Schweizerischer Erdbebendienst
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ETH zürich

Direct measurements of asperity evolution in the laboratory relating to fault reactivation in stimulated reservoirs

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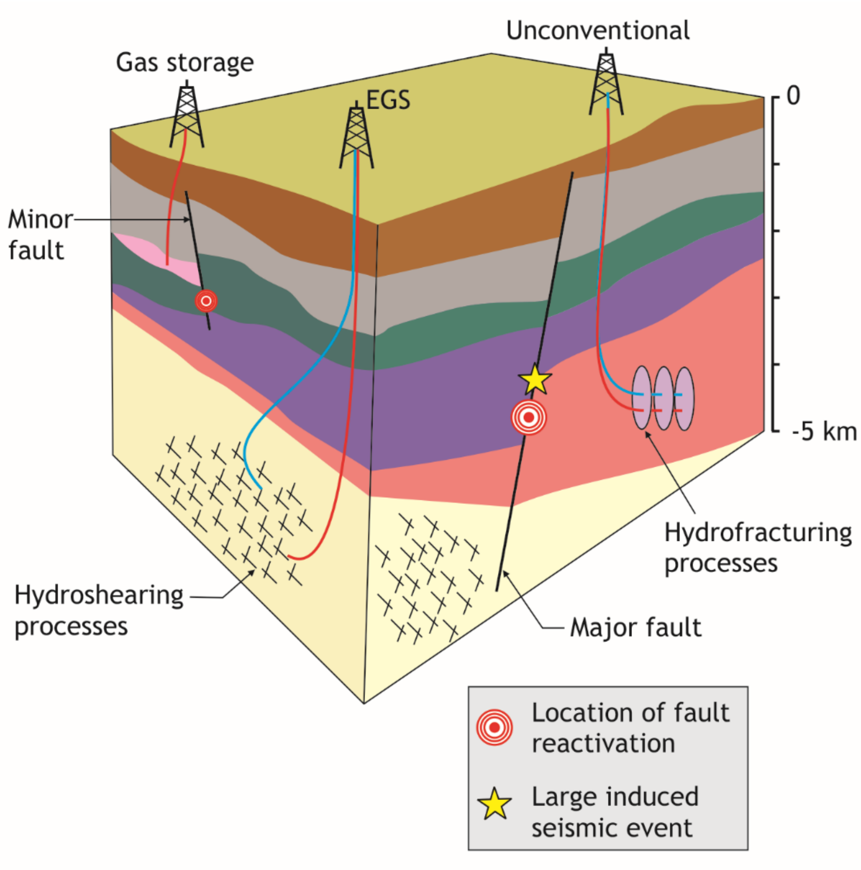
Schatzalp Workshop on Induced Seismicity
Davos, Mar. 16, 2017

