Source scaling relations of km- to cm-scale (M_W 4 to -6) earthquakes: Experiences from mining- and fluid-induced seismicity, volcanic-hybrid seismic events and laboratory experiments

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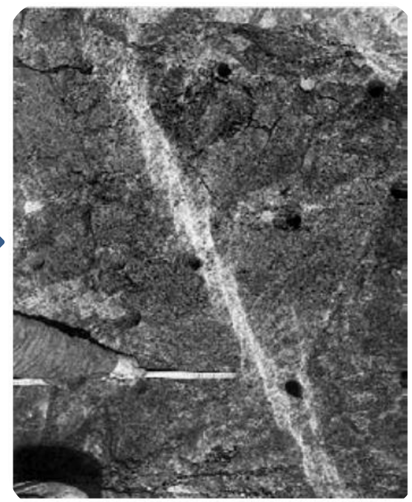
Motivation

Is the rupture process scale-invariant?

cm-scale



m-scale

km-scale

Scaling relations

Seismic moment – corner frequency („Static”)

EQs release same stress per unit fault area regardless of scale

$$\Delta\sigma \approx C \left(\frac{M_0}{\tilde{L}^3} \right)$$

Radiated Energy – Seismic moment („Dynamic”)

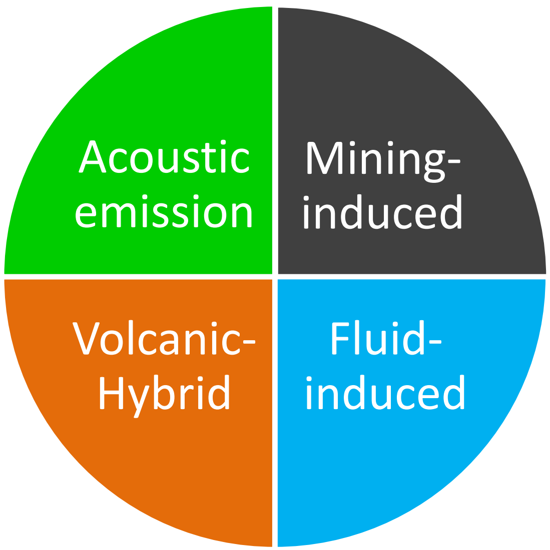
EQs radiate same energy per unit fault area per unit fault slip regardless of scale

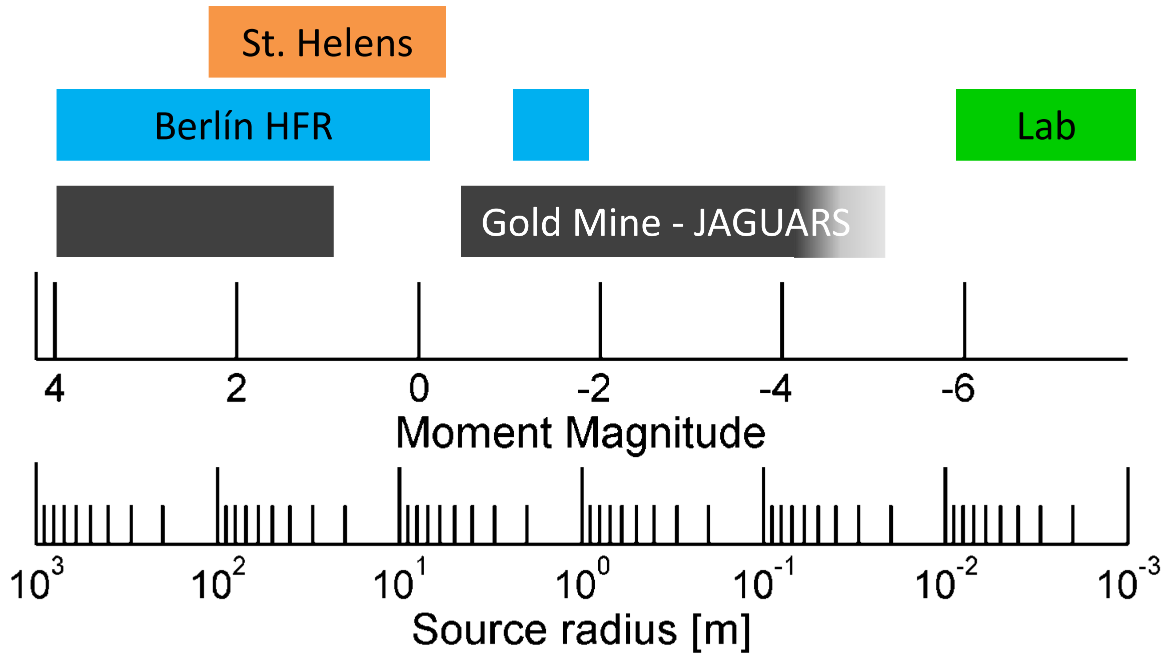
$$\sigma_a = \mu \frac{E_0}{M_0}$$

Breakdown in scaling relations

- Scaling relations generally accepted for larger seismic events
- Debate over the scaling breakdown for smaller earthquakes controversial
  - Changes in rupture process between larger and smaller earthquakes (e.g. different rupture velocity, different governing physics)
  - Inappropriate corrections (e.g. for attenuation)
  - Invalid model assumptions (constant rupture velocity, certain failure mode)
  - Instrument-related (limited frequency band of the sensors)
  - Inappropriate data selection

