Information

Results presented in the presentation has been already published in the following papers:

Kwiatek, G., Goebel, T., and G. Dresen (2014). Seismic moment tensor and b value variations over successive seismic cycles in laboratory stick-slip experiments. GRL 41

Kwiatek, G. and Y. Ben-Zion (2013). Assessment of P and S wave energy radiated from very small shear-tensile seismic events in a deep South African mine. JGR 118

Kwiatek, G., Plenkers, K., and G. Dresen (2011). Source parameters of picoseismicity recorded at Mponeng deep gold mine, South Africa: Implications for scaling relations. BSSA 101

Kwiatek, G., Plenkers, K., Nakatani, M., Yabe, Y., Dresen, G., and JAGUARS Research Group (2010). Frequency-magnitude characteristics down to magnitude −4.4 for induced seismicity recorded at Mponeng gold mine, South Africa. BSSA 100

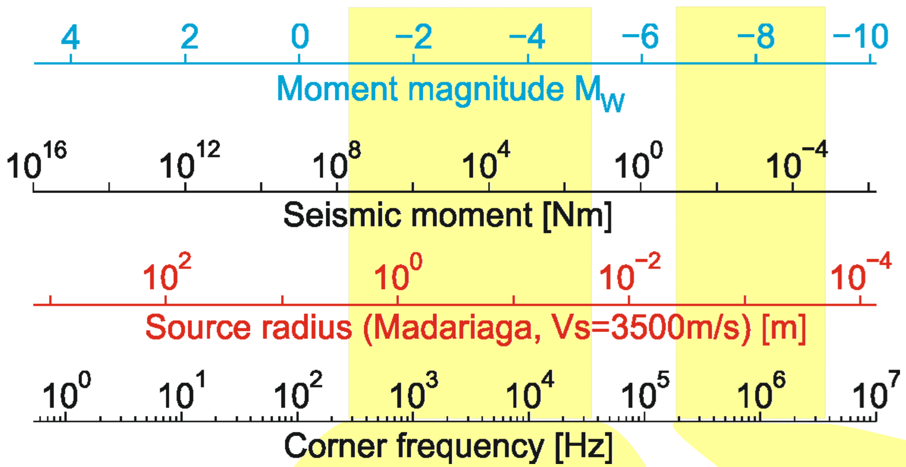
Please consider referring to above papers if you find this presentation useful

Seismological characterization of micro- and macrofracturing processes in a fault zone

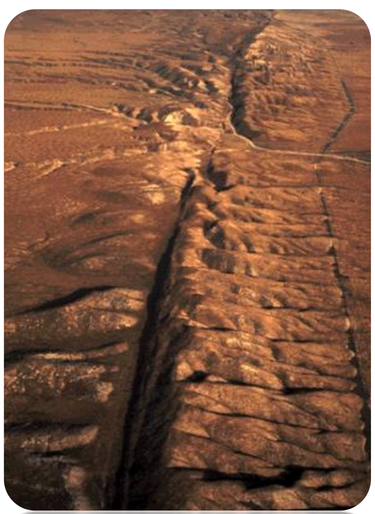
Grzegorz Kwiatek[1], Thomas Goebel[2] , Katrin Plenkers[3],
Georg Dresen [1] and JAGUARS Research Group

1. GFZ Potsdam, Section 3.2 Geomechanics and Rheology, Potsdam, Germany
2. CALTECH, Seismological Laboratory, Pasadena, USA
3. GMuG mbH, Bad Nauheim, Germany

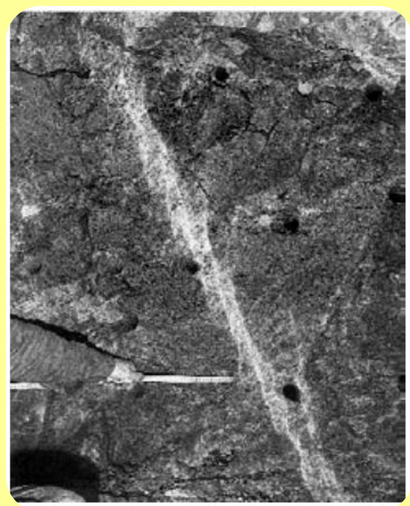
Monitoring of fault zone processes at all scales



km-scale
~Natural earthquakes

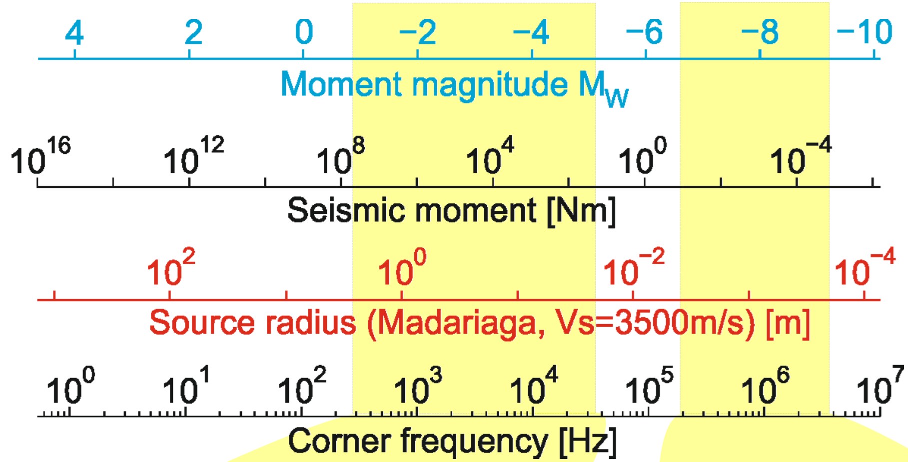


m-scale
~Induced seismicity

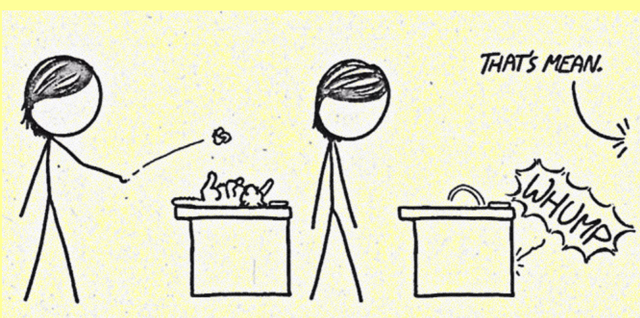


mm-scale
~Laboratory

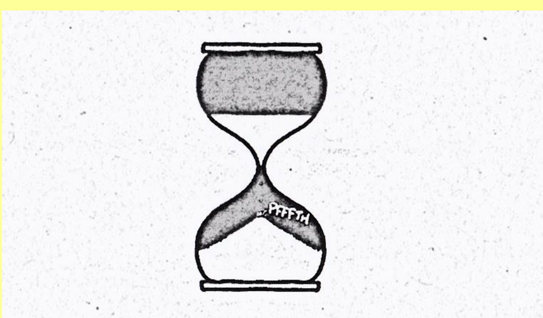
Monitoring of fault zone processes at all scales



Magnitude -2
A cat falling off a dresser

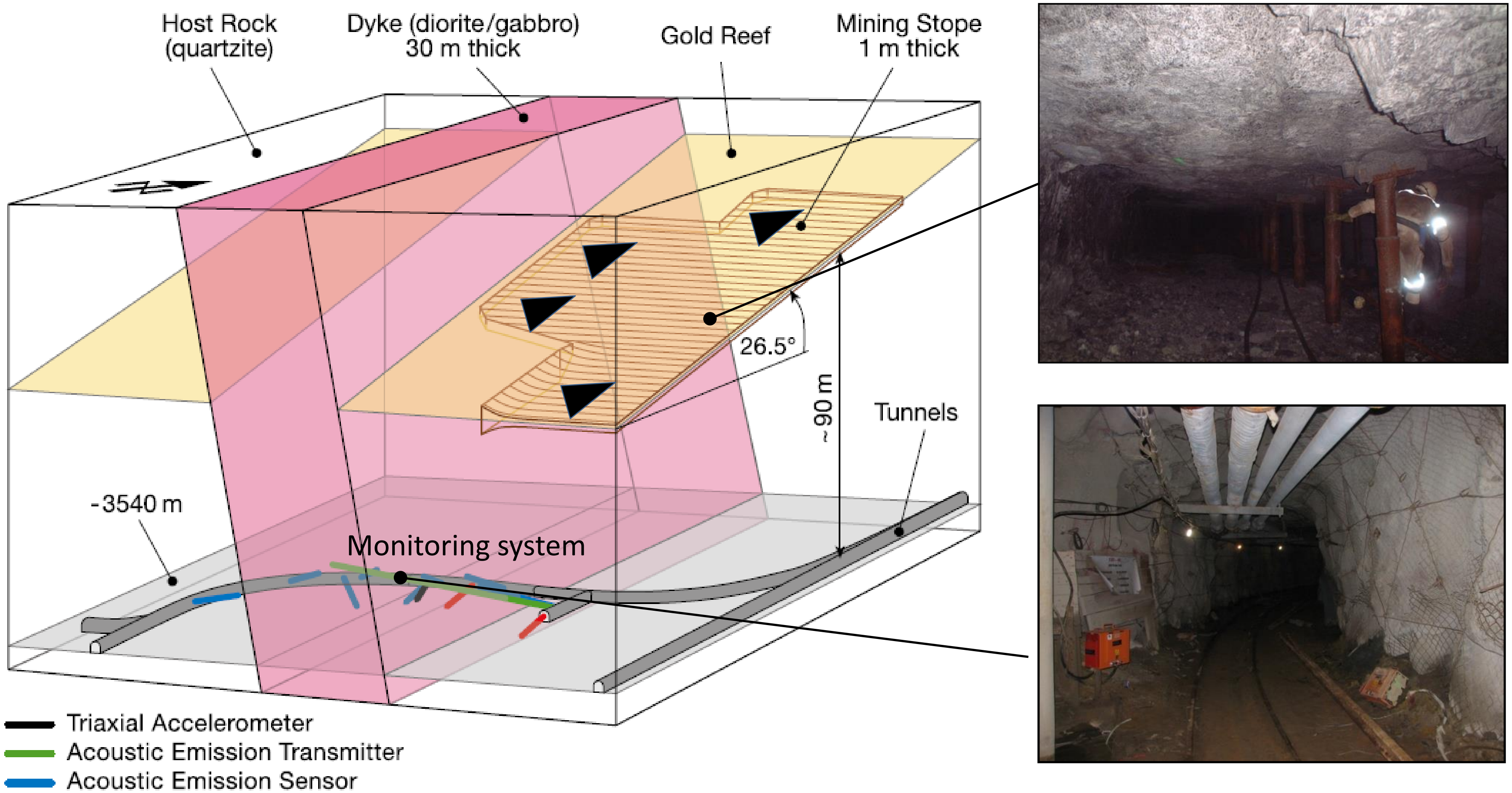


Magnitude -8
A grain sand falling onto the bottom of a tiny hourglass



In-situ geomechanical lab in Mponeng deep gold mine, South Africa

- 300x300x300m volume of rock at depth of >3500m
- Response of the dyke due to stresses changes (exploitation at the stope level)

