The rock-mechanical behavior of Opalinus Clay – synopsis of 20 years of experience at the Mont Terri rock laboratory

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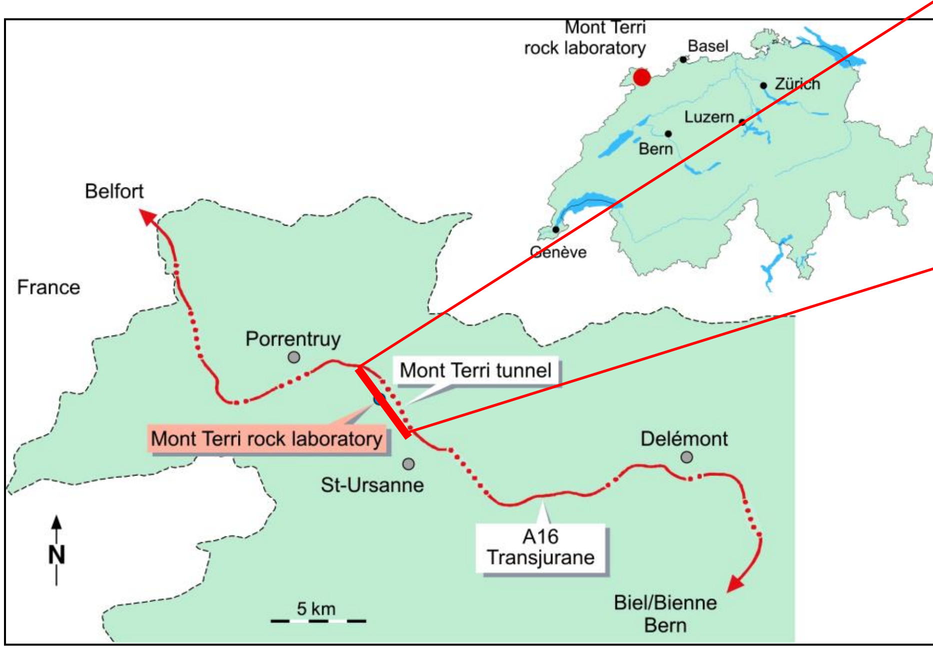
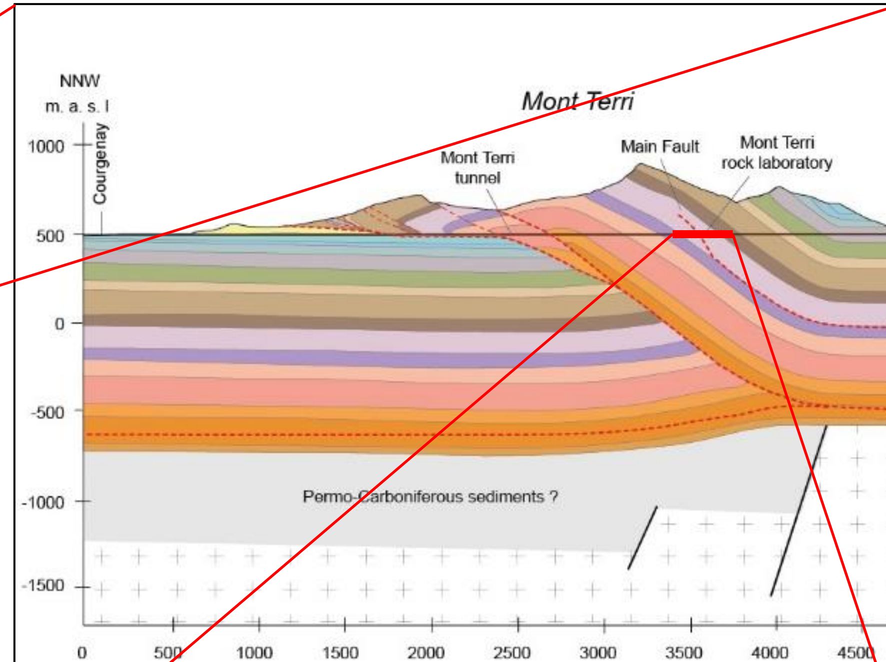
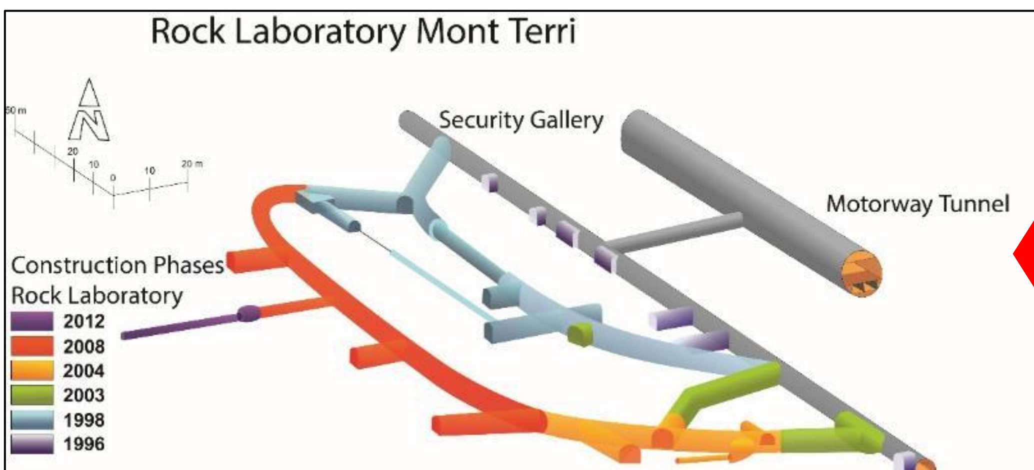
The 16 Partners of the Mont Terri Project

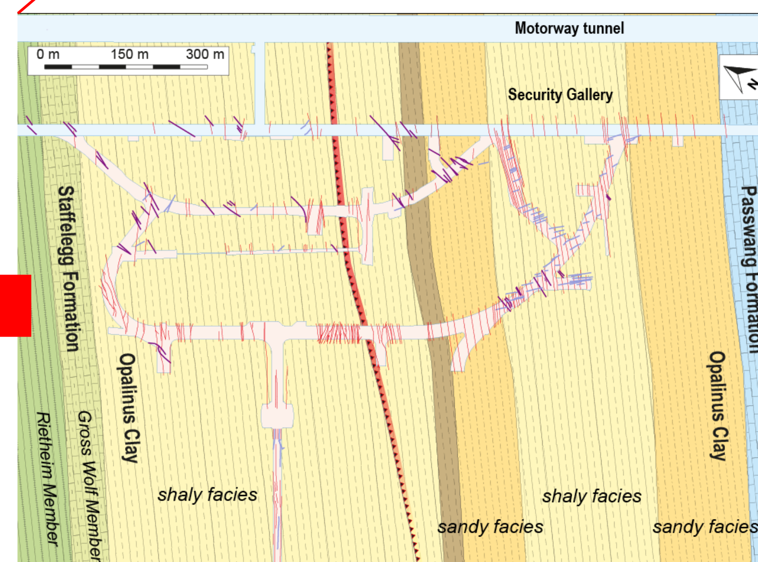
swisstopo	Bundesamt für Landestopografie
NAGRA	Nationale Genossenschaft für die Lagerung von radioaktivem Abfall
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs
IRSN	Institut de Protection et de Sûreté Nucléaire
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbh
ENRESA	Empresa Nacional de Residuos Radiactivos, S.A.
SCK•CEN	Studiecentrum voor Kernenergie, Mol
FANC	Federaal Agentschap voor Nucleaire Controle
JAEA	Japan Atomic Energy Agency
OBAYASHI	Obayashi Corporation
CRIEPI	Central Research Institute of Electric Power Industry
NWMO	Nuclear Waste Management Organisation, Toronto
U.S. DOE	Department of Energy, Washington DC
Chevron	Chevron Energy Technology Company, Houston

