DAMAGE AND CRACK PROPAGATION IN SILICATE GLASSES

SPCSI, CEA-Saclay, France
FRACTURE GROUP
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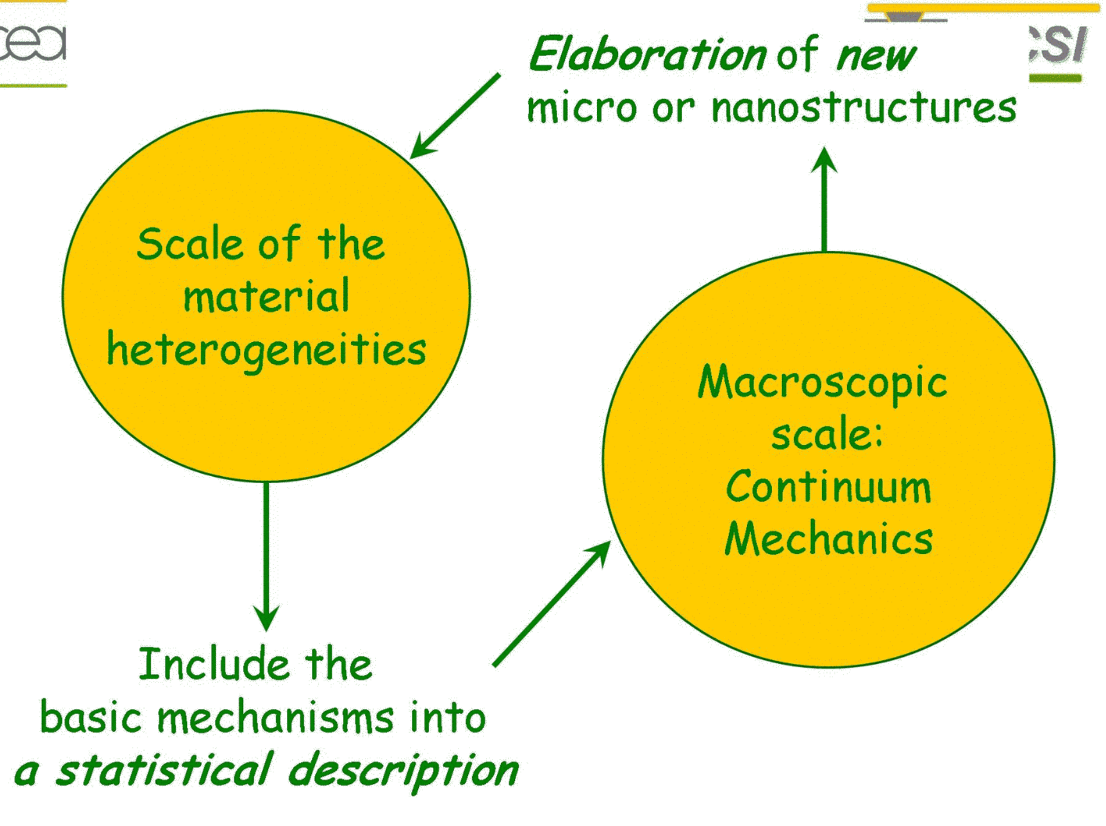
KITP- From the Atomic to the Tectonic… 27/09/05



Crack propagation through heterogeneous materials

- *Universal* features due to *different* microscopic processes

Fracture surfaces → *Universal* morphology

- *Relevant* similarities? Up to *what scale?*

→ *Within a material-dependent range of length scales*

- *Macroscopic consequences* of microscopic processes?

Daniel Bonamy tomorrow!

OUTLINE

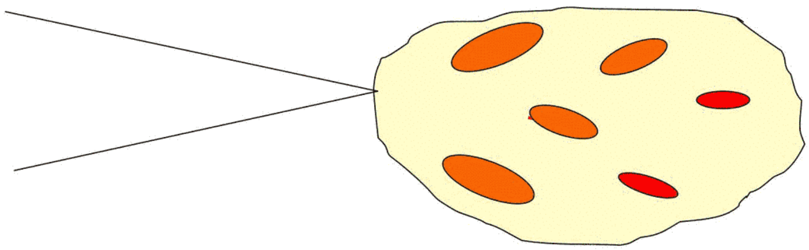
1- Damage mechanism in the stress corrosion fracture of glass

2- Macroscopic consequences

3- Conclusion & Work in progress

1- Damage mechanism

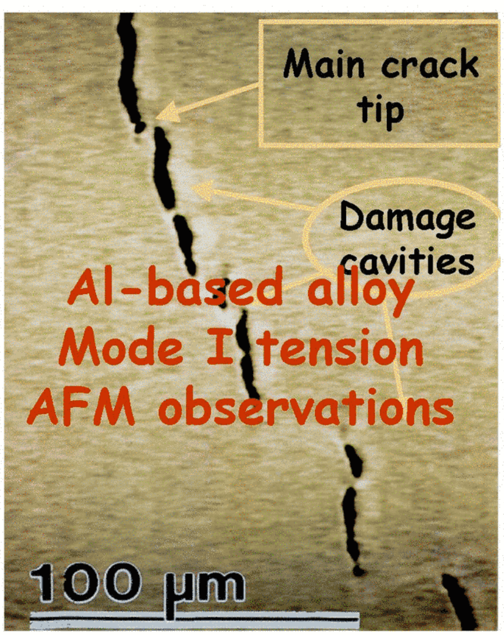
Disorder ⇒ the first bonds to break are unlikely to be closest to the crack tip!

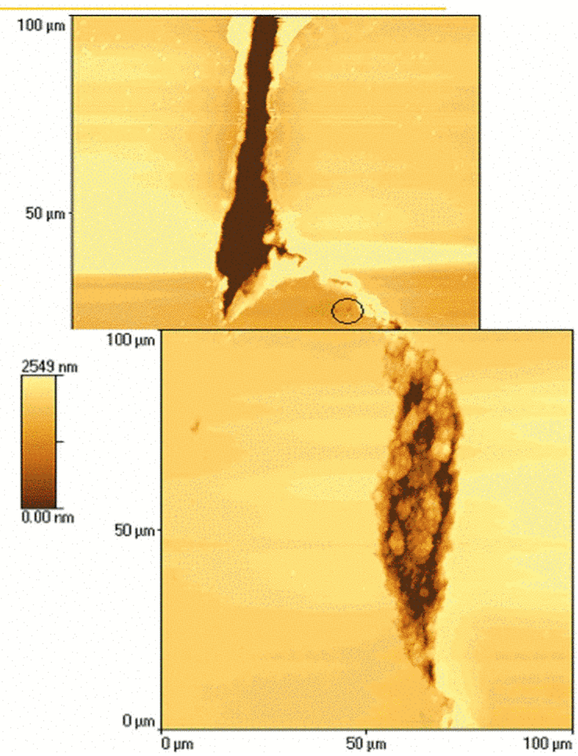


Extent of the damaged zone depends on material & loading conditions

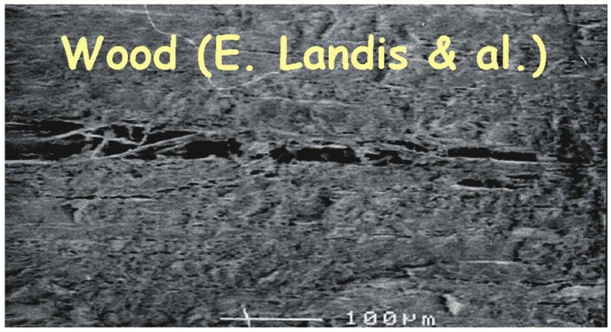
« Plasticity » ⇒
- cracks turn into cavities
- likely to affect nanometric length scales in glasses

