NoRSTRESS

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SINTEF method for Rock Stress Measurement for HEP

NoRSTRESS Seminar 2021

SINTEF NTNU Skagerak Energi Statkraft Hydro Industries that matter Hafslund ECO Sira·Kvina KRAFTSELSKAP The Research Council of Norway

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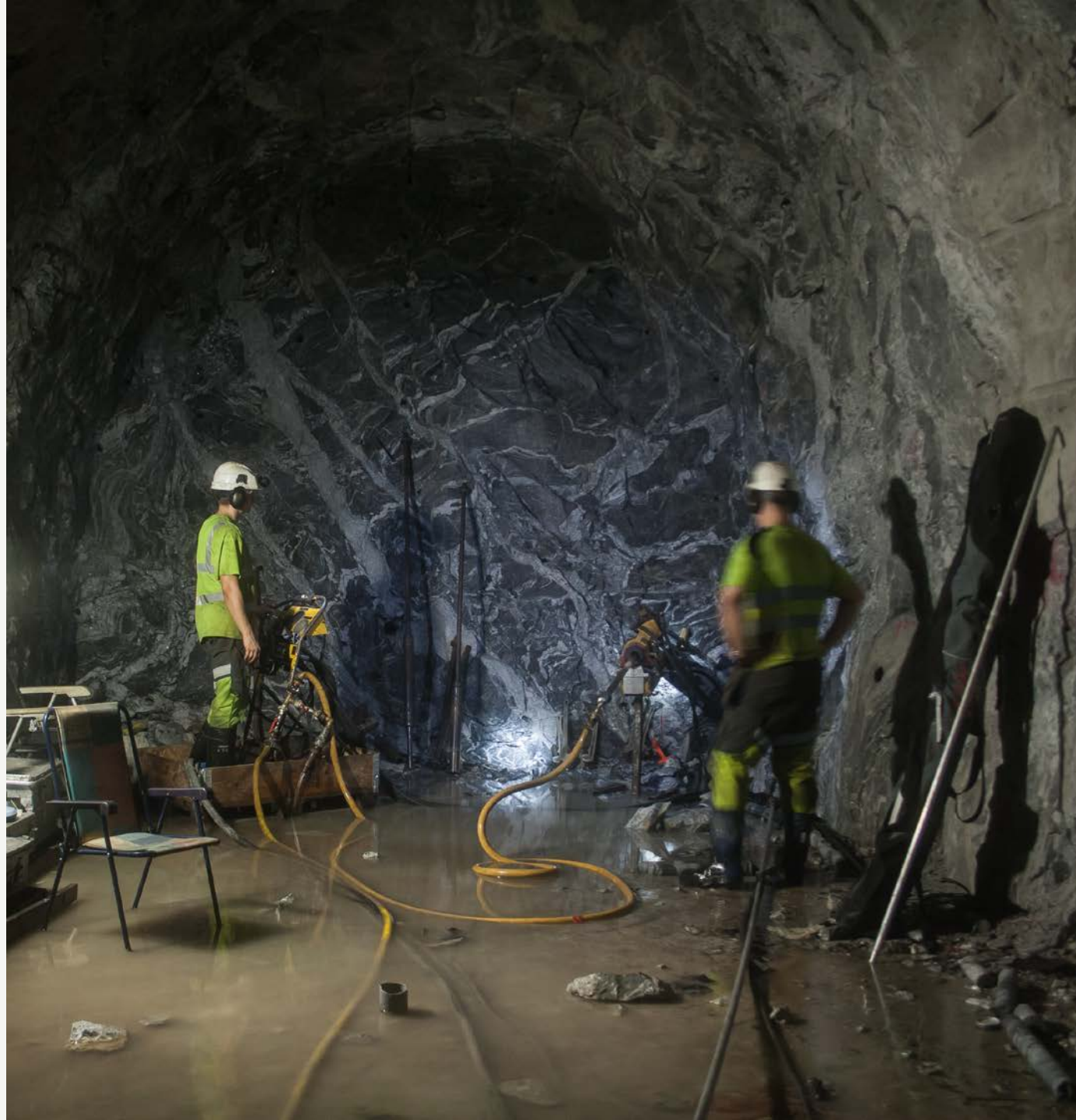


Unlined headrace pressure tunnels

- Utilizing the rock mass to bear the pressurized water – without concrete or steel lining.
- Significant cost and time reduction with this solution.
- **For this solution, the minimal principal stress (σ3) needs to be higher than the internal water pressure**
- Thus, rock stress measurements are performed (mostly close to the penstock cone or other crucial parts of the tunnel)

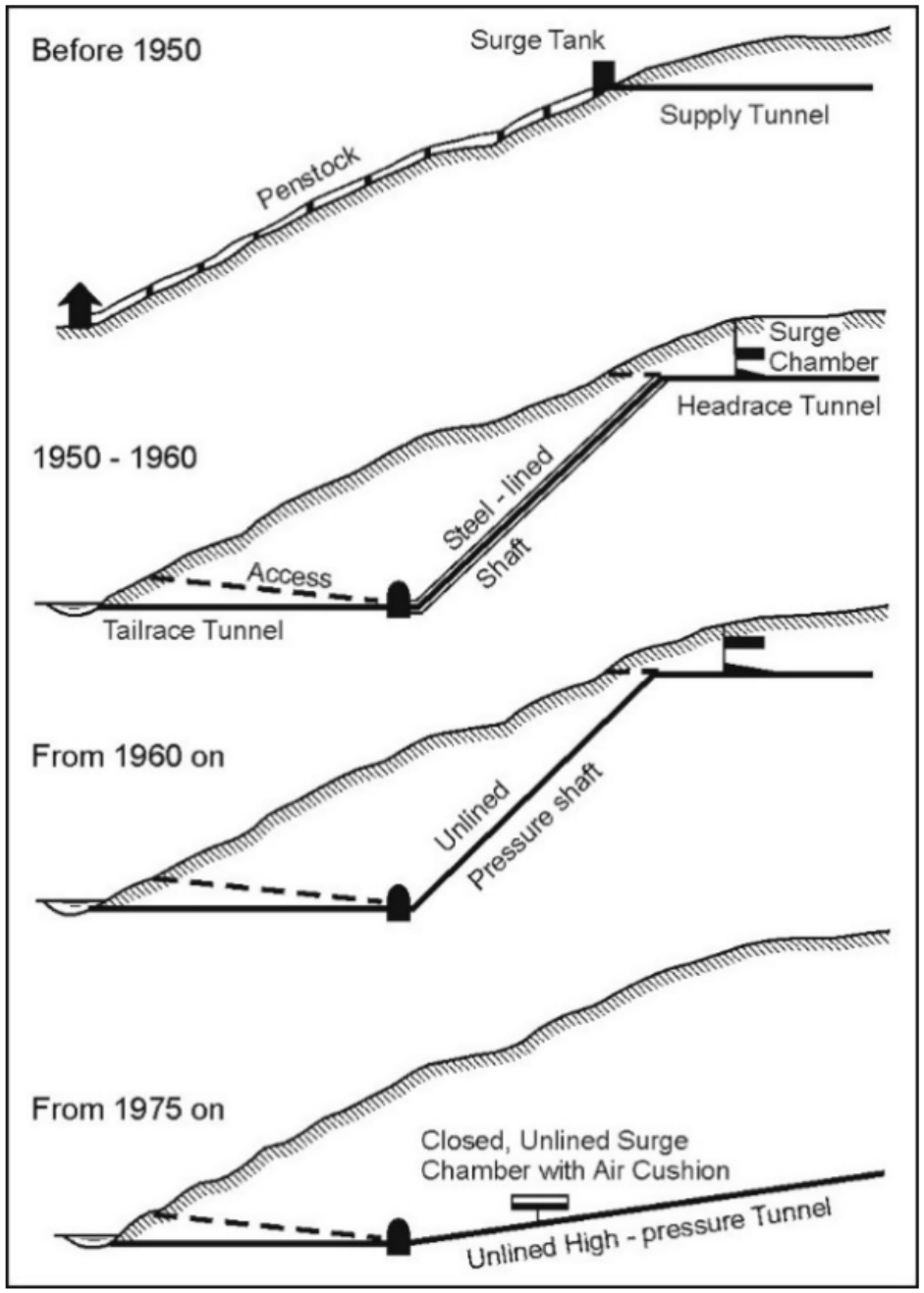
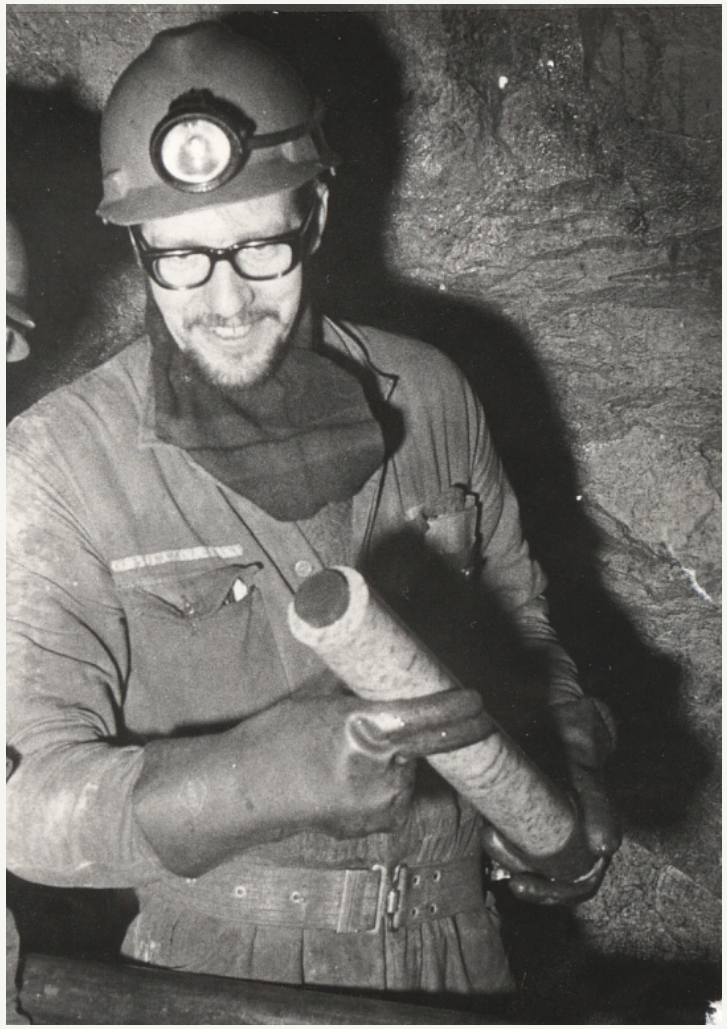


