Overview of geomechanical test results from Opalinus Clay core samples

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

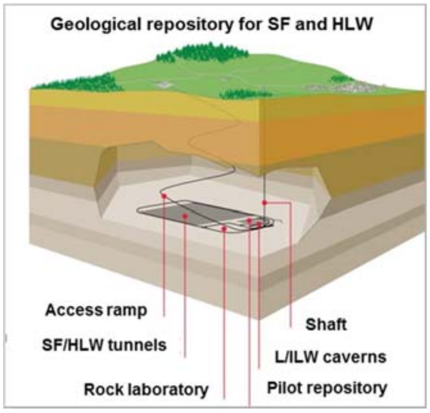
Overview

1. Role of geomechanics in context of repository design
2. Data base/locations of sampled cores for geomechanical testing
3. Geotechnical characterization
4. Unsaturated behaviour and swelling
5. Uniaxial and tensile strength
6. Shear Strength
7. Integrated data analysis

1 Role of geomechanics in repository design

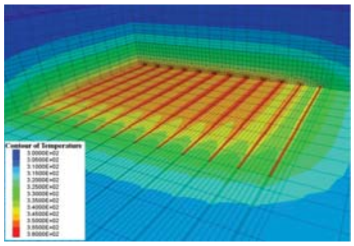
- Cavern construction & operation (incl. access ramp/shaft)
- Boundary conditions of long-term evolution (after backfill)
- Drilling operations (exploration)

Borehole stability issues



Underground structures of a repository

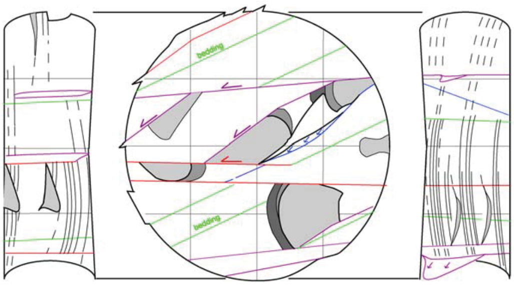
Construction - excavation damage zone



Repository near-/far field: THM processes

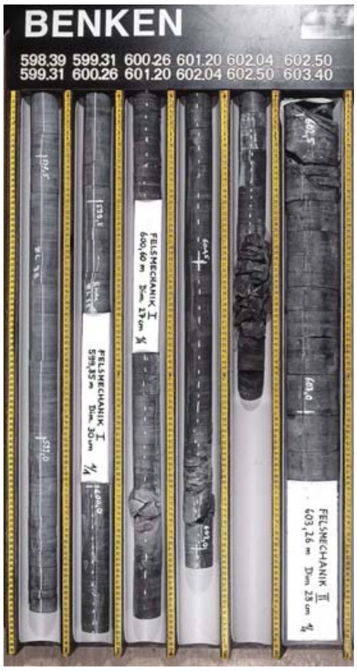
2 Data base

- Material characterization and deformation tests on recovered specimens in the laboratory
  → Focus of this presentation
- Additionally to core sampling for geomechanical testing:
  - Field observations (e.g. structural data)
  - Geophysical logging (boreholes)
  - Excavation/construction works at URL Mont Terri