The Mont Terri rock laboratory – location and situation

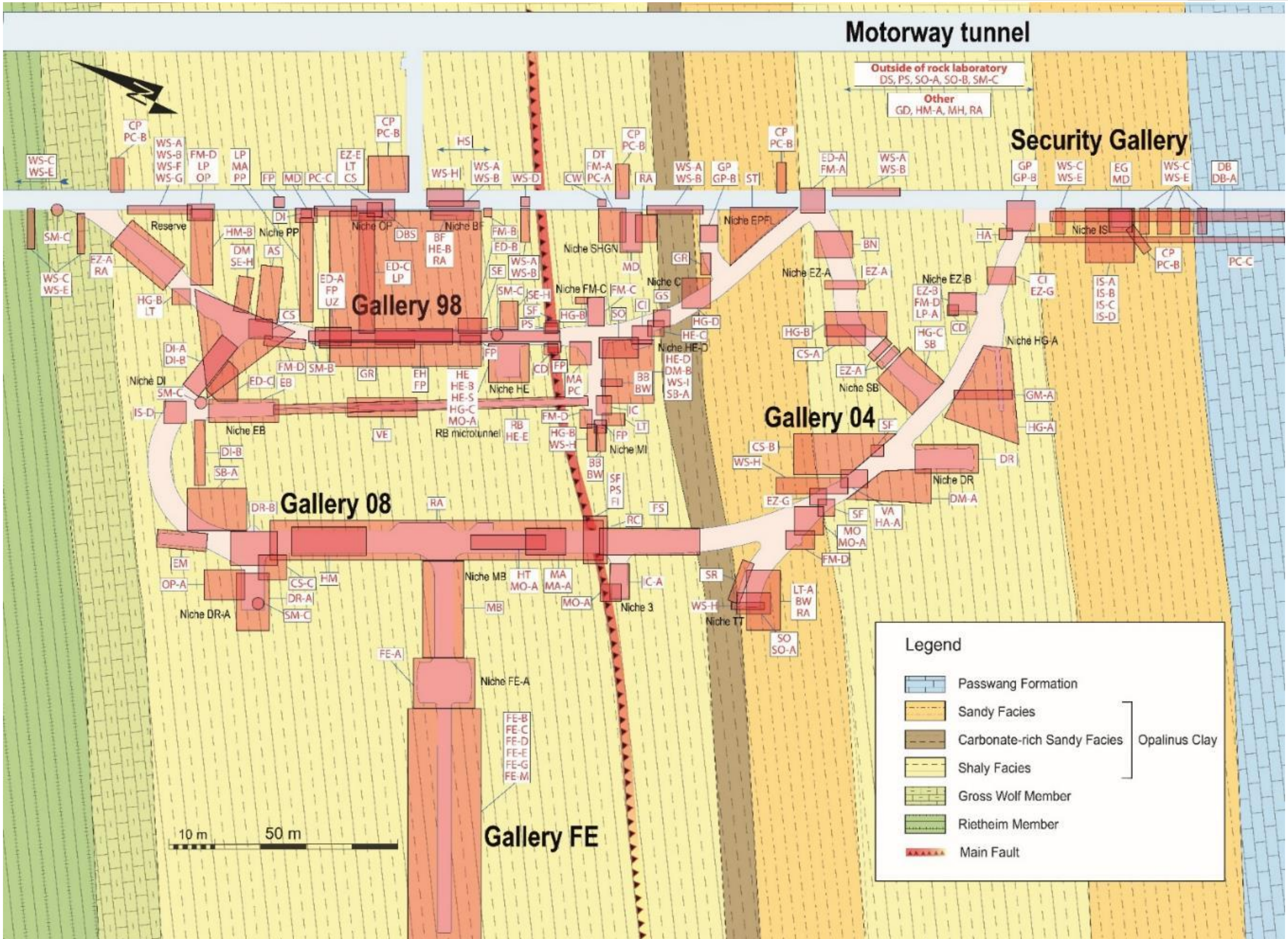




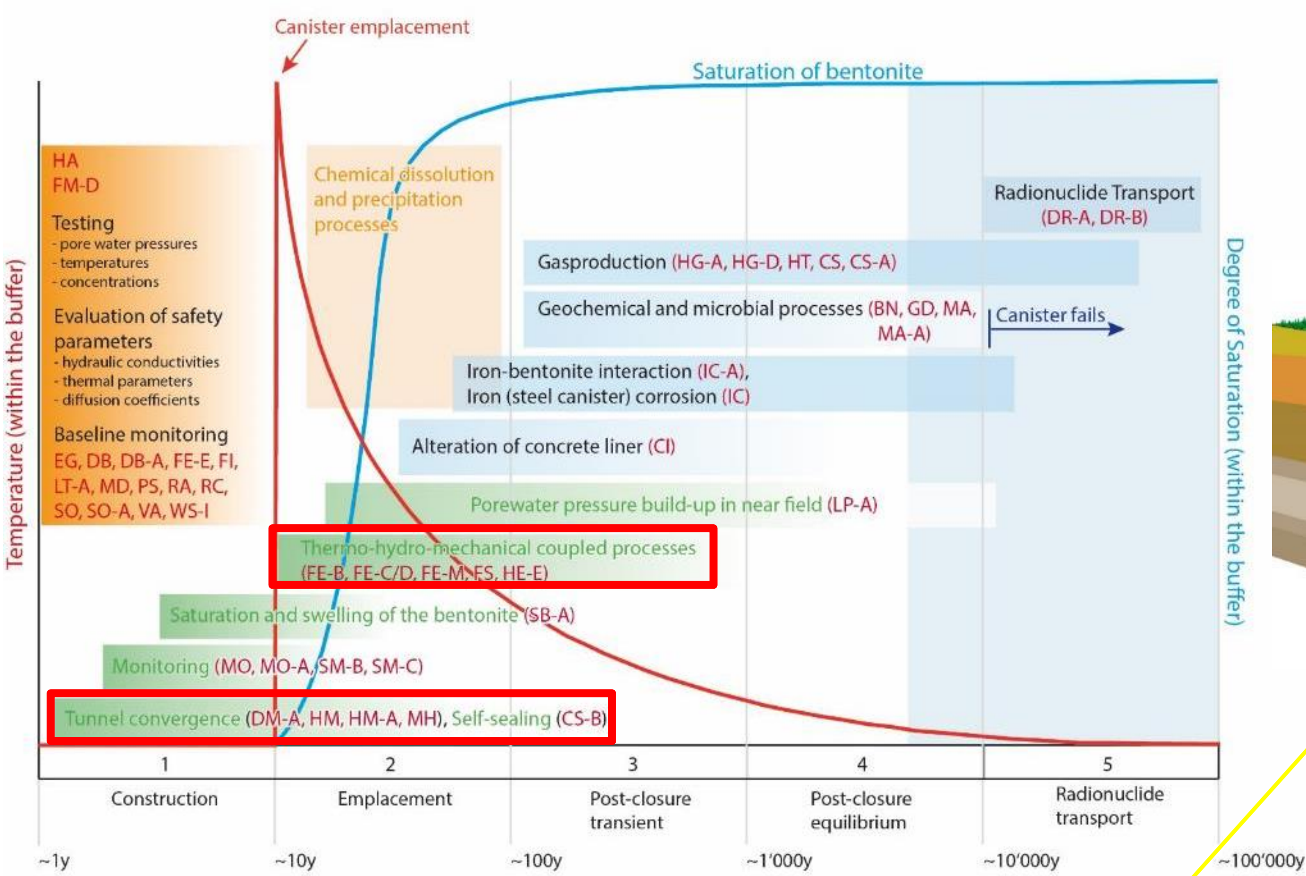


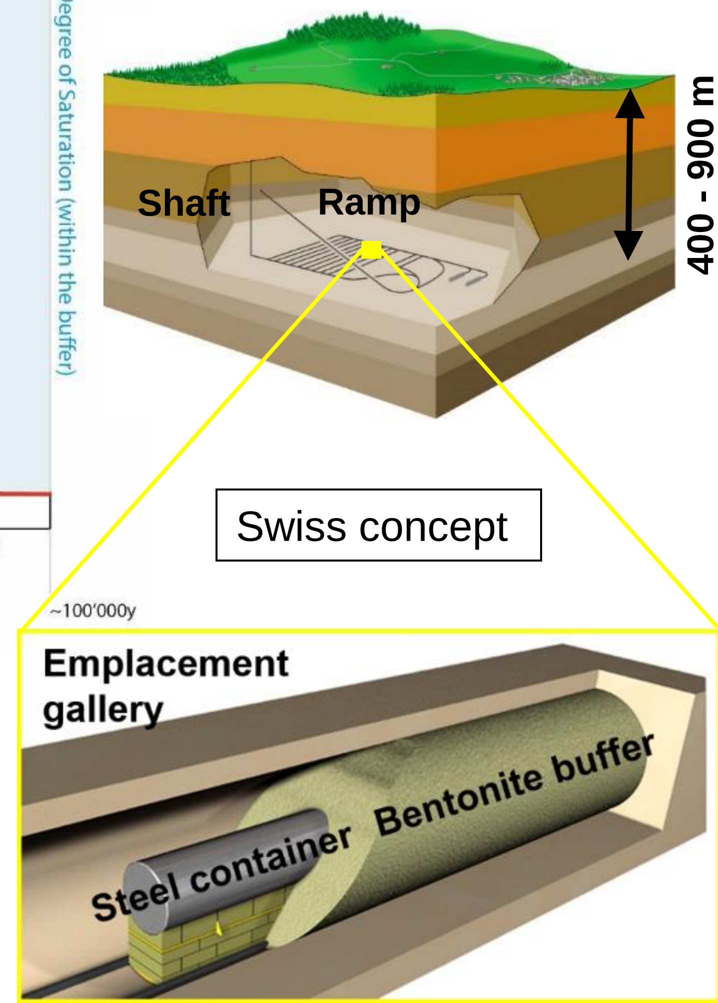


138 in-situ experiments since 1996



Swiss concept and repository evolution





- Experiments are linked to repository evolution
- Mechanical experiments important for construction and emplacement phase

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2. Sampling and rock mechanical testing

3. In-situ stress testing

4. Excavation damaged zone (EDZ)

5. THM-modeling

6. Conclusions

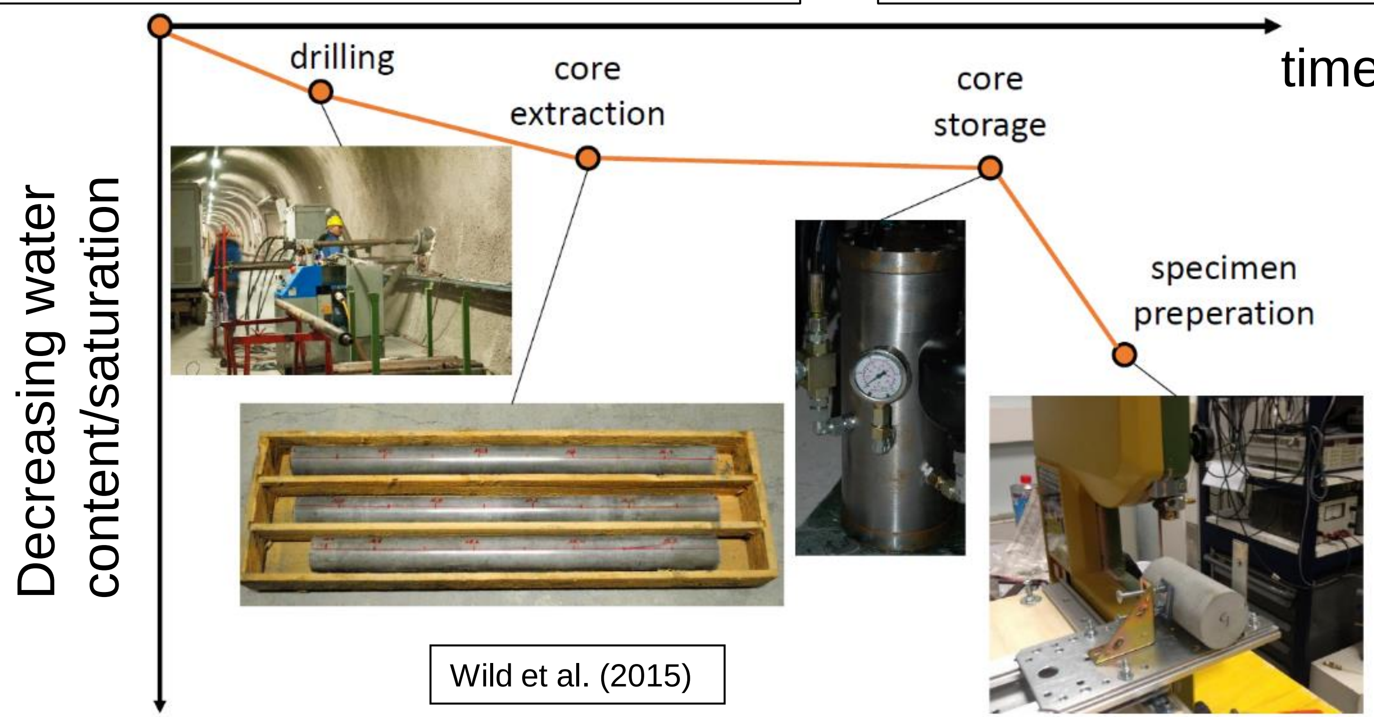
Specimen extraction and sampling strategy

Effects on the clay specimen:

- Stress relief
- Desiccation
- Increased temperature (frictional)
- Mechanical damage, excess pore water pressure

Countermeasures:

- Reduce drilling speed, adapt technique (triple core, air flushing)
- Reduce time of exposure, immediate conditioning
- Use larger diameters



Wild et al. (2015)

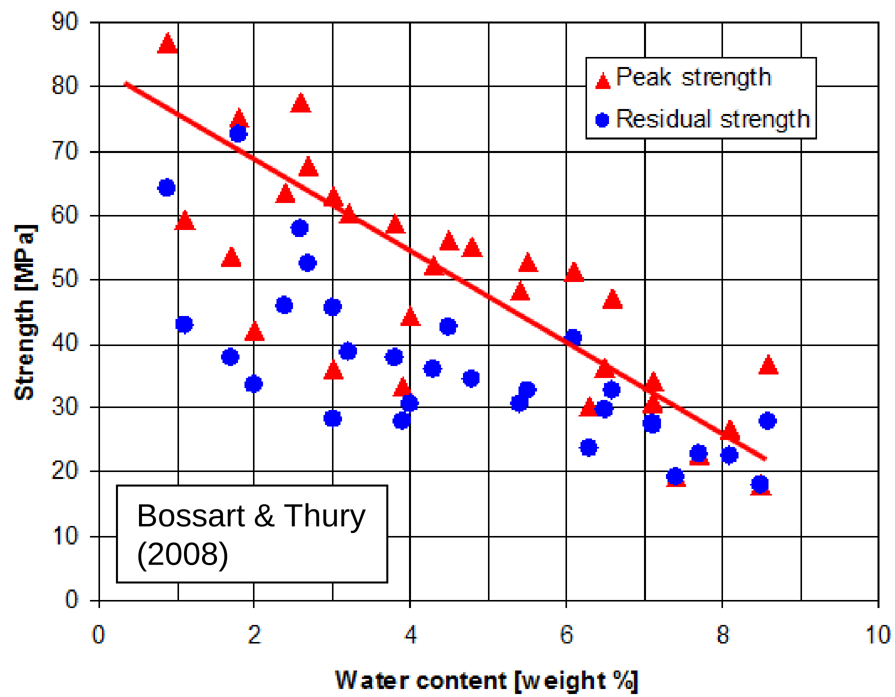
Specimen conditioning

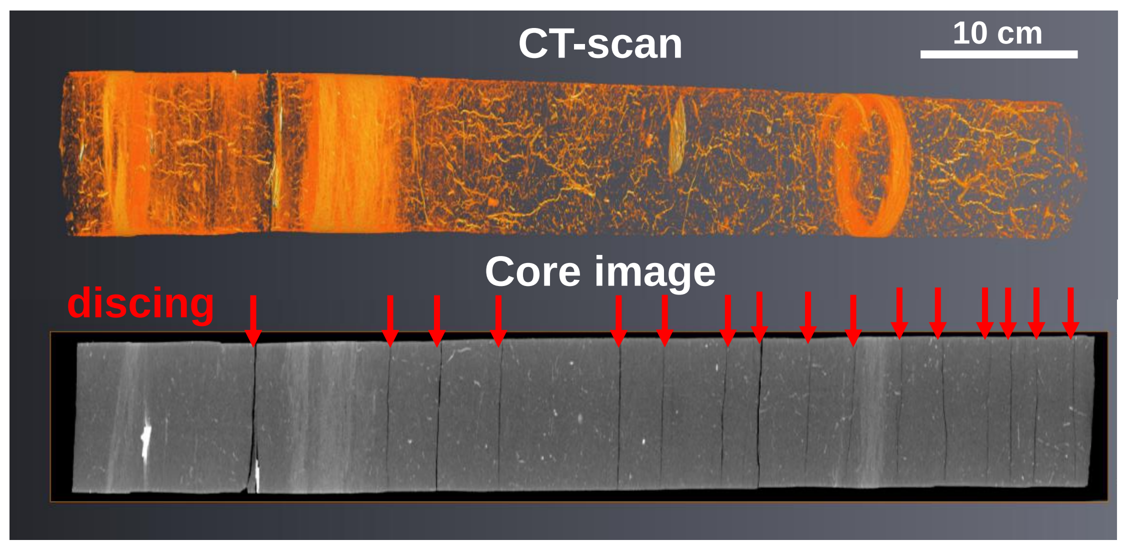
Desciccation leads to:

- Increase of strength
- Desiccation cracks + discing

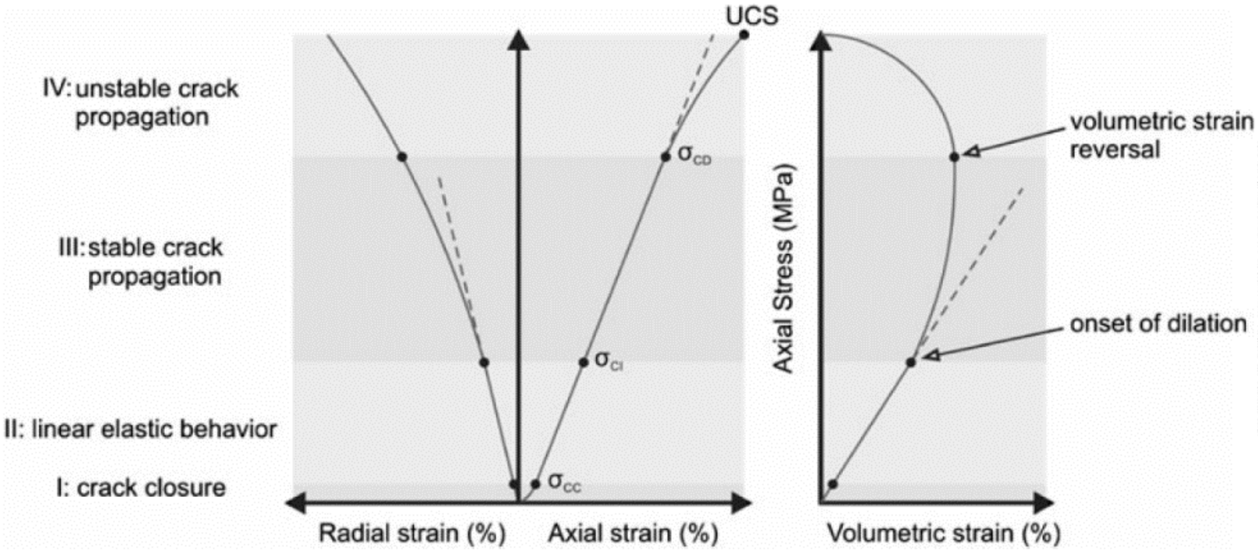
Adapted conditioning:

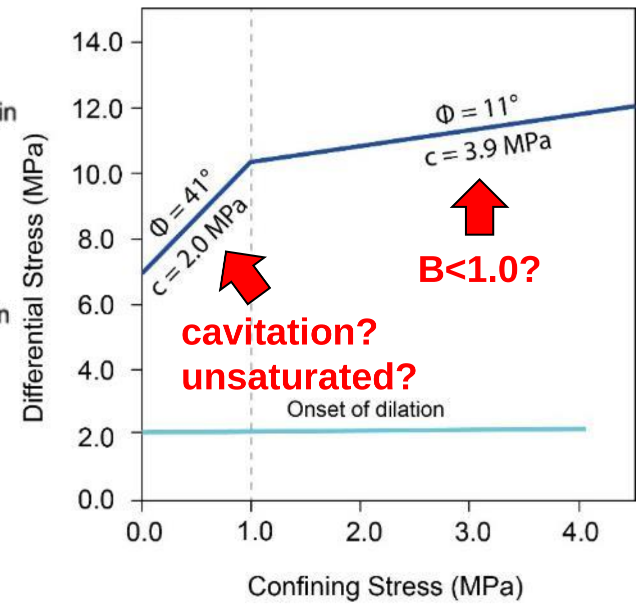
- Triple core drilling
- Determination of water content on-site
- Immediate sealing in aluminum foil
- Saturation of samples to constant suction in lab





Unconsolidated undrained compression tests



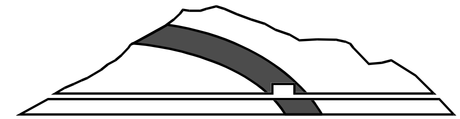


Opalinus Clay shares many similarities with both soils and rocks:

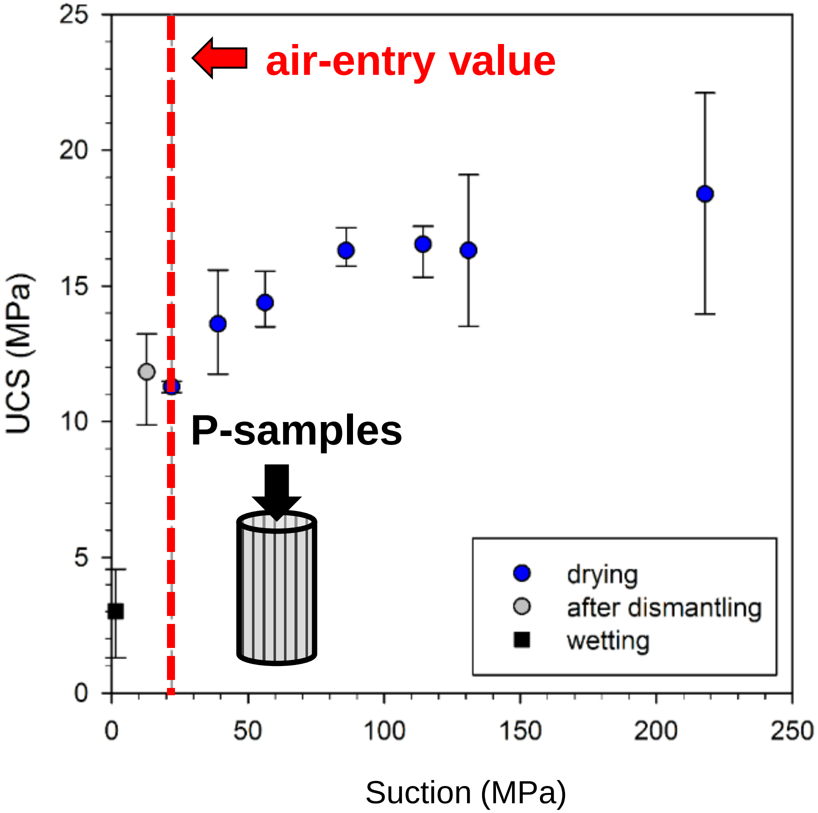
• strong non-linearity	(soil)
• micro-acoustic events	(brittle rock)
• strong dilatancy for σ_3<1MPa	(soil)
• CI independent of σ_3	(brittle rock)

Amann et al. (2011, 2012, 2015)

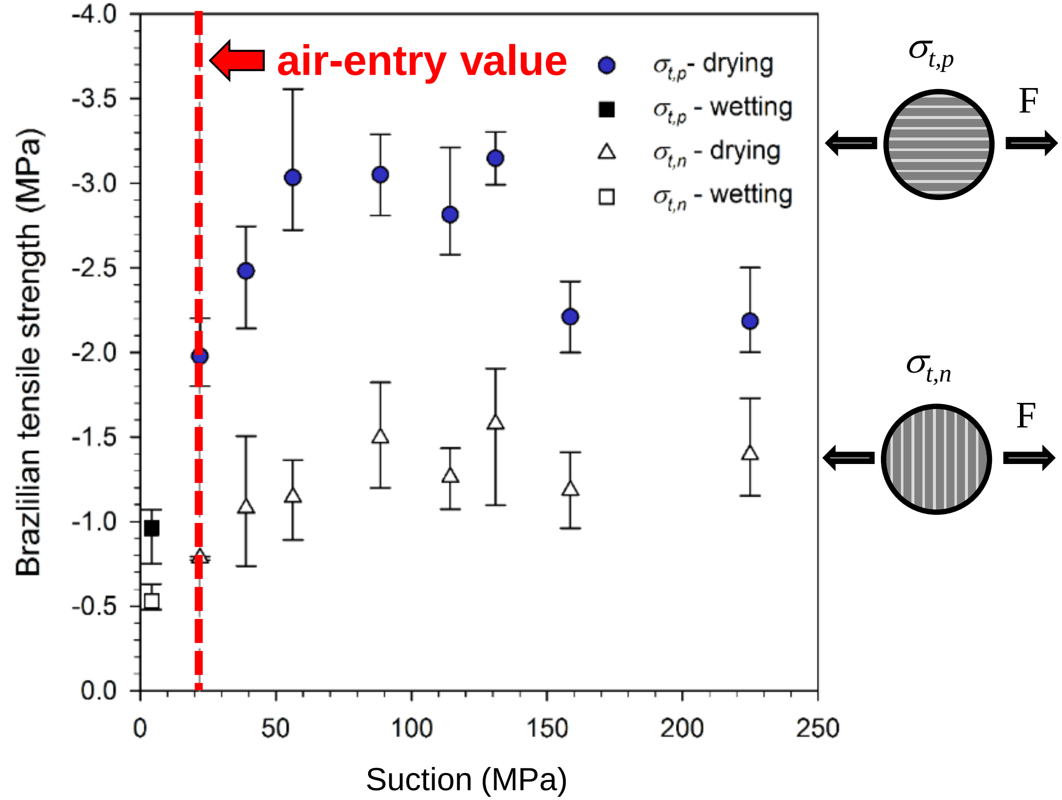
The influence of suction



Uniaxial Compressive Strength (P-samples)



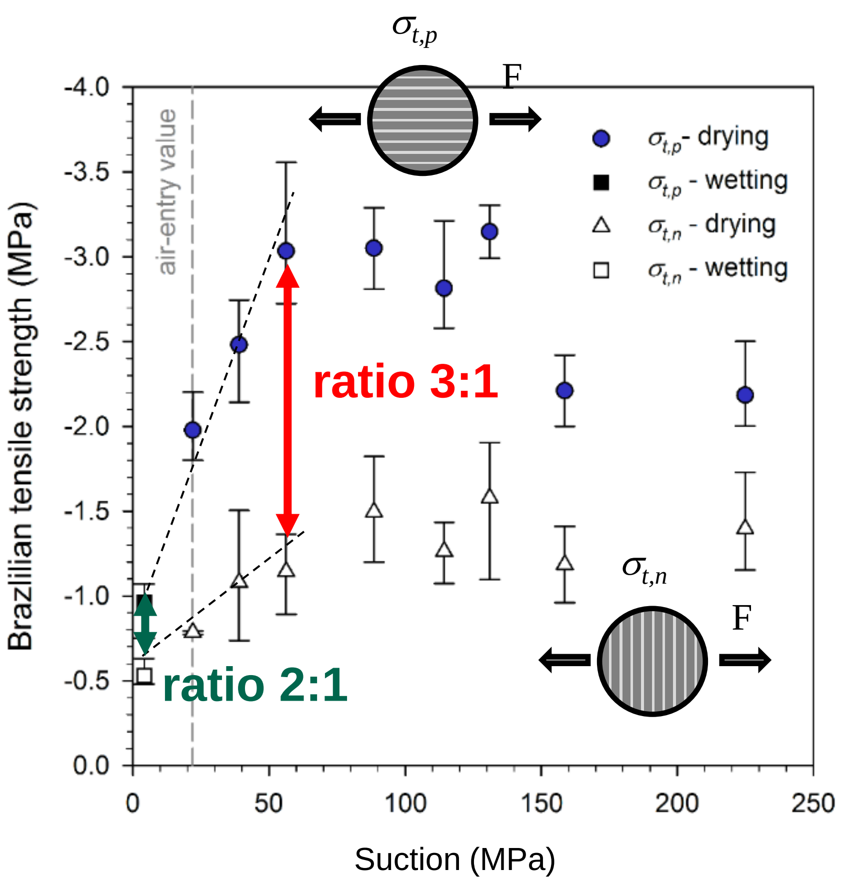
Brazilian Tensile Strength

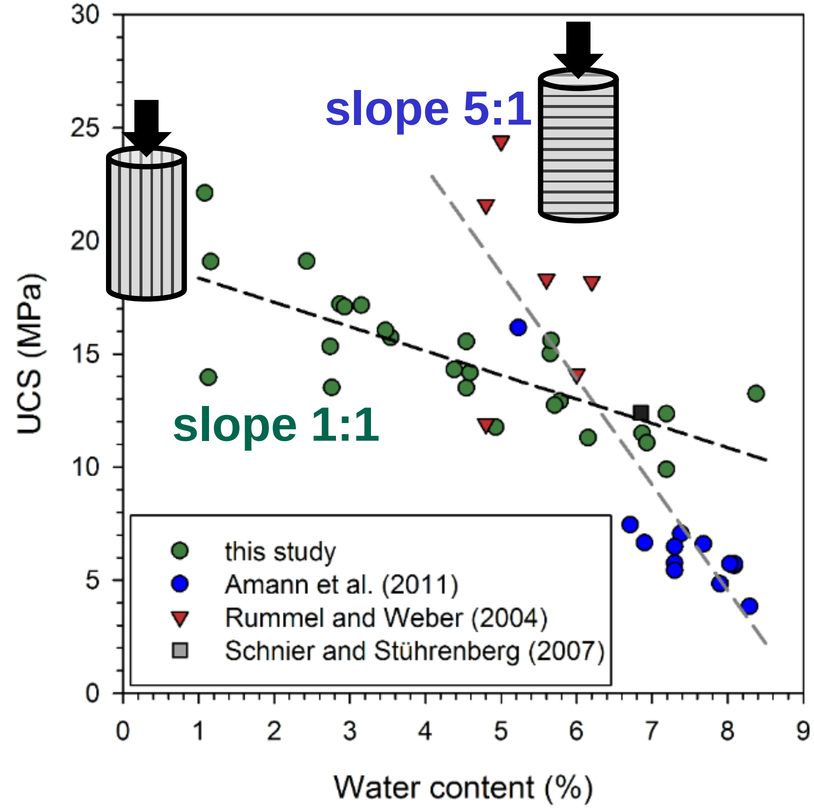


- Substantial influence of suction on strength
- Similarities with soils: “shrinkage limit” equals the “air-entry value”
- Strength loss due to cyclic variations of relative humidity

Wild et al. (2015)

