FEM and the plastic deformation of amorphous silicates

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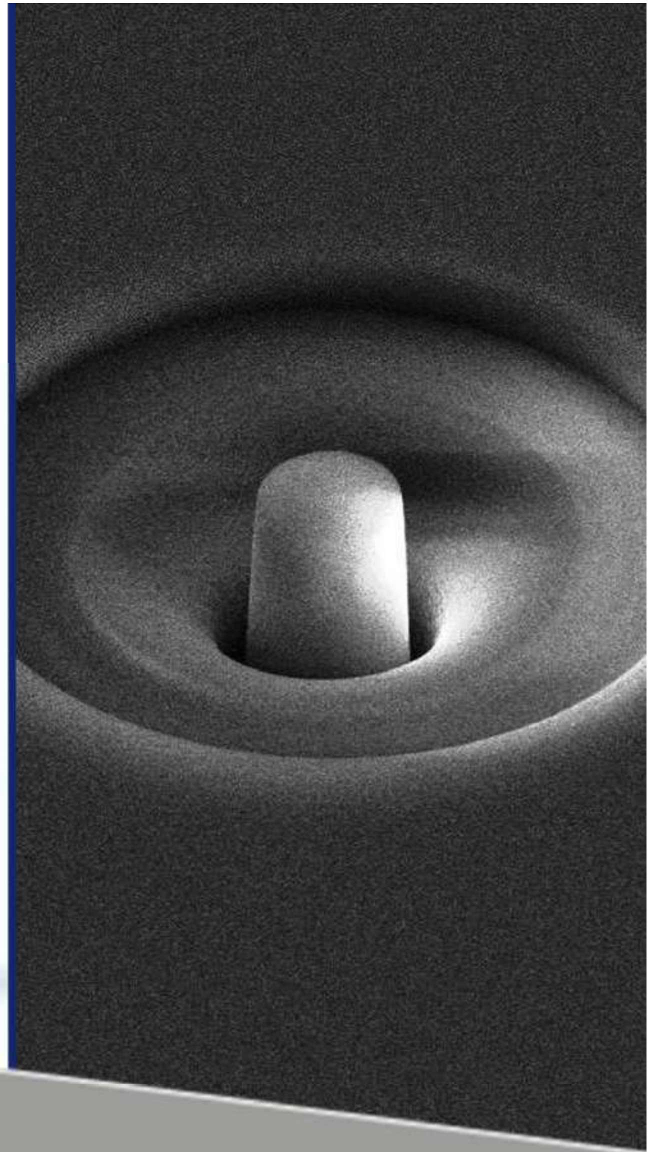


Outline

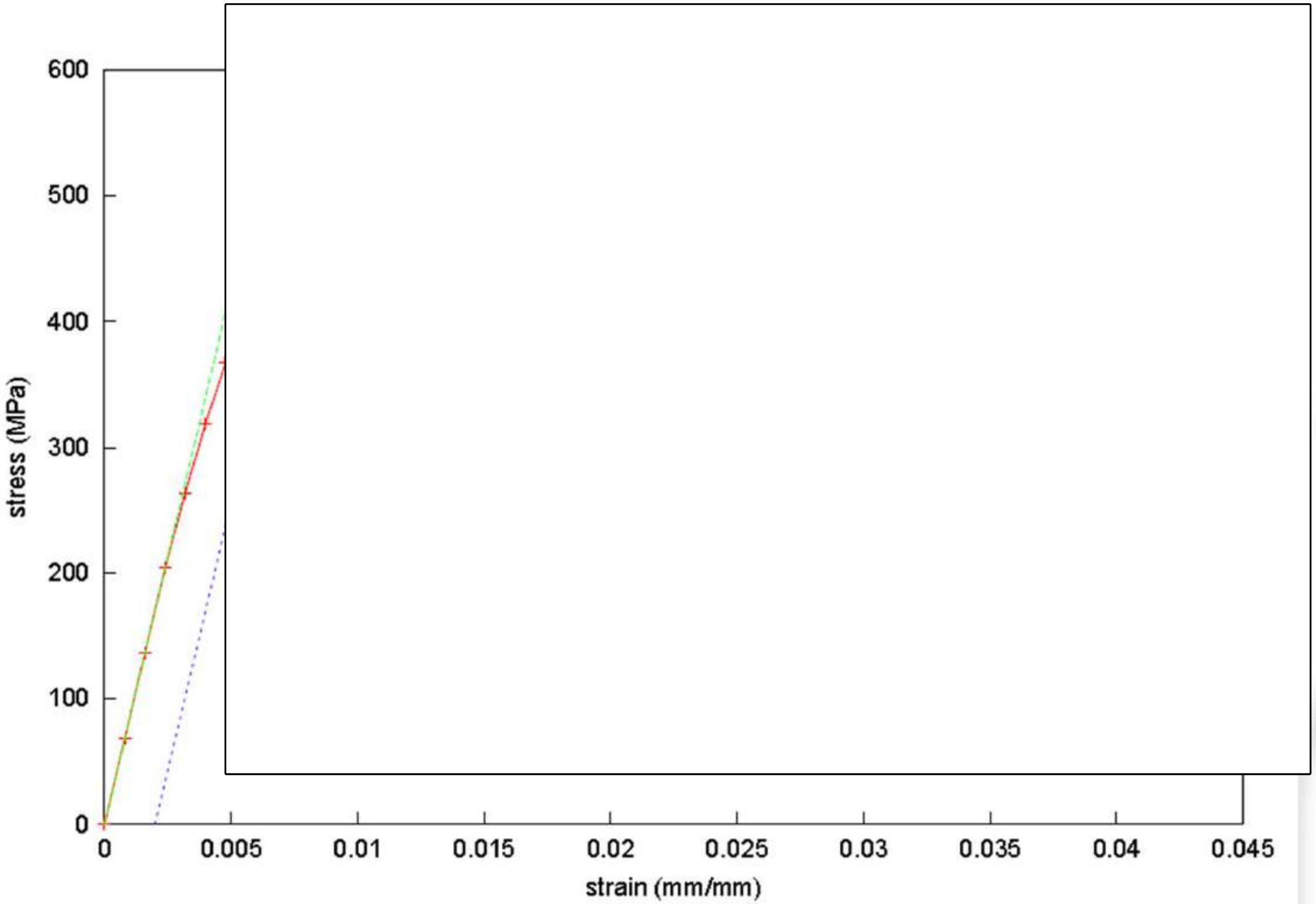
- The micromechanics of silicate glasses
  - Phenomenology
  - Material issues
- Experiments
  - Requirements
  - implementation

Outline

- **mechanics of silicate glasses**
  - **some strange features of silica**
  - **plasticity ?**
    - phenomenology
    - mechanisms (-> A. Tanguy)
- **Experiments**
  - **Requirements**
  - **Modelling**
    - Finite Element Modelling (cours de F. Pigeonneau)

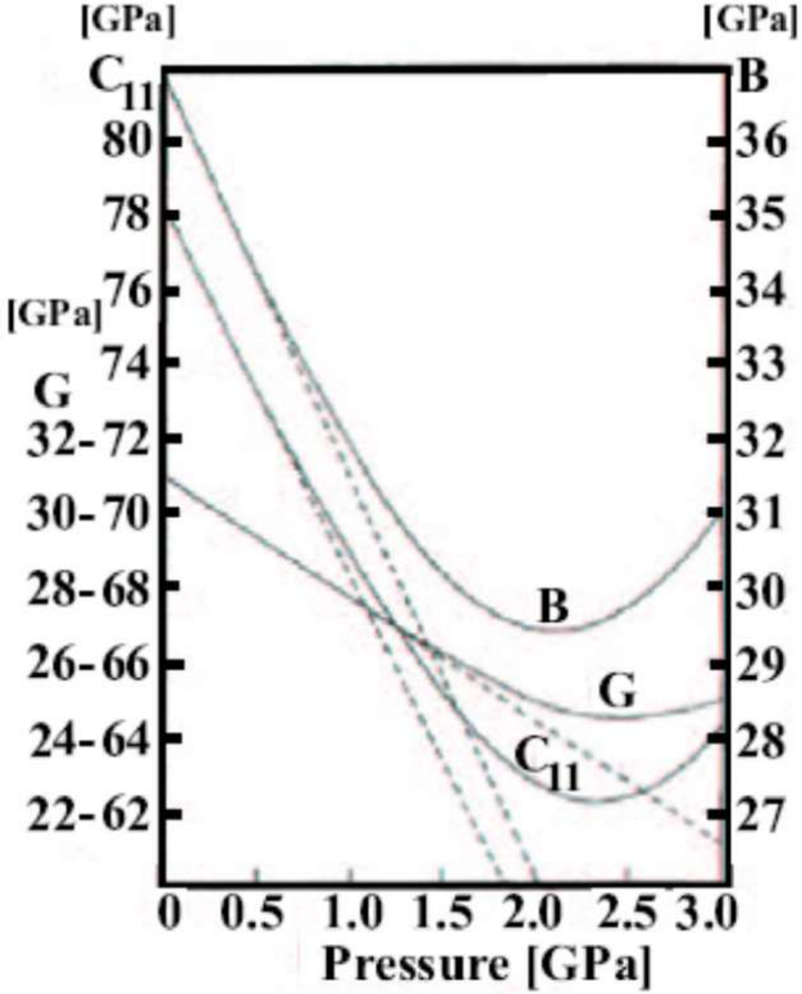
Elasticity

Tension curve – Al alloy



Cailletaud, Centre des Matériaux,
Ecole des Mines, Evry

Non-linear elasticity – silica



Kondo 1984

Mechanical properties of amorphous materials

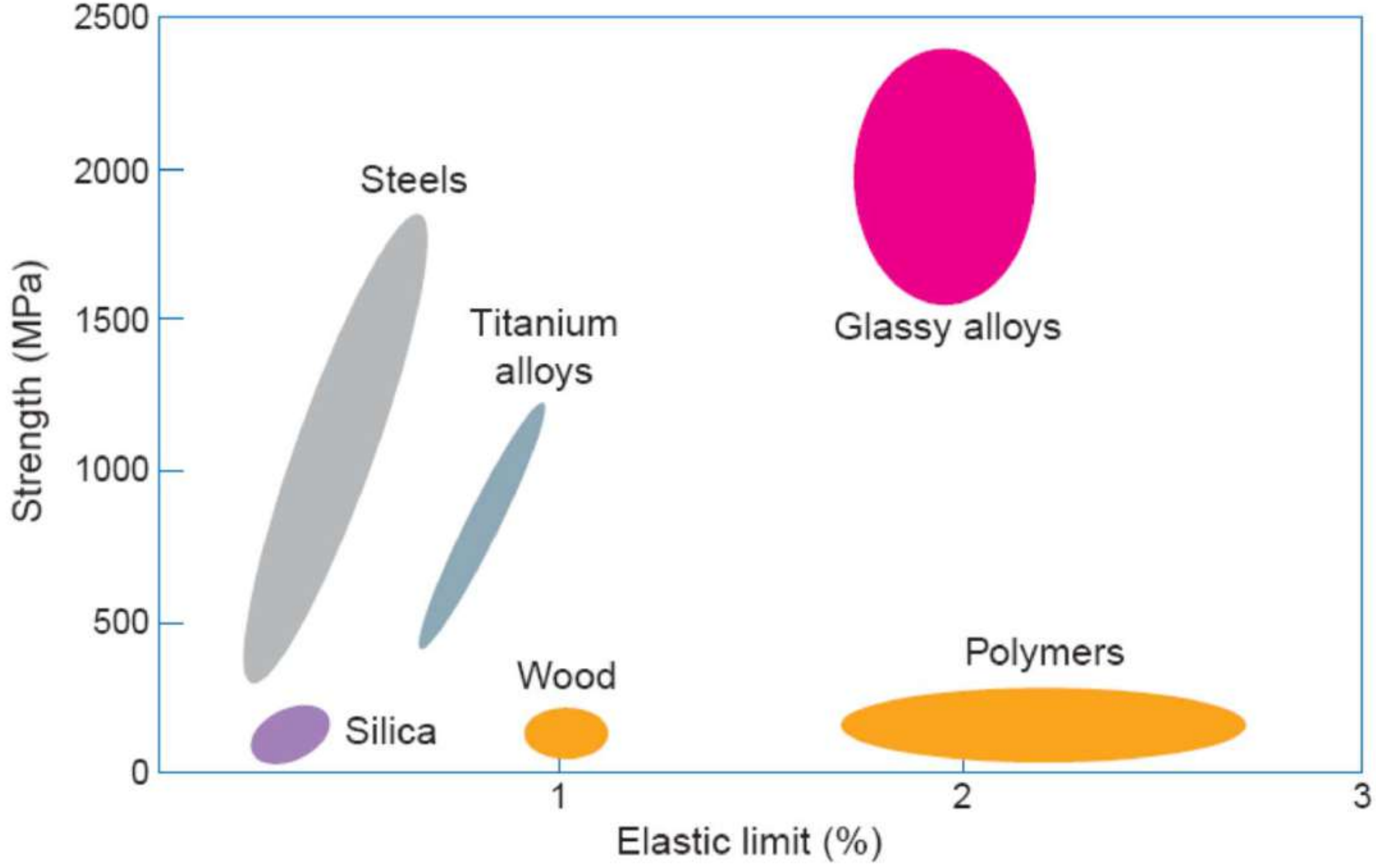


Fig. 3 Amorphous metallic alloys combine higher strength than crystalline metal alloys with the elasticity of polymers.

Telford, Materials Today, March 2004

Silica glass: a brittle material ?

- **Intrinsic strength**

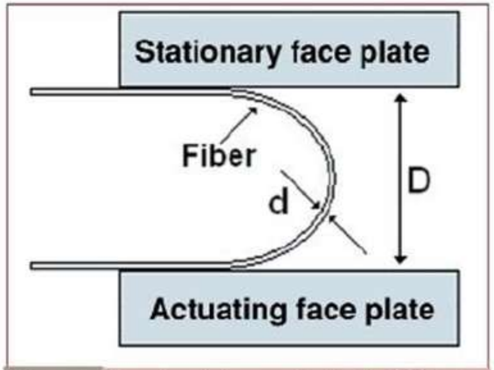
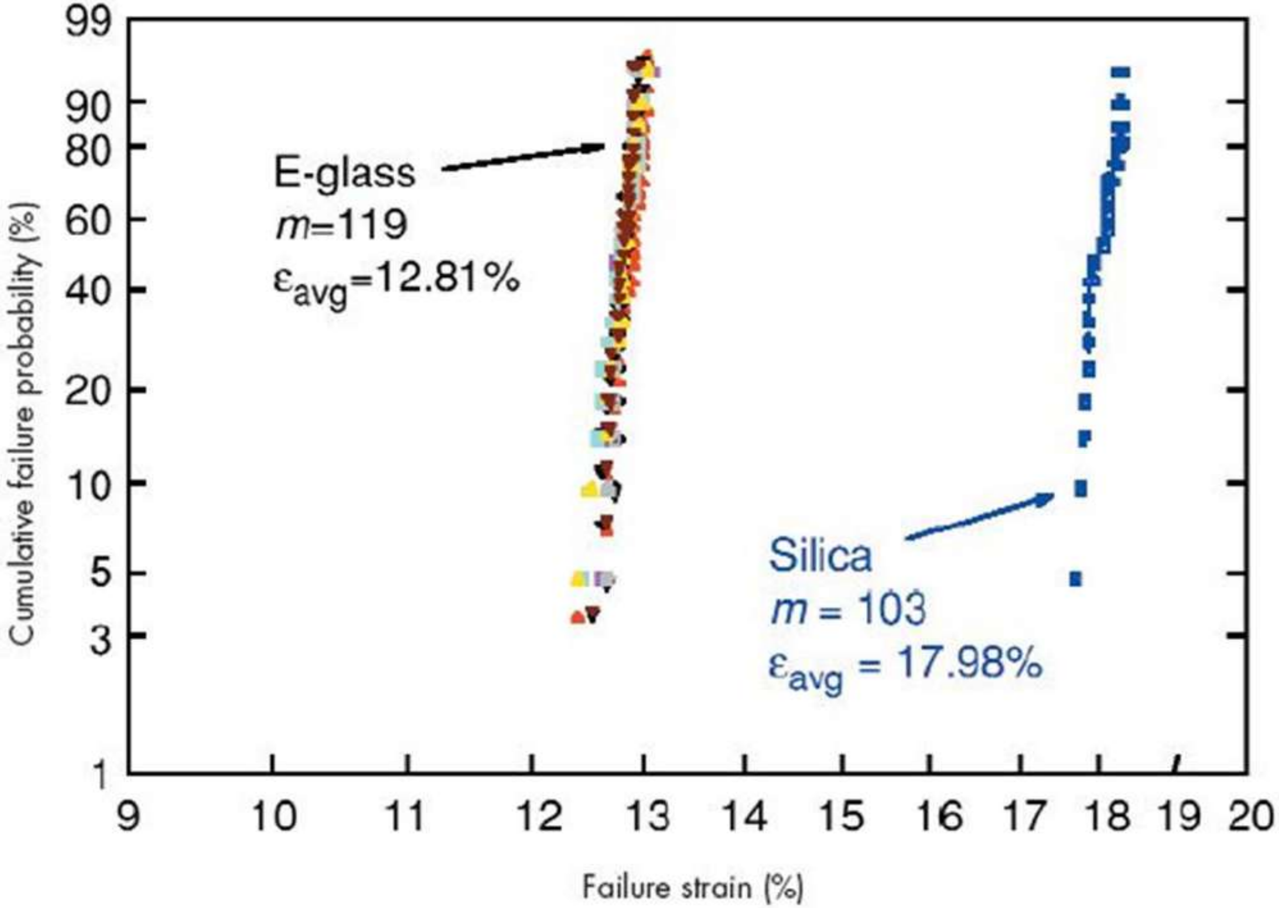


Figure 1 Experimental geometry for the TPB test.



C. Kurkjian Am. Ceram. Soc. Bull. 84 (2005)

Plastic deformation in silicate glasses

Marsh, Proc. Roy Soc A 279 (1964) 420

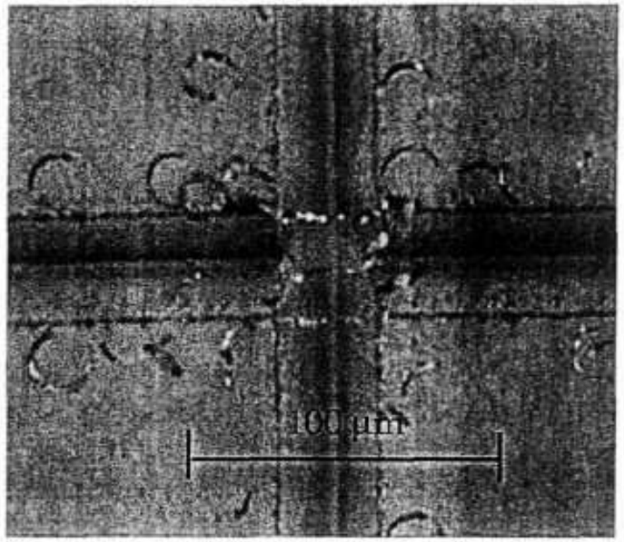
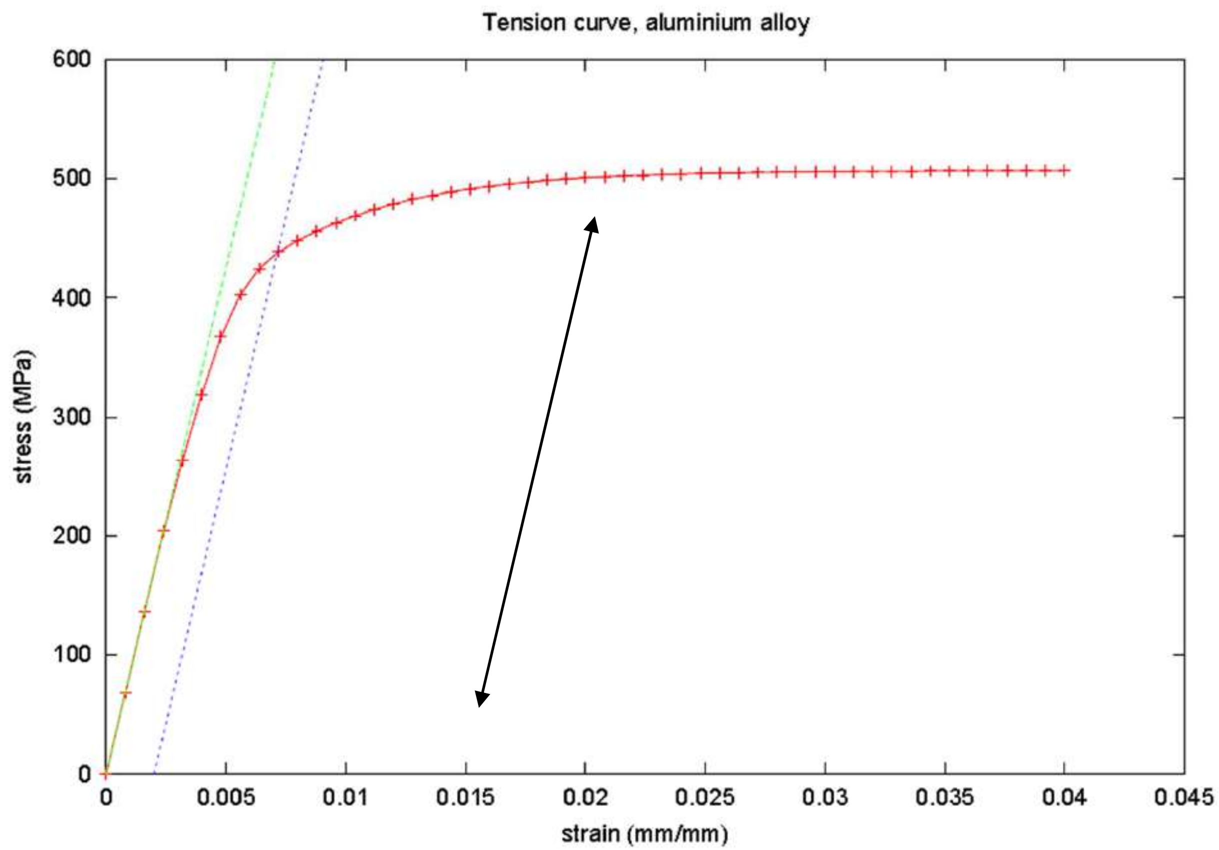


Figure 6 Micro-photograph of a new less-brittle glass scribed by a diamond tool.