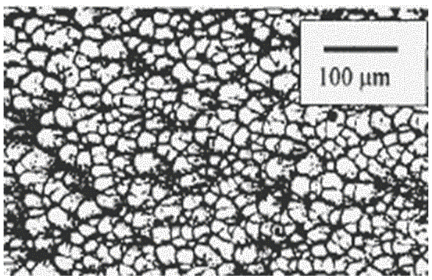
1- Damage mechanism



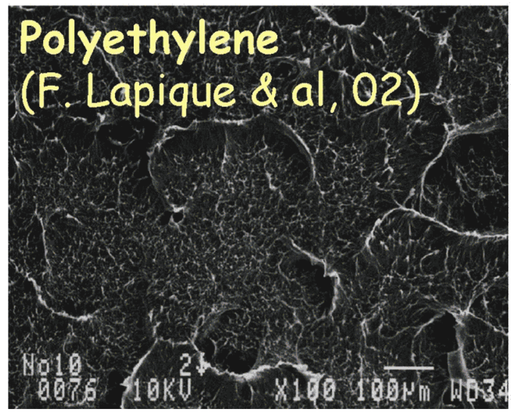


1- Damage mechanism



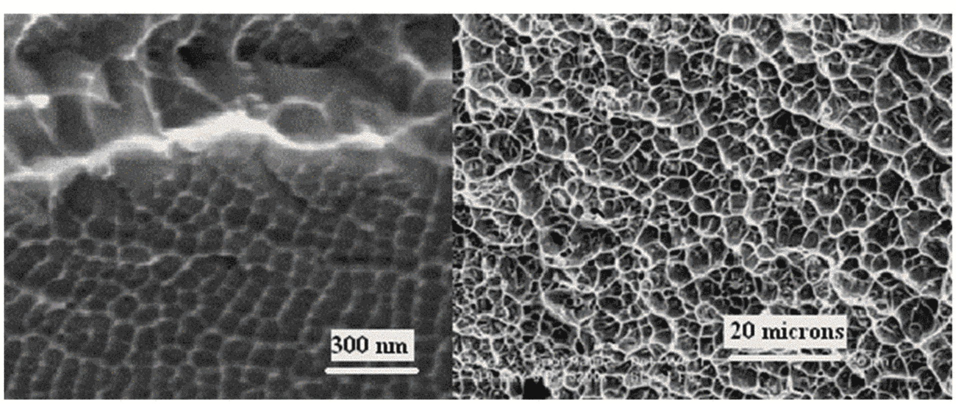


PMMA (K. Ravi-Chandar & al 97)