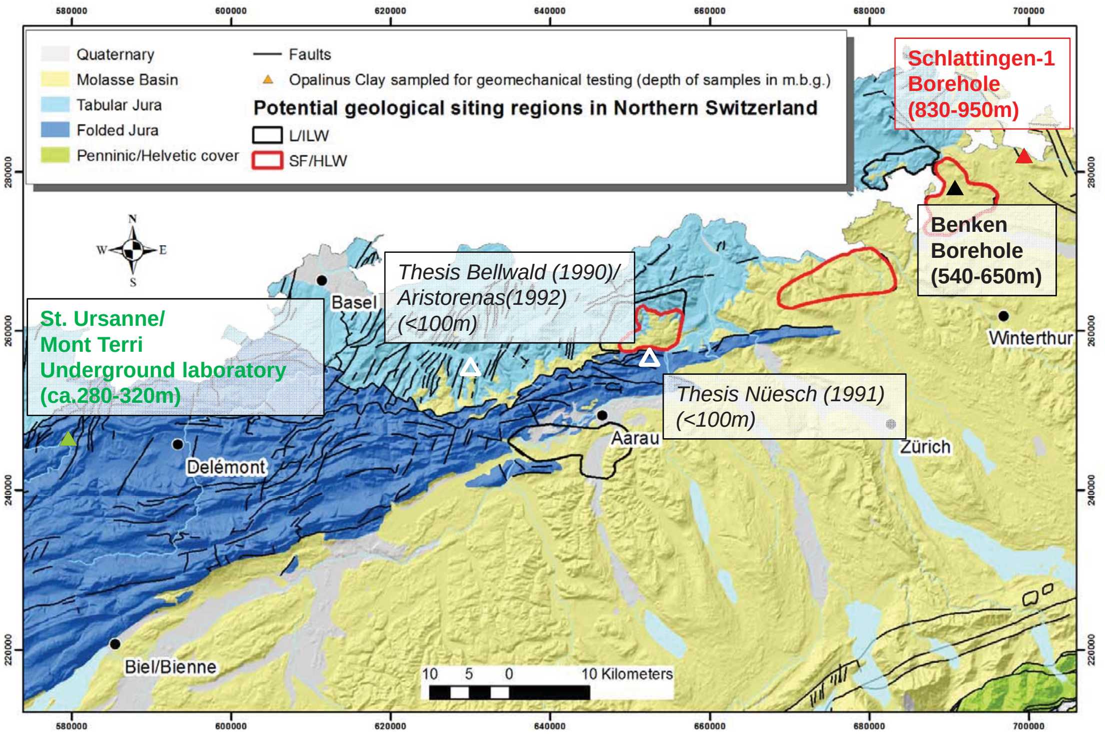
URL MT structural mapping (Madritsch & Vietor , 2010)

Coring at URL MT



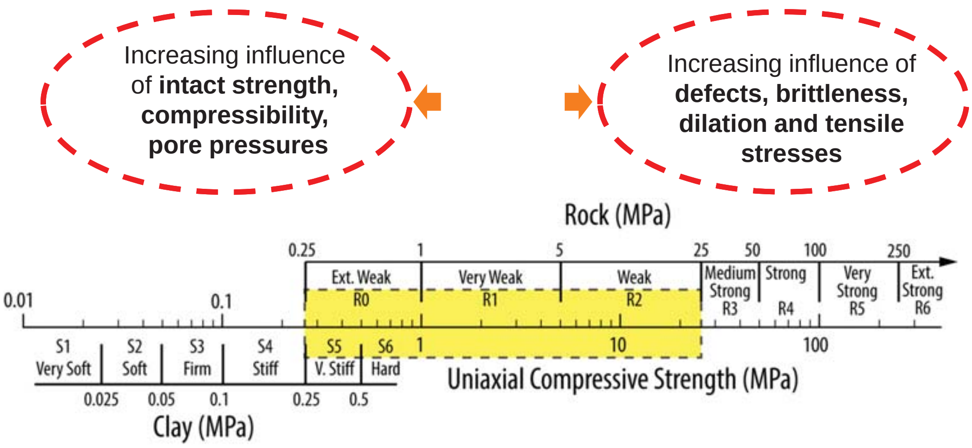
Retrieved cores from Borehole Benken

2.1 Overview data source



3 Geotechnical characterization - purpose

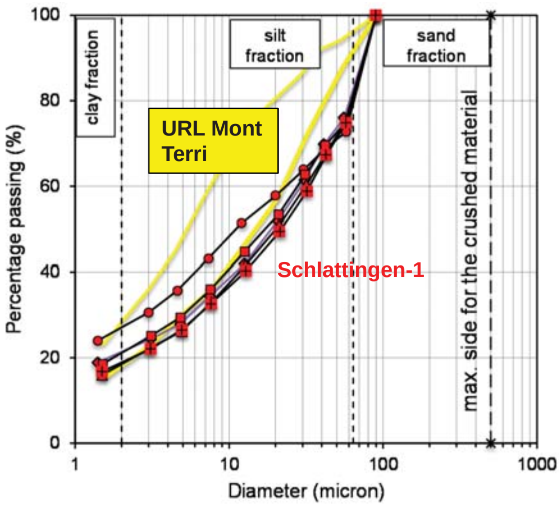
- Opalinus Clay: Weak rock or stiff soil?
- Deformation behaviour of geomaterials in the transition soil ←→ rock?