Ito, The Glass Researcher 11 (2000) 12

Plasticity



Cailletaud, Centre des Matériaux, Ecole des Mines, Evry

Lengthscales

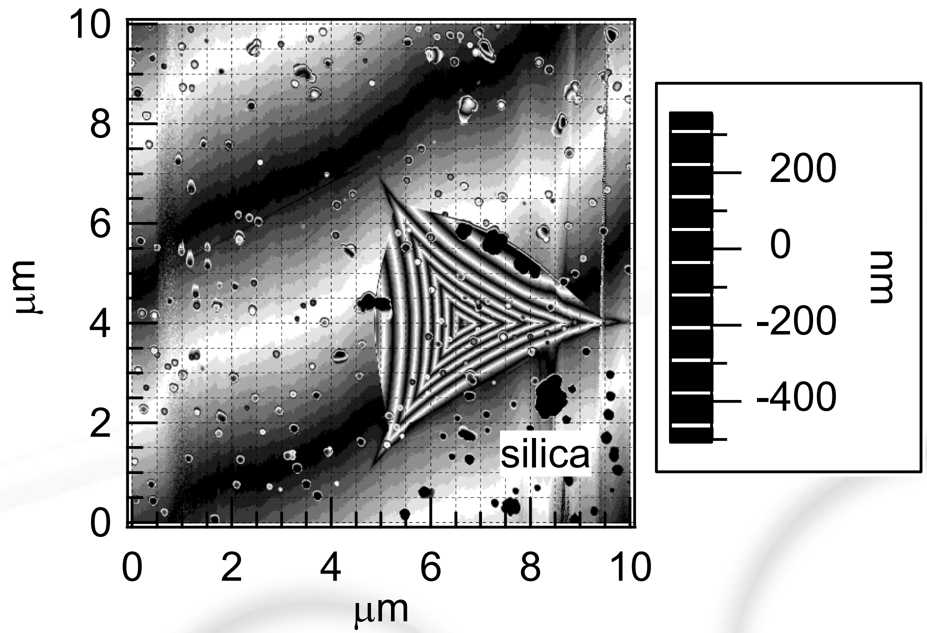
- permanent deformation (plastic)
- *without cracks* at small scale

Taylor, Nature, 1949

$$wa^2 = a^3 \frac{\sigma_y^{\ 2}}{E}$$

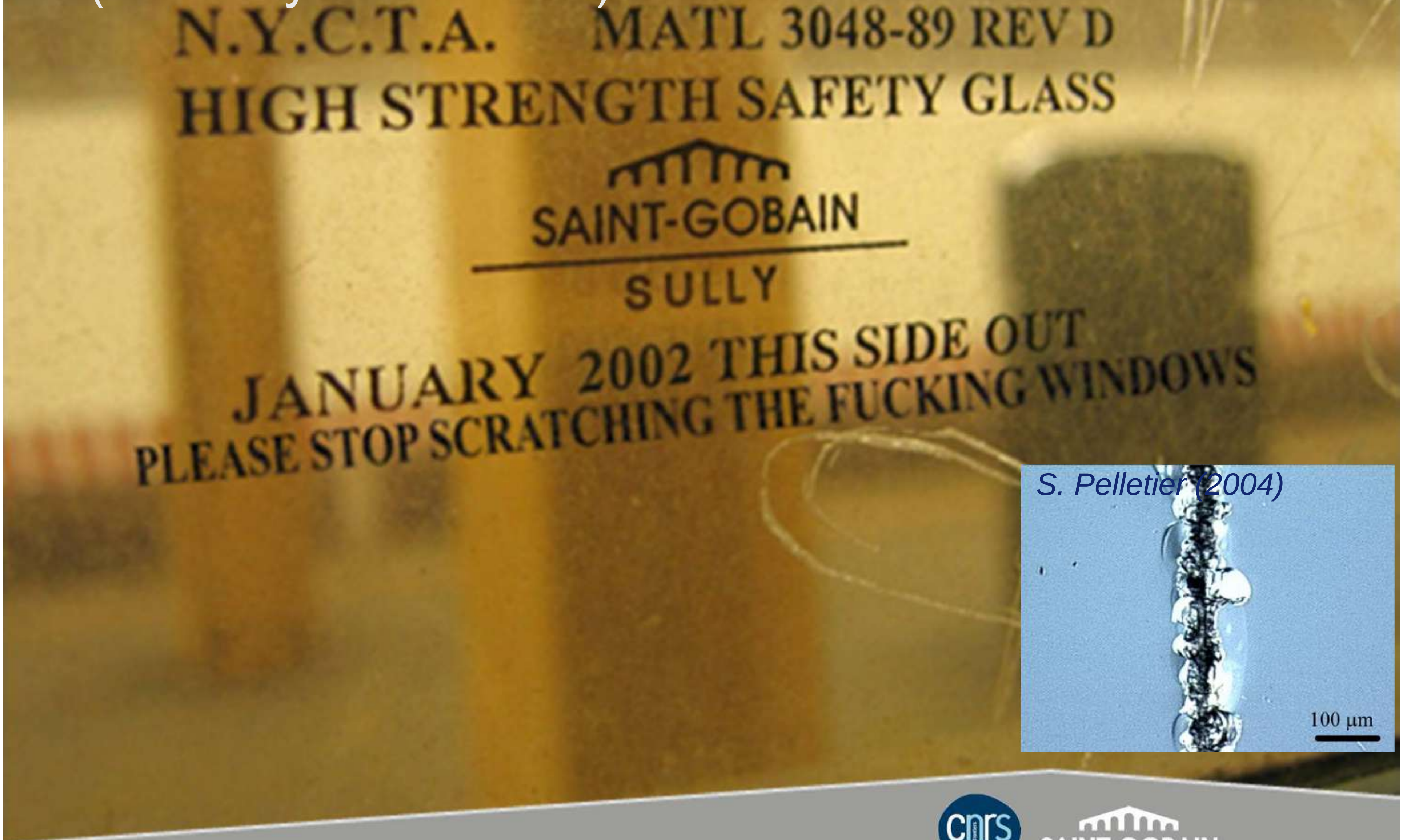
w: cohesion energy
a: spatial extension
σ_y: yield stress
E: elastic modulus

silicate glasses: $a \simeq 10\mu m$



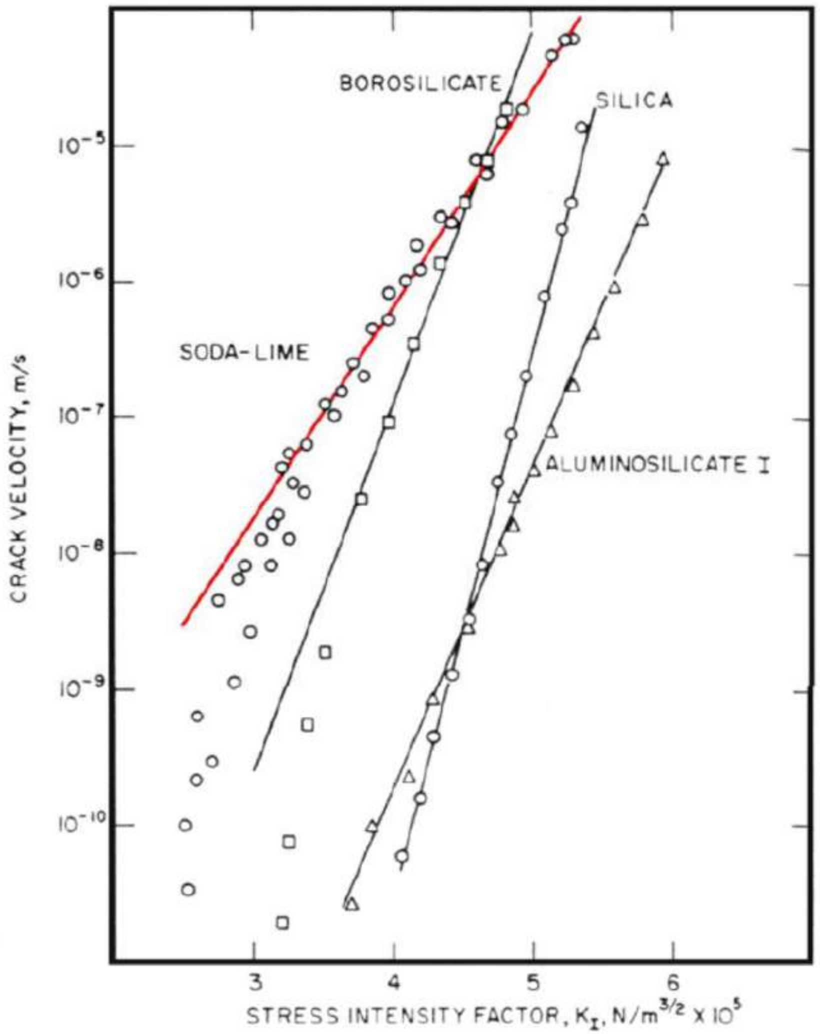
1µm deep indent in SiO_2 with berkovich

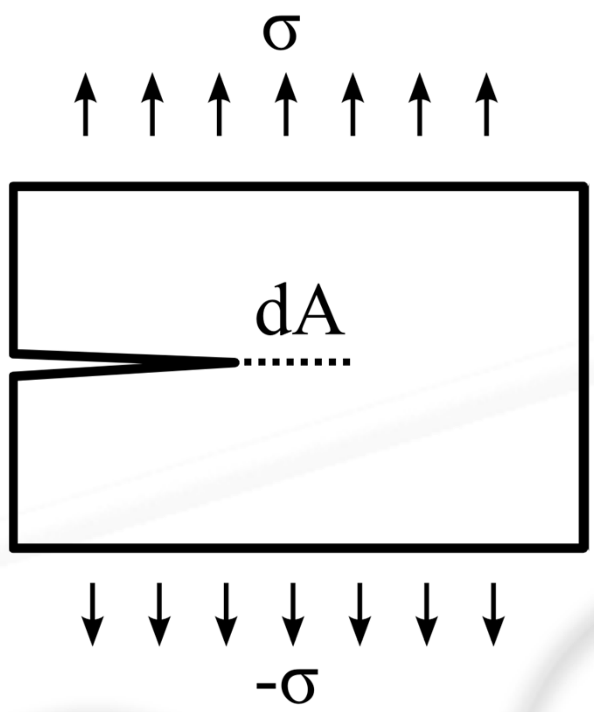
Scratchitti – New York metro (courtesy of G. Duisit)



S. Pelletier (2004)

Silicate glasses toughness





S.M. Wiederhorn & L. H. Boltz (1970)

Indentation

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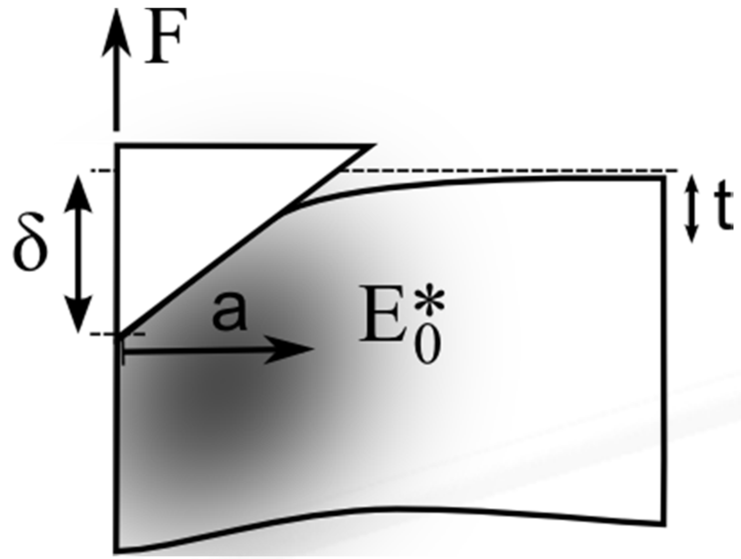
Indentation – representative strain



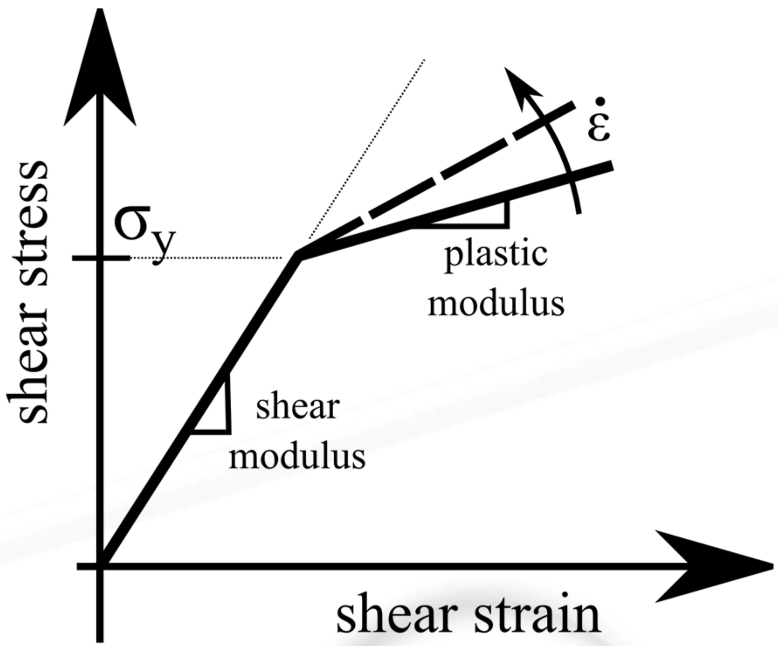
- Hardness

$$\epsilon_{rep} \simeq \frac{\delta}{a} \simeq \frac{1}{\tan\theta}$$

$$\sigma_{rep} = \frac{F}{A} \equiv H$$

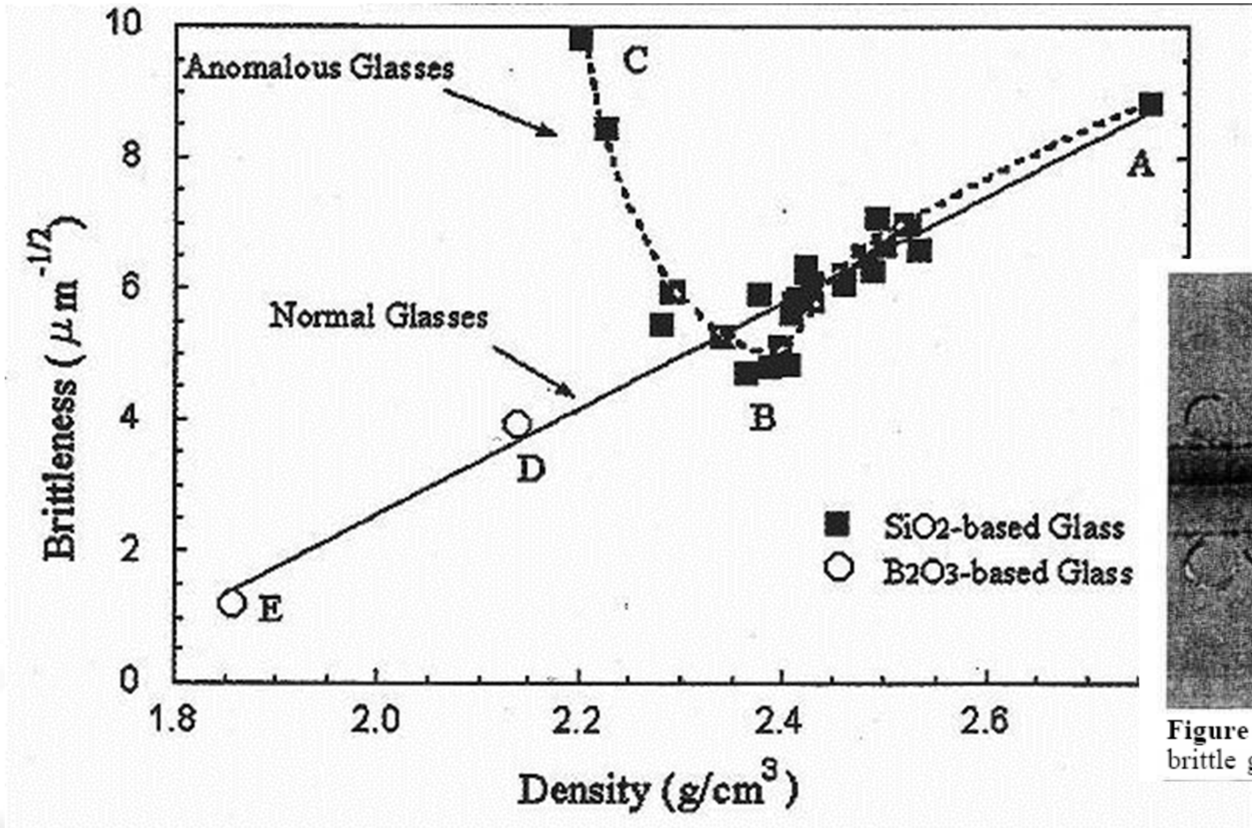
Flow and plasticity

- shear flow
  - « liquid » like
- with threshold
  - plastic response



« Brittleness »

- scratch resistance
  - *control surface damage hence effective toughness*



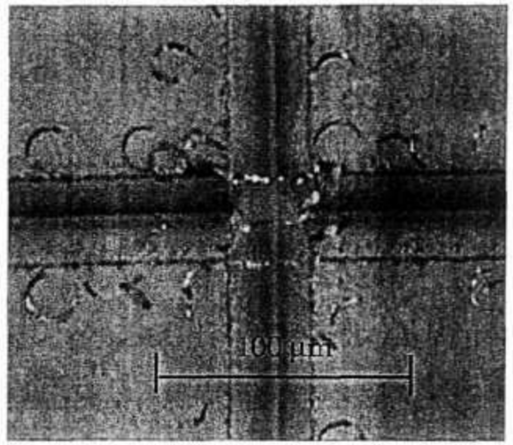


Figure 6 Micro-photograph of a new less-brittle glass scribed by a diamond tool.

Ito, The Glass Researcher 11 (2000) 12

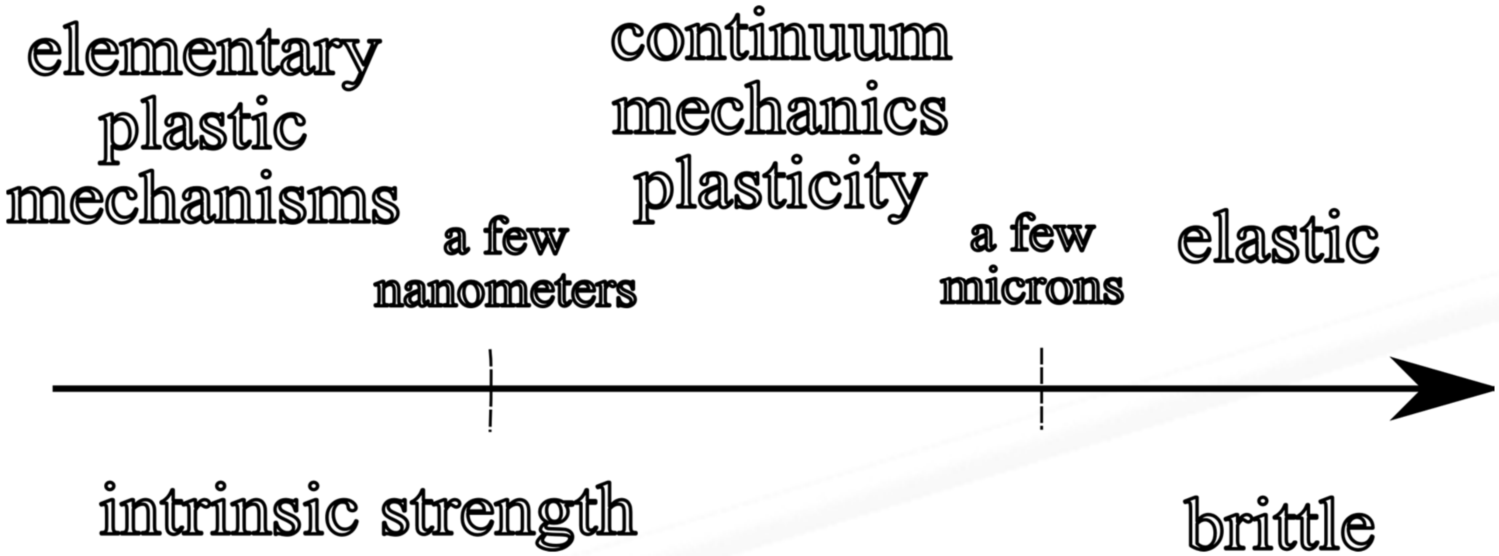
Plastic deformation in silicate glasses

- What kind of plastic deformation mechanisms ? What form for the constitutive equation ?
- Local measurement of residual strain and identification of a constitutive equation for the plastic deformation (amorphous silica)
- What about « normal » silicate glasses ?

Plastic deformation of silicate glasses

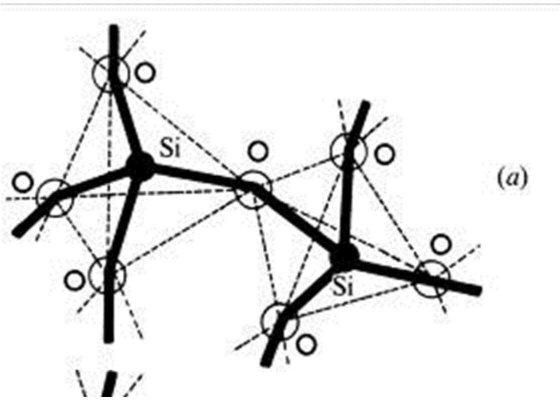
- Taylor (silica, 1946)
- Bridgman Simon (1953) , Cohen Roy (1961)
- MacKenzie (shear, 1963)
- Marsh (yield stress from indentation, 1964)
- Ernsberger (index, 1968)
- Swain (spherical, 1976)
- Arora (indentation fract., 1979)
- Kurkjian (T, sil. Vs SLS, 1995)
- Suzuki (nanoindent, 2002)
- Yoshida (thermal recovery, 2005)
- Rouxel (Poisson ratio, 2008)

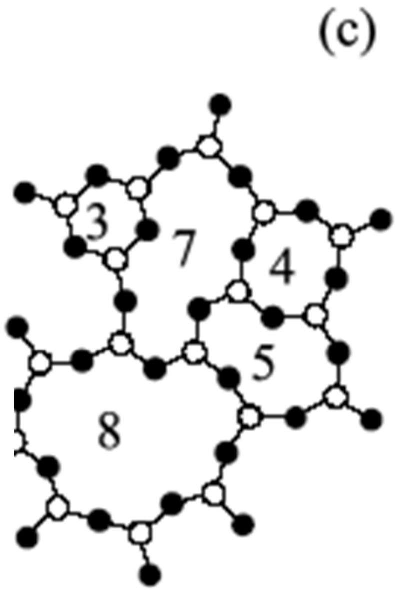
Lengthscales

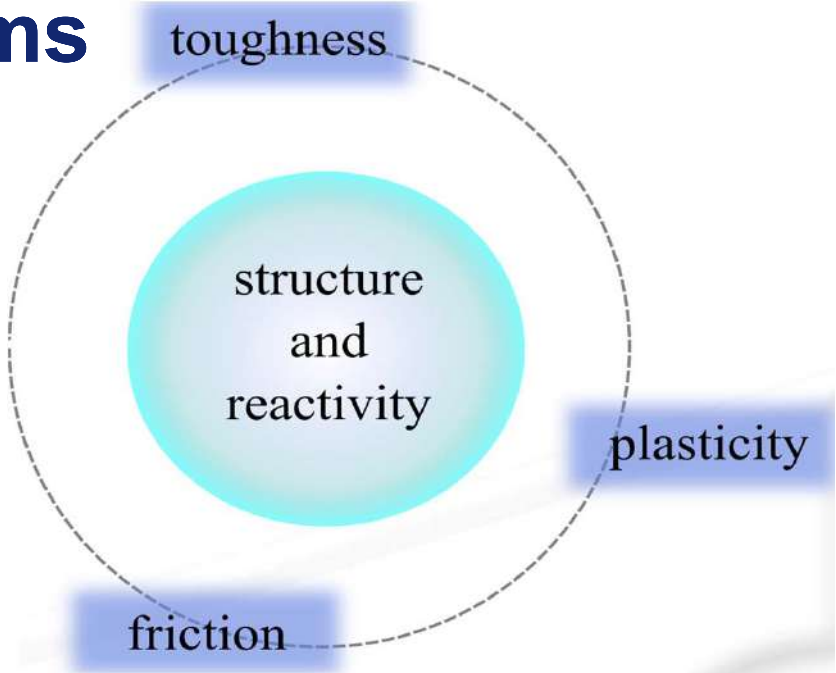


Puttick J. Phys. D 12 (1979) L19-23
Lawn and Marshall J. Am Ceram Soc 62 (1979) 347