Our data... from small- to femtoearthquakes

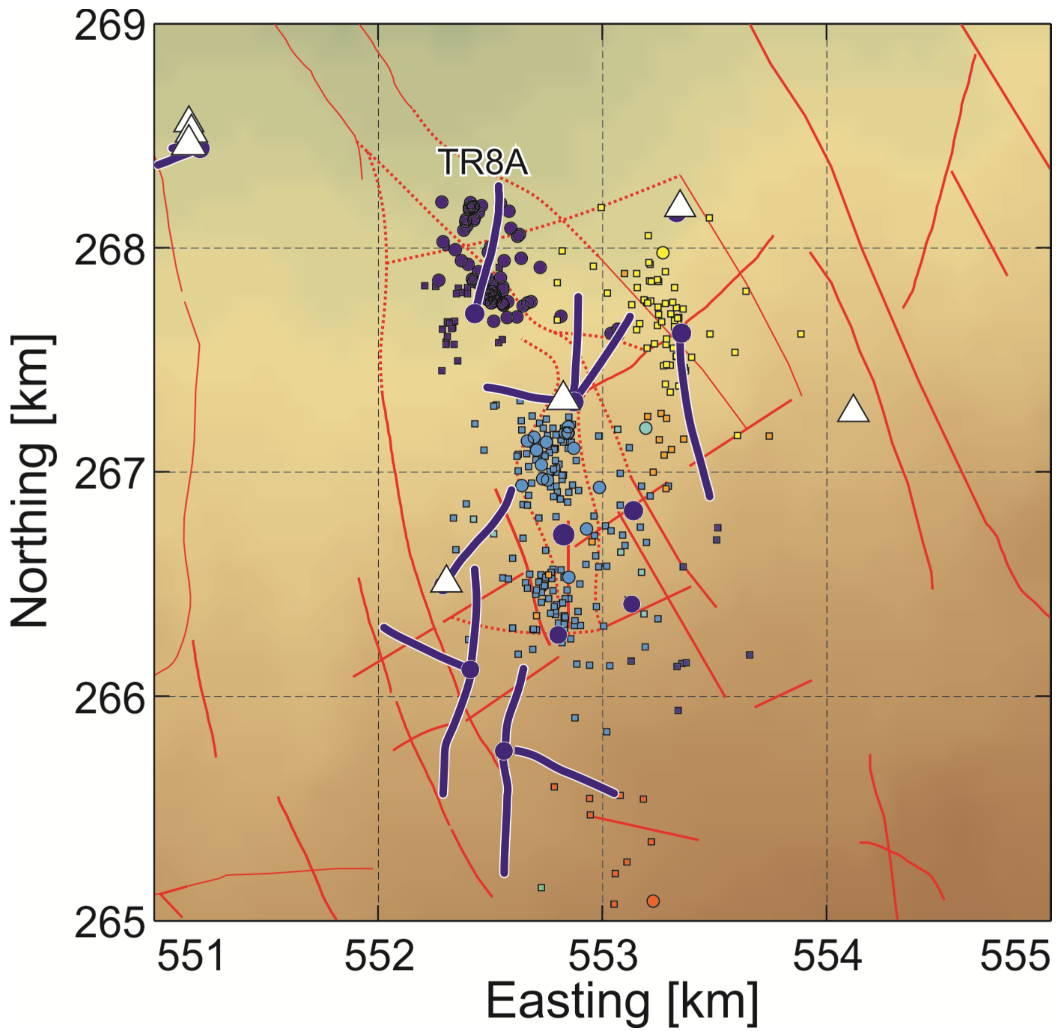




Magnitude range	Class	Length scale	Displacement scale	Frequency scale	Seismic moment*
8–10	Great	100–1,000 km	4–40 m	0.001–0.1 Hz	1 KAk–1 MAk
6–8	Large	10–100 km	0.4–4 m	0.01–1 Hz	1 Ak–1 KAk
4–6	Moderate	1–10 km	4–40 cm	0.1–10 Hz	1 mAk–1 Ak
2–4	Small	0.1–1 km	4–40 mm	1–100 Hz	1 µAk–1 mAk
0–2	Micro**	10–100 m	0.4–4 mm	10–1,000 Hz	1 nAk–1 µAk
–2–0	Nano	1–10 m	40–400 µm	0.1–10 kHz	1 pAk–1 nAk
–4 to –2	Pico	0.1–1 m	4–40 µm	1–100 kHz	1 fAk–1 pAk
–6 to –4	Femto	1–10 cm	0.4–4 µm	10–1,000 kHz	1 aAk–1 fAk
–8 to –6	Atto	1–10 mm	0.04–0.4 µm	1–100 MHz	1 tAk–1 aAk

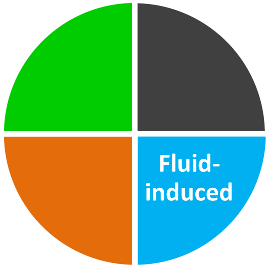
Table: Bohnhoff et al., 2010, paper in „New Frontiers in Integrated Solid Earth Sciences"

Berlín Geothermal field



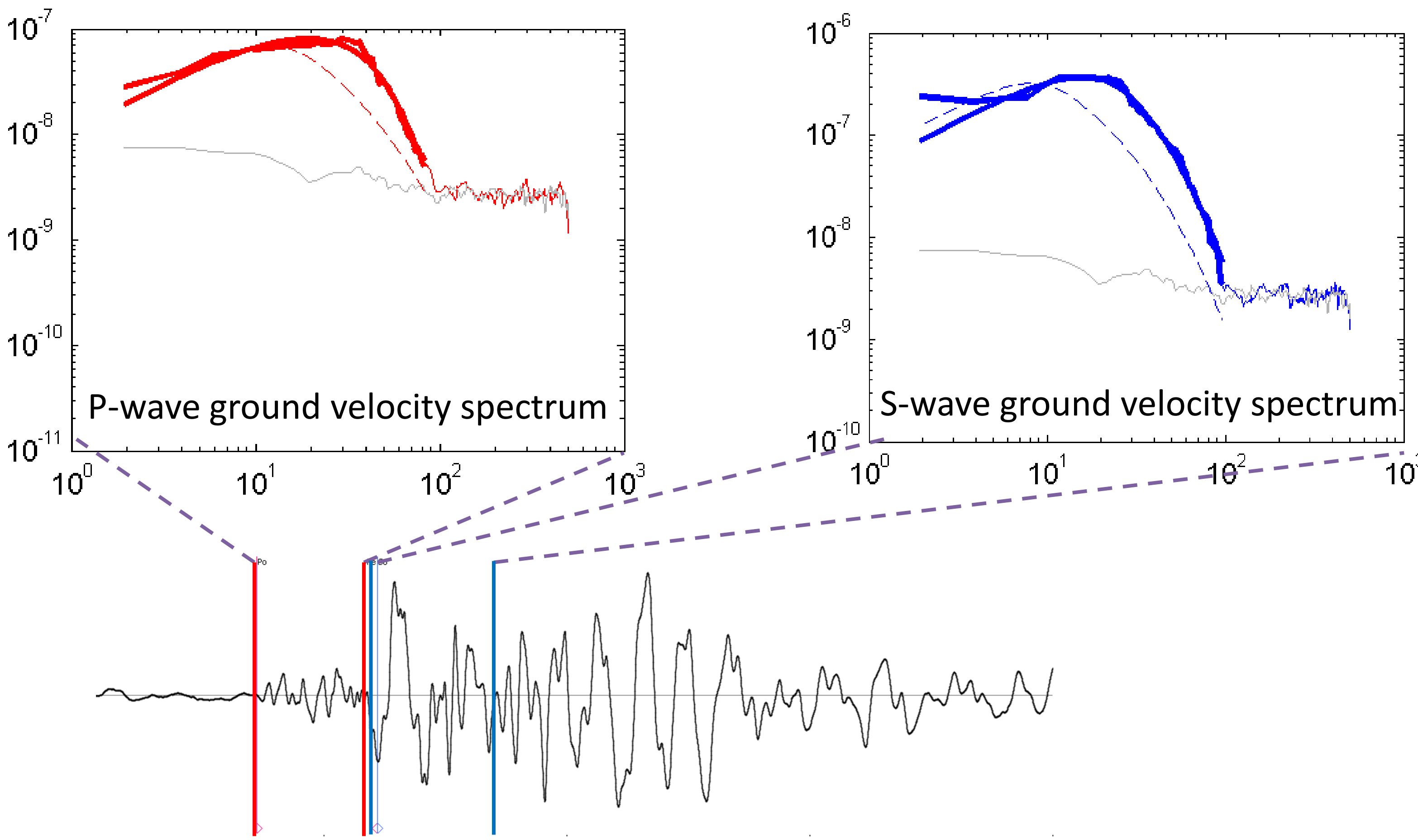
Kwiatek et al., 2012, Special issue of Geothermics(submitted)

- 12 3C borehole sensors used
- 581 events analyzed
- Interesting study to see how attenuation affects the scaling relations



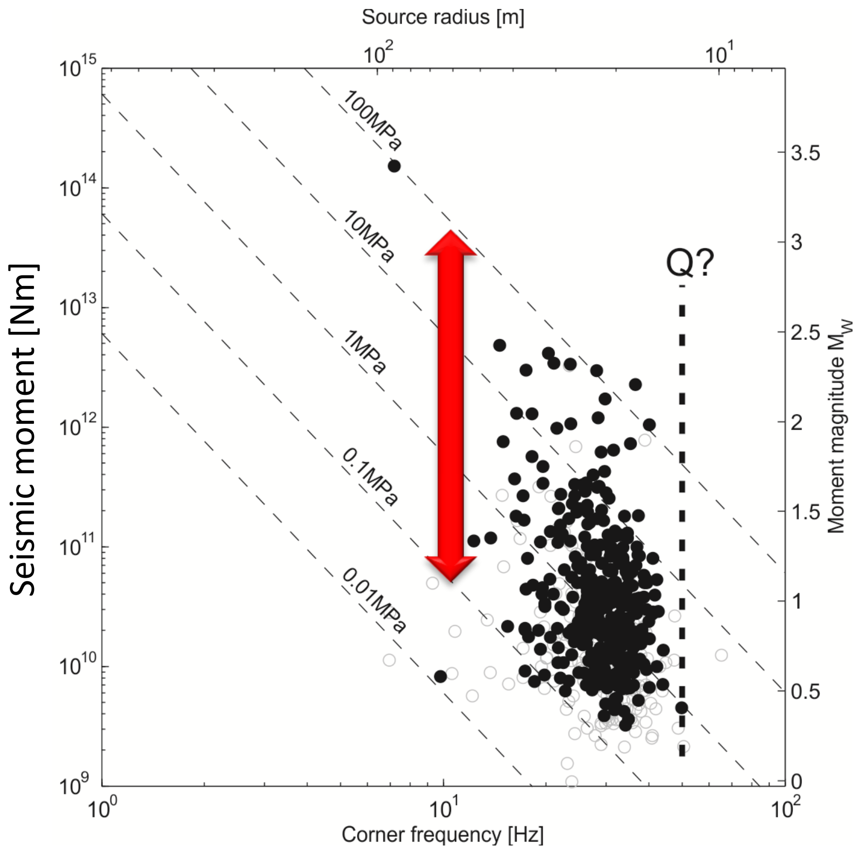
Source parameters using spectral fitting

