Transition from stick-slip to stable sliding: the crucial effect of asperities

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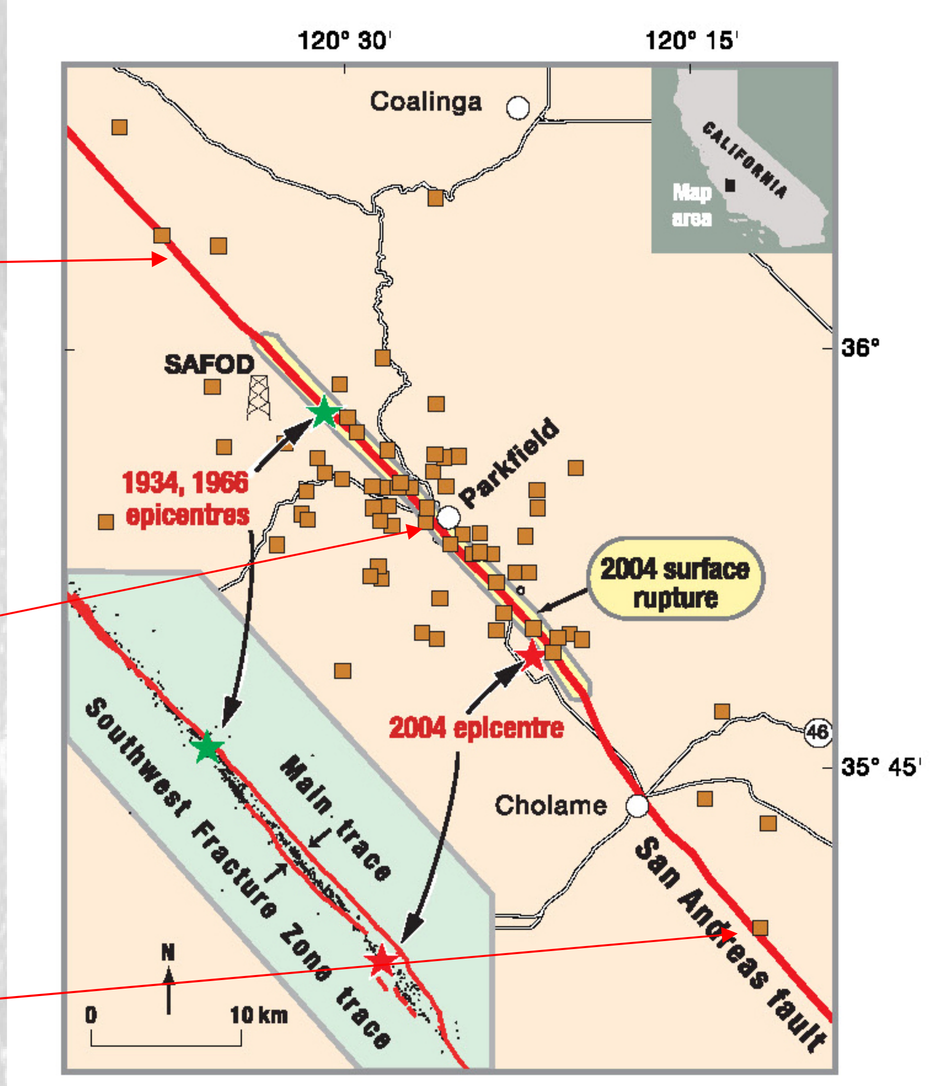
Faults exhibit seismic and aseismic displacements

San Andreas Fault

creep

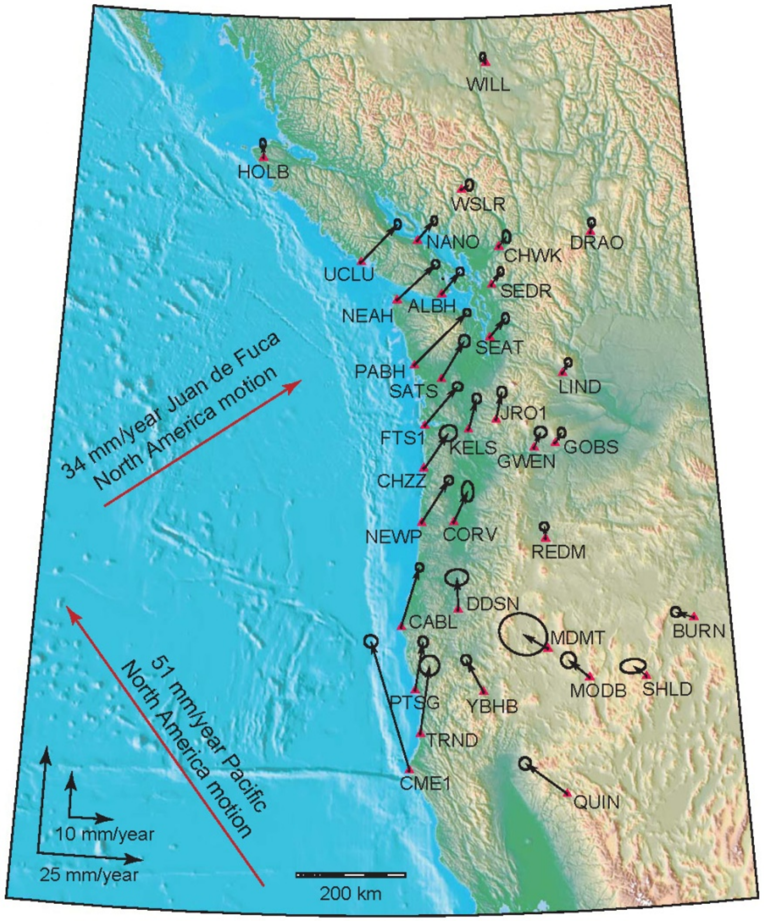
small quasi-periodic earthquakes

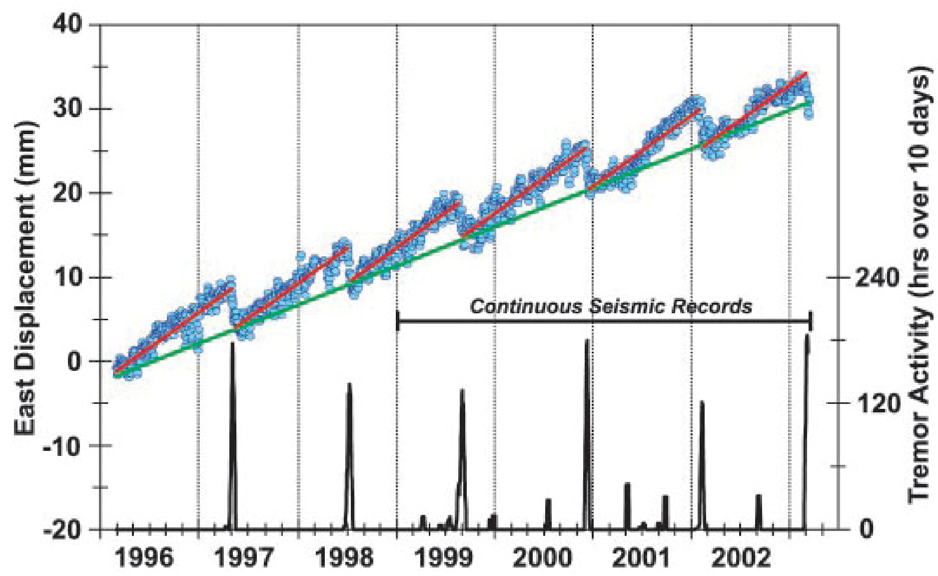
large earthquakes (Fort Tejon, 1857)



Bakun *et al.*, 2005

Periodic slow earthquakes in the Cascadia region (British Columbia)

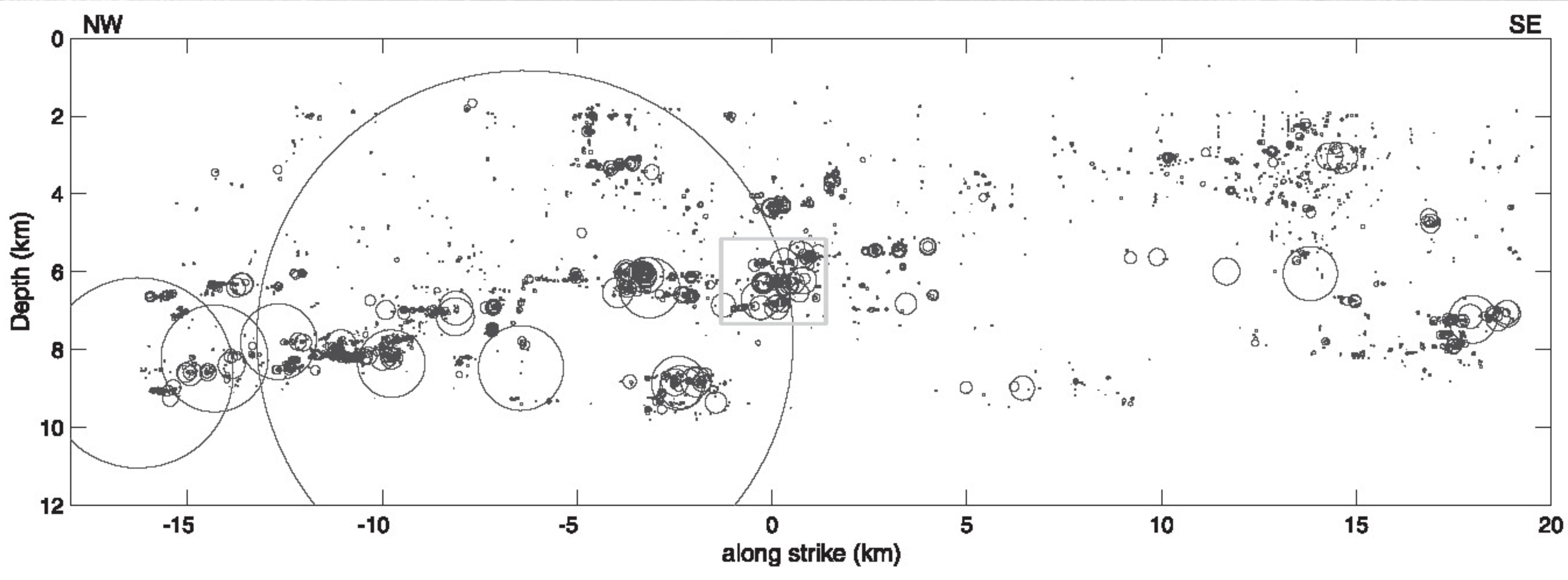




Rogers *et al.*, 2003

Relocated earthquakes on the Calaveras Fault (California) during the period 1984-2002

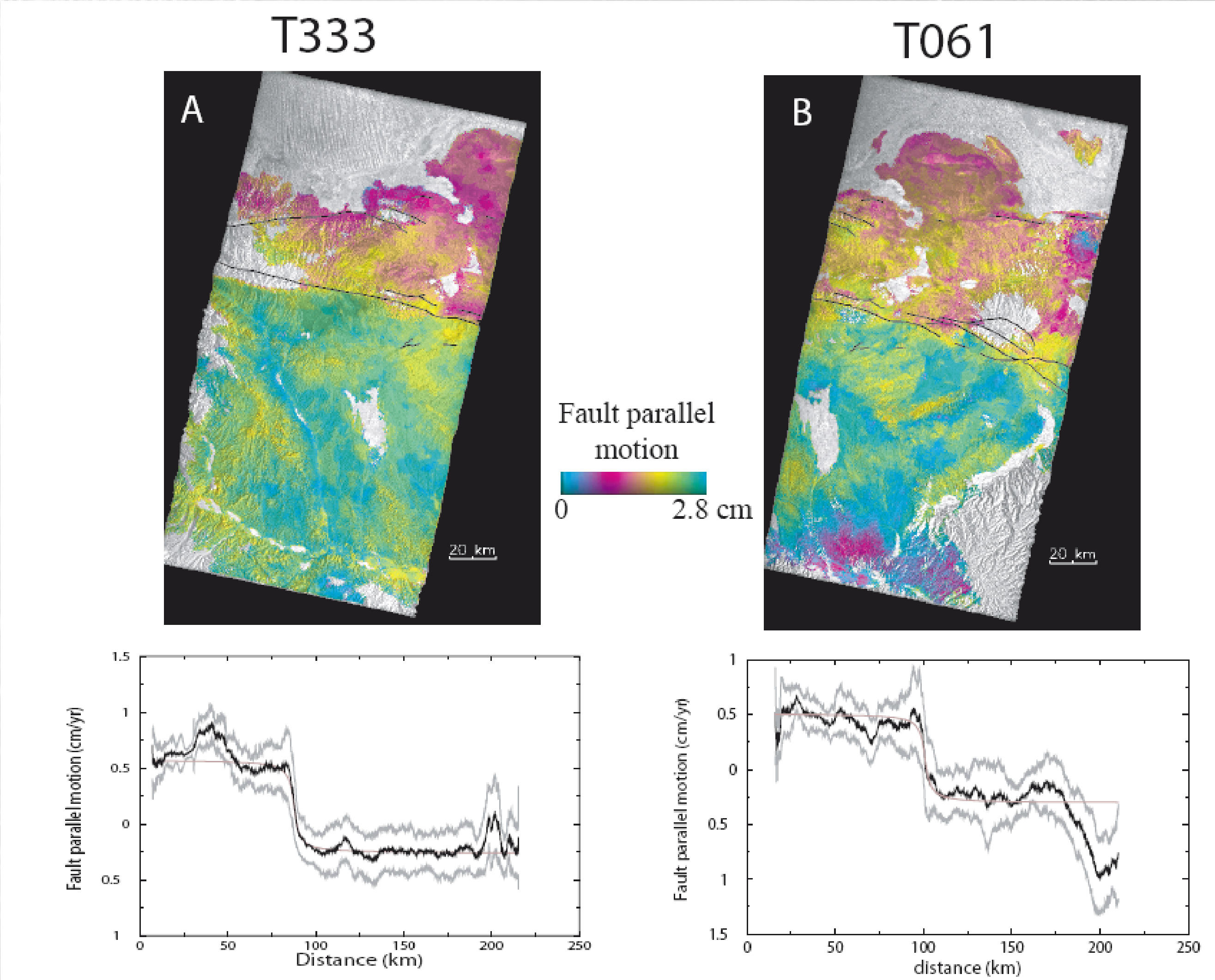
(92% of the total seismicity represented here)



Evidence of: repeating earthquakes, linear clusters, aseismic patches (creep or locked ?)

Schaff *et al.*, 2002

Creep of the Haiyuan fault

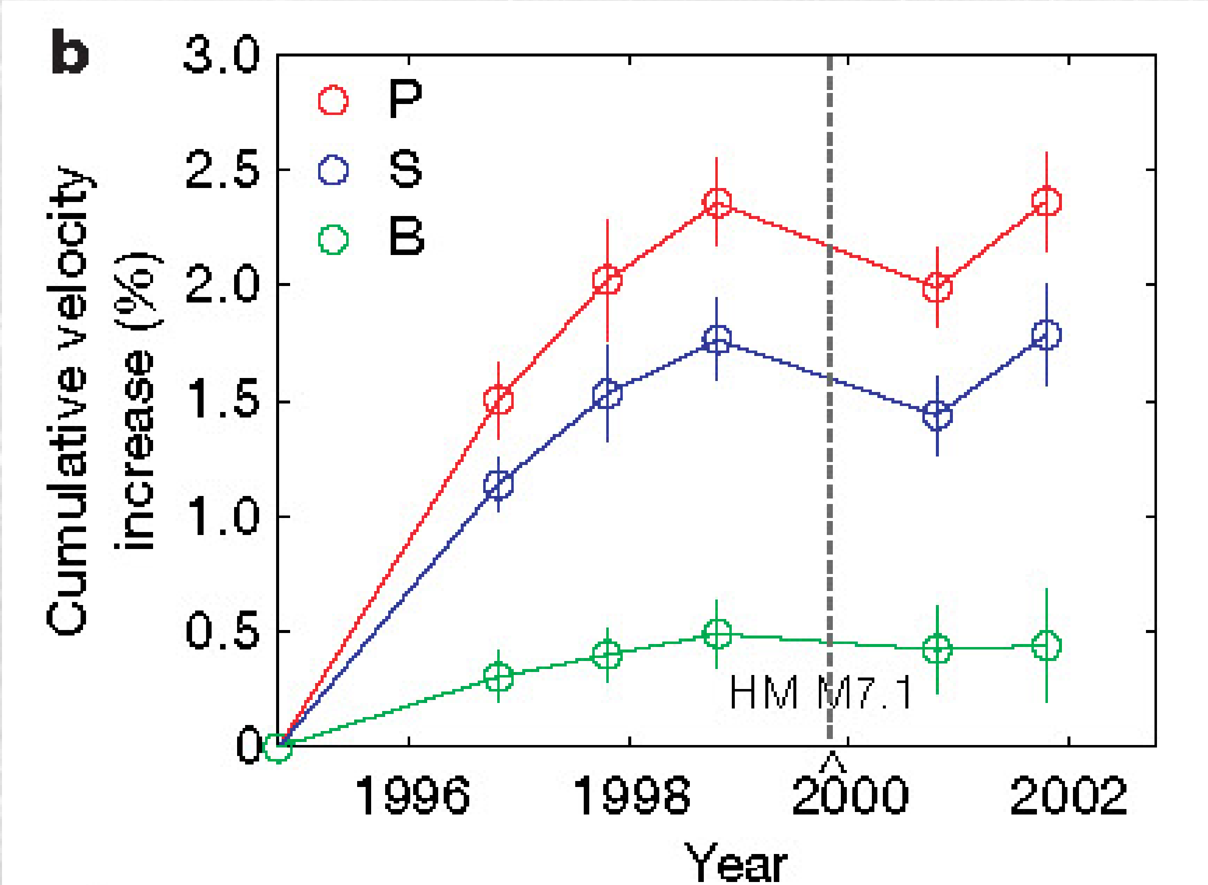


Haiyuan fault, East Tibet. This fault creeps and corresponds to a seismic gap.

