Local damage and stress field evolution before and after laboratory fault slip

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Motivation

- Natural faults display structural variations, segmentation and fault roughness that all affect the stress field on the fault surface and surrounding medium, and earthquake source parameters.

- Mapping the dynamic behaviour of the different involved parameters (moment tensor, stress field) is a challenge but important towards fully understanding earthquake nucleation and propagation (▸ has implications for earth-quake forecasting, assessment of seismic hazard and risk).

This study…

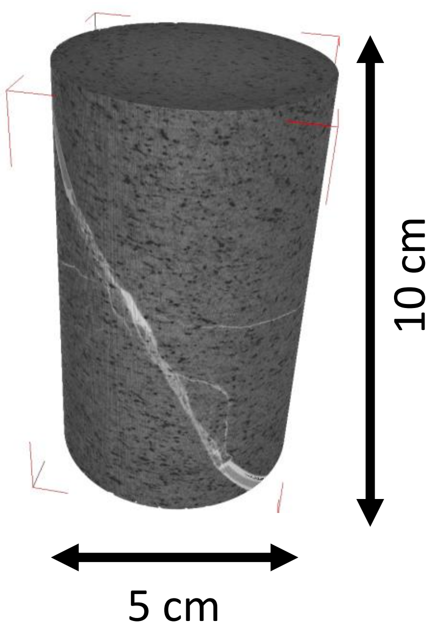
- …provides a framework for detailed characterization of the spatiotemporal evolution of damage and stress field on the rupture plane before and after activation.
- We perform laboratory stick-slip experiments under full acoustic monitoring and subsequent waveform analysis.

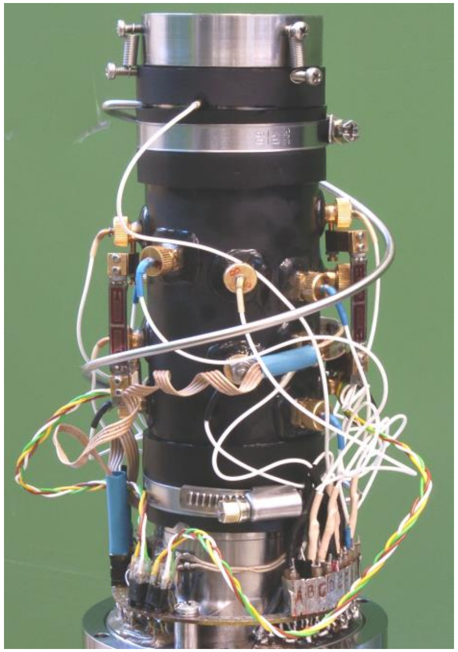
Experimental Setup

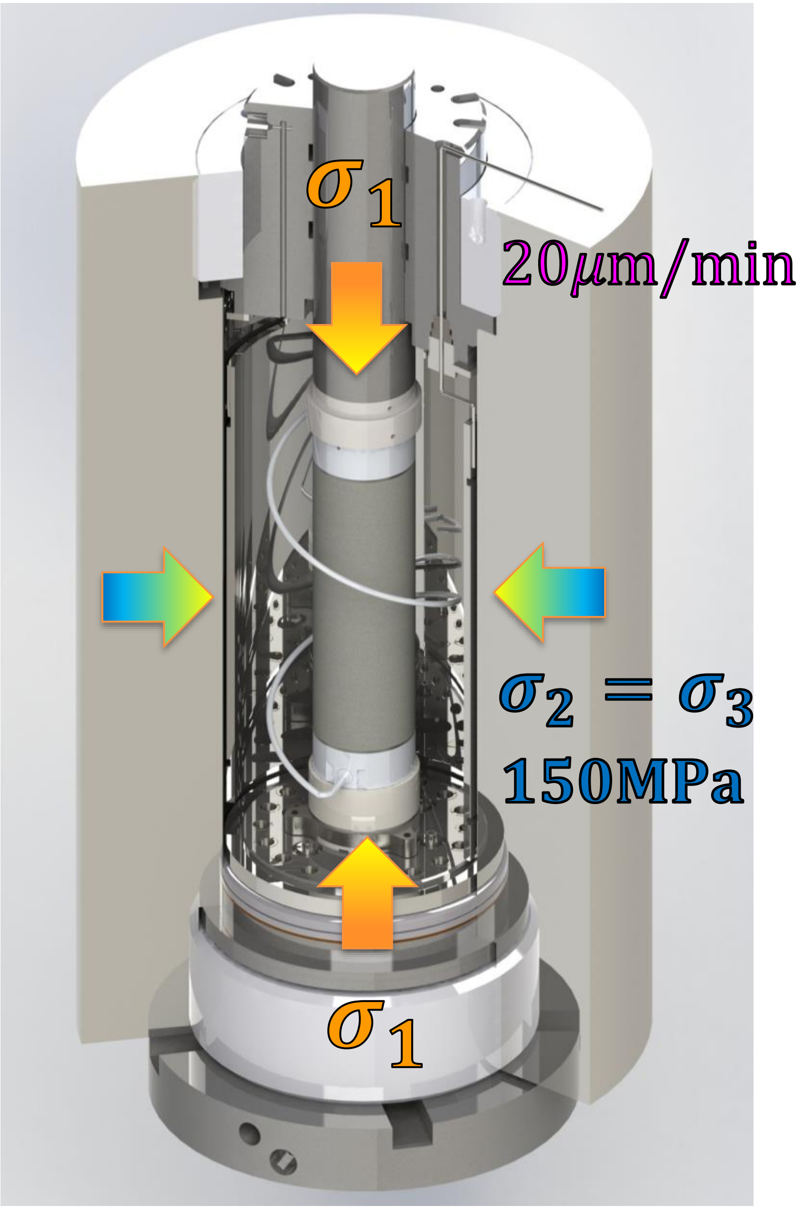
→ Since the seminal work of Brace & Byerlee in the 60s laboratory stick-slip experiment are considered an analog of large natural earthquakes.

- We use triaxial stick-slip experiments on Westerly Granite samples to derive an improved understan-ding of pre-/co- and postseismic processes.

- Seismicity is monitored with 16 AE sensors at full focal coverage, location accuracy ±2mm.

