Institut de Physique du Globe de Strasbourg

Ecole et Observatoire des Sciences de la Terre

PhD Defense 4/12/2009

Experimental study of the role of heterogeneities in the rupture propagation

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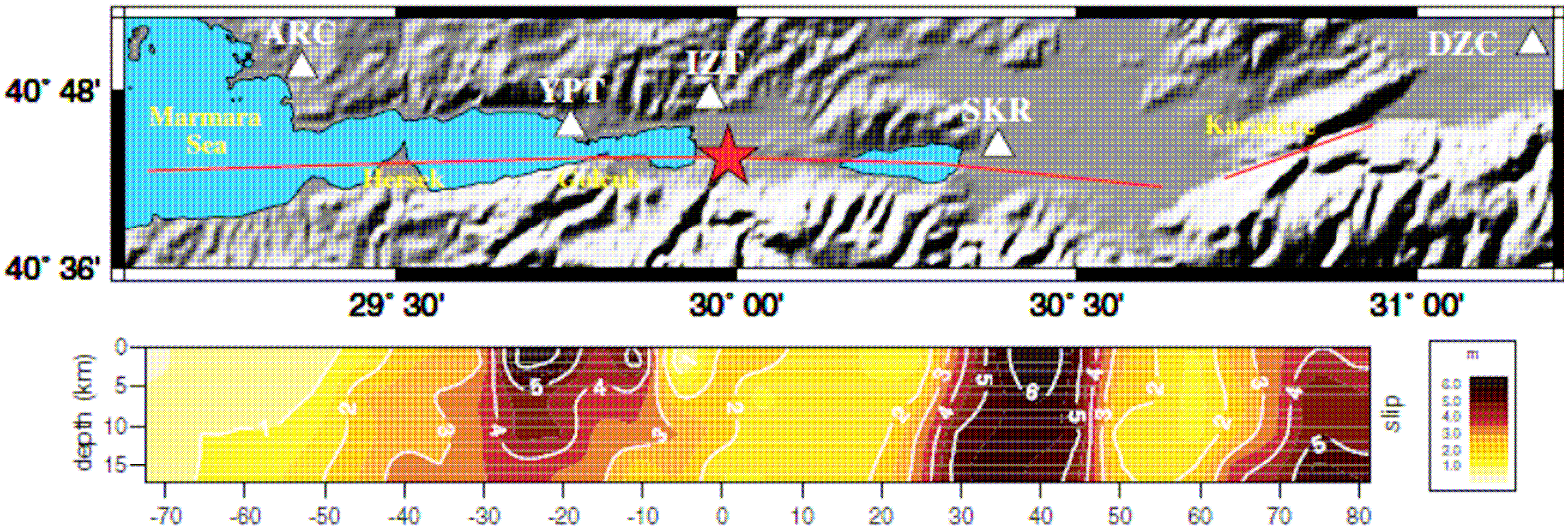
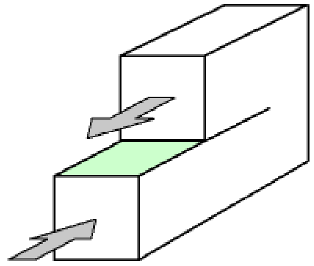
Rupture observation



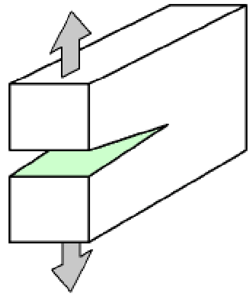


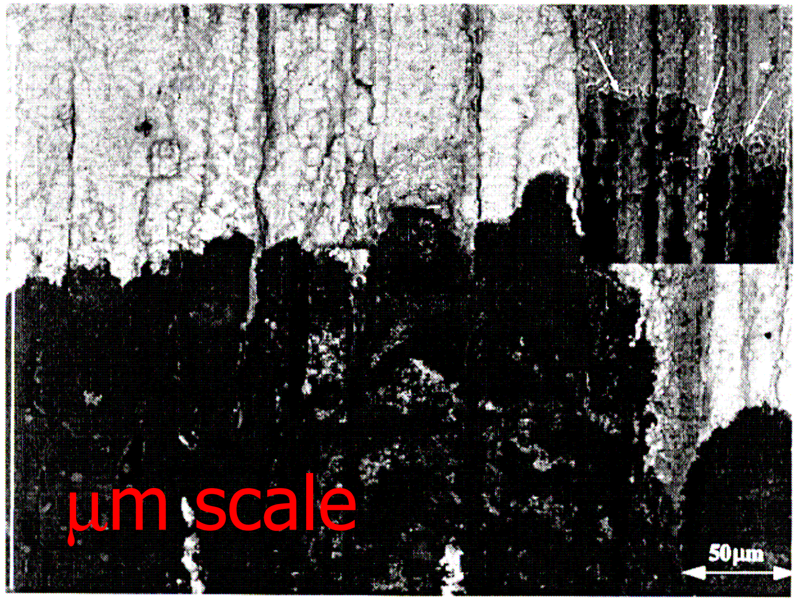
mode II
(shear)

Slip distribution of 1999 Izmit, Turkey,earthquake
Bouchon et al. (BSSA, 2002)

Fracture interface
Bouchaud (J. Phys, 1997)

mode I
(opening)



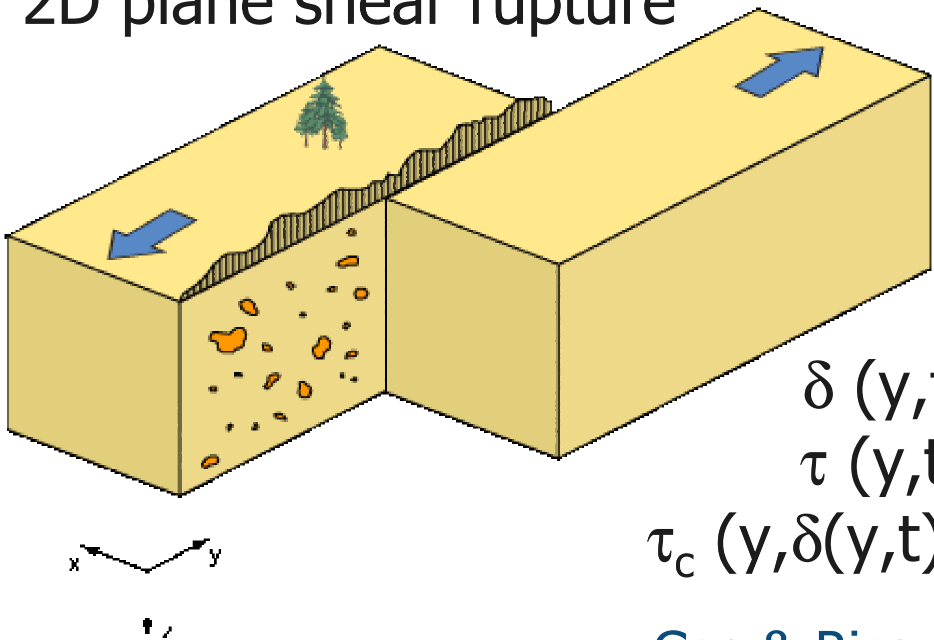


Rupture modelisation

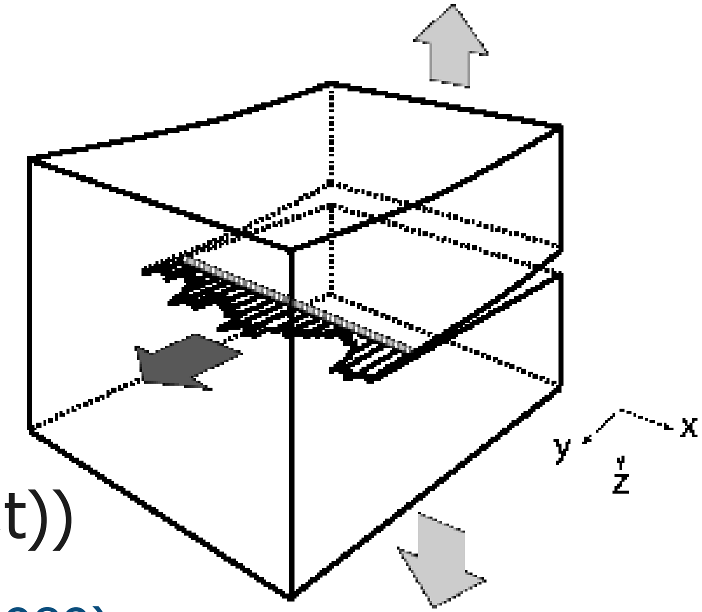
In both cases:

- Fractures along favoured surfaces ⇒ weak planes
- Fluctuations of mechanical properties along plane
- Rough shape of coseismic slip and rupture front

2D plane shear rupture



Mode I interfacial crack



$$\delta\,(y,t) \leftrightarrow a\,(x,t)$$
$$\tau\,(y,t) \leftrightarrow G\,(x,t)$$
$$\tau_c\,(y,\delta(y,t)) \leftrightarrow G_c\,(x,a(x,t))$$

τ = shear stress

Gao & Rice (J. Appl. Mech., 1989)
Schmittbuhl et al. (PAG, 2003)

G = fracture energy

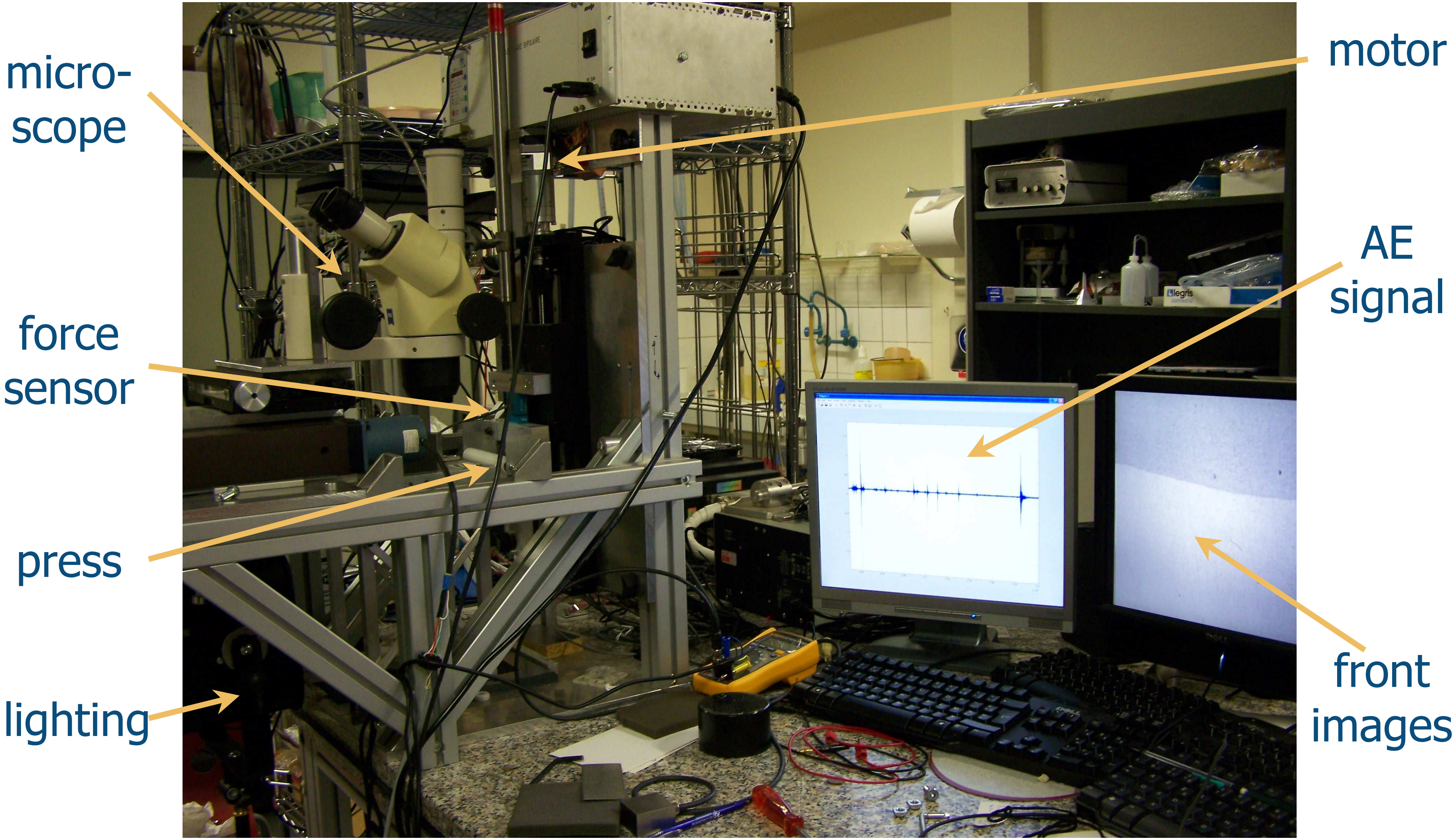
- Can fracture mechanics be inferred from analysis of crack front morphology ?
- What are the links between small and large scales ?
- Can small scale heterogeneities lead to large scale heterogeneities ?
- How do heterogeneities influence rupture propagation ?

- To try to answer these questions:
  - **Optical and acoustic monitoring of a crack propagation along a heterogeneous interface**
  - **Analysis of fixed crack front morphology at high spatial resolution**
  - **Analysis of crack front dynamics during its propagation**

Outlines

- Issue
  - **Morphology of fracture fronts**
  - **Dynamics of rupture propagation**
- Experimental setup
- Results on morphology
  - **scaling analysis ⇒ self-affinity of crack fronts**
- Results on dynamics
  - **scaling law distributions of velocities and acoustic emissions (AE)**
- Comparison between experimental and large scale data
  - **clustering of events in both cases**
- Conclusions and perspectives

Experimental setup



Experimental setup

microscope

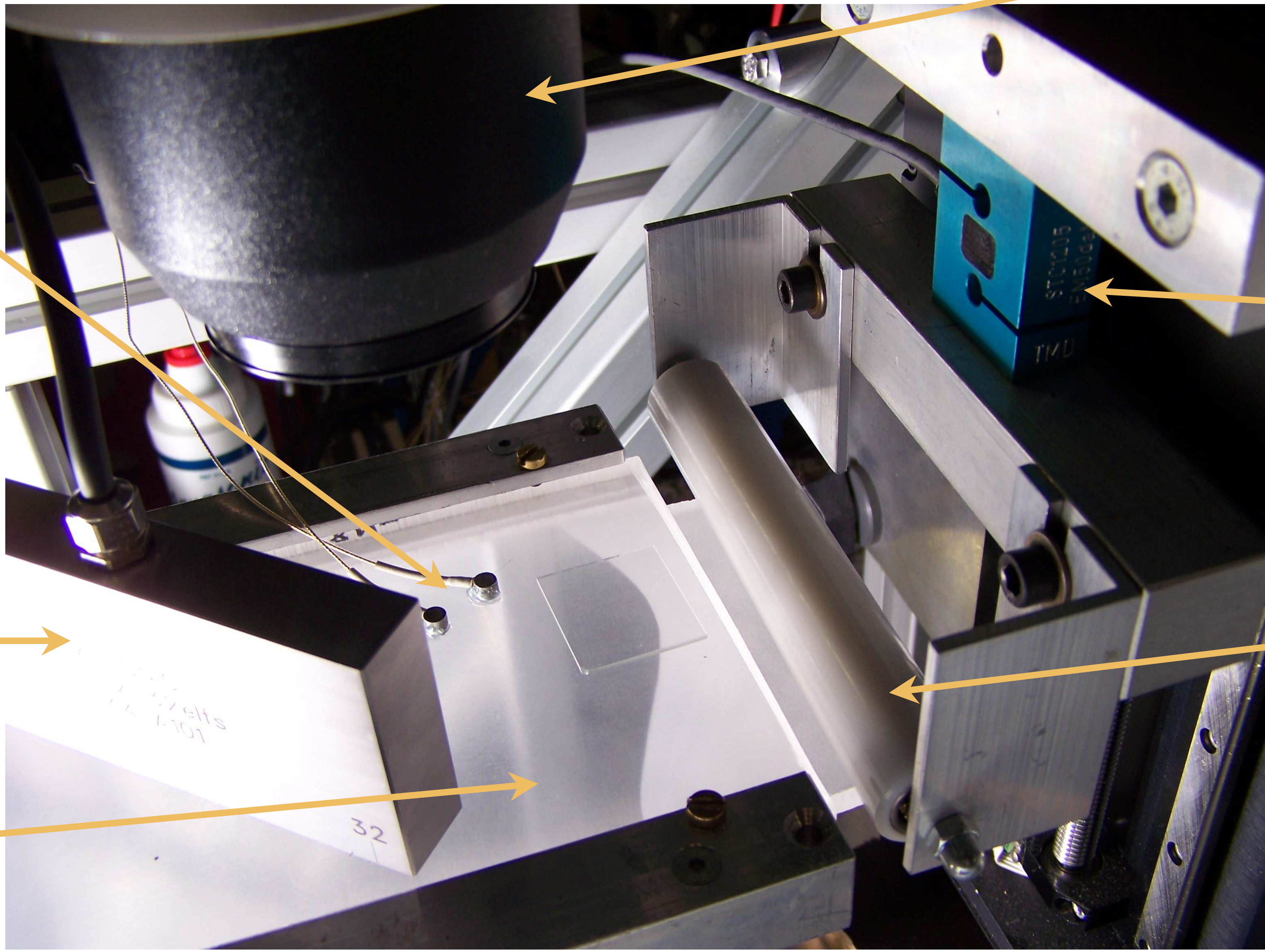
acoustic sensors

force sensor

linear array of acoustic sensors

press

sample



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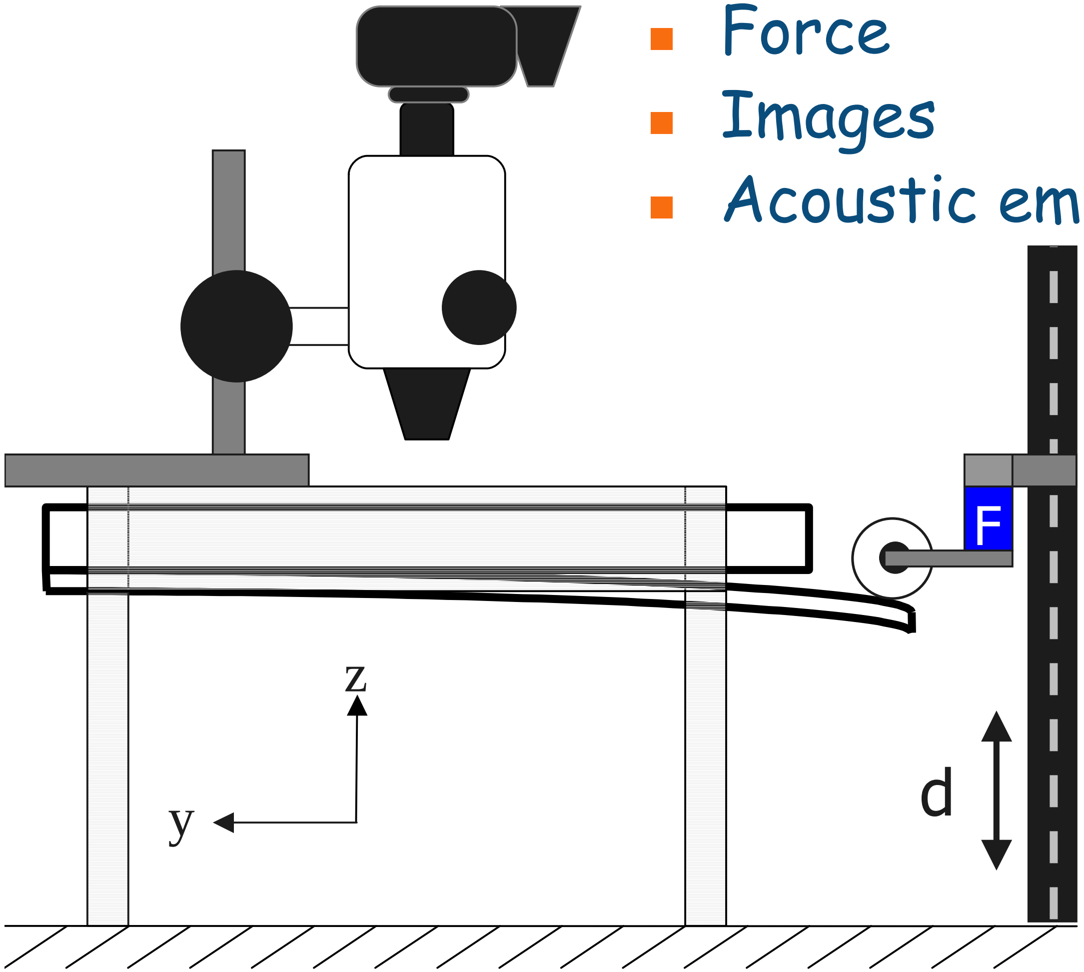
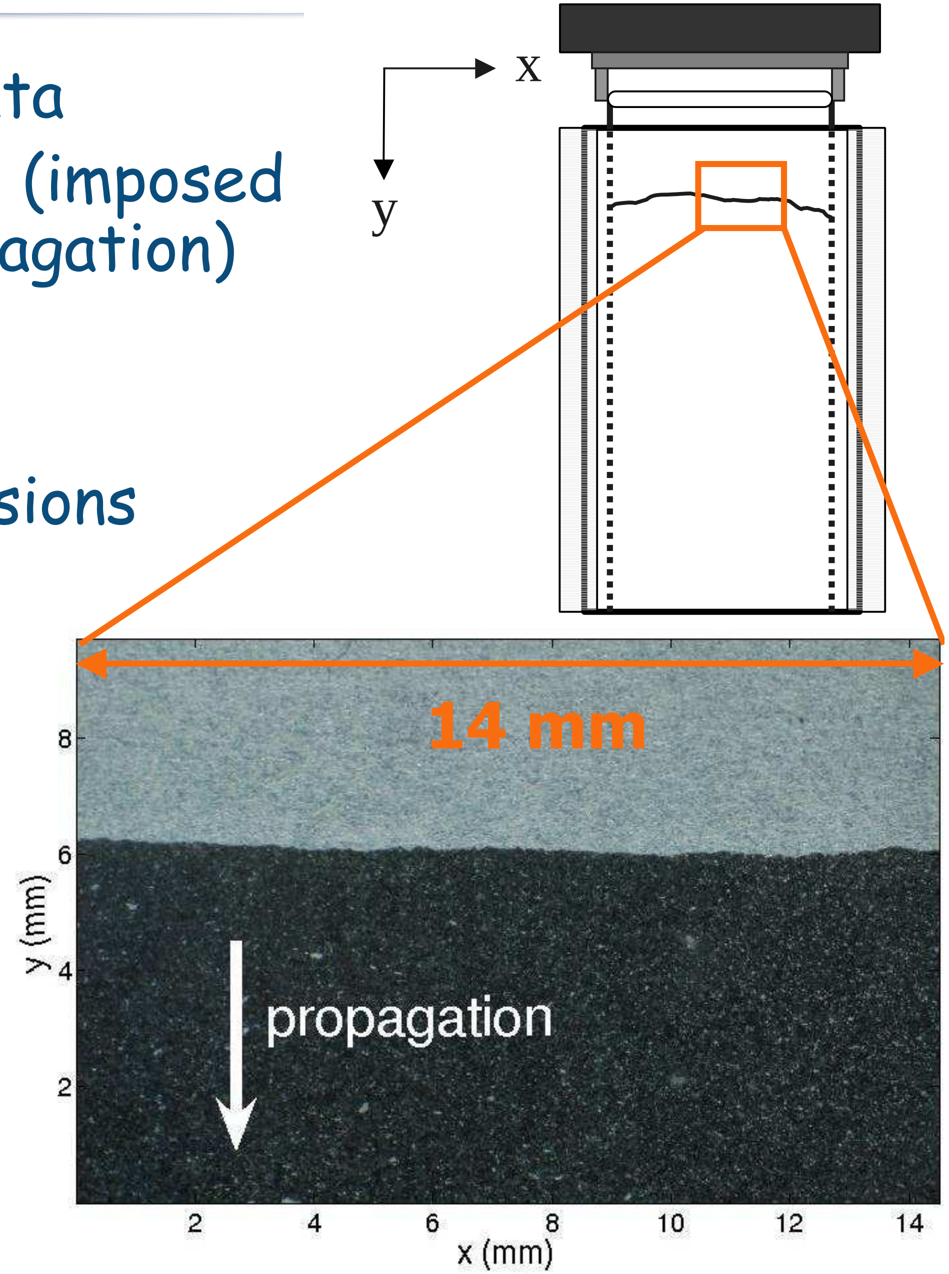
Experimental setup