ISI classification scheme (e.g. Brown, 1981) and Johnston & Novello (1993)

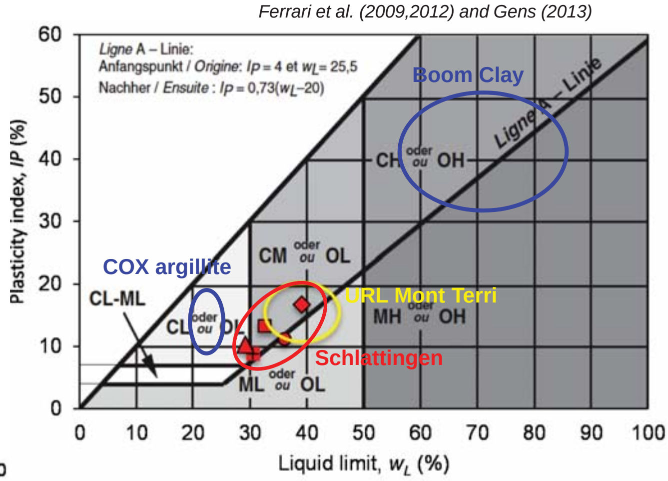
3.1 Geotechnical characterization – grain size & plasticity

- Classification of the material (index properties)
  - Density (particle, bulk), water content, void ratio, degree of saturation
  - **Grain size distribution**
  - **Atterberg limits** (liquid limit, plastic limit, plasticity index)



Ferrari et al. (2009 and 2012)

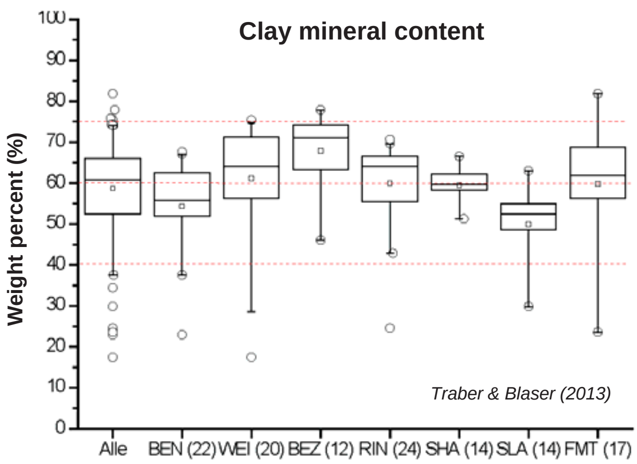
Ferrari et al. (2009,2012) and Gens (2013)