It shows a slip rate of 8.5 ± 3 3 mm/yr, consistent with long-term slip rate, as measured by ERS InSAR interferograms in the 1993-1998 period.

Cavalié, Lasserre *et al.*
AGU 2006

Fault healing and strength recovery in the years after the 1992 Landers earthquake



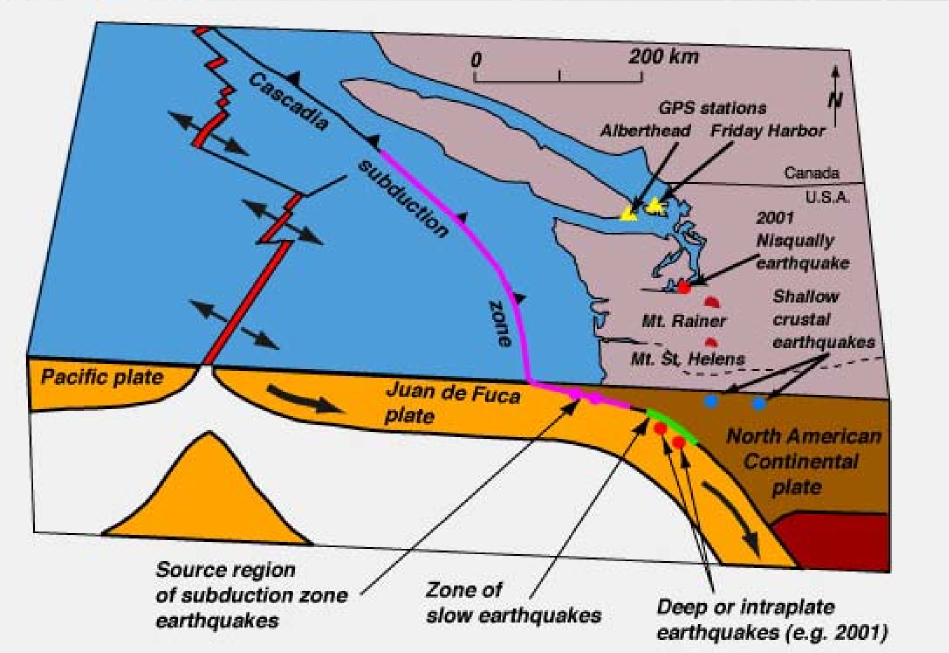
P-waves

S-waves

1 km off-fault

Vidale and Li, 2003

In subduction zones: transition from earthquakes to aseismic slip

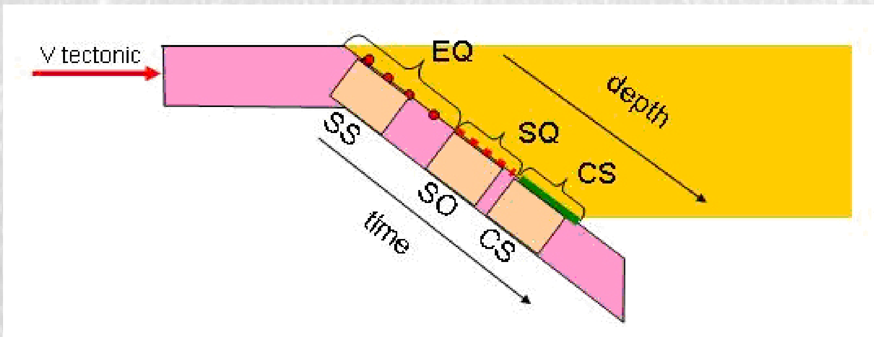


from M. Miller

Various explanations

- fluids
- phase transitions
- P&T increase
- variation of (a-b)

EQ: earthquakes
SQ: slow quakes
CS: continuous sliding



SS: stick-slip
SO: slip oscillations
CS: continuous sliding

Based on these observations …

- A fault can behave both in a seismic and aseismic manner

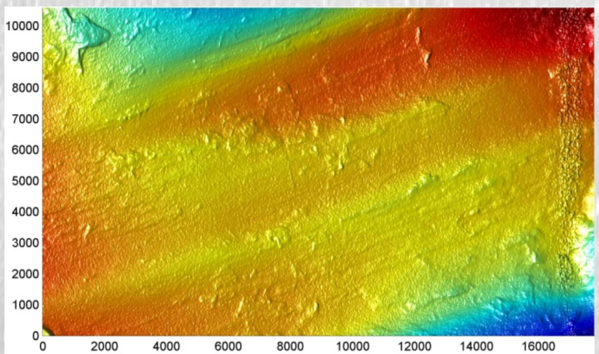
- Faults can creep. The fault strength drops down during the earthquake and increases through time during the interseismic period

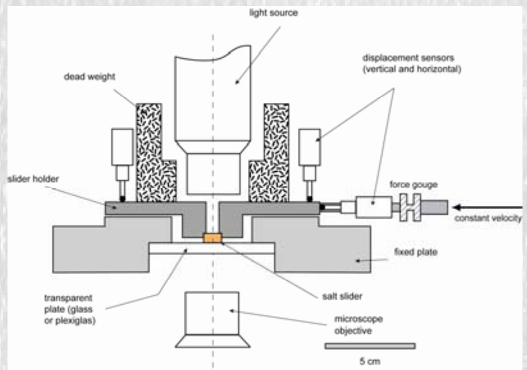
- Fault surface morphology should control frictional properties

We test the hypothesis that the **geometry of the fault surface** and its **effects on the frictional properties** are involved into the transition from seismic to aseismic slip

1) Measurement of the roughness of faults

2) Experiments on a salt slider, a surrogate for natural fault





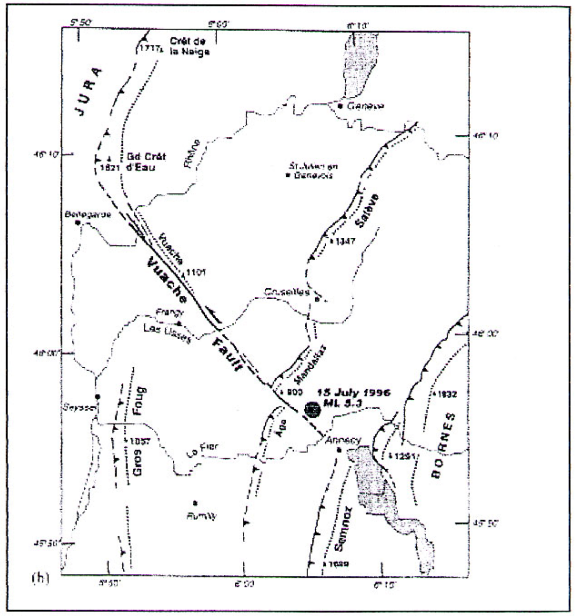
Outline

- Part 1. 3D scanner measurements of fault roughness
- Part 2. Experimental evidence of a transition from stick-slip to stable sliding
- Part 3. Growth of asperities at the contact

Part 1. Roughness of faults

Methodology: high-resolution measurements of the roughness on exhumed fault planes

The Vuache fault plane, Annecy, French Alps



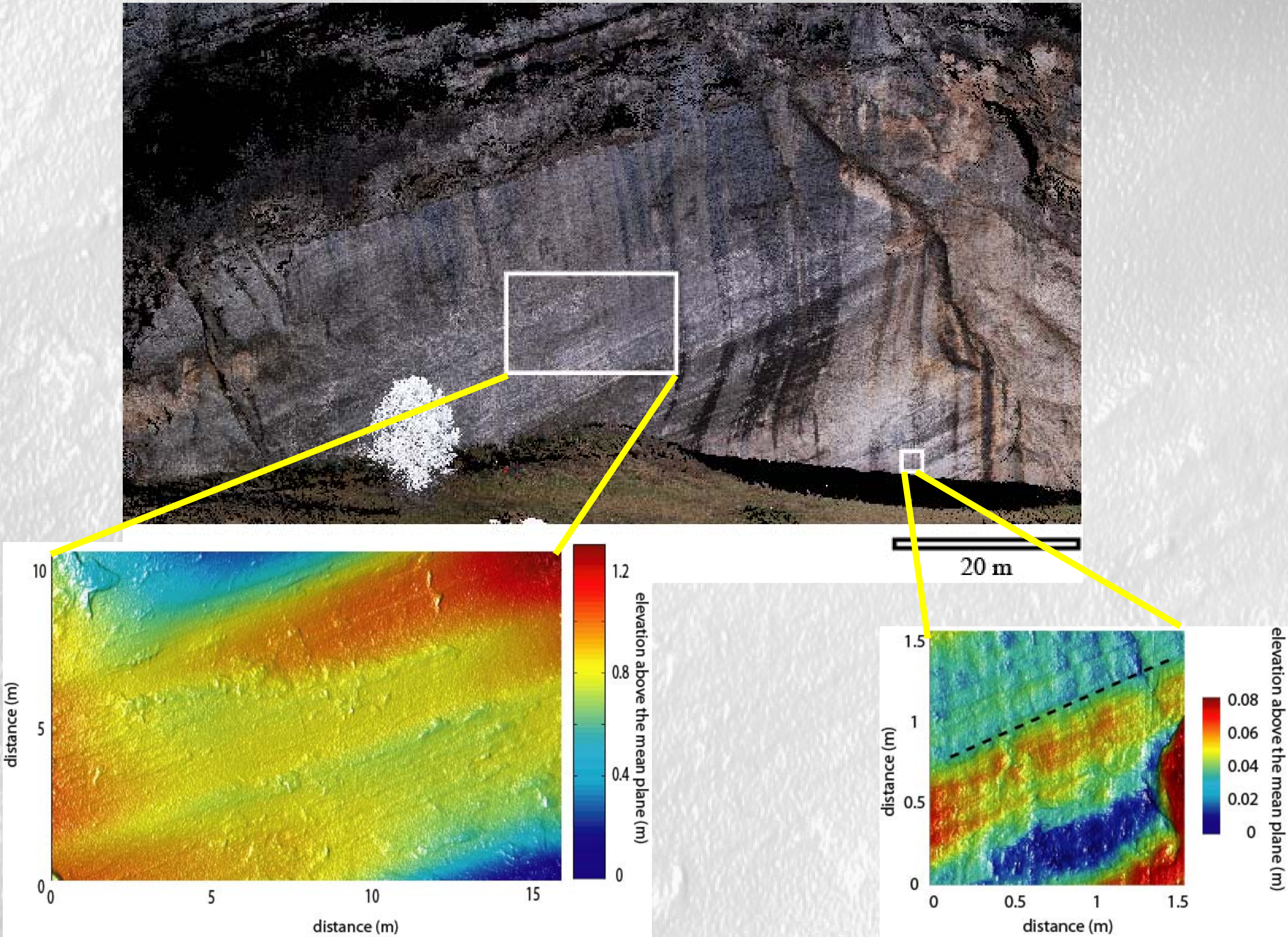
La faille du Vuache joint Semnoz et le Grand Crêt d'Eau. Thouvenot et al., 1998.

Left-lateral strike-slip fault

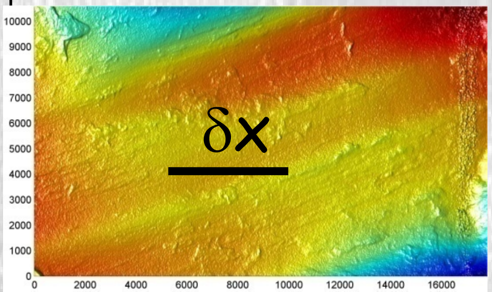
3 different LIght Detection And Ranging (LIDAR) devices

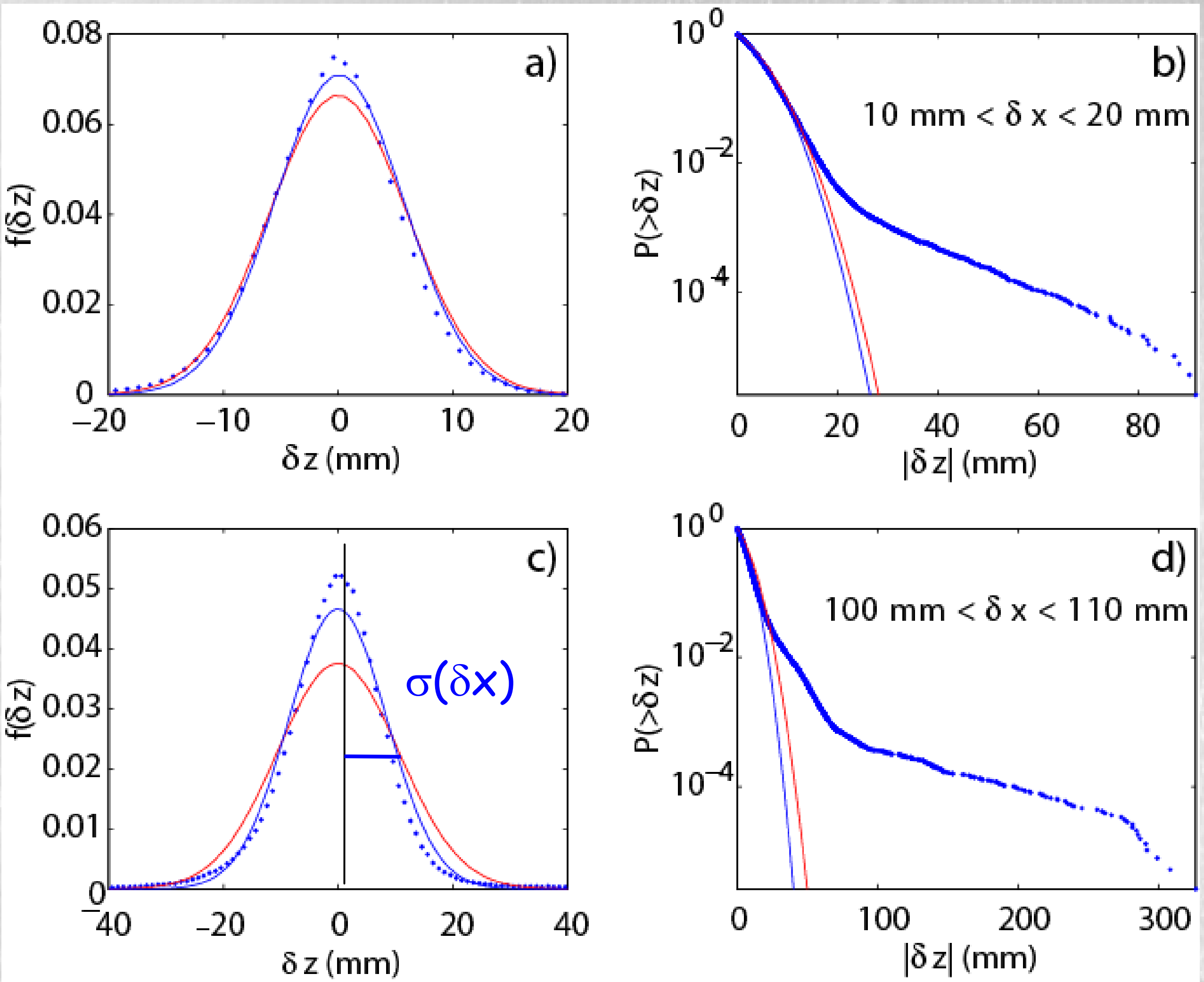
- **MENSI S10: res. ~ 0.9 mm, SA ~ 5 m²**
- **MENSI GS100: res. ~ 4.5 mm, SA ~ 250 m²**
- **RIEGL LMS Z420i: res. ~ 10.2 mm, SA ~ 250 m²**