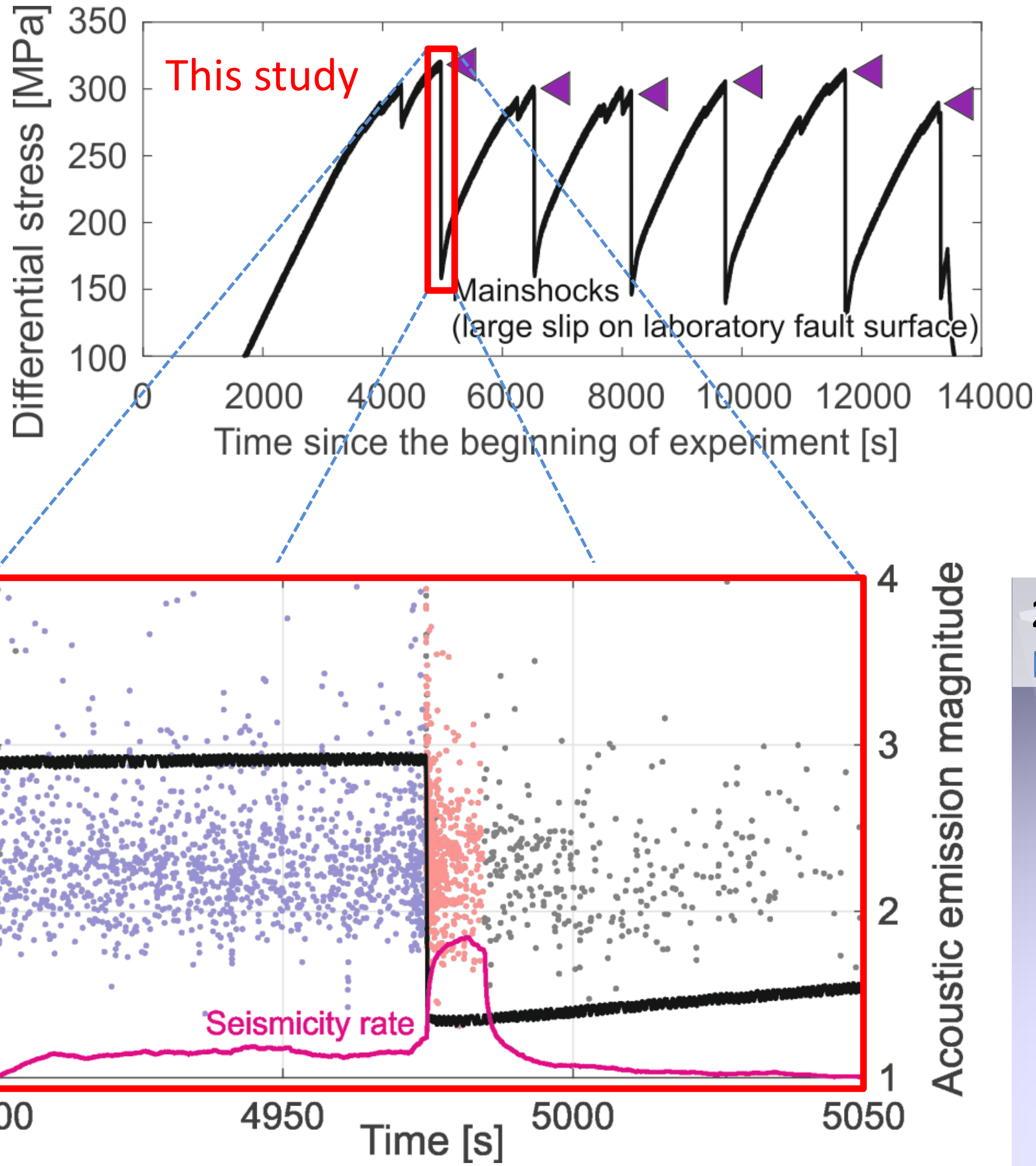




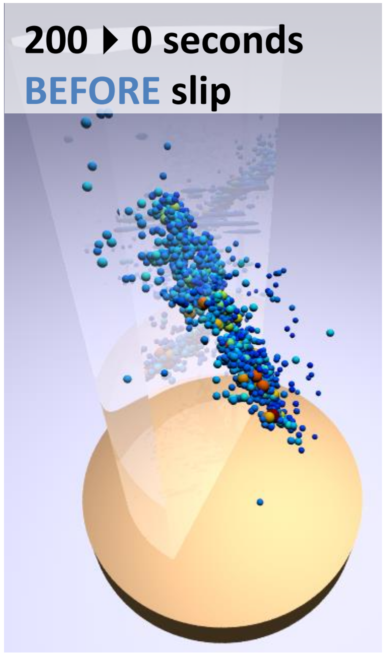


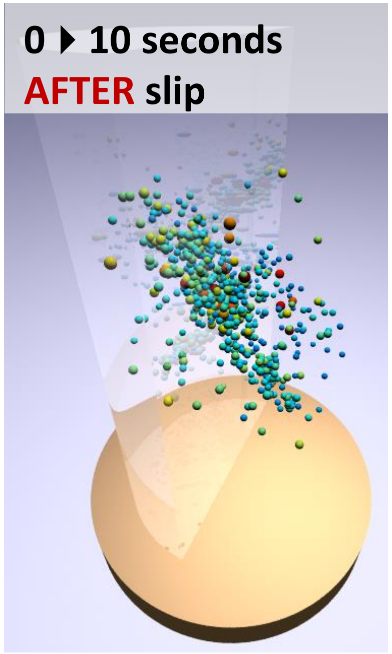
GFZ rock deformation lab

Experiment and Data Acquisition

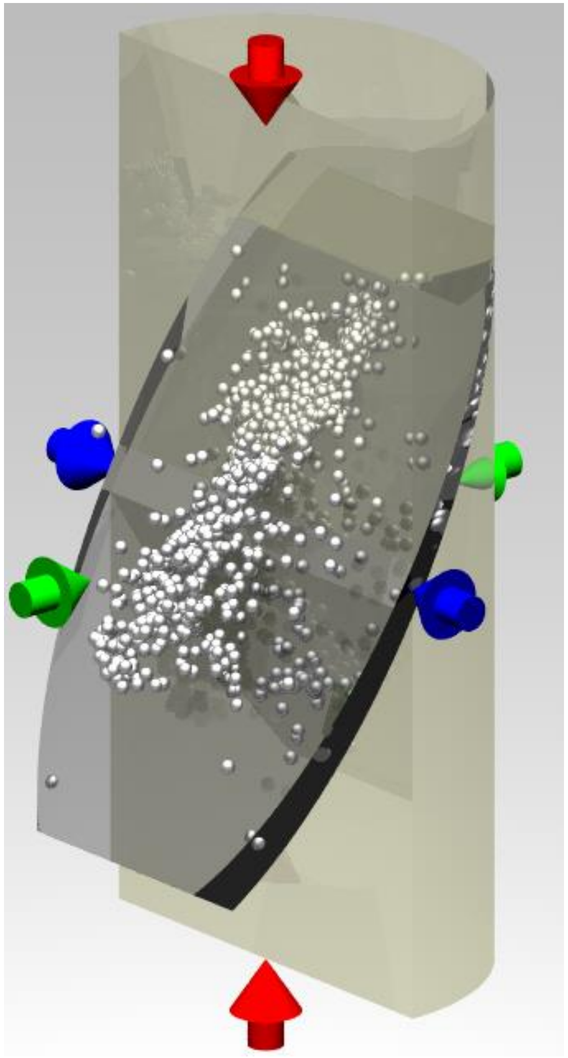


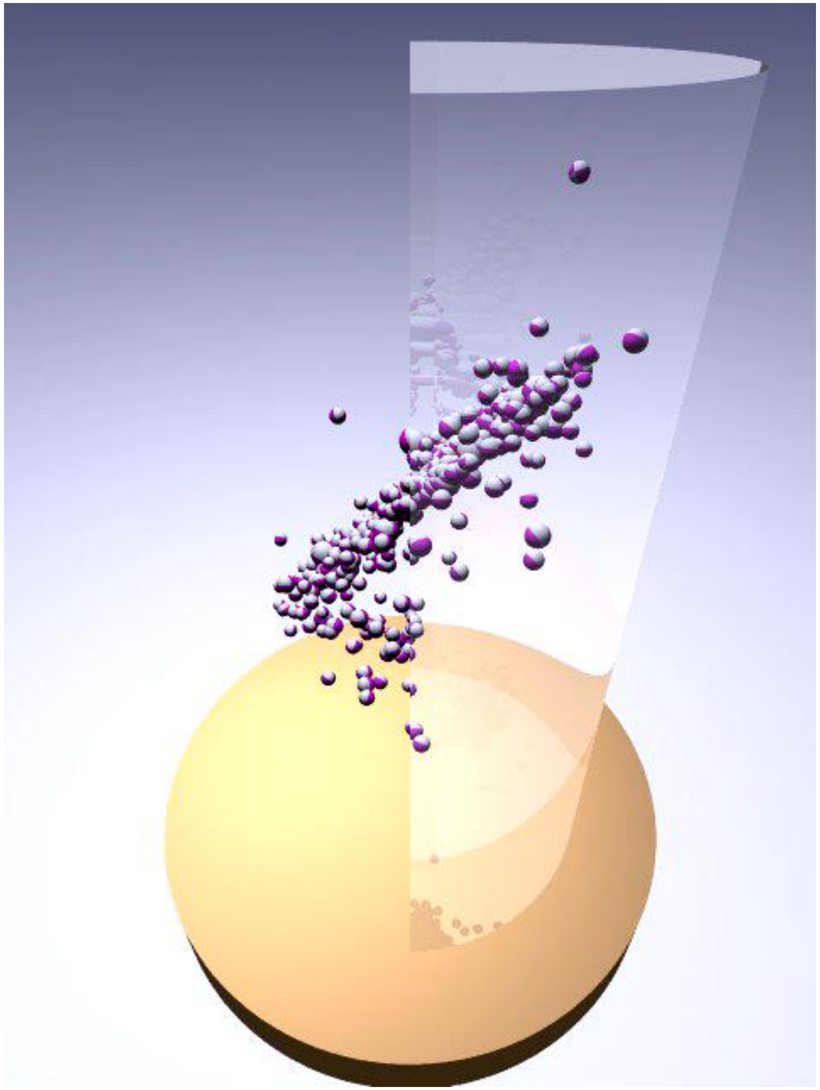
- 6 macroscopic stick-slips w/ stress drops of ~150 MPa.
- We use AE waveform data and apply state-of-the-art waveform analysis methods to study AE physical parameters.





