Time-dependent deformation in rocks

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Time-dependent deformation in rocks

- Phenomenology of brittle-ductile transition in porous Rocks: Transition of failure mode from brittle faulting to cataclastic flow/compaction bands.

- Damage evolution and strain localization.

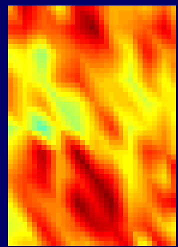
- Time-dependent deformation and failure in rocks: time-dependent failure/compaction.

Waddenacademie (2013)

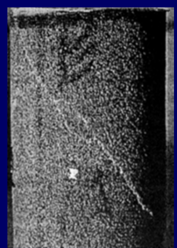
effective mean stress:
$(\sigma_1+2\sigma_3)/3 - P_p$

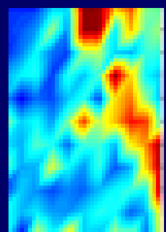
P*: grain crushing pressure**

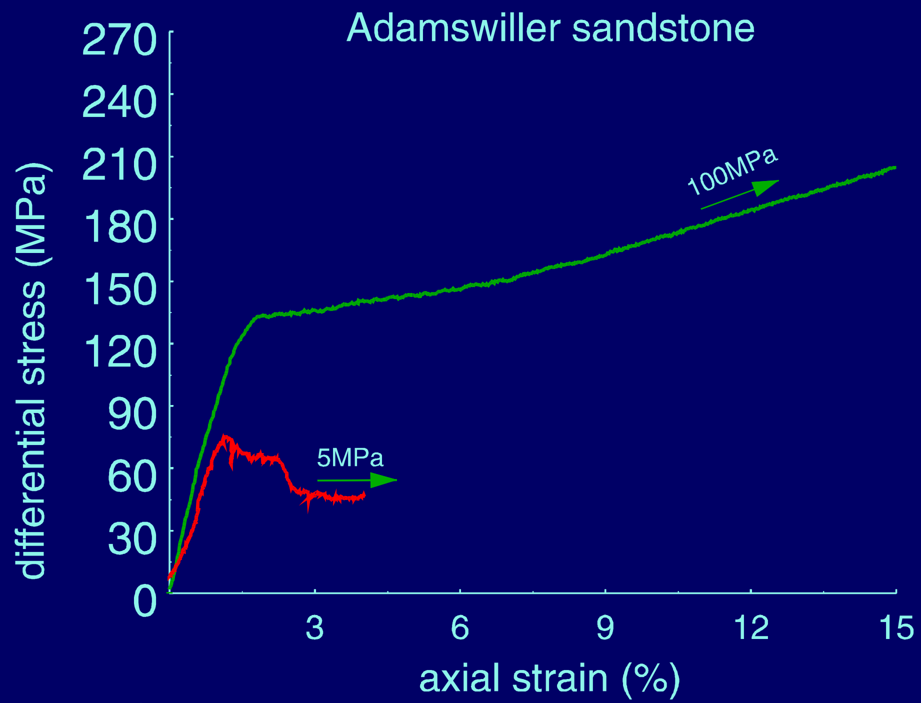
C*: onset of shear-enhanced compaction**

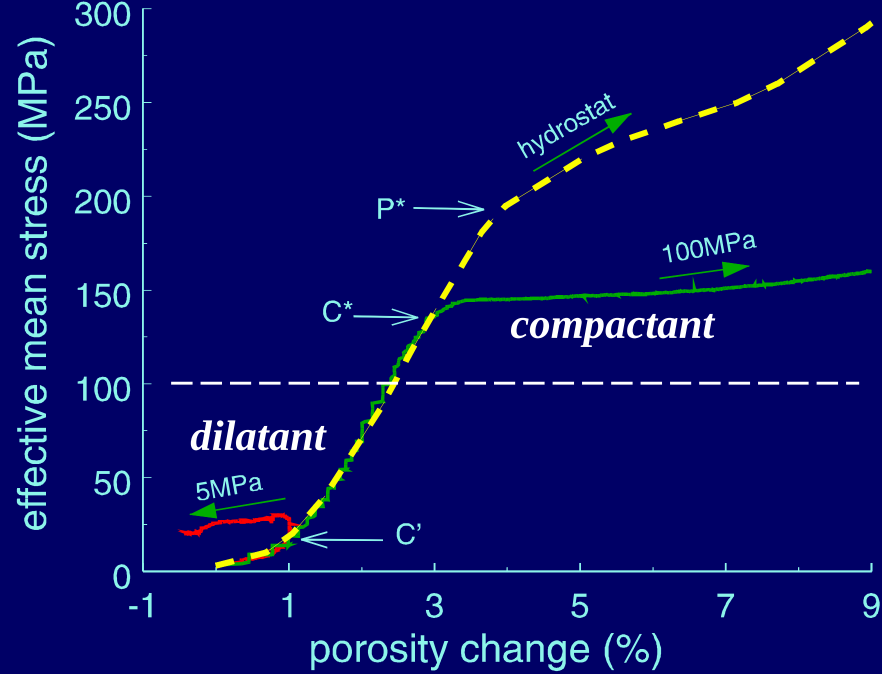


C’: **onset of dilatancy**









Wong, David & Zhu (1997)

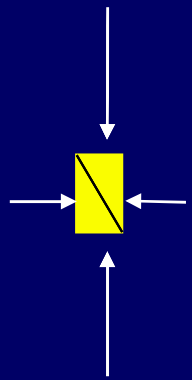
Brittle-Ductile Transition and Failure Modes

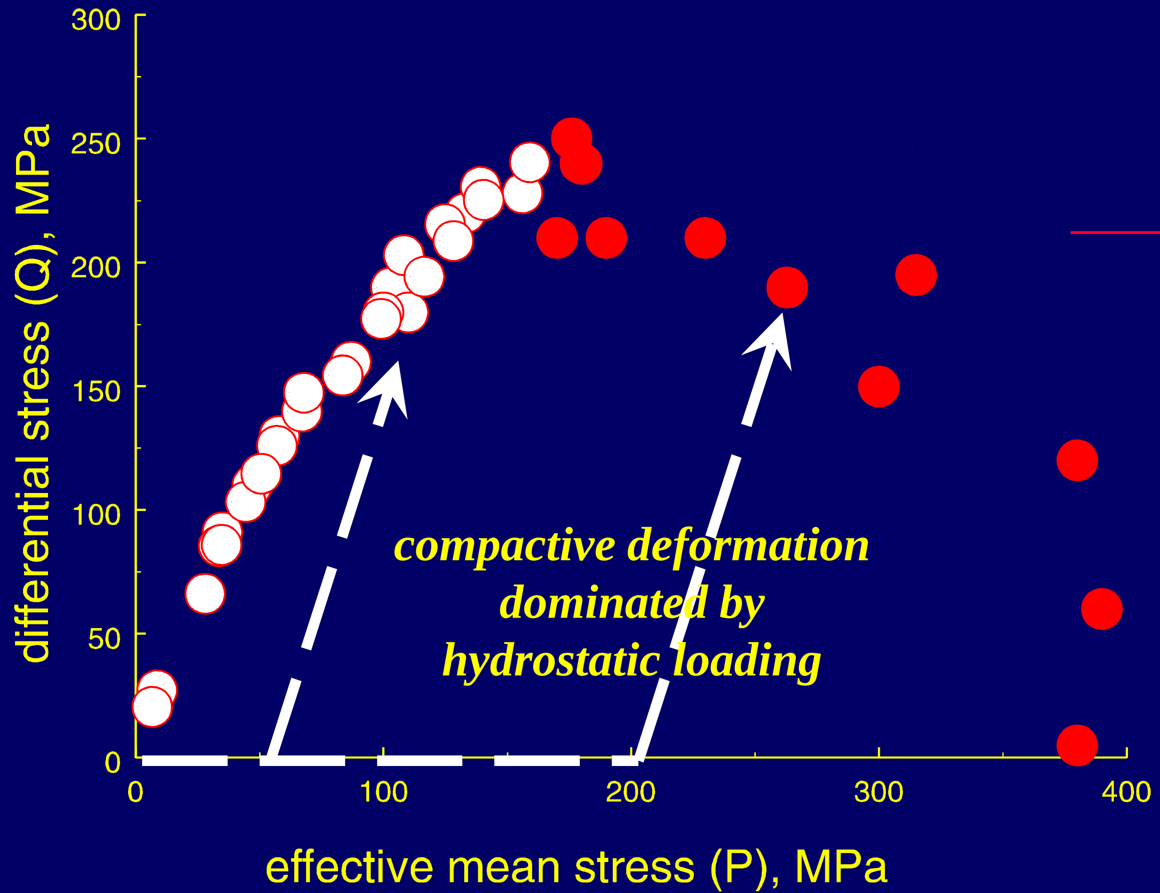
brittle fracture:
shear localization

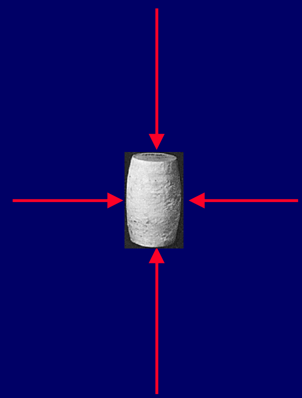
- dilatancy
- low confinement
- high stress