LIDAR roughness measurements



Statistics of height-height differences

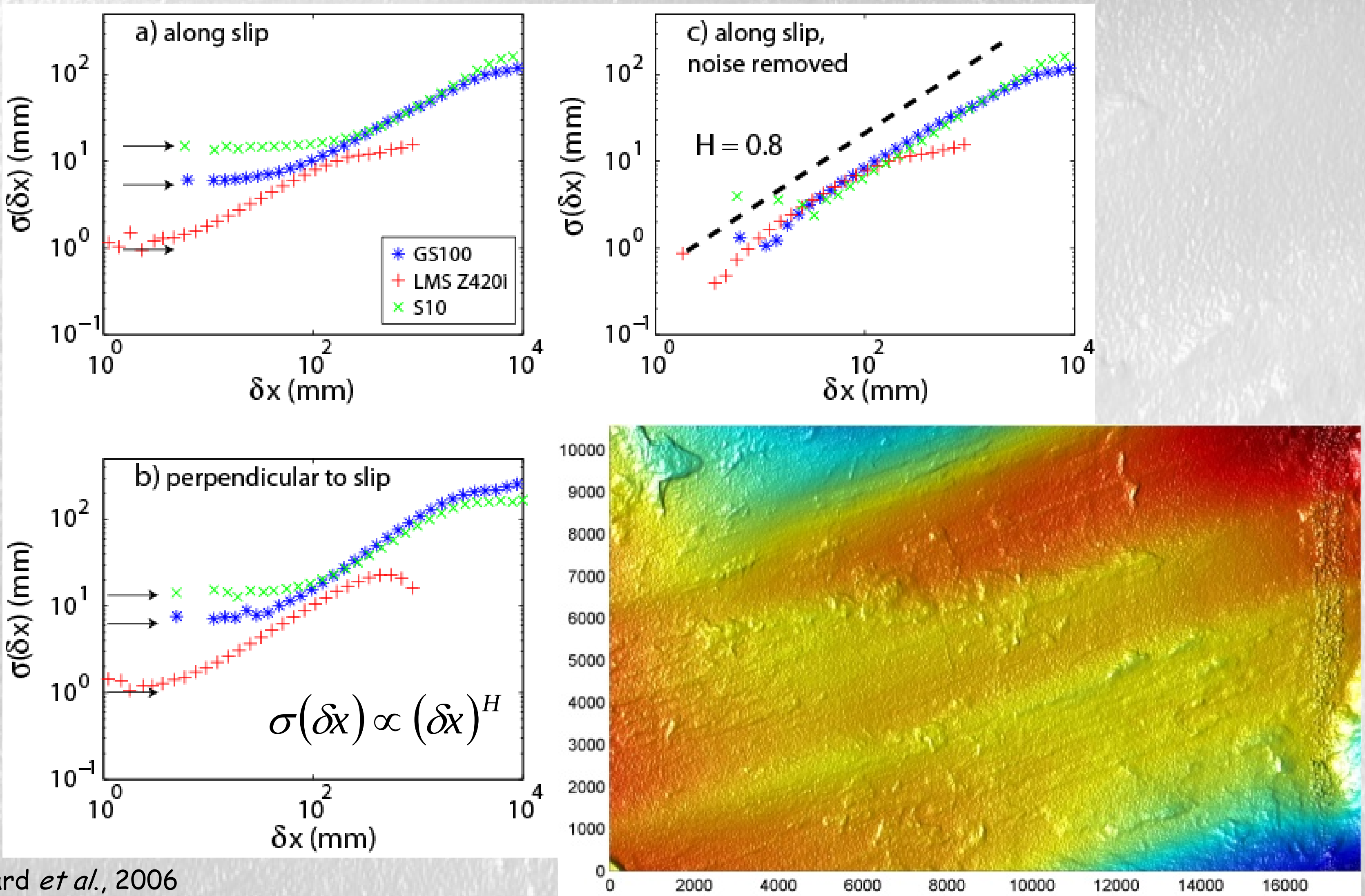




$$\sigma(\delta x) \propto (\delta x)^H$$

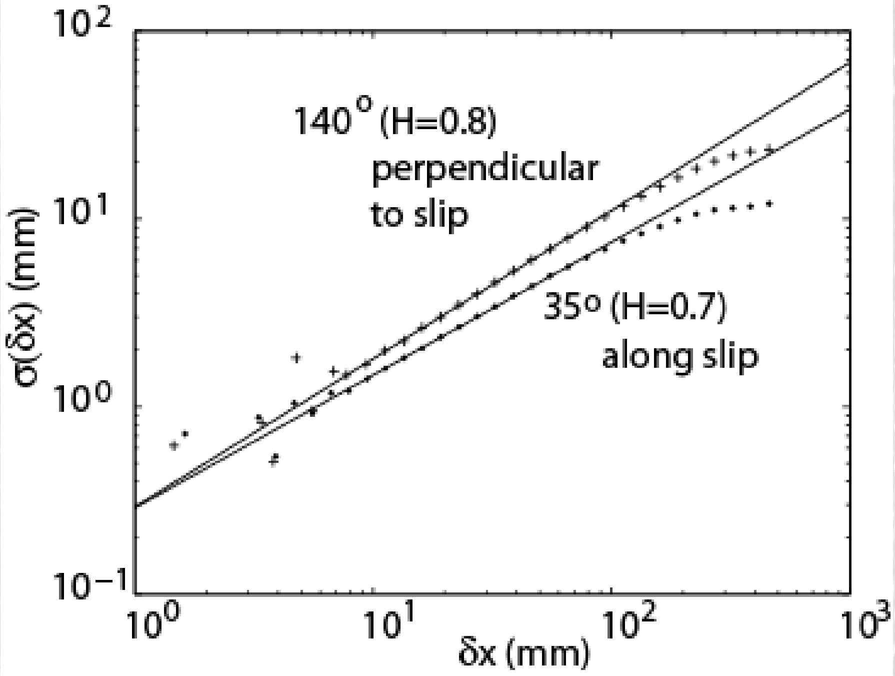
Deviation from Gaussian statistics

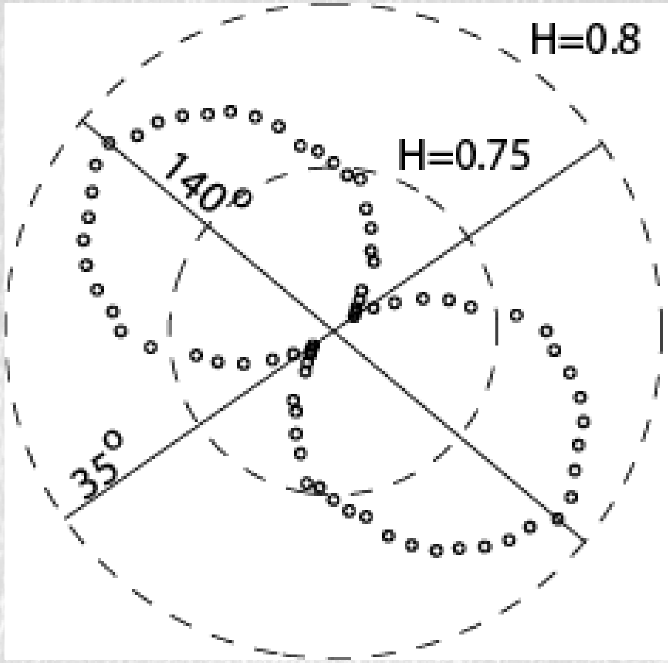
Scaling properties of 1D profiles



Renard *et al.*, 2006

1D scaling properties: effect of the orientation



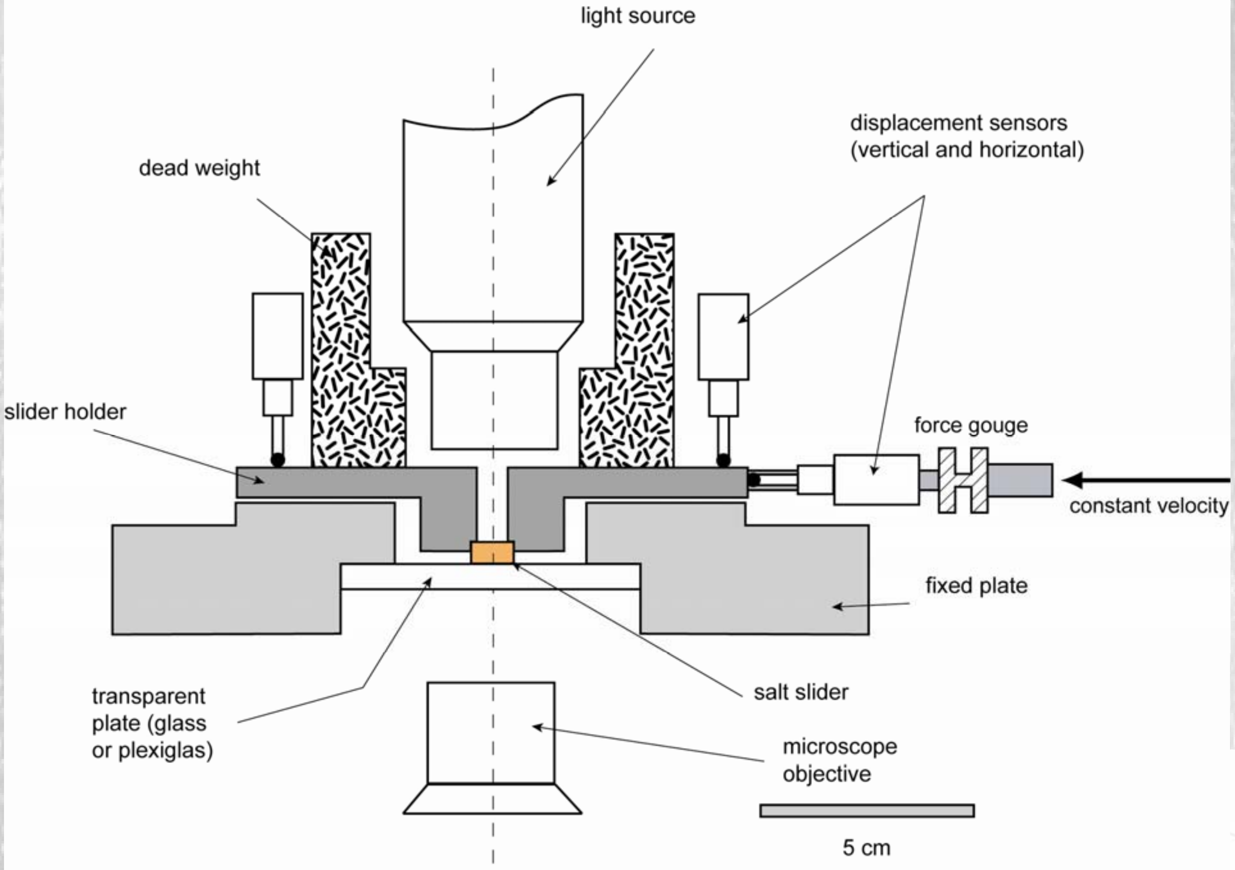


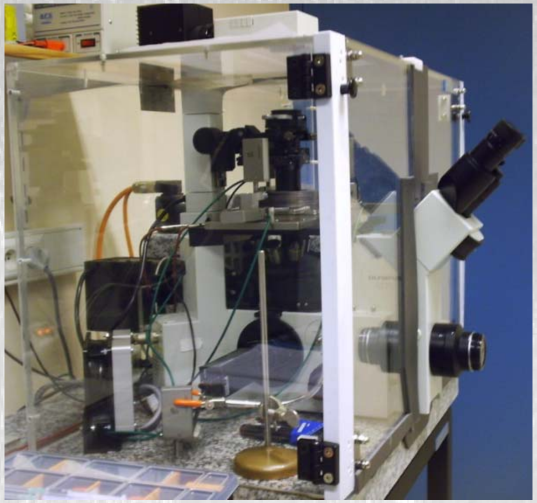
Quantify the direction of slip at all scales from 1D data

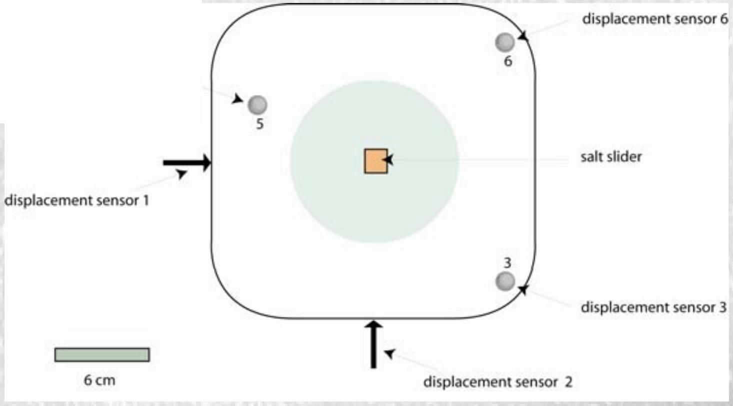
Summary, part 1

- Fault planes are rough at all scales
- This roughness can serve as "stress concentrators" and therefore control rupture initiation and propagation
- How does this roughness form/disappear and what are the implications for the seismic cycle ?

Part 2. Friction with deformation at the interface

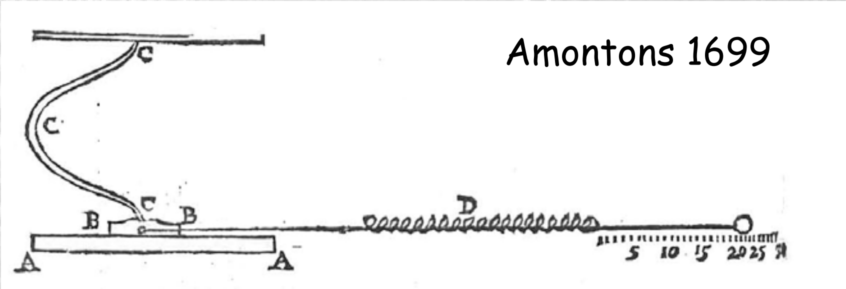






Why doing an analogue experiment ? 1) friction is dimensionless, 2) see-through, 3) « fast » chemical reactions

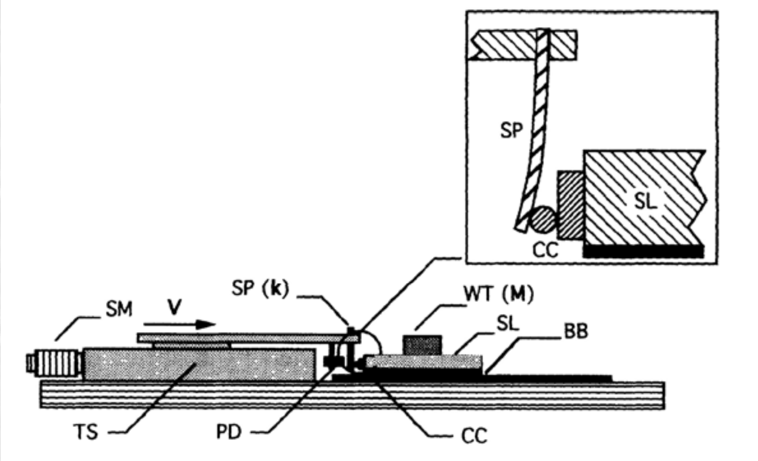
Stick-slip behavior of a block slider: an old story