Fig. 1. Trends in the developments of the general layout of hydropower plants in Norway [Broch, 1982[1]].

Rock Stress measurements since 1964

- 3D overcoring cell developed together with the HEP industry in the 1970s
- Own developed Hydraulic Fracturing Method
- Since then testing in over 120 HEP projects

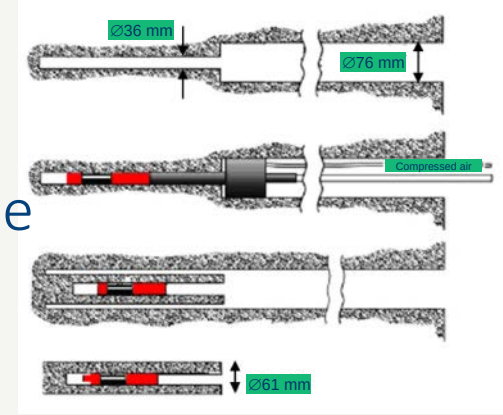


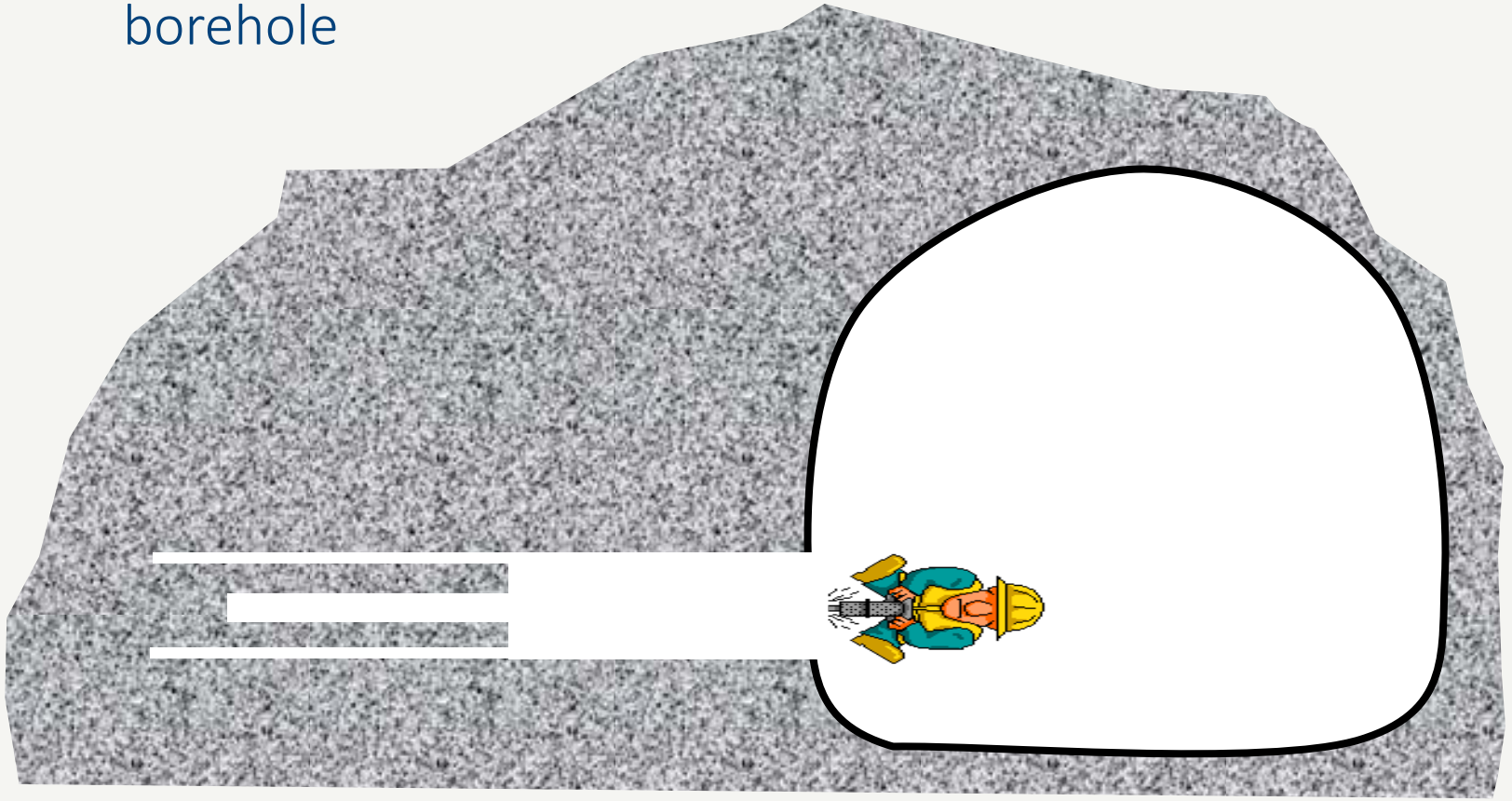
Test arrangement
3D overcoring

- Strain gauge based 3D test cell
- Calculations based on Hooks law
- Testing performed in core drilled boreholes from exciting tunnels
- One test locations performed in 3-4 days