State-dependent anisotropy

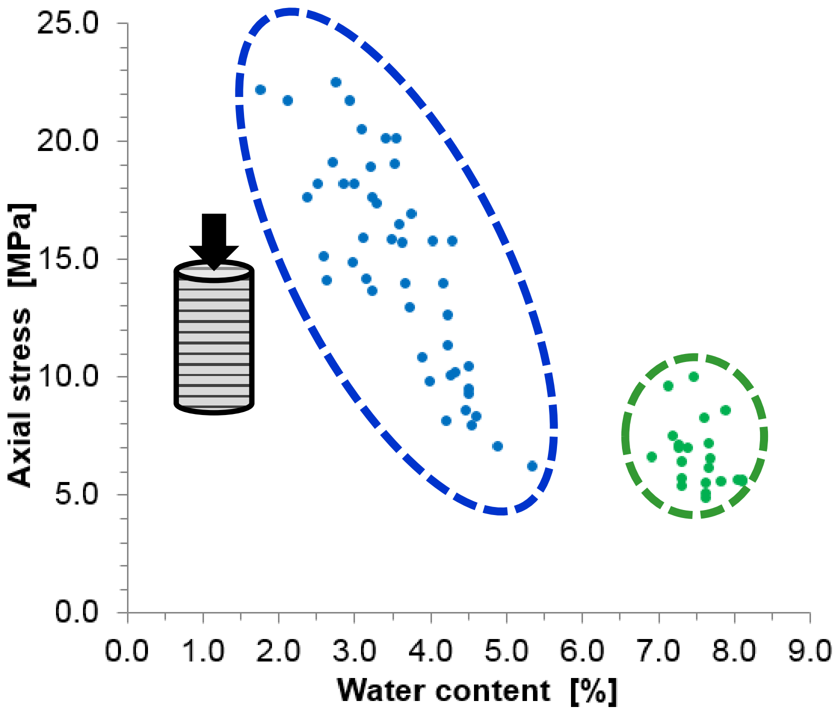


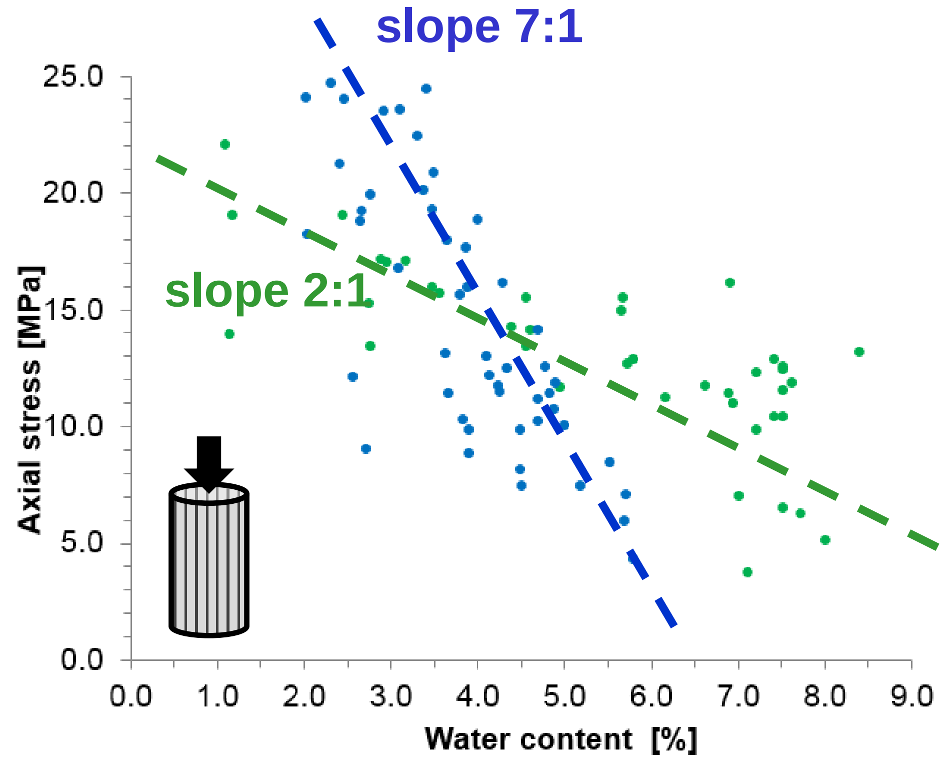


- Effect of orientation to anisotropy higher at higher suction
- UCS versus water content shows steeper slope for s-samples
- Clear influence of anisotropy

Wild et al. (2015)

Impact of facies on rock stiffness



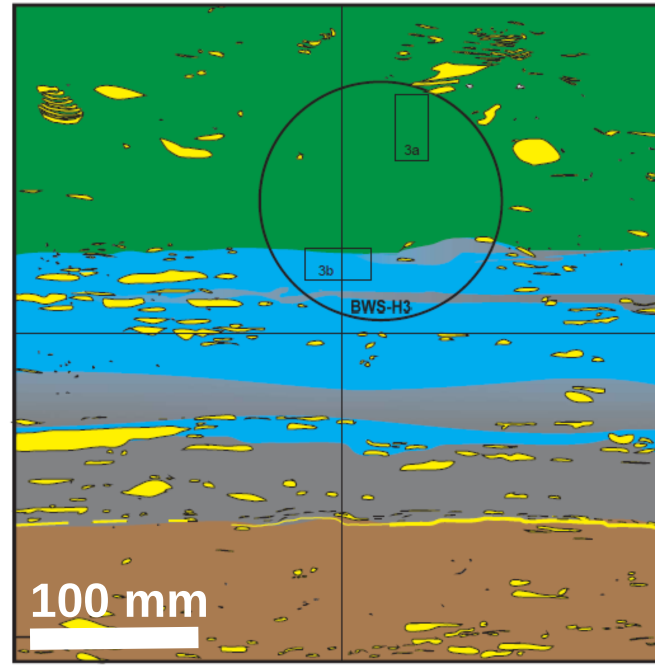


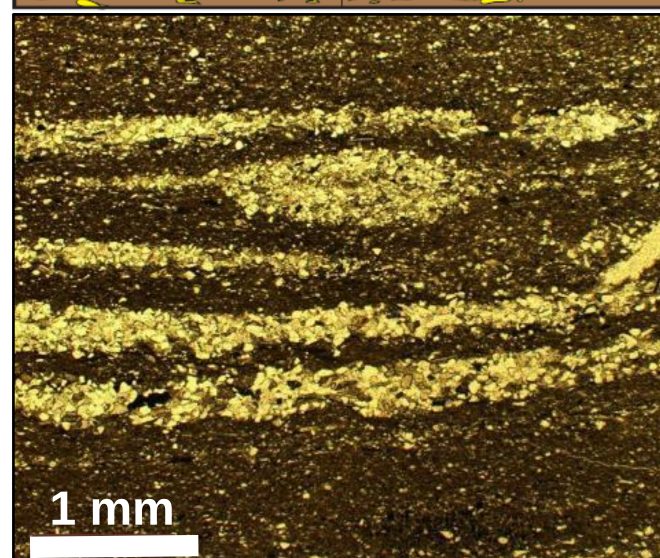
Clear difference between homogeneous **shaly facies** and **sandy facies**

- Scatter of data
- Absolute values
- Slope steeper for sandy facies (P-samples)

Challenges for rock-mechanical testing of Opalinus Clay

- Rock anisotropy
- Significant heterogeneity of sandy facies
- Scale dependency, REV
- Effect of sample size
- Sample extraction and conditioning (suction, damage)
- Few data out of the sandy facies





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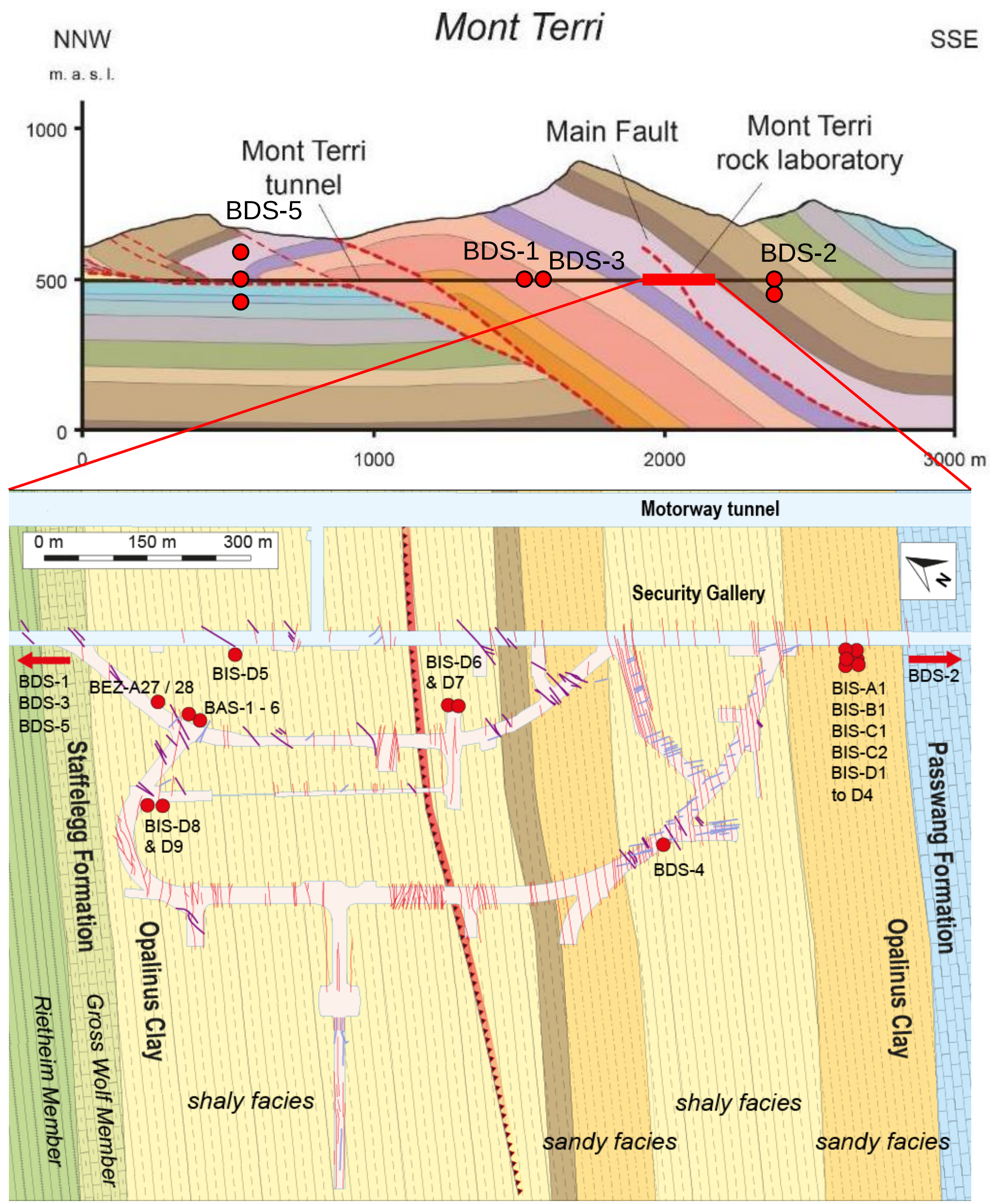
In-situ stress testing at Mont Terri

Experiment	Borehole	Method	Documentation
Determination of stress	BDS-5	Hydraulic stimulation	Jaeggi & Bossart (2015), Vietor & Doe (2015)
Determination of stress	BDS-3	Overcoring	Hesser (2014)
In situ stress, overcoring	BIS-D1 – BIS-D9	Overcoring	Heusermann et al., (2014)
Determination of stress	BDS-1 and BDS-2	Hydraulic stimulation	Rummel et al. (2012)
Determination of stress	BDS-2 and BDS-4	Hydraulic stimulation	Enachescu (2011)
Determination of stress	BDS-1	Laboratory analyses using RACOS®-tests	Jahns (2011)
Anisotropy and rock stress	BAS-1 – BAS-6	Overcoring	Shin (2006, 2009)
EDZ cut-off	BEZ-A27 and BEZ-A28	Overcoring	Lahaye (2005)
In situ stress, borehole slotter	BIS-B1	Dilatometer, Borehole slotter	Bühler (2000), König & Bock (1997)
In situ stress, hydraulic stimulation	BIS-C1 and BIS-C2	Hydraulic stimulation	Evans et al. (1999)
In situ stress, over- and undercoring	BIS-A1	Overcoring, Undercoring	Bigarré (1996, 1997), Bigarré & Lizeur (1997), Bigarré et al. (1997)