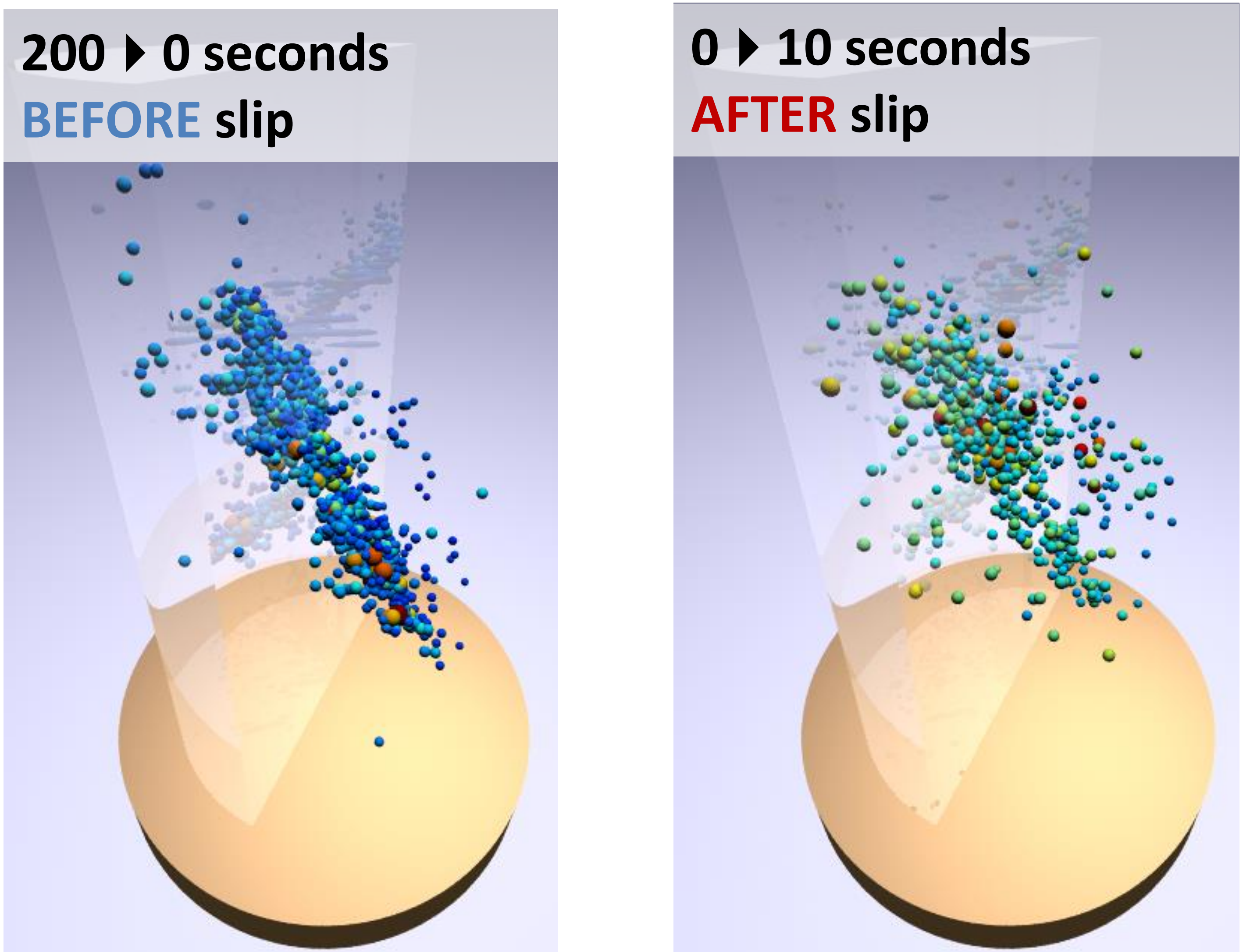
AE Seismic Activity Prior to Fault Activation - Foreshocks

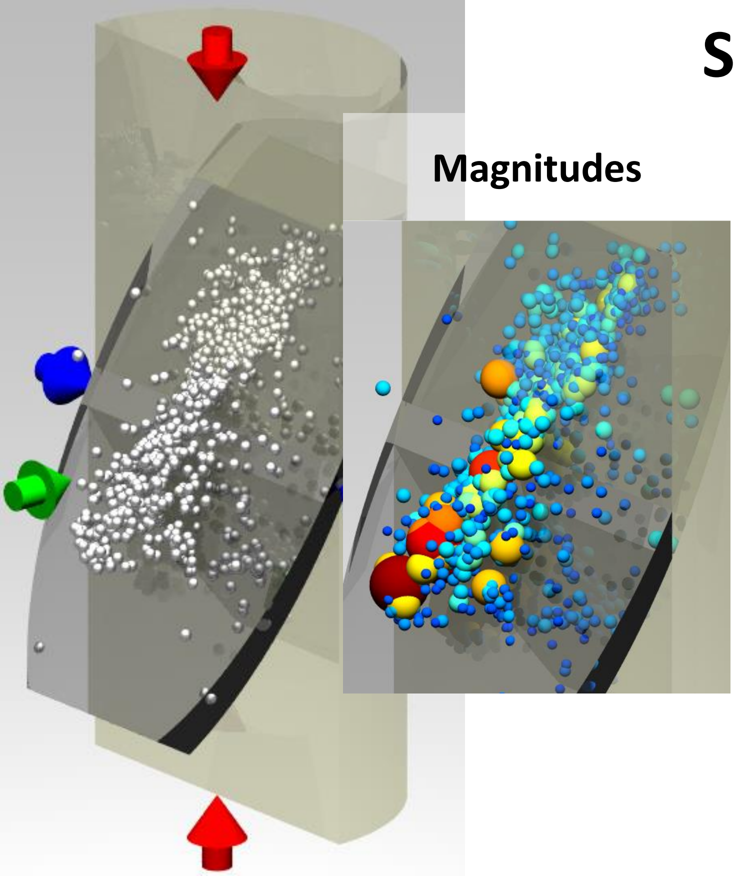




For each AE event we determine source parameters:
Hypocenter, magnitude, full seismic moment tensor.

AE Activity Immediately Before and After (Re-)Activation

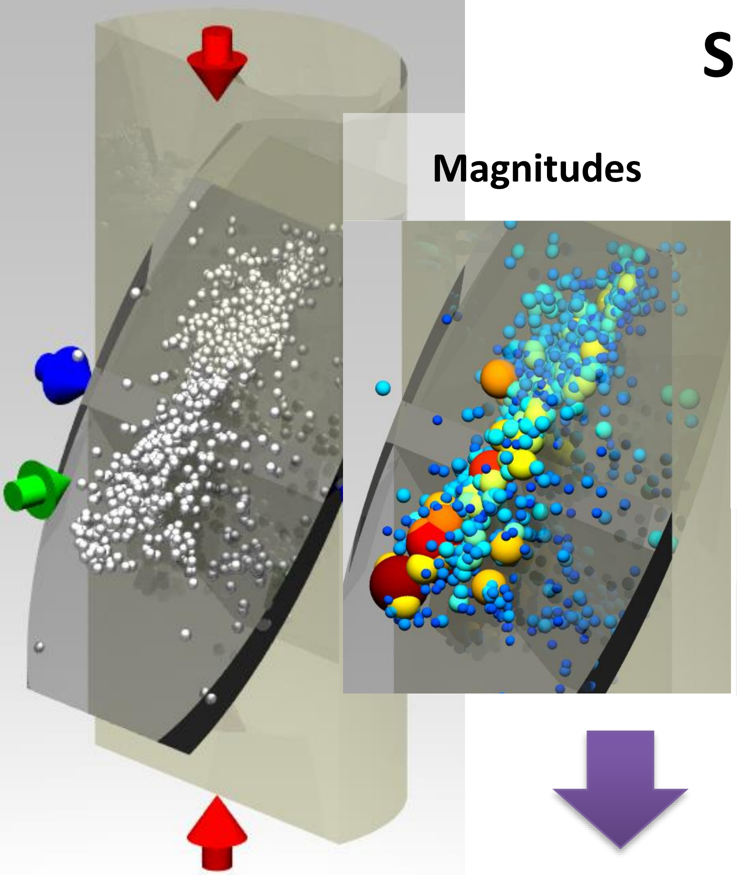




Source and Statistical Parameters

- The AE source parameter are used to calculate a total of 25 different other parameters as spatiotemporal proxies for damage and stress evolution.
- These were then projected on the fault surface.
- The key parameters are discussed in the following:

Source and Statistical Parameters



- The AE source parameter are used to calculate a total of 25 different other parameters as spatiotemporal proxies for damage and stress evolution.
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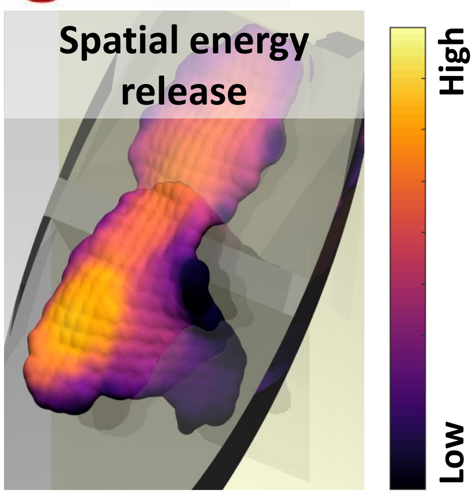
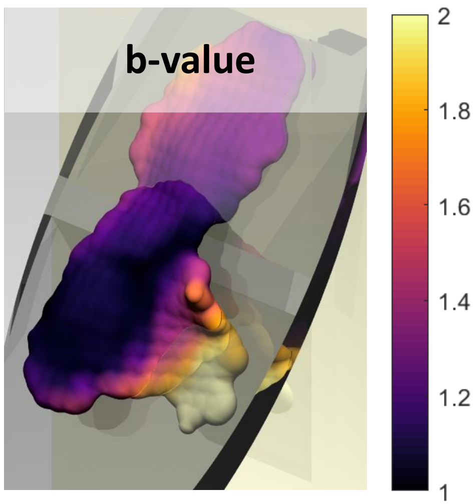
- The key parameters are discussed in the following:

From hypocenter locations and magnitude we calculated the spatial distributions of energy release and b-value on the fault surface.