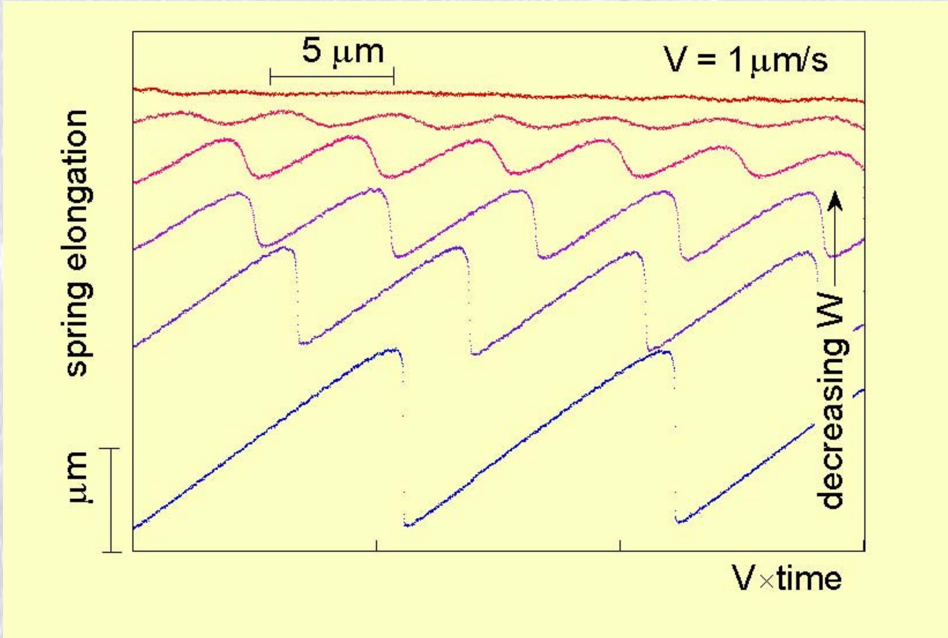
Amontons 1699

Friction = shear load / normal load

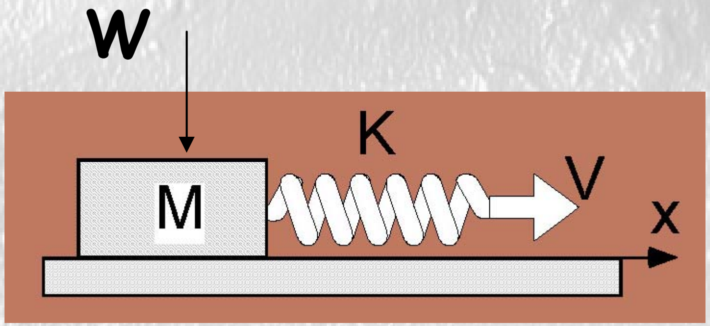
Friction is a dimensionless parameter



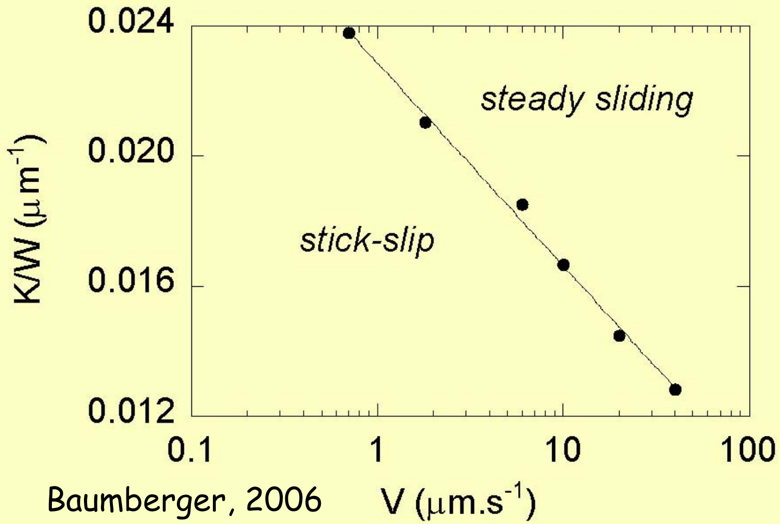
Heslot et al. 1994



Stick-slip to stable-sliding transition is controlled by a single parameter



Baumberger, 2006

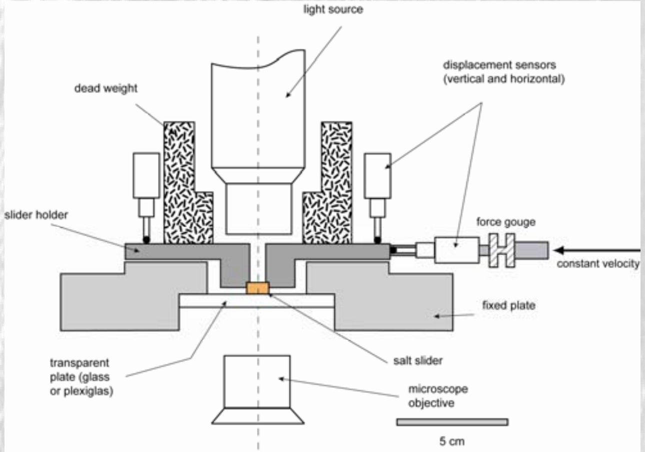


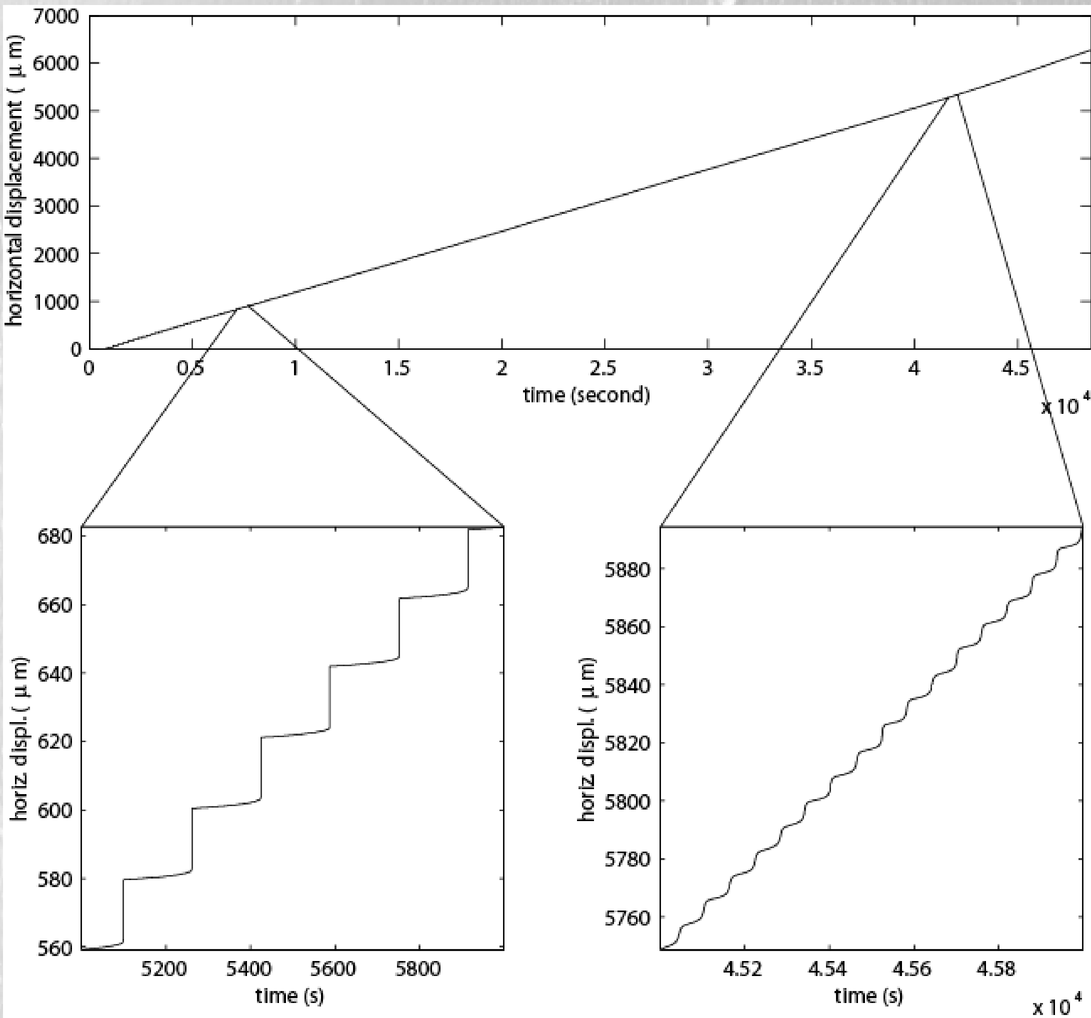
Baumberger, 2006

To ensure stick-slip oscillations, K must obey the following relation:

$$K < K_c = W^*(b-a)/d_c$$

- a and b: material dependent frictional
- W: normal load exerted on the slider, including its own mass
- d_c length scale typical of the interface, *e. g.* the mean size of asperities.

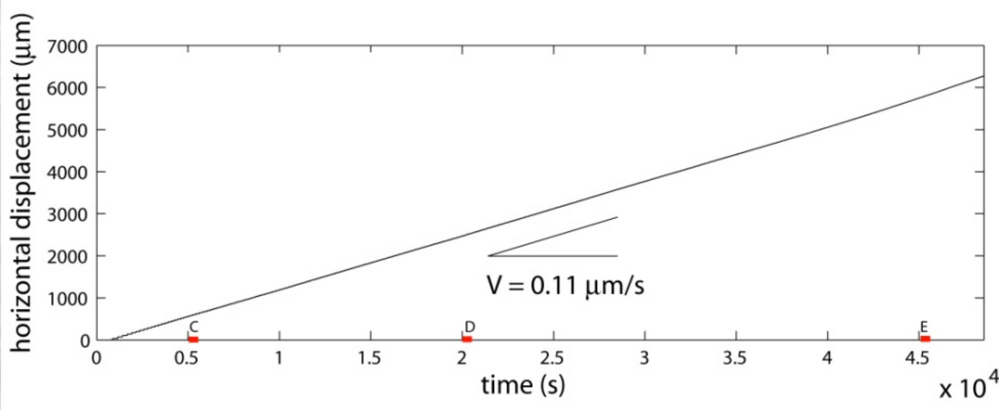


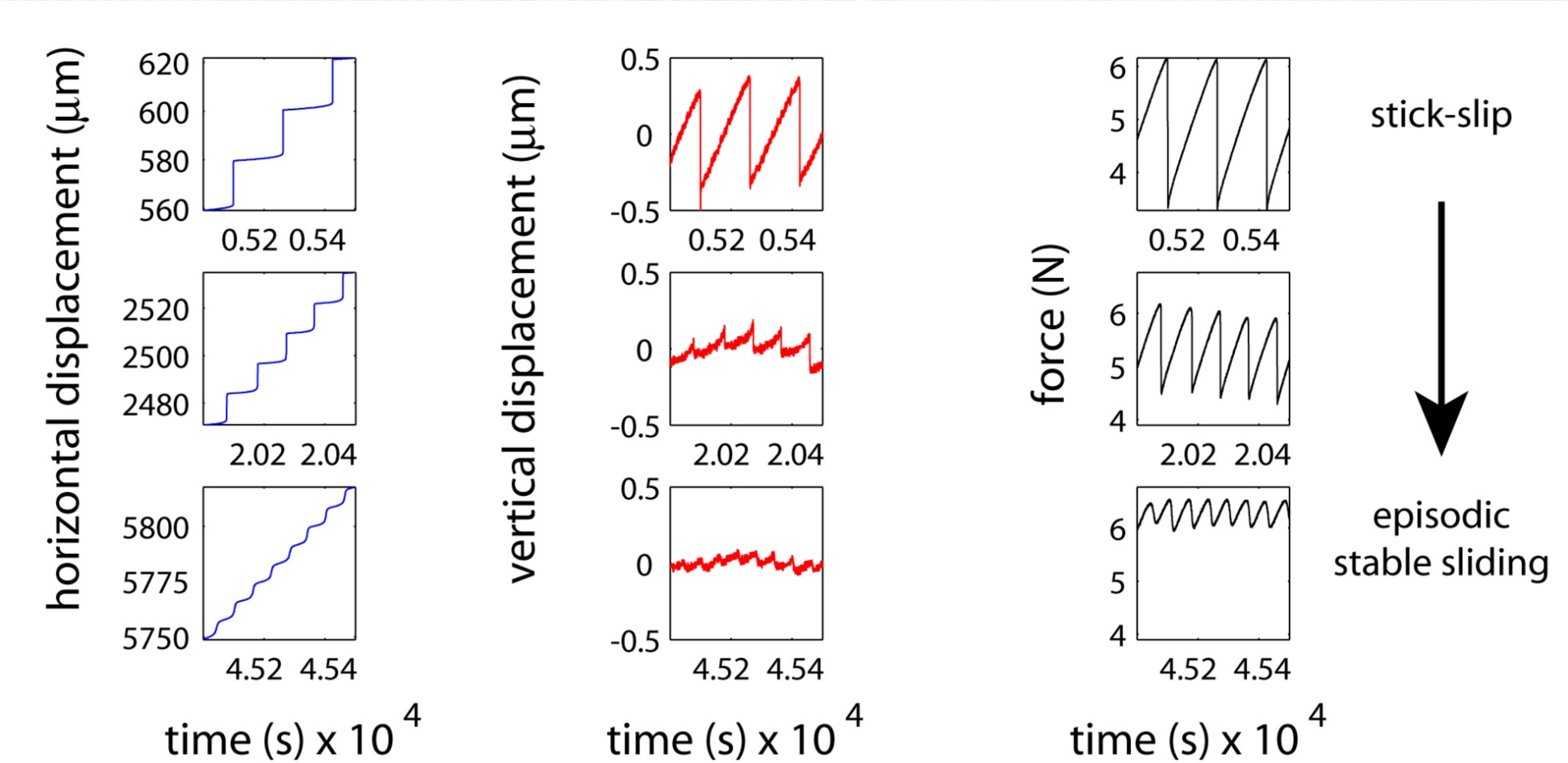


Change in sliding behavior: from stick-slip regime to episodic stable sliding regime