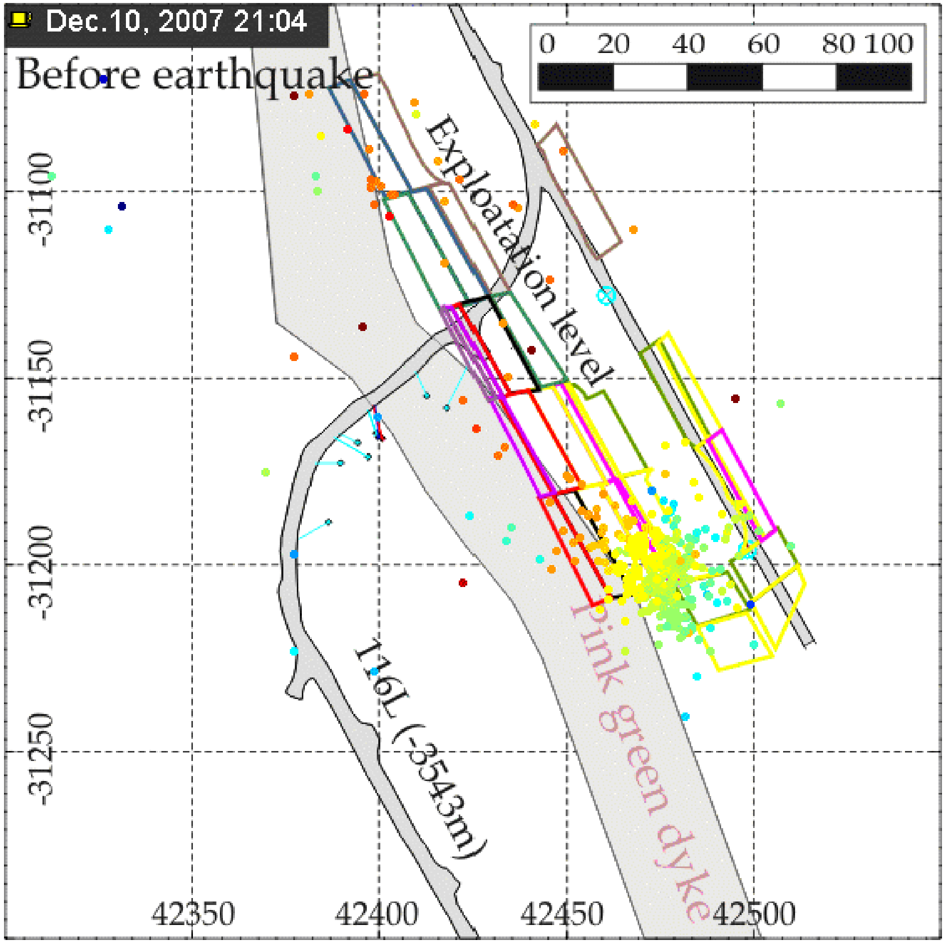


(Kwiatek et al., BSSA, 2010; Plenkers et al., BSSA, 2011)

M_W1.9 „Merry Christmas" earthquake

Normal faulting event in a dyke, 30m from the center of monitoring network

Aftershock sequence of >25000 events with M>-5



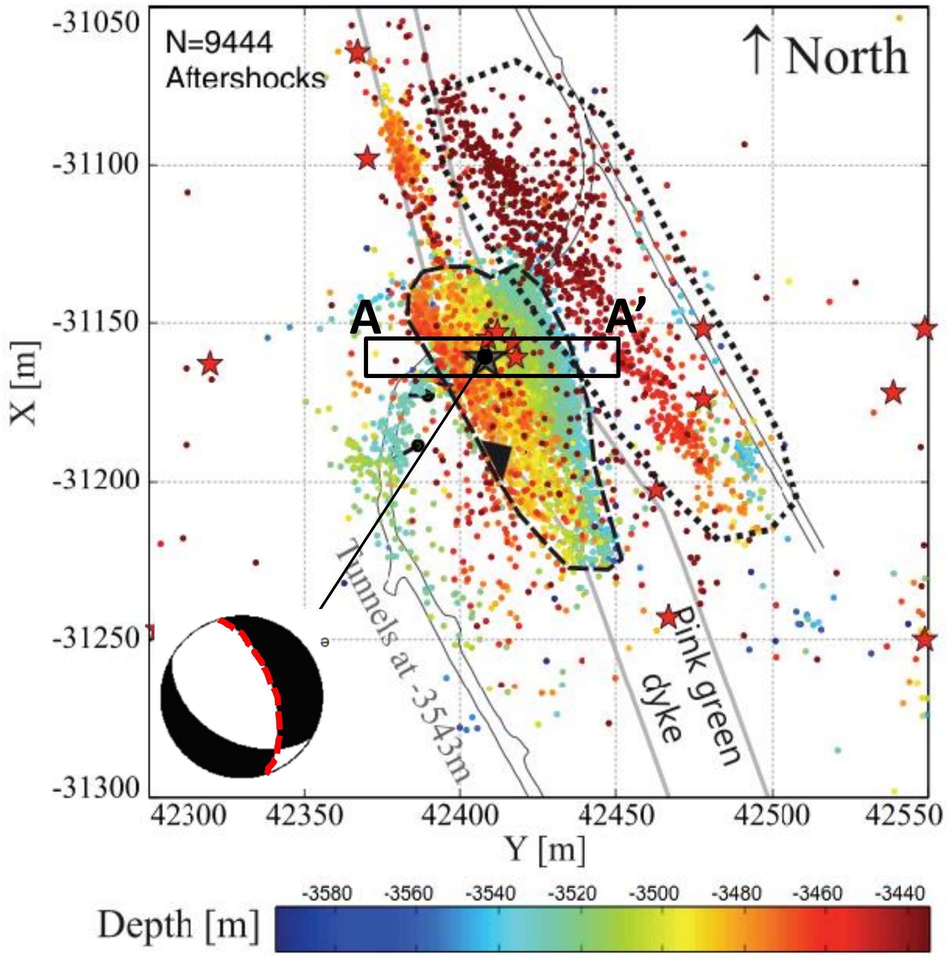
(Kwiatek et al., 2010, 2011, BSSA)

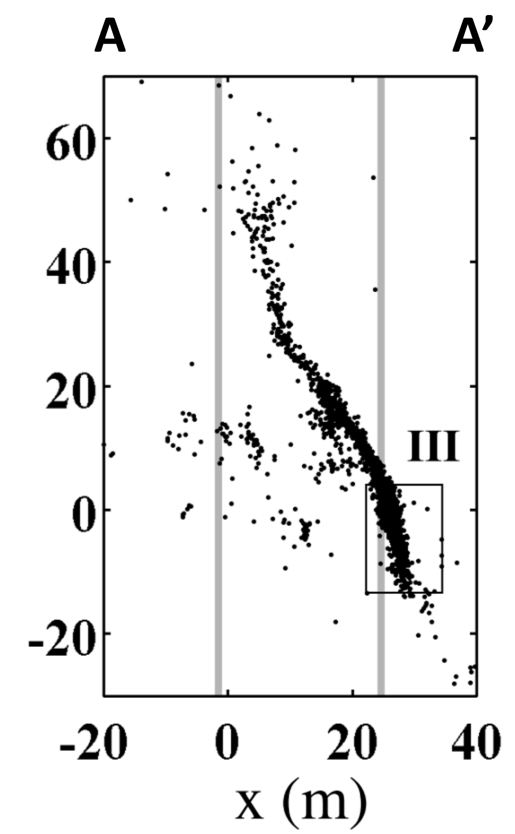
(↑Naoi et al., BSSA, 2011)

M_W1.9 event

Normal faulting event in a dyke, 30m from the center of monitoring network

Aftershock sequence of >25000 events with M>-5



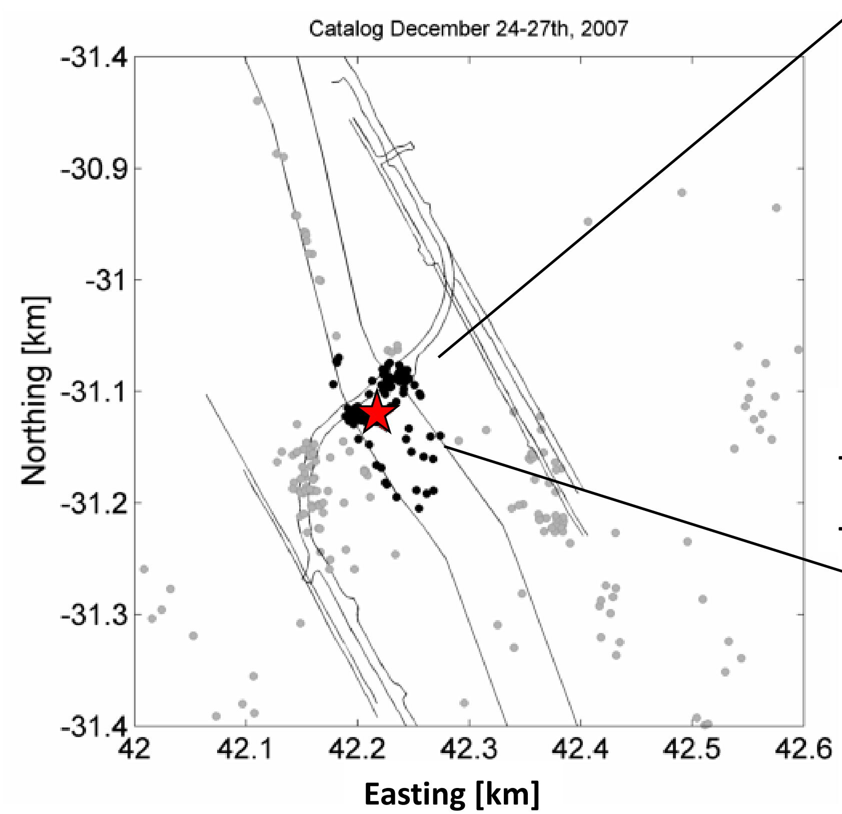


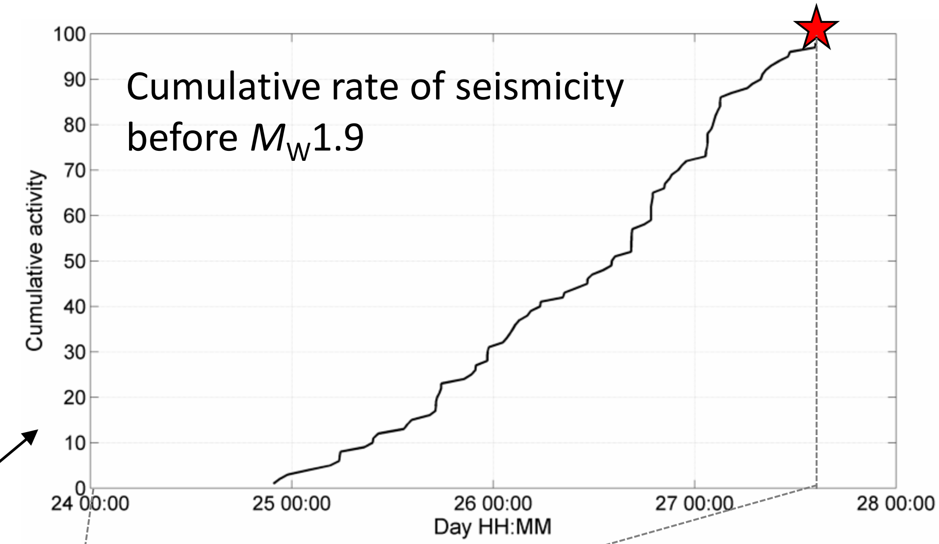
(Kwiatek et al., 2010, 2011, BSSA)

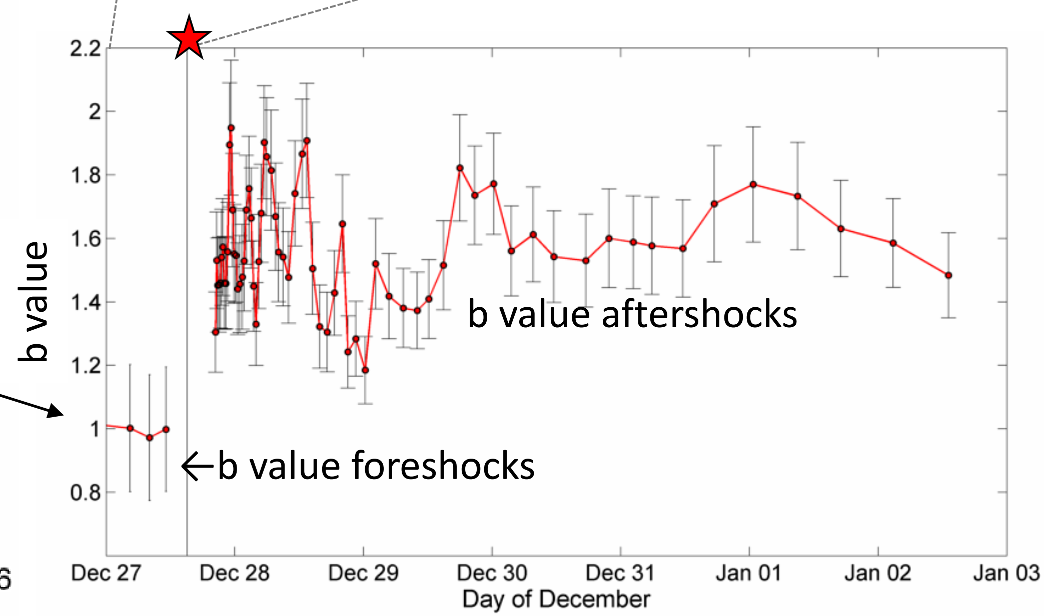
(↑Naoi et al., BSSA, 2011)

