Deformation and failure in limestone surrounding the Andra Underground Research Laboratory at Bure (East of France)

Alexandra Rolland[1,2], Patrick Baud[1], Michael Heap[1], Marion Nicolé[1], Thomas Ferrand[1], Thierry Reuschlé[1], Nathalie Conil[2]

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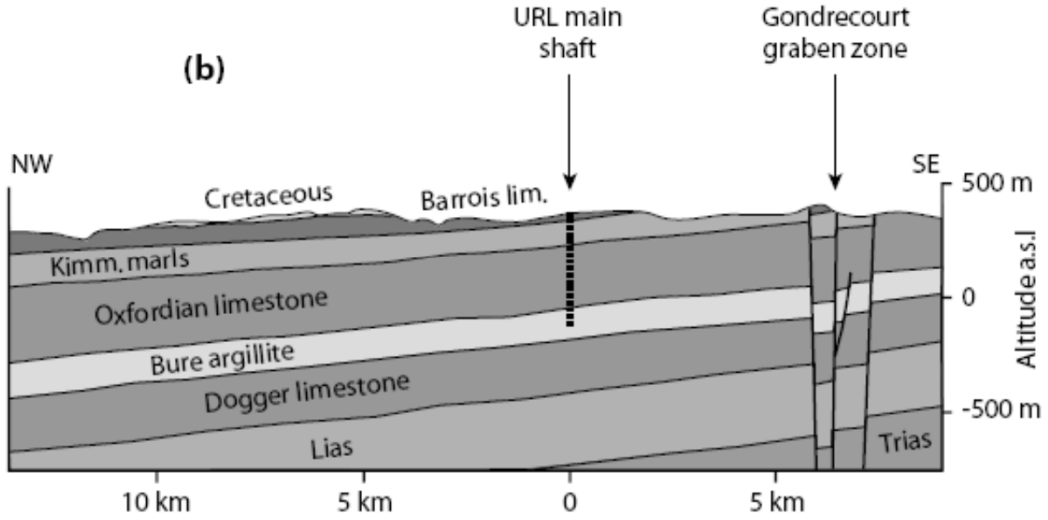
Outline

I. Studied material

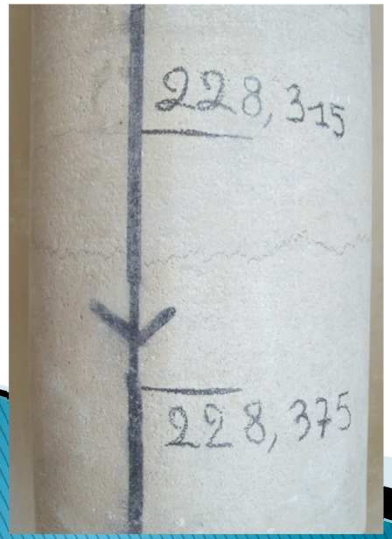
II. Experimental data: effect of water and effect of stylolites on mechanical strength

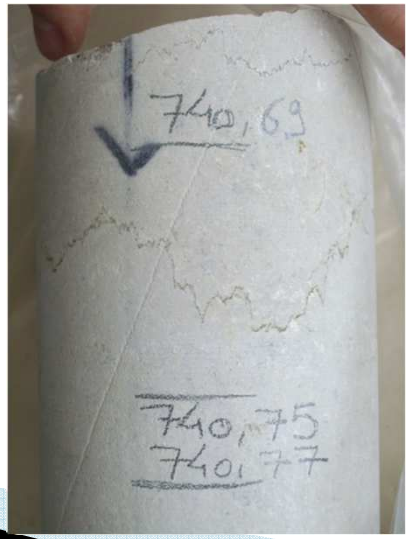
III. Micro-mechanical interpretation

Limestones surrounding the Bure URL



(Gunzburger et Cornet, 2007)

