Formation and Extension of Localized Compaction in Porous Sandstone

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Outline

• What are compaction bands?
• Why are they important?
• What do they look like?
• Why do they form?
• Models for propagation
What are compaction bands?

- **Shear band (fault)**
  - Angle: 55 – 65°

- **Shear-enhanced compaction band**
  - Angle: 10 – 20°

- **Compaction band**
Why are compaction bands important?
From Vajdova, Baud and Wong, JGR, 2004
Permeability evolution during localized deformation in Bentheim Sandstone

In situ permeability measurements inside compaction bands using X-ray CT and lattice Boltzmann calculations


**Figure 2.** (a) Horizontal CT slice from specimen n°2. (b) Horizontal CT slice from specimen n°1.

600 microns
Shortest Flow Path Inside and Outside Compaction Bands

INSIDE CB
\( \phi = 0.14 \)

\[ \tau = 2.79 \]
K = 3.4e-13 m²

\[ \tau = 2.15 \]
K = 5.3e-13 m²

\[ \tau = 2.56 \]
K = 4.4e-13 m²

OUTSIDE CB
\( \phi = 0.21 \)

\[ \tau = 1.77 \]
K = 1.3e-12 m²

\[ \tau = 1.76 \]
K = 1.2e-12 m²

\[ \tau = 1.81 \]
K = 1.3e-12 m²
Uniform compaction

Localized compaction
What do compaction bands look like in the field?
Figure 1. Location of the Valley of Fire State Park, southeastern Nevada (inset), where more than 20 square kilometers of the 1,400-m-thick eolian Jurassic Aztec Sandstone are extensively exposed. Photo shows view northward from the location marked * on the park detail. Throughout the upper half of the Aztec, compaction bands crop out in positive relief as sub-parallel, centimeter-thick, north-northwest-trending, steeply east-dipping tabular fins spaced from centimeters to meters apart.

Figure 3. Close-up of a typical, well-developed compaction band fin in outcrop. Note that depositional bedding extends relatively undisturbed across the band, and is clearly visible on the fin.
Figure 2. Left-hand photo shows an outcrop of widely spaced, relatively planar and parallel compaction bands along the northeast flank of Silica Dome. Arrows indicate opposite tips of a single band 62 m long and up to 15 mm thick (illusory gaps in band continuity are due to outcrop topography and breaks in the telltale fin). A total of 16 tip-to-tip thickness profiles were measured using a steel tape and calipers. Right-hand photo illustrates that, even when closely spaced, compaction bands in this locale tend to remain planar (arrow indicates tip).

From Sternlof, Rudnicki and Pollard, JGR, 2005
Figure 5. Photomicrograph of compaction band sampled 6.0 meters from the tip, where it is about 9 mm thick (dotted black lines). Blue indicates epoxy-filled pore space (~25% outside the band, ~10%
Fig. 4. Pure (PCB) and shear-enhanced (SCB) compaction bands exposed on a bedding plane. a. Pure compaction bands with characteristic wavy trace. Pocket knife for b. Chevron pattern of alternating right- and left-lateral shear-enhanced compaction bands. Chevron-style bands merge with and continue as planar shear-enhanced compaction bands. c. Intersection of sets of shear-enhanced compaction bands. d. Chevron-type compaction bands with out-of-phase alignment of crests and troughs.
Cathodoluminescence image of Compactive Shear Band with 2.5 cm reverse slip

Eichhubl, Hooker, Laubach, J. Struc. Geology, 2010

Outer zone of fractured grains

Inner zone of higher grain-size reduction and shear strain

Detail of

Shear band with 1 cm slip

Macroscopic band is composed of multiple parallel bands of more intense grain-size reduction
Fossen, Schultz & Torabi
J. Structural Geology
Volume 33, Issue 10,
October 2011, 1477-1490
shear enhanced compaction bands

Fossen, Schultz & Torabi
J. Structural Geology
in press

shear enhanced compaction bands; note offset at intersection

pure compaction bands

thin section, pure compaction band

slipped compactional shear band offset equal a few cm

pressure solution
What do compaction bands look like in the laboratory?
Bentheim sandstone: $P_c = 300$ MPa