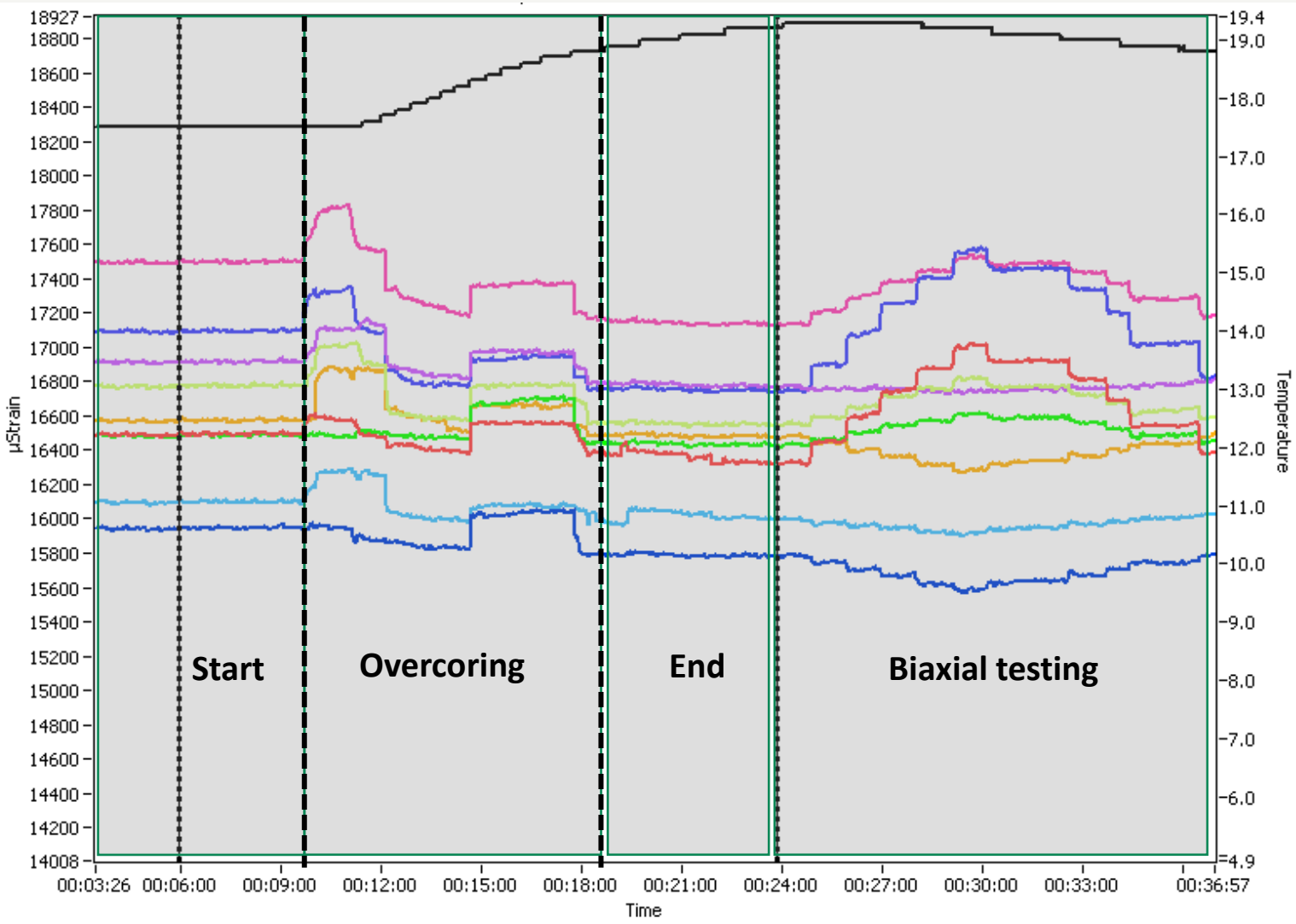
3D overcoring

- Measurements performed outside the influenced zone of the tunnel in a sub-horizontal borehole (1.5x diameter)
- Strain measurements logged during overcoring
- 7 – 10 successive single measurements in a sub-horizontal borehole

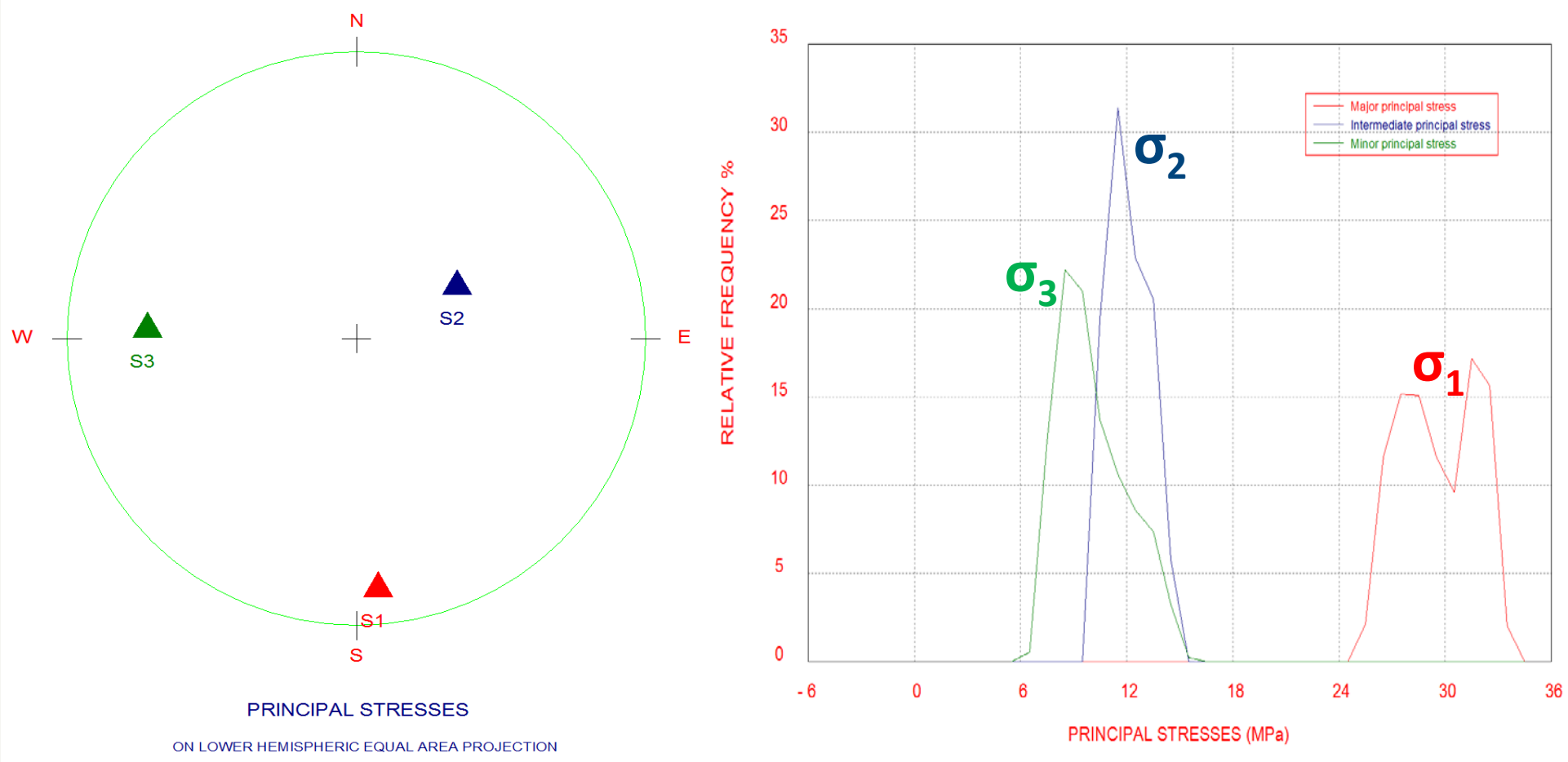




Recorded strains from 3D cell and biaxial testing



Calculating the stresses in DISO



Hydraulic fracturing (HF)

