UNIVERSITY OF TORONTO | Engineering

Department of Civil & Mineral Engineering

POSIVA

Application of advanced laboratory experiments in understanding the cause of localized damage zones in Nuclear Waste Repository in Finland

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Talk summary in two parts:

Part 1:

- **Underground rock characterisation facility at ONKALO, Finland**

- **Posiva's Olkiluoto Spalling Experiment (POSE) and its numerical modeling results/field observation/problems observed**

Part 2:

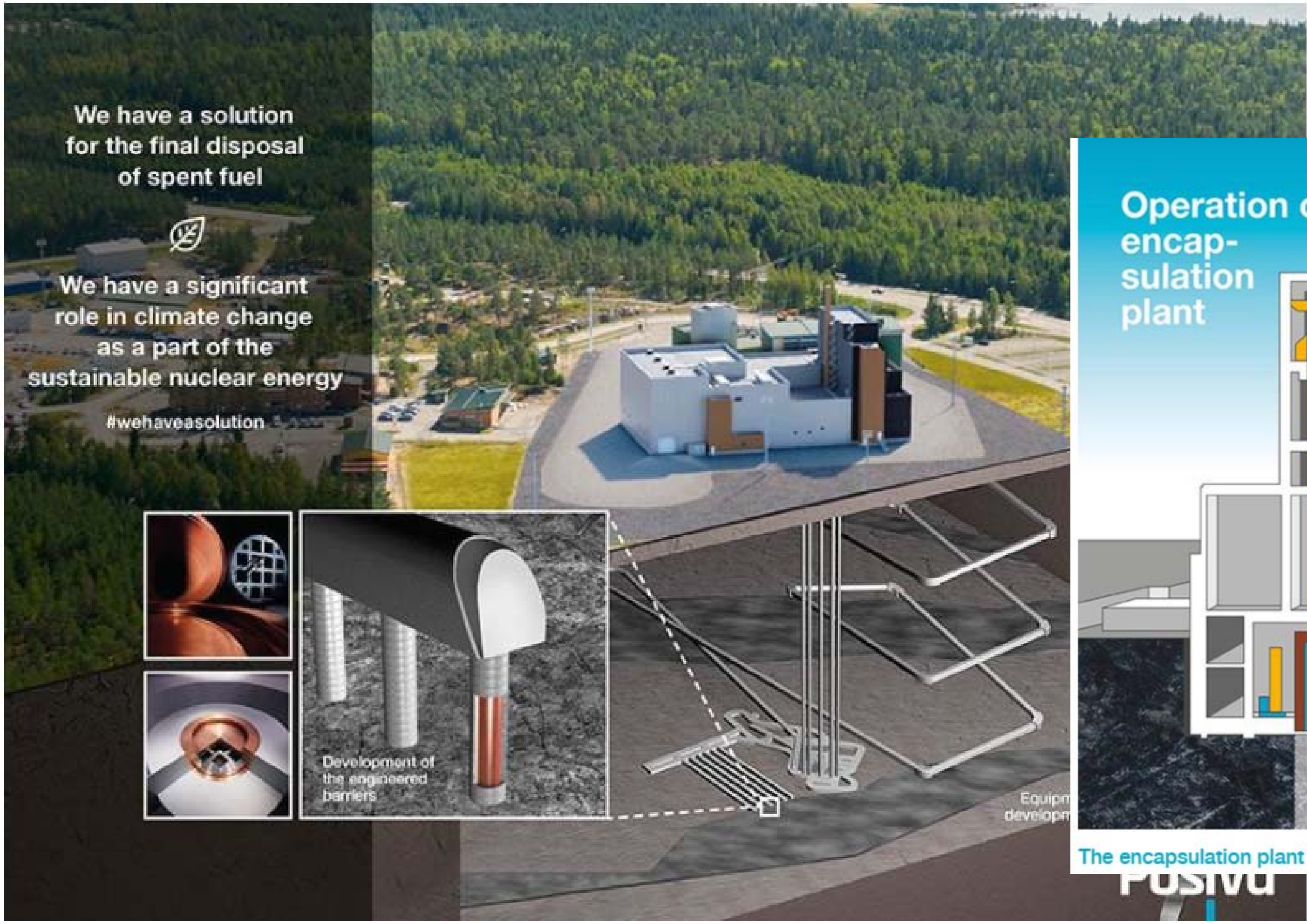
- **Research objectives and our collaboration with Posiva Oy at U of T, the advantage of advanced research laboratory working at the interface of rock mechanics, rock physics and engineering seismology**

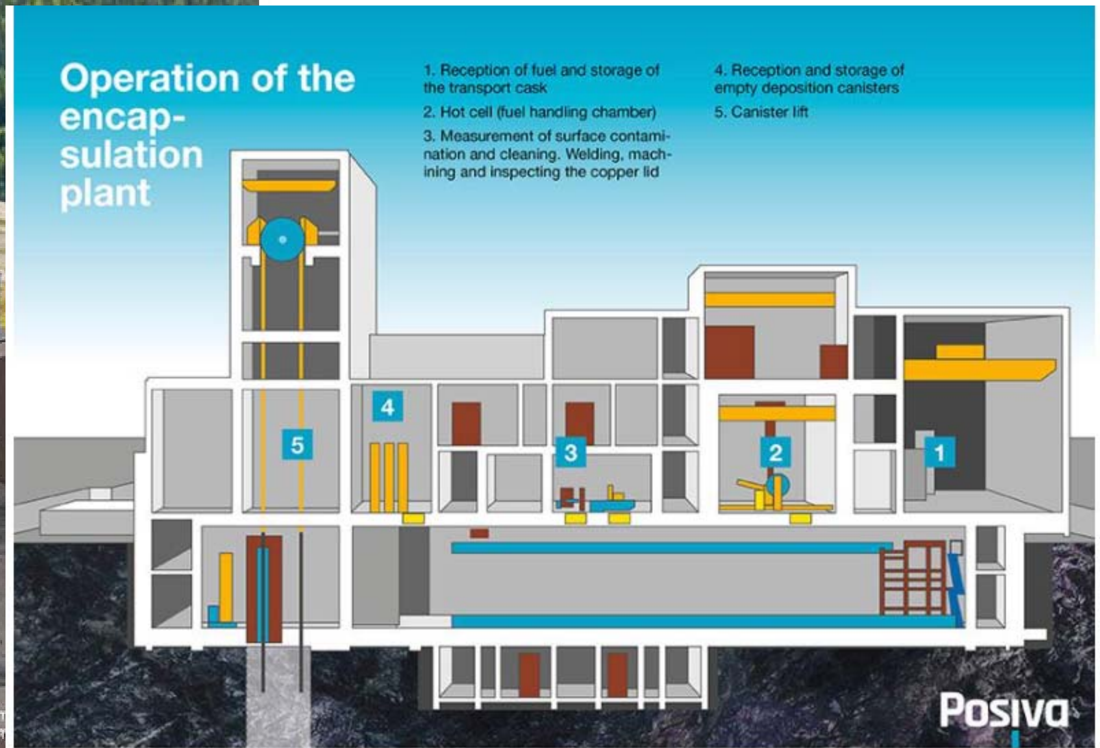
- **Comparison of filed failure of the test holes with the results obtain using true-triaxial experiments at UofT**

- **Conclusion**

Final disposal

Finland is a pioneer of final disposal of spent fuel. No other country has yet reached the implementation phase of final disposal. Many countries using nuclear power have final disposal facilities for low- and medium-level waste, but final disposal of high-level spent nuclear fuel has not yet been launched anywhere.

