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Integrating Acoustic Measurements and Microstructural Analysis to Assess The In-situ State of Stress of Sandstone Reservoirs

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1. Introduction

Geomechanical reservoir modelling is one of the key tools used to predict reservoir deformation in response to exploitation of the subsurface, whether for hydrocarbon or geothermal energy production, or for the injection of CO_2 and waste water. However, to make such predictions, a better understanding of the reservoir state of stress is necessary. Pressure leak-off tests and wellbore break-outs are generally used to assess the in-situ state of stress of a reservoir. These methods require the creation of fractures near the wellbore, which may cause damage to the wellbore and potentially cause drilling problems.
We are investigation the potential to use core material to assess the in-situ stress state by performing true triaxial experiments on reservoir rock, coupled to measuring P- and S-wave velocities and microstructural analysis.

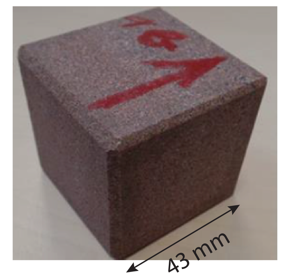
2. Methodology

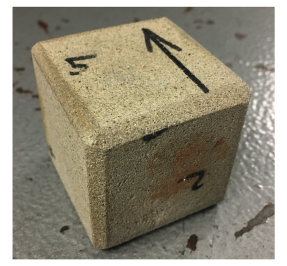
True triaxial experiments + P- and S-wave velocity measurements at room T, under dry conditions:
1. Induce damage in the sample, simulating 'core damage' ($\sigma_2 = \sigma_3$ = 15 MPa)
2. Reload the sample hydrostatically and pinpoint the state of stress imposed during step 1, using wave velocities
3. Analysis of crack development during deformation

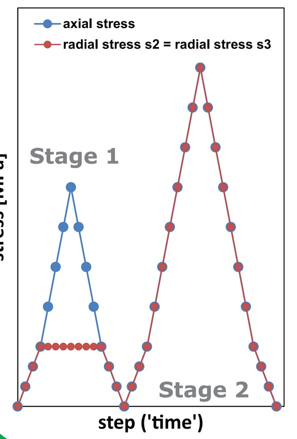
Sandstone sample material:

Flechtinger sandstone (Beberthal)
porosity = 6%
47-58% quartz
20-28% K-feldspar
4-9% mica
12-13% plagioclase
8% calcite

Bleurswiller sandstone
porosity = 25%
~65% quartz
28% feldspar
~5-10% clay
1-2% mica







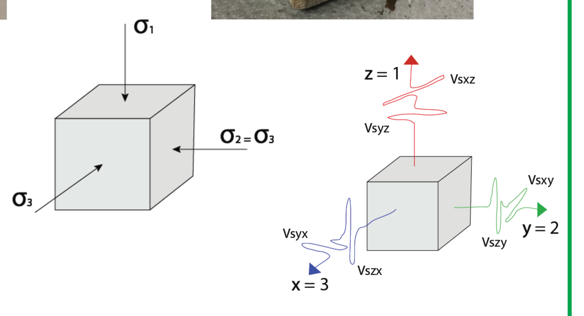


Fig. 1 Stress paths taken during the 'damage' (Stage 1, deviatoric deformation) and 'relaoding' (Stage 2, hydrostatic deformation) phases and indication of stress and velocity directions.

