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Experimental Deformation of Sandy Opalinus Clay at Elevated Temperature and Pressure Conditions

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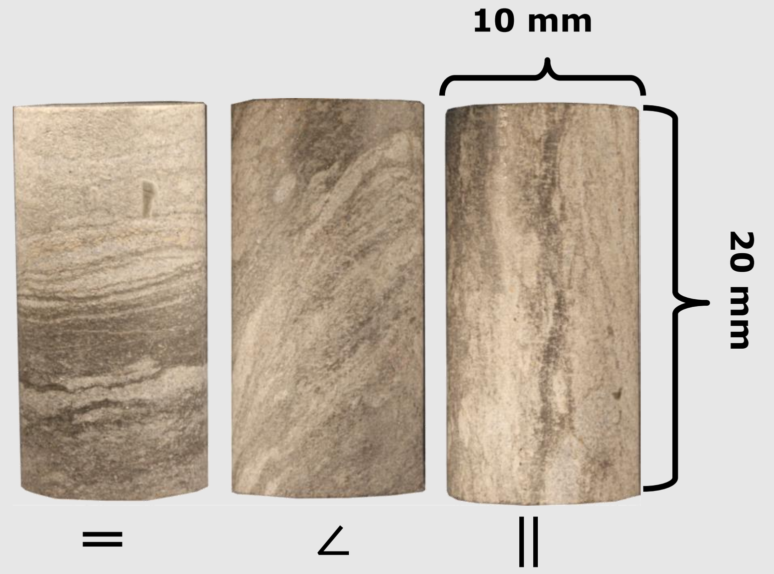
1. Motivation

Across several scales and boundary conditions, clay-rich rocks/shales are encountered in different natural settings such as accretionary wedges, sedimentary basins or fault zones. They also play a fundamental role in engineering applications, as they are suitable as cap-rocks for the geological storage of carbon dioxide and potential host rocks for the storage of nuclear waste. Shales are polymineralic aggregates, often showing compositional heterogeneity and multiscale textural anisotropy, resulting in orientation-dependent mechanical and hydraulic properties. Studying the deformation behaviour of shales is therefore of great interest in order to gain a deeper understanding of the relevant processes that lead to damage or failure in such systems. We investigated experimentally the mechanical behaviour of Opalinus Clay with emphasis on the interplay between sample anisotropy and microstructural deformation mechanisms at varying deformation conditions.

2. Sample Material

The investigated sample material belongs to the Sandy facies of Opalinus Clay, which is an over-consolidated, clay-rich shale, considered as a potential host rock for the disposal of nuclear waste in Switzerland (Nagra, 2002). The dark-grey silty to sandy claystone is characterized by a pronounced lamination with elongated layers of fine sand to silt-grained quartz, cemented by carbonate and kaolinite, and alternating clay-rich layers. The Sandy facies is composed of clay minerals (6-64 wt.%), quartz (16-52 wt.%) and feldspars (3-15 wt.%) (Peters et al., 2011). The porosity ranges between 5.3 and 17.7% and permeability in the order of 10^{-20} m² (Philipp et al., 2017).



*← **Fig. 1:** Sample cores prepared perpendicular, 45° and parallel to the bedding direction.*

