Mont Terri Project

Rock mass behavior during excavations in the Mont Terri Underground Rock Laboratory

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Structure of the talk

- Excavation techniques
- Lining
- Rock mass behaviour during and after the excavation
- Conclusions

Excavation techniques

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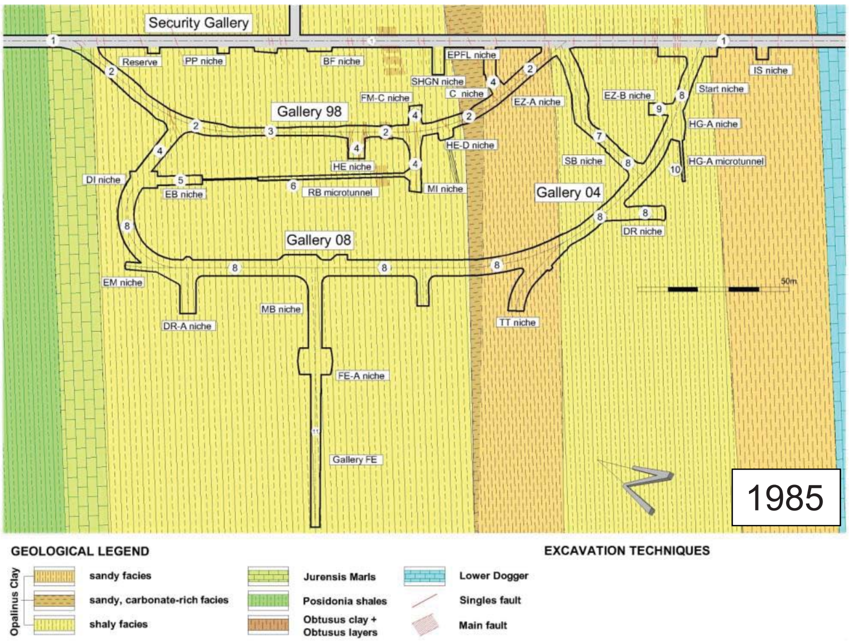

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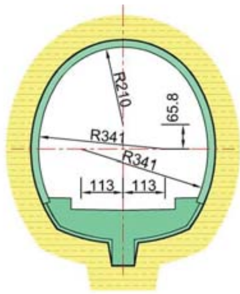

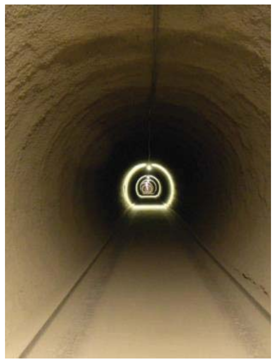

Excavation techniques: drill and blast

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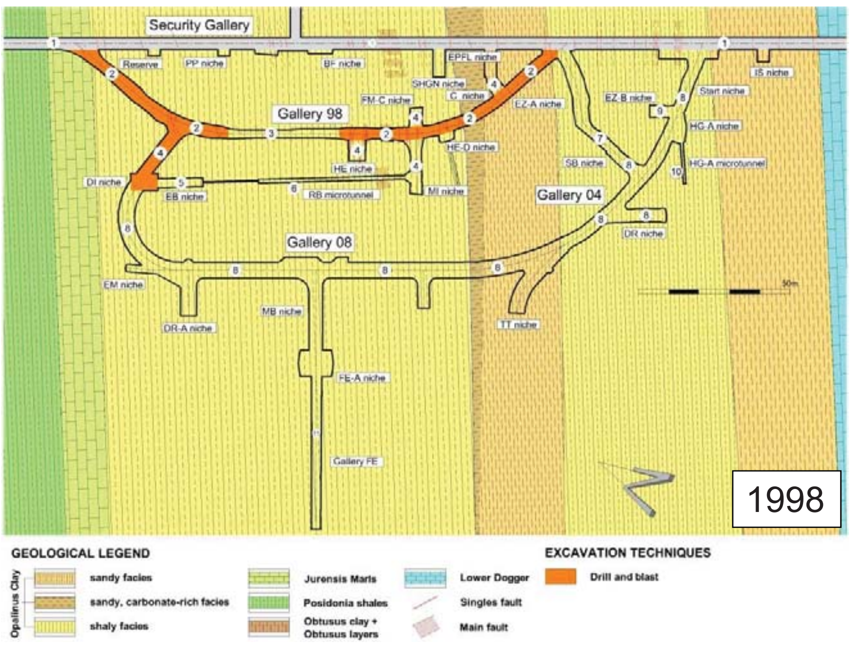
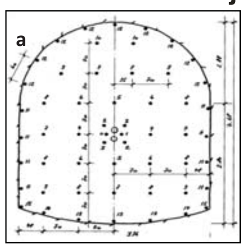
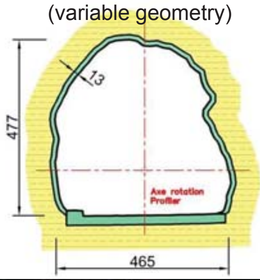
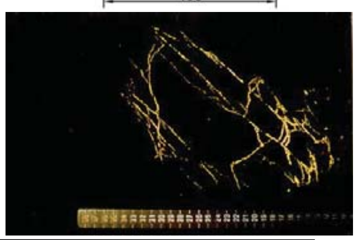




Profile type 2
(variable geometry)





Excavation techniques: road header

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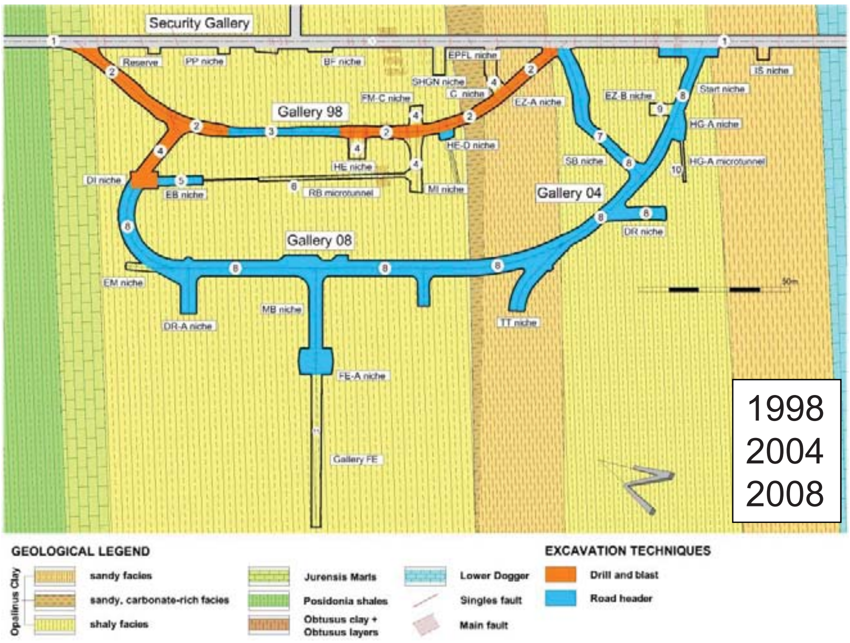
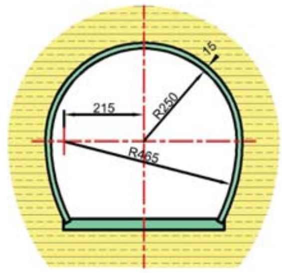


Profile types 3, 7 and 8



Excavation techniques: hydraulic hammer

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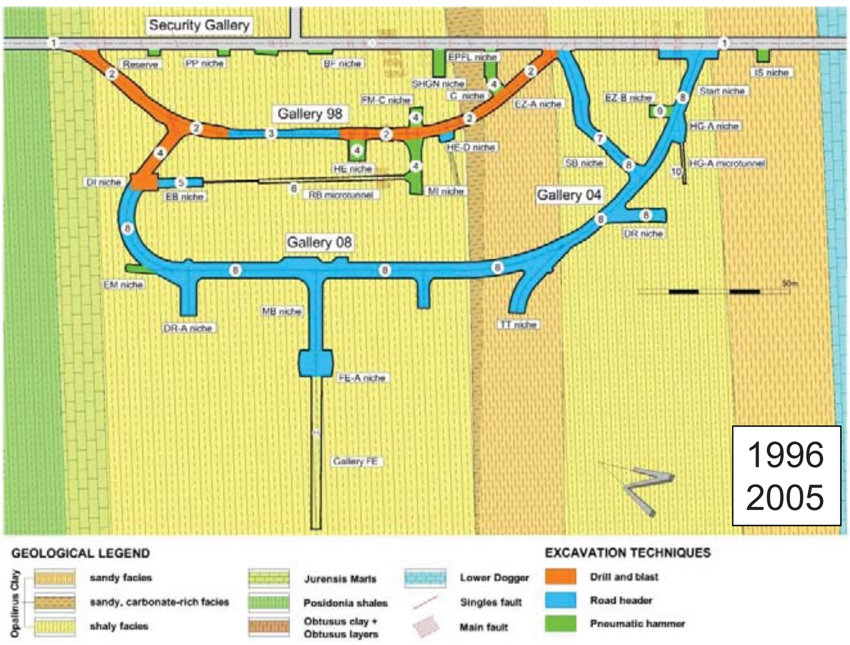
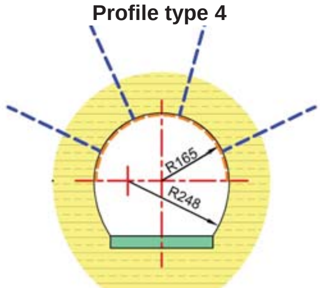