- Inversion for seismic moment, source radius and attenuation



Source parameters using spectral fitting

- Trade-off between source radius and quality factor resulted in problems with interpretation of results (broad scatter of $\Delta\sigma$)

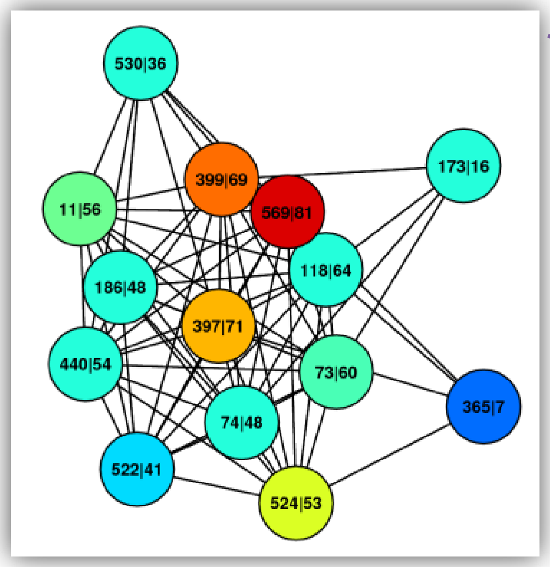


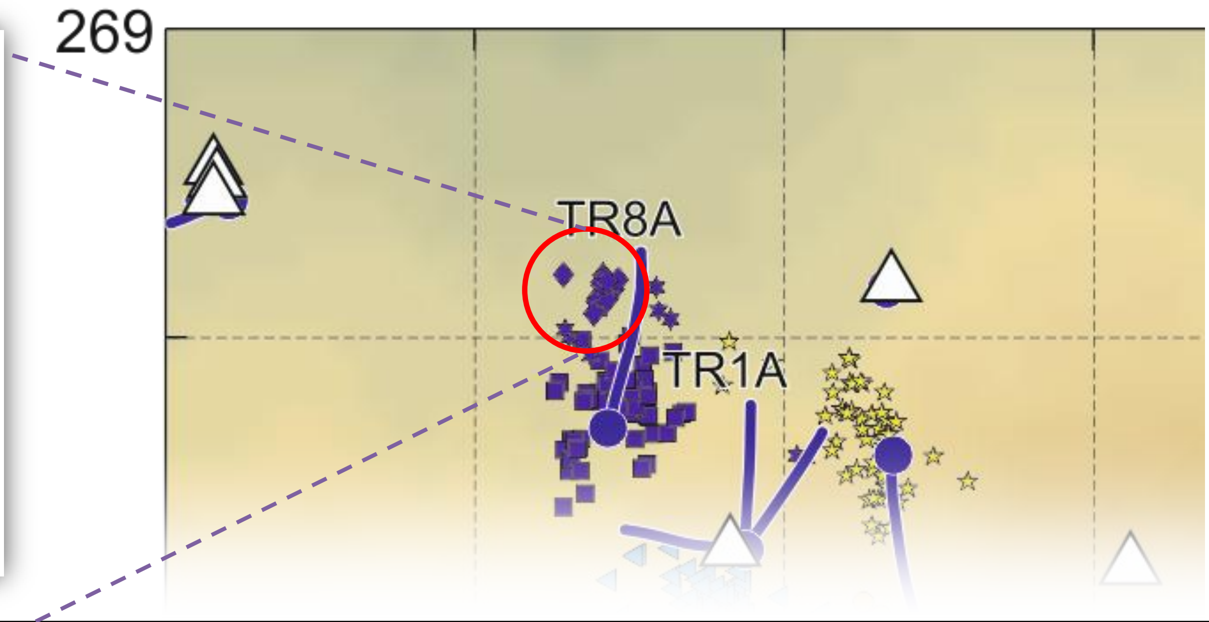
Kwiatek et al., 2012, Special issue of Geothermics (submitted)

Spectral ratio method

- Applied to clusters of data (similar location and travel paths from EQ to receiver)
- Propagation effects effectively supressed by forming spectral ratios

$$\Psi^{ij}(f) = \frac{\dot{u}^i(f)}{\dot{u}^j(f)} = \frac{M_0^i}{M_0^j}\left(\frac{1+\left(f/f_c^j\right)^4}{1+\left(f/f_c^i\right)^4}\right)^{0.5}$$

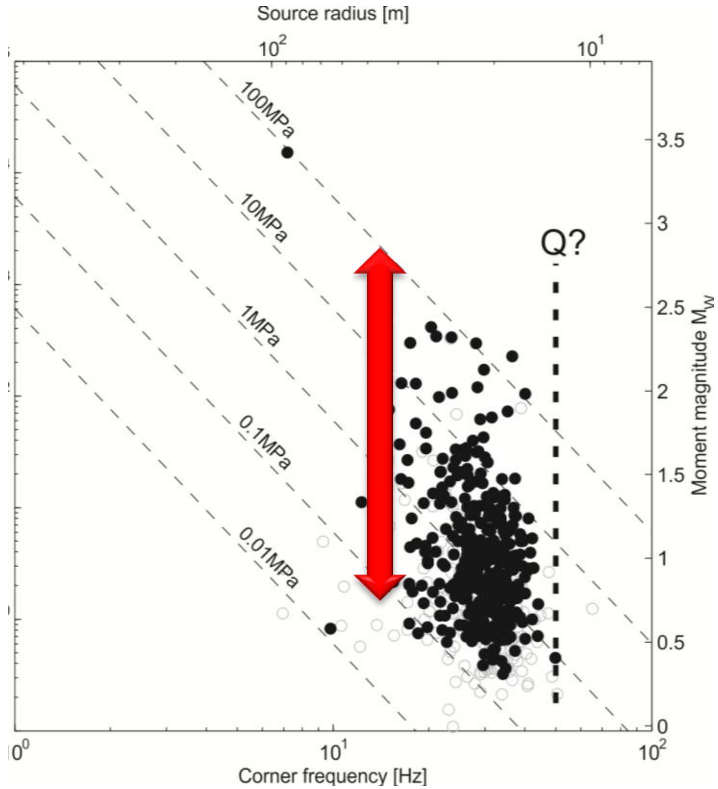




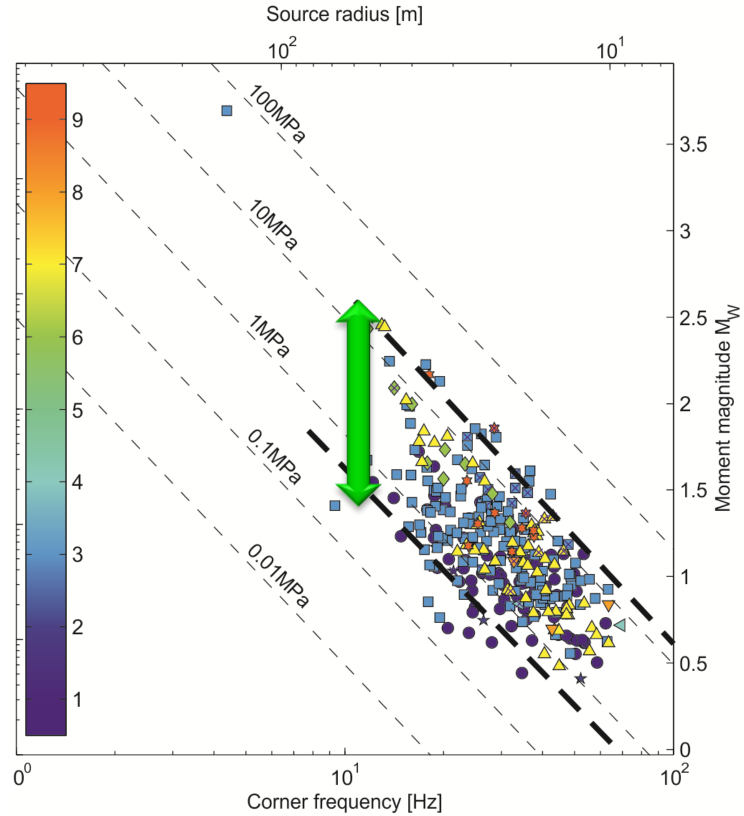
Source parameters using spectral ratio refinement