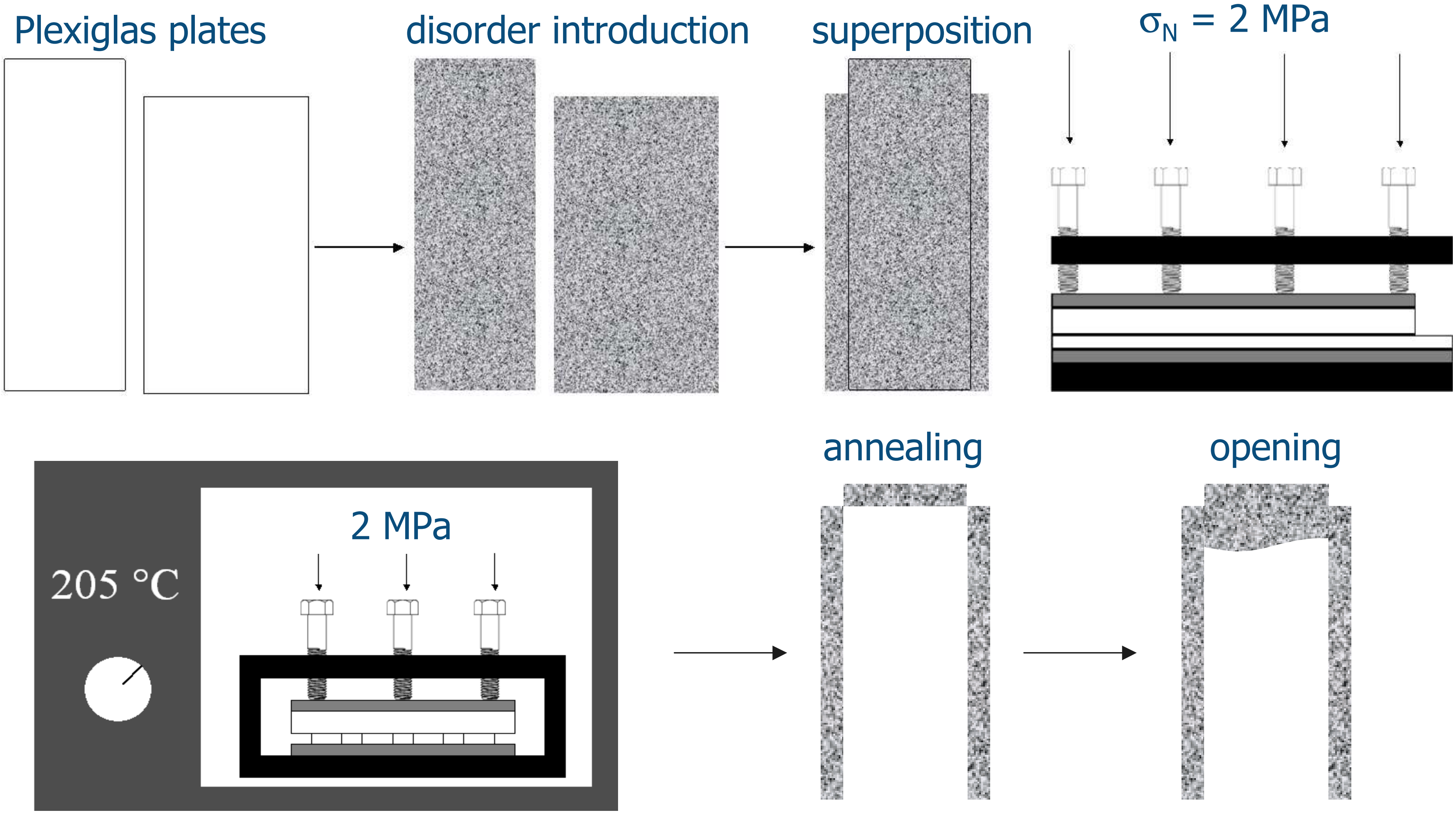
4 observation data

- Displacement (imposed ⇒ stable propagation)
- Force
- Images
- Acoustic emissions