Activity before M_W1.9 event

- Steady seismicity rate
- Concentrated mostly around tunnel walls
- Persistent low *b* value in the area

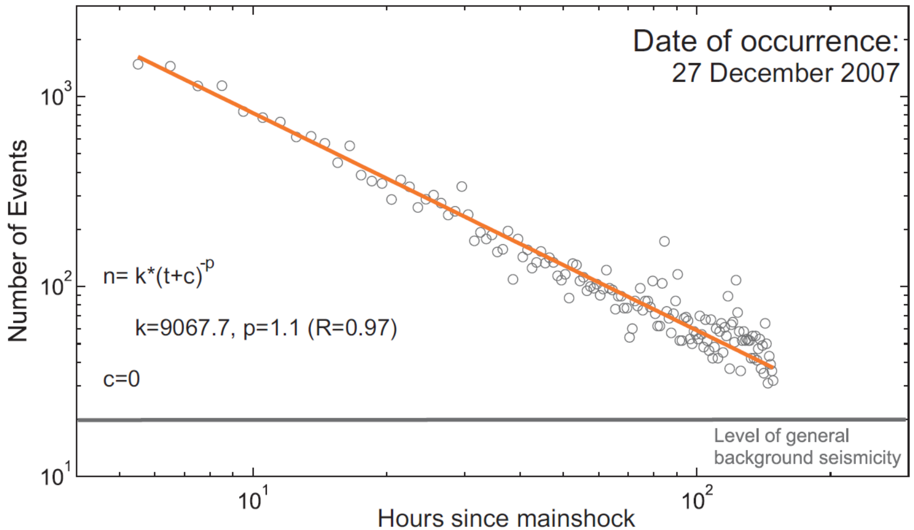




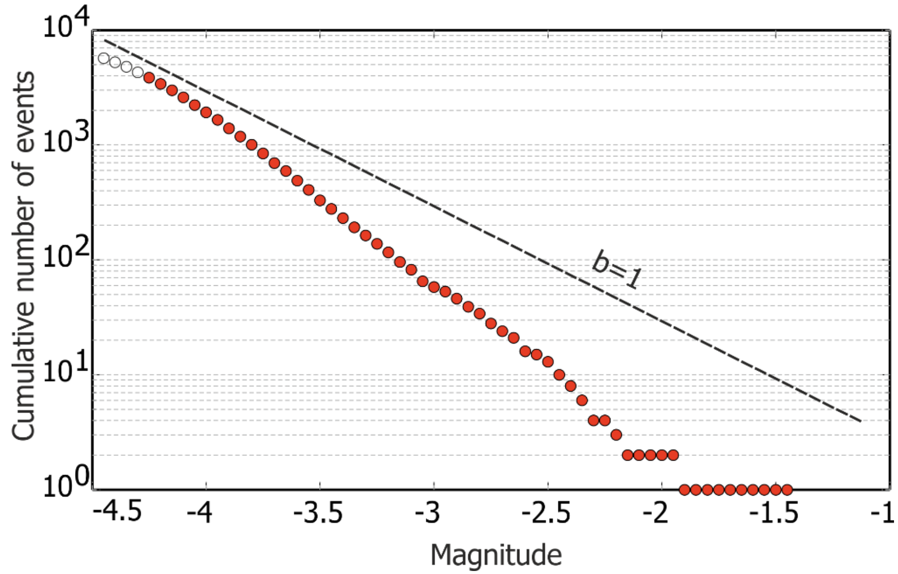


Properties of aftershock sequence

- Follows Omori's law with p=1.1
  (Plenkers et al., SRL, 2010)



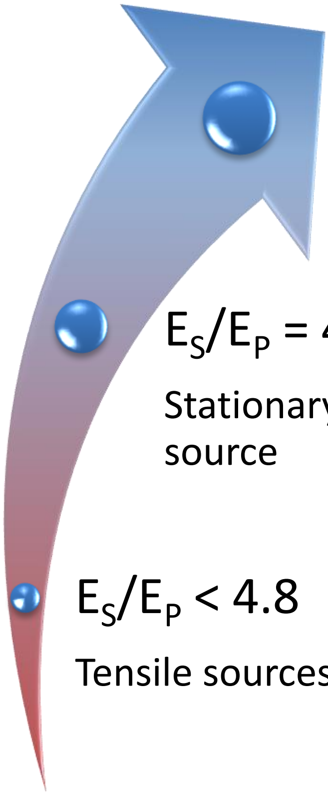
- Follows G-R law with b=1.3
  (Kwiatek et al., BSSA, 2010)



- No significant evidence for magnitude correlations – assumption of independent EQ magnitudes for forecasting rates and hazard assessment justified *(Davidsen and Kwiatek, PRL, 2012)*
- Temporal and spatial distribution of aftershocks can be modeled by rate-and-state formulation for EQ productivity *(Kozłowska et al., JGR, 2014)*

Properties of aftershock sequence

- Aftershocks on the fault plane (-5.2 < M < -2.4) show distinct signatures of non-DC mechanisms *(Kwiatek and Ben-Zion, JGR, 2013)*



$E_S/E_P > 4.5$

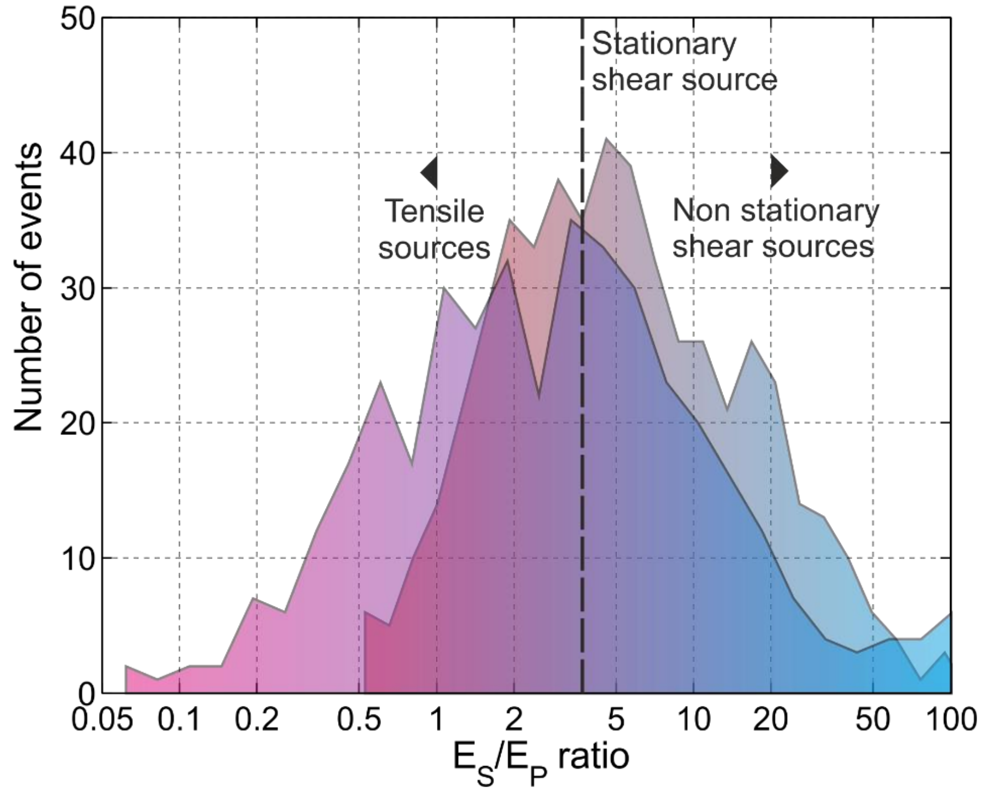
Non-stationary shear sources

$E_S/E_P = 4.5$

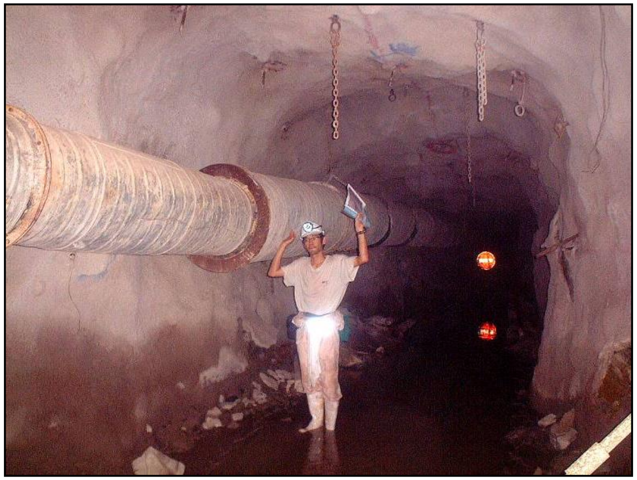
Stationary shear source

$E_S/E_P < 4.8$

Tensile sources



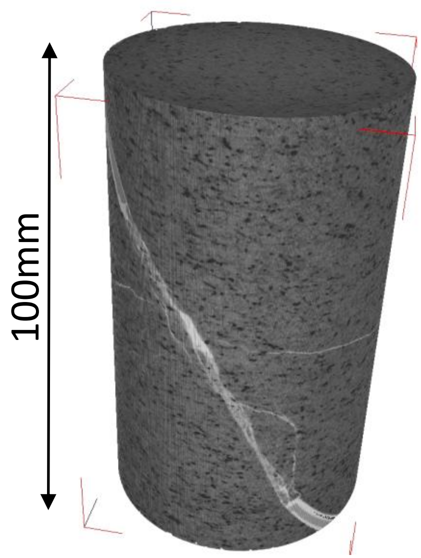
- Physical and statistical properties of the $M_W 1.9$ related fault seismicity shows similarities to that observed in natural faults

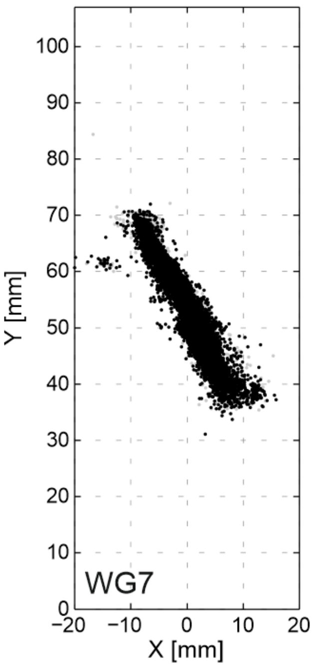


- Analog properties can be observed in laboratory experiments on rock samples through analysis of acoustic emission activity

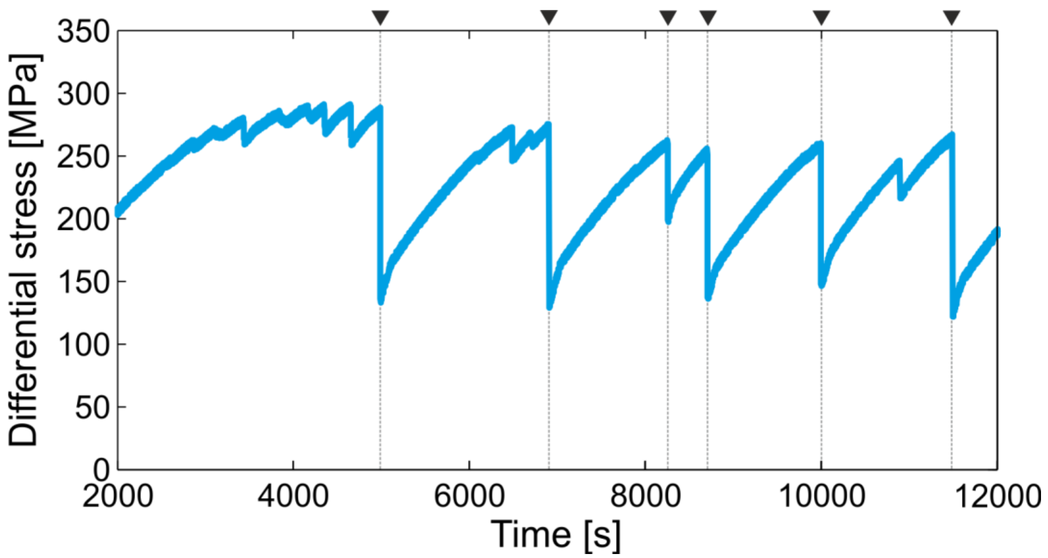
Laboratory faults – rough surface sample