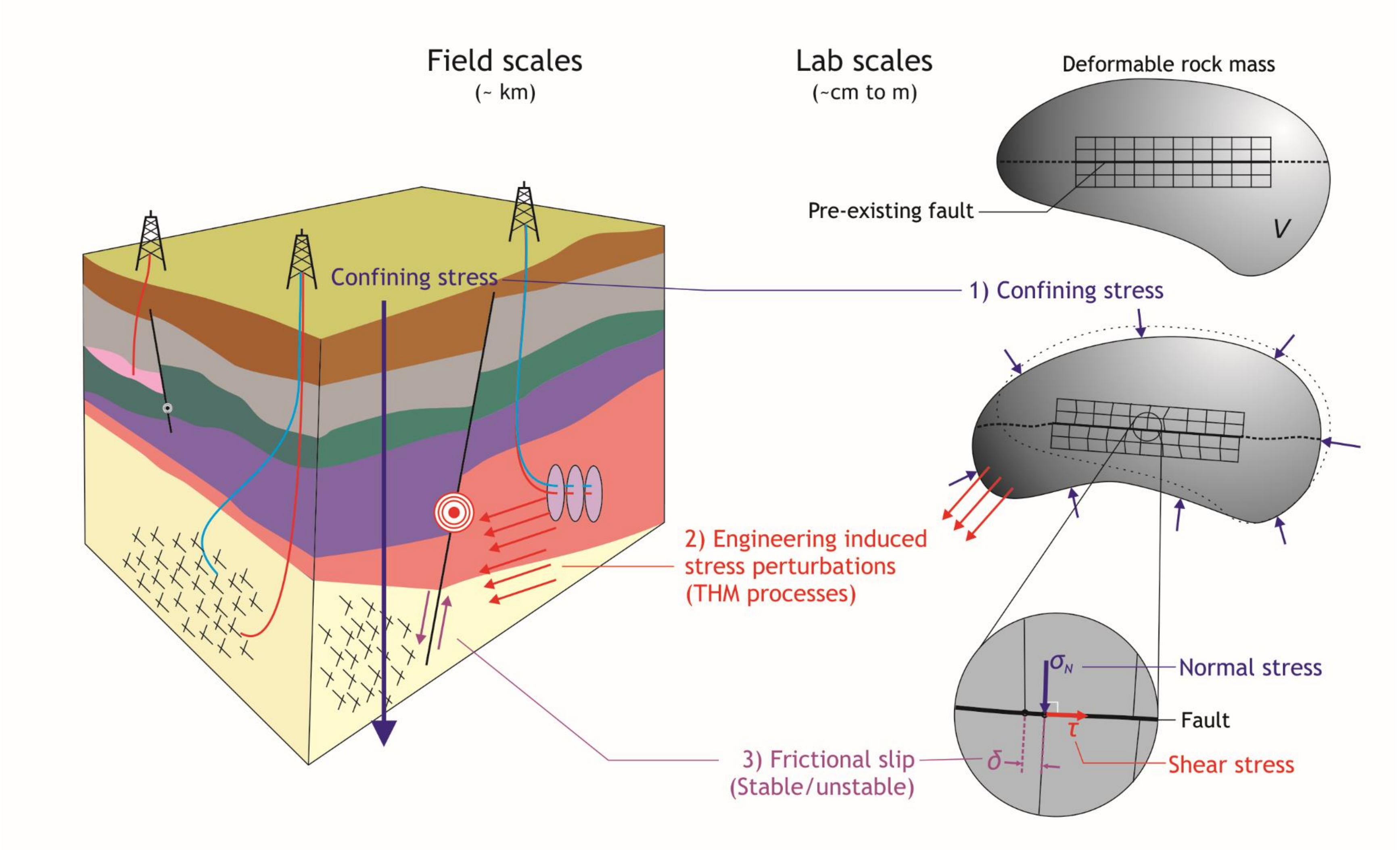
Motivation

- **Reactivation of natural faults** can lead to **induced seismicity** and is a byproduct of a variety of subsurface engineering activities:
  - *Oil and gas production*
  - *CO_2 storage*
  - *Shale gas extraction*
  - *Enhanced Geothermal Systems*
  - *Mining activities*
  - *Impoundment and dam stability*

- Determining the **hazard** associated with fault **reactivation** requires an understanding of the relationship between:
  - **Subsurface rock deformation,**
  - **frictional faulting,**
  - and **seismicity**.



Background: Frictional laboratory studies



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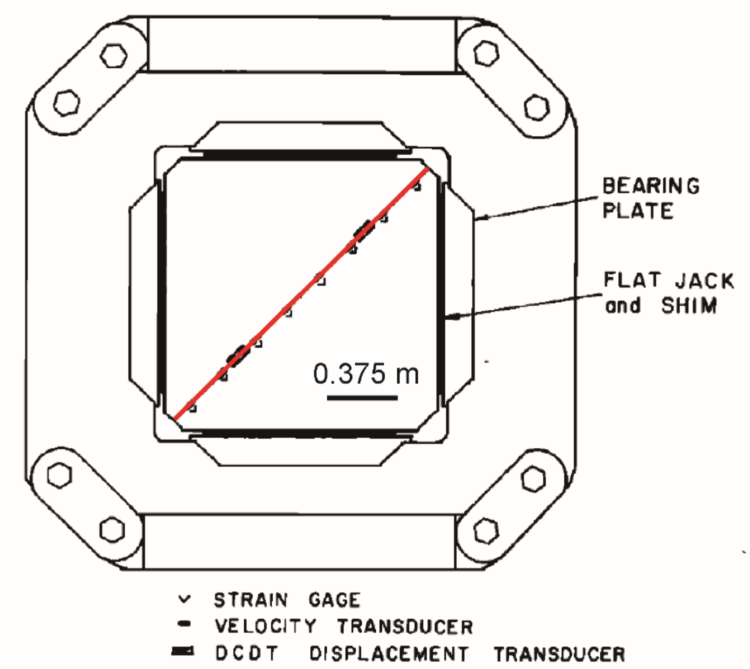
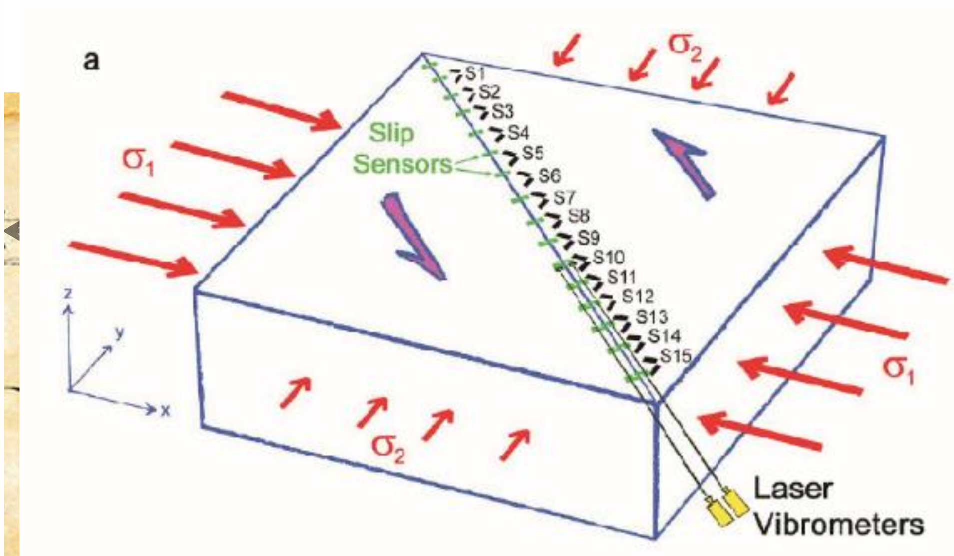