Profile type 4



Excavation techniques: raise boring

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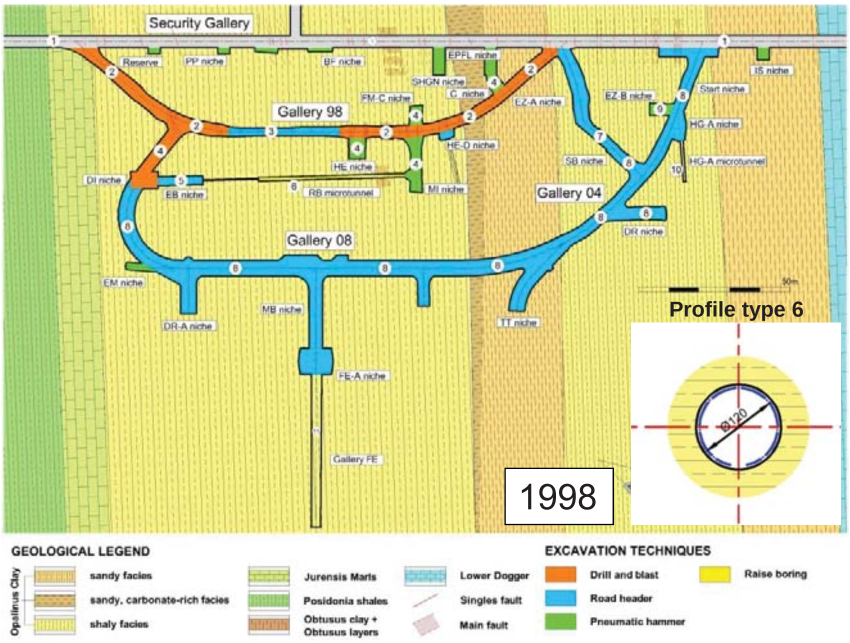

Excavation techniques: steel auger

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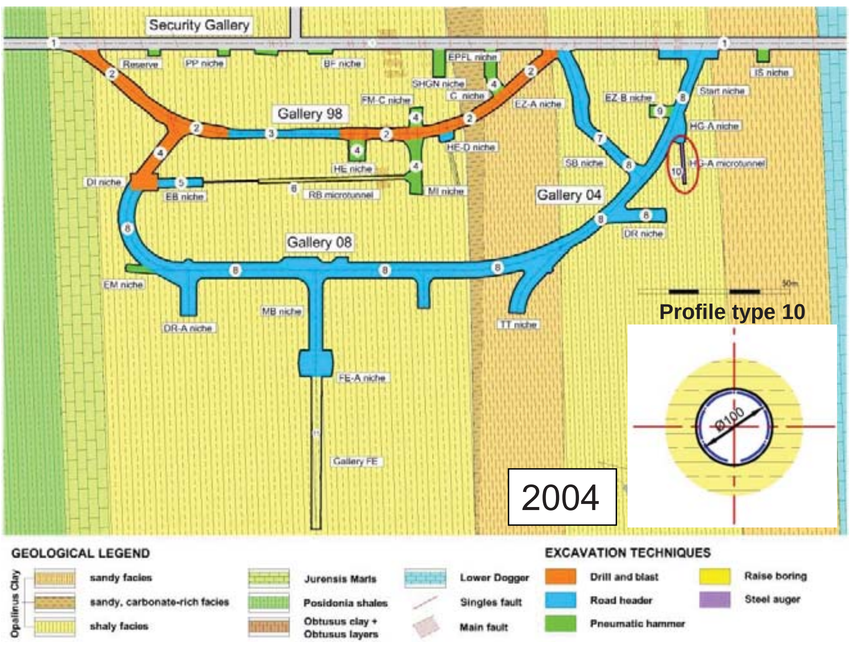

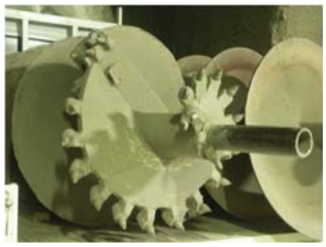

Excavation techniques: hydraulic hammer and road header

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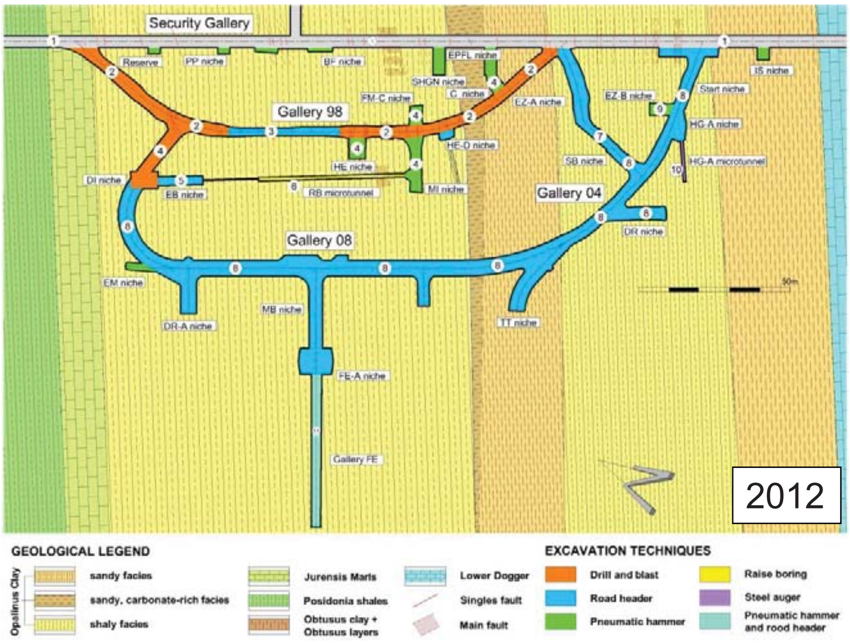

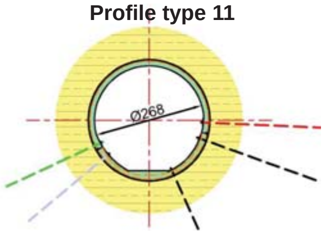

Excavation techniques: dust evacuation

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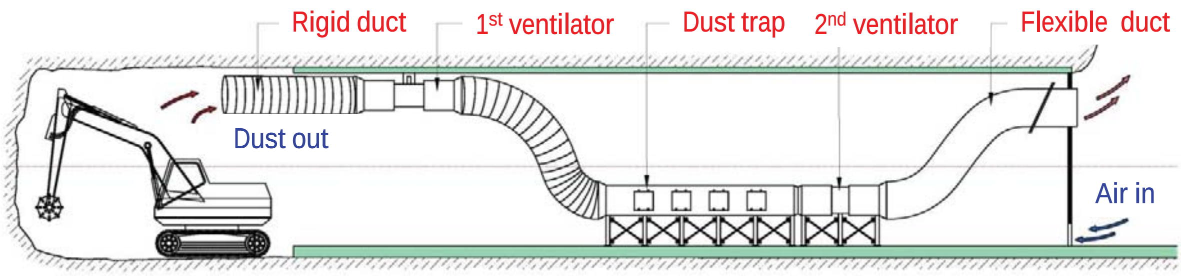

Excavation techniques: experience

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- **No water:** wet excavation and drilling with water cause deformation due to swelling
- **Road header:** best technique in terms of excavation progress, precise profiling and costs
- **Dust evacuation:** closed system with dust trap and 2 ventilators. Suva conditions fulfilled.

Lining: first layer of shotcrete (with fibres)

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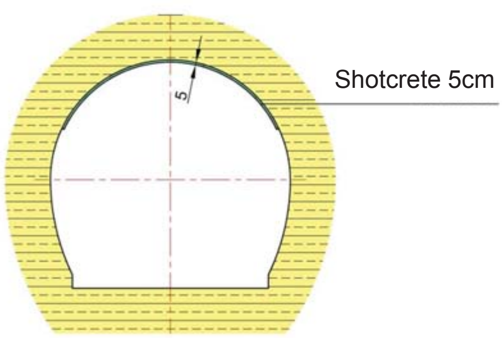

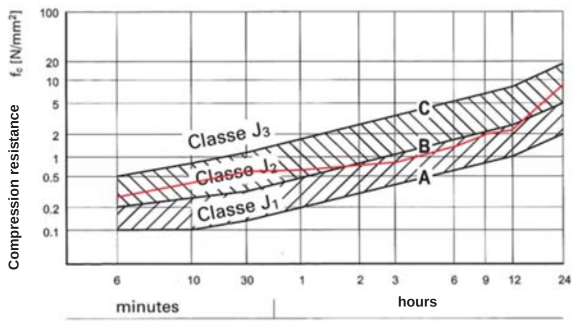

Lining: steel wire meshes

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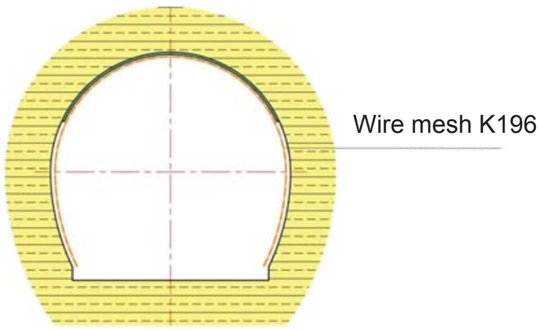

Lining-optional: metallic or fibreglass rock bolts

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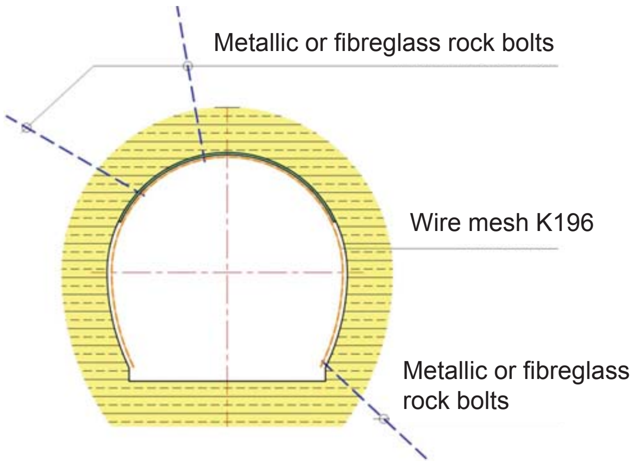