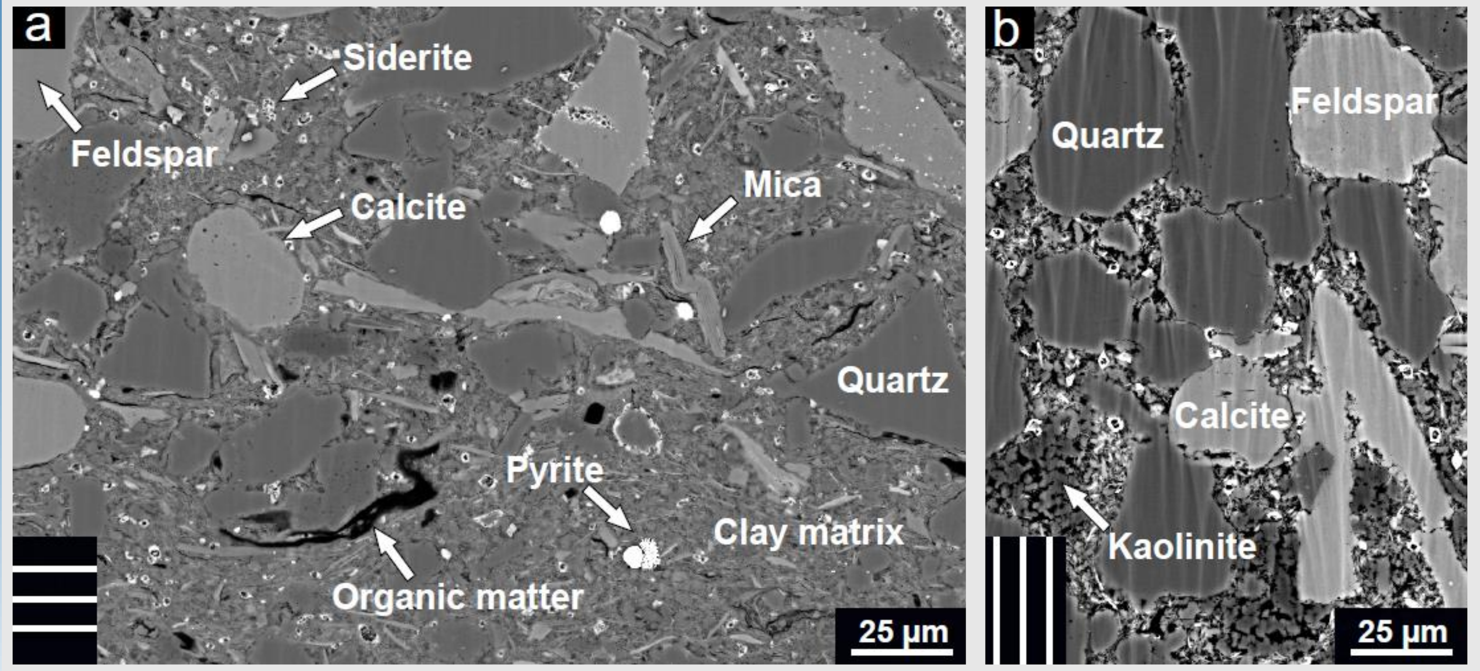


***Fig. 2:** Backscattered electron (BSE) images of undeformed Opalinus Clay of the Sandy facies. **a)** clay layer showing characteristic mineral phases embedded in the clay matrix. **b)** sand layer showing dominant minerals cemented by kaolinite and blocky calcite.*

3. Experimental Methods and Results

Cylindrical samples (Fig.1) were prepared under dry conditions, oriented at of 0°, 45° and 90° to bedding. Samples were subsequently dried at 50° C until a constant weight was reached, corresponding to a residual water content of about 0.4 wt.%. Mean porosity is 12.30±1.2 %, determined by helium-pycnometry. A Paterson-type deformation apparatus was used to perform unconsolidated-undrained constant strain rate experiments, varying either confining pressure (p_c = 50 - 100 MPa), temperature (T = 25 - 200° C) or strain rate ($\dot{\varepsilon}$ = $1*10^{-3}$ - $5*10^{-6}$ s^{-1}). In addition a set of back-saturated (96.1±1.3 %) samples was deformed at p_c = 50 MPa, T = 100° C and $\dot{\varepsilon}$ = $5*10^{-4}$ s^{-1} to study the influence of water content on the mechanical behaviour. For microstructural analysis by electron microscopy, sections were prepared using the broad ion-beam polishing (BIB-SEM).