Toughness, plastic deformation, friction – elementary mechanisms





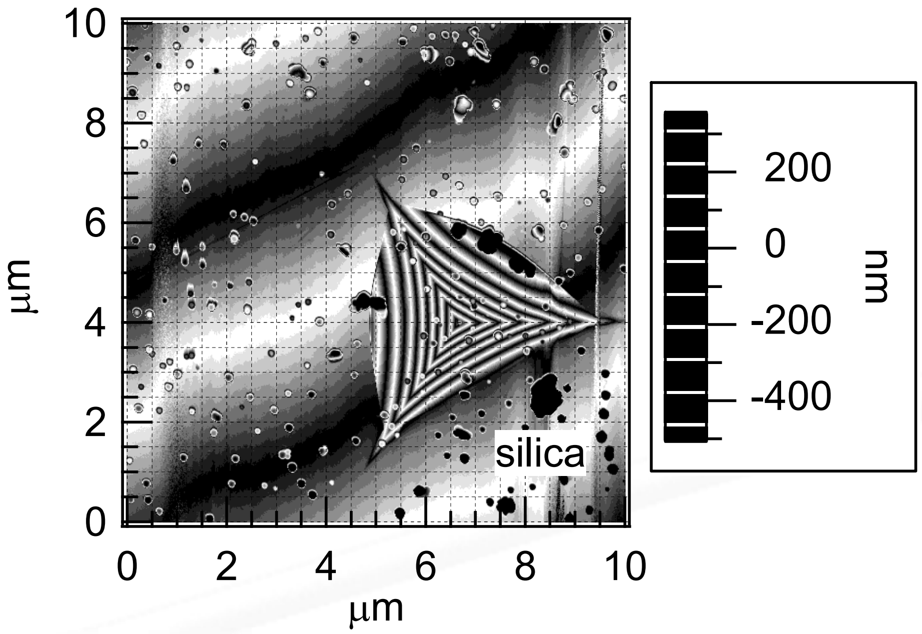


- elementary rearrangements in an amorphous matrix – no dislocation…

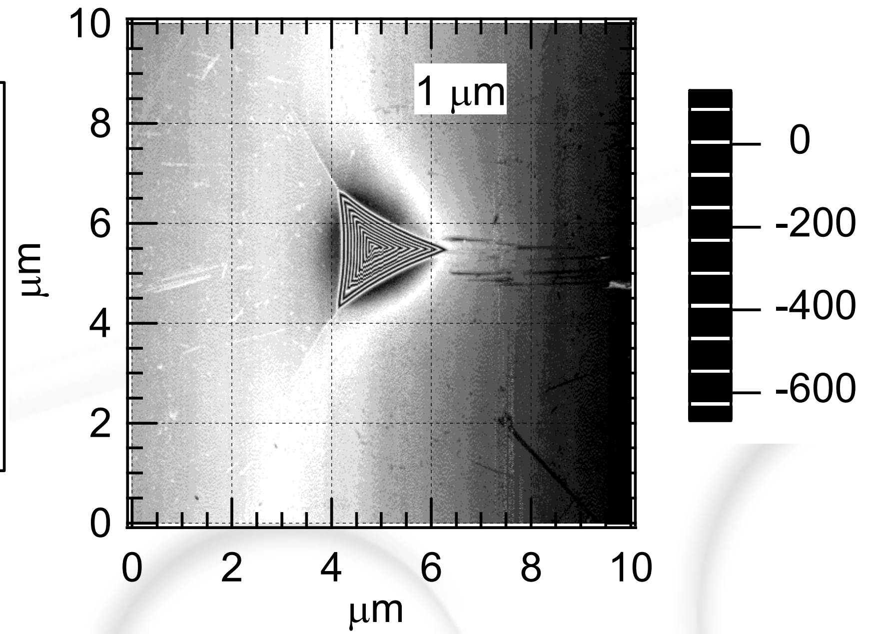
foam

Indent morphologies

- *macroscopic scale*



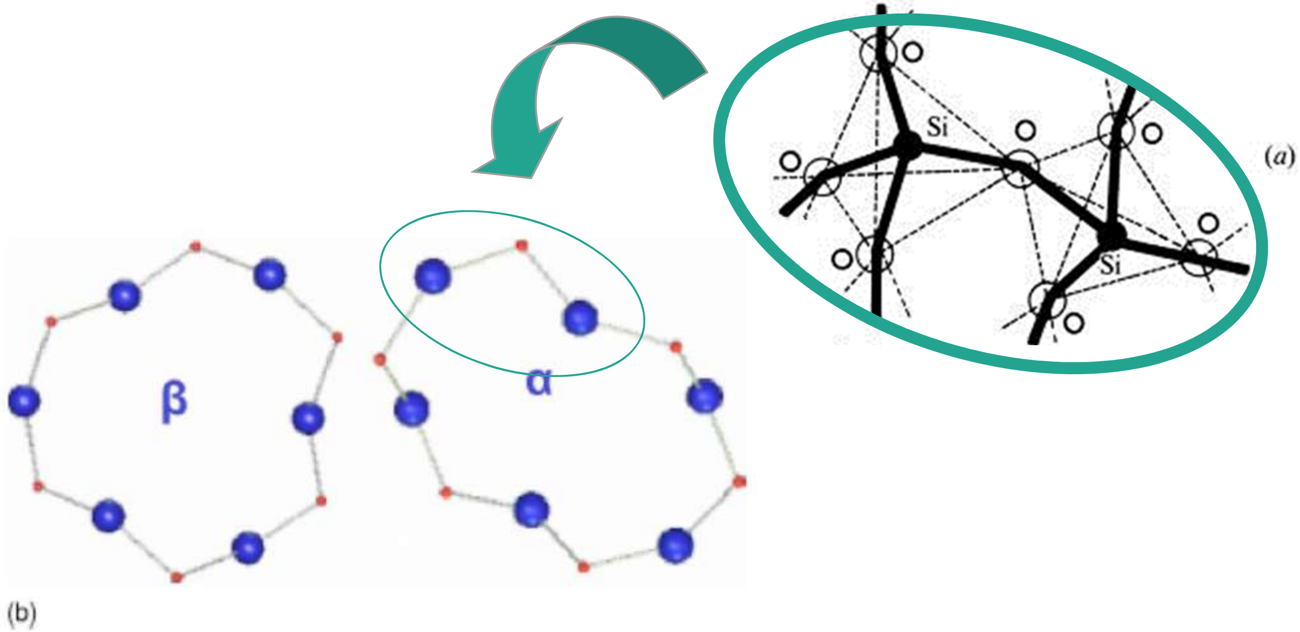
silica, berkovich



silica, cube corner

Plastic deformation – elementary mechanisms

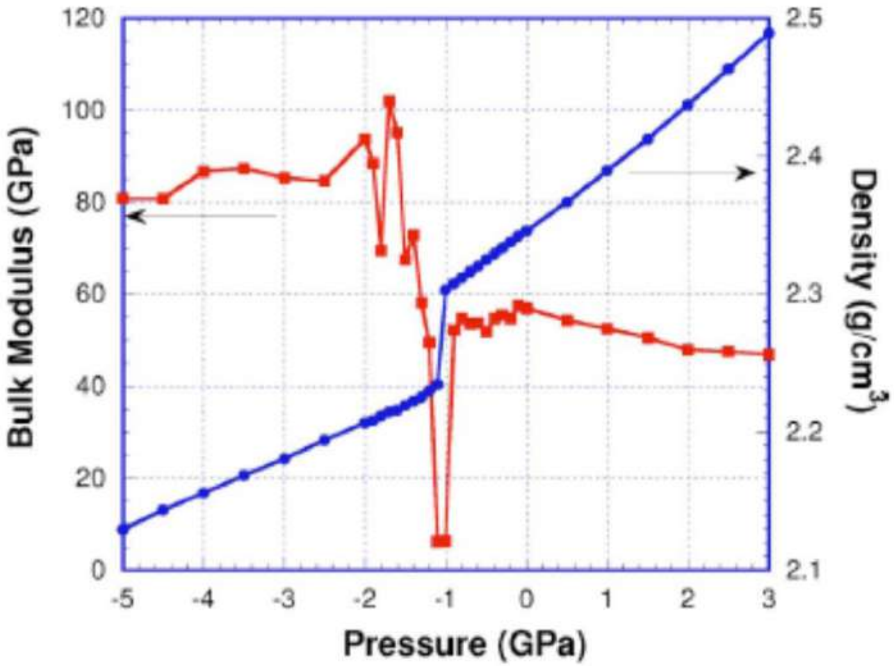
- Elementary, local, rearrangements in an amorphous matrix

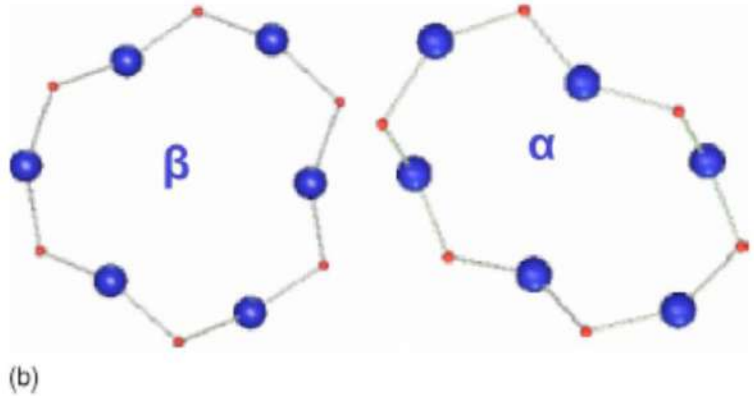


Local transition from β to α cristoballite-like structure
Huang Kieffer 2004

Plastic deformation – elementary mechanisms

- **elementary rearrangements in an amorphous matrix – no dislocation…** cf colloidal glasses, foam

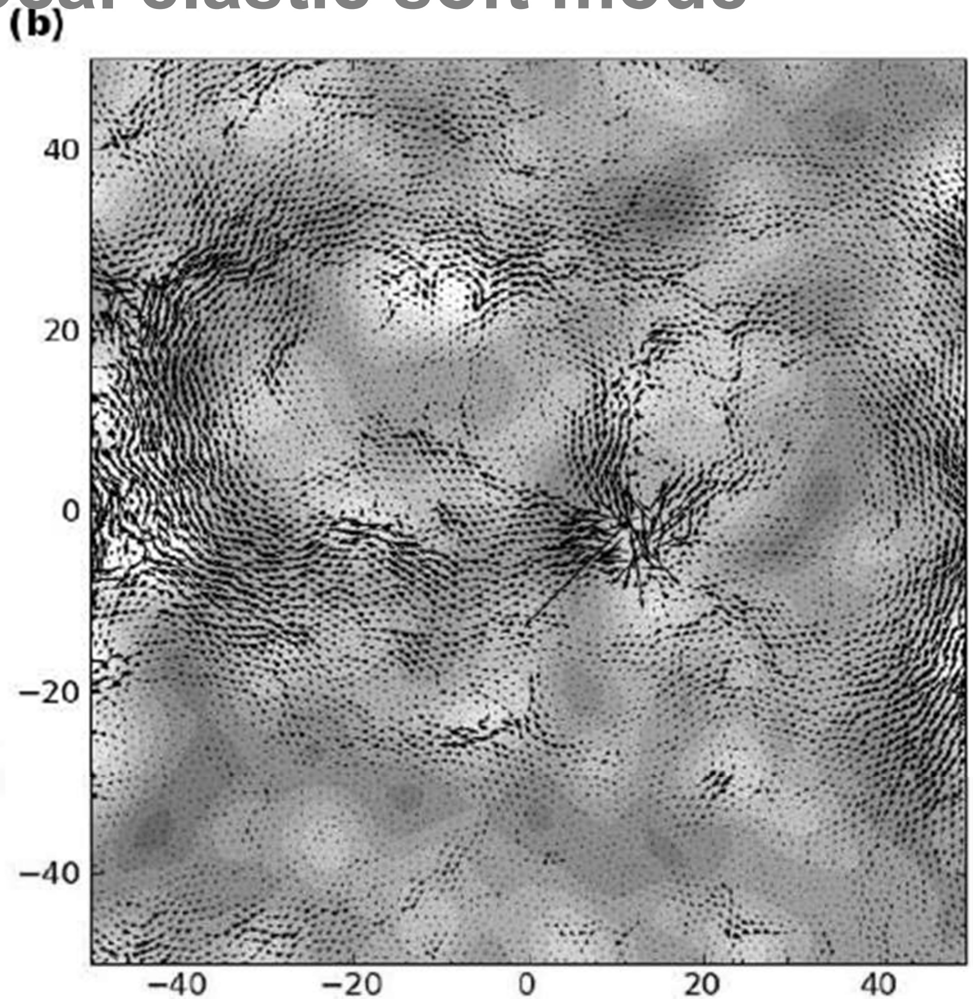




β to α cristoballite
Huang Kieffer 2004

Plastic deformation – elementary mechanisms

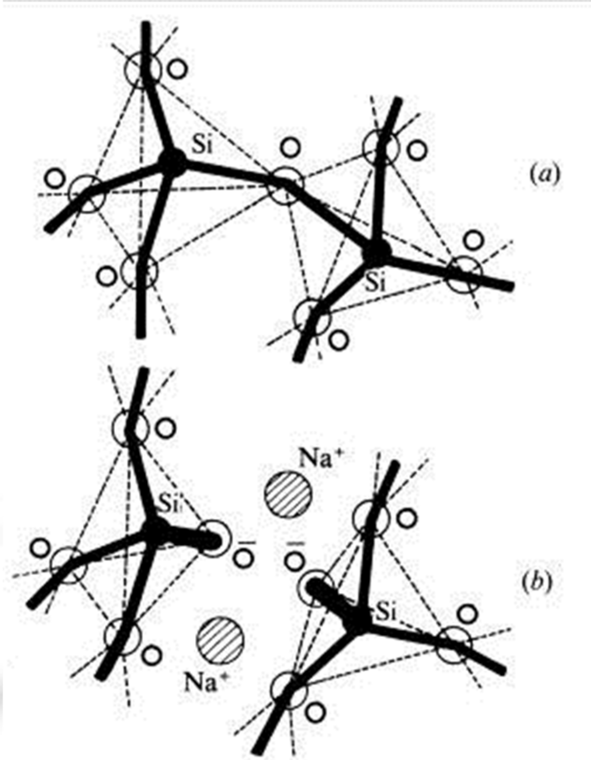
- Local elastic soft mode



Tsamados et al. 2009

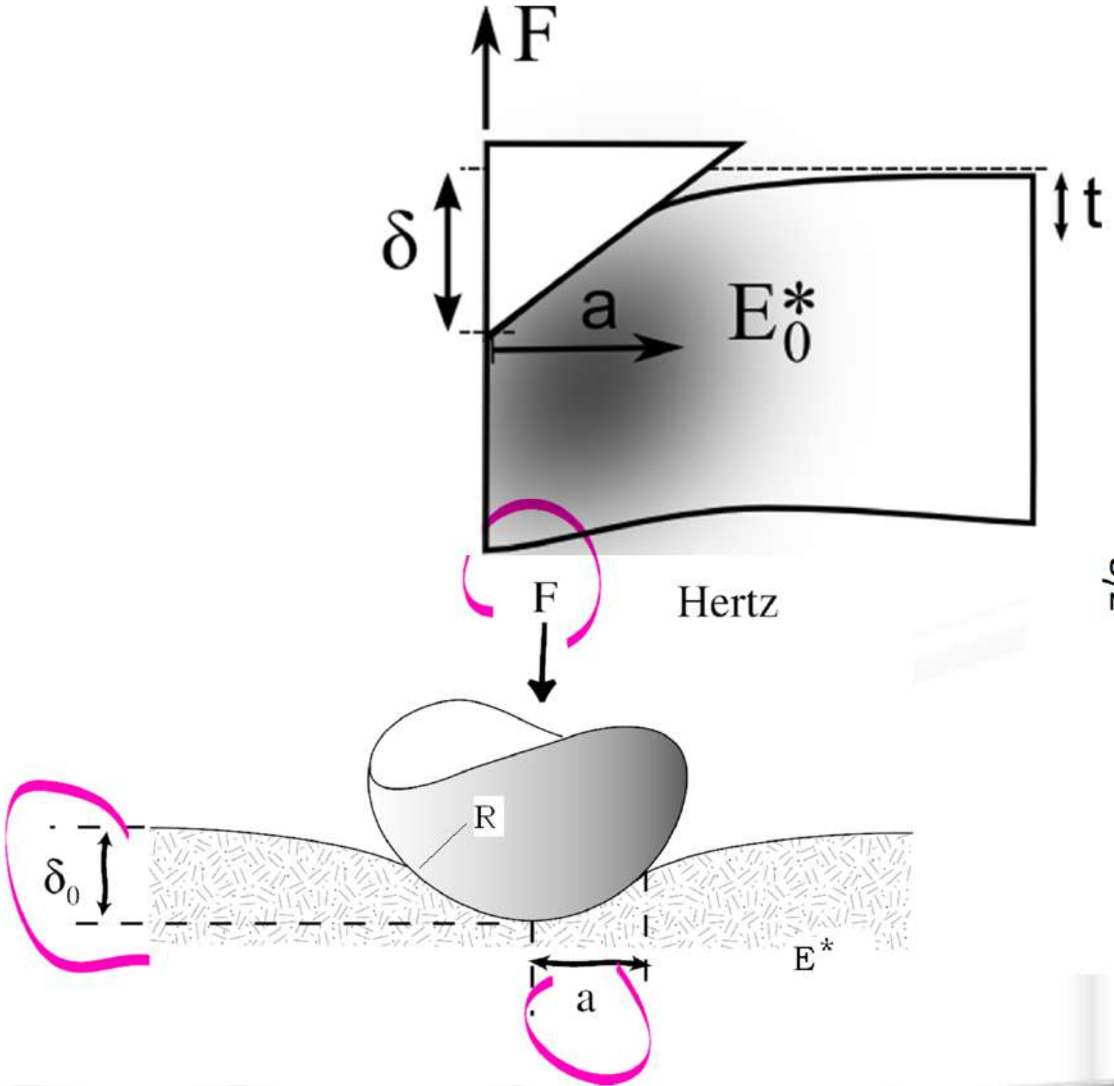
Plastic deformation – elementary mechanisms

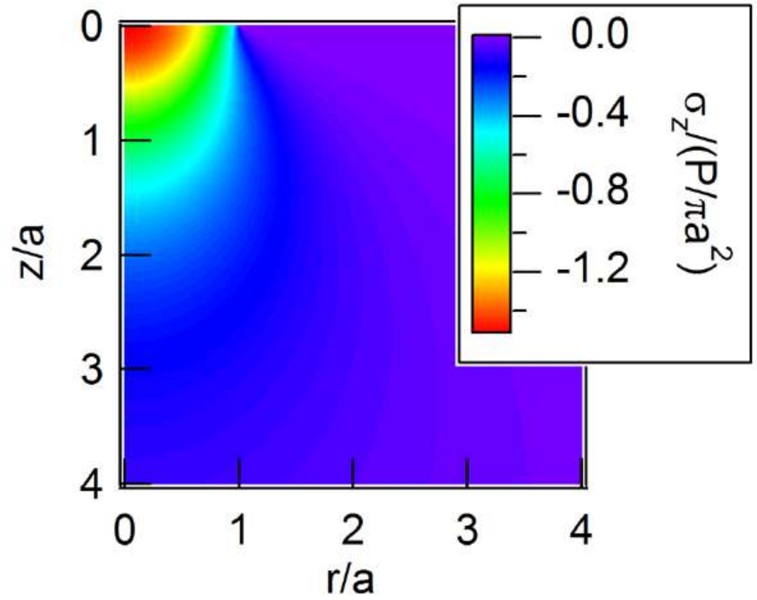
Amorphous silica vs. amorphous silicates



