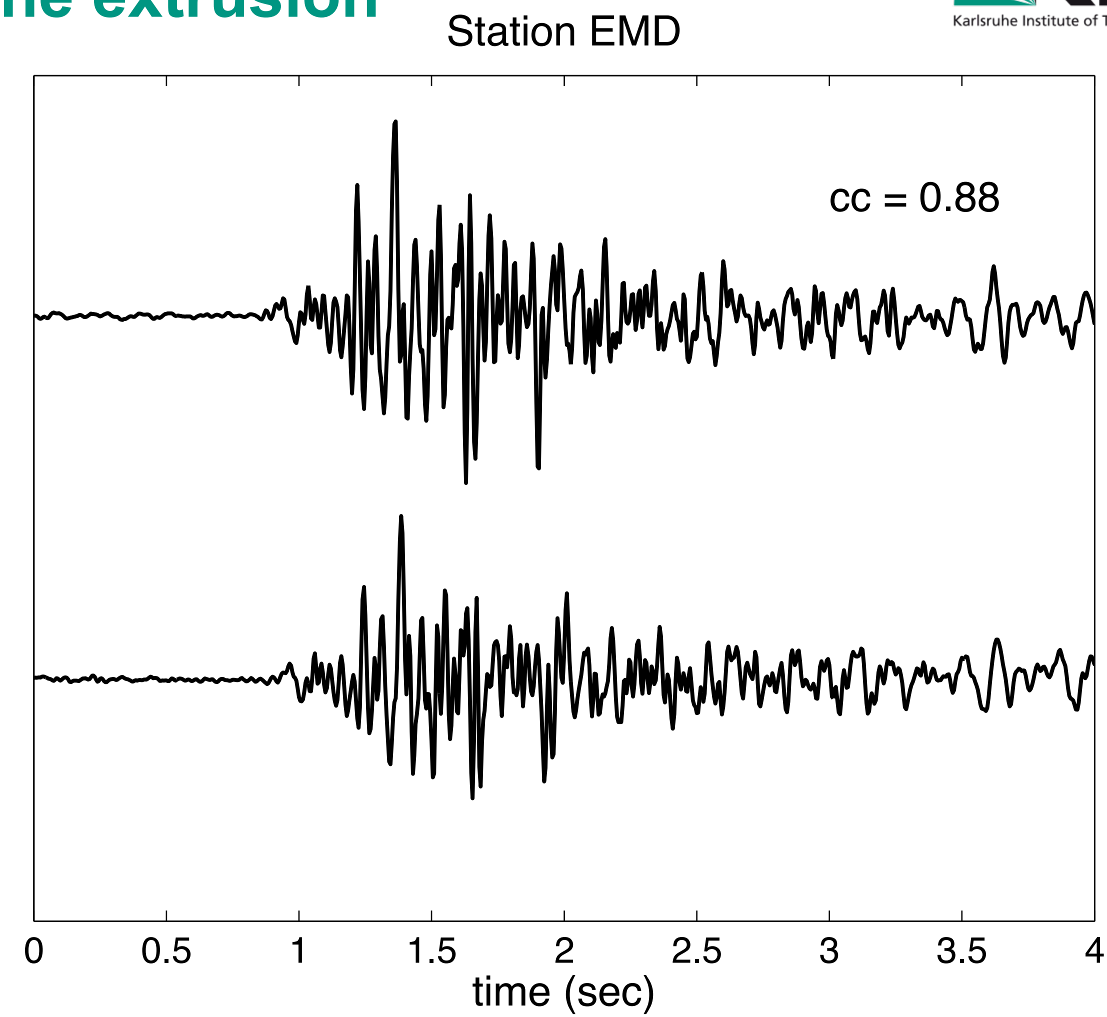


481 events: 35 had clear P-wave arrivals on 6 stations, and could be located to within ± 1km uncertainty. (**Benchmarks**)

Maximum magnitude M_w 2

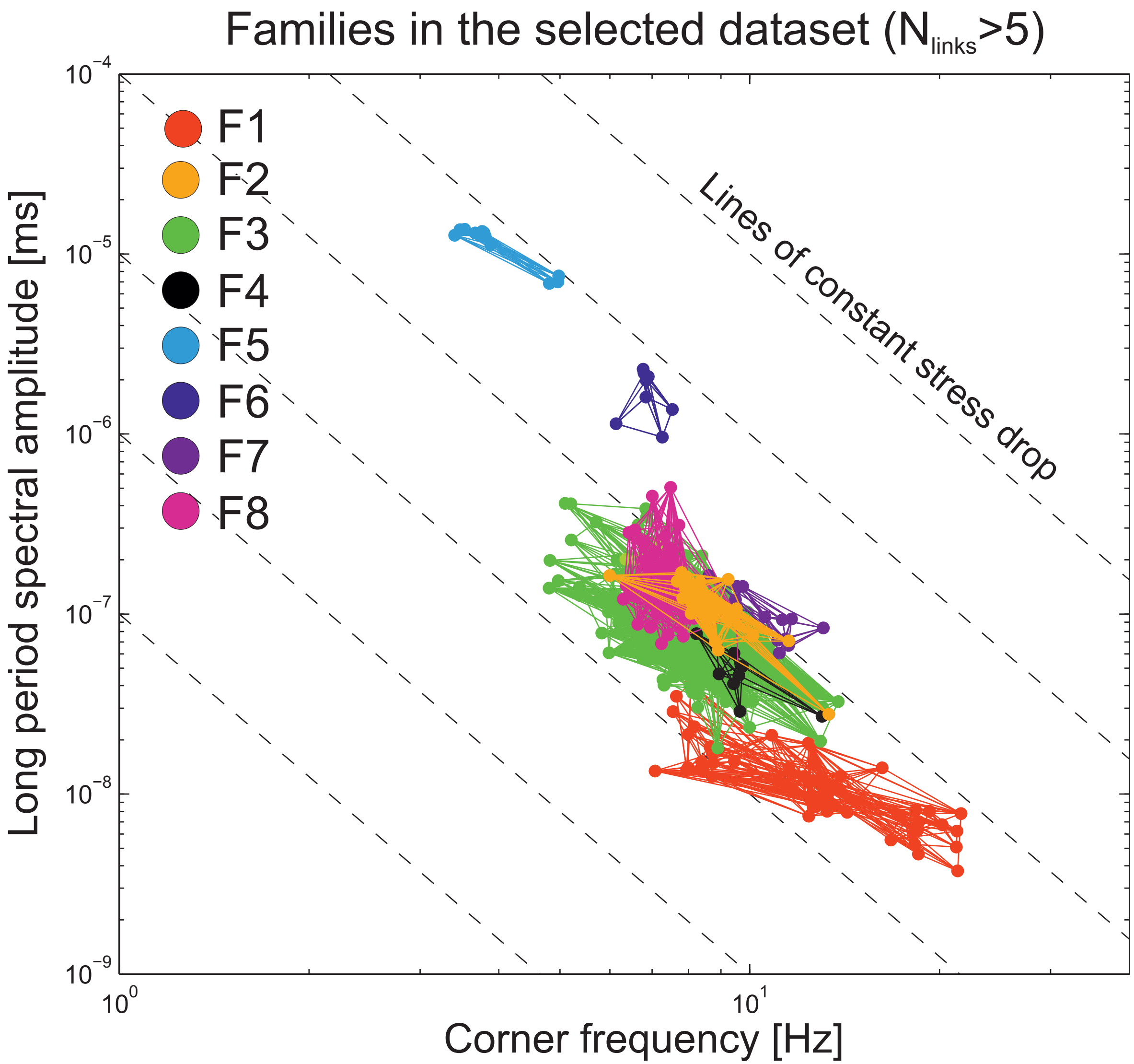
Field data: Typical earthquake pair recorded during spine extrusion