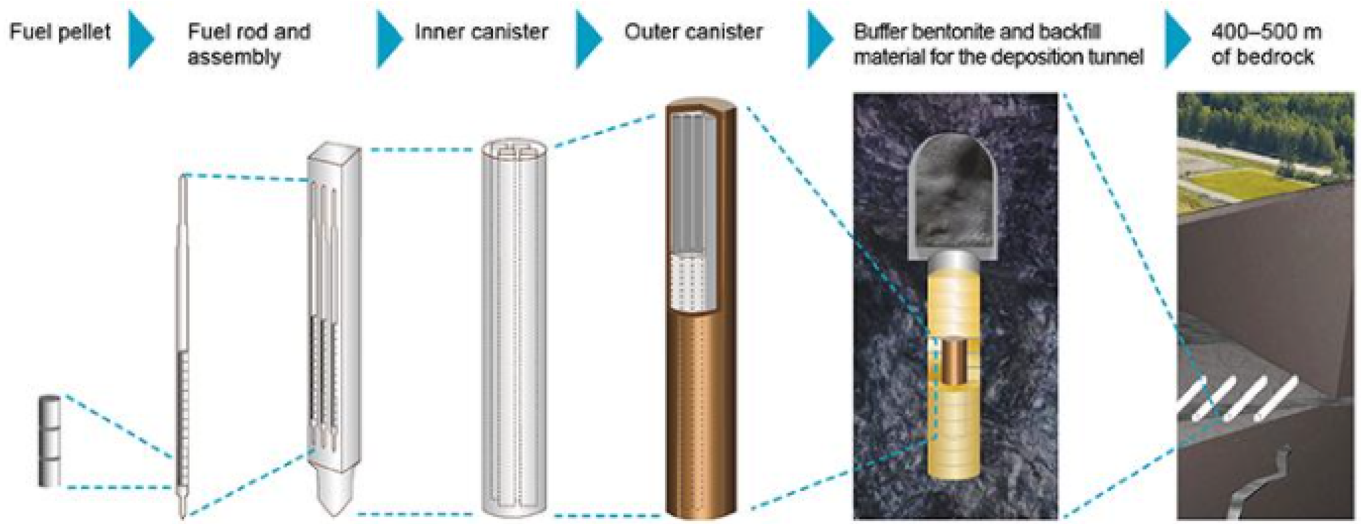


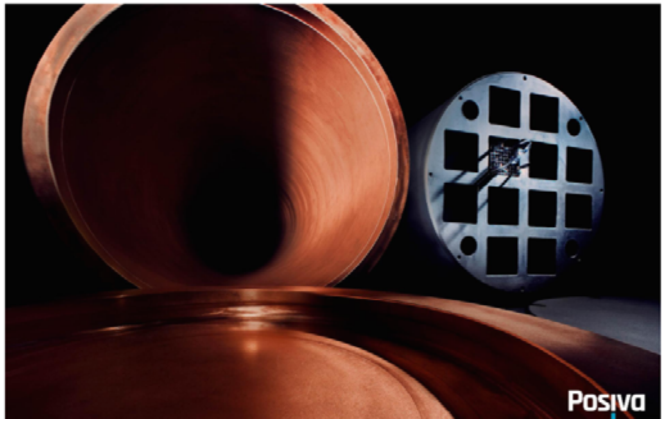


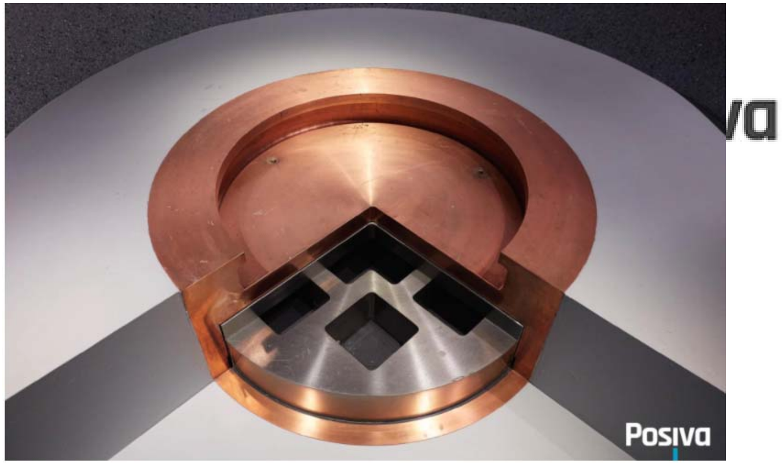
The encapsulation plant in numbers

Only Safe Final Disposal Is Possible

- Multi-barrier principle of final disposal:
  Several release barriers backing up each other ensure long-term safety

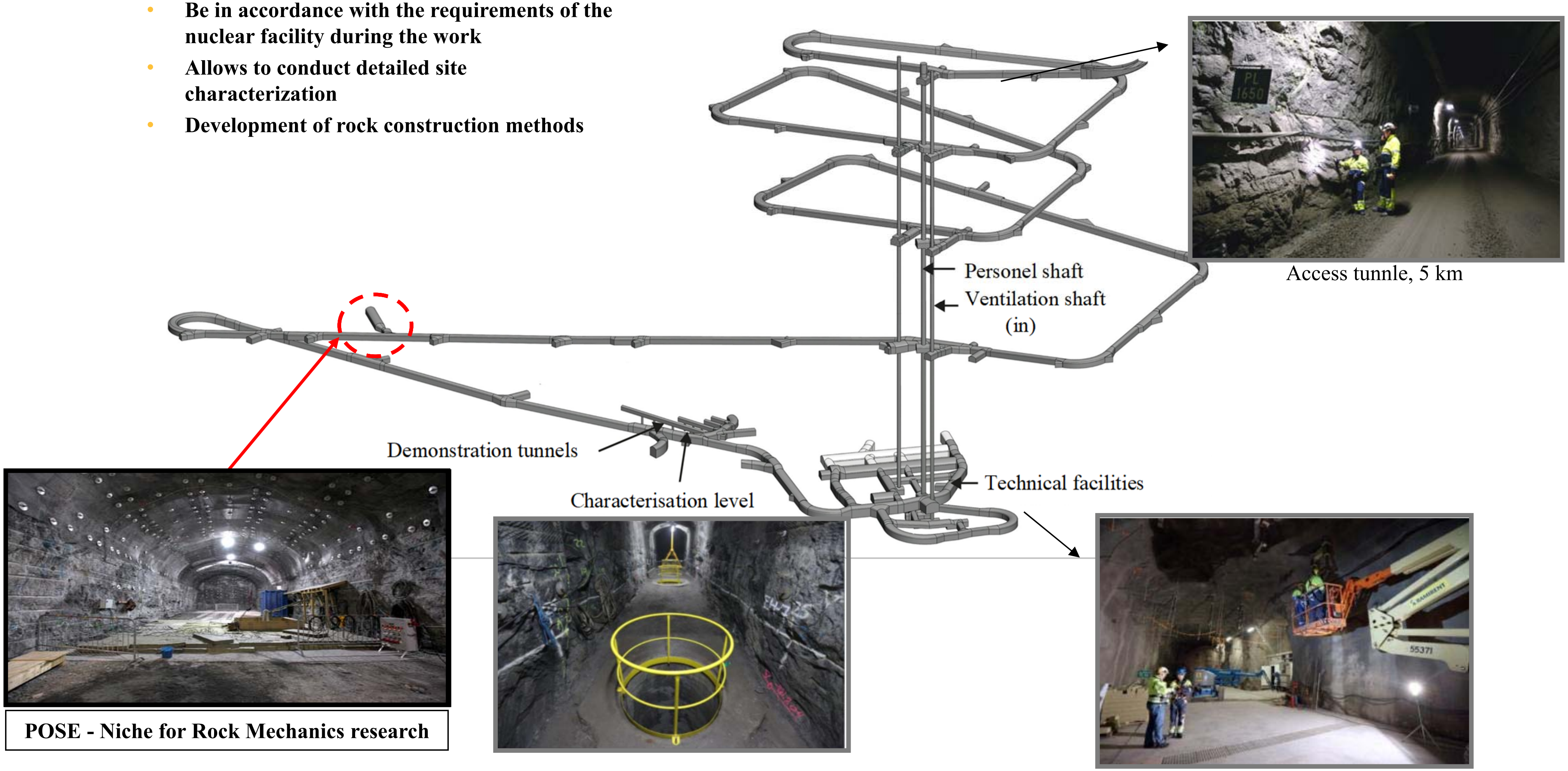






Underground Rock Characterisation Facility ONKALO

- **Construction work started in 2004**
- **Be in accordance with the requirements of the nuclear facility during the work**
- **Allows to conduct detailed site characterization**
- **Development of rock construction methods**



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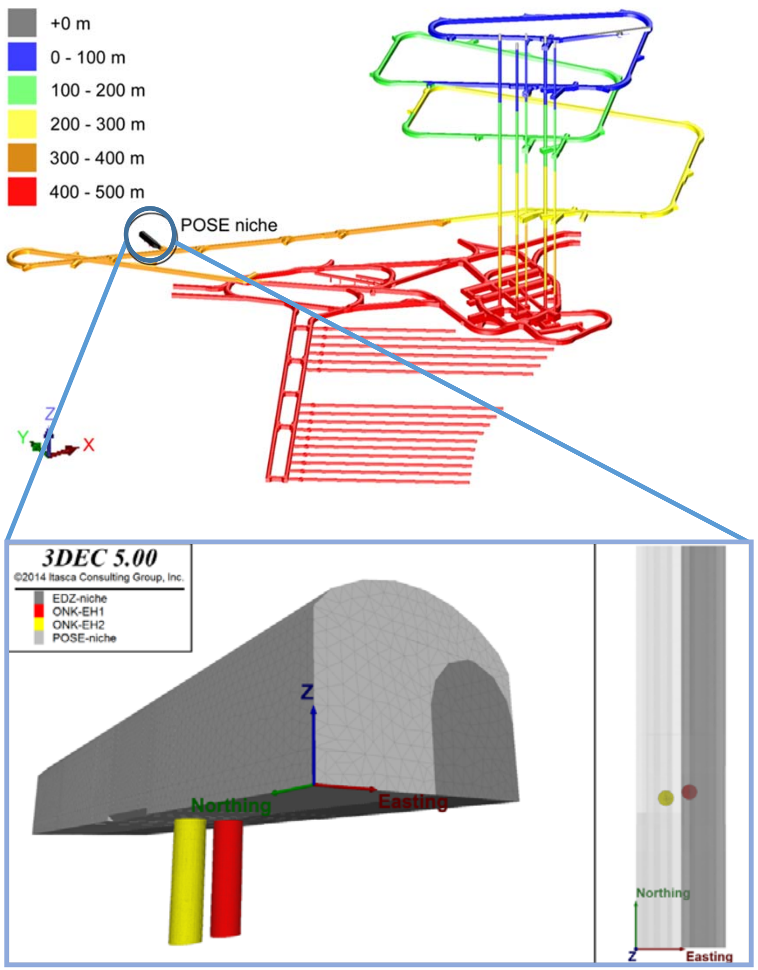
Posiva's Olkiluoto Spalling Experiment (POSE)

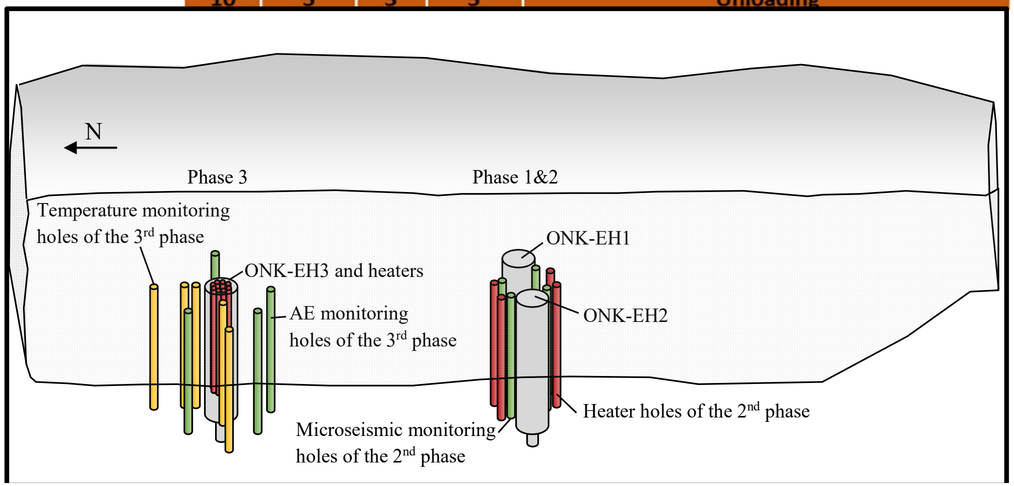


Model geometry with ONK-EH1 in red, ONK-EH2 in yellow. An inset on the right depicts the orientation of the experimental holes when viewed from above (Hakala & Valli, 2012).