- Fractured at 75MPa confinement
- Wide damage zone
- Small and large slips resulting in more than 100,000 acoustic emission events





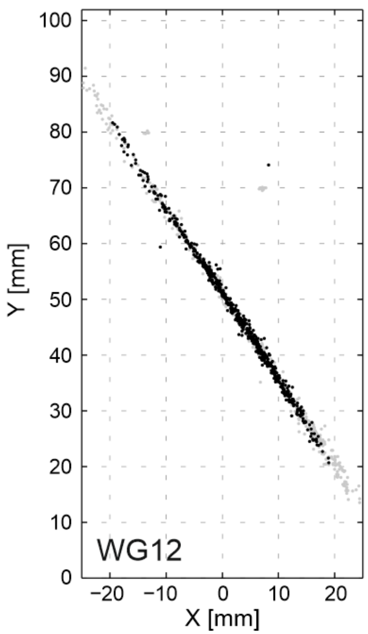
Slip history

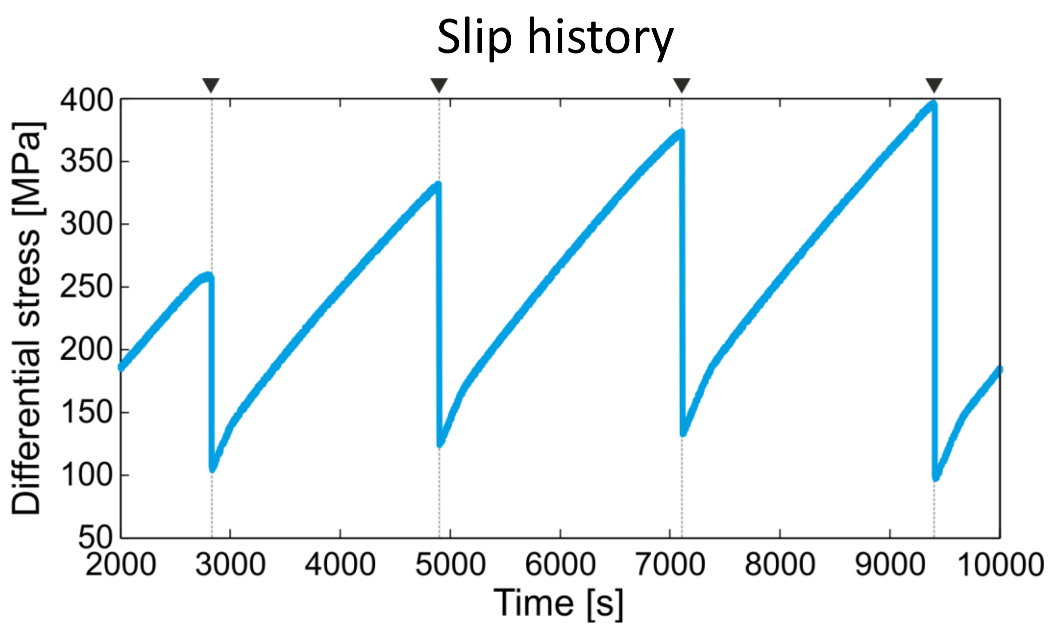


(Kwiatek et al., GRL, 2014; see also Goebel et al., GRL, PAGEOPH 2013)

Laboratory faults – saw-cut surface sample

- Saw-cut before stick-slip
- Thin damage zone
- Only large slips resulting in acoustic emission activity



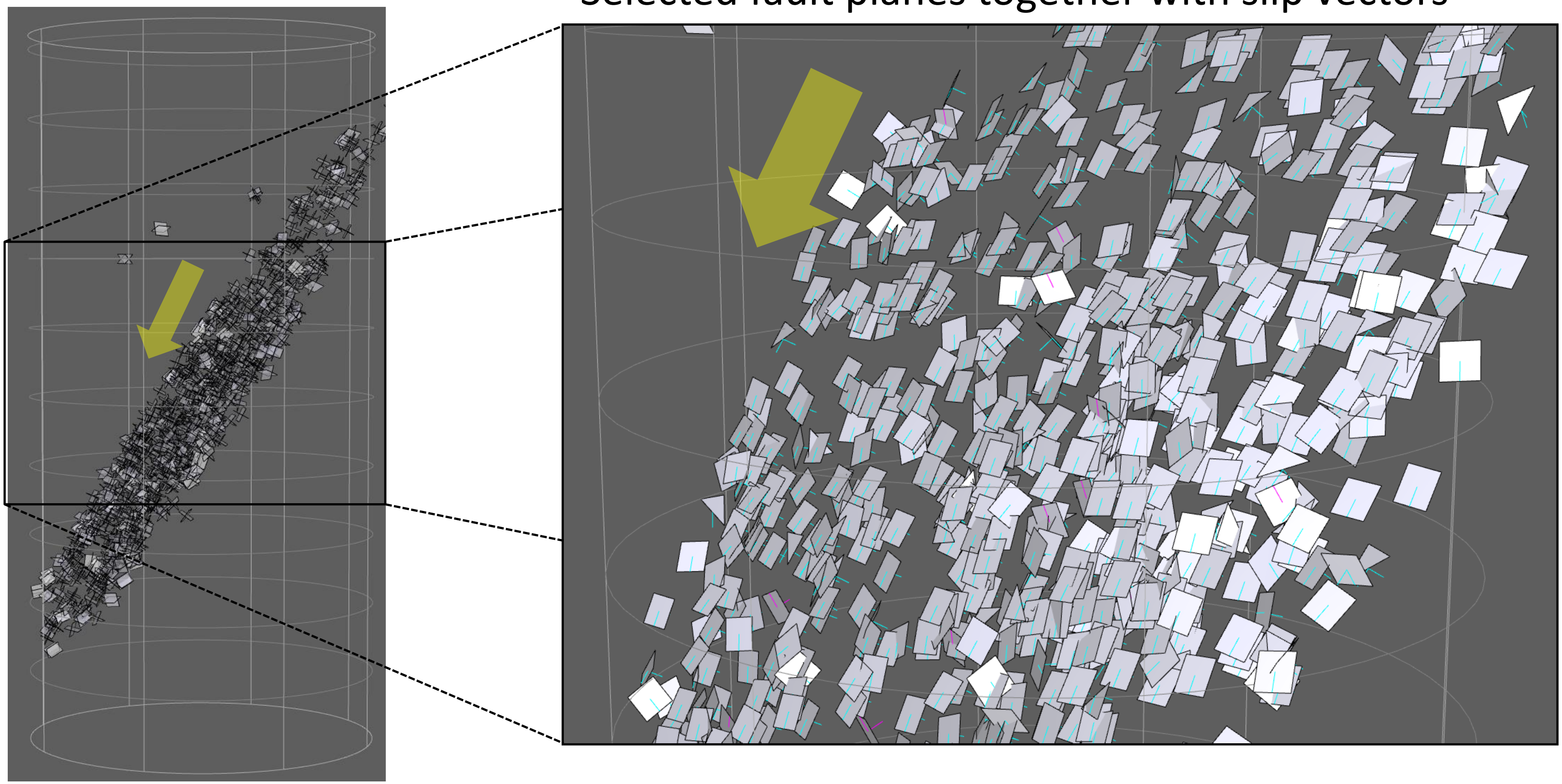


(Kwiatek et al., GRL, 2014; see also Goebel et al., GRL, PAGEOPH 2013)

Example: AE activity and focal mechanisms (saw-cut)

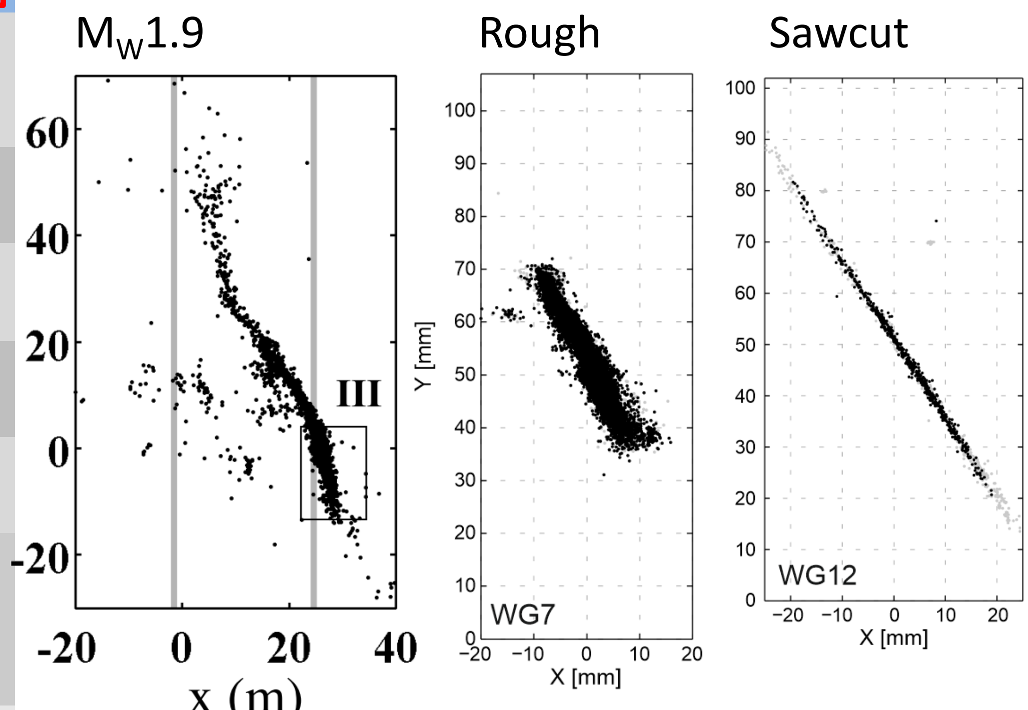
- 1200 AE located, ~1100 MTs calculated

Selected fault planes together with slip vectors



Lab vs nature: Fault thickness/length

	M_W1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	low (1)	low (1.1)	n/a (bimodal)
b value after slip(s)	high (1.3)	high (1.4)	-
Seismic activity	post-slip a/f≈70	post-slip a/f≈100	pre-slip a/f<<1
Activity before/after	low/high	low/high	high/-
Activity after	p=1.1	p=1.2	-
Aftershock mechanisms	Shear + Non-shear	Shear + Compaction	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)

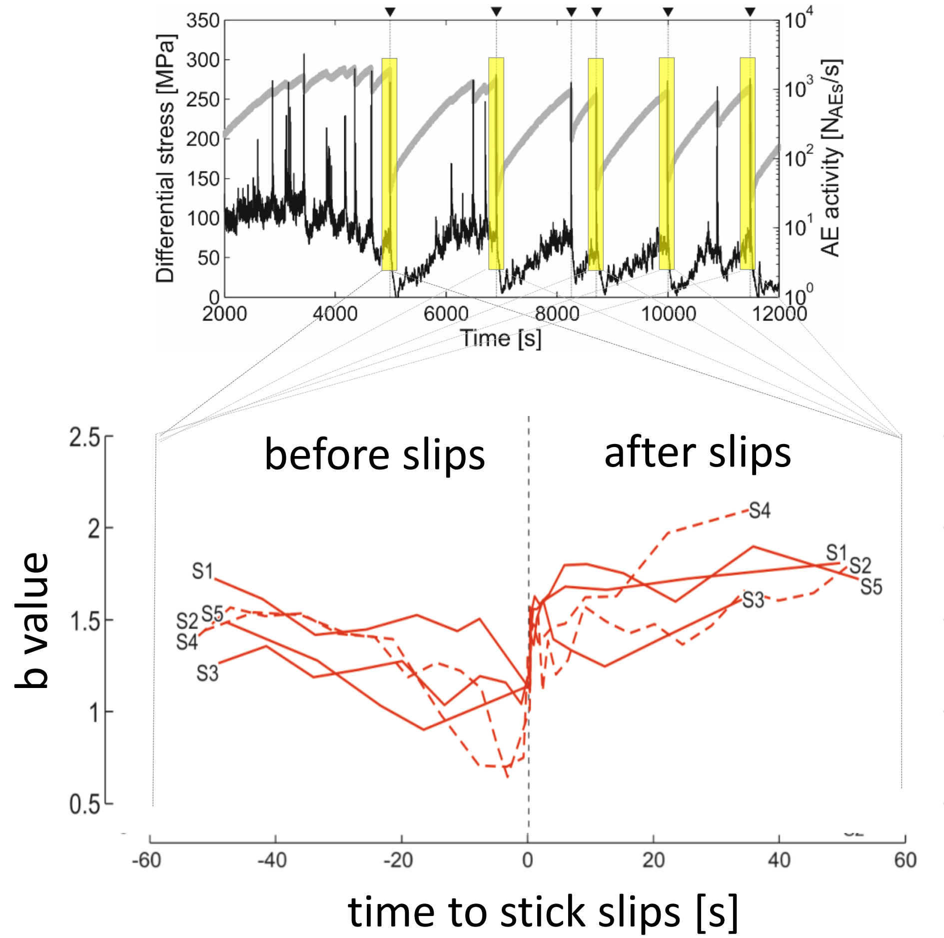


x 10^{-3} scale factor

Lab vs nature: b value/activity (rough sample)

