岩土力學國際學術會議暨第十四次全國岩石力學與工程學術大會國際分會論文集 2016 年12 月14-17 日 中國香港.

International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress, 14-17 December 2016, Hong Kong, China

Fluid Flow in the Extensively Fractured Cobourg Limestone

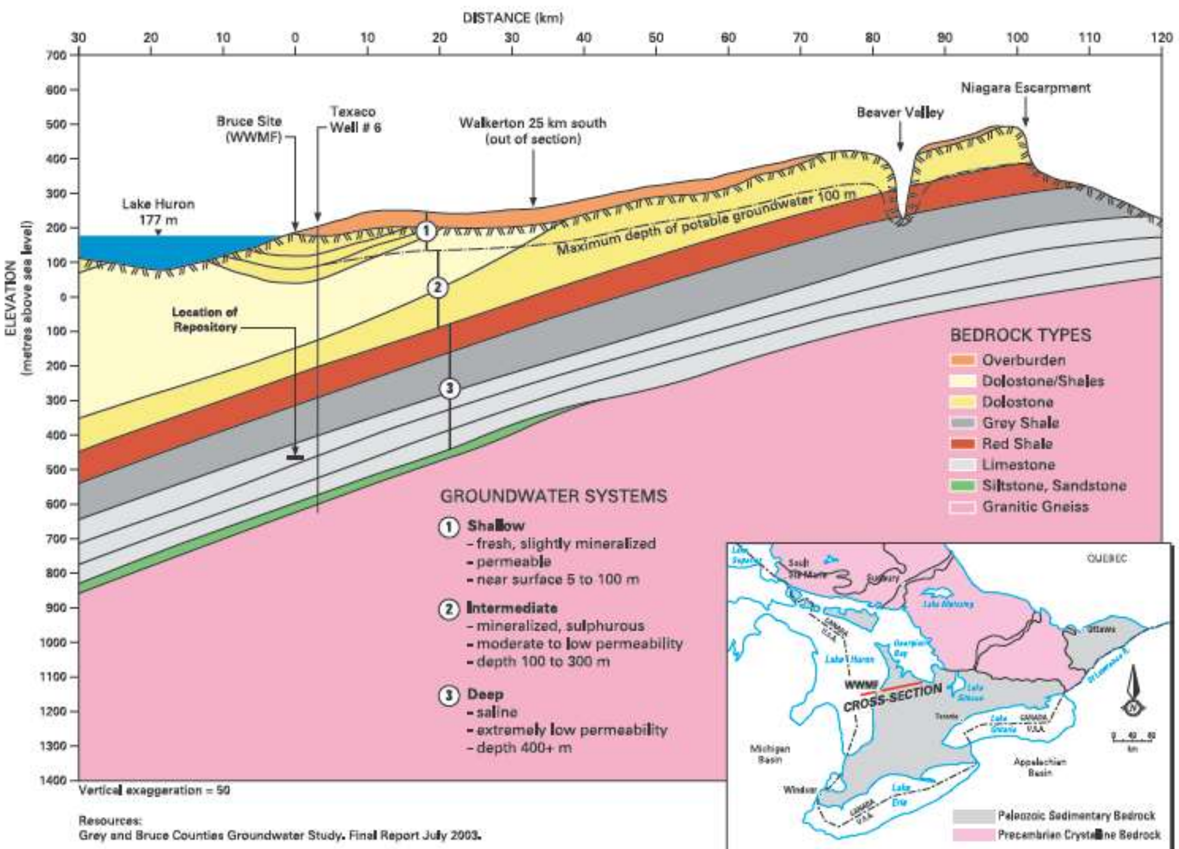
A.P.S. Selvadurai[1] and A. Głowacki[2]

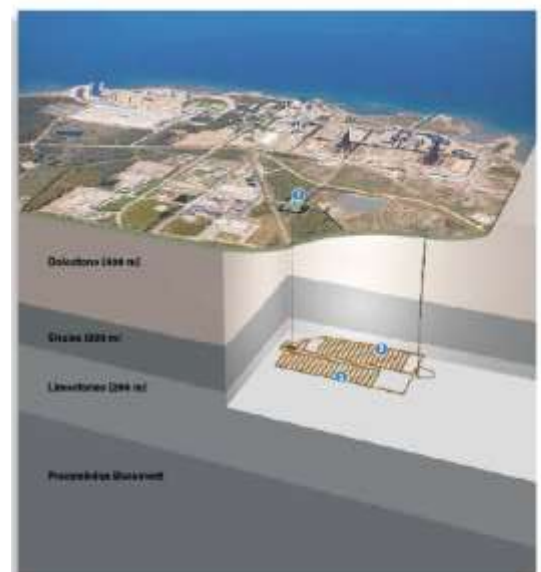
Department of Civil Engineering and Applied Mechanics
McGill University
Montréal, QC, Canada H3A 0C3

[1]*William Scott Professor* and *James McGill Professor*
[2]*Doctoral Student*

The Background

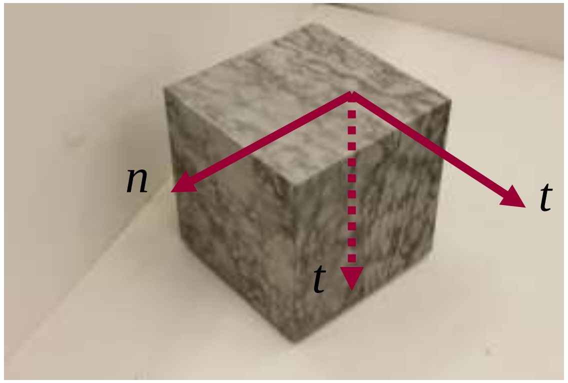
- **The work relates to the proposals by the Nuclear Waste Management Organization (NWMO) for the creation of a Deep Ground Repository (DGR) for the disposal of *Low- and Intermediate-Level Nuclear Waste* (HM).**





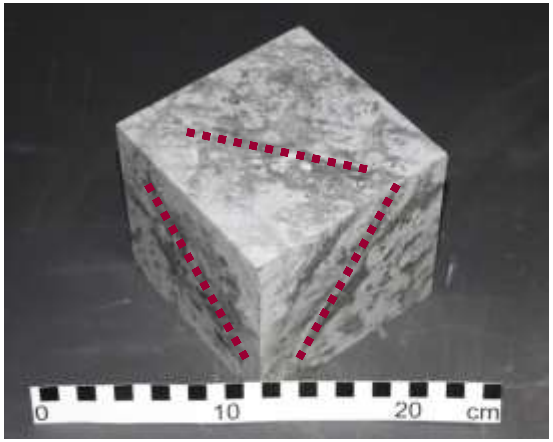
Fabric, Heterogeneity and Stratification

- Surface fabric of Cobourg Limestone demonstrates both heterogeneity and stratification.

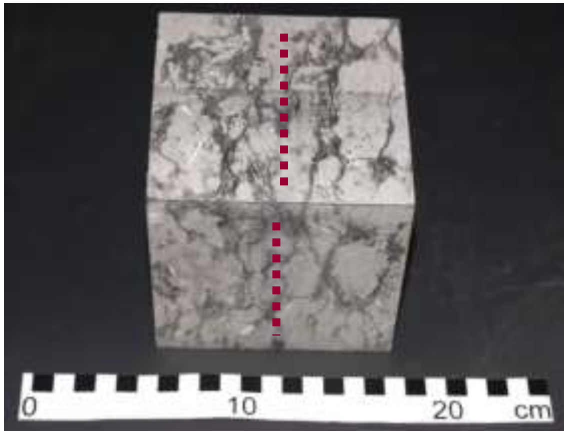


406 mm Cuboidal Sample -Surface Dry

406 mm Cuboidal Sample-Surface Moist

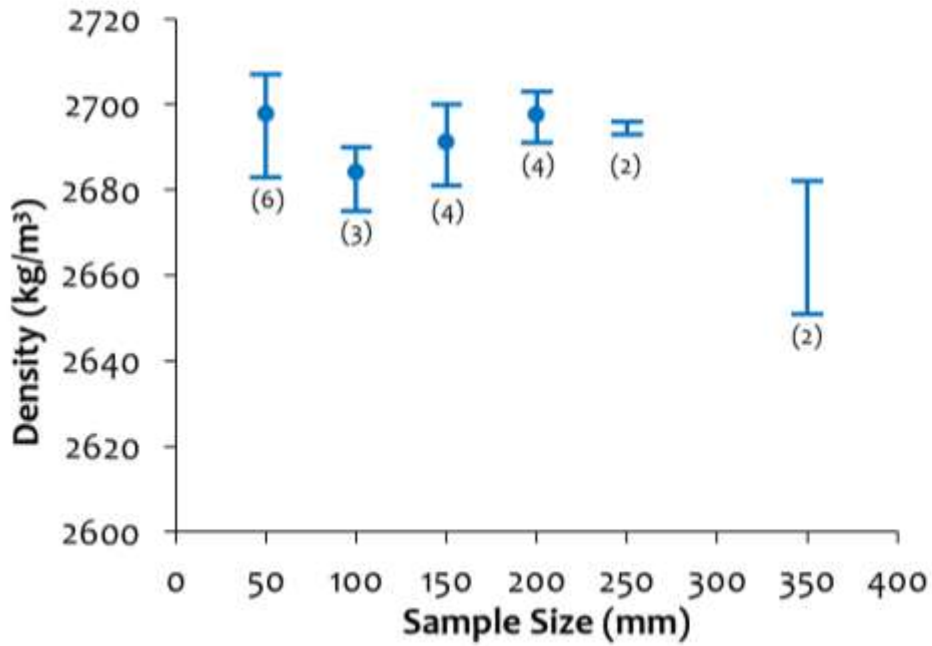


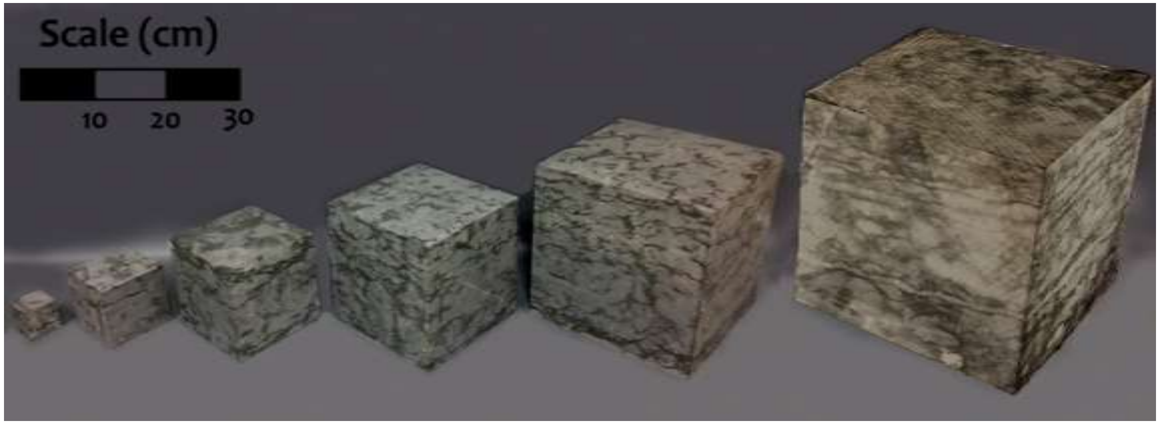
130 mm Cuboidal Sample – 45°



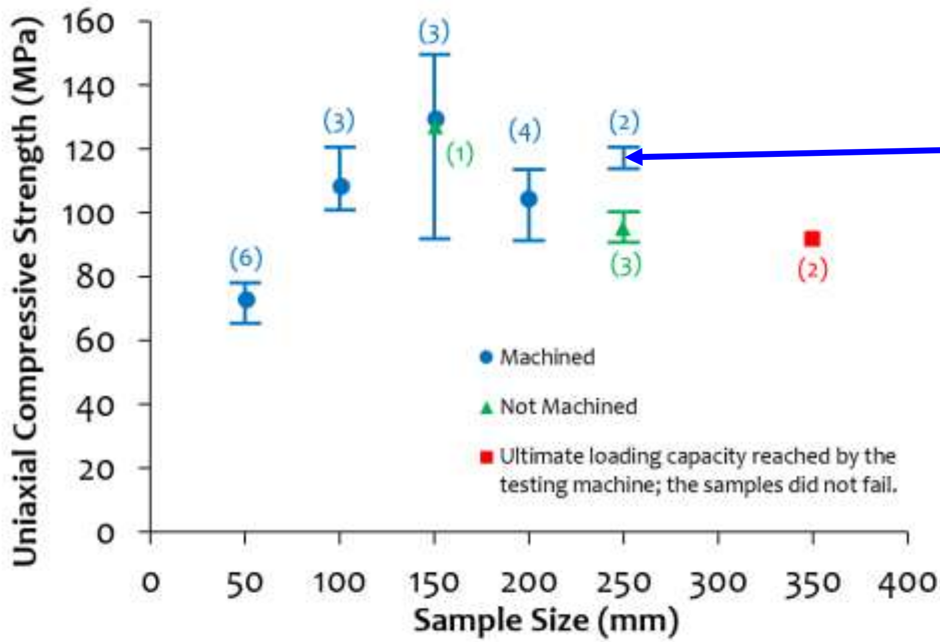
130 mm Cuboidal Sample – 0°

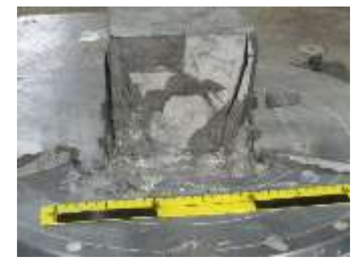
Influences of Scale: Density of the Cobourg Limestone (May 2015)

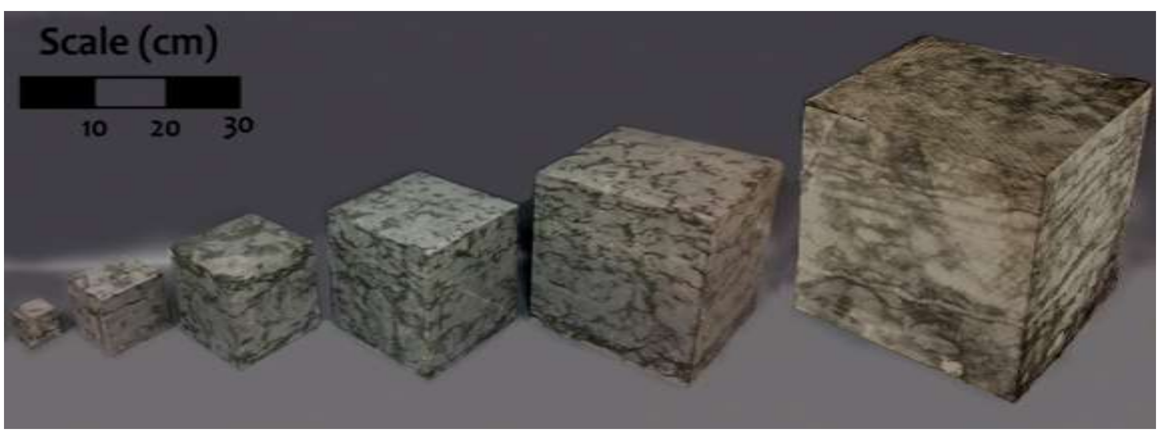




Influences of Scale: Cube Strength of the Cobourg Limestone (May , 2015)