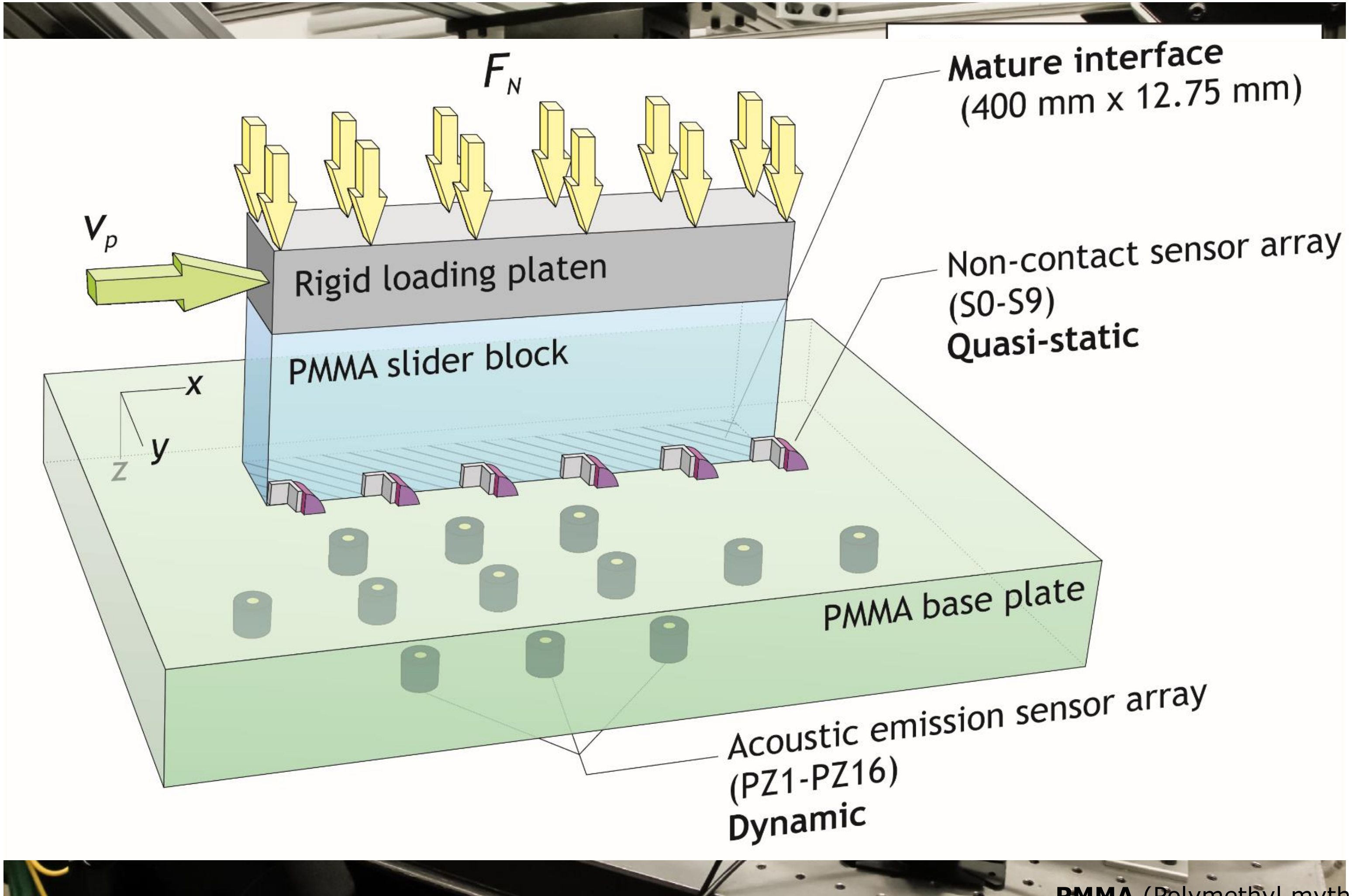
Leonardo da Vinci (ca. 1493)

Biaxial press
USGS, Menlo Park, CA
Dieterich (1978)

37 years →

Biaxial press
USGS, Menlo Park, CA
McLaskey et al. (2015)

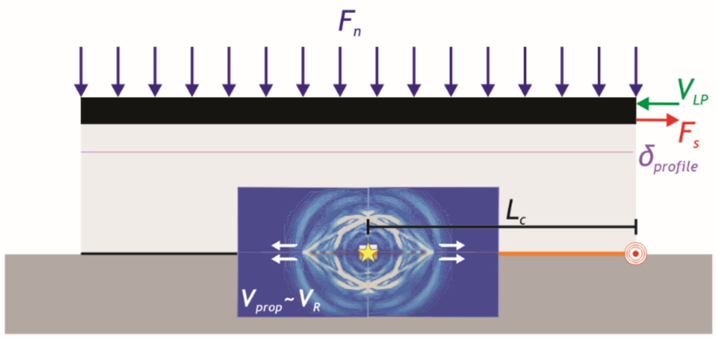
UC Berkeley Direct Shear Friction apparatus

