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中国地震局 China Earthquake Administration

Unstable slip events on large-scale experimental faults with variable along-fault lithologies

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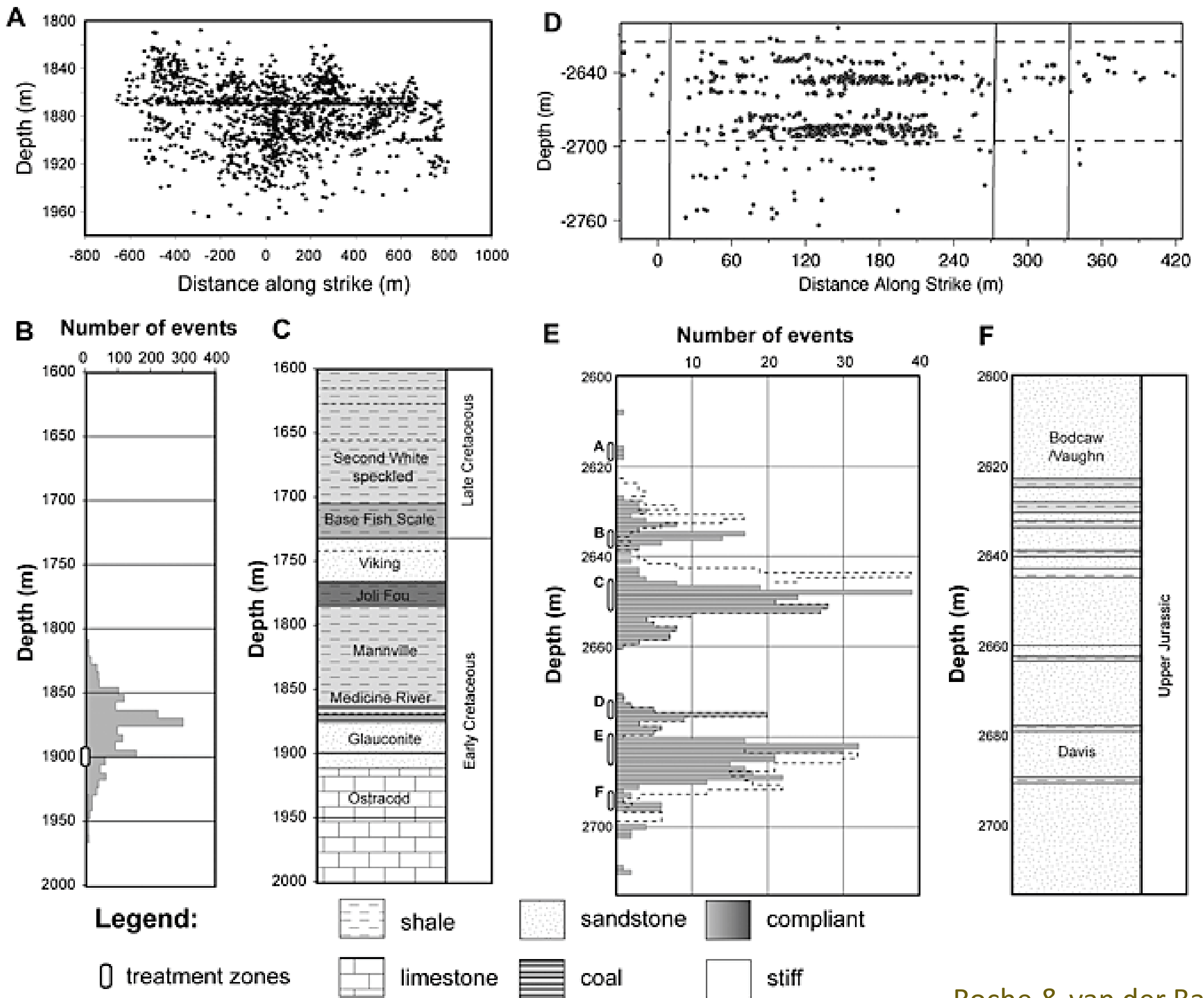
Lithological influence on microseismicity during fracking



- Seismicity related to pressure perturbation..
- … but also to lithology

Roche & van der Baan, JGR 2015

Scope: The effect of heterogeneous lithology on induced seismicity

Induced seismicity controlled by:

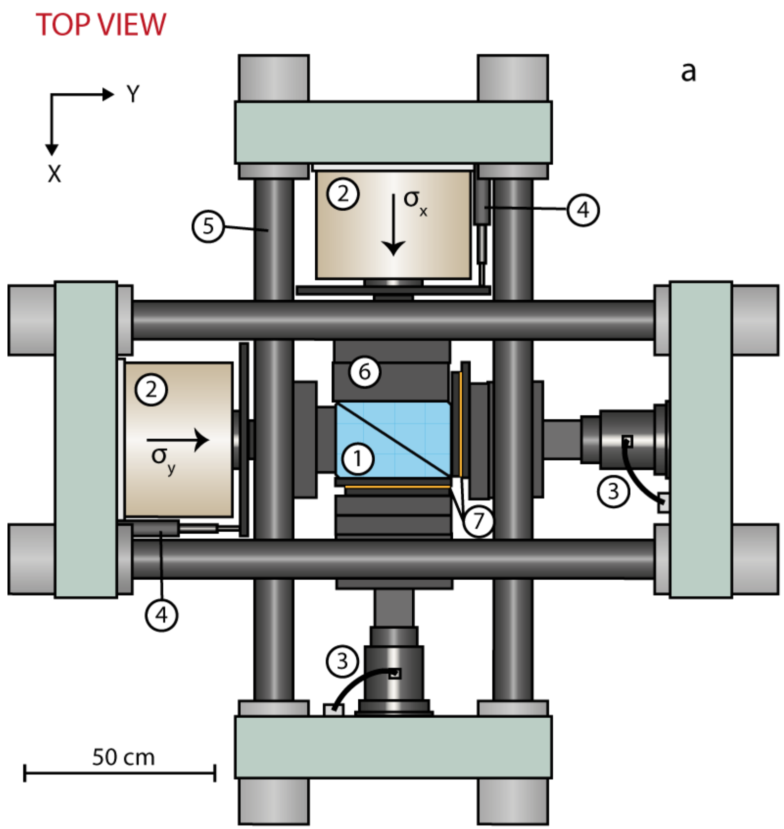
- Loading (stress perturbation)
- Background stress
- Local (fault) geometry
- Lithology

What is the effect of fault lithological variation on induced seismicity?

- How does lithological variation of fault rock affect state of stresses
- … and nucleation and propagation of rupture
- At what length scale do lithological variations matter?
  - (and at what length scale can we start to average the variability?)
  - .. In relation to the critical nucleation size
- How do variations in fault lithology impact the average fault strength?

Scaled Experimental Approach

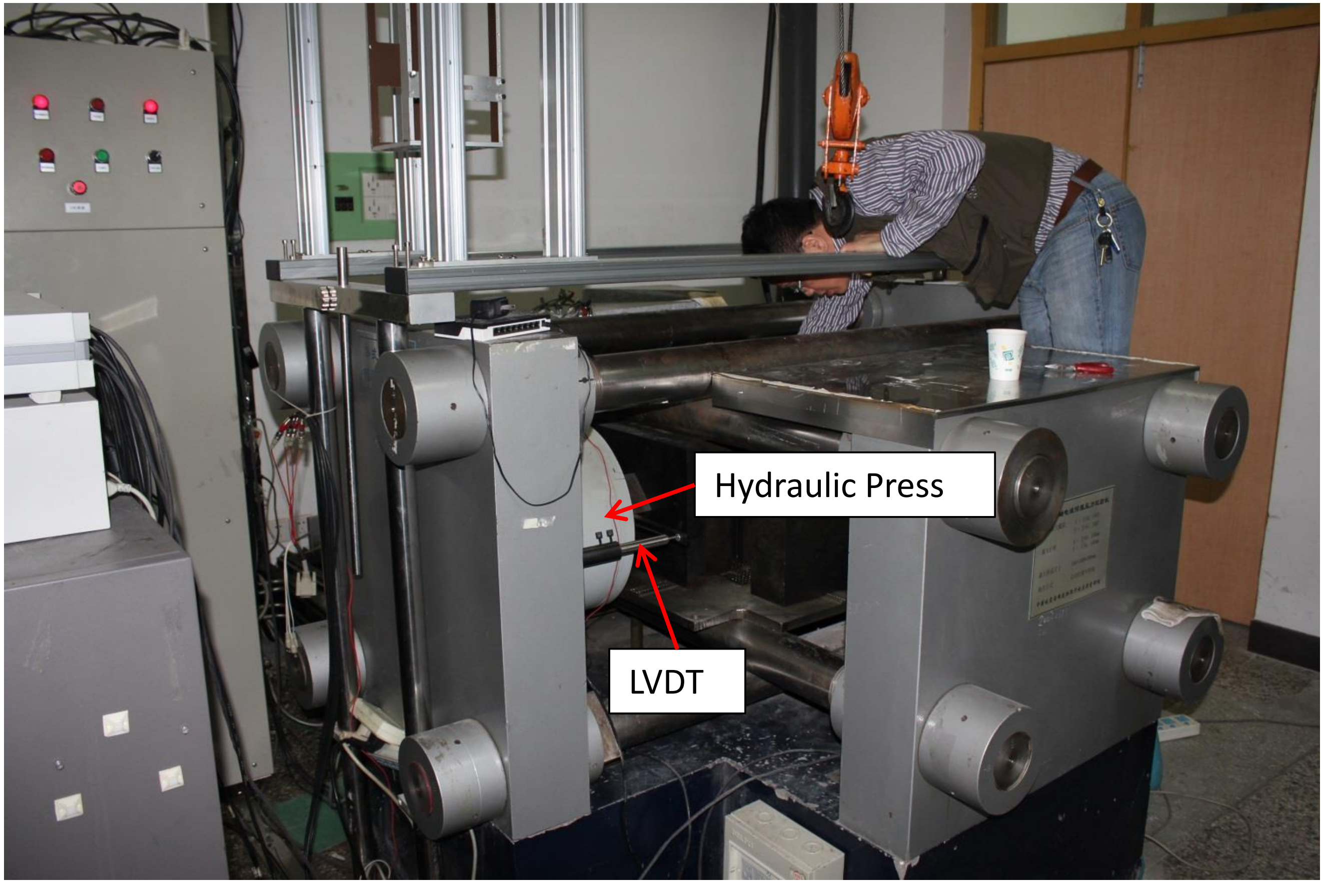
A scaled experimental approach: Biaxial machine



