Time-dependent deformation in rocks

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Waddenacademie (2013)
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.

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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 deformation dominated by hydrostatic loading
COMPACTIVE YIELD ENVELOPE: an elliptical cap with yield stresses dependent on porosity $\phi$ 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

- 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

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

(Wong & Baud, 2012)
Fluid weakening: short-term effect

- significant water weakening in sandstone and limestone

- Mechanical data on brittle strength of anhydrite saturated with CO₂ and subjected to a static pore pressure show that the short-term chemical effect on strength is relatively small.

*Hangx, Spiers & Peach (2010)*

*Cilona et al. (2012)*
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Waddenacademie (2013)
Microstructure: brittle regime

Tavel limestone:
Onset of dilatancy pore emanated-microcracks

Berea sandstone
\((P_{\text{eff}} = 10 \text{ MPa})\)

Stress-induced damage:
- spatial clustering
- anisotropic cracking

Shear localization

(Vajdova et al., 2004)
Hydrostatic Loading: **Cataclastic pore collapse/grain crushing**

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

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

*Berea sandstone*
*Menéndez, Zhu & Wong (1996)*

*Boise sandstone*
*Wong & Baud (2012)*

*Tavel limestone*

*Indiana limestone*

*Majella limestone*
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)*
- Boise sandstone
  - [Image: Boise sandstone with compaction bands](image)
  - [Image: Boise sandstone with compaction bands, scale bar 1 mm](image)

**Compaction localization in carbonates**
- Bentheim sandstone
  - [Image: Bentheim sandstone with compaction localization](image)
  - [Image: Bentheim sandstone with compaction localization, scale bar 0.5 mm](image)

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

Emanuele Tondi a,b, Marco Antonellini b, Atilla Aydin b, Leonardo Marchegiani c, Giuseppe Cello a

Time-dependent deformation in rocks

- Phenomenology of brittle-ductile transition in porous sandstone: 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)
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

\[ \sigma / \sigma_p = 90\% \]  
\[ 85\% \]  
\[ 80\% \]

- 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 $\sigma_p$

- importance of initial damage

- stress stepping methodology
• Influence of effective pressure

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 $2 \times 10^3$ due to the increase in temperature
• Decrease by $3 \times 10^3$ due to the increase effective mean stress
• Increase by $10^3$ due to increase in differential stress

The effects of the well constrained parameters ($P_{\text{eff}}$, $T$) 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)*:
  \[
  \frac{dl}{dt} = i_o \left( \frac{K_i}{K_{ic}} \right)^n
  \]

• Microcrack interactions

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

\[
\dot{\varepsilon} \propto \left[ 1 - k \frac{\sigma_{peak} - \sigma_1}{K_{ic} \sqrt{\pi a}} \right]^{n+1}
\]
Deformation maps: sandstone

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

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

\[ P_{eff} = 20 \text{ MPa}, \quad Q = 99 \text{ MPa} \]

\[ \theta = 0^\circ, \quad \theta = 90^\circ \]

\[ \text{creep @ } 1.2 \times 10^{-9} \text{ s}^{-1}, \quad \text{creep @ } 6.9 \times 10^{-8} \text{ s}^{-1}, \quad \text{creep @ } 4.5 \times 10^{-7} \text{ s}^{-1}, \quad \text{const. strain rate } 10^{-8} \text{ s}^{-1} \]
Time-dependent compaction: sandstone

(Hep 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)