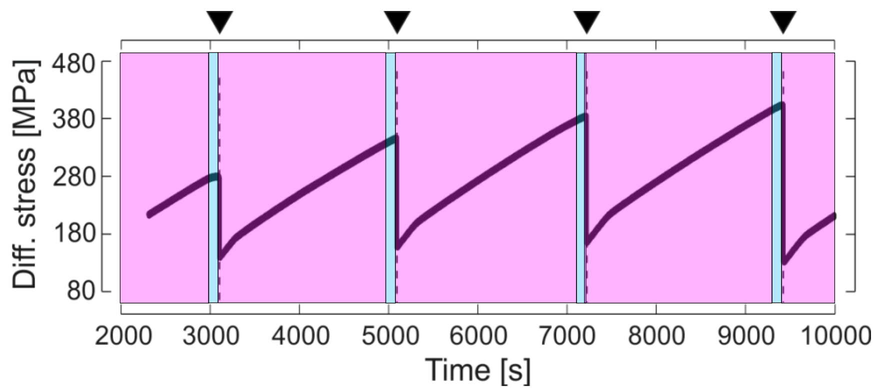
	M_W1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<<1
Activity before/after	**low/high**	**low/high**	high/-
Activity after	**p=1.1**	**p=1.2**	-
Aftershock mechanisms	Shear + Non-shear	Shear + Compaction	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)

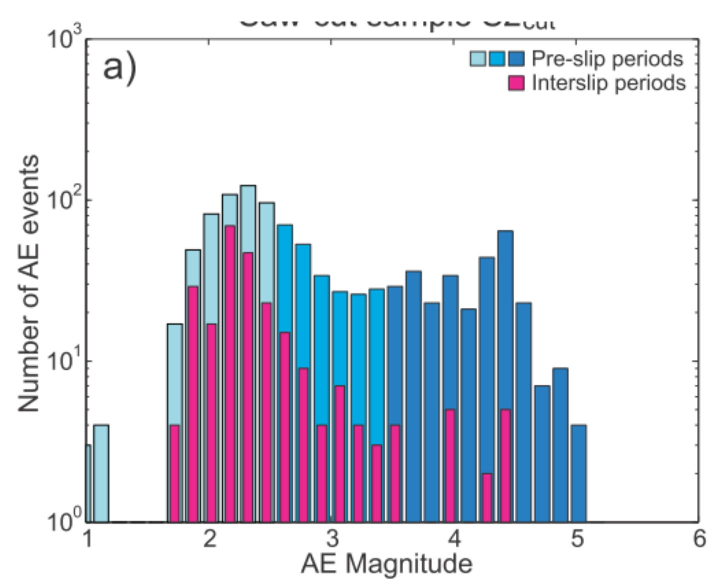
Rough sample



Lab vs nature: b value/activity (saw-cut rample)

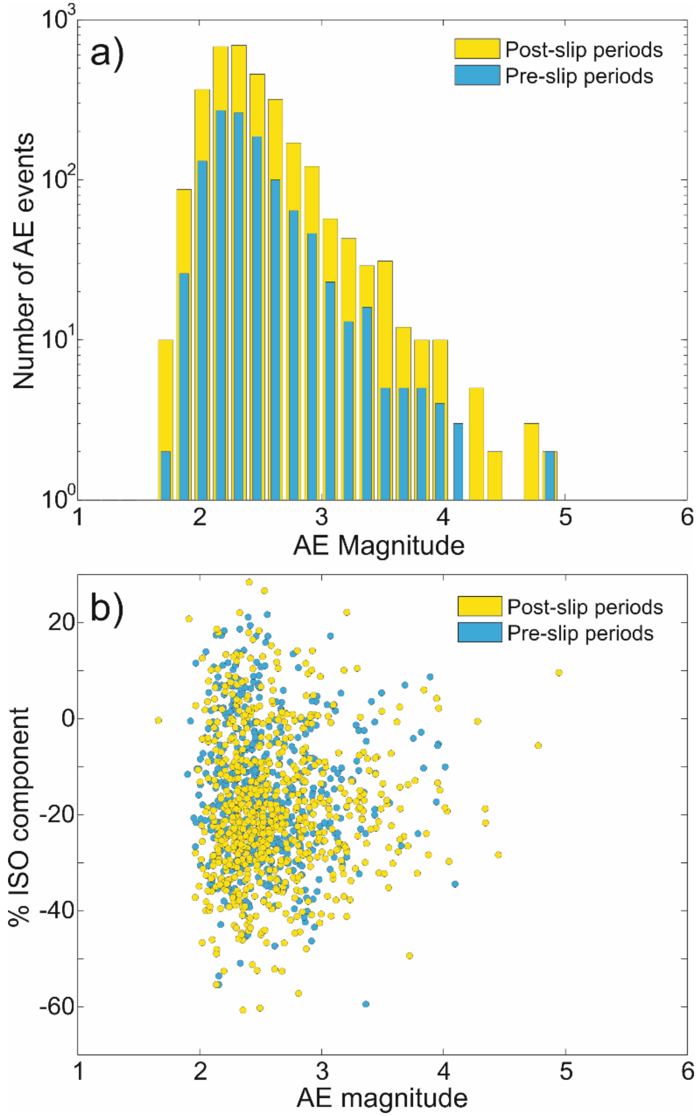
	M_w1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<<1
Activity before/after	**low/high**	**low/high**	high/-
Activity after	**p=1.1**	**p=1.2**	-
Aftershock mechanisms	Shear + Non-shear	Shear + Compaction	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)





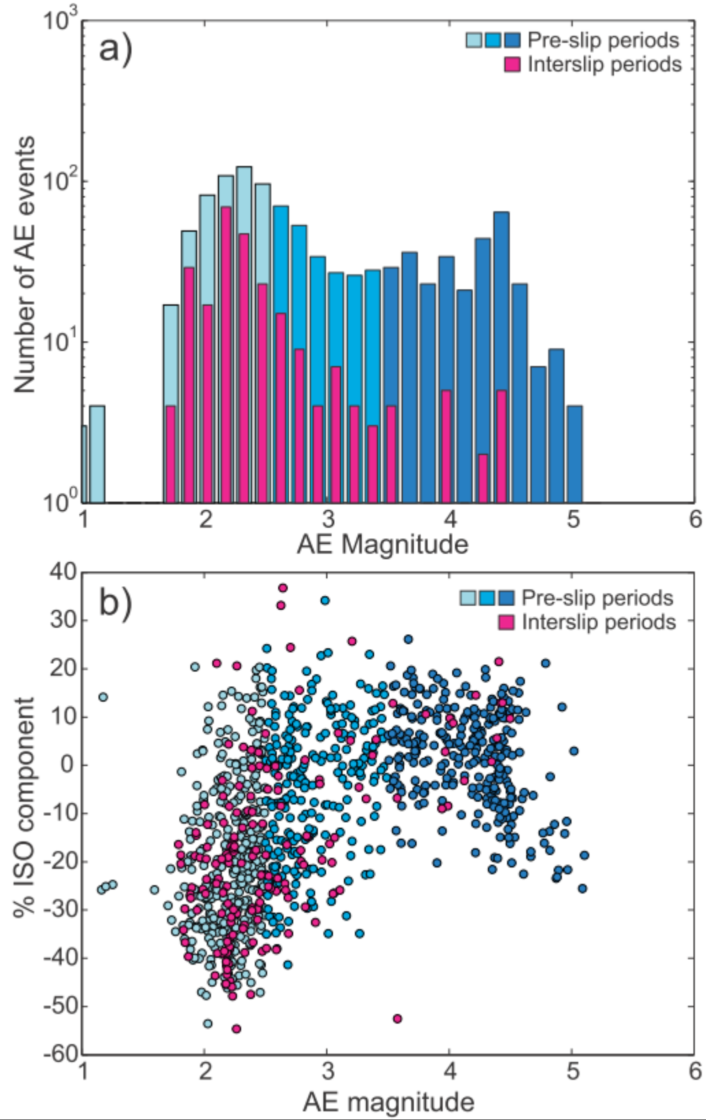
Lab vs nature: Source mechanisms (rough sample)

	M_w1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<<1
Activity before/after	**low/high**	**low/high**	high/-
Activity after	**p=1.1**	**p=1.2**	-
Aftershock mechanisms	**Shear + Non-shear**	**Shear + Compaction**	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)



Lab vs nature: Source mechanisms (saw-cut sample)

	M_w1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<<1
Activity before/after	**low/high**	**low/high**	high/-
Activity after	**p=1.1**	**p=1.2**	-
Aftershock mechanisms	**Shear + Non-shear**	**Shear + Compaction**	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)



Summary

- Physical processes generally do not differ significantly between laboratory scale and ~60m fault
- Classical „coulomb" shear failure of a dyke in Mponeng Mine lead to aftershock sequence with statistical characteristics similar to that observed in smaller and larger scales
- non-DC fault mechanisms abundant in a direct proximity of the fault zone, likely hardly recoverable using classical networks
- M_W1.9 „fresh" fault characteristics generally analogous to rough surface fault in laboratory stick-slip experiment. Is saw-cut fault an analog of a mature fault zone?
- Maturation of the fault zone visible in both stick-slip experiments
- Close-by monitoring essential to understand the processes in the fault zone

Thank you for your attention!

Contact: kwiatek@gfz-potsdam.de
Publications: http://induced.pl/about

Kwiatek, G., Goebel, T., and G. Dresen (2014). Seismic moment tensor and b value variations over successive seismic cycles in laboratory stick-slip experiments. **GRL 41**

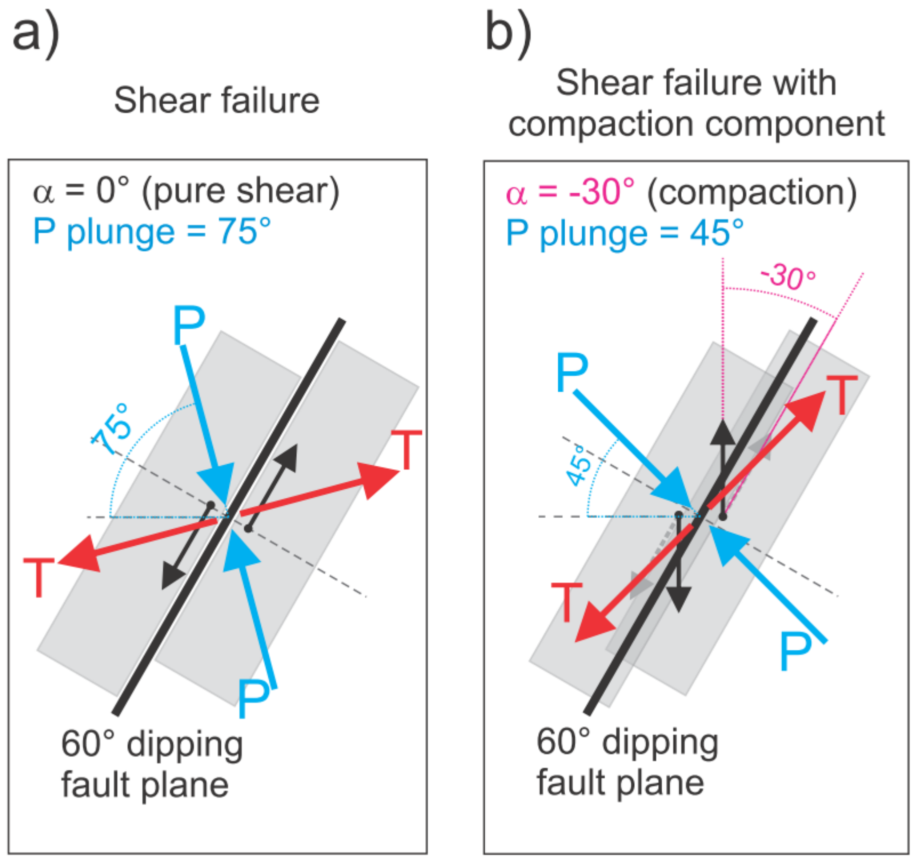
Kwiatek, G. and Y. Ben-Zion (2013). Assessment of P and S wave energy radiated from very small shear-tensile seismic events in a deep South African mine. **JGR 118**