- Note that load is measured 0.5 m away from fault. Actual fault load may vary

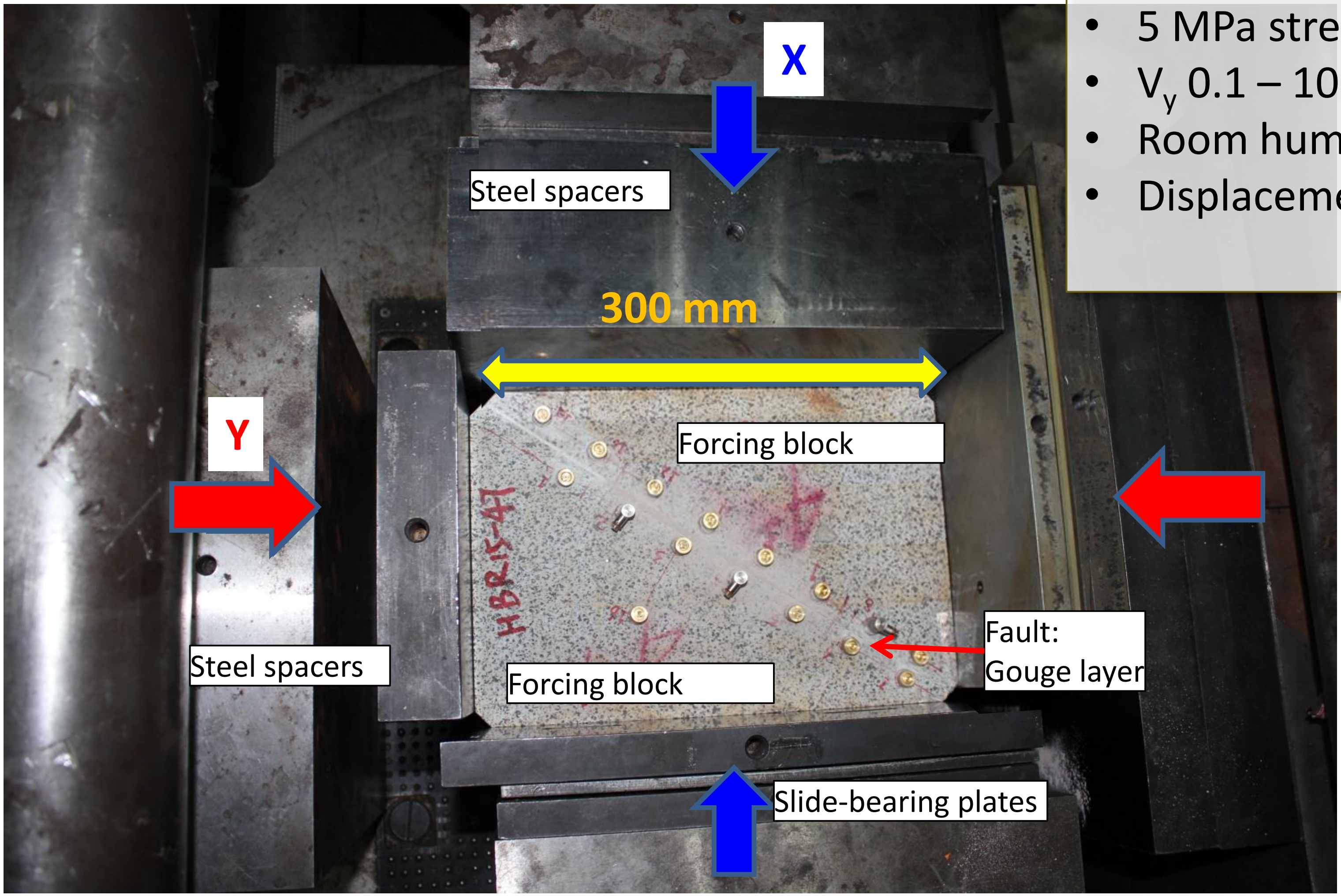
1	Sample (forcing blocks + gouge layer)	5	Loading frame
2	Hydraulic press	6	Steel spacers
3	Force gauge	7	Slide-bearing plates
4	Displacement gauge (LVDT)		

Horizontal biaxial machine loading frame



Located at the China Earthquake Administration, State Key Laboratory of Earthquake Dynamics, Beijing

Biaxial loading



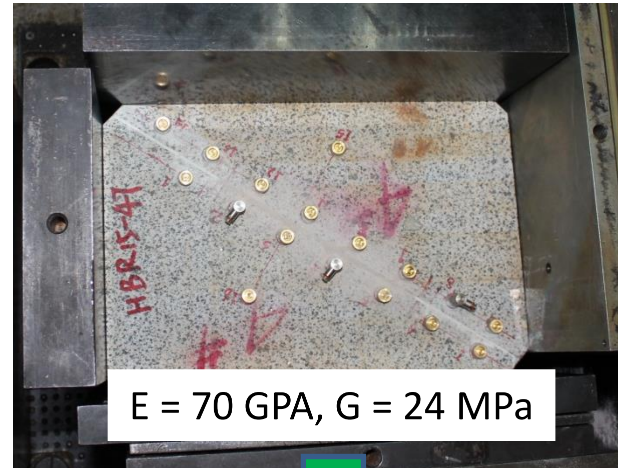
Experimental conditions

- 5 MPa stress in X
- V_y 0.1 – 100 µm/s
- Room humidity
- Displacement 15 mm

Scaling using the stiffness

Use of PMMA forcing blocks

Poly methyl methacrylate, Plexiglass®, Perspex®

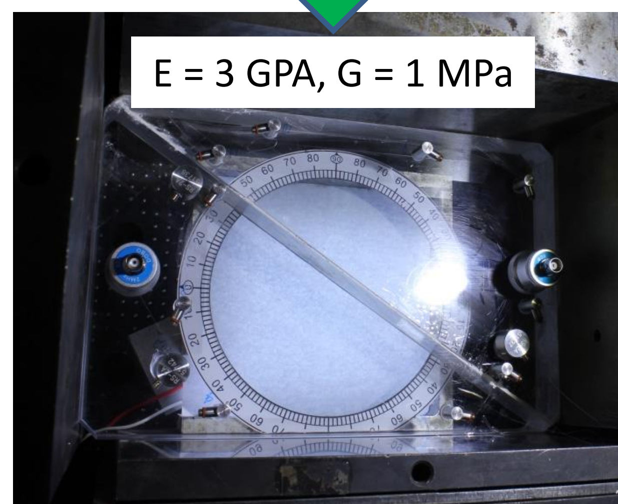


Why PMMA?

- Scaling with low stiffness
  - E=3 GPa , G = 1 GPa
  - → comparable to a granite block of 25 m …
  - Nucleation length L_{nuc} related to G

$$L_c = 1.16 \frac{1}{(1-\nu)} \frac{\boldsymbol{G} D_c}{d\tau}$$

- Easy to manipulate (e.g. create fault roughness)
- Birefringent → image stress



What about the fault properties?