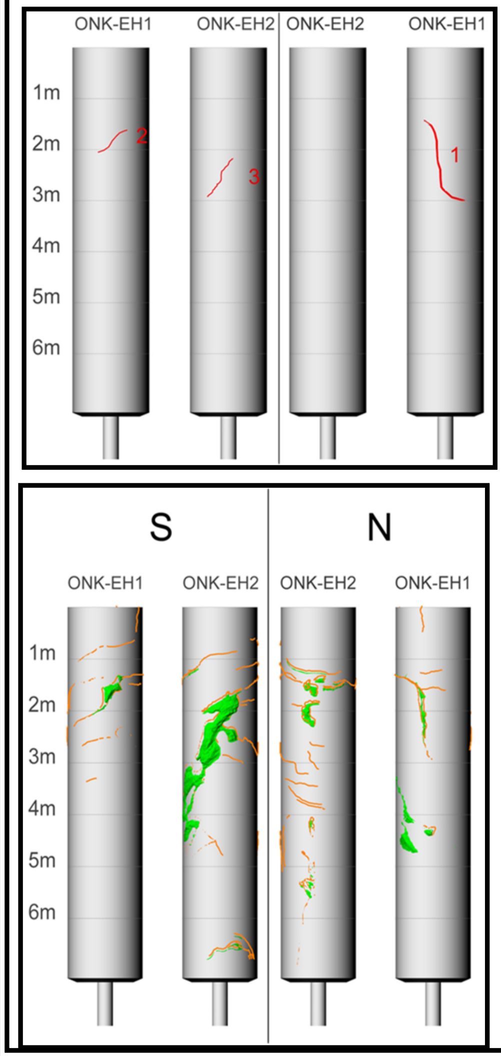
POSE Experiment Stress Path Determination

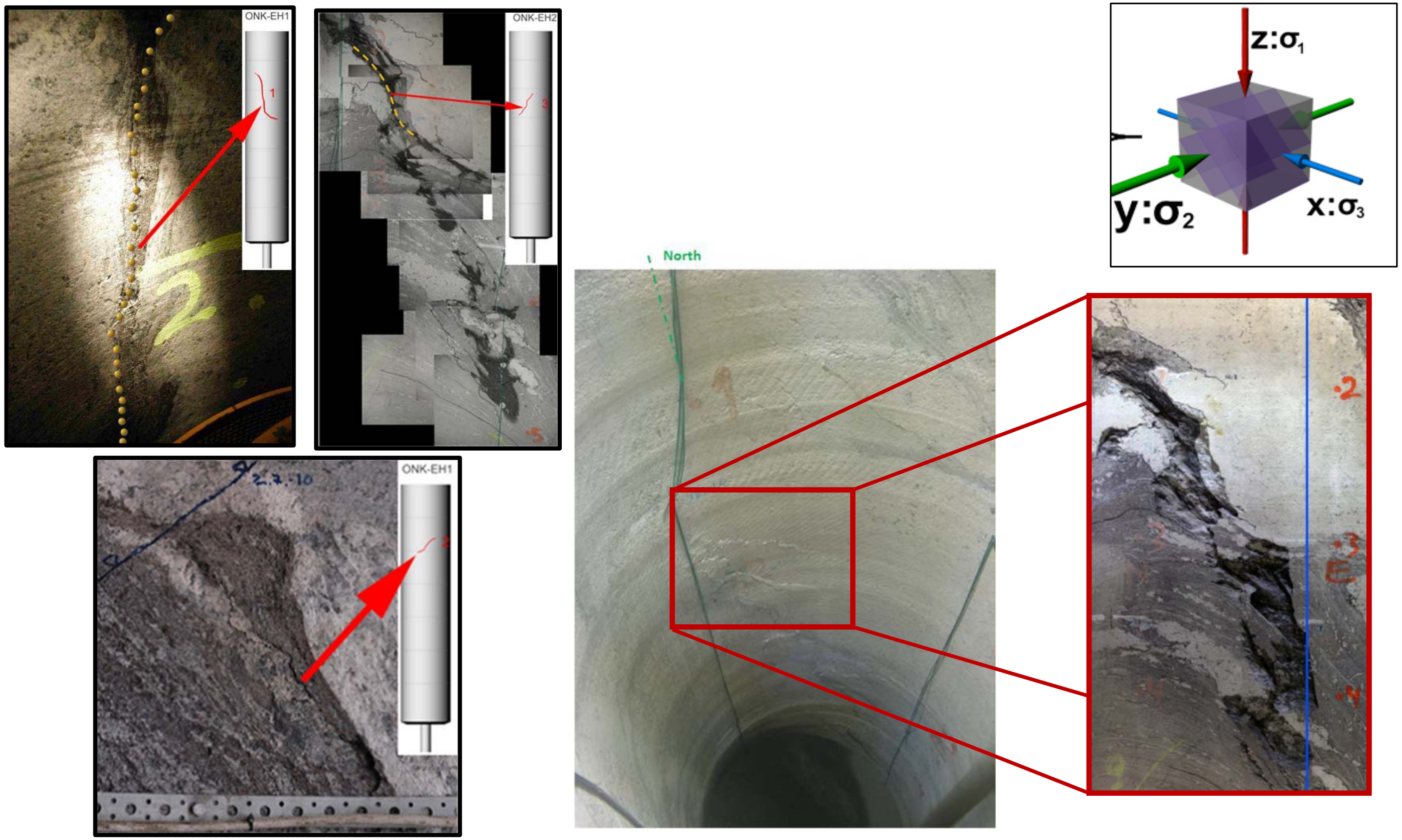
Modelling techniques and theoretical/experimental evaluation of 3D *in situ* stress variation during various stages of excavation at the site show that the three principal stresses change independently in the vicinity of the excavation.

Steps	σ_3 (MPa)	σ_2 (MPa)	σ_1 (MPa)	
0	5	5	5	Zero
1	10	10	10	Build of minimum principal stress (σ_3)
2	10	18	18	Build of intermediate principal stress (σ_2)
3	10	18	27	Build major principal stress (σ_1). In situ stress state of (σ_1, σ_2, σ_3) is reached
4	3	18	55	Excavation of niche and ONK-EH1
5	1	5	55	Excavation of ONK-EH2
6	1	10	85	2 weeks of heating
7	1	30	110	Maximum temperature from POSE Phase 3 model
8	1	20	140	Maximum temperature from Phase 1 & 2 model
9	10	18	27	Cooled to in situ
10	5	5	5	Unloading



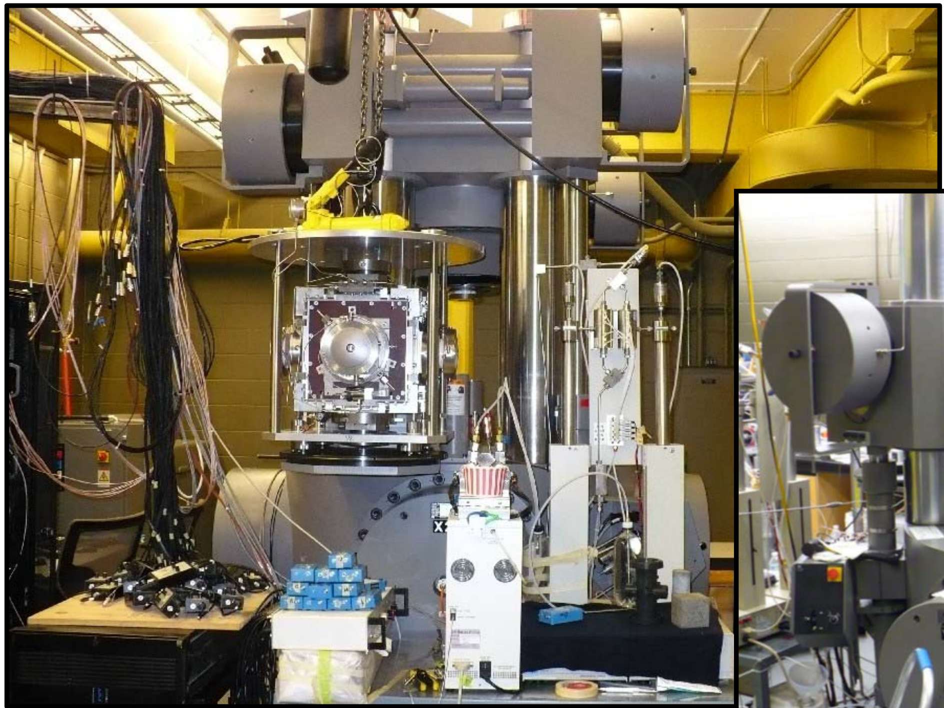
Rock mass response to excavation and thermal load

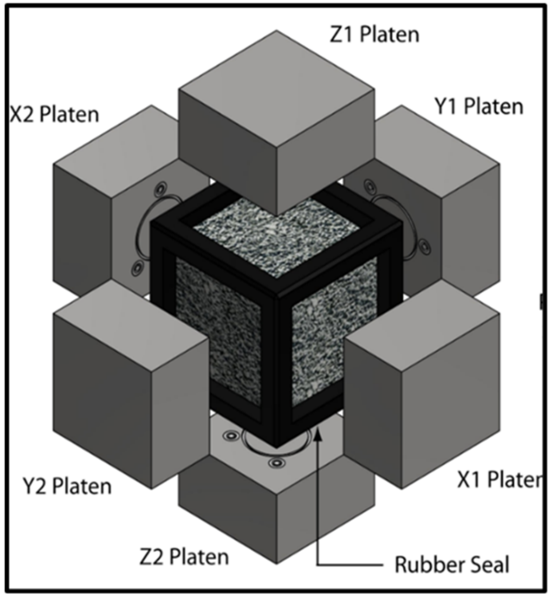




Instead of sapling, the rock mass was observed to fail through fracturing developing in planes of existing flaws, foliation surfaces or lithological contact zones, even in high thermal loads (left below).

