PS X-Ray Imaging for Compaction Band Characterisation in Porous Sandstones*

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Abstract

Compaction bands in porous sandstones are planar zones of finite thickness that form almost normal to the direction of maximum compression. Grain-scale mechanisms indicate porosity reduction by grain crushing and movement of fragments into pores, along with grain movements. Such bands can have important impacts on fluid flow in sandstone reservoirs. We investigate by experiments the grain-scale processes occurring during compaction band formation in two porous (~22%) sandstones with similar grain-sizes (~300µm). Vosges sandstone is 93% quartz, 5% microcline, 1% kaolinite and 1% micas; it is moderately sorted with sub-angular to rounded shapes, and cement occurs mostly as quartz overgrowths. The texture of Vosges is more heterogeneous than the Bentheim, which has rounded grains, and is composed of 95% quartz, 3% feldspar and 2% kaolinite. Cylindrical samples of 40mm/80mm (diameter/length) for Vosges, and 50mm/100 mm for Bentheim, were loaded under triaxial compression with confining pressure of 130–190 MPa. All specimens had a circumferential notch at their mid-length to force localization. X-ray CT was obtained before and after the experiments, defining the changes caused by deformation. The standard deviation of the grey-scale values in Vosges is smaller than that in Bentheim (undeformed), which implies a more homogeneous density for the former due to cementation. Compaction bands created in both sandstones are identified as zones of low standard deviation values, due to compacted material and associated local porosity reduction. In the Bentheim raw X-ray images, compaction bands are also visible as higher-density regions. In both sandstones, compaction bands have curved or irregular shapes rather than the planar ones expected, and have orientations as low as 66° to the shortening. Acoustic emission data shows that the deformation mechanisms involve shear motions as well as volume loss. Local strains calculated with Digital Image Correlation confirm the AE interpretations, revealing both volumetric and shear strains that vary within and near the bands. Pore networks extracted from the 5µm resolution X-ray images of the localized zones allow us to calculate the flow properties of compaction bands and matrix in both sandstones. Permeability reduction is significant (~3 orders), and calculated relative permeability provides insights into the multi-phase flow effects of such bands.

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Background & Perspectives

Compaction bands in porous sandstones

[*Holcomb et al.*, 2007]

- tabular zones of localised deformation
- normal or subnormal to max shortening direction
- grain crushing and pore collapse

Challenge

- to study compaction bands at the laboratory scale using a combination of advanced non-destructive experimental methods

Focus herein

- x-ray imaging (density variations)

Study material

Vosges sandstone

[*Bésuelle*, 2001; *Charalampidou*, 2011]

- ~22% porosity
- 93% quartz, 5% feldspar, 1% kaolinite, 1% mica (+ some oxides)
- ~300 µm mean grain size
- **sub-angular to rounded grains**

Bentheim sandstone

[*Stanchits et al.*, 2009]

- ~22% porosity
- 95% quartz, 3% feldspar, 2% kaolinite
- ~300 µm mean grain size
- **rounded grains**

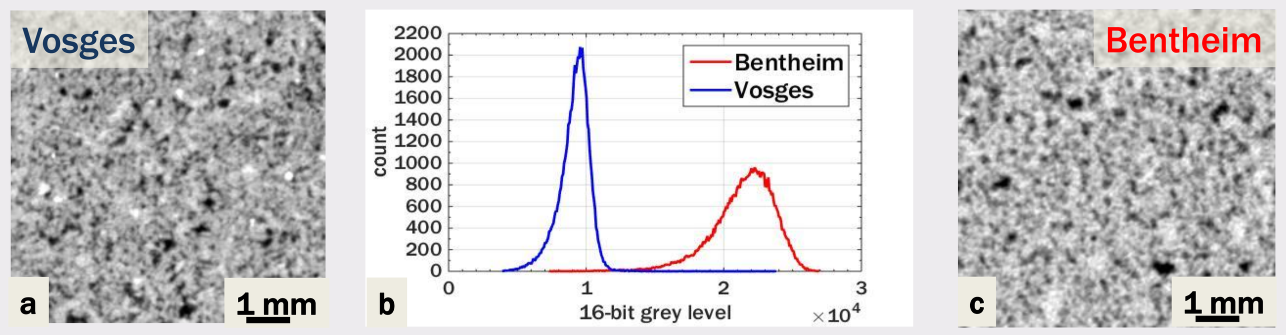

Figure 1: (a) X-ray image of Vosges sandstone (undeformed) with ~30 µm pixel size; (b) histograms of grey level for Vosges and Bentheim (undeformed); (c) x-ray image of Bentheim sandstone (undeformed) with ~30 µm pixel size.