compactive yield: *bulk failure*

- shear-enhanced compaction
- high confinement
- low deviatoric stresses



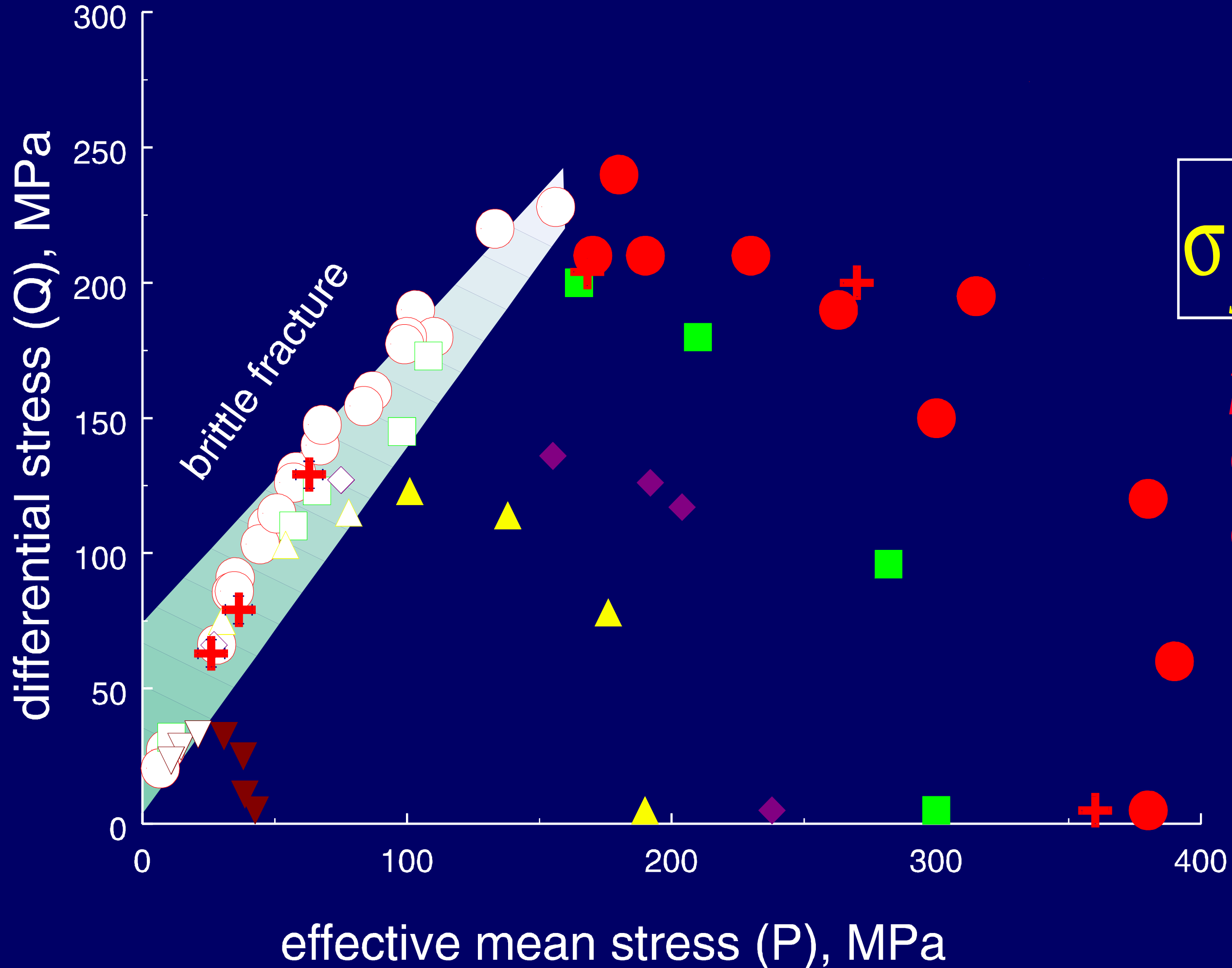




BEREA SANDSTONE

COMPACTIVE YIELD ENVELOPE:

an elliptical cap with yield stresses dependent on porosity ϕ and grain size D

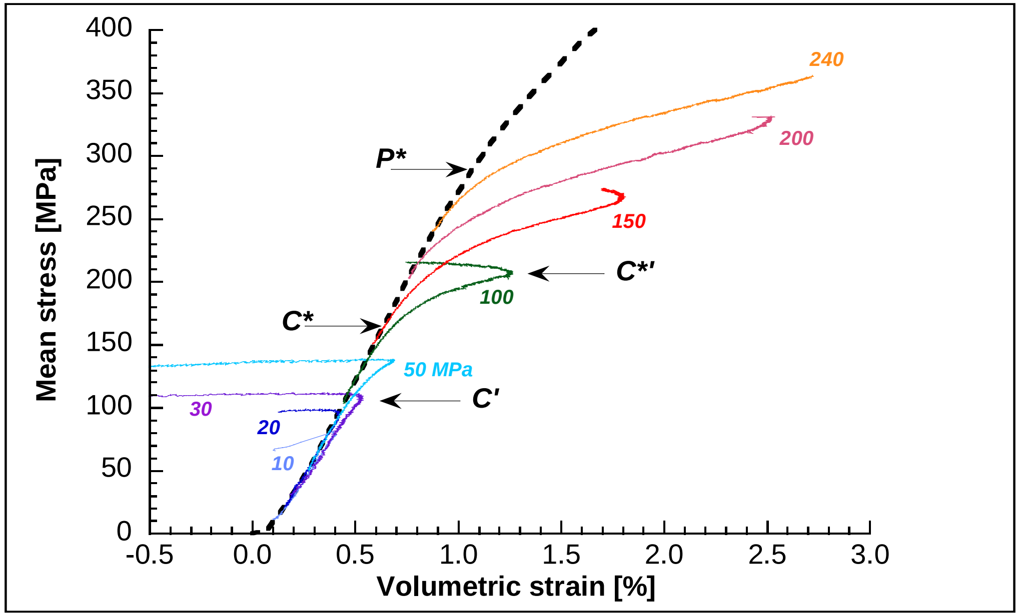


$$\sigma_y \sim (\phi D)^{-3/2}$$

fluid chemistry ?
cementation?
clay content?

Wong, David & Zhu (1997)

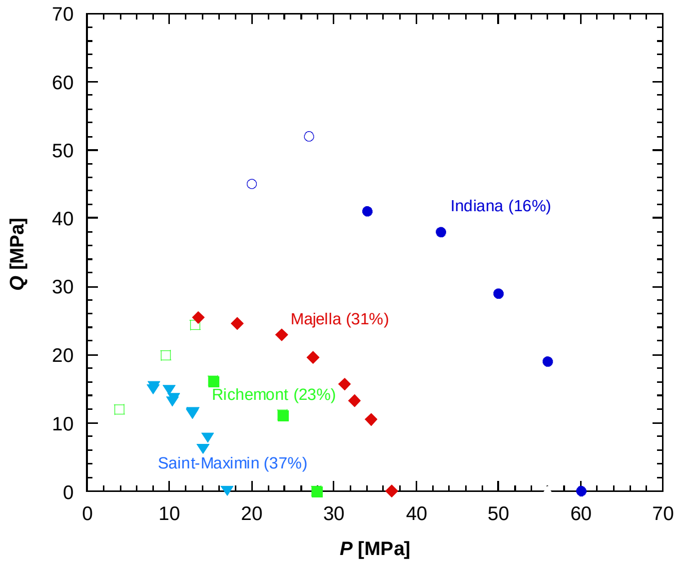
Brittle-ductile transition in porous limestones

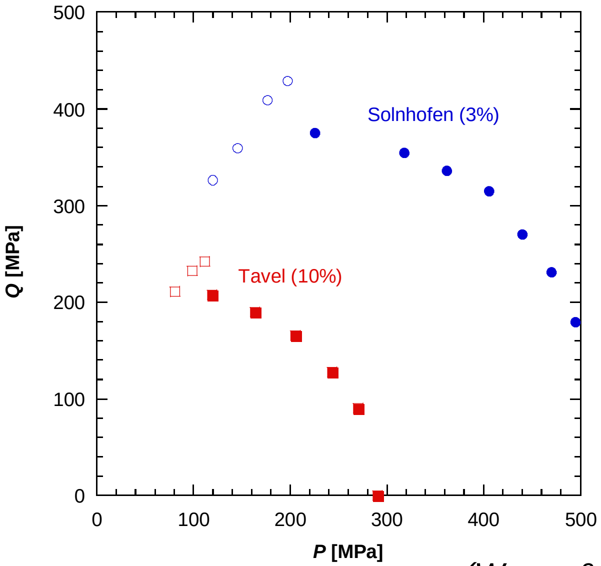


(Tavel limestone, porosity 10%, Vajdova, Baud and Wong, 2004)

- phenomenology similar for limestones with porosities 3-18%
- brittle-ductile transition qualitatively similar to porous sandstone

C' onset of dilatancy
C* onset of shear-enhanced compaction
C*' transition from shear-enhanced compaction to dilatancy

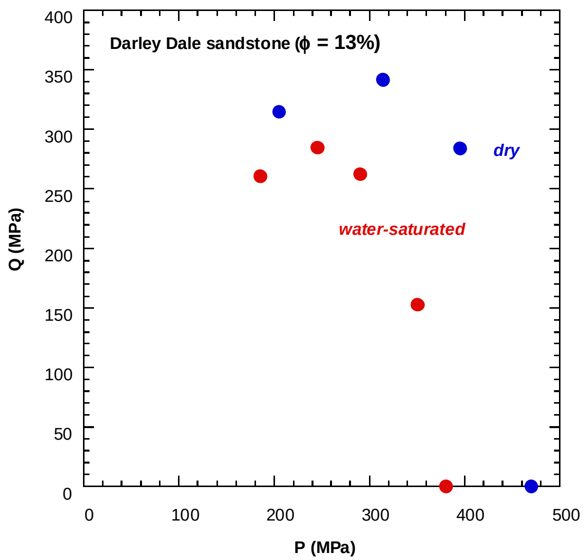


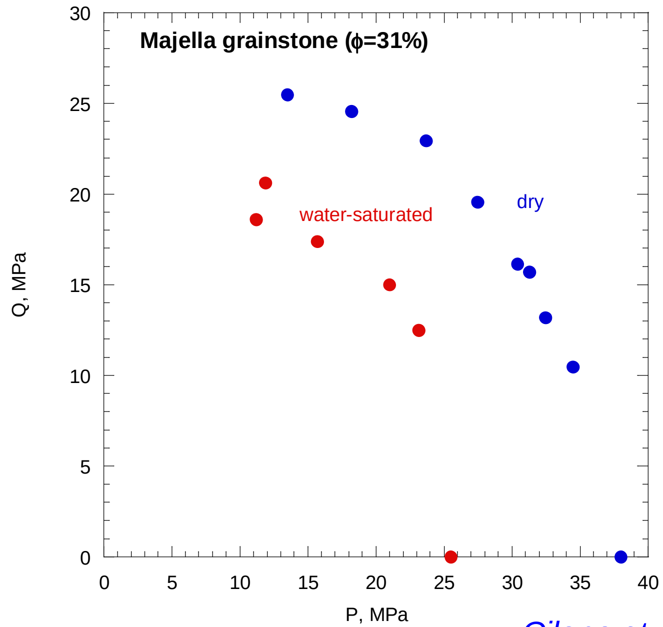


(Wong & Baud, 2012)