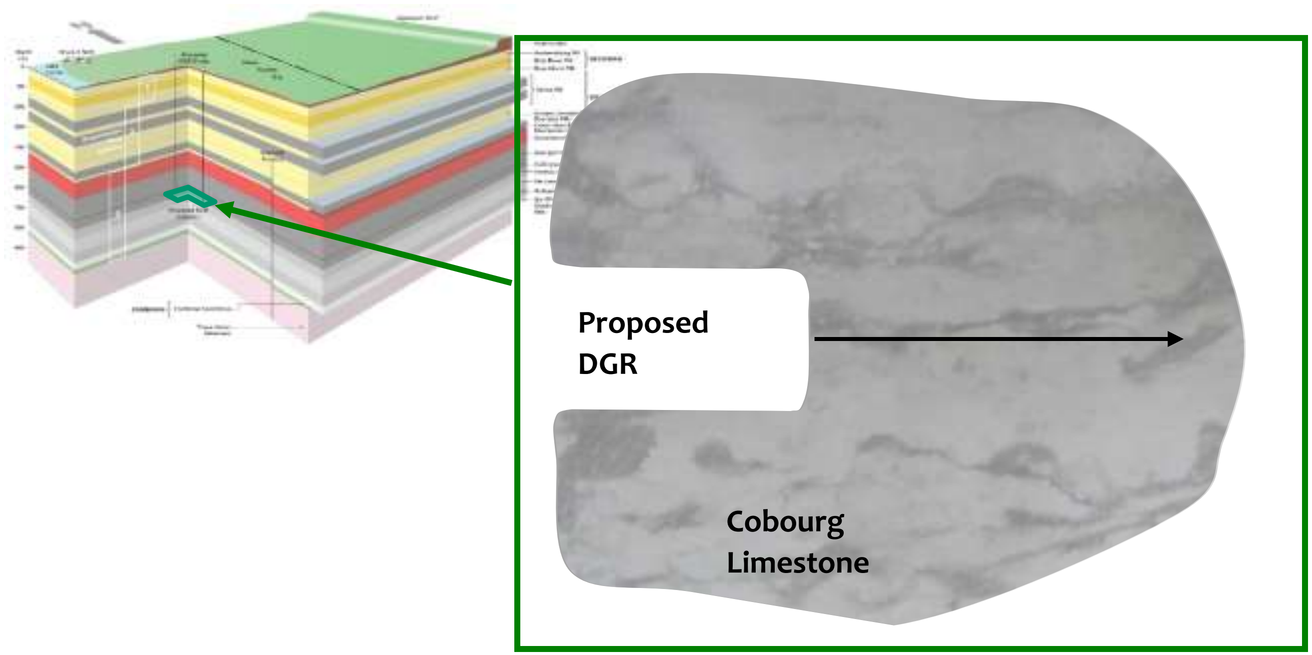




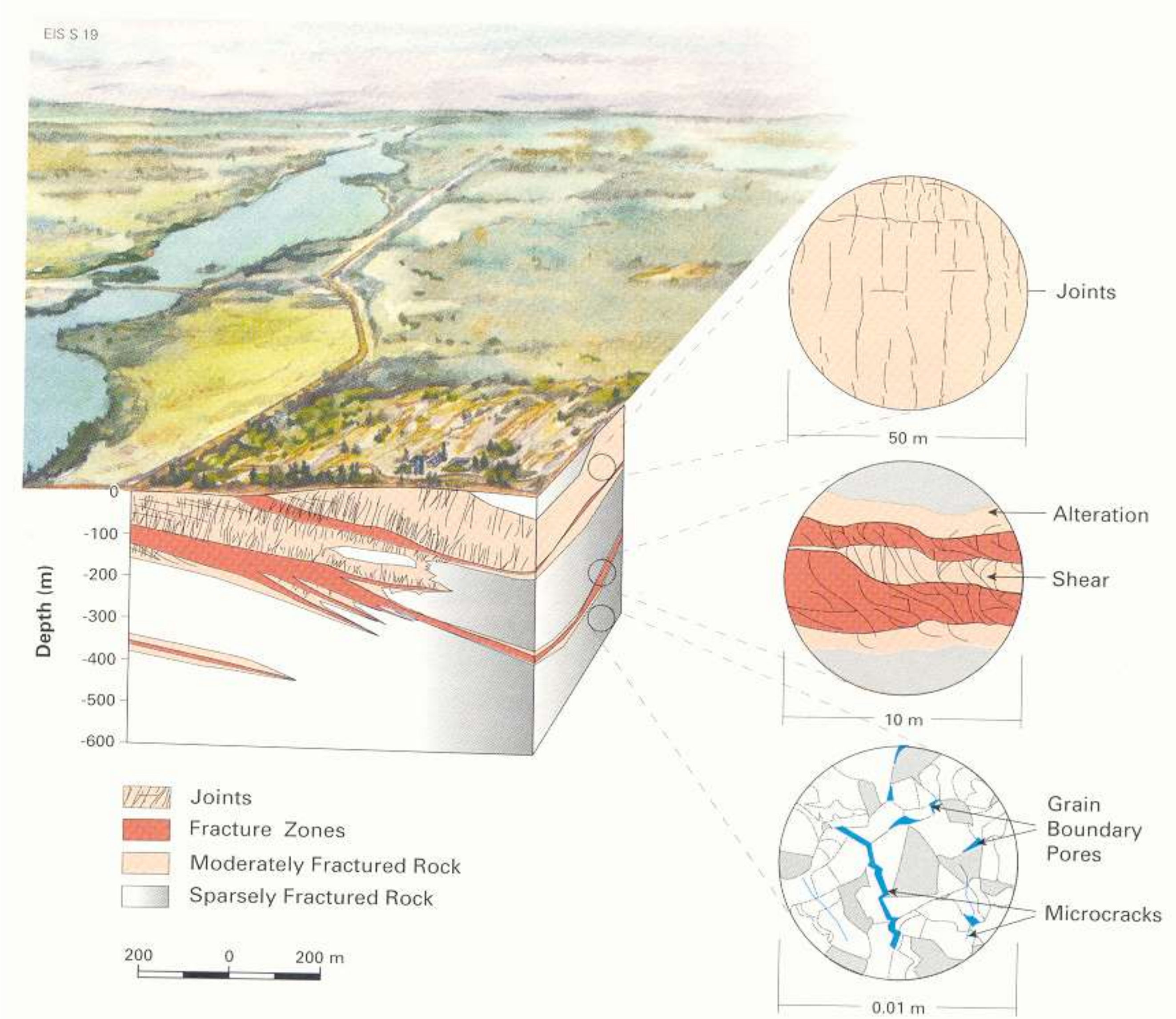


Variation of Permeability of the Cobourg Limestone with the Stress State

- The objective of the research is to investigate experimentally the variation of the permeability of the Cobourg Limestone with the stress state.
- Experiments are restricted to only the application of maximum and minimum principal stresses.

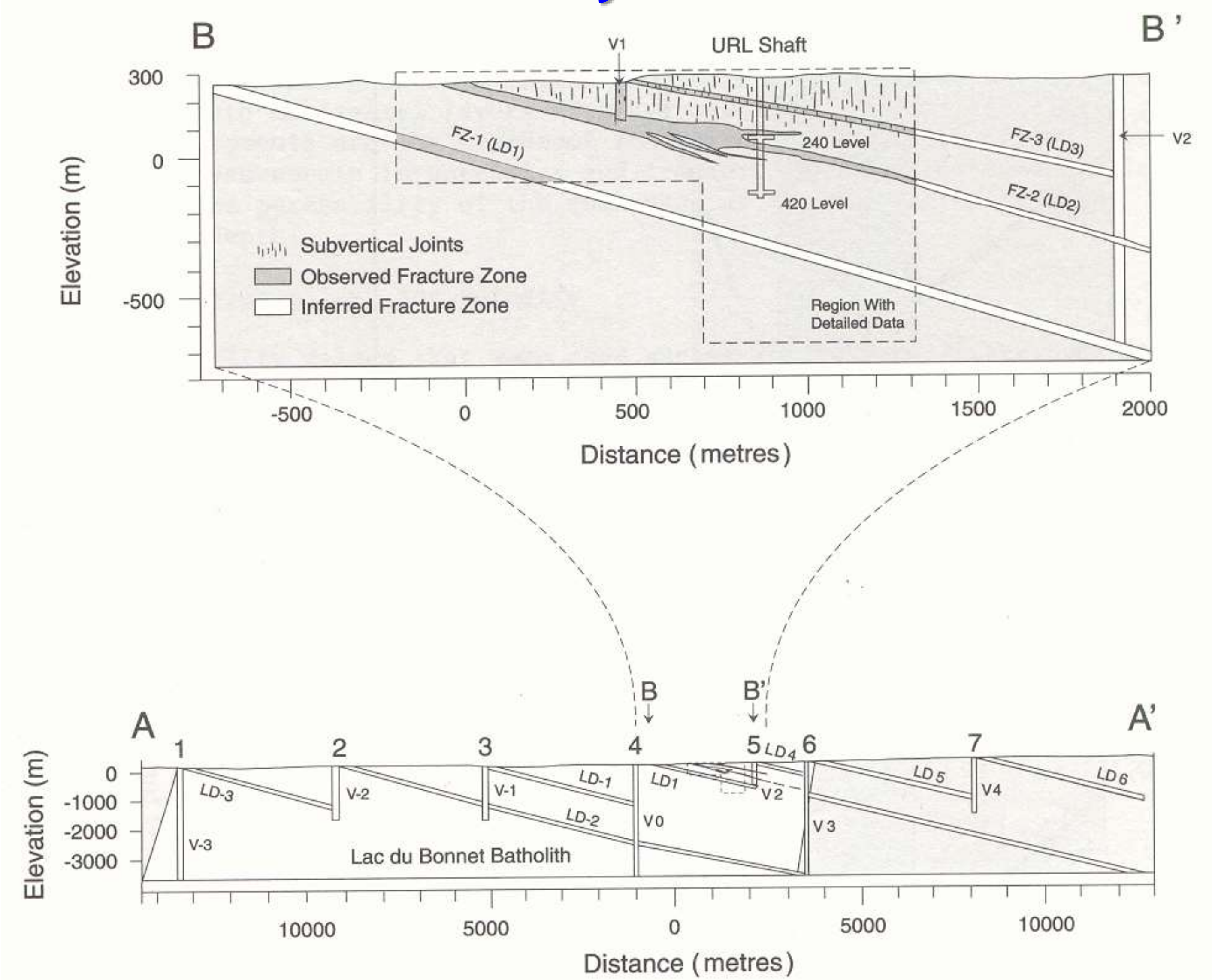


The Natural Geologic Barrier

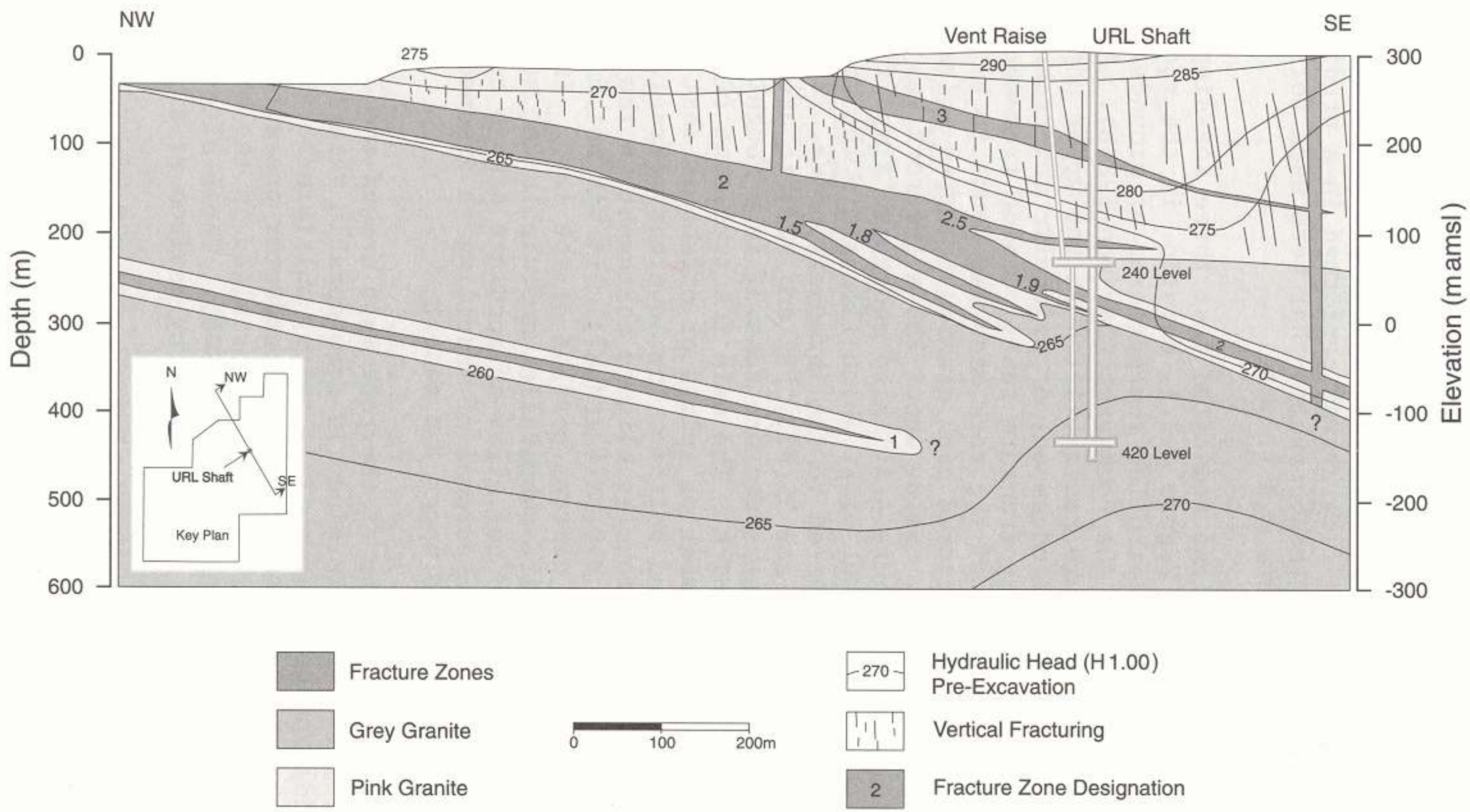


[After AECL (1993)]

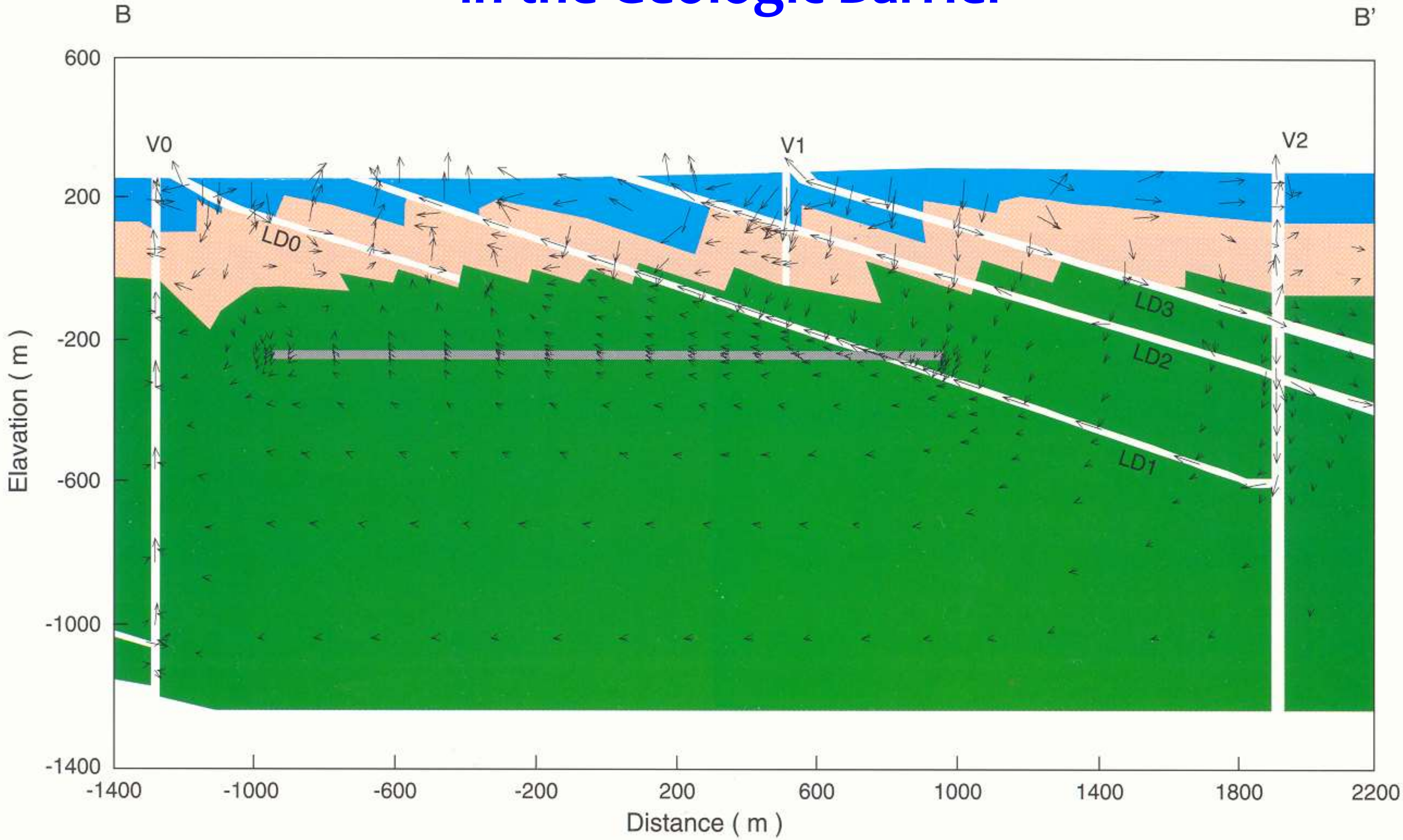
The Geologic Barrier and the Dominant Fracture Systems