Confining Pressure / Temperature / Strain Rate

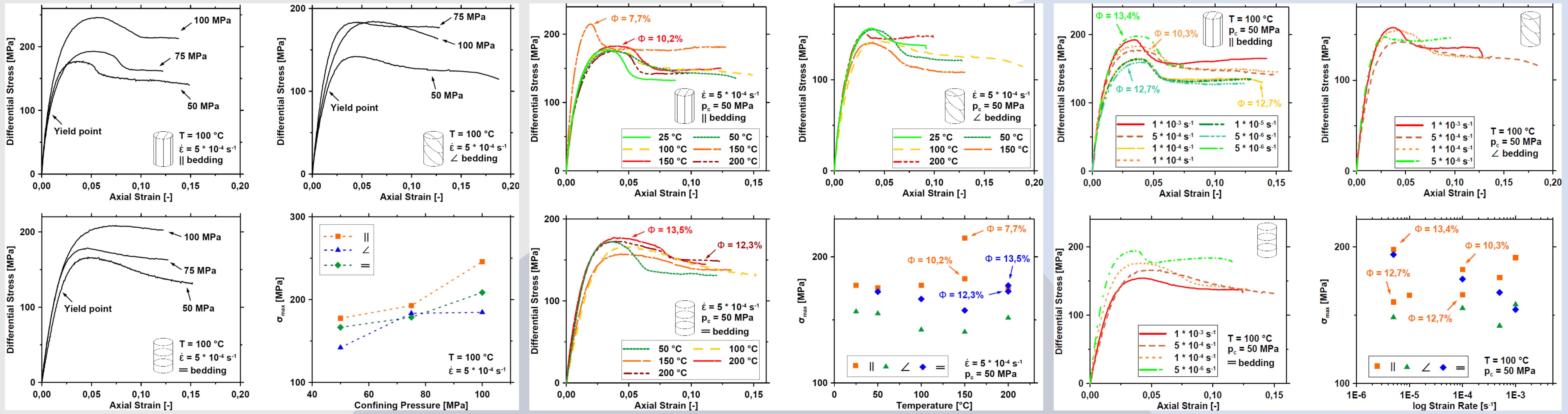


***Fig. 3:** Stress-strain curves showing the influence of confining pressure, temperature and strain rate on deformation behaviour of dried samples deformed parallel, 45° and perpendicular to bedding direction as well as the relation between peak strength and applied test condition. Deformation conditions and sample orientation are indicated.*

Saturation

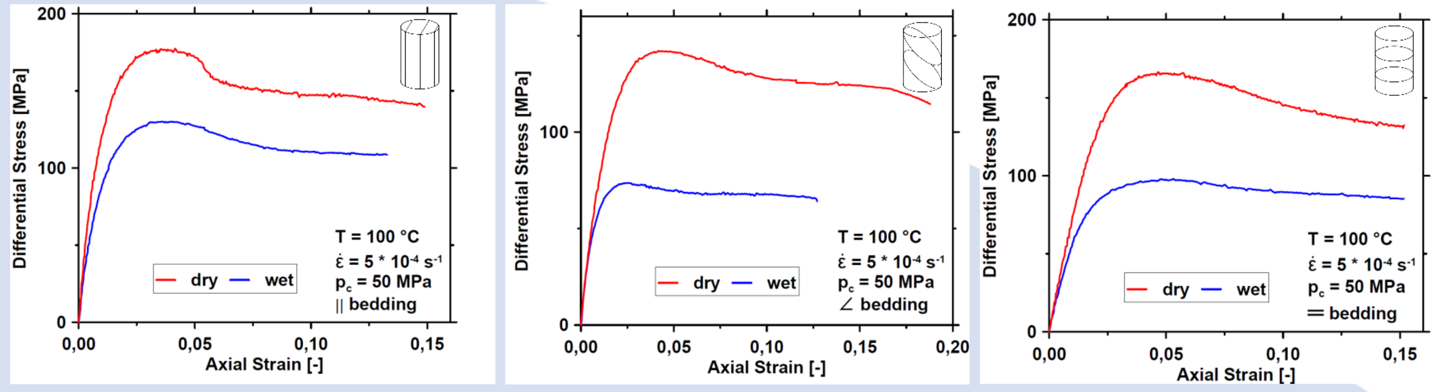


***Fig. 4:** Stress-strain curves showing the effect of saturation on the mechanical response of parallel, 45° and perpendicular oriented samples. Deformation conditions and sample orientation are indicated.*

Depending on bedding orientation and the distribution of sand and clay layers, deformed samples show brittle to semibrittle deformation behaviour over the range of applied loading conditions (Figs. 3-5). At microscale (Fig. 6) it becomes evident that damage is accumulated by a mixture of brittle and plastic processes, leading to the formation of localized and distributed deformation.