Finite Element Modelling

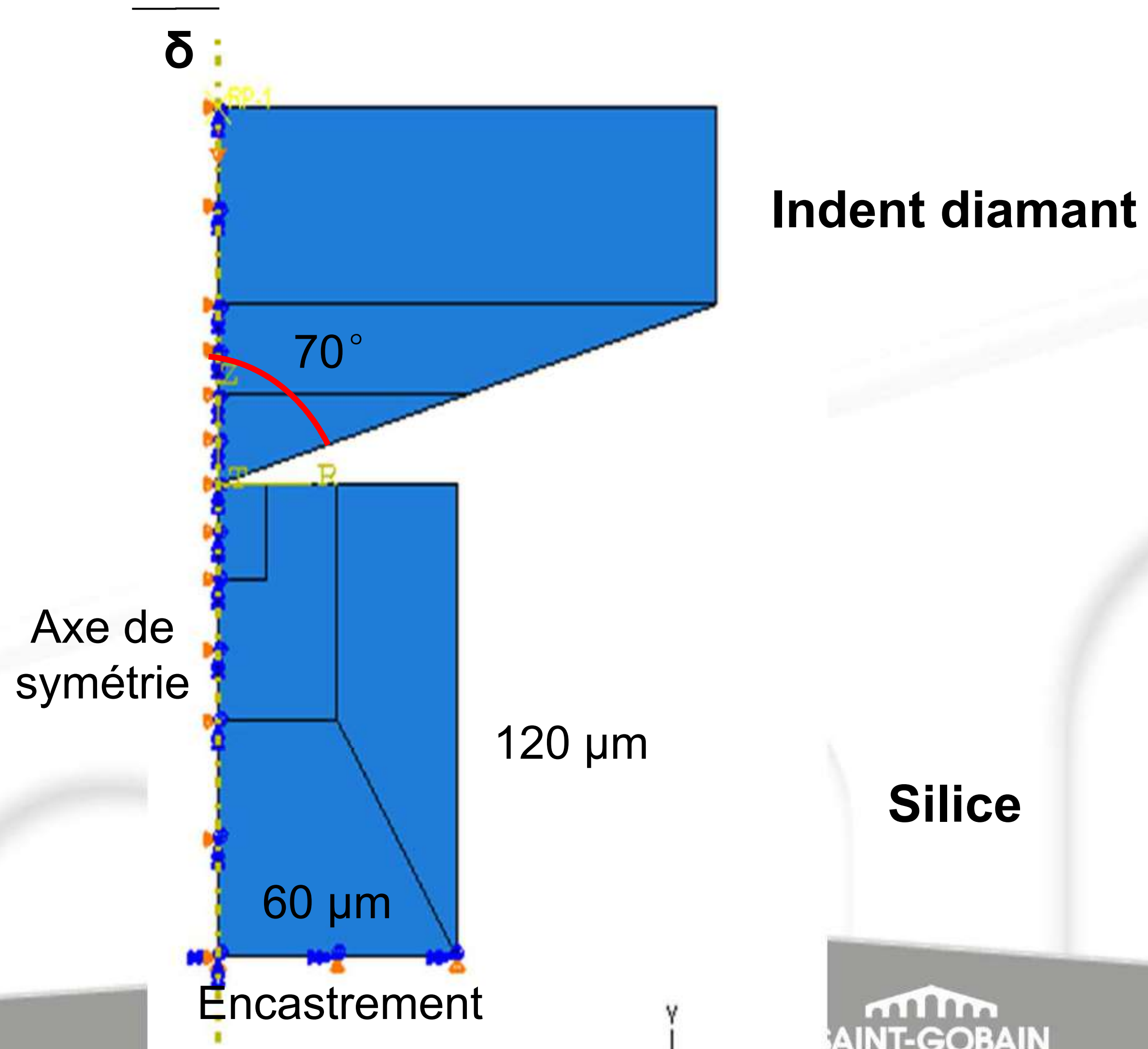
Analytical models – Elastic





Indentations axisymétrique

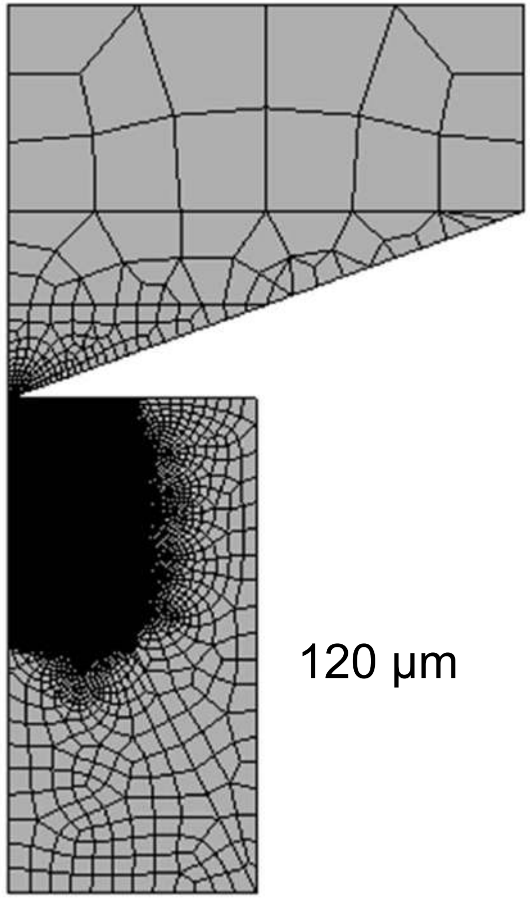
- Conditions aux limites



Indentations axisymétrique

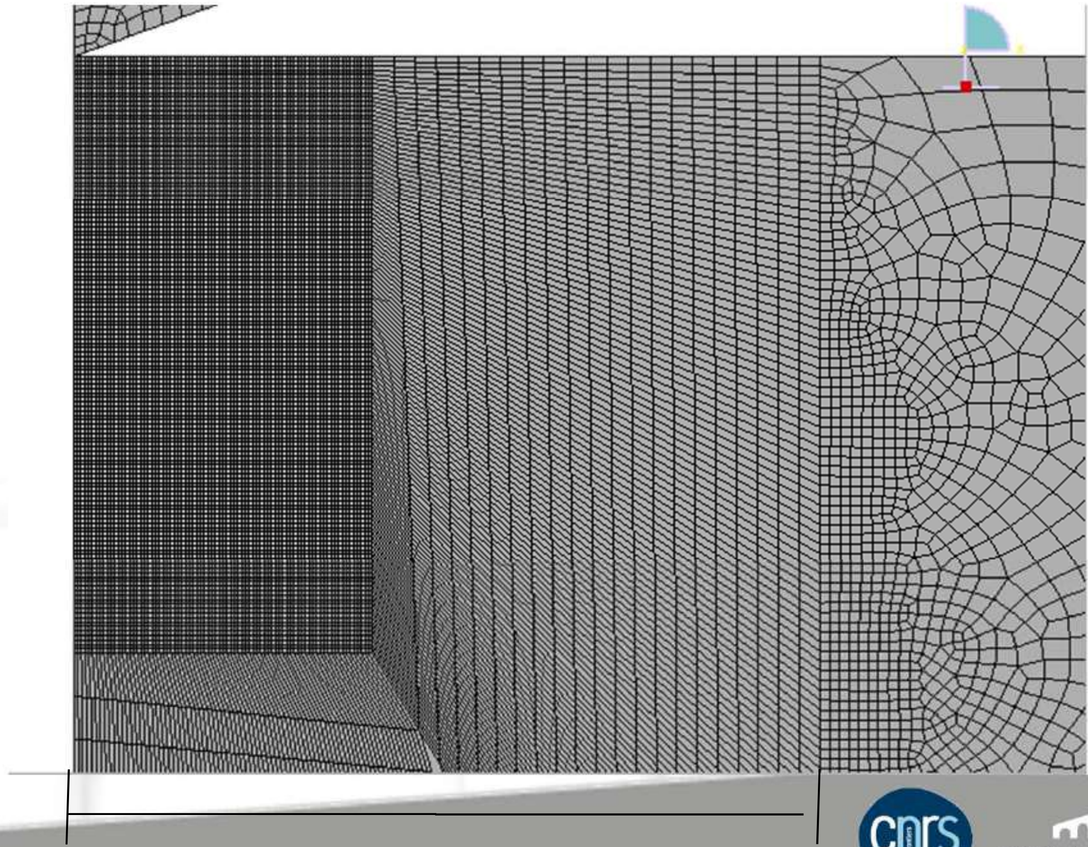
- Maillage

Quadrangles linéaires axisymétriques



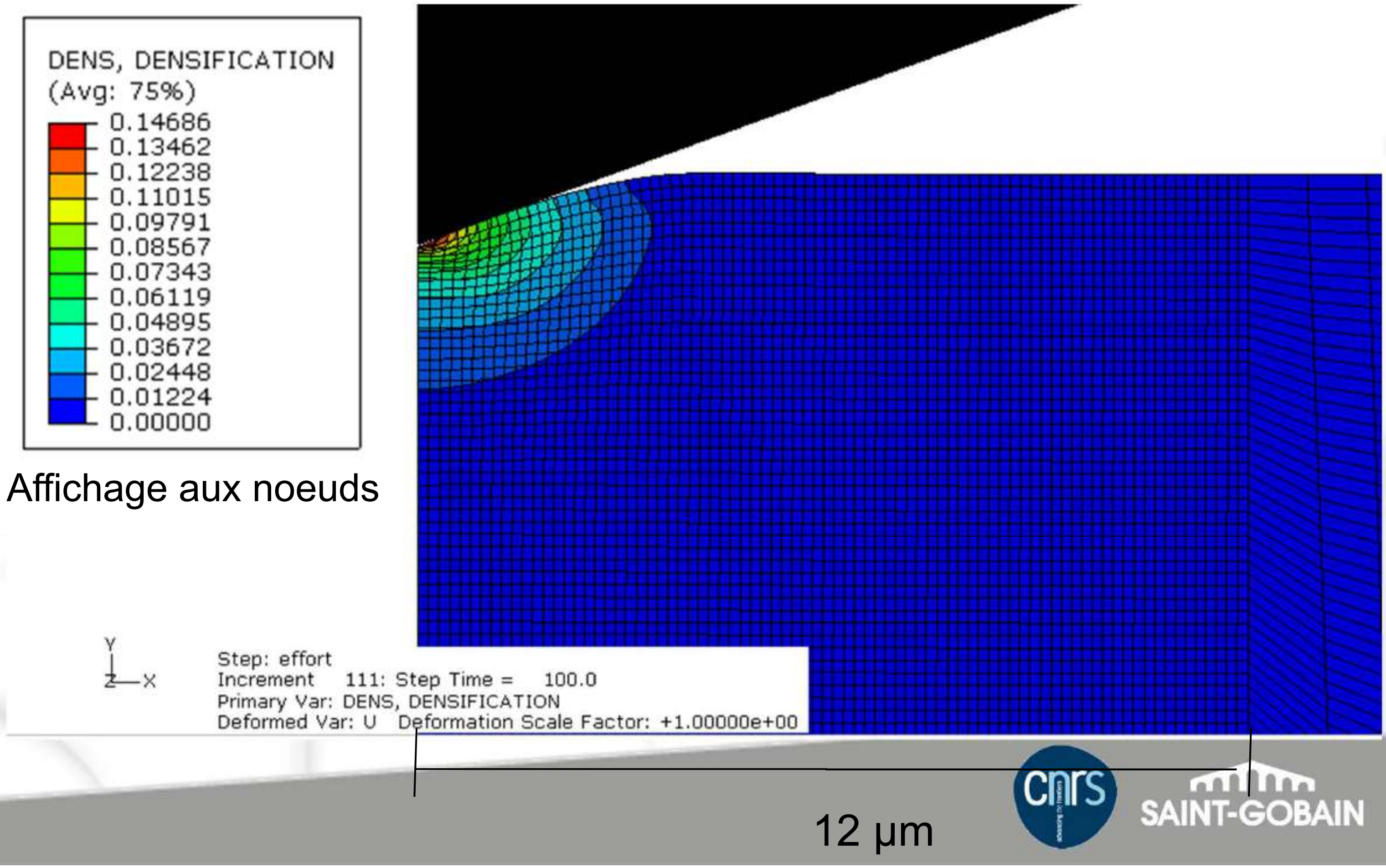
Indentations axisymétrique

- Maillage



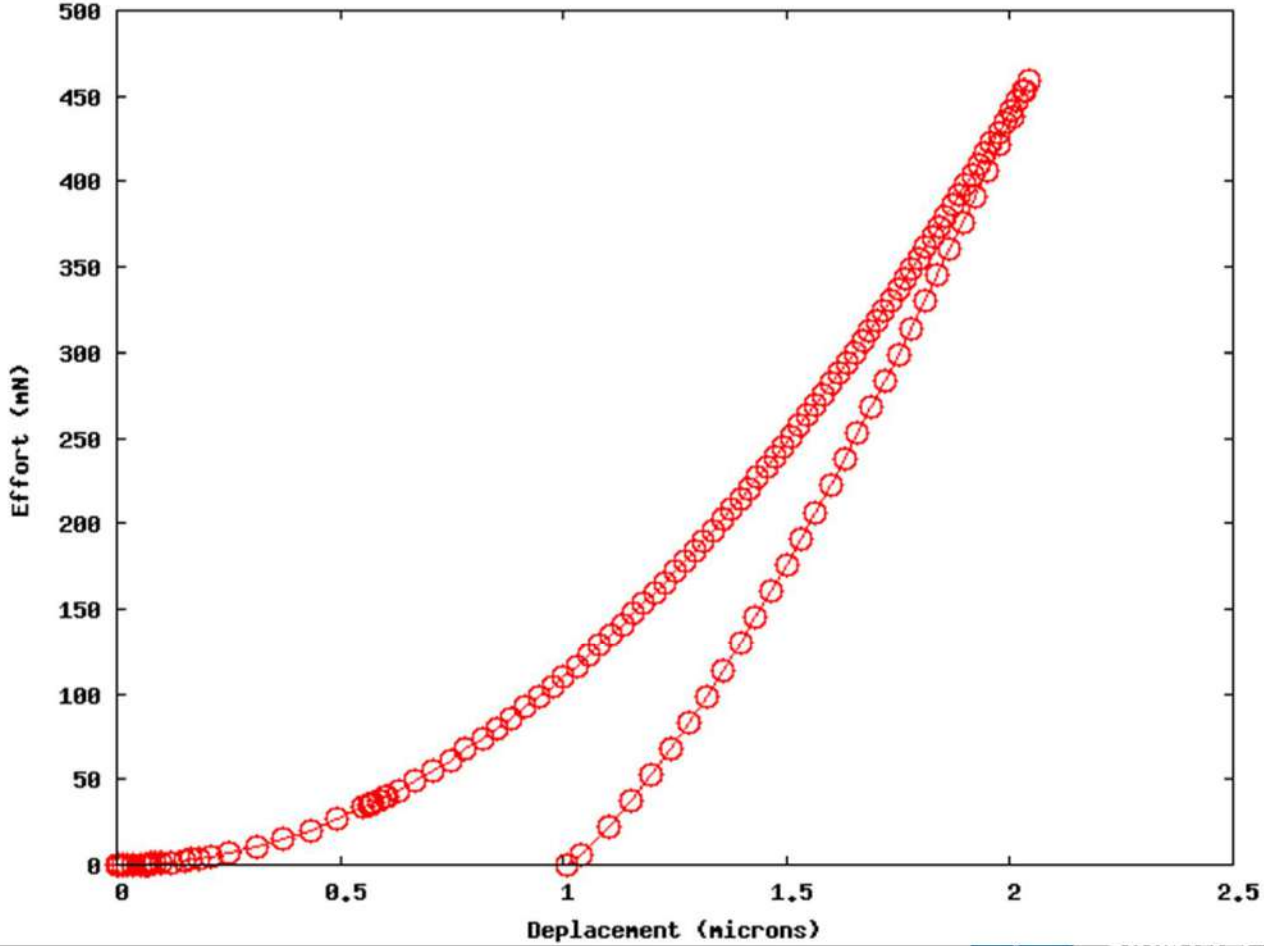
Indentations axisymétrique

- Déformation calculée par élément



Indentations axisymétrique

- Courbe Fδ



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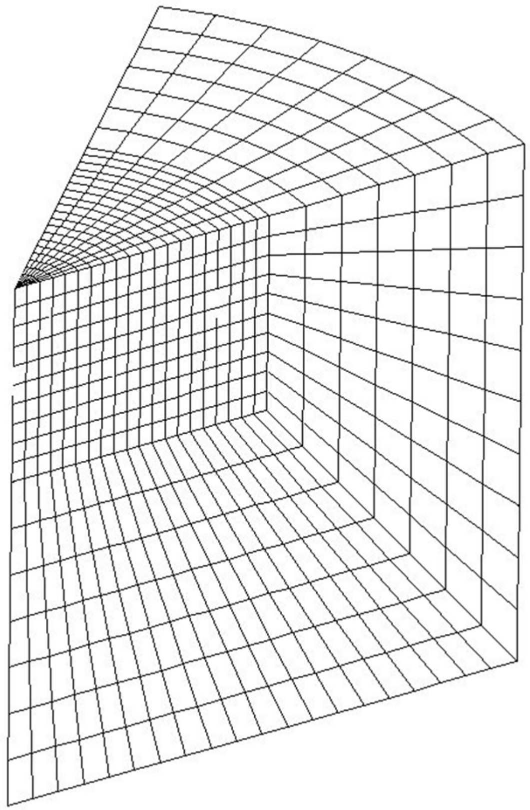
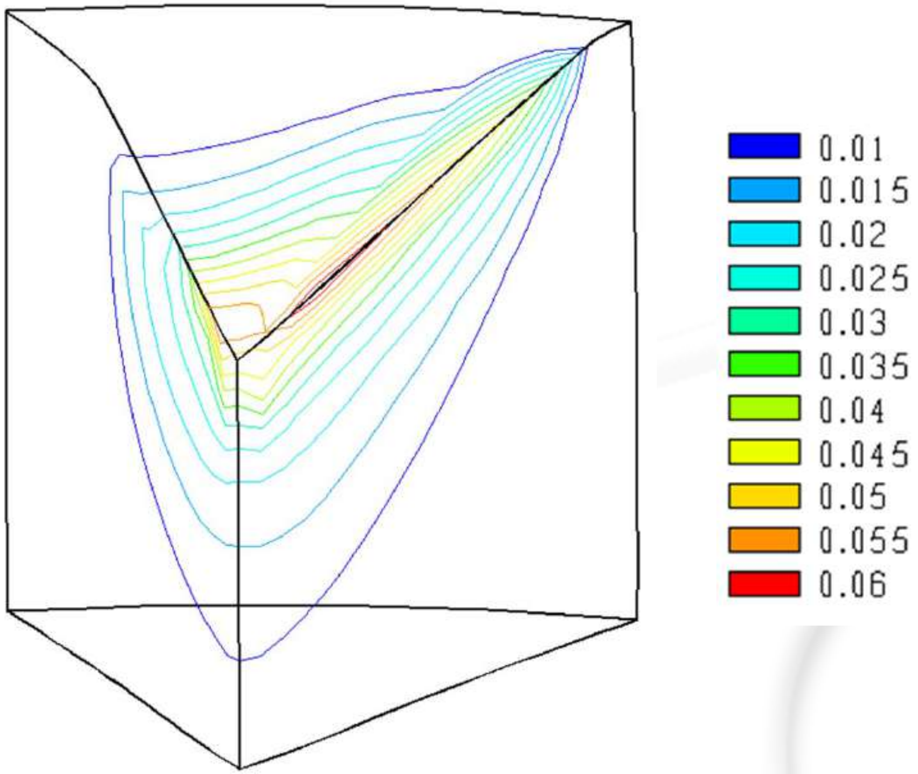
Vickers 3D – FEM calculation of the densification



mesh



Isodensification maps $\frac{\Delta\rho}{\rho_0}$

Constitutive equation

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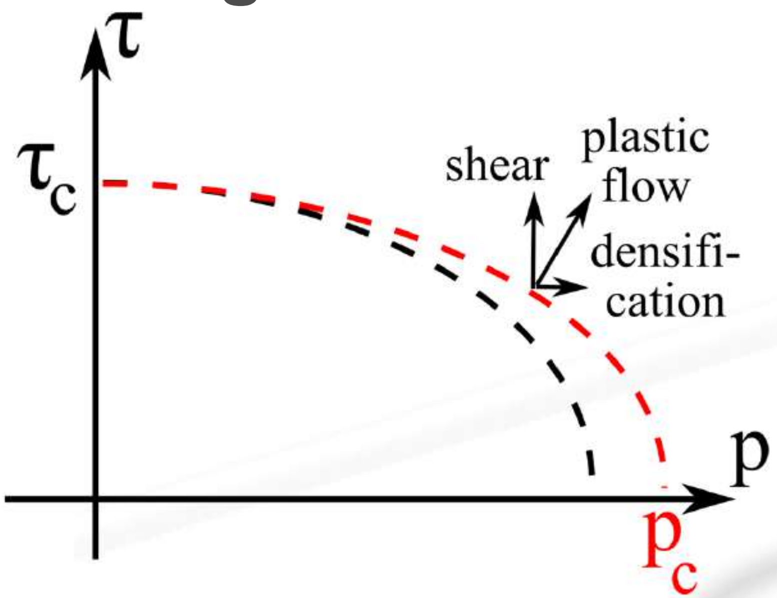
Constitutive relation - Densification

- **Porous media + strain hardening**

von Mises stress	τ_c
hydrostatic pressure	p_c
porous fraction	ϕ

$$\left(\frac{\tau}{\tau_c}\right)^2 + \left(\frac{p}{p_c(\phi)}\right)^2 - 1 = 0$$

$$\dot{\phi} = (1-\phi)\mathrm{Tr}\left(\dot{\bar{\bar{\epsilon}}}_p\right)$$

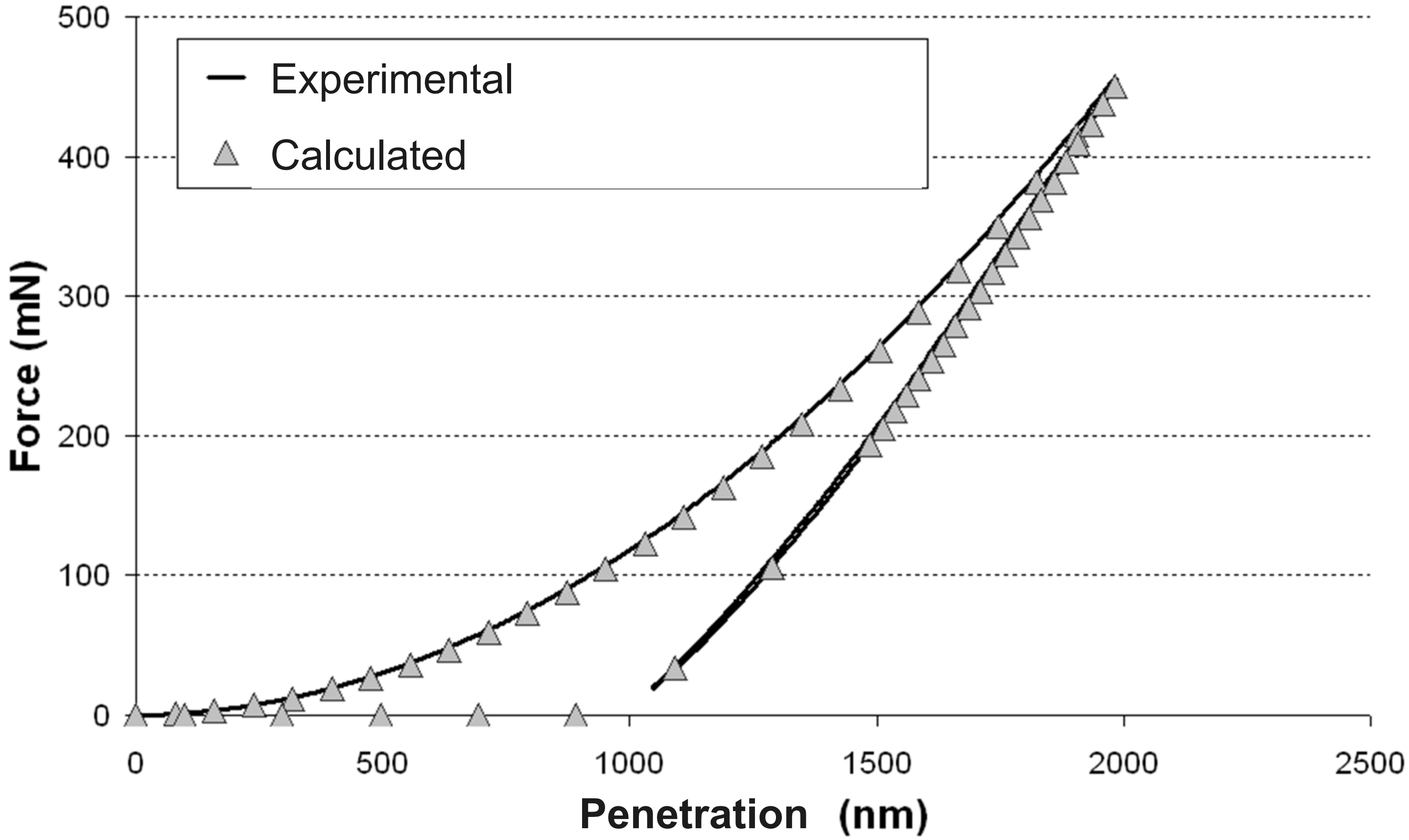


Associated plasticity

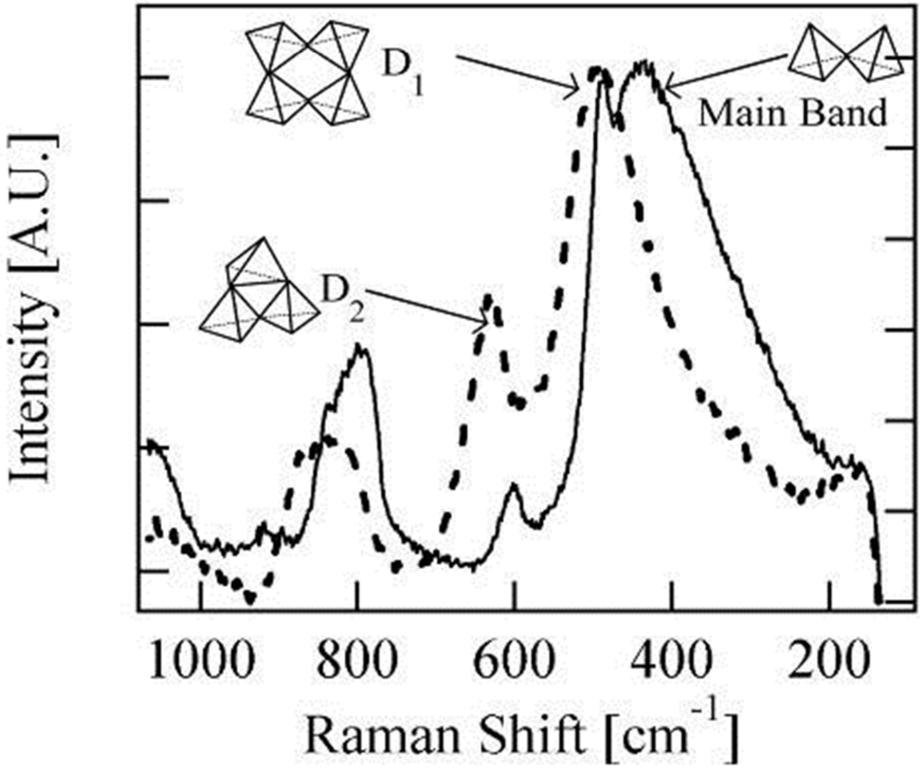
G. Kermouche, et al. , Acta Materialia, 56:3222-3228, 2008

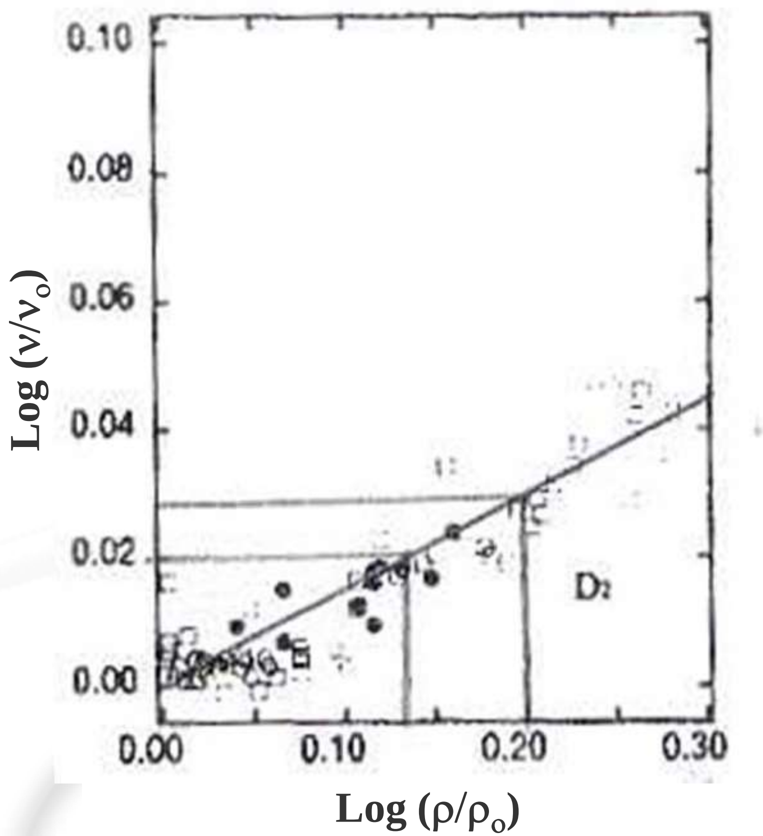
Identification – Silicate micromechanics experiments

Nanoindentation



Densification & Raman spectroscopy





Sugiura et al., J. Appl. Phys. 81(4) (1997)