✓ Vosges (although containing an amount of oxides, i.e. higher density material) shows lower density compared to Bentheim. This is attributed to different scanning conditions (x-ray energy in kV and x-ray intensity in µA) that were adopted to reach the optimum rock visualisation.

✓ The calculated weighted standard deviation value of the grey level for Vosges is smaller to that of Bentheim, which implies that the former has more homogeneous density than the latter.

Experiments

✓ Axisymmetric triaxial compression experiments performed under confining pressures ranging from 130 MPa to 190 MPa. Compaction bands developed in all samples.

✓ Multi-scale techniques, full-field methods, non-destructive and destructive → different sensitivity and resolution. Measurements took place before, during and after laboratory deformation.

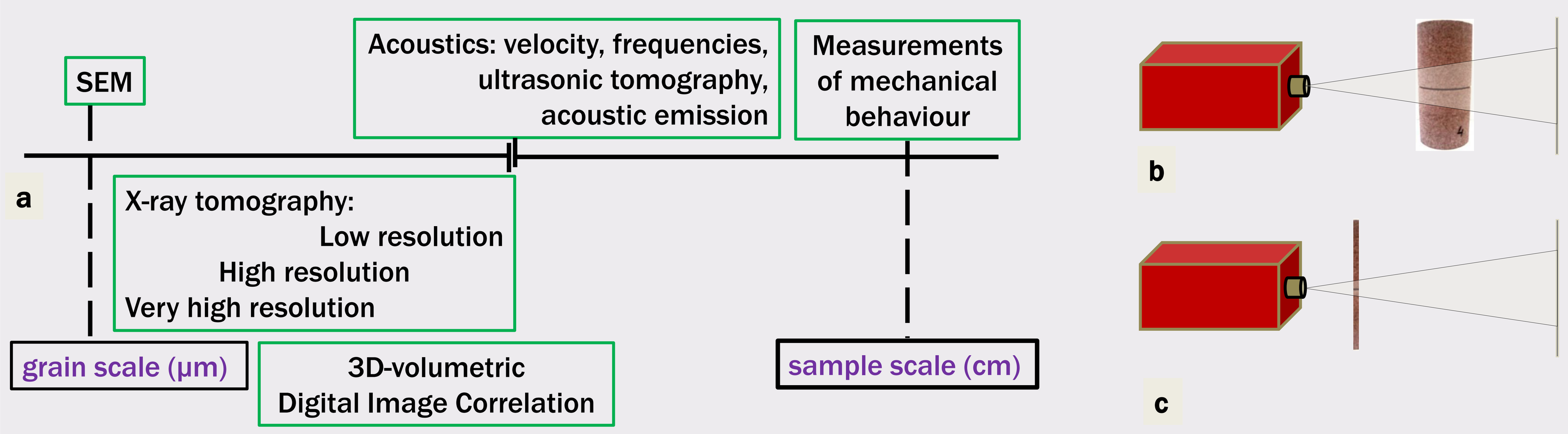

Figure 2: (a) Schematic representation of the multi-scale approach resolution; (b) high resolution (~30 µm voxel size) x-ray tomography of undeformed/deformed samples; (c) very high resolution (~5 µm voxel size) x-ray tomography of undeformed/deformed samples.