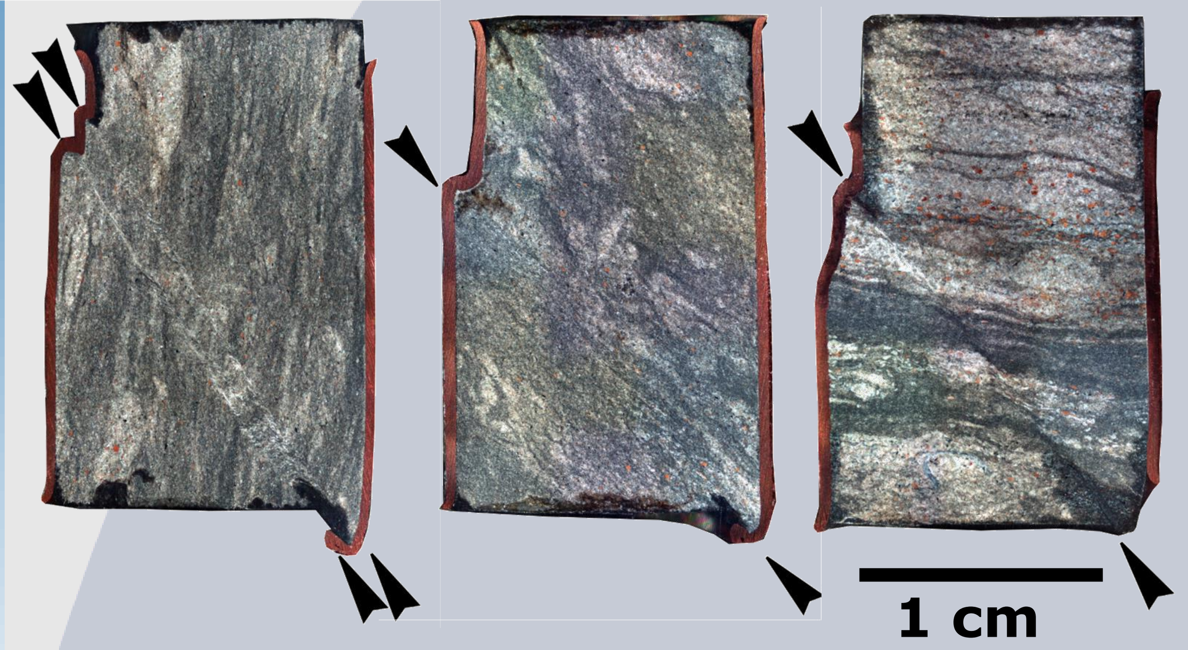


***Fig. 5:** Reflected light micrographs of typical deformation features in the Sandy facies of Opalinus Clay for dried samples deformed parallel (T=200 °C), 45° (T=25 °C) and perpendicular (T=200 °C) to the bedding direction. Black arrowheads indicate the traces of strain localization. Samples were deformed at p_c=50 MPa and $\dot{\varepsilon}$=$5*10^{-4}$ s^{-1}.*