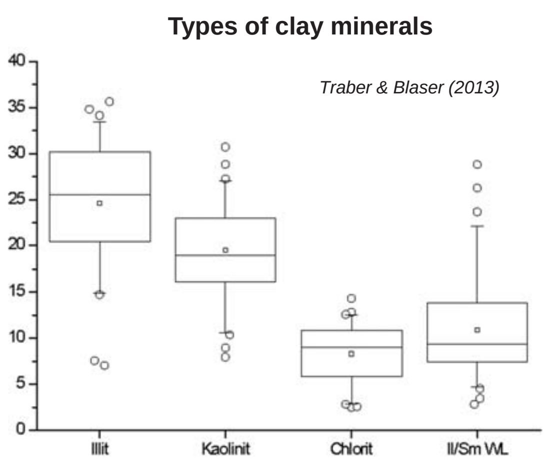


CL	Silty clay with sand	CM	Lean clay with sand	ML	Silt with sand

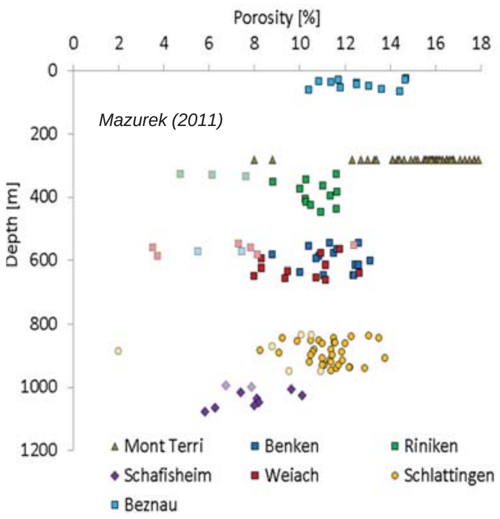
3.2 Mineralogy

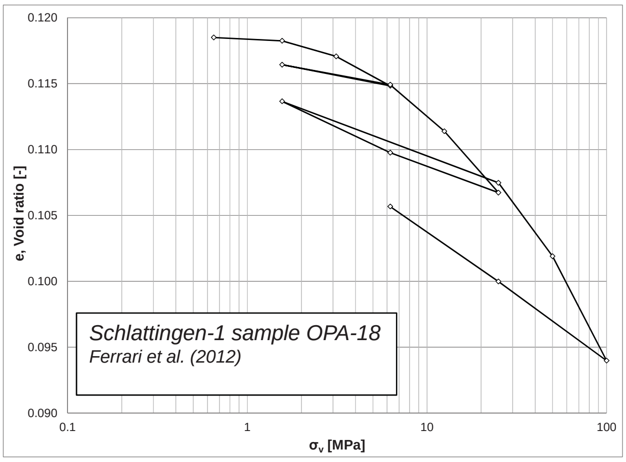
- Relatively homogeneous composition at individual locations and across Northern Switzerland
  - Clay mineral content typically 60wt.% (40-75wt.%)
    (swelling Illite/Smectite interlayers approx. 10wt.%)
  - Quartz/feldspar typically 20wt.%
  - Carbonates typically 20wt.%





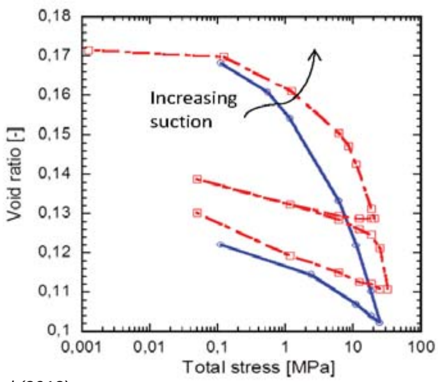
3.3 Physical porosity





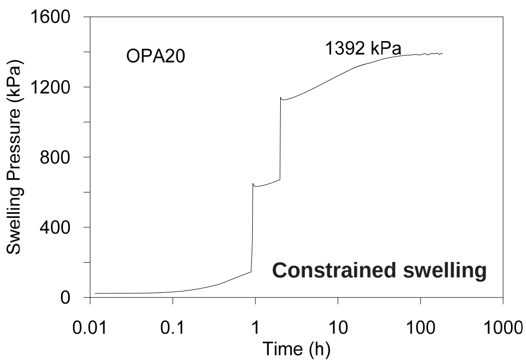
- Values typically 10-12%:
  - N-Switzerland 8% (Schafisheim) to 13% (Beznau); URL MT 16%
- Broad negative correlation of porosity with current burial depth (i.e. with vertical stress)
- Qualitatively also observed in 1-D oedometer testing

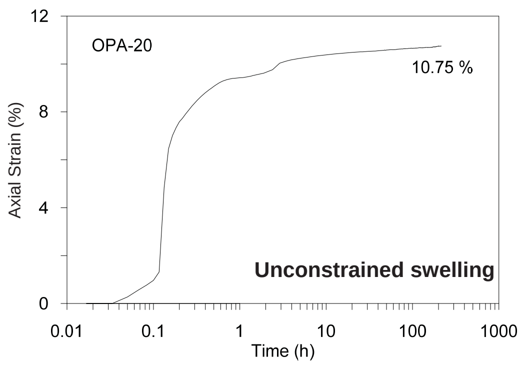
4 Unsaturated behaviour and swelling



- Stiffness is stress-dependent - and affected by suction
- Swelling parameters
  - Anisotropy factor 2 to 6 for both swelling pressure and heave
  - SLA-1 values comparable to Benken, greater than in URL MT