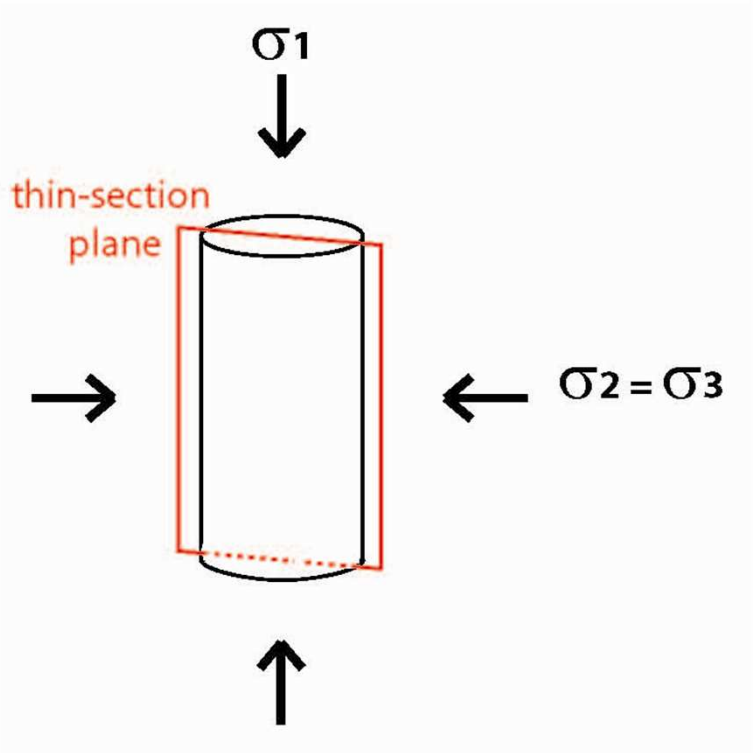




Material properties

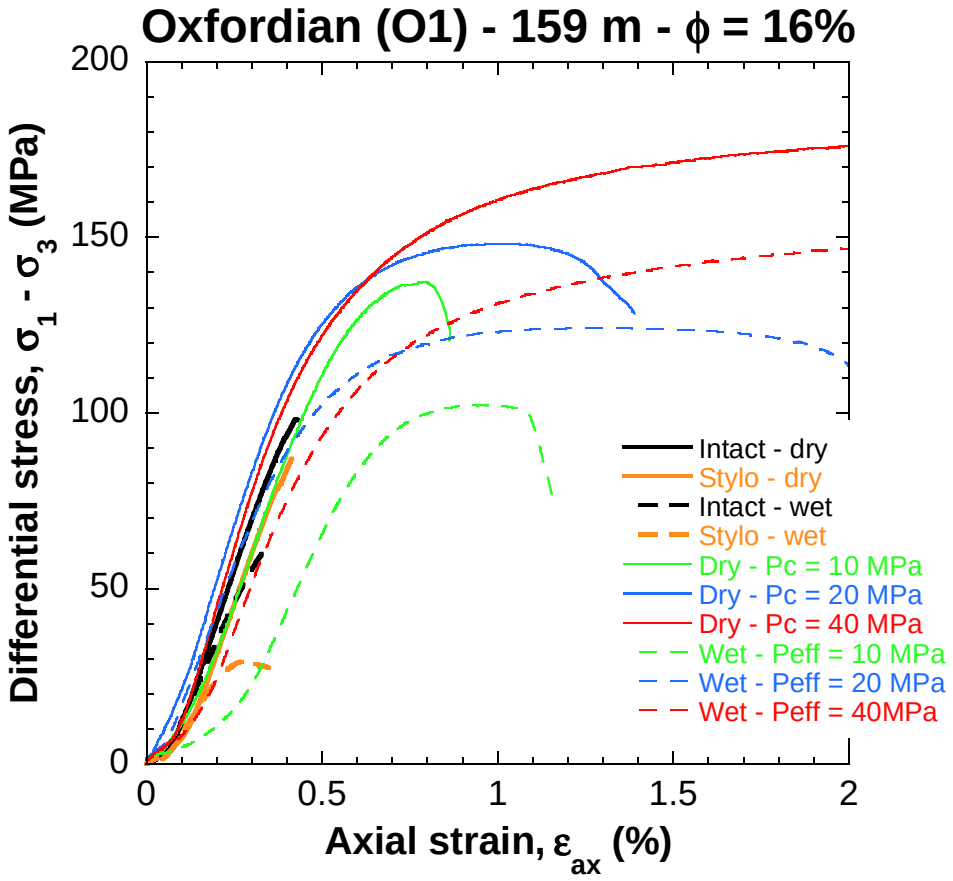
	Oxfordian	Dogger
Depth (m)	159 – 310	719 – 748
Composition	>95% calcite	
Porosity (%)	7 – 18	2 – 6
Vp (km/s)	4 – 6	6 – 7
BET (m^2/g)	0.8 – 1.15	X
E (GPa)	17 – 36	36 – 70
ν	0.35	0.37

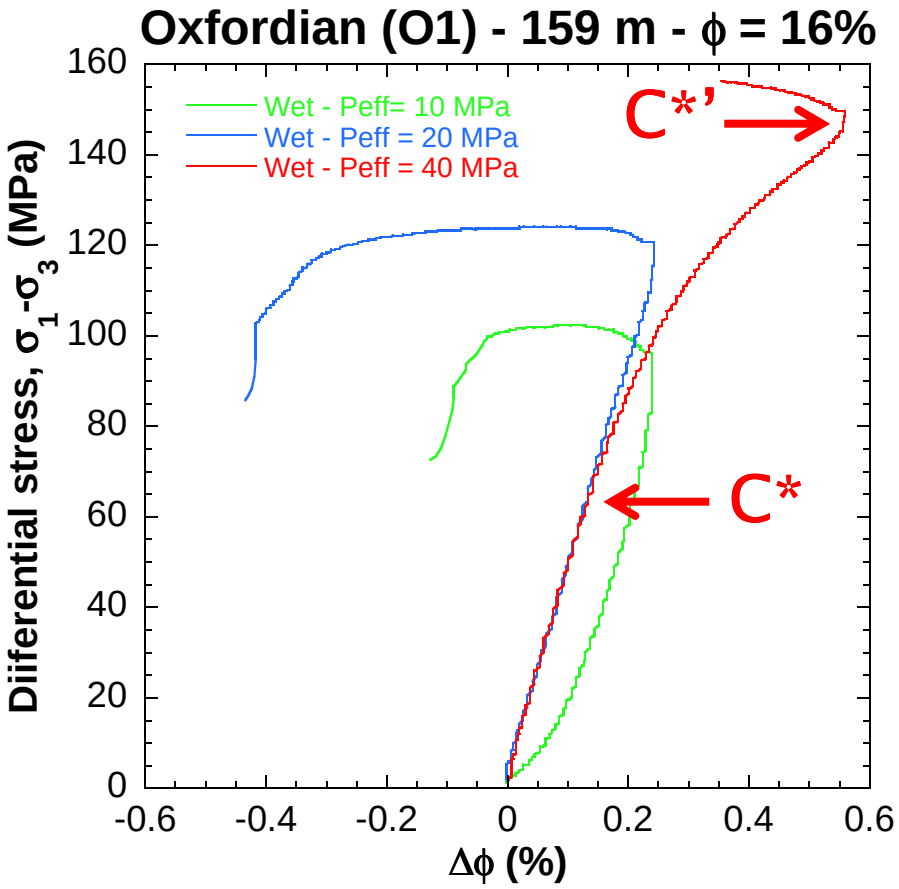
Experimental procedure



- Uniaxial ➔ $\sigma_2 = \sigma_3 = 0$
- Triaxial ➔ $\sigma_1 > \sigma_2 = \sigma_3$
- Room temperature
- Strain rate = 10^{-5} s^{-1}
- Samples size = 20*40 mm
- Dry and wet experiments with or without (intact) stylolite