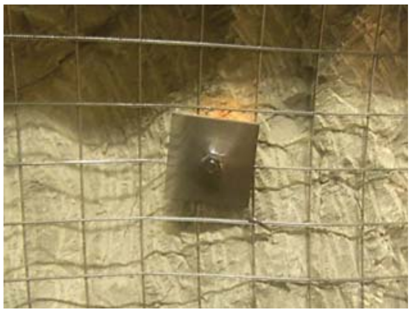

Lining-optional: steel arches

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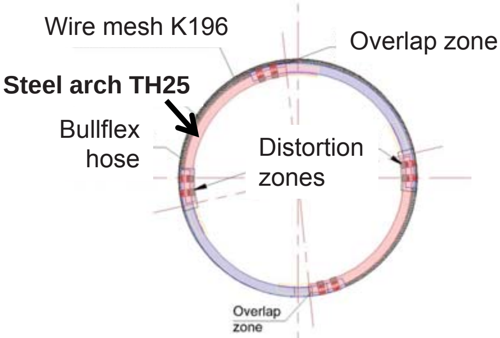

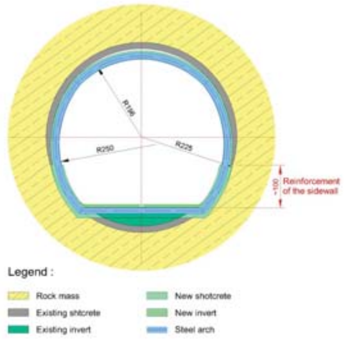

Lining: second (final) layer of shotcrete

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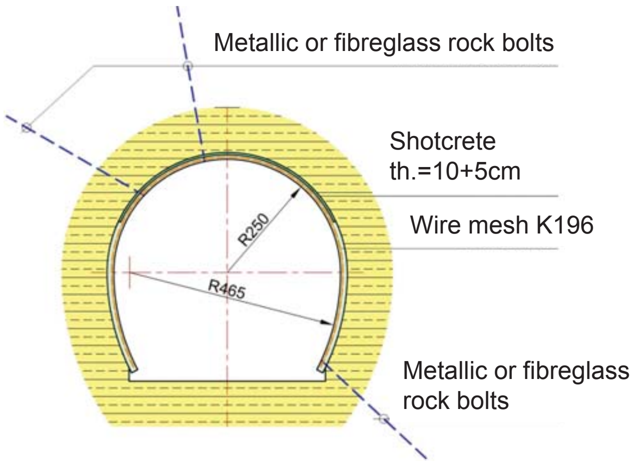

Lining: invert

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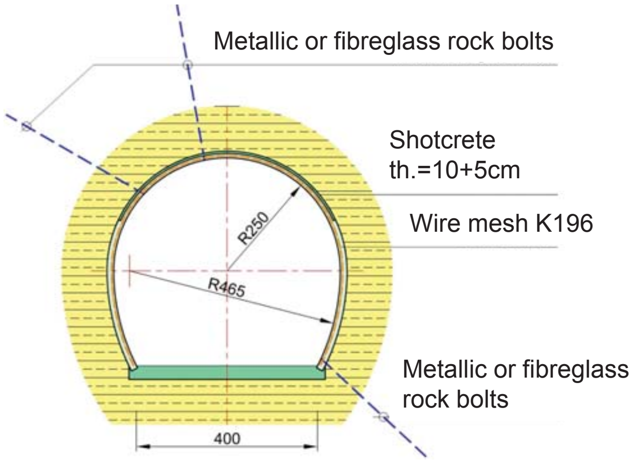

Lining: convergence measurements

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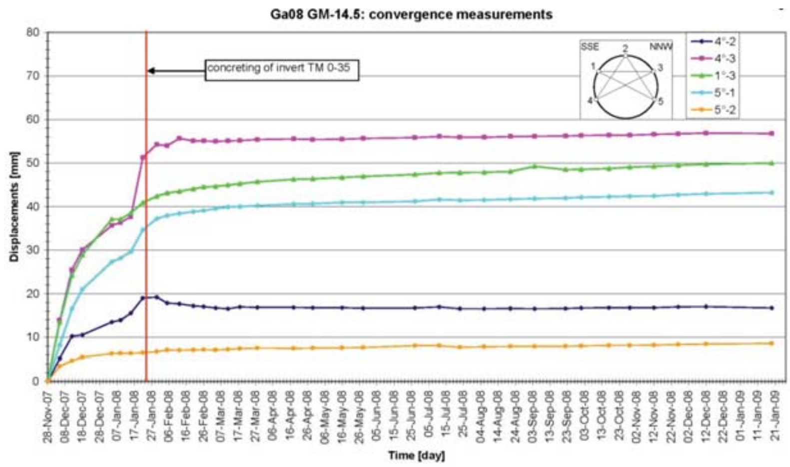
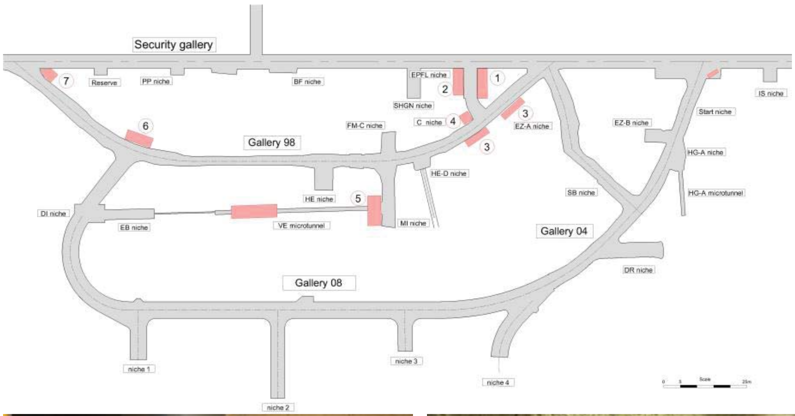
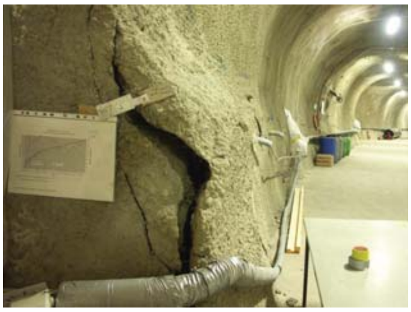


Lining: renovation

Mont Terri Project





Lining: renovation (Gallery FE)

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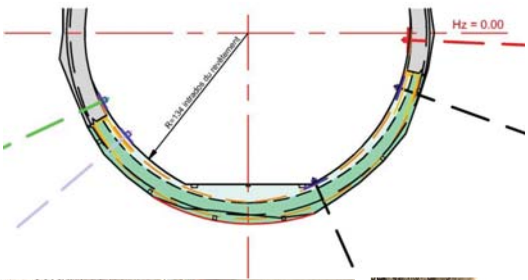
- Removal of liner at the invert
- 1st shotcrete layer and Installation of steel wire meshes
- Installation of new rock bolts
- 2nd shotcrete layer



Lining: experience

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- **Protection of Opalinus Clay:** lining avoids desaturation of Opalinus Clay (shrinkage, desiccation cracks)
- **Convergence confinement method:** final lining is not placed immediately after excavation. Limited convergences are allowed.
- **Safety and stability:**

- short-term safety (accessibility for miners, SUVA conditions)
- long-term safety (stability of galleries)
- monitoring & supervision of convergences (monthly-1/2 year)
- localised shotcrete renovation (after 10 - max. 20 years)

Rock mass behaviour

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Role of

- Anisotropy
- Tectonic Faults
- Excavation Damaged Zone (EDZ)

Rock mass behaviour: location

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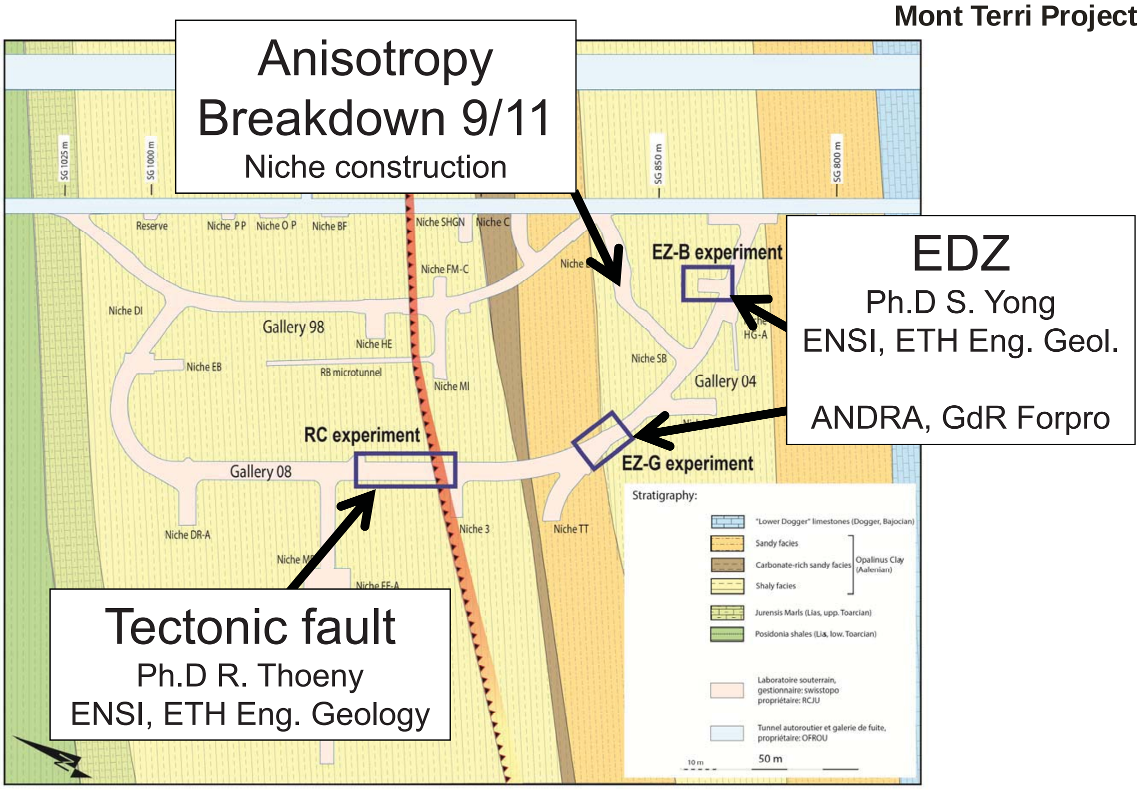

