Structural and hydraulic properties of the excavation damaged zone in the Opalinus Clay, Mont Terri rock laboratory, Switzerland.

Paul Bossart [1)] and Peter Blümling [2)]

1) Federal Office for Water and Geology

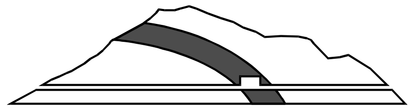
2) Nagra

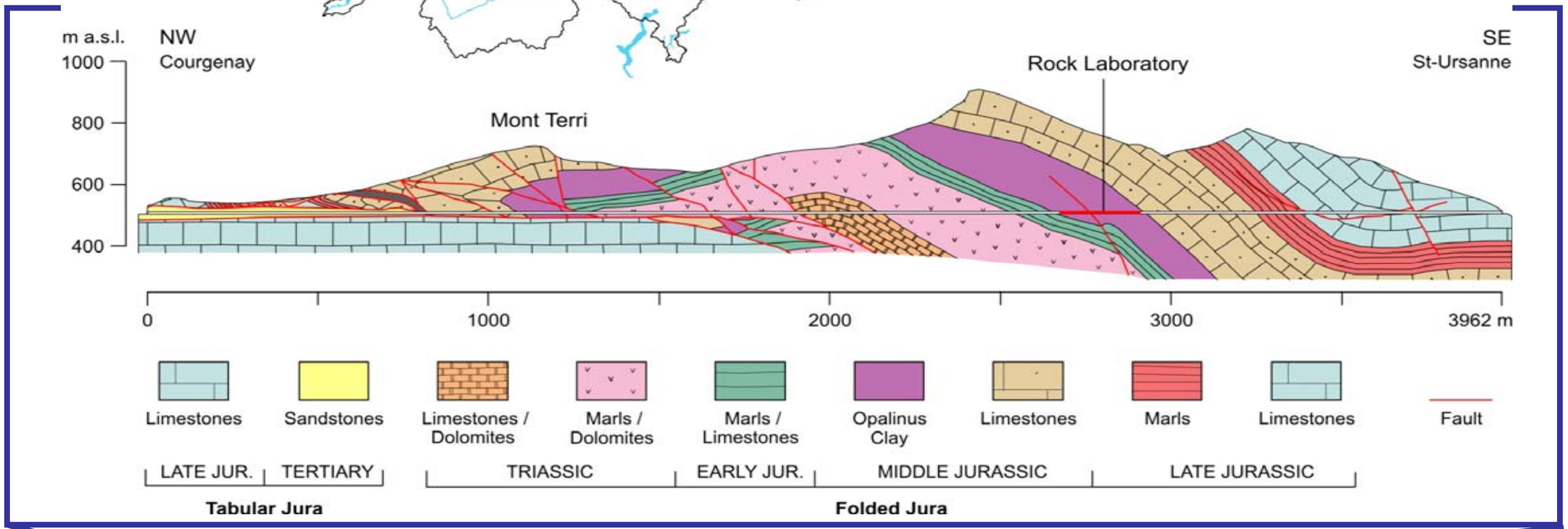
- **The Mont Terri rock laboratory**
- **Structural characterisation of the EDZ**
- **Hydrogeological characterisation of the EDZ**
- **Hydro-mechanical responses in the EDZ**

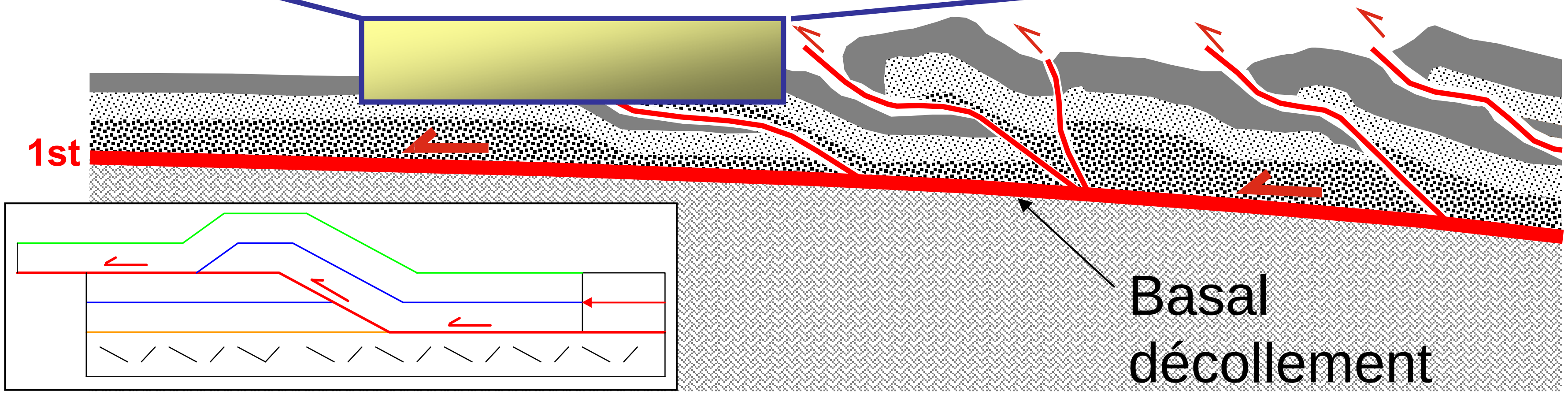
The Partners

FOWG	Swiss Federal Office for Water and Geology
NAGRA	National Cooperative for the Disposal of Radioactive Waste
HSK	Swiss Federal Nuclear Safety Inspectorate
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 Reaktorsicherheit und Strahlenschutz
ENRESA	Empresa Nacional de Residuos Radiactivos, S.A.
SCK•CEN	Studiecentrum voor Kernenergie, Mol
JNC	Japan Nuclear Cycle Development Institute
OBAYASHI	Obayashi Corporation
CRIEPI	Central Research Institute of Electric Power Industry
EC	European Community

Geology

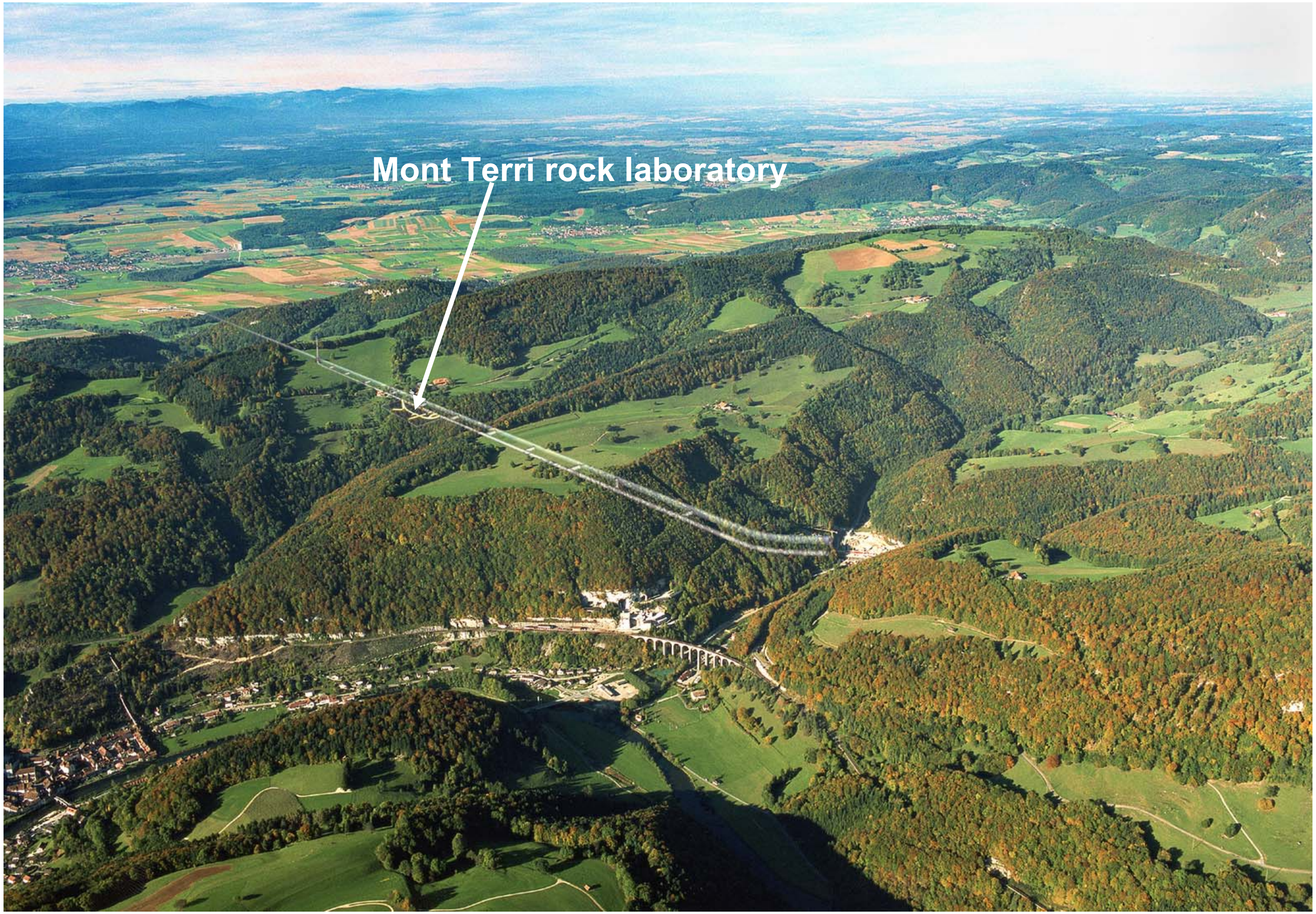


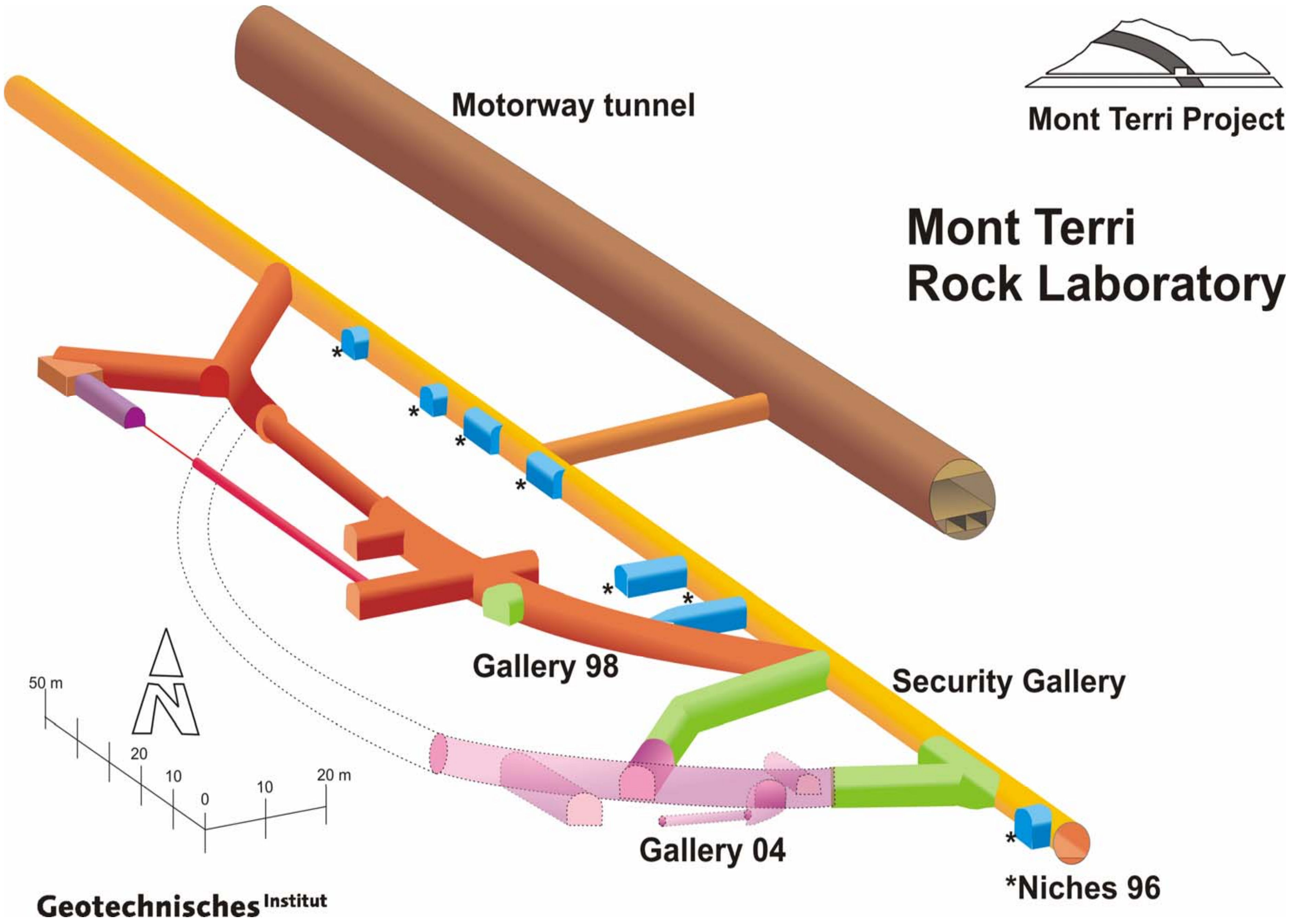




Fault-bend fold

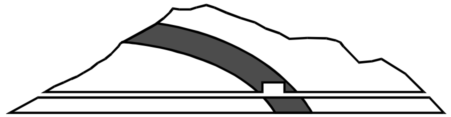
Geography





Mont Terri Project
Mont Terri
Rock Laboratory
Motorway tunnel
Gallery 98
Security Gallery
Gallery 04
*Niches 96
50 m
20
10
0
10
20 m
Geotechnisches Institut