spectral parameter estimation (M_0 and f_c values) via spectral ratio inversion

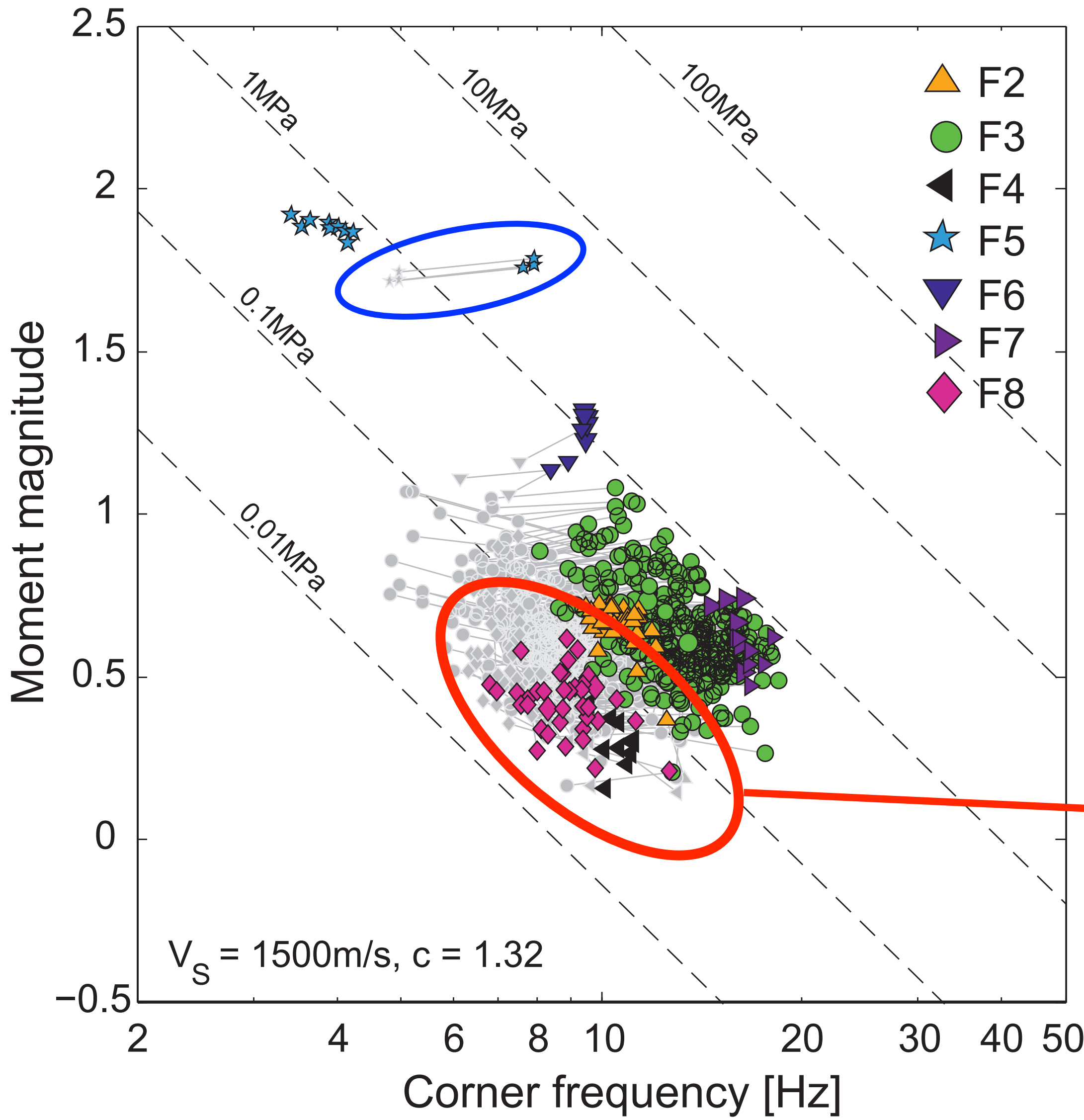


Select events with SNR > 20, and cross-correlation values > 0.8 with at least 5 other earthquakes (481 events)

Observations: size – duration scaling
before spectral ratio inversion (M_0 ~ Amplitude)



Observations: size – duration scaling
after spectral inversion



Lines of constant stress drop are for a circular crack

$$\Delta\sigma = \frac{7}{16} M_0 \left(\frac{2\pi f_c}{1.32\beta} \right)^3$$

Do the lower f_c values result from the assumption of a constant velocity in the top layer?

$$f_c \sim 1/\tau \sim V \sim \beta$$

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Could differences in stress drop for F4 and F8 result from differences in the velocity model?

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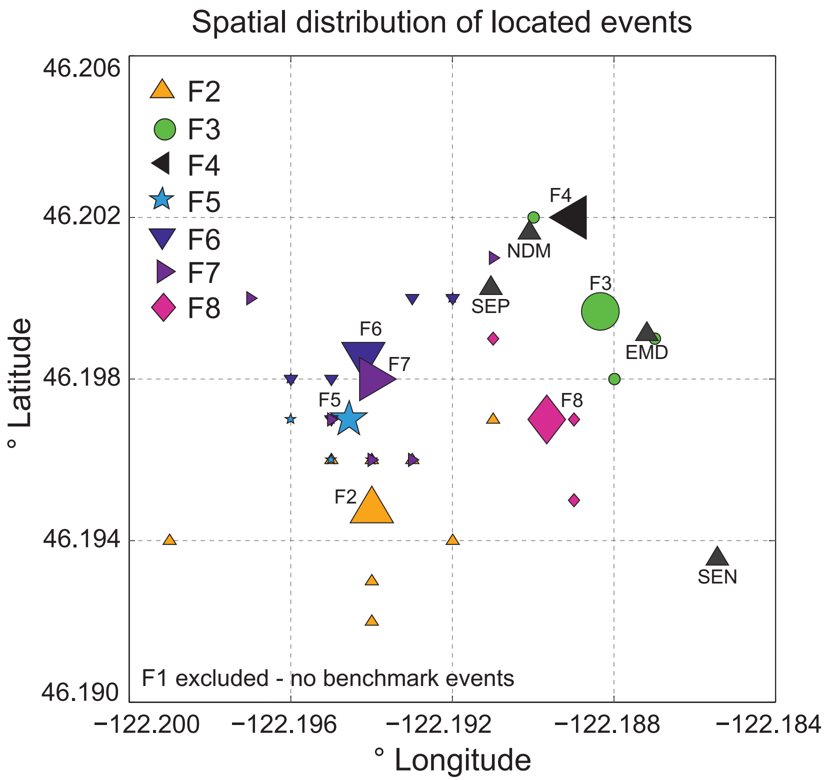
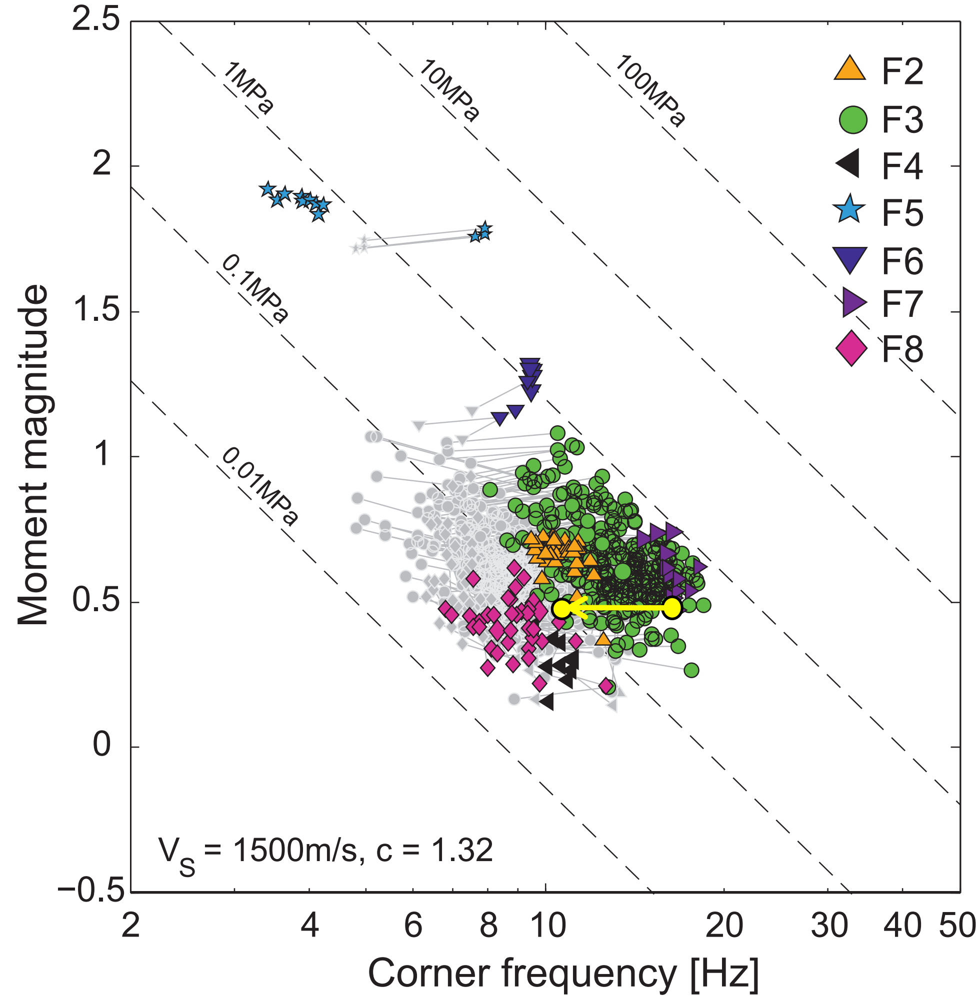