- **Active method** that measures the minimal principal stress directly (Correct oriented borehole)
- Testing performed in drillholes in tunnel or from surface
- Testing performed **outside** influenced zone of tunnel (min. 1.5xD)
- One test location performed in 1 day (24 test sections)

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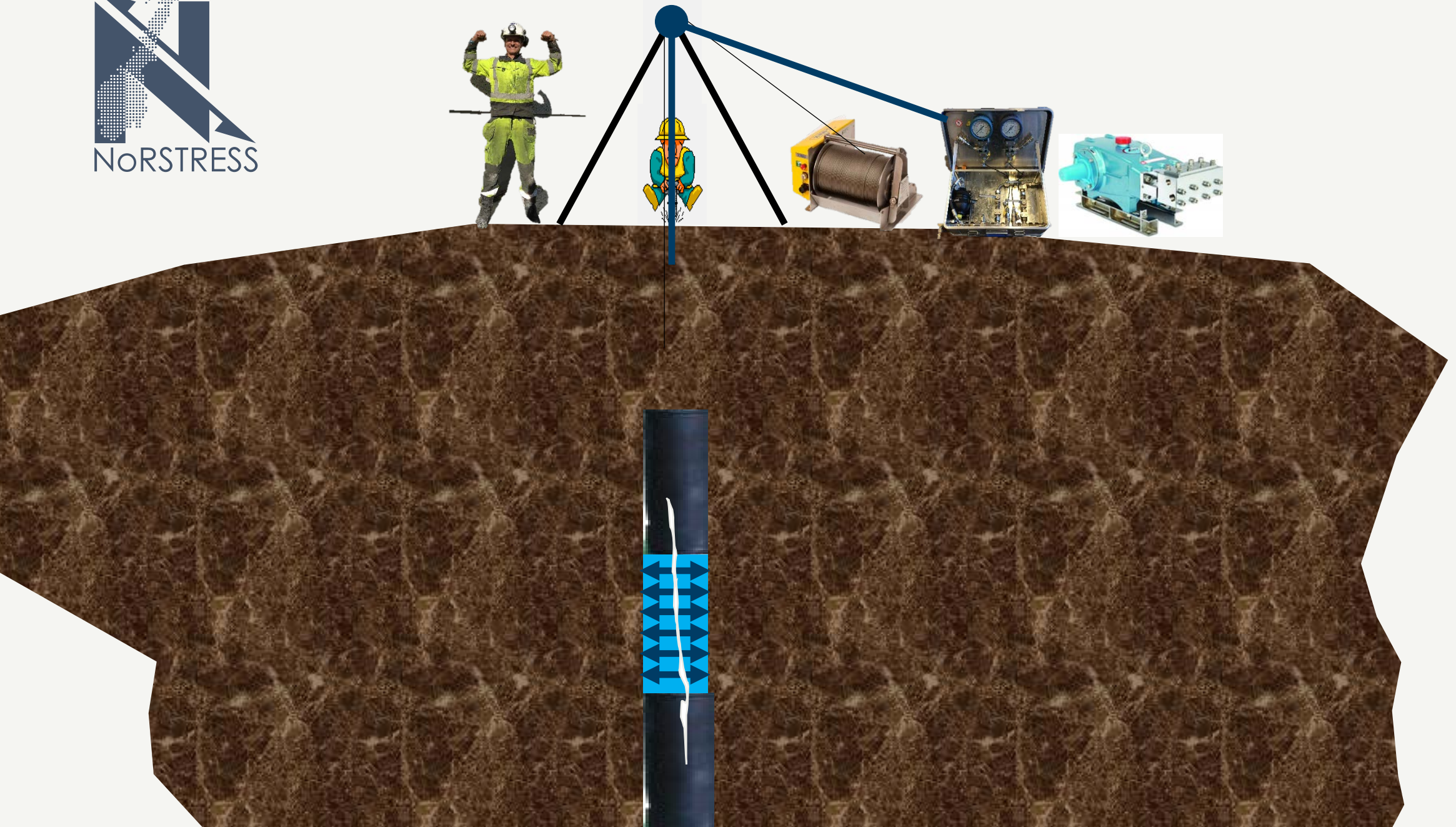
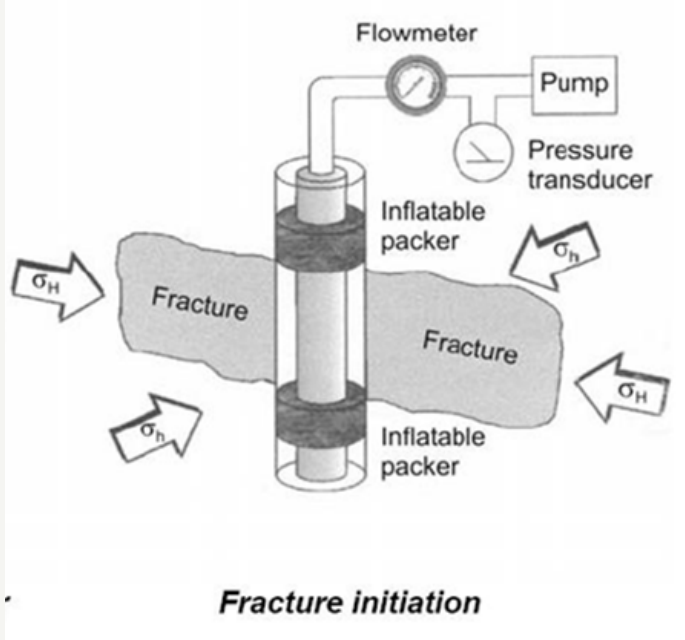
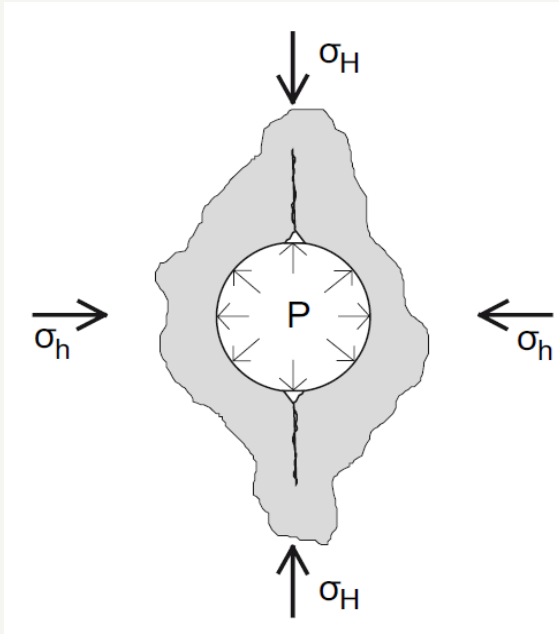