Key parameters



Opalinus Clay

PARAMETRES	RANGE	MEAN VALUE
Bulk density, sat. (g cm^{-3})	2.40 – 2.53	2.47
Water content (wt%)	3.0 – 8.1	5.6
Porosity (%)	7 –18	12
Hydraulic conductivity (ms^{-1})	1E-14 – 1E-12	2E-13
Thermal Conductivity ($Wm^{-1}K^{-1}$)	1.0 – 3.1	2.1
Heat capacity (J Kg^{-1} K^{-1})	970 – 1340	1155
Total dissolved solids in pore water (g/l)	5 - 20	12
Uniaxial Compressive Strength (MPa)	8 – 25	10
Young’s Modulus (MPa)	6000 – 12000	9000
Poisson’s ratio	0.25 – 0.33	0.29
Shear modulus	-	1200

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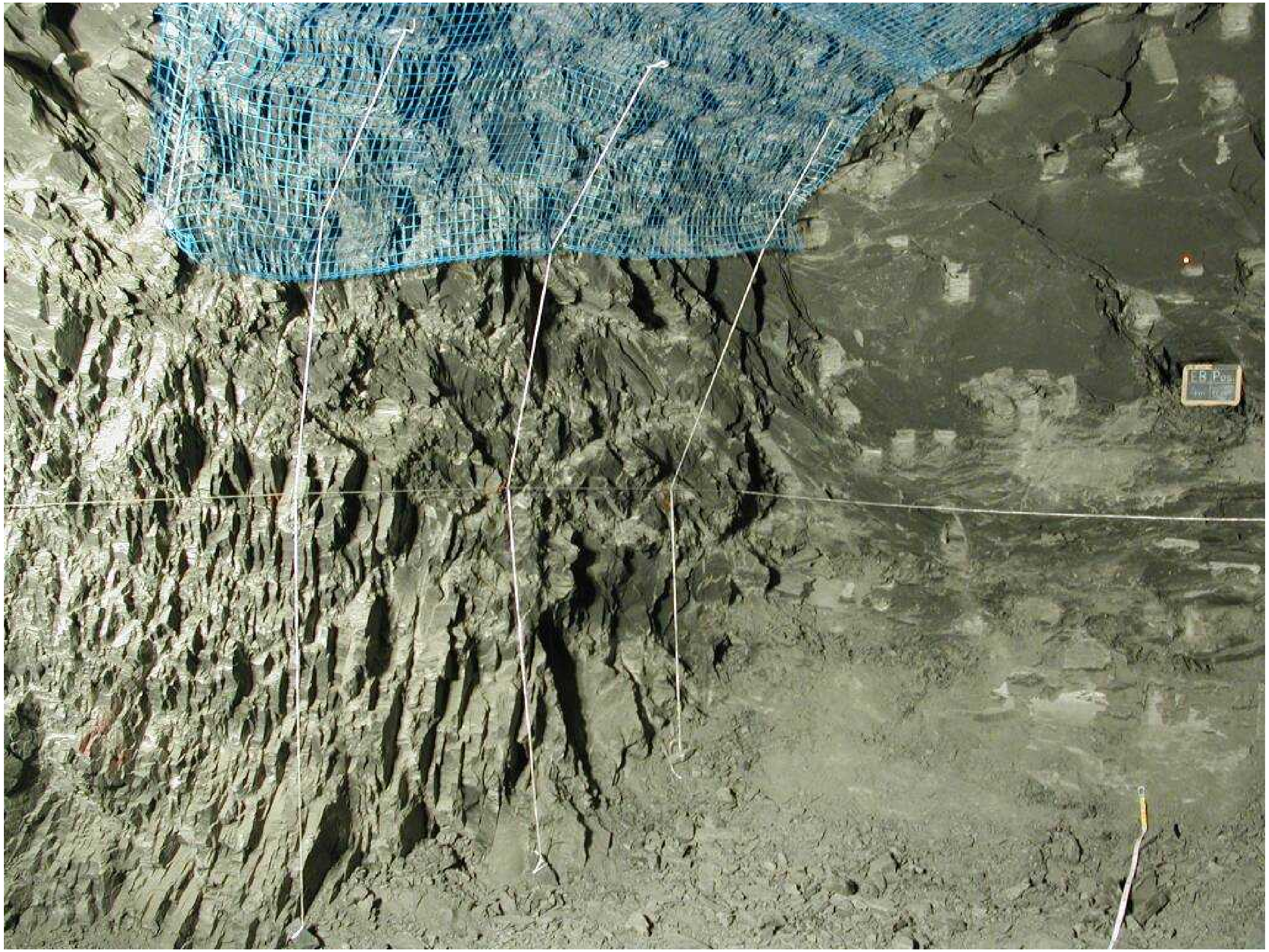
- **Excavation methods**
- **Unloading fractures and bedding parallel slip**
- **Small scale structural mapping**
- **Role of the anisotropy**
- **Borehole deformation and borehole closure**