3A. Results for low-porosity Beberthal Sandstone

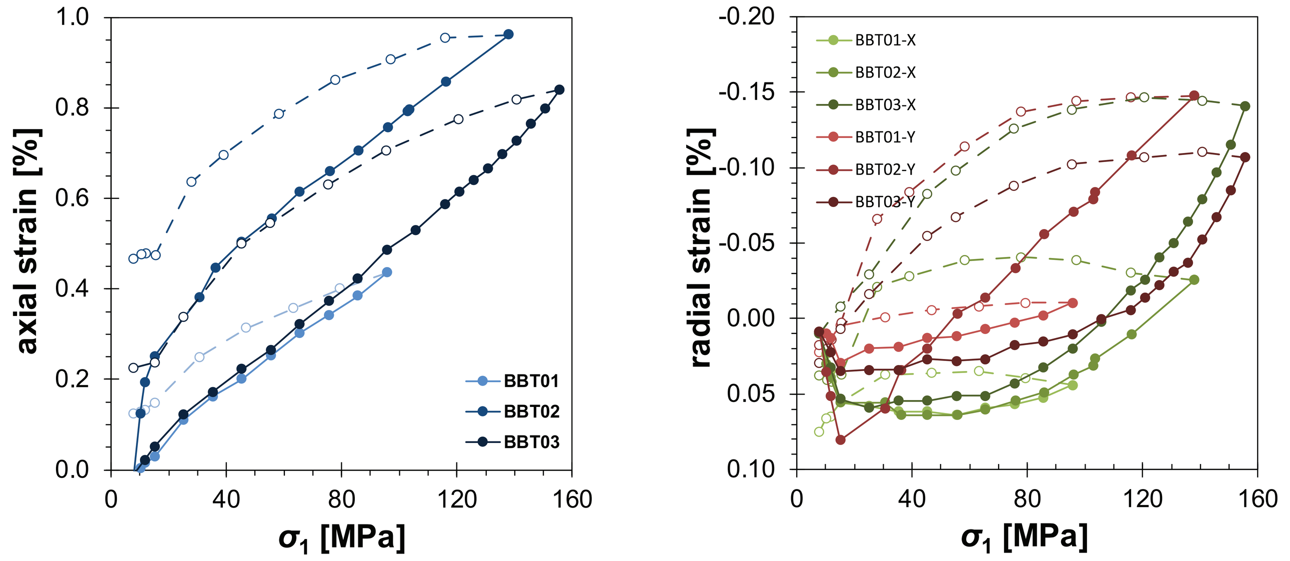


Fig. 2 Mechanical data obtained during the deformaton stage of experiments on Beberthal sandstone (BBT - loading = solid line, unloading = dashed lines). Left: axial strain vs. axial stress; right: radial strains vs. axial stress. Note that BBT-01 was deformed up to 96 MPa, BBT-02 up to 138 MPa and BBT-03 up to 156 MPa axial stress, to induce varying levels of damage.

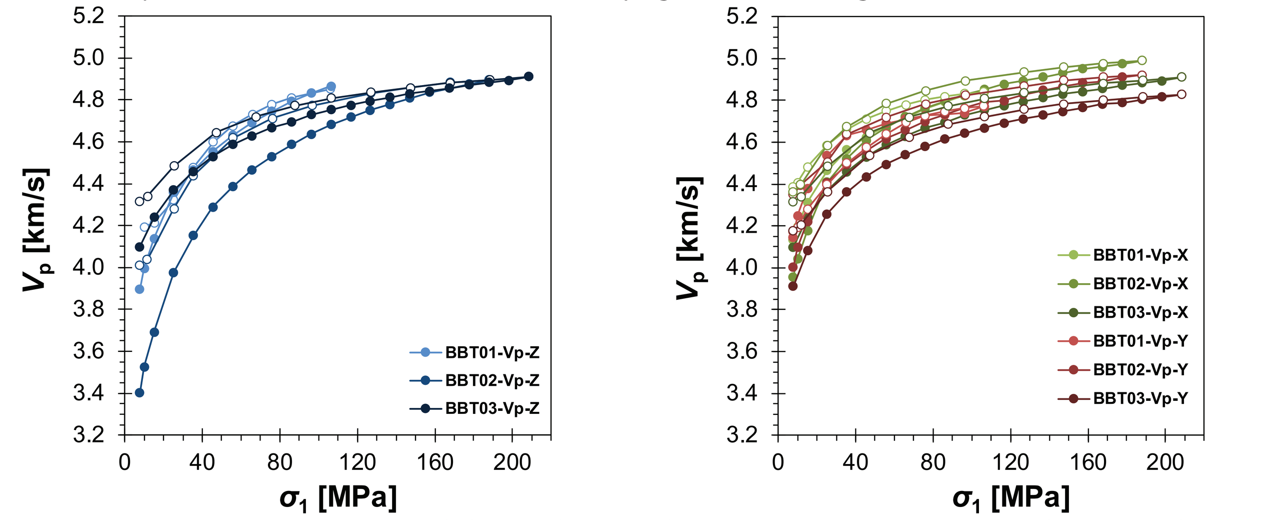


Fig. 3 P-wave velocities measured during the reloading stage vs. axial stress (loading = solid line, unloading = dashed lines). Left: along loading direction, right: perpendicular to loading direction. Note that during the reloading stage the axial stress is equal to the confining pressure!