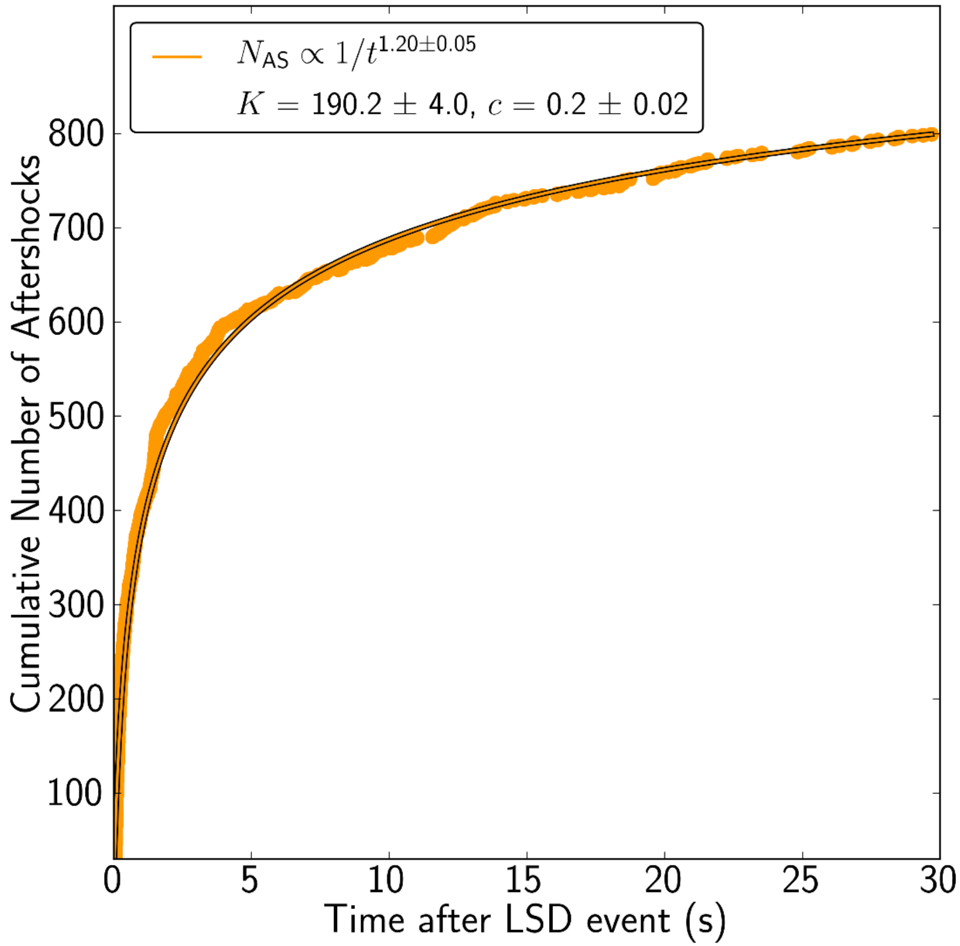
Davidsen, J., and G. Kwiatek (2013). Earthquake interevent time distribution for induced micro-, nano- and picoseismicity. **PRL 110**

Davidsen, J., Kwiatek, G., and G. Dresen (2012). No evidence of magnitude clustering in an aftershock sequence of nano- and picoseismicity. **PRL 108**

Kwiatek, G., Plenkers, K., and G. Dresen (2011). Source parameters of picoseismicity recorded at Mponeng deep gold mine, South Africa: Implications for scaling relations. **BSSA 101**

Kwiatek, G., Plenkers, K., Nakatani, M., Yabe, Y., Dresen, G., and JAGUARS Research Group (2010). Frequency-magnitude characteristics down to magnitude −4.4 for induced seismicity recorded at Mponeng gold mine, South Africa. **BSSA 100**


a)
Shear failure
α = 0° (pure shear)
P plunge = 75°
P
75°
T
T
P
60° dipping
fault plane
b)
Shear failure with
compaction component
α = -30° (compaction)
P plunge = 45°
-30°
P
45°
T
T
P
60° dipping
fault plane


$N_{AS} \propto 1/t^{1.20\pm0.05}$
$K = 190.2 \pm 4.0$, $c = 0.2 \pm 0.02$
Cumulative Number of Aftershocks
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
Time after LSD event (s)

Temporal changes in MT characteristics (saw-cut)

- AEs display dip-slip faulting

Interslip phase (until 80s before slip):

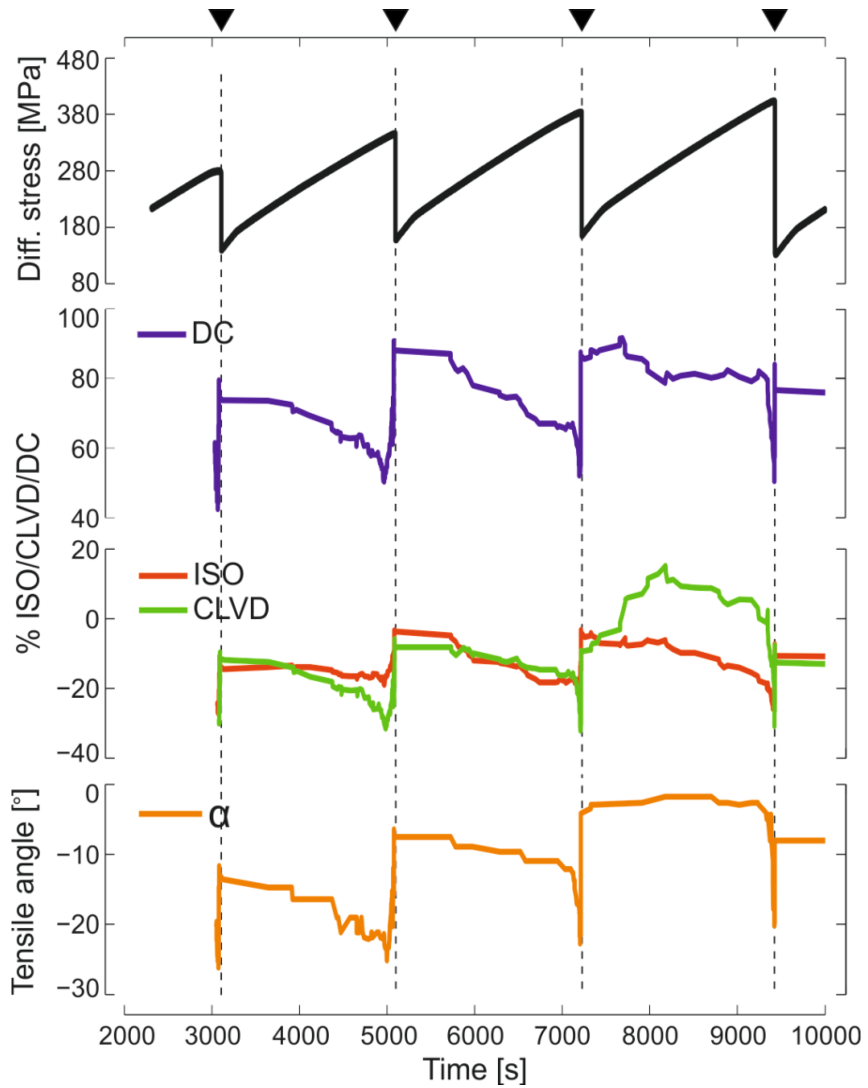
- Increase in the number of AEs displaying non-DC MT components

Pre-slip phase (80 s before slip – slip):

- Rapid increase in AE events displaying high DC components

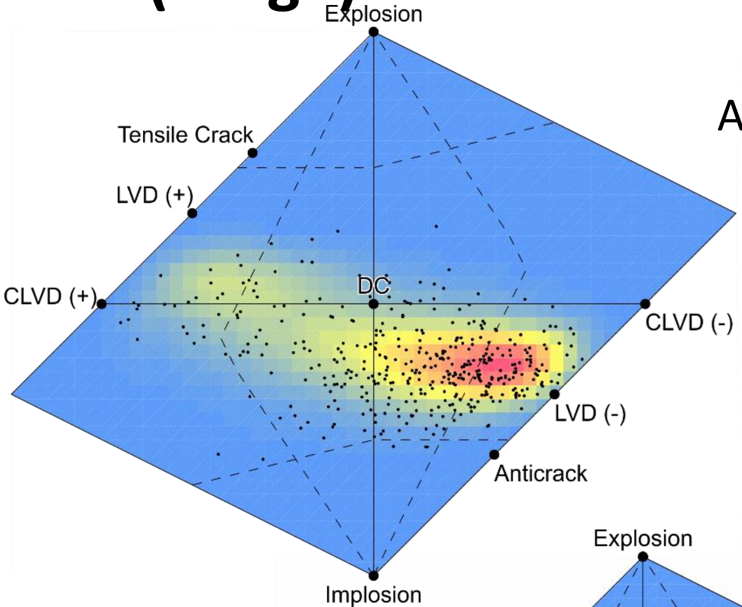
Observed long-term changes:

- Decrease of AE activity with subsequent stick-slips
- Relative increase in AE events displaying high DC components

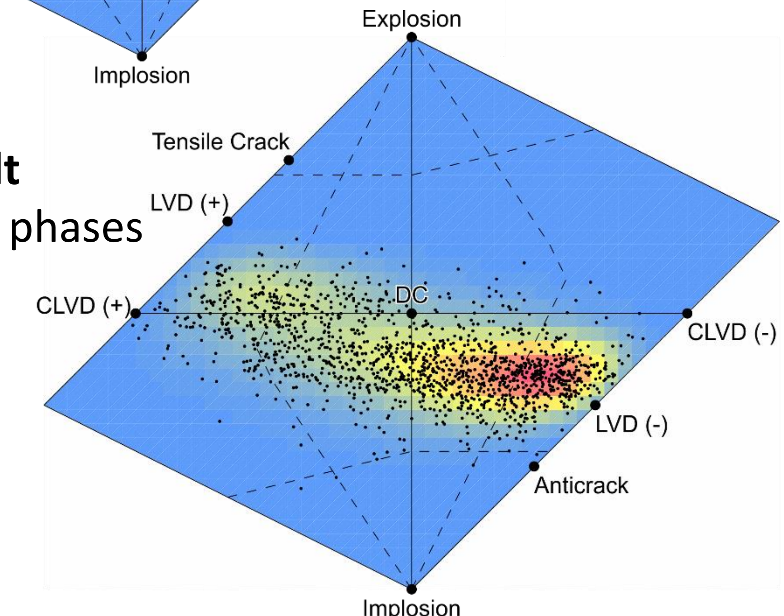


Lab vs nature: Source mechanisms (rough)

	M_w1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<1
Activity before	**low**	**low**	high
Activity after	**high**	**high**	-
Aftershock mechanisms	**Shear + Non-shear**	**Shear + Compaction**	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)



Rough fault
All Post-slips phases(10s)