Excavation methods

Excavation by road header

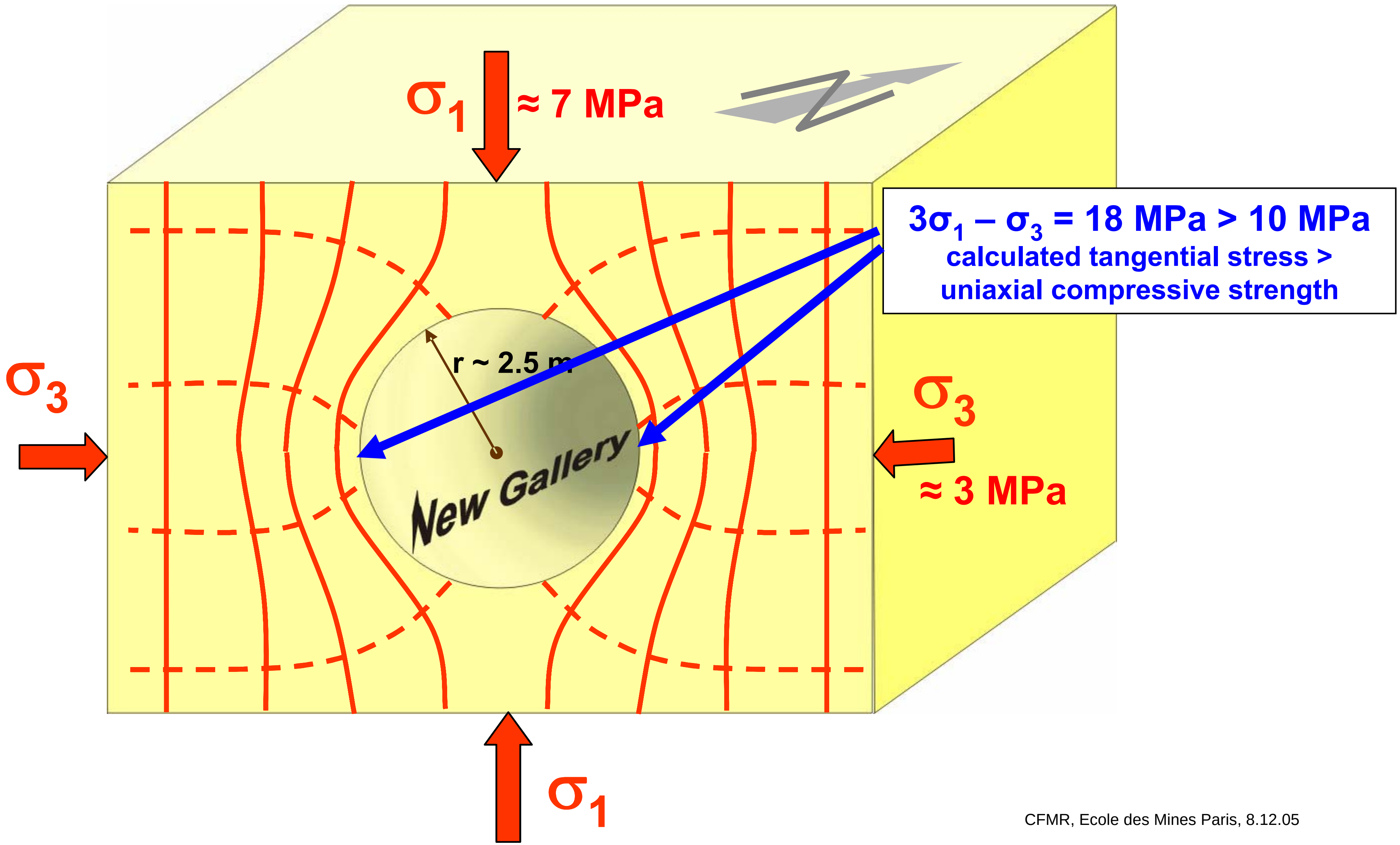
Excavation by pneumatic hammer

EDZ unloading fractures, niche side wall

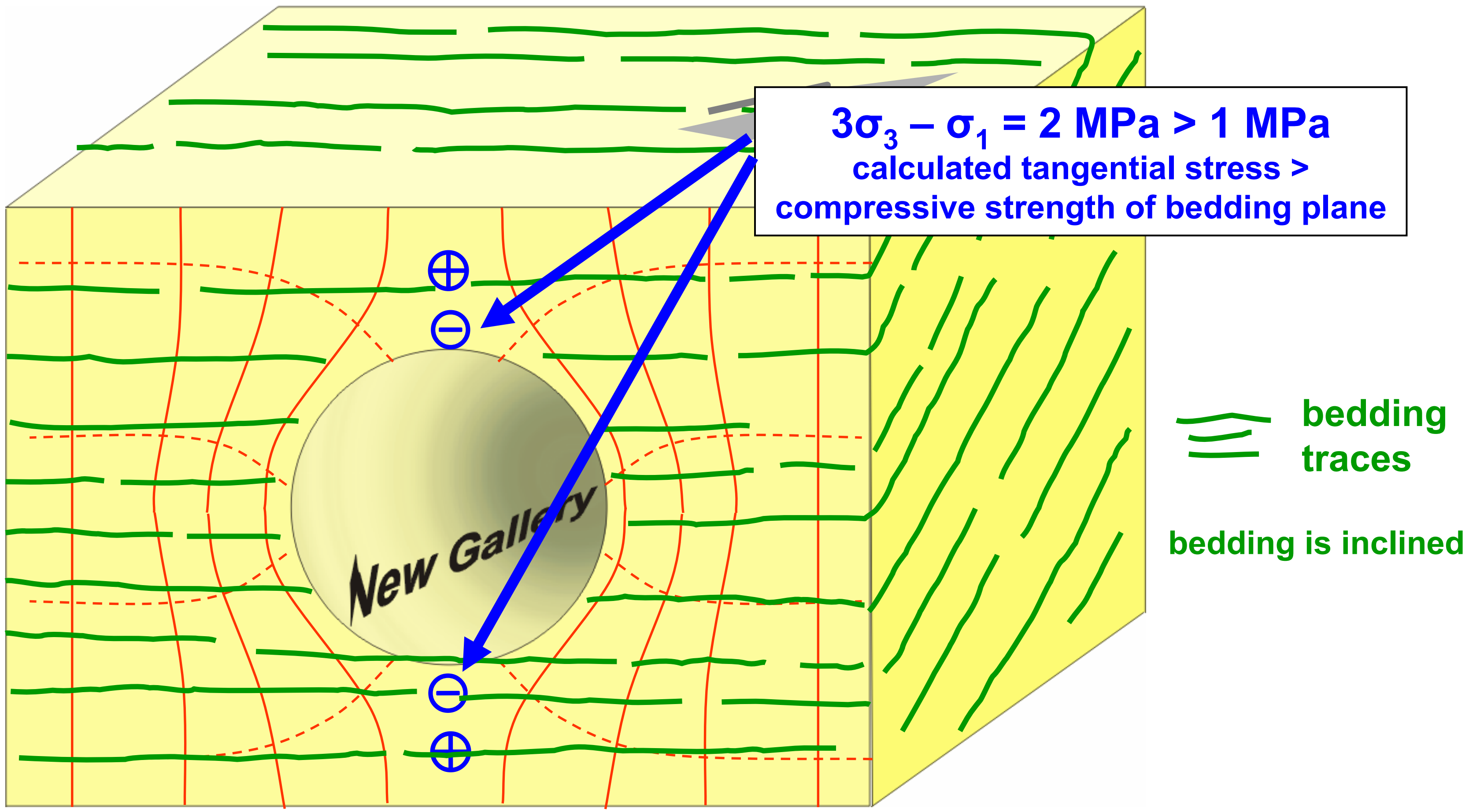


Bedding parallel slip on reactivated bedding planes

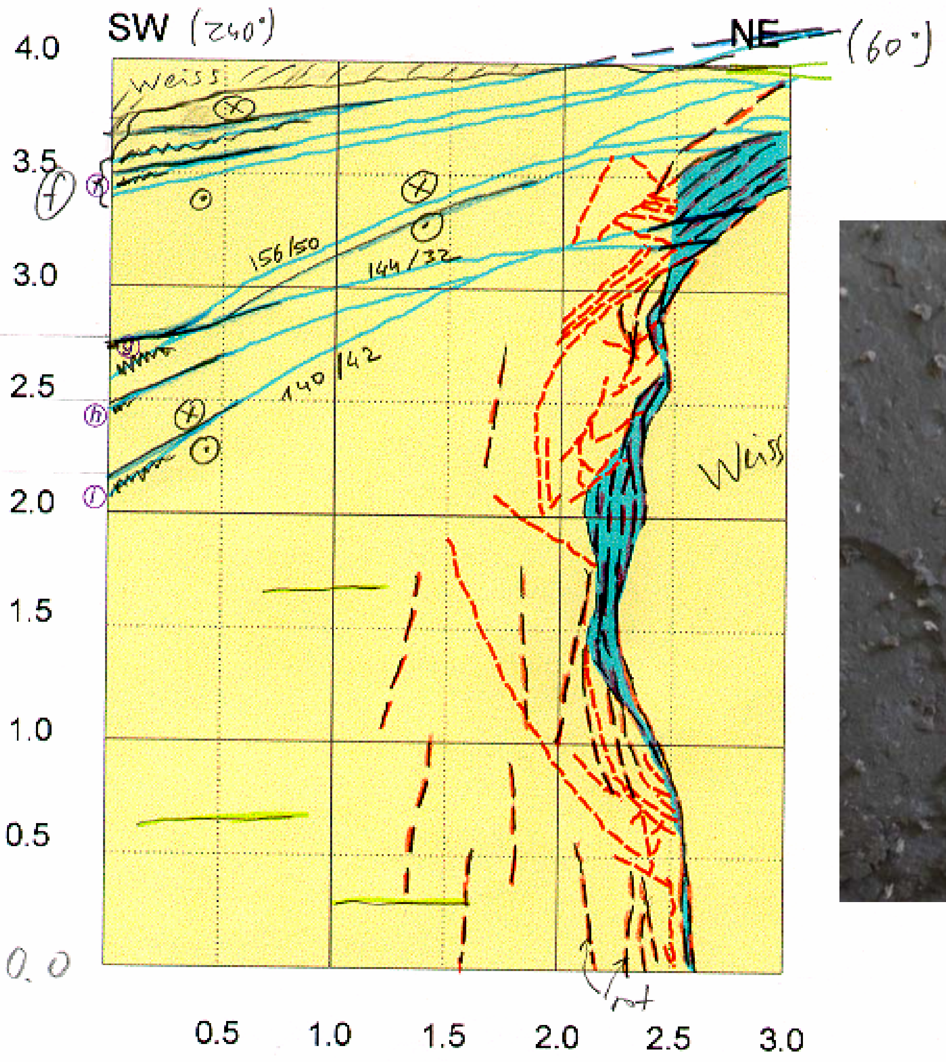
EDZ unloading fractures on side walls



Bedding parallel slip at roof and bottom

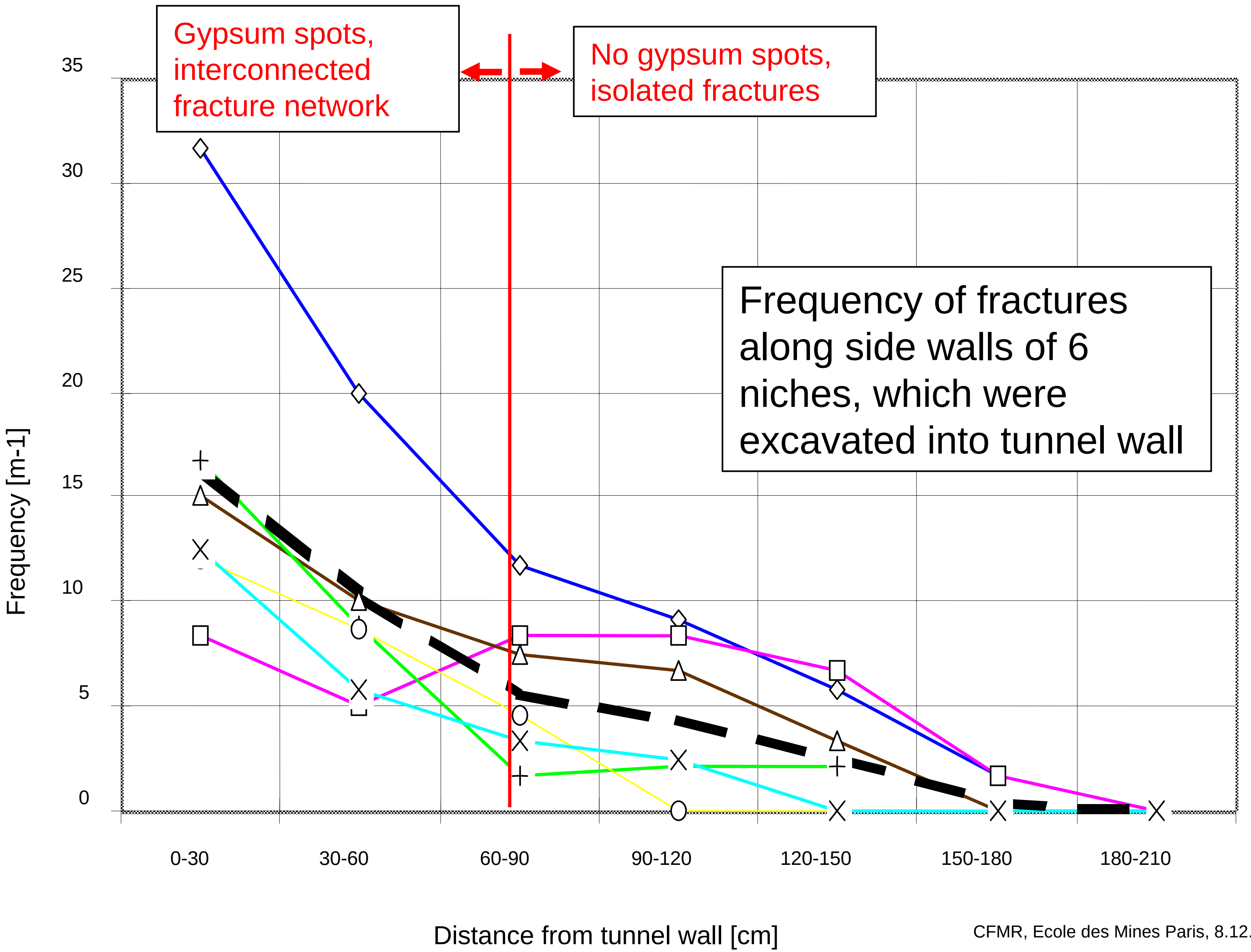


Small scale structural mapping



Gypsum spots on fracture surfaces

Small scale mapping, line countings

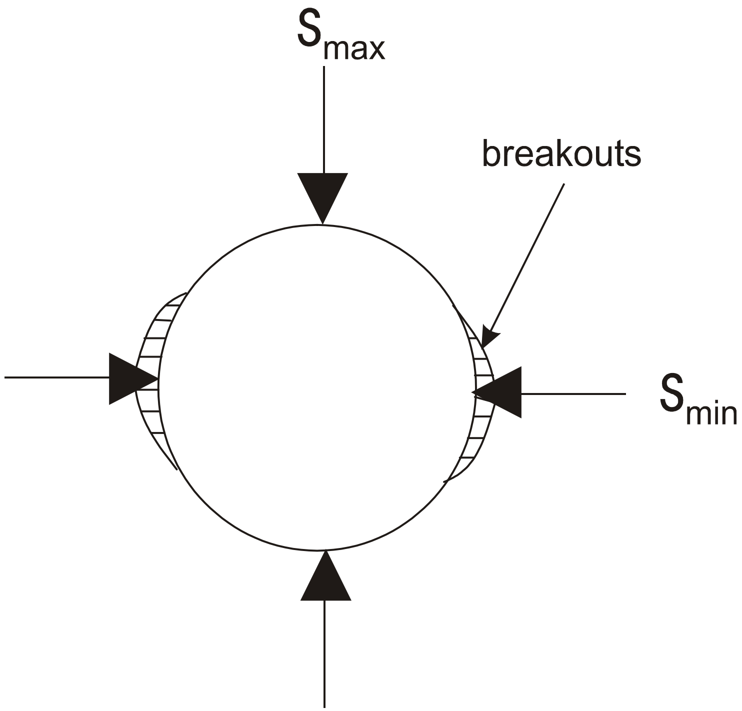


CFMR, Ecole des Mines Paris, 8.12.05

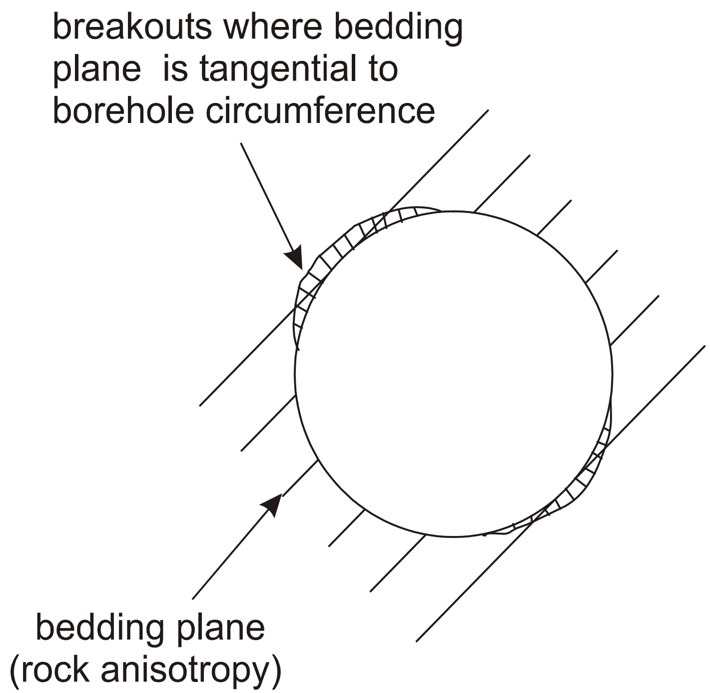
Role of anisotropy

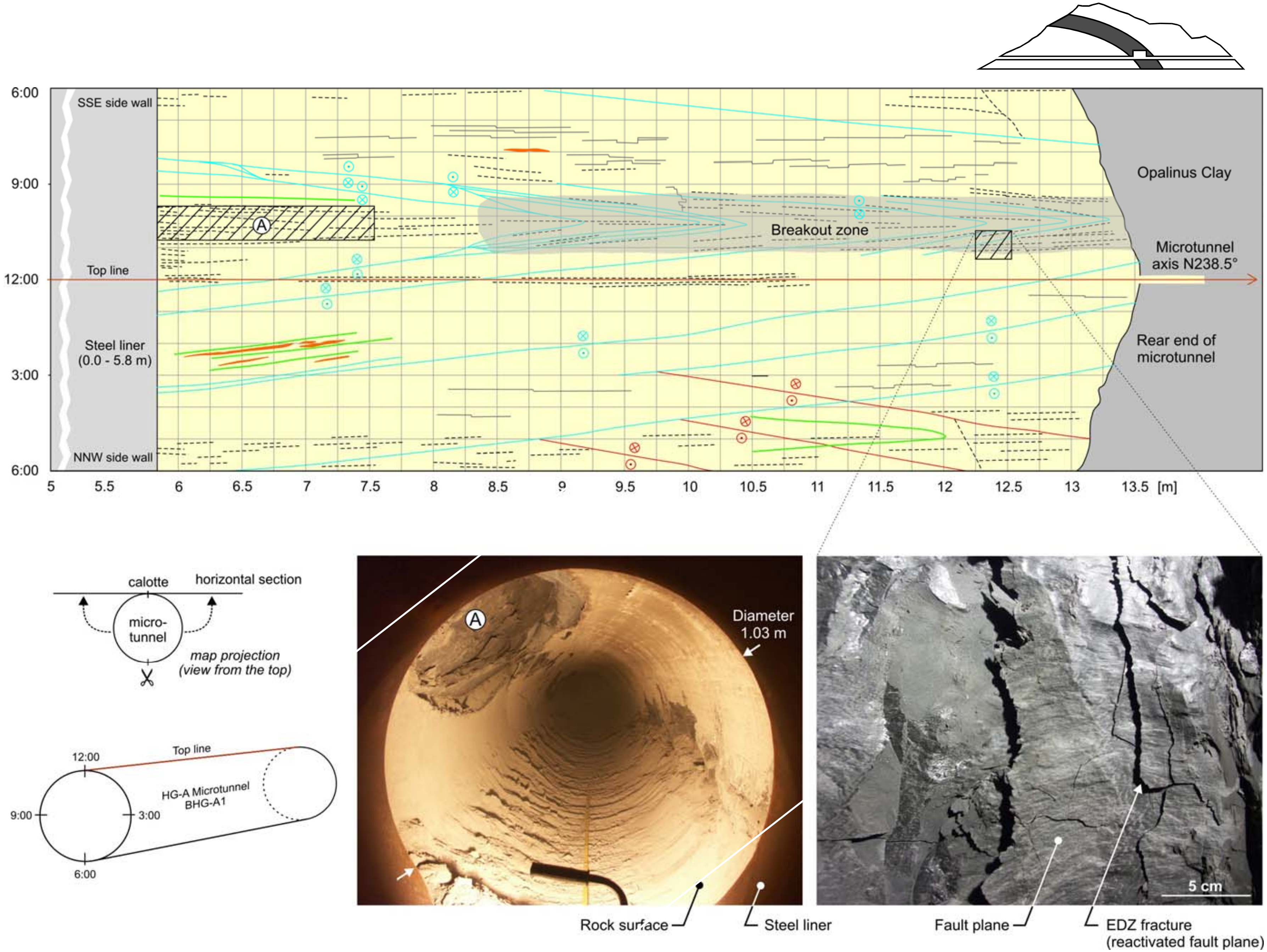
Theory

a) Stress-induced breakouts expected in isotropic rocks with stress anisotropy



b) **Mechanical breakouts**

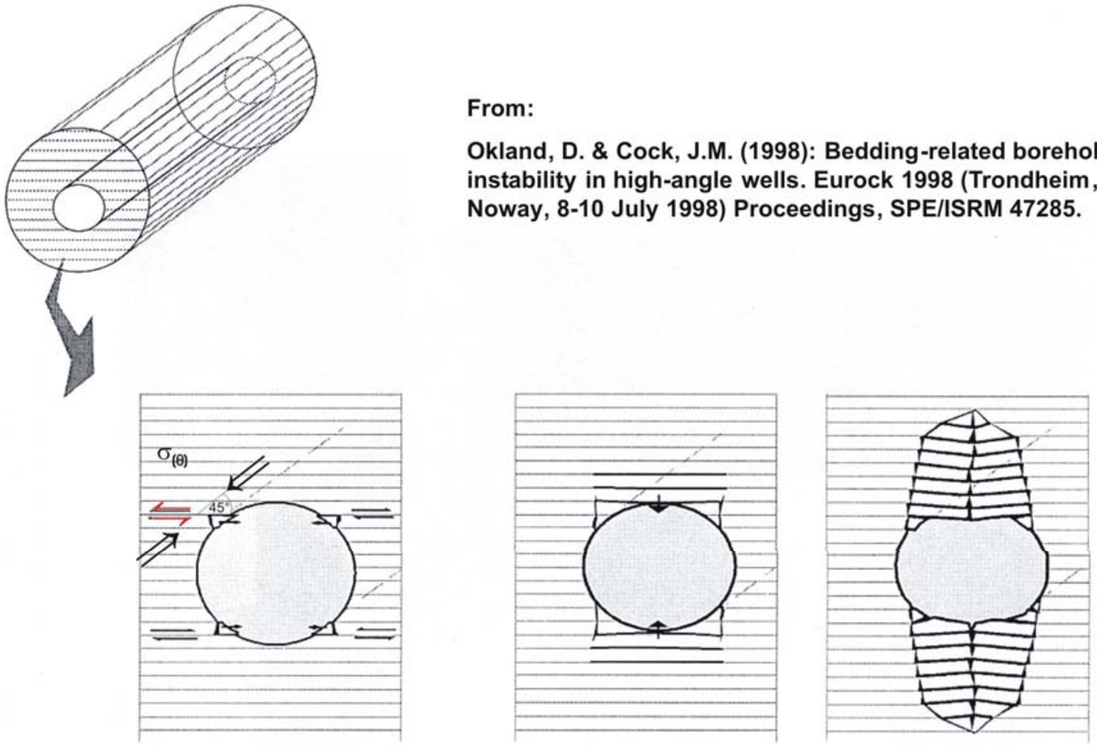




6:00
9:00
12:00
3:00
6:00
SSE side wall
Top line
Steel liner
(0.0 - 5.8 m)
NNW side wall
A
Breakout zone
Opalinus Clay
Microtunnel
axis N238.5°
Rear end of
microtunnel
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5 [m]
calotte
horizontal section
micro-
tunnel
map projection
(view from the top)
12:00
Top line
HG-A Microtunnel
BHG-A1
9:00
3:00
6:00
Diameter
1.03 m
Rock surface
Steel liner
5 cm
Fault plane
EDZ fracture
(reactivated fault plane)