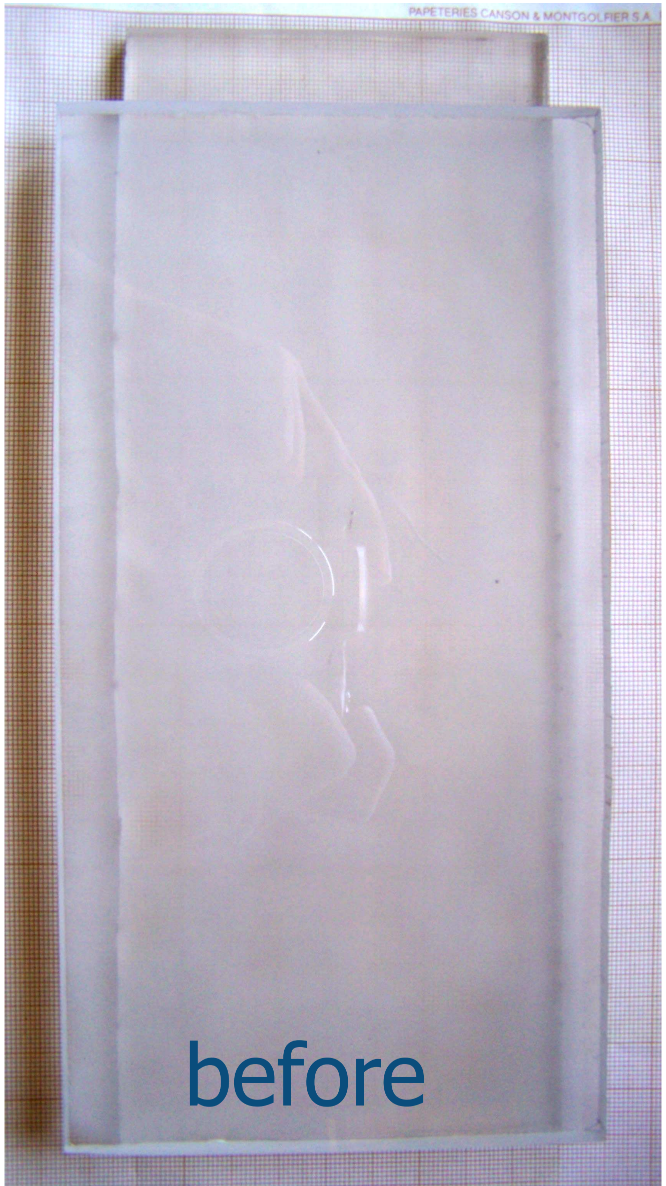


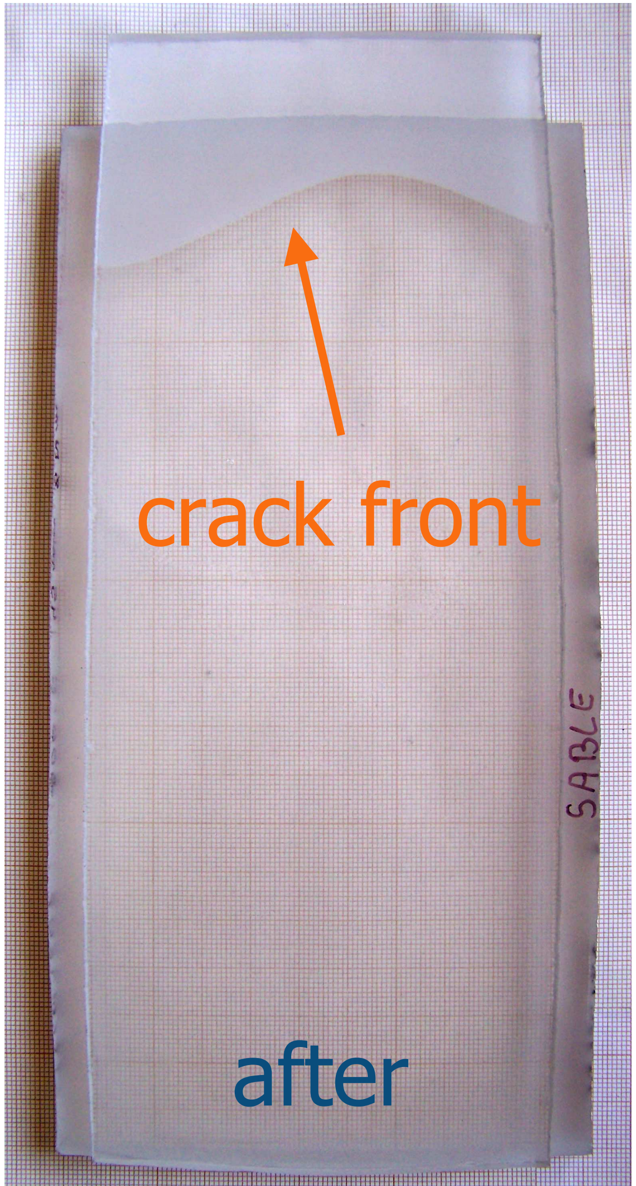


Sample preparation

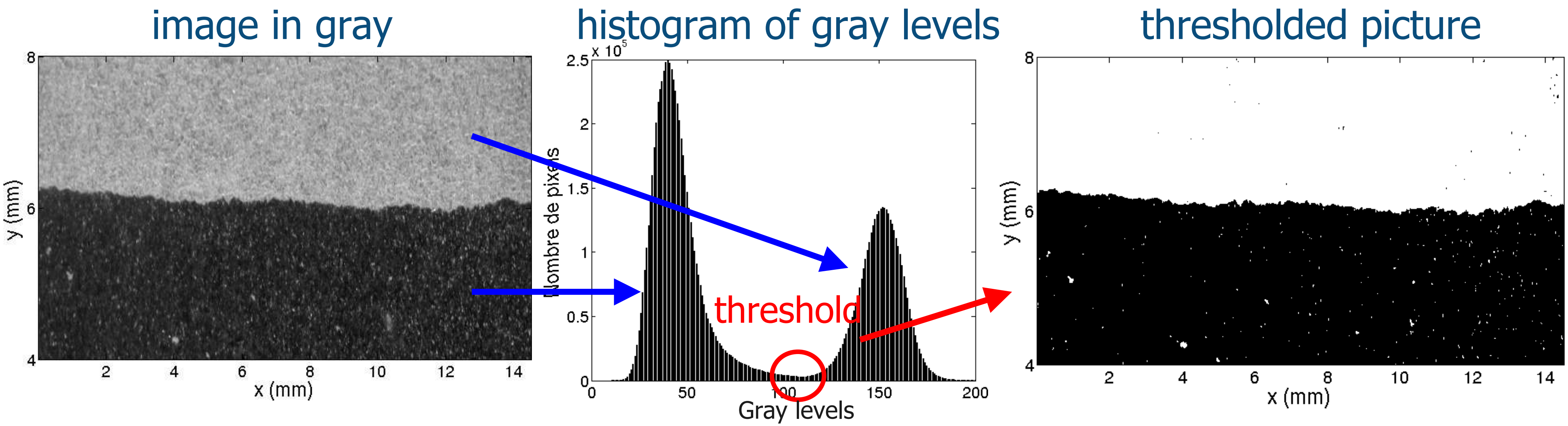


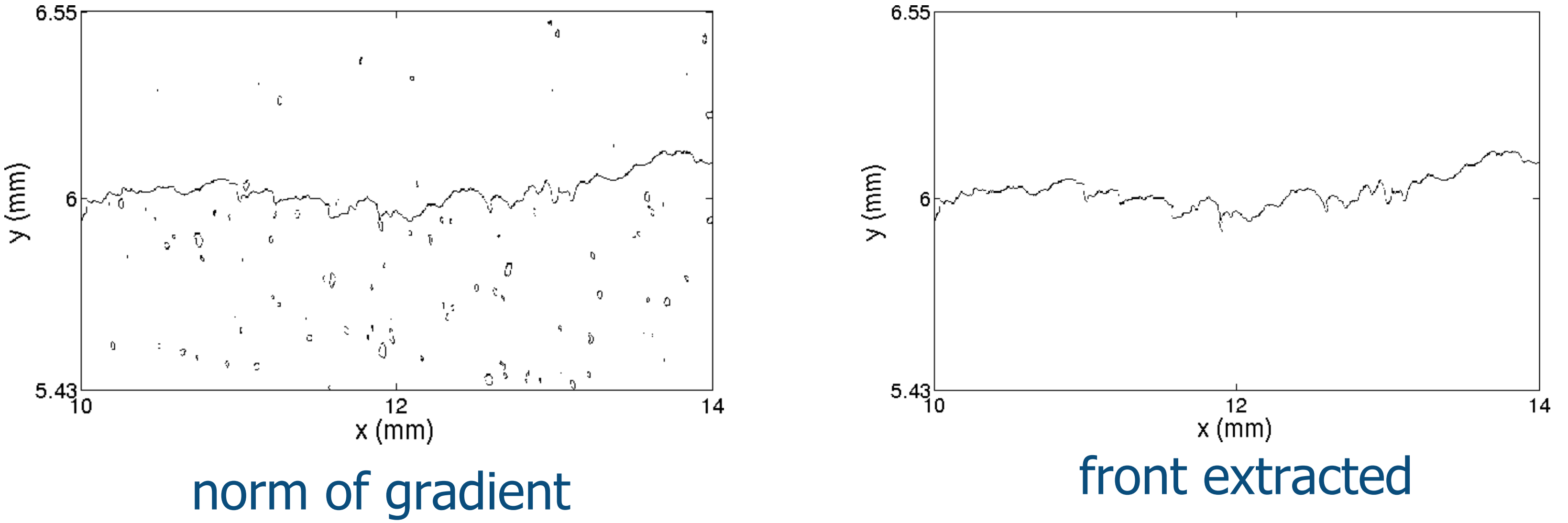
Sample preparation



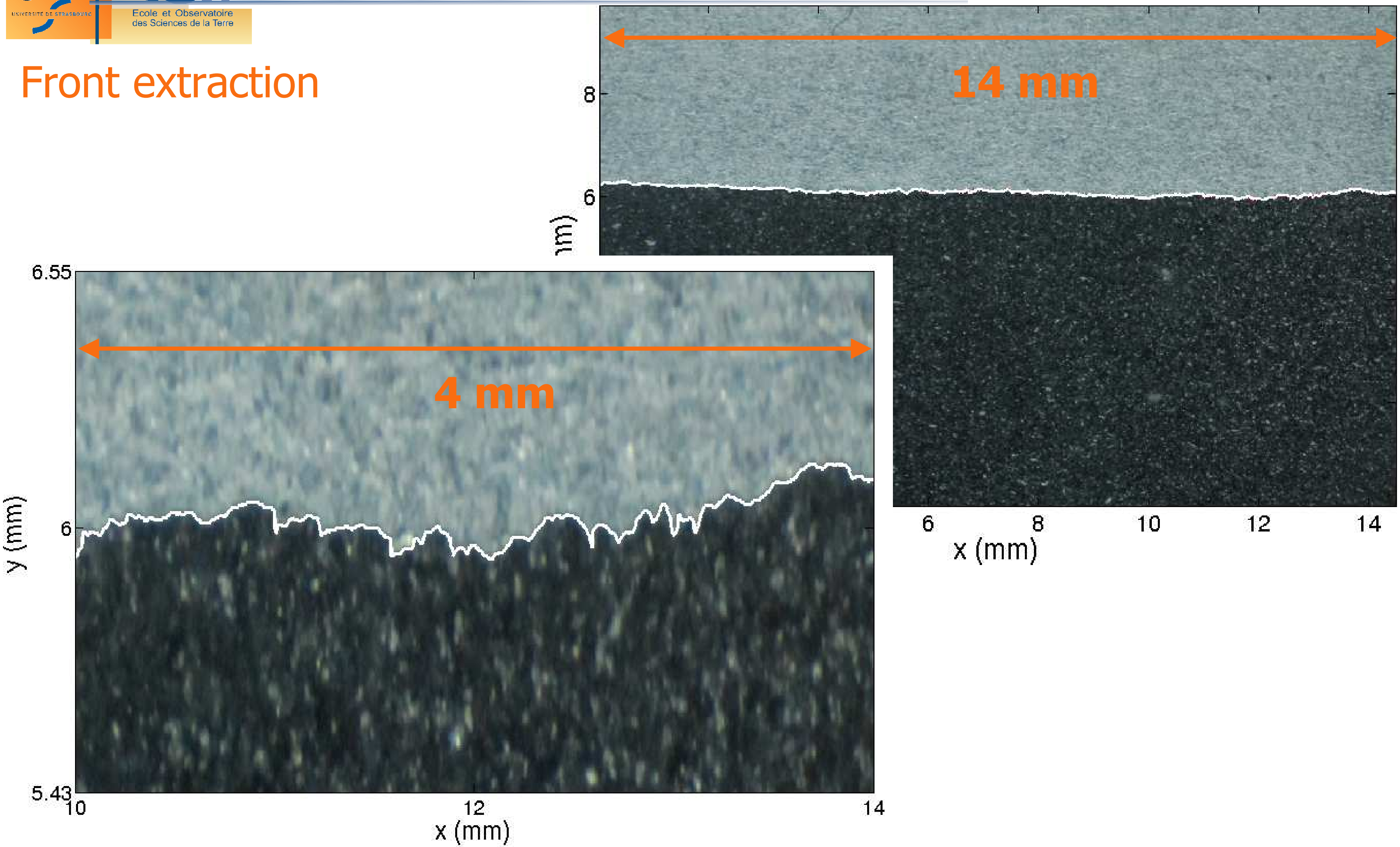


Front extraction





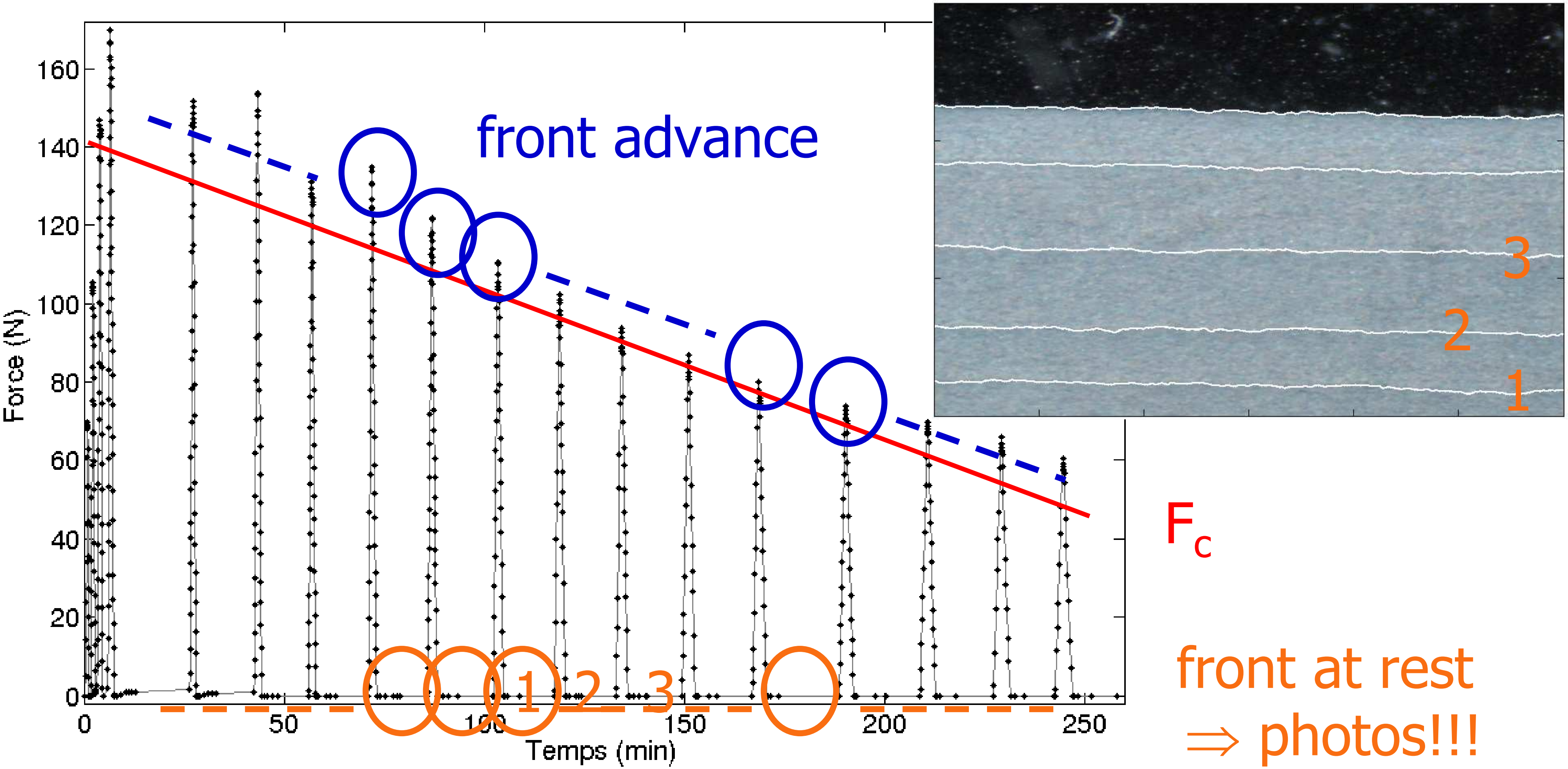
Front extraction



Static experiments

Loading to make front advance

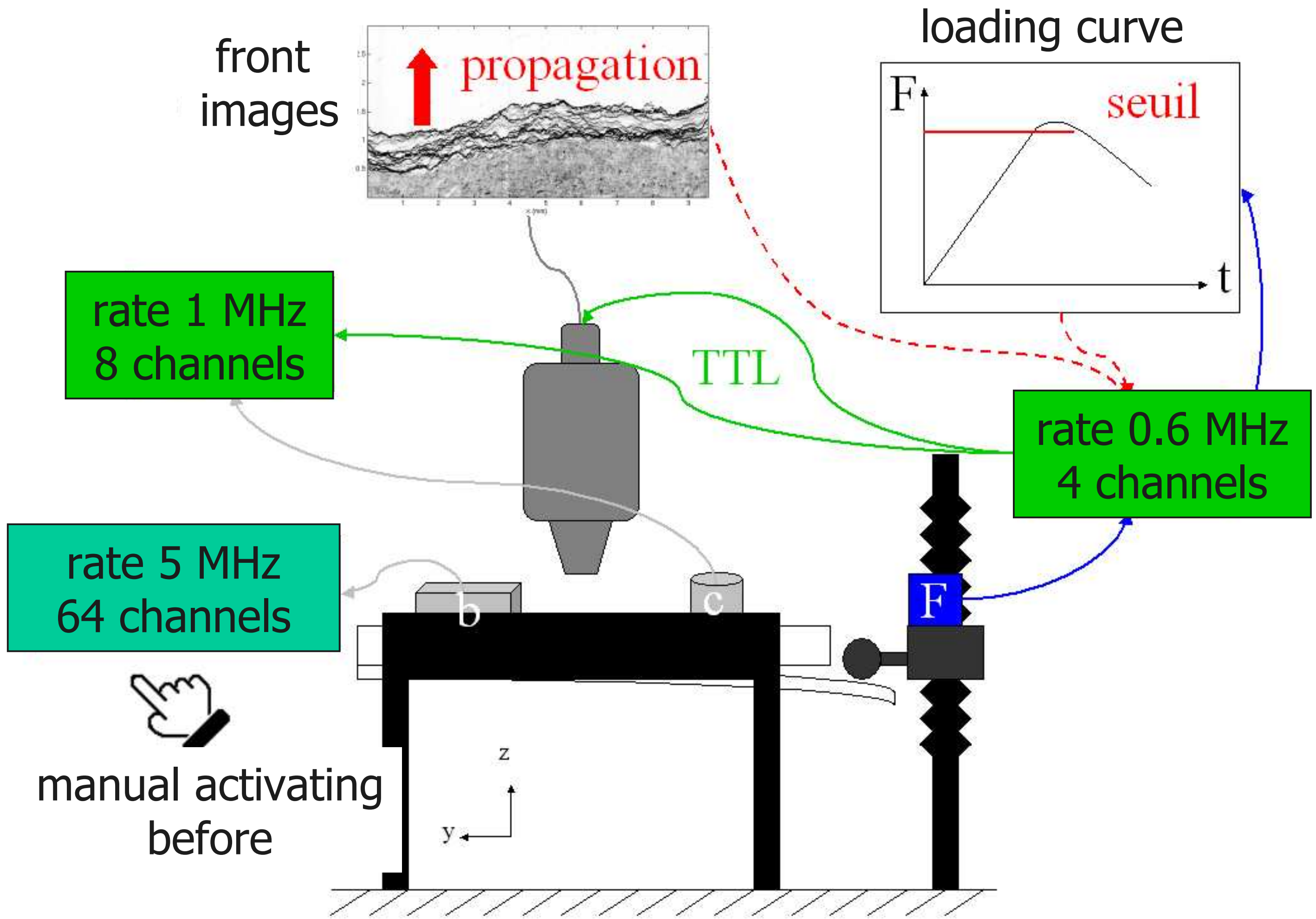
Unloading to take high resolution pictures of front at rest



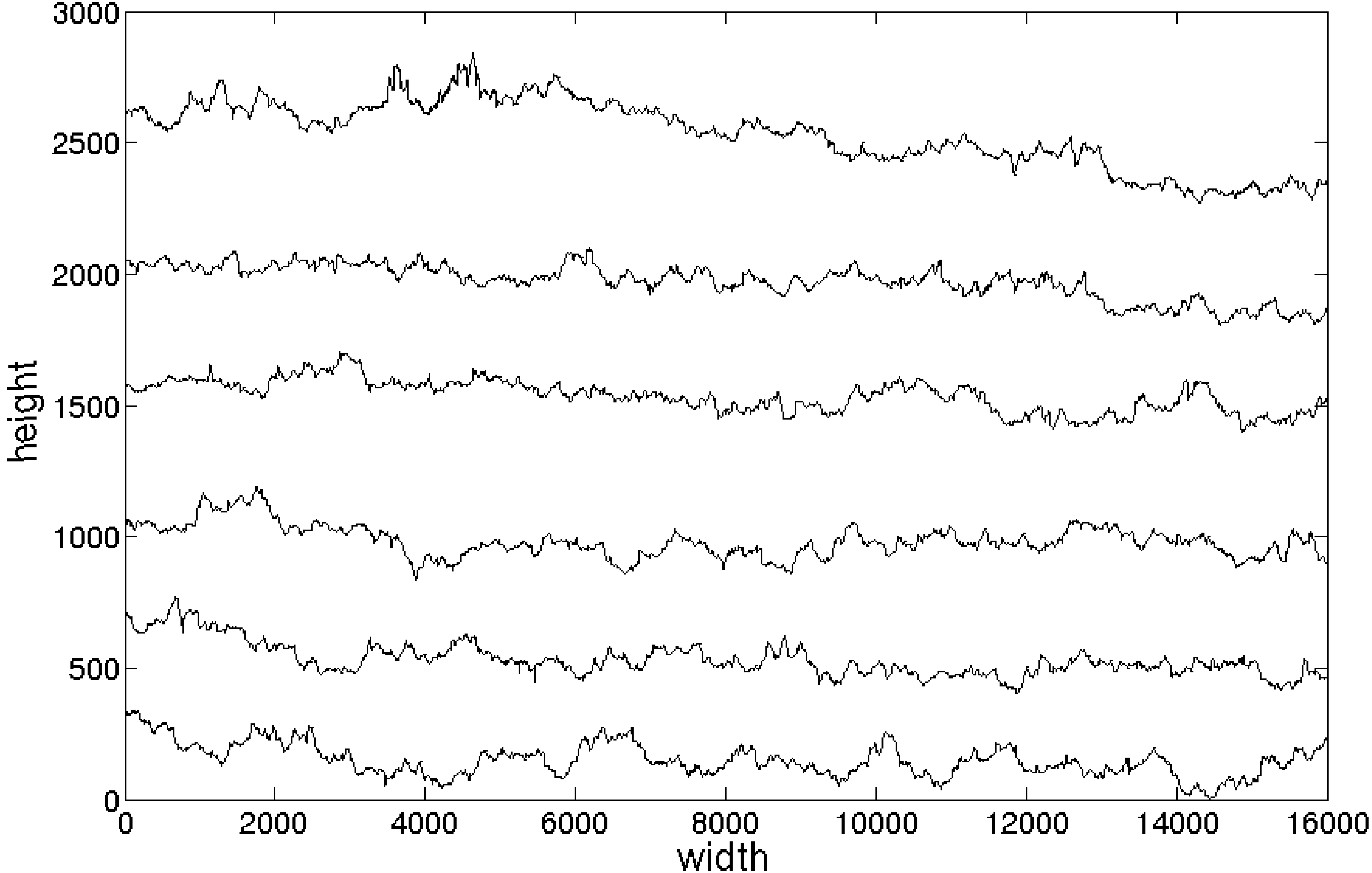
Dynamic experiments

Loading for the duration of experiment at constant speed

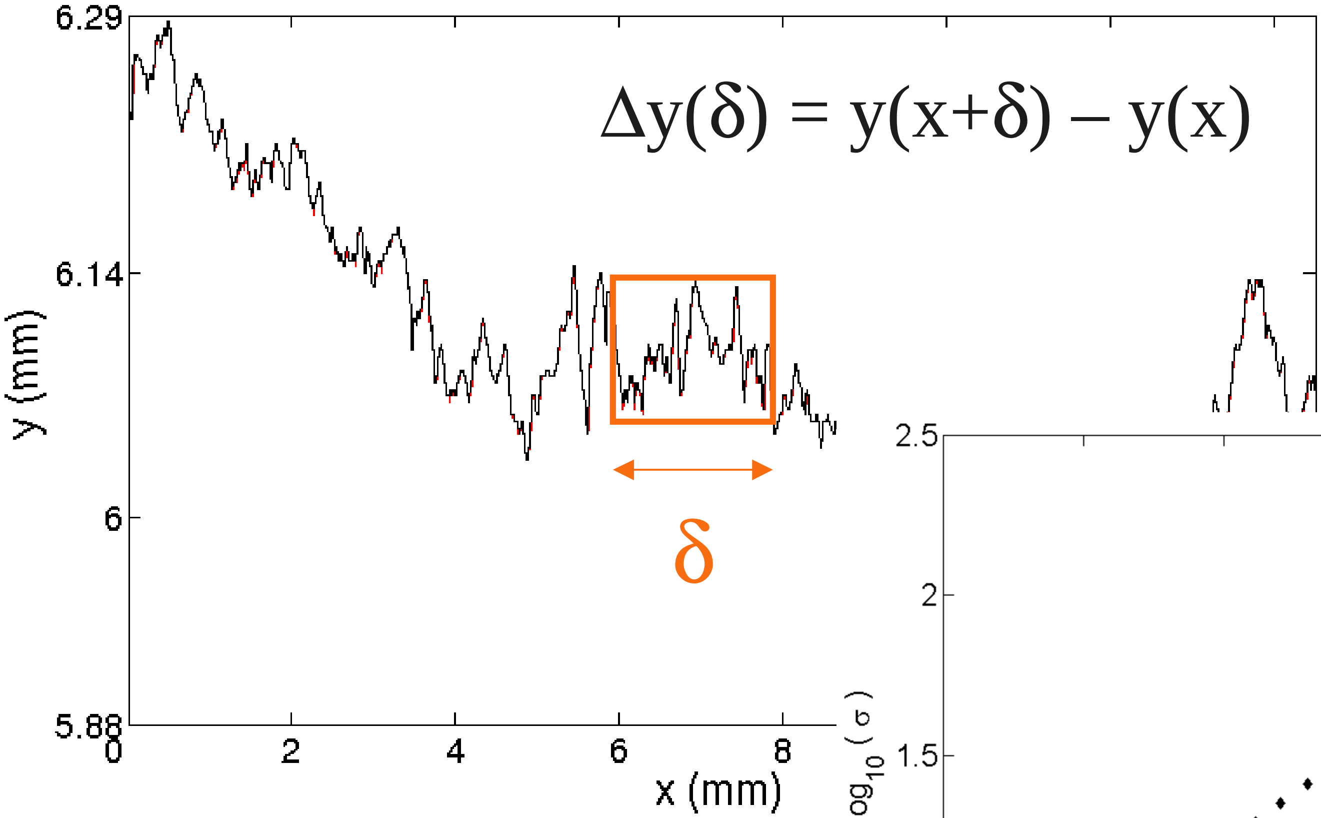
Lots of images taken at high acquisition rate (≈1000 frames / s)

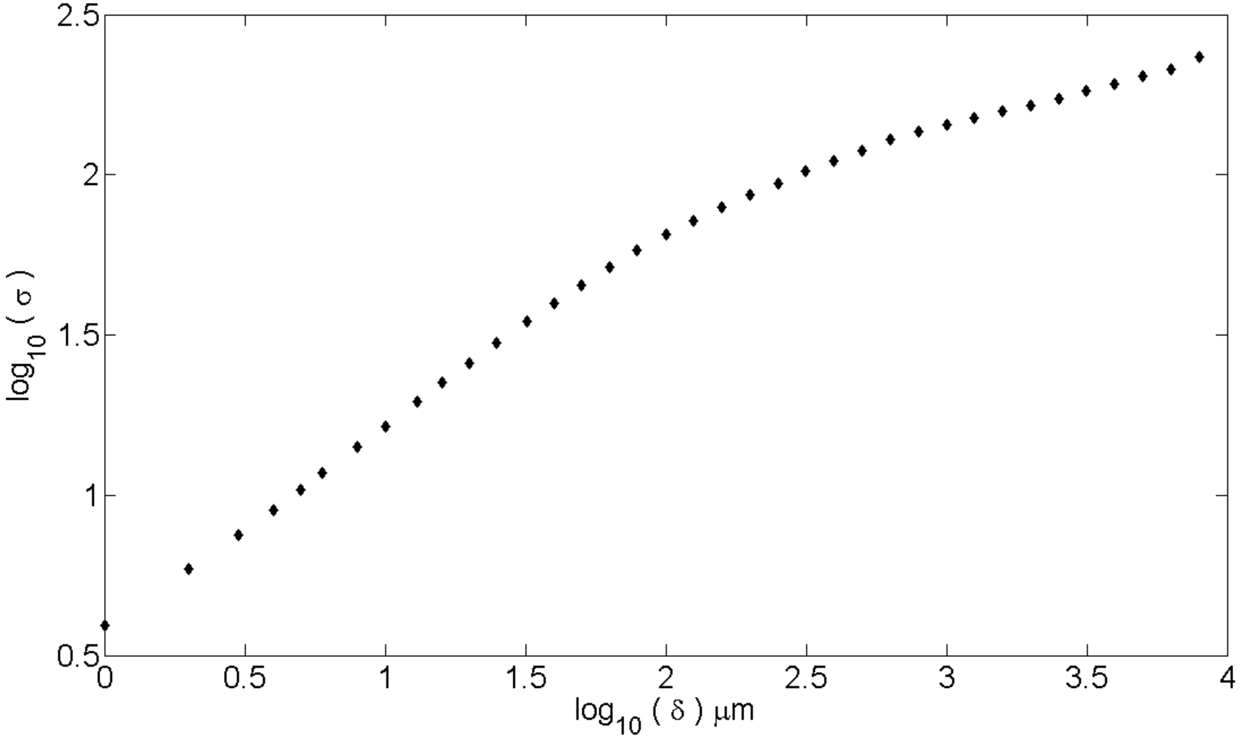


Front morphology analysis



Roughness measurement





- Root Mean Square (RMS)

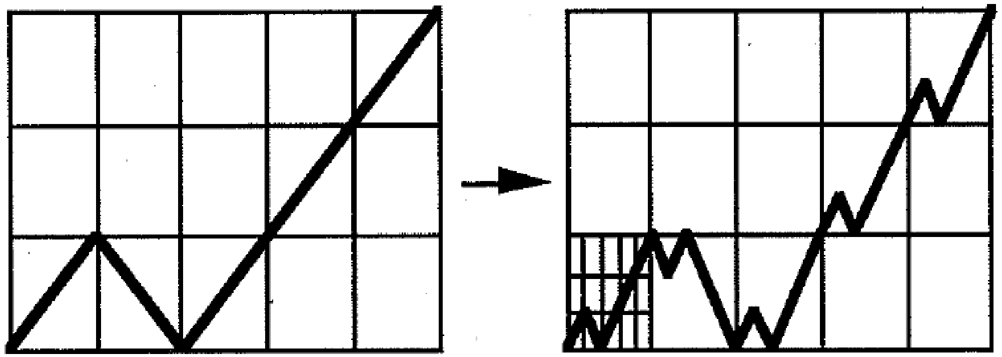
$$\sigma(\delta) = \left\langle \Delta y^2(\delta) \right\rangle^{1/2}$$