Ferrari et al. (2012) and Laloui (2012)





4.1 Unsaturated behaviour– quantification

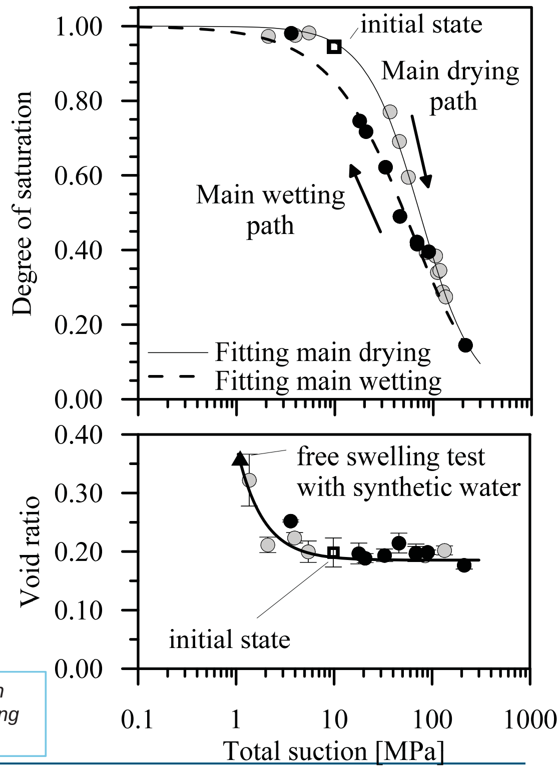
Hydro-Mechanical coupling

Effective stress law for partially saturated condition, e.g. Bishop (1959):

$$\sigma'_{ij} = (\sigma_{ij} - u_a\delta_{ij}) + S_r\, s\, \delta_{ij}$$

Water retention behaviour:

$$S_r = f(s, e)$$



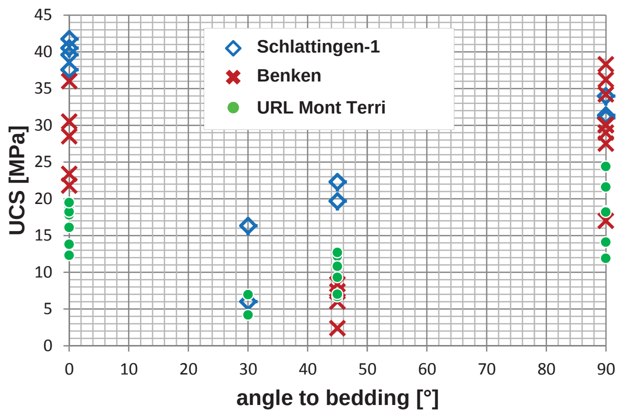
Determination of the water retention capacity:

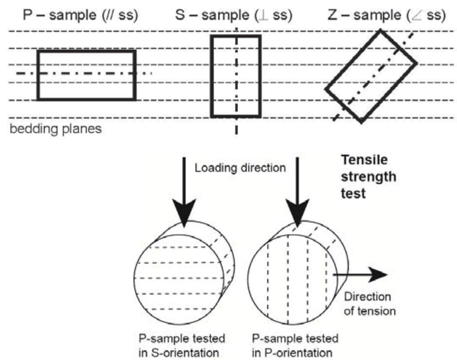
A robust experimental protocol has been developed to analyse the shale retention properties:

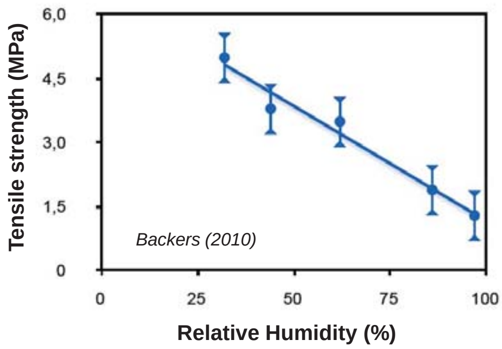
1. Imposition of a given water content on the shale.
2. Total suction measurement.
3. Volume change detection and computation of the degree of saturation.