Variable fault properties: fault gouge

Gouge materials

Gypsum

- U
- V
- Friction 0.4 – 0.6

SEISMIC

Kaoli

- St
- Ve ning
- Fr

STABLE
(& weak)

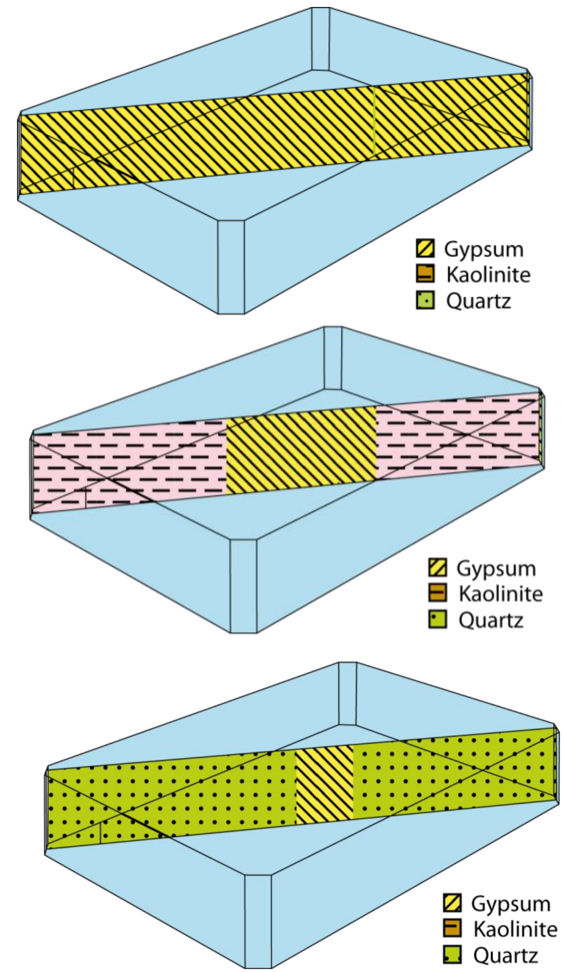
Quartz

-
-
- Friction 0.7 – 0.75

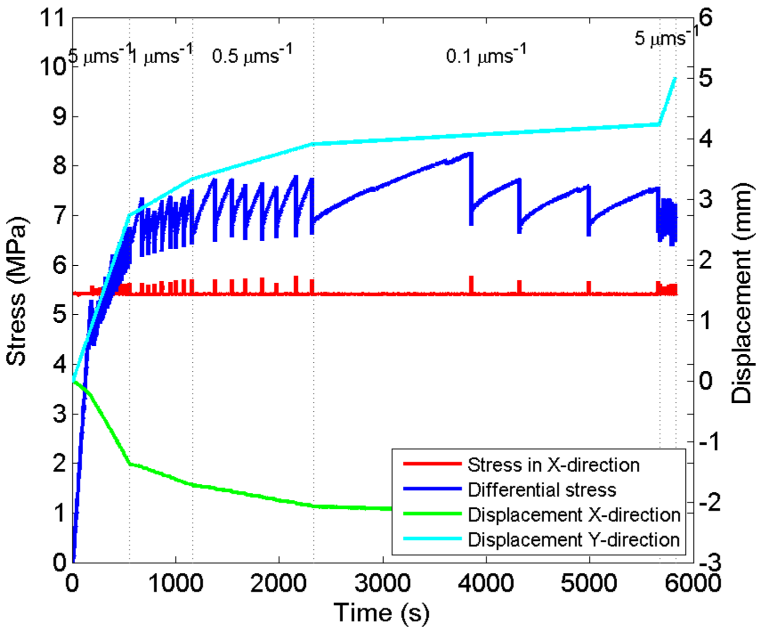
Intermediate

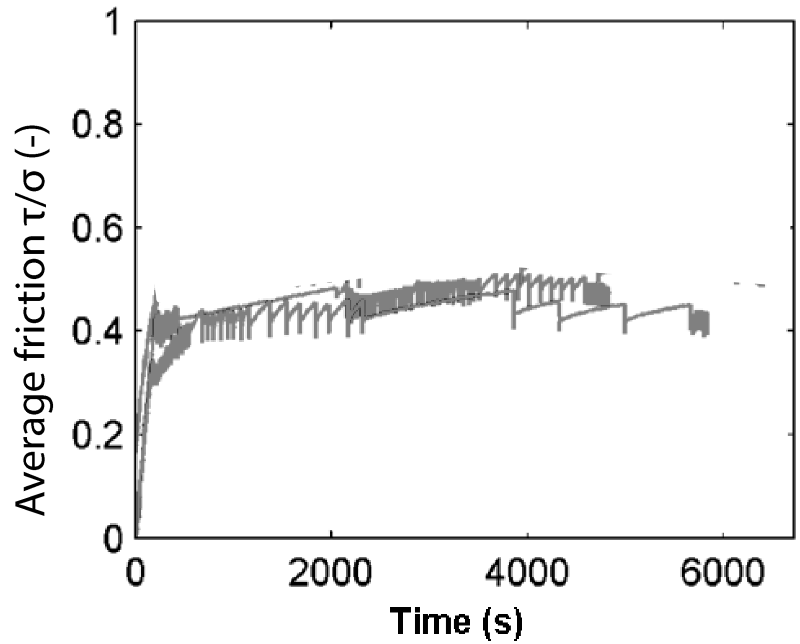
Tested in small scale experiments

Experiments



Single lithology: gypsum fault

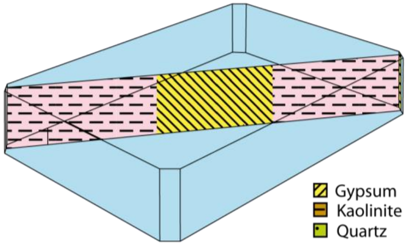


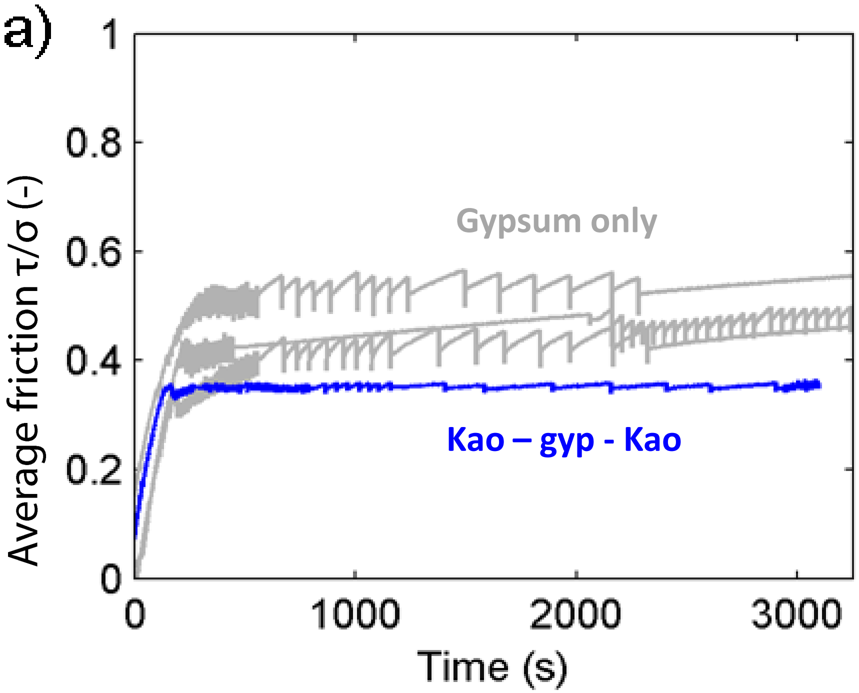


- **Differential stress** 7 – 8 MPa
- Stick-slip (laboratory earthquakes)
- Stress drop ~1 Mpa
- Friction 0.4 – 0.5, Friction drop ~0.08

What happens when different gouges are inserted along the fault?