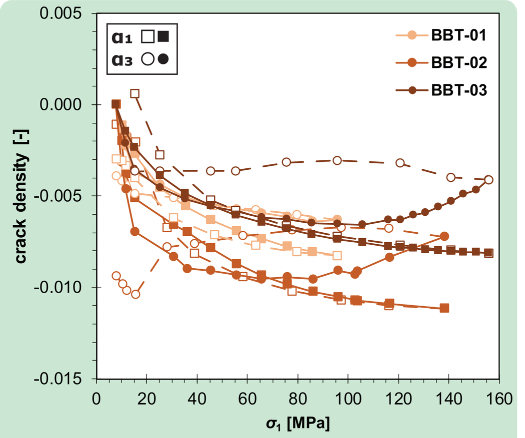
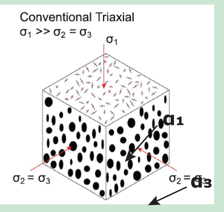


Fig. A Crack density development during the deviatoric stages of all three BBT experiments, as a function of axial stress. Closed symbols/solid lines denote loading, while open symbols/dashed lines denote unloading. Cracks oriented perpendicular to the axial (vertical) stress direction (σ_1) are shown as squares, and cracks oriented perpendicular to the horizontal stress (σ_3) are shown as circles.
Note that BBT-01 does not show the creation of new cracks throughout the experiment, while BBT-03 shows cracks formed parallel to the loading direction at an axial stress of ~100 MPa.

For the applied state of stress, cracks tend to open perpendicular to the loading direction [taken from Browning et al., 2016].



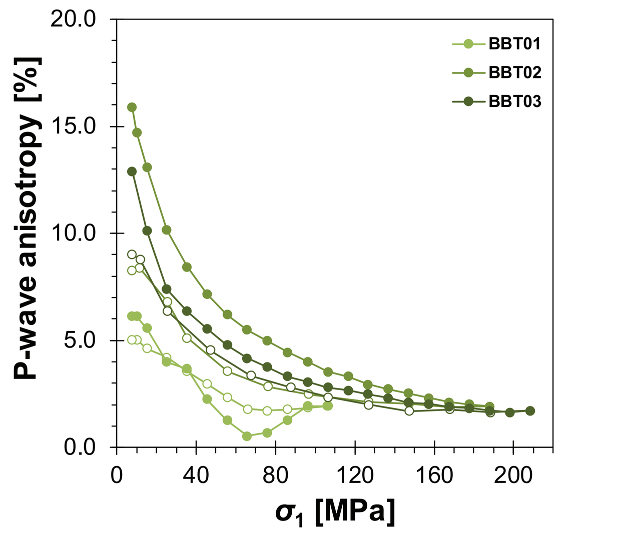


Fig. 4 P-wave anisotropy vs. axial stress (i.e. confinement) for all three BBT experiments. Note that the anisotropy decreases with confinement.