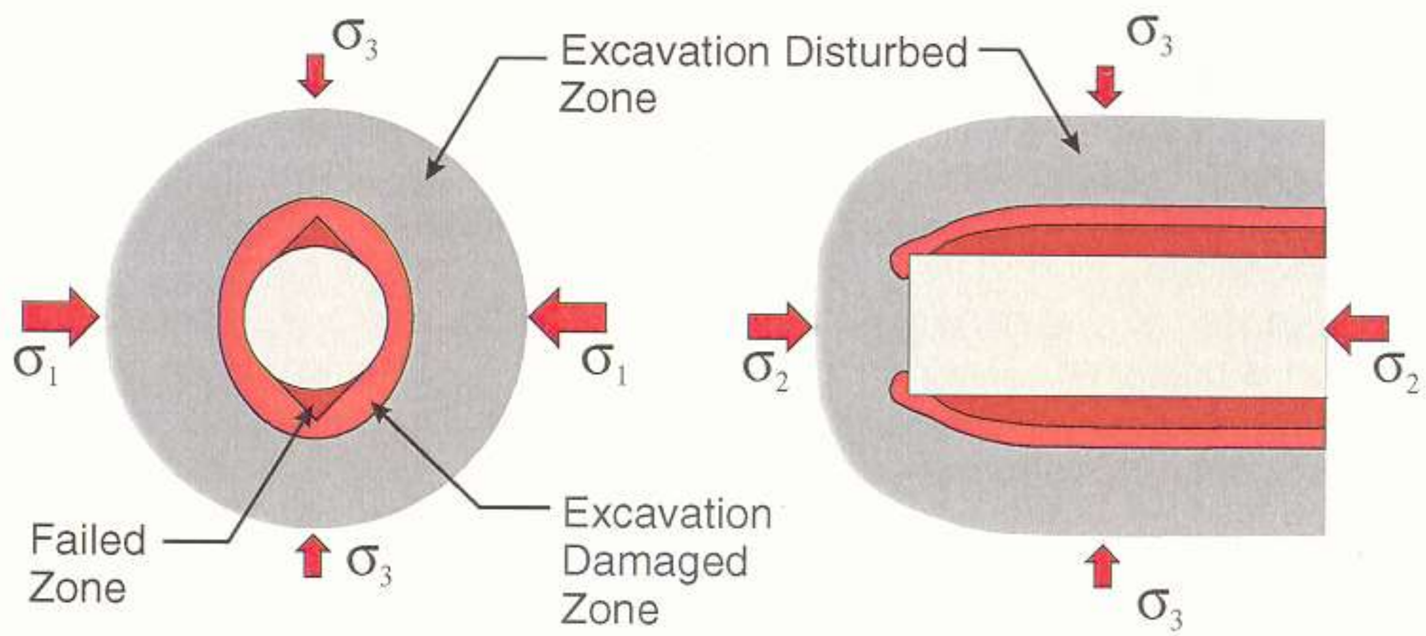
The Geologic Barrier and the Dominant Fracture Systems



The Groundwater Flow Pattern in the Geologic Barrier

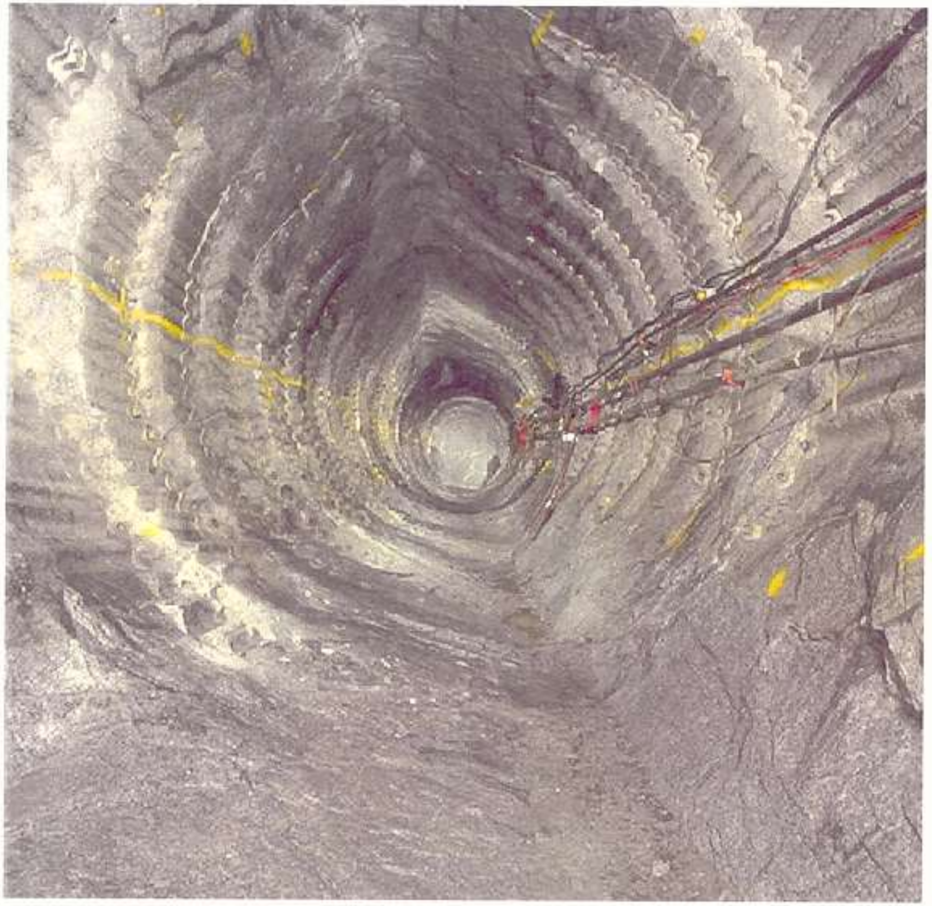


Excavation of Cylindrical Tunnel in a Granitic Rock
Influence of Anisotropic Geostatic Stress State



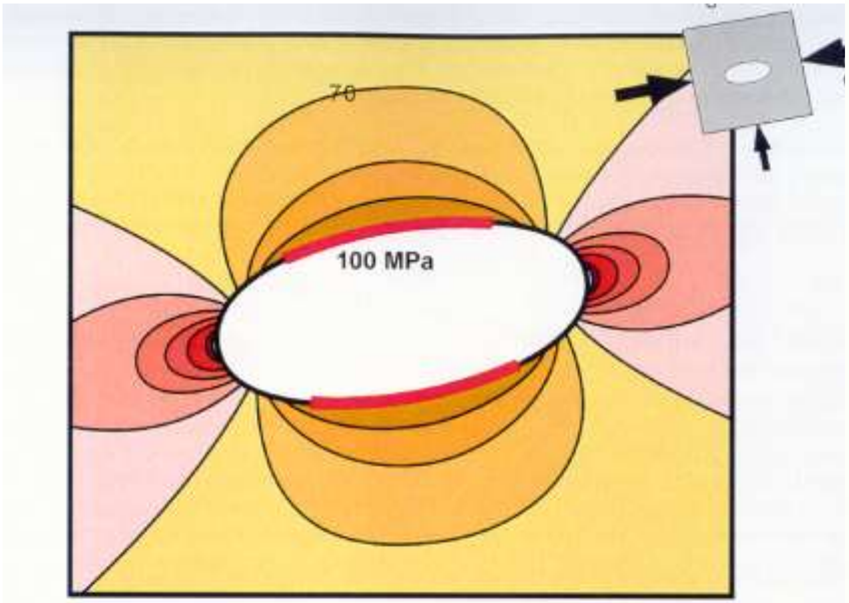
[Read and Chandler *IJRMMS* 2002]

Damage-Induced Evolution of the Shape of the Tunnel

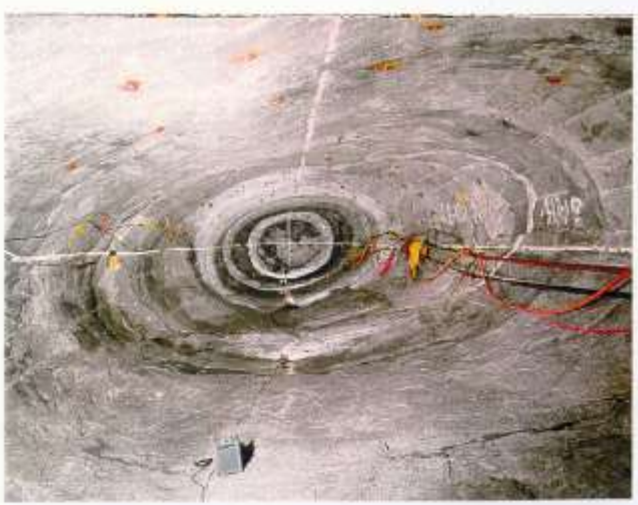


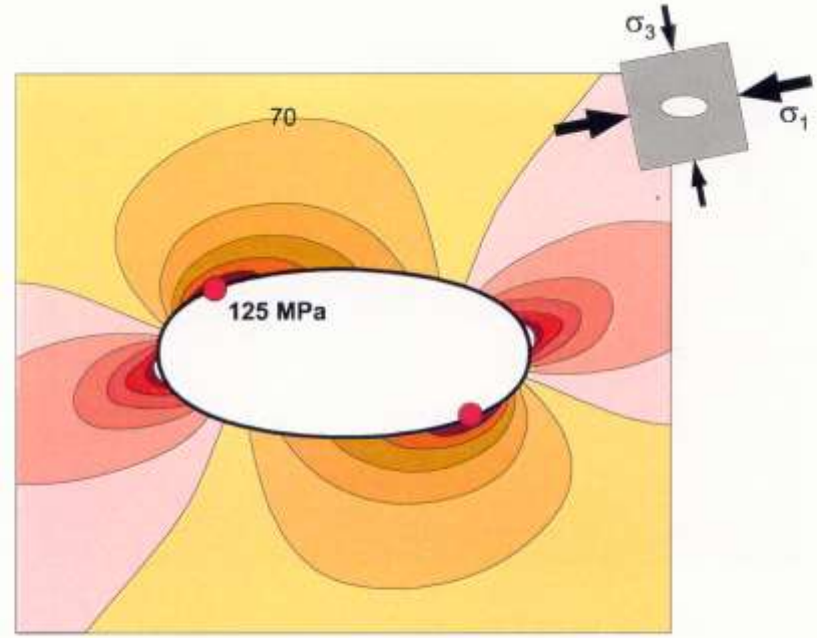
Mine-by Experiment Tunnel Showing Development of V-shaped Notches in the Roof and Floor of the Tunnel

Tunnel Deformations Due to the Anisotropic Stress Field



a





a

b

Local Damage in the Granite Due to the Anisotropic Stress Field

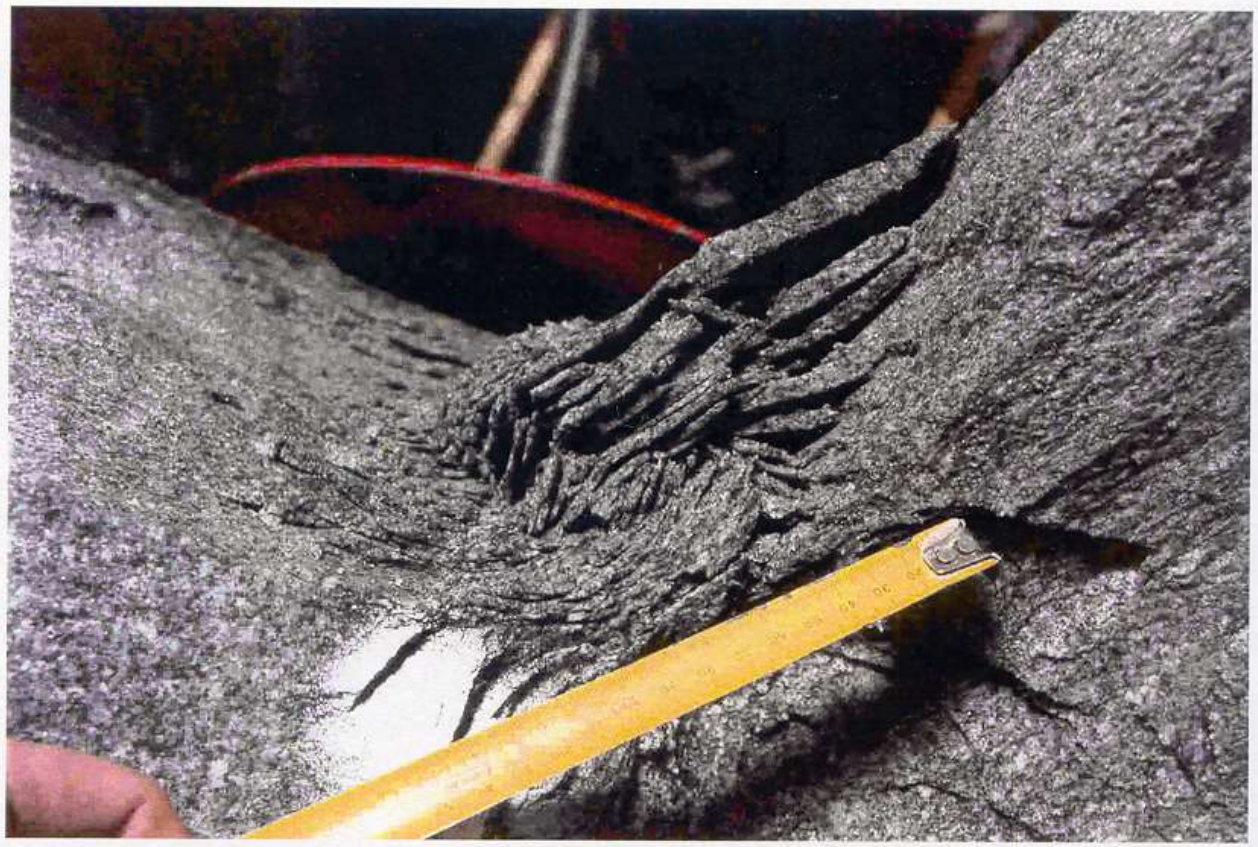
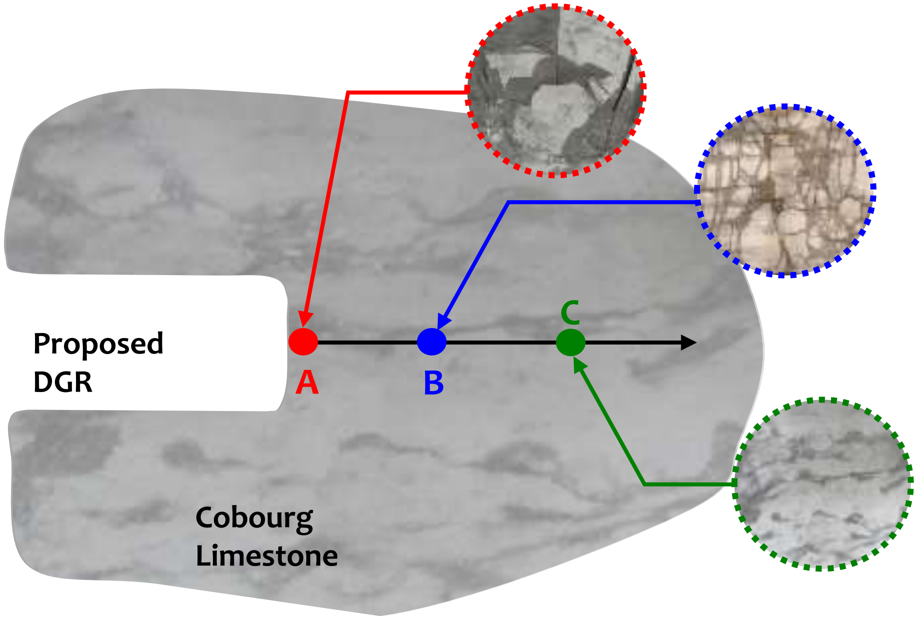