- Strong improvements in the quality of source parameters
- Trade-off between Q and F_0 responsible for scaling problems

Initial spectral fitting method



After spectral ratio refinement

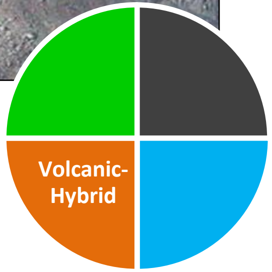


Kwiatek et al., 2012, Special issue of Geothermics(submitted)

Volcanic-hybrid EQs

- Analyzed 6073 events related to spine extrusion at Mt. St. Helens (data Sep 2006)
- Source parameters of >500 events calculated using the spectral ratio technique.

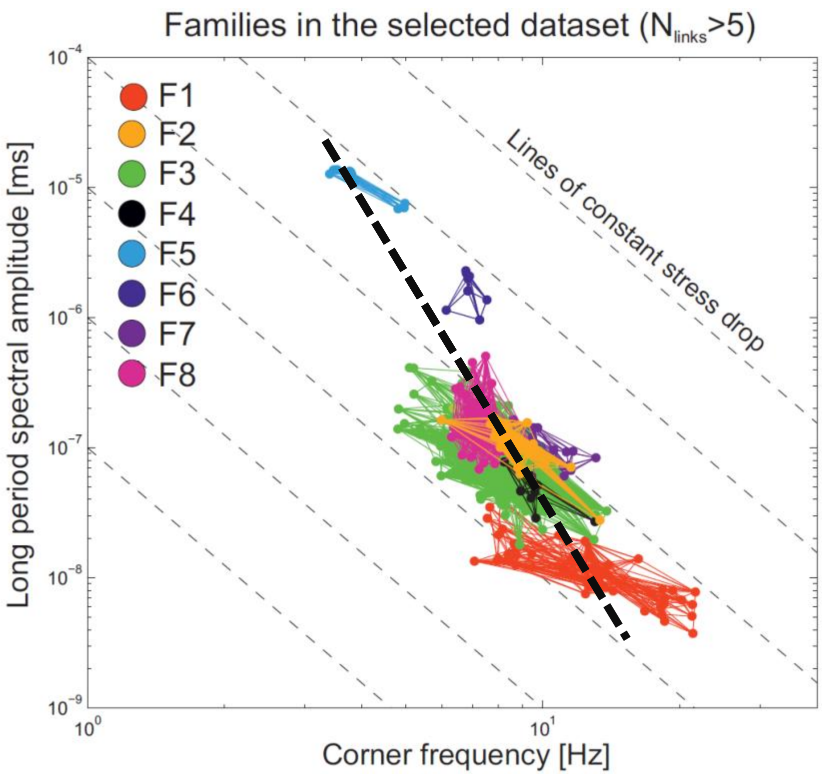
  [See next talk by R. M. Harrington!]

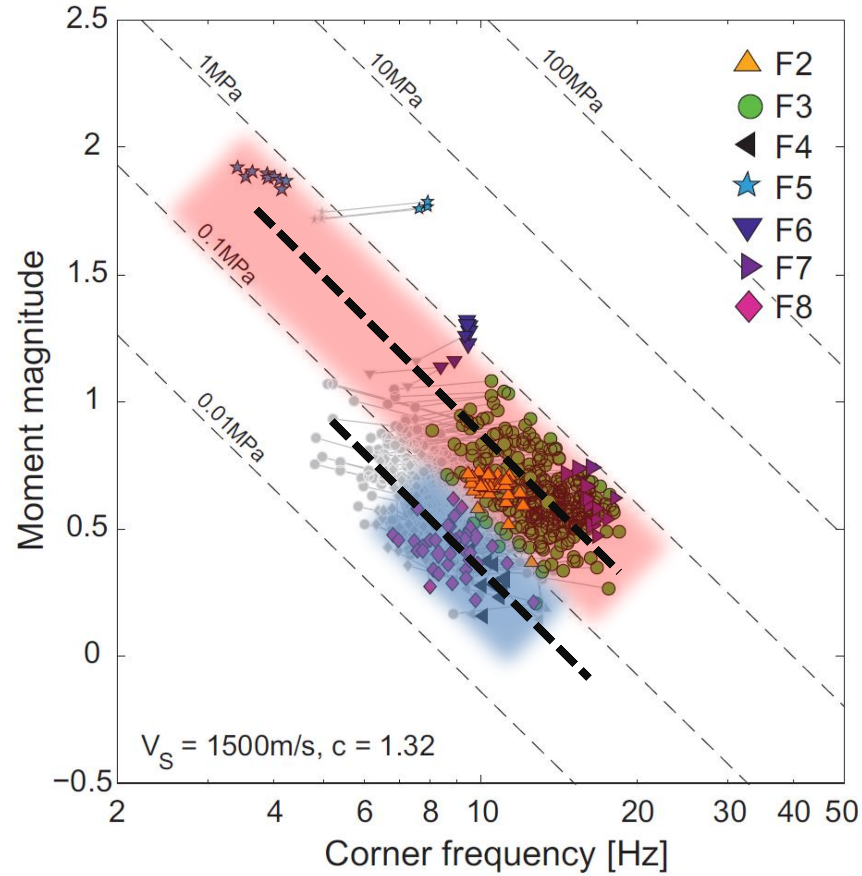


Harrington et al., (in prep.)

Volcanic-hybrid EQs

- Spectral fitting and spectral ratio method applied to 8 families
- Constant $\Delta\sigma$ observed for events originating from similar locations
- Velocity inhomogeneities influences observed stress drops