M_w 0.5 with $\Delta\sigma$ = 0.5 Mpa,
β = 1500 m/s => f_c = 17 Hz.

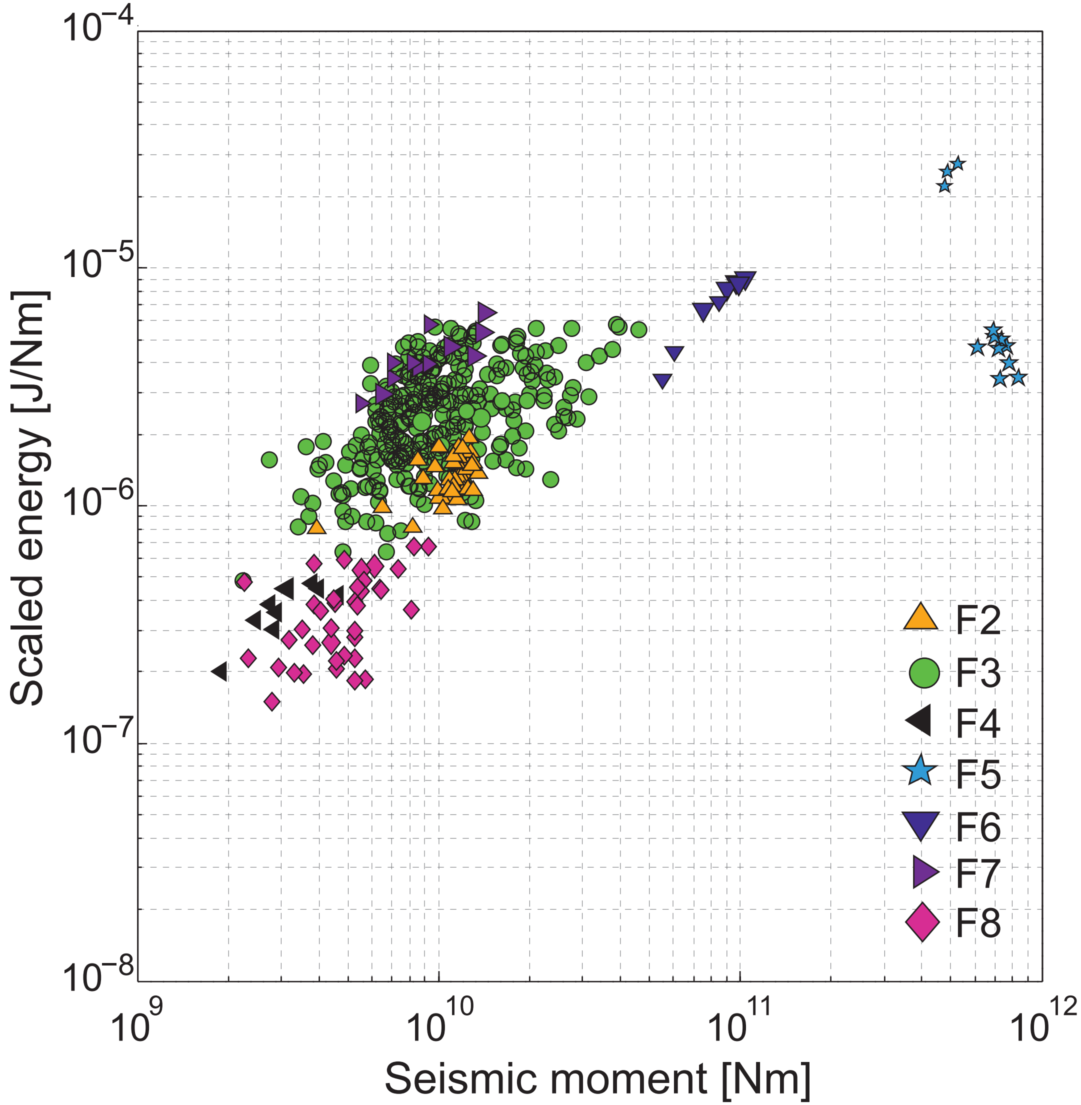
M_w 0.5 with $\Delta\sigma$ = 0.5 Mpa,
β = 1000 m/s => f_c = 11 Hz.



Observations: E_R/M_0 per unit size scaling

Use M_0 and f_c values calculate the E_R/M_0:

$$E_R = \frac{\pi^2}{5\rho\beta^5} M_0^2 f_c^3$$



Summary and Conclusions

Laboratory data

1. We examine the spectral characteristics of simulated volcanic hybrid events both in the presence and absence of water.

2. The analysis of source characteristics points to **a size dependence on duration for brittle failure events (dry)**, and **durations independent of size for events with a fluid component of failure (wet)**.

3. The moment-corner frequency scaling in the dry experiment suggests **brittle failure with a roughly constant value of static stress drop**. Spectra resemble earthquake spectra. **Source parameter scaling differs when water is present**.

Summary and Conclusions

Field data

4. We estimate the spectral source parameters of **481 low-frequency volcanic events** occurring at Mount St. Helens in September, 2006. We calculate the location of **35 benchmark events**, and cluster the earthquakes into **8 families** based on cross-correlation coefficients.

5. We use a spectral ratio inversion to estimate M_0 and f_c. Earthquakes from **5 of 8 families exhibit a self-similar scaling ($M_0 \sim f_c^{-3}$) and constant E_R/M_0 values**, similar to tectonic earthquakes. Scaling differences for the remaining two families may result from velocity model resolution.