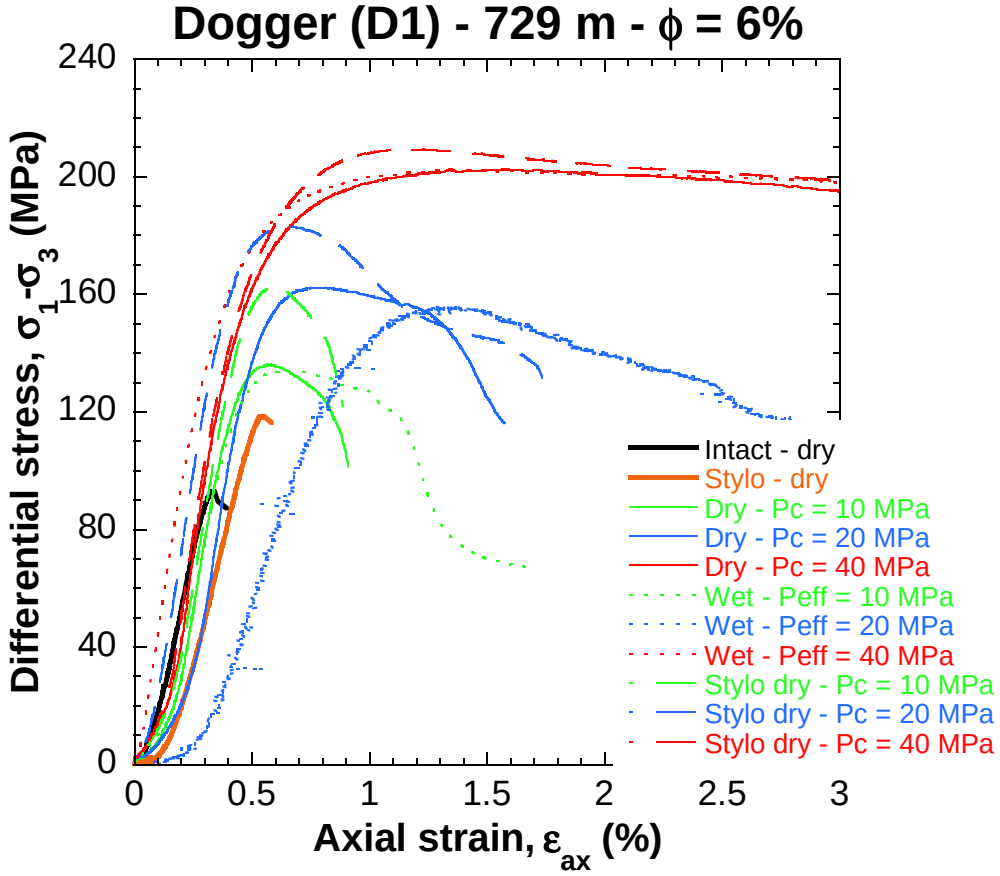
Selected data (1 / 3)

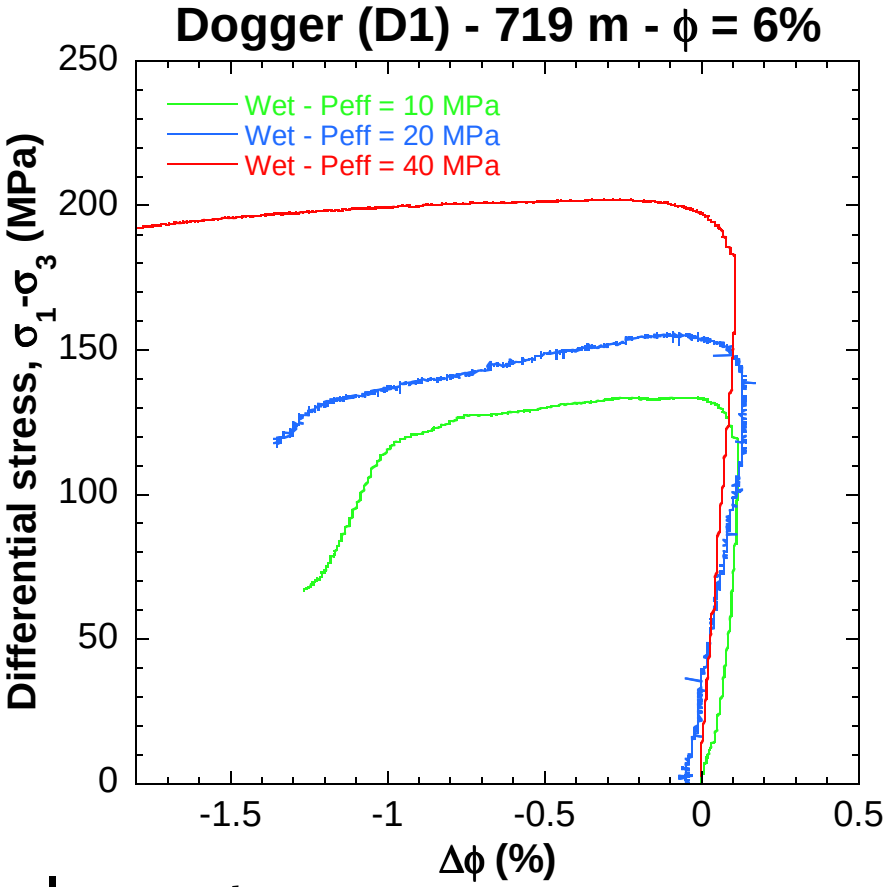




- Weakening effect of water
- Brittle/ductile transition between 20 and 40 MPa

Selected data (2/3)