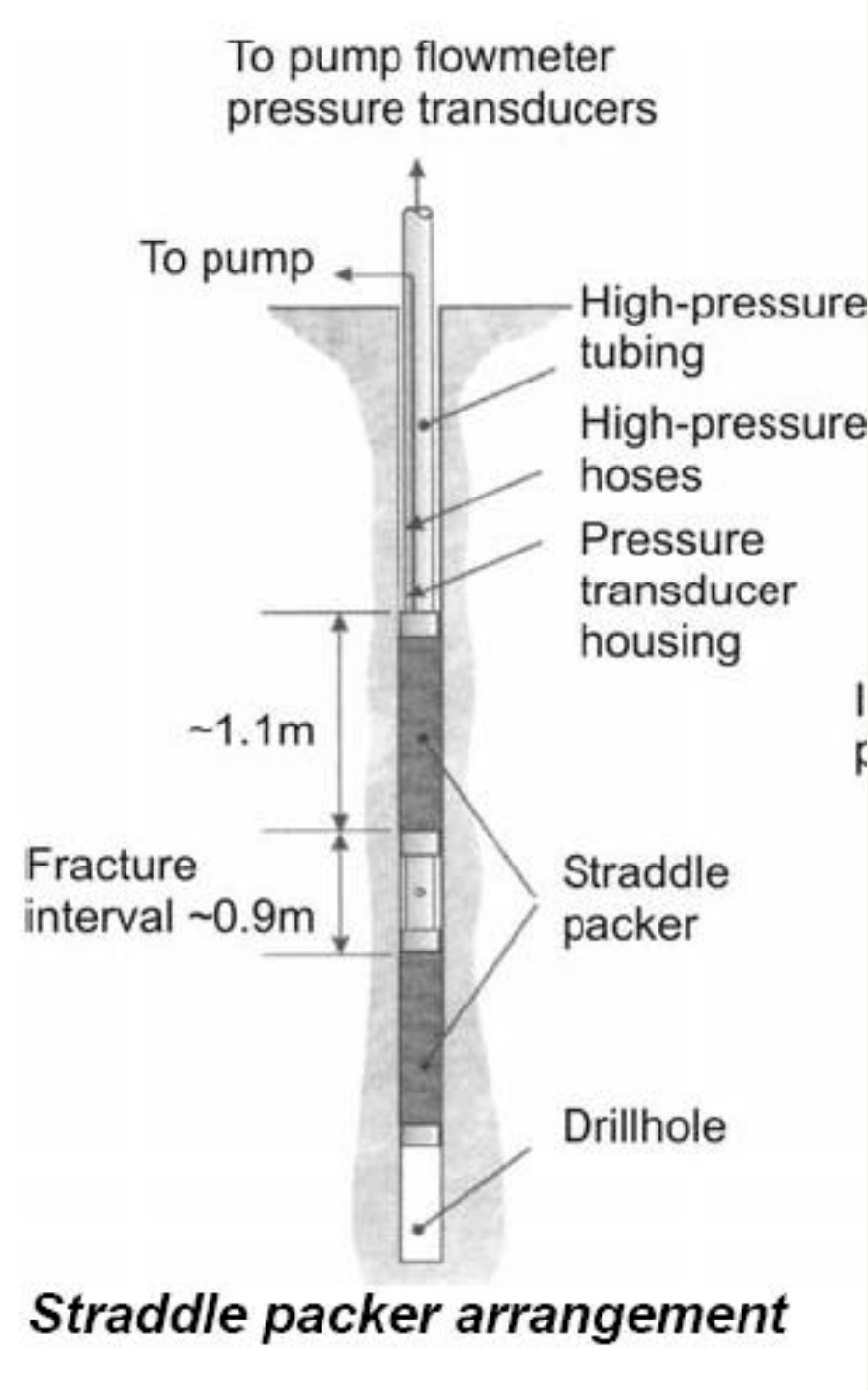
Hydraulic fracturing (HF)

- Pump water into a test section in the drill hole isolated by inflatable double packers.
- Increase water pressure until a new fracture is created in a non-fractured section of the drill hole.