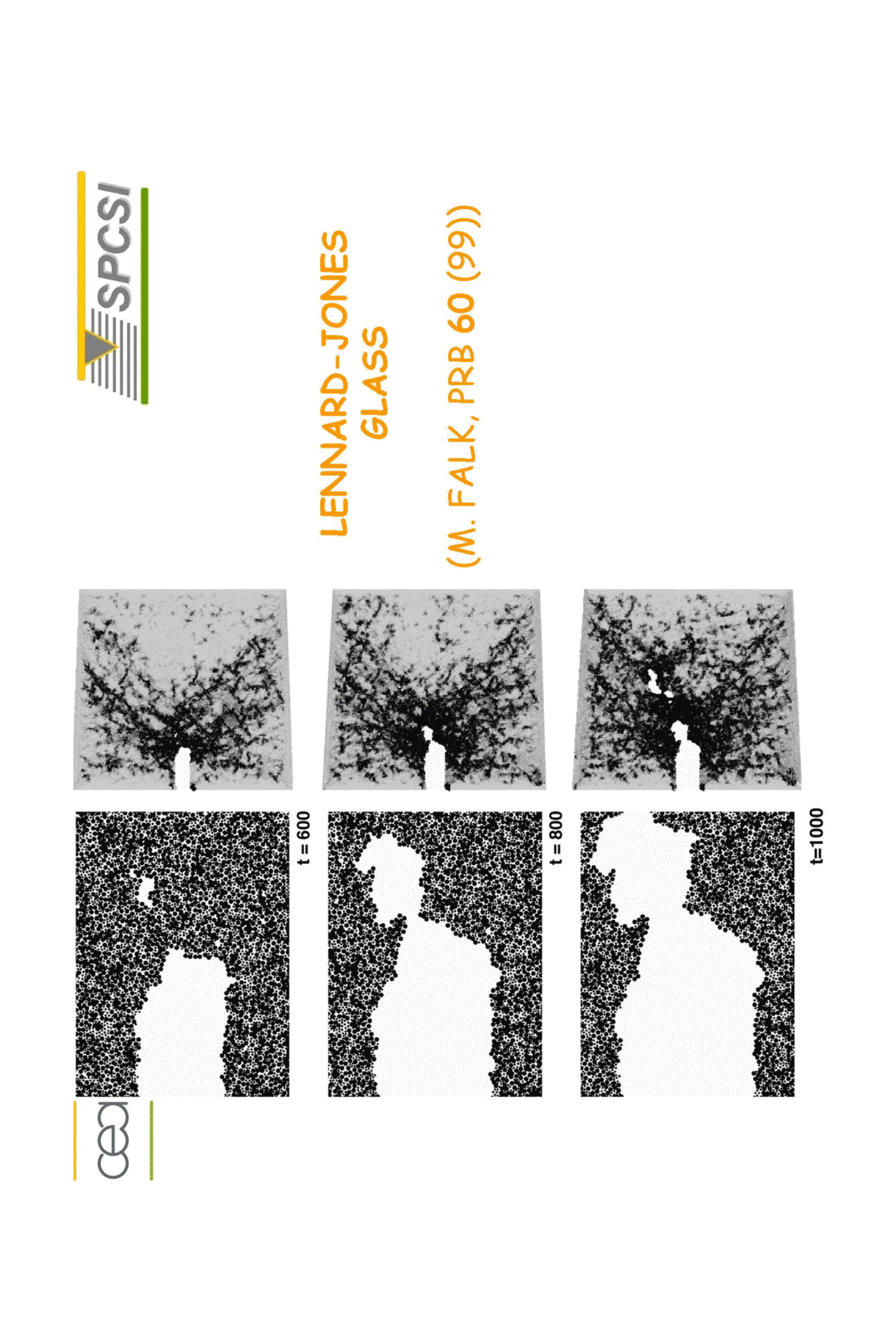
1- Damage mechanism

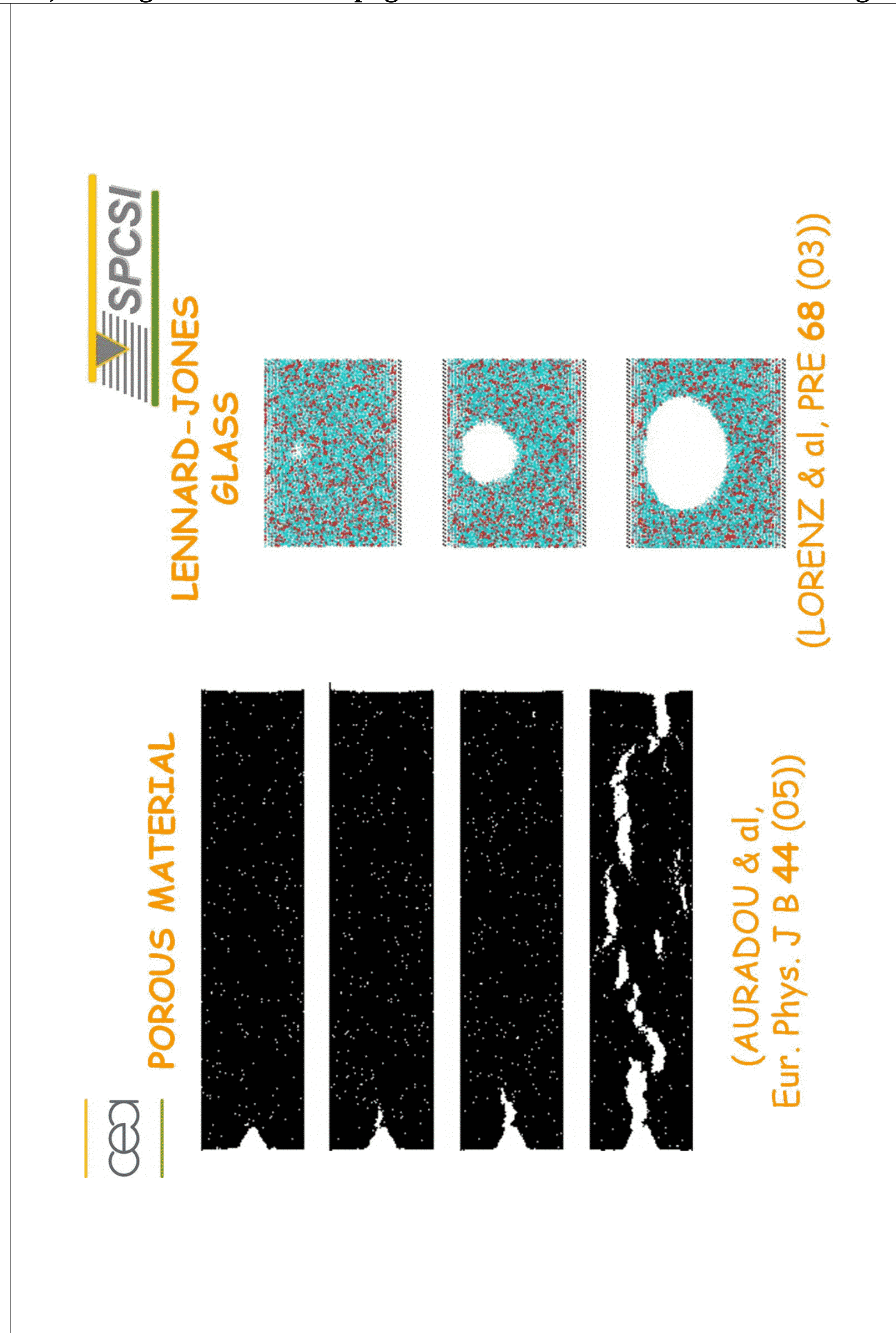
Metallic glasses (Xi et al, PRL **94**, 2005)



Mg-based
K_{Ic}=2MPa$\sqrt{m}$

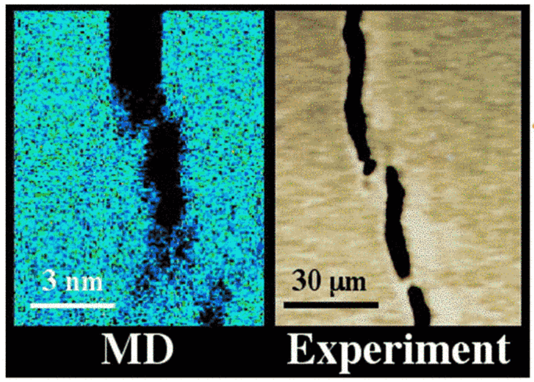
Ce-based
K_{Ic}=10MPa$\sqrt{m}$


SPCSI
LENNARD-JONES GLASS
(M. FALK, PRB 60 (99))
t = 600
t = 800
t=1000


SPCSI
LENNARD-JONES GLASS
(LORENZ & al, PRE 68 (03))
POROUS MATERIAL
(AURADOU & al, Eur. Phys. J B 44 (05))