MTS Poly axial testing frame with True-Triaxial Geophysical Imaging Cell



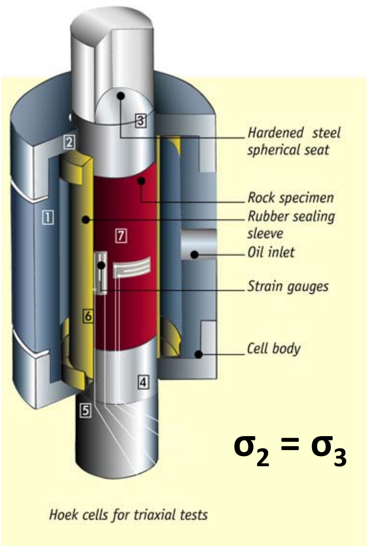


- Polyaxial servo-controlled loading system; 6800 kN axial, 3400 kN lateral , ~1GPa axial stress and 500 MPa lateral on a 8x8x8 cm cube,
- Polyaxial (true triaxial) and triaxial geophysical imaging cells
- Temp. up to 200^{o}C
- Full waveform continuous Acoustic Emission (18 sensor 3D array sampled at 10MHz – up to 8hrs)
    - 3D velocity measurement system (including 6 compressional and 12shear sensors)
    - Pore pressure control and 3D permeability along independently controlled axes

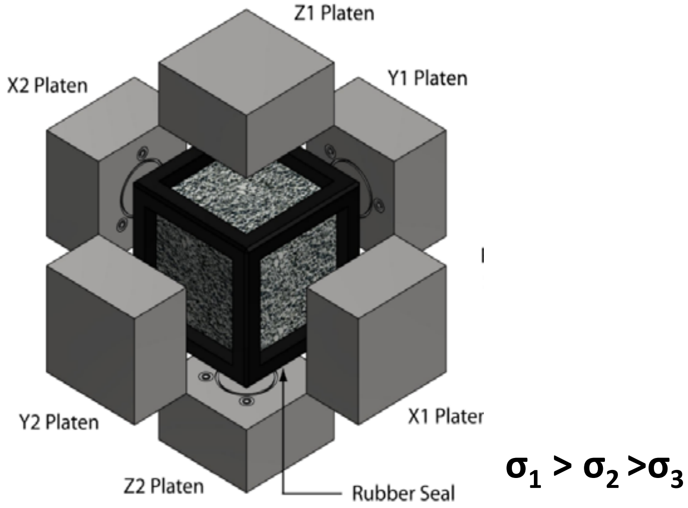
Research Motivation. We had to have a three dimensional testing approach!

- **The Posiva's Olkiluoto Spalling Experiment (POSE) stress path is complex and results in strength and behavioural characteristics that are not replicated with conventional triaxial testing where $\sigma_2 = \sigma_3$**
- **Construction of the planned deep geological repository at the Olkiluoto site involves isotropic and anisotropic rocks of different strength and deformational properties making 3D assessment of changing stresses a complex undertaking.**

Henceforth, the aim of this research investigation is to replicate the POSE - Experiment in controlled laboratory conditions, in which the response of the prevailing rock types along with the effect of anisotropy could be understood further in detail using a unique true-triaxial geophysical imaging cell in which $\sigma_1 > \sigma_2 > \sigma_3$.

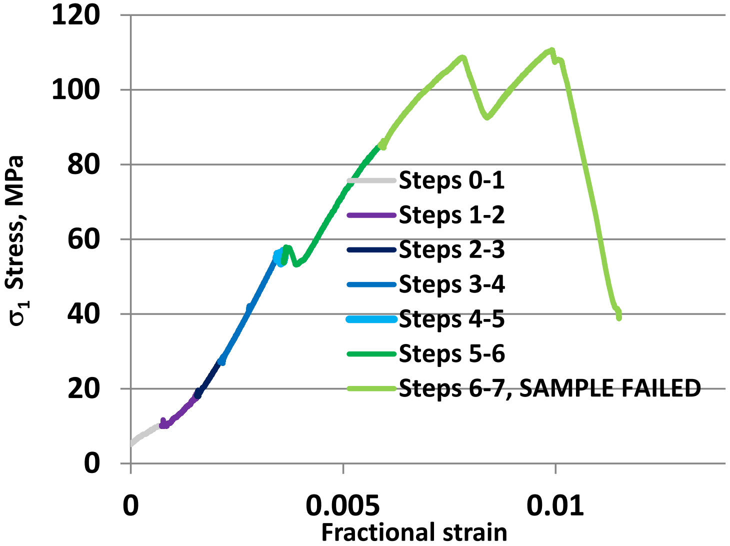


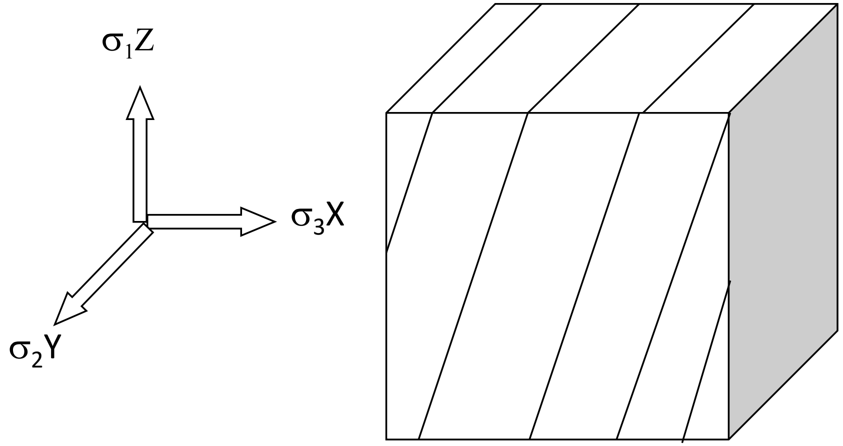
Conventional triaxial testing system



True triaxial testing system

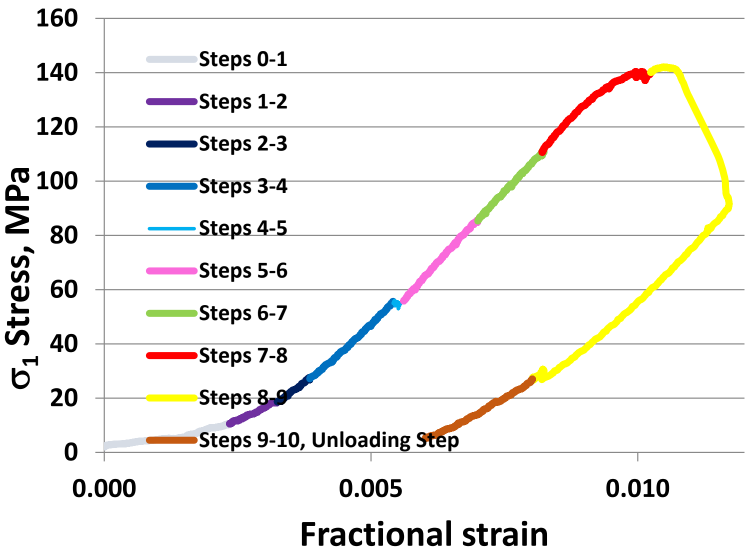
30^{o} specimen, strain-strain, first round