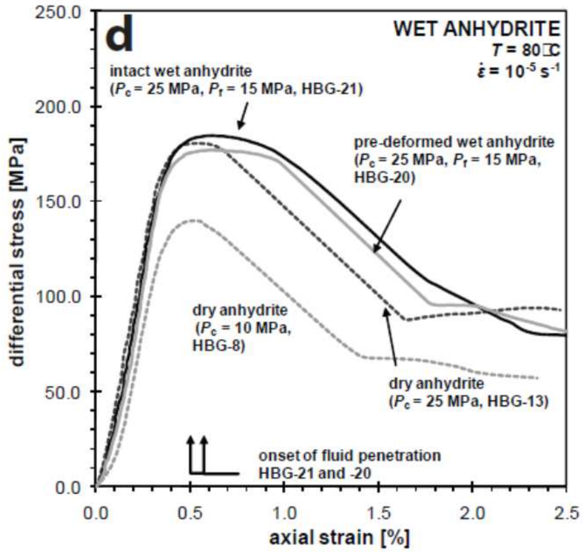
Fluid weakening: short-term effect

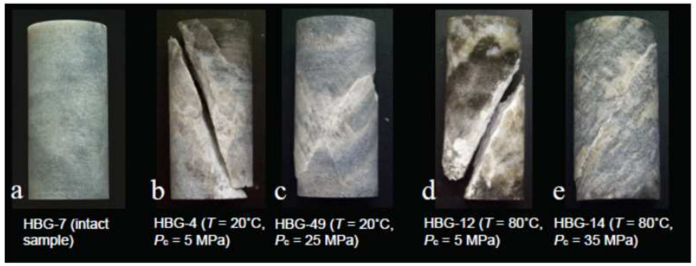
- significant water weakening in sandstone and limestone





Cilona et al. (2012)





- Mechanical data on brittle strength of anhydrite saturated with CO_2 and subjected to a static pore pressure show that the short-term chemical effect on strength is relatively small.

Hangx, Spiers & Peach (2010)

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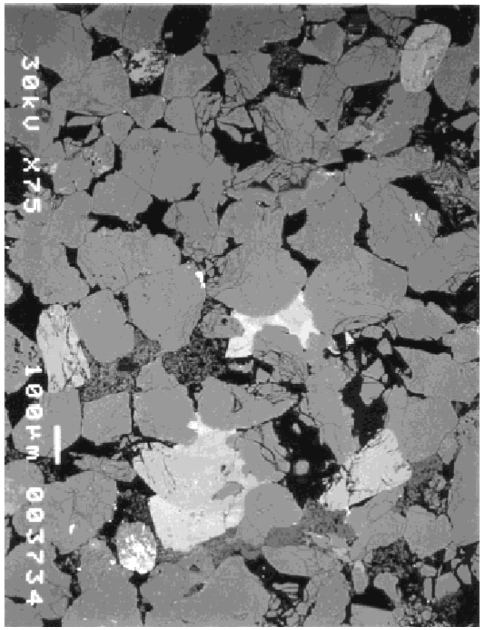
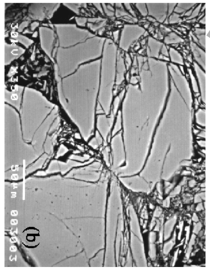
Waddenacademie (2013)

Microstructure: brittle regime

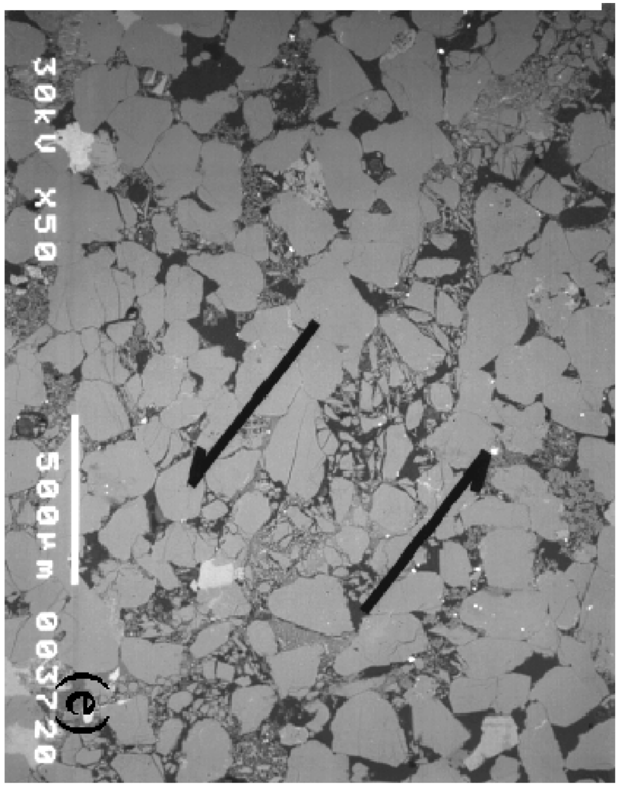
σ_1





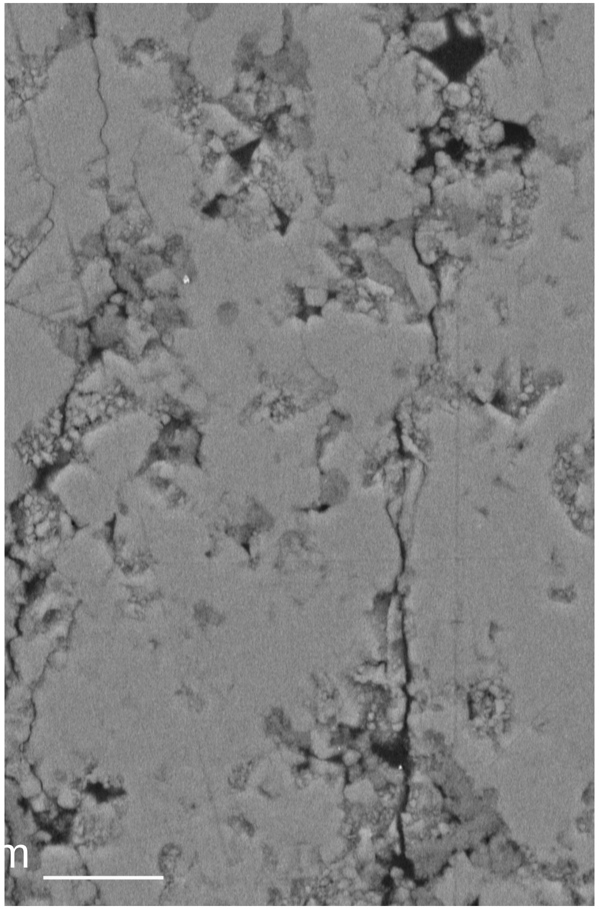
Stress-induced damage:
- ***spatial clustering***
- ***anisotropic cracking***

Berea sandstone
(P_{eff} =10 MPa)



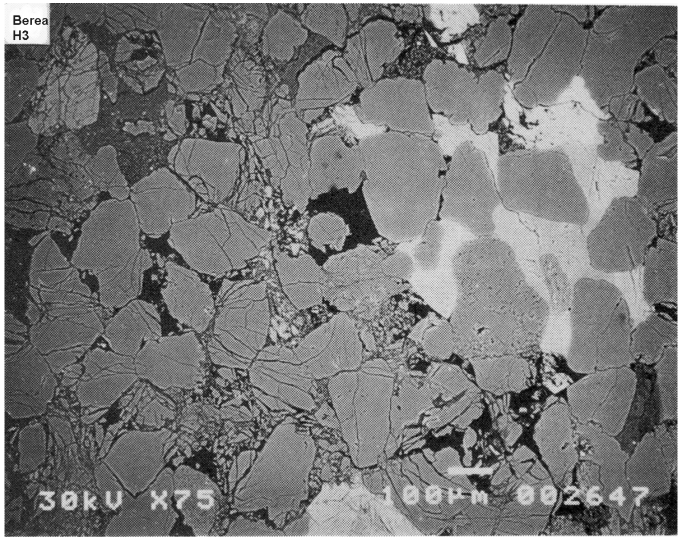
Shear localization

Tavel limestone:
Onset of dilatancy
pore emanated-microcracks

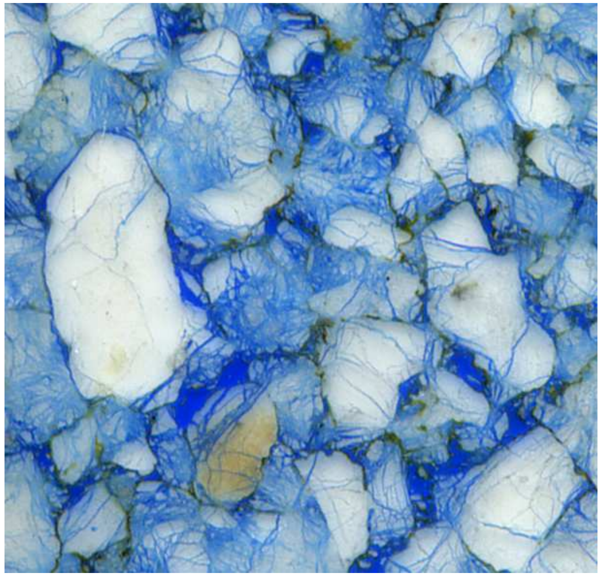


(Vajdova et al., 2004)

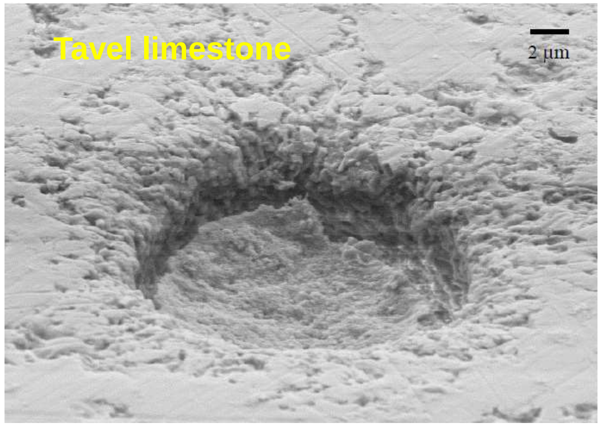
Hydrostatic Loading: Cataclastic pore collapse/grain crushing