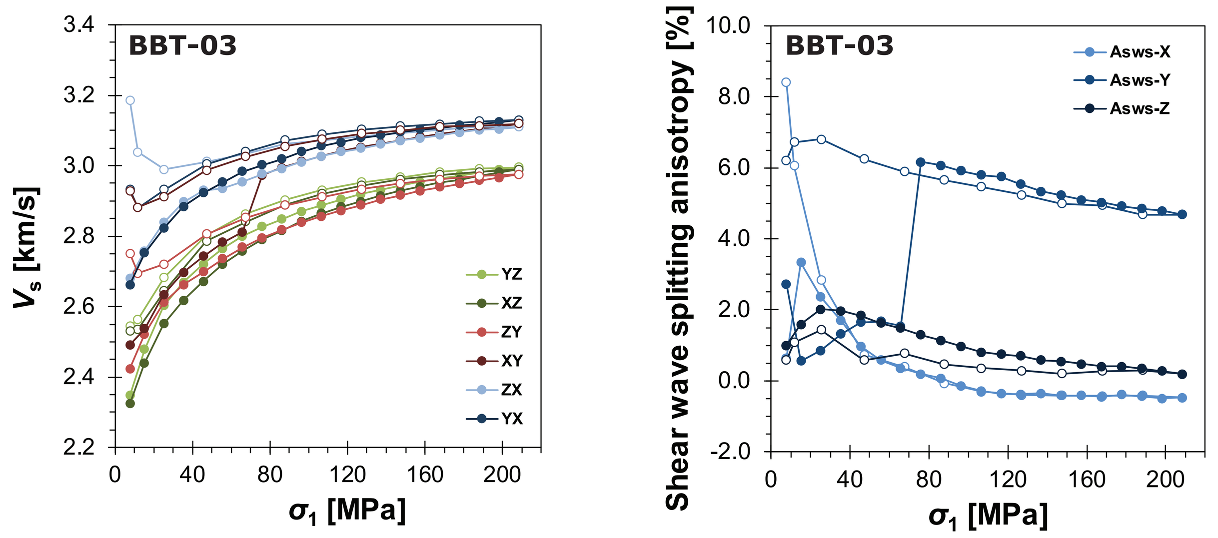


Fig. 5 Left: Shear wave velocities and right: shear wave splitting anisotropy vs. axial stress for BBT-03. S-wave velocities are notably higher in the X-direction (along σ_3). Note the sudden increase in XY-velocity, which may be related to piston-sample contact.

3B. Results for high-porosity Bleurswiller Sandstone

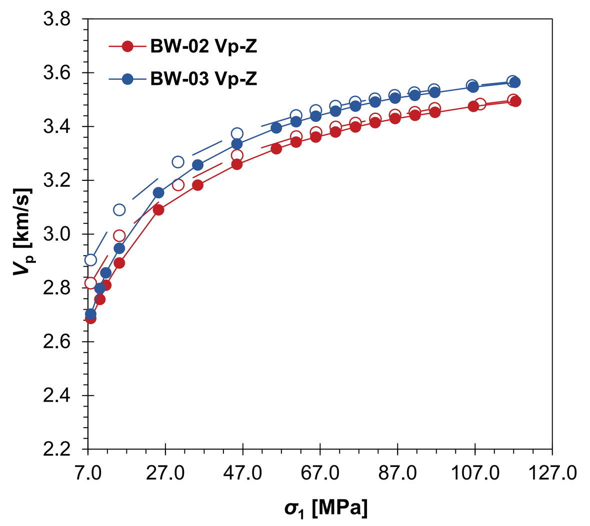
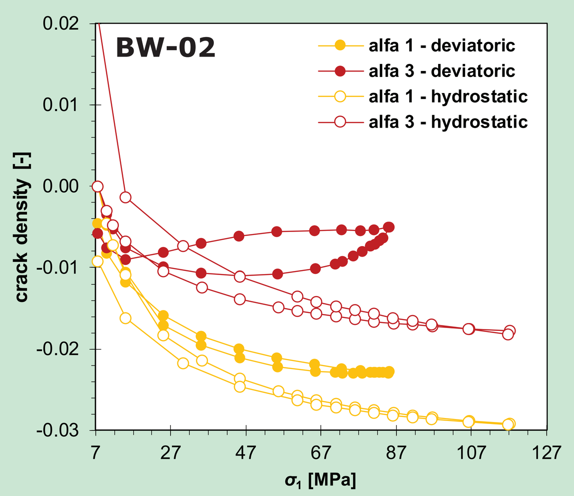
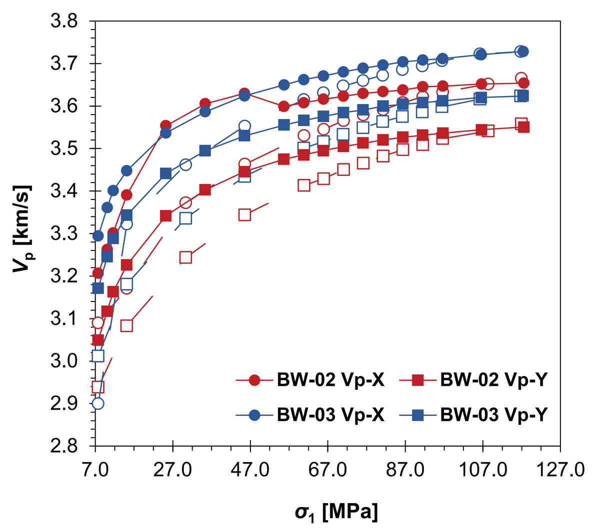


Fig. B Crack density development during the deviatoric (closed symbols) and hydrostatic (open symbols) stages of experiment BW-02 vs. axial stress. It is clear that damage is induced during the deviatoric stress stage. Cracks oriented perpendicular to the axial (vertical) stress direction become closed (σ_1), as the applies stress increases. By contrast, cracks oriented perpendicular to the horizontal stress directions initially also close, but after ~50 MPa applied stress new cracks are being formed (σ_3). Upon hydrostatic reloading, cracks in all directions close. Upon unloading, cracks perpendicular to the horizontal stresses open again, while those oriented perpendicular to the vertical stress remain mainly closed.