Figure 95: Close-up of the Notch Tip in the Mine-by Experiment Tunnel Showing Dilation in the Process Zone

[AECL Report, 1993]

Variation of Permeability of the Cobourg Limestone



- Any discretely fractured state at the ZONE A may be influenced by the orientation of the geostatic stress state and heterogeneities.[Lanyon, *NWMO*, 2011] **(NWMO HDZ)**
- Likely attenuation of damage at the ZONE B due near re-establishment of pre-excavation geostatic stress state. **(NWMO EDZ)**
- Intact Cobourg Limestone the ZONE C with only defects that can be attributed to the "Virgin State". **(NWMO EdZ or EIZ)**

Modelling of Permeability Evolution with Stress State

- If we consider the three hypothetical states in ZONES A, B and C indicated previously, the development of models and associated experimental procedures can be challenging!
- NWMO HDZ: If discrete cracks are initiated, then conditions of (i) crack initiation, (ii) mixed-mode crack extension and orientation in 3D (iii) conditions on the fracture surfaces (open, closed, friction, slip, dilation, degradation, etc.), need to be addressed and the outcomes related to permeability evolution.
- Fluid flow in discrete fracture networks (dilating/non-dilating, etc.) under generalized stress states is not well understood.
- With the Cobourg Limestone this can be compounded by the presence of a dominant fabric. (Does fracture develop in the quarzitic-calcite phase or in the argillaceous phase or at the interface?

Modelling of Permeability Evolution with Stress State

- If we consider the three hypothetical states in ZONES A, B and C indicated previously, the development of models and ass

- NW … itions of … n and ori … open, clo … to be ad … ution.
- Flu … ating, etc … d.
- Wi … y the pr … in the qu … rface?

Modelling of Permeability Evolution with Stress State

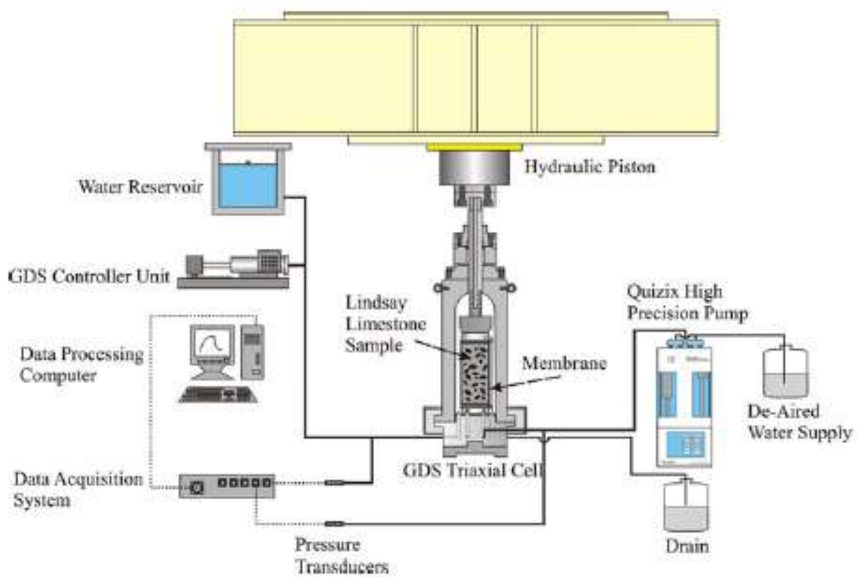
- **NWMO EDZ:** If the defect generation can be attributed to **damage evolution**, then some progress is plausible.
- Again, **where does damage develop** in a **heterogeneous fabric** similar to that observed in **Cobourg Limestone**?
- Also this approach is not without obstacles. If **anisotropic damage mechanics** is adopted, the constitutive relationship for incremental elastic behaviour will contain a **large number of parameters** (21).
- In the **Cobourg Limestone** the damage can occur in the (i) **quarzitic phase**, (ii) the **argillaceous phase** and (iii) at the **interface**.
- **Damage evolution laws** for each phase need to be developed by appeal to principles of continuum mechanics.
- Ultimately **permeability evolution** with **damage** needs to be addressed. **Anisotropy of permeability in damaged materials**..

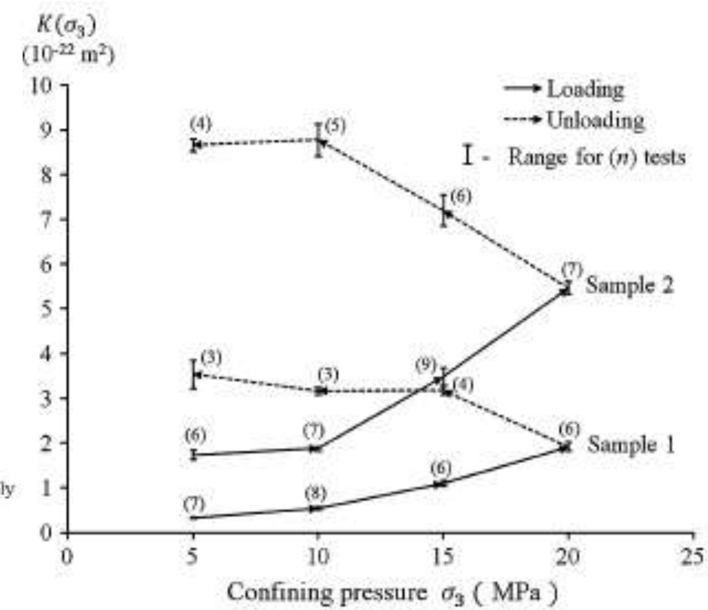
Modelling of Permeability Evolution with Stress State

- **NWMO EdZ or EIZ:** Both the in situ and laboratory permeability characteristics of the intact Cobourg Limestone in the unstressed state has been documented in a number of reports and articles. [Raven et al., *CGJ* 1992; Golder & Assoc., *Rep* 2003; Mazurek, *TUB Rep* 2004; Vilks and Miller, *AECL*, 2007; Gartner Lee Ltd., *Rep*. 2008; APSS and Jenner, *GW*, 2013 ; Neuzil and Provost, *JGR*, 2014; APSS and Najari., *OGST* 2016;…]
- Only limited investigations of permeability evolution in the Cobourg Limestone with the stress state. [APSS et al., *EES* 2011; Nasseri et al, *IJRMMS* 2013;..]
- The measurement of permeability of the Cobourg Limestone is a non-routine exercise; (i) Generally one-dimensional flow, (ii) small thickness samples (loss of RVE) (iii) Extremely low intact permeability (10^{-19} m^2 to 10^{-22} m^2) requires the use of hydraulic pulse tests that are highly sensitive to test procedure [e.g. saturation, air voids in the pressurized cavity, poroelastic effects. [APSS, *GJI* 2011; Najari and APSS, *AWR* 2014; APSS and Najari, *Geotechnique* 2015;…]

Permeability Tests on the Cobourg Limestone

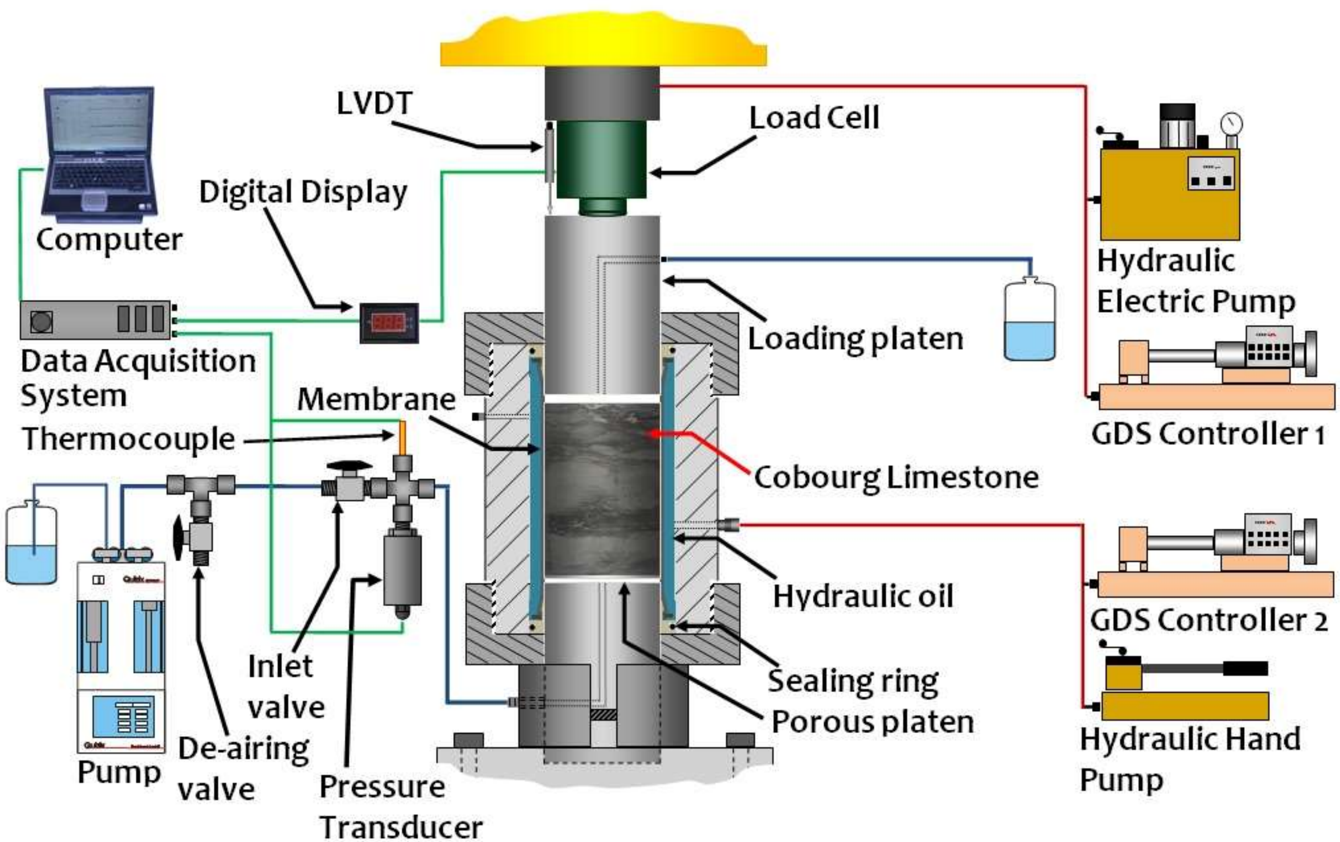
- The **HM/THM model** development for the Cobourg Limestone can be enhanced by the availability of **reliable experimental and field data** on **permeability evolution with stress**.
- The nature of the Cobourg Limestone (i.e. possible **scale effects** and **ultra low permeability** in the intact state, makes experimental evaluations ***non-routine***.
- In research, **permeability evolution with** σ_3 was measured. [APSS et al., *EES* 2011]. Hydraulic Pulse Tests were used to determine $K(\sigma_3)$.





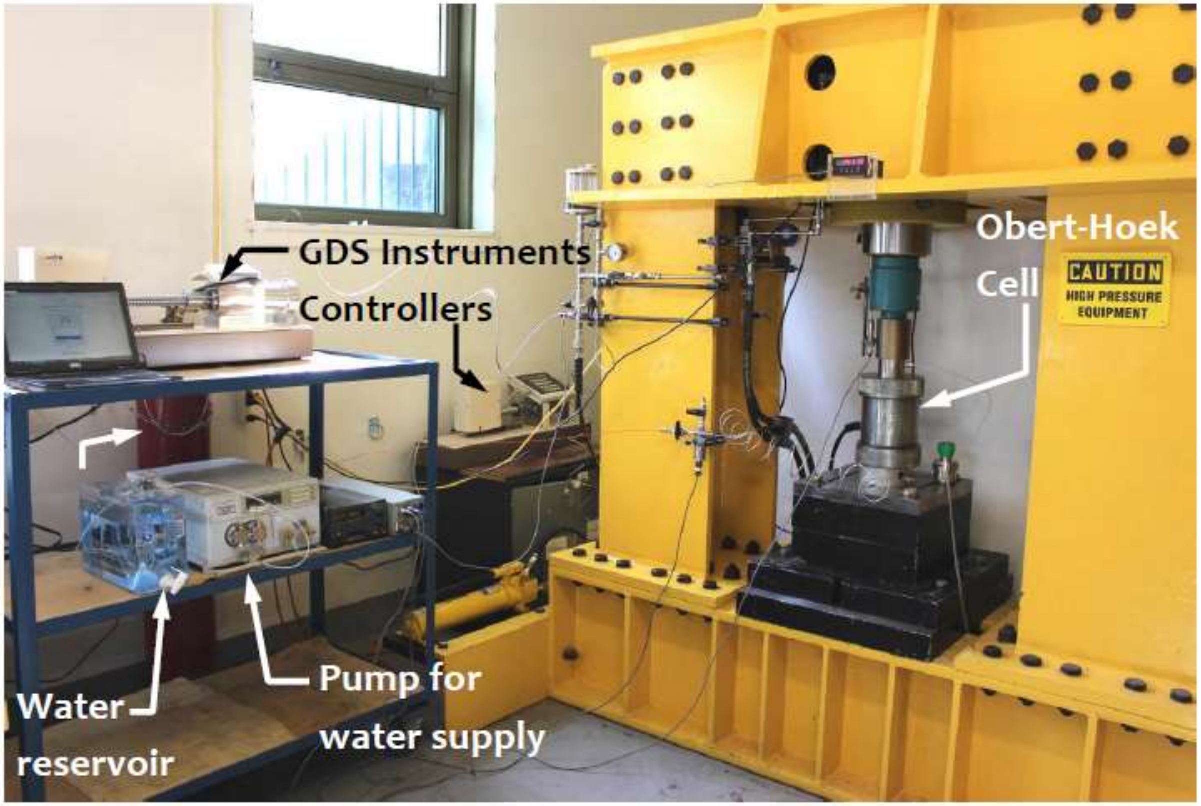
Permeability Tests on the Cobourg Limestone…contd

- The research is extended to the investigation of the influence of σ_1 (maximum) and σ_3 (minimum) principal stresses on the evolution of permeability.
- A modified Obert-Hoek Cell is used in the research.



