Anisotropy of Sandstones

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Aims

Sandstone aquifers are considered to be potential reservoirs for the geological sequestration of industrial carbon dioxide. Porosity and permeabilty of the sandstone as well as textural and compositional anisotropy of the grain phase are important boundary conditions during and after injection of the CO_2. Petrophysical laboratory studies of mechanical and seismic bulk properties revealed their strong dependence upon orientation. To correlate those bulk properties with the microstructure, we attempt to locate the anisotropic directions in the reconstruction volume of the X-ray micro-computed tomography scans.

Method

Aliquots of two Lower Cretaceous sandstones (localities: Bad Bentheim and Obernkirchen, both Germany), have been studied in a 3D multianvil pressure apparatus for cubic samples [1]. The samples were subjected to isotropic stresses up to 100 MPa at a temperature of 20 °C to map the basic relationships between seismic behaviour (P wave velocity) and mechanical behaviour (stress-strain relation).

Subsequent to the geomechanical studies oriented 10 mm cores were drilled from the samples and scanned (at ambient pressure) using the SkyScan 1172 device of the experimental and theoretical petrology group at Kiel University with a beam energy of 100 kV, a flux of 100 µA and Al/CU foil with a resolution of 6.76 µm. Three dimensional stereology image analysis and volume rendering were done using the SkyScan software CT-Analyser.

Results

Cretaceous sandstones that have been investigated in a high-pressure triaxial testing facility for cubic samples under controlled loading and unloading stress paths at a temperature of 20 °C and a maximum pressure of 100 MPa showed marked differences of the observed ultrasonic sound (frequency of Signal input 1MHz) velocities in three directions (Fig. 1 A and B). In both samples the lowest velocities (Z) are found in the direction perpendicular to the bedding. Obernkirchen sandstone shows higher velocities in all directions than Bentheim sandstone, with the highest (X) and intermediate (Y) values being almost similar, whereas the fastest (X) and the intermediate (Y) velocities in Bentheim sandstone exhibit a difference.

In microstructural context, the mean intercept length (MIL) analysis is a measuring tool for the isotropy of a structure. Mean intercept length is found by sending a grid of test lines over a large number of 3D angles through a spherical 3D image volume containing binarised objects, and dividing the length of the test line through the analysed volume by the number of times that the line passes through or intercepts part of the solid phase (see *SkyScan-CTanalyser_parameters.pdf* for more detailed information). This method will give an accurate result if analysing a volume containing a sufficiently large number of objects, which might be the case for the VOI of the reconstructed sandstones: the sphere diameter in µm is the 59-fold

(Obernkirchen) and the 38-fold (Bentheim), respectively, of the mean structural thickness of the grain phase. An ellipsoid is fitted to the 3D distribution of MILs measured over the full range of 3D stereo-angles. This ellipsoid has 3 vectors which are orthogonal and describe the longest orientation (E1), and the length (E2) and width (E3) of the ellipse section at right-angles to the longest orientation.

To link the bulk seismic behaviour to microstructural aspects, we performed MIL analysis on cubic VOIs of 6 mm edge length (see Table 1) based on the grain phase as well as on the pore space. The results of the grain phase based MIL analysis are linked unexpectedly with the bulk seismic properties. The direction of the largest MIL in both oriented drill core samples are parallel to the slowest observed seismic P wave velocities in Z (Obernkirchen MIL || E1: 0.5763 mm, Bentheim MIL || E1: 0.5568). The high velocities in Obernkirchen X and Y are oriented parallel to the short MILs || E3 (0.4410 mm) and || E2 (0.4577 mm). The overall slower P wave velocities in Bentheim X (MIL || E3 0.4491 mm) and Y (MIL || E2 0.4711 mm) are at larger values than the Obernkirchen E3 and E2, respectively, whereas the slowest seismic velocity Bentheim Z has a smaller value than Obernkirchen Z.

Table 1. Directions of seismic P wave velocity and MIL analysis results in sandstone.

