Shear enhanced Compaction Band Identification at the laboratory scale

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**Compaction Bands in porous sandstones:**

- narrow, roughly planar zones of localised porosity loss
- reduced permeability
- barriers to fluid flow – sealing potential

**heterogeneity** of the rock
(re-arrangement of grains, grain breakage, pore collapse, grain crushing)

**Introduction**

- presence in subsurface formations would affect
- applications involving fluid injection or withdrawal
- CO$_2$ storage
- hydrocarbon production

**Important to understand the conditions for their formation & propagation**

**Challenge:**

Use *advanced experimental non-destructive* techniques to investigate how sandstones deform under triaxial compression.
Vosges Sandstone

- mineralogy: 93% quartz, 5% microcline, 1% kaolinite, 1% micas + oxides
- mean grain ~ 300 μm
- average porosity of 22%

[Bésuelle, 1999; 2000; 2001]

- sub-angular to sub-rounded grains
- moderately sorted

Very high resolution x-ray image of the laboratory undeformed sandstone (~6μm voxel size)
**Introduction**

Material

Methods

Results

Conclusions

9th Euroconference on Rock Physics and Geomechanics
Trondheim, Norway, 17-21 October, 2011

Shear enhanced compaction bands at the laboratory scale

**Triaxial compression**

Cylindrical specimens with two flatten surfaces with & without a circumferential notch

MTS Loading Frame (4600 kN)

Confining Pressure Chamber (400 MPa)

AE system

Dry specimens

Confining pressure range: 130 MPa - 190 MPa
Advantages

- usually, non-destructive (see thin sections …)
- different sensitivities to different physical properties

⇒ characterise different aspects of the mechanical processes

Full-field measurements being used in the study of localised deformation in sandstones

**point-wise measurements** at the boundary do not illuminate precisely the mechanics of the system

**full-field → field record quantities**

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Procedure

14 P- and 4S- sensors (glued)

Syn-deformation AEs

Pre-mortem x-ray scans

Post-mortem x-ray scans

Low resolution (~90 µm)
140 x 140 pixels

High resolution (~30 µm)
140 x 140 pixels

3SR

3D-DIC

3SR

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Ve7 specimen [190 MPa confining pressure]

**AE hypocenter locations**

**Damage [in situ]**

**Brittle activity:**
- grain contacts breakage & possibly grain fragmentation

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2mm accuracy of the method

Info on:

✓ number & 3D "network" of the CBs
✓ width of the CBs
✓ orientation of the CBs
Ve7 specimen  [190 MPa confining pressure]

AE hypocenter locations

Info on:

- number & 3D `network` of the CBs
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2mm accuracy of the method
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Ve7 specimen [190 MPa confining pressure]

X-ray CT → Low standard deviation → (reduction in grain size via grain crushing to below the voxel size → homogenisation of the image) → grain breakage, compaction

Raw data
Density variation

Standard deviator of the x-ray grey-scale

Threshold: 0 - 2.6%

Calculations through the image volume, over sub-volumes of 300x300x300 μm³ @ a spacing of 150 μm in each direction
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Ve7 specimen [190 MPa confining pressure]

X-ray CT \(\rightarrow\) density variations

standard deviator

Low standard deviation \(\rightarrow\) grain breakage, compaction

Threshold: 0 - 2.6%

Calculations through the image volume, over sub-volumes of 300x300x300 \(\mu m^3\) @ a spacing of 150 \(\mu m\) in each direction
Ve7 specimen  [190 MPa confining pressure]

**DIC**
Calculations through the image volume, over sub-volumes of 600x600x600 µm³ at a spacing of 600 µm in each direction

**Volumetric strain**

\[ \varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \]

**Shear strains**

\[ \varepsilon_s = \sqrt{\left(\frac{\varepsilon_1 - \varepsilon_2}{2}\right)^2 + \left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right)^2 + \left(\frac{\varepsilon_2 - \varepsilon_3}{2}\right)^2} \]
Ve7 specimen  [190 MPa confining pressure]

**Results**

strains close and far from the notch

single slices $\rightarrow$

*for further details*

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**Standard deviation (x-ray CT) & DIC**