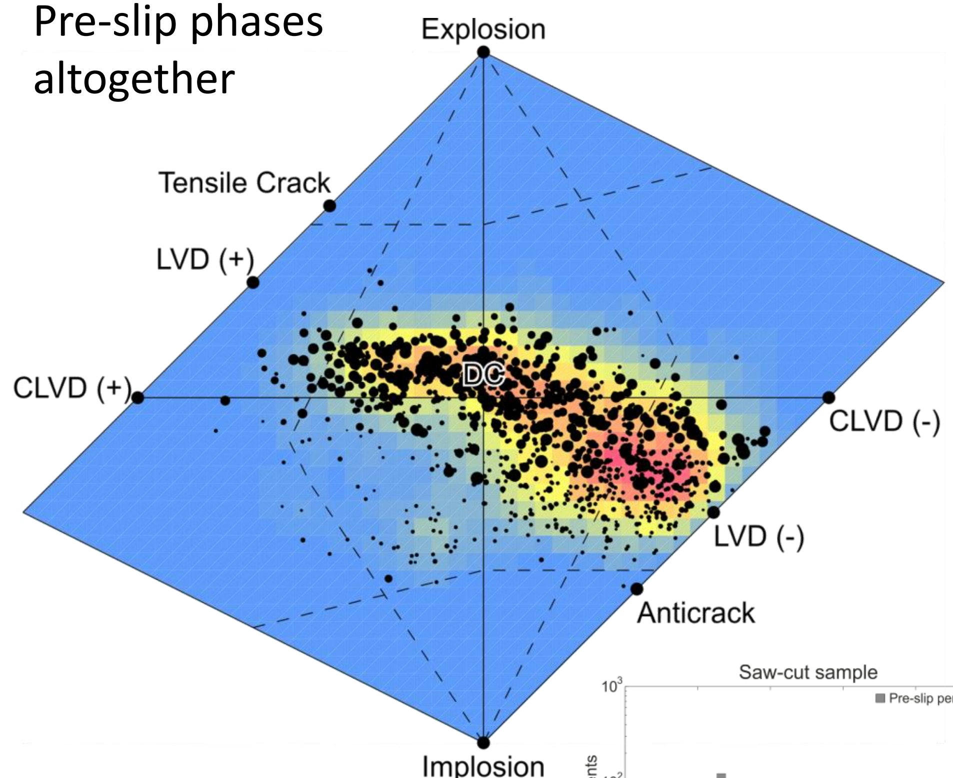


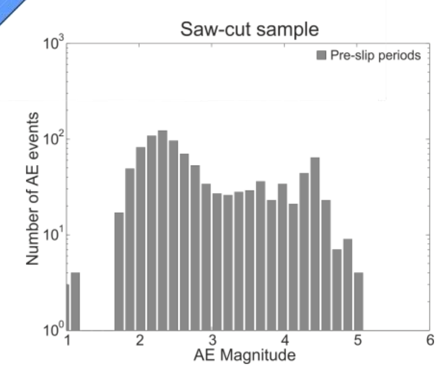
Rough fault
All pre-slip phases (100s)

Lab vs nature: Source mechanisms (saw-cut)

	M_W1.9	Rough fault	Saw-cut fault
thickness /length	**~6%**	~20-30%	**~4%**
b value before slip(s)	**low (1)**	**low (1.1)**	n/a (bimodal)
b value after slip(s)	**high (1.3)**	**high (1.4)**	-
Seismic activity	**post-slip a/f≈70**	**post-slip a/f≈100**	pre-slip a/f<1
Activity before	**low**	**low**	high
Activity after	**high**	**high**	-
Aftershock mechanisms	**Shear + Non-shear**	**Shear + Compaction**	-
Foreshock phase mechanism	n/a	Compaction + Shear + Opening	Compaction (small M) + Shear (large M)

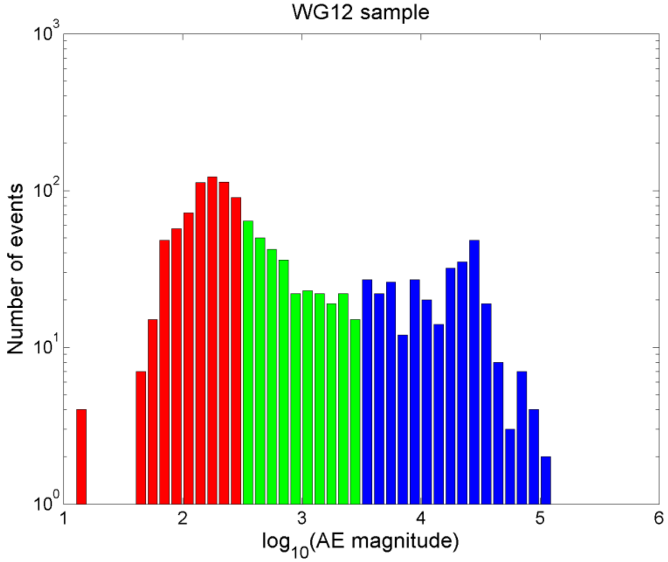
Saw-cut
Pre-slip phases altogether

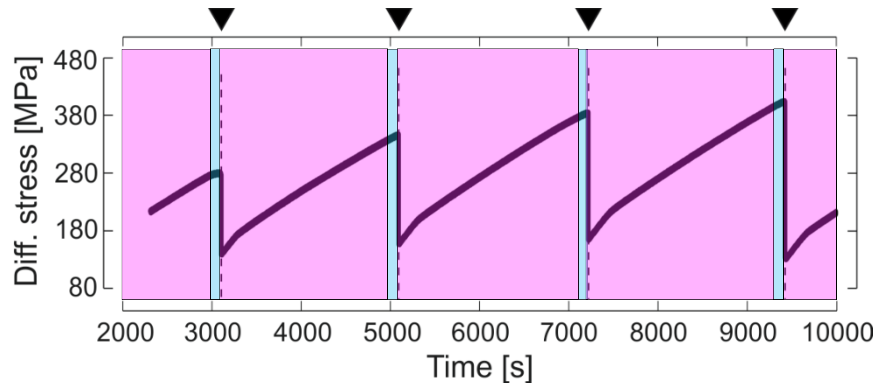


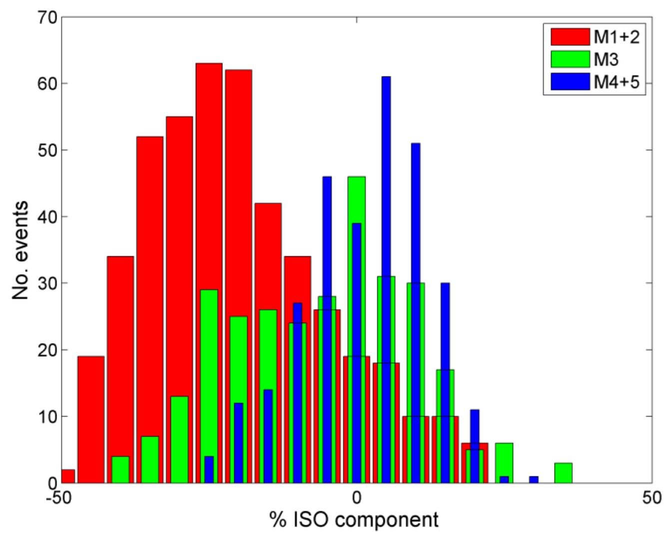


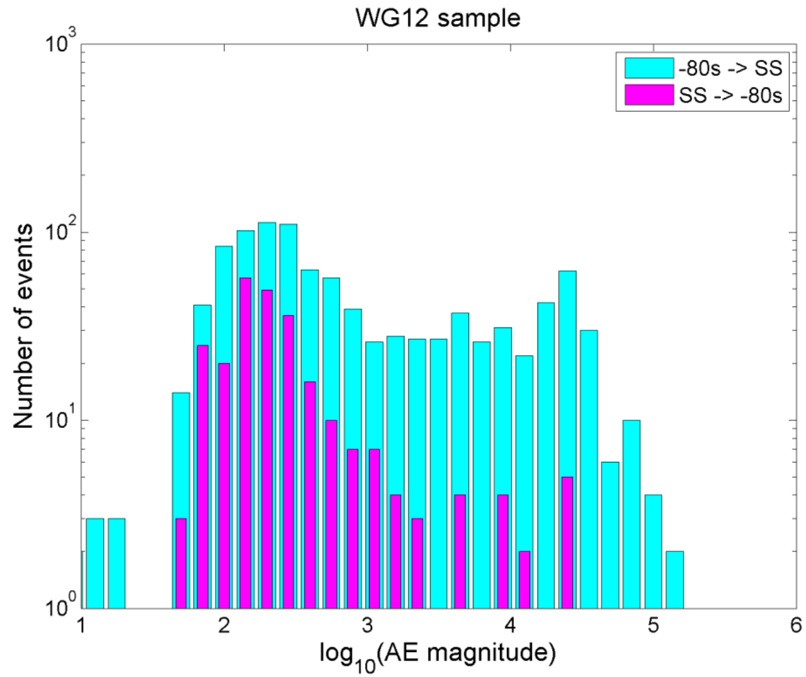
Shear sliding and shear-enhanced compaction (saw-cut)

- Larger AE magnitudes with high DC component observed **just before** slip phases
- Persistent **continuous** shear-enhanced compaction expressed in small AEs



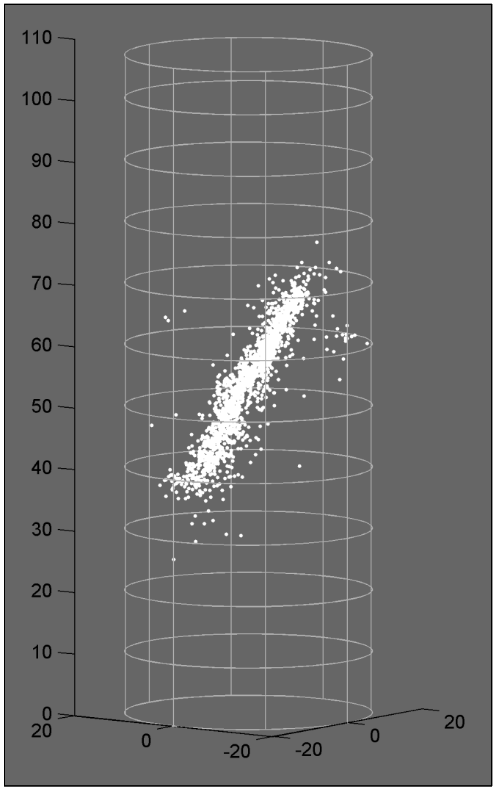


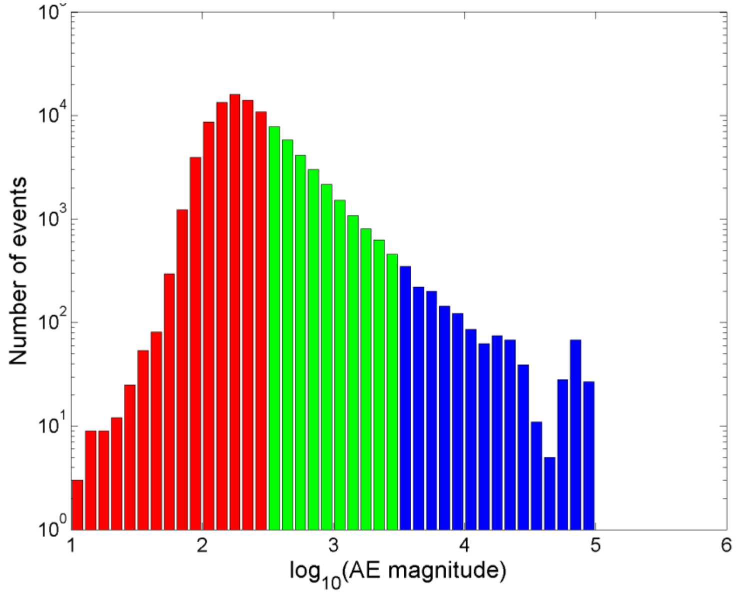


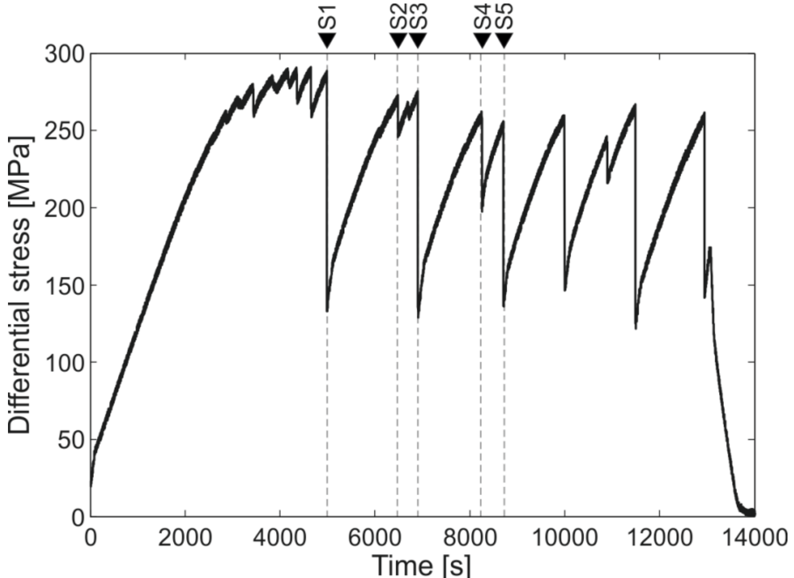


AE activity (rough surface)