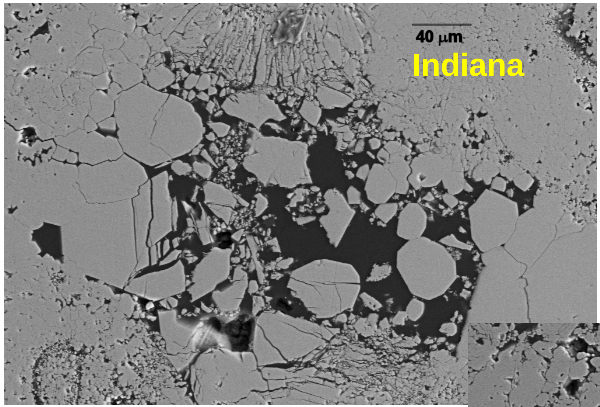


Berea sandstone
Menéndez, Zhu & Wong (1996)

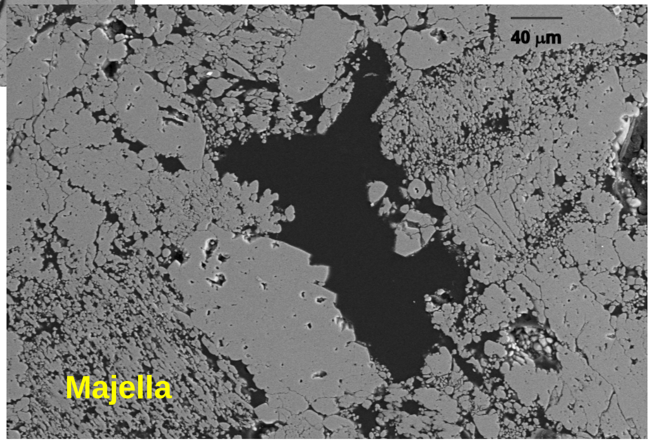


Boise sandstone
Wong & Baud (2012)





LIMESTONE: stress concentration at **periphery** of equant **pore** → **localized cataclastic** damage → **spalled fragments** fall into the void → **pore collapse**

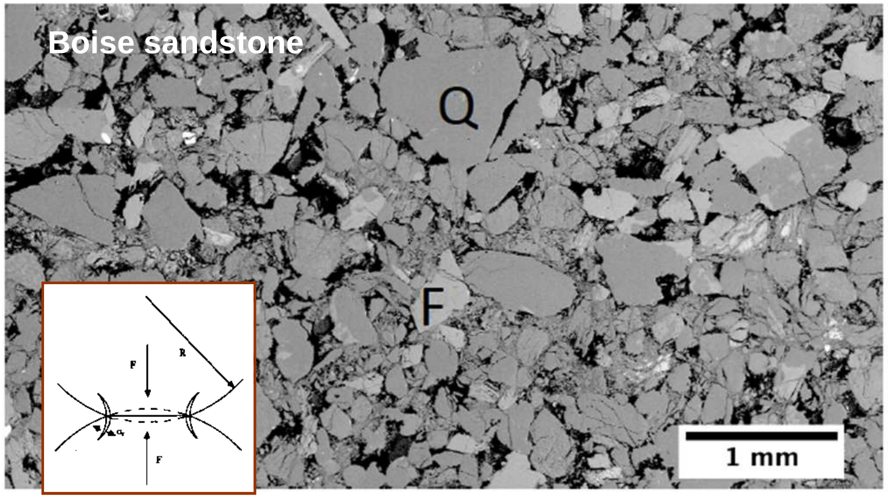


SANDSTONE: stress concentration at **grain contact** → **Hertzian fracture** → intragranular cracking → **grain crushing** → **pore collapse**

Triaxial Loading: compaction bands/homogeneous compaction

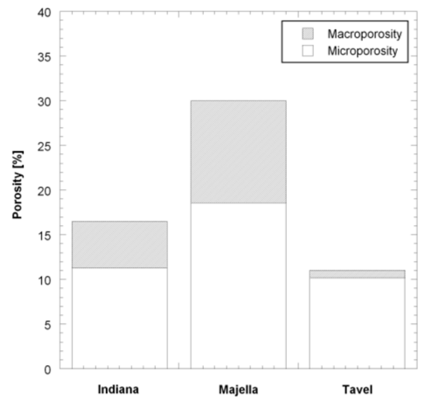
SANDSTONE

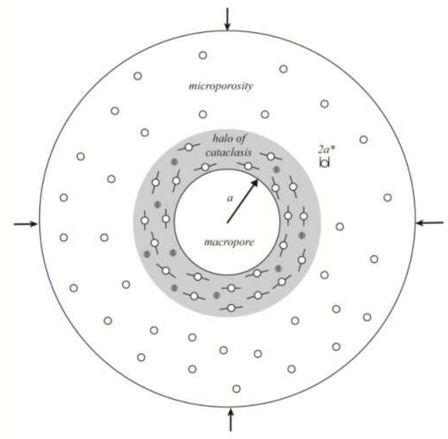
•Cataclastic flow: Hertzian cracking (*Cheung et al*., 2012)



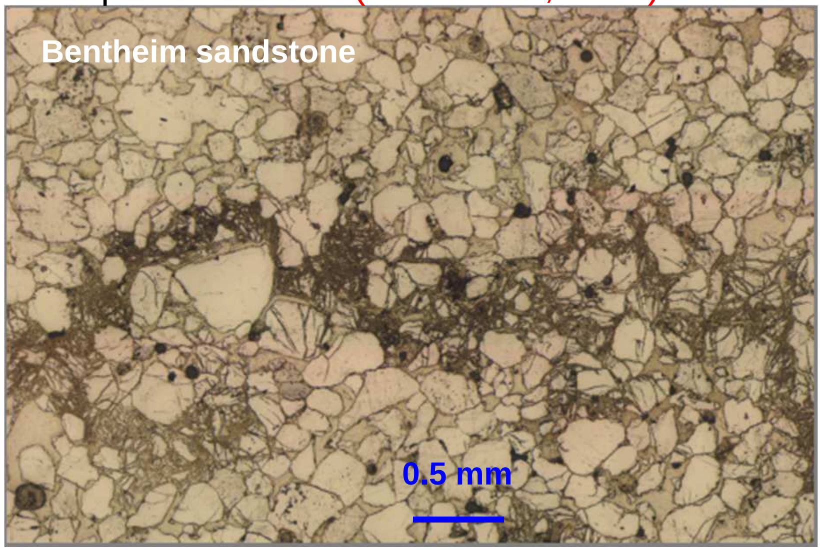
LIMESTONE

•Cataclastic pore collapse (*Zhu et al*., 2010)

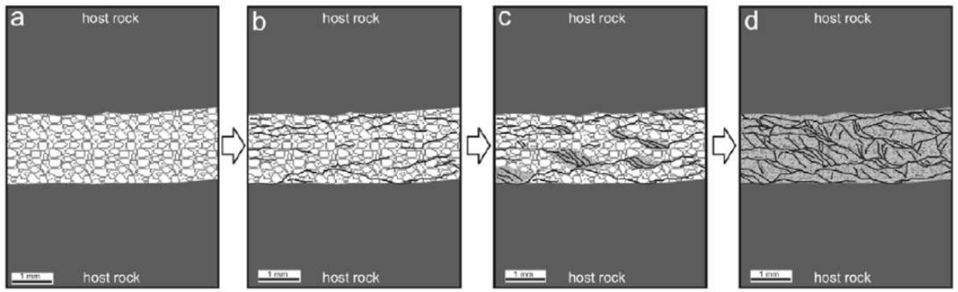




•Compaction bands: (*Baud et al*., 2004)



•Compaction localization in carbonates



a) Compactive shear bands with no cataclasis.
b) Compactive shear bands with band-parallel stylolites but no cataclasis.
c) Compactive shear bands with discontinues pockets of cataclasis, band-parallel sheared stylolite and oblique stylolites.
d) Compactive shear bands with overprinted sheared stylolites, cataclasis and oblique sets of stylolites.

The role of deformation bands, stylolites and sheared stylolites in fault development in carbonate grainstones of Majella Mountain, Italy

Emanuele Tondi [a,*], Marco Antonellini [b], Atilla Aydin [b], Leonardo Marchegiani [a], Giuseppe Cello [a]

Journal of Structural Geology 28 (2006) 376–391

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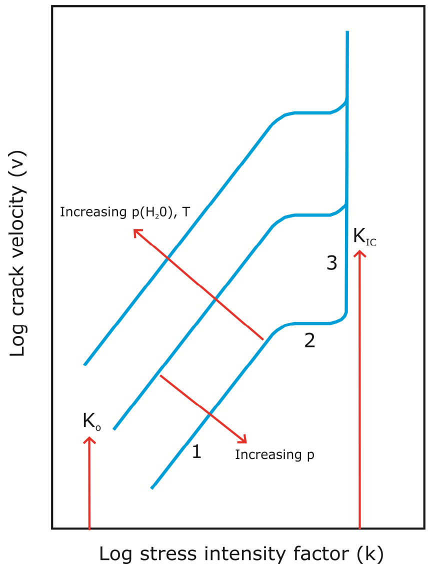
Time-dependent brittle failure: subcritical cracking and creep

- The presence of a fluid phase in porous rocks not only affects the mechanical behaviour of rock, but also allows **chemical rock-fluid interactions** to occur.

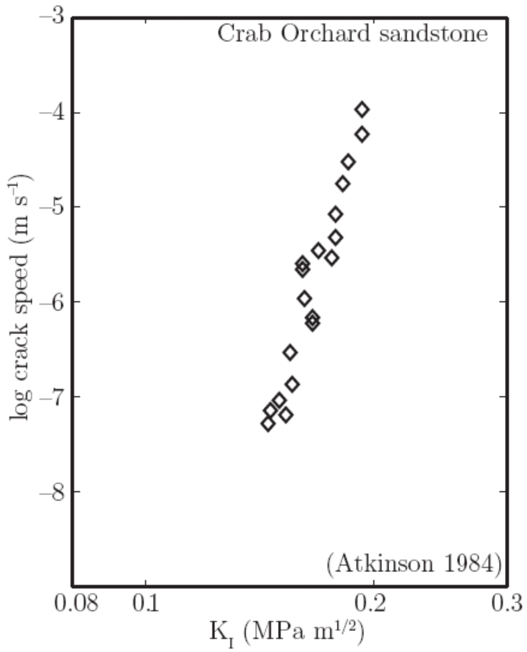
- Subcritical crack processes such as **stress corrosion** [Anderson and Grew, 1977; Atkinson, 1984, Atkinson and Meredith, 1987; Costin, 1987] introduce a **time-dependence** that allows rock to fail at lower stress over extended time.