A. Perriot et al. J. Am. Ceram. Soc. 89 (2006) 596-601

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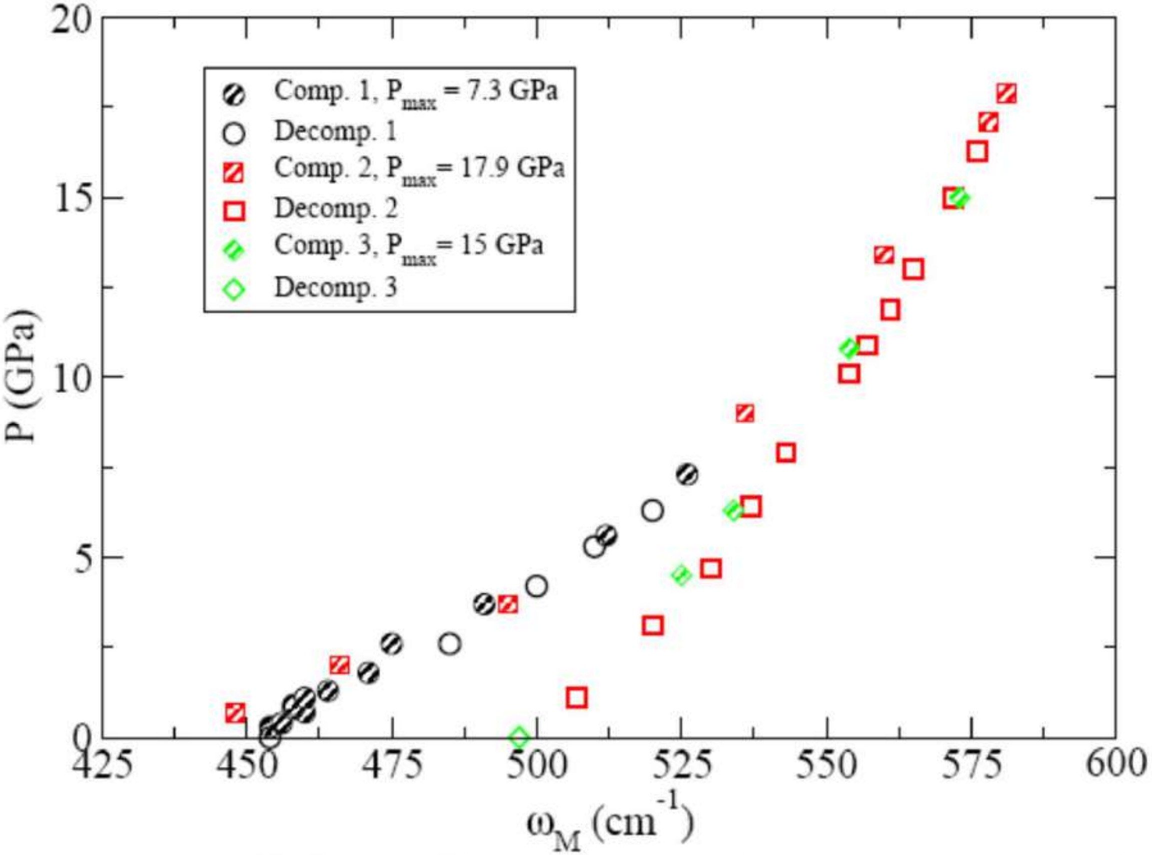
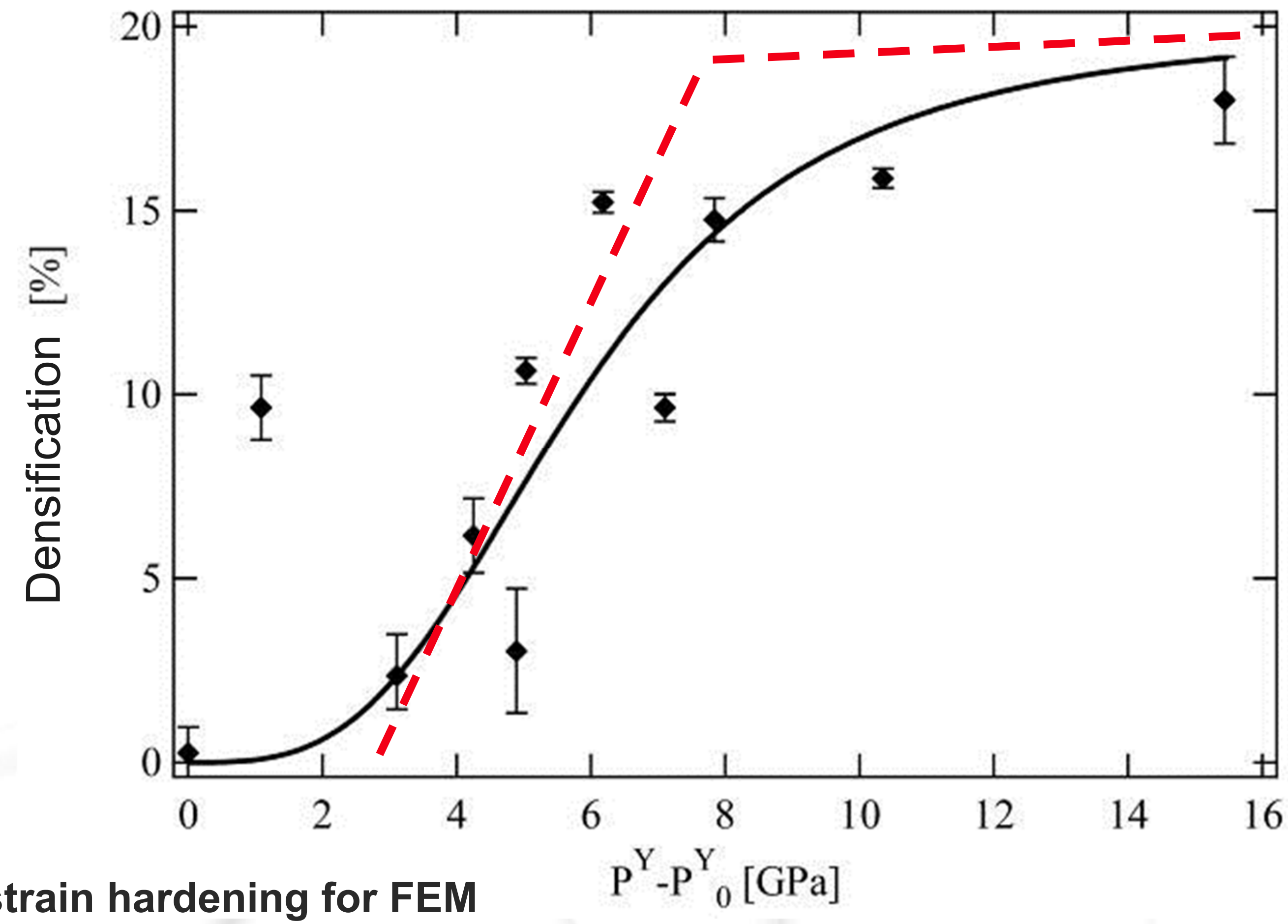
Hydrostatic – Strain hardening



T. Deschamps (Vandembroucq et al. J. Phys.: Cond. Mat. 2008)

MD: Huang Kieffer 2004

Hydrostatic – Strain hardening



strain hardening for FEM

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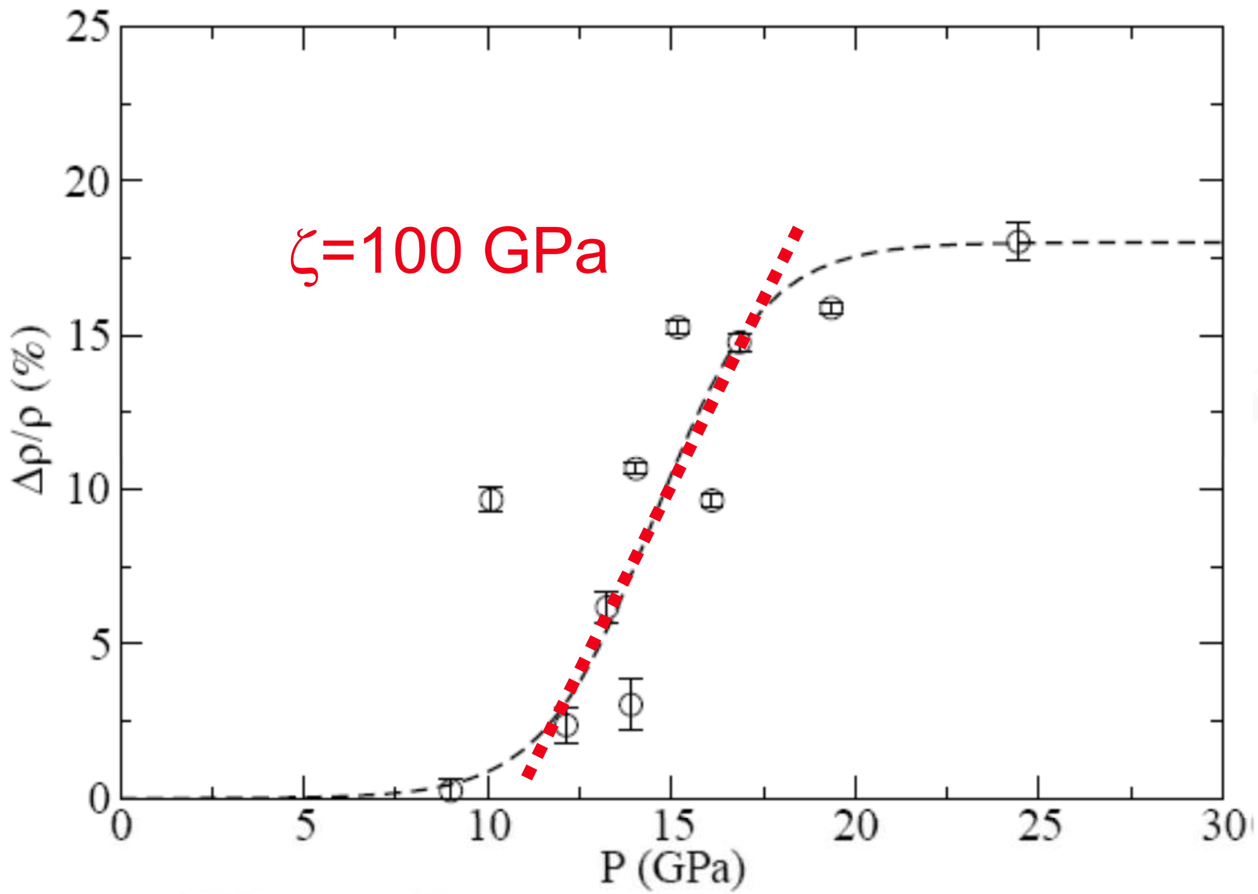
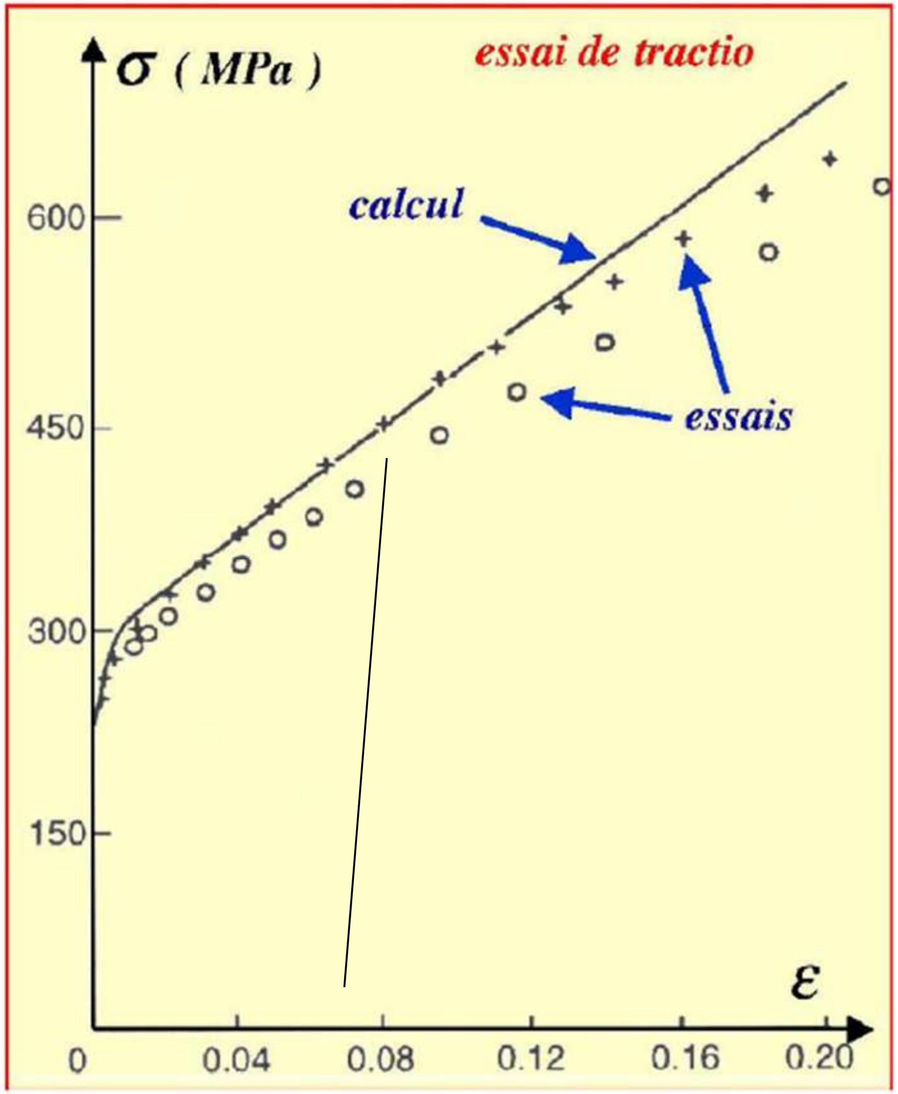
Hydrostatic – Strain hardening

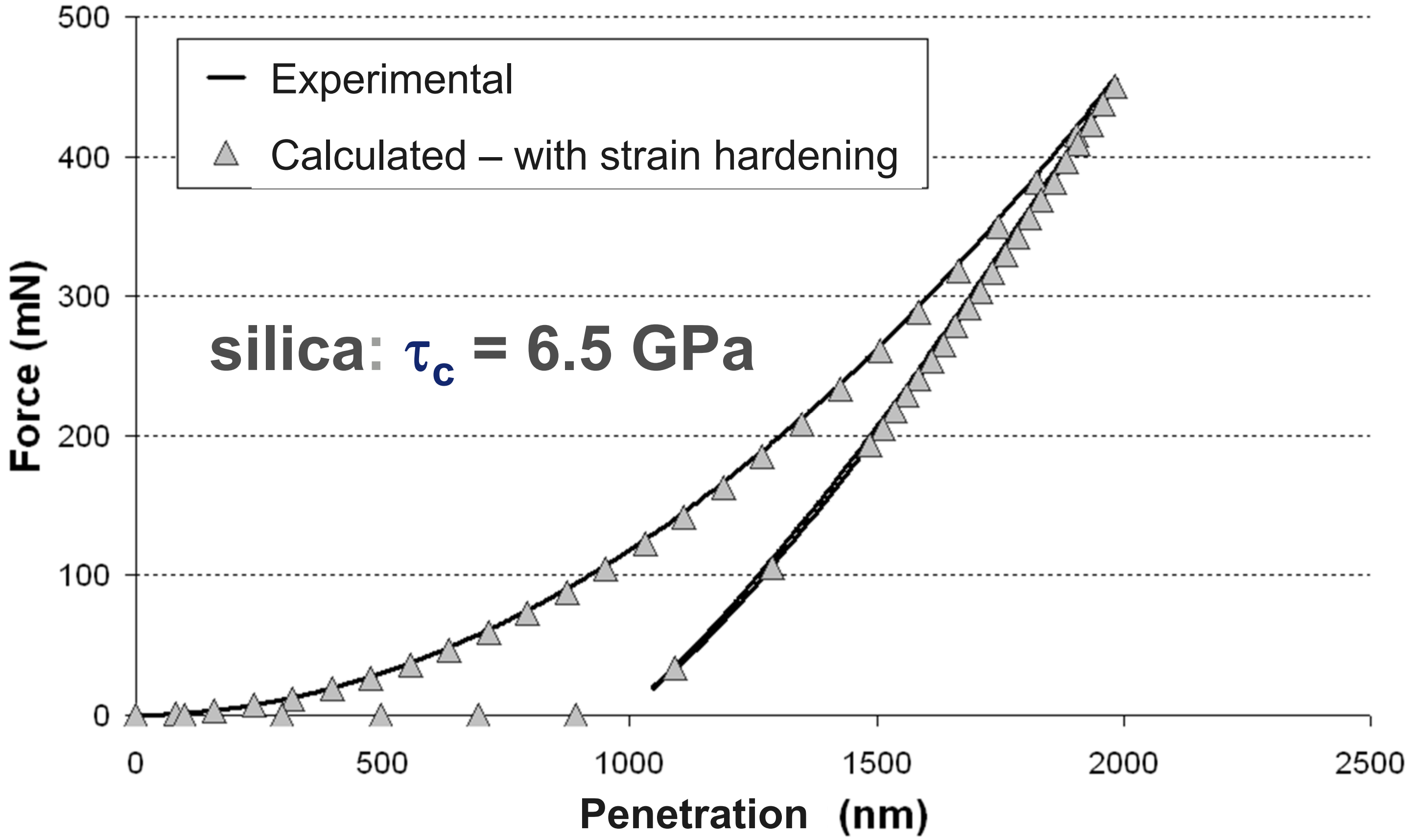


A. Perriot
Vandembroucq et al. J. Phys.: Cond. Mat. 2008

Strain hardening

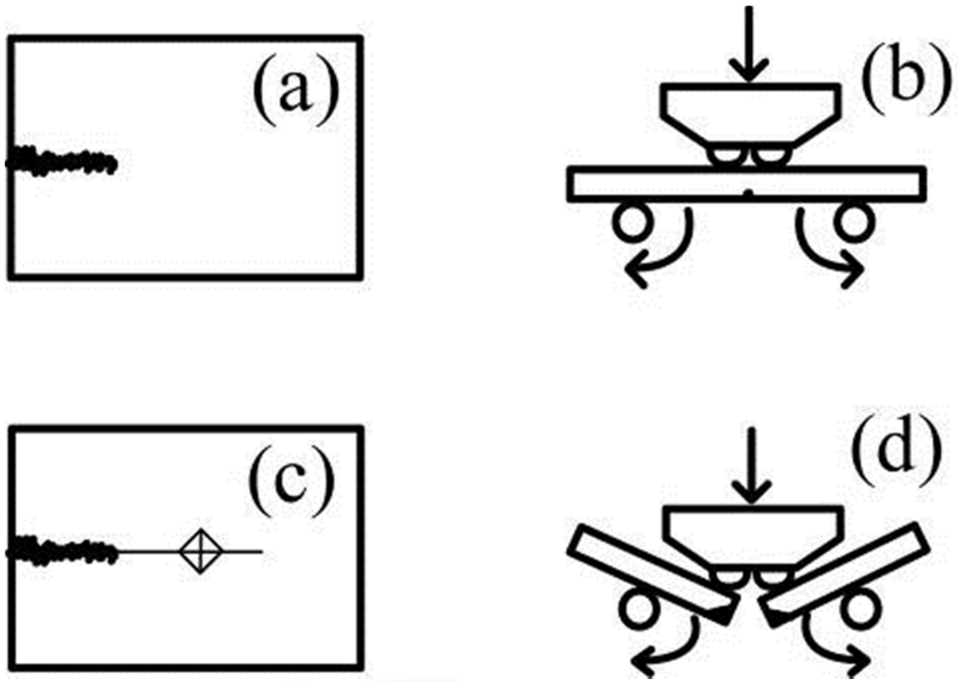


Nanoindentation – Identification of the shear limit τ_c



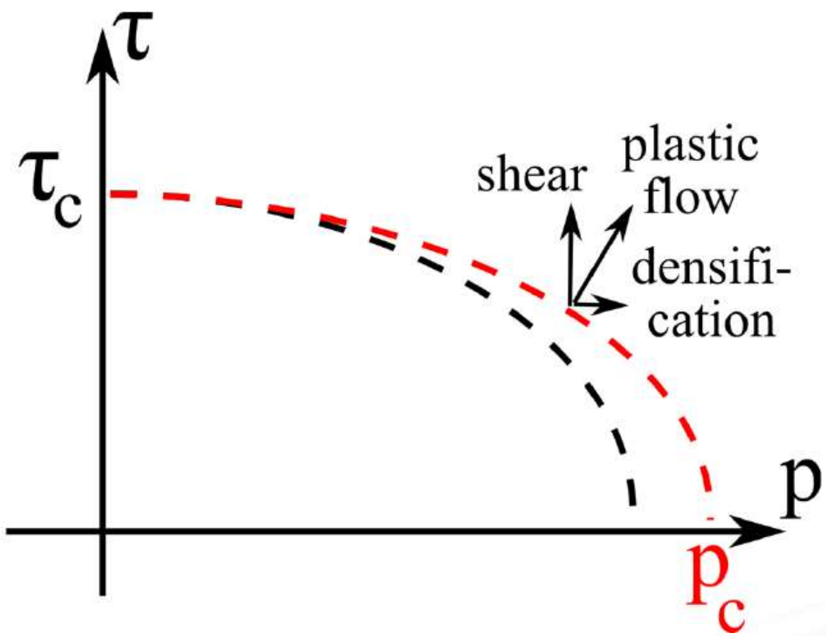
G. Kermouche et al. Acta Materialia 56 (2008) 3222