Ferrari, A., Favero, V., and Laloui, L.: "An insight into the water retention behaviour of shales". Submitted to Journal of Rock Mechanics and Mining Sciences.

5 Uniaxial- and tensile strength



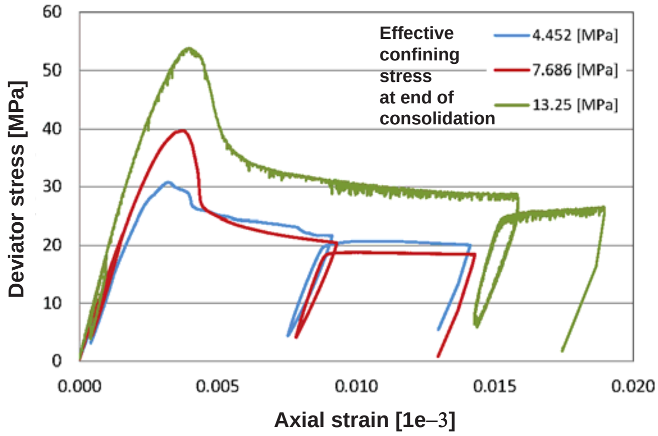




- Strength (and stiffness) anisotropy
- «Weak» to «Medium Strong» rock
- Strength affected by degree of saturation

6.1 Shear strength - undrained triaxial strength (SLA-1 cores)


Gesteinslabor Jahns (2013)



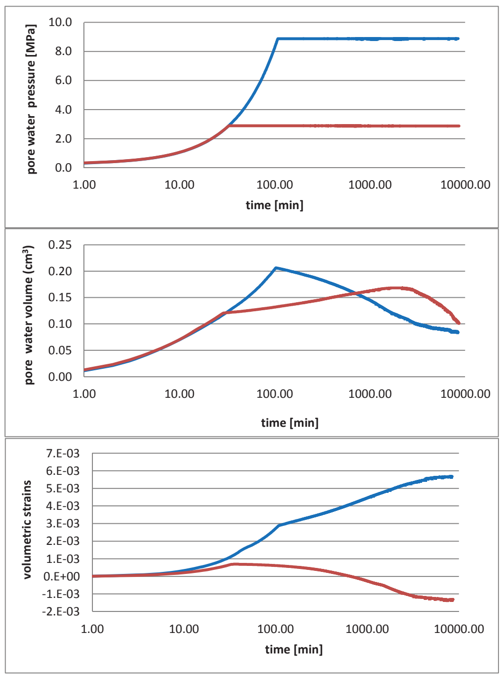
- Consolidation at pre-defined confining stress (7-23MPa) and fluid pore pressure (3 to 9MPa) for up to two weeks
- Saturation-check
- Deformation at strain rate of 1E-06 (1E-04 to 1E-07)
- Strain-softening always observed in tested stress range
- Localized deformation on sample scale

6.2 Shear strength – data analysis and QC workflow

- Test quality assessment as part of the workflow of Geodata at Nagra
- Diagnostic analyses with focus on consolidation equilibrium
- Quality ranking of tests for further interpretation

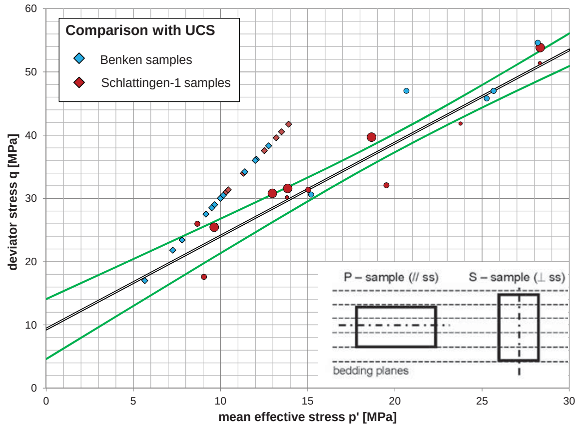
Test	Skempton Test (ref. Table 3-1)	Saturation state (ref. Tables 3-2 to 3-5)	Consolidation/swelling (ref. Tables 3-2 to 3-5)	Q-Level
P09	Incomplete saturation	no	no	D
P10	Incomplete saturation	almost	no	D
P13	Incomplete saturation	almost	no	D
P14	Distorted pwp response	almost	no	B
P109	ok	ok	almost	B
P115	ok	ok	no	B
S03	Consolidation disequilibr.	ok	almost	C**
S05	Incomplete saturation	almost	no	C
S06	Incomplete saturation	almost	no	D
S07	Consolidation disequilibr.	almost	no	D