Roughness measurement

Scaling law

⇒ Self-affine structure = front shape statistically invariant under an affine transformation

$$d_x \rightarrow \lambda_x d_x \,,\; d_y \rightarrow \lambda_y d_y$$



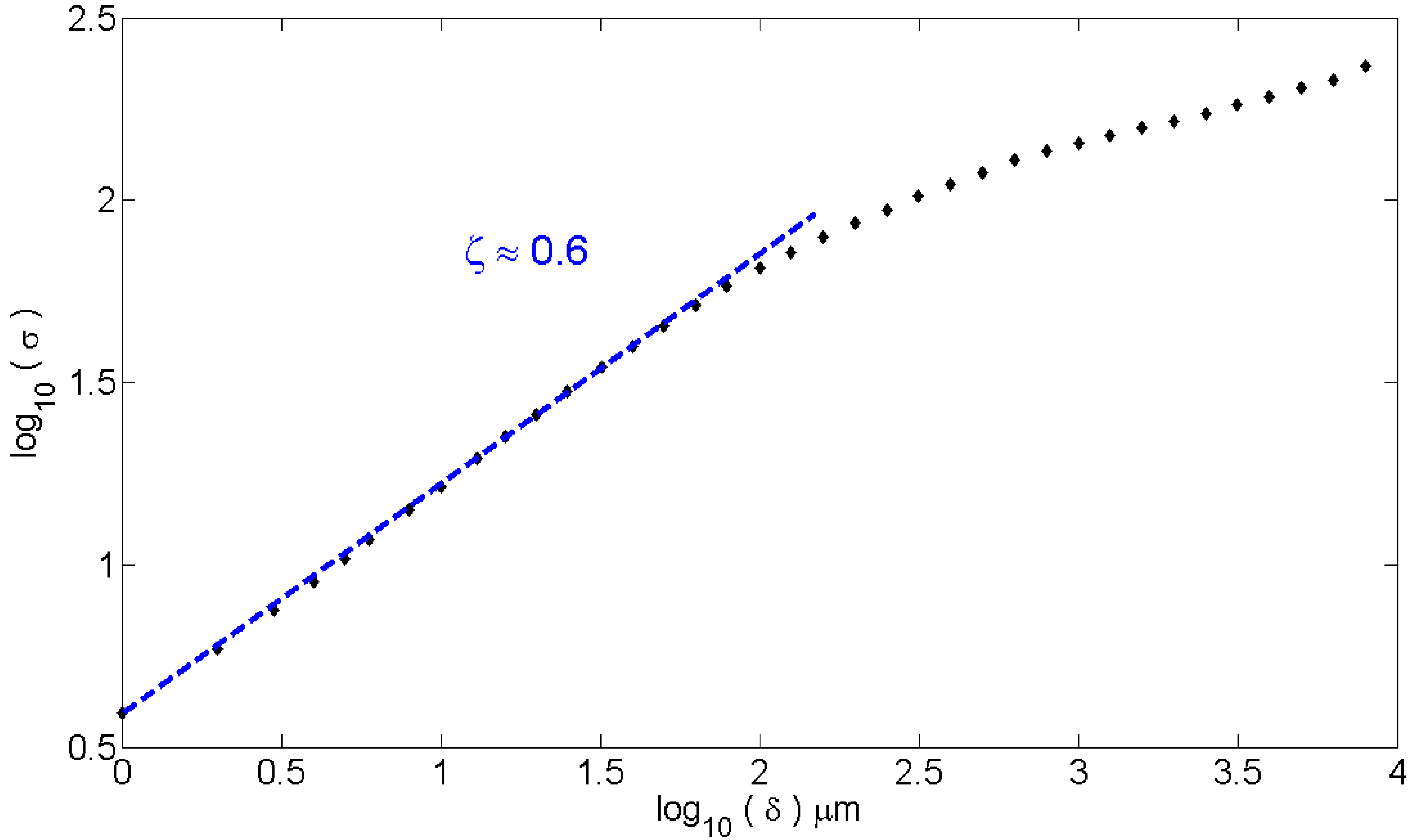
$$\lambda_y = \lambda_x^{\zeta}$$

roughness exponent

⇒ Determination of a roughness exponent ζ

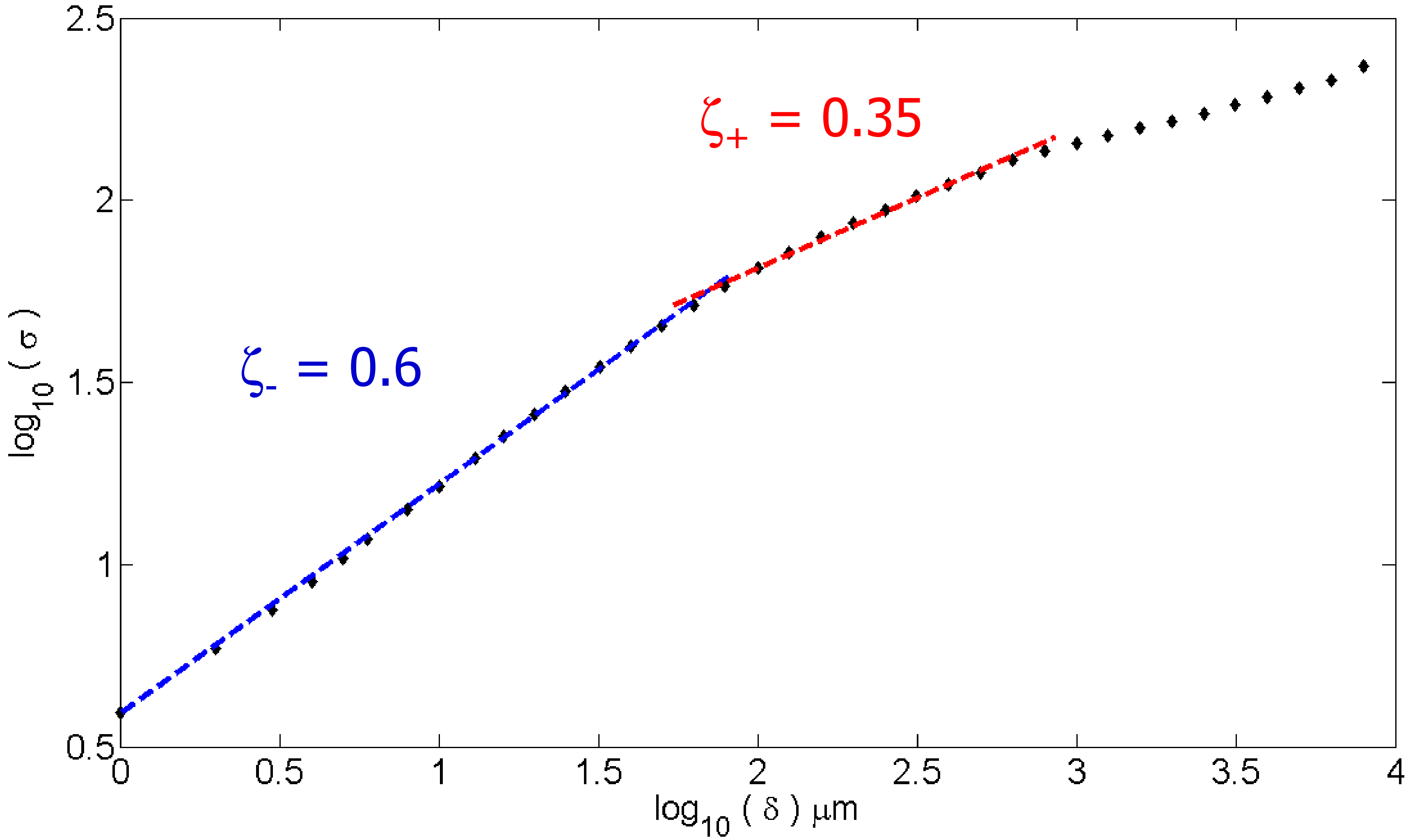
$$\langle \sigma(\delta) \rangle_{x0} \propto \delta^{\zeta}$$

Roughness measurement



Måløy & Schmittbuhl (PRL, 1997)
Delaplace et al. (1999)

Roughness measurement



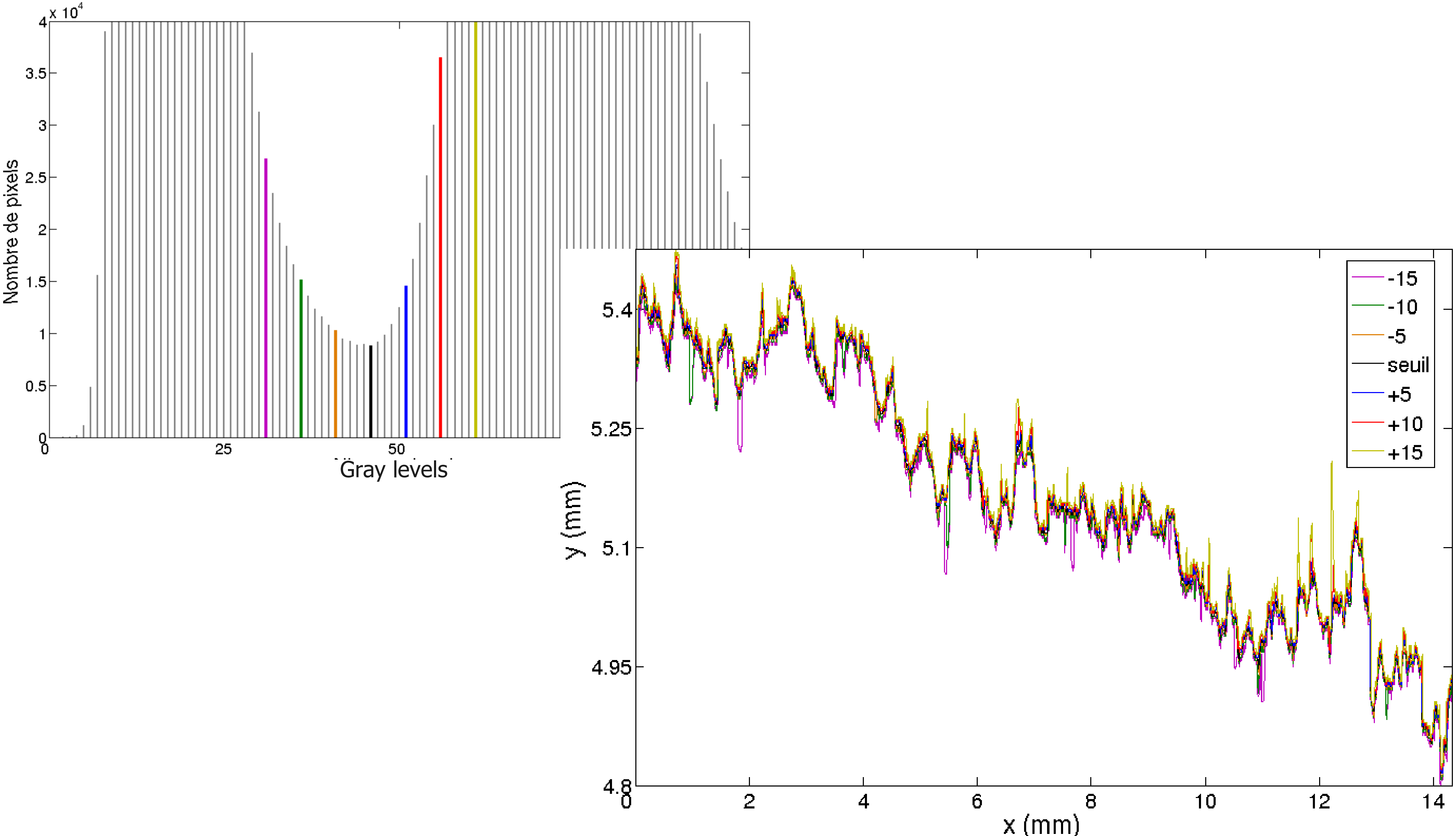
⇒ 2 roughness exponents

Roughness measurement

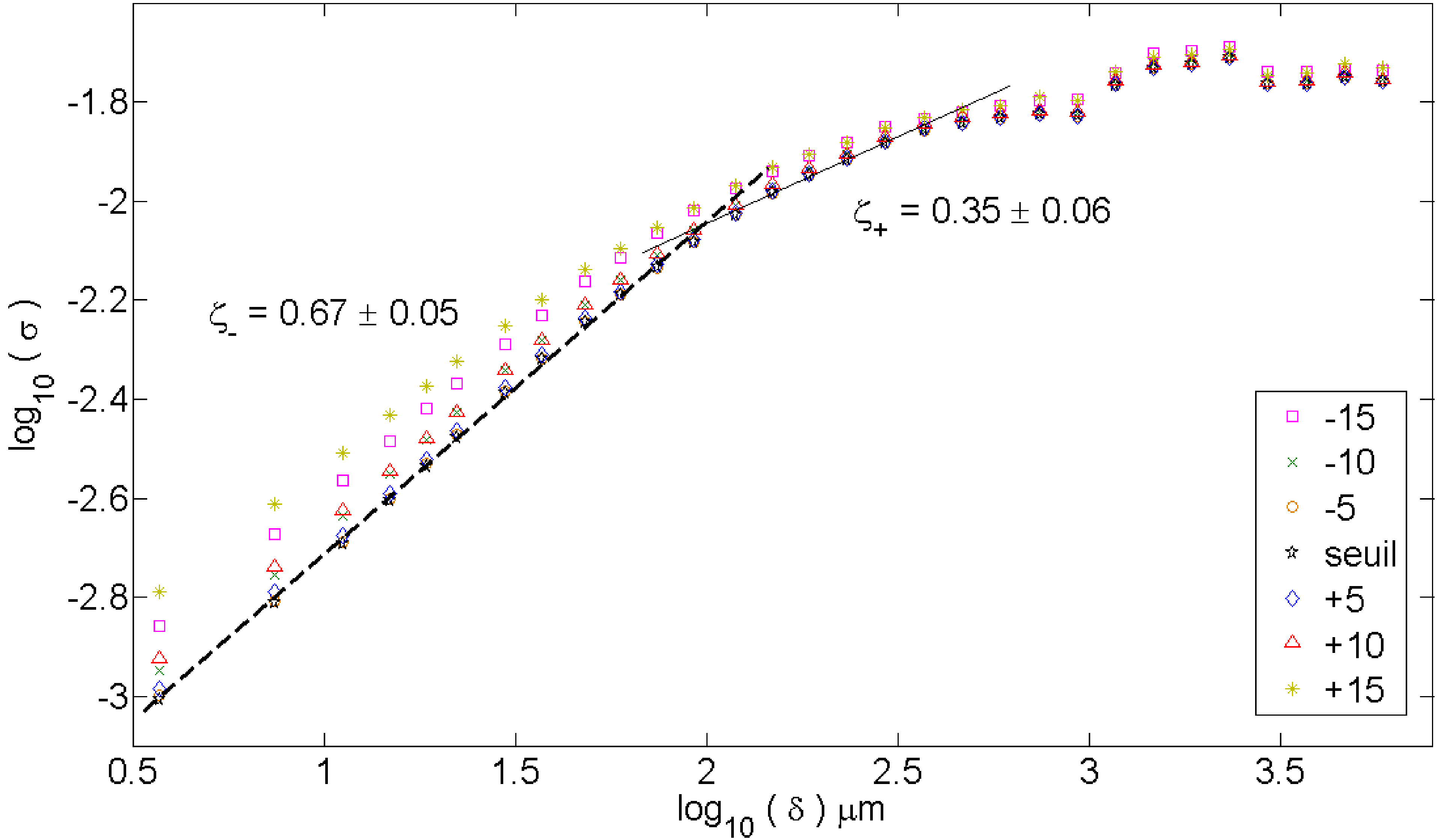
Result independent of parameters from:

- Image processing (threshold value for front extraction…)
- Optical acquisition (resolution = images taken with different magnifications of the microscope…)
- Disorder introduction procedure (sand-blasting with various beads, chemical…)
- Statistical method used to analyse the front morphology