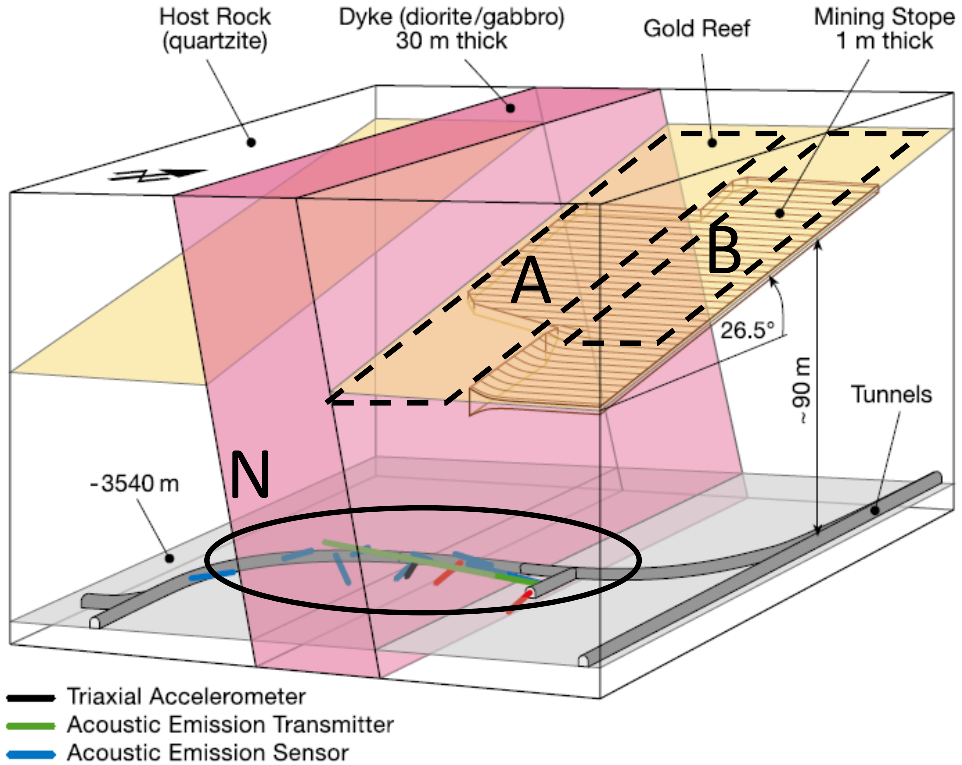


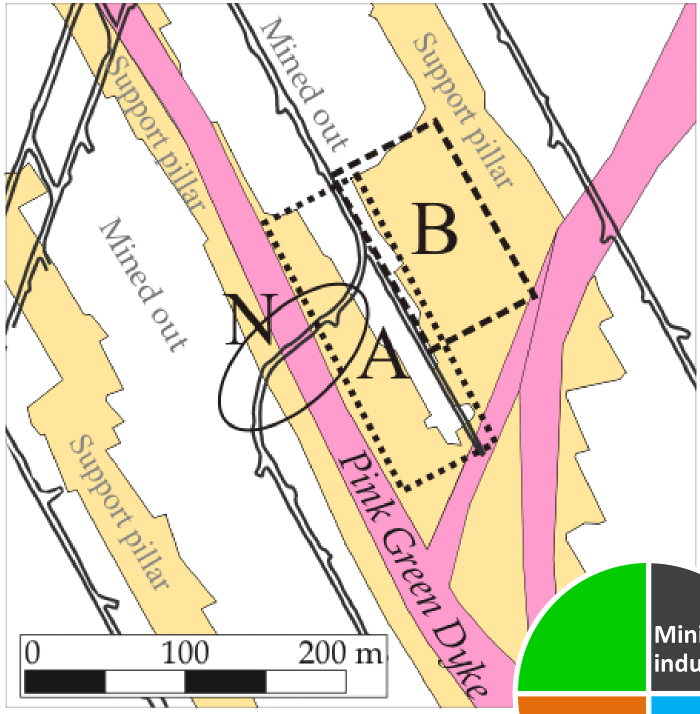


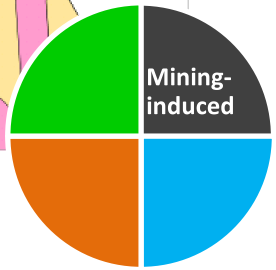
Harrington et al., (in prep.)

JAGUARS project: scaling of picoseismicity

- Mponeng deep gold mine, underground in-situ geomechanical laboratory
- Aim: Investigate the rupture process from nano- to picoscale (m – cm source size)





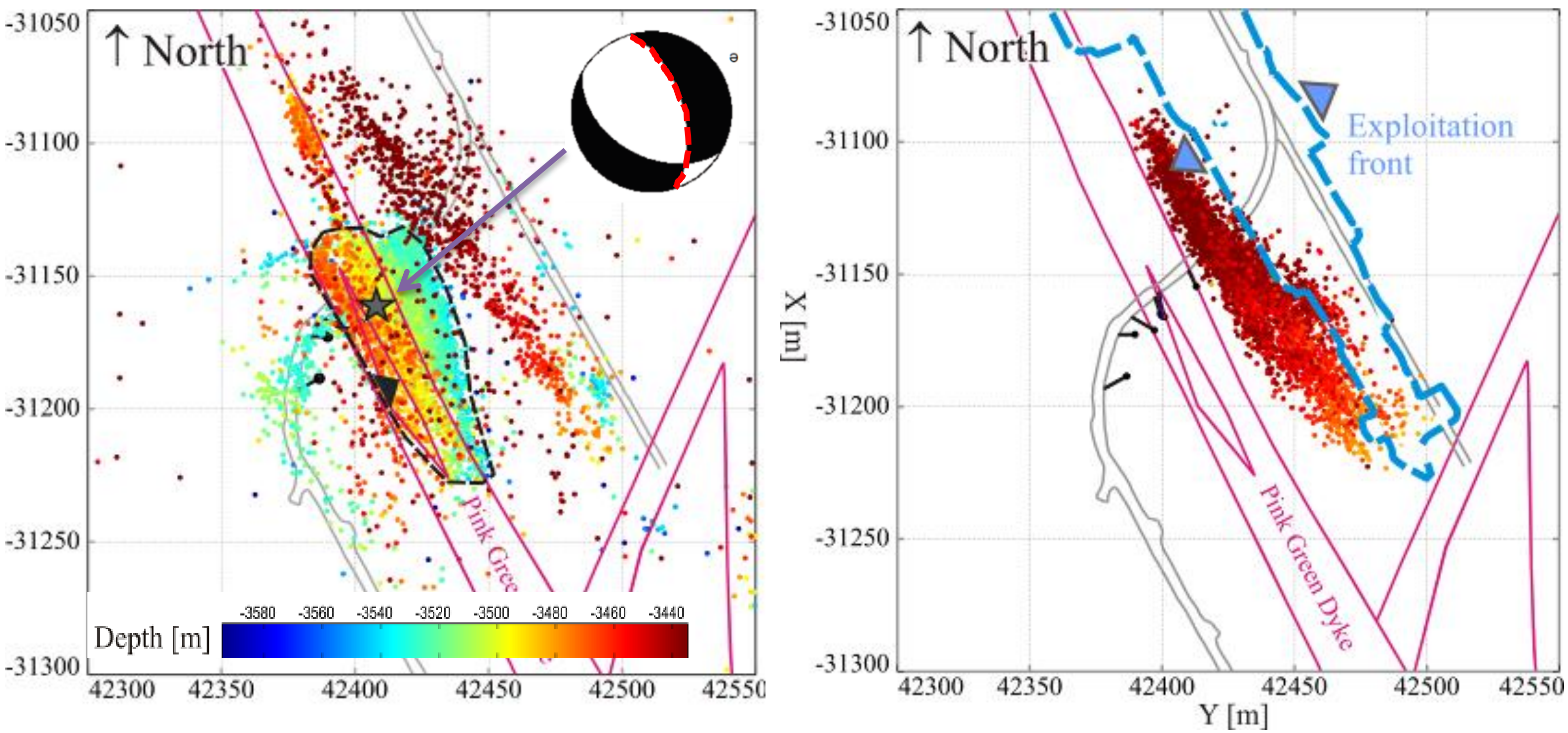


JAGUARS project: scaling of picoseismicity

- Source parameters calculated for two types of data (M_W -4.1 to -0.8)
- Analysis: Spectral fitting / spectral ratio