$\varepsilon_{ax} = 1.4\%$

$\varepsilon_{ax} = 3.1\%$

$\varepsilon_{ax} = 4\%$

$\varepsilon_{ax} = 6\%$

Baud, Klein, and Wong, Compaction localization in porous sandstones:..., JSG, 2004; GRL, 2001
A compaction band in the Bentheim sandstone: typically the lateral width extends over 2 grains or so (~ 600 µm)

Baud, Klein and Wong, Compaction localization in porous sandstones: spatial evolution of damage and acoustic emission activity, J. Struct. Geology, 2004

Why do compaction bands form?
Homogeneous and homogeneous deformation

Continued Homogeneous deformation

Shear band or compaction band

Rudnicki and Rice, JMPS, 1975
Ingredients

1. Kinematic Condition

\[ d\mathbf{u}^\text{band} = \varepsilon d\mathbf{u}^0 + g(\mathbf{a}, \mathbf{x}) = n\mathbf{g} \quad \mathbf{g}_n = d^0 + \frac{1}{2}(\varepsilon + \varepsilon) \]

2. Equilibrium condition

\[ n\sigma d^\text{band} = \sigma d^0 \]

3. Material (constitutive) relation

\[ d\sigma = \mathbf{L} d\varepsilon \]
Elastic-plastic rate-independent constitutive model depending on first and second invariants (Drucker – Prager type).

\[ d\varepsilon^p = \beta d\bar{\gamma}^p > 0 \text{ (dilation)} \]

\[
\begin{align*}
\tau & = \frac{(\sigma_a - \sigma_c)}{\sqrt{3}} \\
\text{for standard test}
\end{align*}
\]

\[
\sigma \text{ (compression)}
\]

\[
\frac{1}{k} \leq k_{\text{crit}} \text{ for localization}
\]

\[
(\sigma_a + 2\sigma_c) / 3 \\
\text{for standard test}
\]
Axisymmetric Compression

Dilation Band

Compaction Band

\[ \theta_{\text{crit}} = \text{angle between fault normal and most compressive principal stress.} \]
\[ \tan \psi = \frac{\Delta \varepsilon^{in}}{\Delta \gamma^{in}} \]

Range of angles for shear – enhanced compaction bands by Eichhubl et al. (2010)

\[ \beta = \mu, \beta - \mu = -1, \beta - \mu = -2, \beta - \mu = +1, \beta - \mu = +2 \]

37 degrees \hspace{1cm} 53 degrees

\[ \tan \psi = \frac{\Delta \varepsilon^{in}}{\Delta \gamma^{in}} \]

\[ \tan \psi = \frac{\Delta \varepsilon^{in}}{\Delta \gamma^{in}} \]

\[ \beta < 0 < \mu \]

Bésuelle and Rudnicki, Localization: Shear Bands and Compaction Bands, in Mechanics of Fluid Saturated Rocks, ed. Guéguen and Boutéca
compaction bands
no shear

No volume change

Range of $\beta$ and $\mu$ from data of Baud, Vajdova and Wong (JGR, 2006) for Adamswiller, Bentheim, Berea and Darley Dale sandstones. Typically $\mu > 0$ and $\beta < 0$ and small.

$\beta = \mu$

$\psi = -90, \theta = 0$

Evaluate for an Elliptic Yield Cap

Rudnicki, JGR, 2004

More elaborate yield surface model:
Grueschow and Rudnicki, Int. J. Solids Struc., 2005
COMPACTIVE YIELD STRESSES OF 4 SANDSTONES:
The critical stress levels $C^*$ at the onset of shear-enhanced compaction were fitted with elliptical caps (yield envelopes)
Baud, Vajdova and Wong, Shear-enhanced compaction and strain localization: Inelastic deformation and constitutive modeling of four porous sandstones, J. Geophys. Res., 2006

Lines are predictions of Dimaggio Sandler cap model
\[
\frac{(\sigma - c)^2}{a^2} + \frac{\tau^2}{b^2} = 1
\]

\(\epsilon = (a/b)^2 = 1.53 \text{ to } 3.0\)

from Wong, David & Zhu (JGR, 1997)