Sandstone sample locality characteristic P wave velocity	**Mean Intercept Length (mm)** ***grain phase*** **; pore space** based MIL analysis pore space MIL ellipsoid vector
Obernkirchen Z, slowest	***0.5763*** **| 0.0740** E-vector 1, largest
Obernkirchen Y, intermediate	***0.4577*** **| 0.0576** E-vector 2, intermediate
Obernkirchen X, fastest	***0.4410*** **| 0.0554** E-vector 3, shortest
Bad Bentheim Z, slowest	***0.5568*** **| 0.1197** E-vector 1, largest
Bad Bentheim Y, intermediate	***0.4711*** **| 0.1008** E-vector 2, intermediate
Bad Bentheim X, fastest	***0.4491*** **| 0.0959** E-vector 3, shortest

The results of the pore space based MIL analysis correlate well (inversely) with the bulk seismic properties. The direction of the largest MIL in both oriented drill core samples are parallel to the slowest observed seismic P wave velocities in Z (Obernkirchen MIL || E1: 0.0740 mm, Bentheim MIL || E1: 0.1197). All three MILs of the Obernkirchen sandstone (0.0554..0.0740), which has higher velocities in all directions than the Bentheim sample, are smaller than the MILs observed for the latter (0.0959..0.1197). The almost identical high velocities in Obernkirchen X and Y correlate with the small and similar short MILs || E3 (0.0554 mm) and || E2 (0.0576 mm) for Obernkirchen. The overall slower but also more different P wave velocities in Bentheim X and Y are met by the MIL || E3 (0.0959 mm) and MIL || E2 (0.1008) values, which are more diverse and at larger values than the Obernkirchen E3 and E2.