Aftershocks of M_W1.9 event

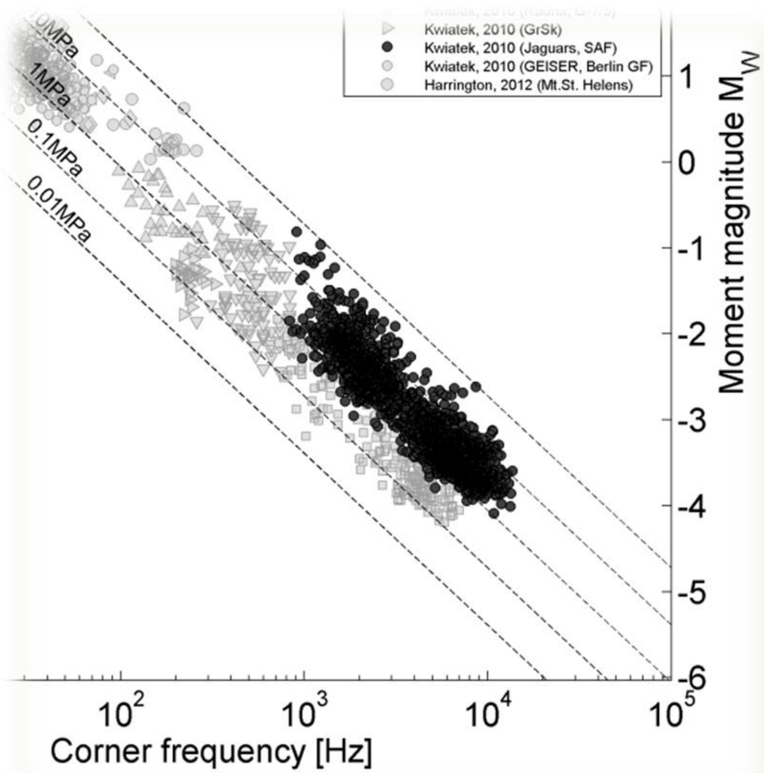
Post-blasting activity

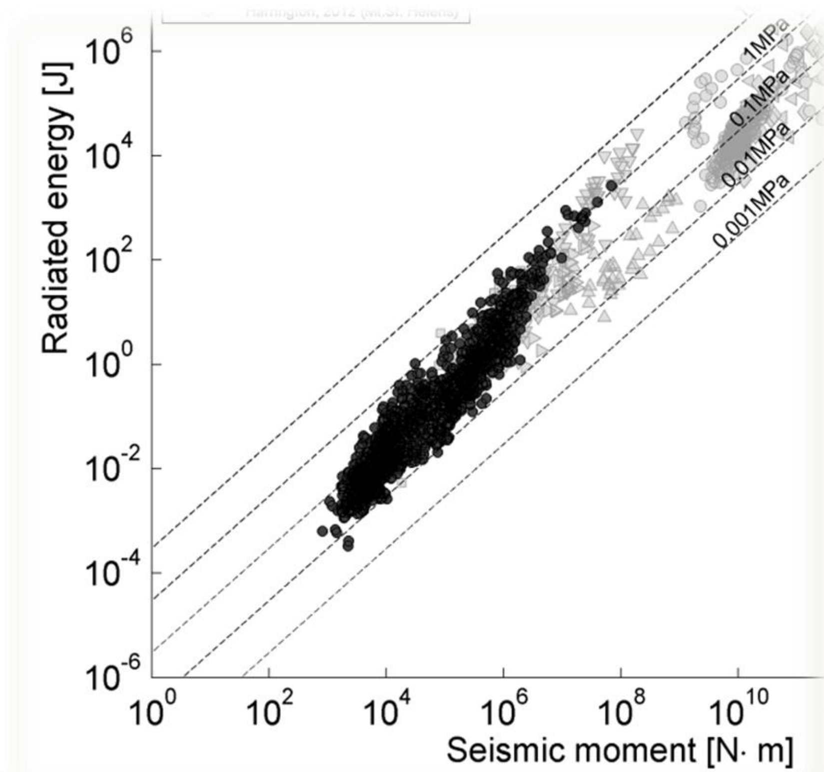


Davidsen et al., 2012, PRL 108; Kwiatek et al., 2011, BSSA 100 (3); Kwiatek et al., 2011, BSSA 101 (6)

JAGUARS project: scaling of picoseismicity

- Earthquake rupture process governed by similar physics over a range of magnitudes (-0.8 and -4.1): supported by G-R relations, dynamic and static source parameters and statistical analysis of magnitude clustering and interevent time intervals.

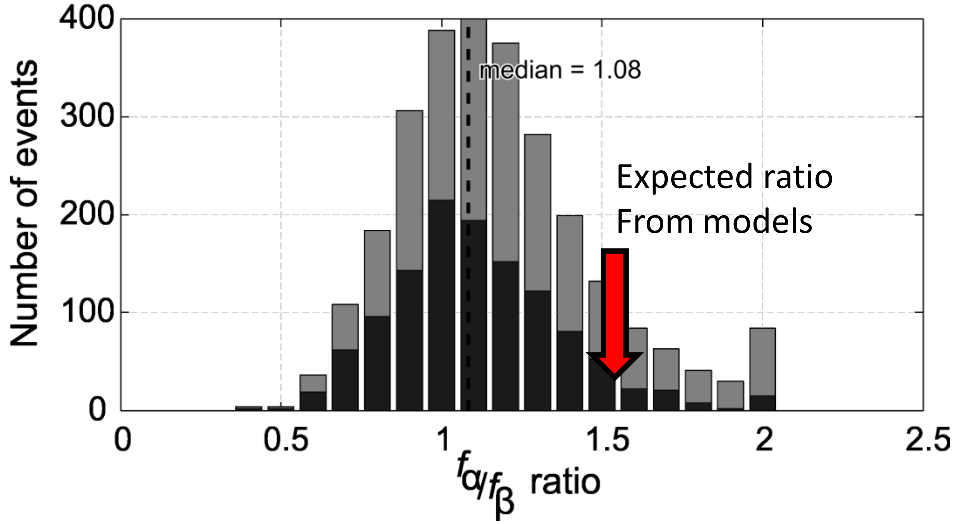


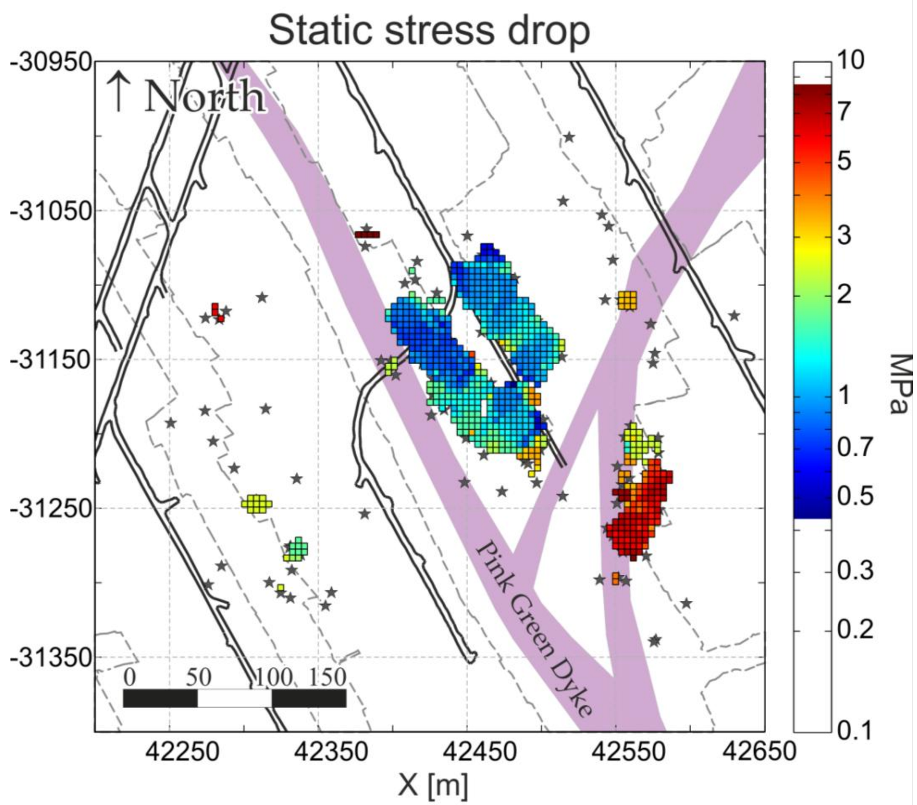


Kwiatek et al., 2011, Bull. Seism. Soc. Am. 101 (6)

Slow rupture processes, $\Delta\sigma$ & σ_a dependendent on local geology

- Low rupture velocities: low P-to-S corner frequency ratio (Collins&Young, BSSA 1990), low radiation efficiency (Brodsky & Kanamori 2004)
- Local variations in $\Delta\sigma$ and σ_a clearly depend on geological setup (~V_R)