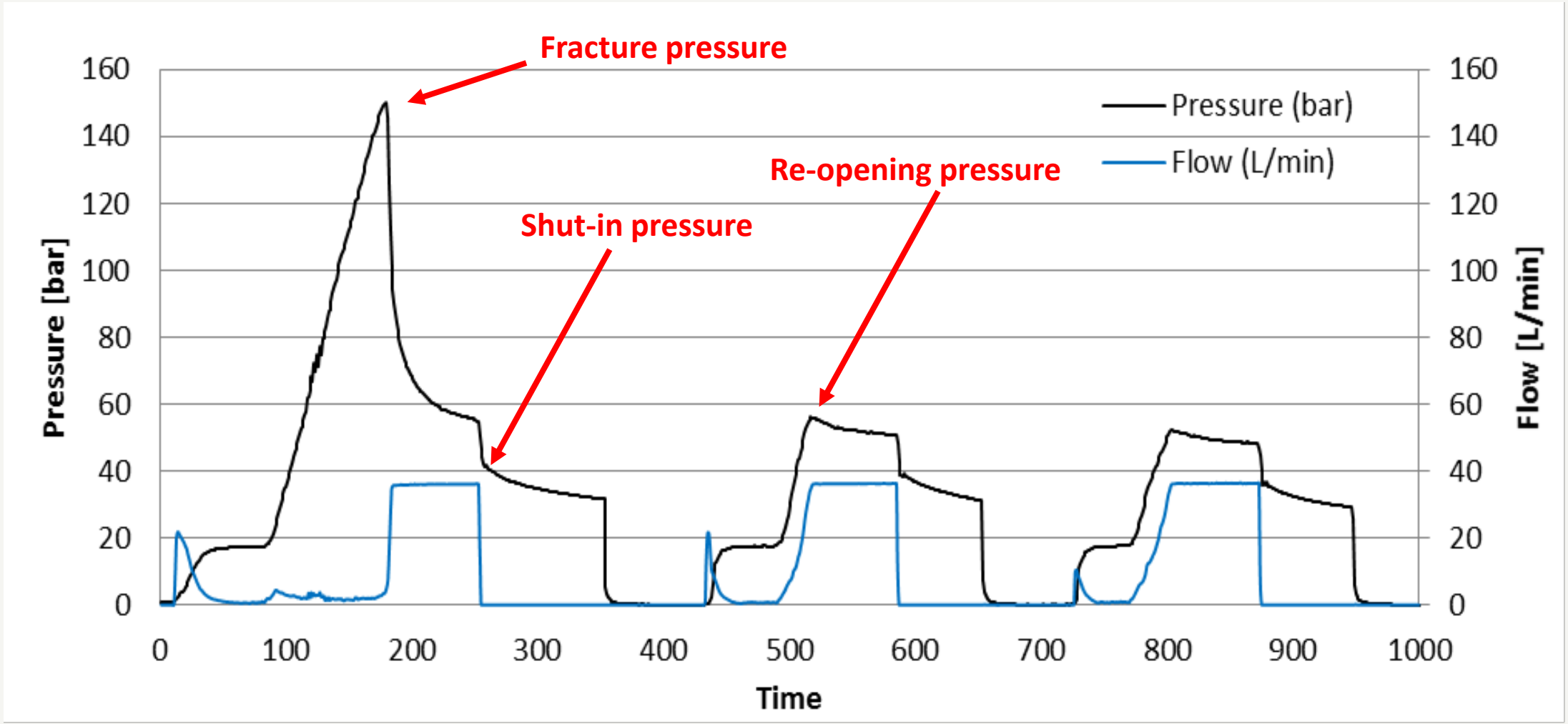
Fracture initiation





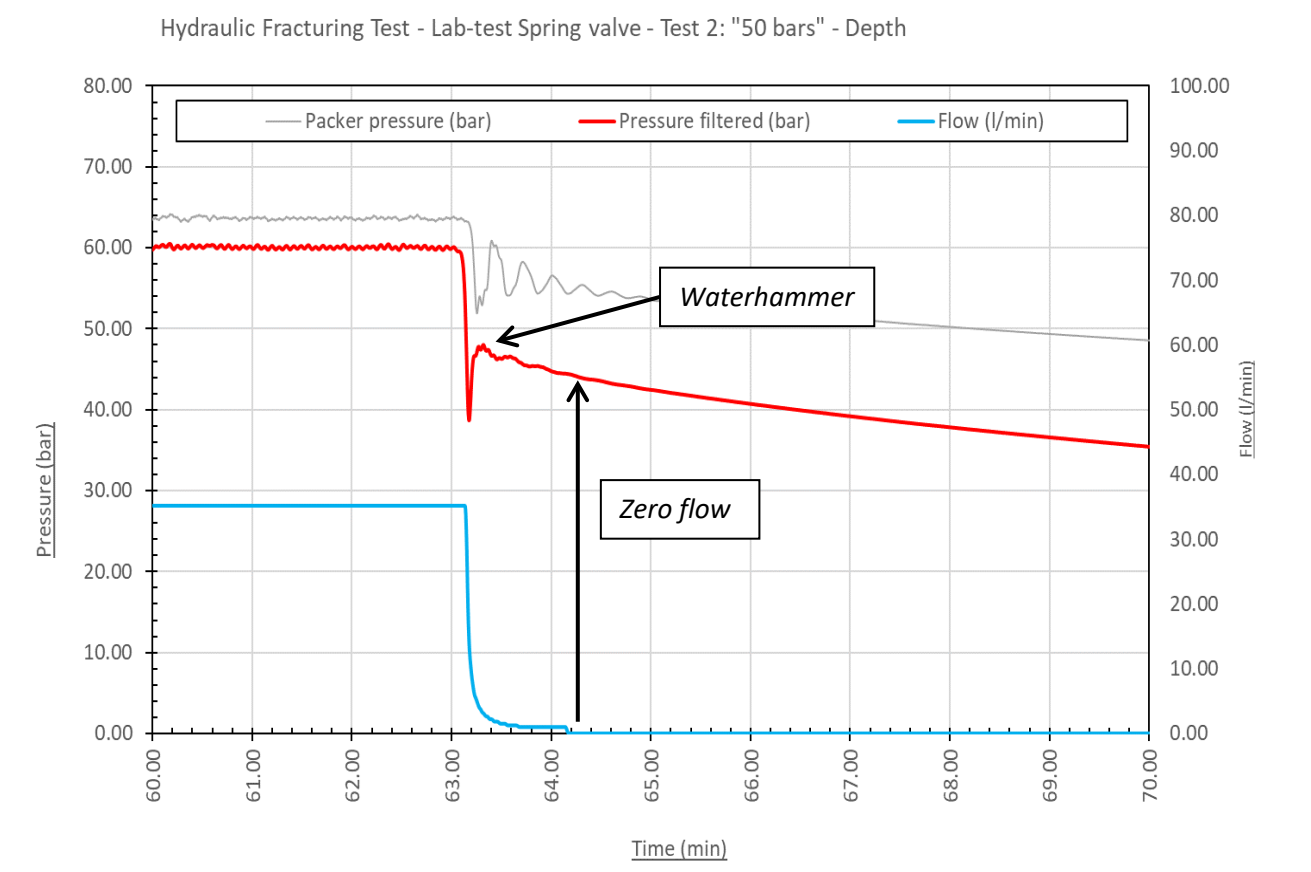
Straddle packer arrangement

Typical HF Test



Hydraulic fracturing stress calculations

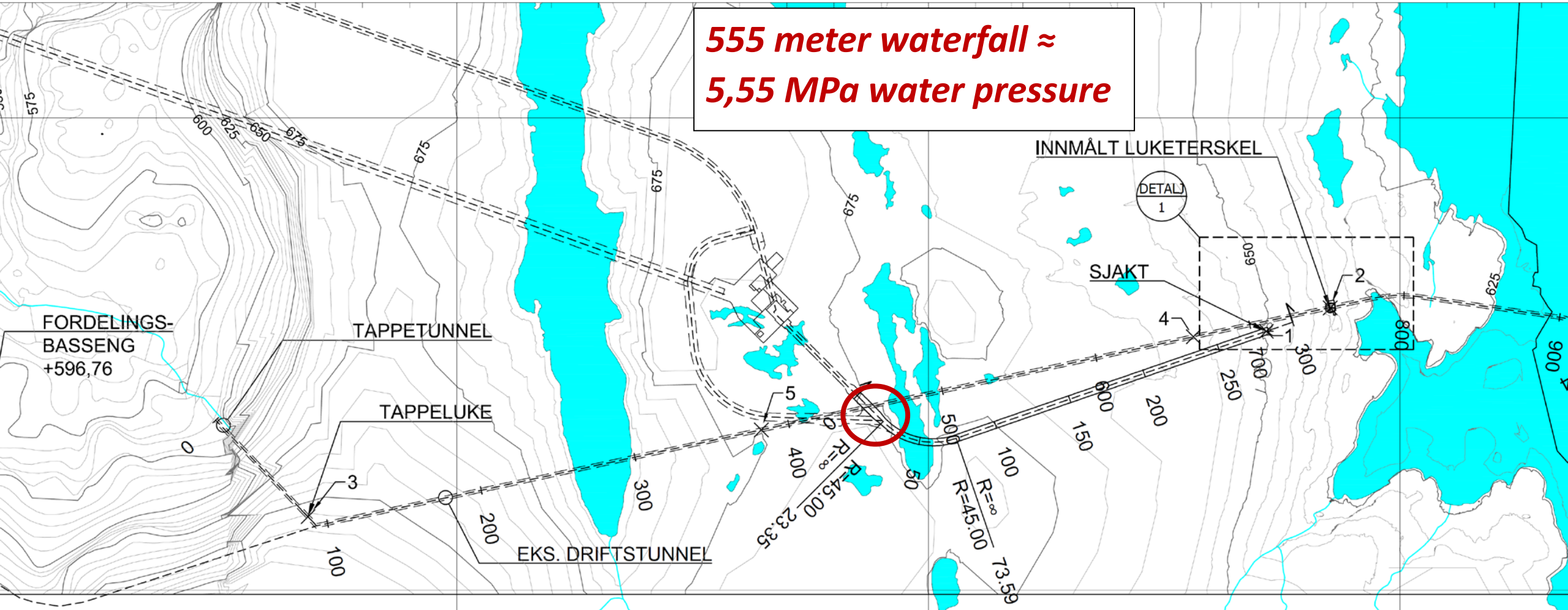
- **Minor principal stress** calculated by readout of **"shut-in"** pressure from test graphs.
- SINTEF uses own direct methods of interpretation of "shut-in" pressure (*Zero flow* and *water hammer*)



HEP Project example

- Hydraulic fracturing is the preferred method for determining the minimal principal stress (σ3)
- To obtain a reliable interpretation of the shut-in pressure, the stress situation must not be disturbed by shear stresses when the fracture opens and closes. Therefore, the **orientation of the drill hole must be parallel** to the orientation of one of the three principal rock stresses.
- To orient the HF drill holes correctly with the orientations of principal stresses, there are few options can be used, such as:
  - (a) empirical knowledge of how the stress situation is influenced by the topography in the area
  - (b) knowledge of the stress situation based on earlier measurements nearby
  - (c) the most appropriate method is to carry out a 3D stress measurement.

3D overcoring at Penstock cone – Correct orientation of HF drill hole



3D overcoring at Penstock cone – Correct orientation of HF drill hole

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* STATISTICAL RESULTS OF IN-SITU STRESSES *

	MEAN	AVERAGE DEVIATION	STANDARD DEVIATION	TREND	PLUNGE
SIGMA1	17.99	0.32	0.41	263.6	71.6
SIGMA2	16.09	1.67	1.80	163.3	3.4
SIGMA3	9.38	0.80	0.95	72.2	18.0

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* IN-SITU STRESSES IN VERTICAL AND HORIZONTAL DIRECTIONS *

STRESS	MAGNITUDE	ORIENTATION
VERTICAL STRESS	17.16	
MINIMUM HORIZONTAL STRESS	10.21	71.8
MAXIMUM HORIZONTAL STRESS	16.10	161.8