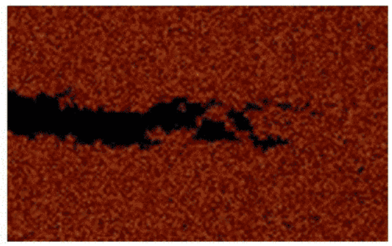
AMORPHOUS CERAMICS

A.NAKANO et al. (94) MD amorphous Si_3N_4



Ti_3Al-based alloy

C. Rountree & R. Kalia (03) MD amorphous SiO_2

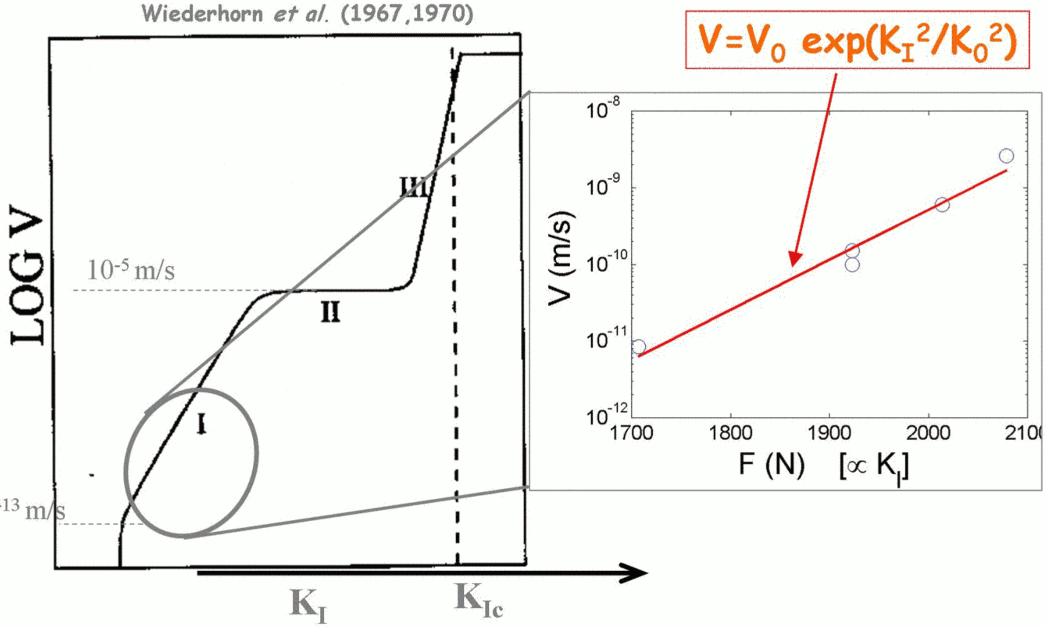


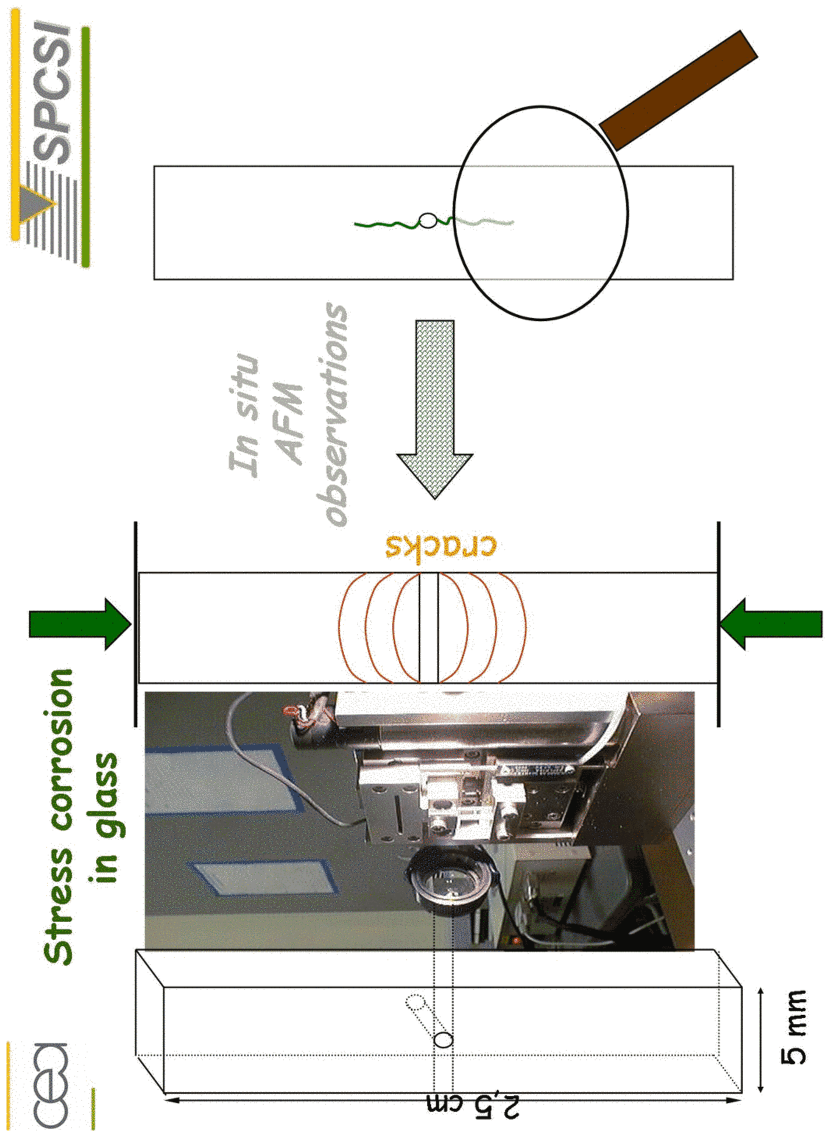
1- Damage mechanism

Stress corrosion in a humid environment

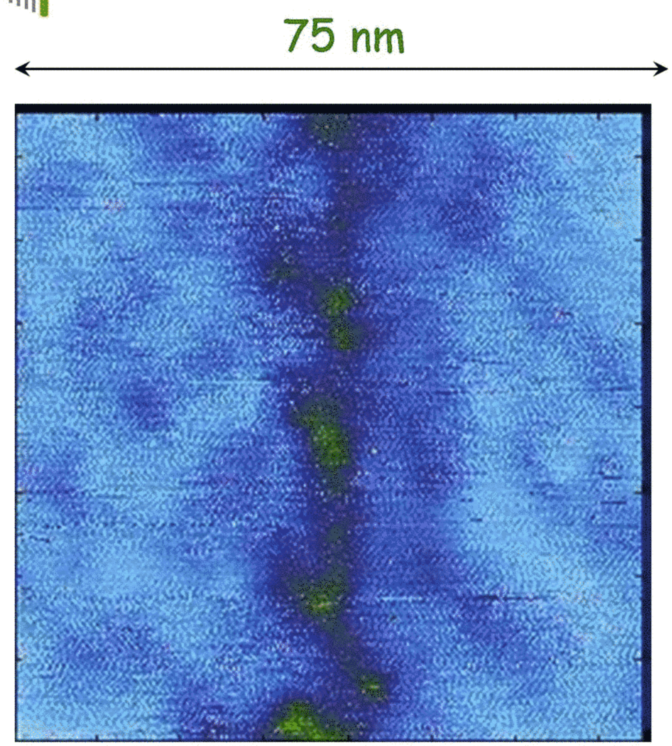
Wiederhorn *et al.* (1967,1970)