Rock mass behaviour: anisotropy

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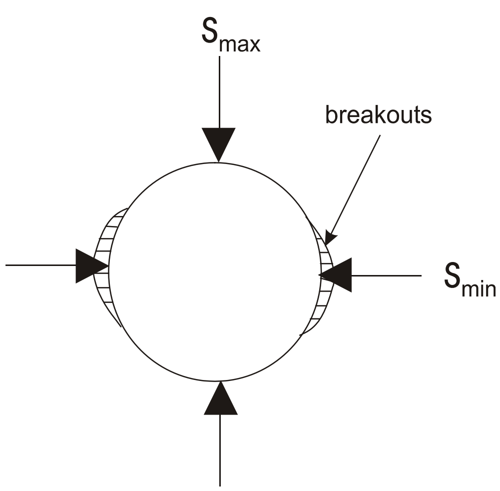
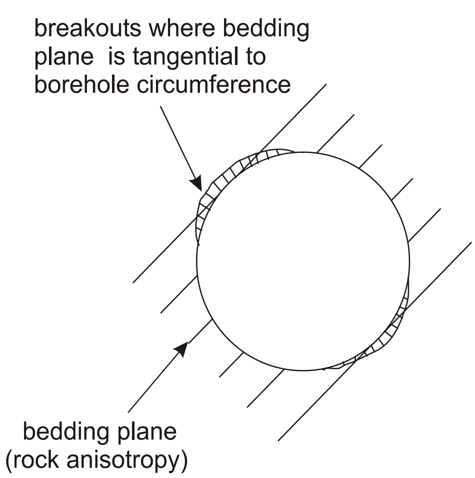
Theory

Stress induced breakouts



Anisotropy induced breakouts



Rock mass behaviour:
Example anisotropy induced breakout (1 of 3)

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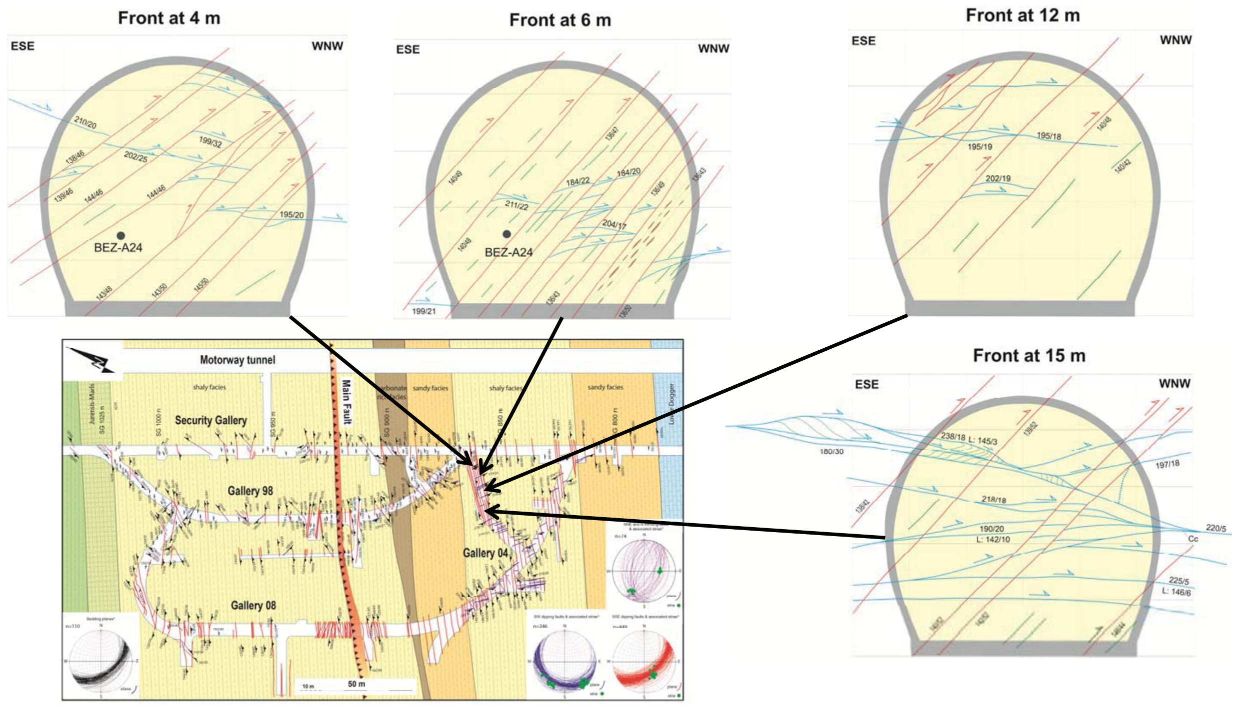

Rock mass behaviour:
Example anisotropy induced breakout (2 of 3)

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09.09.2003, 17:41

11.09.2003, 13:46

11.09.2003, 14:37

Photos: K. Schuster, BGR

11.09.2003, 16:40

11.09.2003, 21:12

12.09.2003, 11:04

Rock mass behaviour: Example anisotropy induced breakout (3 of 3)

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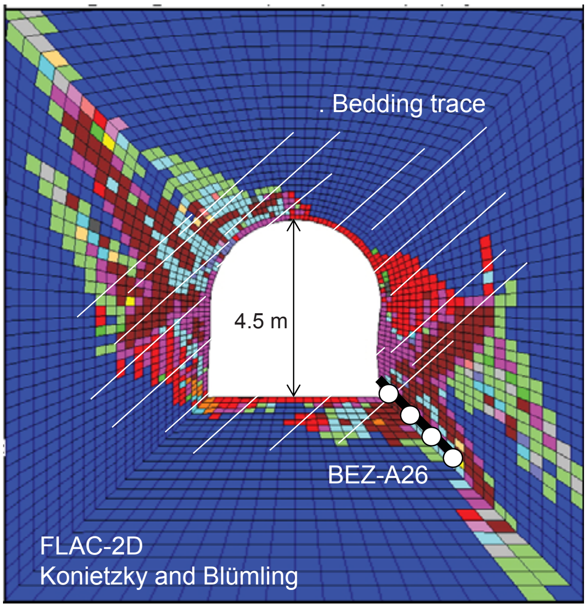
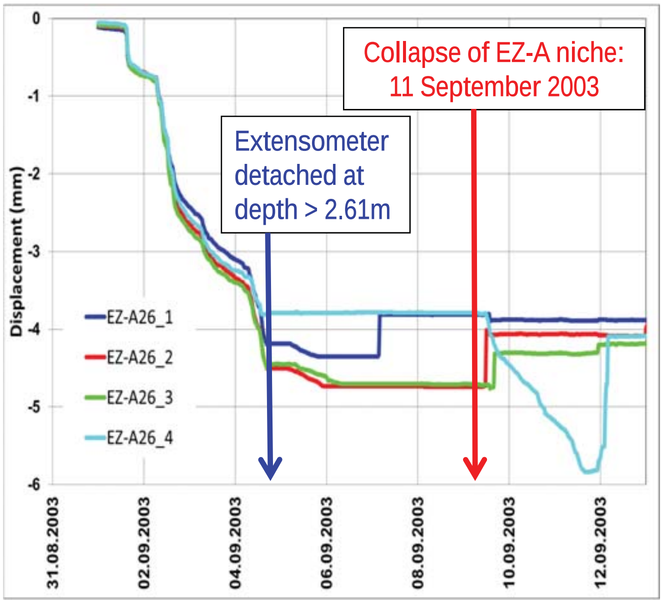
Modelling
Reduction of strength and stiffness
Zone of several tunnel diameters

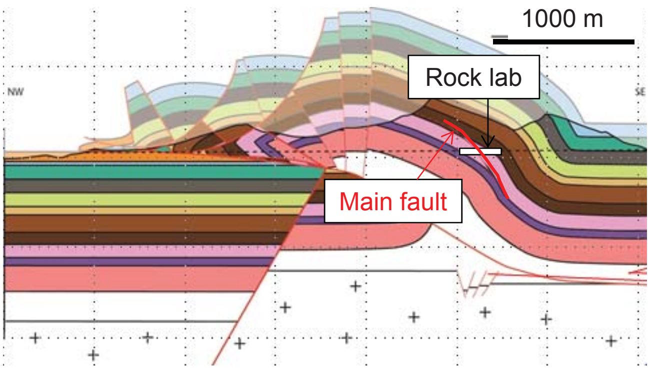


Confirmed by 4-point extensometer which was detached 1 week before collapse in borehole BEZ-A26