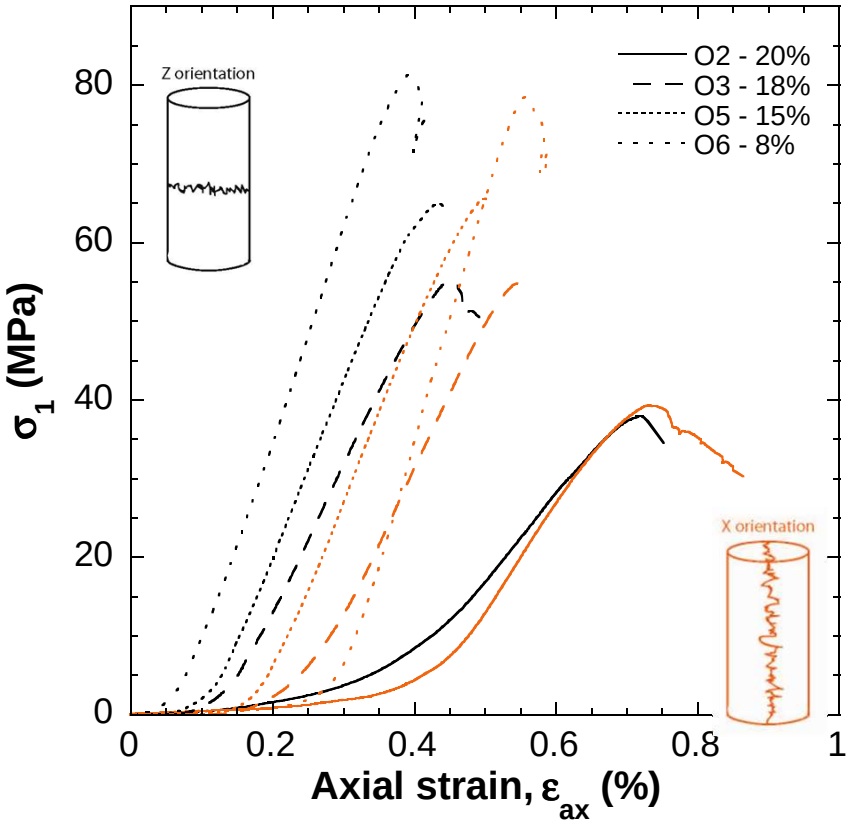




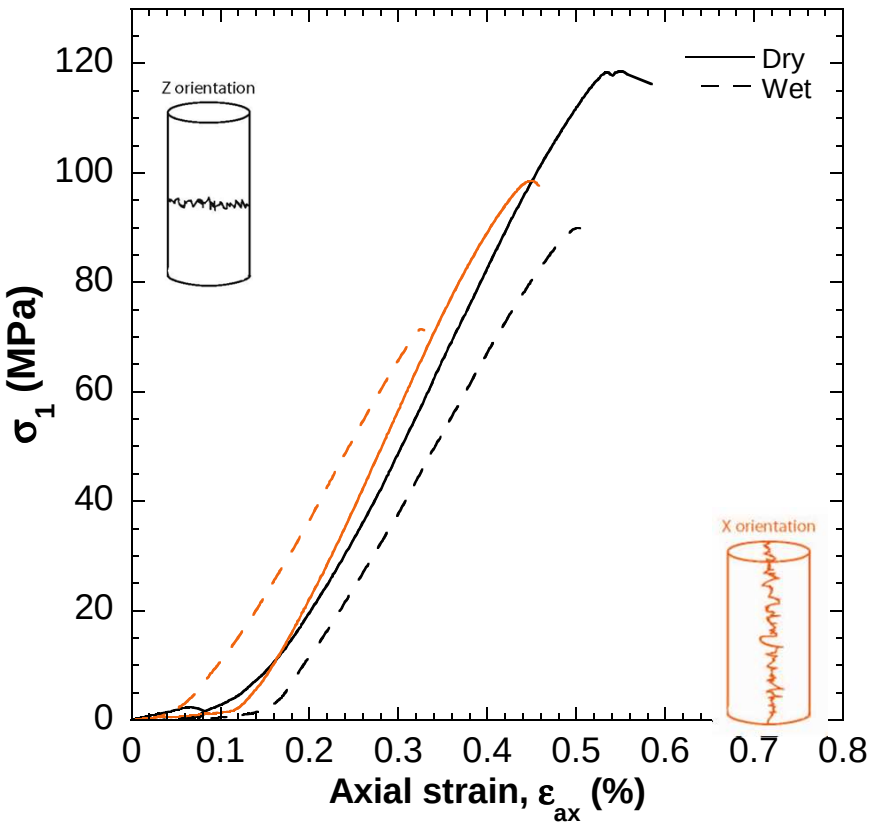
- Water = weaker + Stylo = stronger
- Brittle
- Ductile behavior not reached

Selected data (3/3)