\(\epsilon = 1.268\) for Bentheim Sandstone

from Klein et al. (Phys. Chem. Earth A, 2001)
Elliptical cap
surface

Shear bands

compaction bands

$\sigma$

$\tau$

increasing $k_{crit}$

$k_{crit} = 0$
(for normality)

increasing confining stress

increasing $k_{crit}$
\[ \frac{k_{\text{crit}}}{G} \]

\[ \epsilon = 1.5, \delta = 1.0 \]

\[ S = \frac{(\sigma_c - c)}{a} \]
Tembe, Baud and Wong, JGR, 2008

Development of an array of discrete compaction bands

Mixed failure modes

Shear bands

Shear bands

Development of an array of discrete compaction bands

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>ε\text{ax}</th>
<th>Image</th>
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</thead>
<tbody>
<tr>
<td>a. 10 MPa</td>
<td>2.3%</td>
<td>D19</td>
</tr>
<tr>
<td>b. 30 MPa</td>
<td>3.7%</td>
<td>D15</td>
</tr>
<tr>
<td>c. 40 MPa</td>
<td>3.9%</td>
<td>D10</td>
</tr>
<tr>
<td>d. 60 MPa</td>
<td>3.4%</td>
<td>D5</td>
</tr>
<tr>
<td>e. 150 MPa</td>
<td>1.6%</td>
<td>D14</td>
</tr>
<tr>
<td>f. 150 MPa</td>
<td>2.1%</td>
<td>D13</td>
</tr>
<tr>
<td>g. 150 MPa</td>
<td>4%</td>
<td>D7</td>
</tr>
</tbody>
</table>

**Figure 3.** Transmission optical micrographs of deformed wet Diemelstadt sandstone samples. The effective pressure and the level of axial strain are indicated next to the thin sections. The width of each thin section is ~18 mm. Principal stress σ\text{1} was along the axial direction. Brittle failure in the Diemelstadt sandstone occurs at effective pressures of 10–60 MPa as (a) dilatant conjugate shear-bands, (b) compactant conjugate shear-bands, (c) diffuse conjugate shear-bands, and (d) mixed failure modes of high-angle shear-bands and compaction bands. At higher pressure (>60 MPa), discrete compaction bands are the dominant failure mode. The development of an array of discrete compaction bands at 150 MPa effective pressure can be traced with increasing axial strain: (e) 1.6%, (f) 2.1%, and (g) 4%. The black arrow in Figure 3g points to a layer of oxides separating coarser material below from finer material above. (h) Mosaic showing a discrete compaction band propagating across the sample in the area delimited by a rectangle in sample D13 (f). Significant comminution makes the band appear dark.
Open circles, peak stress at brittle failure
Solid circles, onset of shear – enhanced compaction

Fig. 15. Peak stresses and yield stresses at the onset of shear-enhanced compaction for Darley Dale (a), Berea (b), Rothbach (c) and Bentheim sandstones (d).
How do the bands propagate (extend)?
Energy Release Due to Compaction Band Propagation
Rudnicki and Sternlof, GRL, 2005 (after J. R. Rice, 1968)

strain energy $W^*$

\[ \frac{\Delta}{2} \]

\[ \frac{\Delta}{2} \]

strain energy $= W^*$

energy release rate $G = W_+ - W_-$

\[ = \frac{1}{2} \frac{Mh}{(M/M_b)\xi + (1-\xi)} \left\{ \left( \frac{\Delta}{h} \right)^2 \xi \left( \frac{M}{M_b} - 1 \right) + 2\xi \xi^p \left( \frac{\Delta}{h} \right) - \left( \xi \xi^p \right)^2 \right\} \]
energy release rate \( G = \underbrace{h\xi \varepsilon^p}_{\text{net compaction}} + \underbrace{M(\Delta / h)}_{\text{stress=\sigma^+}} + O(\xi^2) \)

From Sternlof and Rudnicki, GRL, 2005:

\( \sigma^+ = 40 \text{ MPa} \)

\( h\xi = 0.01 \) (1 cm thick CB, spaced 1 meter apart)