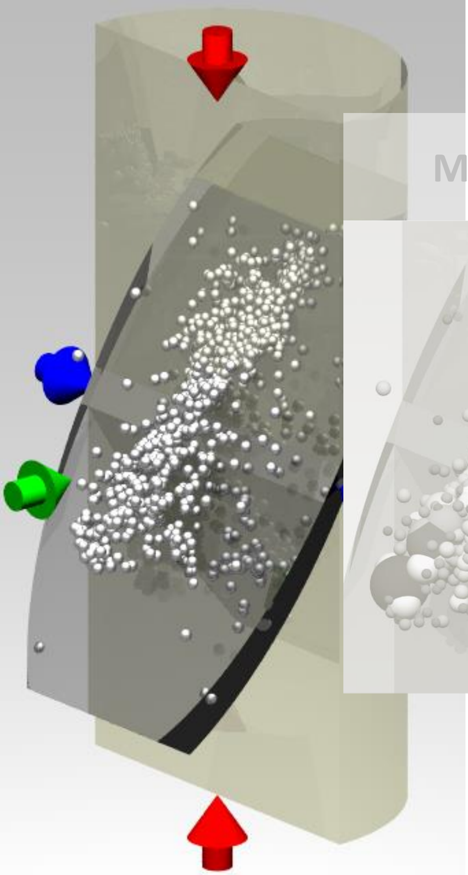


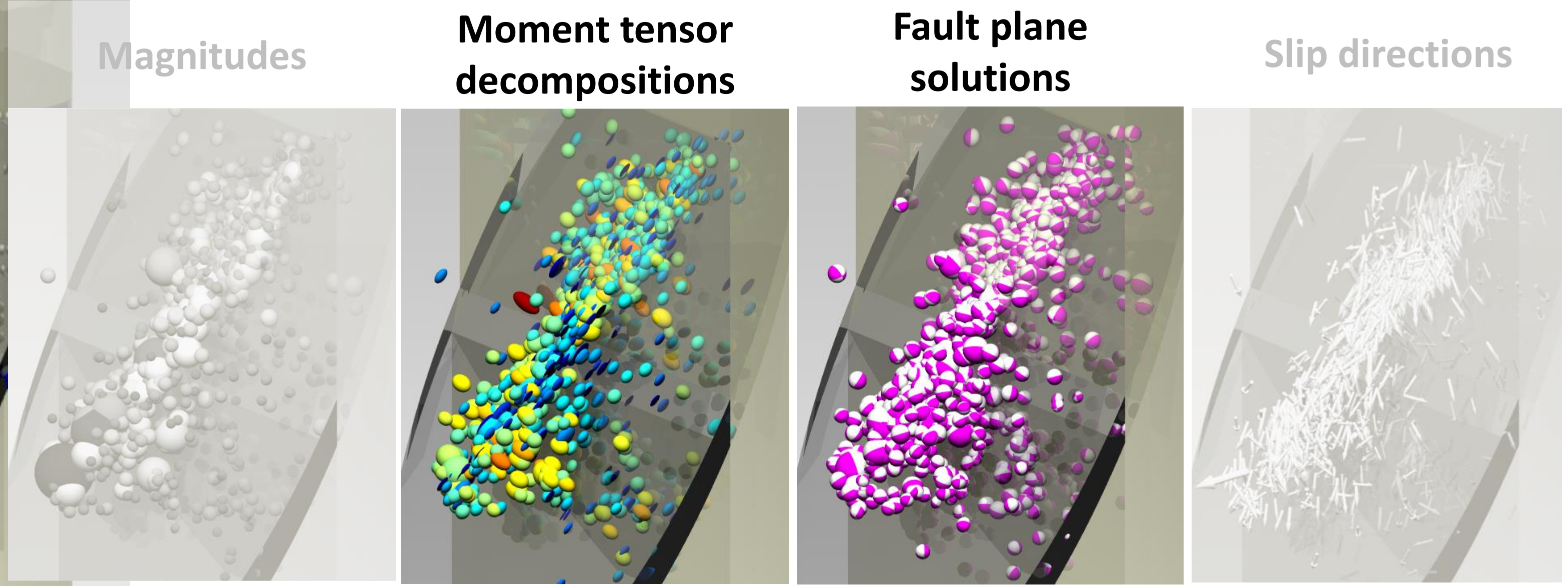


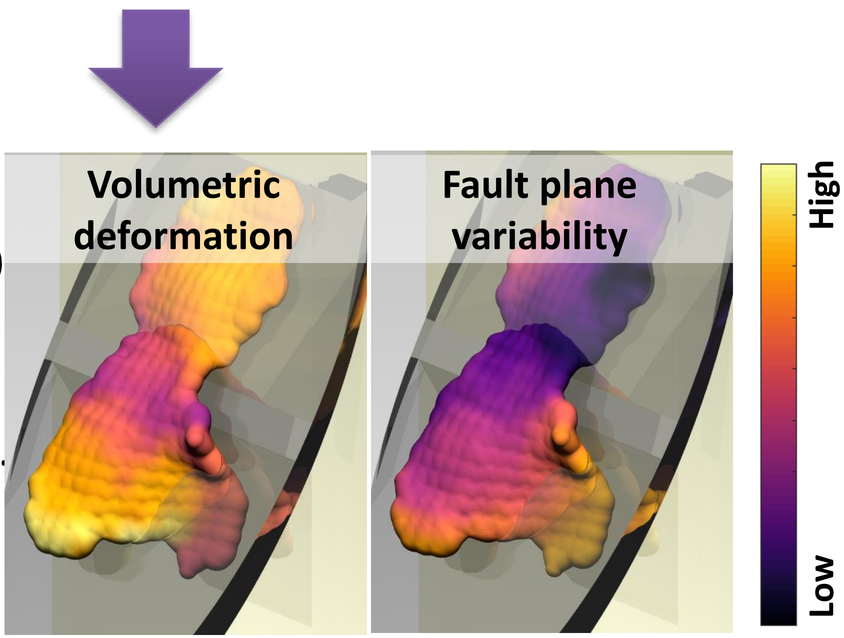
Spatial AE energy release:
Clear variations with spots indicating asperities.

b-value:
Clear variations indicating changes in stress or/and damage.