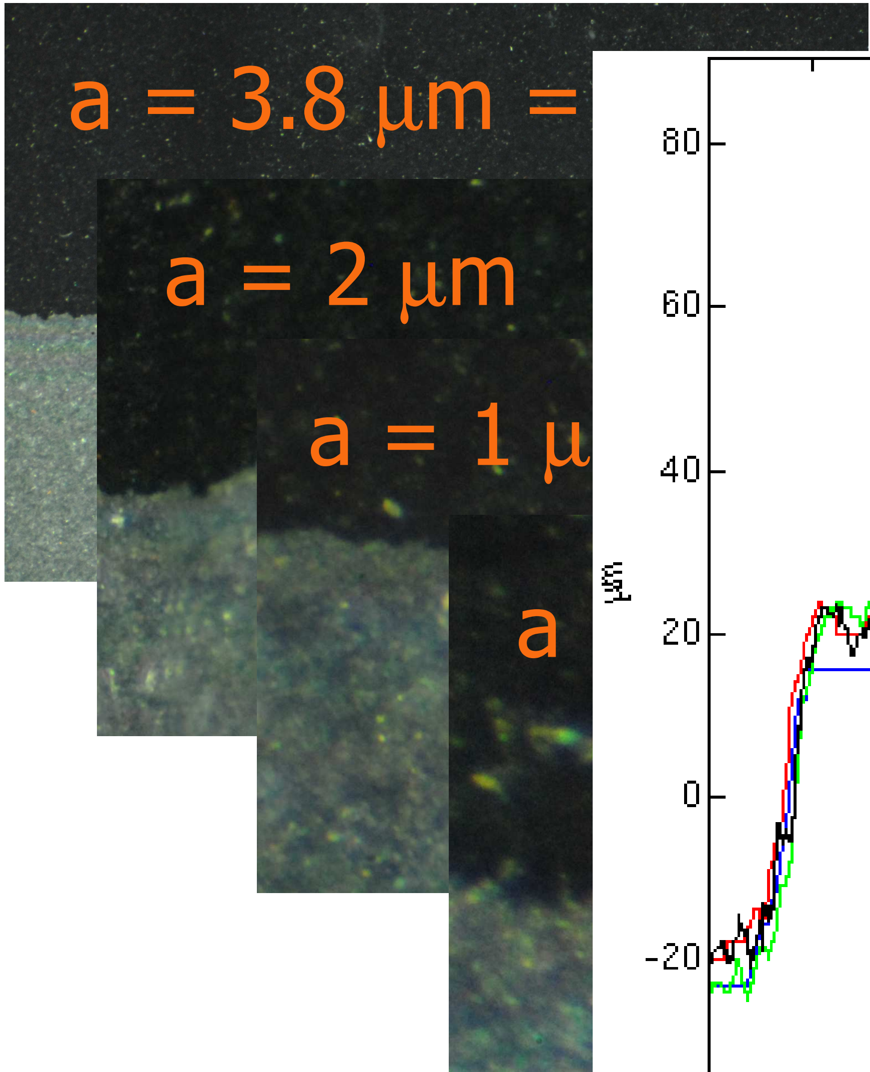
Effects of threshold

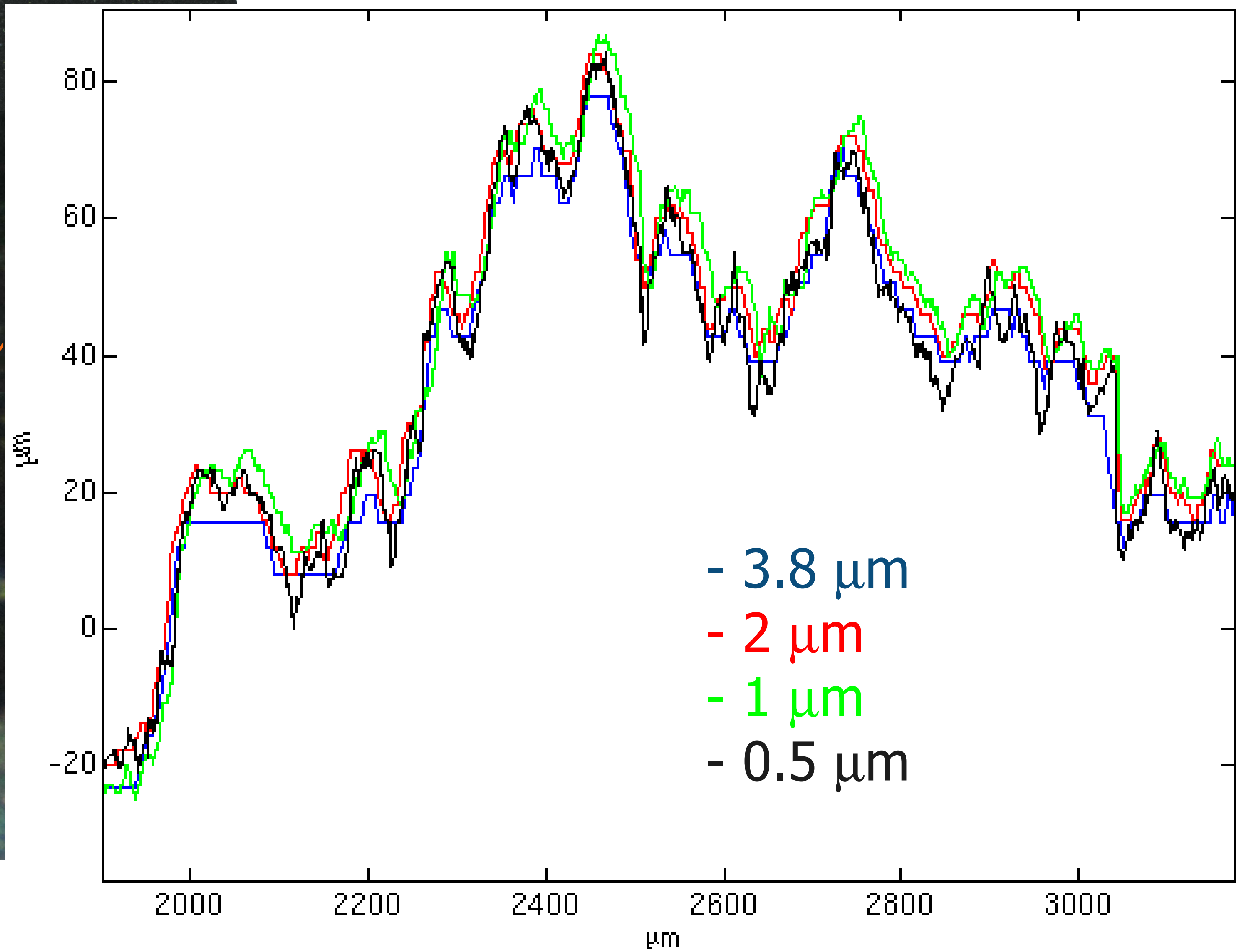


Effects of threshold

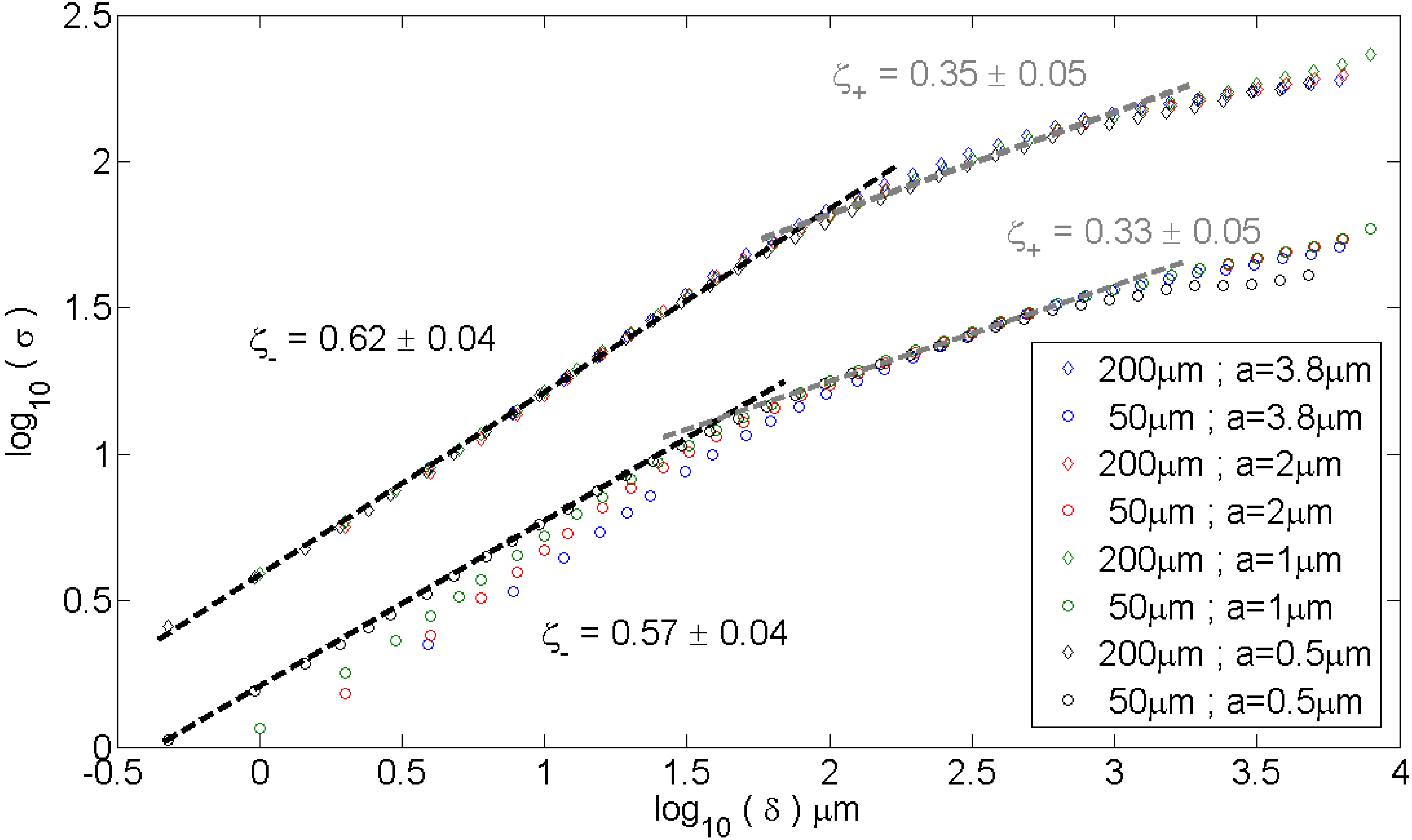


Effects of resolution

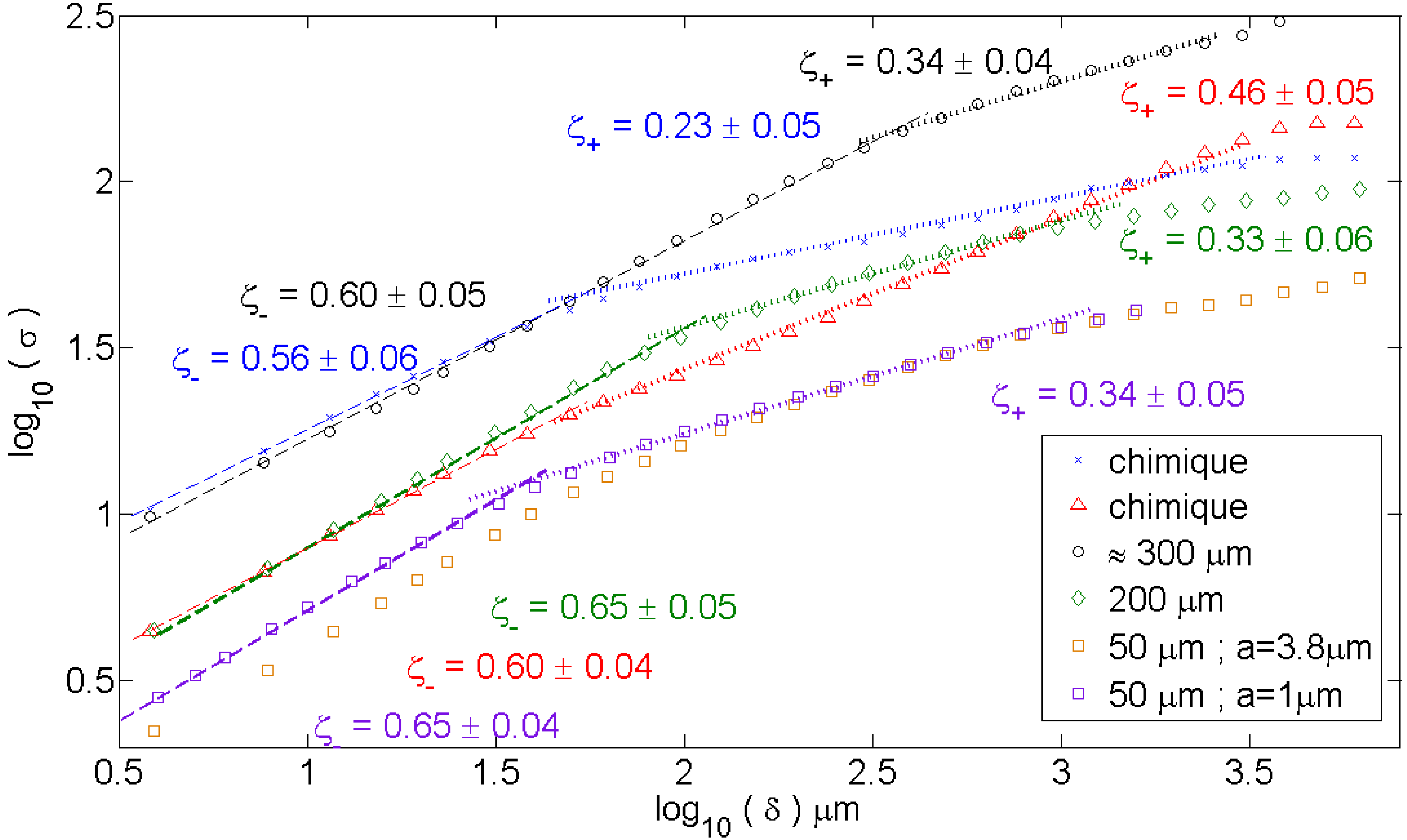




Effects of resolution



Effects of disorder



Coherence of roughness measurement methods

- Maximum-Minimum (MM)

$$\Delta(x_0,\delta)=\max_{x\in[x_0,x_0+\delta]}(y(x))-\min_{x\in[x_0,x_0+\delta]}(y(x))$$

$$\langle\Delta(\delta)\rangle_{x_0}\propto\delta^{\zeta}$$

Schmittbuhl et al. (PR E, 1995)

- Structure functions (SF)

$$C_k(\delta)=\left\langle\left|y(x+\delta)-y(x)\right|^k\right\rangle^{\frac{1}{k}}$$

$$C_k(\delta)=\delta^{\zeta_k}$$

Halpin-Healy (PR A, 1991)

- Power spectrum (PS)

$$P(k)\propto k^{-1-2\zeta}$$

P(k) = TF of $w(\Delta x)=\langle y(x+\Delta x)y(x)\rangle-\langle y(x+\Delta x)\rangle\langle y(x)\rangle$

Schmittbuhl et al. (1995)

- Average Wavelet Coefficient (AWC)

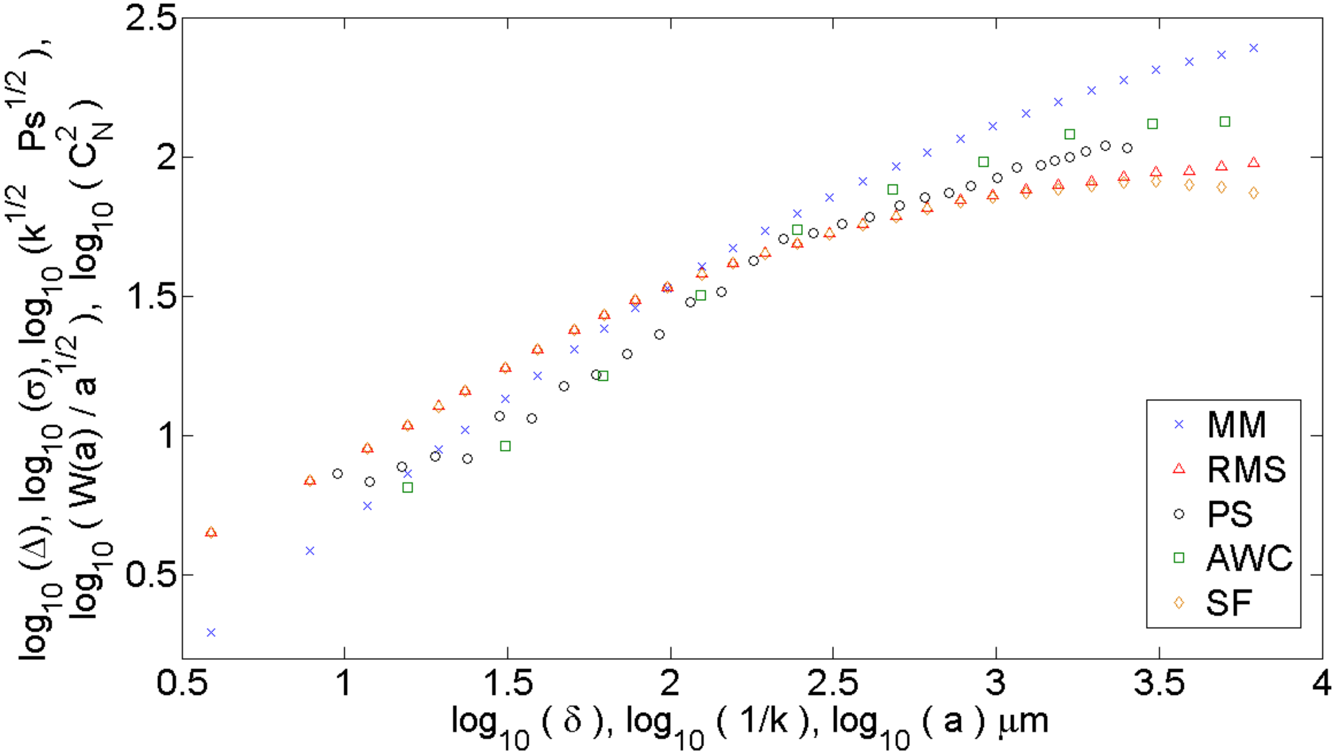
$$W[h](a)\propto a^{\zeta+\frac{1}{2}}$$

$$W[y](a)=\left\langle\left|W[y](a,b)\right|\right\rangle_b$$

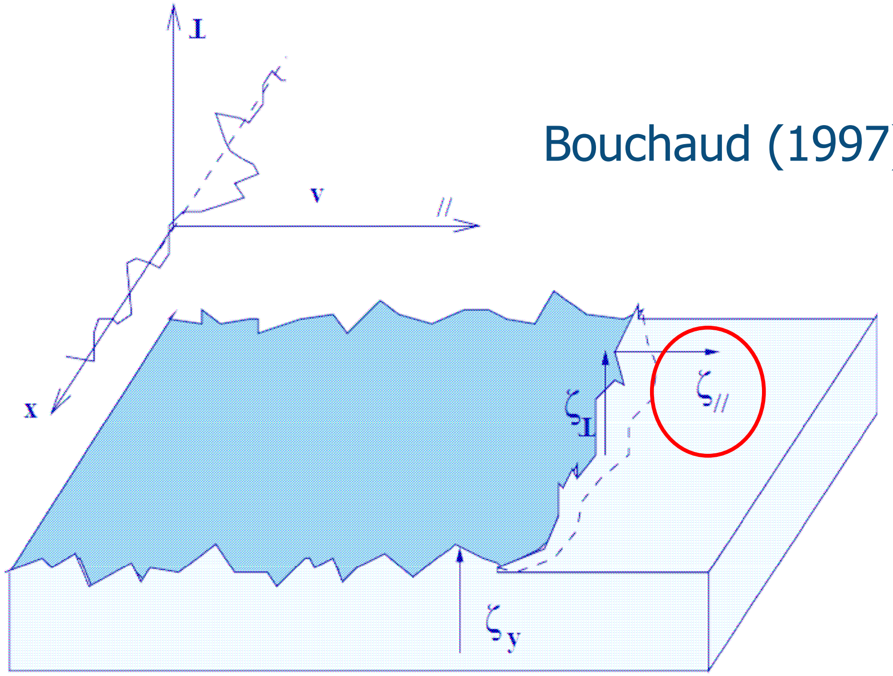
Simonsen et al. (1998)

Coherence of roughness measurement methods

	RMS	SF	MM	PS	AWC
ζ	0.33 ±0.06	0.35 ±0.05	0.44 ±0.05	0.35 ±0.07	0.37 ±0.05
	0.65 ±0.05	0.62 ±0.04	0.80 ±0.06	0.69 ±0.04	0.73 ±0.07

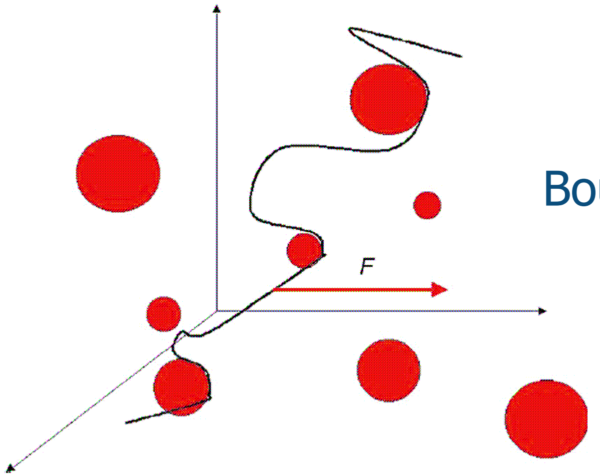


Comparison with former roughness measurements

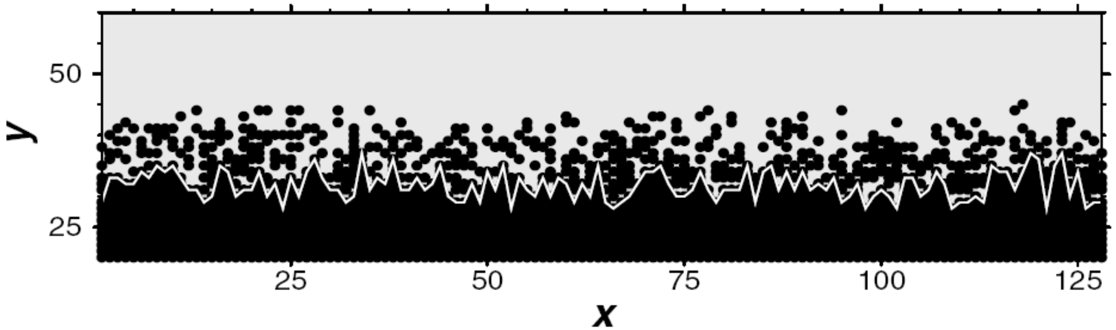


Bouchaud (1997)

	$\zeta_{//}$
modelisation	0.35 Schmittbuhl et al. (1995) 0.6 Hansen et al. (2003)
experiments	0.6 Daguier et al. (1995) Delaplace et al. (1999)



Bouchaud et al. (1990)



Hansen et al. (2003)

Comparison with former roughness measurements

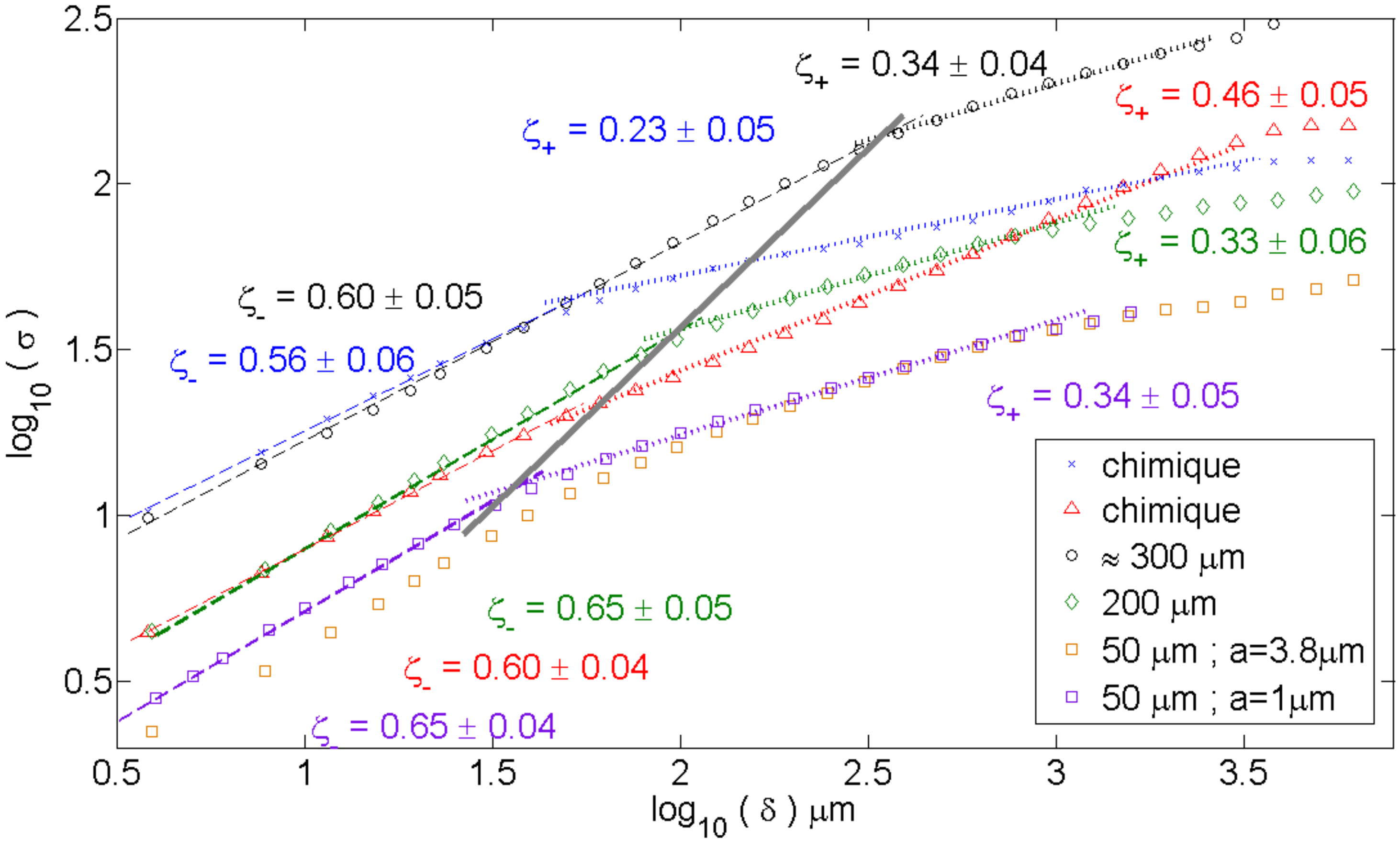
Hypothesis:

- Coalescence processes at small scales
- Fluctuating elastic line at large scales

gray line

σ= 0.35 δ*

with δ* = separating length scale



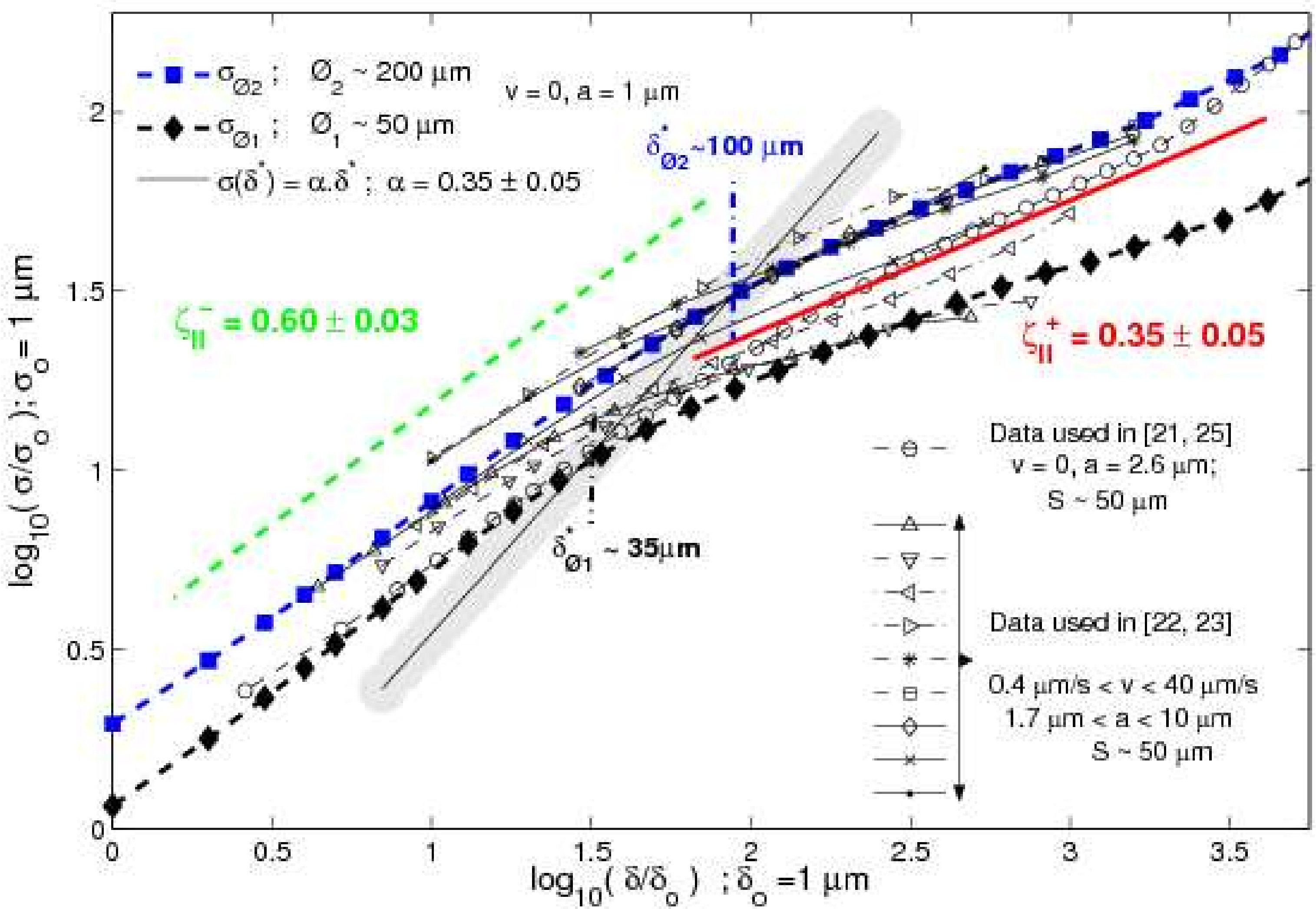
Comparison with former roughness measurements