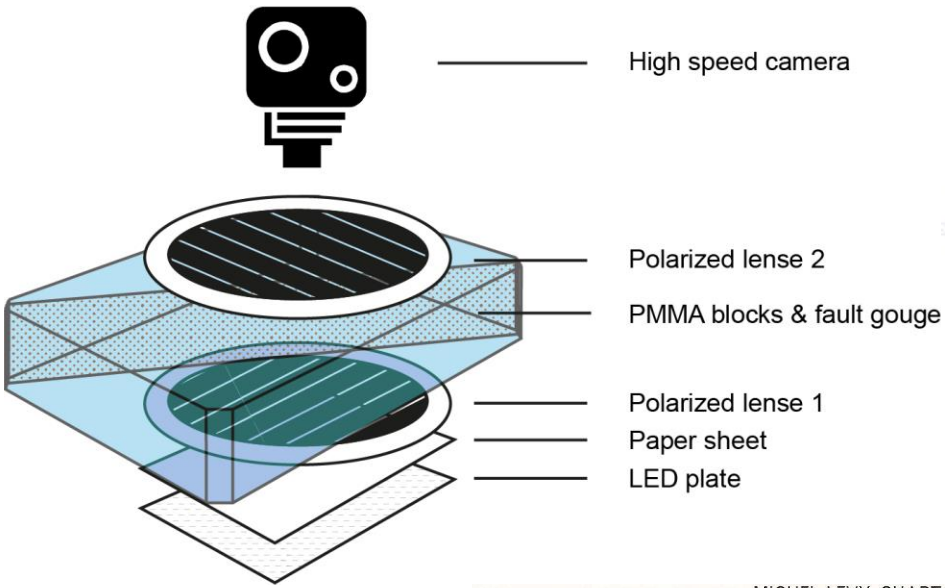
Kaolinite – gypsum - kaolinite

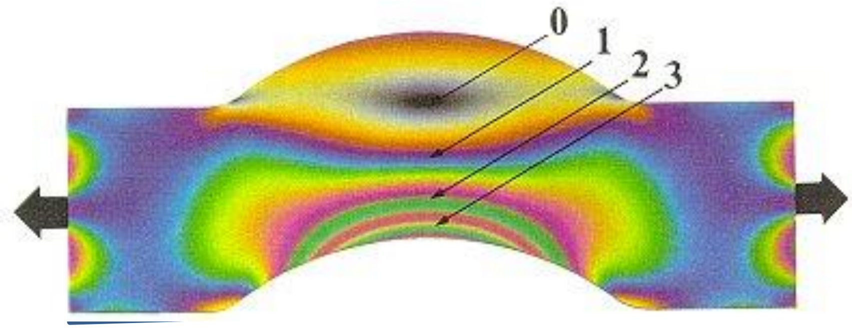




- Lower friction, smaller stick-slip events
- What is the state of stress along the fault?

PMMA → birefringent → photo-elasticity → stress





e.g. curved beam in tension

$$\sigma_1 - \sigma_2 = N\frac{\lambda}{ch} = \frac{Nf_\sigma}{h}, \quad N = n.$$

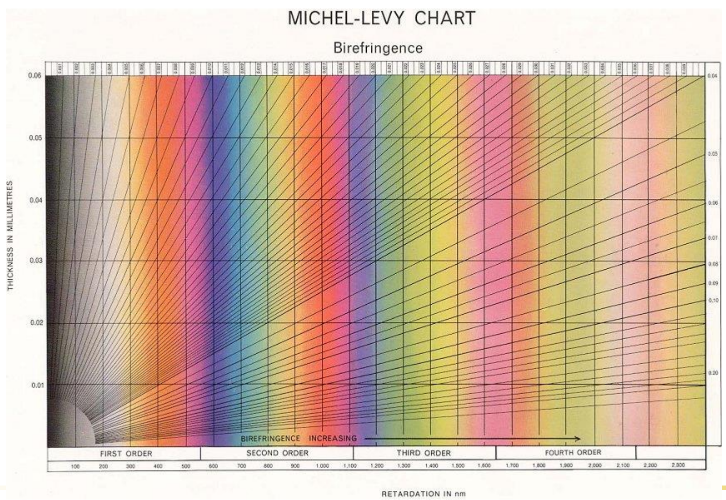
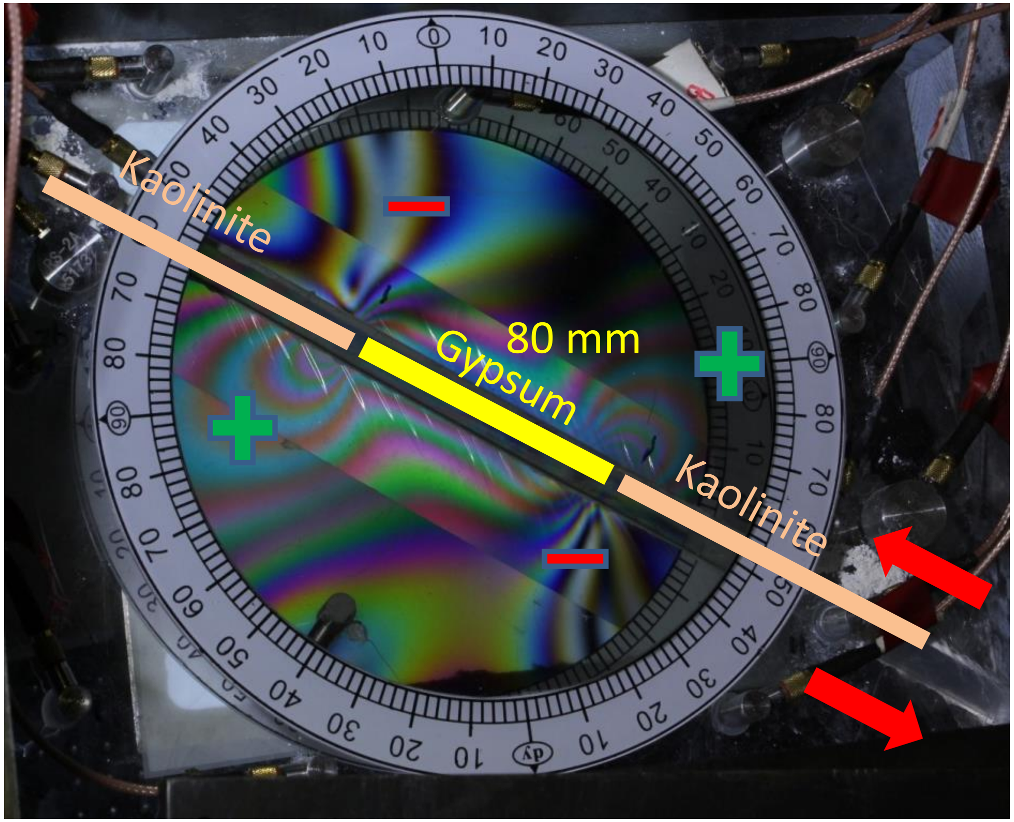


Photo-elasticity



- Stress concentrations at edges

- Video

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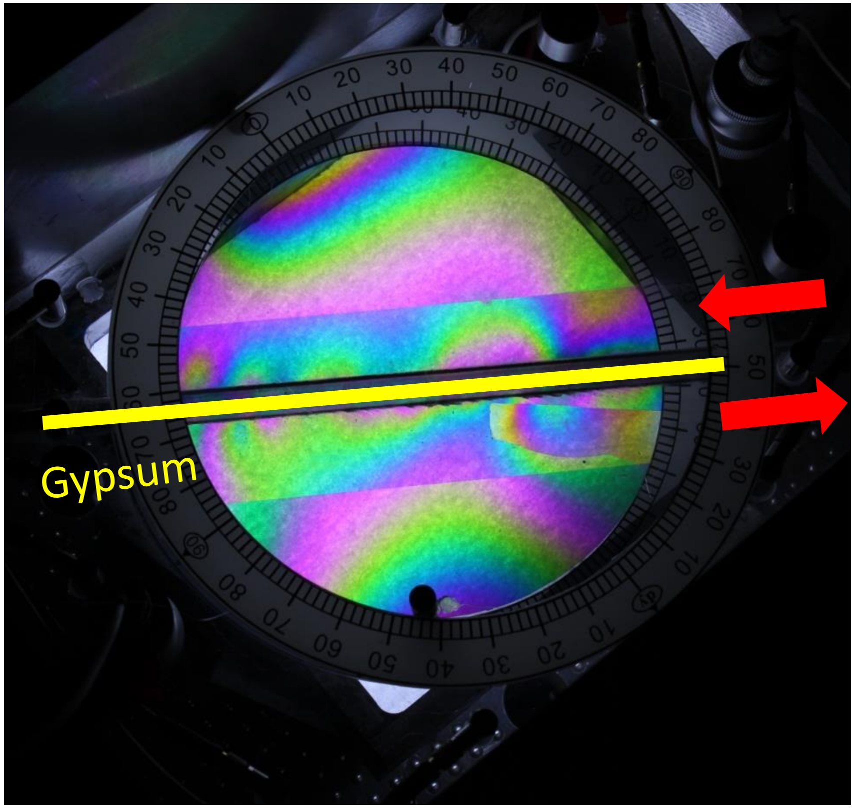
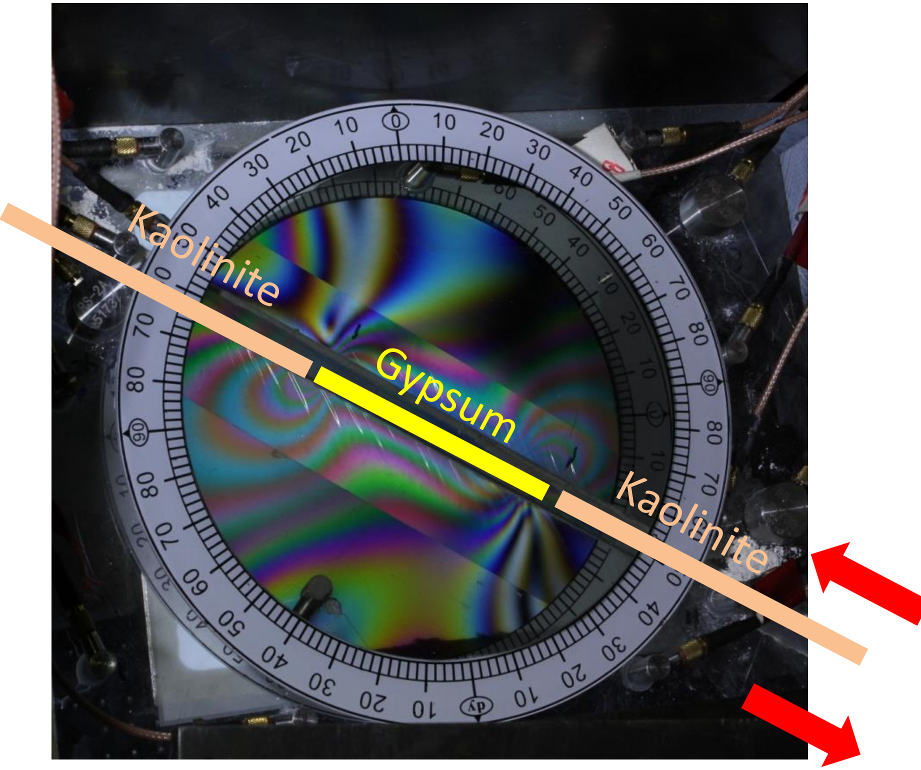
Stresses along homogeneous fault vs. Heterogeneous fault