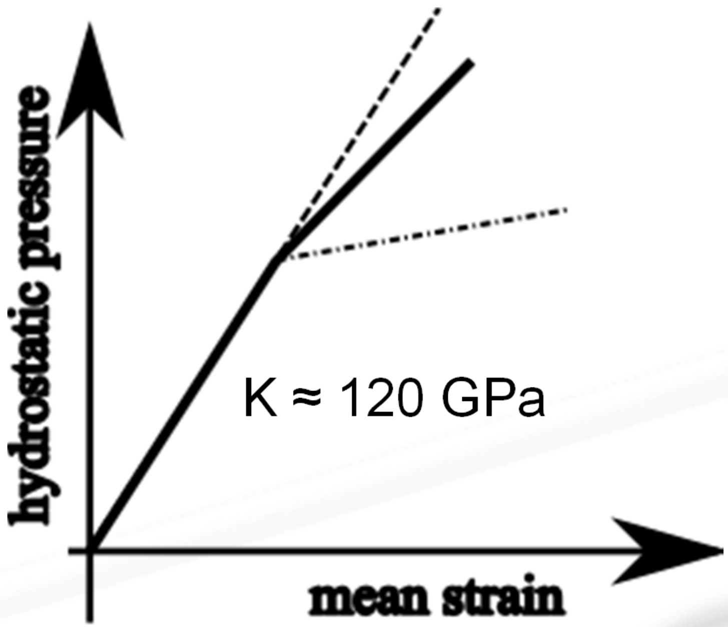
Cross sections – method



G. Kermouche et al. Acta Mater. 56 (2008) 3222

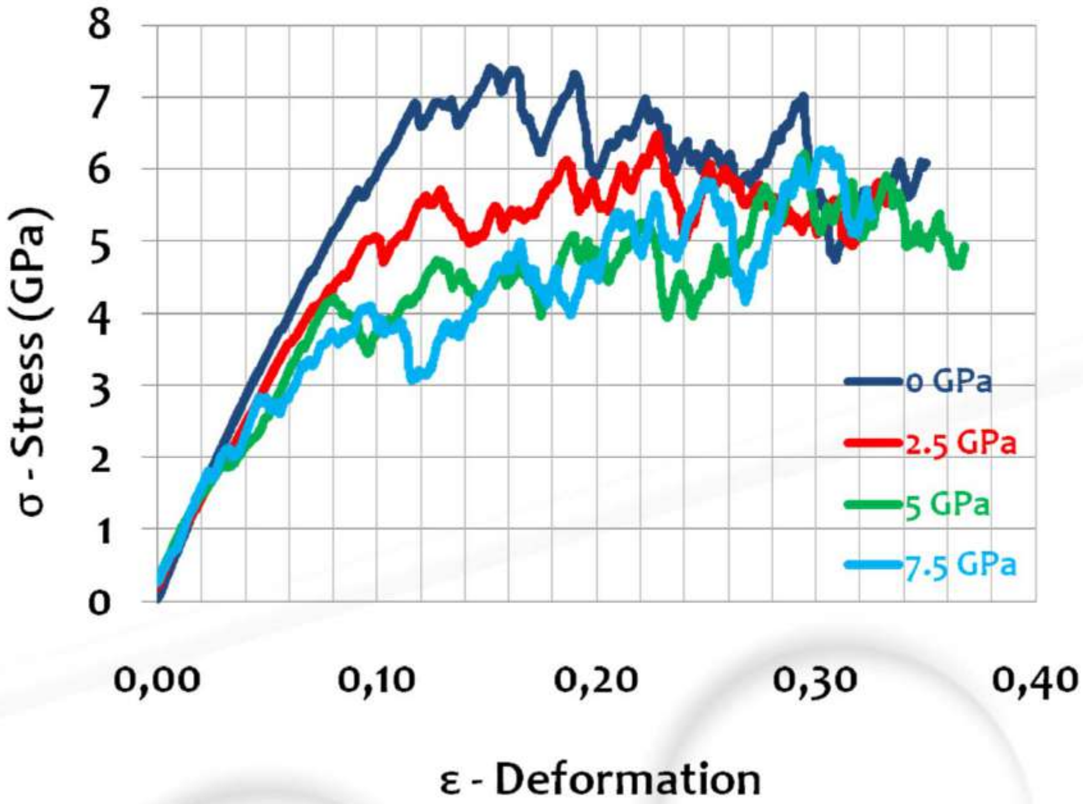
Constitutive relation -- Quantitative





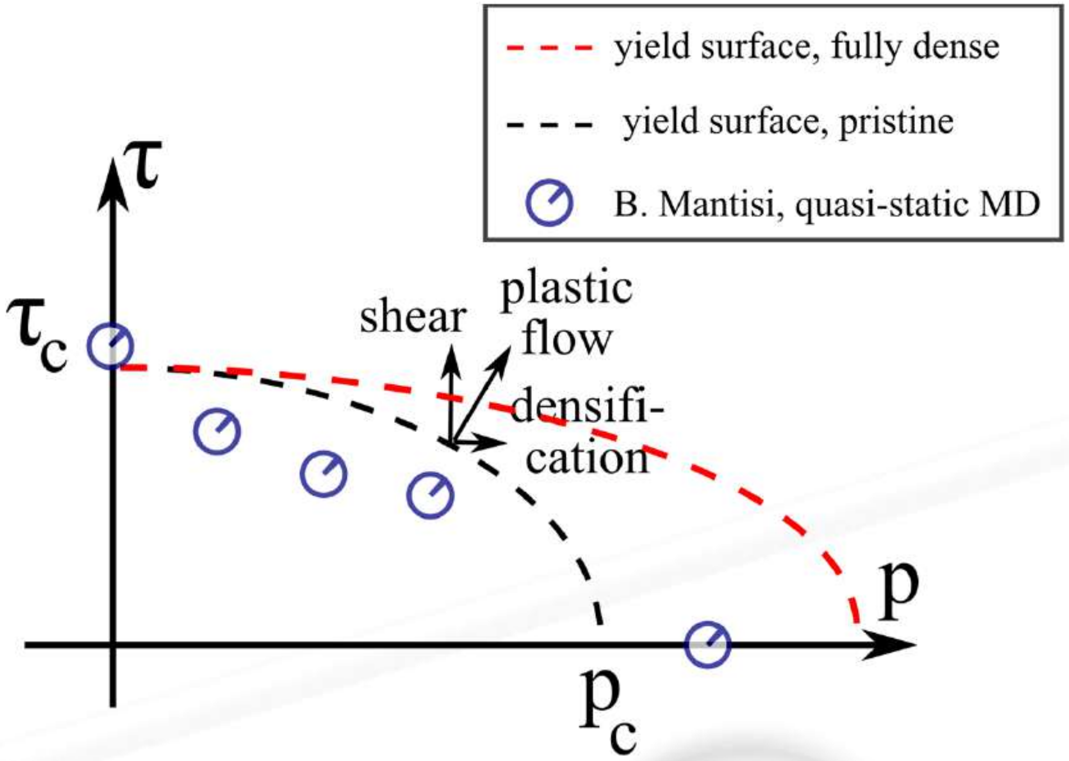
	E (GPa)	ν	p_c (GPa)	τ_c (GPa)	ϕ_0
silica	72	0.18	11.5	6.5	17.5

BKS Wolf truncated, mod. S. Ispas

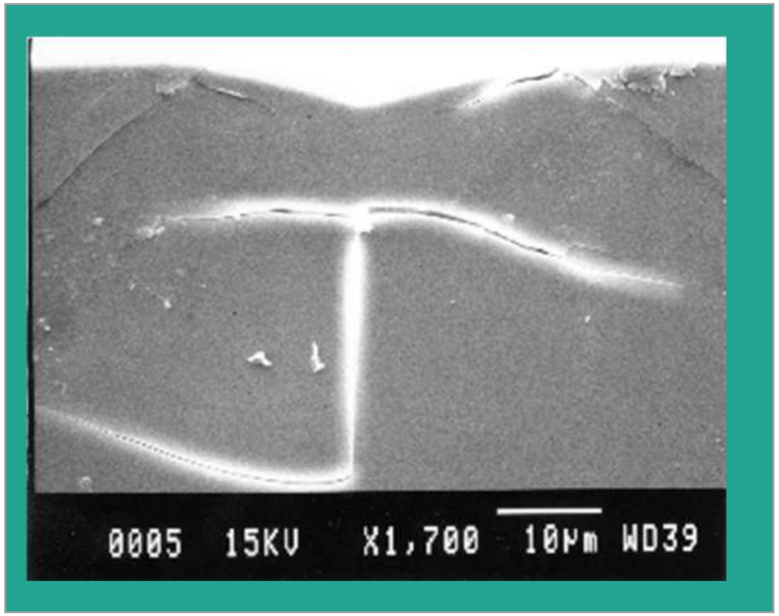


B. Mantisi, A. Tanguy (quasi static MD)

Constitutive eq. *vs.* MD

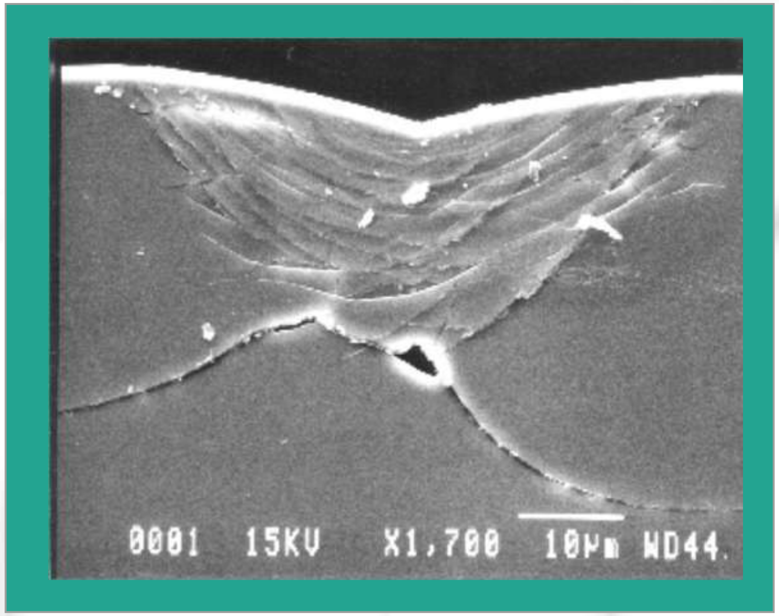


Macroindents – cross sections



Anomalous glasses (amorphous silica)
densification

Normal glasses (float glass)
shear bands



Vénard (1999)

Hagan, J. Mater. Sci. 15 (1980) 1417

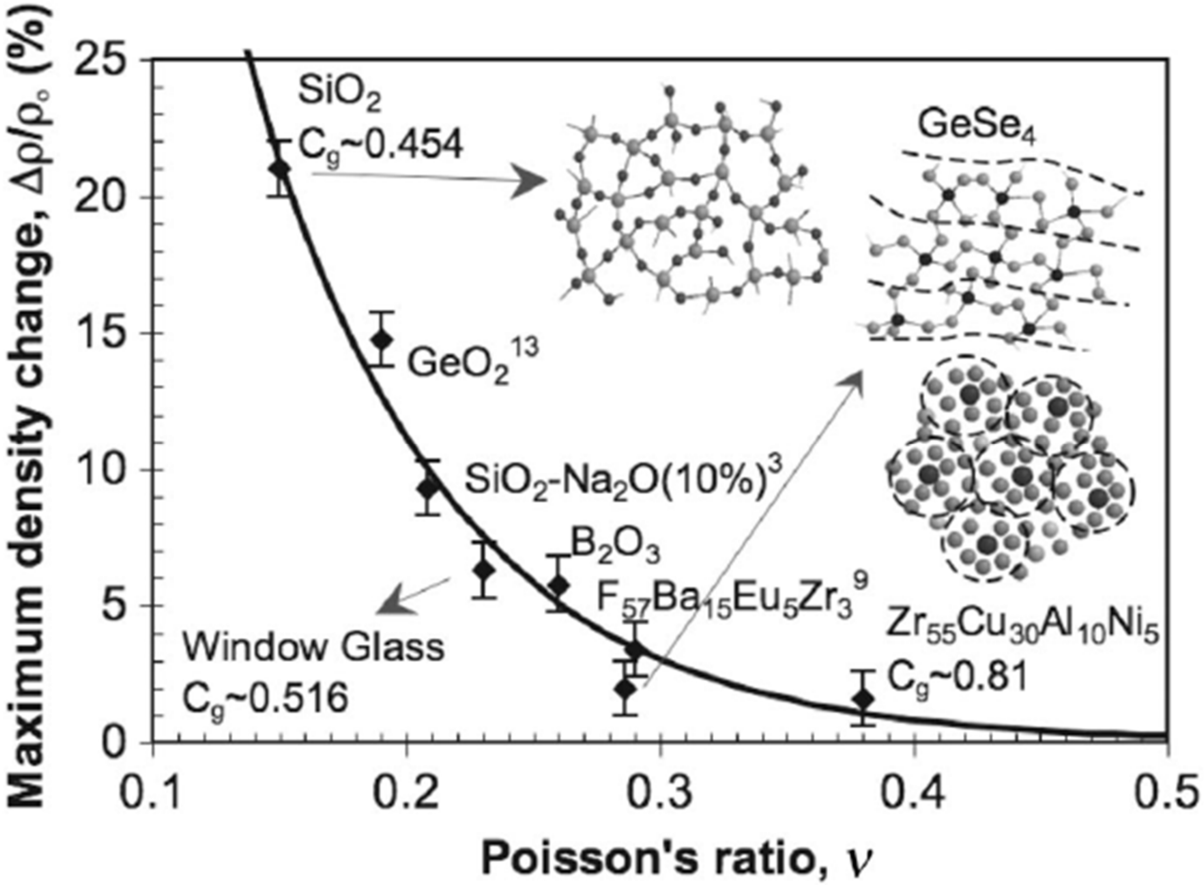
Other silicate glasses

Silicate glasses – compositions

- decreasing propensity to densify

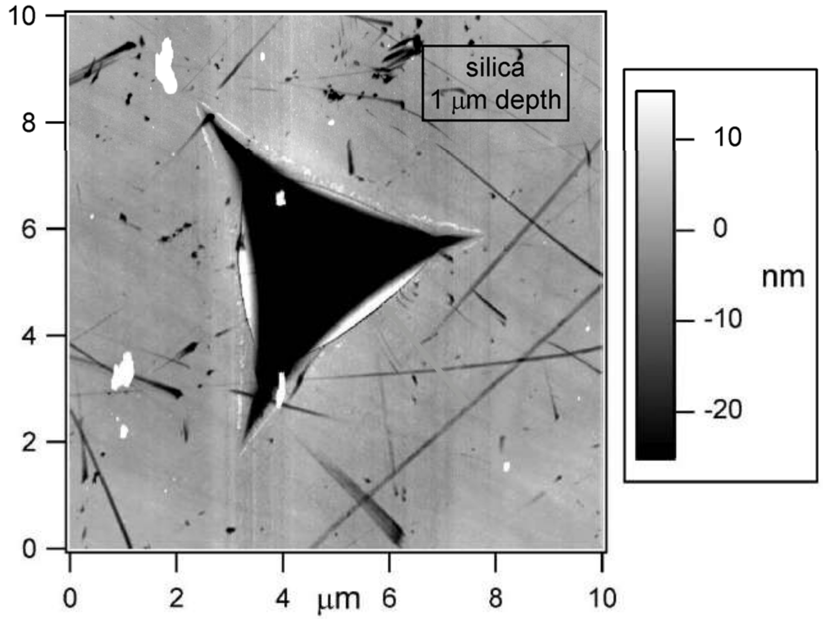
Material	Silica	alumino-boro-silicate	alumino-silicate + alcali	Soda-lime silica
Adjustable parameter	H_2O	no alcali	alcali	alcali
densification	20 %	?	?	4-6 %

Correlation between Poisson ratio and density

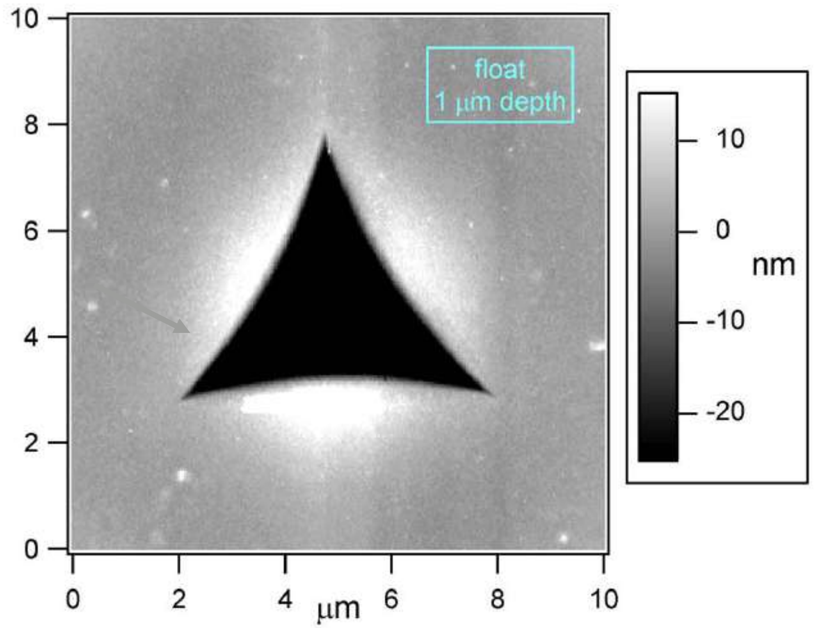


Rouxel, PRL 2008

Surface morphology of the indents



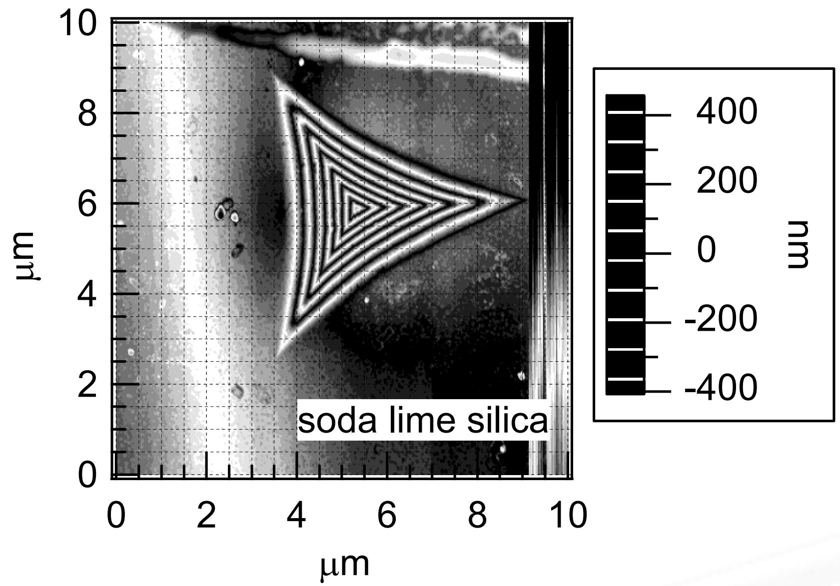
Silica: the edge of the indent is flat, with flakes sticking out.

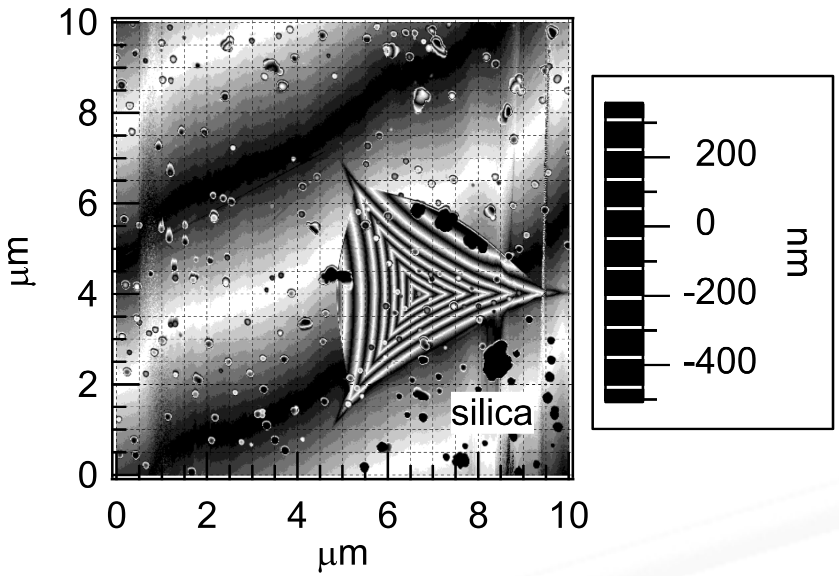


Float glass: the edges exhibit pile-up.

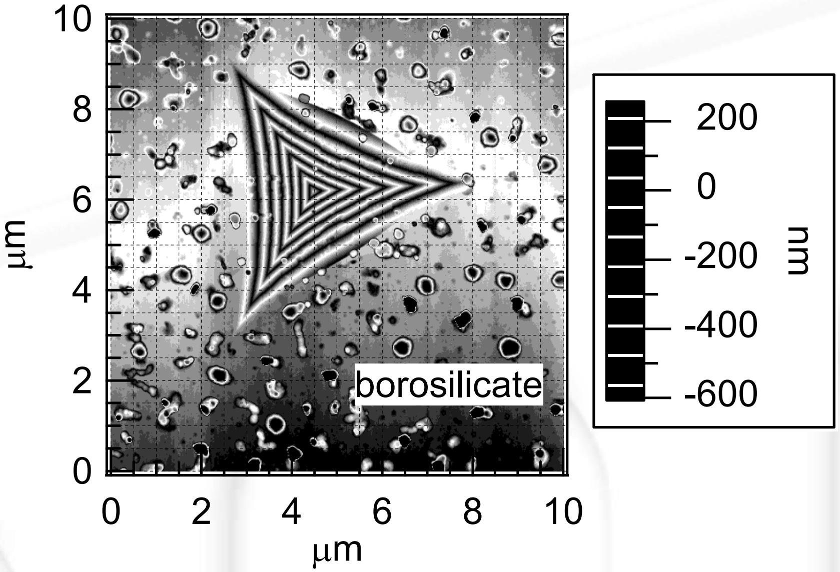
Impact of the nature of the silicate glass