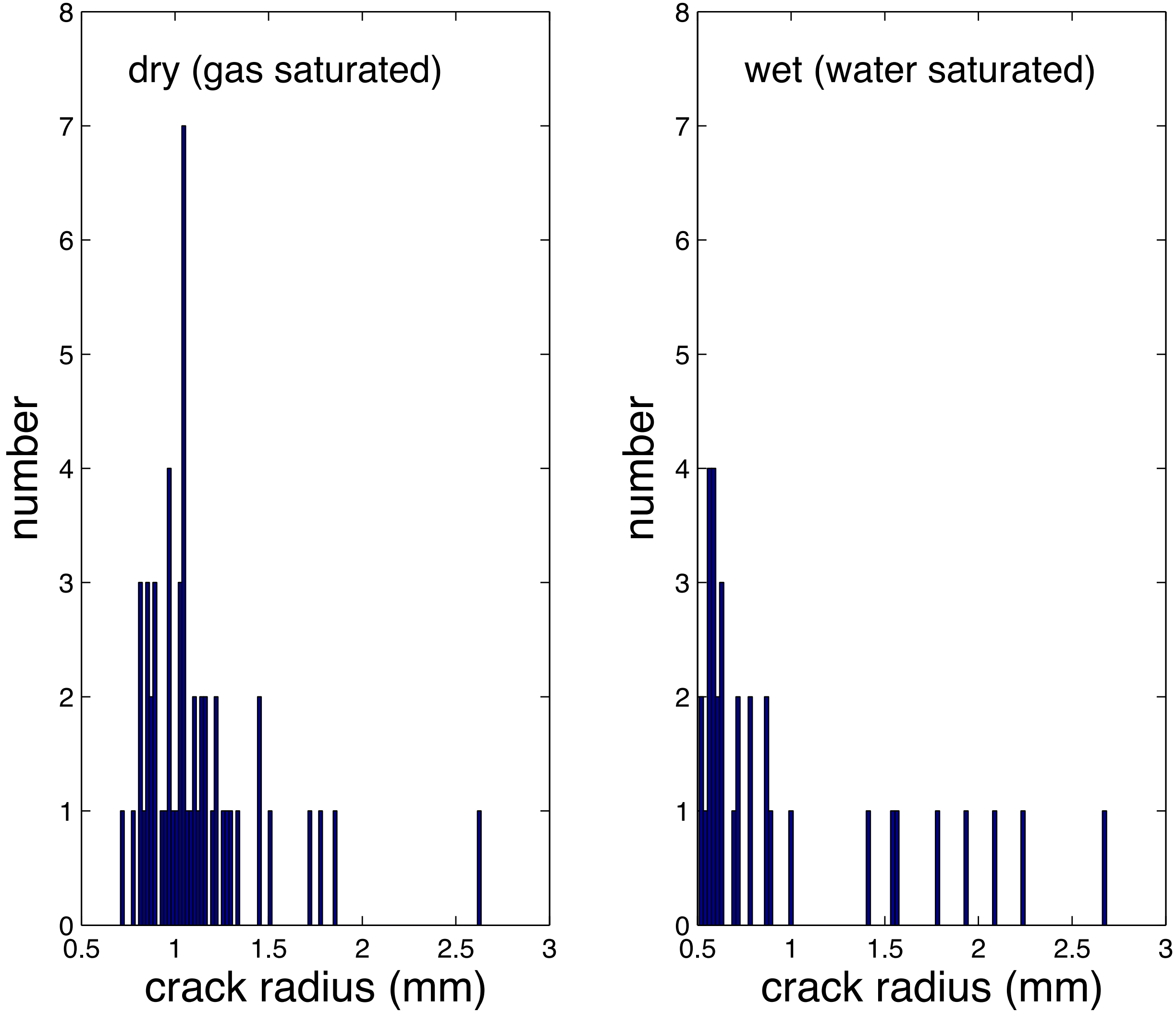
6. Scaling observations for volcanic seismic events **made possible by dense station coverage**; observations of self-similar scaling is unique for such a large group of events.

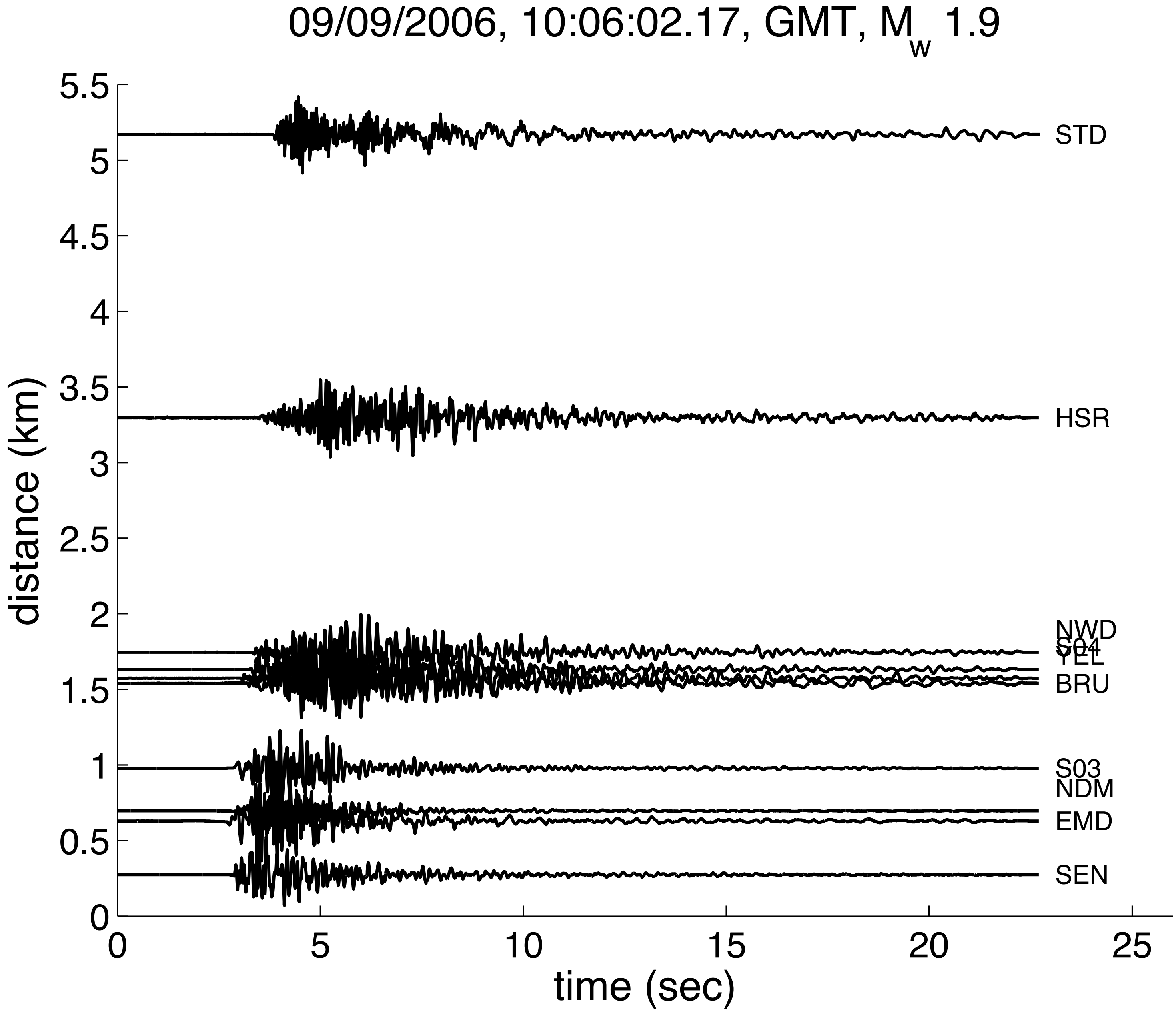
Summary and Conclusions

The scaling characteristics of low-frequency volcanic seismic events can be self-similar over a wide range of magnitudes (down to the ~1mm crack-sized scale), suggesting similarity in the rupture process with tectonic earthquakes.

Thank you!