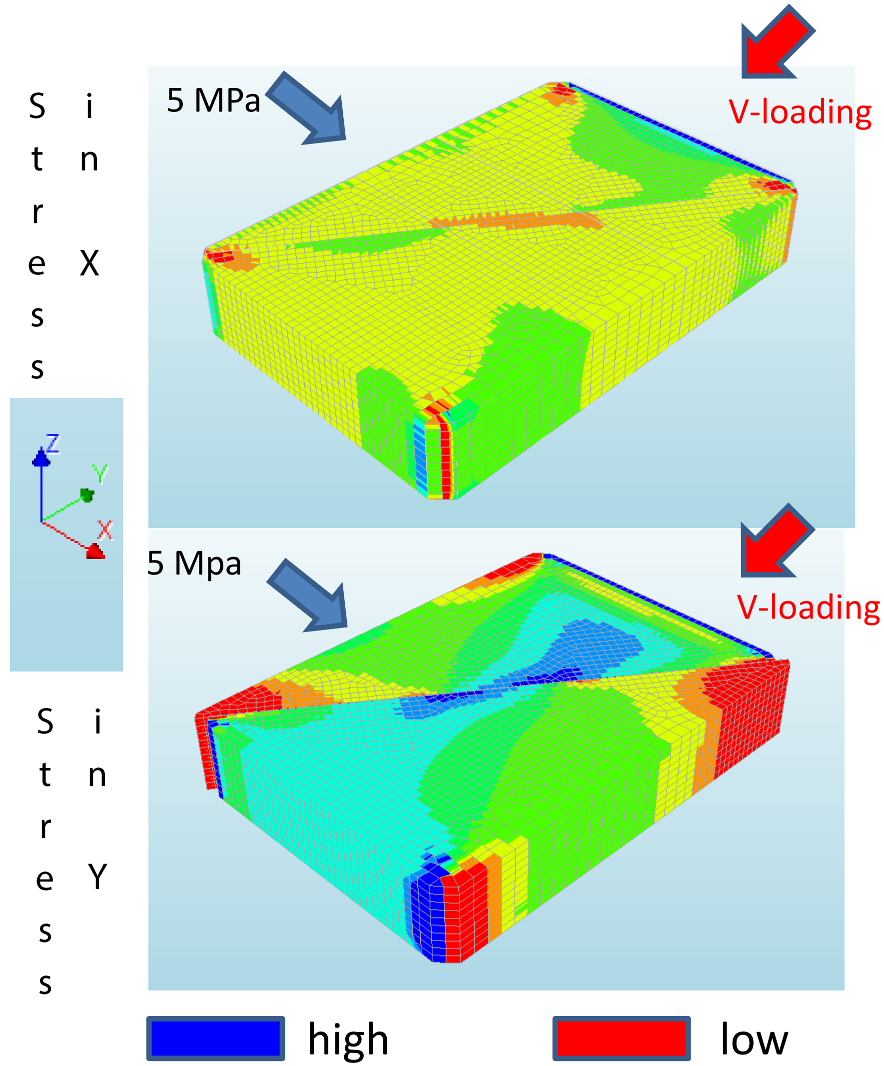
Stress differences related to heterogeneous lithology dominate over smaller heterogeneities in a single gouge itself

- Where do we expect nucleation of unstable slip?
  - Can we model the observed stresses

FE model nucleation of slip

- First results FE modelng
- DIANA FEA
- PMMA linear elastic
- Slip-weakening (SW) gypsum segment
  - Static friction 0.6
  - Dynamic friction 0.5
  - Dc 50 micrometer
- Kaolinite segment
  - Static friction 0.3

- Stress concentrations near sample edges
- Stress concentrations near gypsum segment