Borehole deformation

Borhole deformation: Buckling and breaking apart of bedding planes

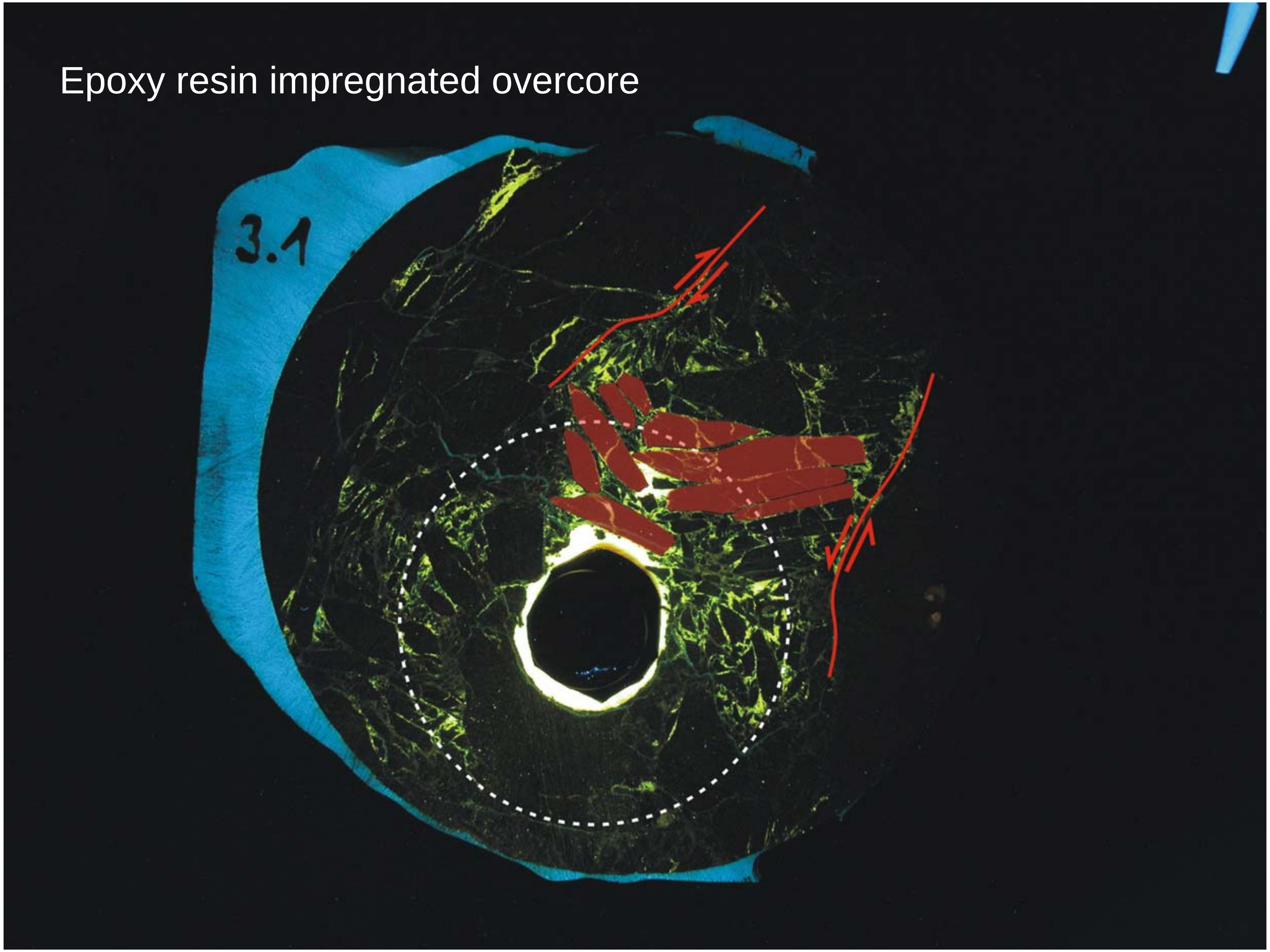


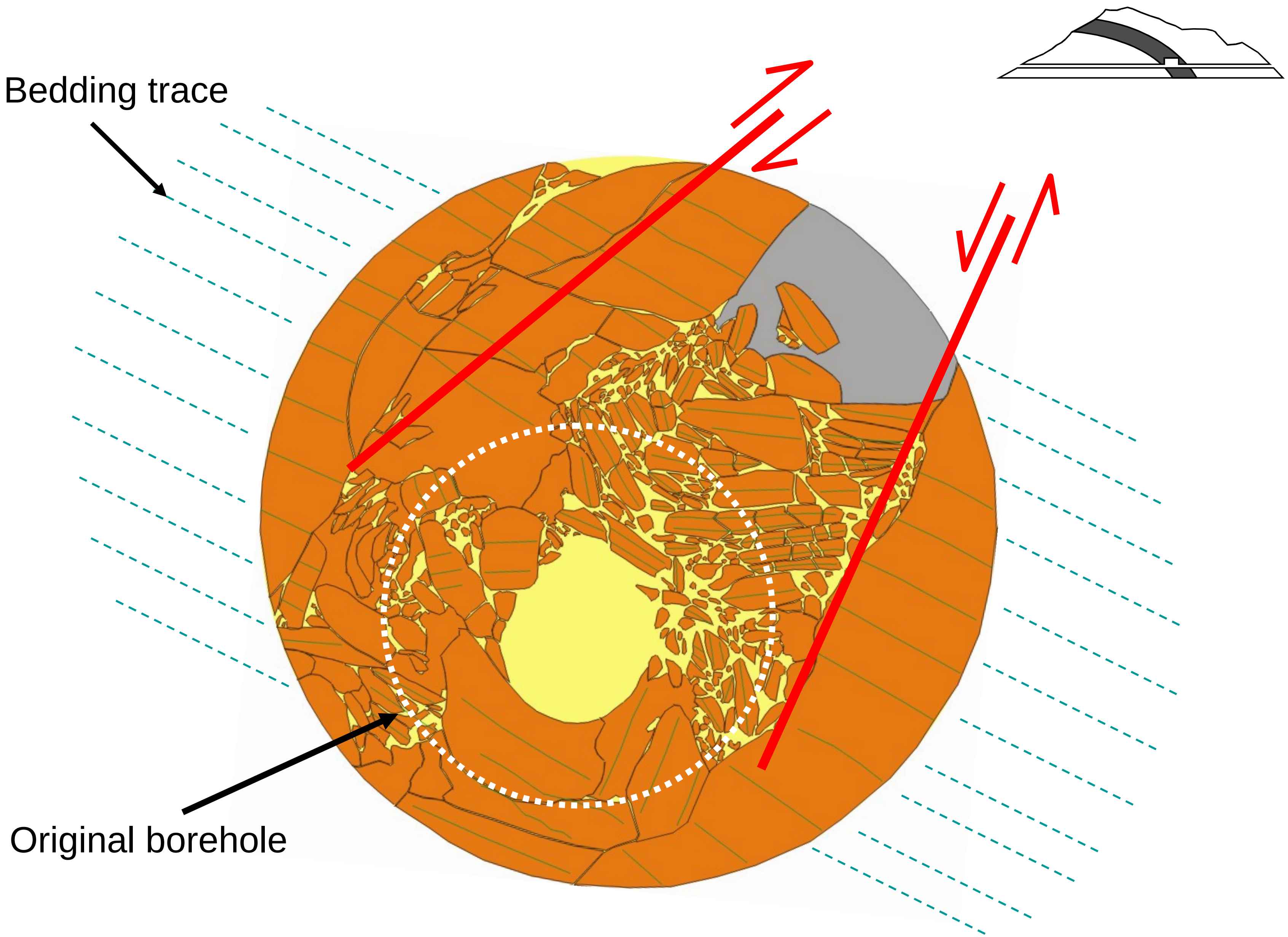
a. b. c.

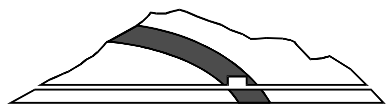
From:

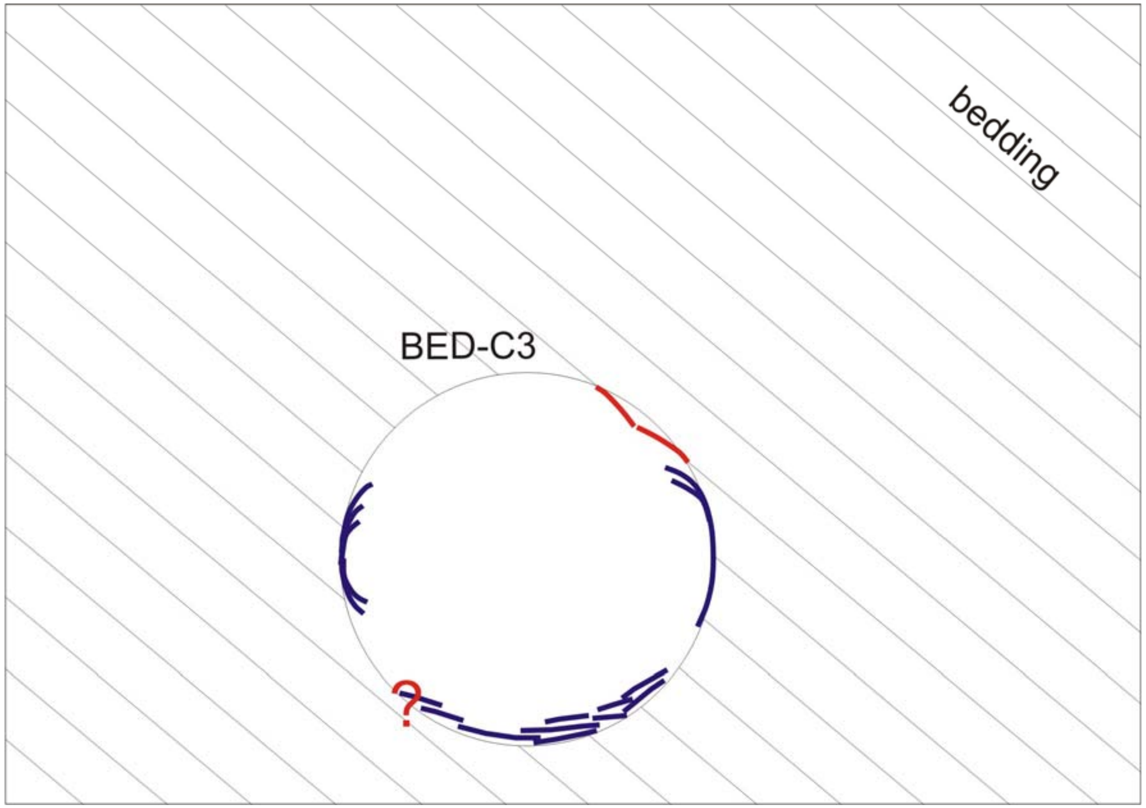
Okland, D. & Cock, J.M. (1998): Bedding-related borehole instability in high-angle wells. Eurock 1998 (Trondheim, Noway, 8-10 July 1998) Proceedings, SPE/ISRM 47285.