Oxfordian - Stylolite orientation



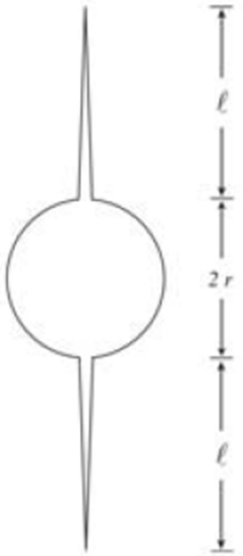
Dogger (D1) - Stylolite orientation



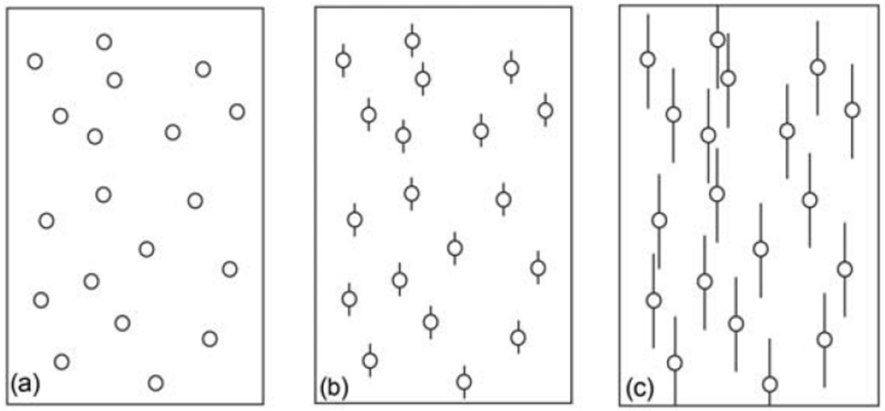
- Oxfordian = no effect
- Dogger = weaker ➔ porosity? Microstructure?

Dry and wet UCS: Sammis and Ashby's pore-emanated cracking model (1986)

- Pore emanated crack (Vajdova et al., 2010)
- Elastic medium with circular pores of radius r
- Propagation of wing cracks to a distance ℓ with crack interactions



(Sammis and Ashby, 1986)



Sammis and Ashby's pore-emanated cracking model (2/2)

- Sammis and Ashby (1986) :Triaxial case

➔ $$K_I = -L^{1/2}\left\{\frac{1.1\,(1-2.1\,\lambda)}{(1+L)^{3.3}} - \lambda\right\}\sigma_1\sqrt{\pi a.} \quad + \quad K_I^I = \frac{\sqrt{2}}{\pi}\sigma_1\sqrt{\pi a}\,f_A^{1/2}(L+1)^{1/2}$$
$$\left\{\left[1-\frac{8}{\pi}f_A\lambda(L+1)^3\right]\left[1-\frac{2}{\pi}f_A\lambda(L+1)^3\right]\right\}^{1/2}.$$

where $\lambda=\sigma_3/\sigma_1$

- Sammis and Ashby (1986) : Uniaxial case

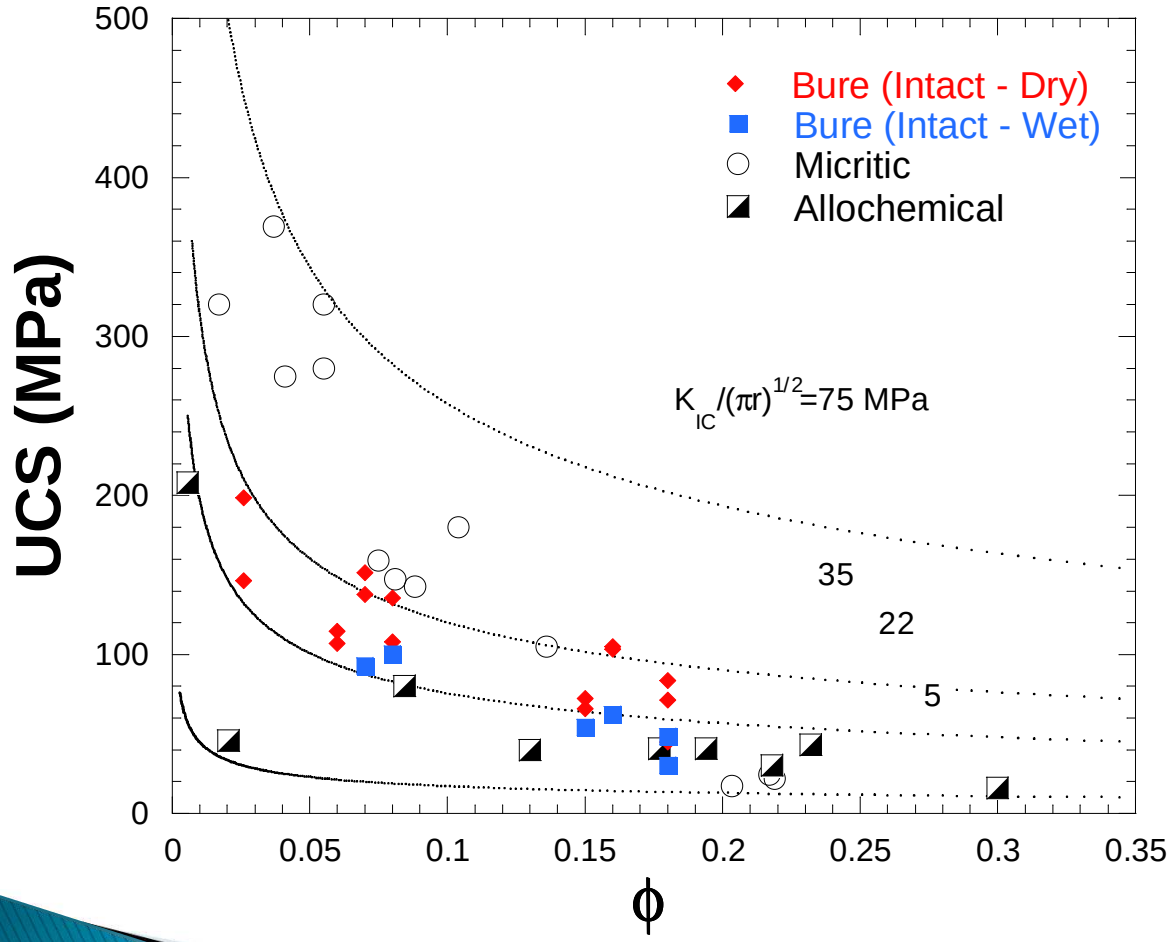
external loading + crack interaction

➔ $$\sigma(L) = \frac{K_{IC}}{\sqrt{\pi r}}\left[\frac{1.1\sqrt{L}}{(1+L)^{3.3}} + \frac{\sqrt{2}}{\pi}\sqrt{\Phi(1+L)}\right]^{-1}$$ where $L=\ell/r$