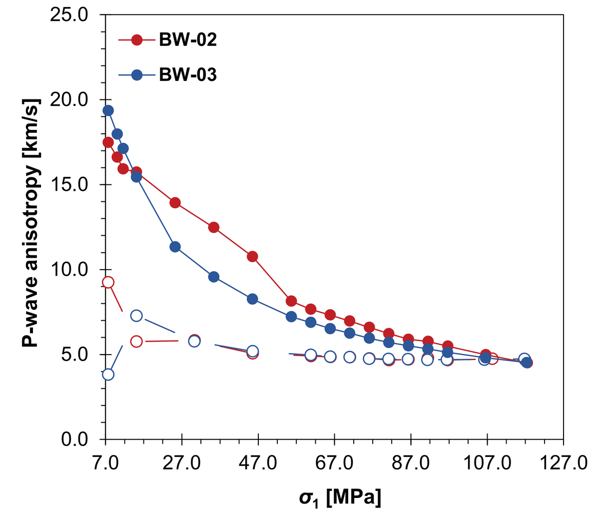


Fig. 6 The damage stages of the Bleurswiller (BW)-experiments showed similar behaviour as BBT-03, with dilatant behaviour and increased crack densities (cf. Fig. B) at axial stresses over 45 MPa - not shown here. Both samples were initially deformed up to an axial stress of ~85 MPa.
Velocities measured during the reloading stage (loading = solid line, unloading = dashed lines). Top left: P-wave velocity in axial direction; bottom left: P-wave velocity in radial directions. Note that both BW-02 and BW-03 show reproducable behaviour. Bottom right: P-wave anisotropy during re-loading. As the maximum axial stress applied during the first stage is approached, velocities tend to become near constant suggesting pre-exsisting cracks are closing. Upon unloading, anisotropy is only partially recovered.

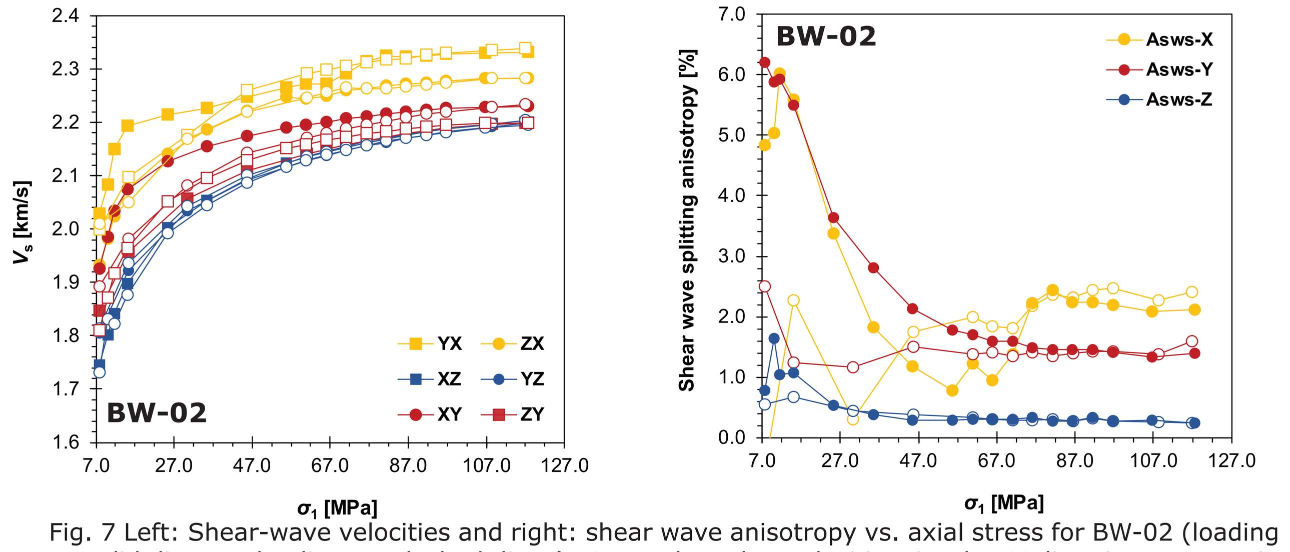


Fig. 7 Left: Shear-wave velocities and right: shear wave anisotropy vs. axial stress for BW-02 (loading = solid line, unloading = dashed lines). Note that the velocities in the X-direction are again systematically higher. While velocities increase, anisotropy reduces during hydrostatic loading, approaching near constant values after ~85 MPa.