- Stress corrosion describes the reactions that occur preferentially between a **chemically active pore fluid**, most commonly water, and the strained atomic bonds close to crack tips.

- slow crack propagation:
  $K_I < K_{IC}$

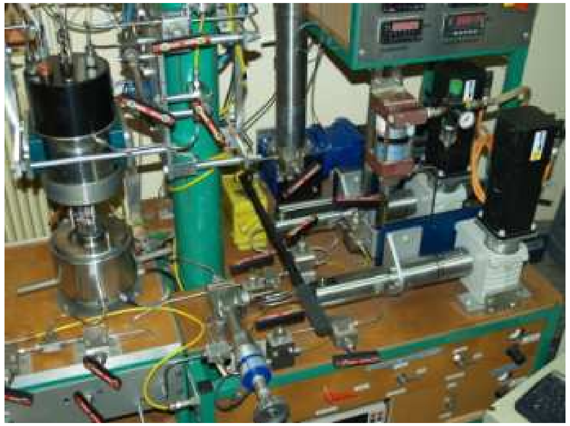


- extremely sensitive to stress (*Atkinson & Meredith*, 2007)

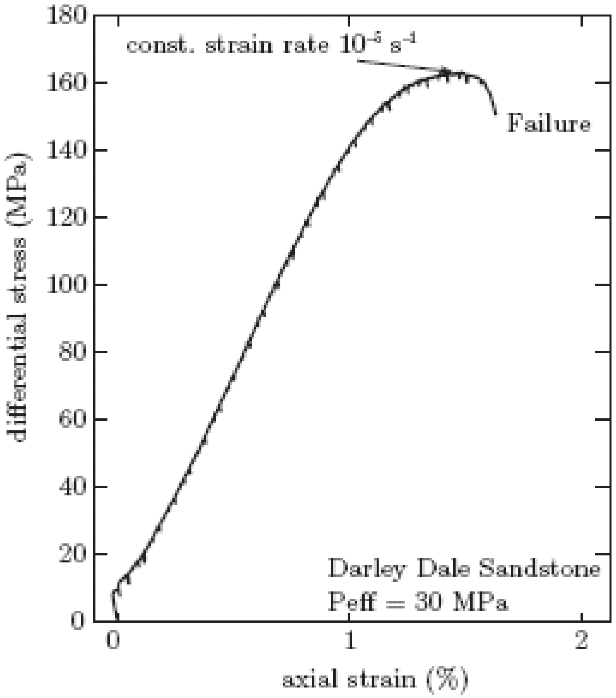


Triaxial experiments

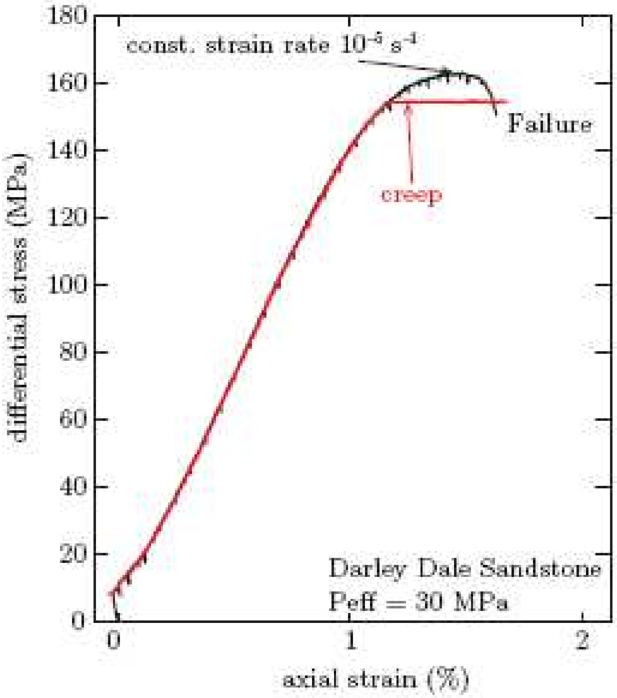
- water-saturated samples, drained conditions (P_p = 10 MPa)
- sample size: 100 mm x 40 mm
- acoustic emission location
- internal furnace



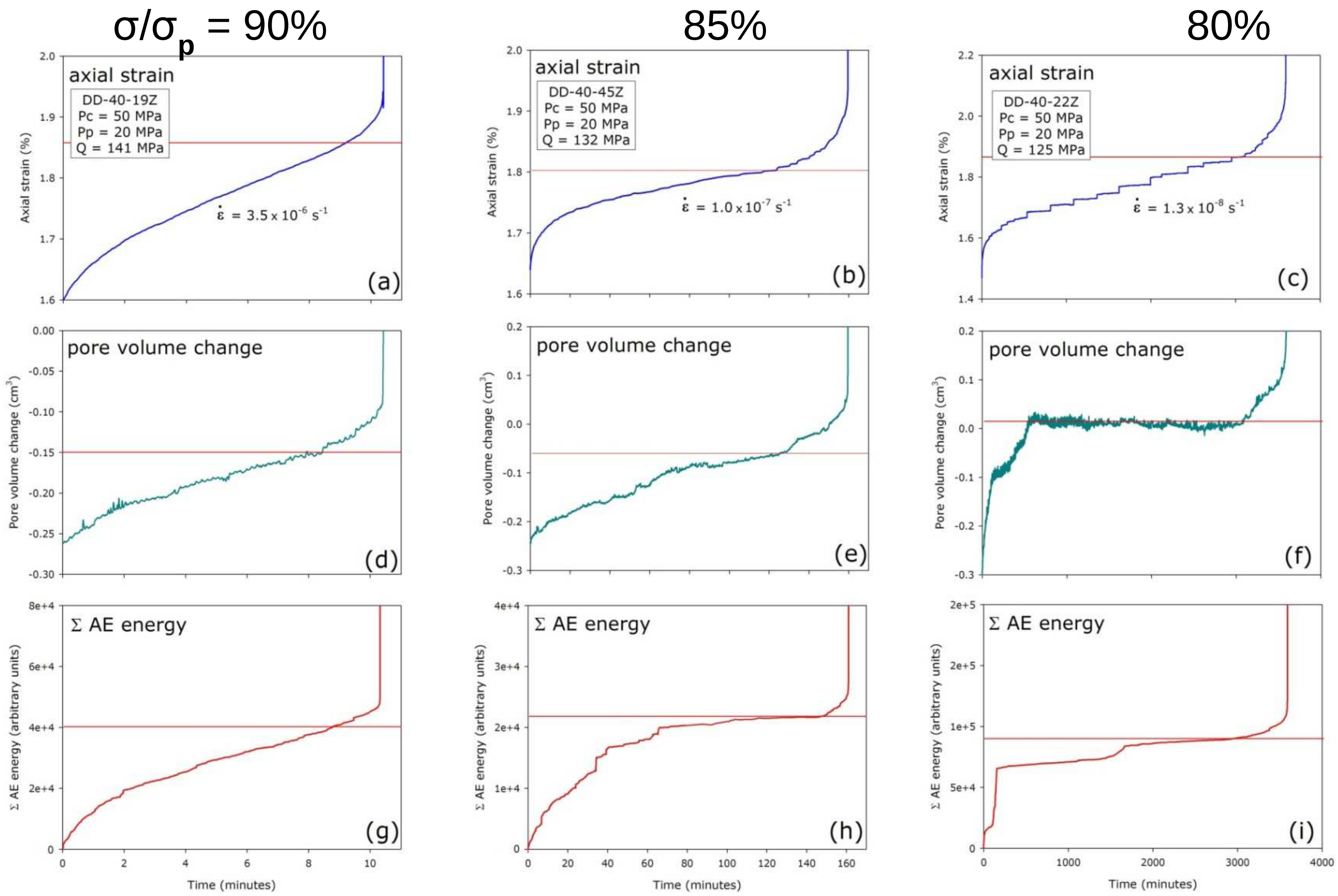
- conventional triaxial experiment: imposed fast strain rate (10^{-5}/s) until failure
- large quantity of data on many rocks



- creep tests: imposed constant stress
- strain rates between 10^{-9}/s and 10^{-5}/s
- paucity of data



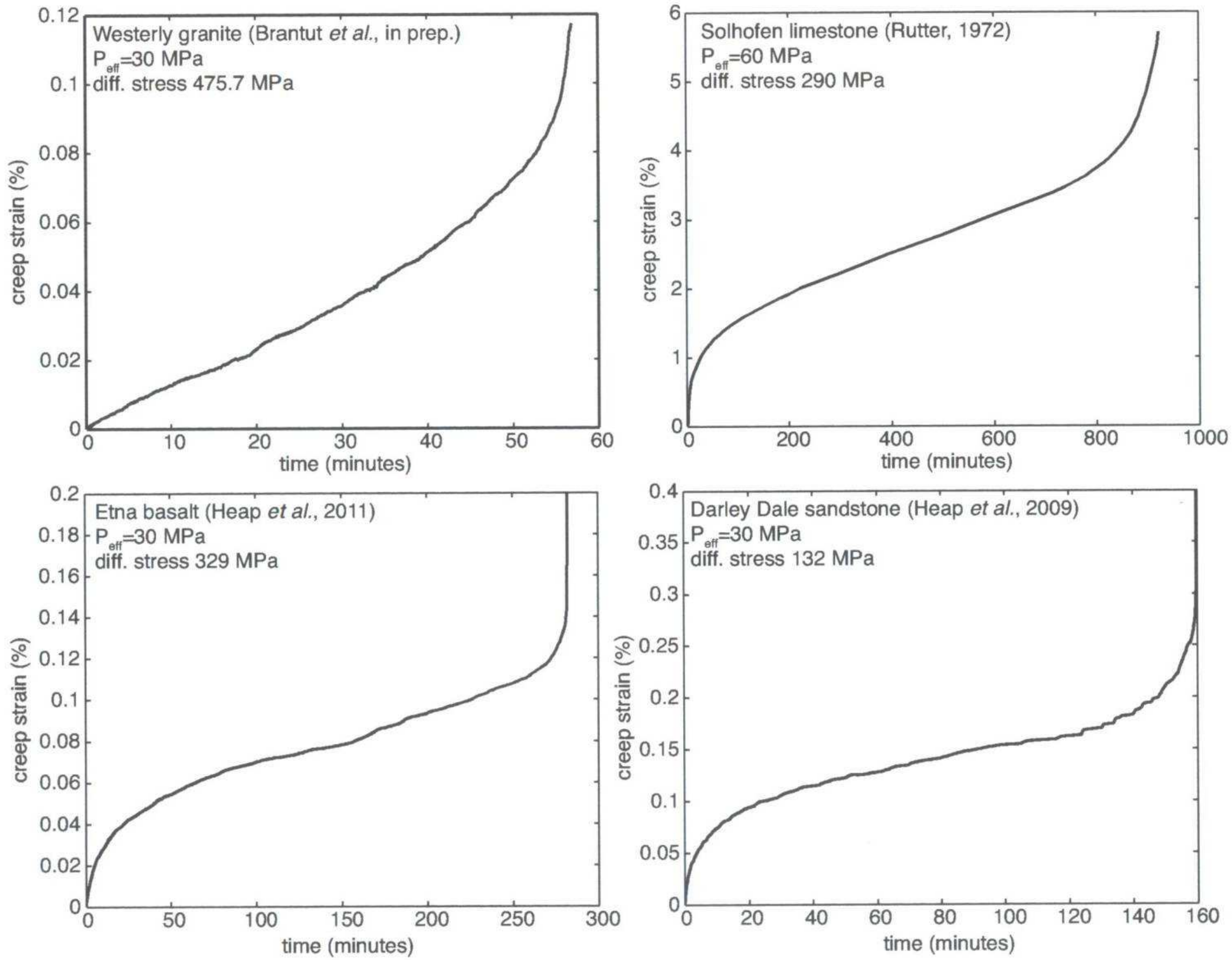
Creep experiments (static fatigue): sandstone