Robust because found for former experiments too

gray line

σ= 0.35 δ*

with δ* = separating length scale



Conclusions on morphology

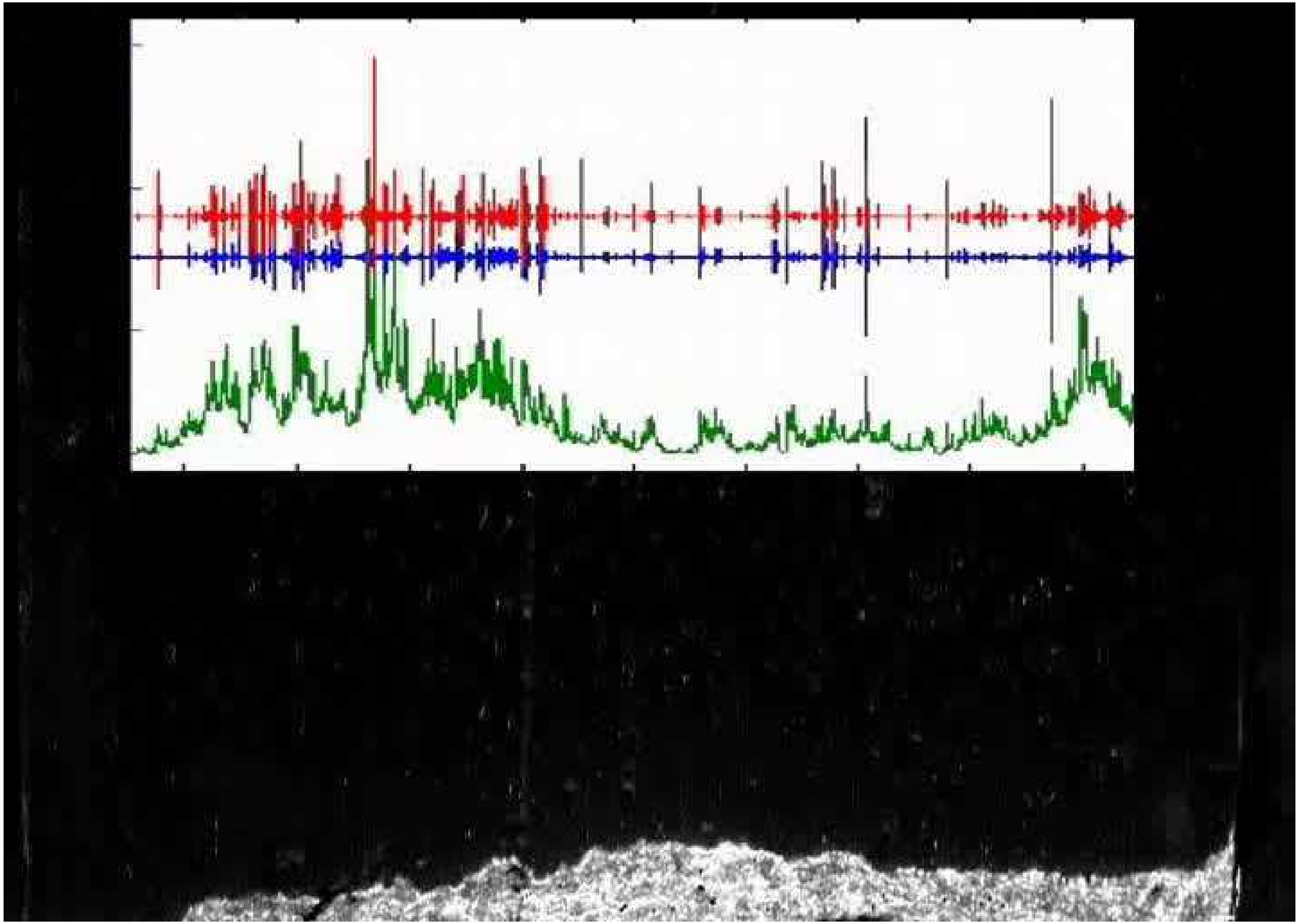
- Two roughness regimes: $\zeta \approx 0.6$ at small length scales and $\zeta \approx 0.35$ at large length scales
- Robust for different parameter changes (disorder preparation, resolution…)
- Threshold length scale around disorder typical length

⇨ Regime at small length scales due to coalescence processes
⇨ Regime at large length scales due to long-range elastic interaction processes
⇨ These roughness regimes seem universal

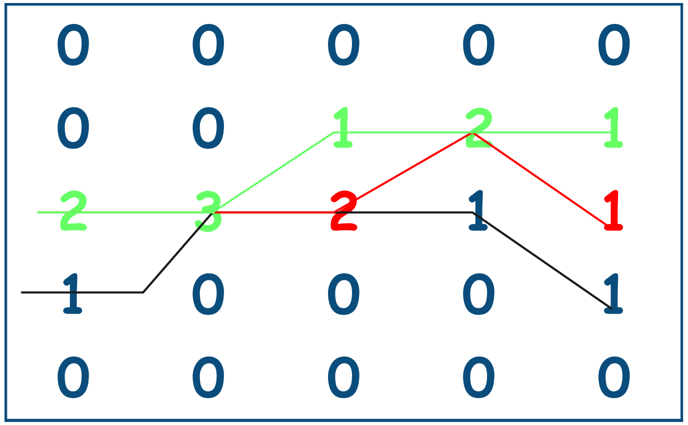
Front dynamics analysis

AE signal
sensor 1
sensor 2

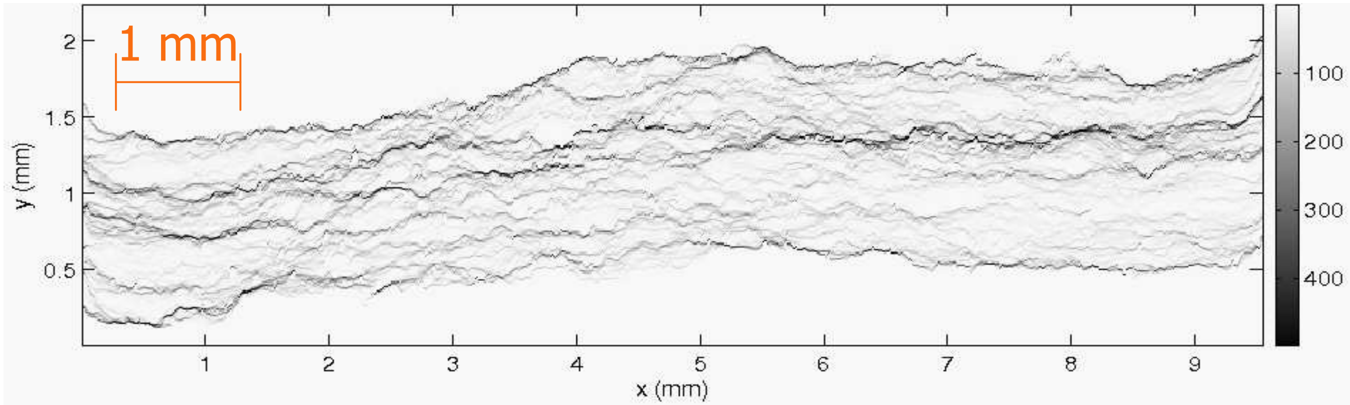
Mean front velocity ⟨V⟩



Local velocities



Waiting time matrix W(x,y)

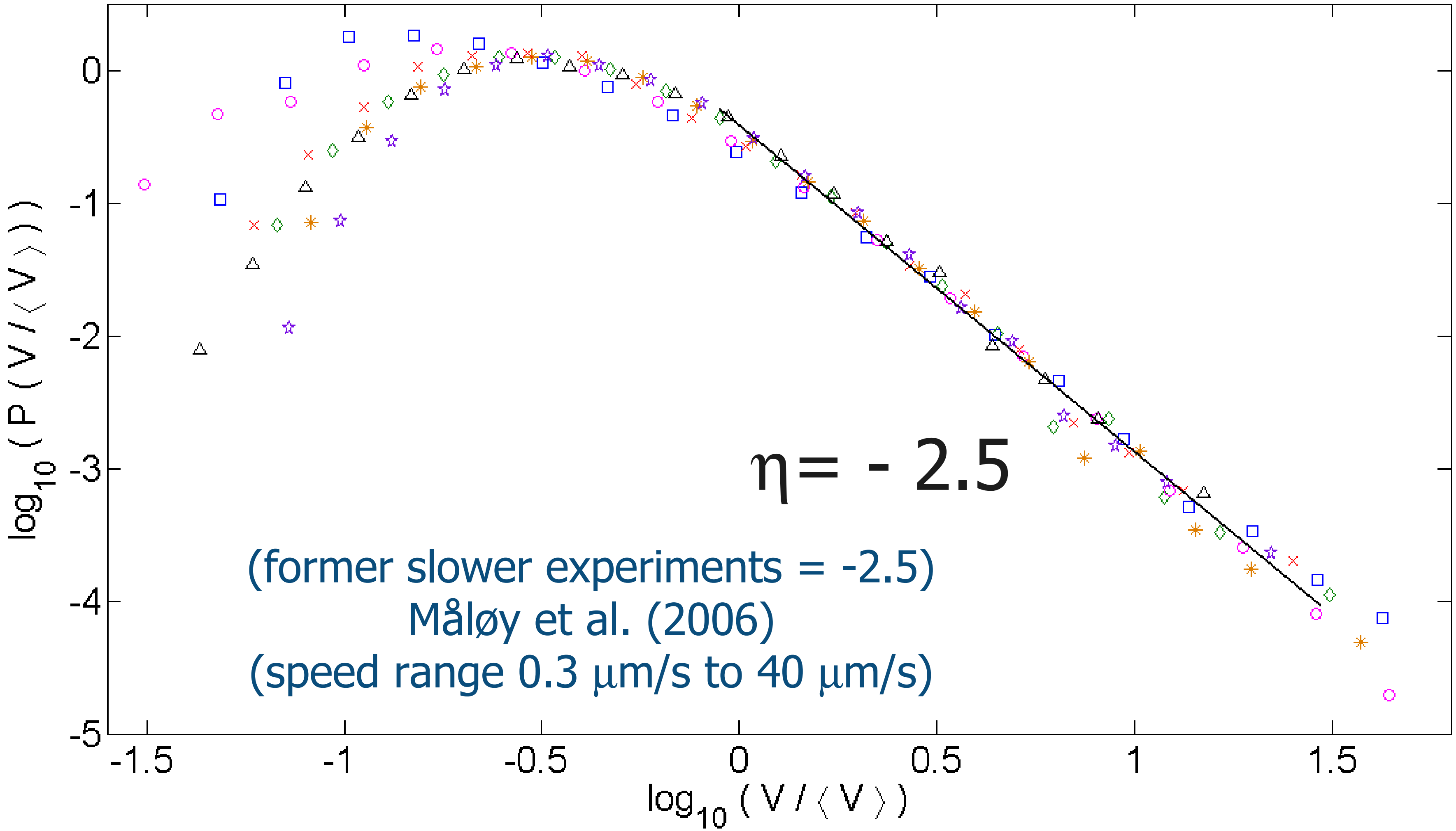


Velocity matrix: $V(x,y) = \frac{\alpha}{\delta t} \frac{1}{W(x,y)}$ $\begin{cases} \alpha = 10\ \mu m \\ \delta t = 1\ ms \end{cases}$

$150\ \mu m/s < \langle v \rangle < 1000\ \mu m/s$

Local velocities

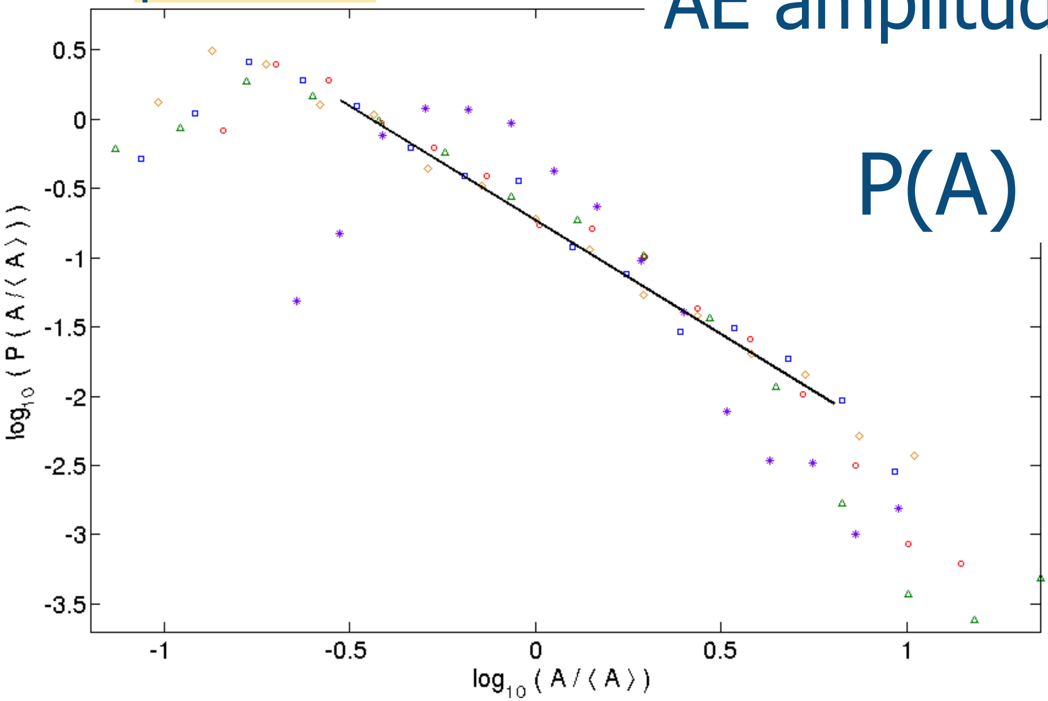
≠ colors and signs ⇒ ≠ disorders
≠ mean front velocities



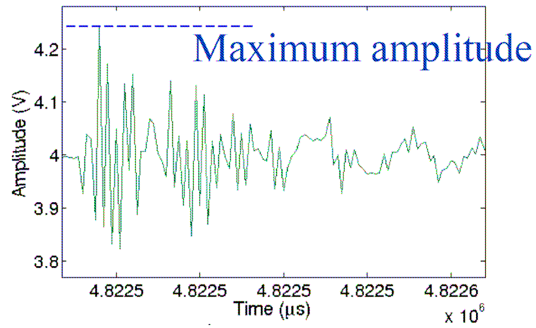
$\eta = -2.5$

(former slower experiments = -2.5)
Måløy et al. (2006)
(speed range 0.3 μm/s to 40 μm/s)

AE amplitude distribution



$$P(A) \propto A^{-1.65}$$



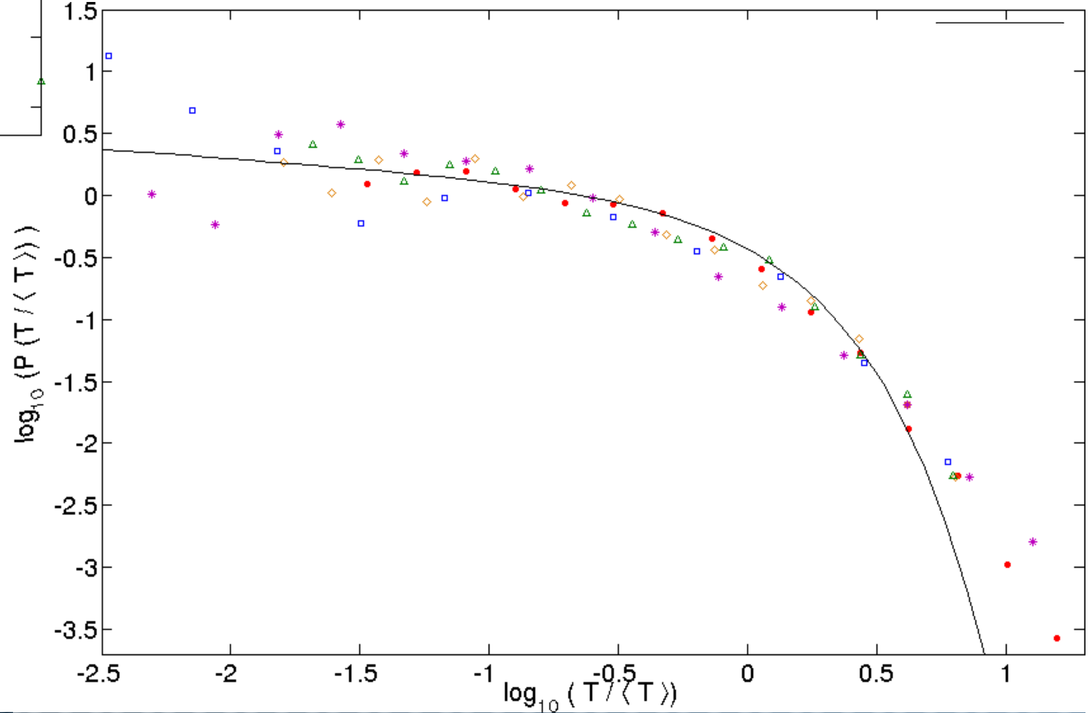
≠colors and signs
⇒ ≠ disorders
≠ mean front velocities

AE waiting time distribution

$$P(T) \propto T^{-(1-\gamma)} \exp(-T/B)$$

$$\gamma = 0.85 \; ; \; B = 1$$

(idem Davidsen et al., PRL, 2007)

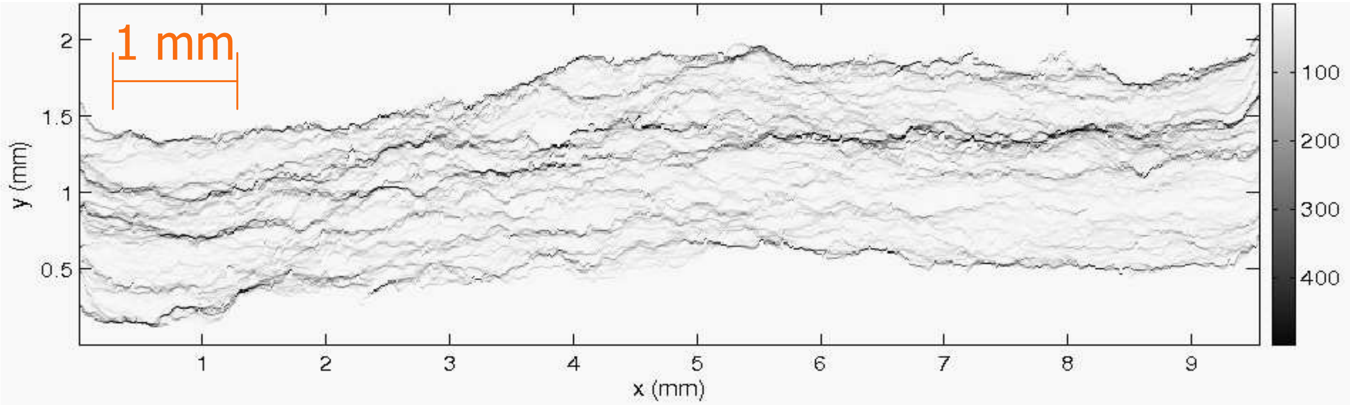


Conclusions on dynamics

- Distribution of velocities follows a power law ⇒ robust for different disorders and front speeds
- Preliminary results on AE show scaling law distributions of amplitudes and waiting times