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* GRAVITY STRESS *

VERTICAL STRESS: 16.41 HORIZONTAL STRESS: 8.45

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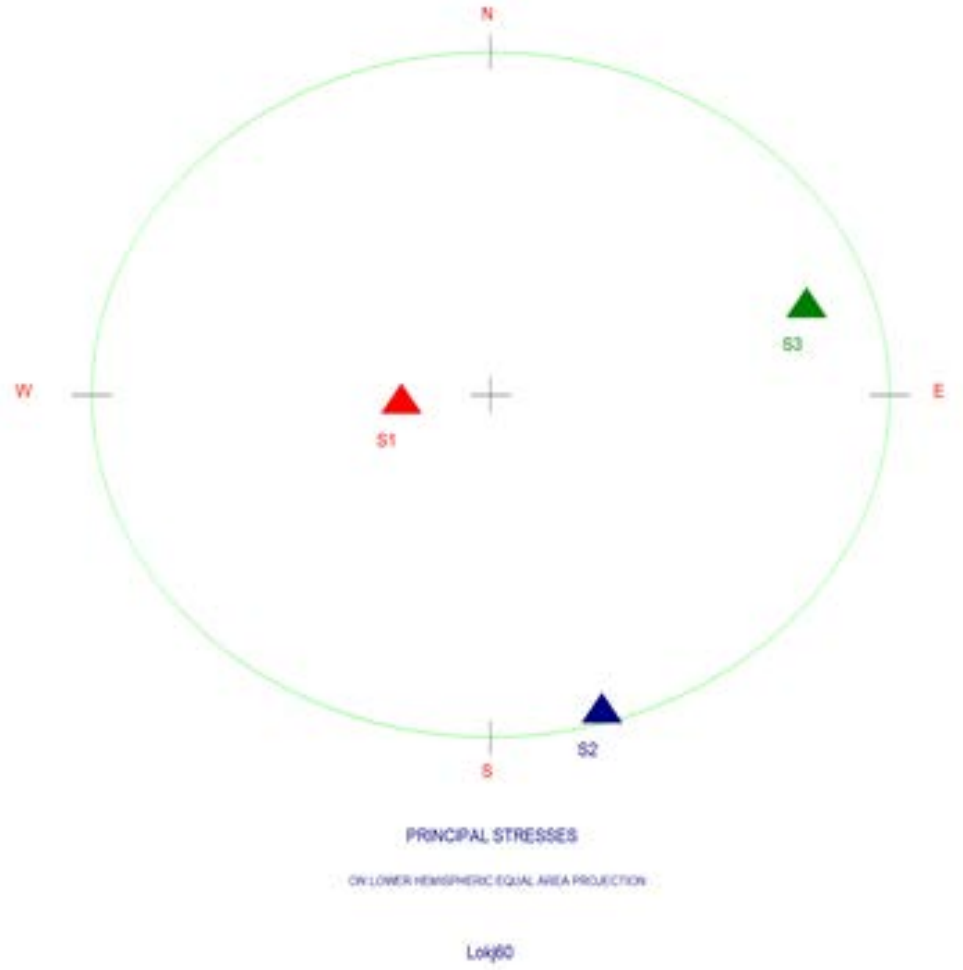
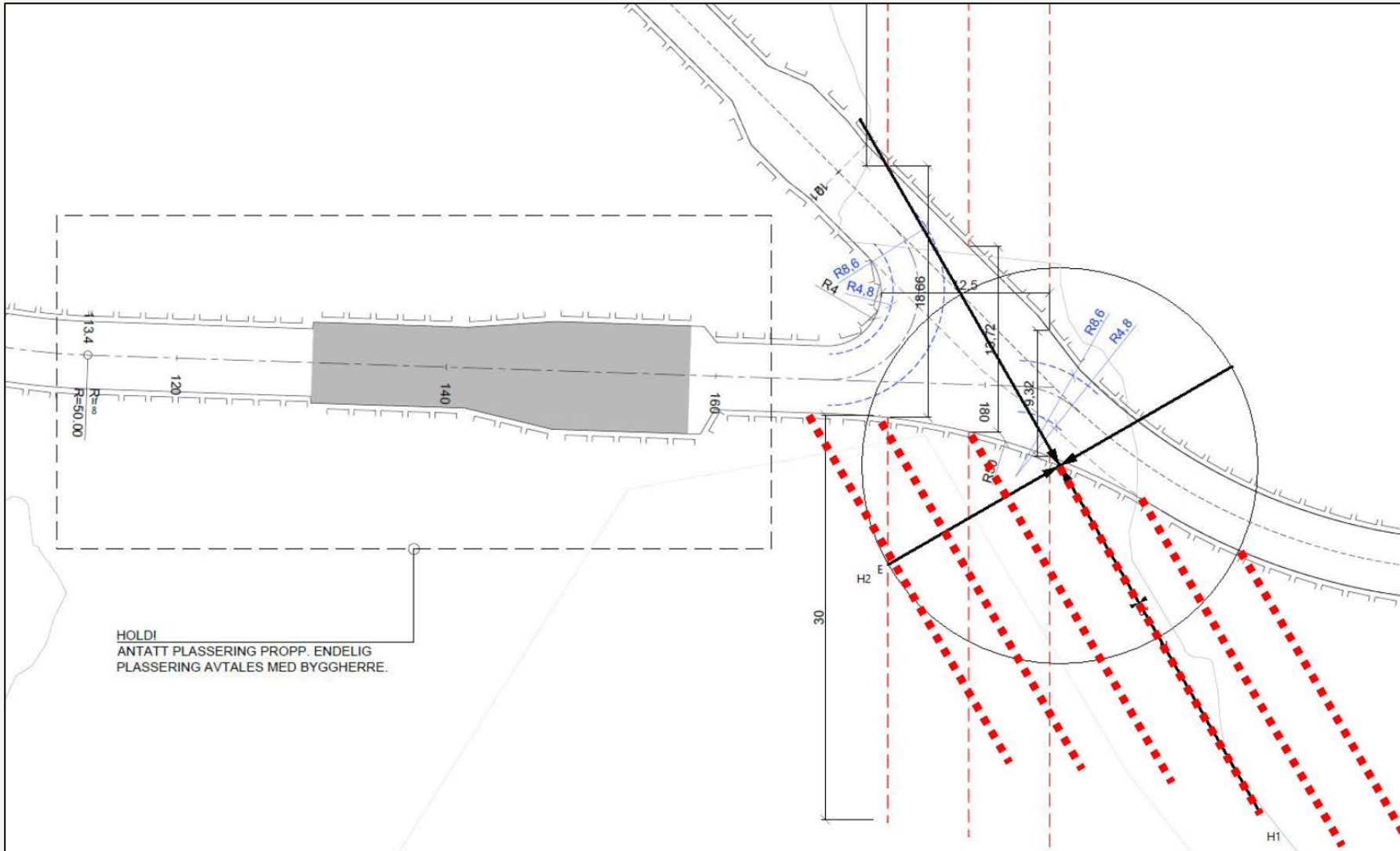
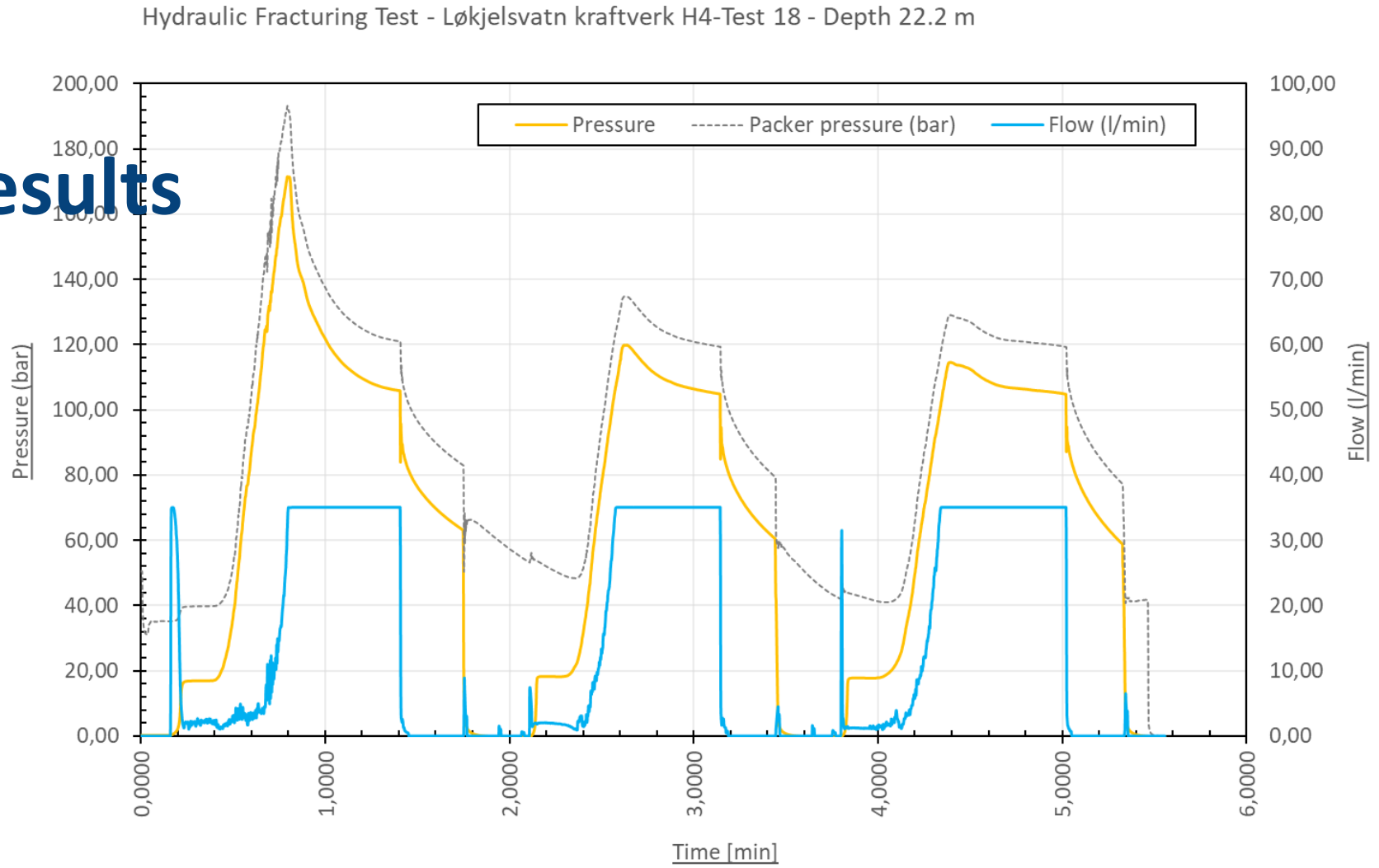