- 100,000 AEs located; 42,000 moment tensors calculated
- Late stick slip phases investigated

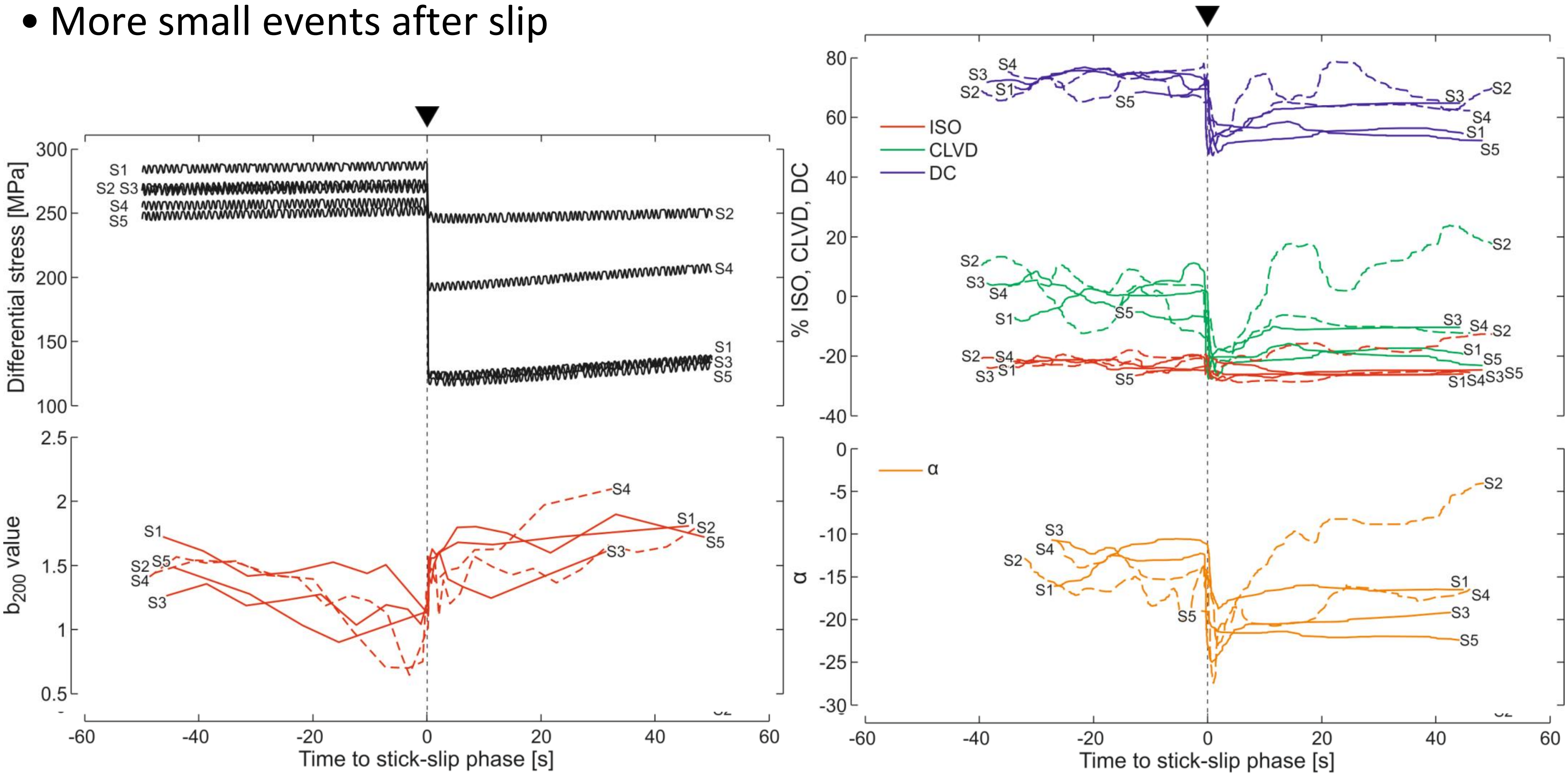






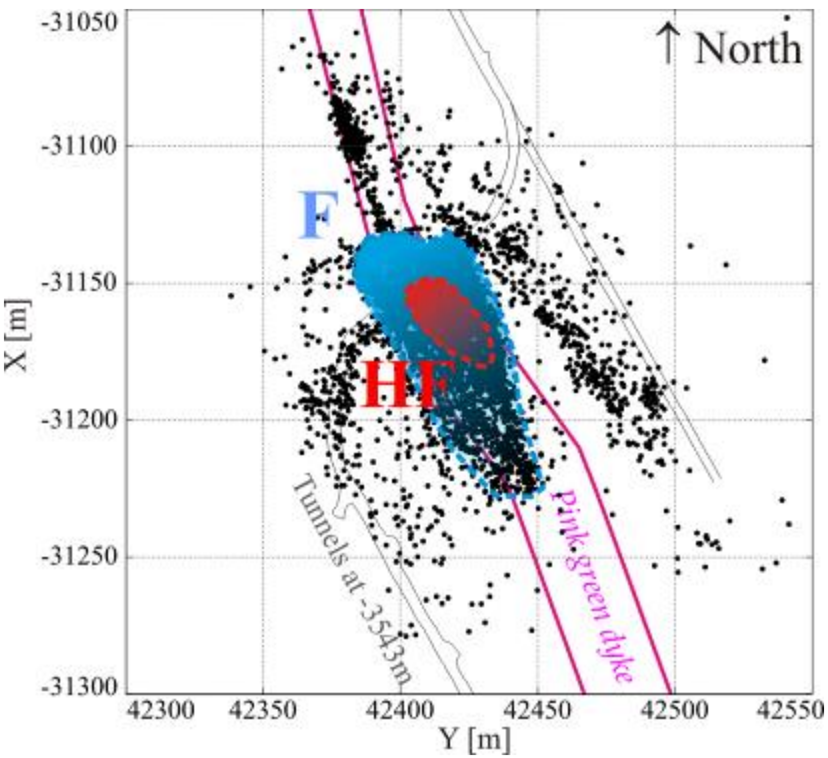
Temporal changes in MT characteristics (rough surface)

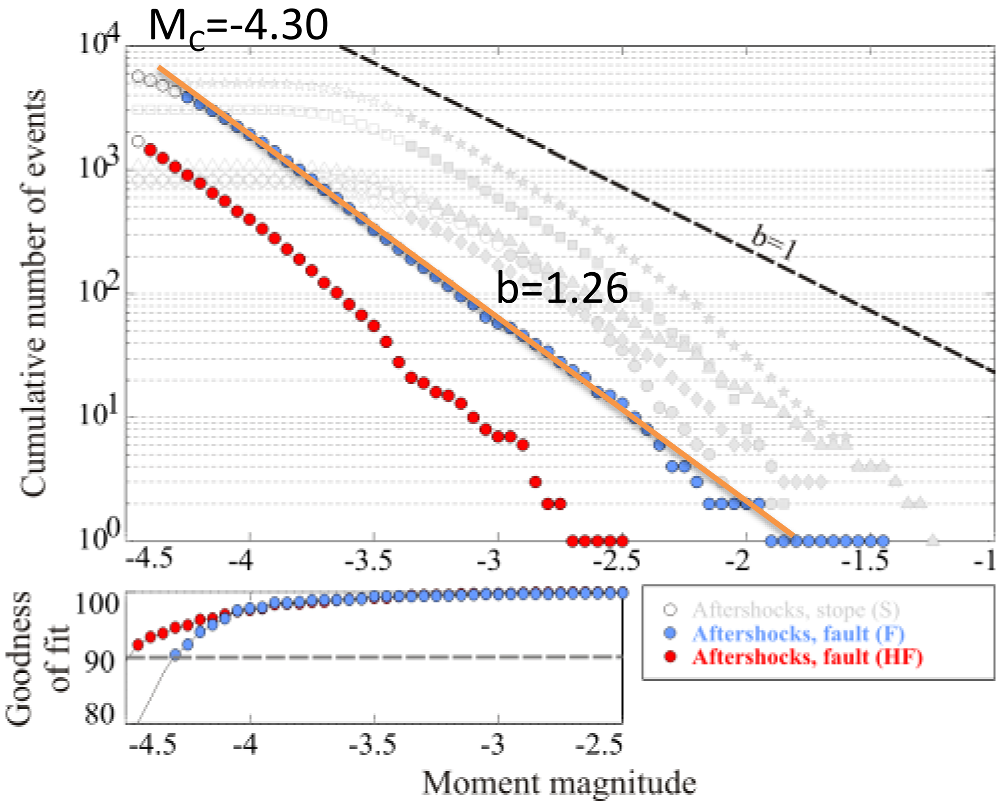
- Persistent compaction throughout the experiment
- Shear-enhanced compaction after slip
- More small events after slip



Seismic data | Aftershock sequence

- Aftershock activity follows Gutenberg-Richter scaling relation
- b=1.26, M_c=-4.30 for the fault plane (**F**)

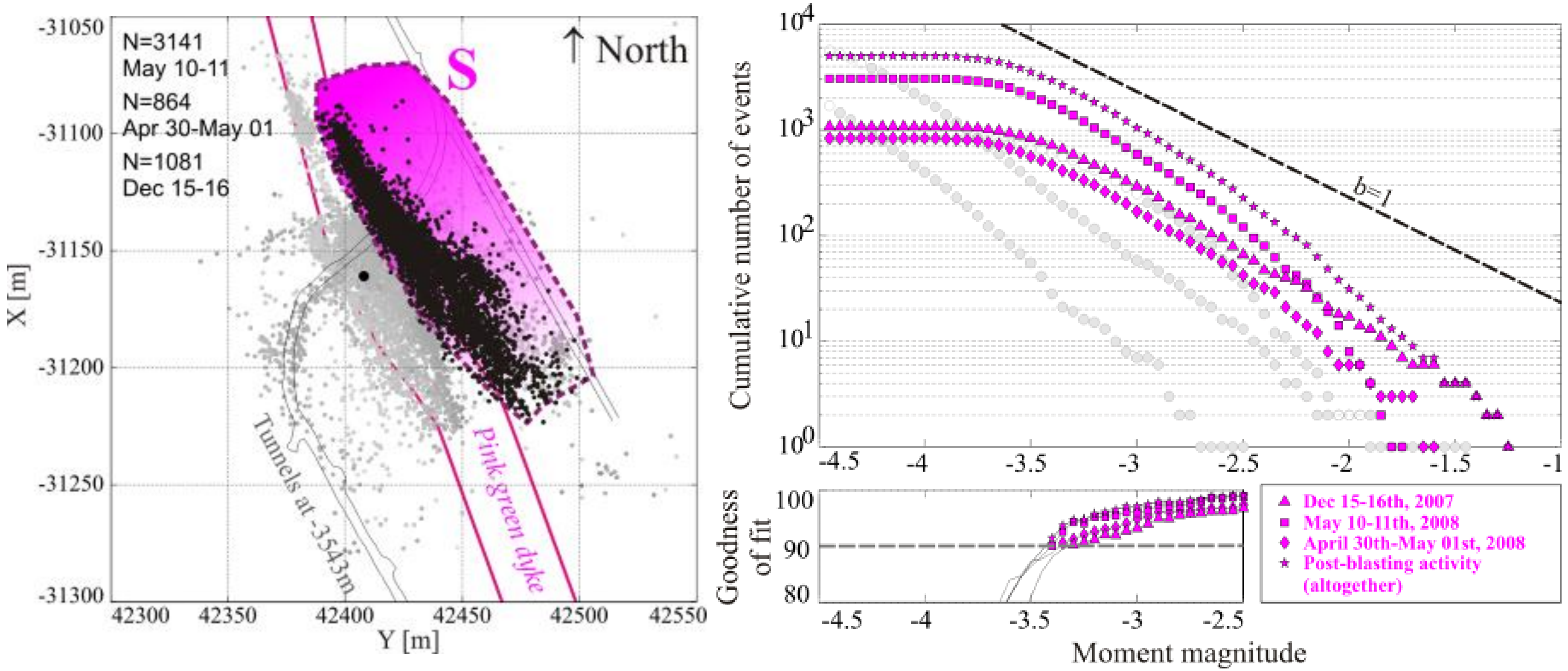




(Kwiatek et al., 2010, Bull. Seism. Soc. Am. 100)

Seismic data | Post-blasting activity

- Post-blasting also follows scaling relations with b=1.16



(Kwiatek et al., 2010, Bull. Seism. Soc. Am. 100)