$V=V_0 \exp(K_I^2/K_0^2)$





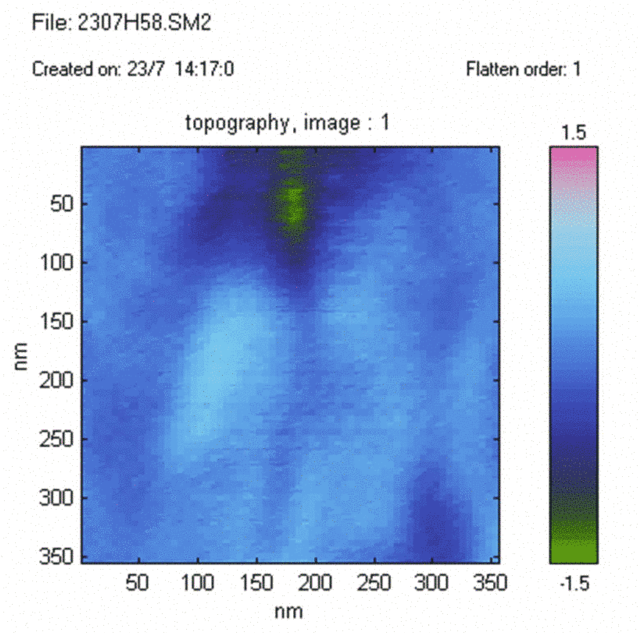
In situ AFM observations
amorphous aluminosilicate
$V=3.\ 10^{-10}$ m/s



Collaboration with F. Célarié, L. Ferrero & C. Marlière (LdV , Montpellier University)

1- Damage mechanism

SPCSI



In situ AFM observations

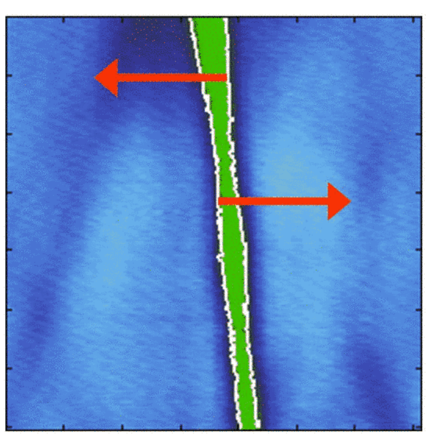
Pure silica glass

V=3. 10^{-11} m/s

1- Damage mechanism

SPCSI

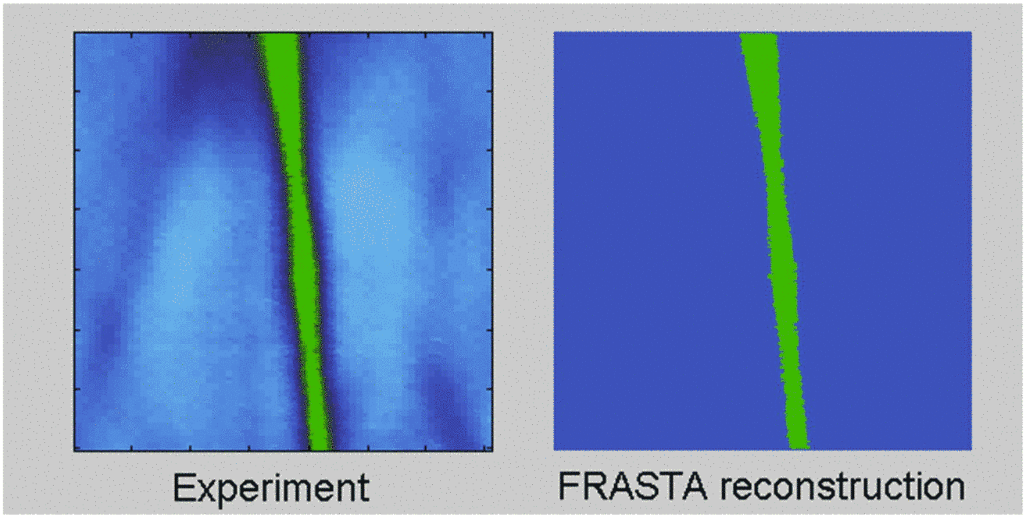
FRASTA METHOD



Final image: definition of contours

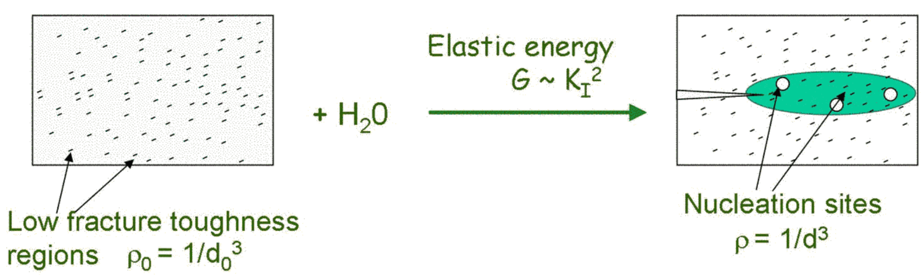
Relative movement of the contours: going back in time.

1- Damage mechanism



The *observed* cavities are *printed* on the final fracture lines

1- Damage mechanism



$\rho \propto \rho_0 \exp(-K_I^2/K_0^2)$

$V \propto V_0 \exp(K_I^2/K_0^2)$

$\rho \propto \rho_0 V_0 / V$

$\rho \approx \rho_0$ for $V > V_{zonell}$

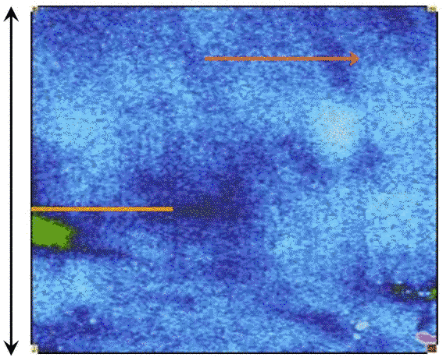
$$d \approx d_0 (V_{zonell} / V)^{1/3}$$

$V_{zonell} \approx 10^{-5}$ m/s
(Wiederhorn et al., 67)

Dynamic fracture
$d_0 \sim 1$ nm (C. Rountree)

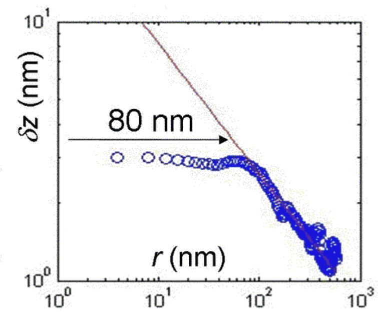
Stress corrosion
$V=10^{-10}$ m/s => d ~ 40 nm
$V=10^{-11}$ m/s => d ~ 100 nm

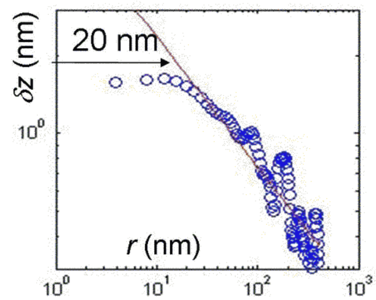
2- Macroscopic consequences



Linear elasticity :