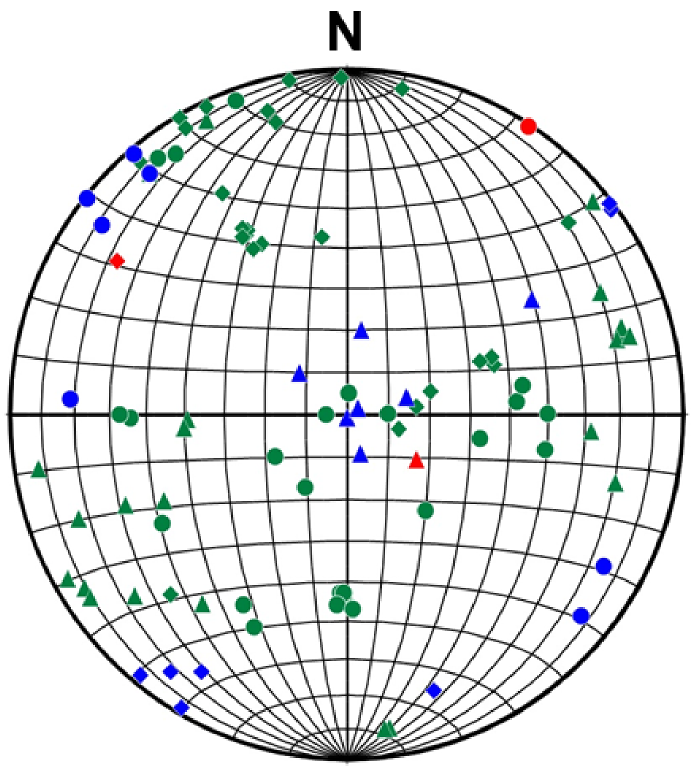
In-situ stress measurements methods

- **Hydraulic methods** (provide only direct measure of stress)
  - Hydraulic Testing on Pre-existing Fractures (HTPF)
  - Hydraulic stimulation
- **Borehole failure methods** (useful in high-stress situations)
  - Borehole breakouts
  - Drilling-induced tension fractures
- **Stress relief methods** (measure strain, not stress)
  - Overcoring (various types of gauges)
  - Borehole slotter
  - Under-excavation technique
- Earthquake fault plane solutions (large-scale stress)

Methods applied at Mont Terri are highlighted in red

Results from 33 analyzed tests

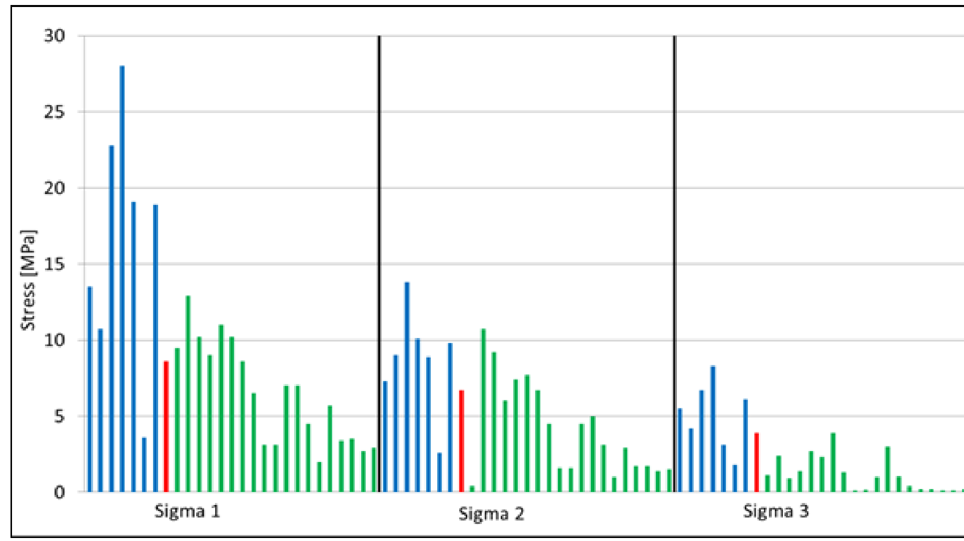
Orientations of principal stresses



(Lower hemisphere equal area)

n=33

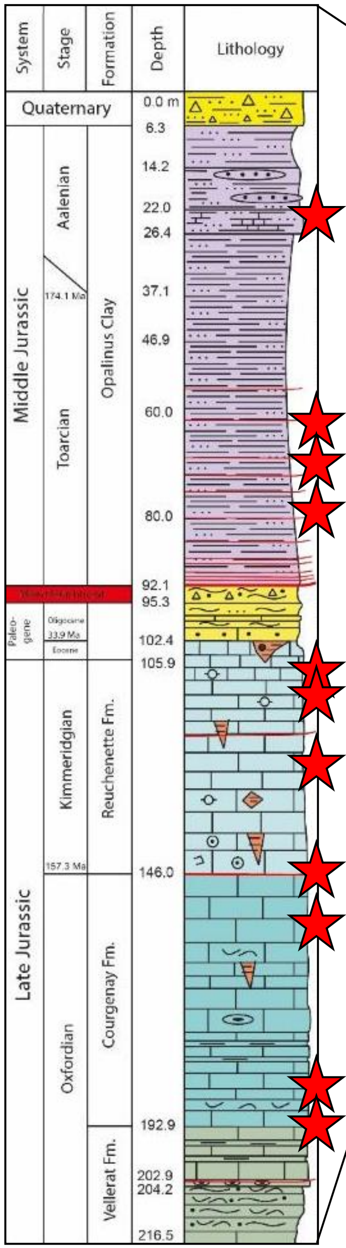
Magnitudes of principal stresses

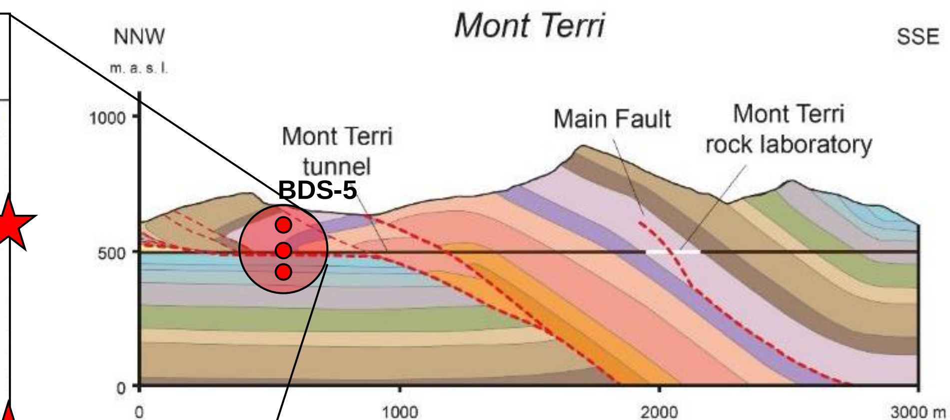


Properties of tests	σ_1	σ_2	σ_3
Deep borehole >20 m	●	▲	◆
Competent rock (limestone)	●	▲	◆
Rock lab, incompetent rock (shale)	●	▲	◆

Jaeggi & Bossart (2016), in prep.

In-situ stress testing across décollement



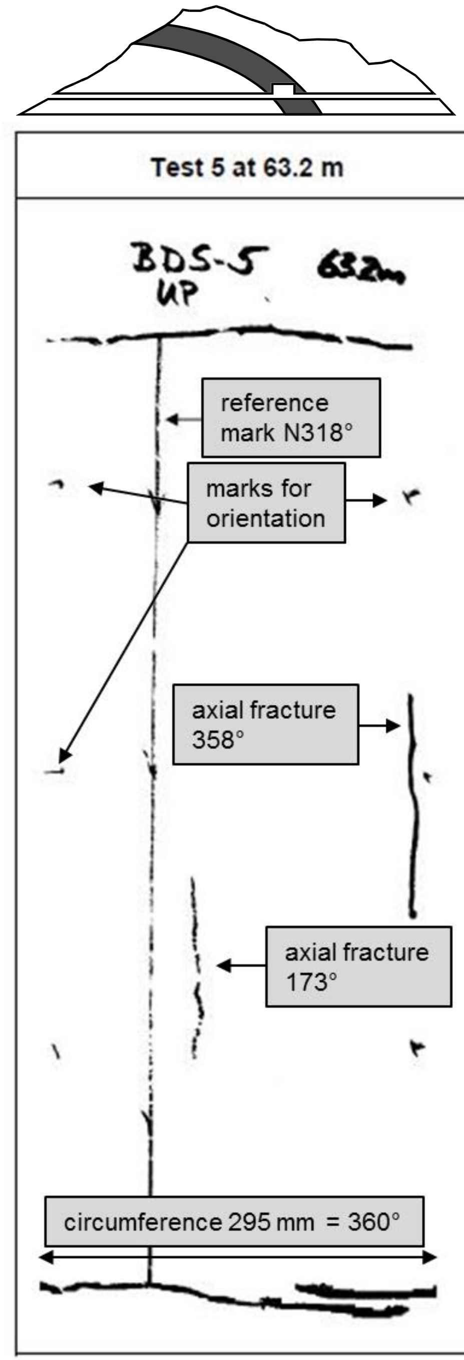


- BDS-5 drilled across the main décollement
- Opalinus Clay thrust onto upper Jurassic limestones
- Opalinus Clay strongly tectonized

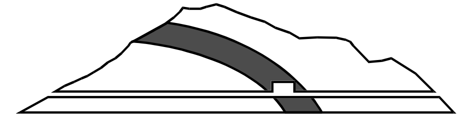
→ Decoupling across décollement?

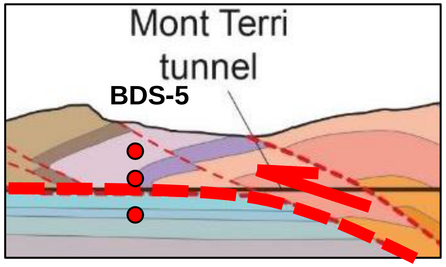
- 11 hydraulic stimulation tests ★
- 10 impression packer tests
- pre- and post-frac ABI

Jaeggi & Bossart (2016), in prep.



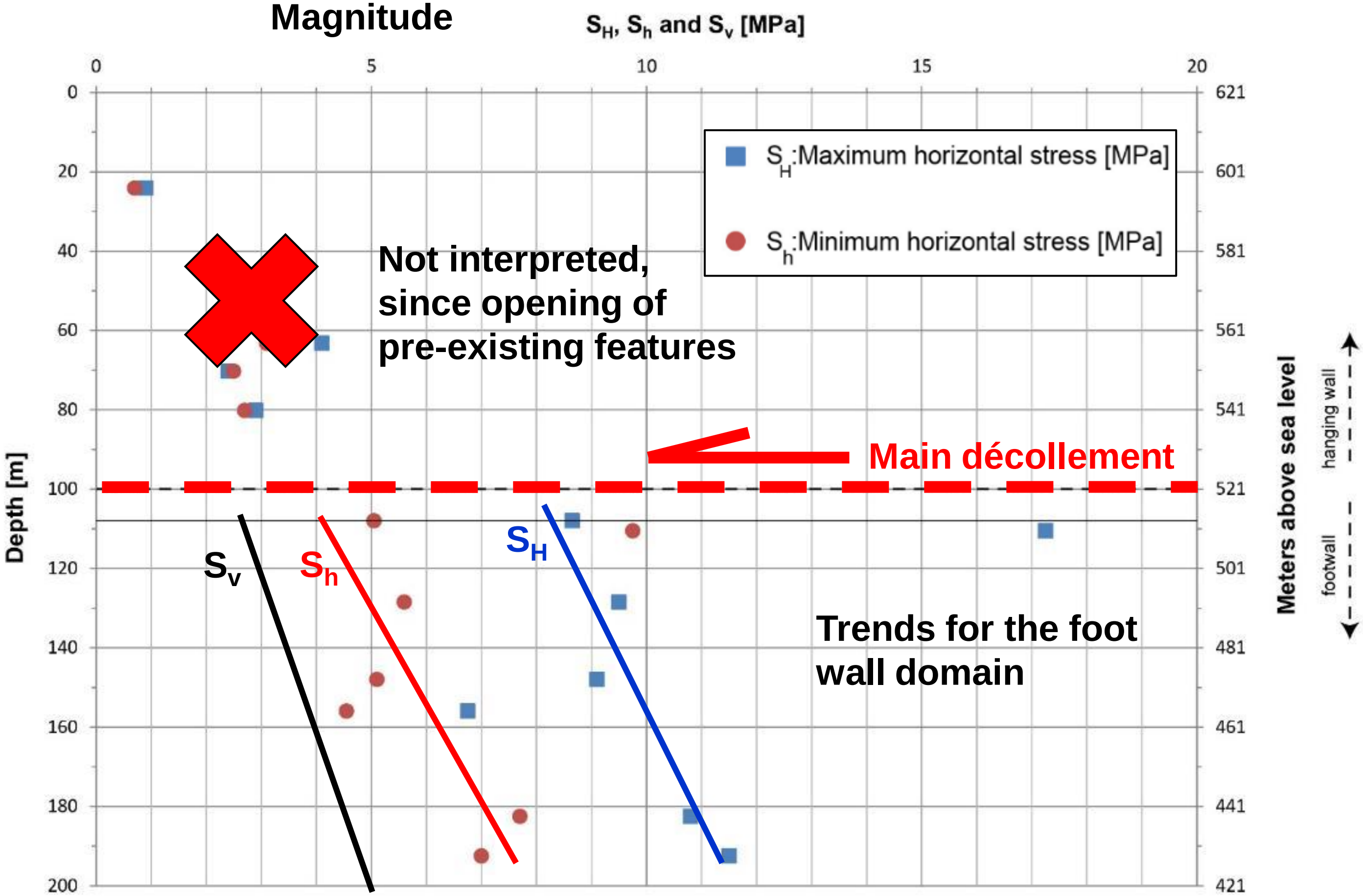
Hydraulic stimulation data of BDS-5



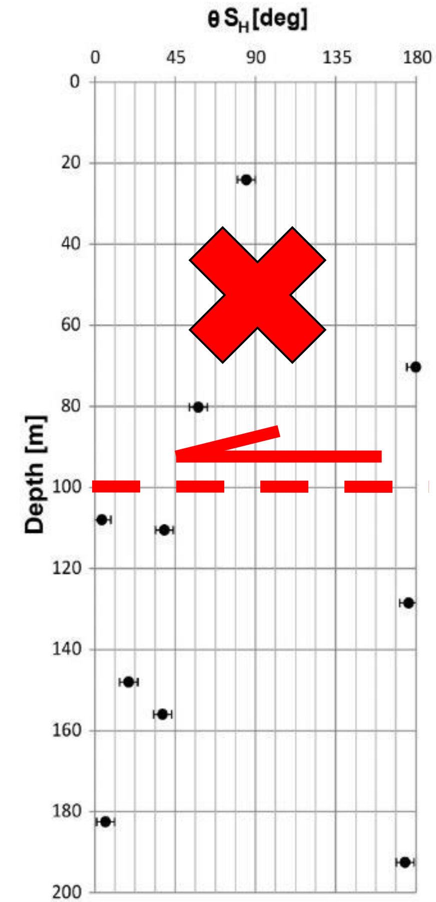


Stress components	Magnitude [MPa]	Stress direction (footwall) [°]
S_H	8.3	14±19
S_h	4.3	284
S_v	2.7	-