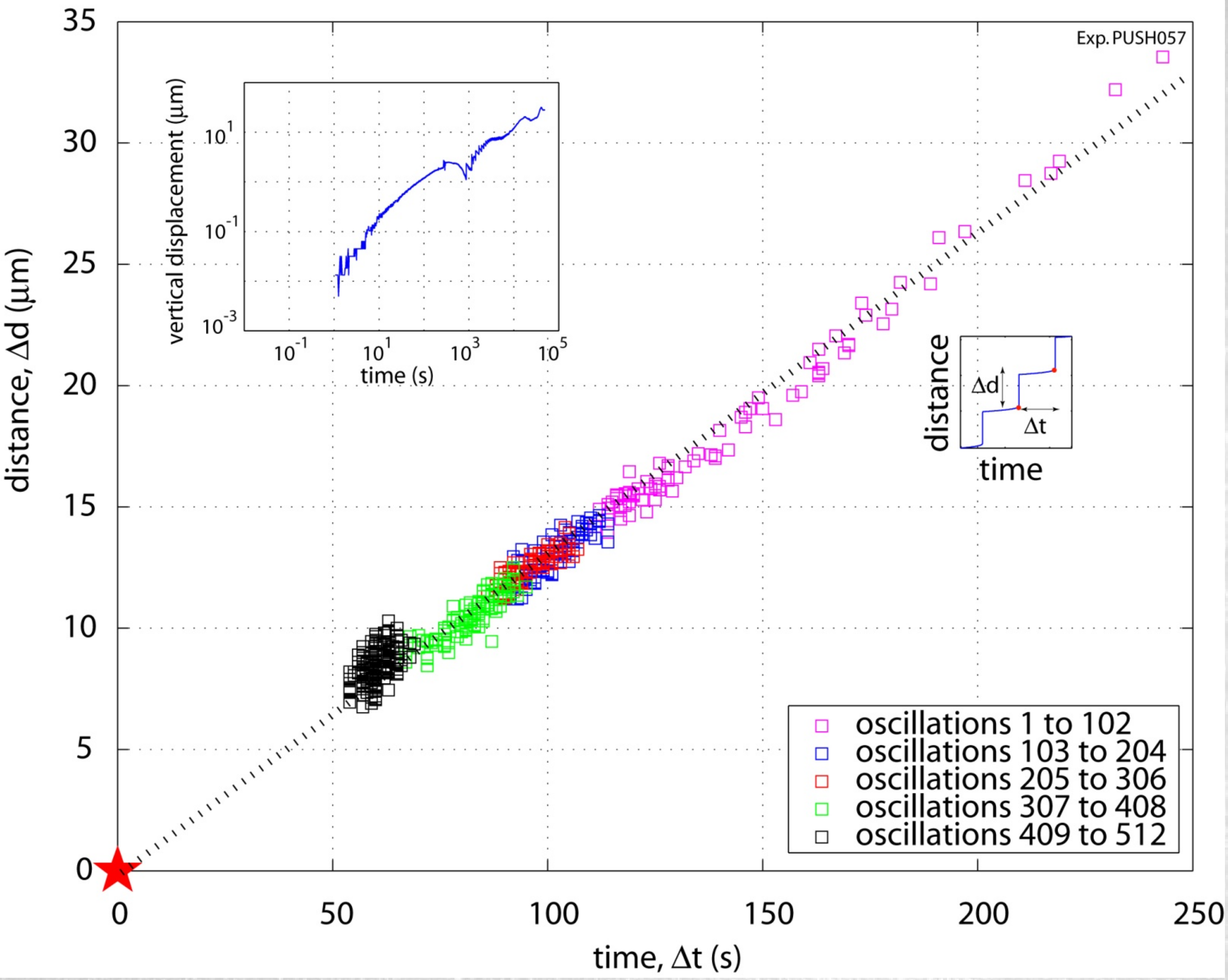
Voisin *et al.*, 2007

Change in frictional behavior: from stick-slip to stable sliding

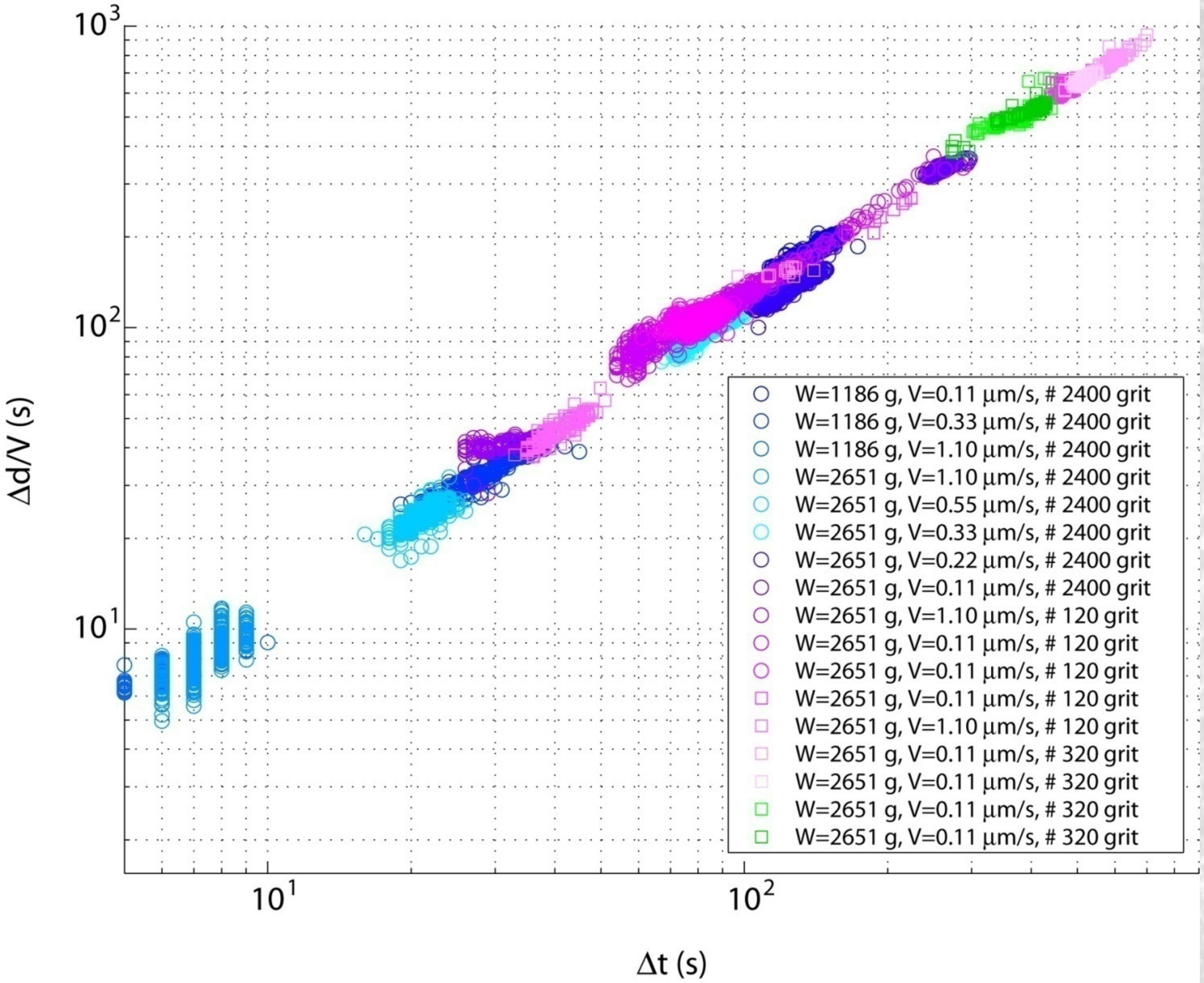


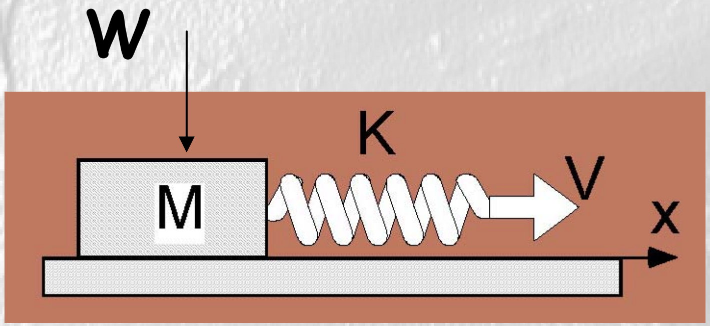


Evolution of the stick-slip amplitude and period with cumulated slip

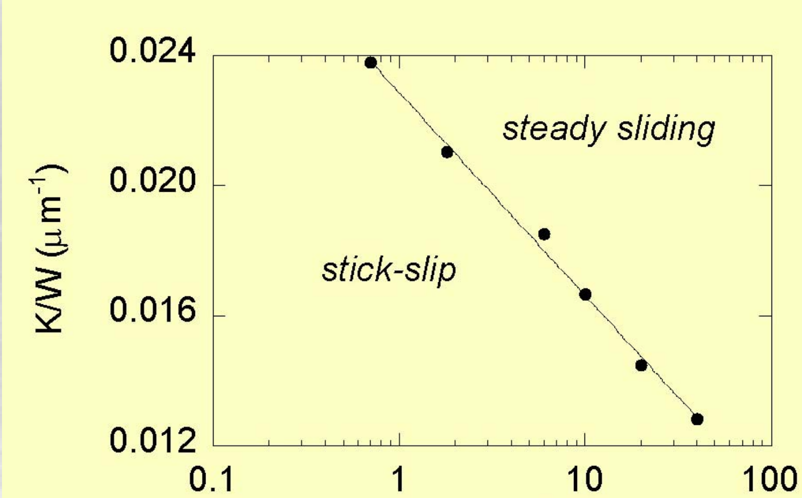


Similar behaviour for various velocities, initial roughness, normal loads, glass or Plexiglas plate





Baumberger, 2006



Baumberger, 2006

To ensure stick-slip oscillations, K must obey the following relation:

$$K < K_c = W*(b-a)/d_c$$

- a and b: frictional parameters typical of the materials in contact
- W: normal load exerted on the slider, including its own mass
- d_c length scale typical of the interface, e. g. the mean size of asperities.

In the experiment: W, K are constants

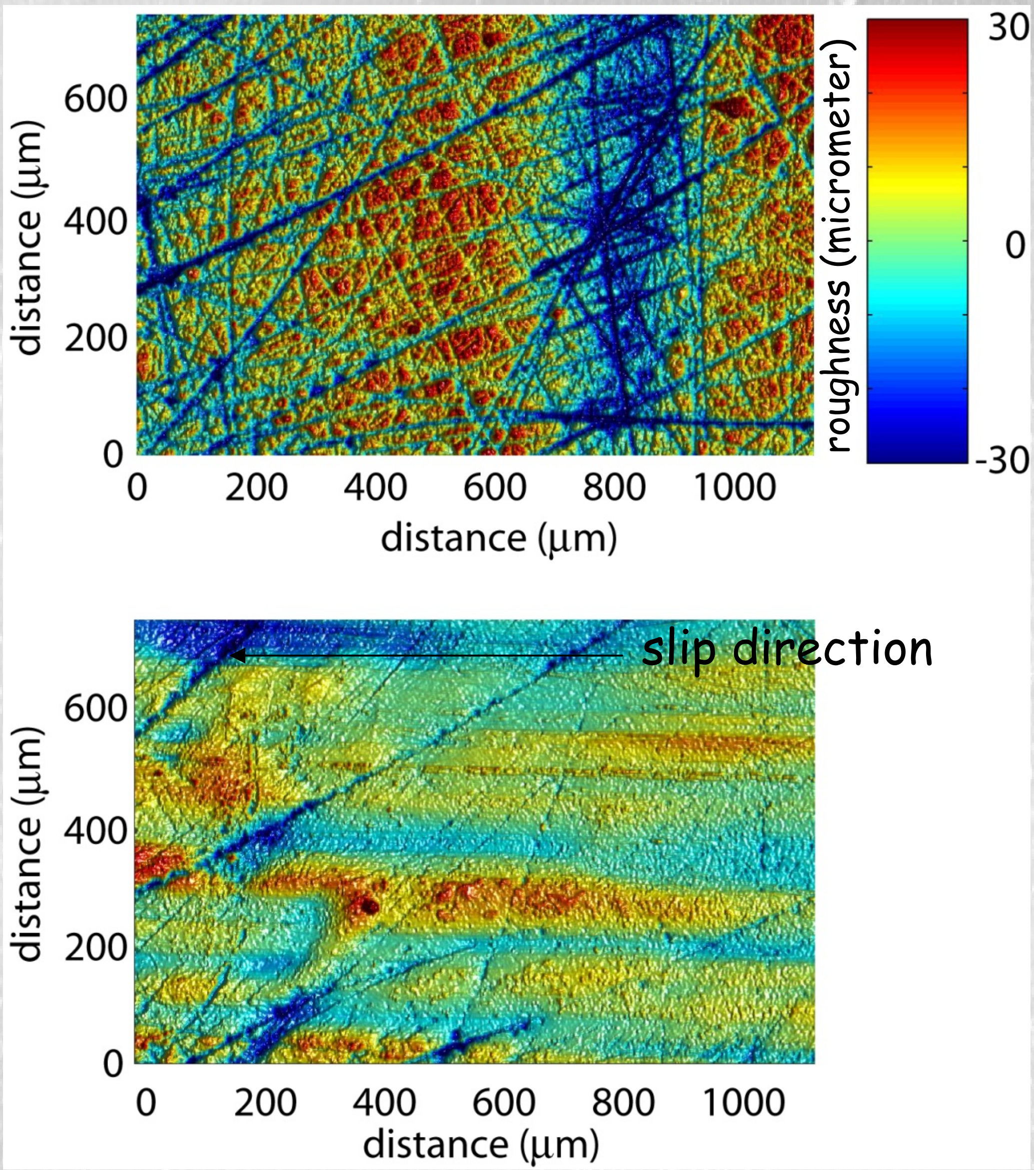
Decrease in (b-a)

Increase in d_c

Ageing of the interface: evolution of the topography

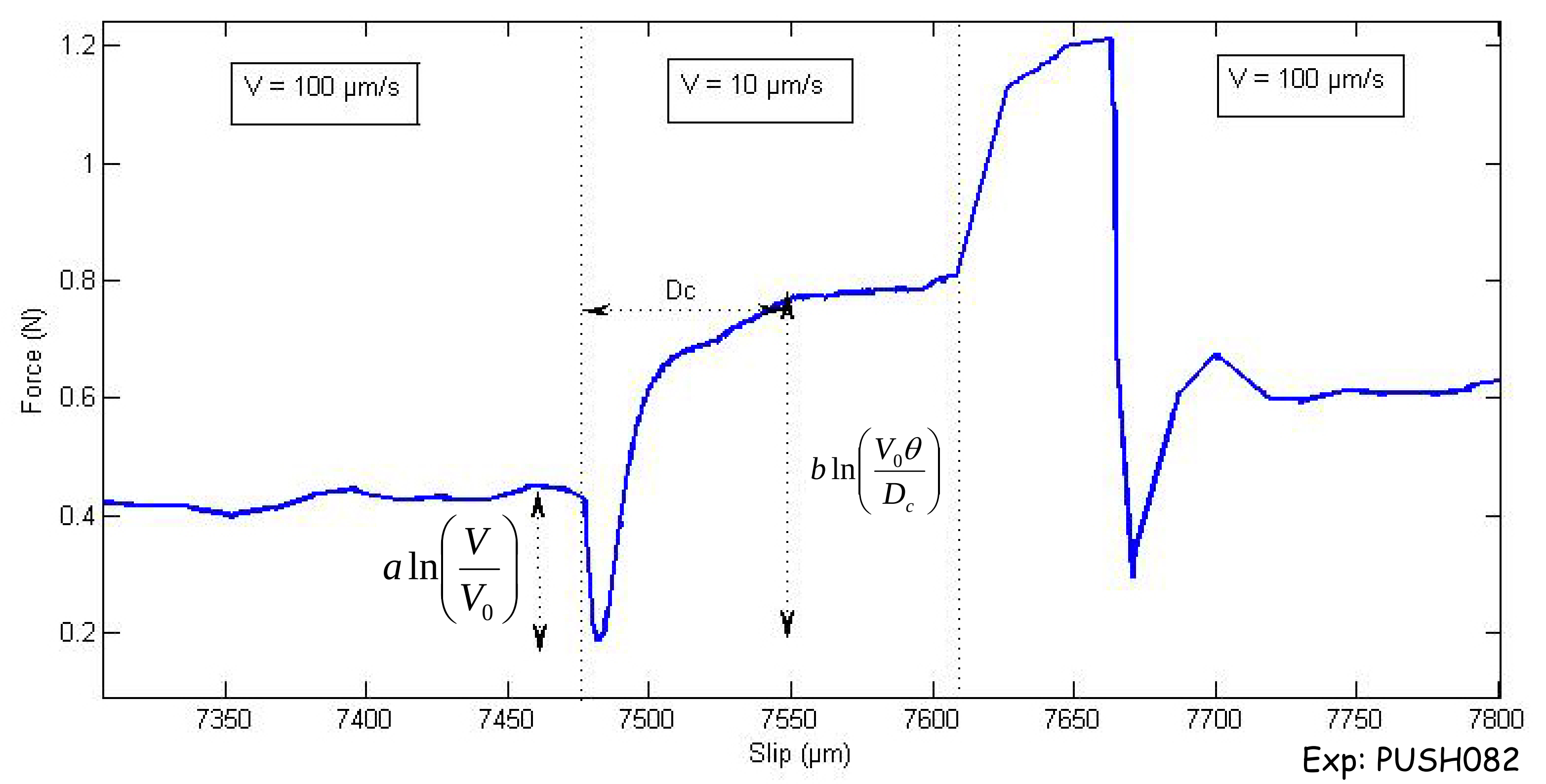
before

after



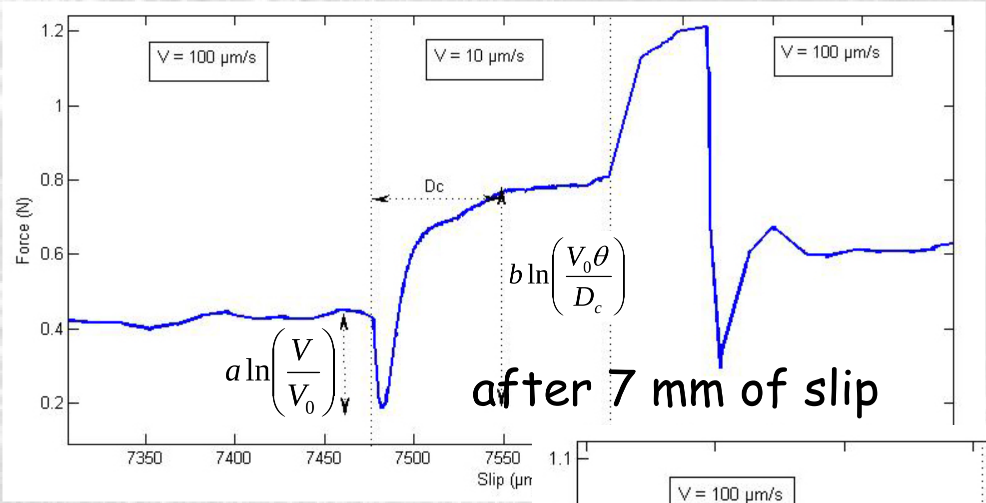
D_o, the characteristic size of the roughness increases with time

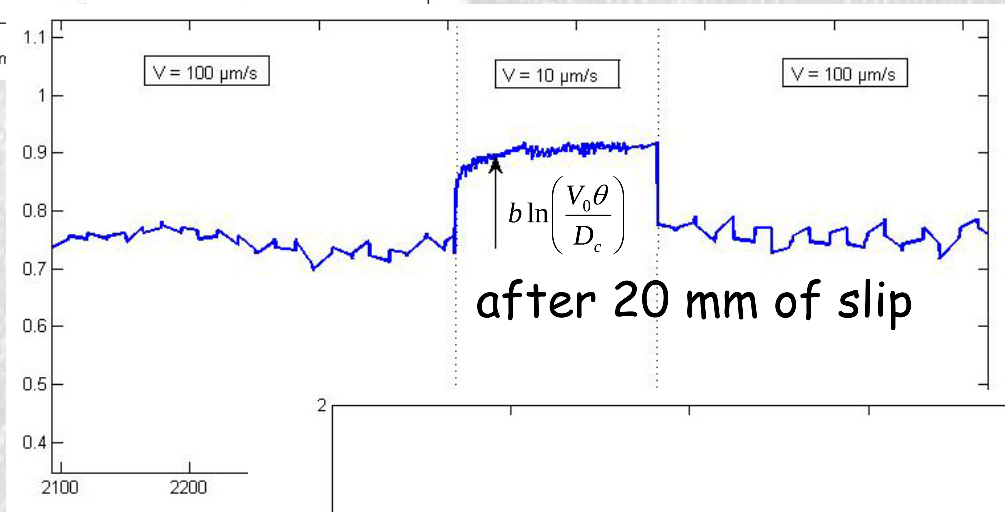
Experimental evidence for a continuous change of a & b using velocity jumps

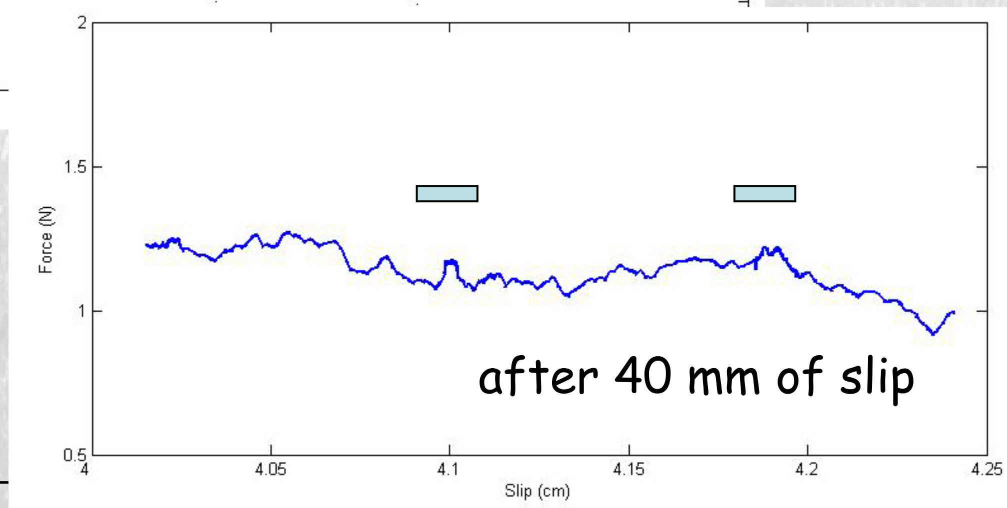


Velocity jumps:
a: direct effect
b: change in dynamic friction
d_c: critical distance

$$\mu_{ss} = \mu_0 + a \ln\left(\frac{V}{V_0}\right) + b \ln\left(\frac{V_0\theta}{d_c}\right)$$