Microfracture kinematics

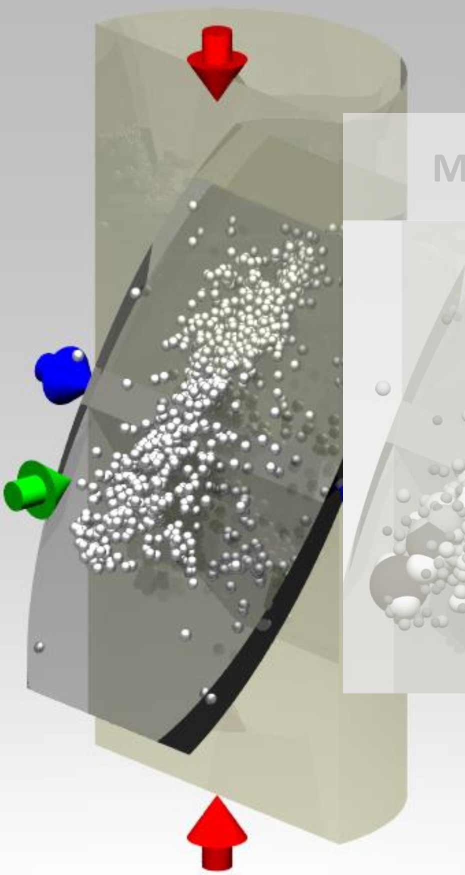


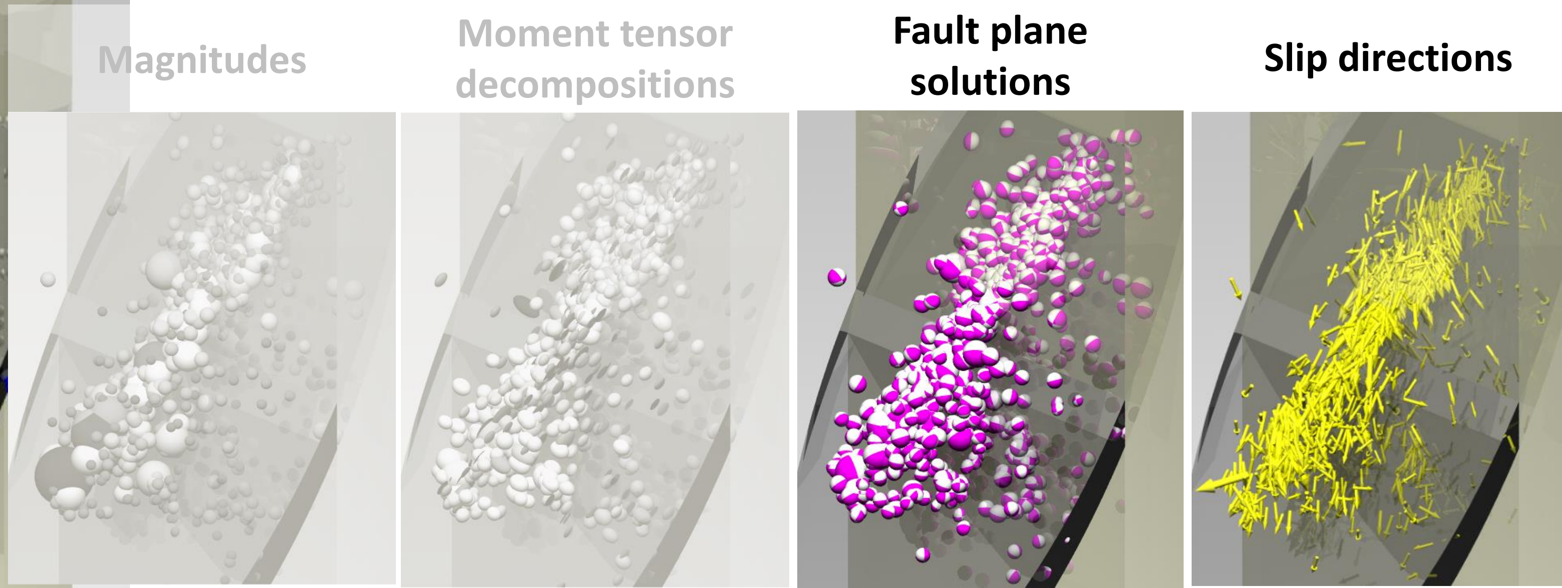


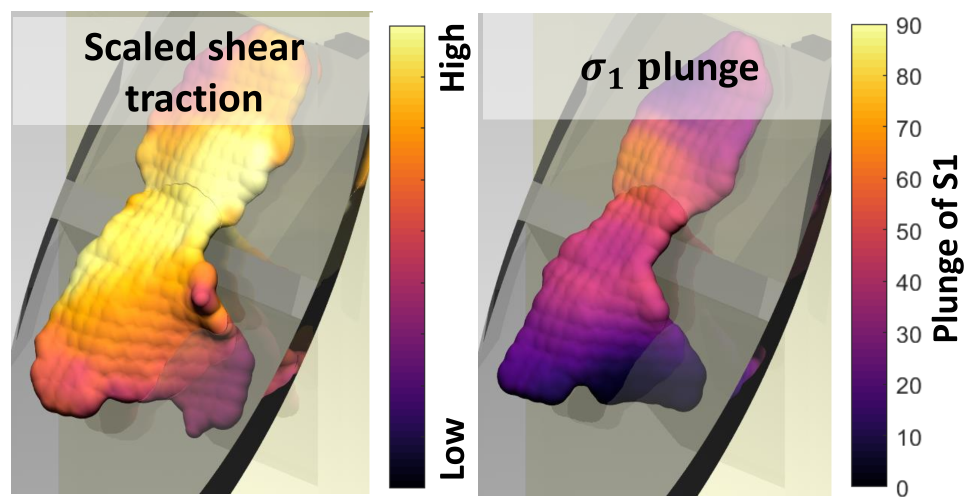


- Moment tensors determined from amplitude inversion using the hybridMT **(Kwiatek et al., SRL, 2016)**
- Decomposition of the AE moment tensors allows to discriminate shear vs. volumetric deformation. Clear variation on fault plane (mostly compaction).
- Fault-plane variability allows to map variations of fracture and stress on the fault plane.

Variations of Local Stress Field Orientation







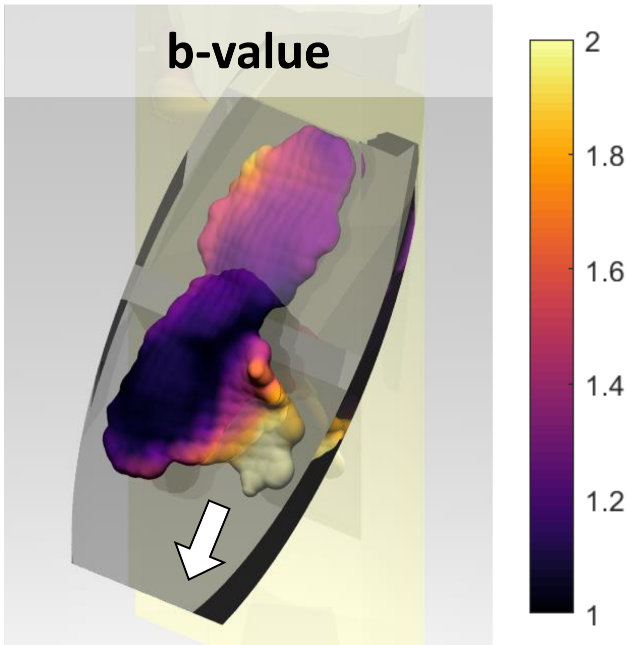
- Stress tensor inversion from fault plane solutions using the MSATSI software **(Martinez-Garzon et al., SRL, 2014).**
- Fracture alignement with local stress field.
- Variations of local stress field orientation throughout rupture plane.

Testing Different Parameters for Similarity of Their Distributions

Is one distribution similar to the other one?

E.g. is the b-value a measure of damage or stress?

DAMAGE? **STRESS?**



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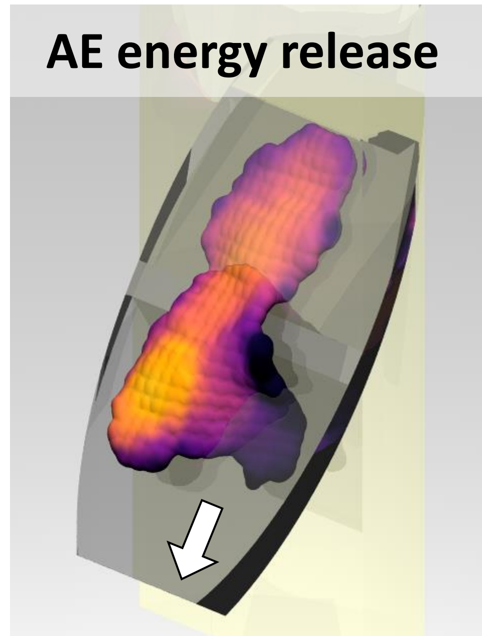

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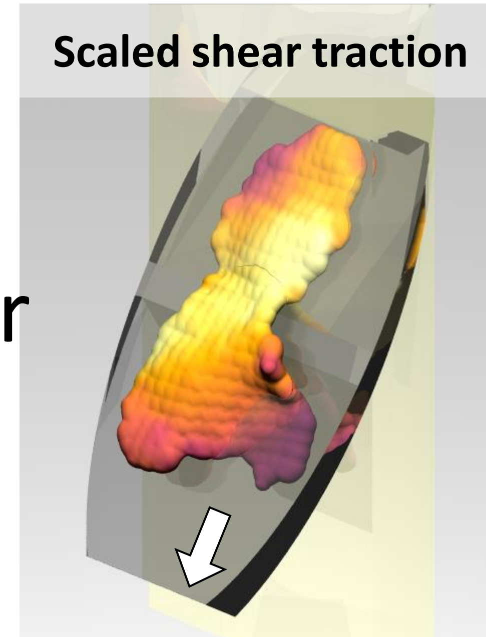
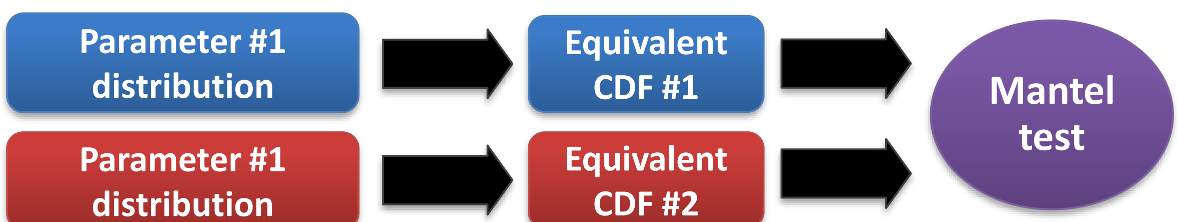




Equivalent Dimension Hyperspace ▸ *Lasocki, 2014, GJI*

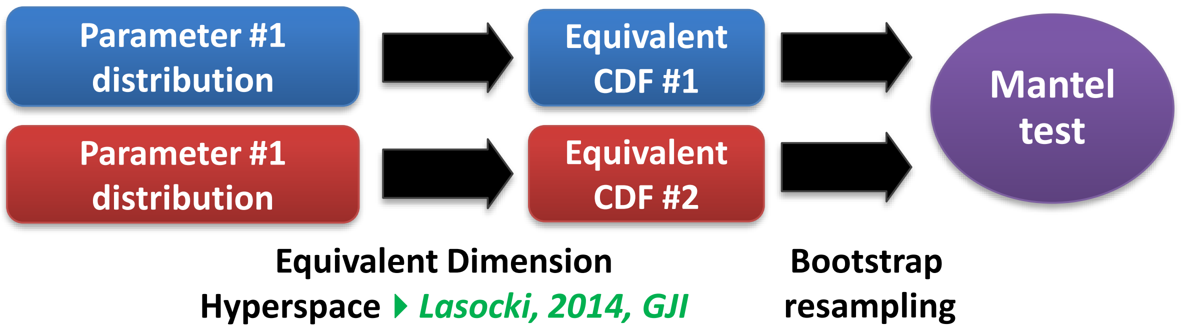
Bootstrap resampling

Testing Different Parameters for Similarity of Their Distributions

- Surface distributions of two parameters were compared for the same time interval to check whether correlations between parameters are statisticially significant.