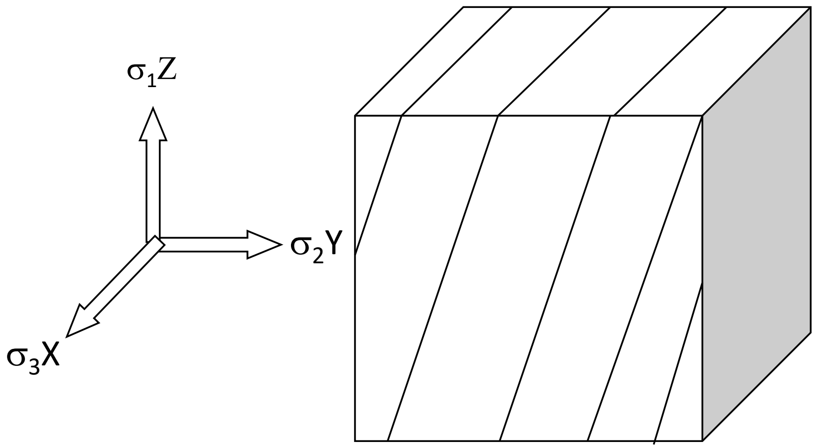




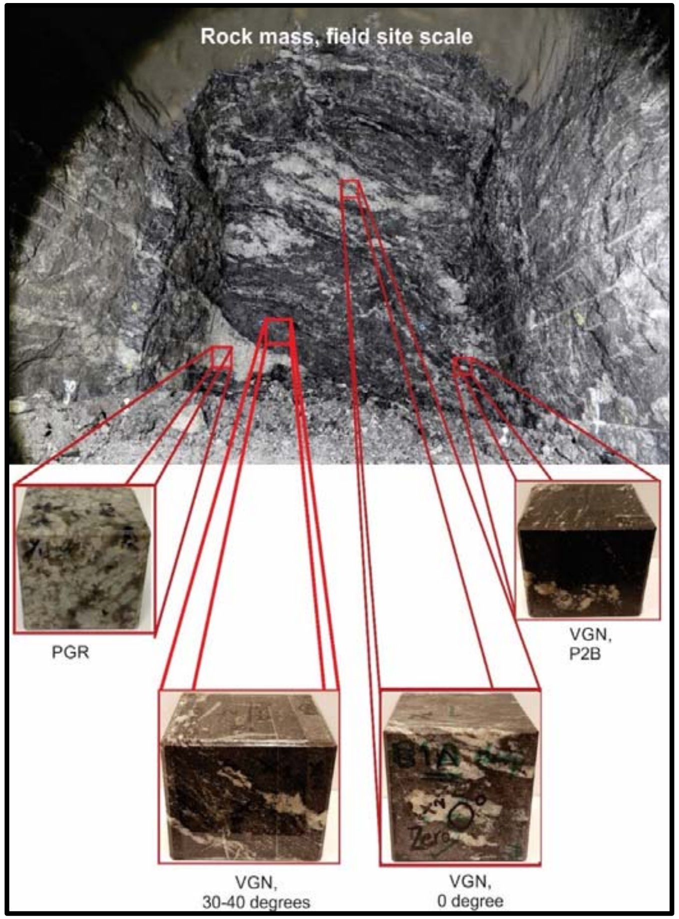
Loading steps for the TTT experiments

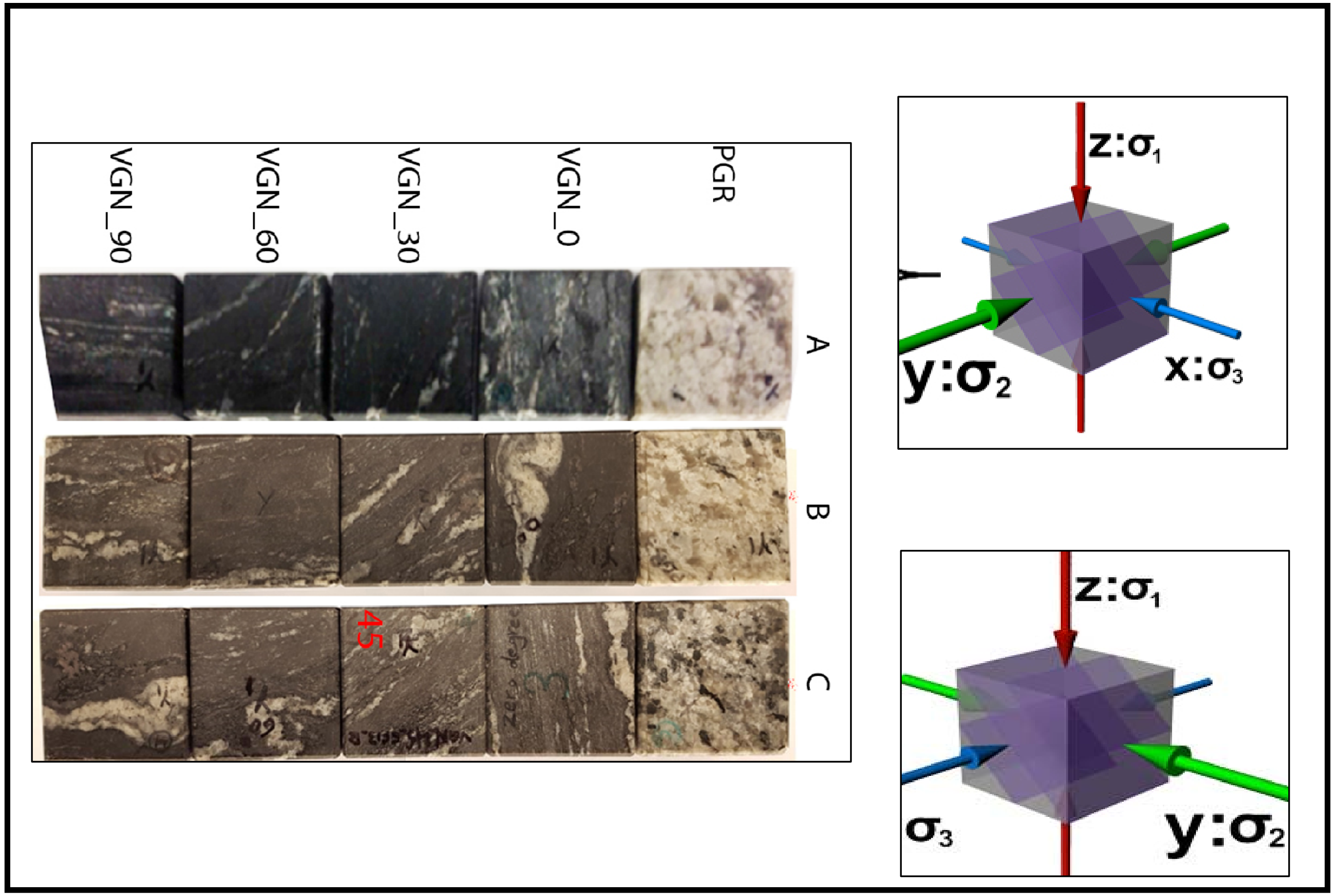
Step	s3 MPa	s2 MPa	s1 MPa	
0	0	0	0	zero
1	10	10	10	build s3
2	10	18	18	build s2
3	10	18	27	build s1 = In situ
4	3	18	55	Exca_test hole 1
5	1	5	55	Exca_test hole 2
6	1	10	85	heating 2 weeks
7	1	30	110	heating EH3 max
8	1	20	140	heating HE3 max
9	10	18	27	cooled to in situ
10	0	0	0	zero





Effect of anisotropy on strength, deformational and seismicity under TTTE Underground research laboratory in ONKALO, Finland





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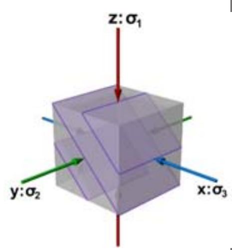
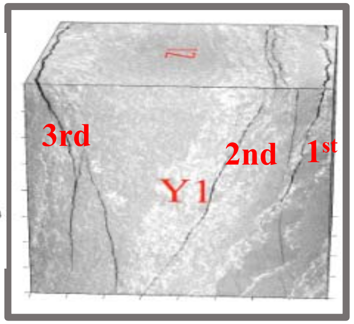
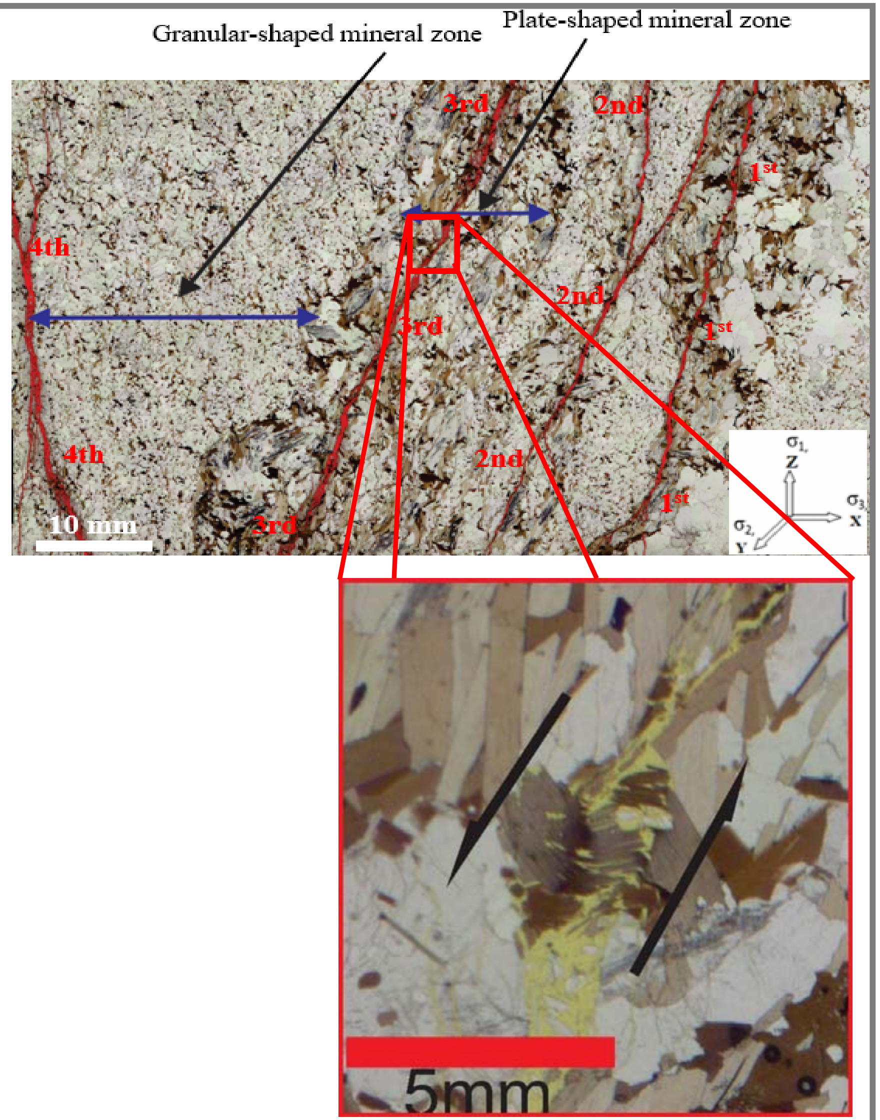
Recognition of sequence of fracturing, using AE events and thin section analysis, 30º specimen