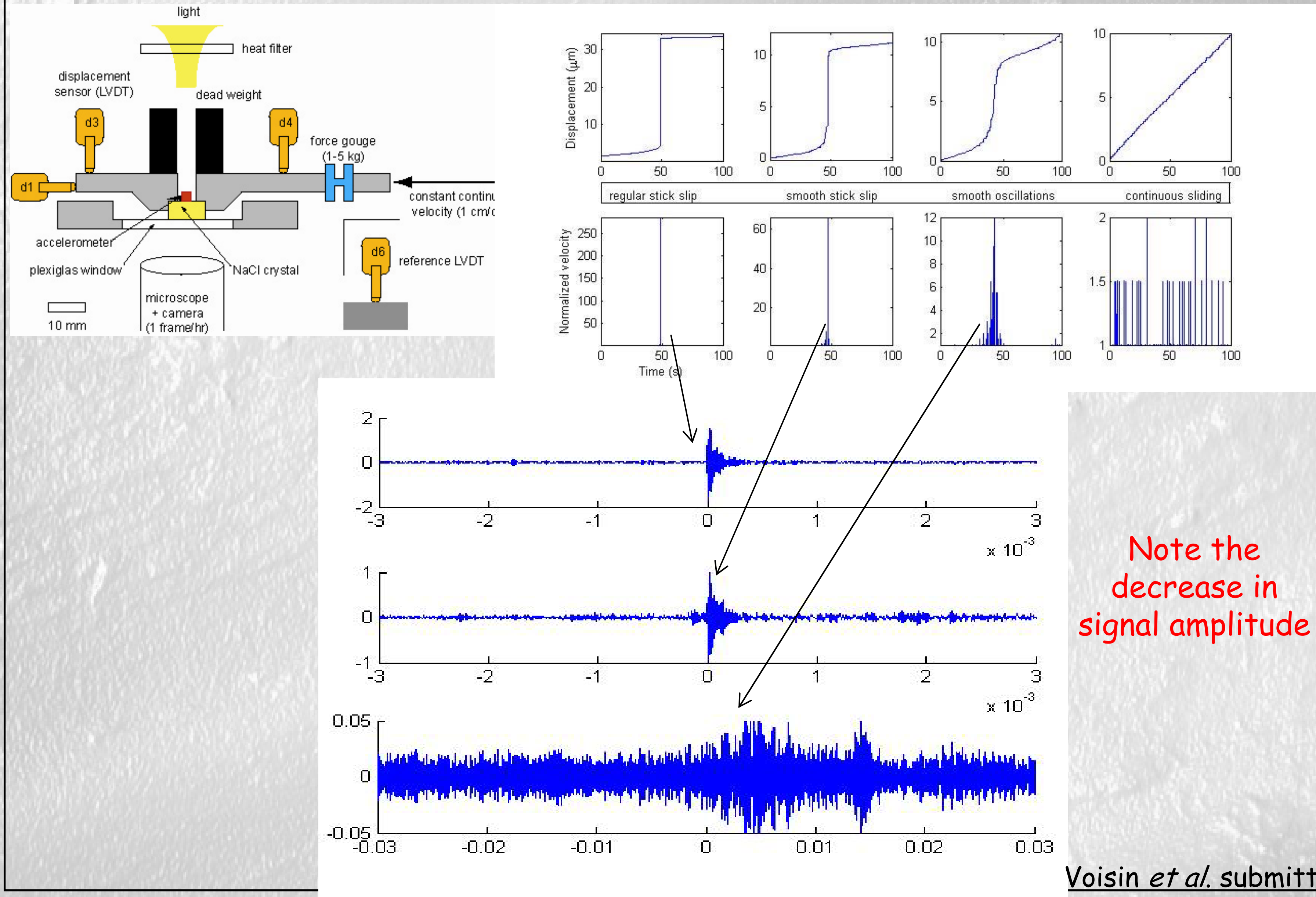
a: vanishes to zero

b: decreases

(b-a) decreases

where are the velocity jumps ?

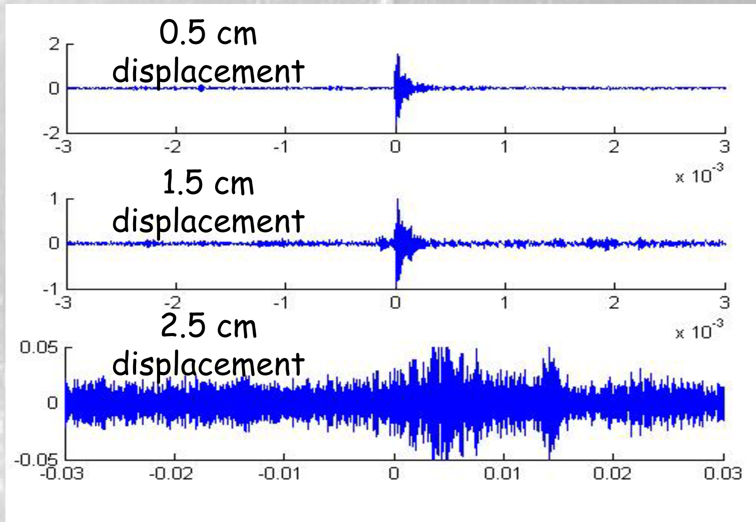
Acoustic record

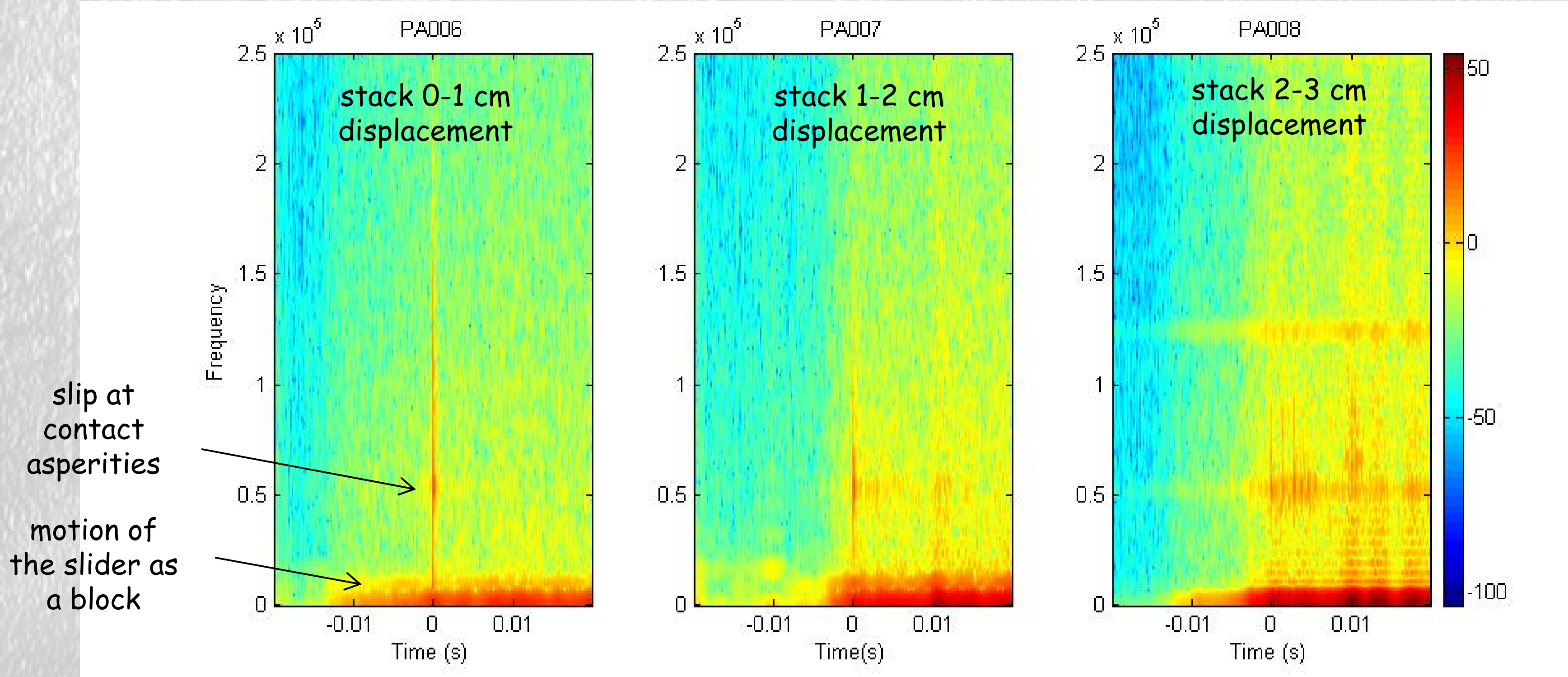


Note the decrease in signal amplitude

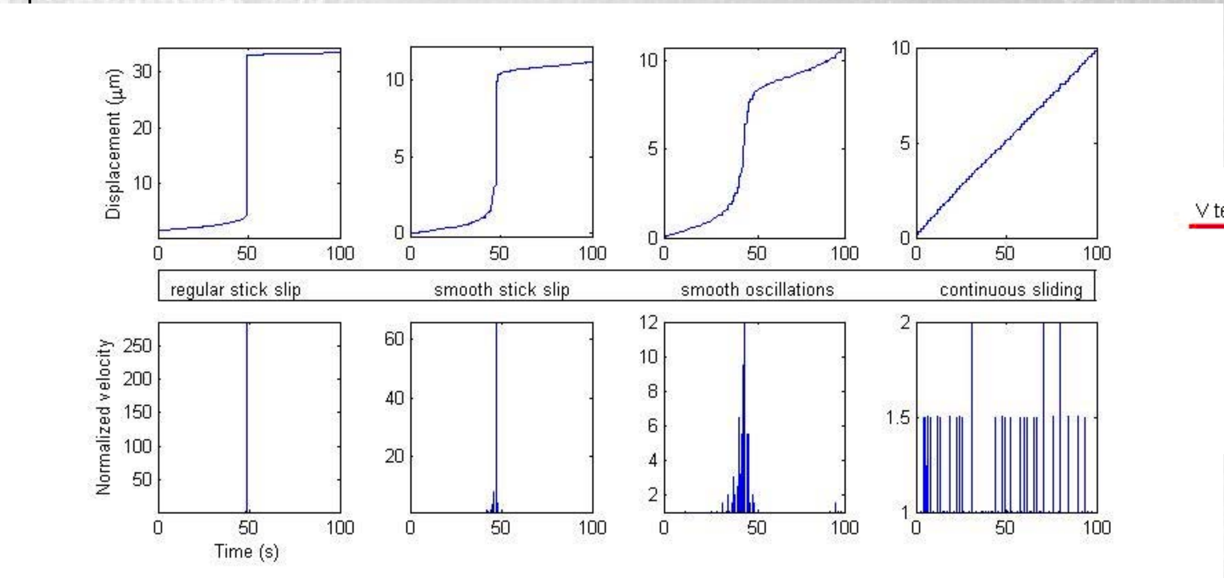
Voisin *et al.* submitted

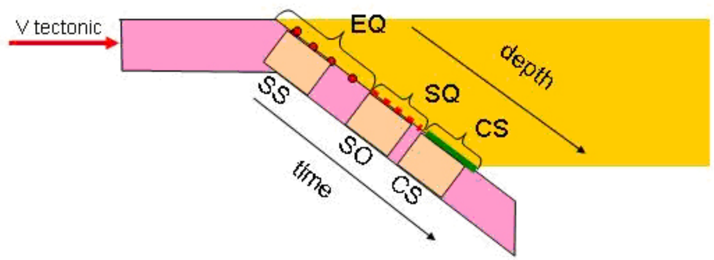
Spectrogram of a stack of acoustic events





Comparison with subduction zones : evolution from unstable (quake like) to stable (silent quake), and continuous sliding



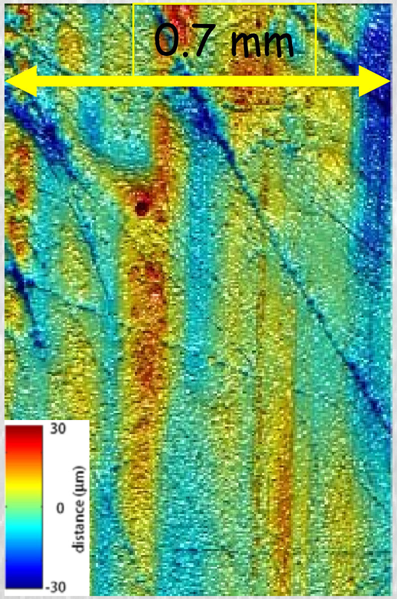


	subduction zone			analogue experiment		
slip	earthquake ~1 m	slow event ~0.5 m	silent quake ~0.1 m	stick slip ~30 μm	smooth stick slip ~10 μm	smooth oscillation ~5 μm
slip ratio	1	2	10 (*2*)	1	3	6
duration	1 min	hours-days	days-years	<0.05 s	~5 s	~25 s
duration ratio	1	$10^{-1} – 10^{-3}$	$10^{-3} – 10^{-5}$	1	$< 10^{-2}$	$< 2.10^{-3}$
$V_{event} / V_{driving}$	earthquake $\sim 10^9$	slow event $\sim 10^7$	silent quake ~2-10	stick-slip 6.10^3	smooth stick-slip ~20	smooth oscillation ~2

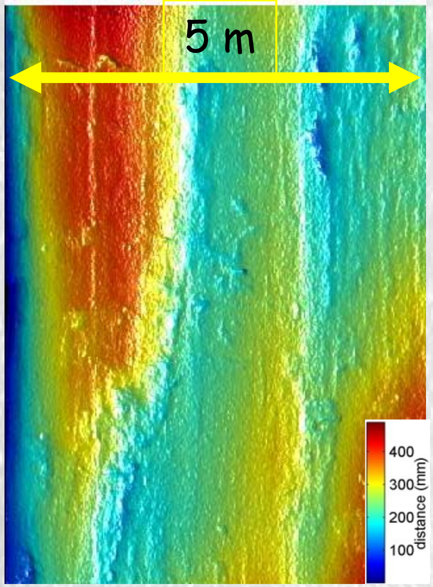
Voisin *et al.* submitted

Summary, Part 2

- Analogue to active faults: variety of slip patterns with cumulated slip
- In the experiment (a-b) and d_c may control the transition from earthquakes to stable sliding.
- D_c ? knowing that D_0 is changing

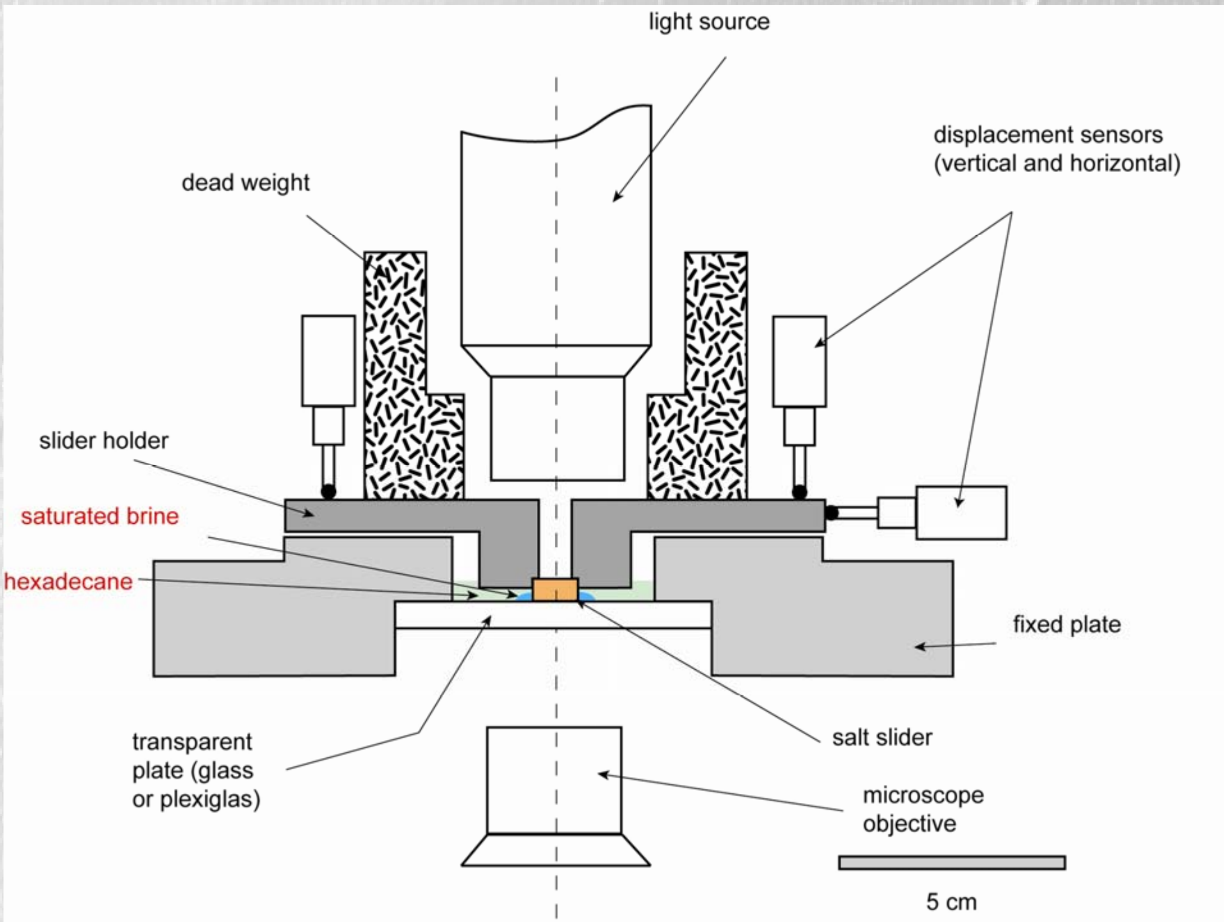


Experimental striations development (Voisin *et al.* 2007)