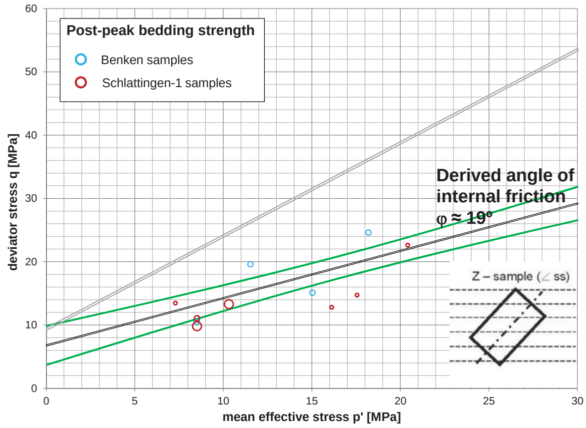
Total confining stress consolidation: 7.6MPa, 22.6MPa



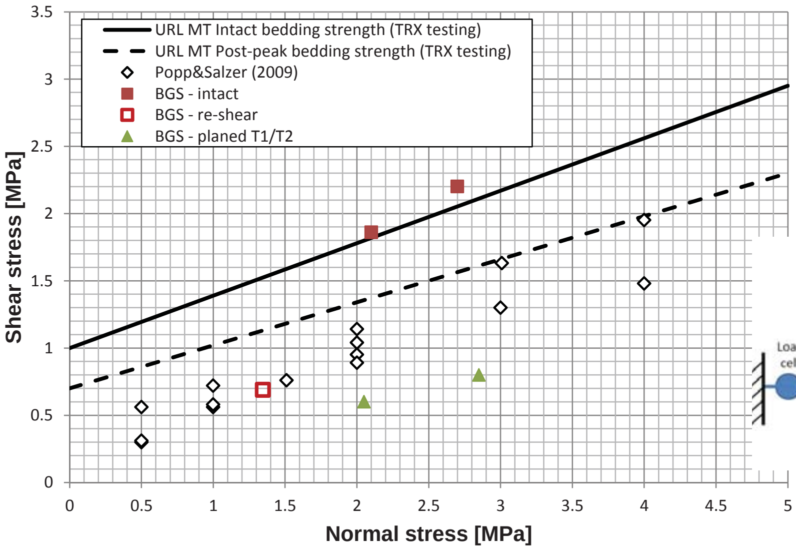
Favero et al. (2013)

6.3 Shear strength – compilation and interpretation

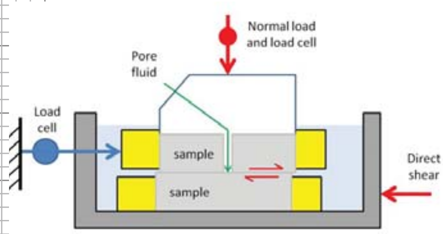




6.4 Shear strength – comparison to direct shear configuration



- Greater absolute displacements (10 mm vs. 1-2mm in triaxial testing)
- Lateral stress and pore fluid pressure control difficult

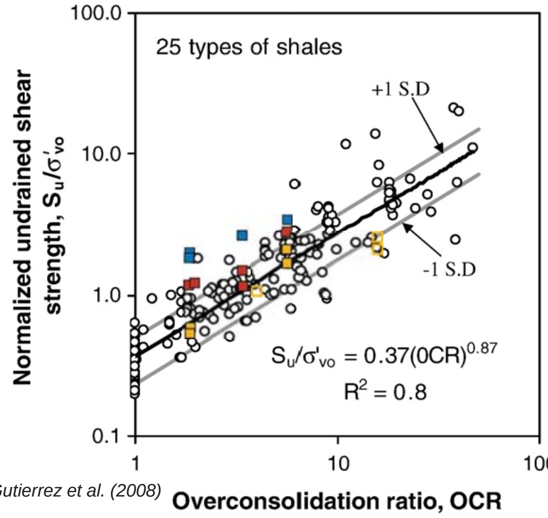


- Direct shear configuration used by Nagra to address transmissivity evolution of fractures (self-sealing: Cuss et al. (2009, 2012)) → no robust study on strength evolution. Findings:
  - Sample fractured in the rig in good agreement with strength estimated from TRX testing
  - Re-shearing after several days of injection of a chemically balanced fluid → slightly lower strength than estimated from TRX, but well within trend of Popp & Salzer (2009)