Building catalogs

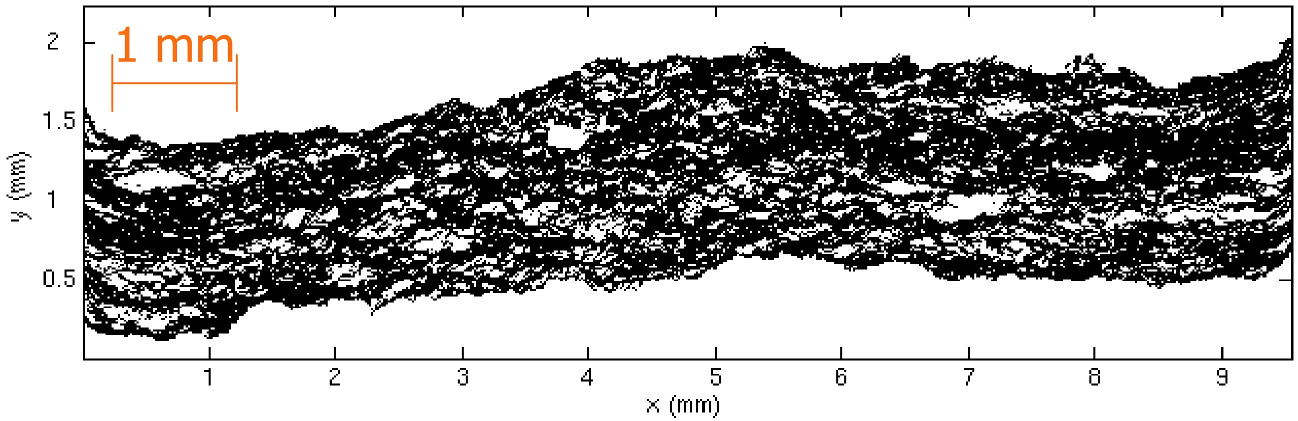
Waiting time matrix W(x,y)



Velocity matrix: $V(x,y) = \frac{\alpha}{\delta t} \frac{1}{W(x,y)}$ $\begin{cases} \alpha = 10\,\mu m \\ \delta t = 1\,ms \end{cases}$

$$v = \begin{cases} 1 \text{ if } v > C \langle v \rangle \\ 0 \text{ else} \end{cases}$$

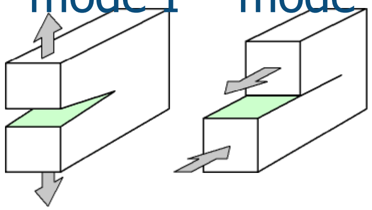
$150\ \mu m/s < \langle v \rangle < 1000\ \mu m/s$

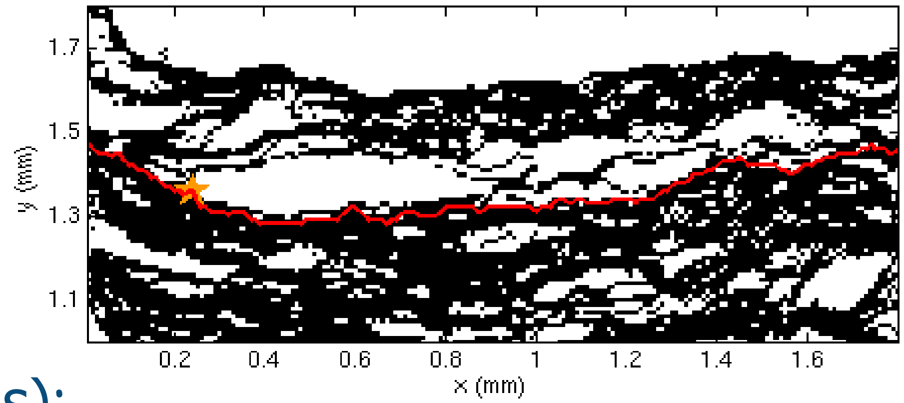


Building catalogs

Parameters for each event:

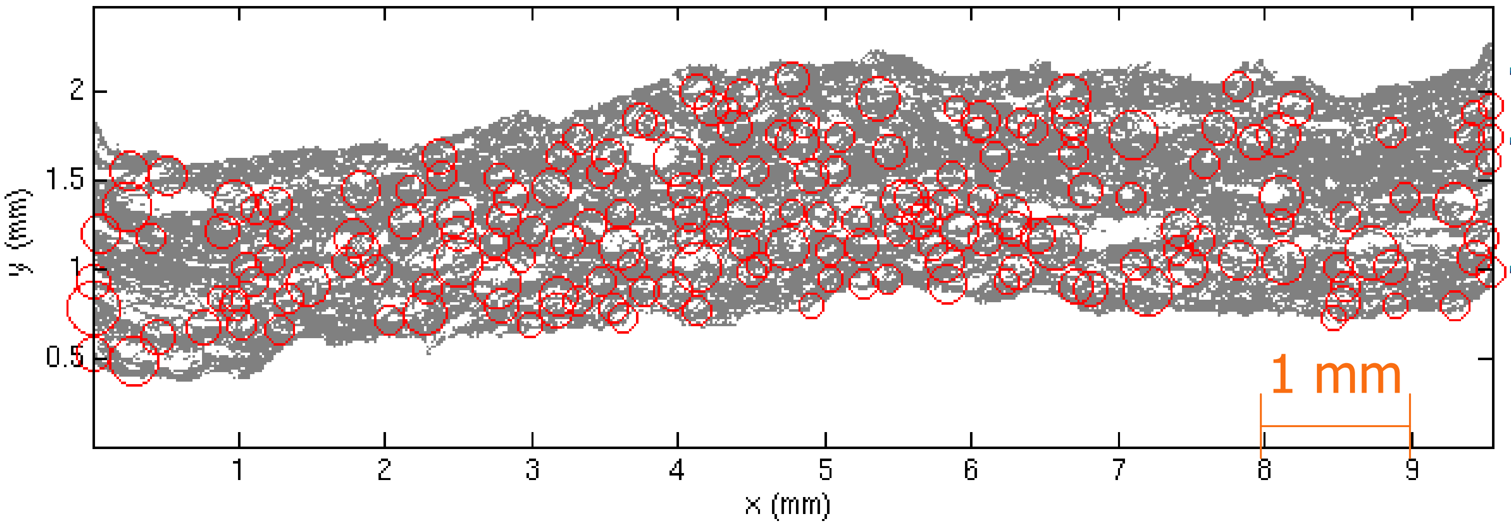
- Time of occurrence t
- Epicenter position (x,y)
- Moment M ≈ area A of event (nb of pixels):





$M \approx E_I \times A \times$ Opening (constant)

(Seismic moment: $M_0 \approx \mu \times S \times D$ with S=cracked area & D=fault offset)

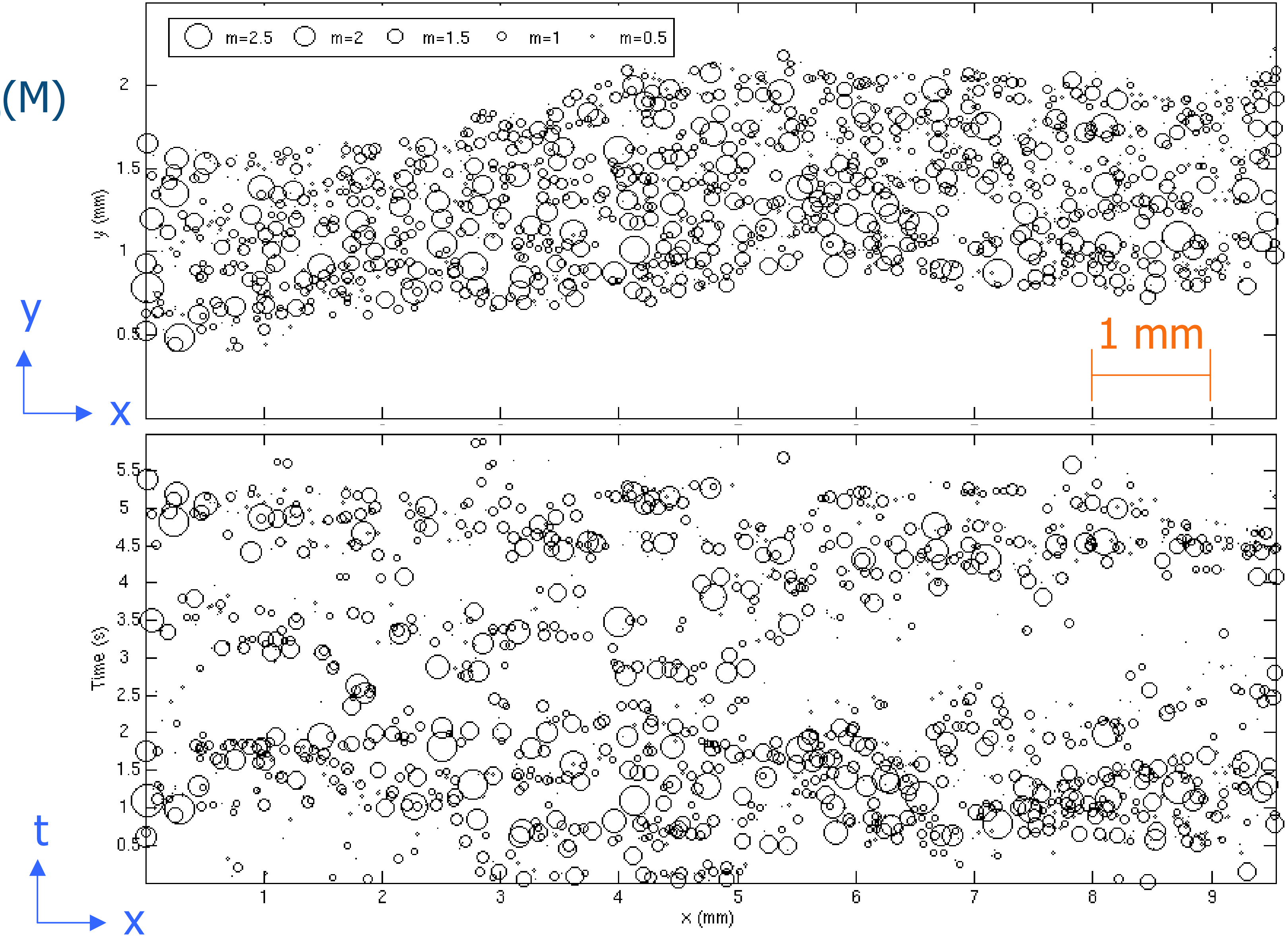


- Circles = events
- Diameter of circles ≈ $\log_{10}(M)$
- Only events with $\log_{10}(M) > 1.5$ represented

- Circles = events
- Diameter ≈ $\log_{10}(M)$

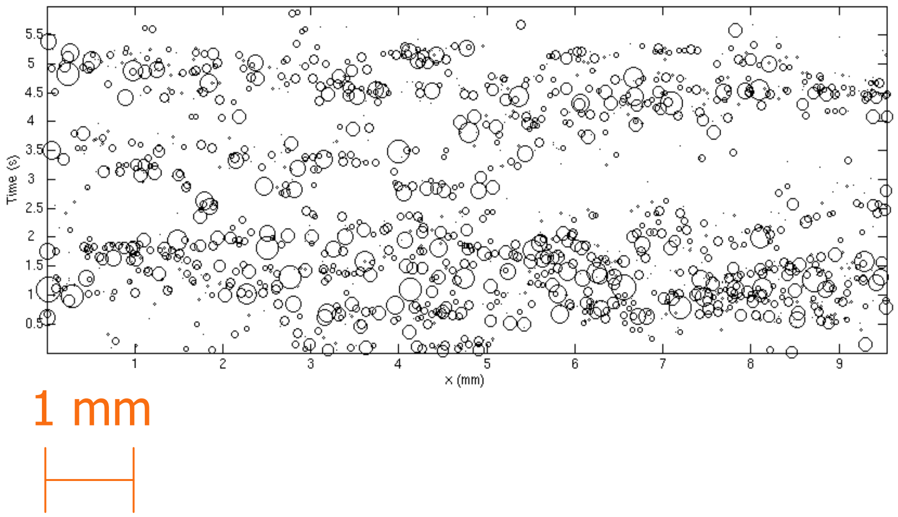
x – y map

x – t map

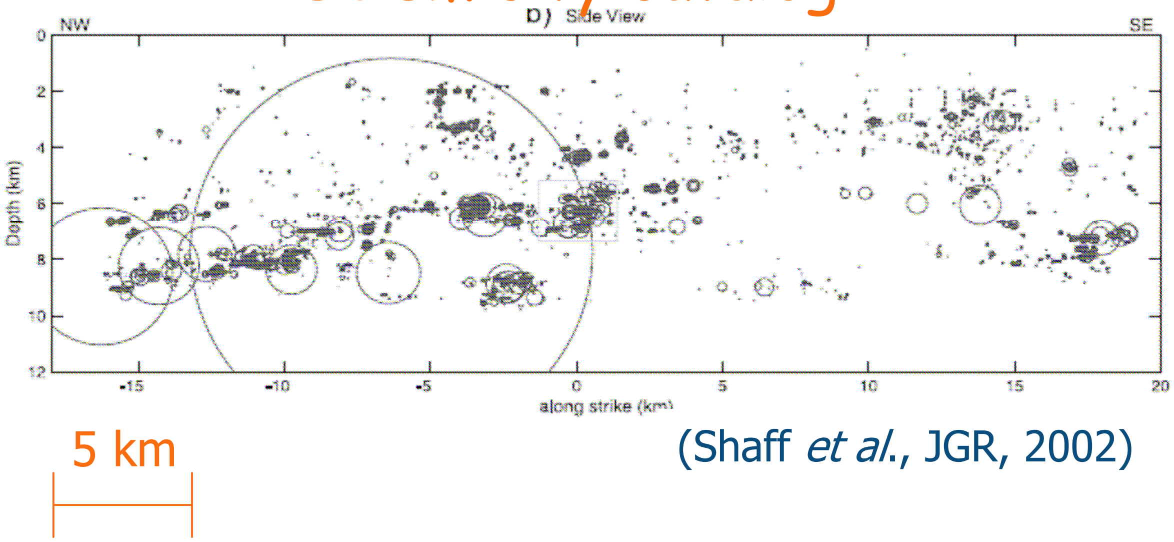


- Definition of event = avalanche
- Building quake catalogs similar to seismicity catalogs

Experimental catalog



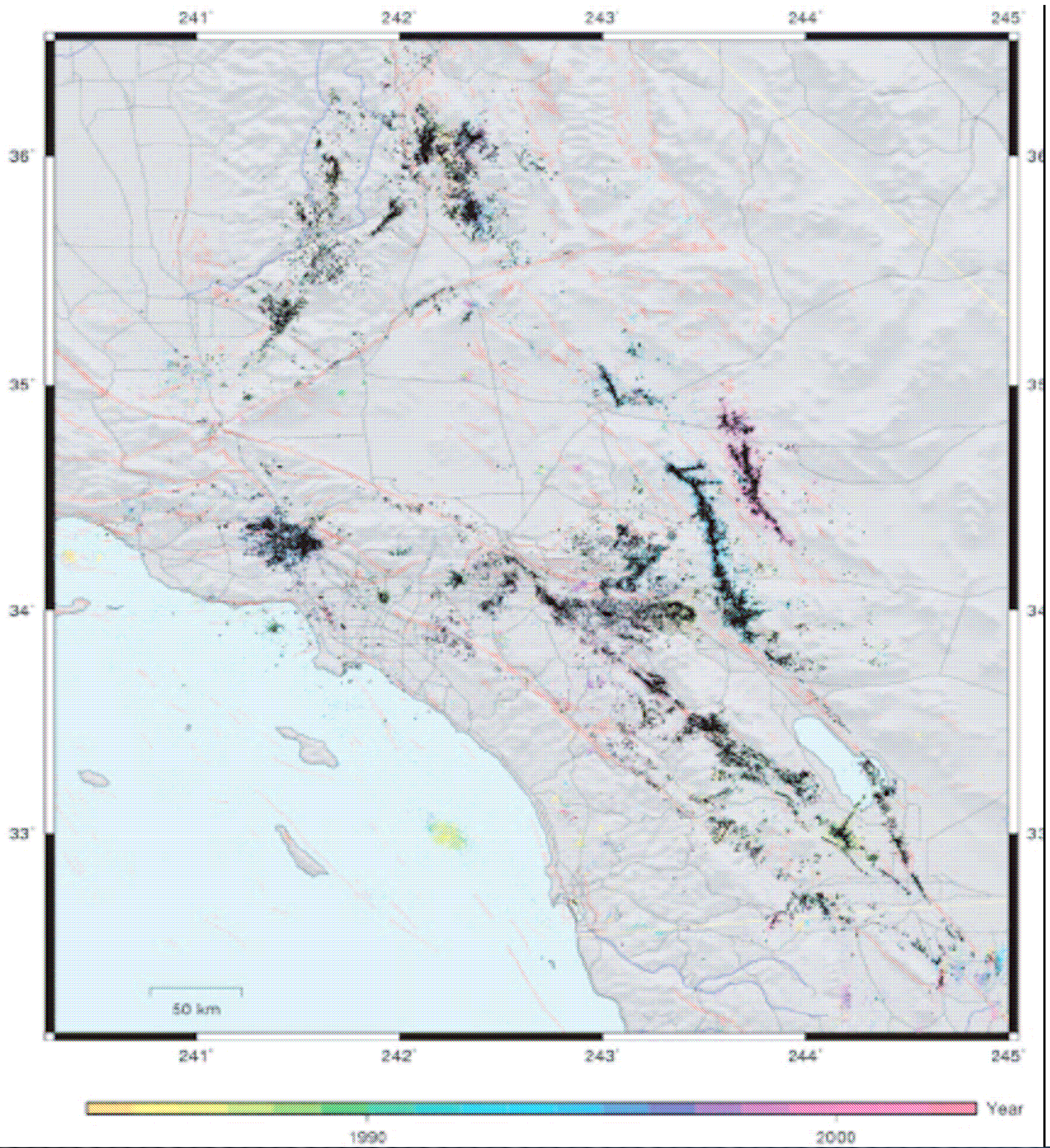
Seismicity catalog



(Shaff *et al.*, JGR, 2002)

⇨ **Link between the two catalogs?**

⇨ **What explanation for the similarities?**



Southern California seismicity 1984-2002
(Shearer *et al.*, BSSA, 2005)

- Homogeneous from 1984 to 2002
- Complete for earthquakes with magnitude > 2.5
- Area (120.5°W,115.0°W) x (32.5°N,36.0°N)
- 22217 events
- Magnitude M_w ⇨ seismic moment M_0 (in N.m)

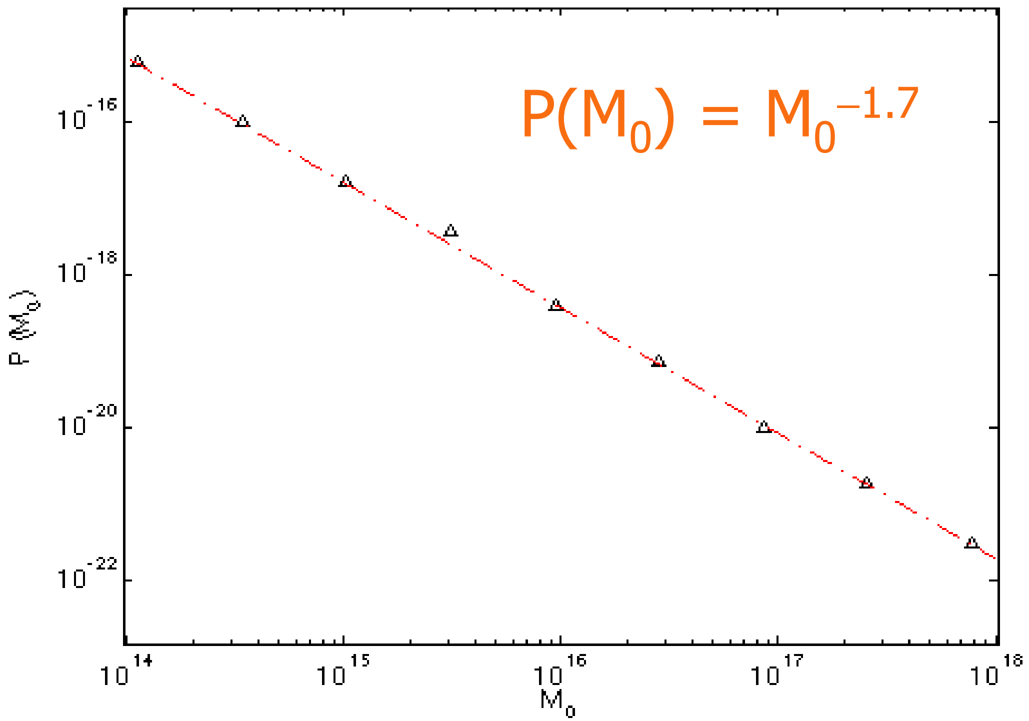
$$\log_{10}(M_0) = \frac{3}{2} M_w + 9.1$$

(Kanamori, JGR, 1977)