Step	s3 MPa	s2 MPa	s1 MPa	
0	0	0	0	zero
1	10	10	10	build s3
2	10	18	18	build s2
3	10	18	27	build s1 = In situ
4	3	18	55	Exca_test hole 1
5	1	5	55	Exca_test hole 2
6	1	10	85	heating 2 weeks
7	1	30	110	heating EH3 max
8	1	20	140	heating HE3 max
9	10	18	27	cooled to in situ
10	0	0	0	zero

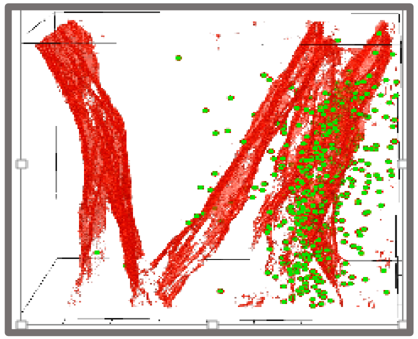




3D X-ray Micro-CT image

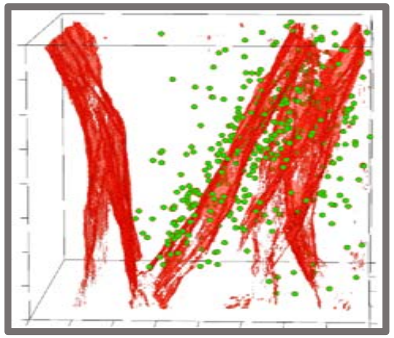


First episode of AE



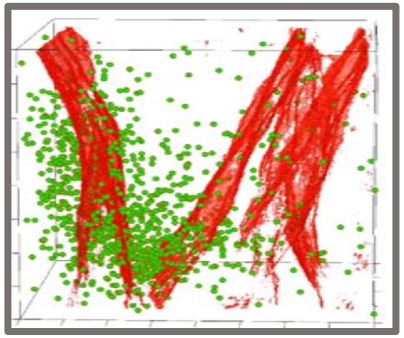
$\sigma_1 = 55$, $\sigma_2 = 5$, $\sigma_3 = 1$MPa
Beginning of steps 5

Fracture propagation and second episode of AE



$\sigma_1 = 109$, $\sigma_2 = 28$, $\sigma_3 = 1$MPa
Middle of step 7

Third AE activity and failure

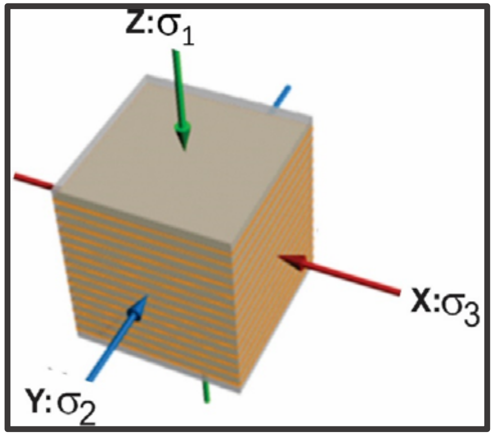


$\sigma_1 = 111$, $\sigma_2 = 18$, $\sigma_3 = 1$MPa
End of step 7

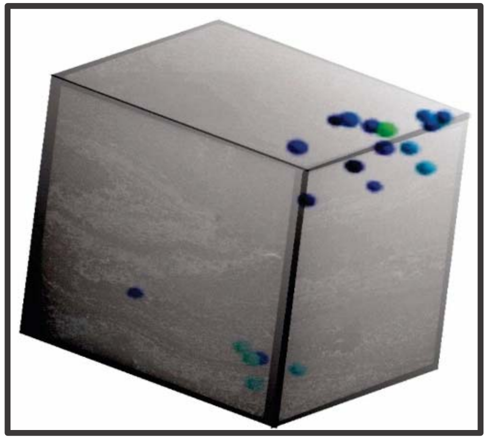
90º specimen

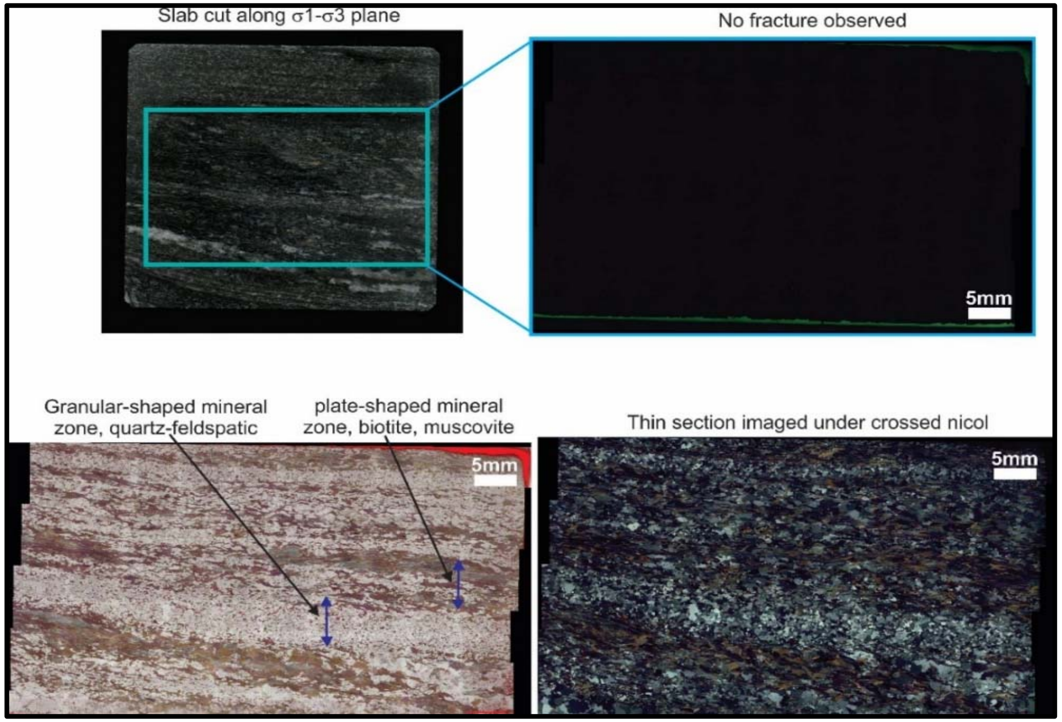
Loading steps for the TTT experiments

Step	s3 MPa	s2 MPa	s1 MPa	
0	0	0	0	zero
1	10	10	10	build s3
2	10	18	18	build s2
3	10	18	27	build s1 = In situ
4	3	18	55	Exca_test hole 1
5	1	5	55	Exca_test hole 2
6	1	10	85	heating 2 weeks
7	1	30	110	heating EH3 max
8	1	20	140	heating HE3 max
9	10	18	27	cooled to in situ
10	0	0	0	zero