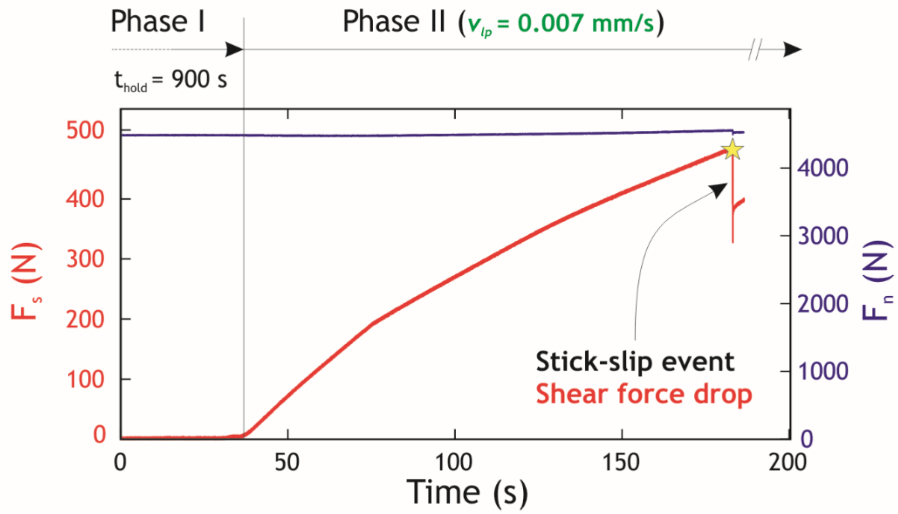


PMMA (Polymethyl mythacrylate)

Direct shear experimental procedure

1. Mature **interface** is created between a slider block and base plate
2. Phase I: Normal force F_n is applied to the fault for t_{hold} = 900 s
3. Phase II: Loading platen driven at a constant velocity V_{LP} . Fault becomes reactivated
   i. Shear rupture expands steadily and is determined by the "kink" in the slip profile ($\delta_{profile}$).
   ii. Localized seismicity is observed when rupture front enters a specific section of the fault
   iii. Upon reaching a *critical size* (L_c), the rupture front accelerates rapidly and a "stick-slip" event is observed.





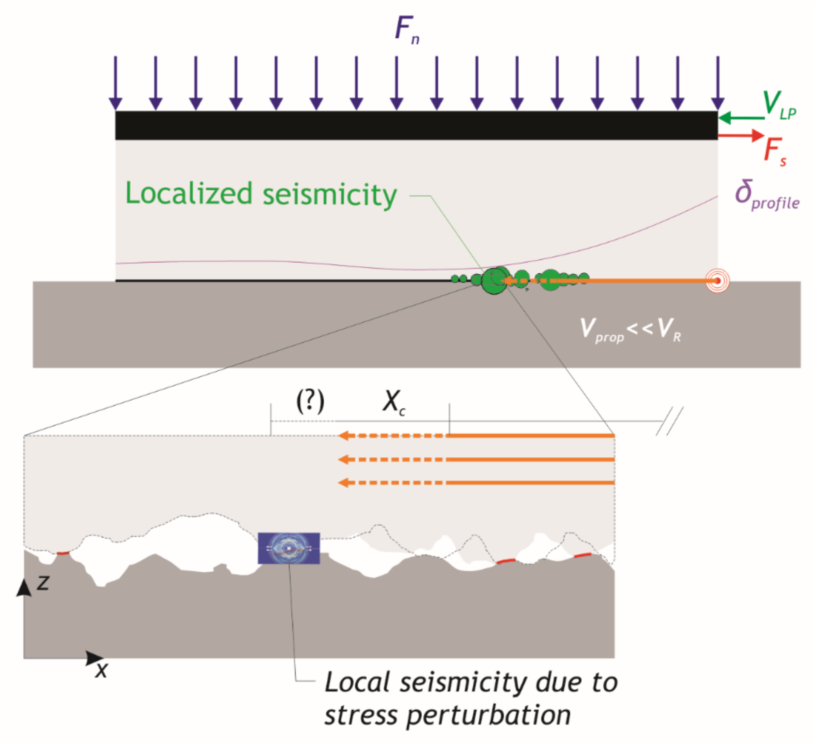
Results from Selvadurai and Glaser (2015, JGR)

What is happening in the "seismogenic" section?

- Mature, unlubricated, rough-rough **frictional interface**
- Monitoring localized seismicity is a new development imparted by **improved AE sensors and techniques**.
- How is **localized seismicity** affected by:

1. **Rupture front & speed (V_{prop}),**
2. **Loading velocity (V_{LP}),**
3. **Normal force (F_n)** and
4. ***Asperity distributions (b_{asp})***

is not well known.