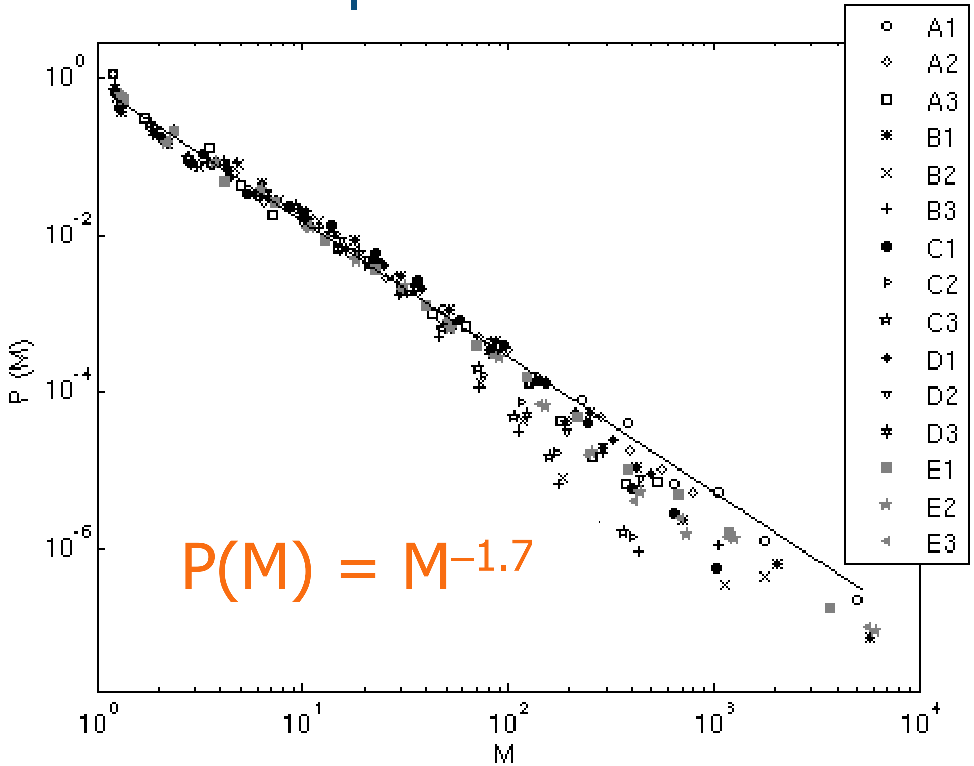
Gutenberg-Richter relationship: $N(M_0) \approx M_0^{-1-\beta}$

(Gutenberg and Richter, BSSA, 1944)

Seismicity data



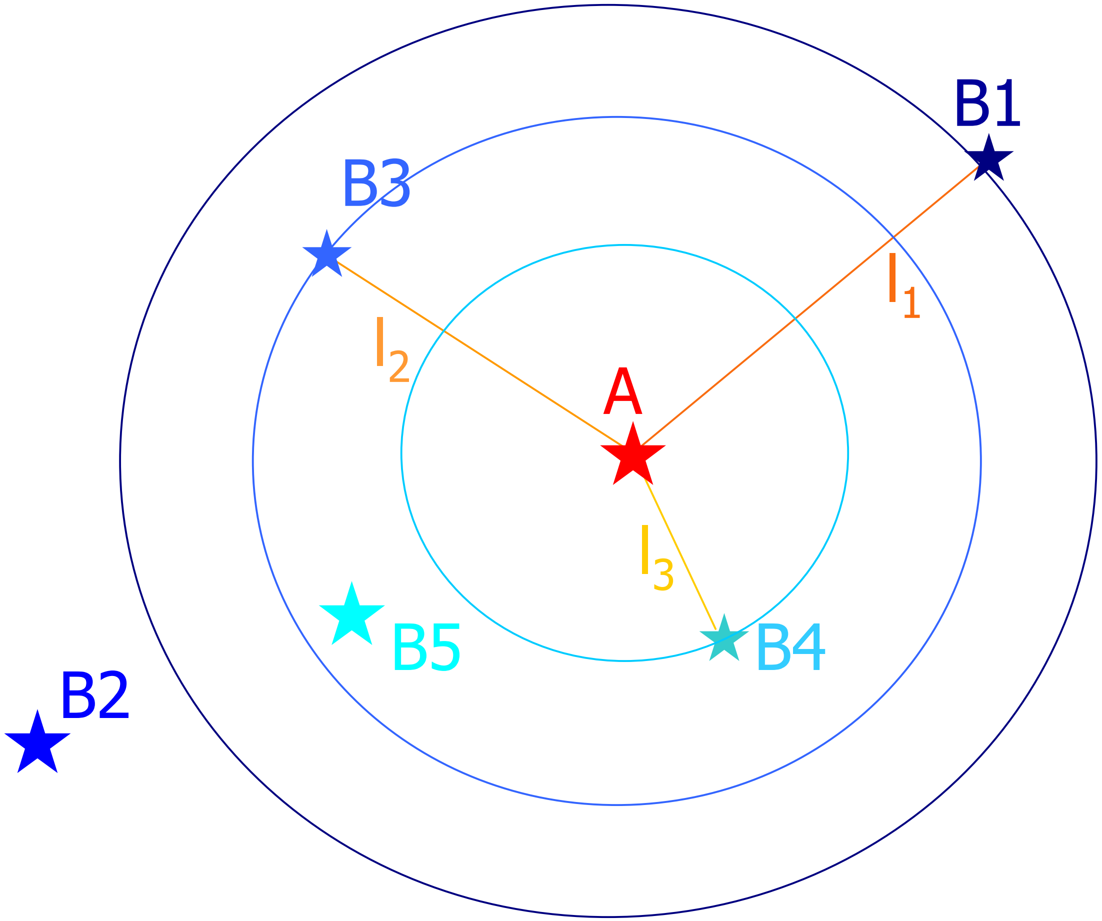
Experimental data



15 experimental catalogs from 5 experiments, each with 3 different C values

B is a record of A if no event happens within the disc of radius AB (distance l) centered on A during $[t_A,t_B]$, with $t_A < t_B$ (time interval $T=t_A-t_B$).

(Davidsen *et al.*, GRL, 2006)



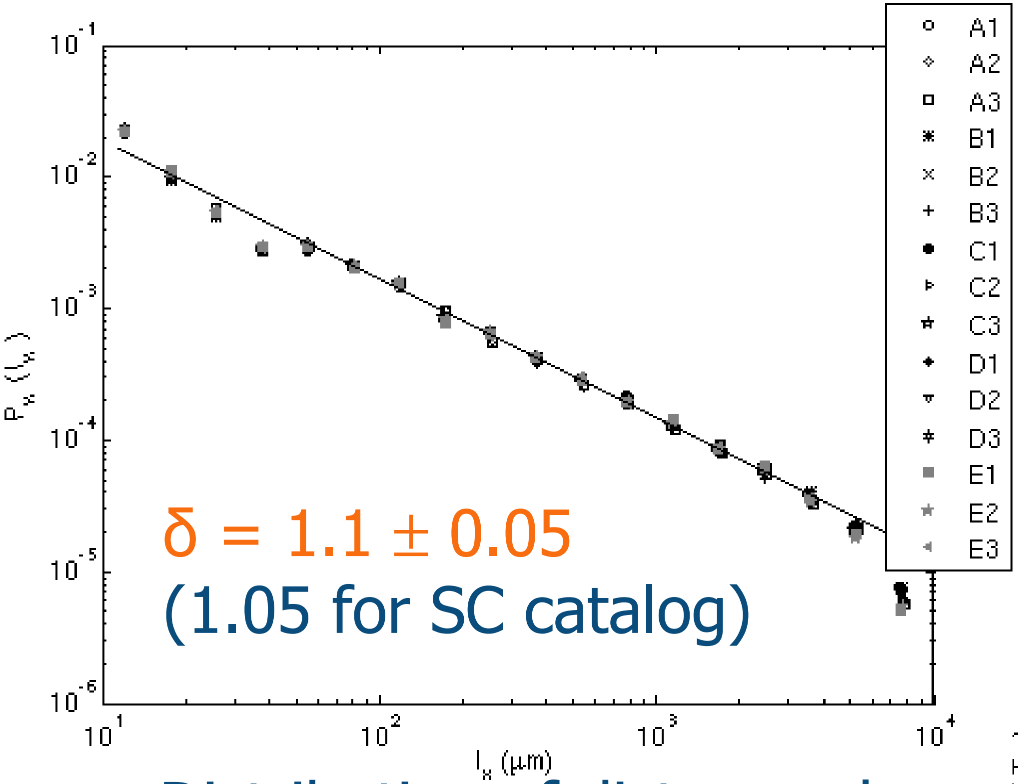
- All events B happen after event A.
- Numbers represent the order of occurrence of events in the catalog.
- Records of A = B1, B3 and B4.
- Distributions of distances:

$$l_i = | x_0 - x_i |$$

- Distributions of time intervals:

$$T_i = t_0 - t_i$$

15 experimental catalogs from 5 experiments, each with 3 different C levels

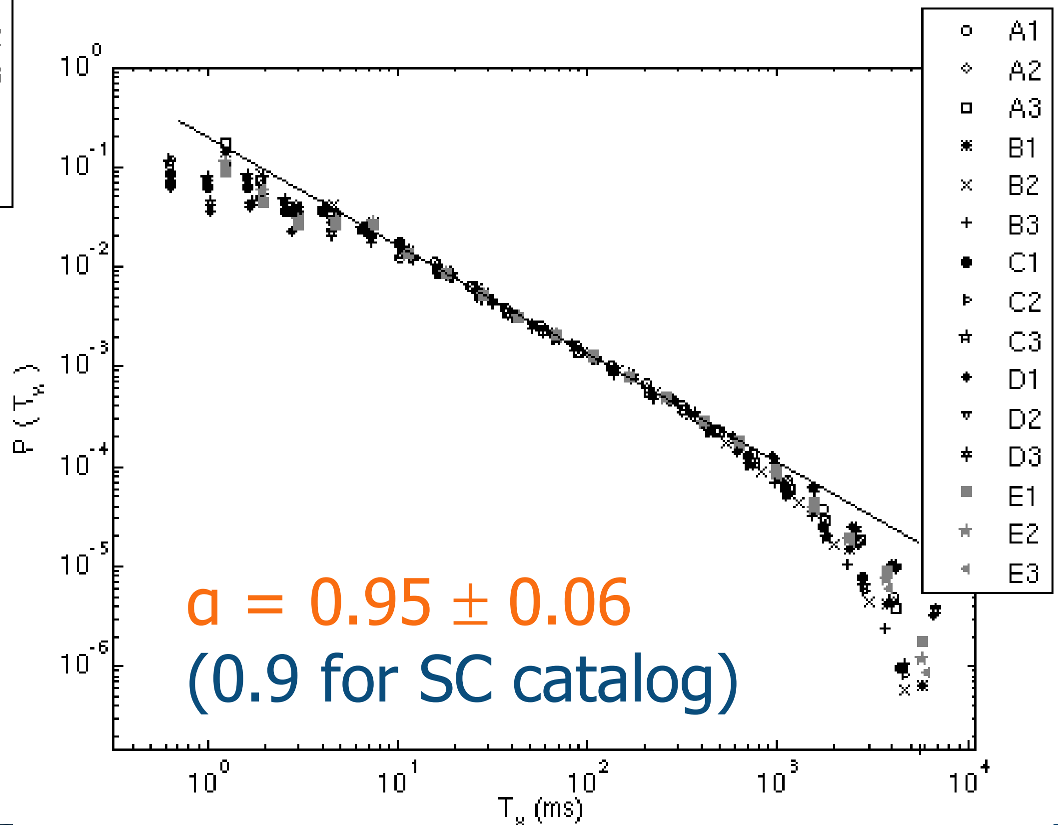


$\delta = 1.1 \pm 0.05$

(1.05 for SC catalog)

Distribution of distances l

Distribution of time intervals T



$\alpha = 0.95 \pm 0.06$

(0.9 for SC catalog)

Conclusions for comparison with large scale data

- Quake catalogs with a large number of events (typically a few thousands)
- Obey same scaling laws as seismicity data (Gutenberg-Richter, distribution of recurrent distances, distribution of recurrent time intervals) despite different spatial and time scales, different physical mechanisms and different geometries

⇨ Microstructures control the dynamics of crack propagation at large scales

⇨ Global dynamics of rupture propagation depend on event interactions

⇨ The long range elastic coupling between heterogeneous microstructures control these interactions

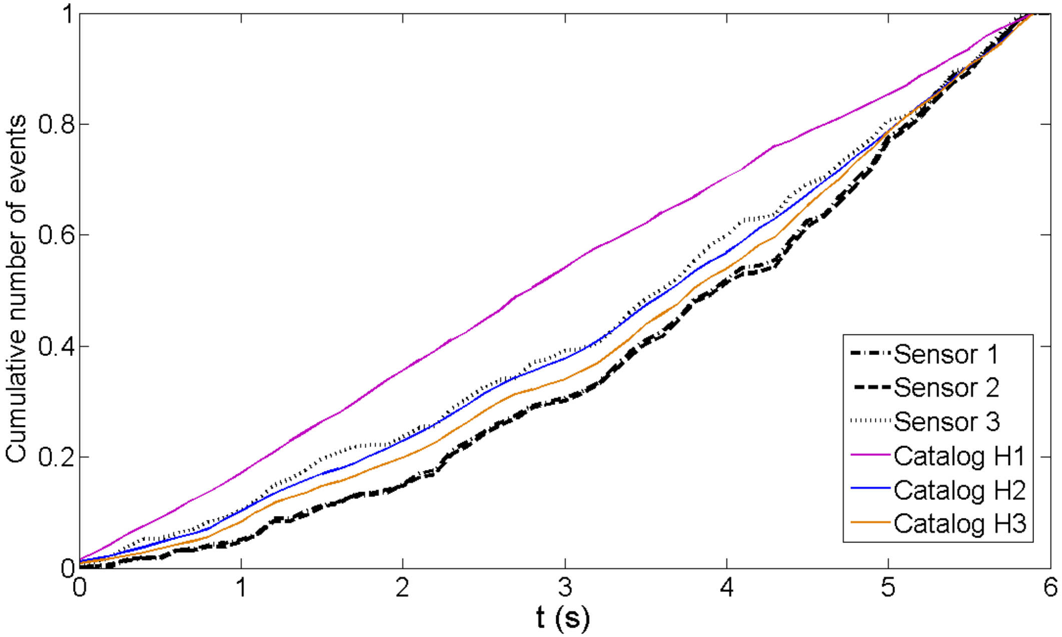
- Optical and acoustic monitoring of a crack propagation along a heterogeneous interface at high spatial resolution or high time rate

- Two roughness regimes, $\zeta = 0.6$ at small and $\zeta = 0.35$ at large scales, separated by a typical length scale, robust for different parameter changes

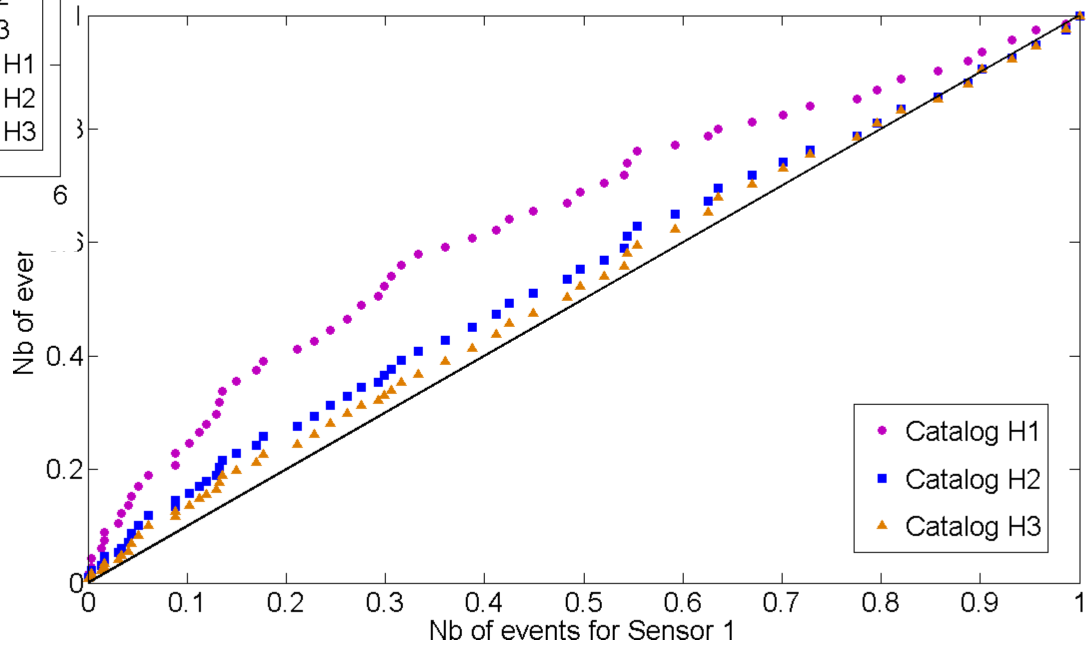
- Distributions of quakes ranked in catalogs obey same scaling laws as seismicity data (Gutenberg-Richter, distribution of recurrent distances, distribution of recurrent time intervals) despite different spatial and time scales, rupture mechanisms and configurations

Perspectives

Comparison between AE time series and optical catalogs



H1, H2 and H3 = 3 catalogs from same experiment with ≠ velocity thresholds



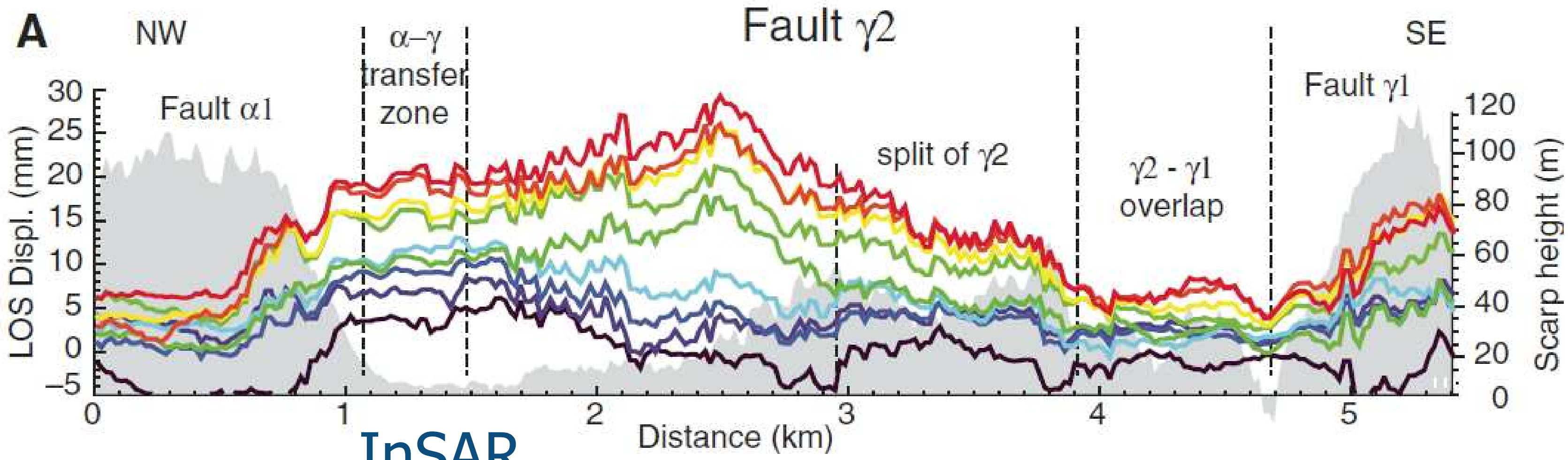
- Acoustic emissions probably due to local depinning of the rupture front

⇨ Building catalogs from AE analysis to compare with optical events

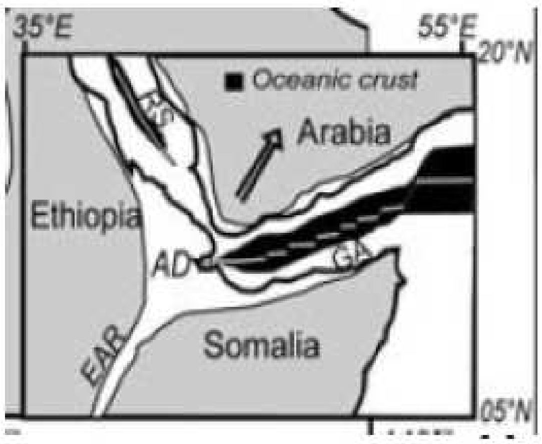
Perspectives

⇨ Comparison with other large scale data sets

Doubre et al. (Geology, 2005)

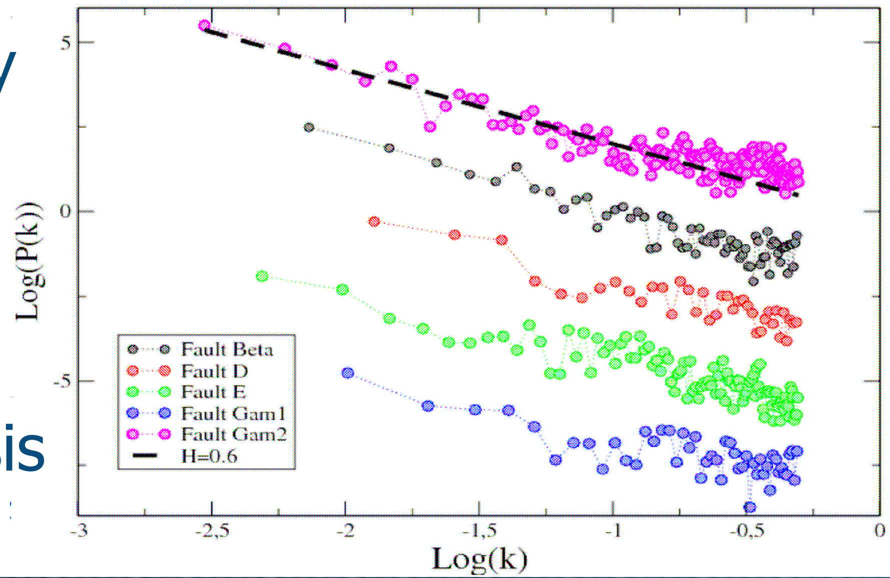


InSAR
1997-2005 slip history



Asal Rift

Slip front
morphology analysis



Thanks for your attention…

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a whole bunch of Plexiglas cakes, cooked with love…