Borehole closure




Bedding trace
Original borehole





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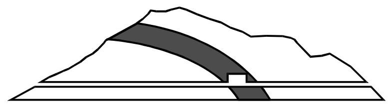
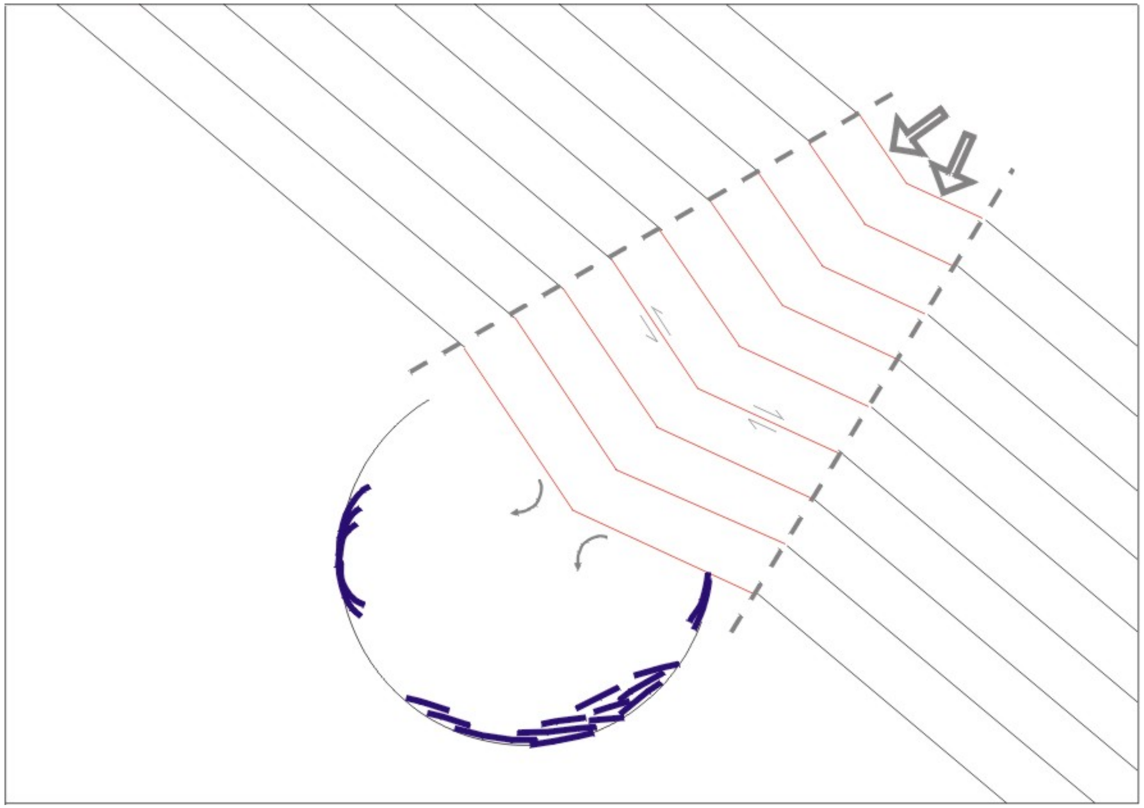
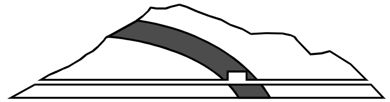
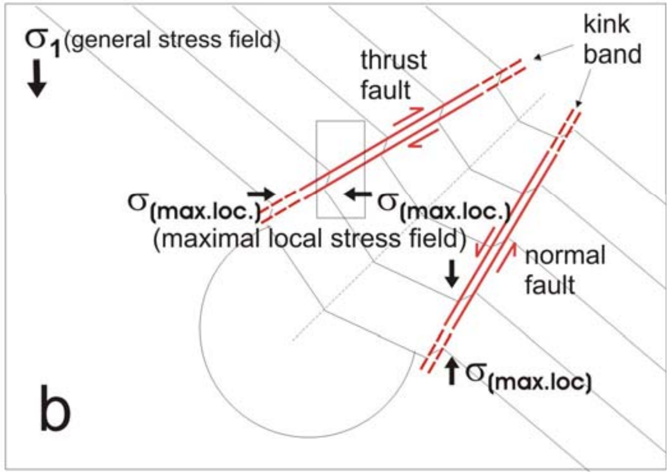
Buckling / kinking of bedding





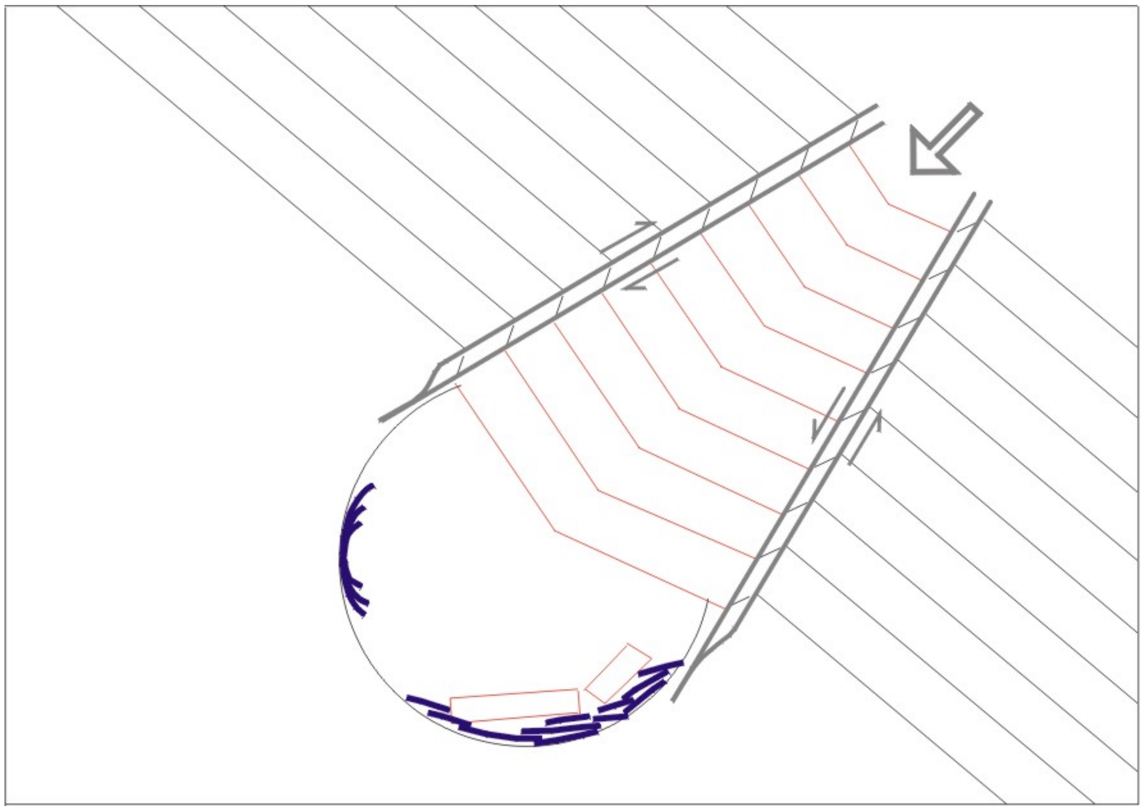


Detail of kink band: fault zone with extension splays

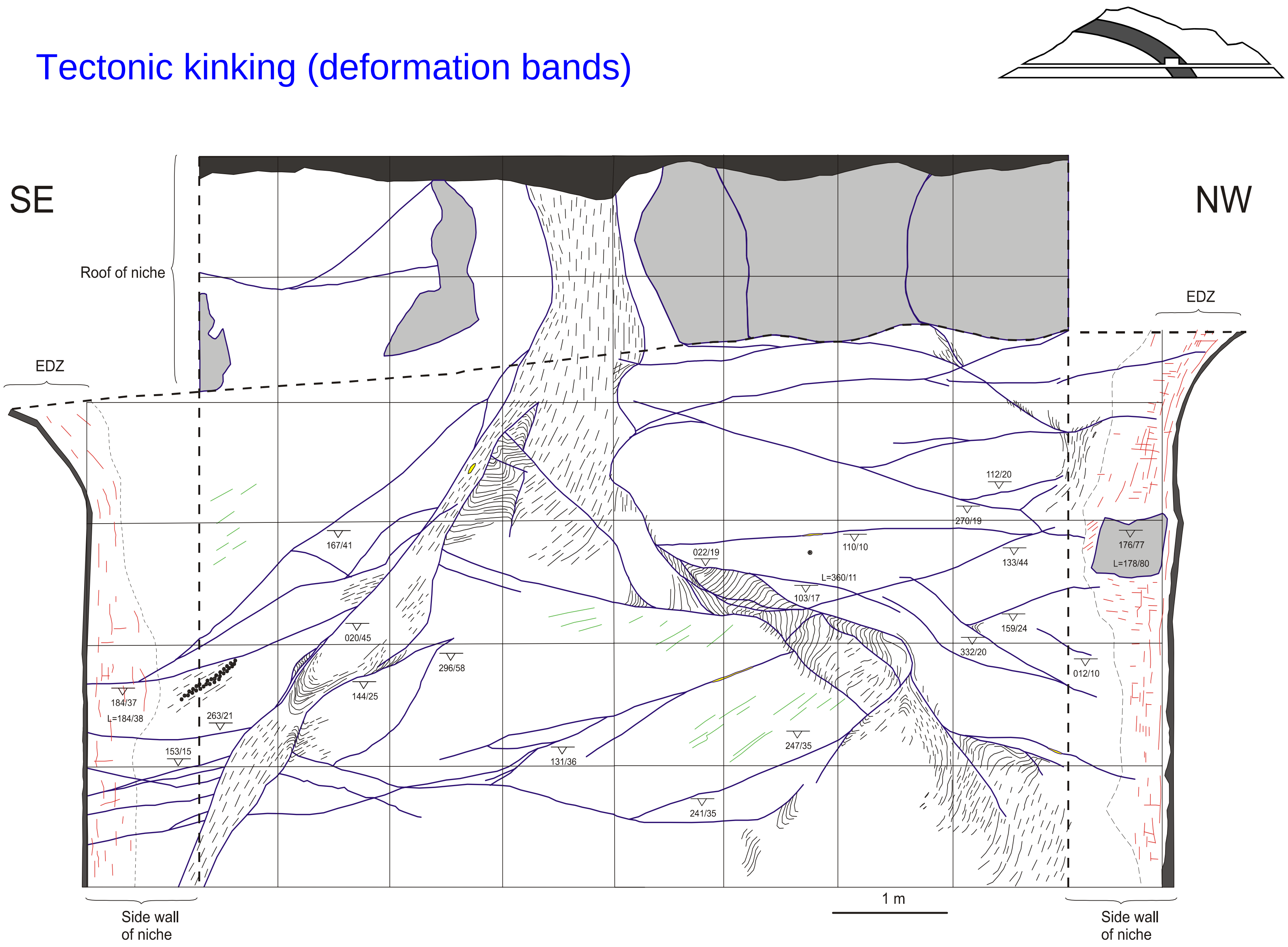


„Borehole closure“ due to bedding kinking combined with displacement along brittle fault zones.

Same process may be true for tunnel closure.



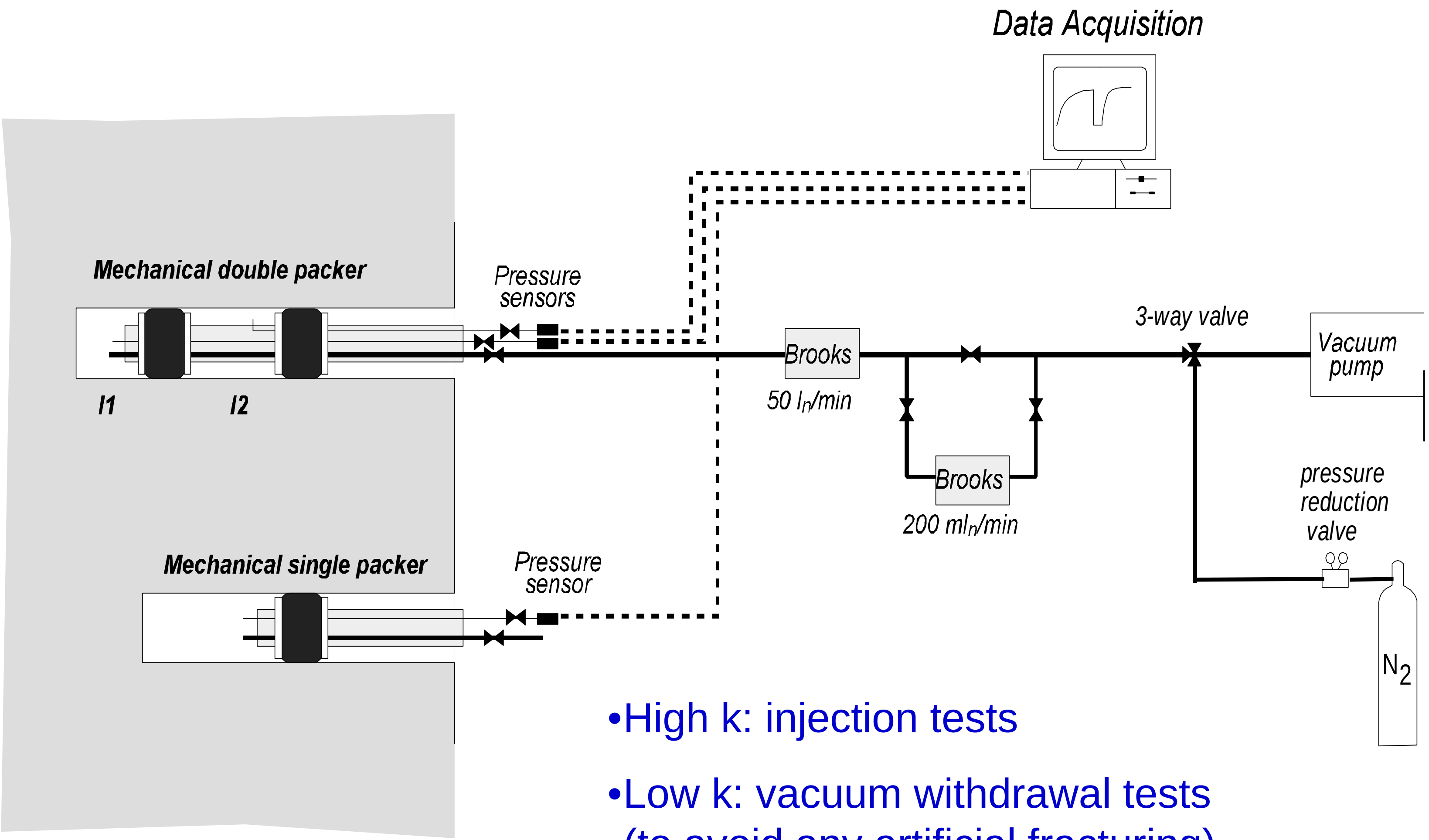
Tectonic kinking (deformation bands)



- The Mont Terri rock laboratory
- Structural characterisation of the EDZ
- Hydrogeological characterisation of the EDZ
- Hydro-mechanical responses in the EDZ