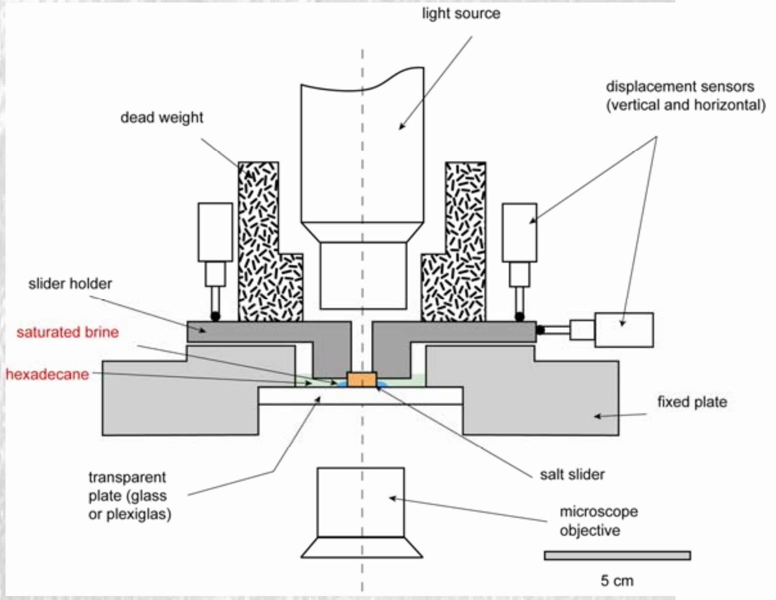
LIDAR roughness measurements on a strike-slip fault (Renard *et al.* 2006)

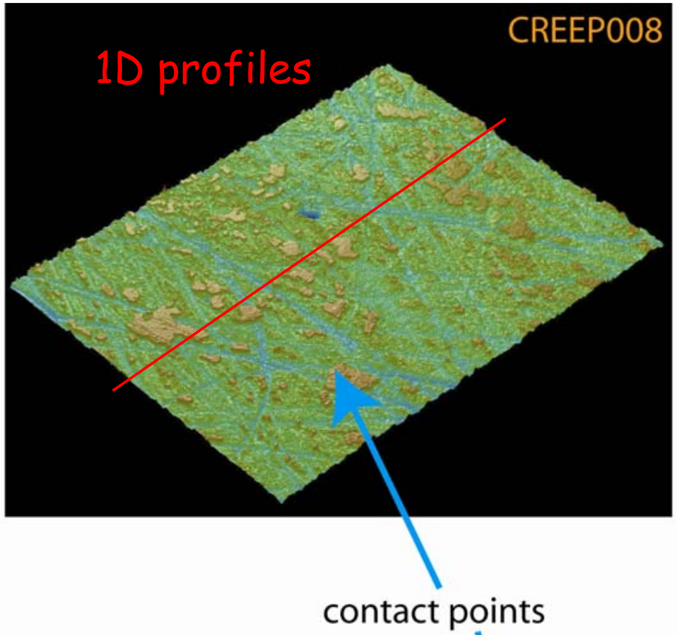
3. Growth of asperities at the contact



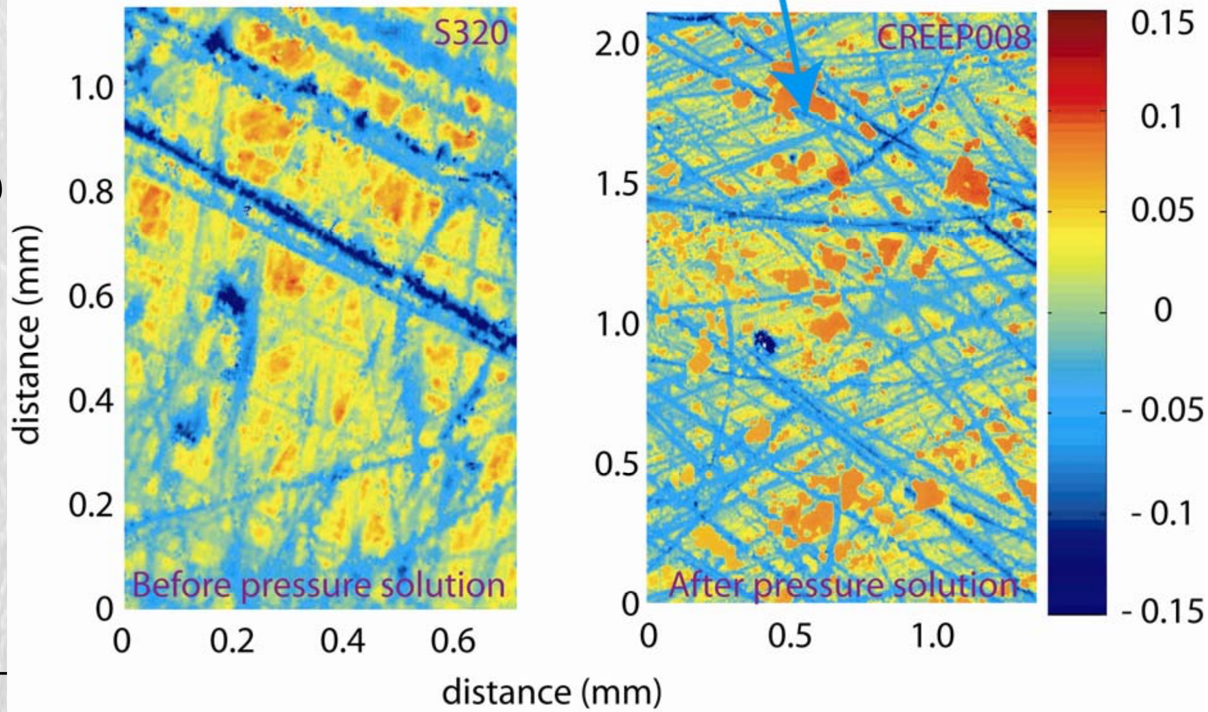
Dry interface: no visible contact, but increase of the strength of the interface with hold time

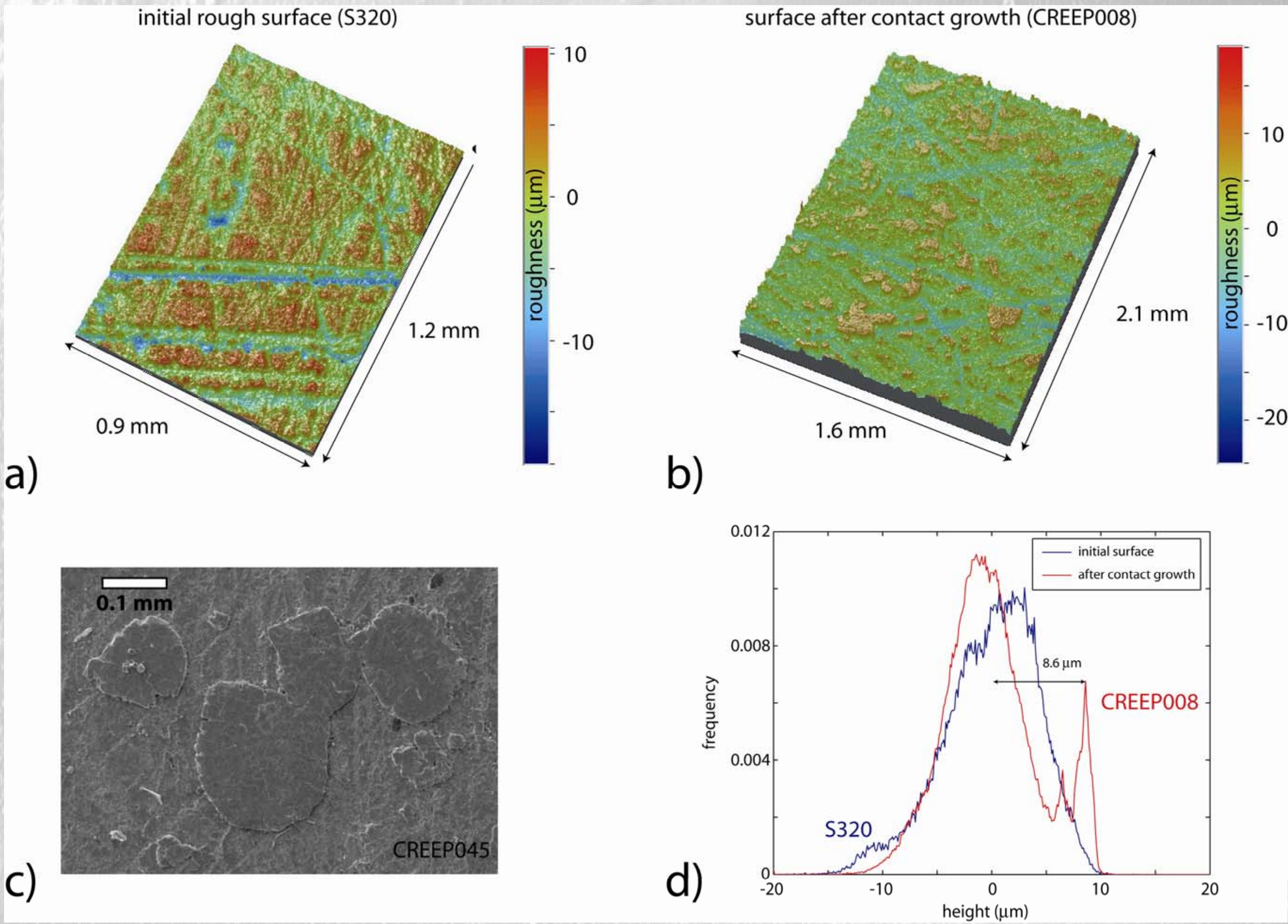
Wet interface: rich dynamics of contact growth and strength increase





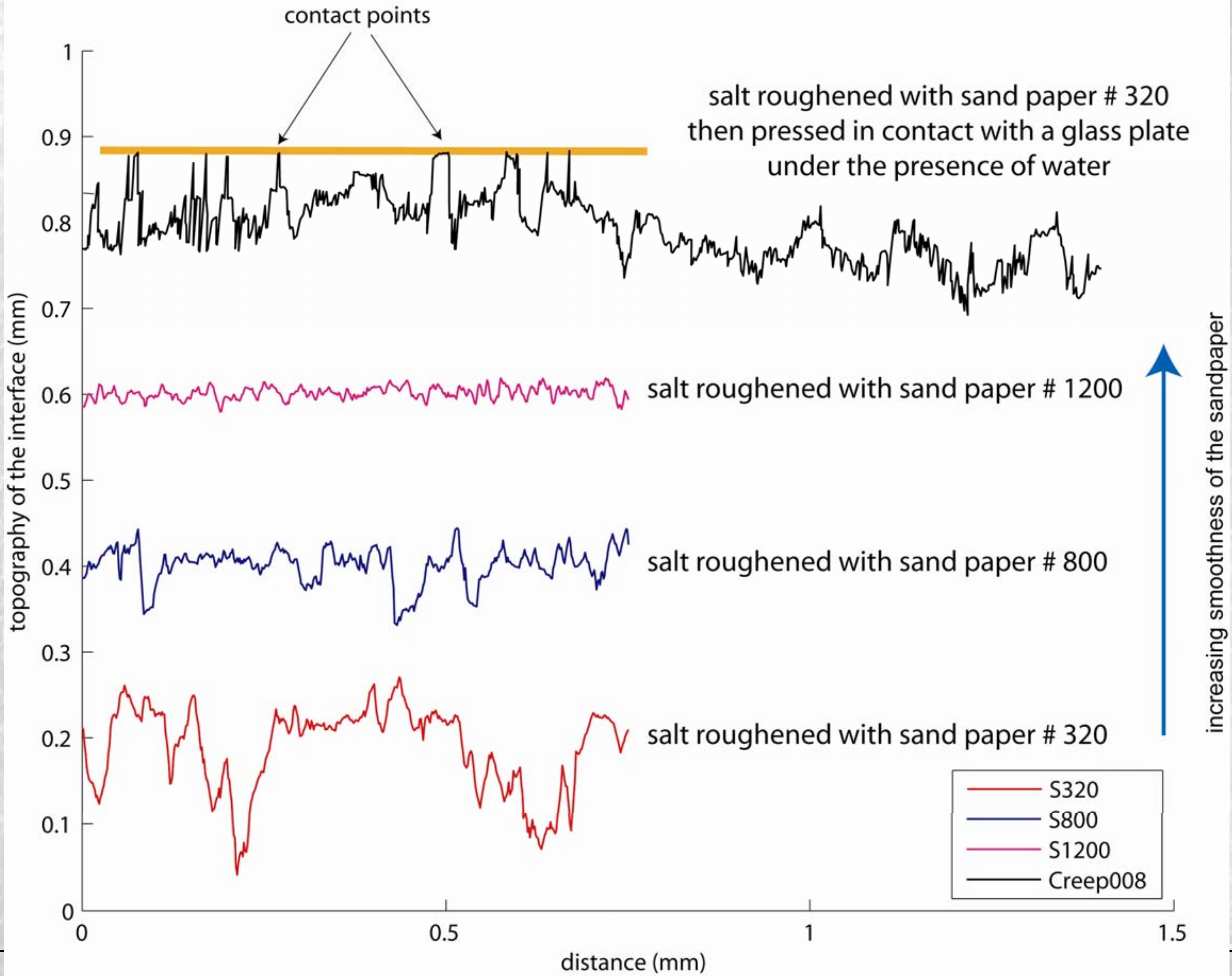
Geometry of the interface after creep growth of the contacts by a dissolution-precipitation process



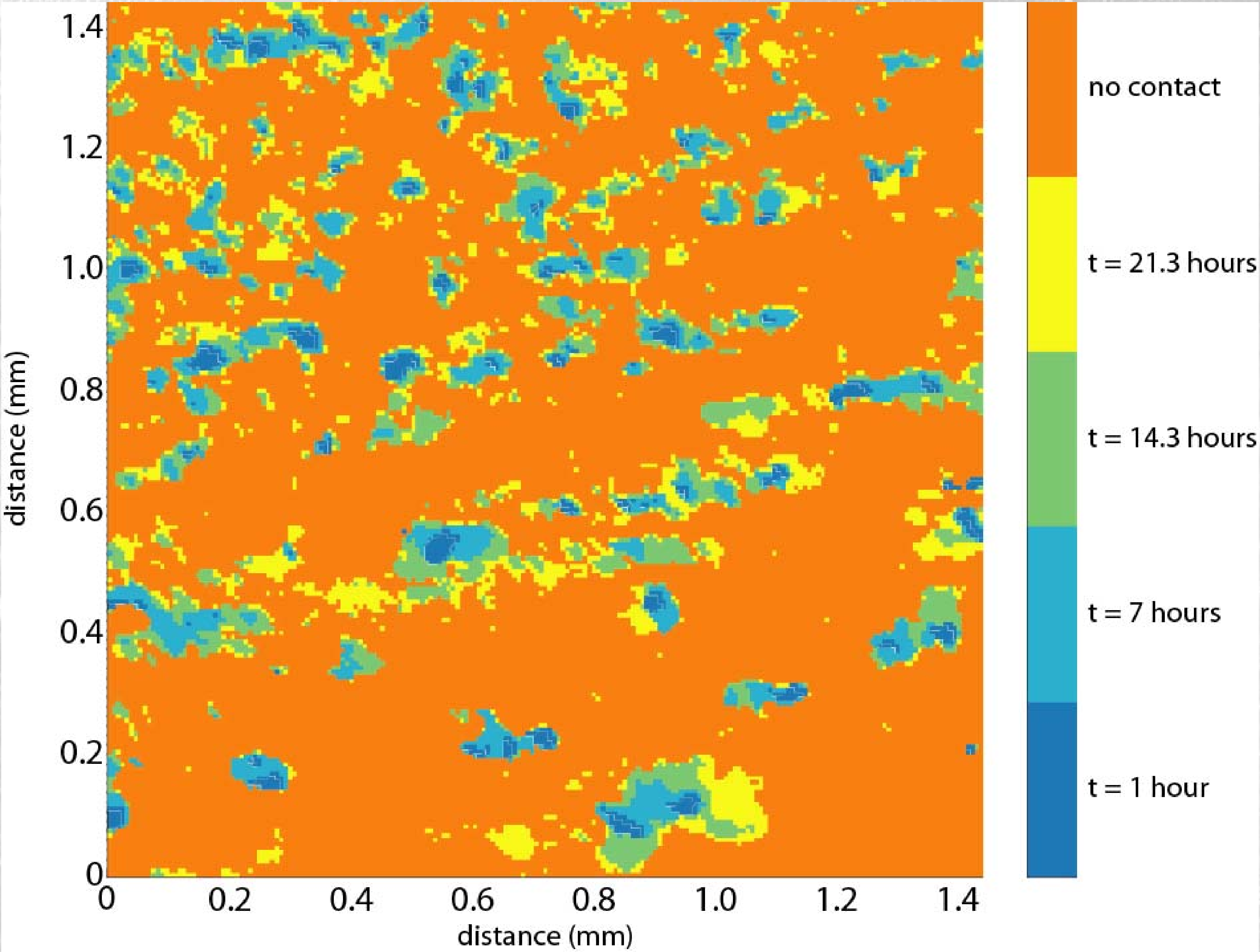


initial rough surface (S320)
surface after contact growth (CREEP008)
roughness (µm)
10
0
-10
1.2 mm
0.9 mm
a)
2.1 mm
1.6 mm
-20
b)
0.1 mm
CREEP045
c)
initial surface
after contact growth
8.6 µm
CREEP008
S320
frequency
height (µm)
0.012
0.008
0.004
-20
20
d)