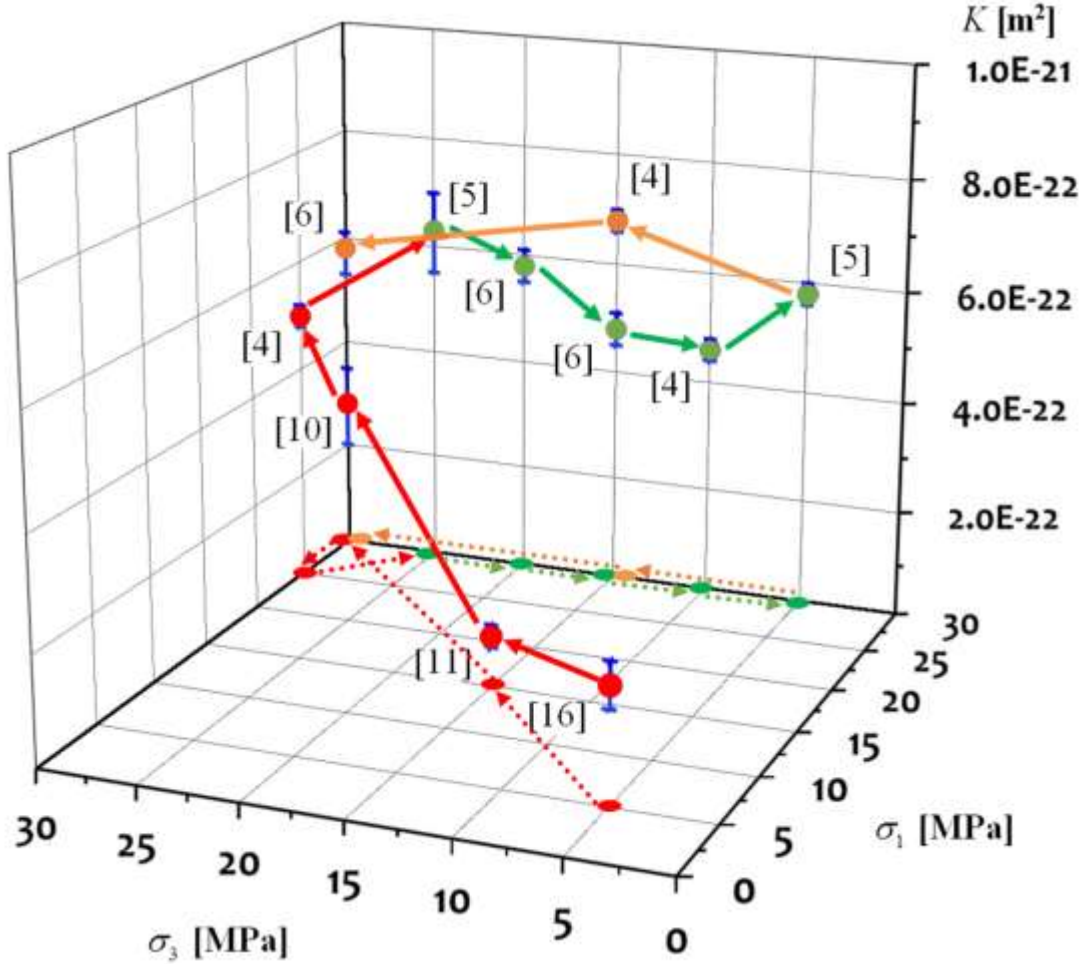
Permeability Tests on the Cobourg Limestone…contd

- The first stage of testing is intended to investigate permeability changes with of σ_1 and σ_3 without the generation of discrete fractures. (NWMO EDZ to NWMO EdZ).
- Altogether 83 hydraulic pulse tests were conducted taking into account the **APSS-Najari** (2015) - **procedure for correction** of ***compressibility of the pressurized fluid*** for air voids.



Permeability Tests on the Cobourg Limestone… contd

- The experimental were conducted for permeability estimation during loading-unloading and reloading paths, with the isotropic stress state limited to 5 MPa to prevent interface leakage



Permeability Tests on the Cobourg Limestone… contd

- The "State Space" for permeability evolution can be approximated by elementary relationships that take into consideration the loading-unloading-reloading sequence. [APSS and Głowacki, *Rock Mech Rock Eng* , 2017]
- In the loading stage

$$\frac{K(\sigma_1,\sigma_3)}{K_0}=\exp\left(\lambda_1^m\frac{\sigma_1}{\sigma_0}\right)\exp\left(\lambda_3^m\frac{\sigma_3}{\sigma_0}\right)$$

- In the unloading stage

$$\frac{K(\sigma_1,\sigma_3)}{K_0}=\exp\left(\lambda_1^u\frac{\sigma_1}{\sigma_0}\right)+\exp\left(\lambda_3^u\frac{\sigma_3}{\sigma_0}\right)+\lambda_0^u$$

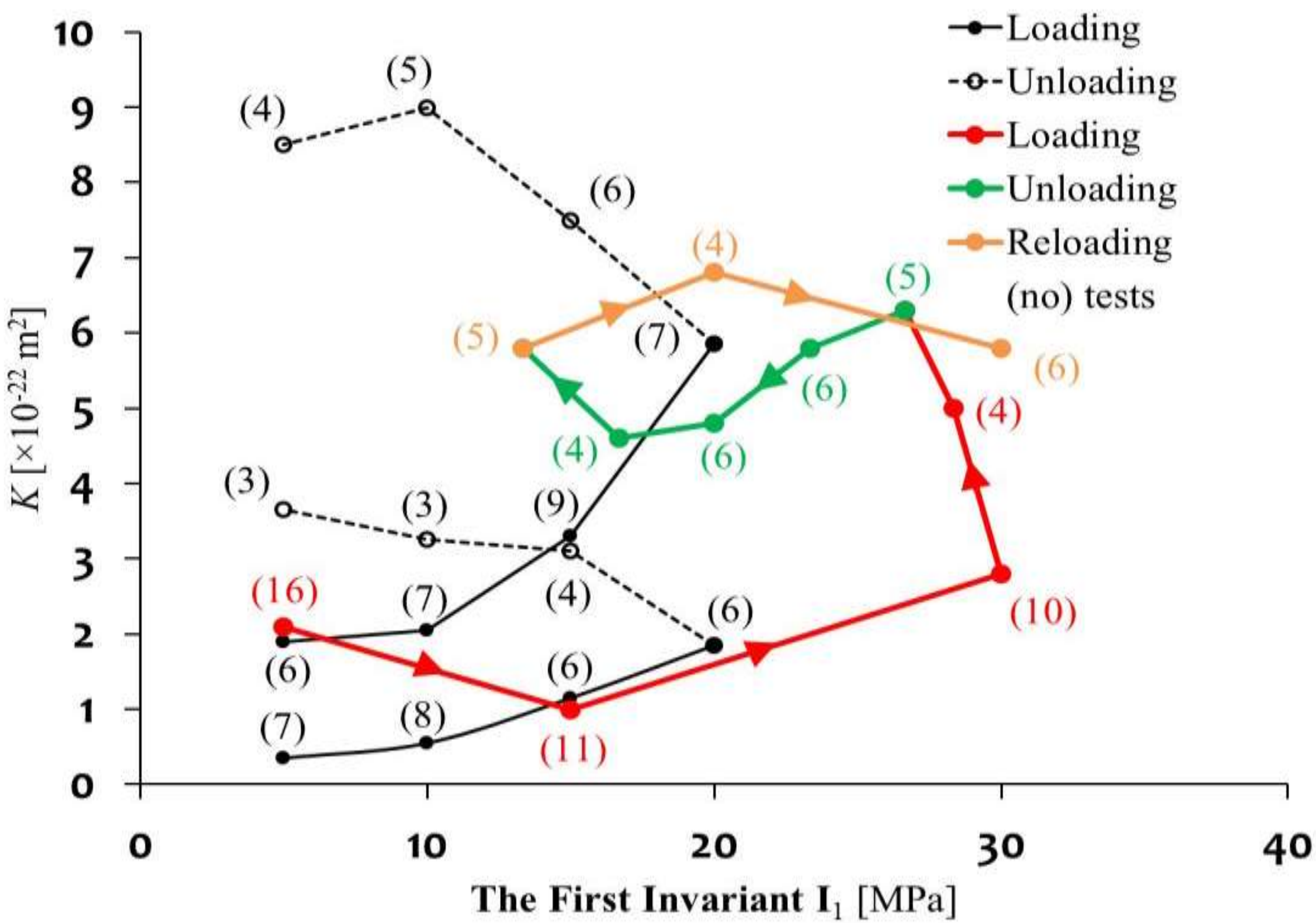
- In the re-loading stage (with limits)

$$\frac{K(\sigma_1,\sigma_3)}{K_0}=\exp\left(\lambda_1^r\frac{\sigma_1}{\sigma_0}\right)\exp\left(\lambda_3^r\frac{\sigma_3}{\sigma_0}\right)$$

- The primary limitation of the study is the inability of the experimentation to capture stress states where *tension could be present*. Most likely not an issue in regions remote from a DGR (NWMO EdZ).

Permeability Tests on the Cobourg Limestone… contd

- **Stress dependency of permeability** in the **near intact state (NWMO EdZ).** The results can be compared with previous experiments reported by APSS et al. *Env Earth Sci* (2011)



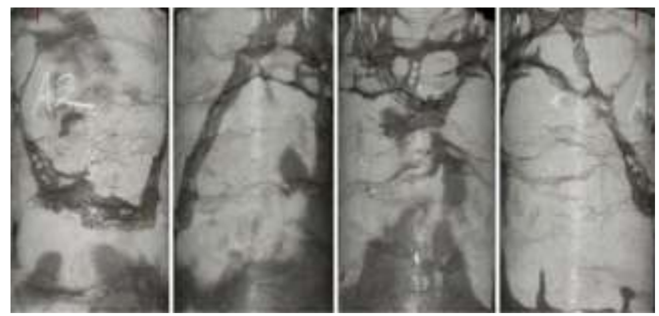
Permeability of the Stressed Cobourg Limestone-Damaged Samples (NWMO HDZ to NWMO EDZ)

- **Samples of the Cobourg measuring 85 mm in diameter and 170 mm in length were tested in a previous phase of the research [APSS *Unpublished NWMO Report, 2016*].**

Intact Sample

Failed Sample:

$$\sigma_{rr} = 30 \text{ MPa} \quad ; \quad (\sigma_{zz})_{failure} = 233 \text{ MPa}$$



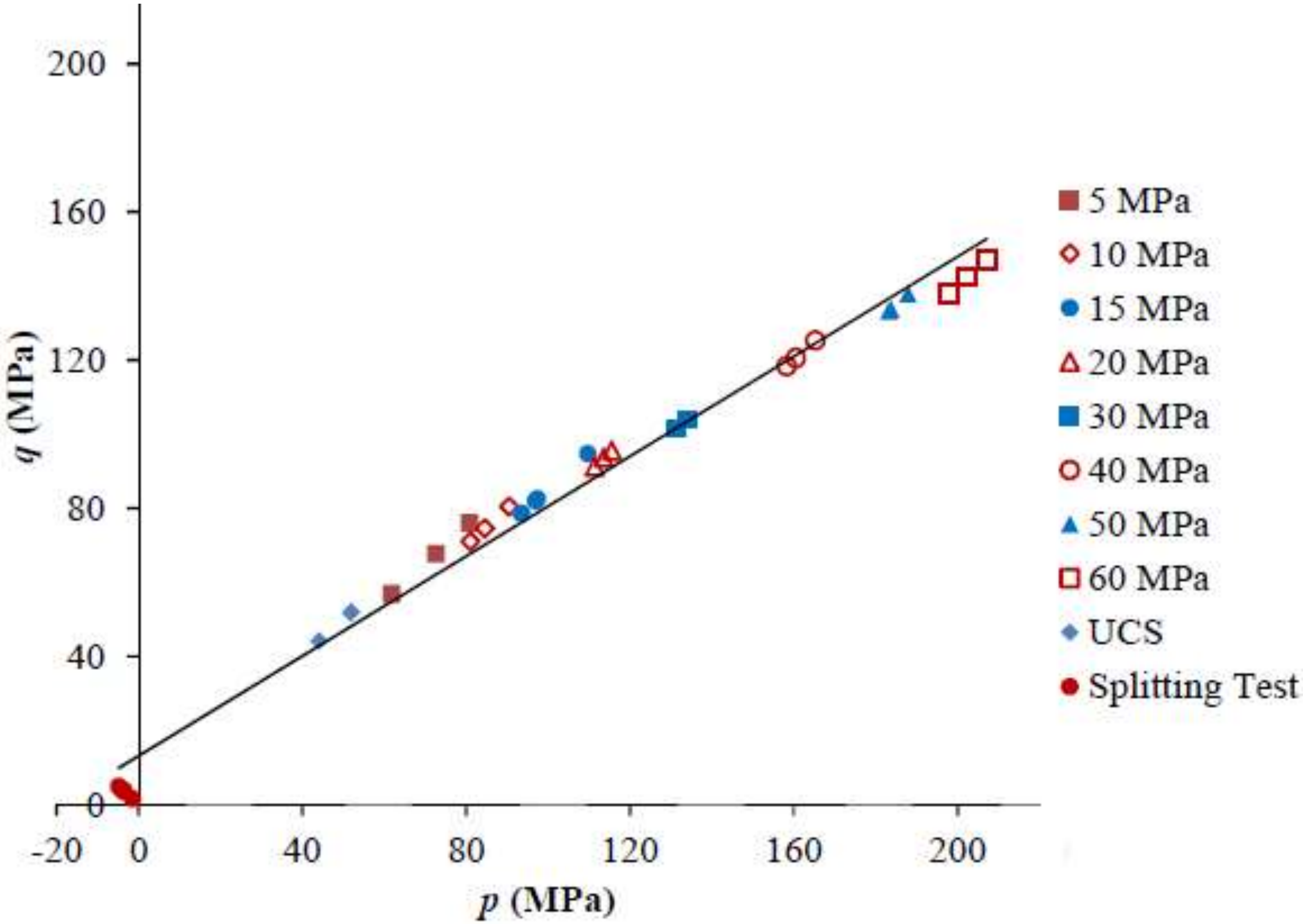
Intact Sample

Failed Sample:

$$\sigma_{rr} = 50 \text{ MPa} \quad ; \quad (\sigma_{zz})_{failure} = 317 \text{ MPa}$$

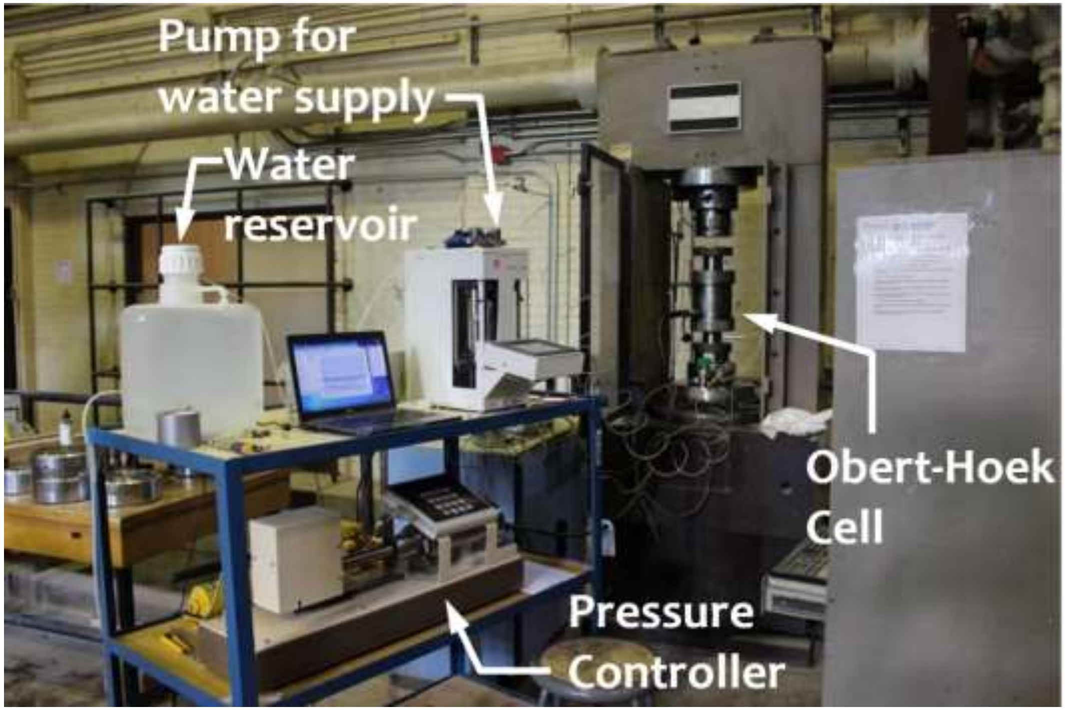
Failure Criterion for the Cobourg Limestone