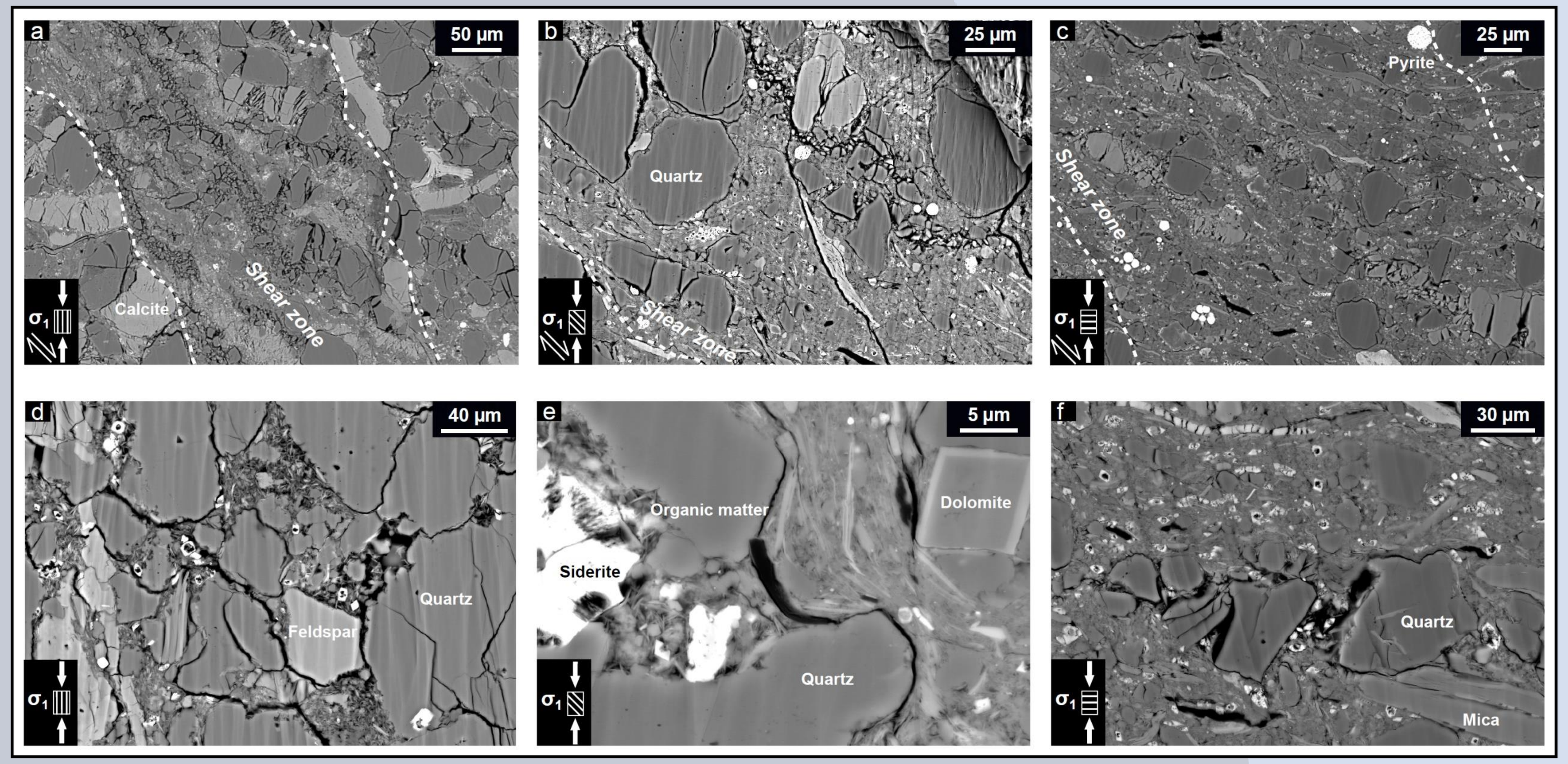


***Fig. 6:** BSE images of Opalinus Clay of the Sandy facies showing deformation-induced shear zones of samples deformed parallel (**a**), 45° (**b**) and perpendicular (**c**) to bedding direction. Loading and shear direction are indicated. All samples were deformed at p_c=50 MPa, $\dot{\varepsilon}$=$5*10^{-4}$ s^{-1} and T=100 °C. **d)** sand layer with multiple trans- and intergranular fractures sub-parallel to principle stress axis. **e)** highly compacted clay matrix along bottlenecks of mineral clasts next to nearly intact clay matrix, strain-shadowed by grain supported framework. **f)** matrix intrusion in fractured quartz grain indicating a repetitively process of fracturing and rotation.*

4. Discussion and Conclusion

Influence of deformation conditions on the mechanical behaviour of the Sandy facies of Opalinus clay:

Confining pressure: strong
→ coefficient of internal friction: $\mu_{0°}$ = 0.44, $\mu_{45°}$ = $\mu_{90°}$ = 0.31 (Mohr-Coulomb)

Temperature: weak
→ slight strengthening at T = 200° C, likely by thermal degradation of clay minerals

Strain rate: weak
→ apparent weakening at high rate for 90° samples

Degree of saturation: strong
→ potentially induced by excess pore pressure in undrained tests

Samples loaded parallel to bedding are stronger than 45° and 90° samples. Multiple trans- and intergranular fractures evolved in strong minerals, leading to grain-refinement in highly deformed shear zones. The clay matrix is highly compacted and deformed in high-stress regions.

At all deformation conditions, compositional heterogeneity as well as pre-existing rock fabric, also shown by porosity caused variations, have a strong influence on localization. In the investigated p_c-T- $\dot{\varepsilon}$ range, the prevailing deformation mechanism are highly influenced by the sample heterogeneity and anisotropy.

References and Acknowledgement

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