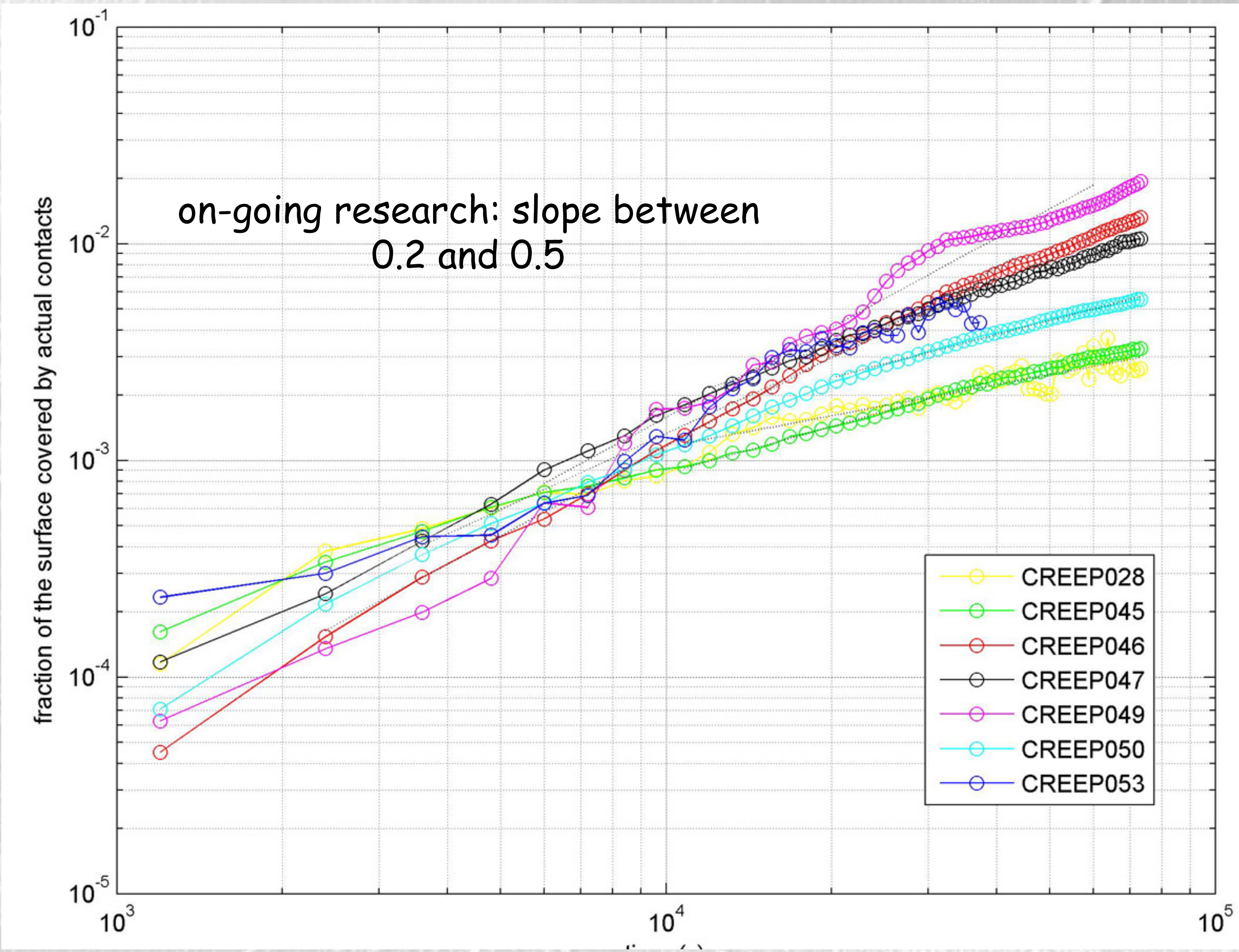
Topography of the interface measured using white-light interferometry



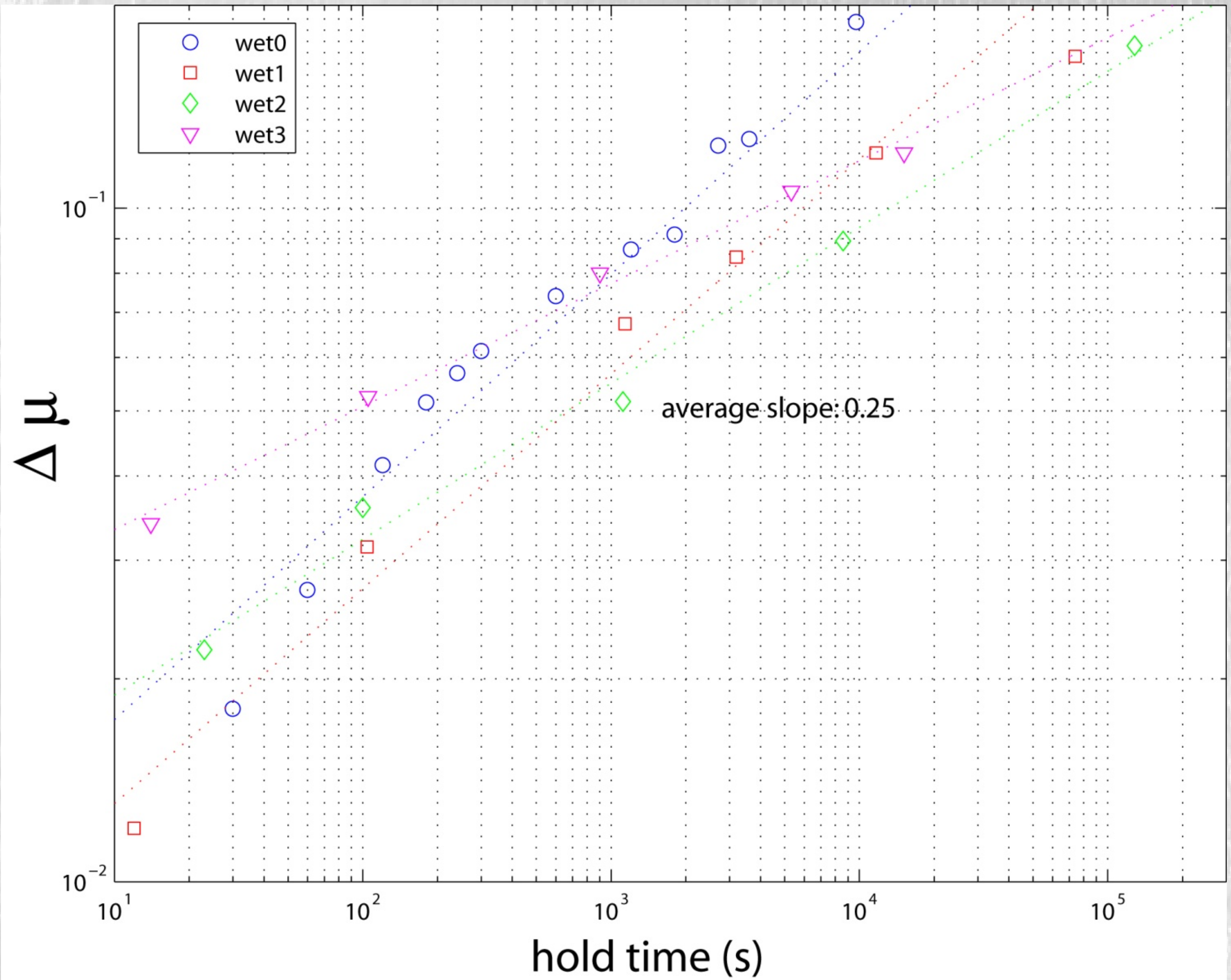
Time evolution of the actual contact surface area



Evolution of contact surface area with time



Evolution of static friction with hold time

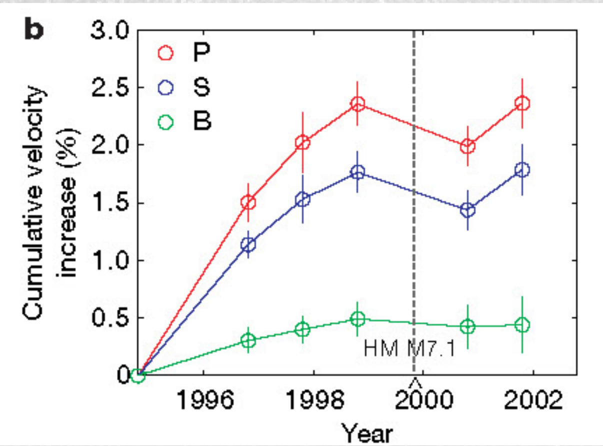


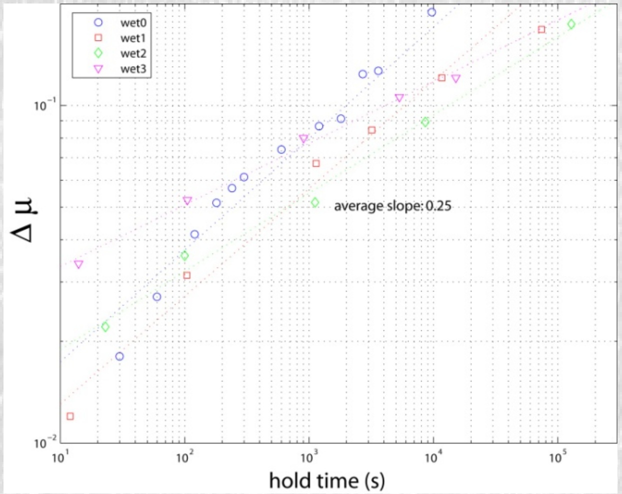
Summary, Part 3

Analogue to natural faults: healing occurs with time because of chemical reactions

Under dry conditions, no healing was observed, while when water was added a rich dynamics involving fracture healing and contact points expansion was observed.

The rate of closure is strongly dependent on the initial roughness of the fracture.





Vidale and Li, 2003

Conclusions

- Cumulated slip on a fault can form **striations at all scales** (abrasion, plastic flow, chemical reactions)

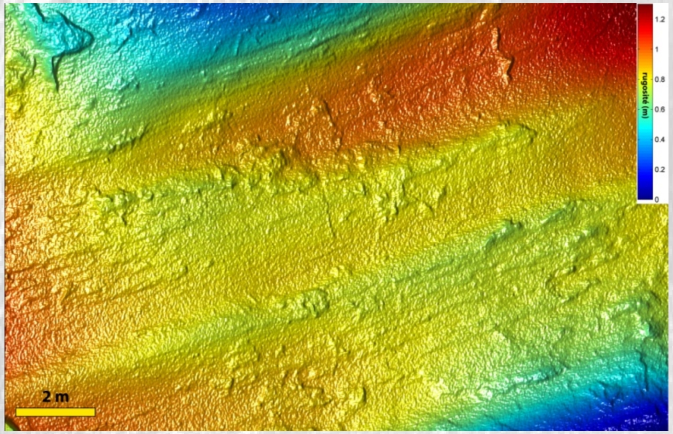
- Reproduced under laboratory conditions, striation development is linked to a **transition from stick-slip to stable sliding**. Acoustic emission records this transition.

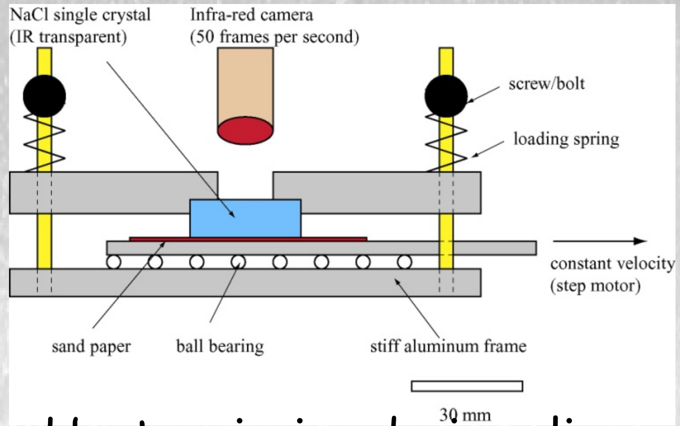
- When chemical reactions are involved, our analogue fault can heal, with strong modifications of the frictional properties. There roughness is rebuilt

- The dynamics of fault reflects an interplay between **weakening and strengthening processes**, with specific time scales

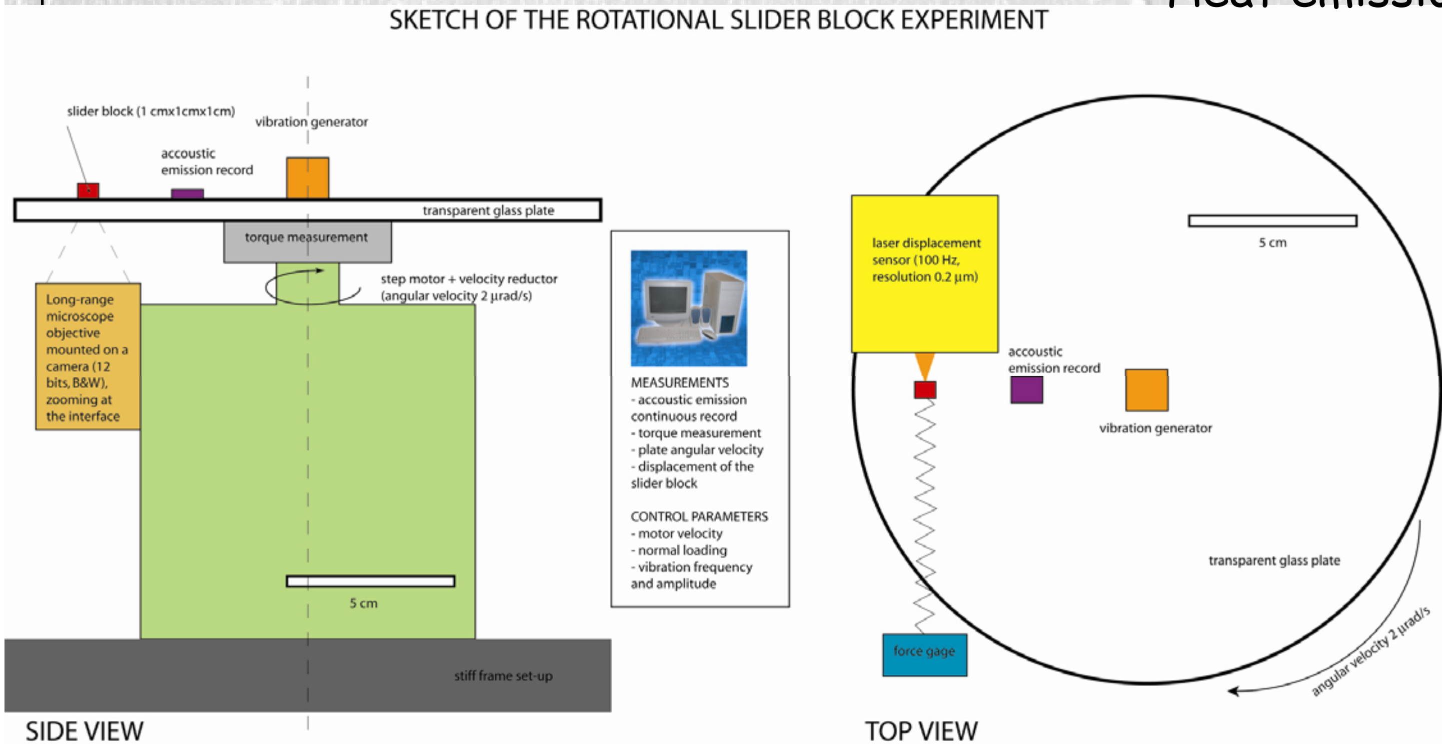
What's next ?

synthetic surfaces





Heat emission during slip



Rotational slider block experiment (large number of stick-slip cycles)