Visualisation of compaction bands

Bentheim sandstone

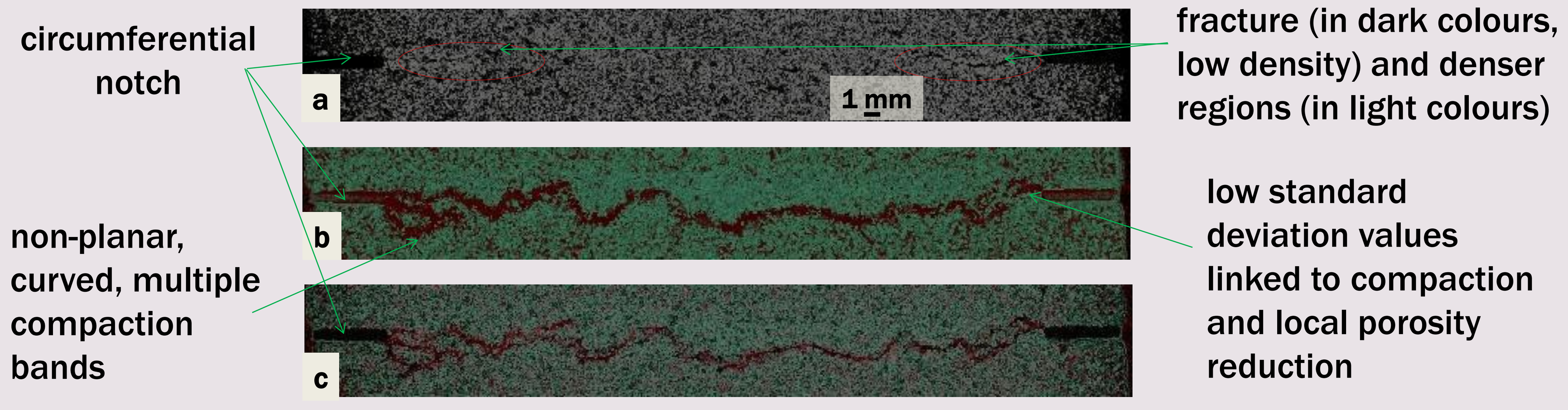

Figure 3: Compaction bands in Bentheim (sample deformed under 185 MPa). Images zooming in the mid-height of the sample: (a) raw data ~30 µm pixel size; (b) local standard deviation; (c) raw data and local standard deviation superimposed.

Vosges sandstone

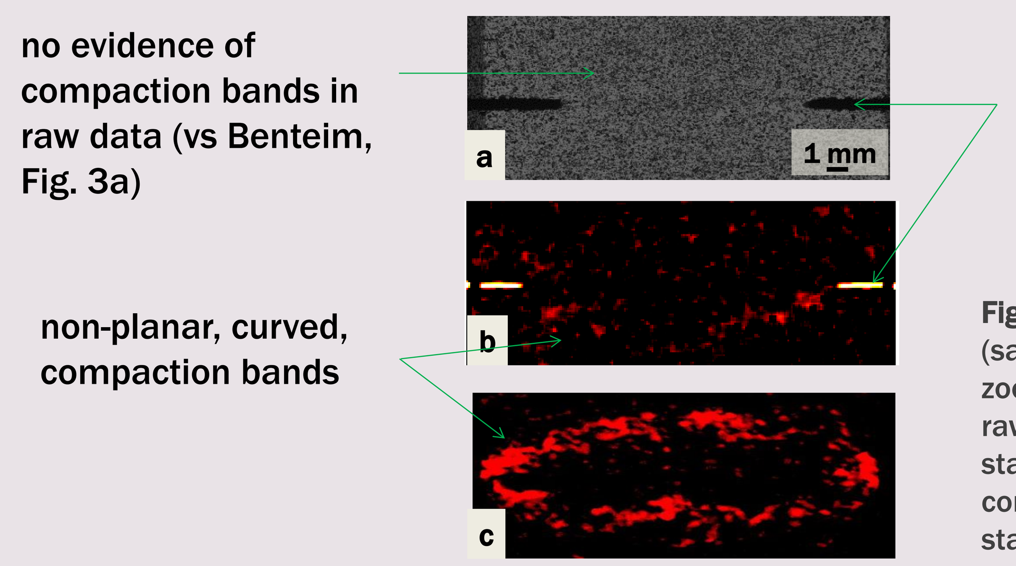

Figure 4: Compaction bands in Vosges (sample deformed under 130 MPa). Images zooming in the mid-height of the sample: (a) raw data with ~30 µm pixel size; (b) local standard deviation; (c) 3D structure of the compaction band derived from the low standard deviation volume.

✓ Acoustic Emissions (AE) show that compaction band deformation mechanisms involve principally volume loss (expressed via collapse type AE events) and shear motion (expressed via shear type AE events) [*Charalampidou et al.*, 2014].

✓ Local strain calculations (3D – volumetric Digital Image Correlation using TomoWarp software, for more details see [*Hall et al.*, 2009]) reveal both volumetric and shear strain that vary within and near the compaction bands [*Charalampidou et al.*, 2011; 2014]. Volumetric strains inside compaction bands are always compactant with smaller values measured close to the notches [*Charalampidou*, 2011].

✓ Intense grain damage, expressed via grain fracturing and grain crushing, is observed in regions where compaction band developed.