<table>
<thead>
<tr>
<th>Slice</th>
<th>Distance (mm)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>13.136</td>
<td>0.022</td>
</tr>
<tr>
<td>b</td>
<td>23.148</td>
<td>0.027</td>
</tr>
<tr>
<td>c</td>
<td>29.372</td>
<td>0.037</td>
</tr>
<tr>
<td>d</td>
<td>33.505</td>
<td>0.024</td>
</tr>
<tr>
<td>e</td>
<td>190 MPa</td>
<td>0.038</td>
</tr>
<tr>
<td>f</td>
<td>33.505</td>
<td>0.002</td>
</tr>
<tr>
<td>g</td>
<td>29.372</td>
<td>0.019</td>
</tr>
<tr>
<td>h</td>
<td>23.148</td>
<td>0.003</td>
</tr>
<tr>
<td>i</td>
<td>13.136</td>
<td>0.004</td>
</tr>
<tr>
<td>j</td>
<td>33.505</td>
<td>0.002</td>
</tr>
<tr>
<td>k</td>
<td>29.372</td>
<td>0.003</td>
</tr>
<tr>
<td>l</td>
<td>23.148</td>
<td>0.001</td>
</tr>
</tbody>
</table>

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Summary of the mechanical results

<table>
<thead>
<tr>
<th>name of specimen</th>
<th>notches</th>
<th>confining pressure (MPa)</th>
<th>deformation bands</th>
<th>measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ve2</td>
<td></td>
<td>130</td>
<td>CB</td>
<td>UT</td>
</tr>
<tr>
<td>Ve3</td>
<td></td>
<td>130</td>
<td>CB</td>
<td>AEs</td>
</tr>
<tr>
<td>Ve4</td>
<td></td>
<td>160</td>
<td>CB</td>
<td>x-ray CT</td>
</tr>
<tr>
<td>Ve5</td>
<td></td>
<td>160</td>
<td>CB</td>
<td>3D DIC</td>
</tr>
<tr>
<td>Ve6</td>
<td></td>
<td>190</td>
<td>CB</td>
<td>thin sections</td>
</tr>
</tbody>
</table>

Map yield surface caps with negative slopes in the p-q plane

Vosges sandstone (onset of localization)
### Summary of strain measurements

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Min volumetric strains inside the band [%]</th>
<th>Max volumetric strains inside the band [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ve4</td>
<td>0.26</td>
<td>0.87</td>
</tr>
<tr>
<td>Ve6</td>
<td>0.87</td>
<td>1.86</td>
</tr>
<tr>
<td>Ve5</td>
<td>0.91</td>
<td>1.89</td>
</tr>
<tr>
<td>Ve7</td>
<td>0.82</td>
<td>1.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Min shear strains inside the bands [%]</th>
<th>Max shear strains inside the bands</th>
<th>Indicative shear strains outside the bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ve4</td>
<td>0.6</td>
<td>0.9, 1.2 (notch)</td>
<td>~0.3</td>
</tr>
<tr>
<td>Ve6</td>
<td>0.8</td>
<td>1.9 (notch)</td>
<td>~0.5</td>
</tr>
<tr>
<td>Ve7</td>
<td>0.8</td>
<td>1.5, 2.1 (notch)</td>
<td>~0.4-0.6</td>
</tr>
</tbody>
</table>

Increasing axial strain \(\rightarrow\) increase in strain field values (DIC)

Max shear strain @ the notch; lower shear strain inside the band
Summary of dipping angles

- Increasing confining pressure → decrease in dipping angles
- Higher strain → smaller dipping angles (e.g. Ve6)
- Absence of notch → smaller range of dipping angles (e.g. Ve5, Ve1)
- **Shear enhanced compaction bands** → high compactant volumetric strains together with shear strains
- Absence of pure compaction bands
- Onset at the notch (stress concentration) → propagation inwards
- AE concentration (*breakage of grain cements and grains*)
- Low standard deviation values (*reduction in grain size via grain crushing*) to below the voxel size and thus homogenisation of the image
- Compactant volumetric strain (*porosity reduction*)
- Shear strain (*grain rearrangement and sliding*)

Thank you for your attention!