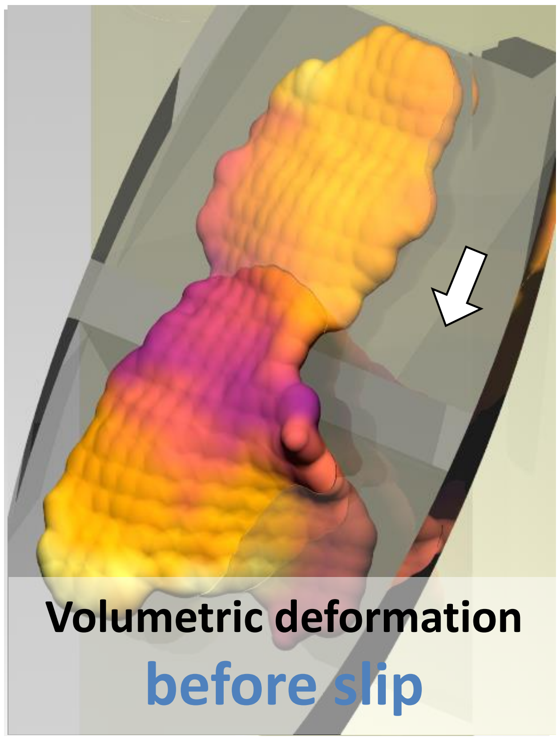
- The statistical test procedure relies on standardization of spatial distributions of two different parameters into a common (probabilistic) domain using the ‚Equivalent dimension hyperspace method‘ (Lasocki et al., GJI, 2014).

- The level of similarty between surface distributions was then tested using the bootstrap resampling and mantel test.



Testing Individual Parameters for Temporal Similarity

Do distributions for one parameter differ with time (***before* and *after* activation)?**



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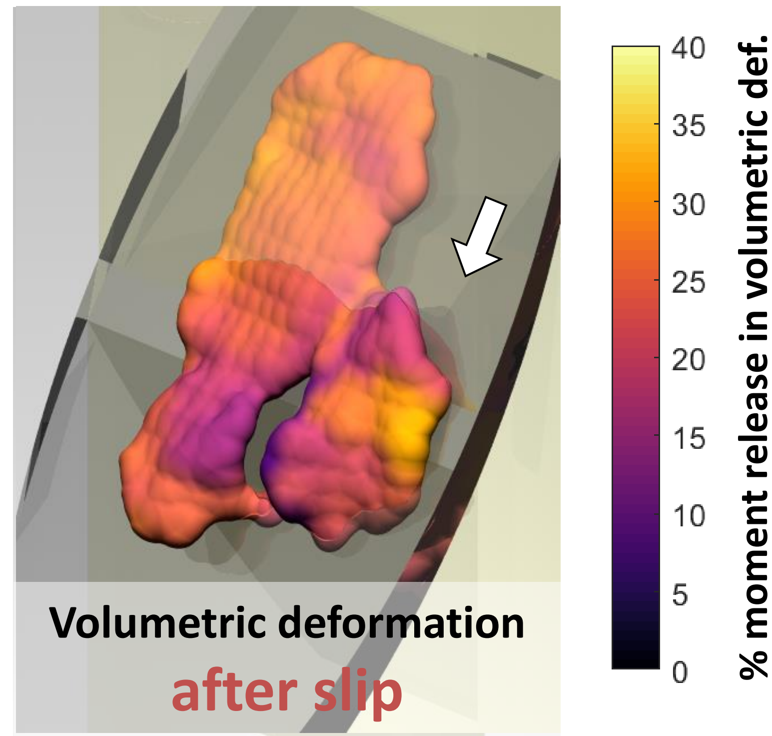


Parameter distribution BEFORE slip → **Equivalent CDF #1** →

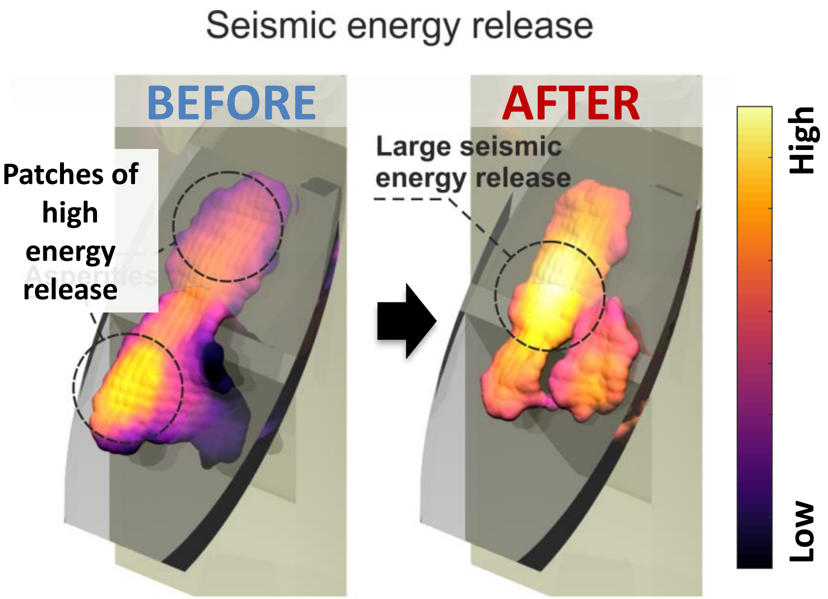
Parameter distribution AFTER slip → **Equivalent CDF #2** →

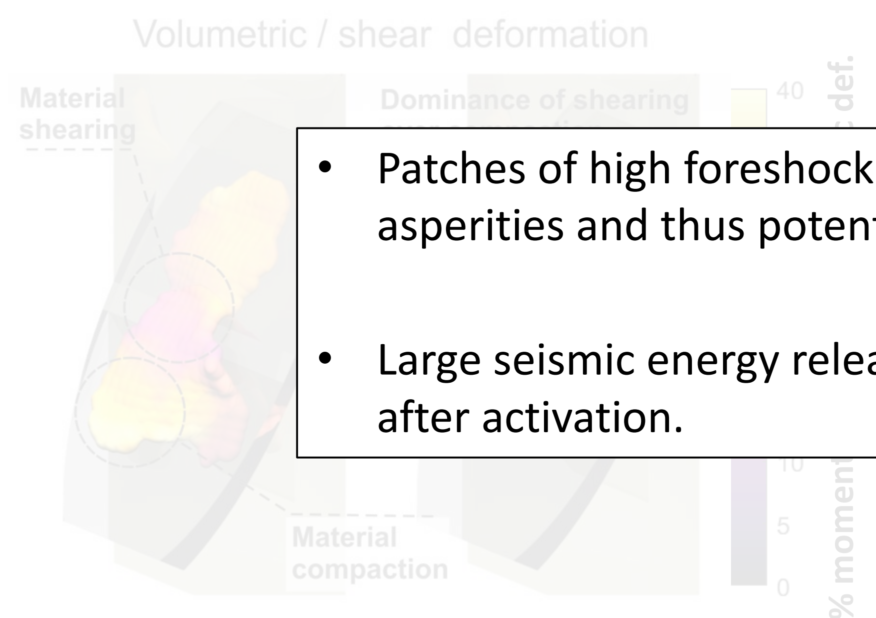
Bhattacharyya metrics
Kullback-Leibler Divergence
Standardized RMS error
Squared correlation coeff.

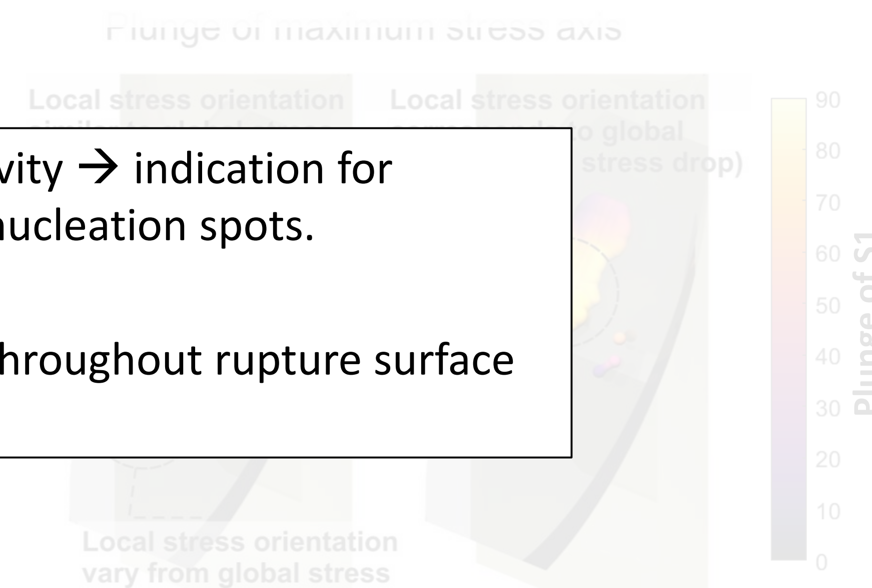
Equivalent Dimension Hyperspace ▸ ***Lasocki, 2014, GJI***