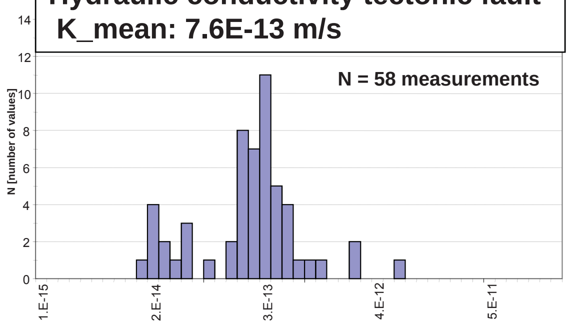


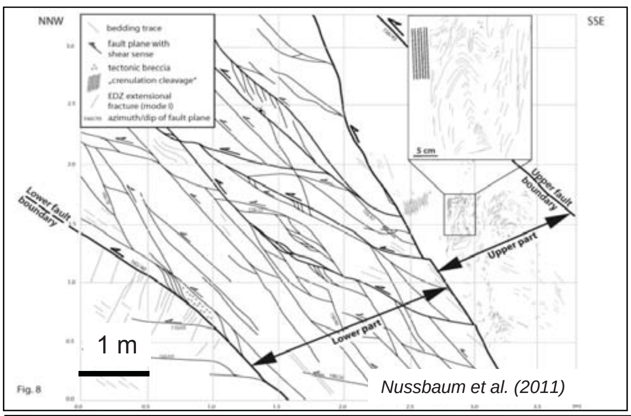
Rock mass behaviour: Tectonic Fault

Mont Terri Project

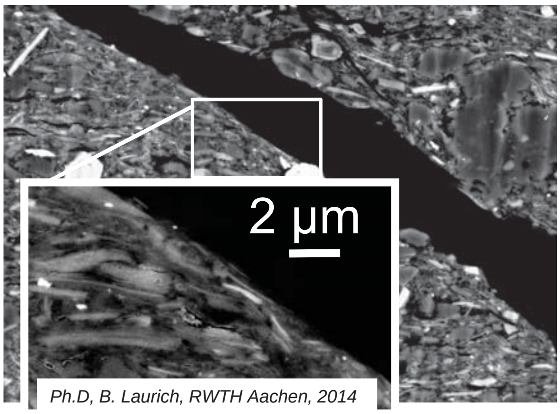


Hydraulic conductivity tectonic fault
K_mean: 7.6E-13 m/s





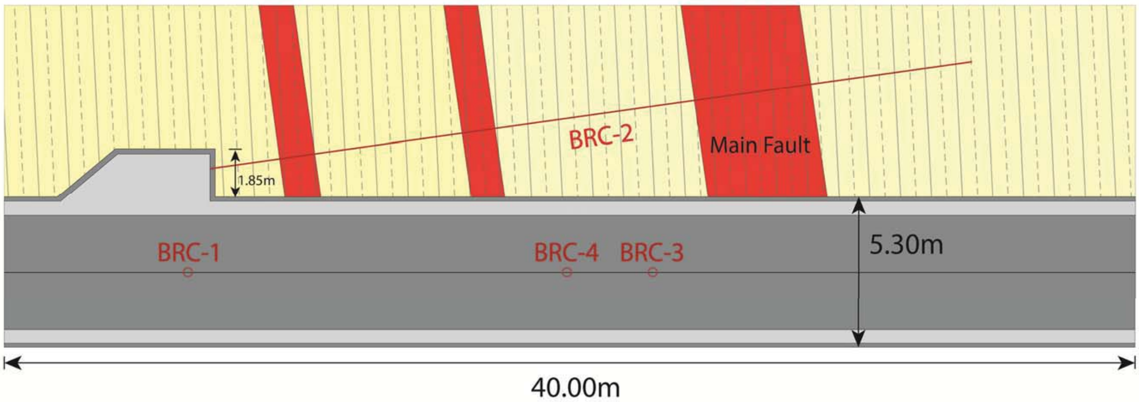
Nussbaum et al. (2011)



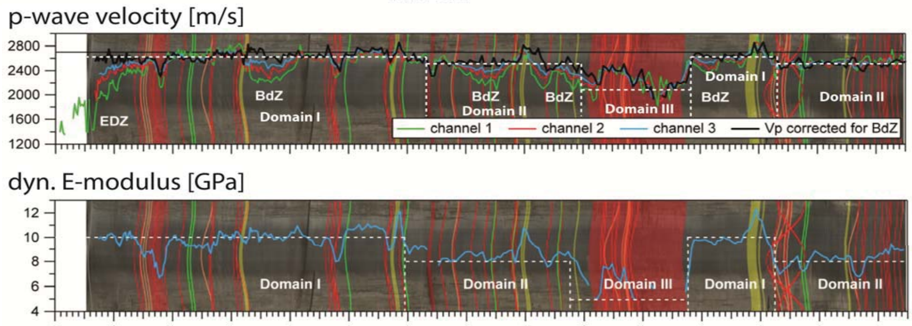
Ph.D, B. Laurich, RWTH Aachen, 2014

Rock mass behaviour: Tectonic Fault
Reduced seismic velocity & E-modulus

Mont Terri Project

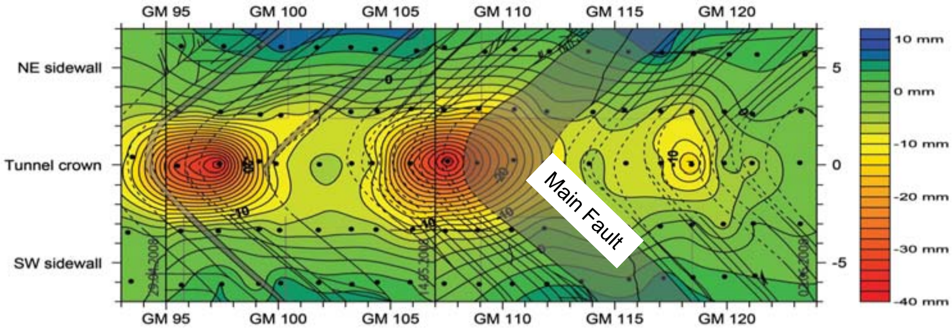


Seismic data from K. Schuster (BGR) in Ph.D, R. Thoeny, (ETH), 2013



Rock mass behaviour: Tectonic Fault

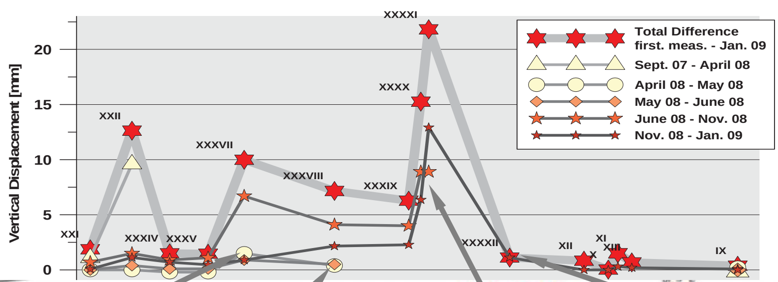
Mont Terri Project



Cumulative vertical displacements at crown up to 40 mm

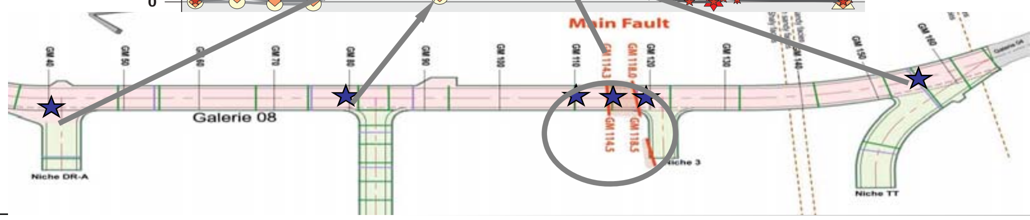
Ph.D. R. Thoeny, ETH, 2013.

RC experiment Geodetic displacements



Monitoring of invert uplift, 22 mm over 1.5 years

(M. Kistler, swisstopo)



Rock mass behaviour: Main Fault
Integration of results, conclusion

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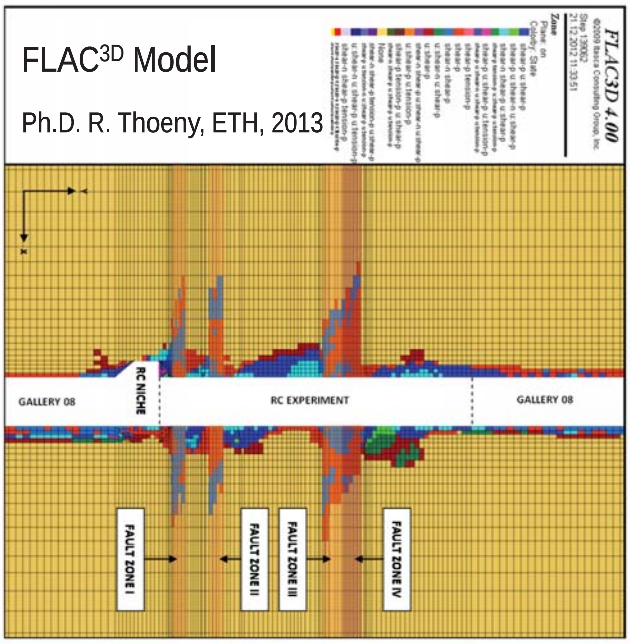

Stress tensor of Martin and Lanyon (2003) was used

- Heterogeneous system (stiffness contrast between faults and matrix)
- Bedding- and fault-parallel shear displacements ahead of excavation front, vertical displacements at crown and invert
- Extension fracturing in sidewalls (EDZ fractures)
- Extent of plastic deformations: 2-3 tunnel diameters

Rock mass behaviour: Excavation damaged zone (EDZ)