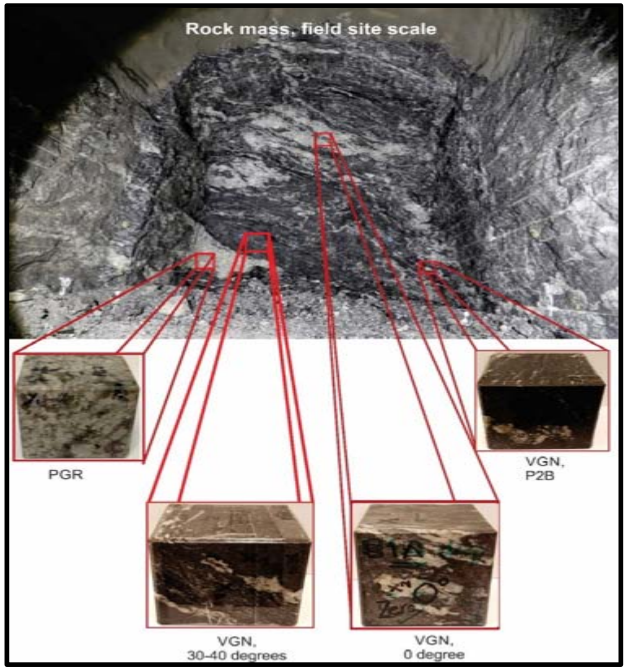
Tested specimen

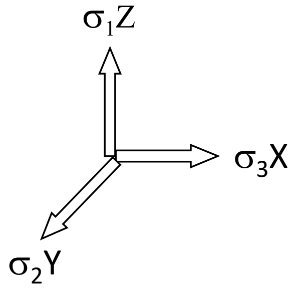


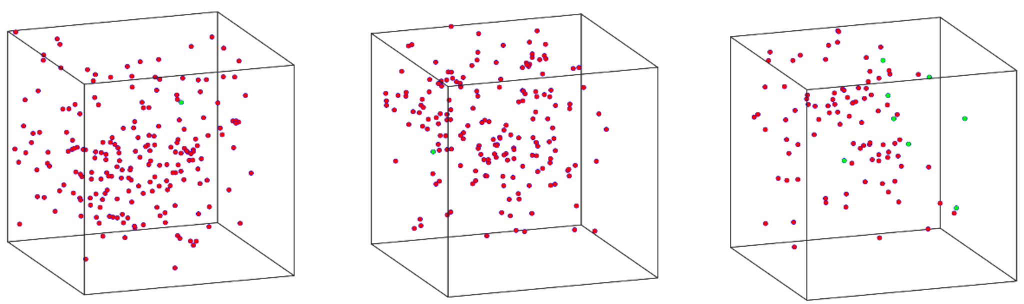


AE response
End of step 9

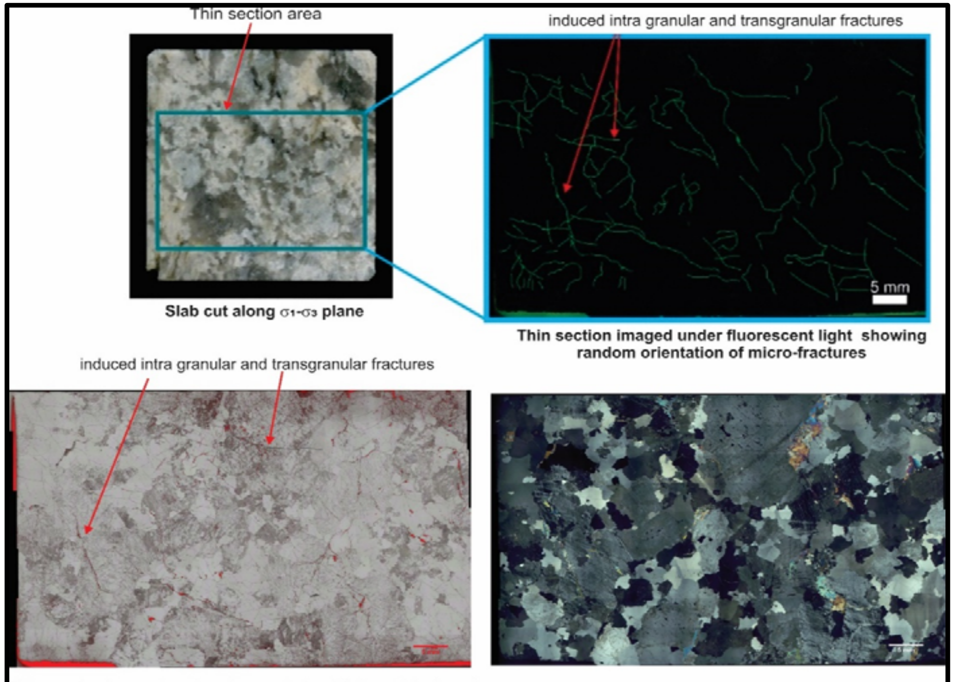
Opening and closure of pre-existing fractures, using AE events and thin section analysis, pegmatite specimen







PGR1	PGR2	PGR3
Number of AE related to:	Number of AE related to:	Number of AE related to:
Excavation = 1	Excavation = 1	Excavation = 8
Heating = 203	Heating = 177	Heating = 90



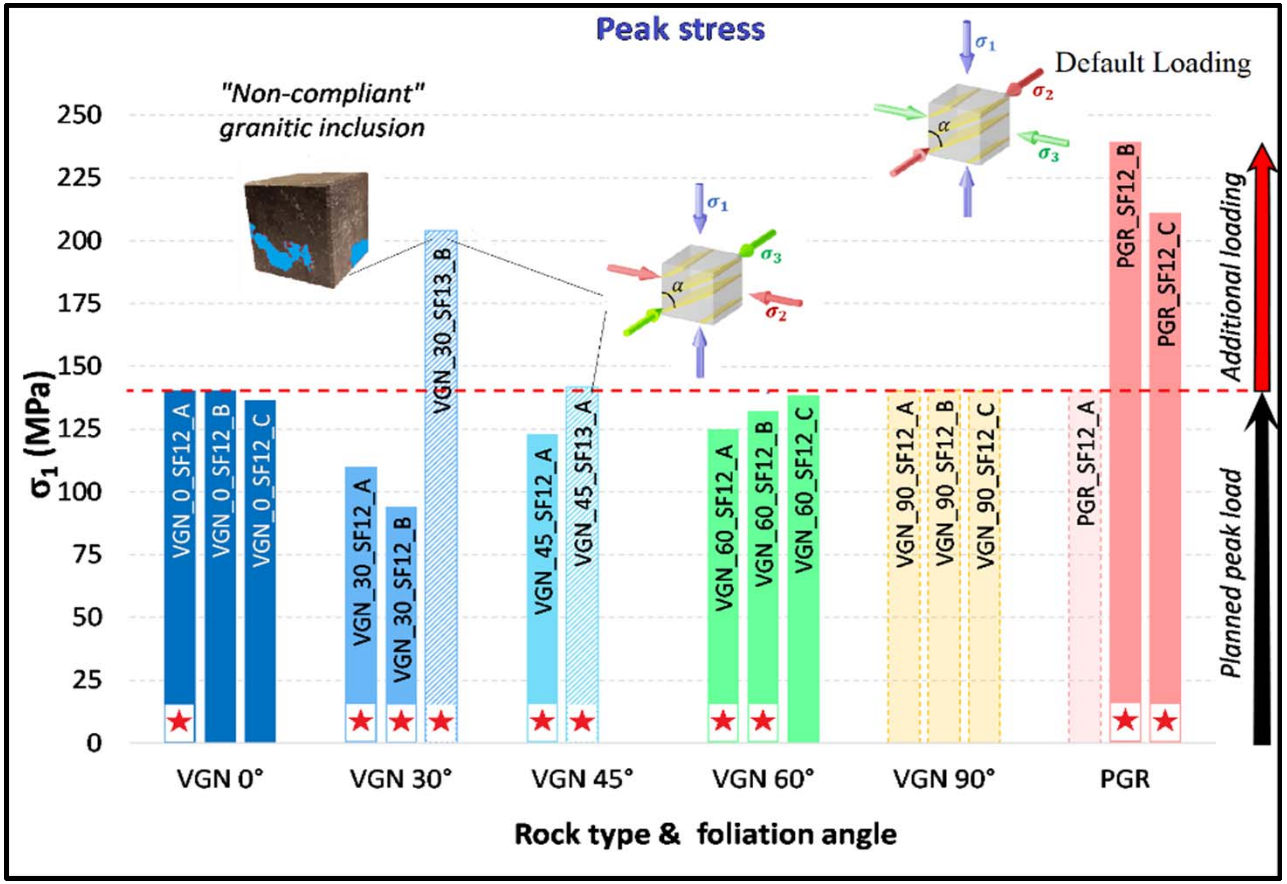
Slab cut along σ_1-σ_3 plane

Thin section imaged under fluorescent light showing random orientation of micro-fractures

Thin section imaged under plane polarized light with induced fractures marked in red

Thin section imaged under crossed nicol showing quartz-felspatic minerals of various size

Results for all 17 tested specimens



The peak stress results for VGN and PGR, with VGN results plotted according to the foliation determined from the specimens a priori. The hatch pattern indicates specimens that were tested with σ_2 perpendicular to foliation. Specimens that were loaded over the planned peak load exceed the dashed red line. Red Stars indicate samples that failed.

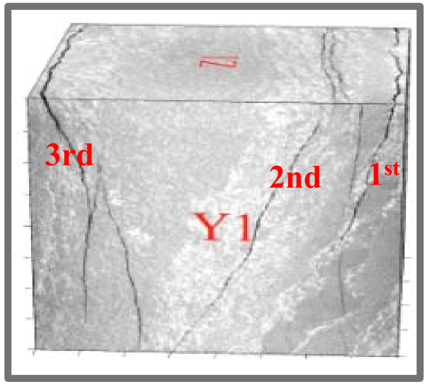
Conclusion

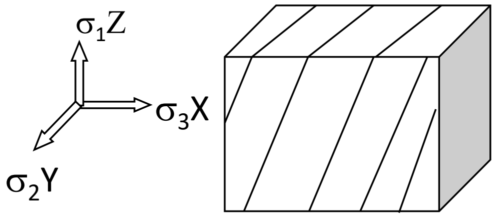
- The 30^{o} micaceous gneissic specimens show the lowest strength and start the initiation of fracturing as early as loading in step 5 i.e. during the excavation of the second test hole.
- 90^{o} gneissic specimen did not fail and looked intact after the test and showed little AE activity at the end of loading step 8.
- AE activity highlights the failure plane in the tested specimens 0^{o}, 30^{o} and 60^{o}.
- Spatial and temporal AE events studies shows that the failure pattern in gneissic specimen is localized along foliation planes (0^{o} , 30^{o} and 60^{o}) in comparison to pegmatite specimen which does not show localized damages.
- We conclude that where ever along the length of the test holes the induced in-situ main principal direction stress exceeds 50 MPa and makes an angle of about 30^{o} with micaceous gneiss rock type or at the boundary with pegmatite fracture initiation is triggered and leads to full failure during the heating and cooling stages in the second test hole.
- Based on the true-triaxial test results, it became easier to understand the cause of localized excavation damages in an anisotropic rock mass selected for nuclear waste repository site in Finland.

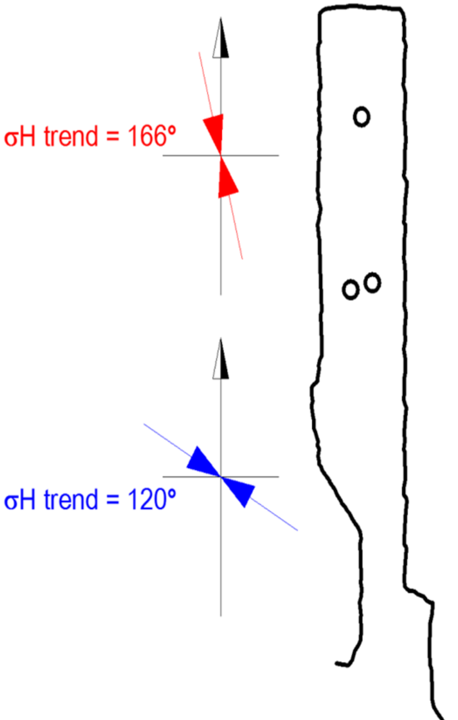
- **Acknowledgment:** **My special appreciation to Mr. Laszlo Lombos for their continuous support with many industrial projects during my 25 years of research career at University of Toronto.**
- **Special thanks to:**
- **R. M. Sehizadeh,**
- **Dr. Maria Tibbo**
- **Dr. Willian Feng**
- **Dr. Sherveen**