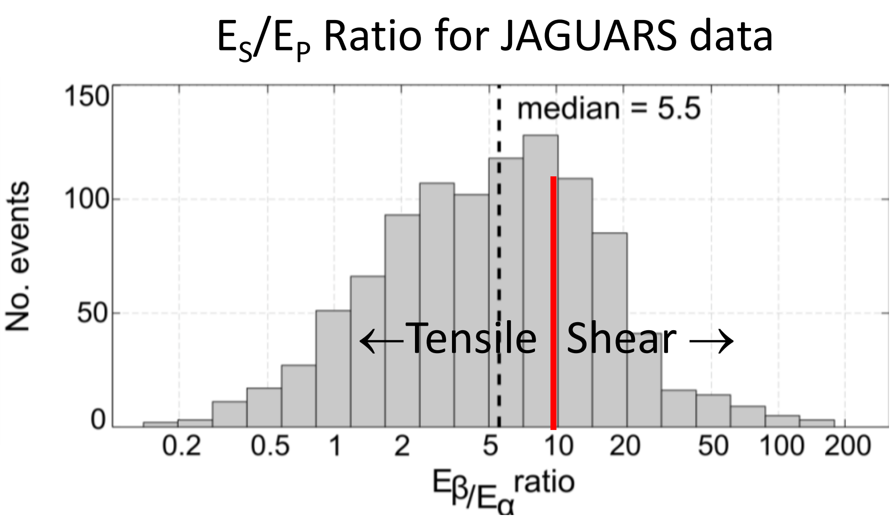


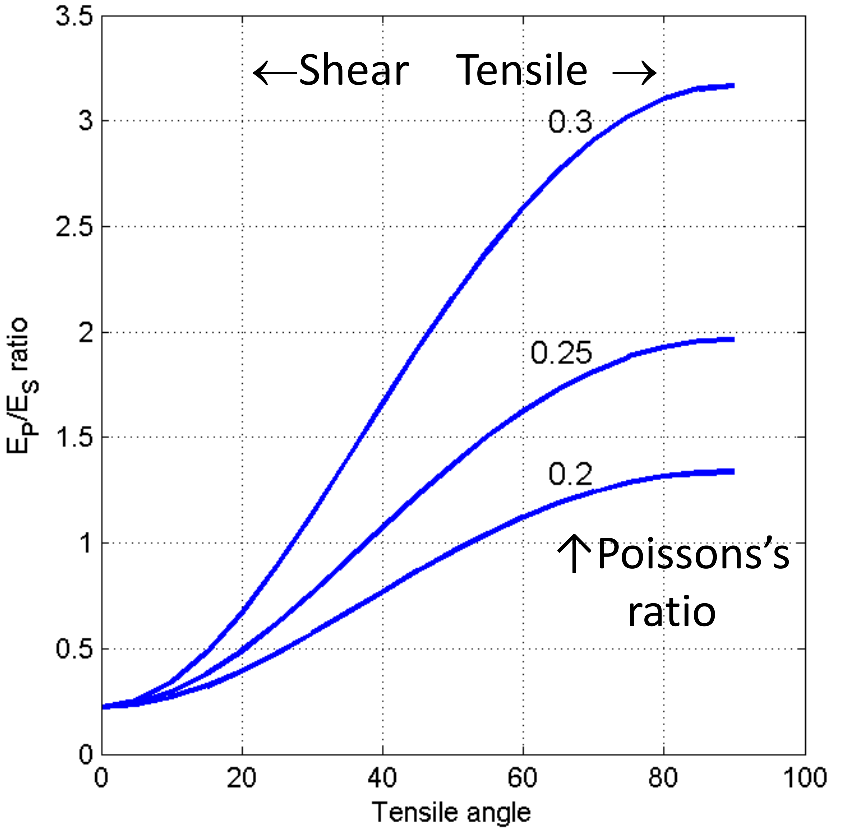


Kwiatek et al., 2011, Bull. Seism. Soc. Am. 101 (6)

Non-DC components in nano/picoscale

- Low E_S/E_P ratio observed – possible non-DC rupture processes
- P-wave energy cannot be ignored while estimating radiated energy

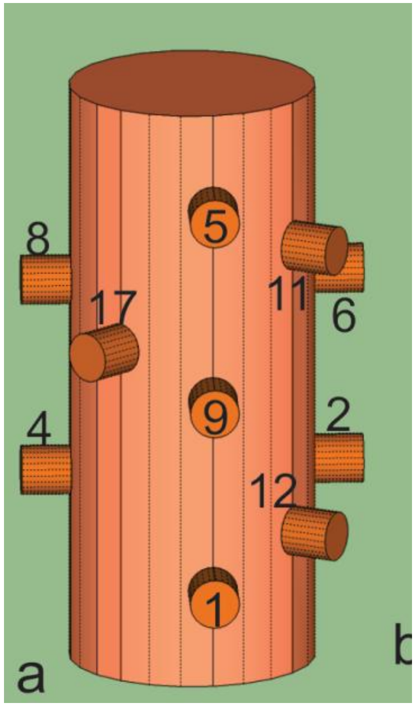


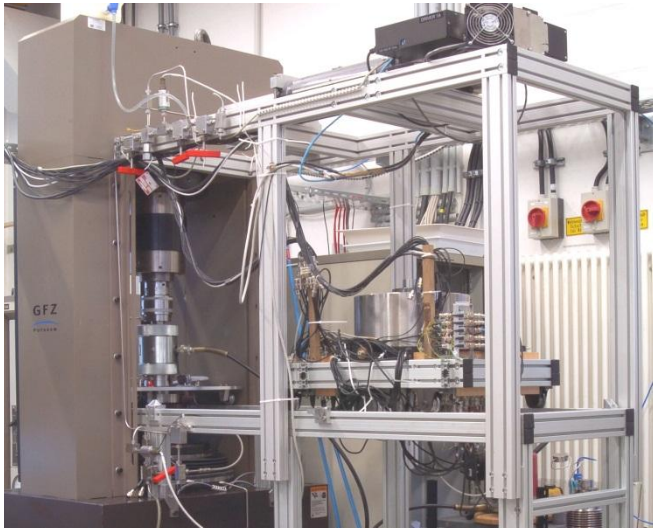


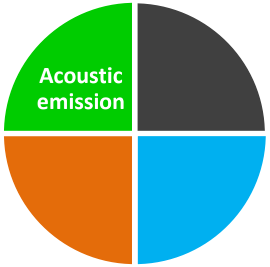
Kwiatek and Ben-Zion, in prep.; Kwiatek & Ben-Zion, proc. EGU2012

Scaling relations in laboratory experiments

- Fractures < 1mm (expected magnitude M < -6)
- Challenge: AE sensors not calibrated in absolute sense, coupling issues
- Only relative methods apply for source parameters estimation