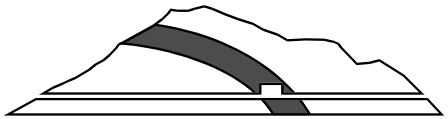
Magnitude



Stress direction



Controls on in-situ stress and mechanisms



- Excavation controlled stresses
  - Primary and secondary stress field
  - 2-3 tunnel diameters
- Depth controlled stresses
  - Topography important at shallow levels
  - Tectonic bench-vice at deeper levels
- Lithology controlled stresses
  - Rock competence (UCS, elastic parameters)
  - Backbone and stress transfer in stiff rocks

Proposed stress tensor

σ_1	6-7 MPa	210/70°	subvertical
$\sigma_{2/3}$	4-5 MPa	320/10°	subhorizontal
$\sigma_{3/2}$	2-3 MPa	050/15°	subhorizontal

Martin & Lanyon (2003), Bossart & Wermeille (2003) - $\sigma_{2/3}$ in plane but not well defined

σ_1	8.6 MPa	033/0°	horizontal
σ_2	6.7 MPa	123/70°	subvertical
σ_3	3.9 MPa	303/20°	subhorizontal

Enachescu (2011)

σ_1	15 MPa	320/0°	subhorizontal
σ_2	8 MPa	070/0°	subhorizontal
σ_3	4 MPa		subvertical

Shin (2006, 2009)

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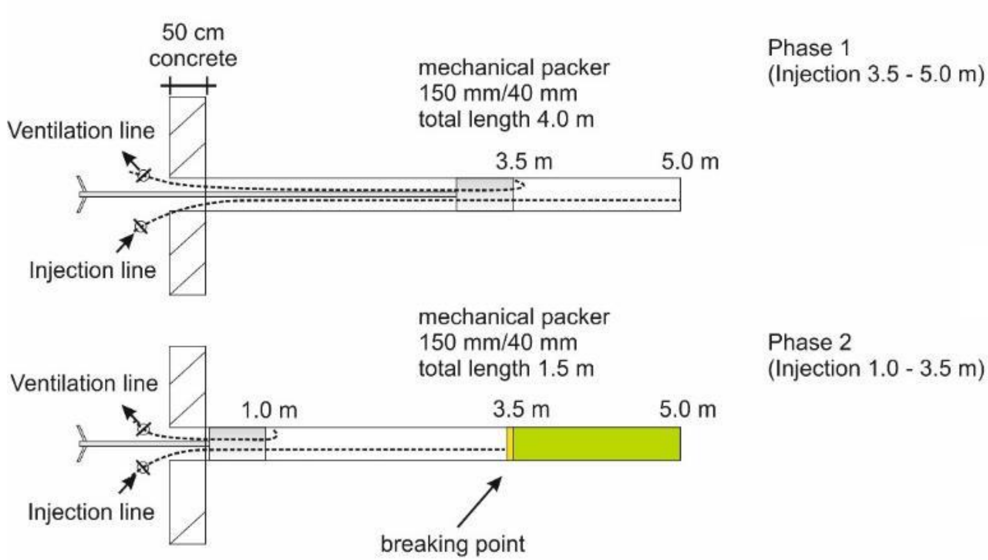
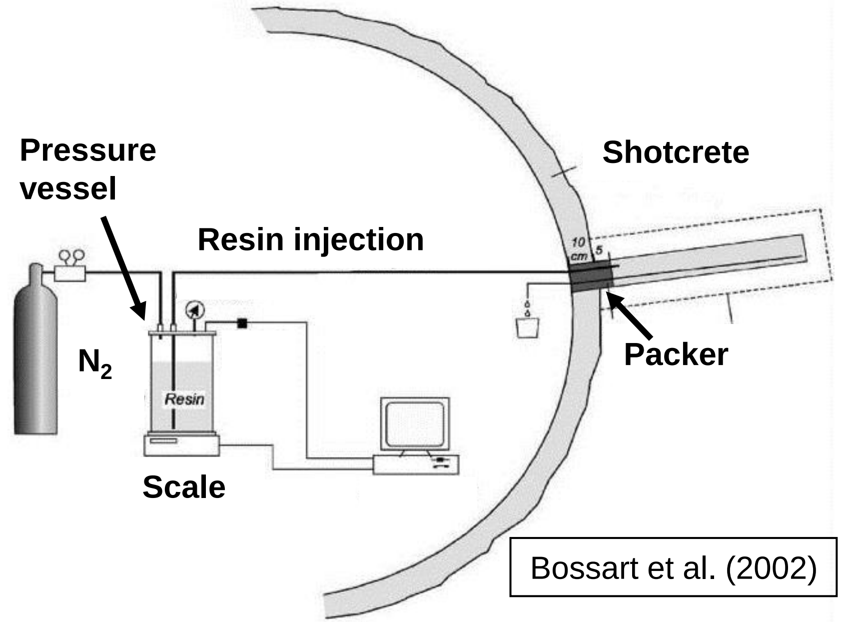
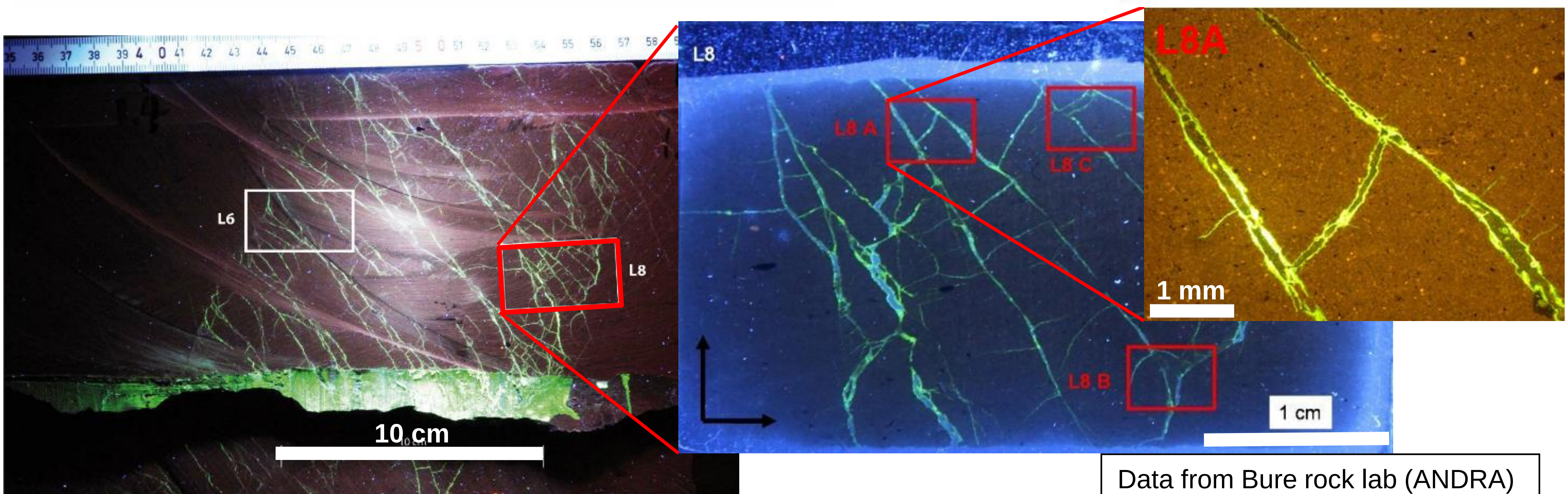
Resin impregnation technique for EDZ characterization

Borehole length: 5.0 m, diameter: 42 mm, slightly inclined





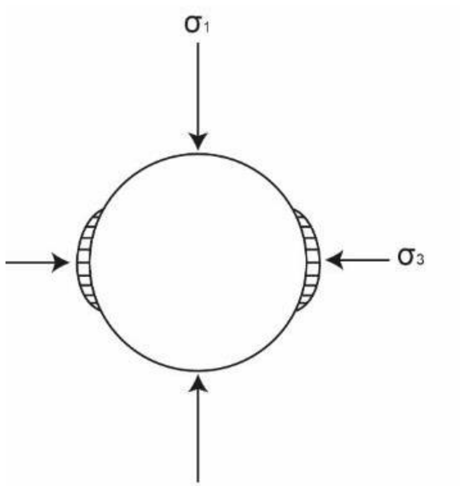
Bossart et al. (2002)

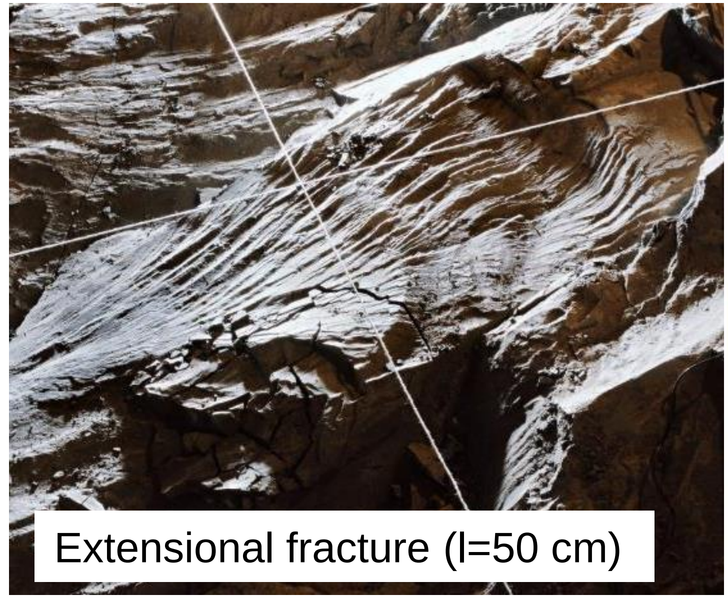


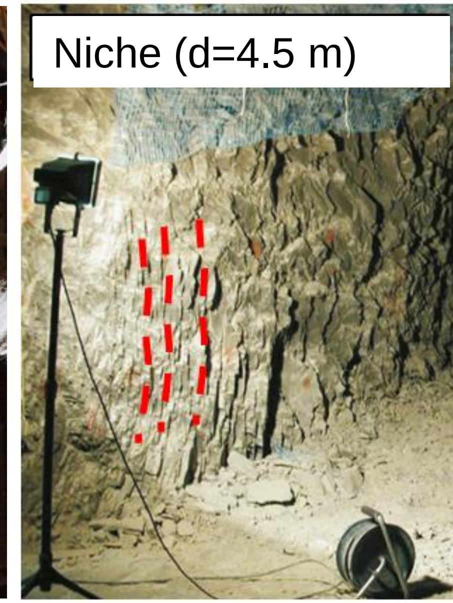
Data from Bure rock lab (ANDRA)