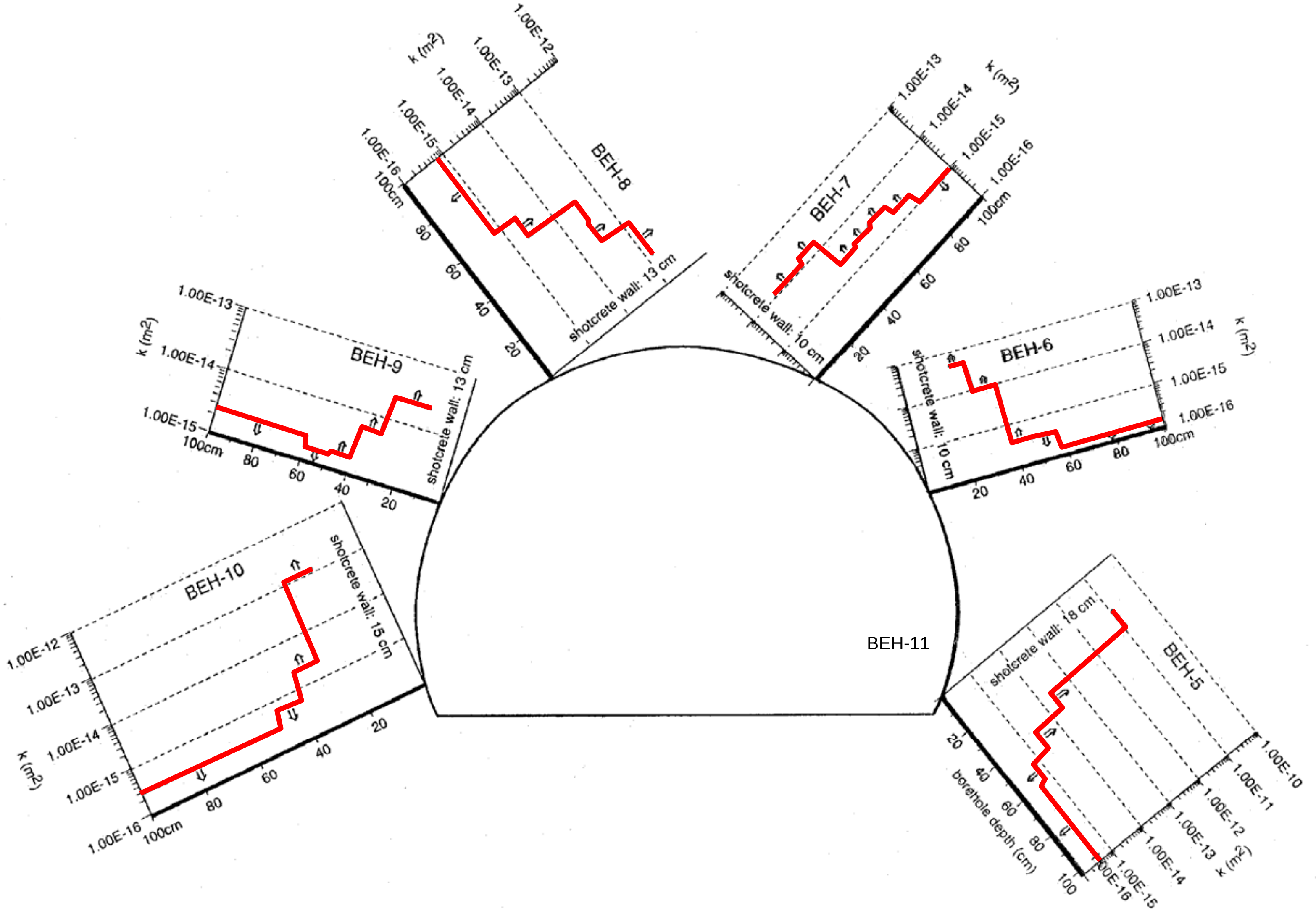
- **Pneumatic testing, EDZ air permeability**
- **Hydraulic testing, EDZ transmissivity**
- **Self-sealing, observations**
- **Self-sealing, transmissivity evolution**

Principle of pneumatic testing

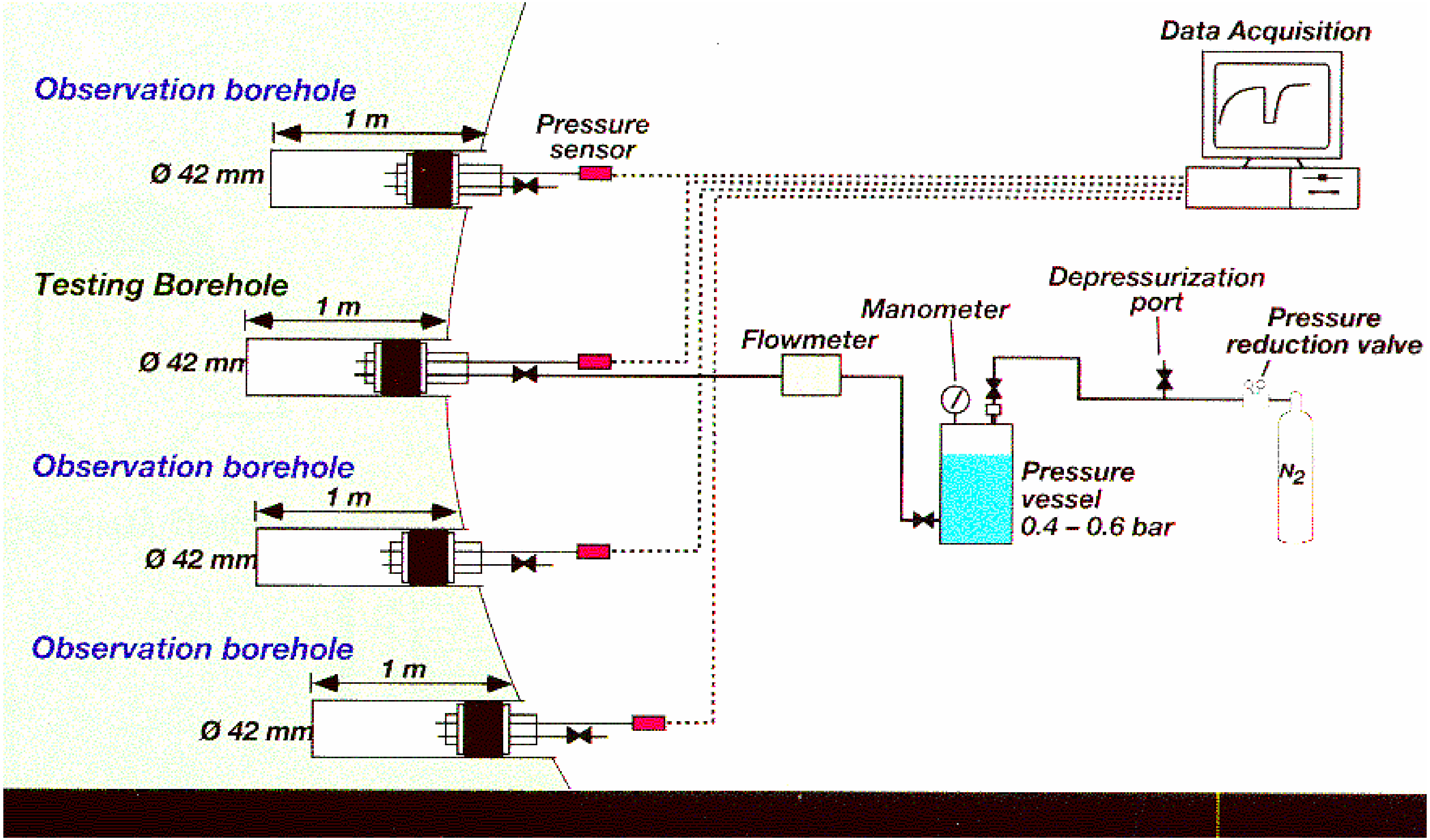


- High k: injection tests
- Low k: vacuum withdrawal tests (to avoid any artificial fracturing)

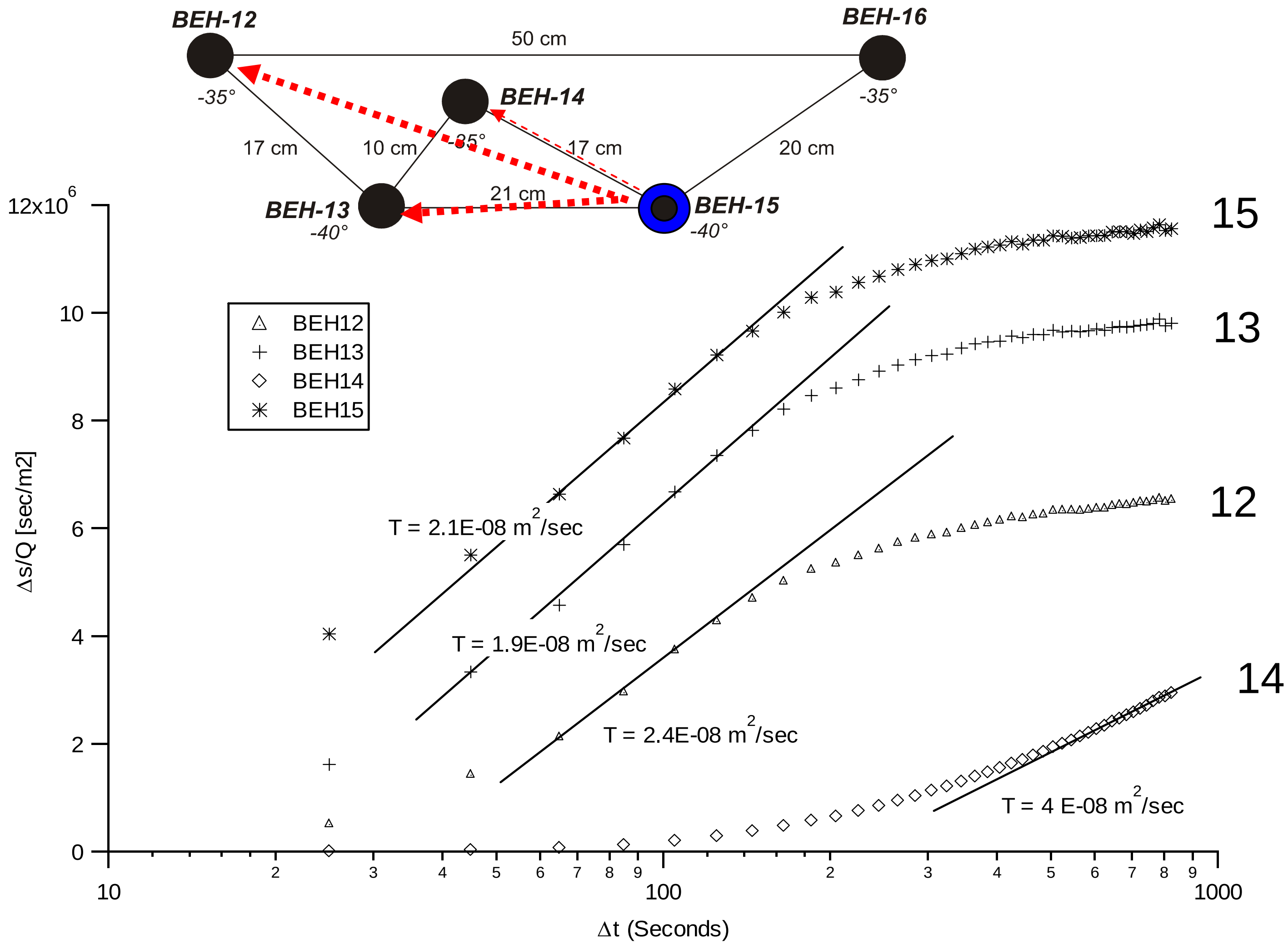
Pneumatic testing: permeability profiles, after excavation



Principle of hydraulic injection testing



Hydraulic Testing of single fracture: Estimation of transmissivities

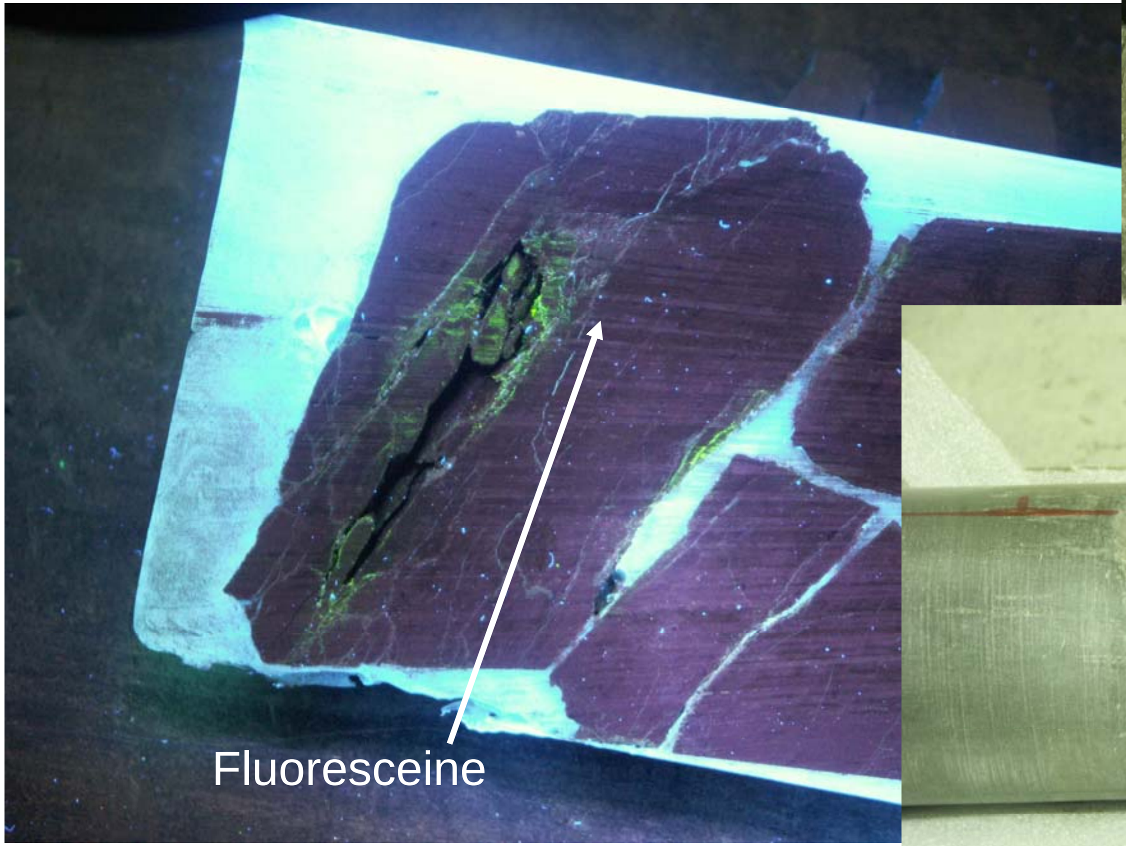


Self-sealing

After repository closure, the EDZ will be slowly saturated (transient phase) by pore water or by water from a bounding aquifer.