- Zhu et al. (2010): $d\sigma/dL=0$

➔ Analytic approximation $$\sigma_u = \frac{1.325}{\Phi^{0.414}}\frac{K_{IC}}{\sqrt{\pi r}}$$

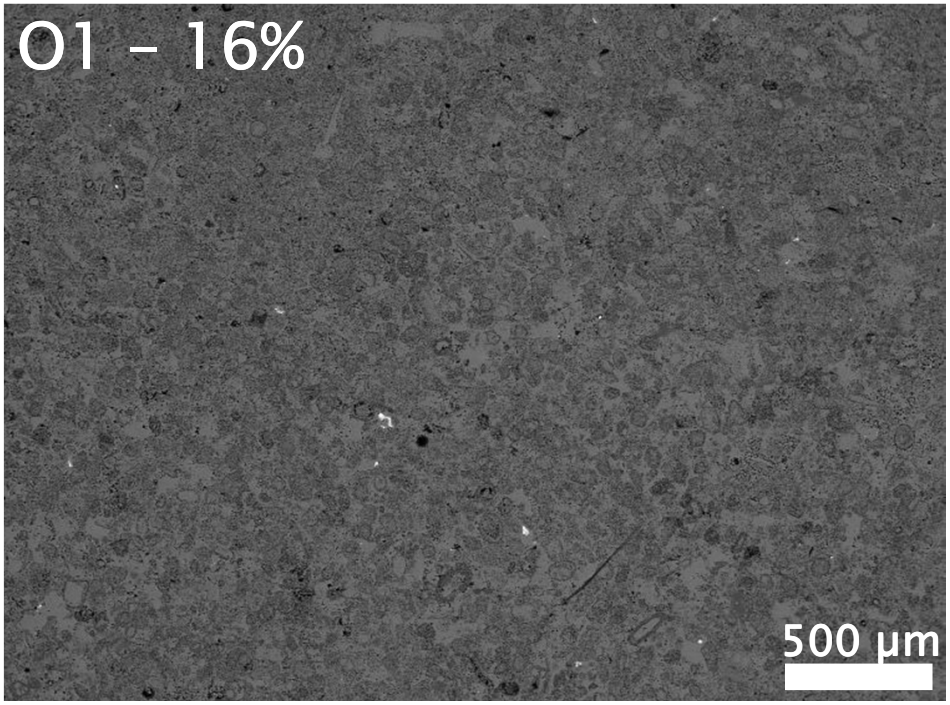
Application to limestones

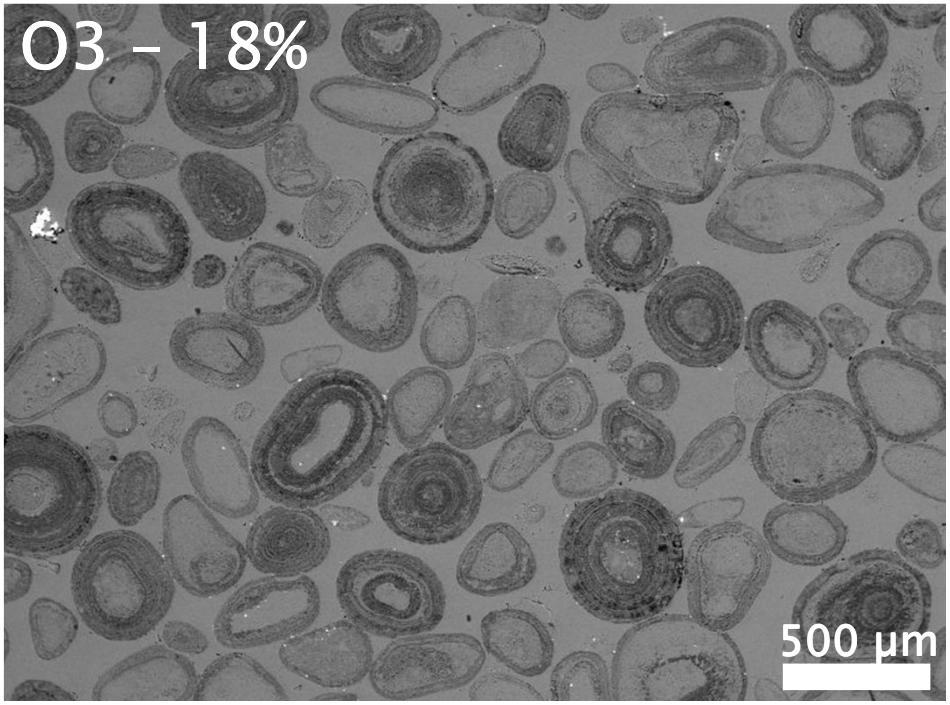


- Zhu et al., 2010:
  2 families
  $K_{IC}^{calcite}$=0.2 MPa.m$^{1/2}$
  ➔ r_M=2-10µm
  r_A=26-500µm