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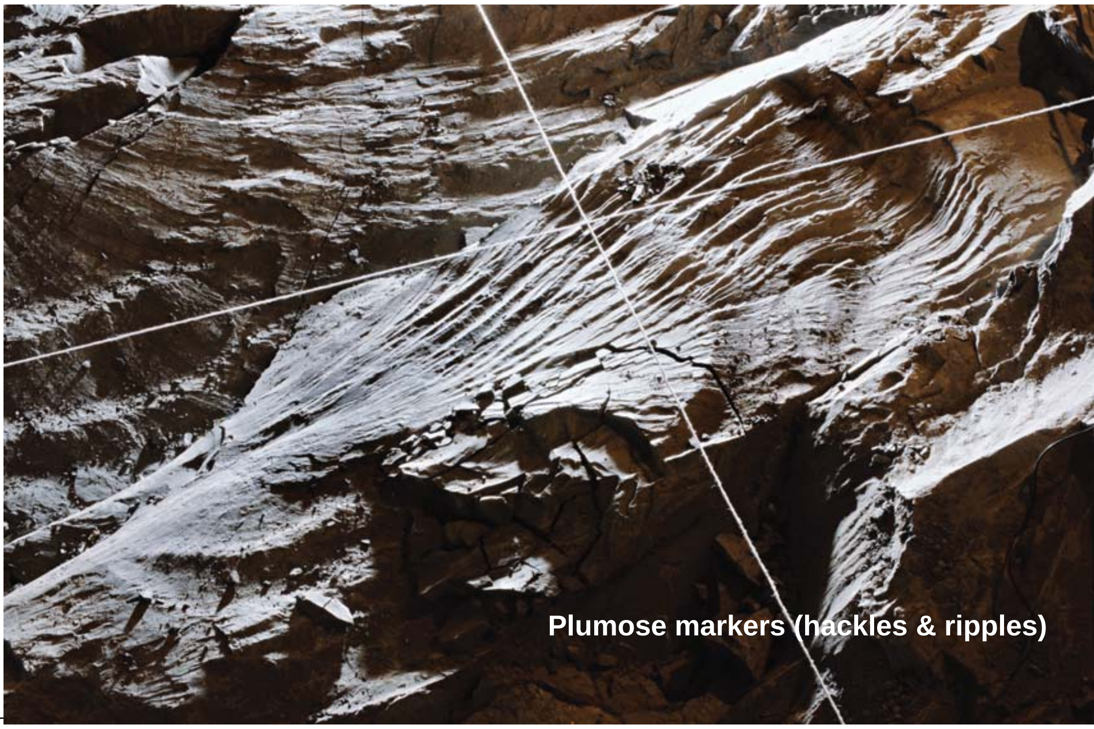

Rock mass behaviour: Conceptual model of EDZ (HM-coupling)

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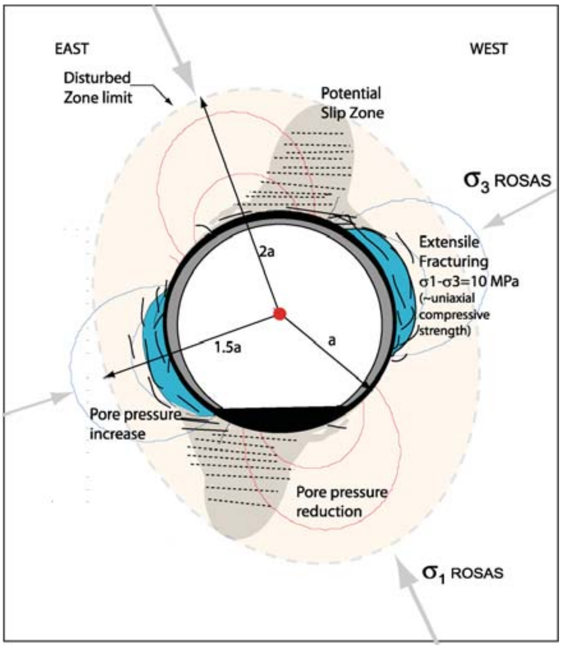
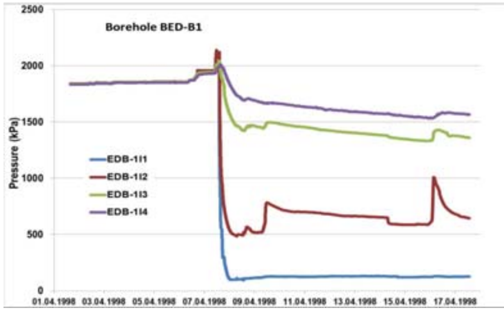
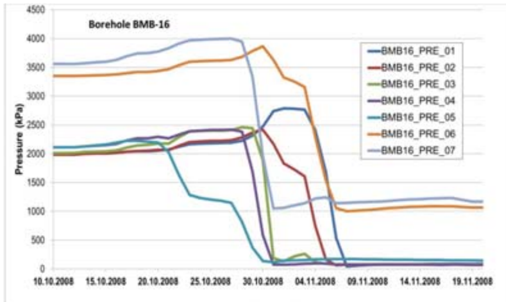


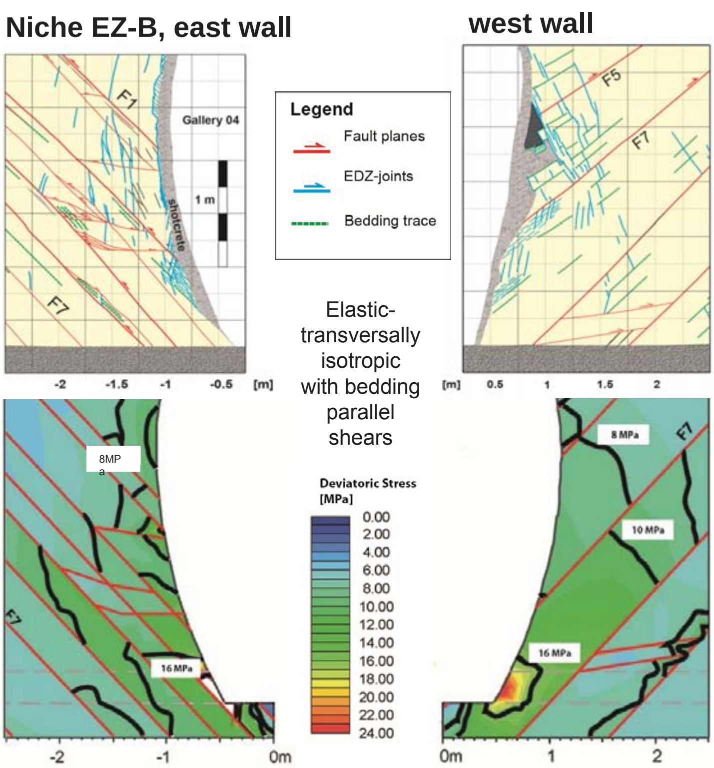




Martin, D.D. and Lanyon, G.W., 2001

Rock mass behaviour: EDZ

Mont Terri Project



Ph.D, S. Yong, (ETH), 2011; Yong et al., 2010

Small scale mapping

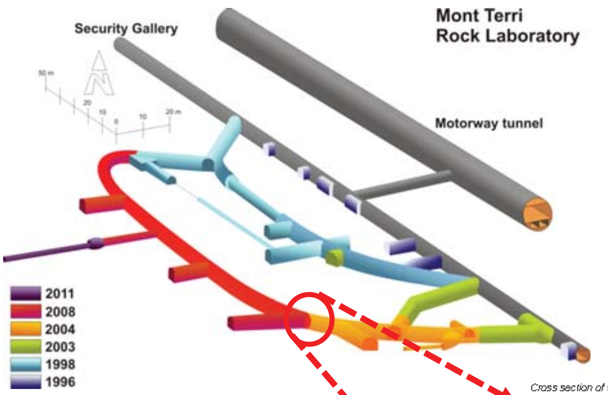
- EDZ-fracture termination near tectonic fault planes
- Tectonic fault reactivation (fault plane parallel shear)

Modelling (3DEC)

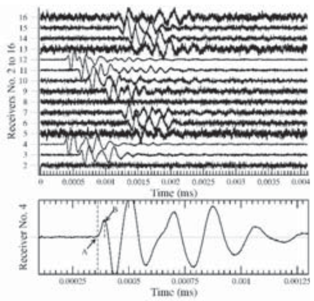
- Matrix: extension fractures (deviatoric stress > 8 MPa)
- Fault: tectonic shear zones are reactivated (fault plane parallel shear)

Rock mass behaviour: EDZ

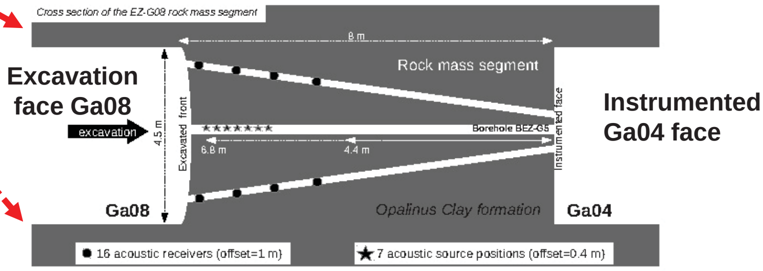
Mont Terri Project



Monitoring of the EDZ with active and passive geophysical methods: the EZ-G experiment



Ga04 face: 4-years old EDZ
Advancing Ga08 face: newly formed EDZ



Rock mass behaviour: EDZ
Locations of micro-seismic events (SE)

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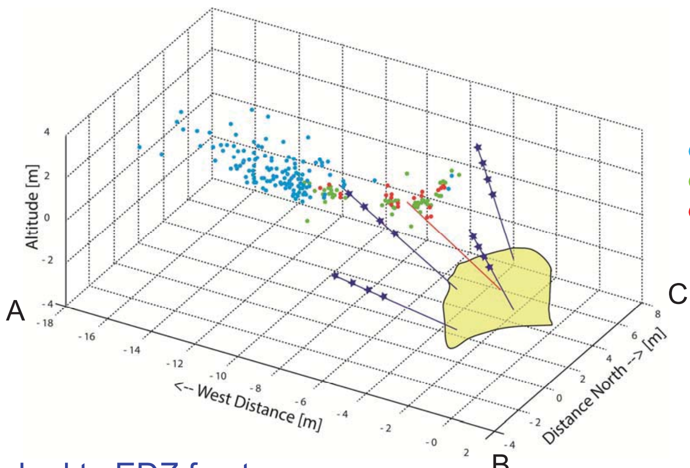
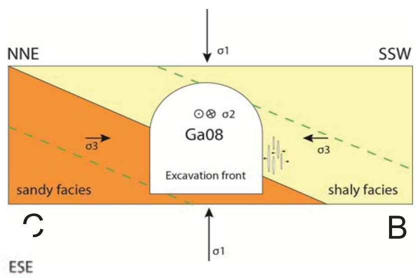
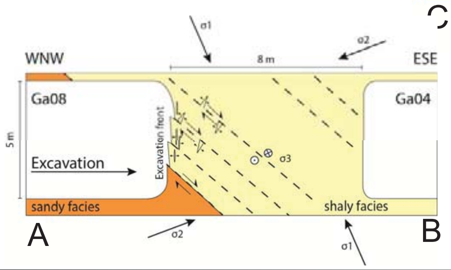


56'446 events detected
278 processed true events
11 July 2008 (**191** events)
12 July 2008 (**71** events)
13 July 2008 (**16** events)



- SE linked to EDZ fracture formation
- Fractures formed simul-taneously to excavation
- Fractures concentrated to shaly facies; sandy facies aseismic?