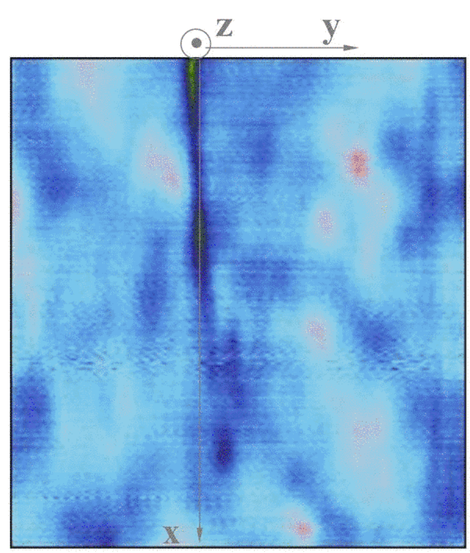
$\delta z \propto r^{-0.5}$

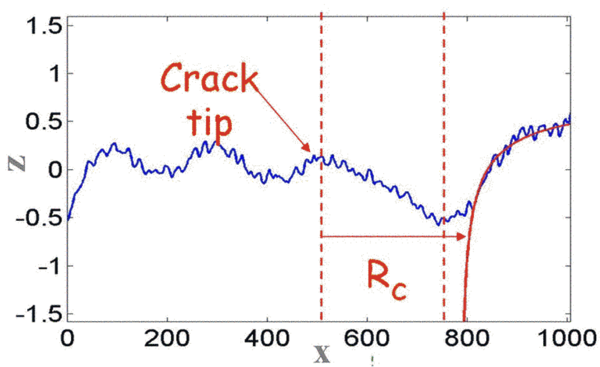


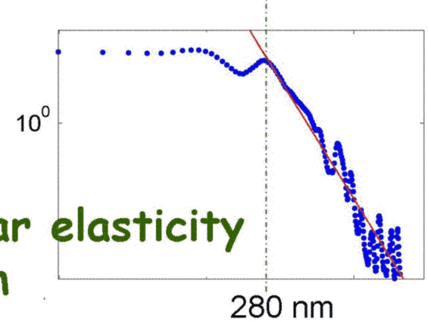


Departure from linear elasticity within the damage zone (20nmx80nm)