- This study:
  ➔ Intermediate
  ➔ Pore radius
  r=10-26 µm

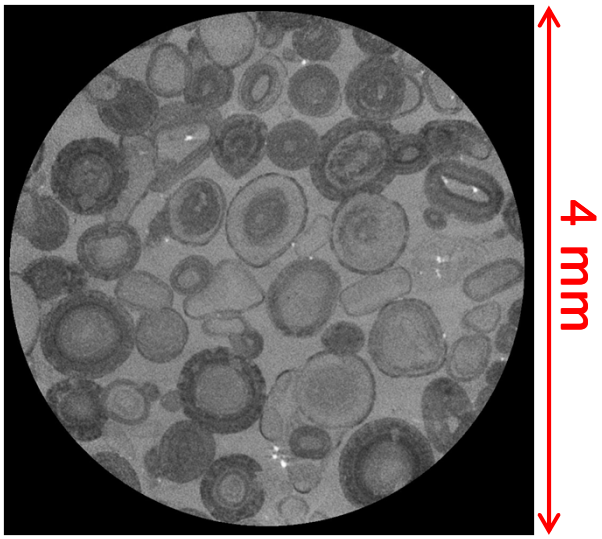
Microstructure (1/2)



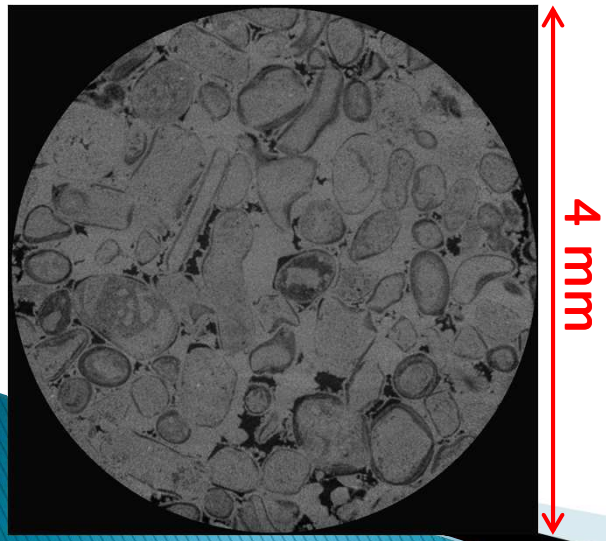


- Allochemical limestones with a wide range of grain size
- No crack porosity

Microstructure (2/2)

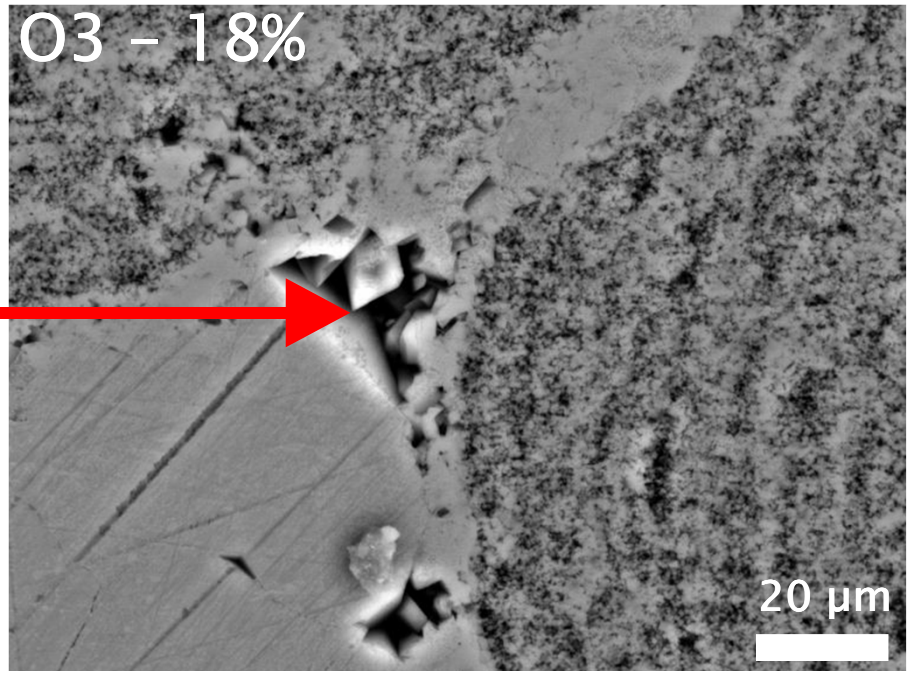


(This study – O3 – 18%)