Le Gonidec et al., submitted to GJI

Conclusions (1 of 2)

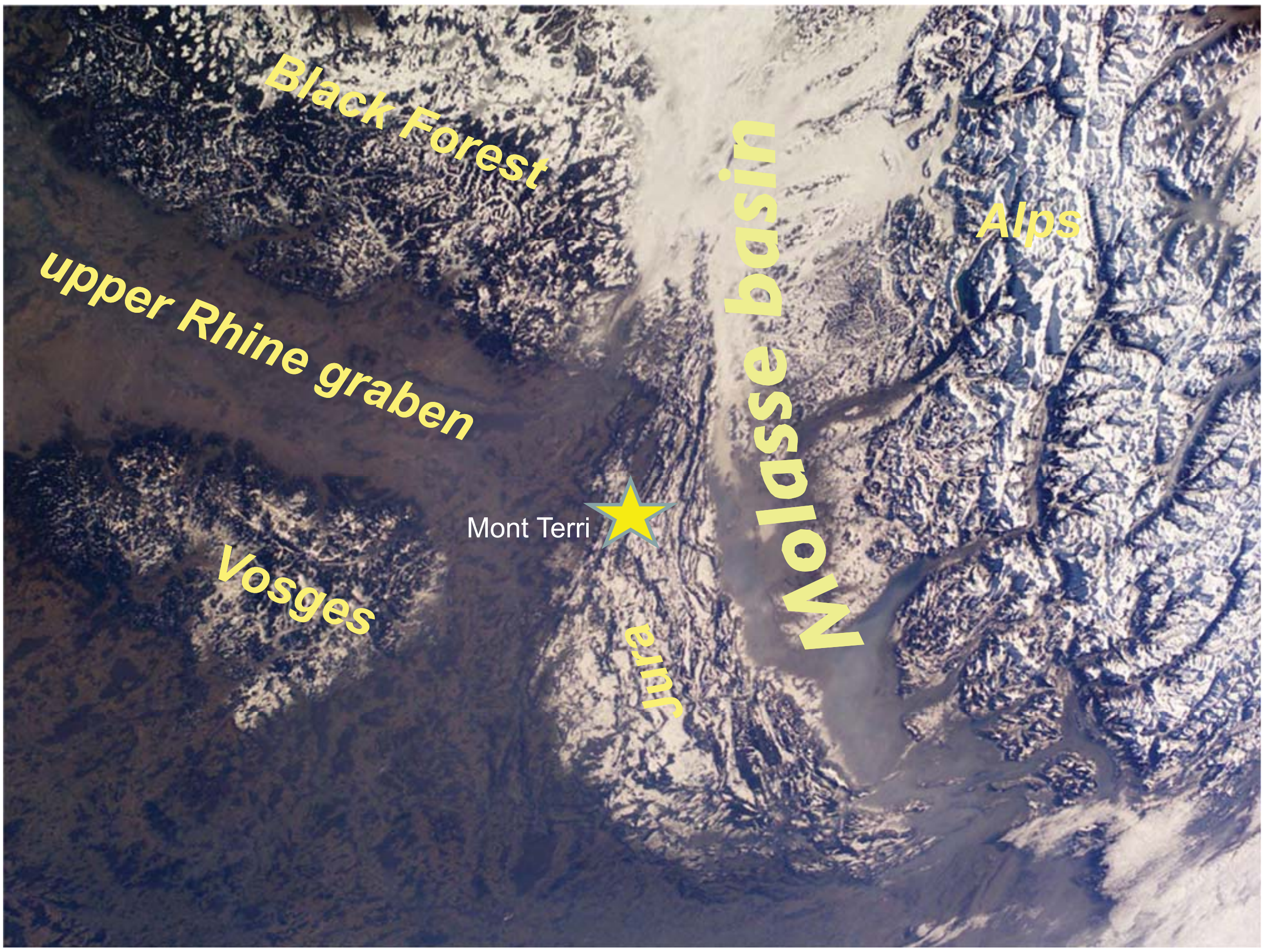
Mont Terri Project

Which results from Mont Terri can be transferred to a future repository for high level waste in the Opalinus Clay?

- Role of anisotropy: partly transferable (rotation of 45°). Enhanced convergences and breakouts at tunnel roof and floor. Not transferable is the stress field.

- Role of tectonic faults: partly transferable. Clearly lower fault frequency at potential future sites (*Mont Terri = worst case, tectonically active faults?*). However fault zones at future repository sites cannot be excluded

- Role of EDZ: partly transferable. Clearly more pronounced than at Mont Terri (Mont Terri: 300 m, future site for HLW between 400 and 900 m)



Conclusions (2 of 2)

Mont Terri Project

Which facies to be selected for a repository in the Opalinus Clay?

- Sandy facies is recommended (higher UCS, higher elastic moduli). Higher short- and long-term safety, better (cheaper) maintenance.

- Shaly facies at Mont Terri in a depth of 300 m is a proxy for the sandy facies in a future repository in a depth of 600-900 m.

Rock mass behaviour: stress field

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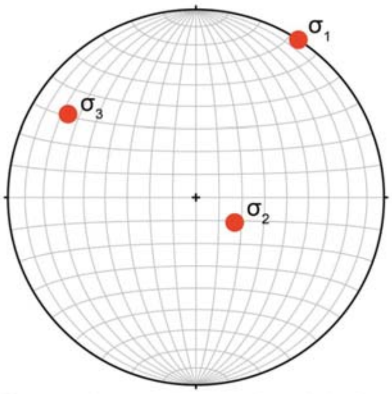
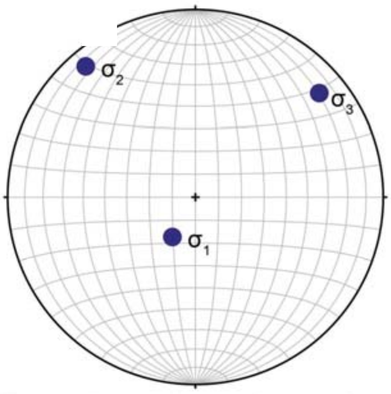
Remote stresses Hauptrogenstein



Principal Stress	Magnitude	Trend	Plunge
σ_1	8.6 MPa	33°	0°
σ_2	6.7 MPa	123°	70°
σ_3	3.9 MPa	303°	20°

Remote stress Opalinus Clay in rock lab



Principal Stress	Magnitude	Trend	Plunge
σ_1	6.5 MPa	210°	70°
σ_2	4.0 MPa	320°	10°
σ_3	2.2 MPa	50°	15°

- Orientations are derived by breakouts analysis
- Magnitudes are obtained by borehole slotter hydraulic fracturing, over- and undercoring
- Stresses in Opalinus Clay not well constrained
- Different stress field in Opalinus Clay and bounding limestone formations

Borehole closure

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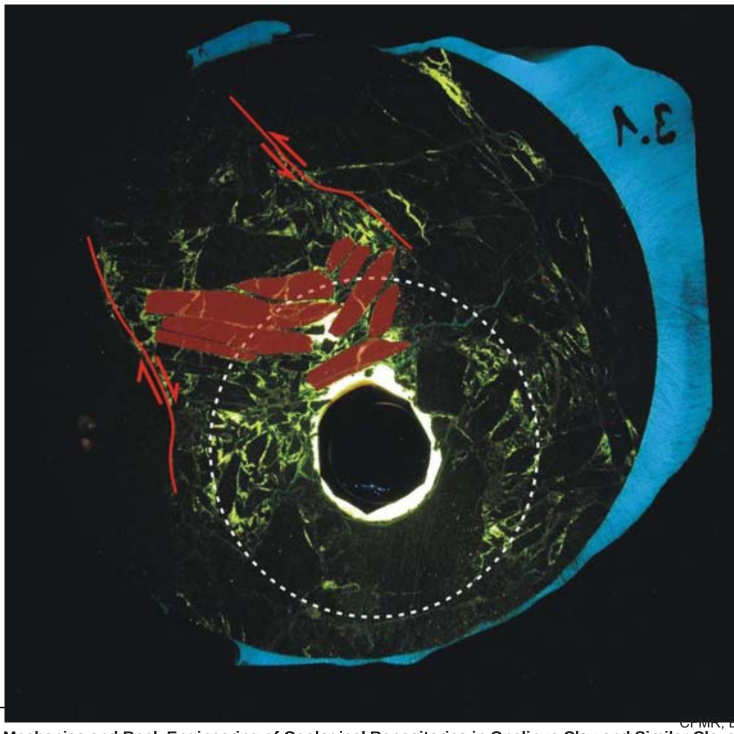

