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Brittle/Ductile Transition and Rupture Dynamics: Experiments on Gypsum

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Christmas Tree Model



Figure: Brace W. & Kohlstedt D.L., JGR 1980.

This view is quasi-static: no influence of slip velocity, and no correlation with seimic/aseismic behaviour.

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A Renewed View



Figure: Shimamoto T., JSG 1989.

Experiments on halite. The effect of slip and slip rate is clearly emphasized (out of equilibirum diagram ?). The relation with seismic/aseismic behviour is assumed.

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More Complexity



Figure: Brodie K. & Rutter E., APG 1985

Dehydration : weakening and then hardening (stiffer reaction products).

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Use new technologies to describe as precisely as possible the behaviour of rocks at the brittle/ductile transition.

Material Used

Our Approach

- Need for a rock that experience B/D transition and dehydration under laboratory conditions,
- Gypsum is OK.

Experimental Devices

• Triaxial Apparatus, P_c up to 100 MPa and T up to 200°C,

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- Elastic wave velocities measurement,
- Continuous AE recording.

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Tri-axial Rig @ ENS



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Sample Set-up



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AE Recording System



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Stress-strain Behaviour



- Transition around $P_{\rm c} = 10$ MPa,
- Brittle behaviour: single shear band,
- Numerous stress drops during the "ductile" behaviour.

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Microstructural Observations



Numerous shear bands at $P_c = 50$ MPa

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Microstructural Observations



Presence of plastic deformation (kinks) and crack opening

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Conclusions

Wave Velocity Data

- Active survey every 5 minutes.
- Relative measurements using cross-correlation technique.

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Wave Velocity Data

Continuous, linear decrease of wave velocities with increasing axial strain.



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Interpretation in Terms of Crack Density



- Linear evolution of crack density with increasing deformation.
- The material accumulates cracks without losing cohesion: typical semi-brittle behvaiour.

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occoCoLethal Weapon: Continuous Records (Mini Richter
System)



- AE activity has a peak just before the yield point,
- at RT: no correlation between AE and stress drops;
- at 70°C: all stress drops are accompanied with large AE.

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Conclusions

Various Types of AE



- "regular" AE are short and at high frequency; they do not correspond with a macroscopic change of stress,
- AE that occur during a stress drop at high T are long and at low frequency.

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Conclusions

Duration of a Stress Drop Event

- the formation of a shear band correspond to a stress drop,
- a shear band accumulates damage in it and close to it,
- Ithis damage produces high frequency acoustic signal,

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Conclusions

Duration of a Stress Drop Event

- the formation of a shear band correspond to a stress drop,
- a shear band accumulates damage in it and close to it,
- this damage produces high frequency acoustic signal,
- we can estimate the duration of an event by measuring the duration of the HF activity within the large AE signal.

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Processing



Figure: Low Frequency AE processing.

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Scaling Laws



- There may be a correlation between the "rupture" duration and the amplitude of the signal...
- but nothing with the stress drop amplitude (∝ mechanical magnitude).

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Scaling Laws



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Compaction and Fluid Volume Change



Hydrostatic tests, drained at $P_{\text{fluid}} = 5 \text{ MPa.}$

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Reaction Progress



Reaction rate calculated from pore volumometry and compaction.

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Dramatic Decrease

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Decrease of both V_p and V_s . Increase post-reaction due to time dependent compaction at elevated P_c .

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Poisso	on's Ratio			



Poisson's ratio actually *decrease* $! \rightarrow$ gypsum is remplaced by a stiffer phase (bassanite).

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Differential, Self-Consistent Effective Medium:

$$\begin{cases} \frac{1}{K} \frac{dK}{d\Phi} &= -(1-\zeta) P_{\alpha}(\nu,\zeta), \\ \frac{1}{G} \frac{dG}{d\Phi} &= -Q_{\alpha}(\nu,\zeta), \end{cases}$$
(1)

where

Interpretation

$$\zeta = \frac{K_f}{K}.$$
 (2)

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 \rightarrow Calculation of V_p , V_s as functions of porosity and pore aspect ratios (α). P_{α} , Q_{α} are complex functions of parameters.

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Inversion Results



Fit with rather opened cracks, $\alpha \leq 0.1$.

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Full Waveforms



Large number of AEs during the dehydration, nothing before, nothing after.

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Locations

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NB: Most AEs have implosive focal mechanisms

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- Gypsum has an interesting semi-brittle behaviour: suitable for the B/D transition study in the lab.
- There are large AEs associated with a plasticity induced phenomenon (shear banding and kinks).
- Dehydration is characterized by an important compaction and strong velocity decreases.

- Poisson's ratio tends to *decrease* during dehydration.
- AE are associated with compaction (implosions).

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