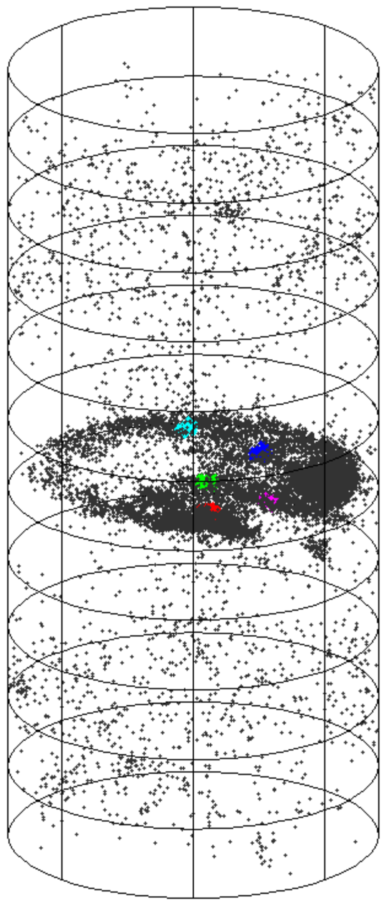


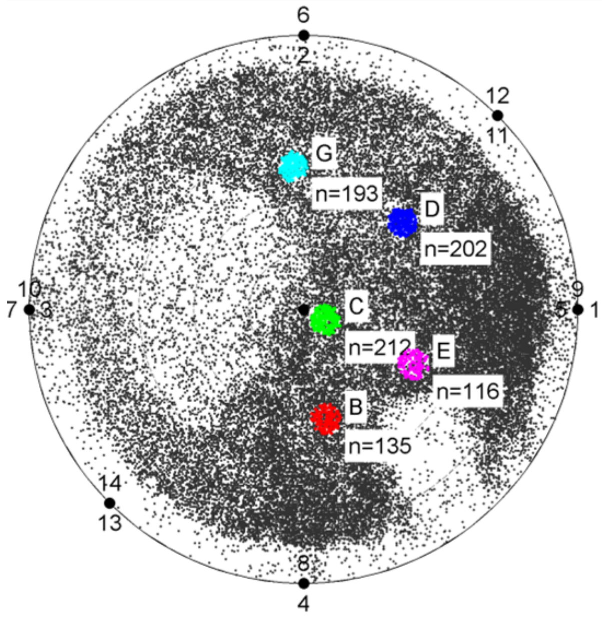


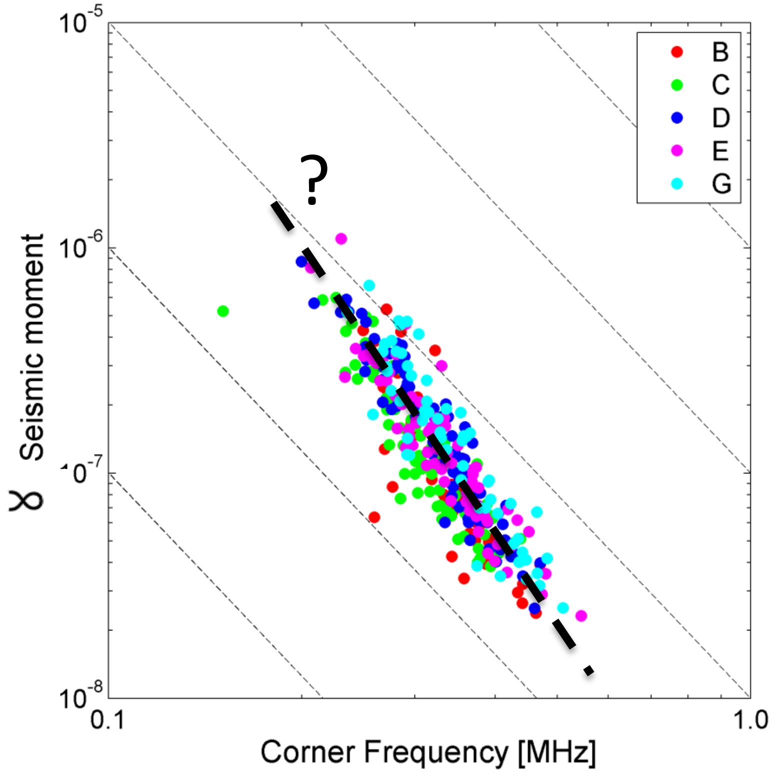


Static scaling for compaction band experiment

- Investigated 5 clusters of AE activity in a compaction band (116-212 events)
- Spectral ratio inversion used

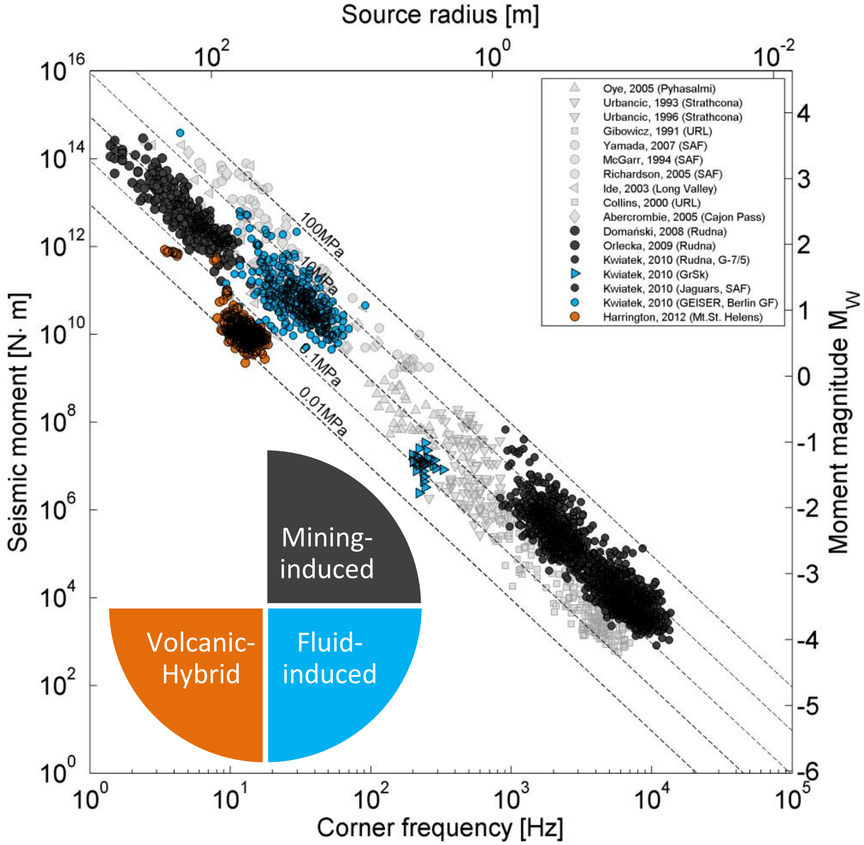


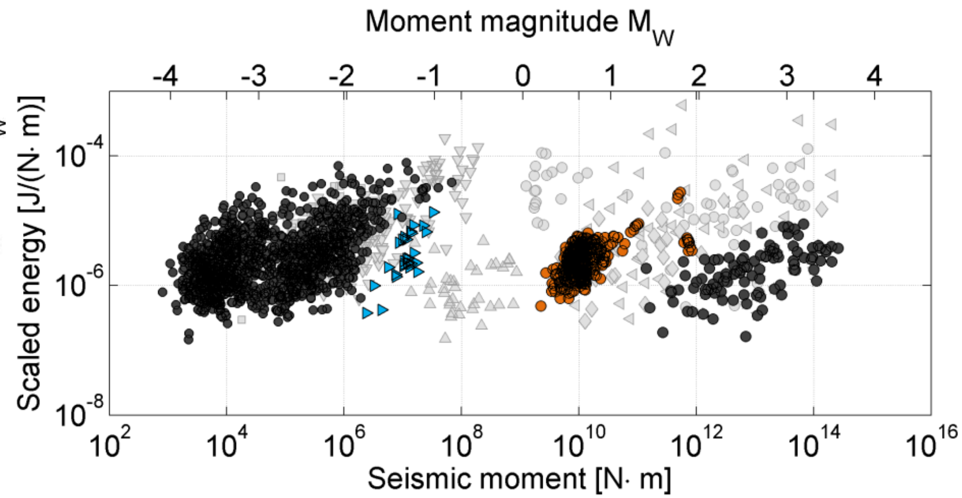




Summary

- Spectral ratio method applied to a few datasets including natural, mining- and fluid-induced seismicity and AE data
- No scaling breakdown observed down to at least M_W -4.1





Summary

- Apparent breakdown of self-similarity due to insufficient attenuation corrections

  (Mt. St. Helens, Berlin Geothermal Field, JAGUARS project)

- Evidences for slow rupture process

  (JAGUARS, Rudna Copper Mine)

- Local rock properties affect scaling relations (e.g. stress drop / apparent stress)

  (~rupture velocity, JAGUARS project)

- Non-DC components affect radiation pattern. Need to account for radiated energy from P phases while calculating the total energy

  (JAGUARS project)

Thank you for your attention!