Bootstrap resampling

Damage and stress evolution BEFORE ▶ AFTER Activation



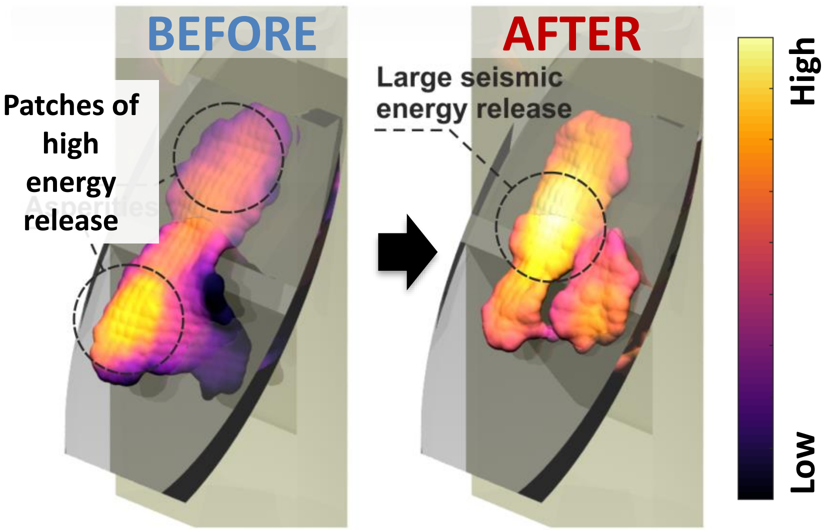




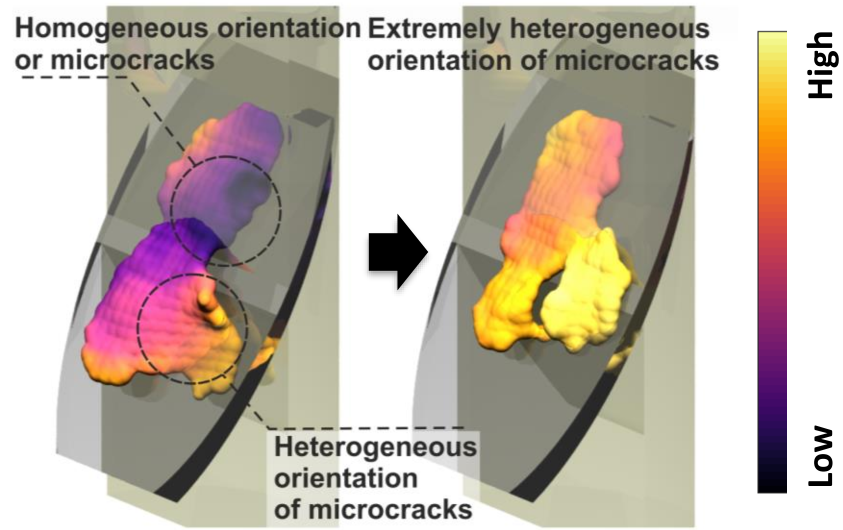
- Patches of high foreshock activity → indication for asperities and thus potential nucleation spots.
- Large seismic energy release throughout rupture surface after activation.

Damage and stress evolution BEFORE ▶ AFTER Activation

Seismic energy release



Microcrack orientation heterogeneity

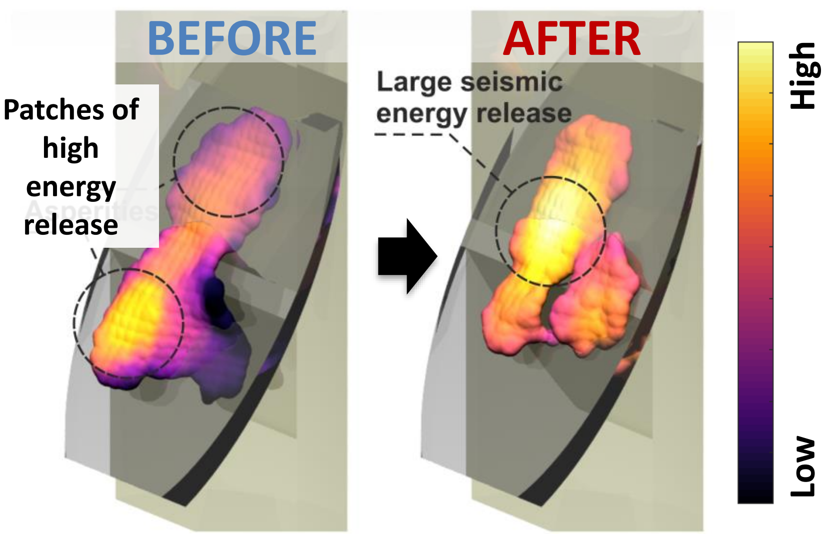


- Higher variation of microcrack orientation after activation than before.
- But: Decreasing variability with repeated activation.

→ Increasing smoothness of the fault ('fault-zone evolution leading to larger earthquakes with time (?)

Damage and stress evolution BEFORE ▸ AFTER Activation

Seismic energy release



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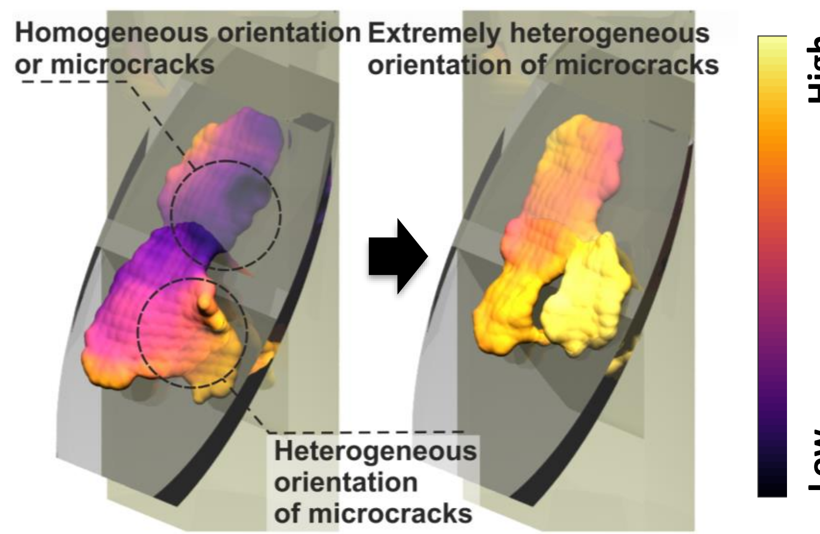
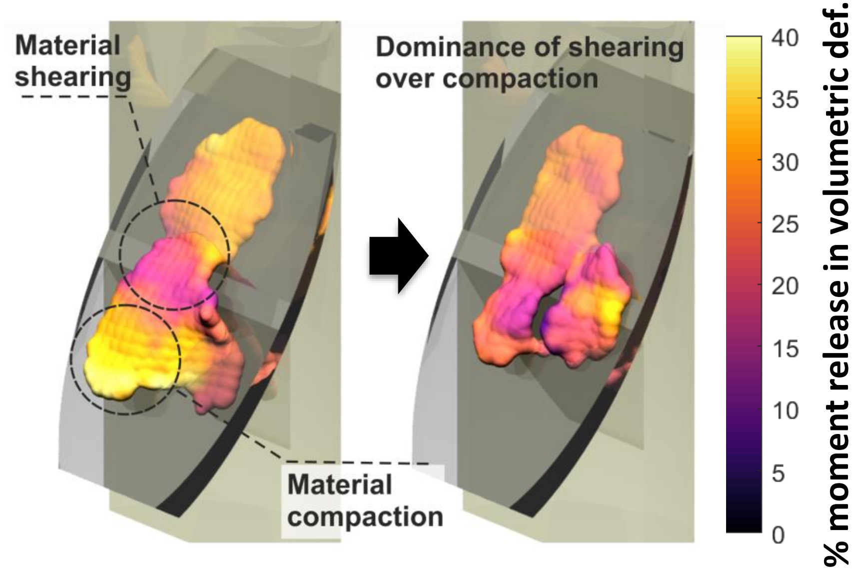


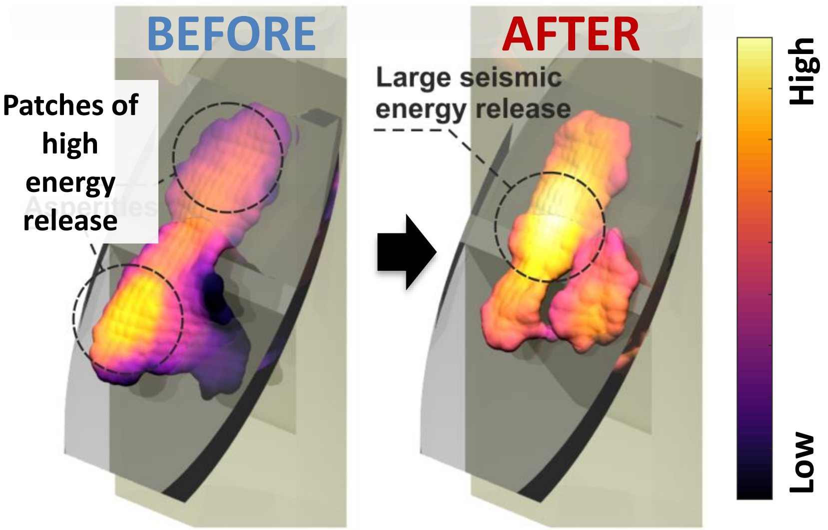
Volumetric / shear deformation



- Significant portions of volumetric deformation reflecting material compaction before fault activation.
- Dominantly shear faulting after fault activation.