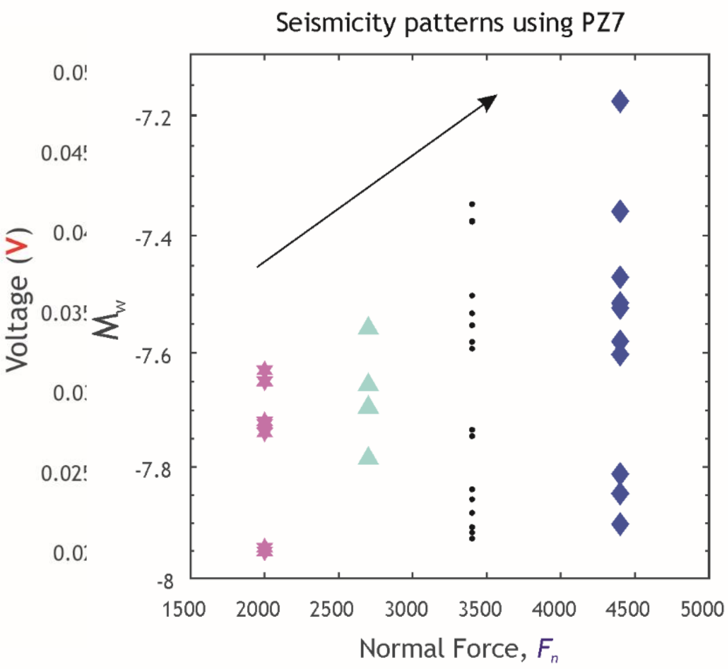


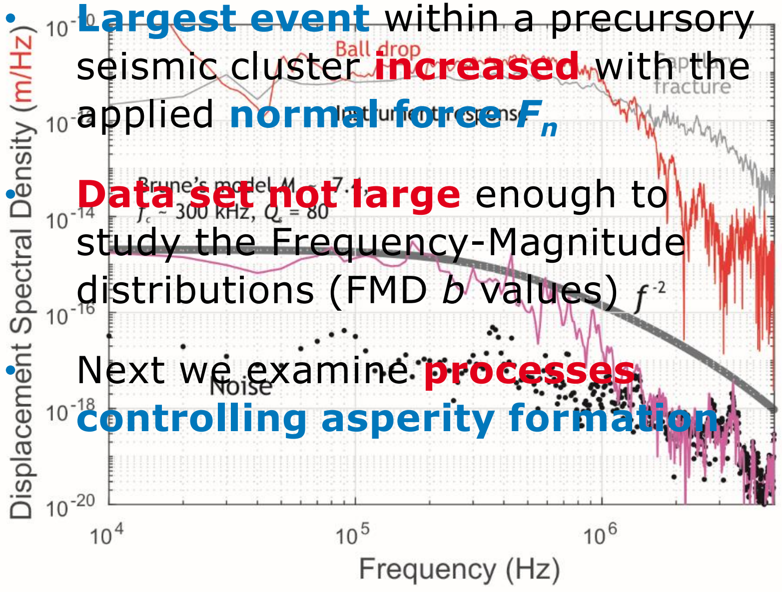
"The best way to find a fault is to light them up with earthquakes" – Dr. Gail Atkinson

Experimental: Goebel et al. (2012, 2013), McLaskey and Kilgore (2013), McLaskey et al. (2014), McLaskey and Lockner (2014), Passelègue et al. (2016), Selvadurai and Glaser (2015, 2017)

AE sensor advances and localized seismicity patterns

- AE sensor were absolutely calibrated → Frequency response in units [**m/Hz**]
- Precursory seismicity was located using ***P*-wave arrivals**
- Using **Brune's model** we estimate the **magnitude M_w**



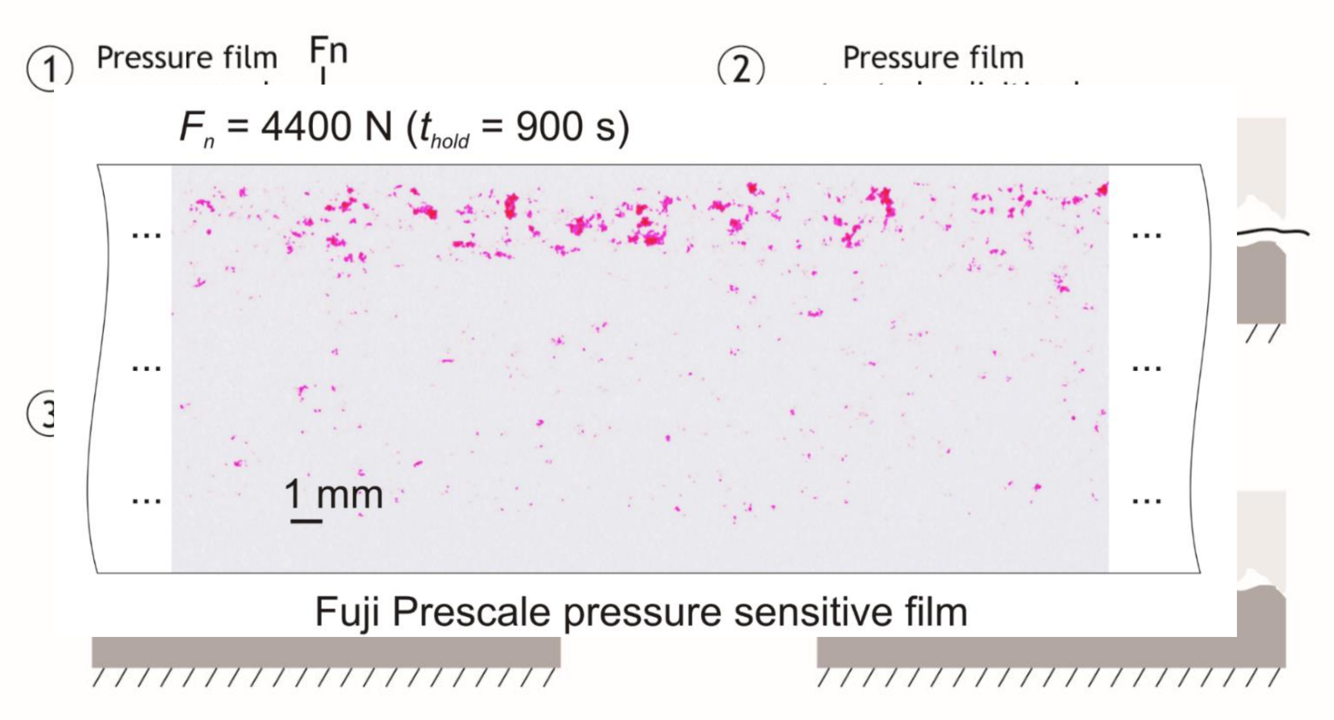


- **Largest event** within a precursory seismic cluster **increased** with the applied **normal force F_n**
- **Data set not large** enough to study the Frequency-Magnitude distributions (FMD *b* values)
- Next we examine **processes controlling asperity formation**