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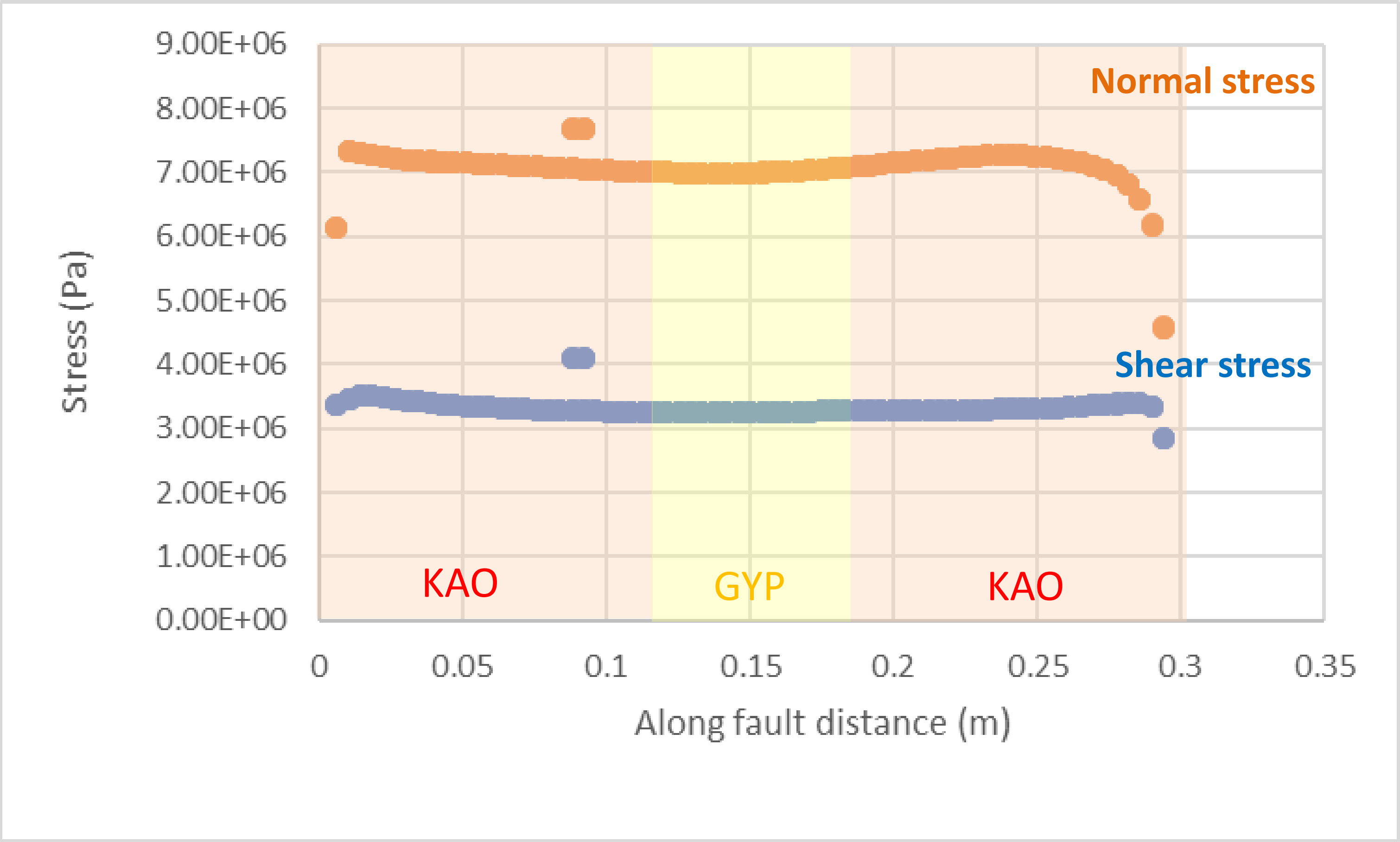
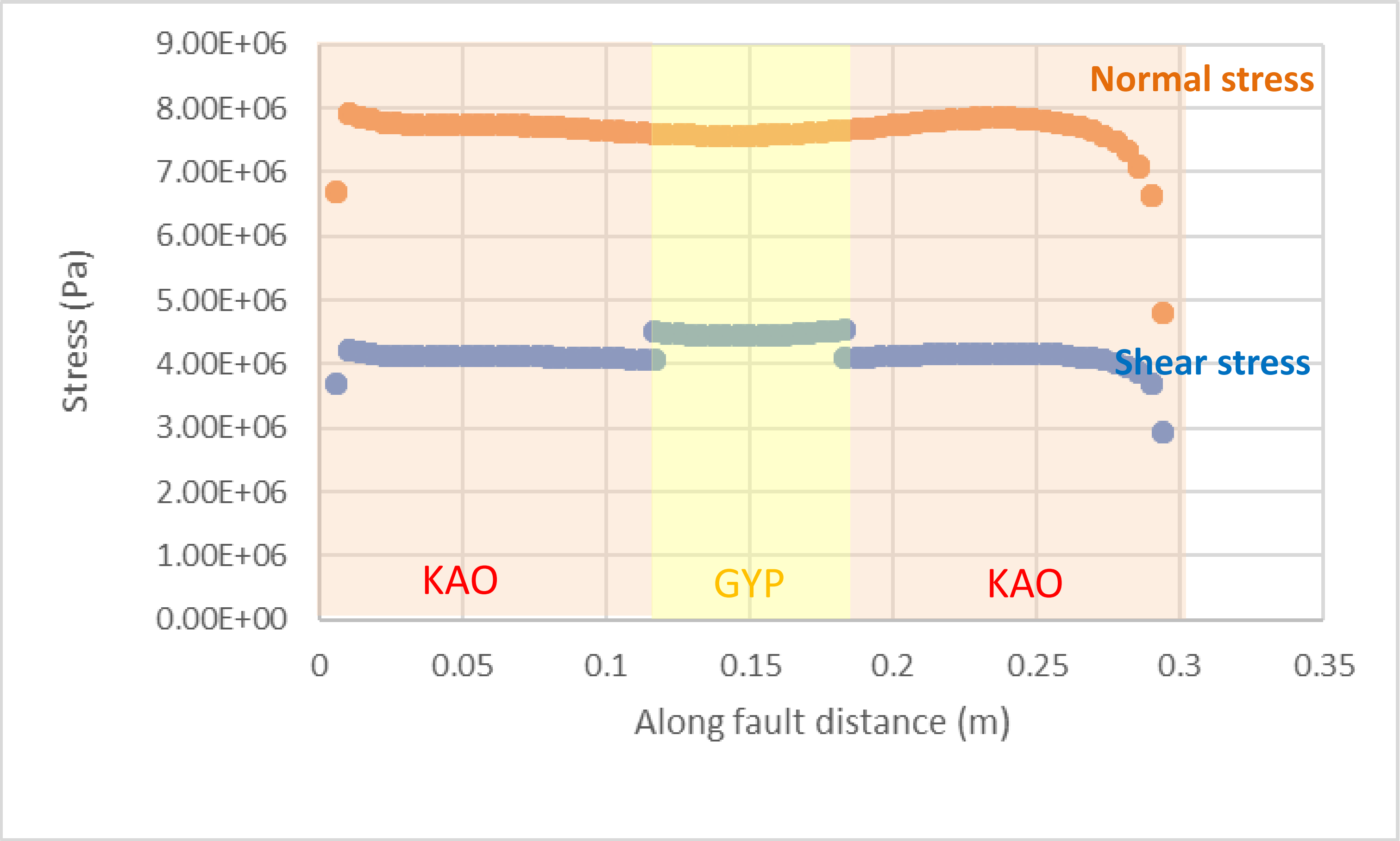
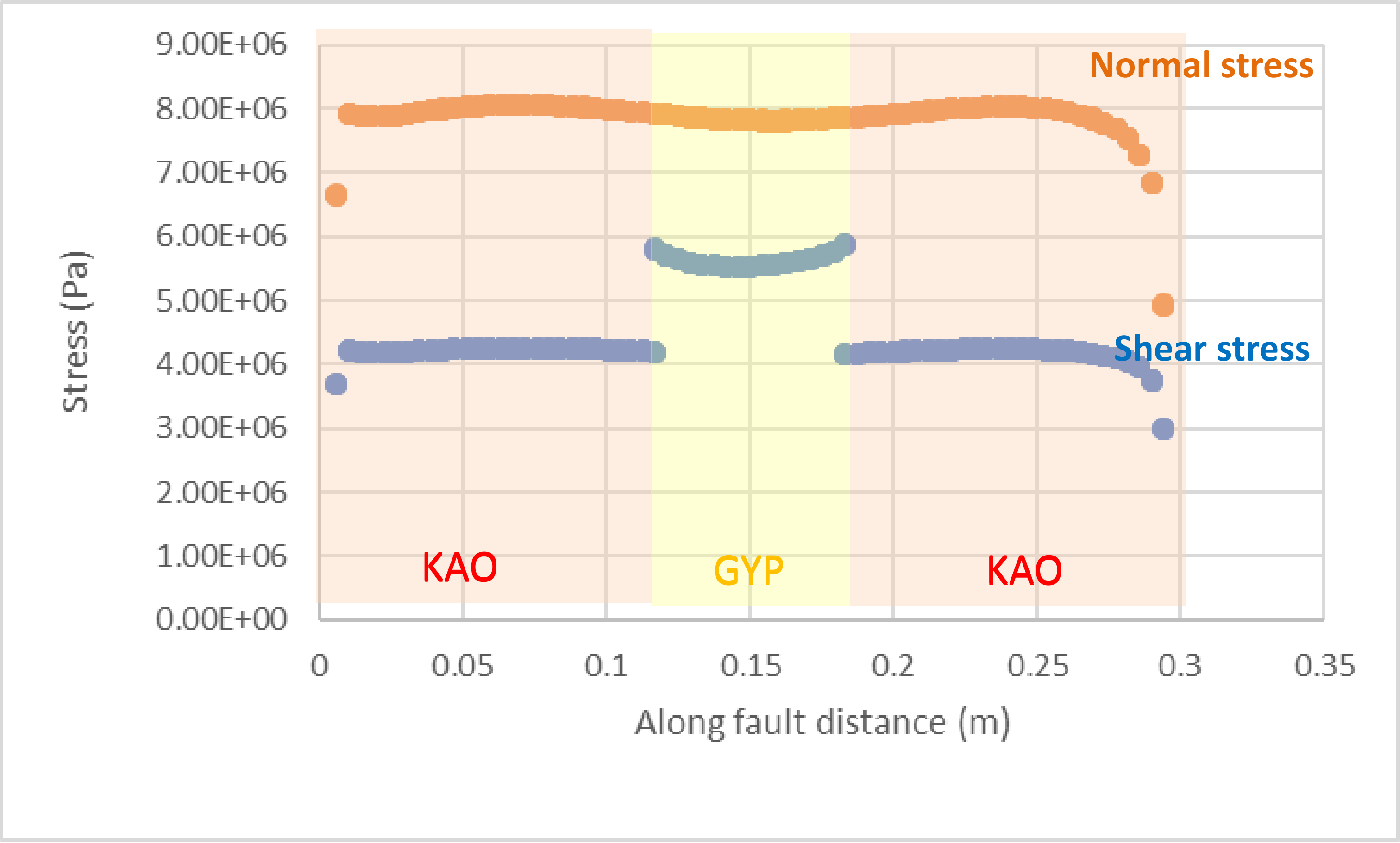
Stresses on modeled fault: Elastic loading