Failure of test holes after heating stages

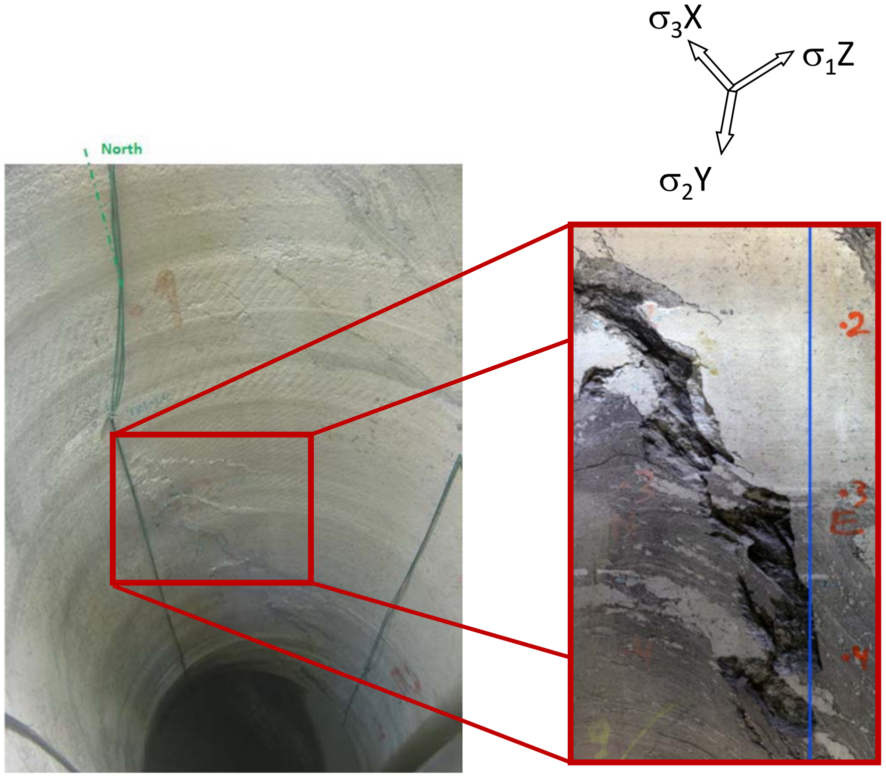
MRI image of the 30 degree micaceous gneiss tested in the laboratory





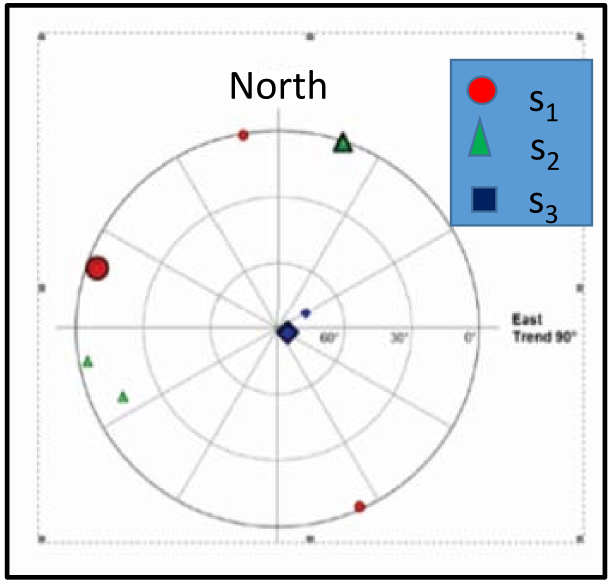


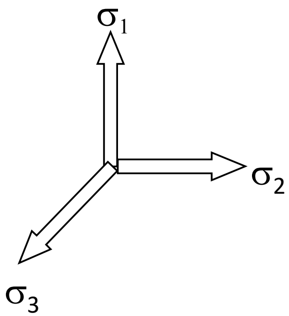
The trend of the maximum principal stress according to two interpretations: the EDZ/access tunnel trend in red and the ONK-EH3 trend in blue (Hakala & Valli, 2013).

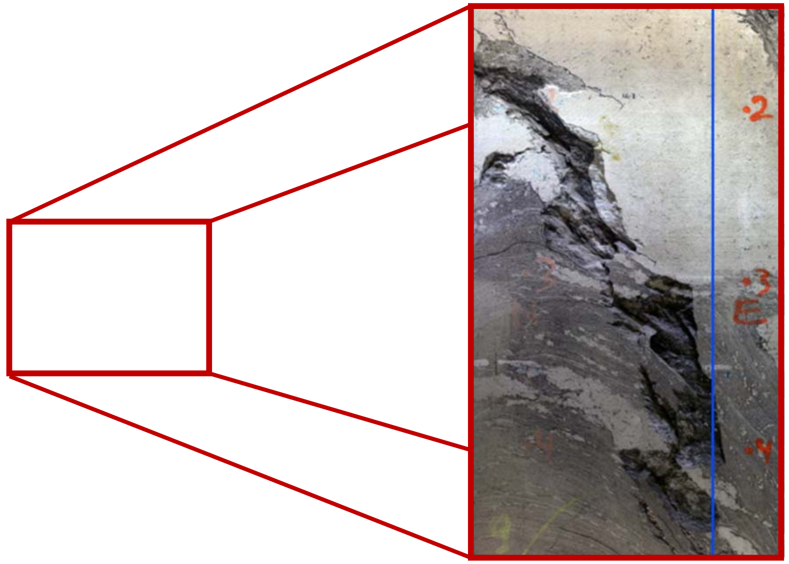


A close-up of heating induced damage in ONK-EH2 at a depth level of 2 – 5 m from the top of the hole. The pillar centre line is indicated by a blue line (Johansson et al. 2013).

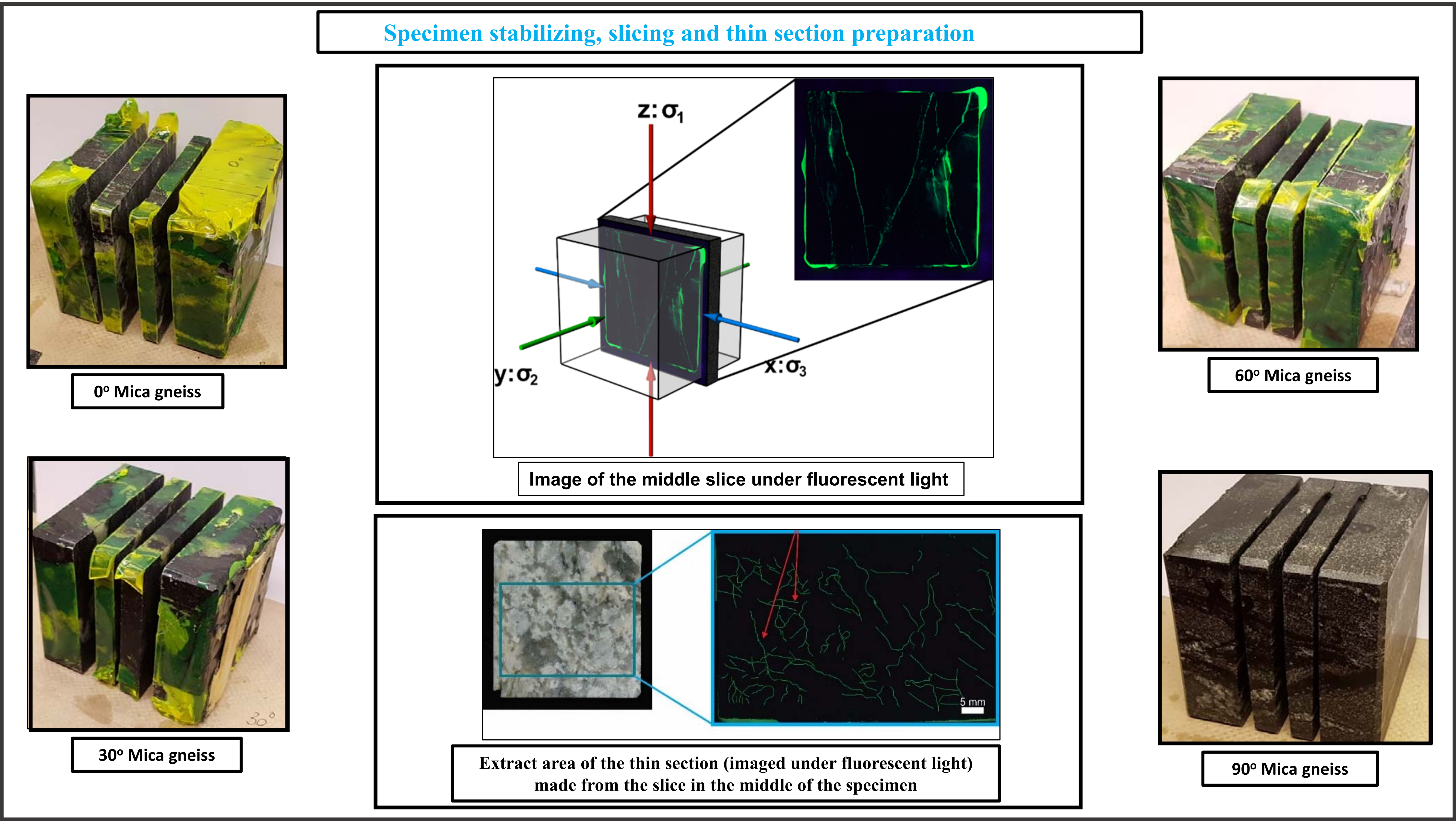
The Deposition Hole Test Results and Observation: Effect of Changes in Main Principal Stress Magnitude and orientations with Respect to weak planes
Our field visit and Examination of selective failure of heating test holes







A close-up of heating induced damage in ONK-EH2 at a depth level of 2 – 5 m from the top of the hole. The pillar centre line is indicated by a blue line (Johansson et al. 2013).



Specimen stabilizing, slicing and thin section preparation
0º Mica gneiss
30º Mica gneiss
z: σ1
y: σ2
x: σ3
Image of the middle slice under fluorescent light
5 mm
Extract area of the thin section (imaged under fluorescent light)
made from the slice in the middle of the specimen
60º Mica gneiss
90º Mica gneiss