Calibration techniques: McLaskey and Glaser (2012, NDT)

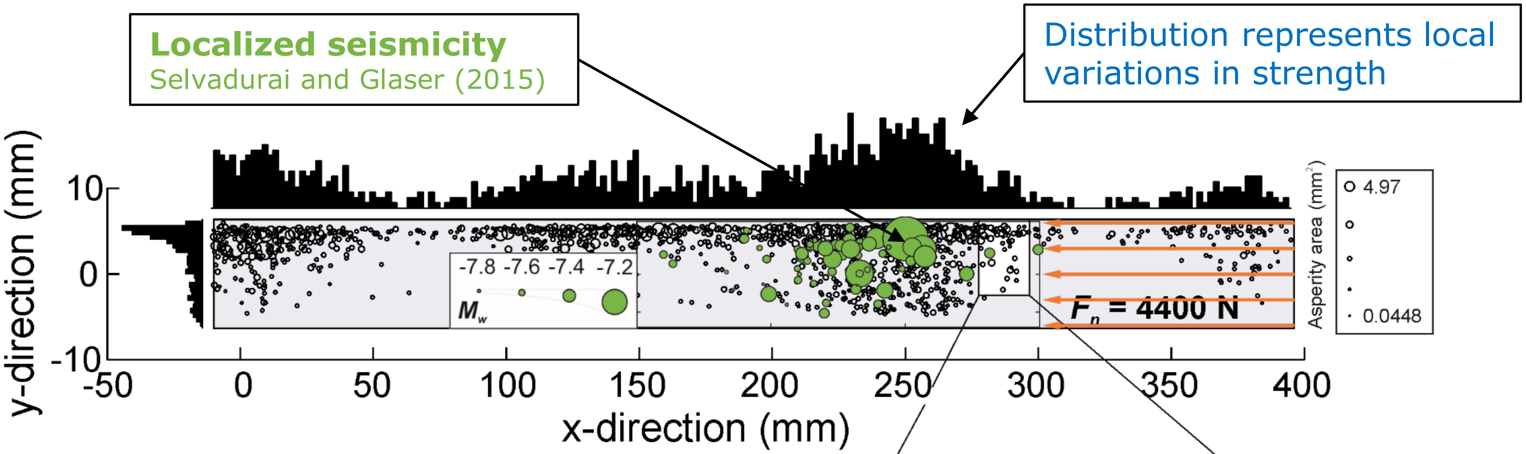
Interface characterization:

- Calibrated pressure sensitive film (FUJI Prescale Medium 12- 50 MPa)
- Compressed along interface, extracted and digitized.
- Provides *a priori* measurements of asperity distribution



Spatial resolution Selvadurai and Glaser 2017, GJI
Normal stress Selvadurai and Glaser 2015, Sensors

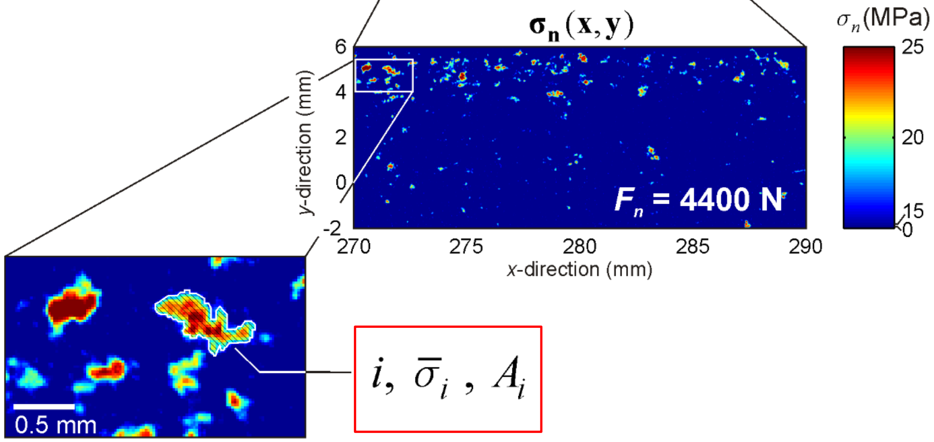
Asperity measurements



i = i[th] asperity

$\bar{s}_i$ = Mean normal stress (MPa)