- damage proxies: strain, porosity, AE
- critical level of damage

Heap et al., JGR, 2009

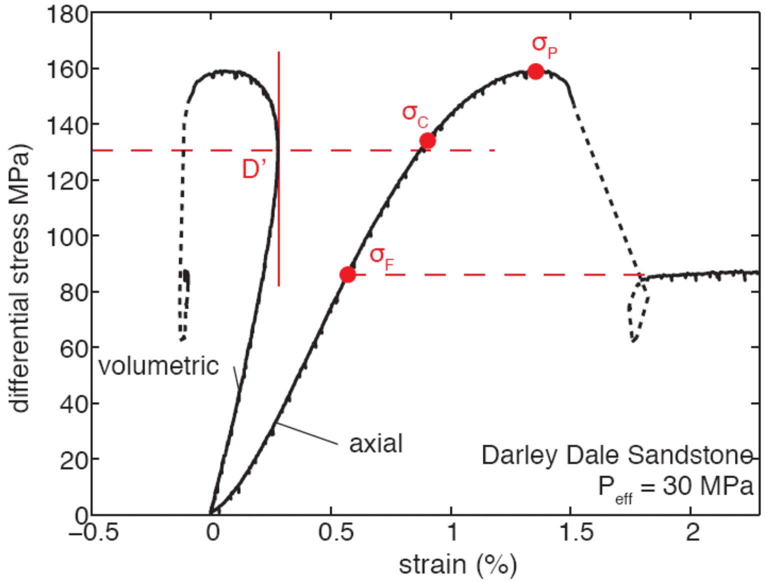
Brittle creep: same phenomenology in other rock types



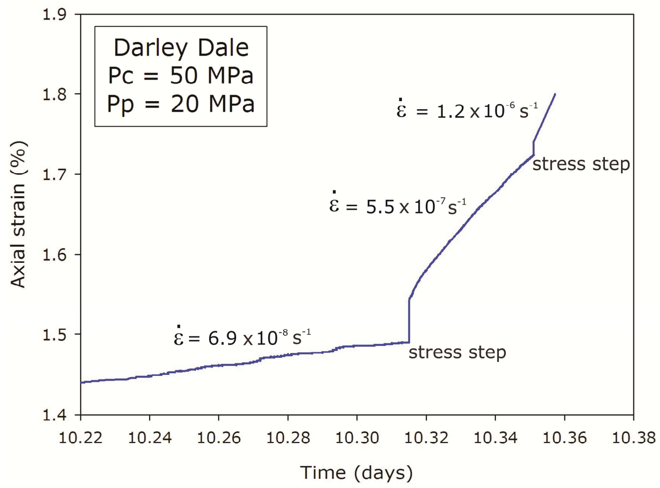
Brantut et al., Journal of Structural Geology, 2013

Creep experiments

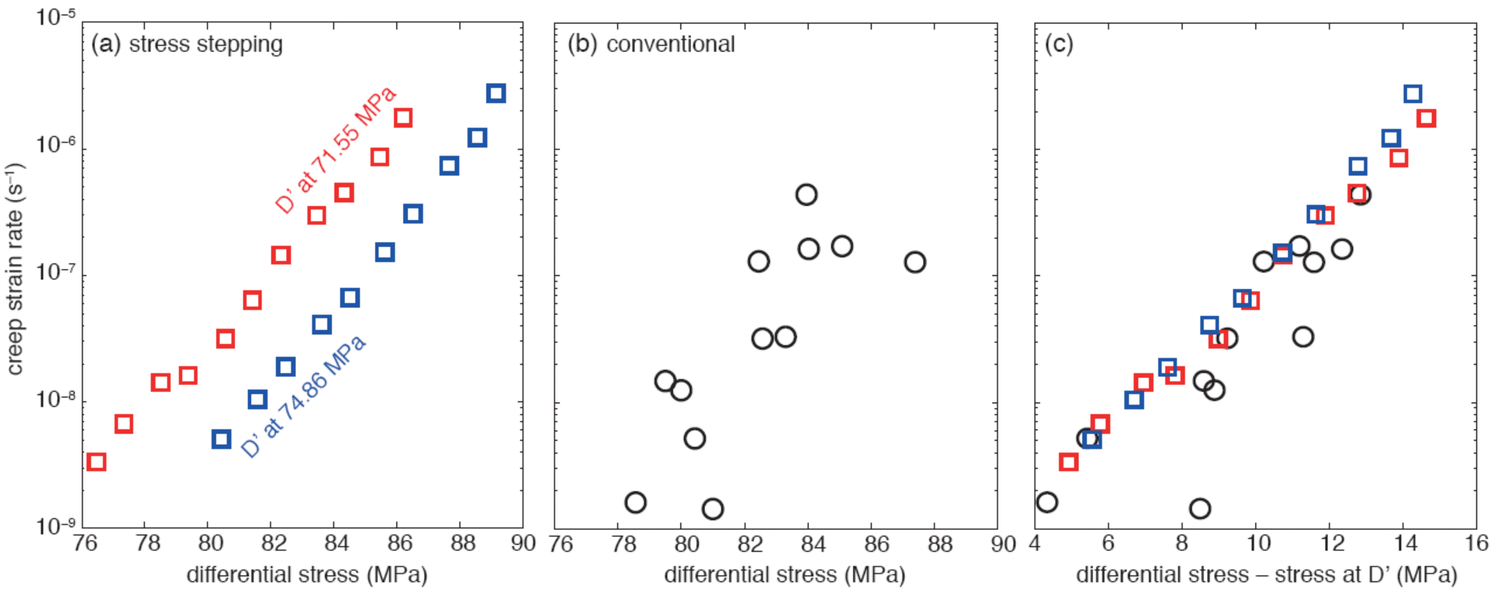
- creep between D' and σ_p



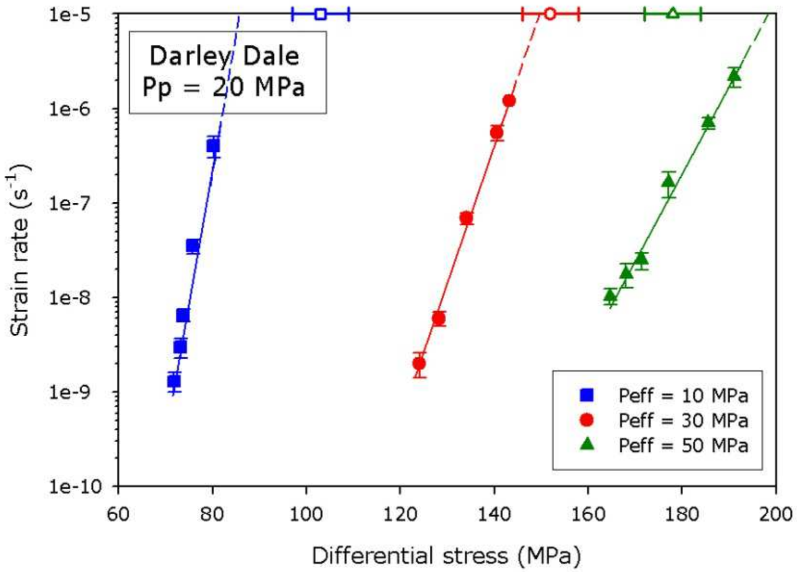
- stress stepping methodology



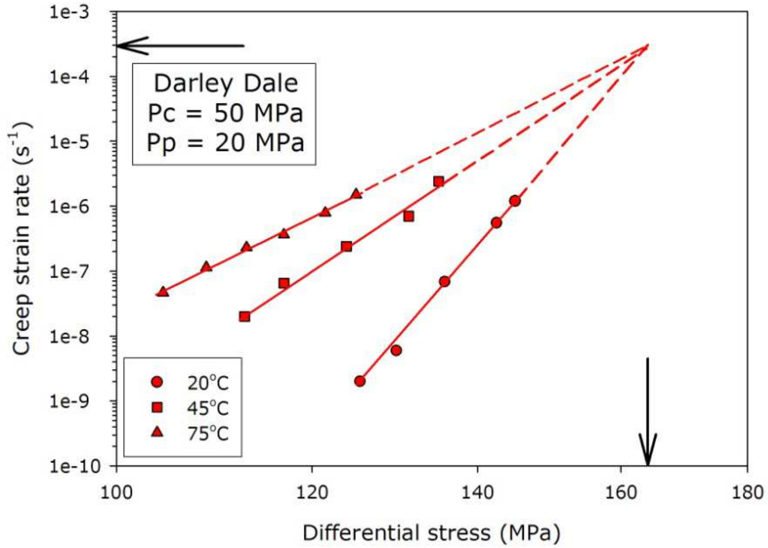
- importance of initial damage



•Influence of effective pressure



•Influence of temperature



Using a simple uniaxial strain model for Darley Dale sandstone at 1 km depth

Expected changes in creep strain rate over a depth of 2km
Experimental data on Darley Dale sandstone suggest:

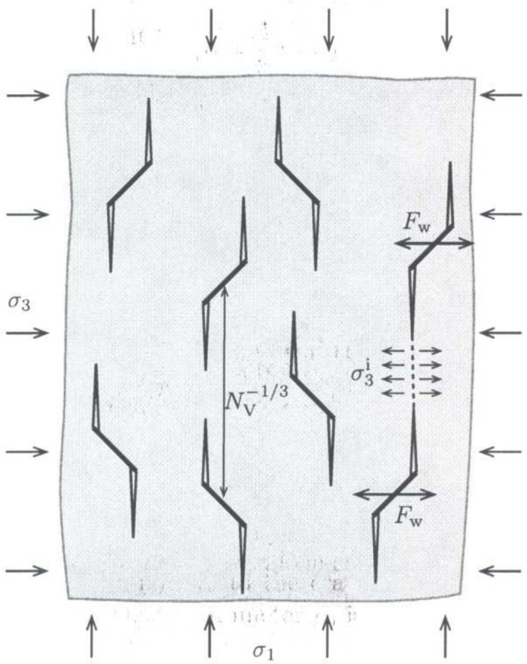
- Increase by 2 x 10^3 due to the increase in temperature
- Decrease by 3 x 10^3 due to the increase effective mean stress
- Increase by 10^3 due to increase in differential stress

The effects of the well constrained parameters (P_{eff}, T) almost exactly balanced. This suggests that the key parameter controlling the strain rate of brittle creep in the crust is the **differential stress**, and this will vary significantly with tectonic regimes. Interpretation of local creep rates would therefore require a specific knowledge of the local stress regime and its evolution with depth.

Heap et al., GRL (2009)

•Micromechanical model for brittle creep
(*Brantut, Baud, Heap, Meredith*, *JGR*, 2012)

• Starting geometry (*Sammis & Ashby*, 1990)

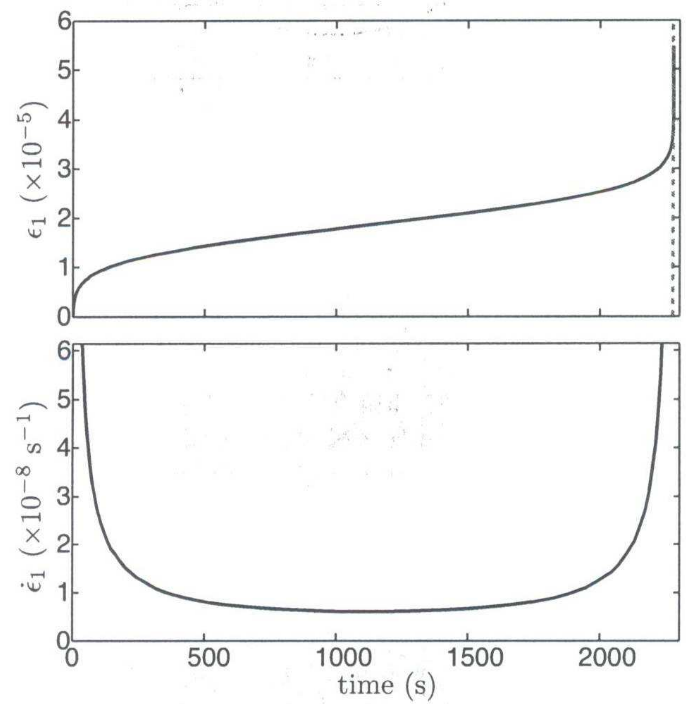


• Subcritical crack growth (*Charles*) :

$$\frac{dl}{dt} = \dot{l}_0 \left(K_I / K_{IC} \right)^n$$

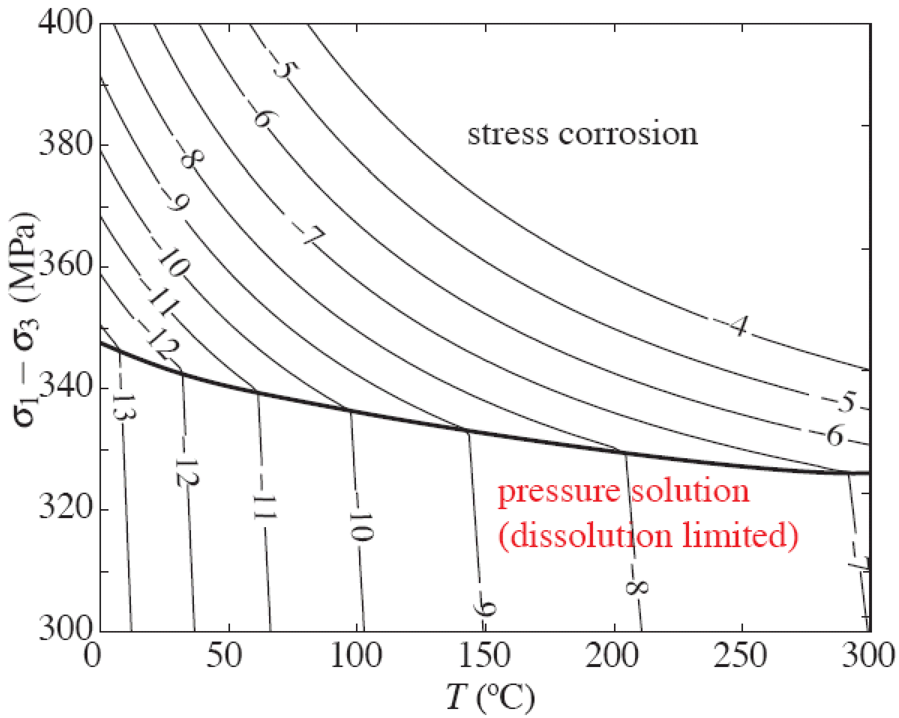
• Microcrack interactions

• The model reproduces the macroscopic phenomenology and in particular primary, secondary and tertiary creep.

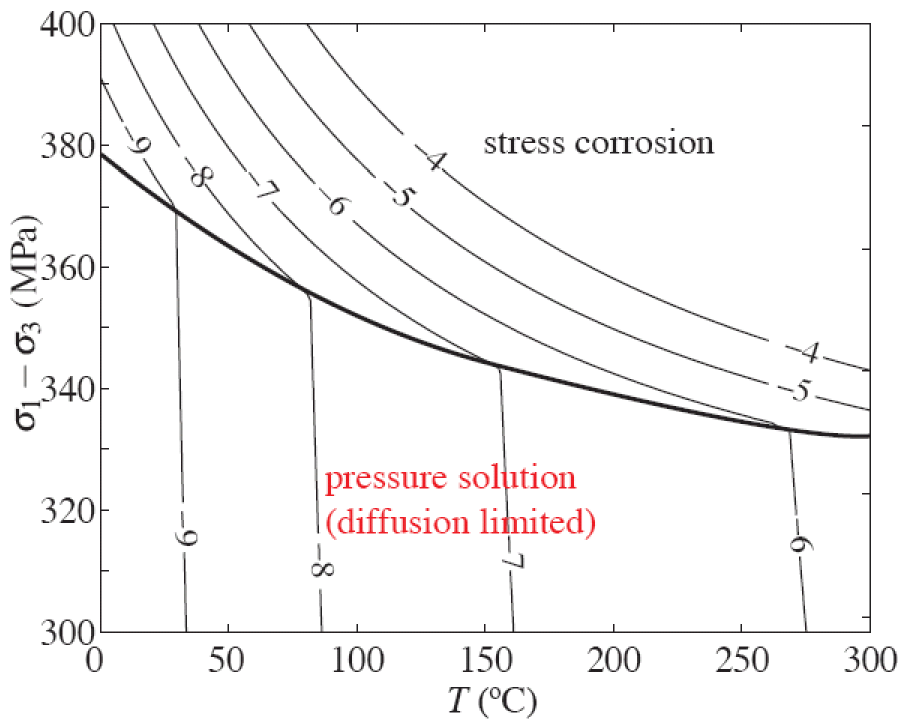


$$\dot{\varepsilon} \propto \left[1 - k \frac{\sigma_1^{peak} - \sigma_1}{K_{IC}\sqrt{\pi a}} \right]^{n+1}$$

Deformation maps: sandstone



PS strain rate calculated from model of Niemeijer et al. (2002) for dissolution-limited creep.



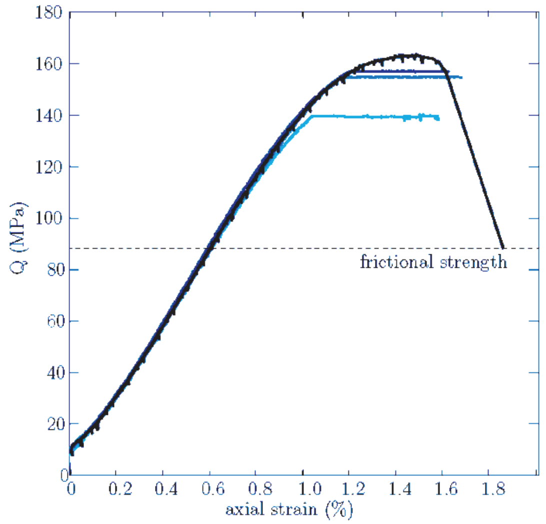
PS strain rate calculated from model of Rutter (1983) for diffusion-limited creep.