EDZ development and observations on various scales

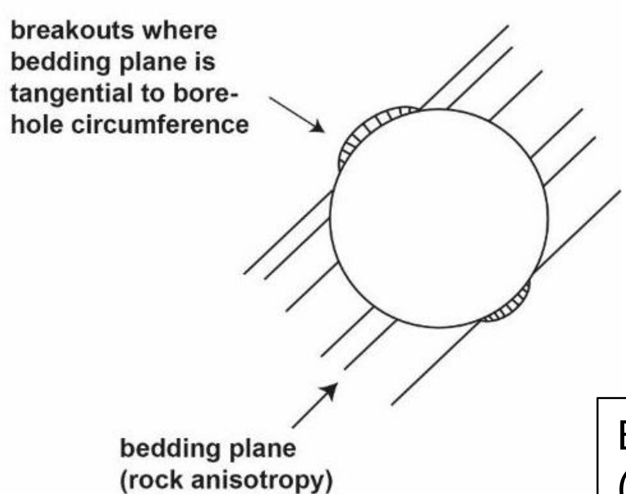
Stress-induced breakouts

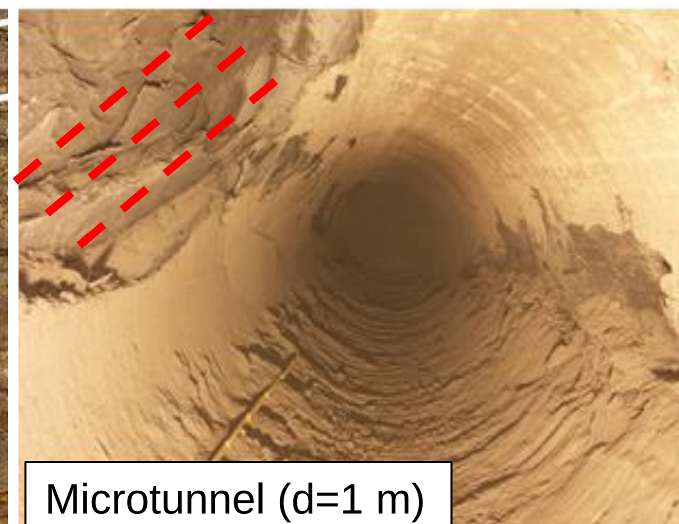




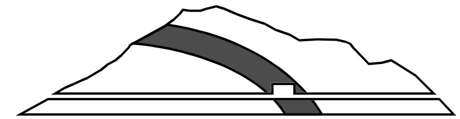


Mechanical controlled breakouts

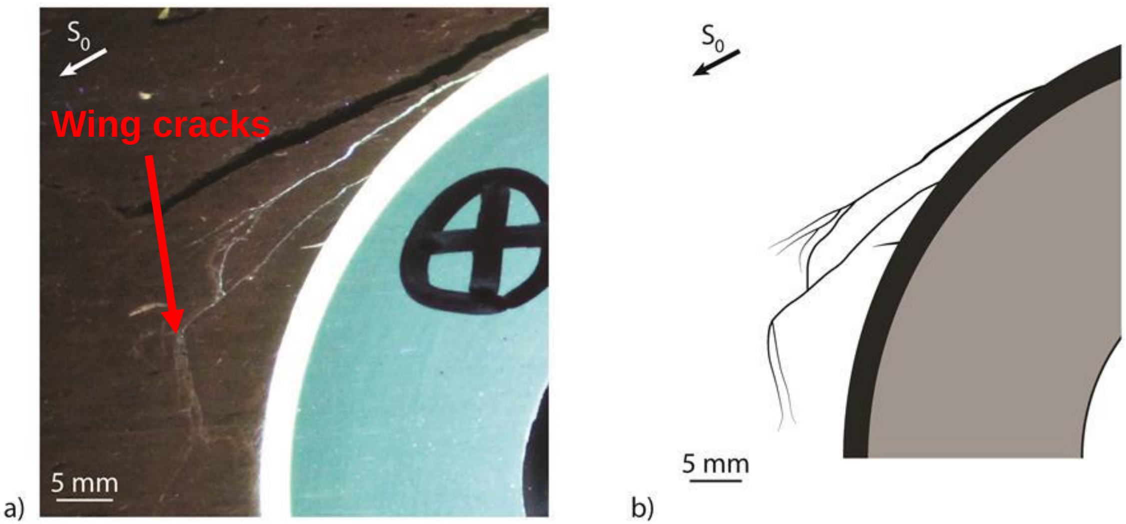




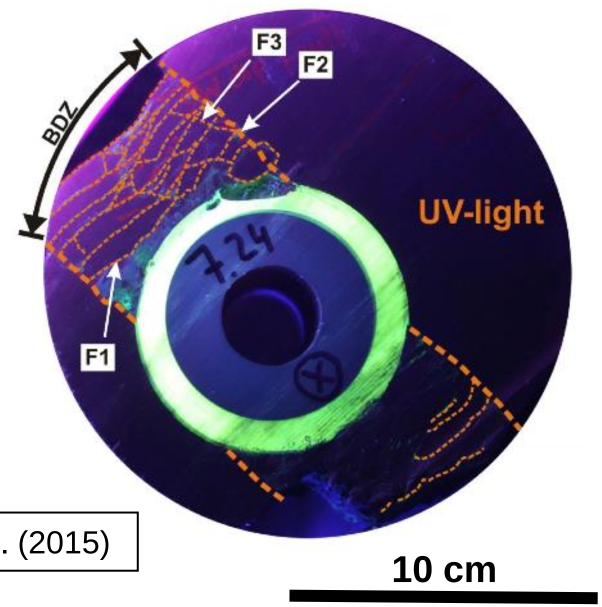
Temporal evolution of borehole disturbed zone



Short-term BDZ



Intermediate-term BDZ

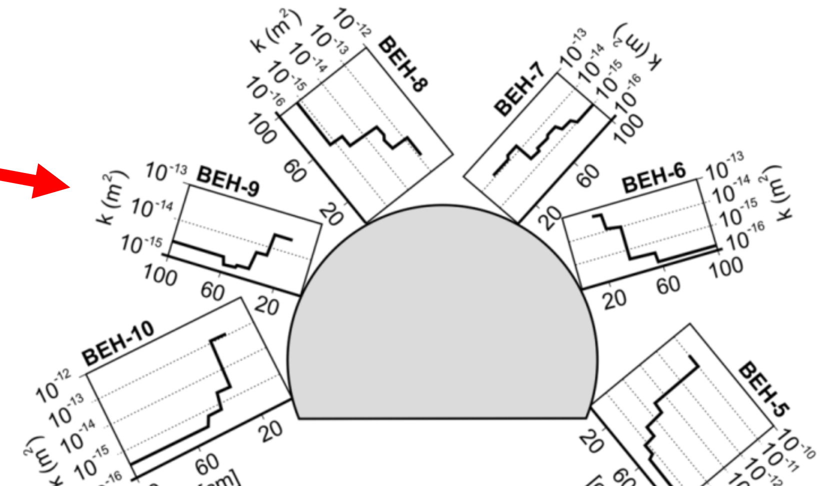


Kupferschmied et al. (2015)

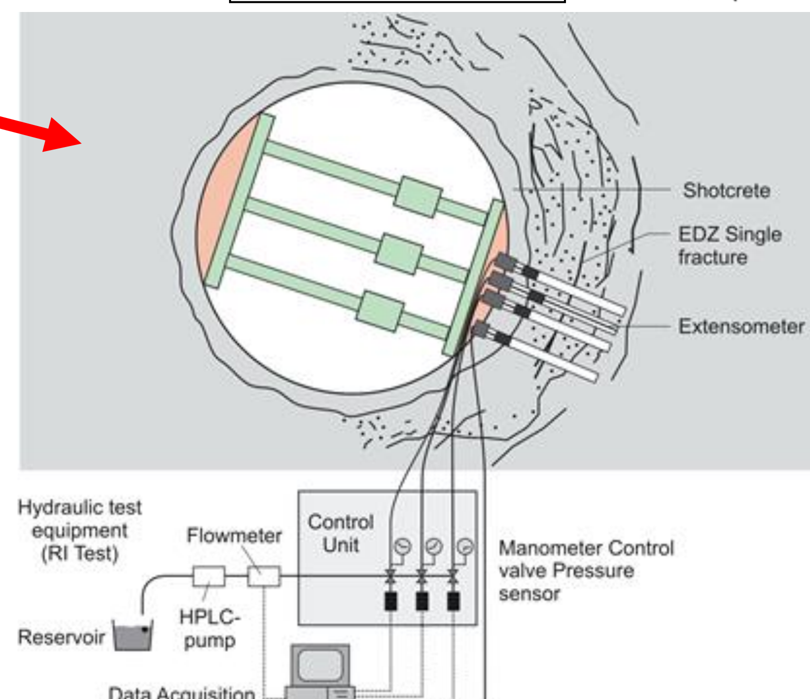
- Short-term BDZ (within hours)
  - tangential shear fractures
- Extensional fractures and secondary shear fractures
  - interconnected fracture network
- Intermediate-term BDZ (within days)
  - tangential fractures in the opposing direction
  - further bedding parallel fractures, buckling chimney

EDZ - hydraulic properties and self-sealing

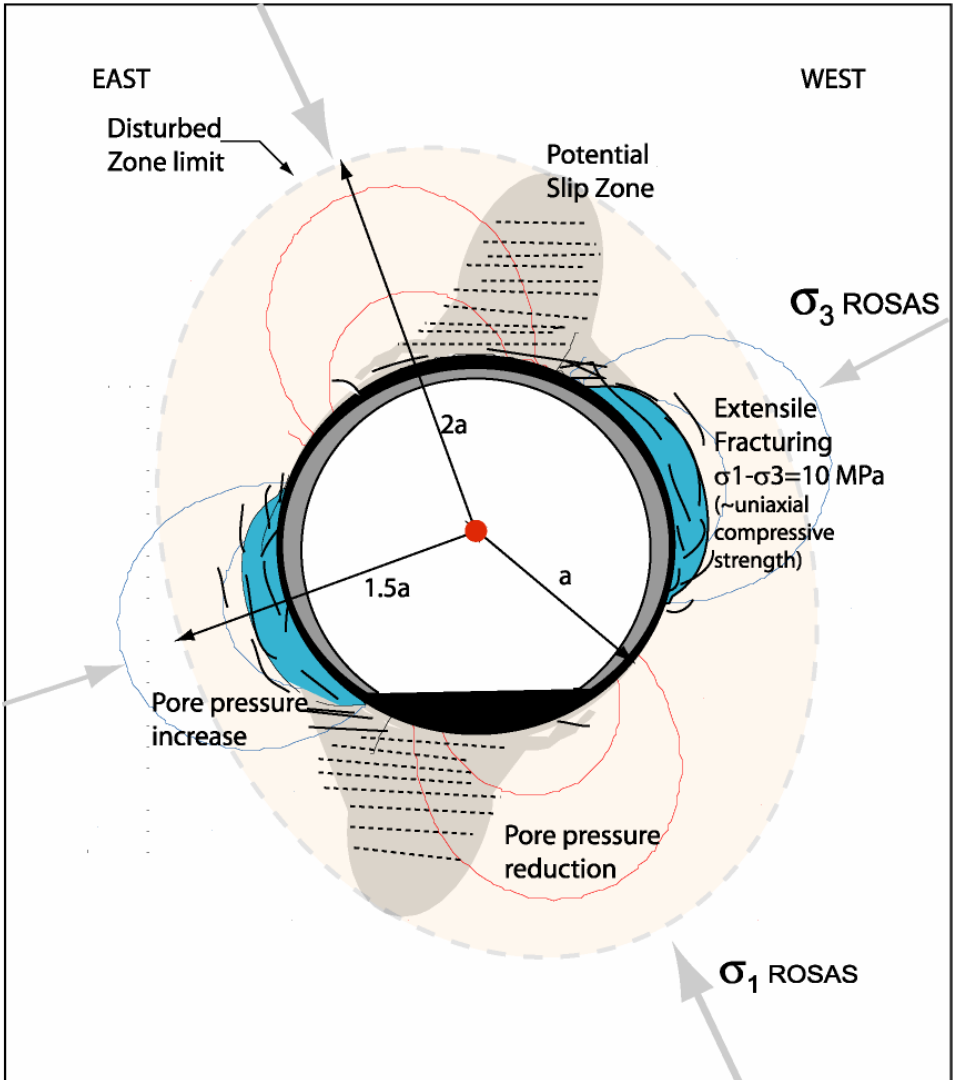
- Pneumatic tests / short intervals:
  - Gas permeability high close to tunnel wall
- Self-sealing tests (hydraulic):
  - Swelling closes fractures
- Self-sealing tests (mechanical):
  - Mechanical confinement through buffer
- Cyclic deformations:
  - Humidity variations change properties of EDZ

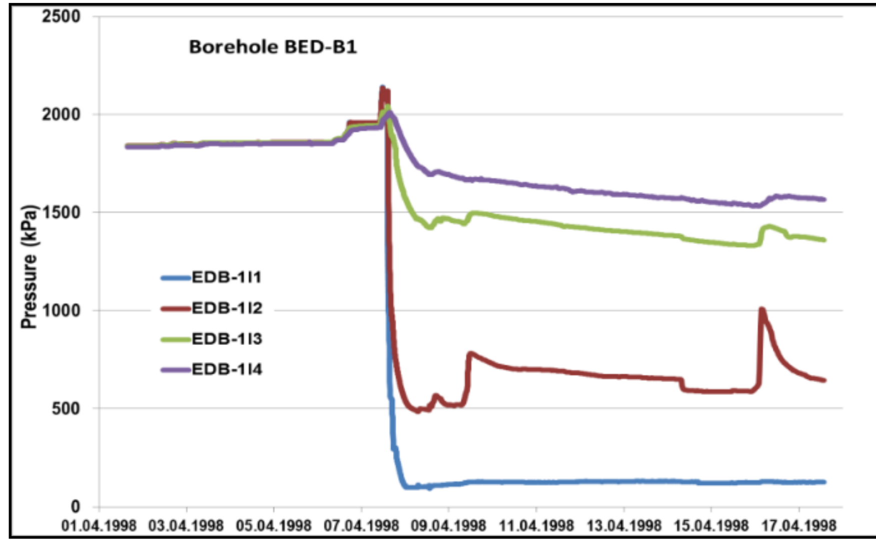


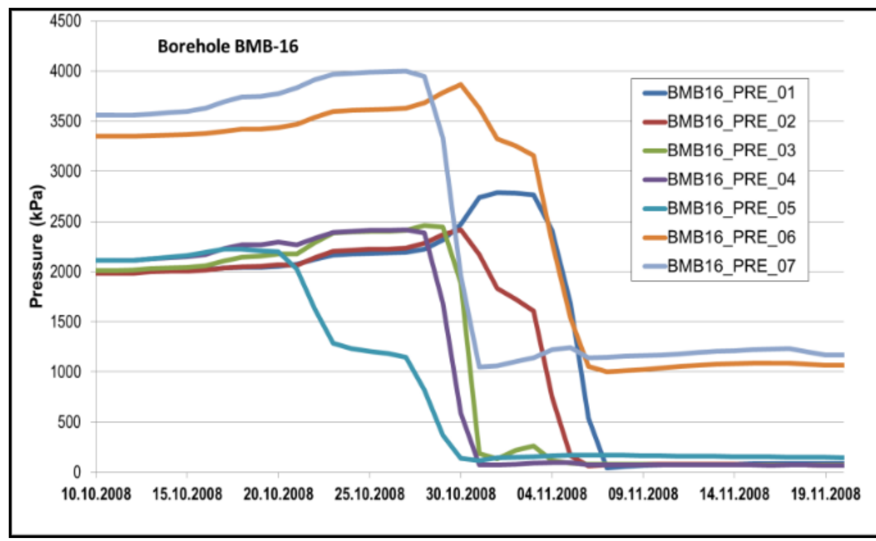
Bossart et al. (2002)