Stress redistribution

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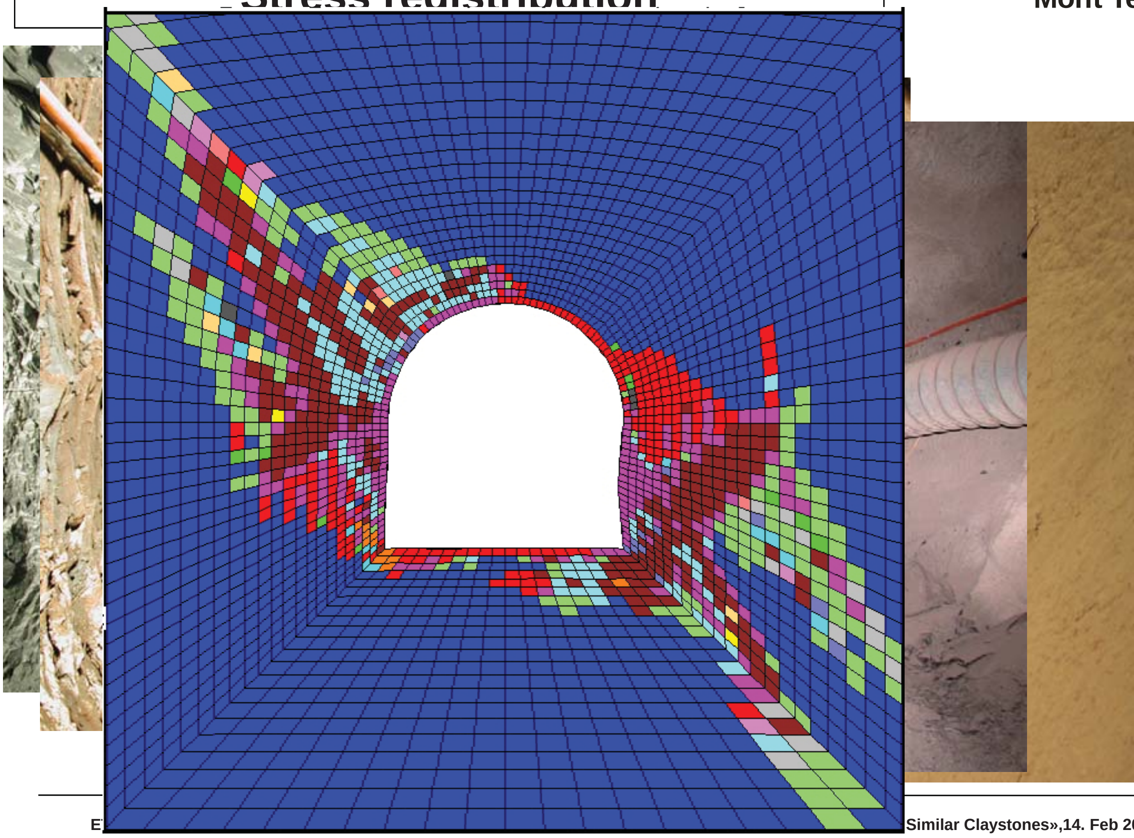

CAMPUS: Circular Profiles 1 and 2, inversion with cut-off at 50 Ωm

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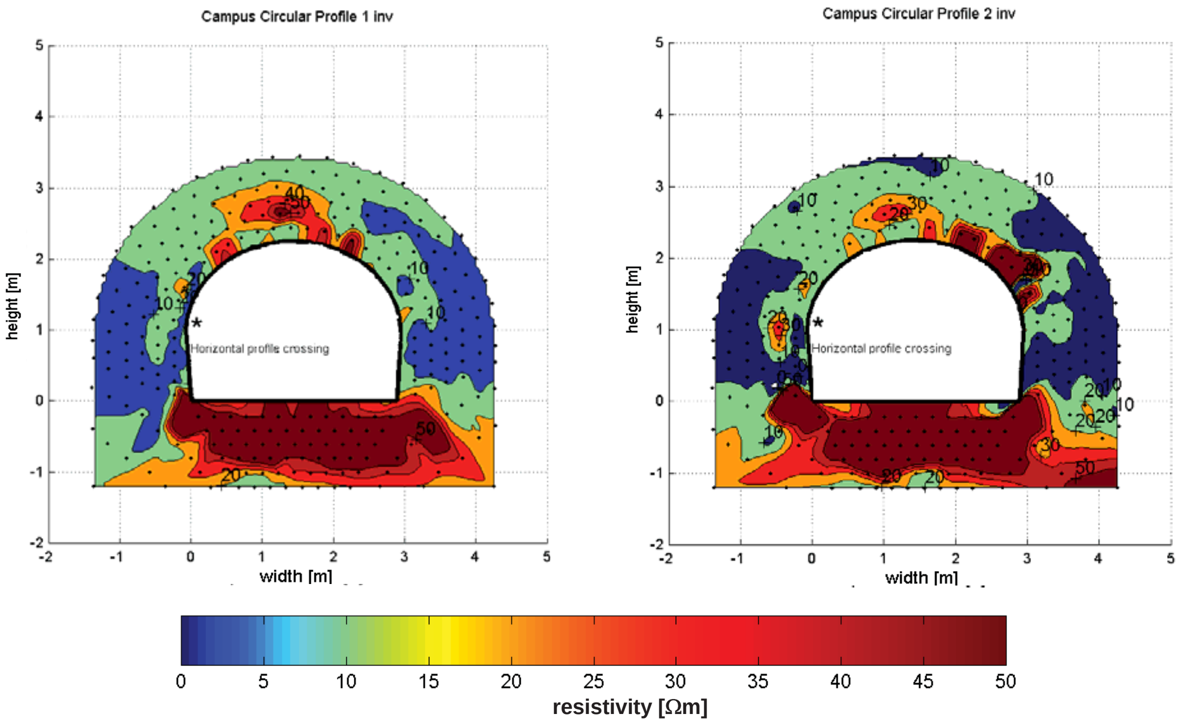

Rock mass behaviour: anisotropy
Example of breakdown (3 of 4)

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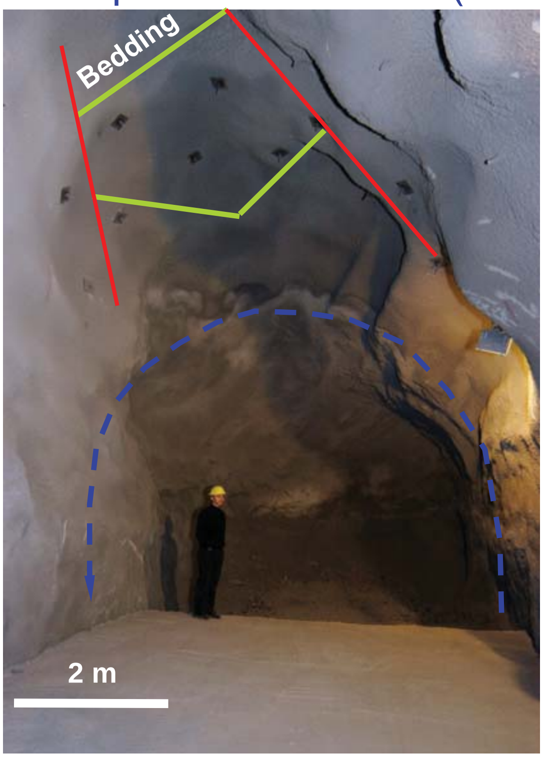

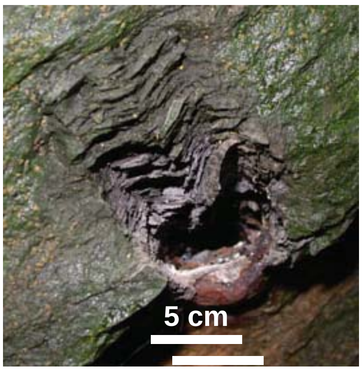

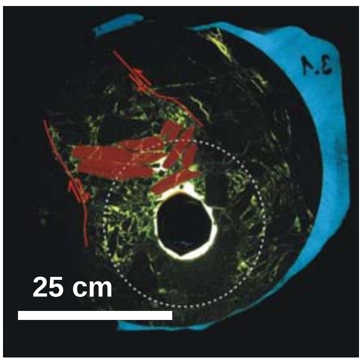

Rock mechanical variability in the Opalinus-Ton

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Sample orientation	Parameter [unit]	Sandy Facies	Shaly Facies
S P	UCS [MPa]	7 – 22 Mpa 7 – 25 MPa	15 MPa 11 MPa
S P	Youngs Modulus [GPa]	0.5 – 19 GPa 2 – 35 GPa	14 GPa 22 GPa
S P	Poissons Ratio	0.05 – 0.4 0.15 – 1	0.25 0.26
Water content		2-5%	6%
Remarks		Very heterogeneous	Best estimates
Authors		After Gschwind (2013)	After Bock (2009)

- No standard approach for conditioning and testing of samples
- Heterogeneous samples of sandy facies cause large variations
- Variable water contents between different datasets, tests should be performed as a function of suction
- No individual test series which comprise the whole range of facies types
- Still only scarce data from the sandy or carbonate-rich facies

EZ-G experiment: Spatial location and source mechanisms of microseismic events related to EDZ

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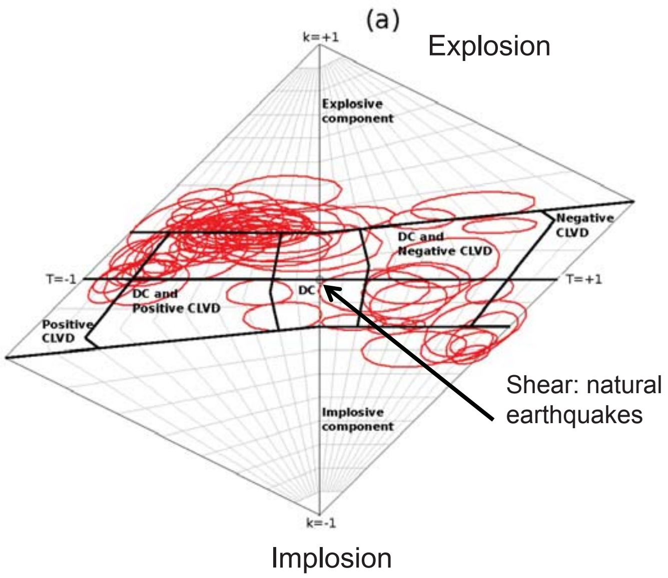
Hudson T-k plot



Le Gonidec et al., submitted to GJI

Lining: triangular steel arches in FE-A niche

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