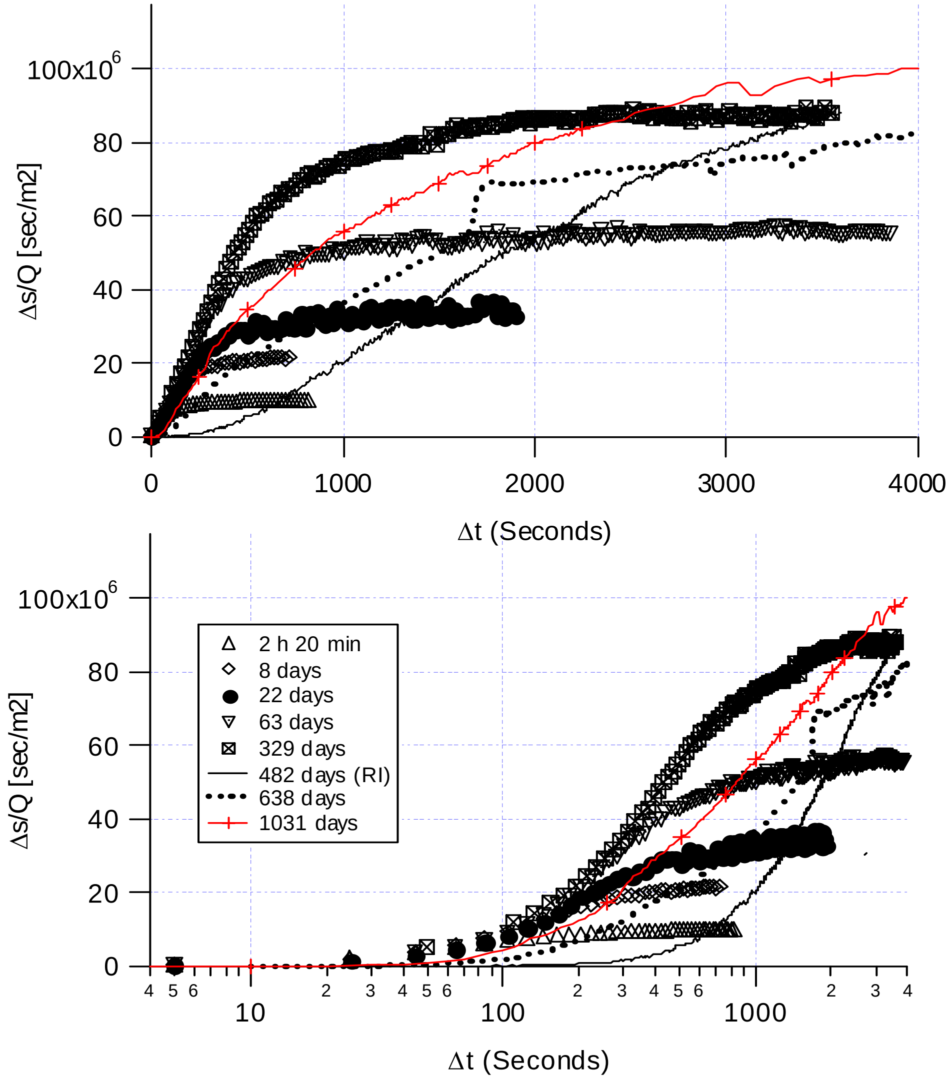
The aim of this experiment is to evaluate if the interaction of this water with clay could lead to a **self-sealing of EDZ fractures** by processes such as swelling and creep.

Self-sealing observations



Oxidation spots

BEH-13 (injection borehole BEH-15)



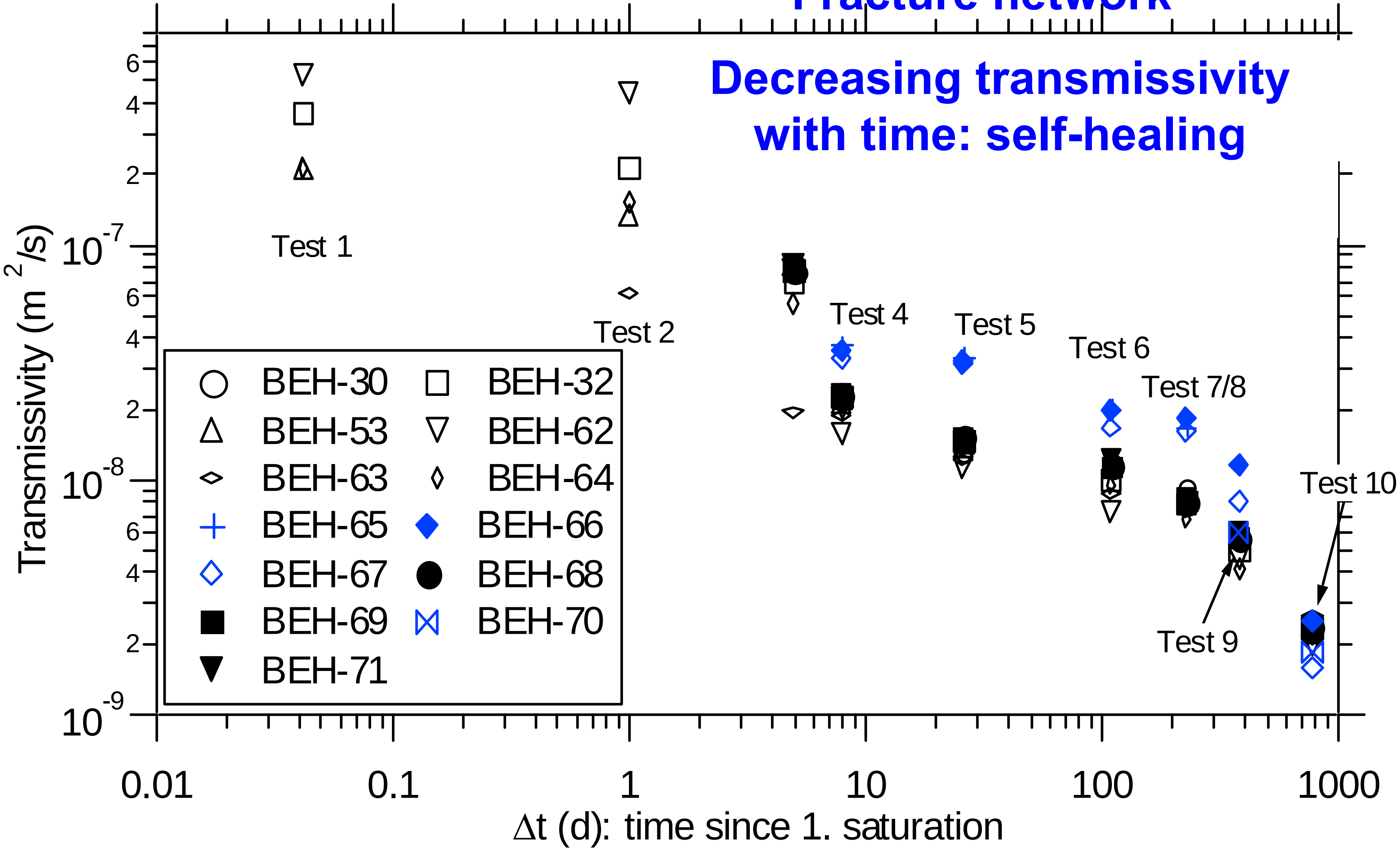
Single fracture

Decreasing transmissivity

with time: self-healing

$$\frac{1}{T} = \frac{\Delta s_b - \Delta s_a}{Q} \cdot \frac{4\pi}{\ln\left(\frac{t_b}{t_a}\right)}$$

Fracture network



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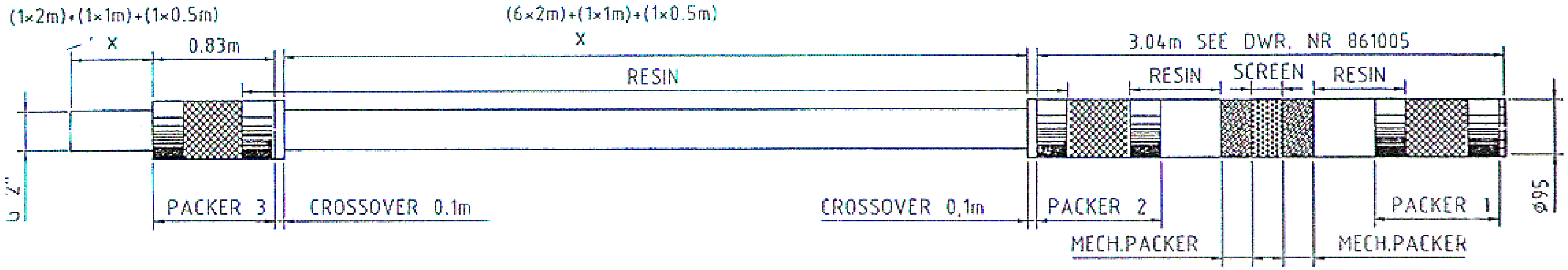
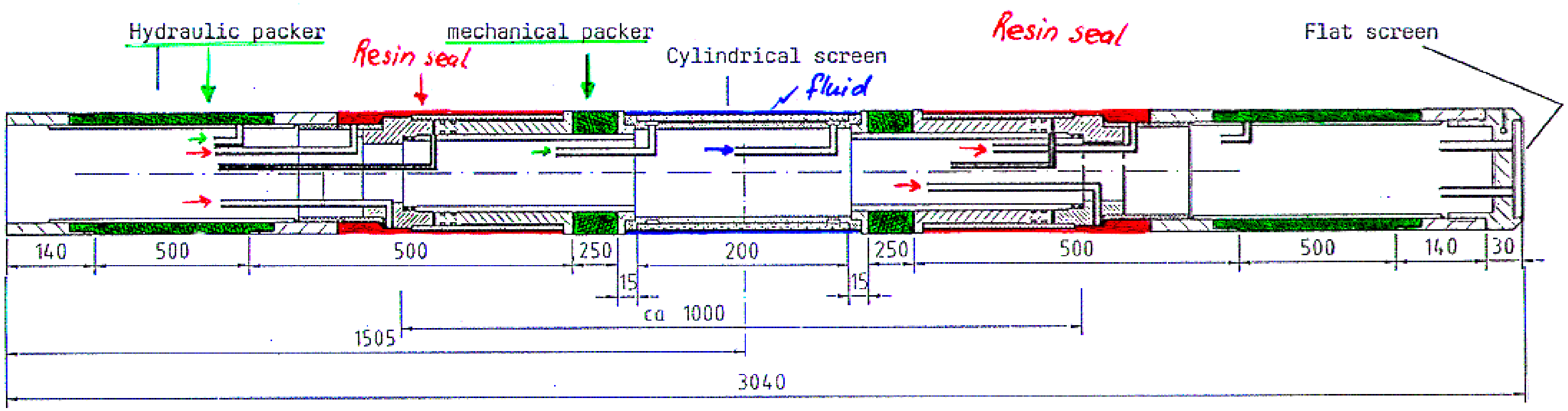
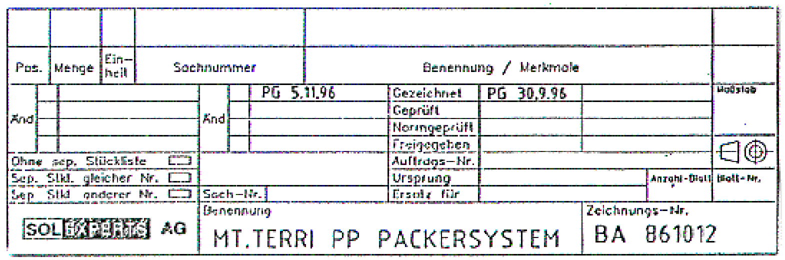
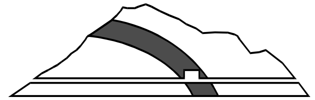