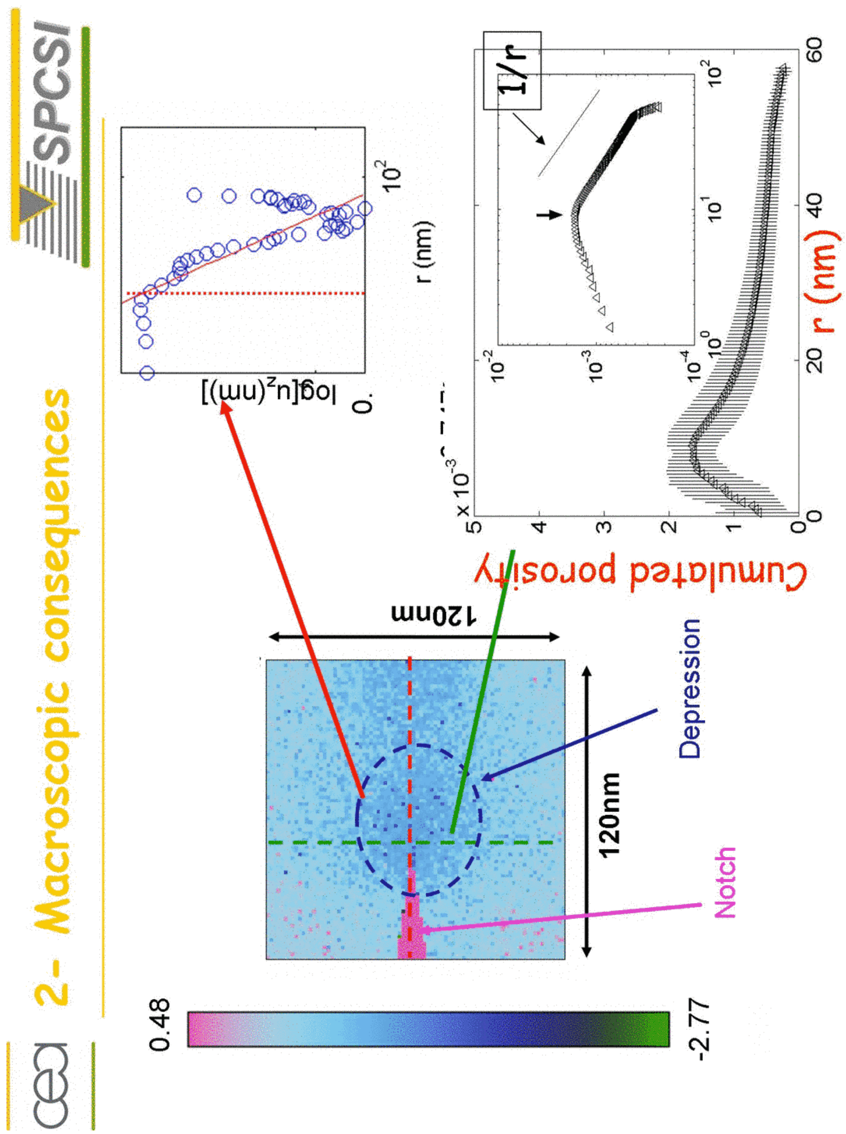
2- Macroscopic consequences

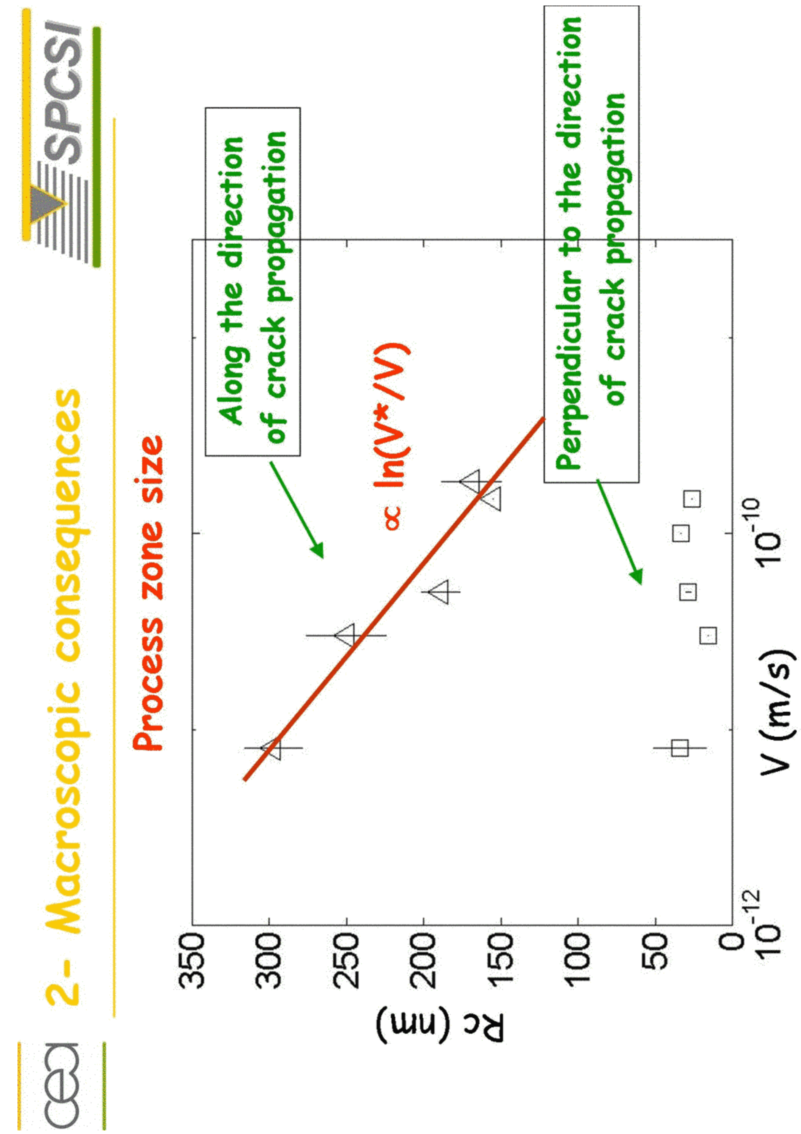






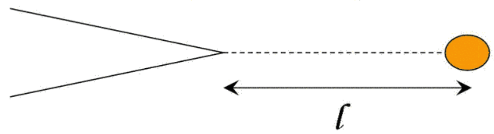
Departure from linear elasticity Rc≈280nm


2- Macroscopic consequences
SPCSI
0.48
-2.77
120nm
120nm
Depression
Notch
log[u_z(nm)]
r (nm)
1/r
Cumulated porosity
r (nm)


2- Macroscopic consequences
SPCSI
Process zone size
Along the direction of crack propagation
∝ ln(V*/V)
Perpendicular to the direction of crack propagation
Rc (nm)
V (m/s)

2- Macroscopic consequences

Collaboration with K. Ravichandar
(University of Austin, Texas)



$K_I(1+2r)/(2\pi\ell)^{0.5} > \sigma^*$

$R_c = 1/2\pi\ ((1+2r)K_I/\sigma^*)^2$

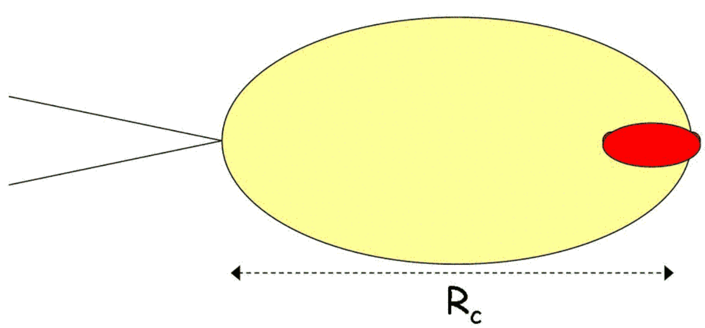
$r \approx 1\text{-}2$

Dynamic fracture: $\sigma^* \approx 12$ GPa; $K_I \approx K_{Ic} = 1 MPa\sqrt{m}$
$R_c \approx 10\text{-}40$ nm

SC fracture: $\sigma^* \approx 3\text{-}4$ GPa; $K_I \approx K_{Ic} = 0.4\text{-}0.5 MPa\sqrt{m}$
$R_c \approx 15\text{-}110$ nm

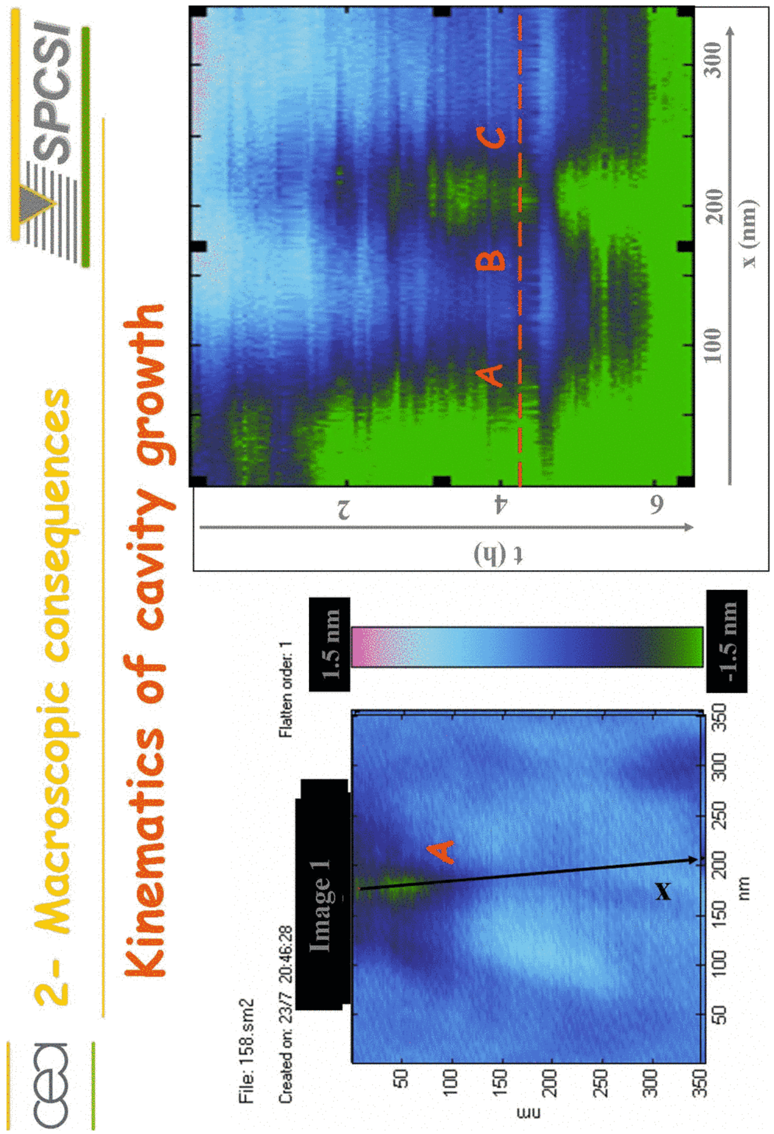
r, σ^* depend on V...
Integrated process over the whole sample thickness
$\Rightarrow$ account for water diffusion within the PZ.