- **Dry samples of the Cobourg Limestone measuring 85 mm diameter and 170 mm long. Both deformability and failure characteristics have been determined. [APSS, *NWMO Rep* 2016]**

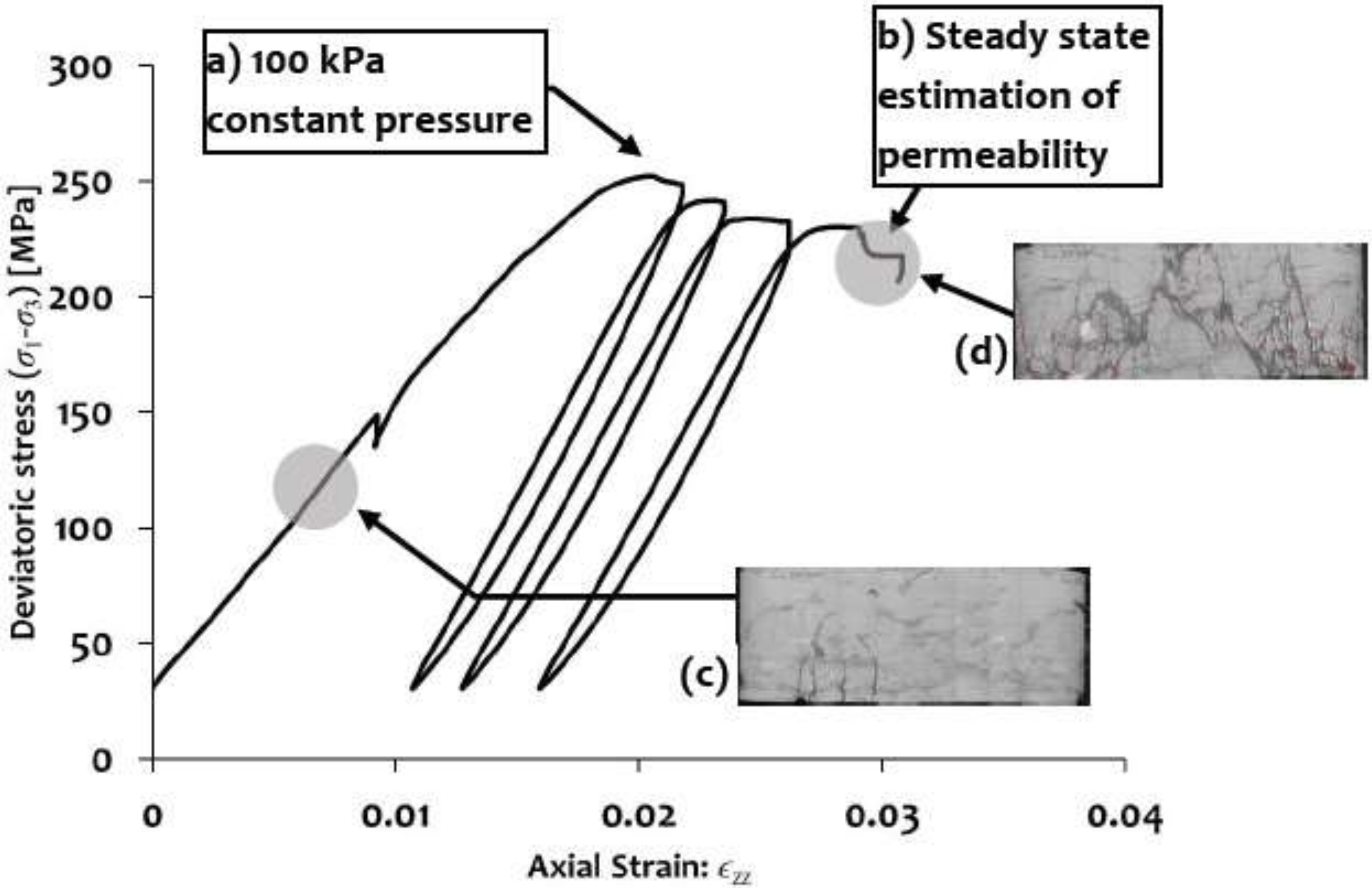


Typical Stress-Strain Behaviour of the Cobourg Limestone

- The stress-strain behaviour is used to determine the stress levels at which the permeability is measured.
- The Obert-Hoek Cell is not suitable for examining the mechanical behaviour of the Cobourg Limestone in the strain softening range.
- For this reason, a Servo-Controlled Rock Testing Machine was used in conjunction with a Electro-Mechanical controller to maintain σ_3 constant.

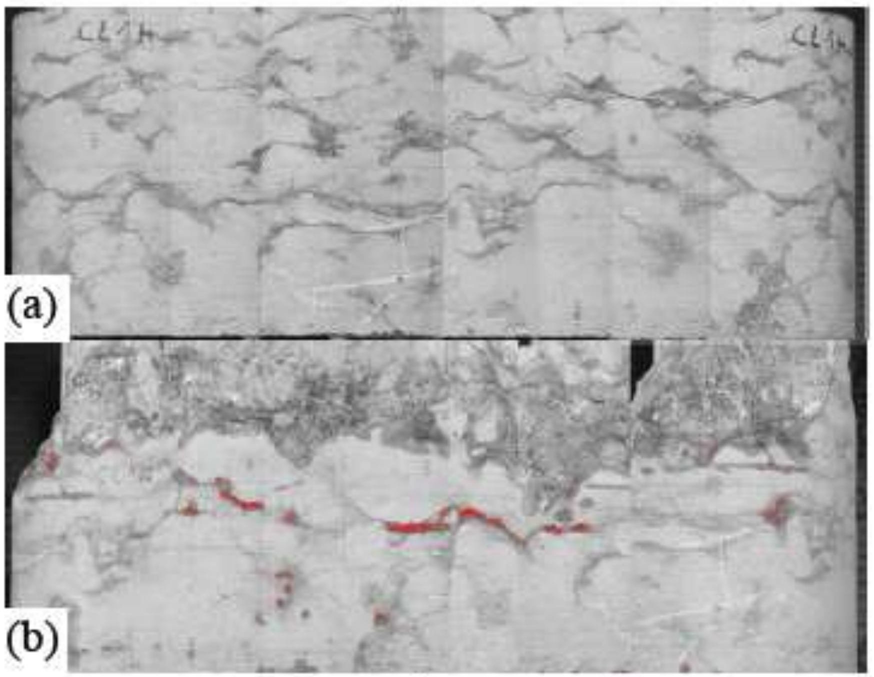


Post-Peak Range Testing of the Cobourg Limestone

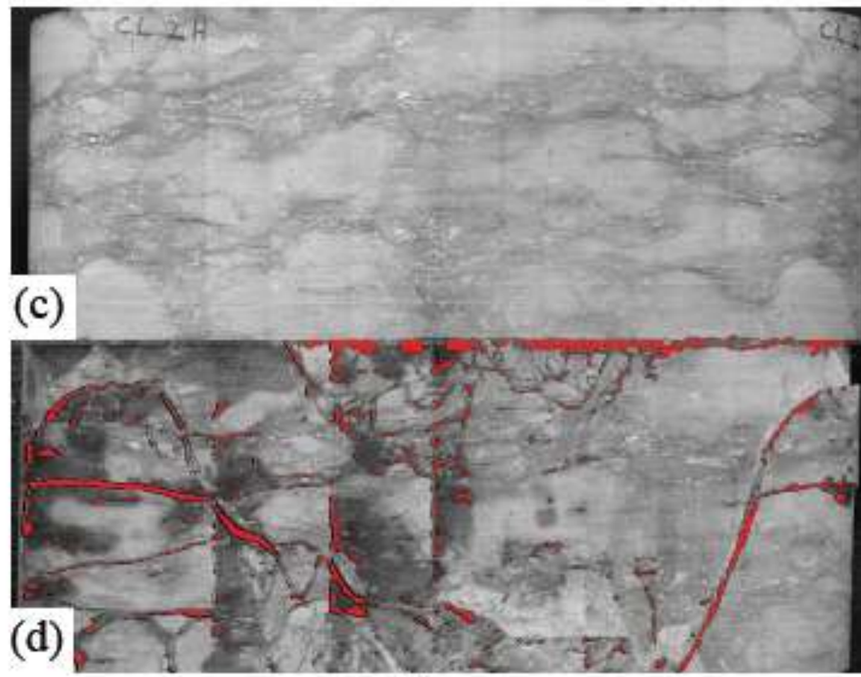


Failure Patterns of the Cobourg Limestone

- **The stress-strain behaviour is used to determine the stress levels at which the permeability is measured. After each test, a panoramic view of the fractures on the cylindrical surface is detected using an image processing technique.**

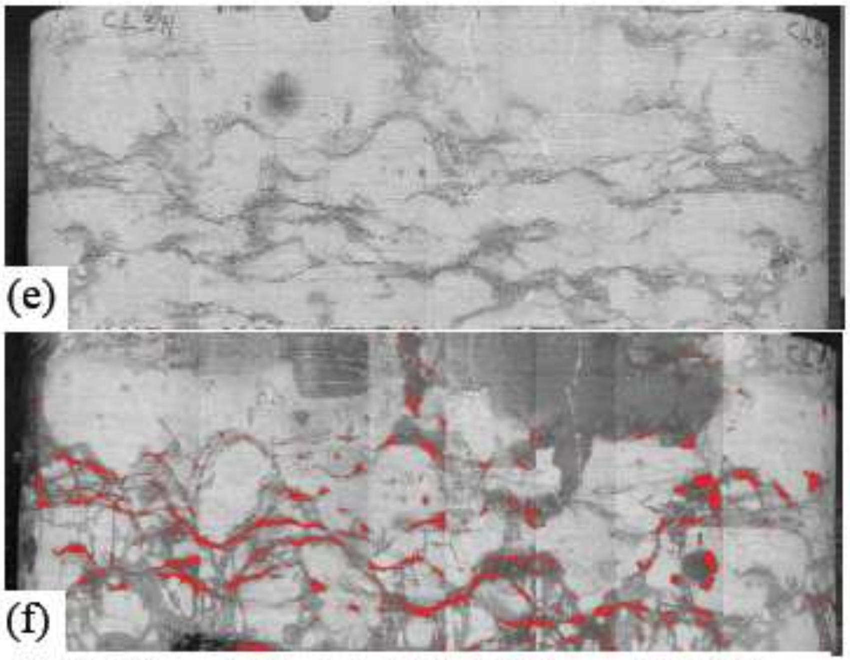


CL1H: $K_{PD} = 3.5E-22\,\mathrm{m}^2$; D=85.6 mm H=132.0 mm

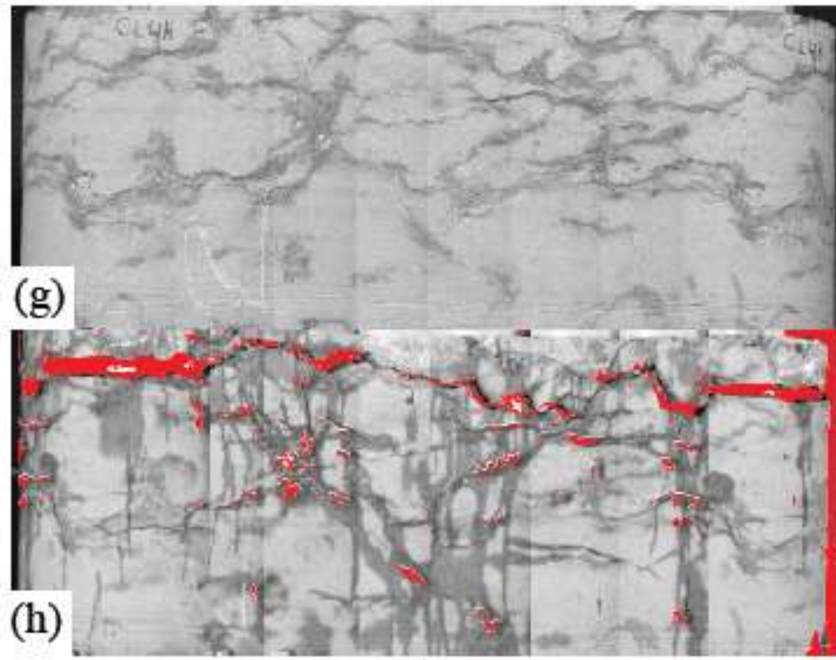


CL2H: $K_{SS} = 3.7E-18\,\mathrm{m}^2$; D=85.2 mm H=134.8 mm

Failure Patterns of the Cobourg Limestone… contd.

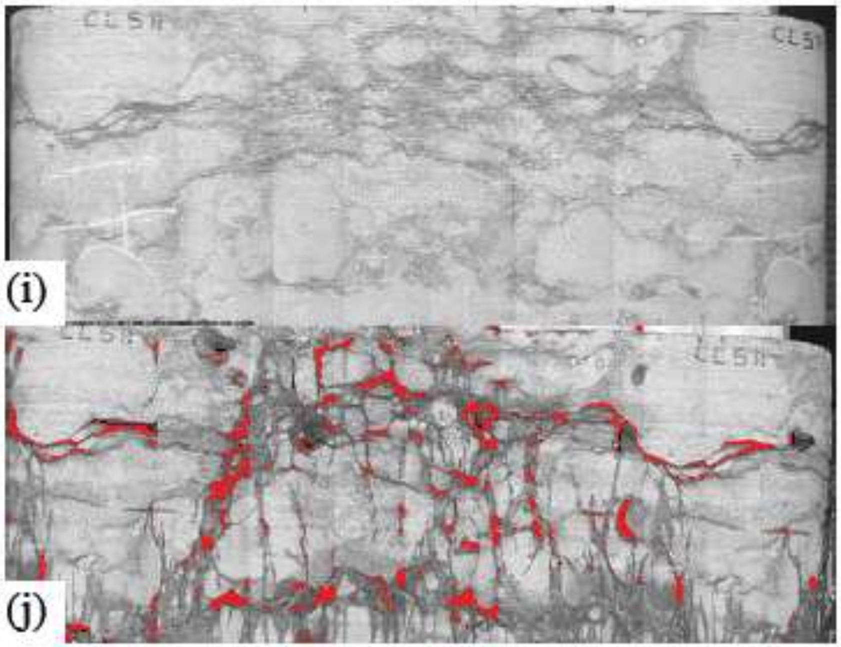


CL3H: $K_{SS} = 2.0E-18\,m^2$; D=85.4 mm H=119.8

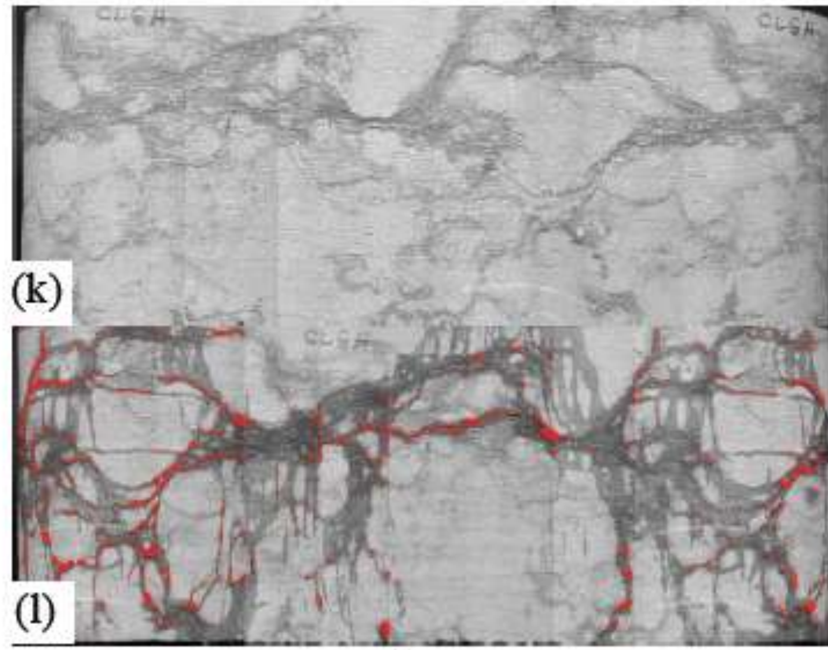


CL4H: $K_{SS} = 1.6E-16\,m^2$; D=85.0 mm H=120.4 mm

Failure Patterns of the Cobourg Limestone… contd.