\( \varepsilon^p = 0.1 \) (corresponding to 10% porosity reduction)

\( \Rightarrow G = 40 \text{ kJ/m}^2 \) (10 to 60 kJ/m\(^2\) for range of stress estimates)

Tembe et al., JGR, 2006 estimate “compaction energies” (equivalent to energy release rate) of 16 – 43 kJ/m\(^2\) for Berea and Bentheim sandstones.
Figure 1: Compaction Band Data

Linear fit: \( y = A + Bx \)

\( A = 0.43240, \quad B = 0.49891 \)

after Tembe, PhD Thesis, SUNY, Stony Brooke
Ellipsoidal band with uniform inelastic compactive strain $\varepsilon^p$

compactive displacement $= \frac{w \varepsilon^p}{1 - \varepsilon^p} \approx w \varepsilon^p$

$2w = \text{band width}$

compressive stress ahead of the band is elevated sufficiently to cause compaction

For aspect ratios typical of the field, $10^{-3}$ to $10^{-4}$, initial thickness can be neglected entirely

“anti-crack” model
Fletcher and Pollard Geology, 1981
Combined “anti-crack” and “anti-dislocation” model

uniform compactive displacement, $2w$

uniform resistive normal traction

$a$ $a$

$L$ $L$
\[
K = \frac{\mu w}{(1-\nu)} \sqrt{\pi} \left[ \frac{k \sqrt{L-a}}{E(k) - (1-k^2)K(k)} \right]
\]

where \( k^2 = 1 - (a/L)^2 \)

\[
G_{\text{crit}} = \frac{(1-\nu)}{2\mu} K_{\text{crit}} \Rightarrow K_{\text{crit}} = \sqrt{\frac{2\mu G_{\text{crit}}}{(1-\nu)}}
\]

\[
\therefore 2w = \sqrt{L} \sqrt{\frac{8(1-\nu)G_{\text{crit}}}{\pi \mu}} \left( F(k) \right)_{\approx 1}, \quad L \gg a
\]

For \( \nu=0.2, \mu = 8.333 \text{ GPa}, \quad G_{\text{crit}} = 40 \text{ kJ/m}^2 \)

\[
\Rightarrow \frac{G_{\text{crit}}}{\mu} = 4.8 \times 10^{-3} \text{ mm}
\]

\( \text{(Sternlof, Rudnicki & Pollard, 2005)} \)

\[
\Rightarrow \frac{2w}{\sqrt{L}} = 0.003127 \text{ m}^{1/2}
\]
Linear Fit: $y = A + Bx$

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
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</thead>
<tbody>
<tr>
<td>All Data</td>
<td>0.48021</td>
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<tr>
<td>Field Data</td>
<td>0.43240</td>
<td>0.49891</td>
</tr>
<tr>
<td>Sternlof (2006)</td>
<td>0.39549</td>
<td>0.52629</td>
</tr>
<tr>
<td>Model</td>
<td>0.49514</td>
<td>0.5</td>
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Conclusions

• Compaction bands are predicted to occur on portions of the cap surface where they are (roughly) observed to occur.
• Predictions are roughly consistent with lab data but do not agree very well quantitatively.
• Need for better constitutive data and modeling and a better understanding of the micromechanical factors affecting macroscopic response.
• More complex load paths (now being used) should be more useful for constraining constitutive models.
Conclusions

• A simple fracture and dislocation model indicates a (surprising) consistency between lab and field data.
• Model is, however, speculative since little information is available on the initiation and propagation of bands in the field.
• Field and laboratory observations of the breakdown process near the tip of bands would be helpful in constructing more elaborate models.
Questions

• How do lab, field and theoretical results fit together?
• What properties (or factors) other than porosity affect compaction band formation?
• What is a good physical microstructural model?
• How do microscale properties and lithology translate to macroscopic material (constitutive) behavior?
• What controls band thickness (and changes in thickness), spacing and deviations from planarity?
• If bands formed under saturated conditions how does interaction of fluid flow with deformation affect formation and extension?
• How do we model the transition from initial band formation to extension of a fully formed band?
Thanks!

Questions for me?