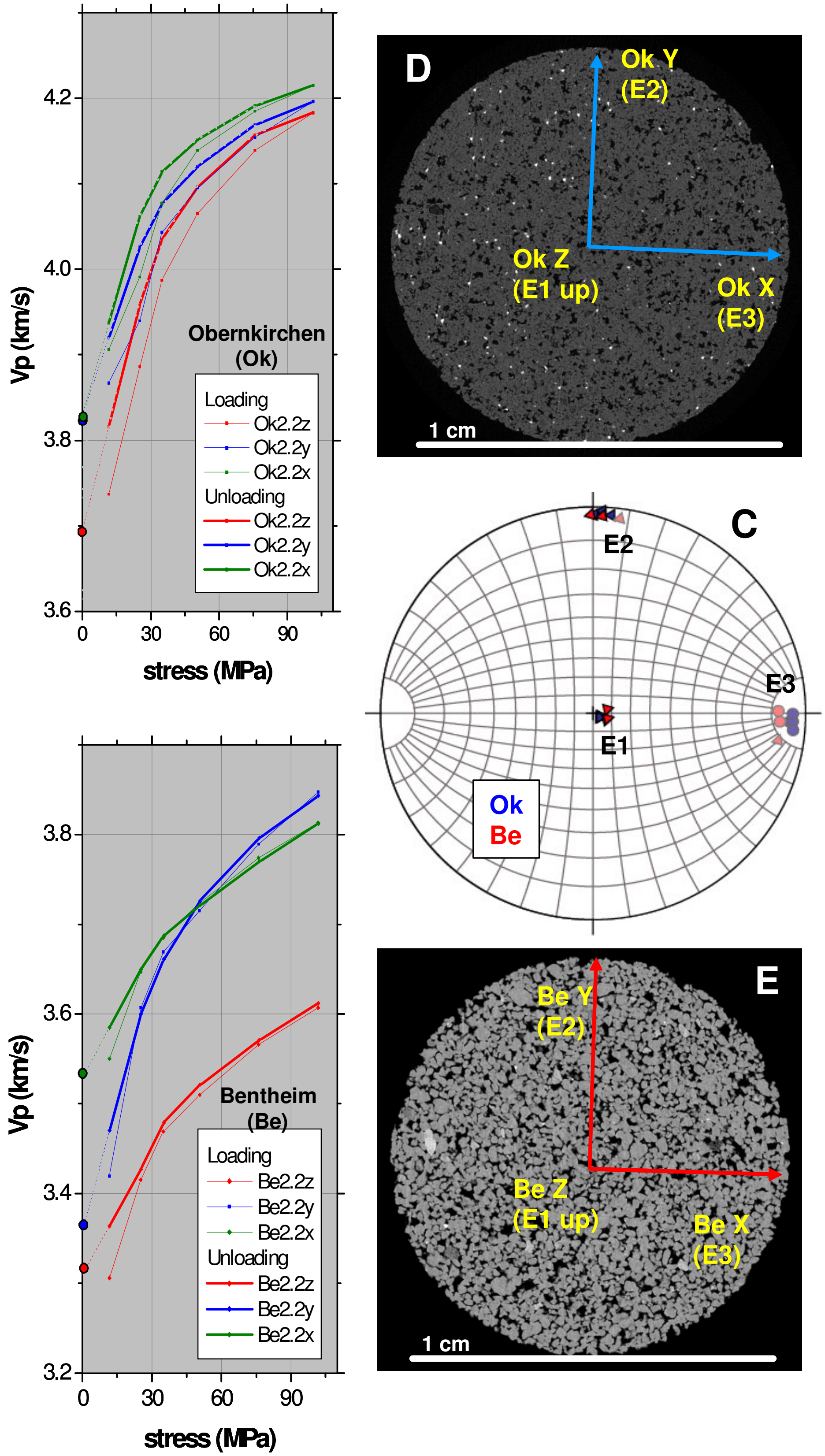

Figure 1: Bulk seismic anisotropy and microstructural anisotropy (directions of stereological MIL analysis) in two Cretaceous sandstones. Anisotropy of P wave

velocities *(A)* in Obernkirchen sandstone and *(B)* in Bad Bentheim sandstone with velocity in Y direction being the fastest and in Z the slowest. *(C)* The Eigen vectors of the pore space MIL ellipsoids plotted in a stereographic projection (using *Stereo32 1.0.1* by K. Röller and C. A. Trepmann). Eigenvector E3 denotes the shortest mean intercept length, E1 the largest. Orientations of the Eigen vectors shown in the reconstruction volume of *(D)* Obernkirchen sandstone and *(E)* Bad Bentheim sandstone. The orientation of the slowest seismic veloctity, the Z axis, in the oriented drill cores is upward, which is the orientation of the direction with the largest pore space MIL.

The directions of the E-vectors of the pore space based MIL analysis that describe the 3D variation of the mean intercept length of the pore space within the VOI are plotted in a stereographic projection (Fig. 1C). The orientation of the main directions of MIL variation is also visualized in two reconstruction images of Obernkirchen and Bentheim sandstone (Fig. 1 D and E). Both images are taken from the level that contained the origin of the spherical 3D volume, which was used for the mean intercept length analysis.

Conclusion

Two oriented cores of sandstone samples that previously have been used in petrophysical laboratory experiments to study ultrasonic sound velocities were investigated using X-ray micro-computed tomography. It was possible to correlate the main orientations as well as the relative amounts of bulk anisotropic sound velocities (frequency of Signal input 1MHz) and mechanical behaviour to the main directions of microstructural anisotropy of the pore space in the reconstruction volumes. On this basis we will start to investigate the effect of the connectivity of the grain frame work on mechanical strength. Furthermore, the linkage between bulk seismic behaviour and the rock microstructure may allow the assessment of seismic tortuosity.

References:

1. Kern, H.; Ivankina, T. I.; Nikitin, A. N.; Lokajíček, T.; Pros, Z. "The effect of oriented microcracks and crystallographic and shape preferred orientation on bulk elastic anisotropy of a foliated biotite gneiss from Outokumpu." - Tectonophysics 457, 143-149 (2008)