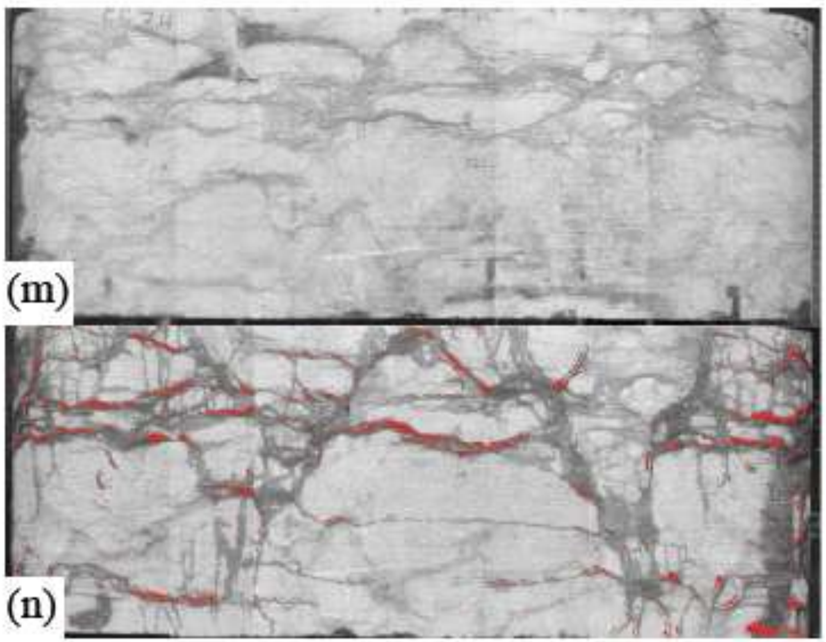


CL5H: $K_{ss} = 2.5E-18\,\mathrm{m}^2$; D=85.6 mm H=132 mm

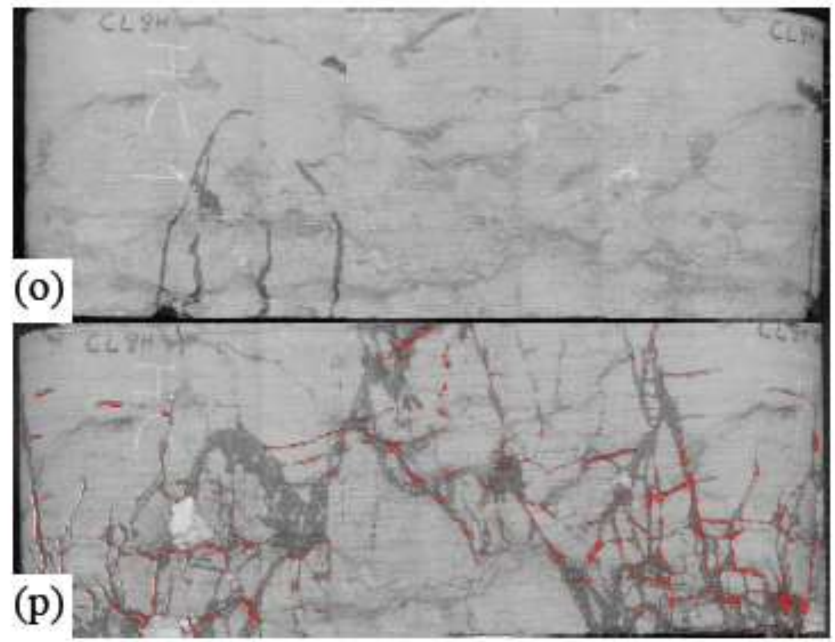


CL6H: $K_{ss} = 2.0E-17\,\mathrm{m}^2$; D=85.3 mm H=121.4

Failure Patterns of the Cobourg Limestone… contd.



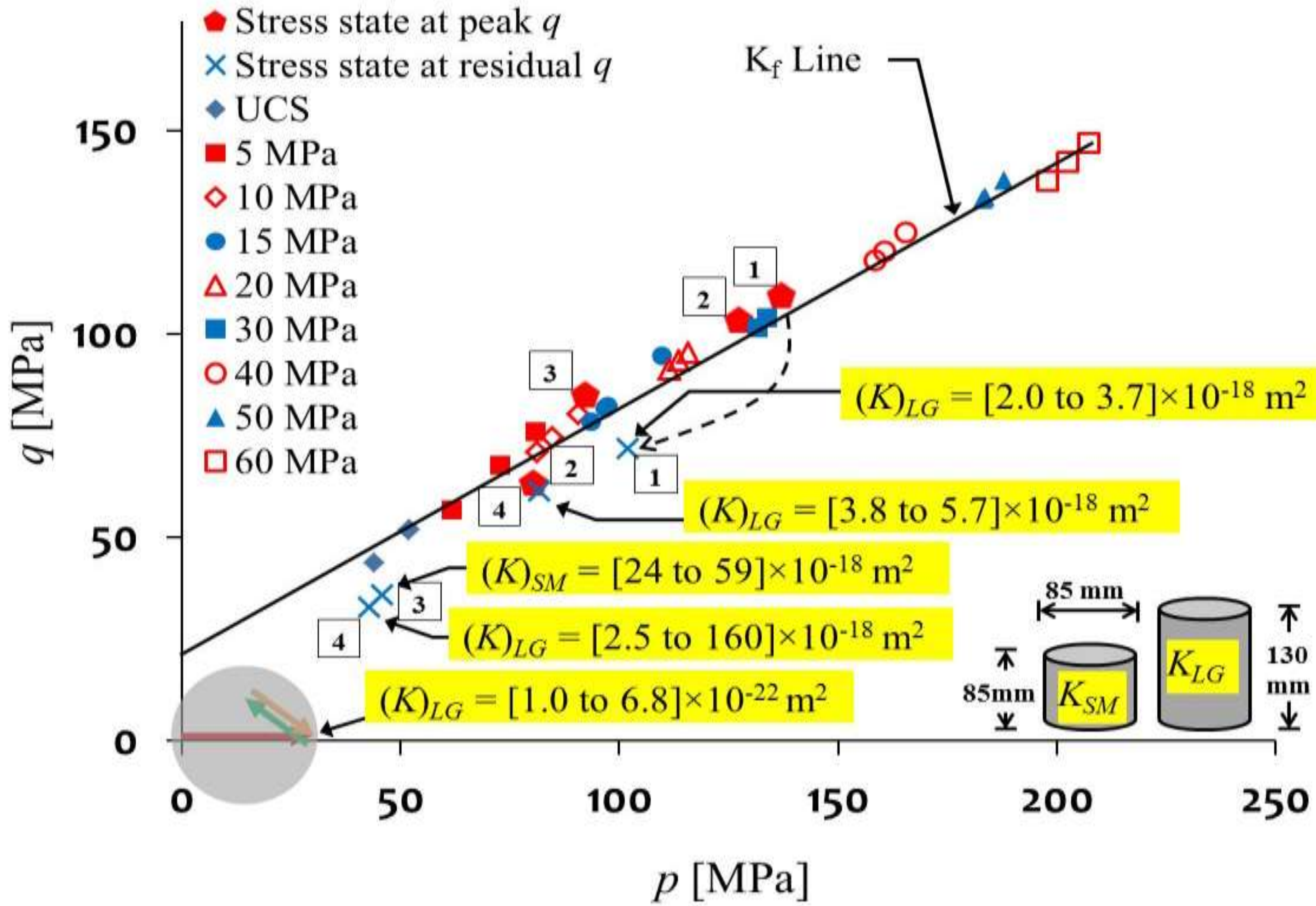
CL7H: $K_{PD} = 2.3\mathrm{E}-20\,\mathrm{m}^2$; D=85.3 mm H=121.4



CL8H: $K_{SS} = 5.7\mathrm{E}-18\,\mathrm{m}^2$; D=85.3 mm H=121.4

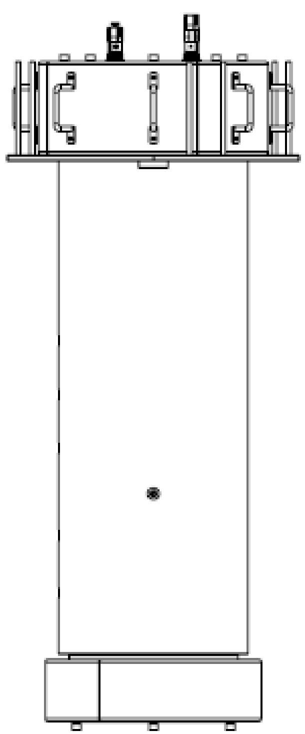
Failure Criterion for the Cobourg Limestone

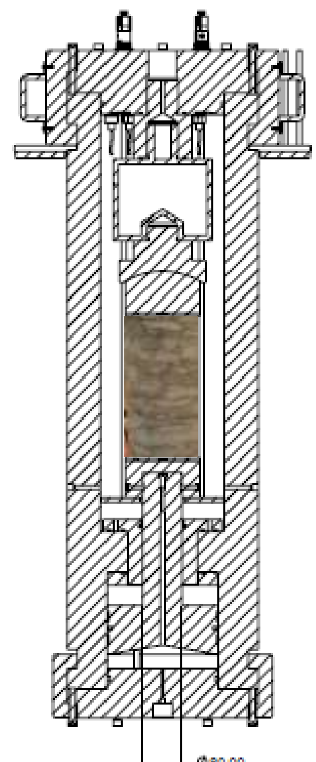
- **The permeability characteristics of the "failed" Cobourg Limestone are determined at a stress level "post- peak". Even at peak values the rock still maintains a low permeability.**



Large Specimen Triaxial Testing of the Cobourg Limestone-McGill EGL

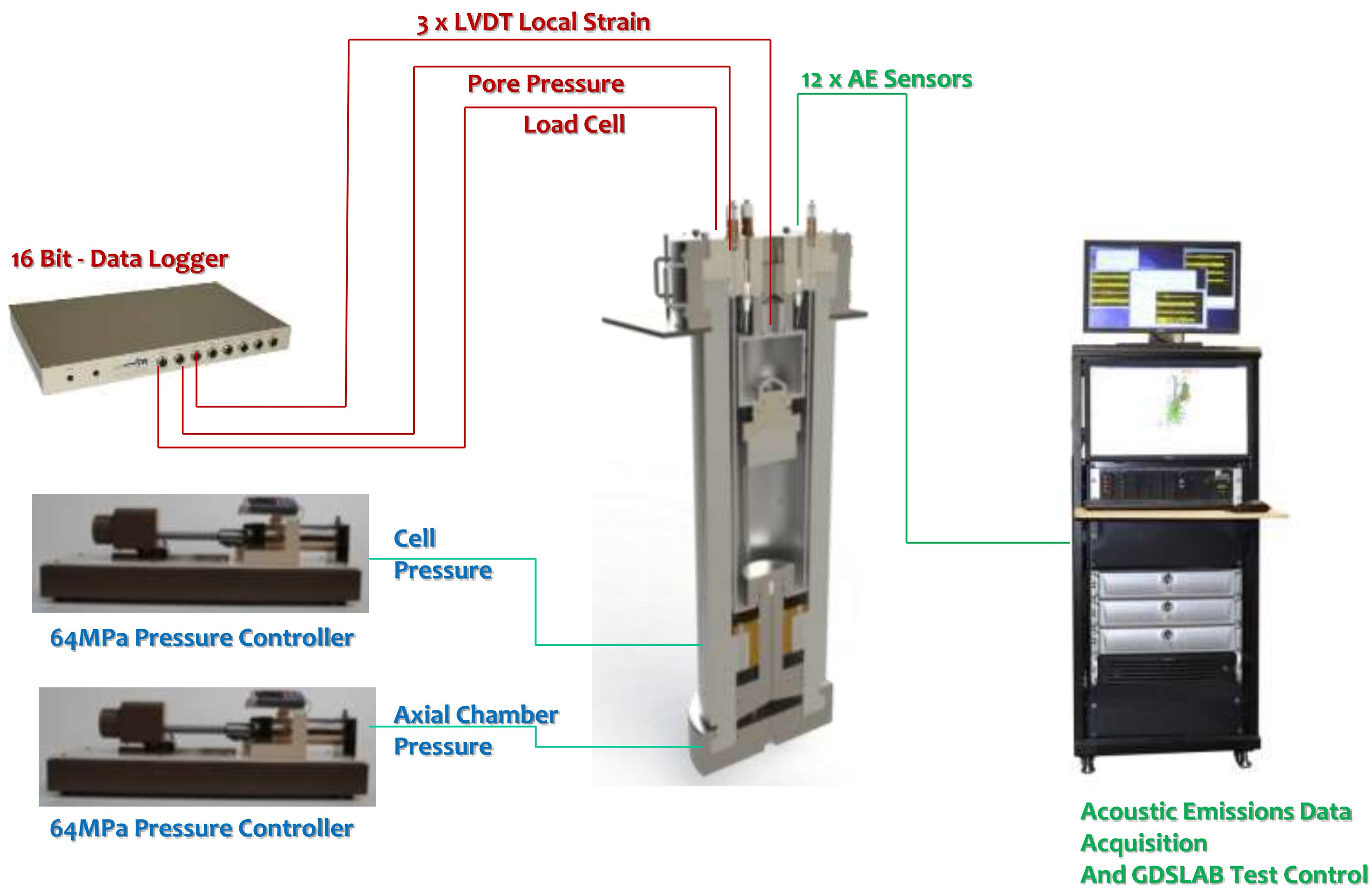
- Recent NWMO and NSERC Sponsored research efforts at the Environmental Geomechanics Laboratory at McGill are directed towards testing of large diameter triaxial specimens (150 mm diam. and 350 mm long.)