Crack size estimated from f_c





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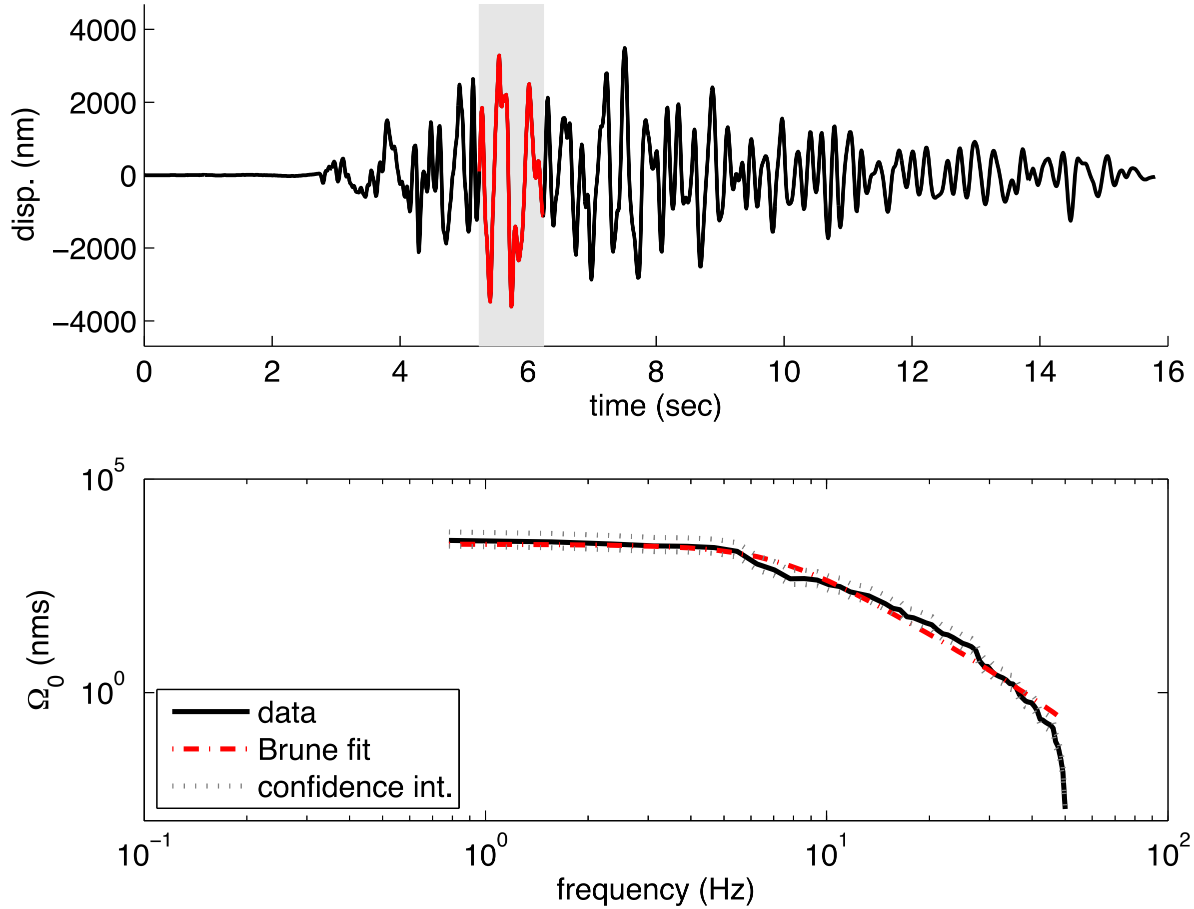


4000
2000
0
−2000
−4000
disp. (nm)
0
2
4
6
8
10
12
14
16
time (sec)
10^5
10^0
Ω_0 (nms)
data
Brune fit
confidence int.
10^{-1}
10^0
10^1
10^2
frequency (Hz)

Station YEL

What are volcanic hybrids?

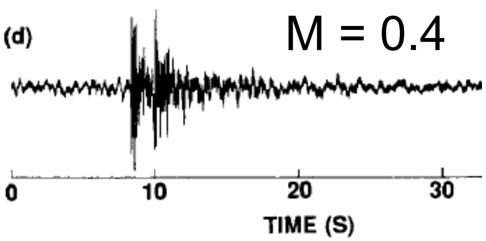
Four main types of volcanic earthquakes

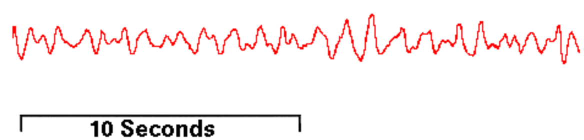
High-frequency (shear fracture)

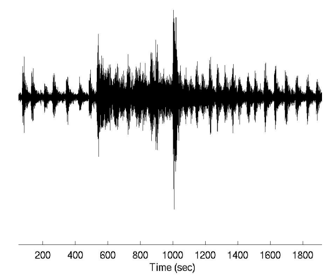
Low-frequency (fluids?)

Harmonic tremor

Explosions

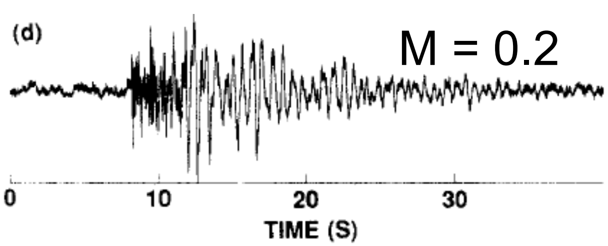


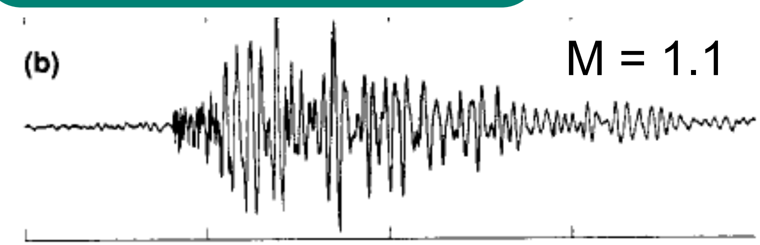




Hybrids

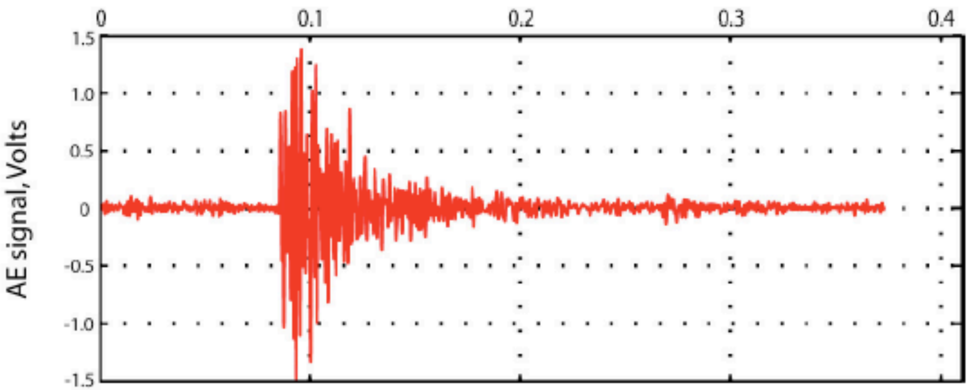
Long-period EQ's





Lahr et al., *JVGR*, 1994

M_L Calculation for laboratory events



Root mean square amplitude calculated using N stations

$$W_{RMS} = \sqrt{\frac{\sum_{i=1}^{i=N} W_i^2}{N}} \qquad (1)$$

A local magnitude M_L is calculated using the RMS waveform Amplitude and the ray path length d_m.

$$M_L = \log\left(\frac{\sum_{m=1}^{m=N} \left\{ W_{RMS_m} \bullet d_m \right\}}{N} \right) \qquad (2)$$

Crack size estimated from f_c

Poorly constrained gain constants → seismic moments relative

We can use f_c values to estimate the crack size

compressional wave corner frequency (ν) and crack radius (r), are related by:

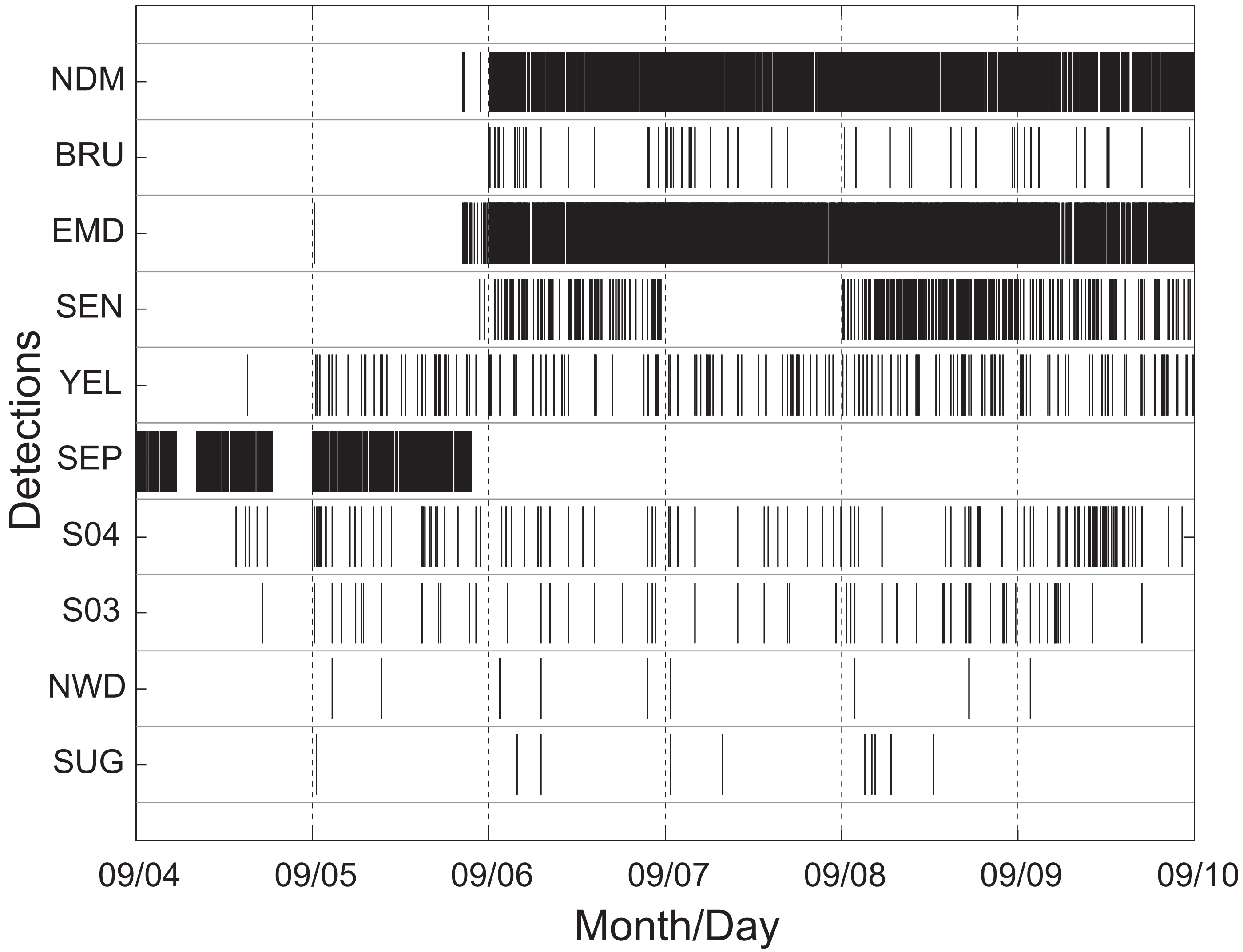
$$r = 0.32\frac{\beta}{f_c}$$

using a value of β given by P-wave velocity and the relationship for a Poisson solid,