- *macroscopic scale*



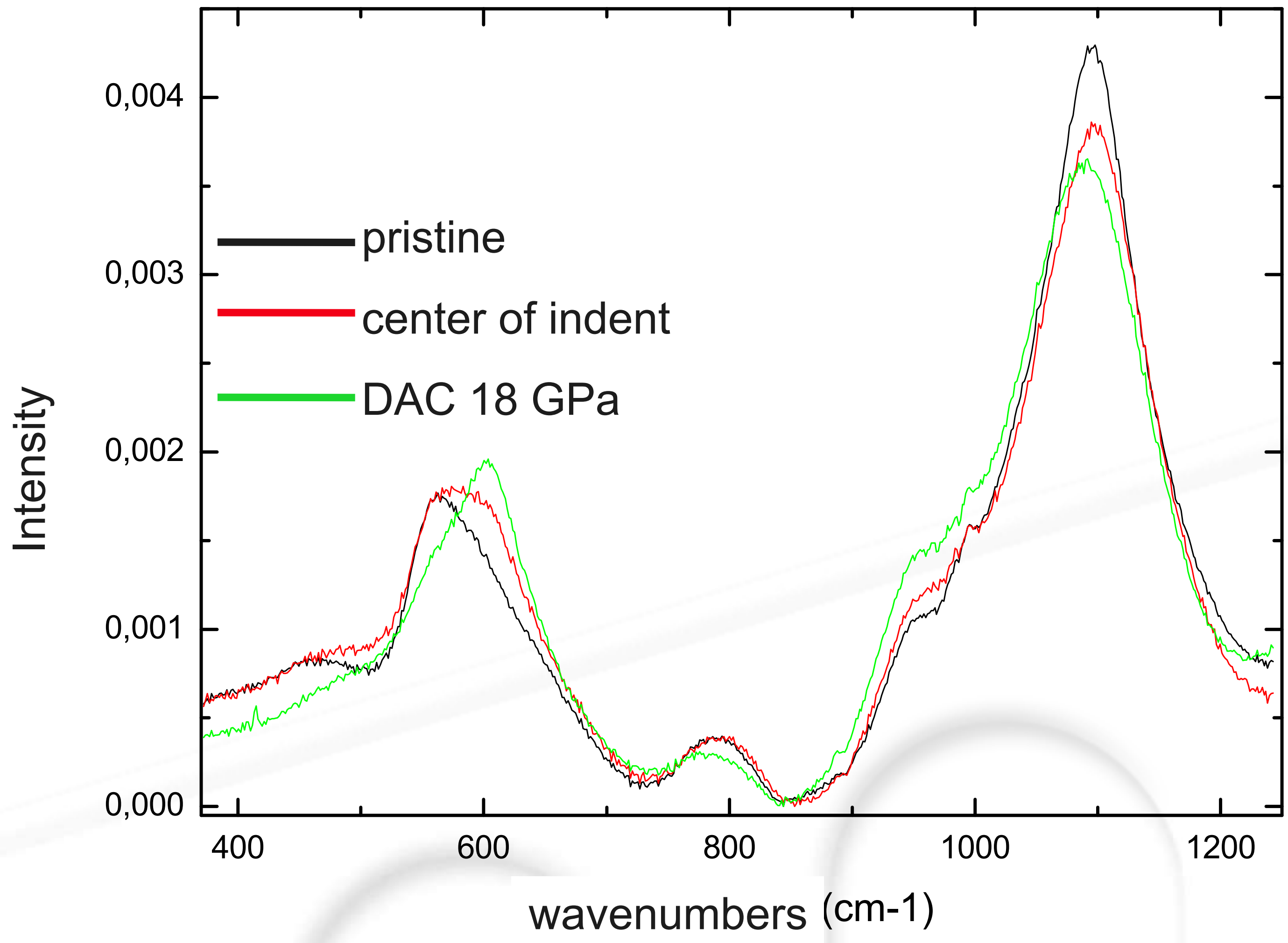


silica



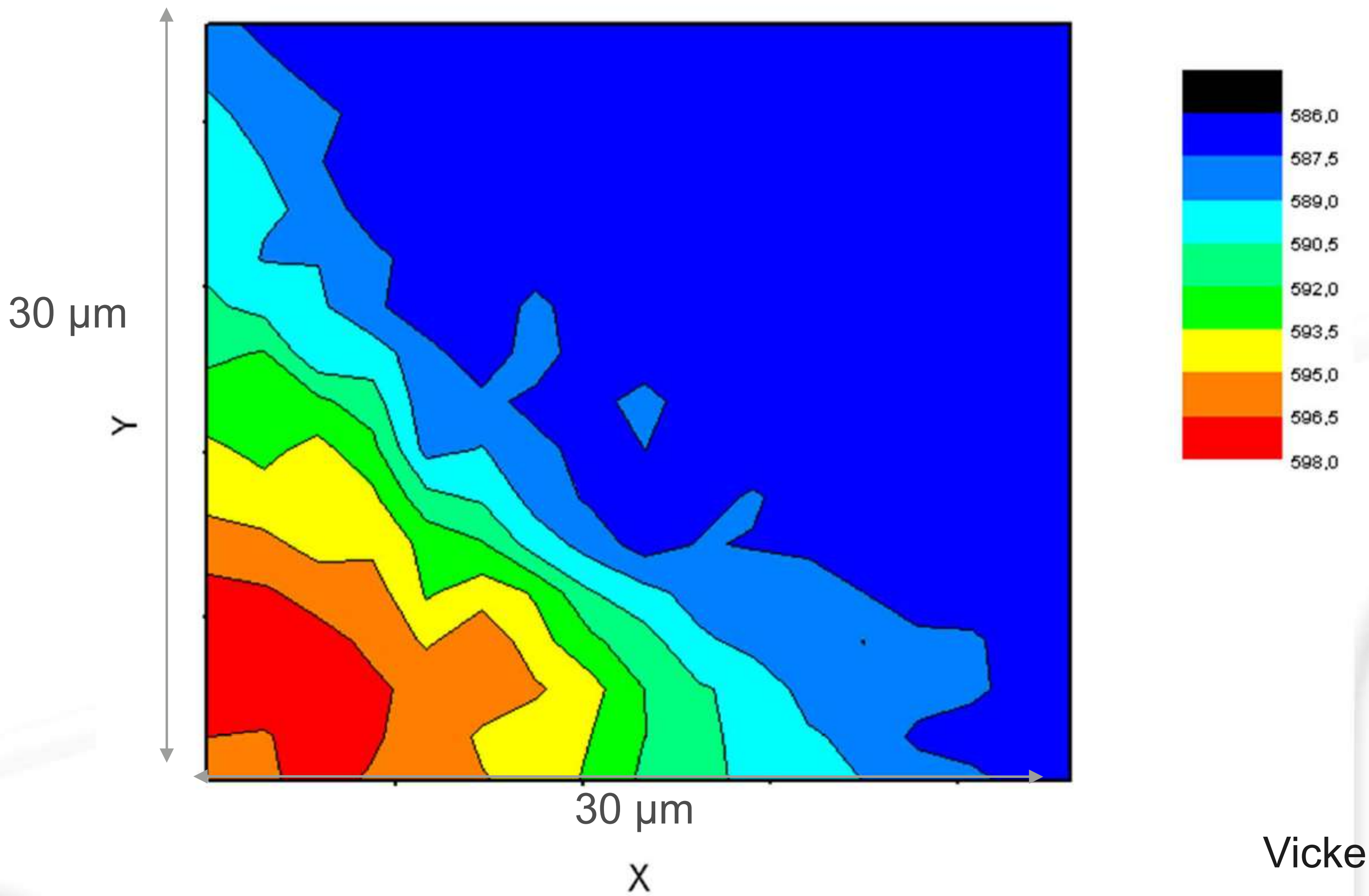
boro-silicate

Float glass – Raman µ-spectroscopy



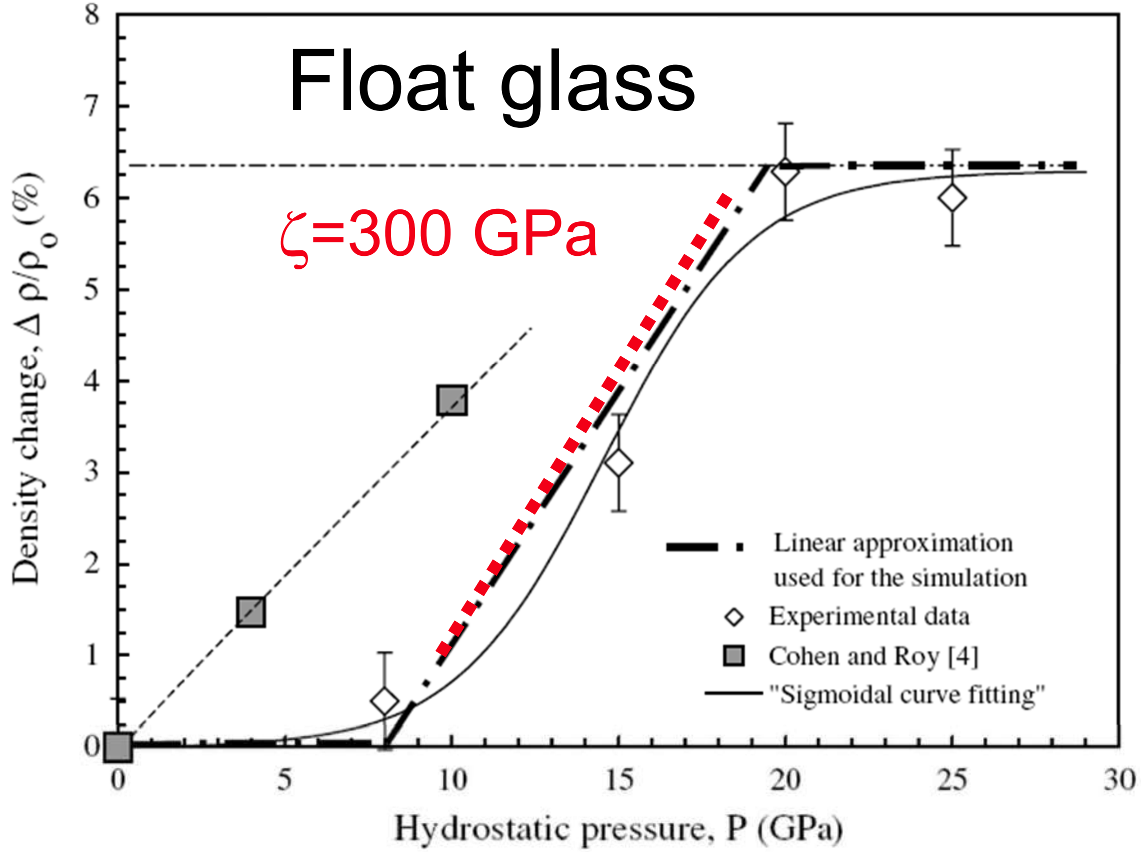
Float glass – Raman maps

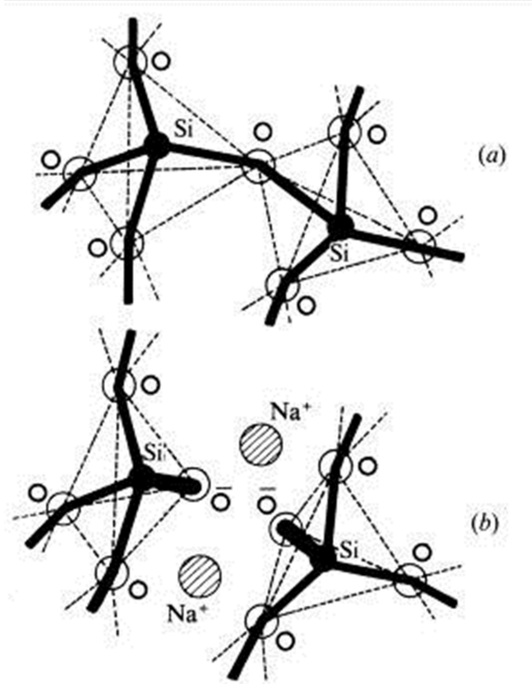
600 cm-1 band position, top view



Vickers 1Kg

Float glass – Strain hardening

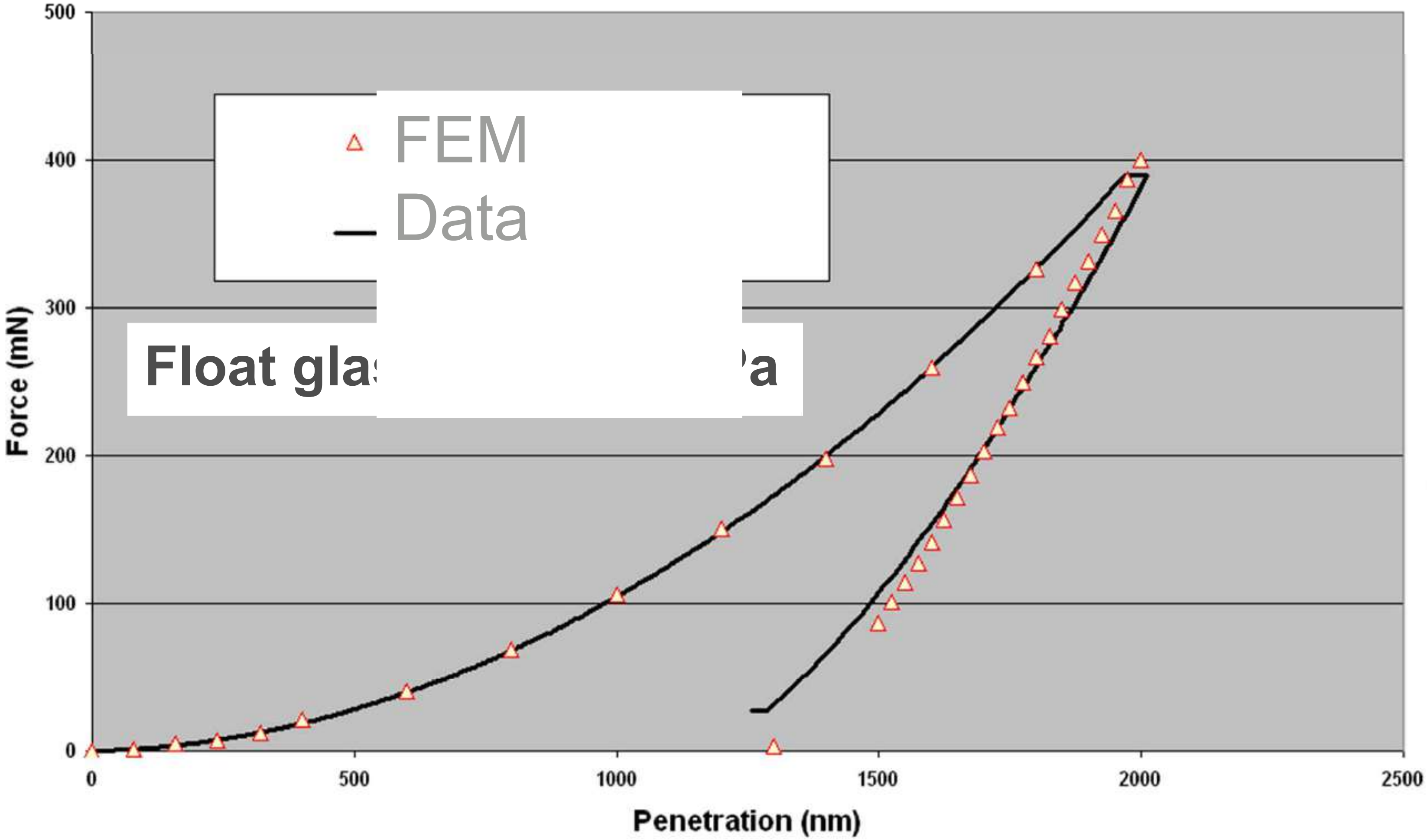




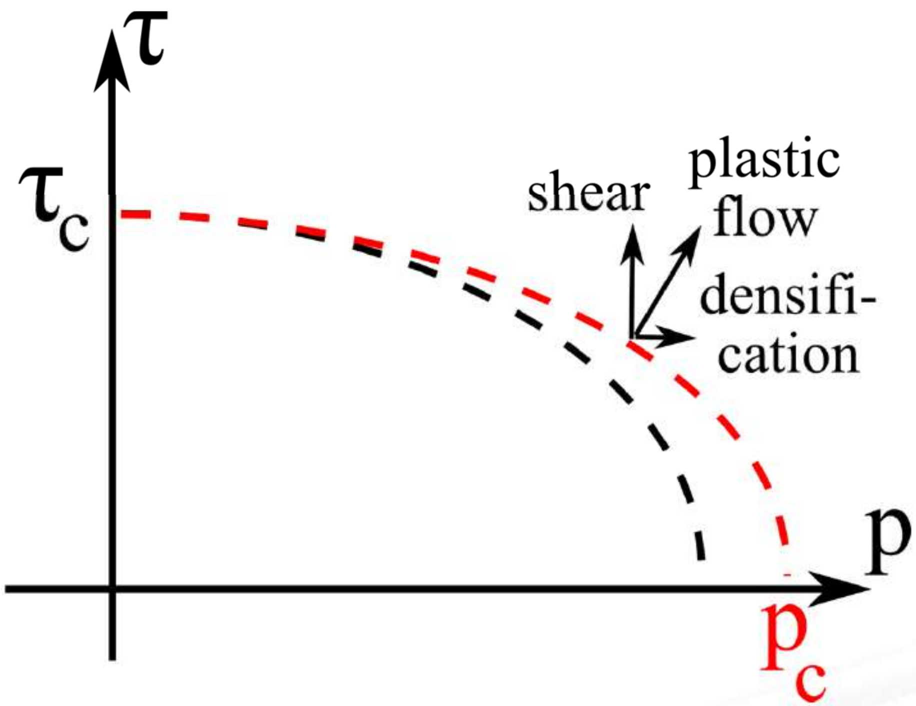
Ji et al. Scripta Materialia 2006

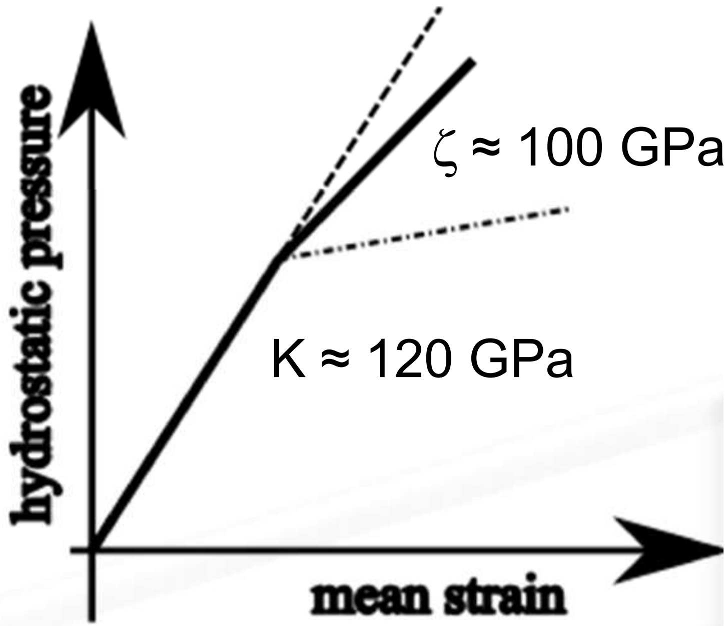
Float glass – Nanoindentation

Identification of the shear limit τ_c



Constitutive relation – silica vs. float glass

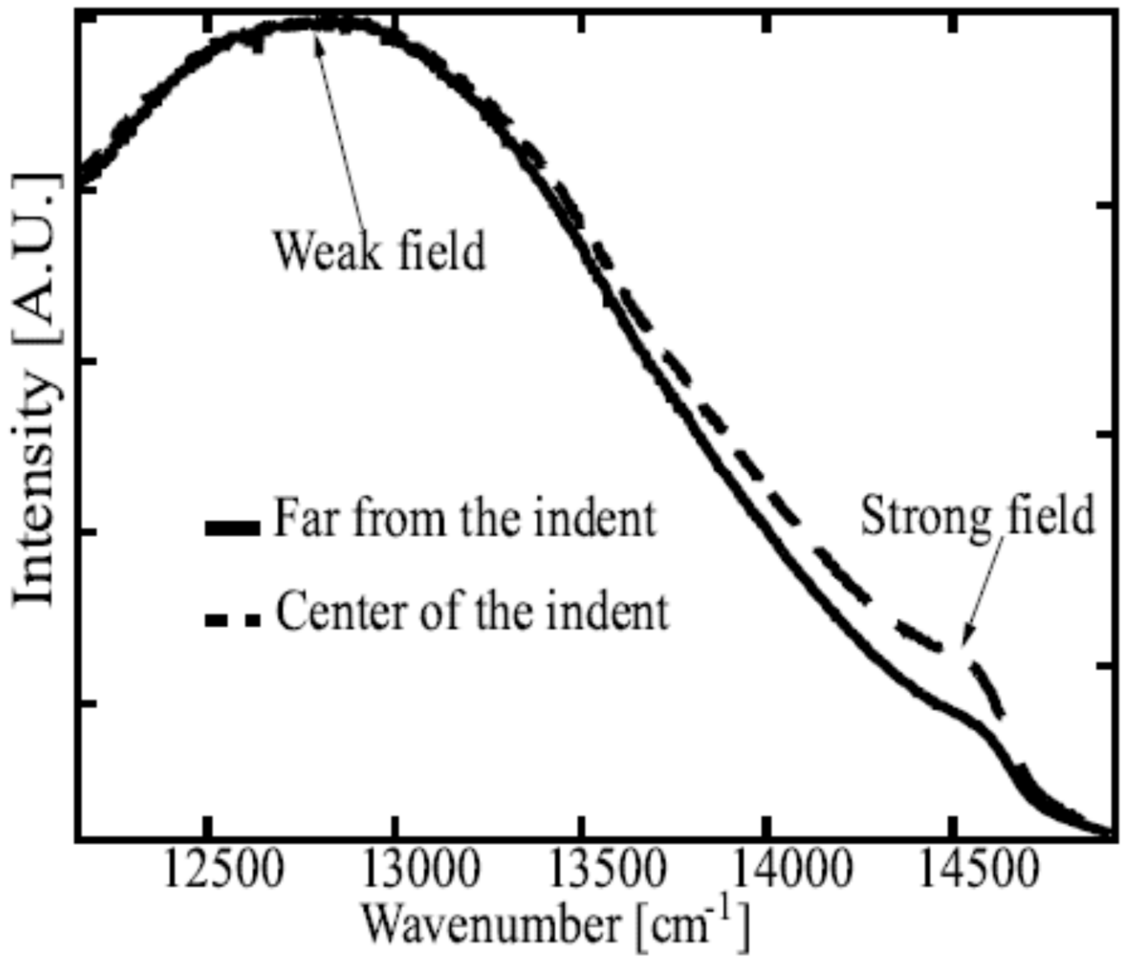




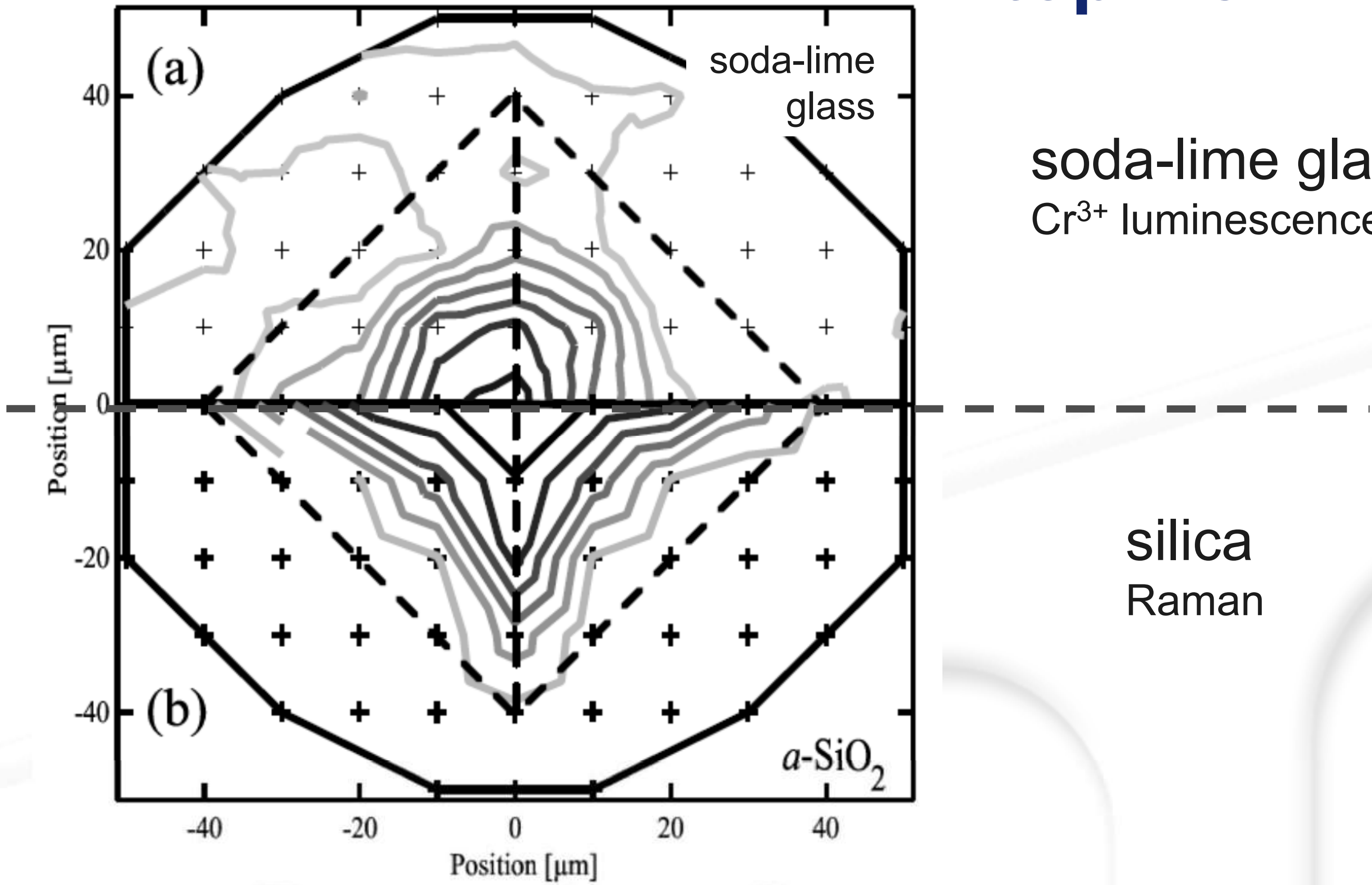
	E (GPa)	ν	p_c (GPa)	τ_c (GPa)	ϕ_0 (%)
silica	72	0.18	11.5	6.5	17.0
soda lime silica	75	0.22	8.5	3.3	5.5

CNRS SAINT-GOBAIN

Cr^{3+} luminescence



Silica vs soda-lime glass – isodensification – top view

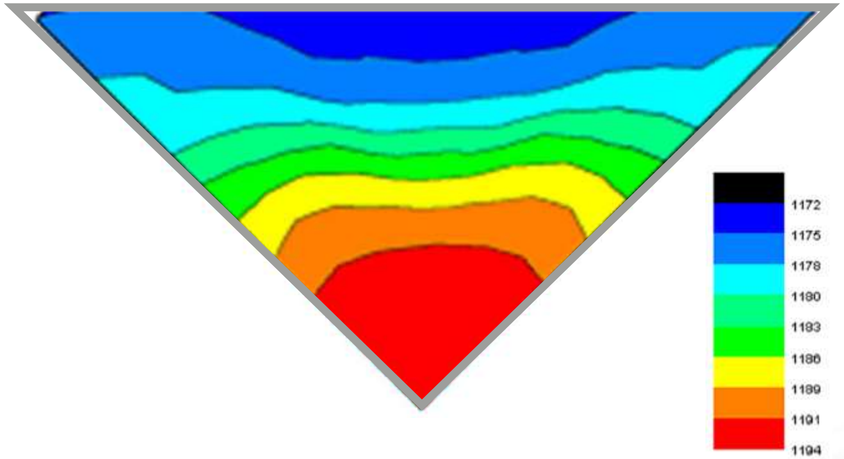


soda-lime glass
Cr^{3+} luminescence

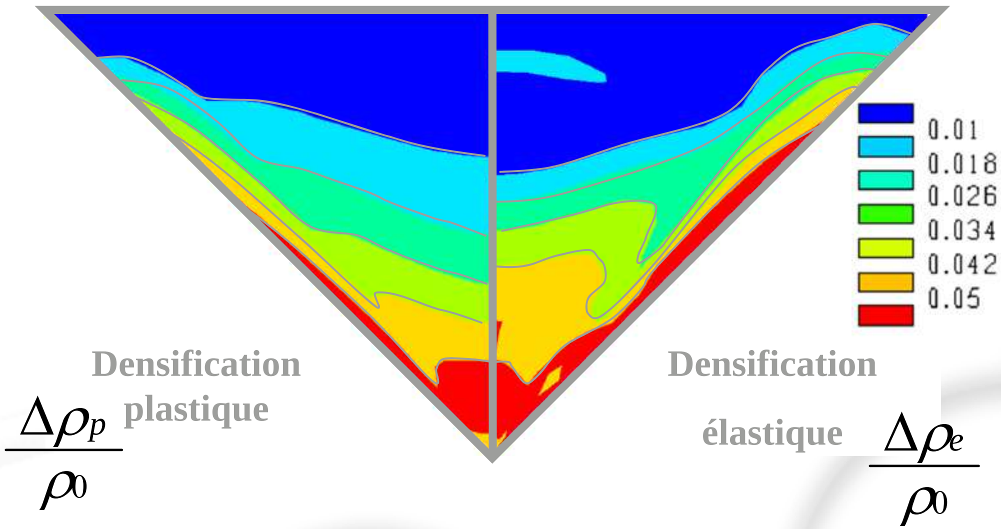
silica
Raman

A. Perriot et al., Phil. Mag., 2010

Float glass – densification – top view



Carte de niveau Raman de la bande à 600 cm^{-1}



Carte d'isodensification (Eléments-Finis)