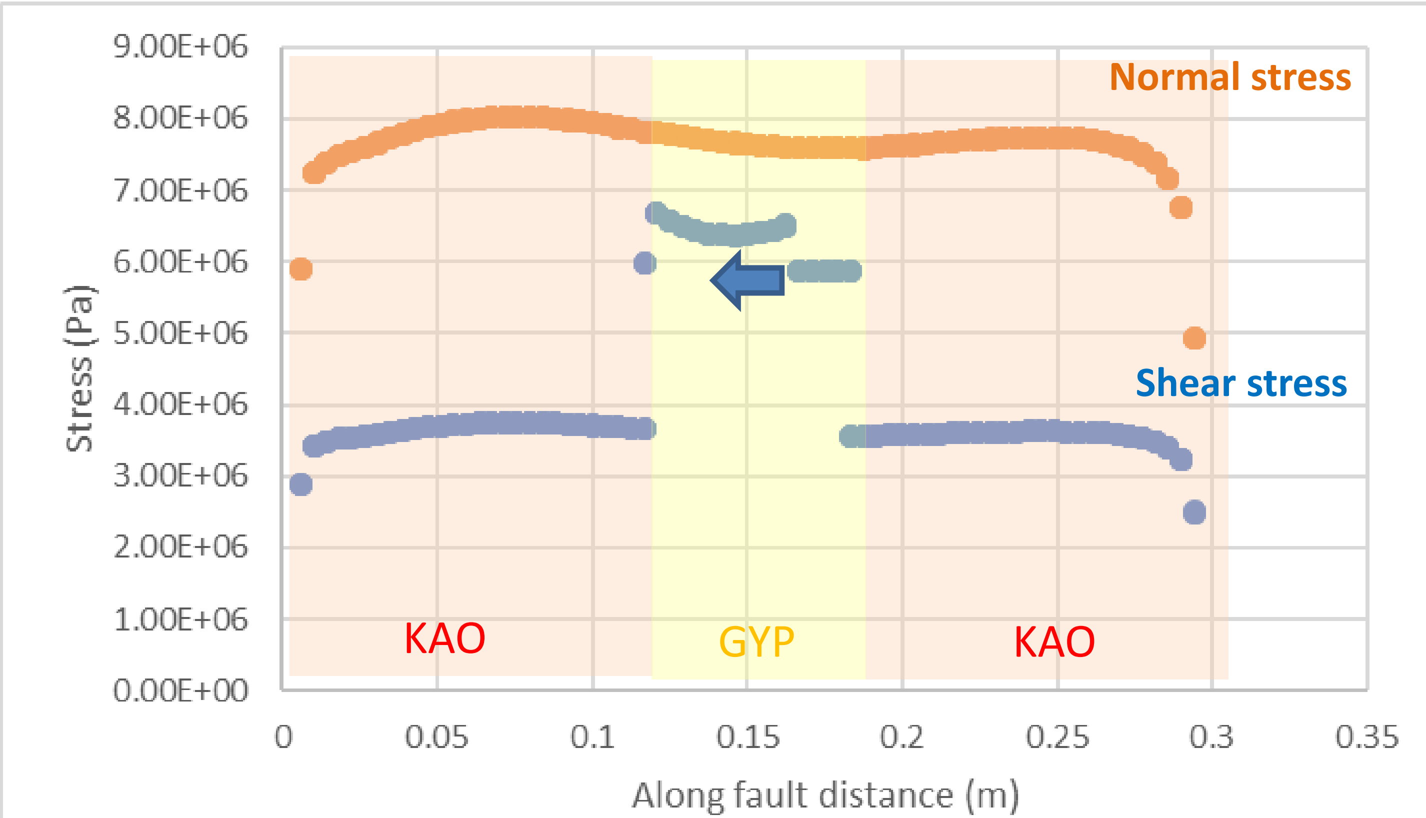
Stresses on modeled fault: Slip on kaolinite segments



Stresses on modeled fault: Stressing of unstable segment



Stresses on the fault: Nucleation of slip at patch edge

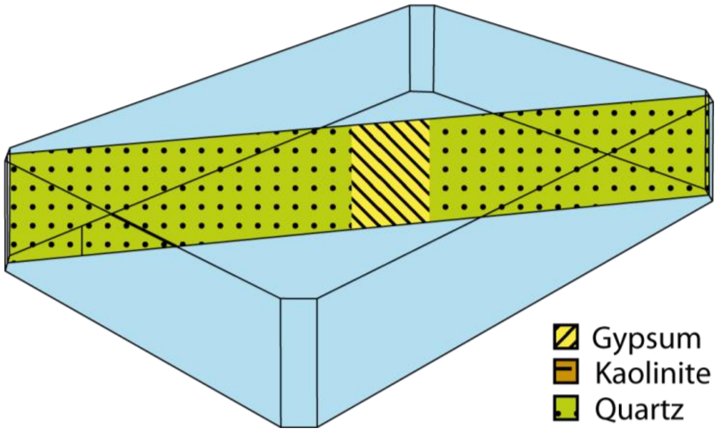


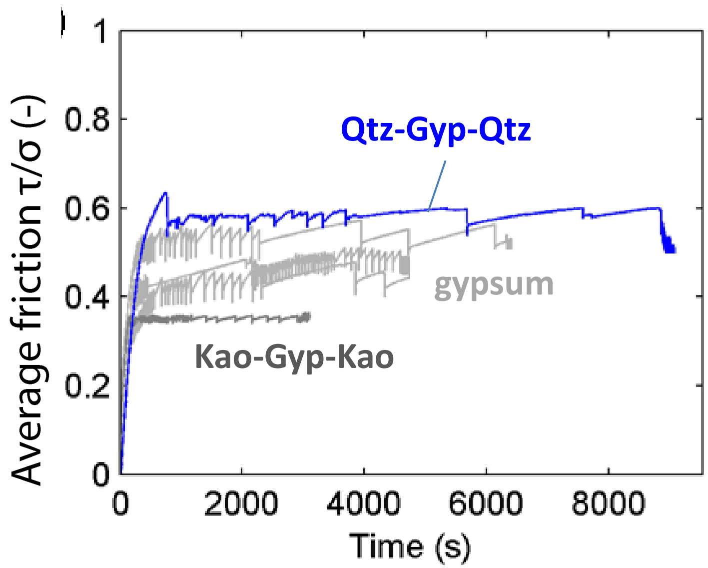
Average apparent friction at time of nucleation → 0.52 (whereas gypsum friction = 0.6)

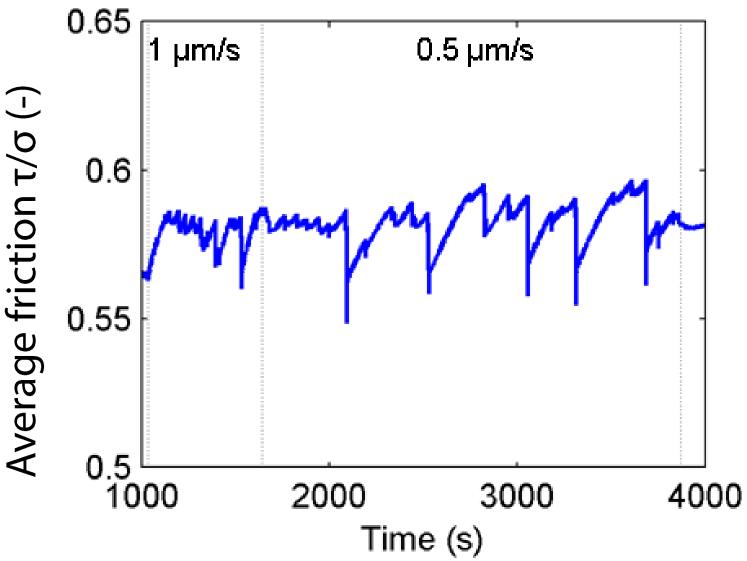
The presence of the stress concentration promotes rupture at a relatively low far-field loading stress (below static friction of gypsum segment)

Quartz-gypsum-quartz fault

- 4 cm gypsum segment flanked by quartz
- Apparent friction 0.58
  - Pure quartz 0.75, gypsum 0.4-0.6
- Smaller stick-slip than pure gypsum
- More irregular stick-slip sizes