$$\beta = \alpha/\sqrt{3}$$

we compute the estimated crack radius

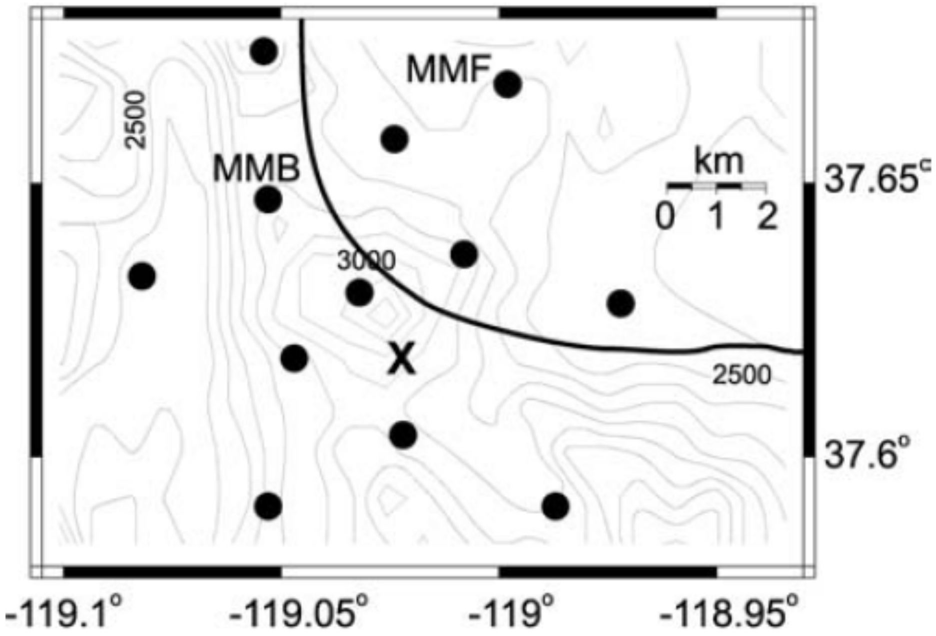
Station operation times

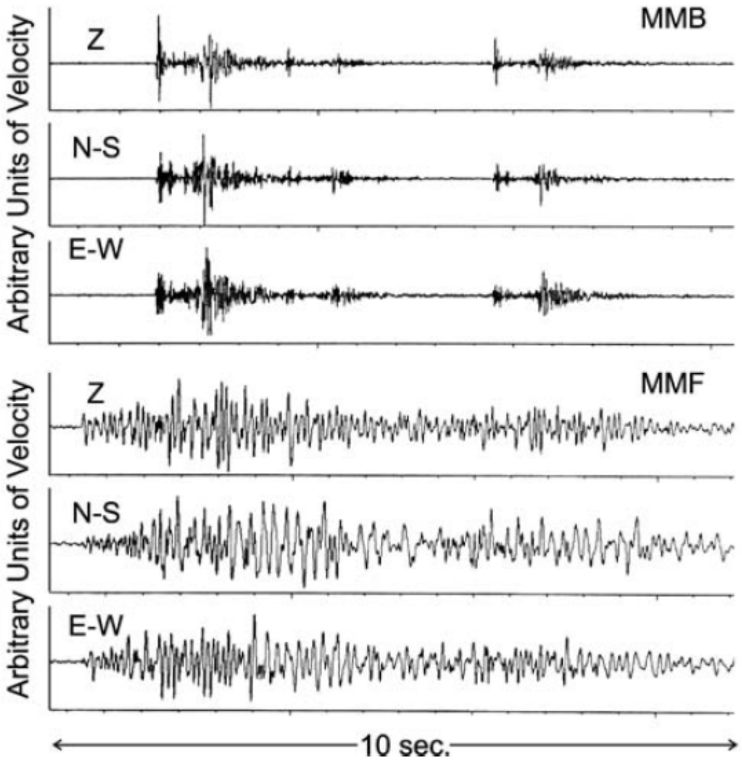


Obtaining the source-time-function: removing path effects

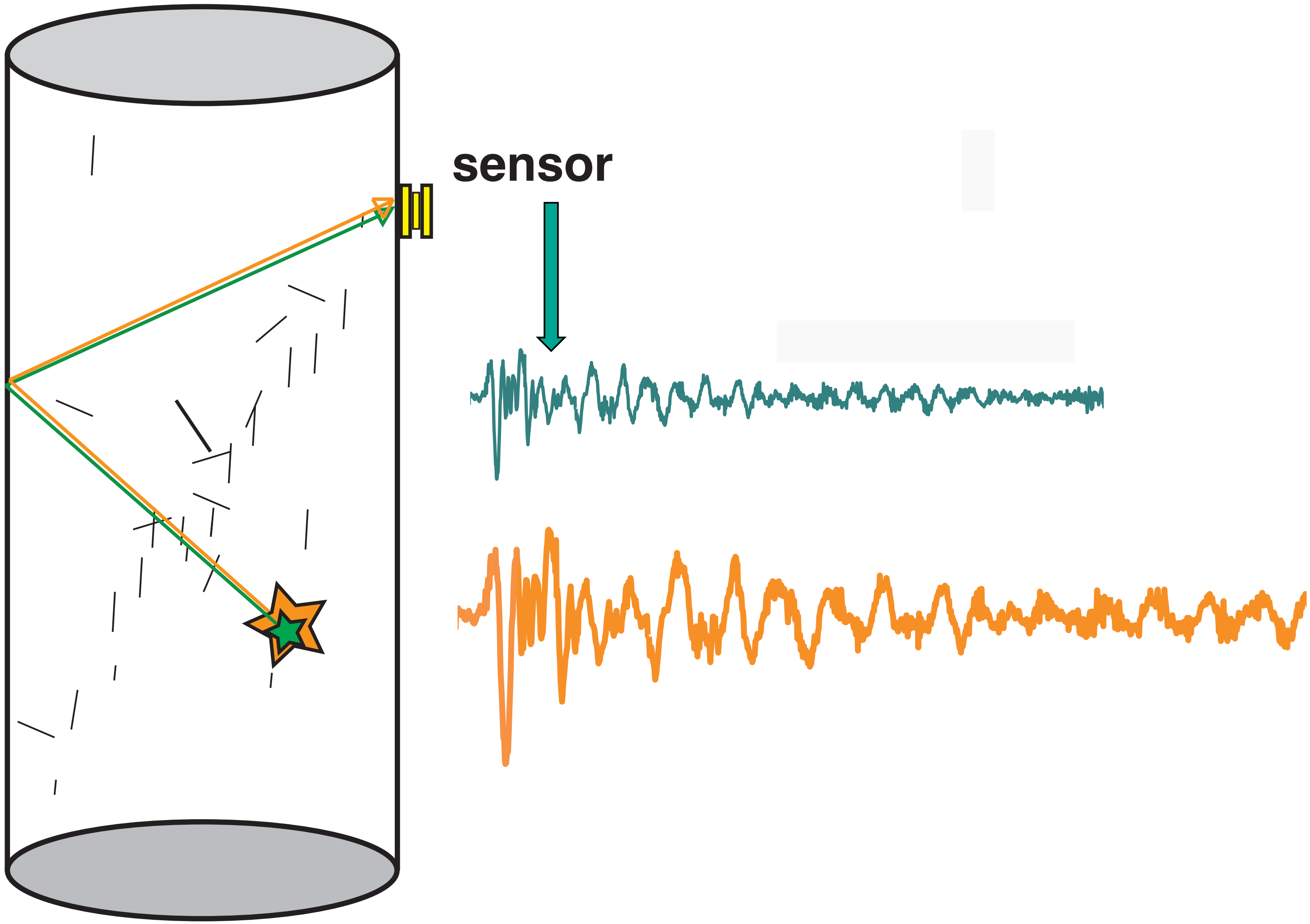
- Strong path effects require accurate attenuation correction

Two recordings of the same earthquake near Long Valley Caldera



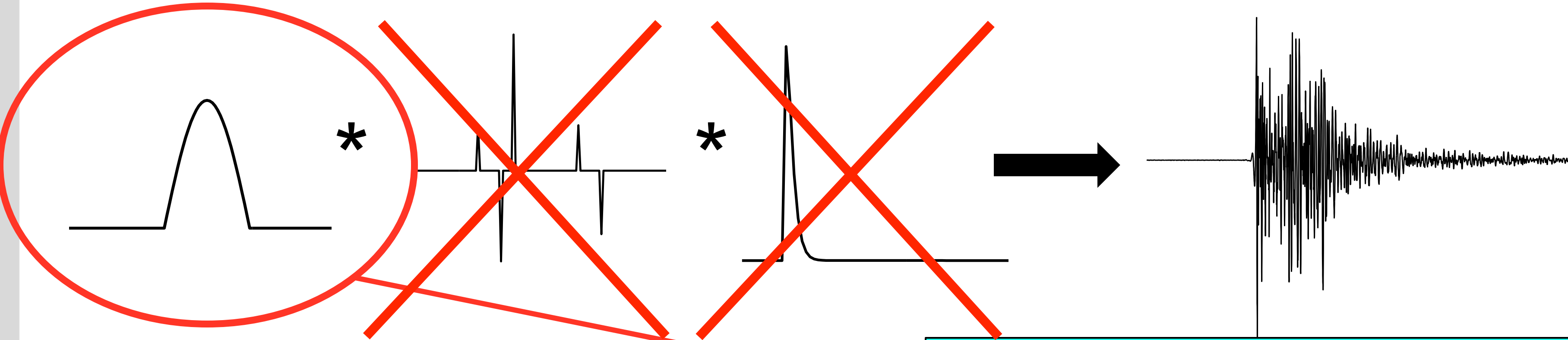


Obtaining the source-time-function: empirical Green's function approach



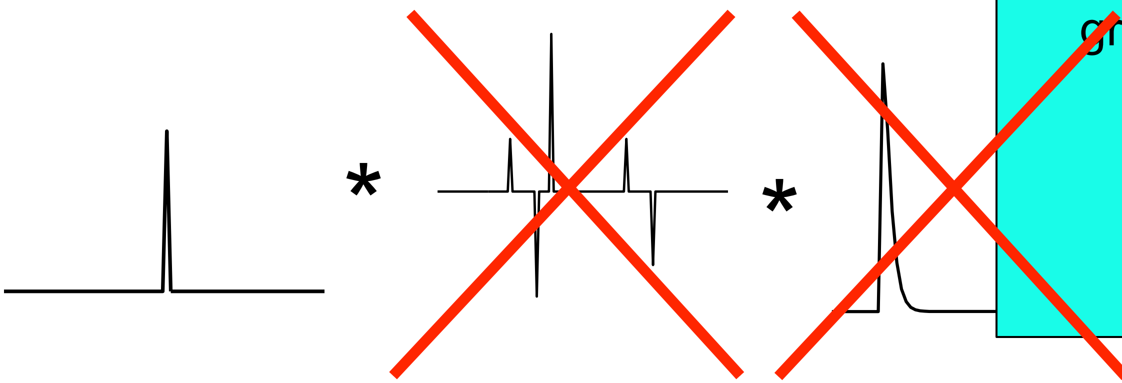
empirical Green’s function approach

main event:



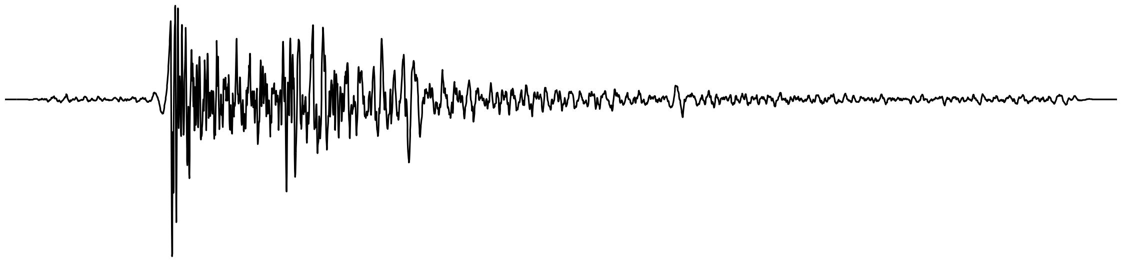
want to isolate the **source time function** (how the event grows with time)

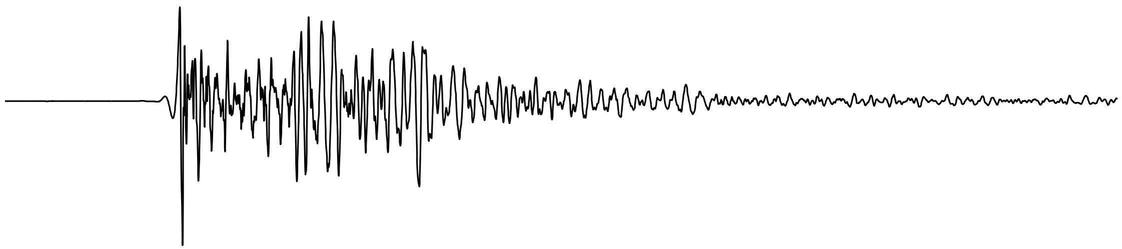
empirical Green’s function event:



empirical Green's function approach

normalized waveforms



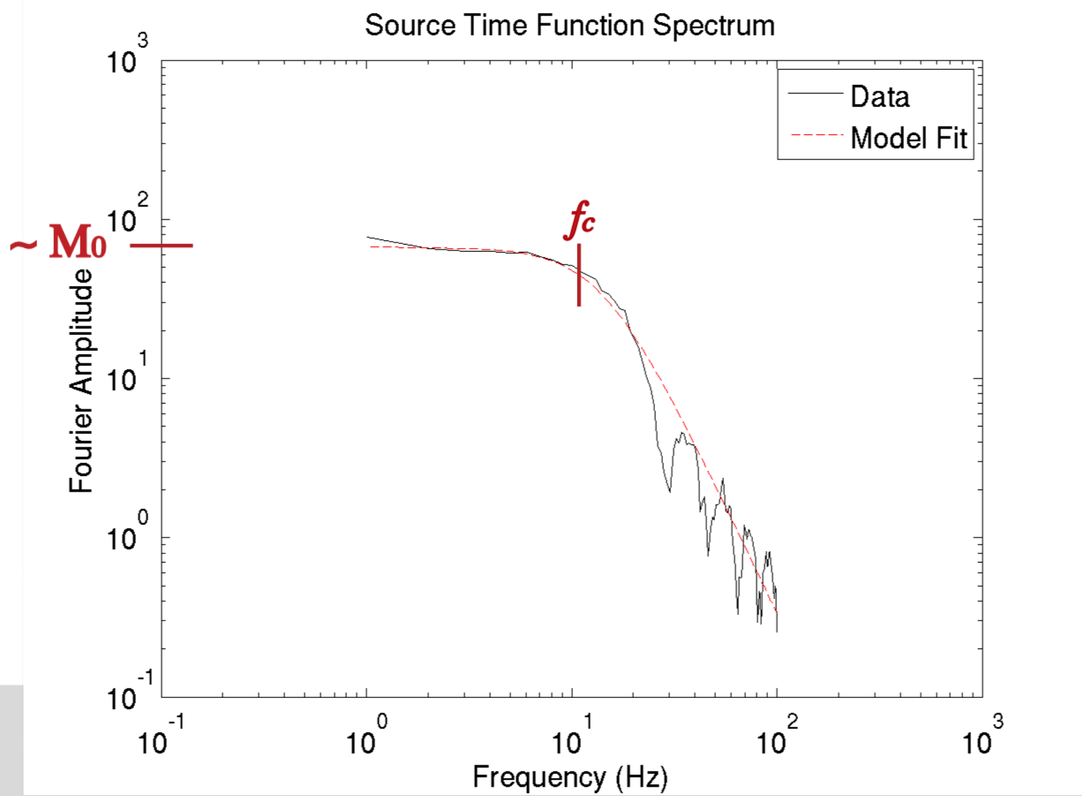


What information is in the event spectrum?

- **Empirical Green's function pairs**

- **Source time spectra** ---> moment (M_0) and corner frequency (f_c).

Corner frequency is a measure of source duration ($f_c \sim 1/\tau$).



Methods: spectral parameter estimation (M_0 and f_c values)

- Sort 481 events into 8 families based on correlation values

- Estimate the M_0, f_c, and Q values of the benchmark events by minimizing errors relative to model velocity spectrum (Brune spectral model):

$$\dot{u}(f) = \frac{\langle U_{\phi\theta} \rangle}{4\pi\rho c^3 R} \Omega(f) \exp\left(\frac{-\pi R f}{cQ}\right), \text{ where } \quad \Omega(f) = \frac{2\pi f M_0}{1 + \left(f / f_c\right)^2}$$

- Average Q = 15 between all benchmark events.

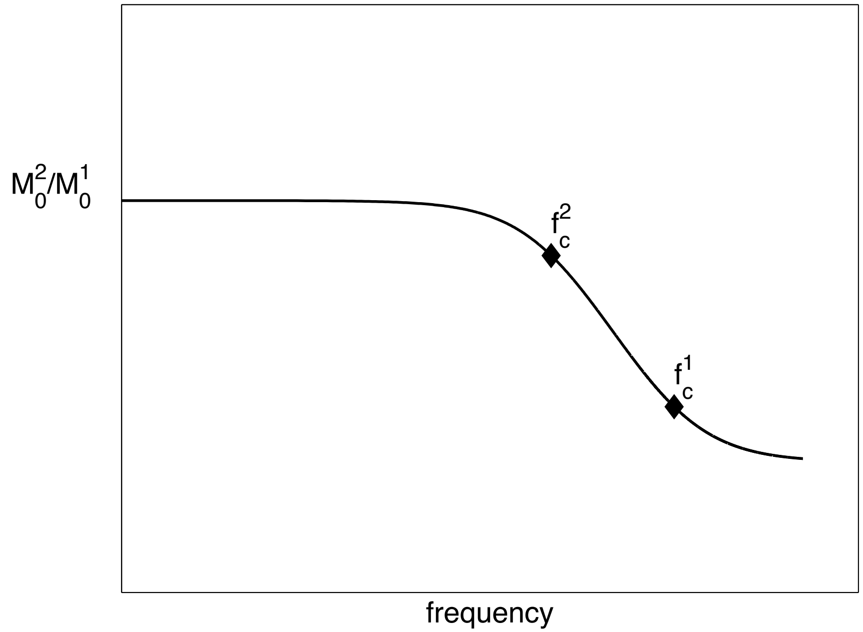
- M_0 and f_c values determined with Q used in the spectral ratio inversion (fixed for benchmarks).

Methods: spectral parameter estimation (M_0 and f_c values)

481 earthquakes, 8 families

Calculate the spectral ratio from the observed spectra:

$$\Psi^{1,2}(f) = \frac{\dot{u}^2(f)}{\dot{u}^1(f)} = \frac{\Omega^2(f)}{\Omega^1(f)}$$



Estimate the M_0 and f_c values by minimizing the difference between observed and theoretical spectral ratios (cost function):

$$\varepsilon\left(f_c, M_0\right) = \sum_k \sum_{(i,j)\in A} w_{i,j} \left\| \log \Psi^{i,j} - \log \Psi_{obs}{}^{i,j,k} \right\|_{L_1}$$

Methods: spectral ratios
(M_0 and f_c values for all events)

Two events with
CC ≥ 0.8

=> co-located