SECTION A-A

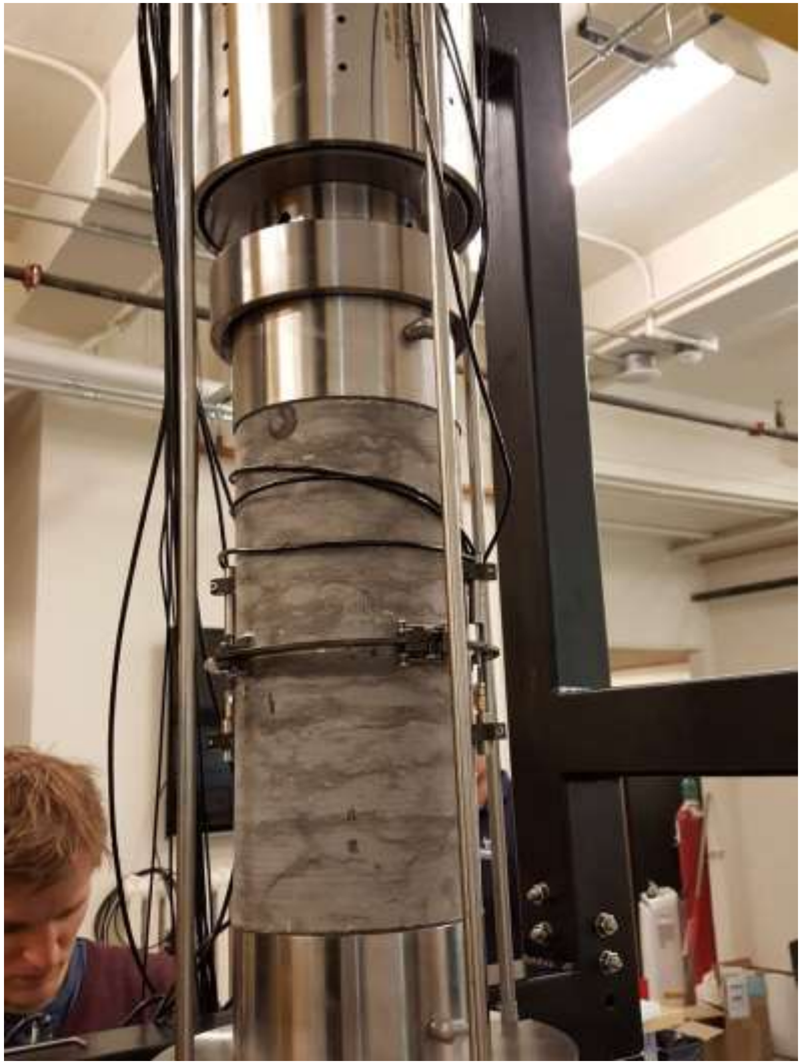
Large Specimen GDS Active Cell Triaxial Testing of the Cobourg Limestone-McGill EGL



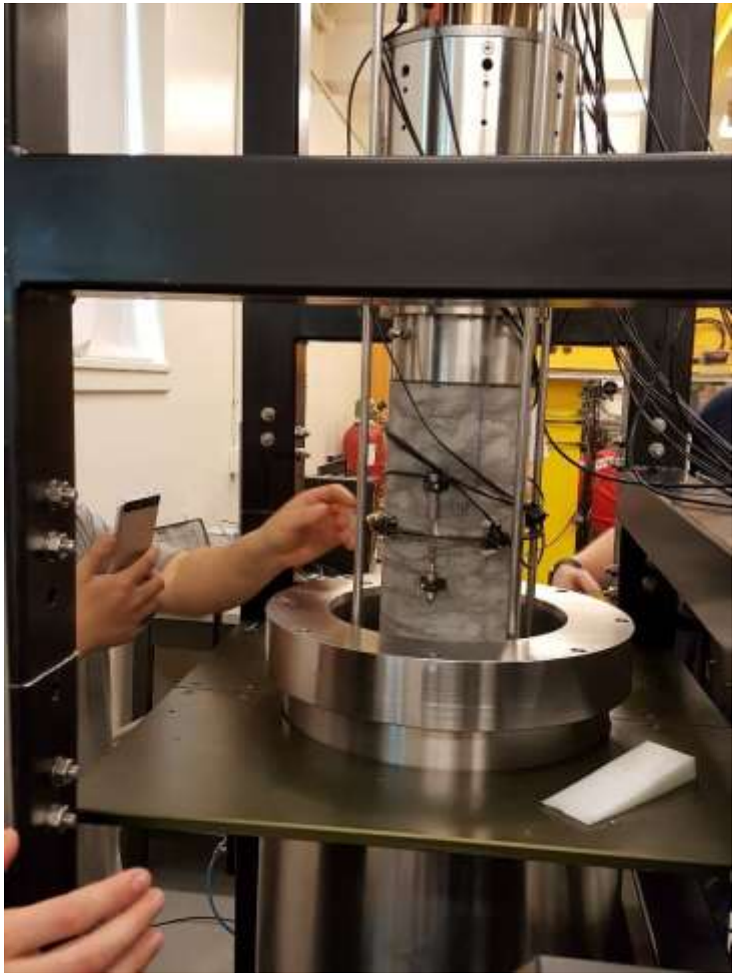
Large Specimen Triaxial Testing of the Cobourg Limestone-McGill EGL

- Recent NWMO and NSERC Sponsored research efforts at the Environmental Geomechanics Laboratory at McGill are directed towards testing of large diameter triaxial specimens (150 mm diam. and 350 mm long.)

Large Specimen Triaxial Testing of the Cobourg Limestone….contd.

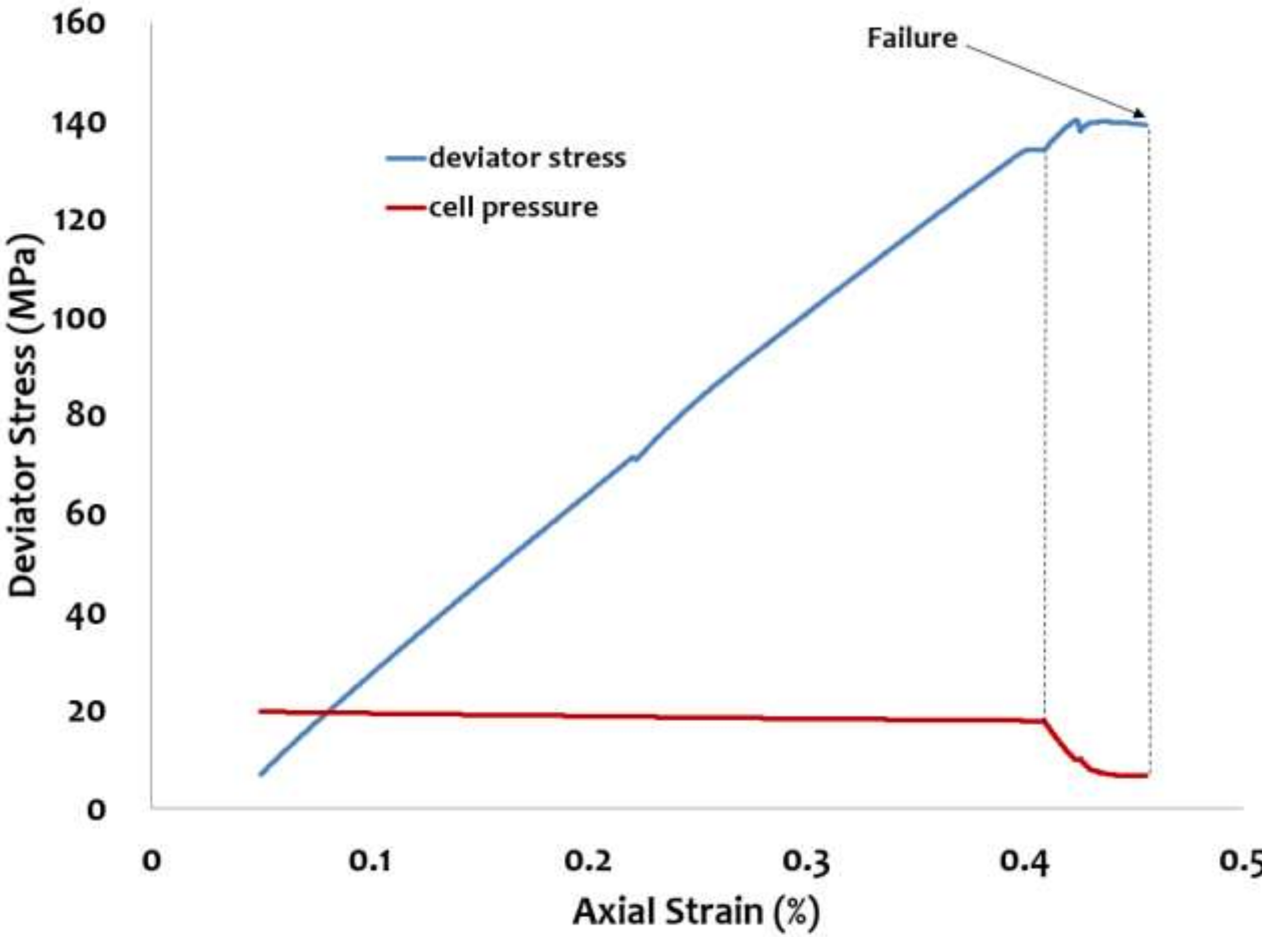


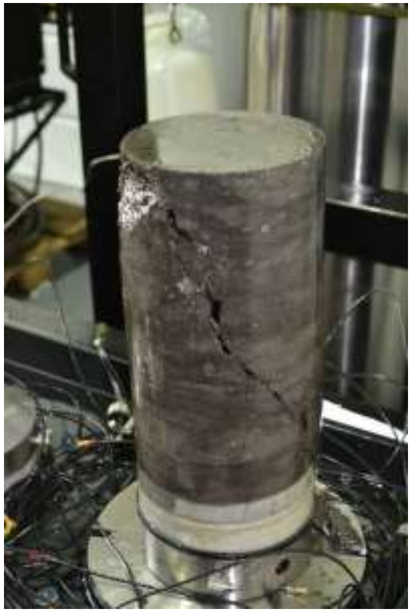
Large Specimen Triaxial Testing of the Cobourg Limestone….contd.



Large Specimen Triaxial Testing: Cobourg Limestone- Acoustic Emission Monitoring

Large Specimen Triaxial Testing: Cobourg Limestone- Preliminary Results





Concluding Remarks

- The Cobourg Limestone displays a dominant internal fabric, which could influence the evolution of permeability with stress. [*Species testing in progress*]
- The experiments confirm the possible increase in permeability with increase in isotropic compression [APSS et al. *EES*, 2011]

NWMO EdZ

$$K \in (1 \text{ to } 7)\mathrm{E}(-22)\ \mathrm{m}^2 \qquad [\mathrm{E}(-22)\ \mathrm{m}^2 \approx \mathrm{E}(-7)\mathrm{mD}]$$

- The Cobourg Limestone maintains its low permeability at stress states at/or close to the peak value. A moderate reduction in the deviator stress past the peak is sufficient to substantially increase the permeability.
- In this research, the permeability is interpreted as a SCALAR measure, determined from one-dimensional flow experiments (either hydraulic pulse tests in the pre-failed state or steady state flow in the fragmented state.) **NWMO EDZ** to **NWMO HDZ**

$$K \in (2 \text{ to } 160)\ \mathrm{E}(-18)\ \mathrm{m}^2 \qquad [\mathrm{E}(-18)\ \mathrm{m}^2 \approx \mathrm{E}(-3)\mathrm{mD}]$$

Concluding Remarks… contd.

- From a computational perspective, the ideal approach is to identify, in relation to a failure threshold for the Cobourg Limestone, initiated by

  (1) DGR construction,

  (ii) Thermal loadings (if any),

  (iii) Re-establishment of groundwater regime,

  (iv) Glaciation Scenarios, etc.,

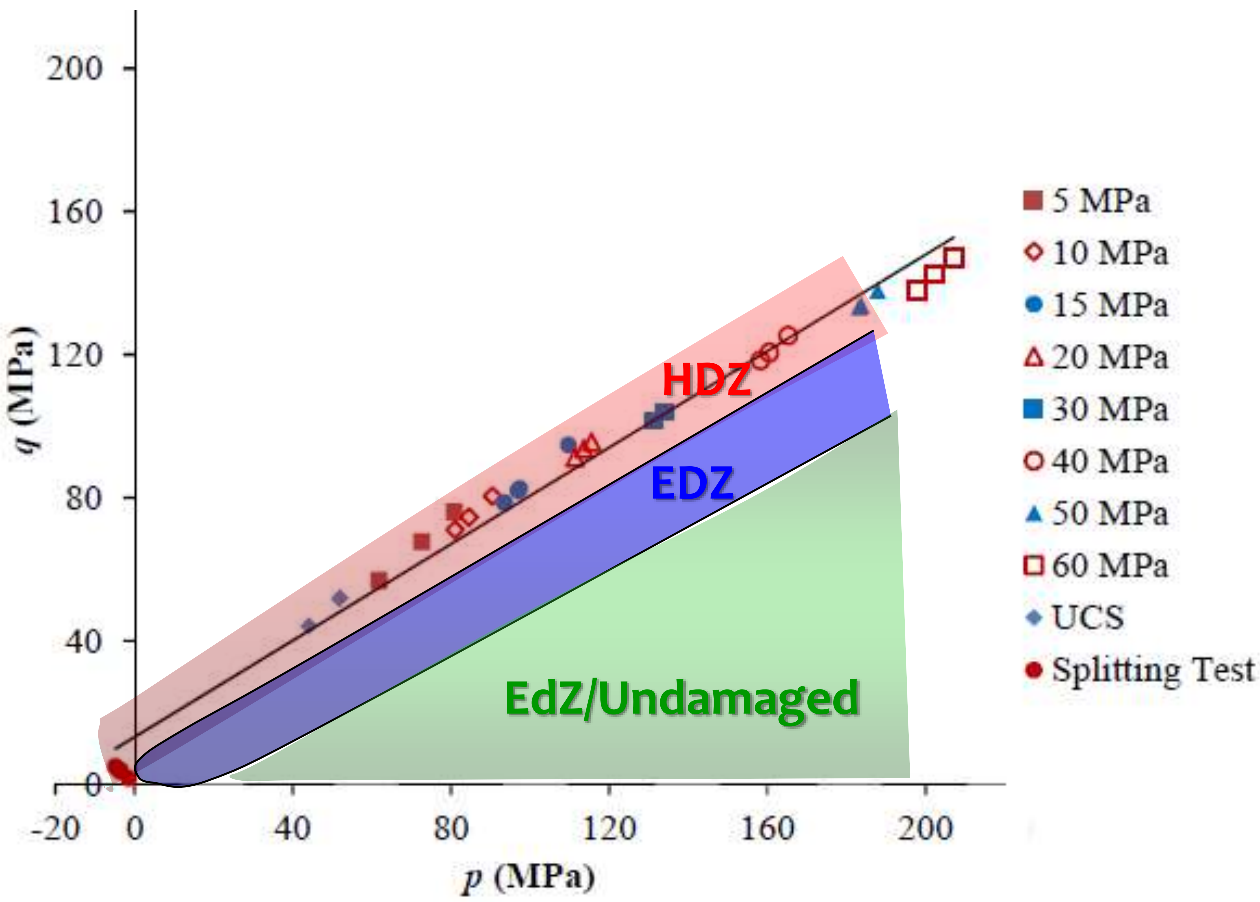
the regimes of the geological setting for which the THM properties are either unchanged or will undergo substantial alterations.

- **HDZ** : Changes to ALL THM Properties (K_D, G_D, n, α_T, α, K, c, k, ..)

- **EDZ:** Changes to CRITICAL THM parameters (K_D, G_D , α, K.....)

- **EdZ:** NOMINAL changes to THM Properties (K_D, G_D, n, α_T, α, K, c, k, ..)

Concluding Remarks… contd.



Acknowledgements

The participation of the *Graduate Students* and *Technical Staff* of the *Environmental Geomechanics Group :*

A. Głowacki, M. Najari, A. Letendre, P.A. Selvadurai,

B. Hekimi, L. Jenner, C. Couture, C. Cao, J. Bartczak

at McGill University is gratefully acknowledged. The research support was provided by *NWMO* and through *NSERC* (Discovery, Strategic and Research Tools) Grants and through the *James McGill Professorship*. The *NWMO Staff* (Mr. Mark Jensen and Mr. Tom Lam) provided valuable advice and critique.