Anisotropy

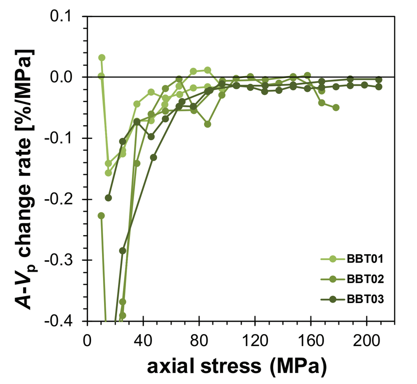
The simultaneous measurement of wave velocities in the three orthogonal directions and the relation of the sample reference system to inherent fabric elements (i.e. crack orientation) allows the calculation of velocity anisotropy A

for P-wave anisotropy:
$A\text{-}V_p = (V_{p,max} - V_{p,\,min})/V_{p,\,mean} \times 100\%$

similarly, for shear wave splitting:
$A\text{-}V_{s,i} = (V_{s,max\ i} - V_{s,\,min\ i})/V_{s,\,mean\ i} \times 100\%$

where i is any of the three principal directionx, X, Y or Z (see Fig. 1).

4. Preliminary conclusions



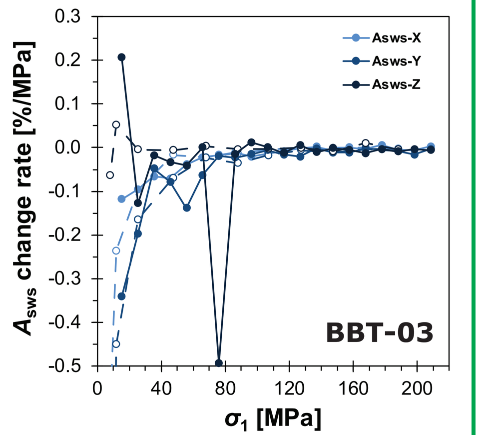
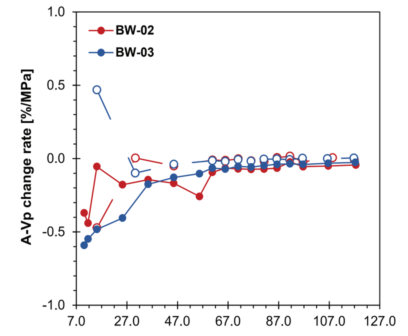


Fig. 8 Rate of change of wave-anisotropy during the reloading stage (loading = solid line, unloading = dashed lines). Top: change in P-wave anisotropy for all BBT samples; right: change in S-wave anisotropy for BBT-03.



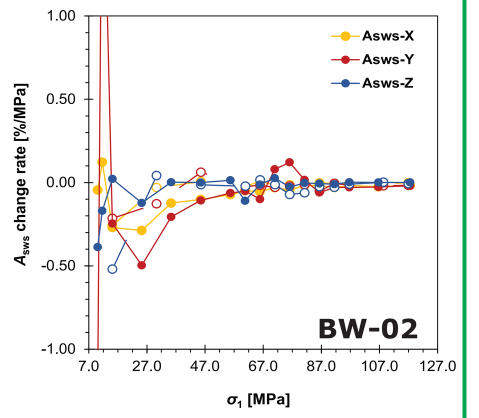


Fig. 9 Rate of change of wave-anisotropy during the reloading stage (loading = solid line, unloading = dashed lines). Top: change in P-wave anisotropy for all BW-samples; bottom: change in S-wave anisotropy for BW-02.

It appears that the rate of change of anisotropy may be a good indicator to pinpoint previous stress states experienced by the material. Particularly the shear wave anisotropy gives a good indication. Overall, the rate of change of anisotropy tends to go to zero once the previous stress state is exceeded.

For the S-wave anisotropy along the loading axis, this occurs at the maximum mean stress achieved during the damage stage (62 MPa for BBT-03, 38 MPa for BW-02). For the S-wave anisotropy perpendicular to the loading direction, this occurs at the maximum axial stress aplied during the damage stage (156 MPa for BBT-03, 83 MPa for BW-02).

For future experiments we plan to also test different loading paths as well to verify these preliminary results.