2- Macroscopic consequences

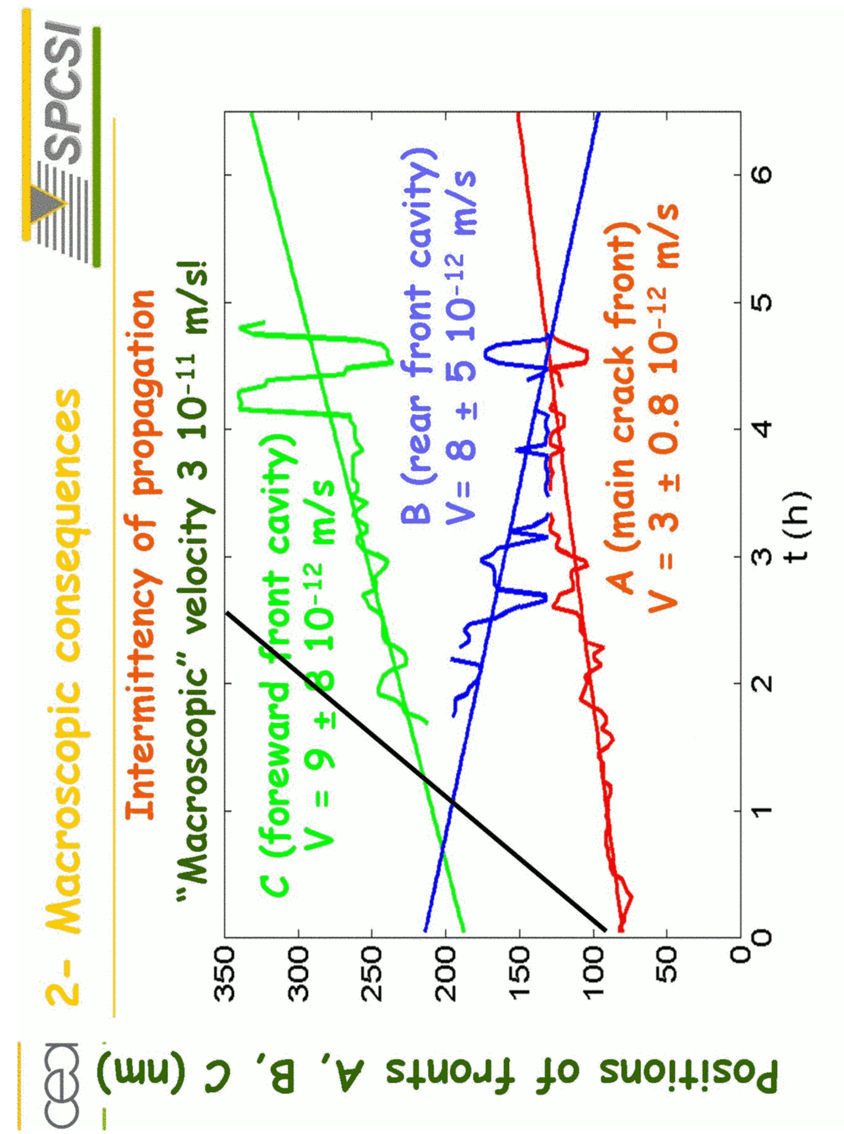


Stress field at distance R_c from the crack tip:
$K_I/(2\pi R_c)^{0.5} < \sigma^*$ still elastic !

Except at the tips of the micro-crack
$K_I(1+2r)/(2\pi R_c)^{0.5} \approx \sigma^*$
« plastic » deformation
$\rightarrow$ micro-crack becomes a cavity

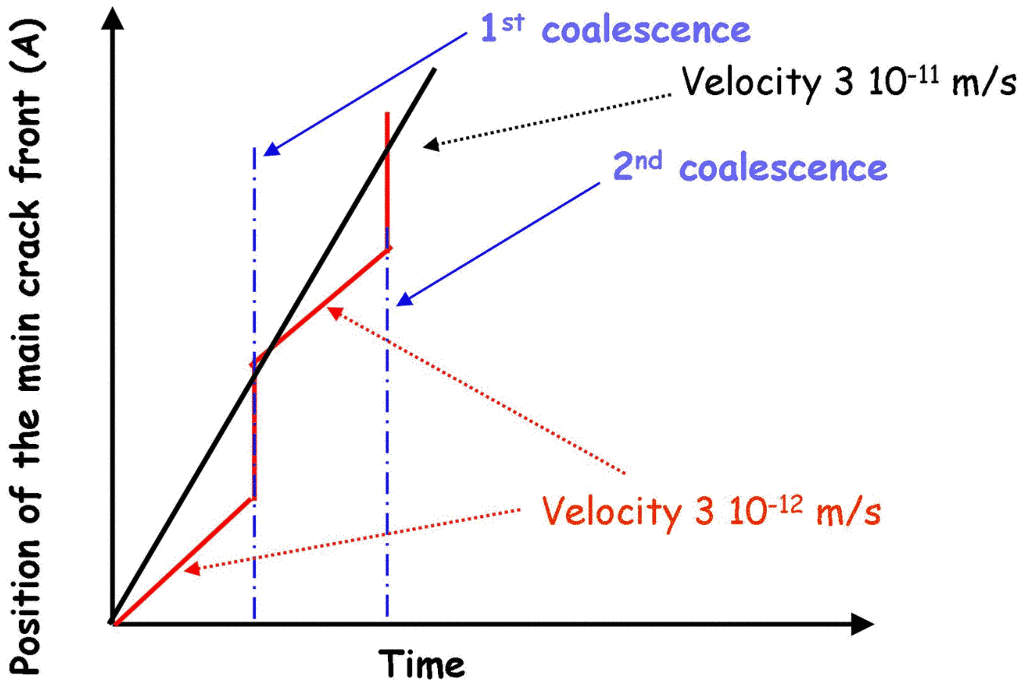


SPCSI
2- Macroscopic consequences
Kinematics of cavity growth
File: 158.sm2
Created on: 23/7 20:46:28
Image 1
Flatten order: 1
1.5 nm
-1.5 nm
A
x
nm
A B C
t (h)
x (nm)



SPCSI
2- Macroscopic consequences
Intermittency of propagation
"Macroscopic" velocity 3 10^{-11} m/s!
C (foreward front cavity)
V = 9 ± 8 10^{-12} m/s
B (rear front cavity)
V= 8 ± 5 10^{-12} m/s
A (main crack front)
V = 3 ± 0.8 10^{-12} m/s
Positions of fronts A, B, C (nm)
t (h)

2- Macroscopic consequences



3- Conclusion

- SC damage in glass
  - observed at nanometric length scales
- Damage cavities
  - ❖damage due to "intrinsic disorder" (glassy state)
  - ❖microcracks turn into cavities due to localized plasticity
- Macroscopic consequences:
  - Non linear elastic deformations
    - ~ *several 100 nm!*
  - Sample lifetime

3- Work in progress

Damage in 3D: *post mortem* AFM observations
& FRASTA in 3D

Link with the glass structure?

Cavities/micro-cracks: plasticity of glass ?

- Structural changes?
- Cavity extension ?
- Implications for the kinematics of cavities?

→ MD simulations (coll. USC & CNRS/Saint-Gobain)

Implications on the morphology of fracture surfaces ?
Daniel Bonamy's talk...