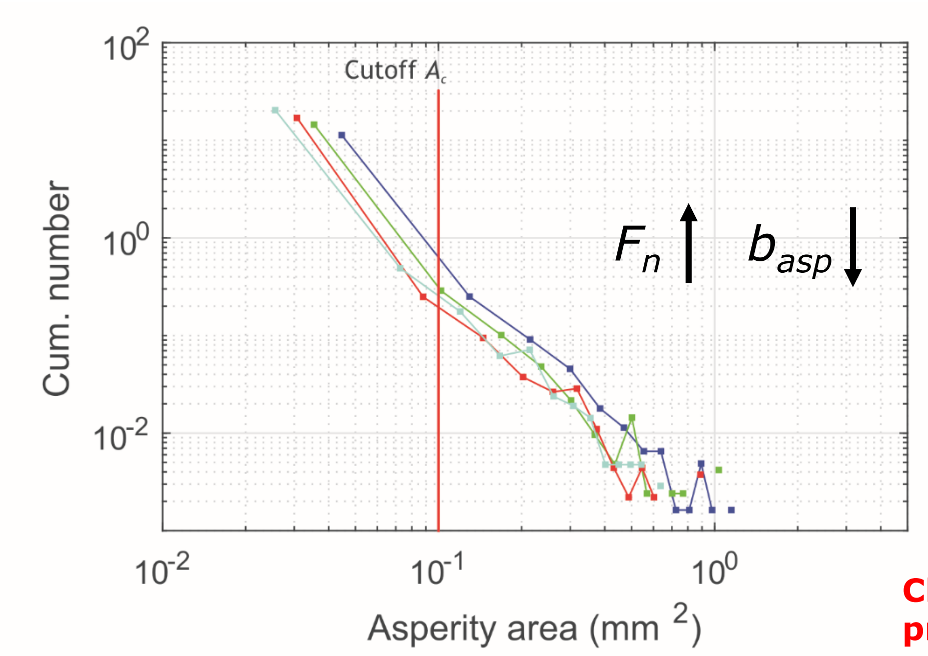
A_i = Area (mm^2)

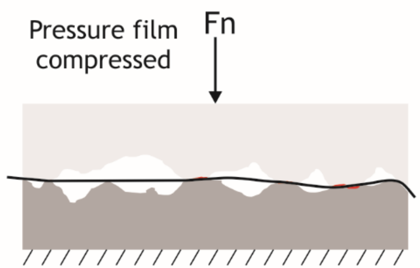


Frequency-Asperity size distribution (FASD):

- We use a "pseudo" *b*-value (b_{asp}) to describe asperity size distributions with changing normal loads in the seismogenic section of the fault

$$b_{asp} = \log_{10}(\exp) / \left(A_{mean} - \left(A_c - \frac{A_{bin}}{2} \right) \right)$$





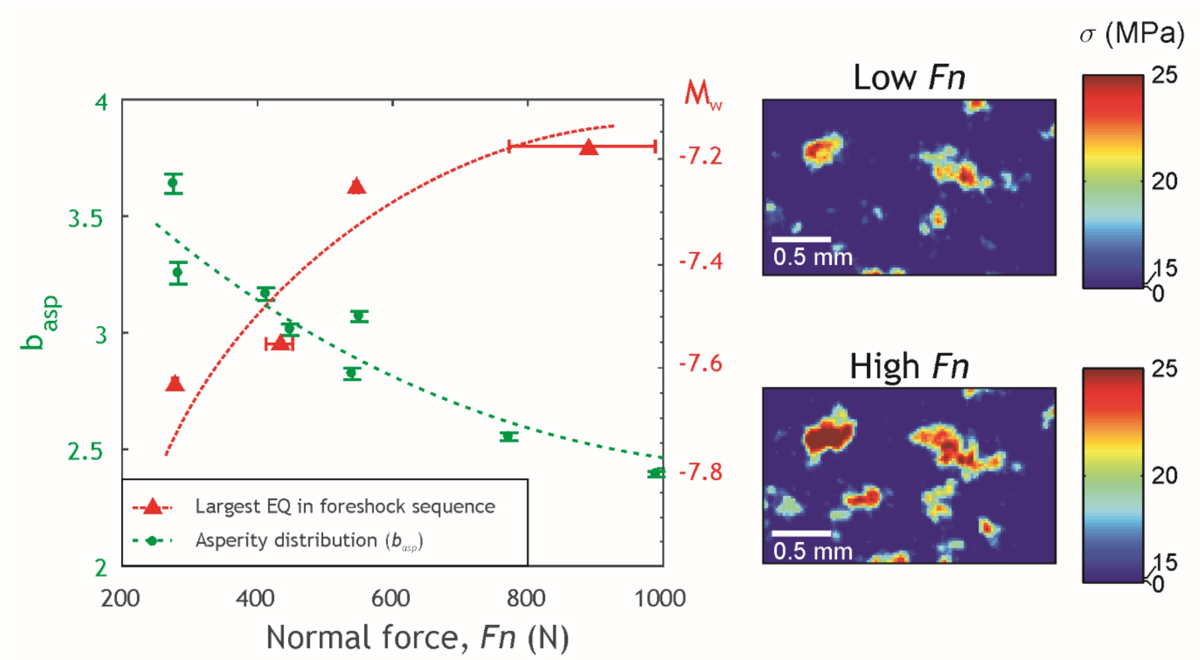
b_{asp} =2.3939,	N =226,	Fn = 989.6 N
b_{asp} =2.8237,	N =134,	Fn = 540.1 N
b_{asp} =3.0127,	N =115,	Fn = 448.7 N
b_{asp} =3.6386,	N =78,	Fn = 276.1 N

Changes in b_{asp} should be related to **contact processes** and **surface roughness**

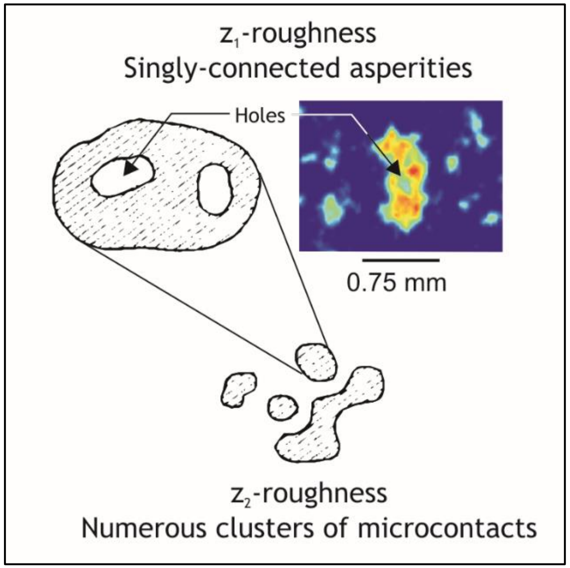
Equation from Wiemer and Wyss (2002, Adv. Geophys)