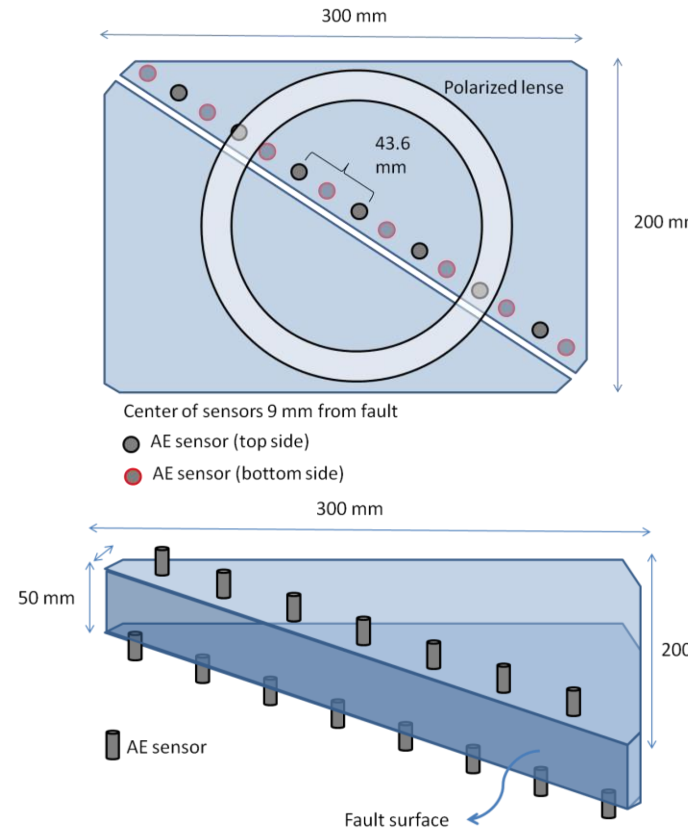






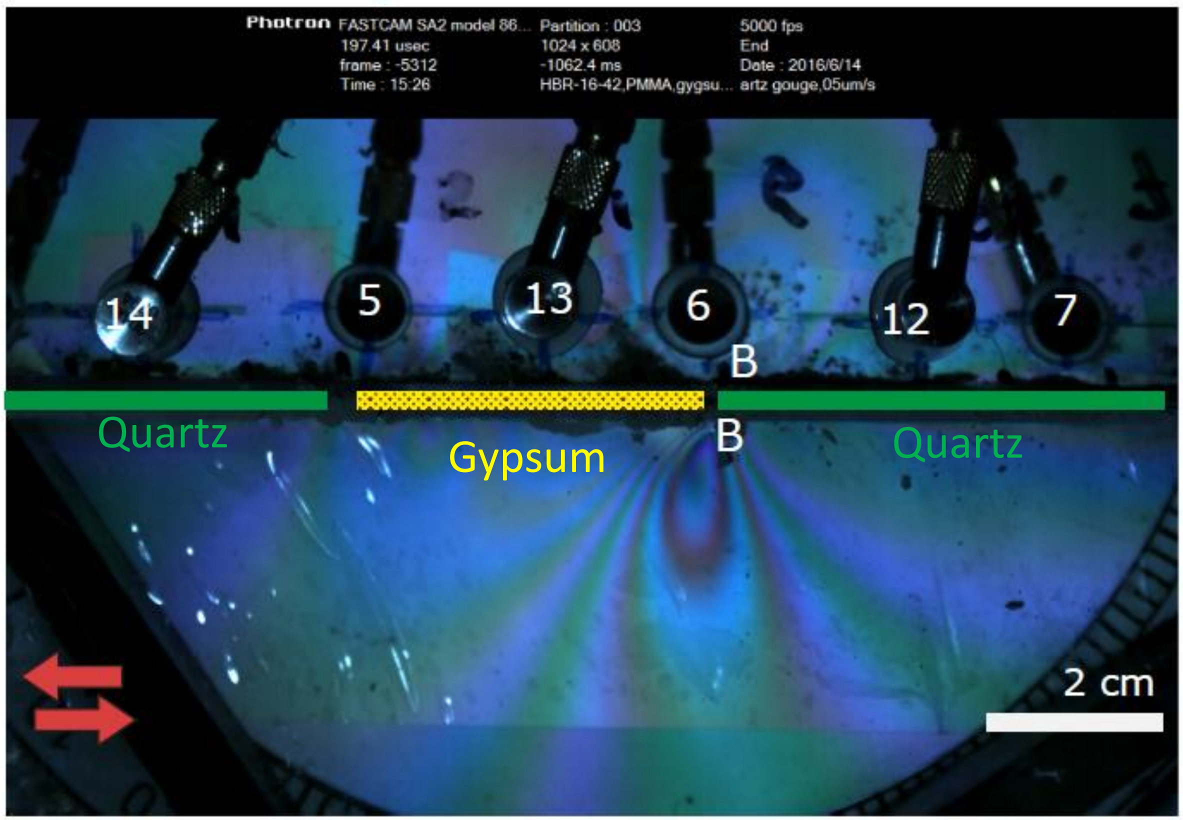
Average frictional strength dominated by gypsum segment

Acoustic emissions on the quartz-gypsum-quartz fault



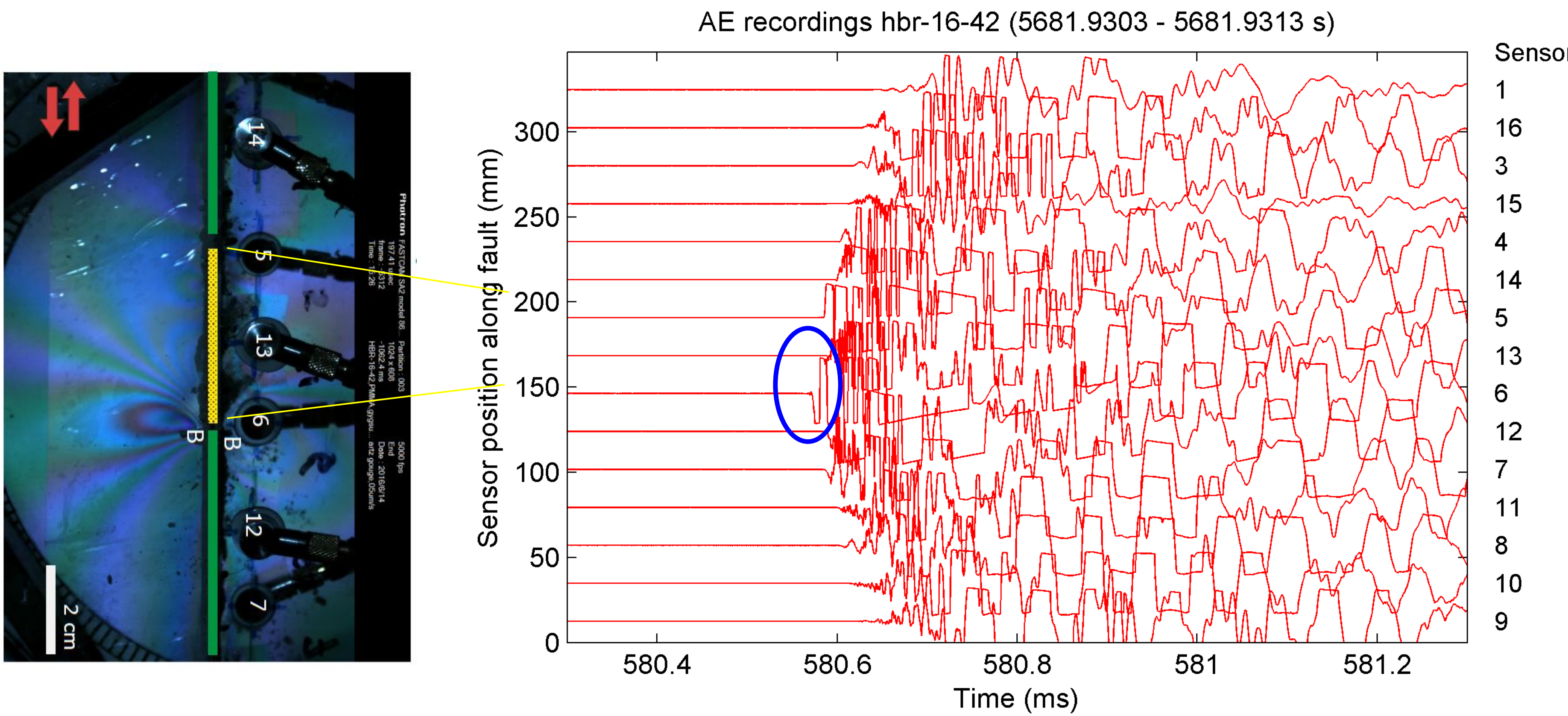
- 15 sensors along the fault (AE204V) , 3 MHz continuous recording
- 100 – 1000 kHz
- Setup allows for good localization of start of rupture

Photo-elasticity quartz – gypsum – quartz fault



- Again a stress concentration is observed

Nucleation of slip from the unstable segment



- First onset → Slip nucleation may be near the edge of the gypsum patch
- Rest of signal is clipped → we cannot detect passing rupture front and propagation
- → Strain gauges are required

Conclusions / Discussion

- Lithological variations → stress concentrations for strong segment embedded in weaker stable fault → may promote slip at relatively low loading stress
  - → take into account in modeling induced seismicity
- Lithological variations determine the nucleation location of seismicity (for uniform loading)
- Presence of unstable segment may dominate the average fault strength and behavior

- Scaled experiments
  - Help bridge to gap between cm-scale to 100-scale
  - Allow for simultaneous imaging of stress, acoustic emission
  - Useful for testing hypotheses, model validation

Thank you!!