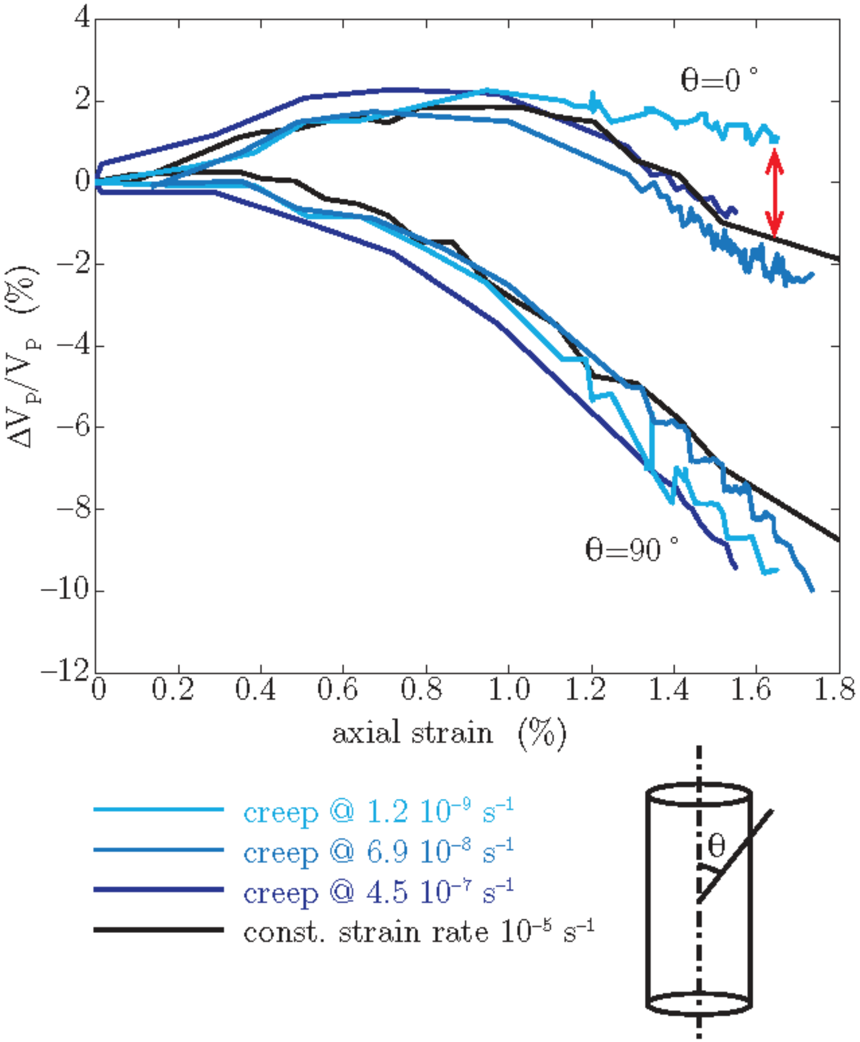
It therefore appears that PS is likely too slow to explain our experimental data at ambient T.

(*Brantut et al*.,*JGR*, 2012)

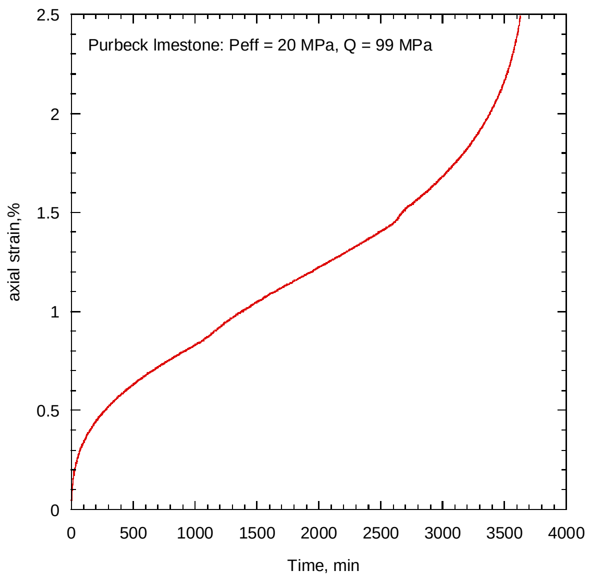
Other mechanism(s)?

- sandstone: less cracking at slow strain rates

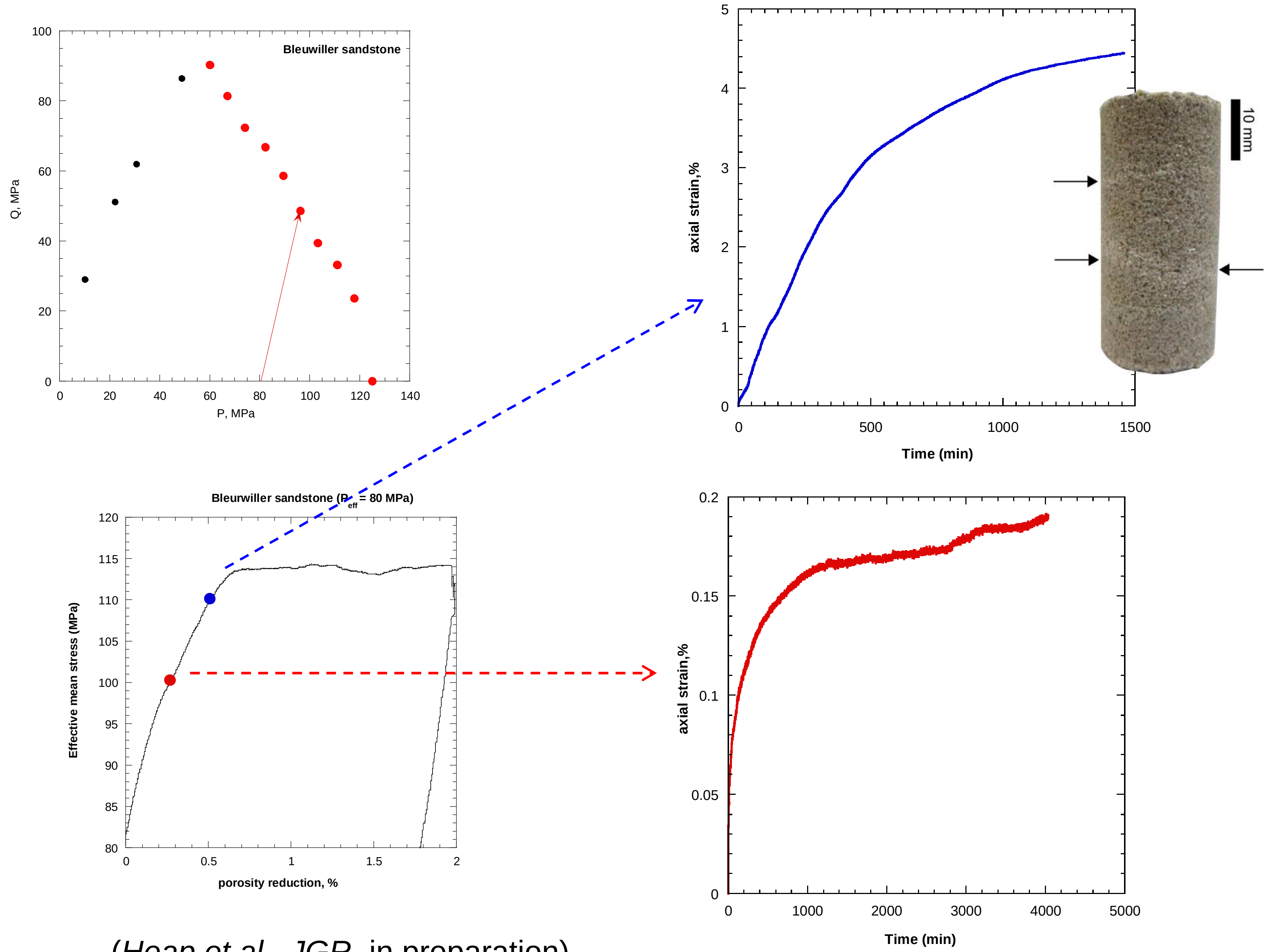




- limestone: larger amount of strain



Time-dependent compaction: sandstone



(*Heap et al*., *JGR*, in preparation)

Conclusions and perspectives

• Experiments on sandstone enabled to quantify the influence of in situ conditions on brittle creep.

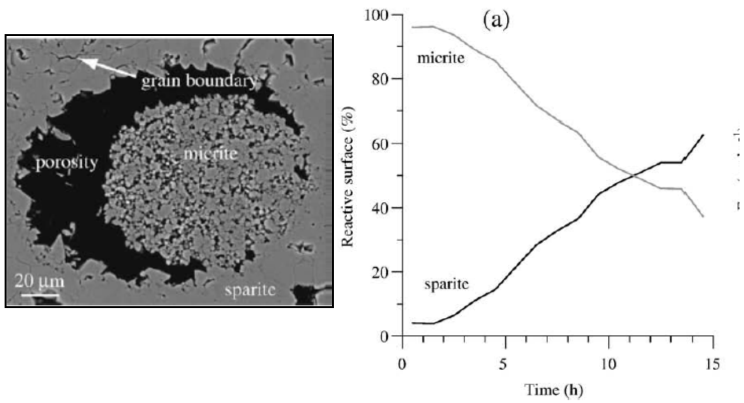
• The experimental data suggest that the creep strain rate at depth is controlled by the differential stress.

• A simple micromechanical model explains how brittle creep operates and is in good quantitative agreement with data.

• Useful for predictions of long term strength of the brittle crust.

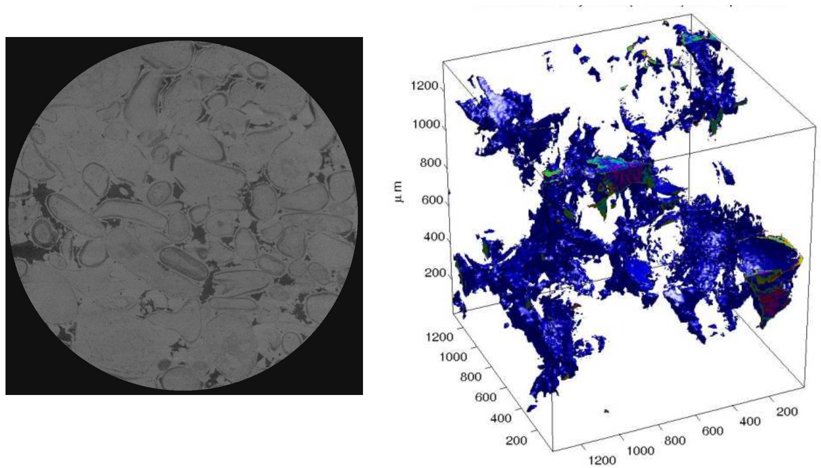
• Current work on time-dependent deformation in limestone and compactant creep.

Upper Miocene limestone from Mallorca (~16%)



Noiriel et al. (2009)

Multiscale X-ray CT imaging



Ji et al., Oil & Gas Sci. Tech. (2012)