- **residual** strain mapping **on micro-indent cross sections (Raman, lum.)**

A. Perriot *J. Am. Ceram. Soc.* 89 (2006) 596

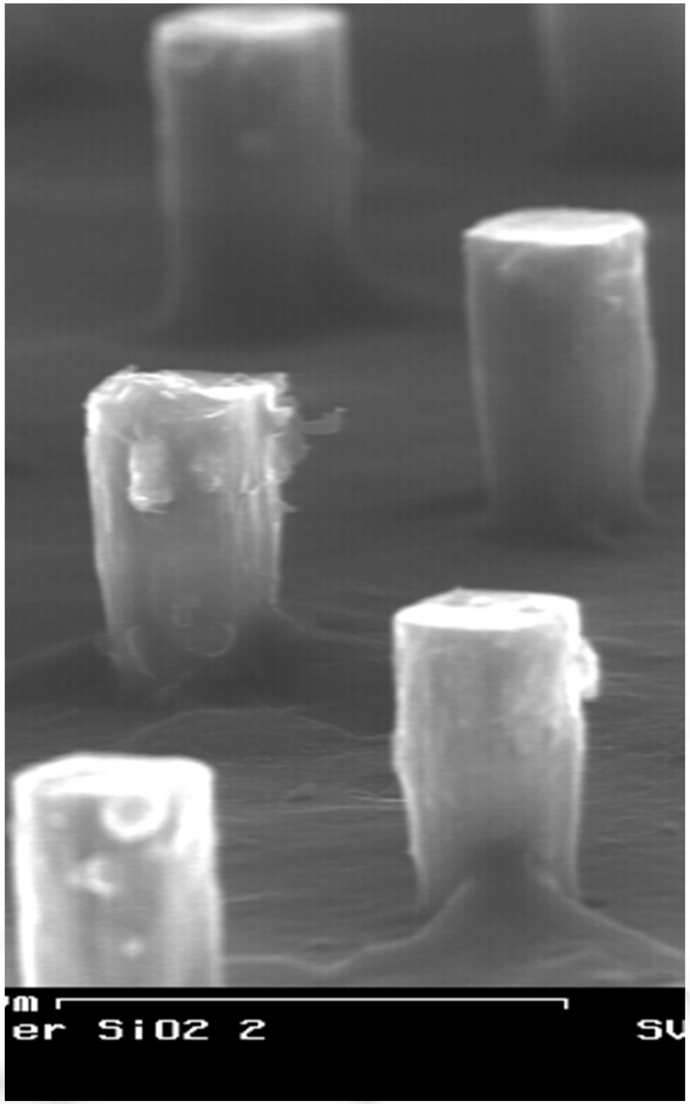
- **a quantitative constitutive equation for amorphous silica including** densification **and** strain hardening**.**

G. Kermouche, *Acta Materialia* **56**, 13 (2008) 3222

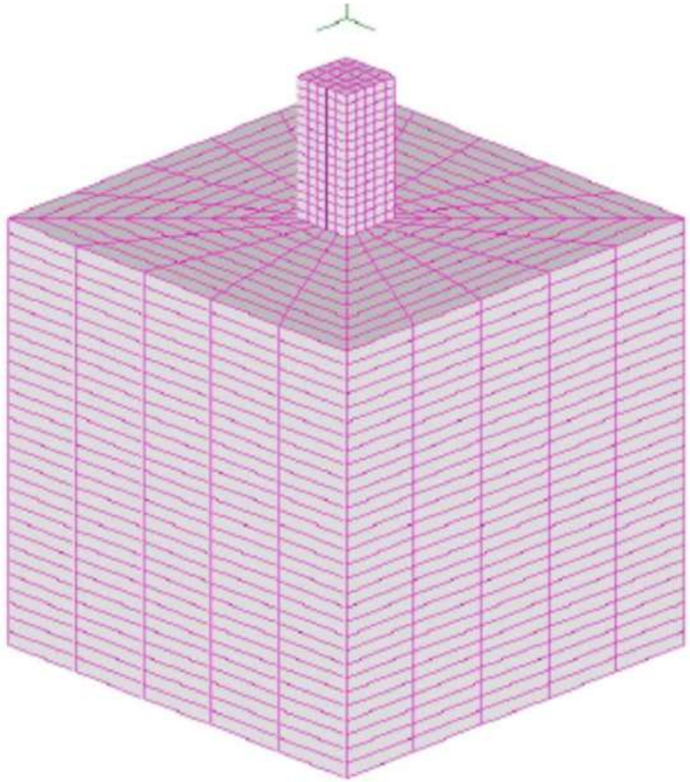
- **other silicate glasses;**
    - Requires a different constitutive equation

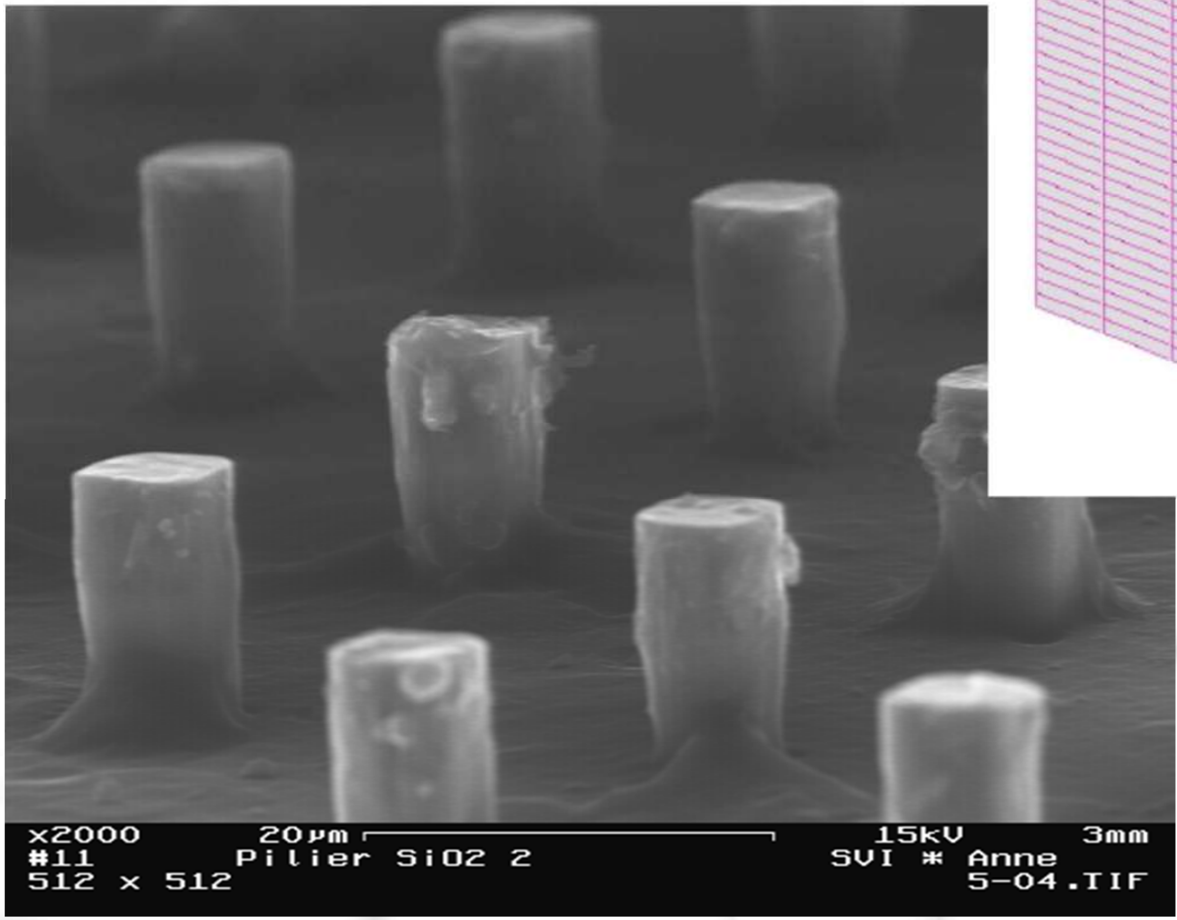
- **other simple loadings: uniaxial compression test, traction ?**

Silica pillars

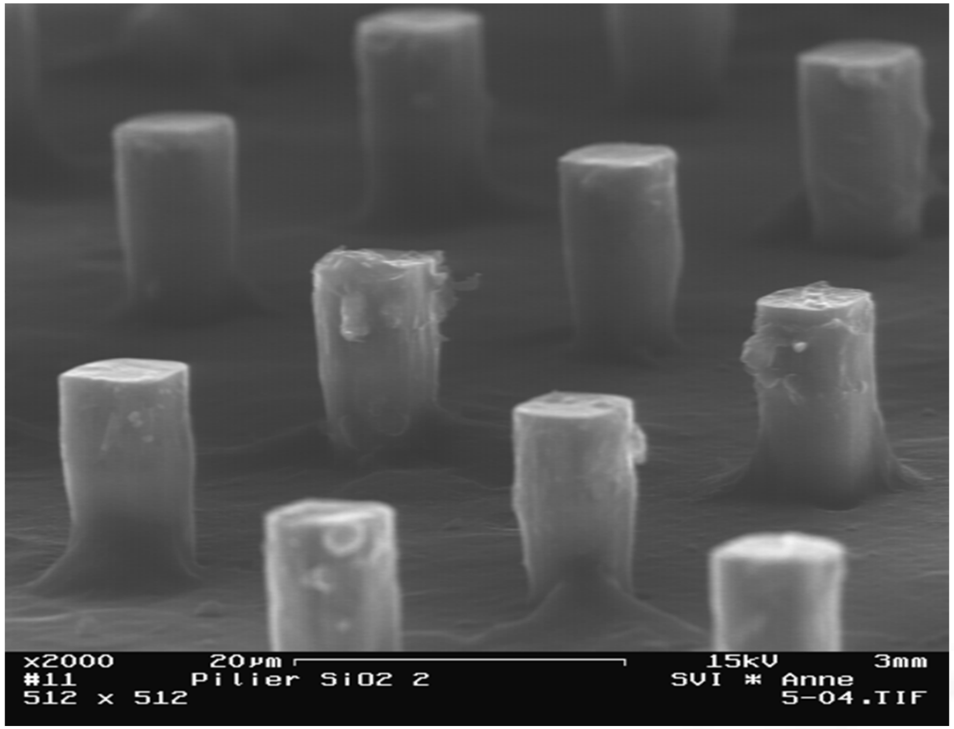


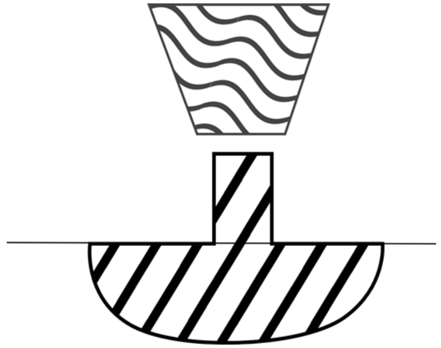
Silica pillars

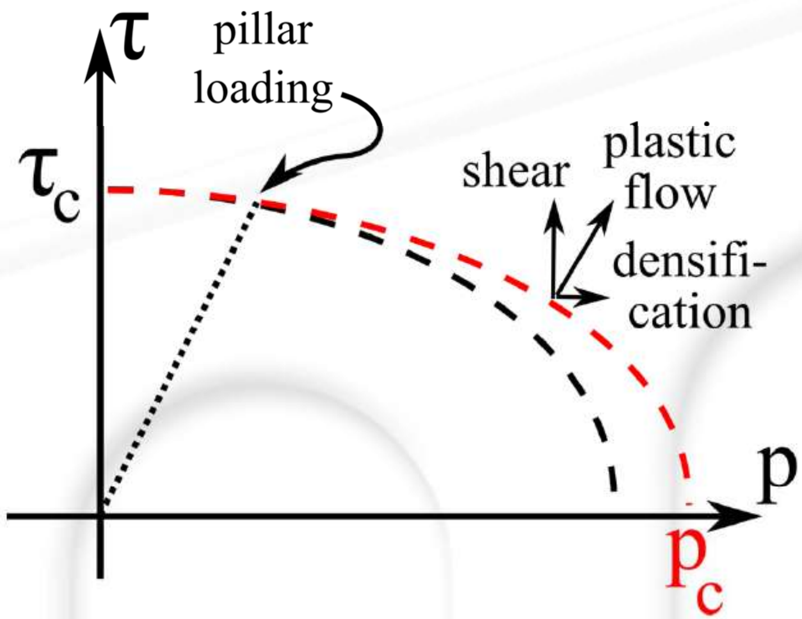




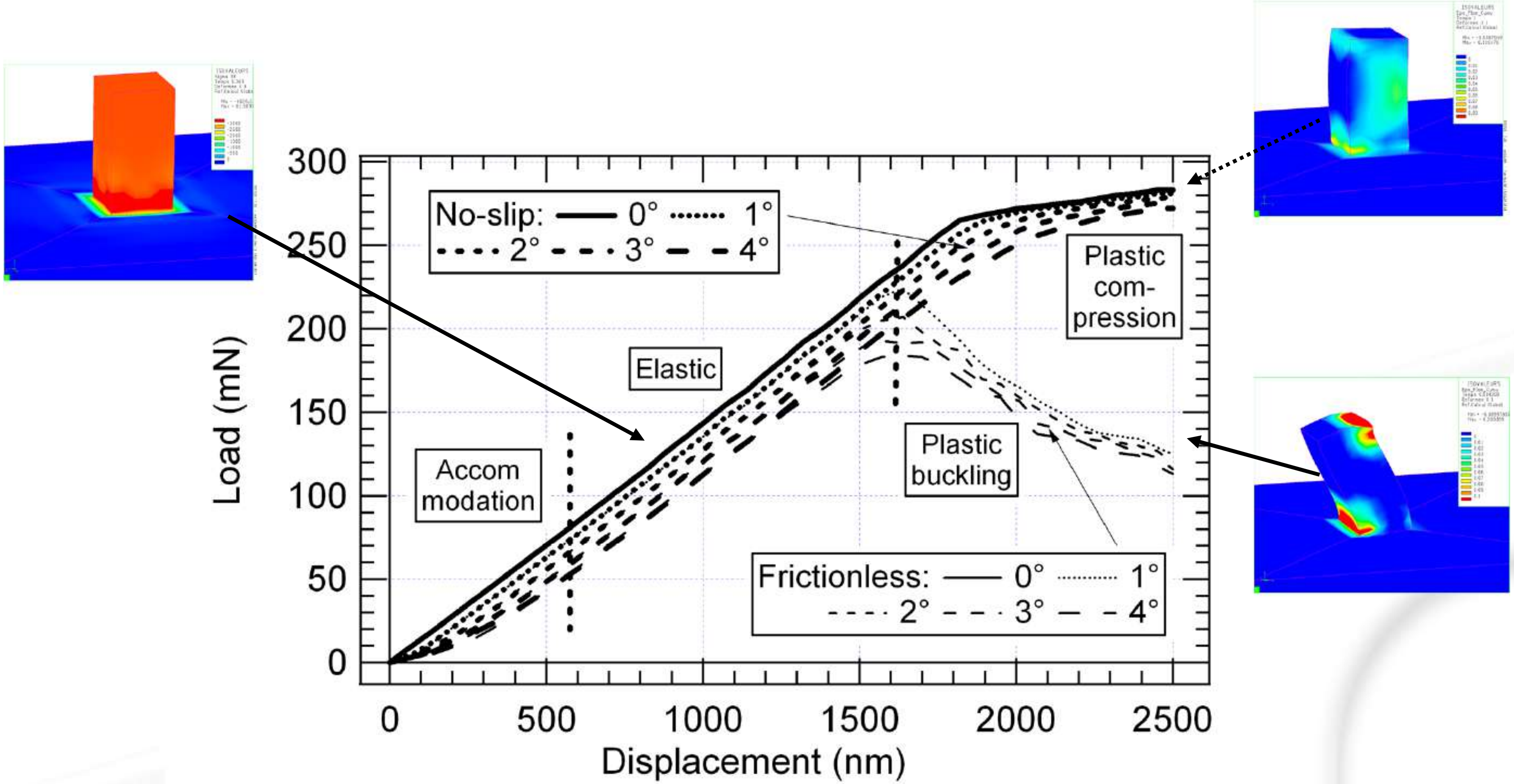
Silica pillars





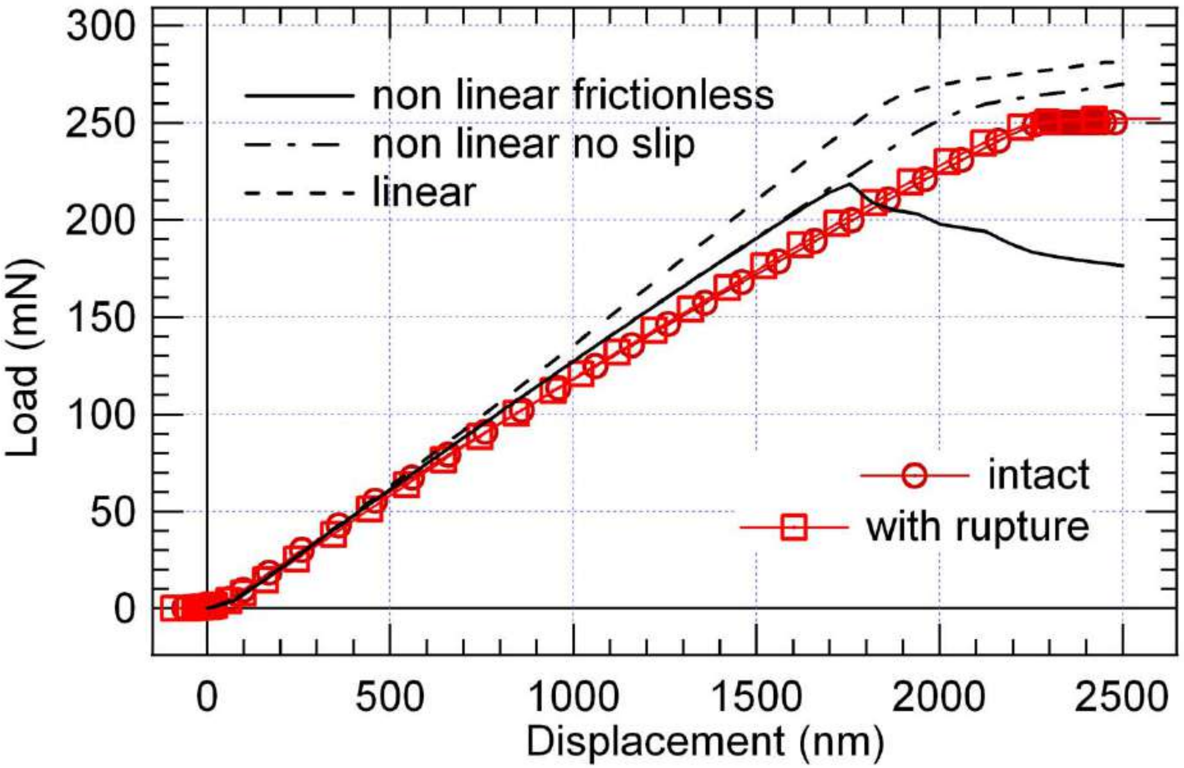


Imperfect geometry



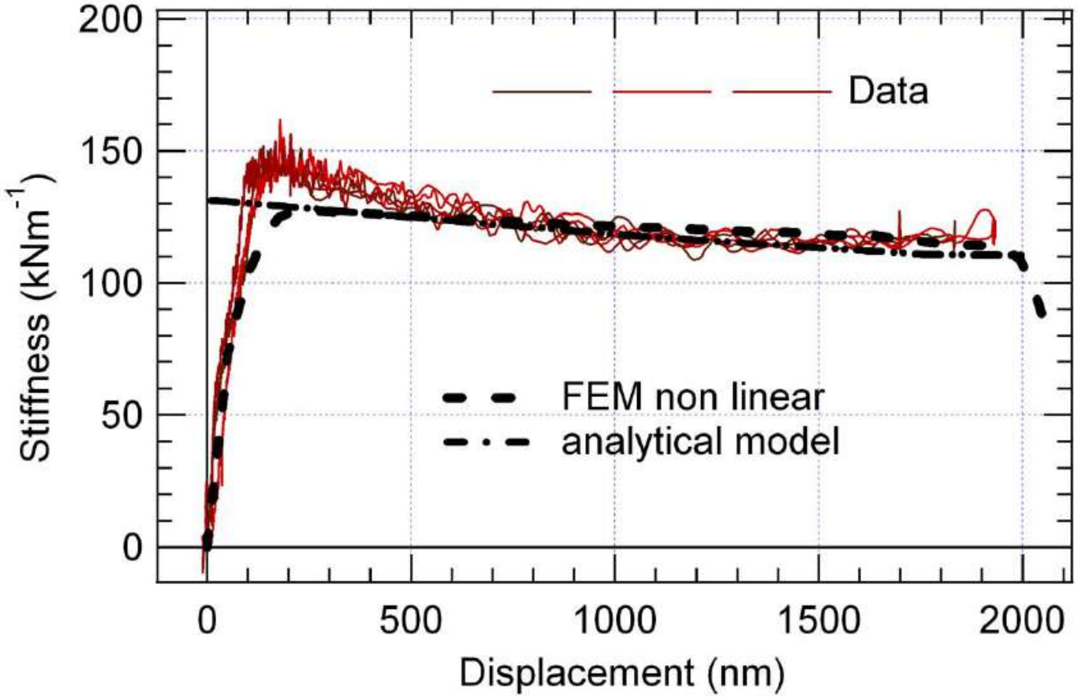
V. Chomienne

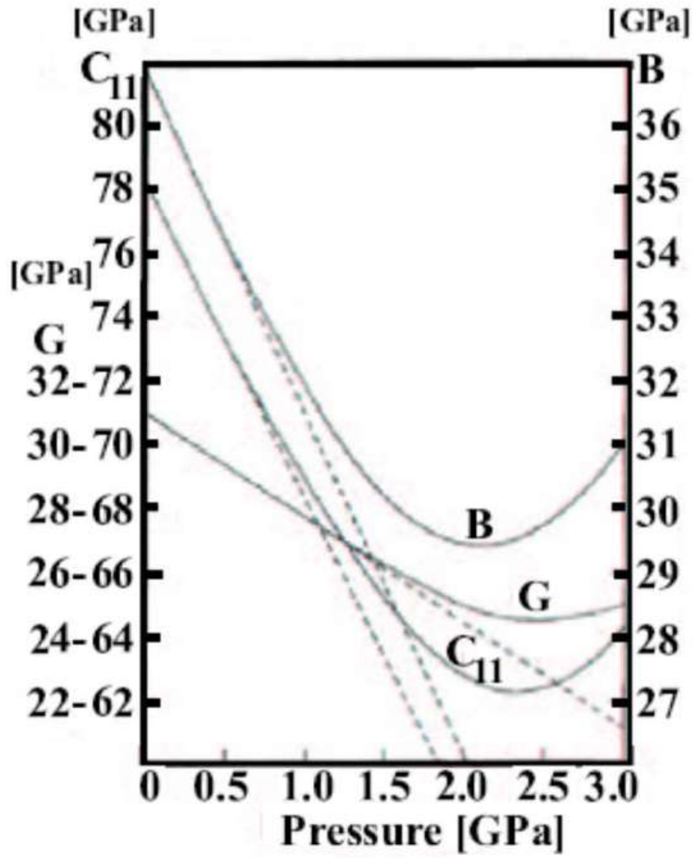
Silica pillars – elastic limit



V. Chomienne

Silica pillars – Stiffness





Kondo 1984

V. Chomienne

Conclusion

* methodology
    * micromechanics experiments
    * infer constitutive equation
    * connect with MD
* results
    * provide constitutive equation with predictive power
    * extension to more complex glasses
    * MD can give insight into the form of the constitutive equation