Orientation of HF drill holes at penstock cone

- Oriented parallel to major principal stress (σ1)
- 6 drill holes à 30 m



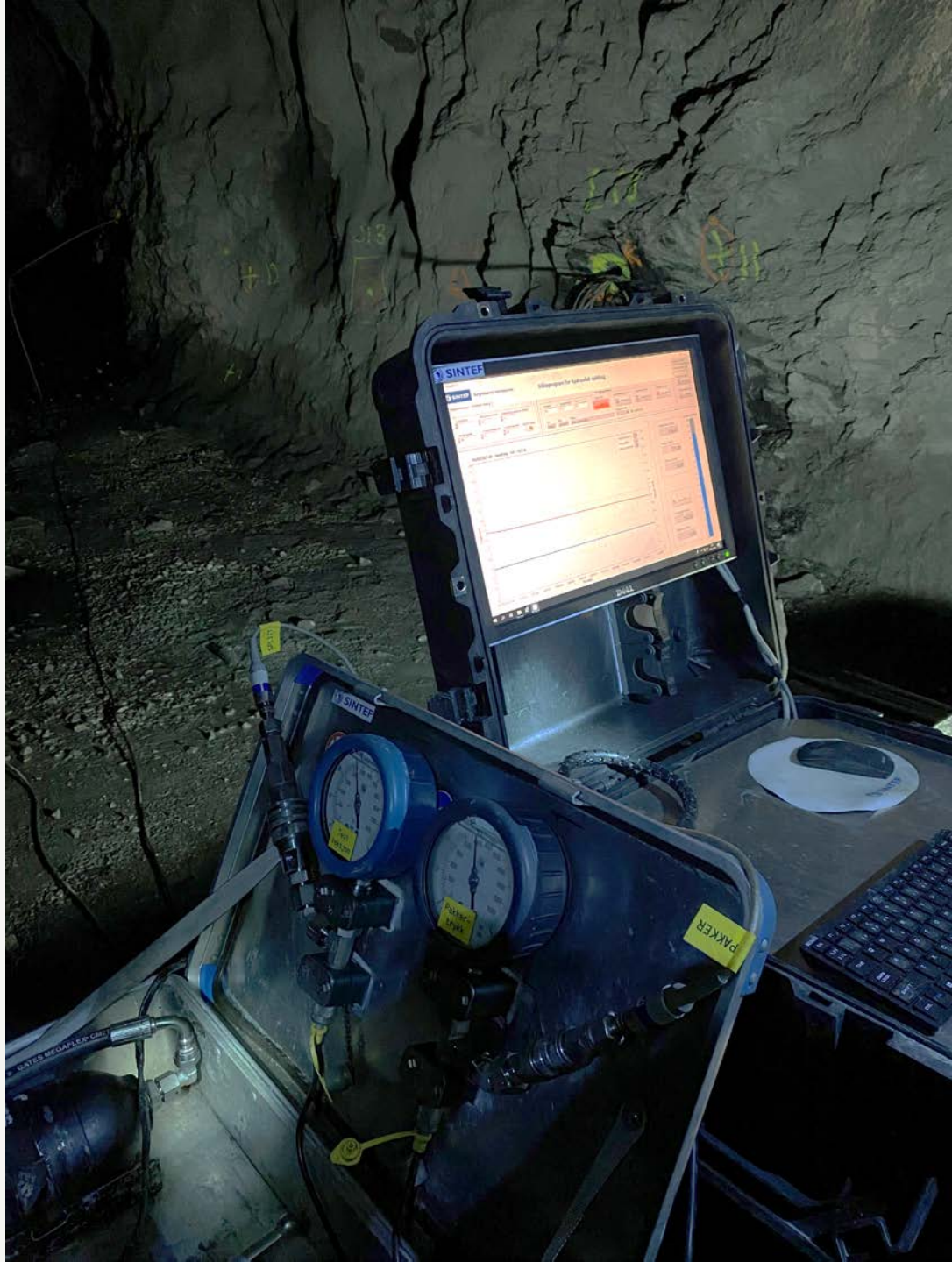
HF Test results



TEST NR	BOREHULL	BOREHULL ORIENTERING [strøk/fall]	TESTDYBDE [m]	SPLITTETRYKK P_F [MPa]	GJEN				
1	H1	N150/+5	28,2	23,3					
2	H1	N150/+5	25,2	23,2					
3	H1	N150/+5	22,2	19,5					
4	H1	N150/+5	19,2	23,0					
5	H1	N150/+5	16,2	20,6					
6	H1	N150/+5	13,2	21,1					
7	H2	N150/+5	28,2	21,6					
8	H2	N150/+5	25,2	23,9					
9	H2	N150/+5	22,2	24,9					
10	H2	N150/+5	19,2	25,6					
11	H2	N150/+5	16,2	28,8					
12	H2	N150/+5	13,2	15,8					
13	H3	N150/+5	28,2	26,7					
14	H3	N150/+5	25,2	23,1					
15	3D	N150/+5	17,5	31,9					Pakker sprakk (hull er 76 mm diameter)
16	H4	N150/+5	28,2	18,9	15,3	8,4	8,1	8,3	
17	H4	N150/+5	25,2	21,5	10,0	8,1	7,6	7,3	
18	H4	N150/+5	22,2	17,2	12,0	8,1	8,0	8,1	
19	H4	N150/+5	19,2	21,8	21,8	7,7	8,8	9,7	
20	H4	N150/+5	16,2	19,2					Gjennåpning
21	H4	N150/+5	13,2	25,8	18,0	13,2	12,8	11,7	
	H5	N150/+5							Ikke mulig å sette inn pakkere i hullet
	H6	N150/+5							Ikke mulig å sette inn pakkere i hullet

Test results Summary

- Minimal principal stress (σ3) measured by 3D to be **9.4 ± 1.0 MPa**
- Average shut-in pressure (σ3) from successful tests in H4 to be **8.2 ± 0.6 MPa**
- Minimum shut-in pressure (σ3) from successful test in H4 to be **7.3 MPa**
- Water pressure in tunnel is calculated to be **5,55 MPa** at the Penstock Cone, this gives a safety factor of **1.32**



Future work in NoRSTRESS

- AE sensor straddle packer for full fracture propagation during test for better control of measurements quality, dip and strike.
- Guideline for stress measurements in HEP projects.

Thanks for your attention!

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Industries that matter

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