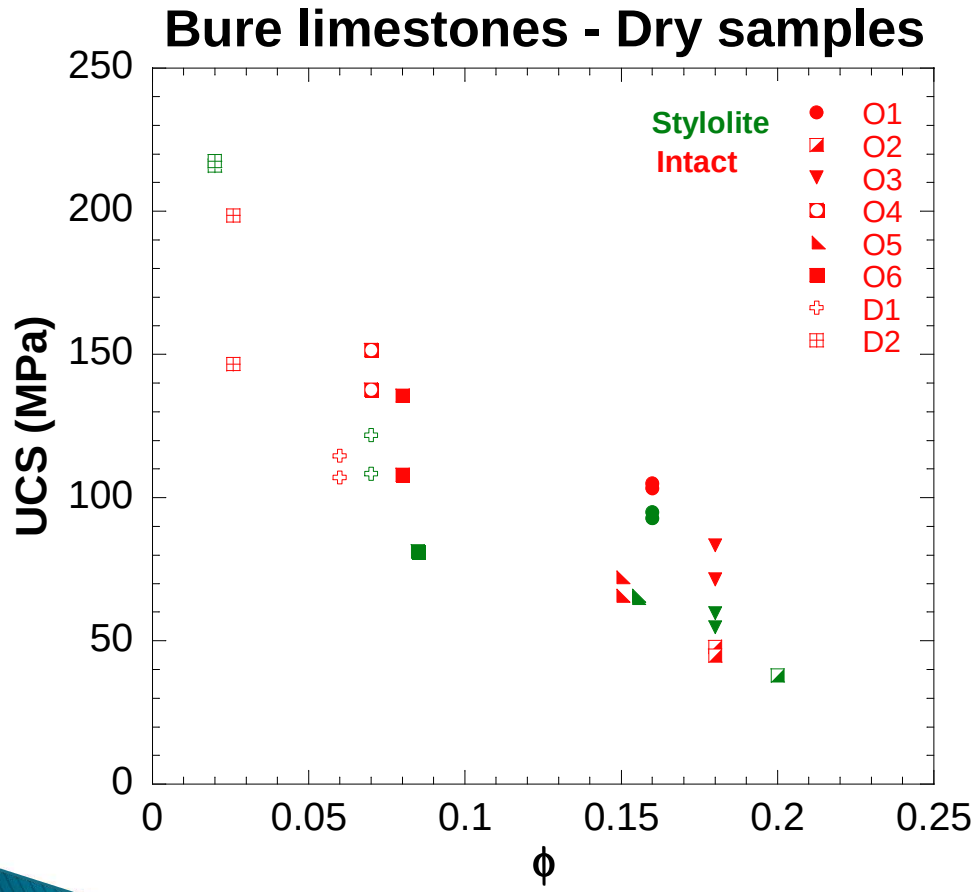


(Ji et al., 2011 – Indiana – 16%)

- Absence of macropores but microporosity at the periphery of grains and in the cement



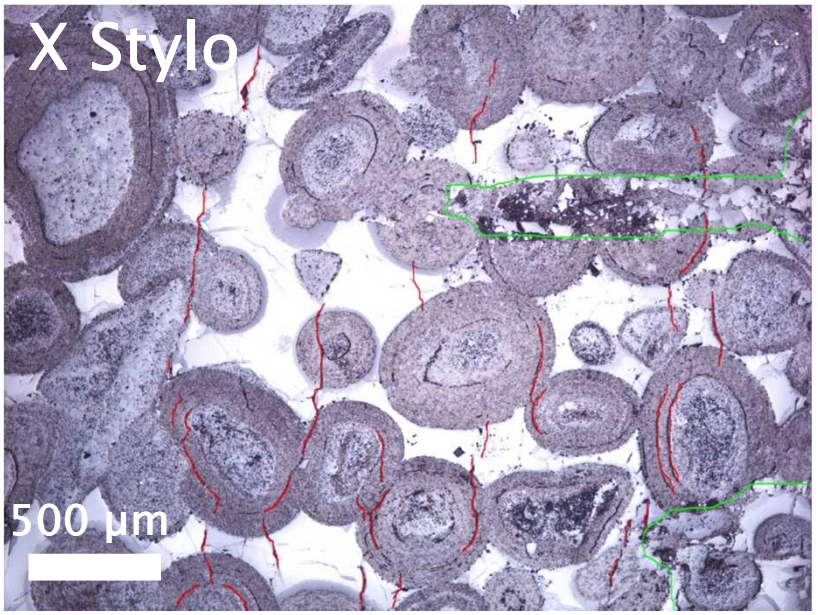
Effect of stylolites – dry tests



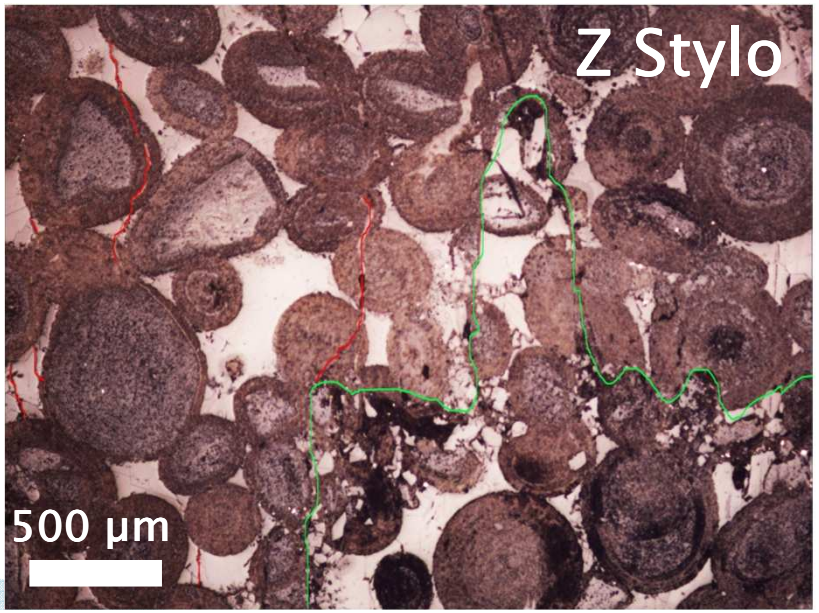
- Dogger = stronger
- Oxfordian = weaker

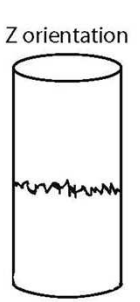
Preliminary microstructural observations

σ_1



- Cracks parallel to σ_1
- Complexe interaction between stylolite and induced damage





Conclusions

- Bure limestones have a mechanical strength intermediate to micritic and allochemical ones
- Weakening effect of water ➔ reduction of K_{IC}
- Effect of stylolites not obvious for Dogger horizon but weakening for Oxfordian layer ➔ stress concentrator?
- No effect of stylolite orientation in dry conditions ➔ stylolite ≠ plane of weakness