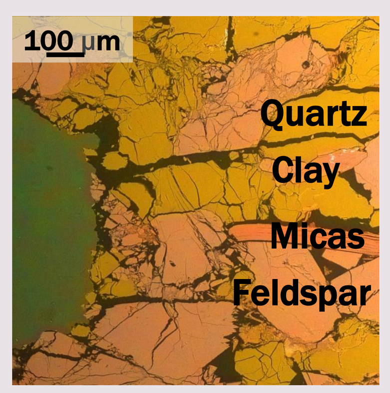

Figure 5: False colour image using the Si, K, Al x-ray scans of the same region. Quartz, Feldspars, Clays and Micas were identified (Vosges sandstone). Shear and compaction resulted in further re-arrangement of grains and fragments and in porosity reduction. The maximum shortening was vertical. This figure is courtesy of Jim Buckman, presented in [*Charalampidou*, 2011].

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Porosity and permeability calculations

Vosges sandstone

Samples of 10 mm in diameter were cored from (lab) deformed Vosges sandstone samples (40 mm in diameter) that developed compaction bands. These small-diameter samples, which contained part of the developed compaction bands, were x-ray scanned (~ 5 µm voxel size) afterwards. Porosity and permeability have been calculated using the x-ray volumes (Fig. 6c) and an in-house software (see [*Jiang et al.*, 2007]).

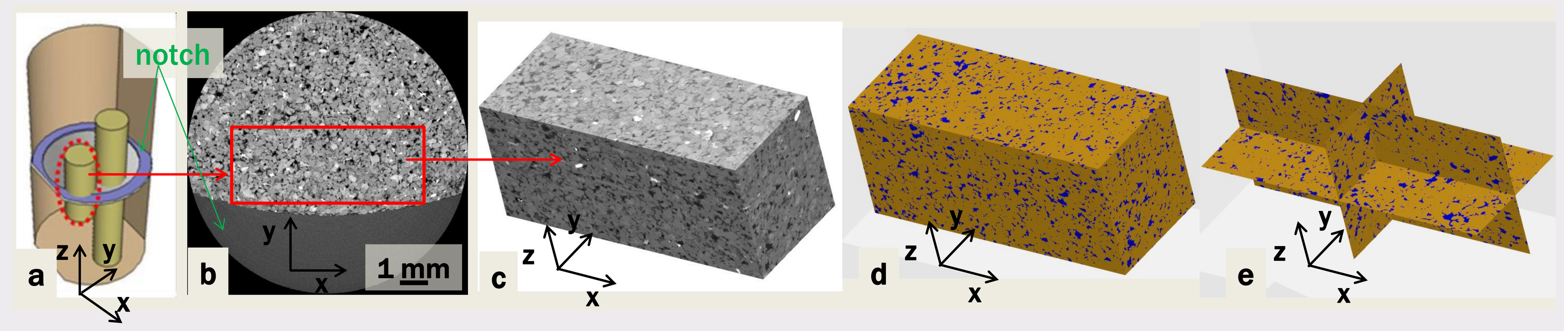

Figure 6: (a) Schematic representation of the position of two small cores coming from a Vosges sandstone sample (deformed under 130 MPa); (b) x-ray slice coming from a height at the notch level (small-diameter sample); (c) x-ray volume from a region close to the notch (highlighted in red in (b)) including part of the compaction band (see grain damage on an equivalent region in Fig. 5) used for the porosity and permeability calculation; (d) binarised volume showing grains (yellow) and pores (blue); (e) 2D perpendicular slices of the binarised volume in x, y-, z- direction.

porosity and permeability

- volume including mainly the **compaction band** (Fig. 6c)
  - 9.5% porosity
  - small (abs.) permeability values
  - permeability along x-direction → 22 mD
  - permeability along y-direction → 26 mD
  - permeability along z-direction → 13 mD

- volume from an **undeformed** sample (Fig. 2c)
  - 21% porosity
  - small (abs.) permeability values
  - permeability along x-direction → 1145 mD
  - permeability along y-direction → 1184 mD
  - permeability along z-direction → 913 mD

✓ These calculations on lab deformed samples show a considerable reduction in both porosity and permeability. Calculations on compaction bands in the field revealed an order of magnitude (approx.) permeability reduction [Sun et al., 2011], which is not far from our calculations.

Conclusions

The compaction bands in this study (experimentally created in porous sandstones) make profound local changes to rock texture, hence properties, with permeability reduction of ~10^{-2} compared to that of the matrix (undeformed rock). These non-planar, curved bands are characterised by grain fracturing and crushing, compactant and shear strains as well as porosity decrease.

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