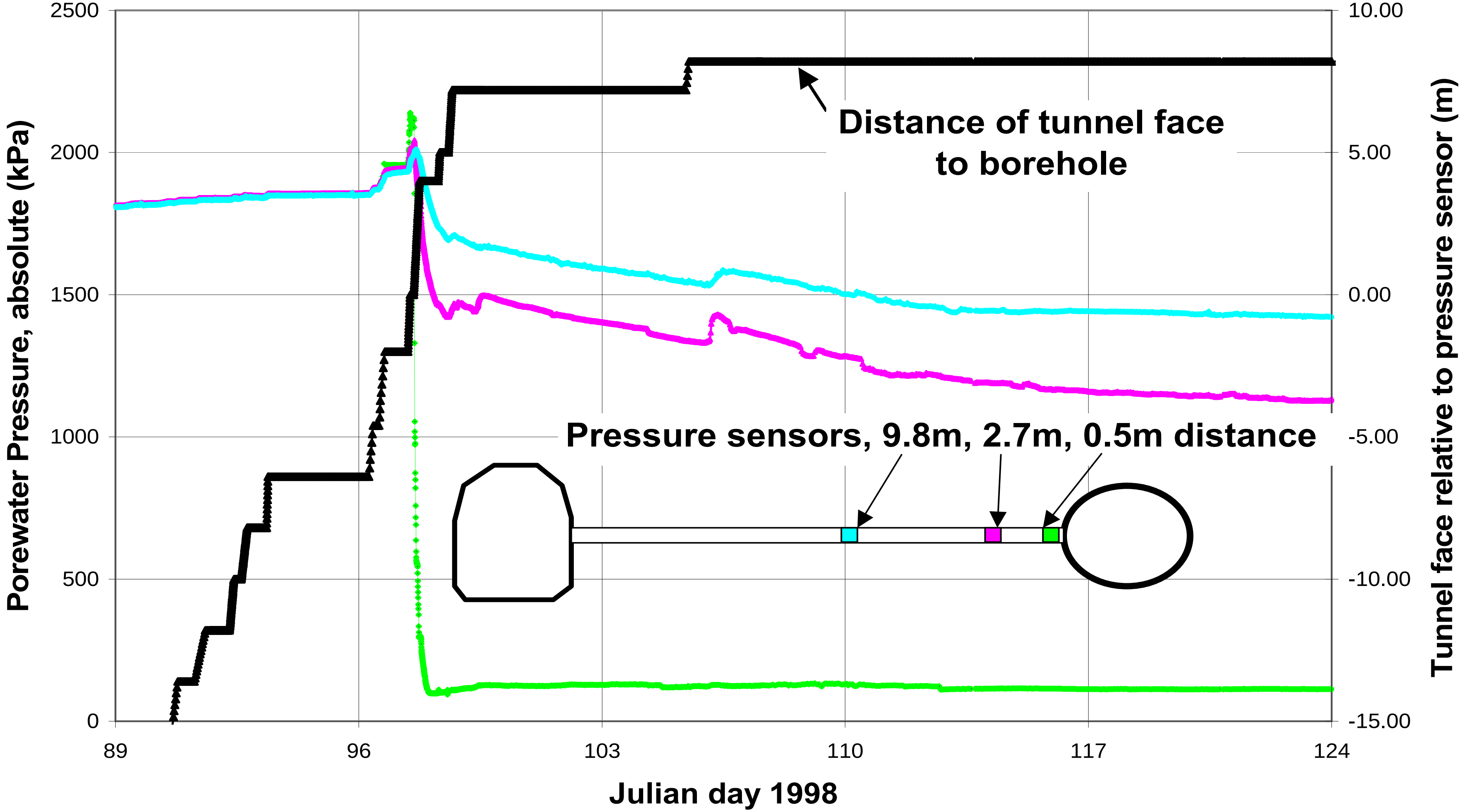


Principle of pore pressure measurements



Pore pressure changes due to stress redistributions, measured





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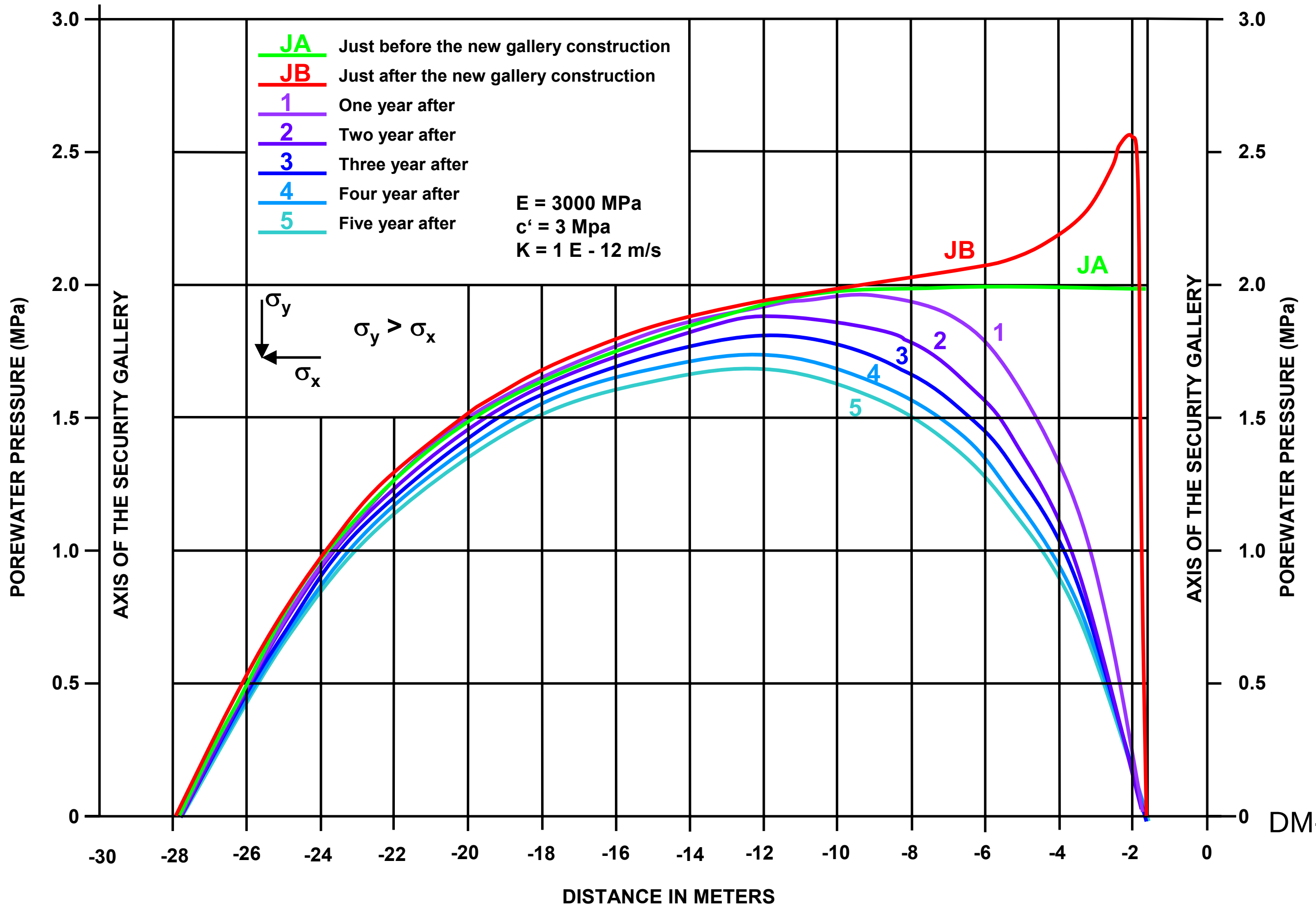
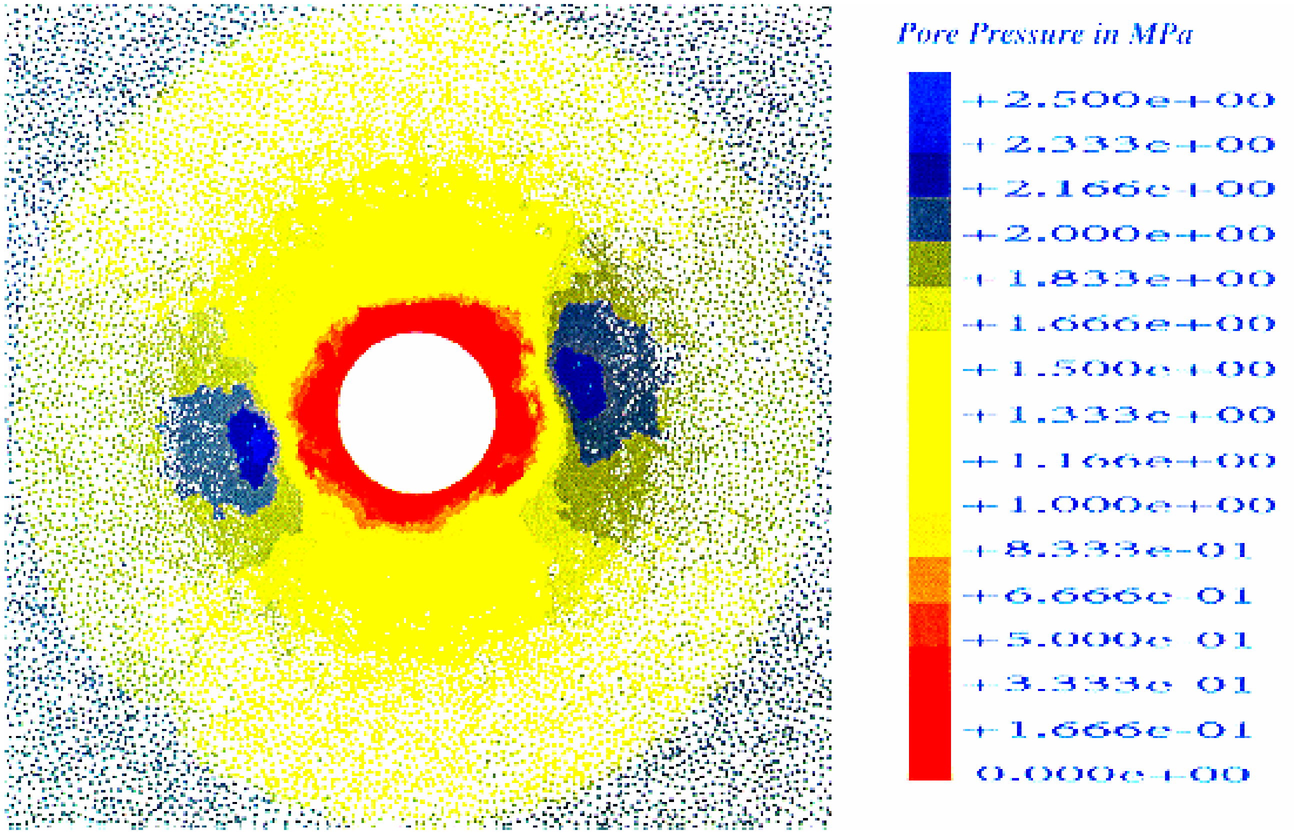
Pore pressure changes due to stress redistributions calculated

Flac 2D: predictive modelling



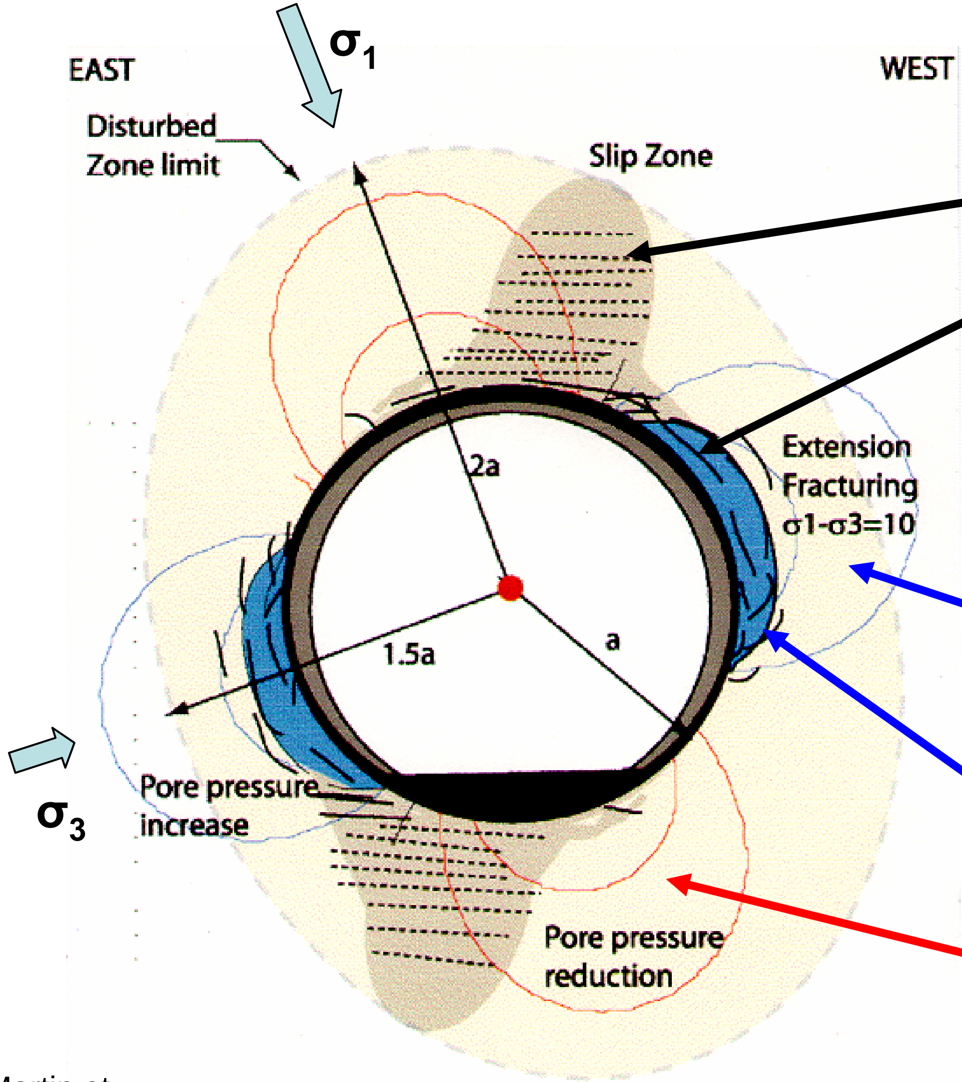
DM-Iberia-modelling

Pore water pressure evolution, PFC modelling



Itasca-modelling

The EDZ model for hydro-mechanical coupling



Bedding parallel slip where compressive strength of bedding is exceeded

Unloading joints where uniaxial compressive strength is exceeded

Dynamic pore pressure increase during excavation (high tangential stresses, low hydraulic conductivities).

Pressure drops to zero at formation of EDZ fractures

Expected pore pressure reduction during excavation (low tangential stresses)

After D. Martin et al., TR 2000-01

• Conclusion (1 of 3)

EDZ mechanisms, microstructures

- Deformation in the excavation damaged zone (EDZ): Stress induced deformations and mechanical induced deformations, the latter due to a pronounced bedding anisotropy.

- Reason of discontinuity formation in EDZ: generally UCS is exceeded. Special case: CS of discontinuities is exceeded. Reactivation of bedding- and tectonic-planes.

- EDZ structures: extensile brittle fractures (unloading joints) bedding parallel slip.

- Borehole-deformation and -closure: buckling, kinking. Conjugate brittle fault zones, where material is displaced into opening. Cataclastic flow.

• Conclusion (2 of 3)

EDZ pneumatic and hydrogeological testing & self-sealing

- Methodology: Pneumatic testing (vacuum tests or air injection tests), followed by classical hydrotesting (constant head!). May be combined with geoelectrical resistivity measurements and seismic tomography.
- Determination of EDZ air permeability. Extent of EDZ can clearly be traced, where permeability is increased by 2-4 orders of magnitude.
- Determination of EDZ pore water transmissivity: classical hydrotesting, careful saturation of fracture network, selection of artificial pore water. Means in the order of 2E-8 m2/s, max. transmissivities of 1E-6 m2/s.
- Self-sealing: Transmissivity decrease: 2 orders of magnitude during a period of 800 days. Processes: disjoining of fabric, chemico-osmotic effects, induced creep (?), chemical precipitation reactions (gypsum spots).

• Conclusion (3 of 3)

EDZ hydro-mechanical coupling

- Requirement: piezometers which measure pore pressure (and not borehole deformations!)
- Deformations: elastic responses ahead in the frontal wall. Clear plastic responses when frontal wall passes piezometers in the sidewalls.
- Coupling: pore pressure changes due to stress redistributions. The lower the hydraulic conductivity the higher the pressure changes.
- Tunnel stability is a function of wall saturation. Tunnel ventilation is necessary in order to maintain de-saturation. Recovery of pore pressures results in unstable tunnel (mainly bedding parallel slip). Application of effective stress concepts.