Asperity distributions versus normal load

- ***b_{asp}* decreased** as ***F_n*** was **increased**
- Lower b_{asp} values indicate that the **ratio of large to small asperities increased**
- The **potential for a large localized event** may be linked to lower b_{asp} values

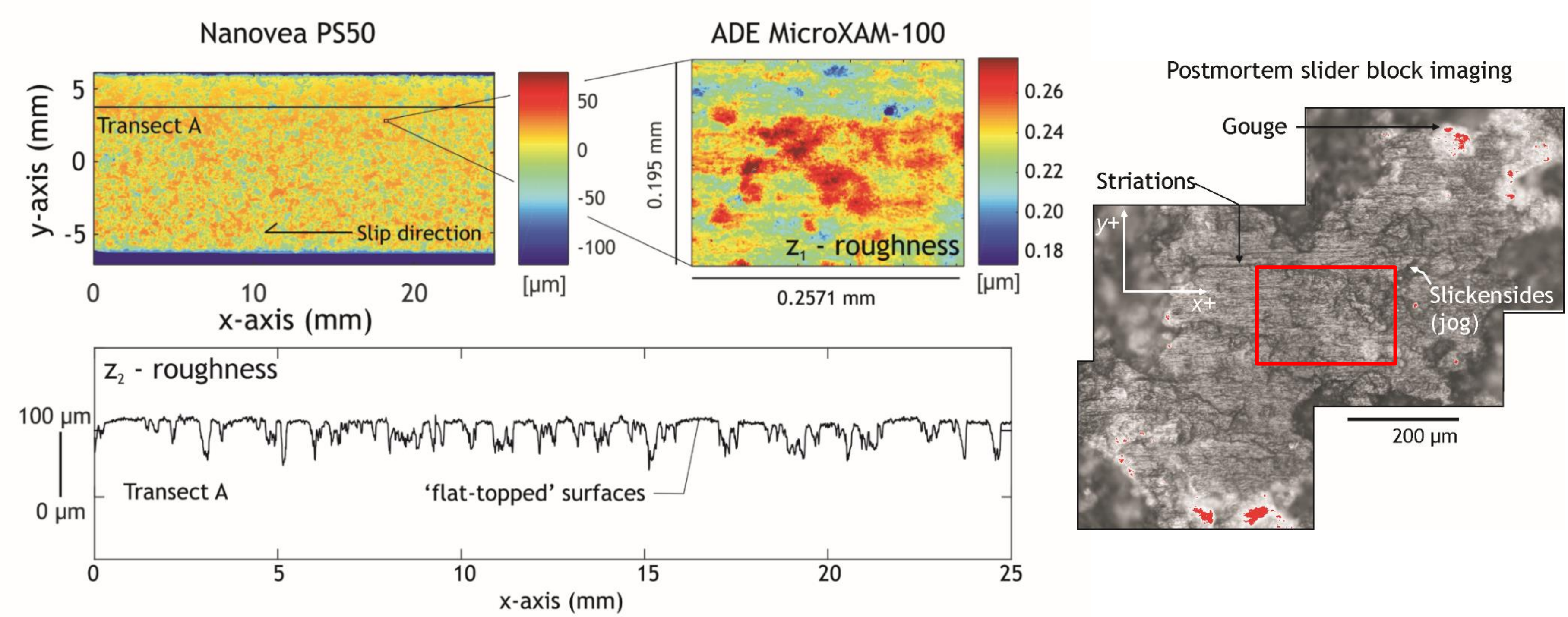


Nayak's (1973) dominant wavelengths asperity model



Asperity distributions related to mature roughness

- **Nayak's contact model** may explain how asperities formed in our tests based on **postmortem roughness** measurements of the slider block
- Dominant **longer** and **shorter** length scales in roughness



Roughness Selvadurai and Glaser (2017, GJI)

Summary of findings

We performed a frictional study on a mature **PMMA-PMMA frictional fault** where the **normal load was varied** systematically

Local precursor seismicity (M_w ~ -7.1 to -7.9) was observed during the passage of a **slow nucleation front**

During foreshock sequences, **larger precursory seismicity** was present in sequences with **additional normal force**

This may **be linked to the manner in which asperities form** (measured using the pressure sensitive film)

Asperities formed due to **two dominant roughnesses** → could be linked to length scale dependent adhesive wear mechanisms*

Adhesive wear mechanism Aghababaei et al. (2016, Nature Comm.)

Thank you! Questions? *paul.selvadurai@sed.ethz.ch*

- ***Acknowledgements***:
  - National Science Foundation Grant # 1131582 (S. Glaser)
  - Jane Lewis Fellowship (P. Selvadurai)
  - NSERC, PGS-Doctoral Fellowship (P. Selvadurai)
  - Department of Defense Fellowship (J. Parker)

- ***References***: https://polybox.ethz.ch/index.php/s/AogZK8R8fgoePPE