Conceptual model of EDZ for tunnel towards South (HM-coupling)







Martin & Lanyon (2002)

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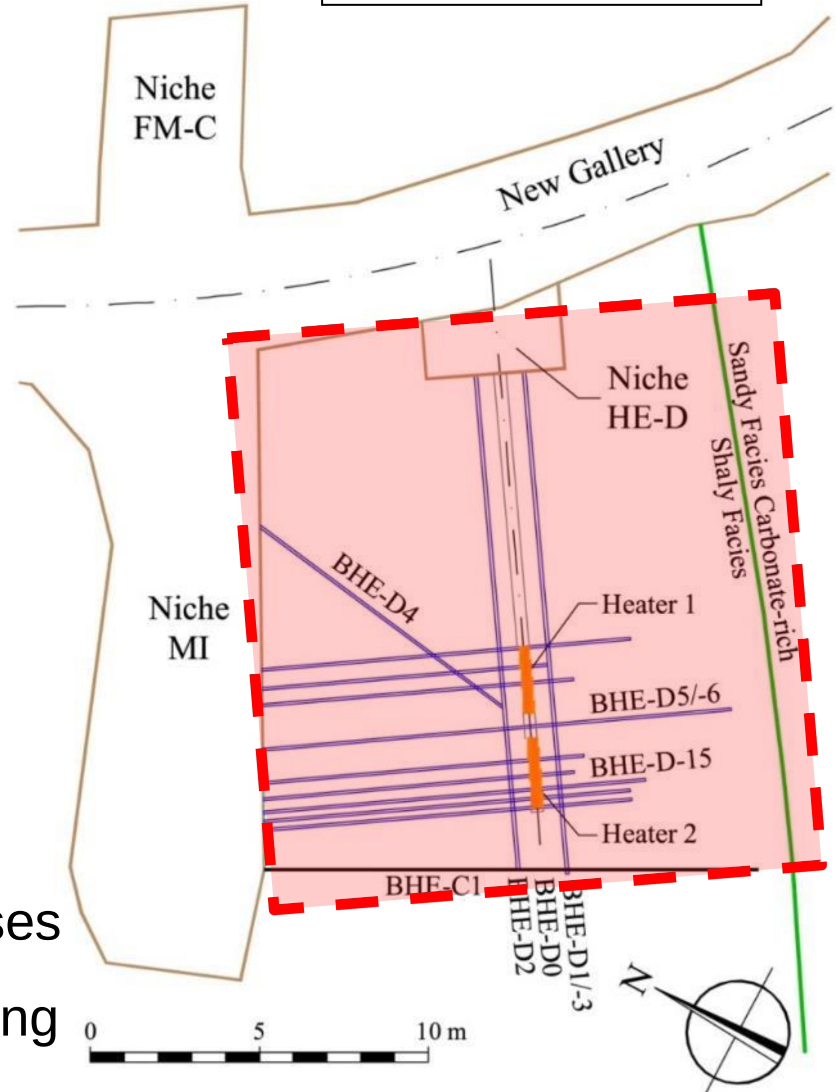
Selection of numerical models applied at Mont Terri

Experiment	Year	Content	Model type	Constitutive Model	Code
HM-A	2015	HM- modeling tunnel of rock lab (collaboration swisstopo, EPFL)	Hydro-Mechanical coupled	Bilinear strain-hardening/softening ubiquitous joints APD (Anisotropy, plasticity, damage)	FLAC 3D CODE-ASTER
FE	2012	Predictive modeling of FE	Hydro-Mechanical coupled	Bilinear strain-hardening/softening ubiquitous joints	FLAC 3D
DR	2010	Modeling of diffusion experiment	Hydro-Chemical	Reactive transport model	PHREEQC
MB	2009	Excavation of MB niche	Hydro-Mechanical coupled	Bilinear strain-hardening/softening ubiquitous joints	FLAC 3D
EZ-A	2006	Stability of EDZ around EZ-A	Hydro-Mechanical coupled	Elastoplastic, Mohr Coulomb	FLAC 3D
Gallery04	2005	Deformations in EZ-B and HG-A niches	Hydro-Mechanical coupled	Elastoplastic, Mohr Coulomb	FLAC 3D
VE	2004	Modeling of micro tunnel	Hydro-Mechanical coupled	Elastoplastic model	CODE-BRIGHT
HE-D	2004	Modeling HE-D Experiment	THM	Elastoplastic model Elastoplastic model Isotropic poroelastic model	FLAC 3D, CODE-BRIGHT CODE-ASTER
HE	2002	Modeling of HE niche excavation	Hydro-Mechanical coupled	Elastoplastic ubiquitous joints	FLAC 3D
RA	2001	Modeling EDZ behavior	Hydro-Mechanical coupled	Bilinear strain-hardening/softening ubiquitous joints	FLAC 3D
DM	1999	Deformation mechanisms, new constitutive law	Hydro-Mechanical coupled	Bilinear strain-hardening/softening ubiquitous joints	FLAC 2D
ED-B	1999	Numerical modeling of the EDZ with PFC	Hydro-Mechanical coupled	Isotropic Mohr Coulomb Isotropic particle flow, incl. damage	FLAC 3D PFC
ED-B	1998	Modeling EDZ Gallery 98 section	Hydro-Mechanical coupled	Elastoplastic ubiquitous joints	FLAC 3D

Coupled THM simulation of a heater experiment

Team	F.O.	Country	Code	2D/3D
UFZ	BGR	Germany	OpenGeoSys	3D
CAS	CAS	China	EPCA3D	3D
LBNL	DOE	USA	TOUGH-FLAC	3D
ENSI	ENSI	Switzerland	OpenGeoSys	3D
CNSC	IRSN	Canada/France	COMSOL	3D
JAEA	JAEA	Japan	THAMES	3D
KAERI	KAERI	South Korea	FLAC	3D
CNWRA	NRC	USA	FLAC-xFlo	2D

Decovalex, ANDRA, GRS

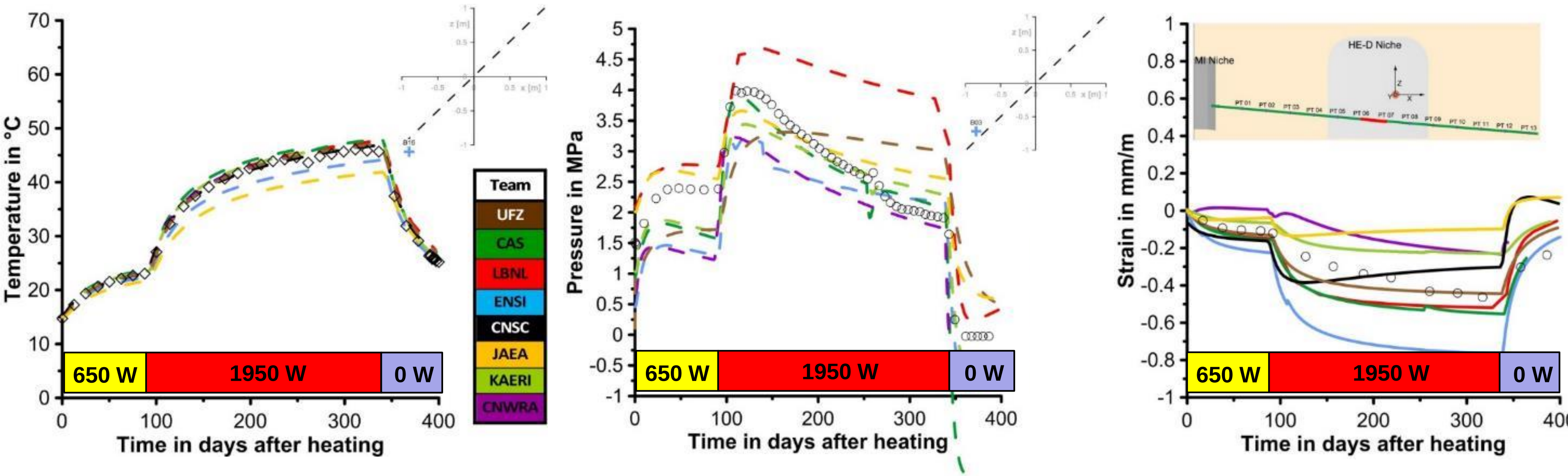


- Heater experiment HE-D, THM responses
- Equilibration, 2 phases of heating, cooling
- Benchmarking with 8 modelling teams, different codes

Coupled THM simulation of a heater experiment

Distance to heater: 1.42 m

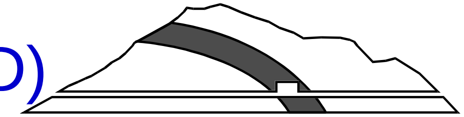
Distance to heater: 1.11 m



- Good agreement for temperature
- Higher differences for pore water pressure (not all aspects of evolution covered)
- General trend for deformation with much more variations

Decovalex, ANDRA, GRS

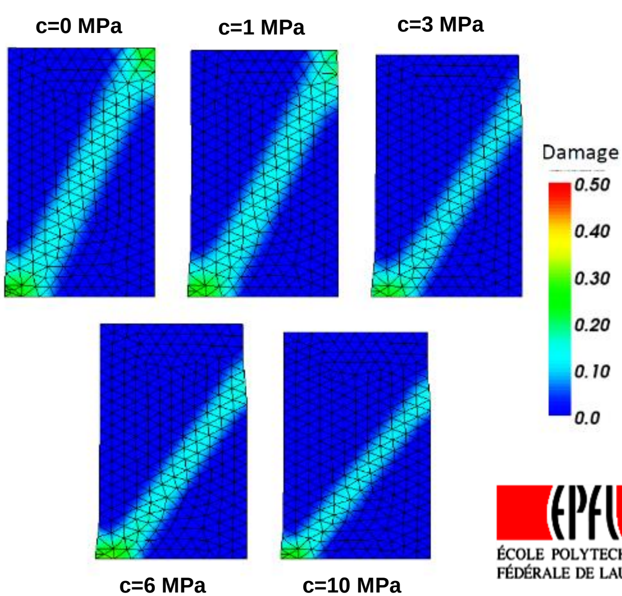
New constitutive law for Opalinus Clay (APD)



- Anisotropy (calibration through non-linear regression)
- Plastic formulation (Non-linear yield function with bounding surface)
- Damage formulation (Damage coupled with plastic hardening, modification to account for residual value of damage)
- Localization and regularization (Fernandez & Chambon, 2008)

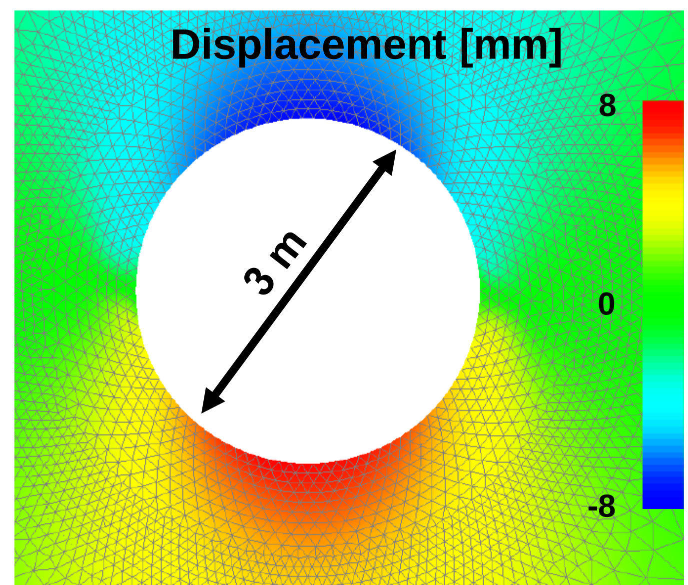
→ Numerical implementation into *Code_Aster*

Parisio et al. (2015)



Effect of confinement on localization

Vertical displacement field



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Conclusions

- Standardized protocols for sampling and conditioning of shale-rock samples are required.
- More data from the heterogeneous sandy facies have to be acquired.
- Magnitude and orientation of in-situ stress tensor depends on local geometry, depth, rock stiffness
- The EDZ has a large impact on tunnel stability. It exhibits a high complexity in tectonized, anisotropic and heterogeneous rocks.
- Prediction of deformation in Opalinus Clay is still a challenging task due to its post-failure behavior. New tools are available now.

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