Damage and stress evolution BEFORE ▶ AFTER Activation

Seismic energy release



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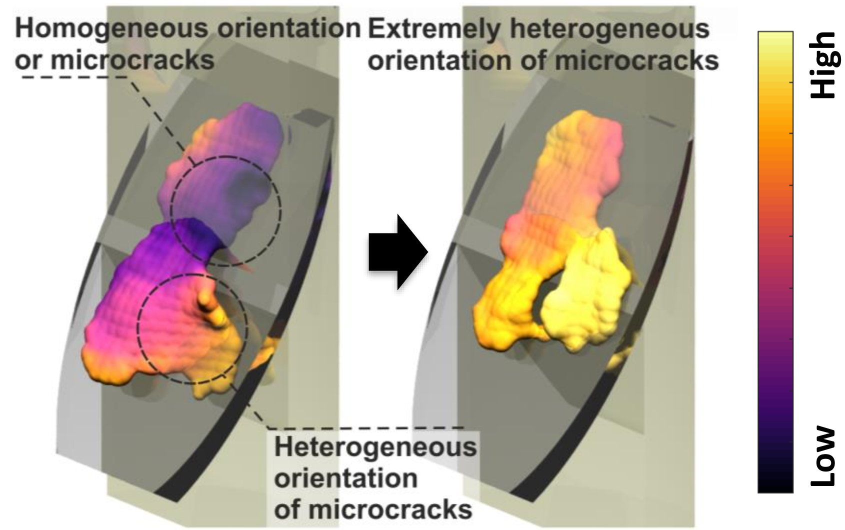
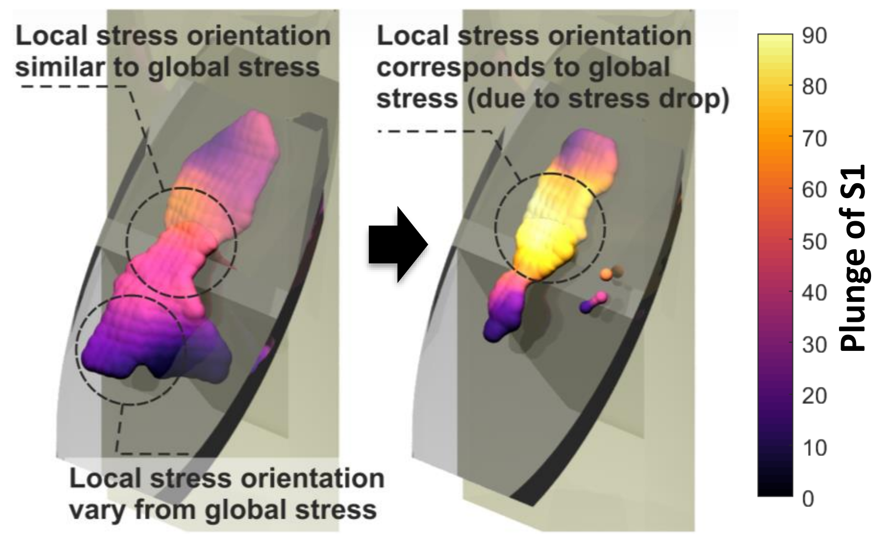


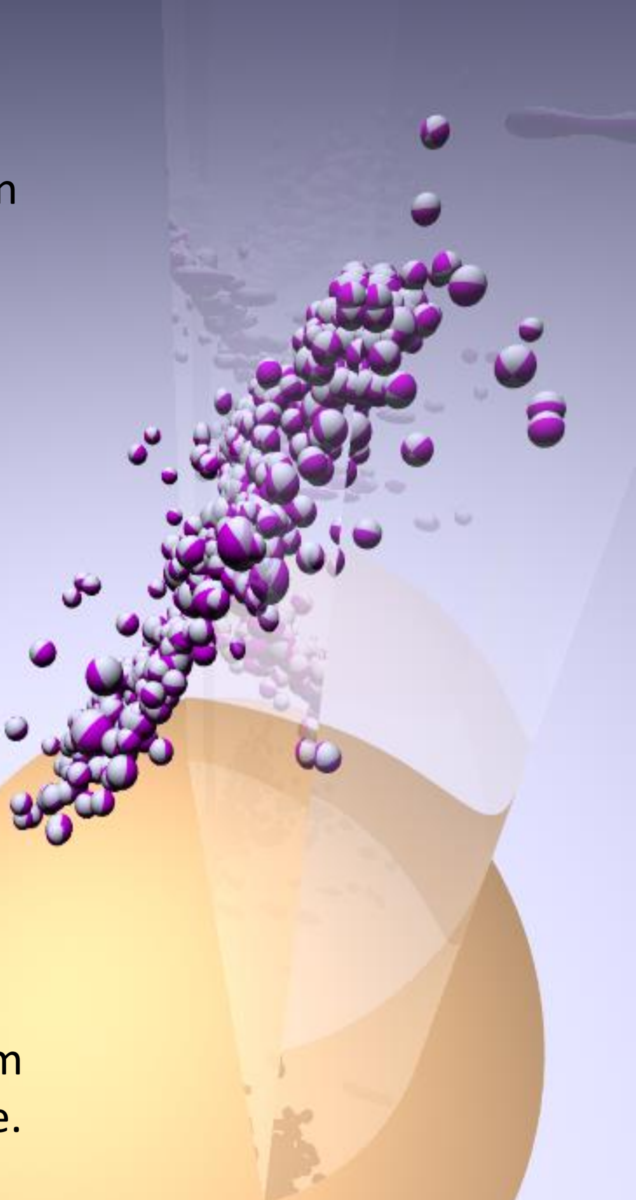
Plunge of maximum stress axis



- Before activation: Local stress orientation on fault surface generally similar to global stress. Local variations.
- After activation: Clear change in stress field orientation in areas of high postseismic energy release.

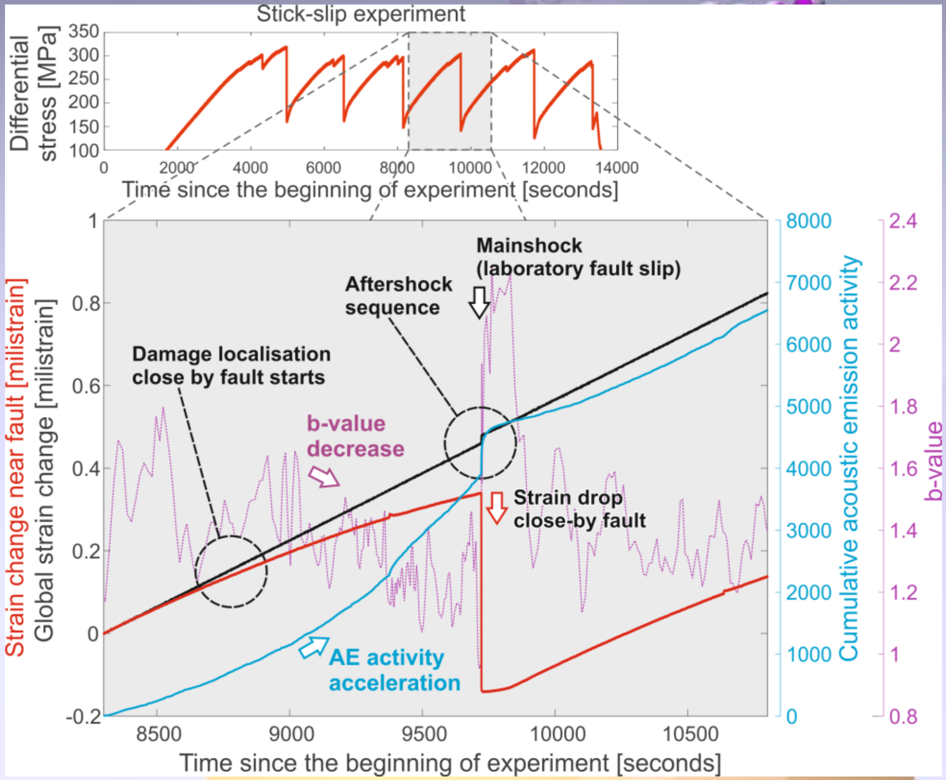
Summary

- We used AE data to characterize the spatio-temporal evolution of local damage and local stress field before and after fault activation during laboratory stick-slip experiments.
- Our mapping revealed a complexity of the rupture nucleation and a post-slip stress redistribution.
- Pre-slip is characterized by significant localized volumetric deformation occuring on uniformly oriented microfractures at local asperities. The local stress field is homogeneous but rotated strongly wrt far-field stress orientation.
- Post-slip deformation is characterized by dominantly shear deformation with highly varying orientation of microcracks under significantly lowered traction. The local stress field is closer to the far-field stress orientation.
- Fault plane roughness decreased between subsequent slips indicated by reduced fault plane variability and a more uniform stress field. This might reflect a smoothening of the fault plane.



Outlook

- Tracking temporal changes of stress and damage parameters leading to slip
  - Slip precursors ‣ Forecasting.
- Effect of fault surface complexity on nucleation patch and magnitude of mainshock.
  - Damaging potential (stress drop, magnitude → Mmax).
- Structural evolution of fault plane and long-term evolution of local stress state at the fault plane.
  - Implications for long-term seismic hazard.



Thank you for your attention!

Questions?

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*Goebel, T.H.W., Kwiatek, G., Becker, T.W., Brodsky, E.E. and G. Dresen (**2017**). What allows seismic events to grow big?: Insights from b-value and fault roughness analysis in laboratory stick-slip experiments.* ***Geology 45 (9), 815-818.***

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