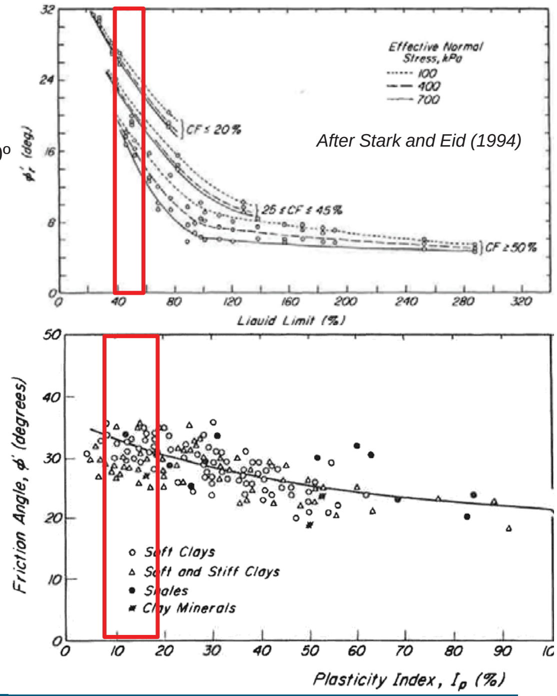
    → Planed samples show significantly lower strengths.

7 Integrated data analysis – consistency check

- Example 1 - undrained peak shear strength:
  - Normalized shear strength in comparison to other overconsolidated clays/shales
- Example 2 – residual friction angle
  - From laboratory testing: 18-20º
  - Empirical correlation ('ultimate' state)
    - Liquid Limit: >20º (CF<45%); Plasticity Index: >20º



Gutierrez et al. (2008)



After Stark and Eid (1994)

Summary

- Careful material characterization is critical:
  - For appropriate storage/sample preparation for geomechanical testing
  - To anticipate/understand processes during geomechanical testing
  - Understand apparent 'artefacts' due to unsaturated conditions
  - Enable empirical comparison with similar materials
- Consistent data set of Opalinus Clay sampled at different depths
  - Greater burial depth correlates with decreasing porosity, greater stiffness and increasing strength (URL MT→BEN→SLA-1)
- Use multiple lines of evidence to assess data
  - 'Simple' and well accepted standard' (index) tests coupled with empirical correlations
  - Sophisticated and difficult tests (e.g. undrained triaxial)
  - Comparison to literature data with results of similar material

Zusammenfassung

- Sorgfältige Charakterisierung des Probenmaterials ist entscheidend:
  - Für angemessene Lagerung/Probenpräparation vor dem Deformationsexperiment
  - Für das Prozessverständnis der beobachteten Phänomene während dem Experiment und möglicher Artefakte aufgrund ungesättigter Verhältnisse
  - Für empirische Vergleiche mit ähnlichen Materialien
- Für den Opalinuston kann ein konsistenter, geomechanischer Datensatz hergeleitet werden, der die Tiefenlage berücksichtigt
  - Grössere Tiefenlage korreliert mit geringerer Porosität und grösserer Steifigkeit sowie Festigkeit (URL MT→BEN→SLA-1)
- Die Dateninterpretation sollte sich auf unterschiedliche Evidenzen stützen
  - 'Einfache' bzw. 'Standard' (Index-)Versuche gekoppelt mit empirischen Korrelationen
  - Komplexere aber auch ungleich schwierigere Tests (Triaxialversuche)
  - Vergleich mit Literaturdaten mit Resultaten aus ähnlichen Materialien

thank you
for your attention

nagra