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# Thermo-Poromechanics of Geologic Media

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**Williams Scott Professor* and *James McGill Professor*

# HM-Modelling

- The primary work in HM modelling is performed by considering geologic media within the framework of classical ; poroelasticity where pore space is fully occupied by either compressible or incompressible pore fluids.

- The modern basis for the continuum theory of poroelasticity originates with the work of Biot (*JAP* 1941). [see also articles by Yue and APSS, *IJES*, 1995; APSS *AMR*, 2007; the volumes by Coussy, *Poromechanics*, 1995; APSS, *Mech Poroelastic Media*, 1996; Lewis and Schrefler, *The FEM in …* 1998; Ehlers and Bluhm, *Porous Media*, 2002; and the Proceedings of the *Biot Conferences on Poromechanics*; the 2017 meeting in Paris.]

- The theory has also been re-derived by appeal to the continuum theory of mixtures [Bowen, *ARMA* 1976; Atkin and Craine, *QJMAM* 1979; Auriault et al., *IJES* 2002 ; Coussy, *IJSS* 2005].

# THM-Modelling

- The classical theory of Thermo-Poroelasticity extends Biot's classical model to include the coupled processes of mechanical deformations, heat flow and fluid transport in a porous elastic medium.

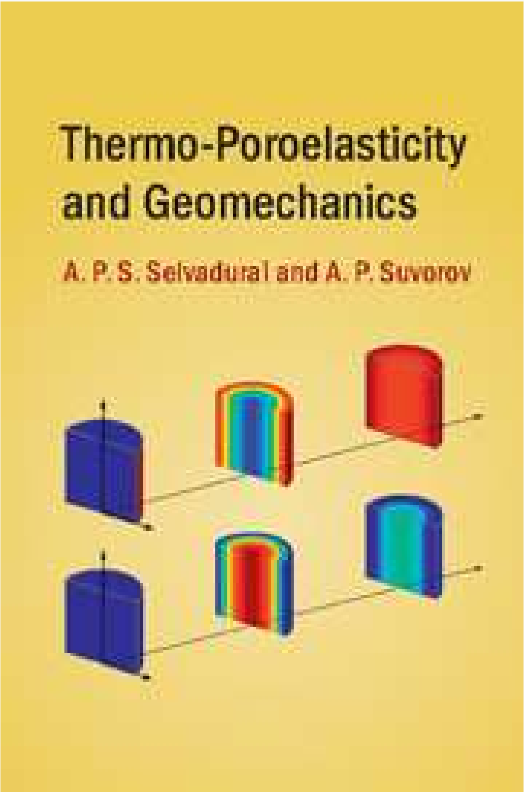
- The dependent variables in the developments are the displacements $\mathbf{u}(\mathbf{x},\mathbf{t})$ of the porous skeleton, the representative temperature field $T(\mathbf{x},\mathbf{t})$ at a point in the entire porous medium and the fluid pressure $p(\mathbf{x},\mathbf{t})$ in the pore space.

- More sophisticated double-porosity THM models (e.g. Fractured Media) are also available in the literature [see e.g. Khalili and APSS, *GRL* 2003], but the basic model is an extension of Biot's model to include thermal effects.

# THM-Modelling

- **A recent volume in THM Modelling is by APSS and Suvorov, *Thermo-Poroelasticity and Geomechanics*, Cambridge University Press, 2016.**
- **Professor *James R. Rice*, *Mallinckrodt Professor of Engineering Sciences and Geophysics* at *Harvard University* offers the following evaluation:**

***"Selvadurai and Suvorov provide a thorough and rigorous introduction to the foundations of thermo-poro-mechanics of fluid-infiltrated elastic media, focused on geophysical and geotechnical applications. Fundamental analytical solutions are derived for simple geometries (cylinders, spheres) and compared to results of popular computational methodologies, with results serving as basis for application to key current areas of geoscience and geotechnology."***



# THM Background

- **Computational approaches have been the backbone of several initiatives related to validation of concepts for deep geologic storage of high-level heat emitting nuclear wastes; e.g. performance prediction for large time scales. [DECOVALEX]**

- **The computational models should, in general, be capable of addressing coupled effects of**

  **Heat transfer in the saturated medium (T)**

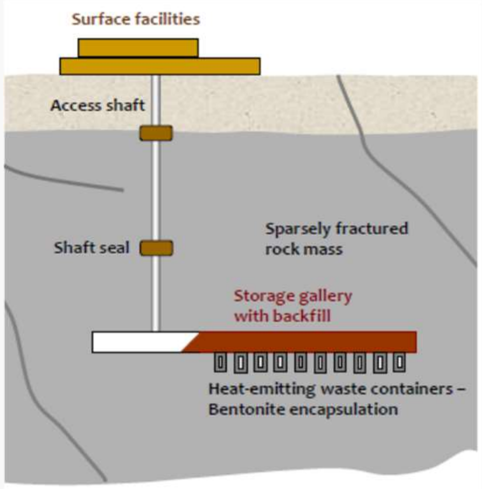
  **Fluid transport in the pore space (H)**

  **Mechanical deformations of the porous fabric (M)**

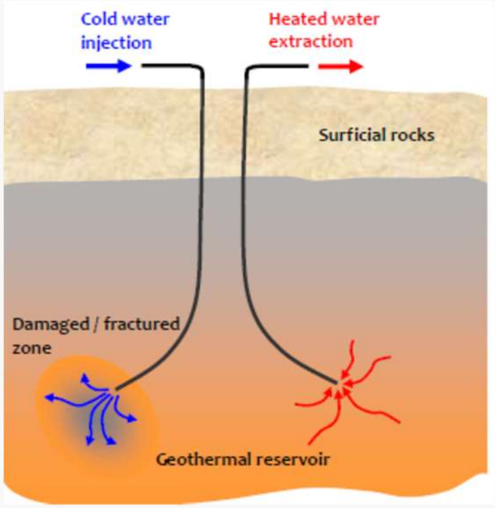
- **The advances in this area are summarized in a number of articles: APSS and Nguyen *C&G* (1995), Stephansson et al. *IJRMMS* (2004) Rutqvist et al. *IJRMMS* (2005), Belotserkovets and Prevost *IJES* (2011), APSS and Suvorov *Proc Roy Soc A* (2012, 2014); APSS, *Ch 20, Handbook of Porous Media (Ed. K. Vafai)* (2015).**

# THM: Areas of Application

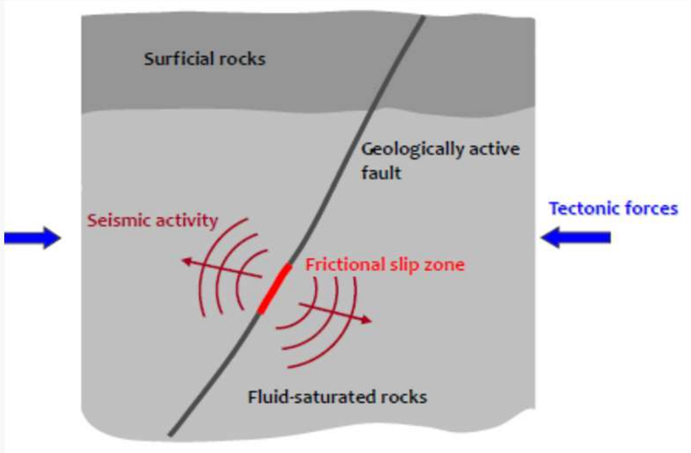
- **THM behaviour is prominently featured in a number of areas of geomechanics and geosciences:**



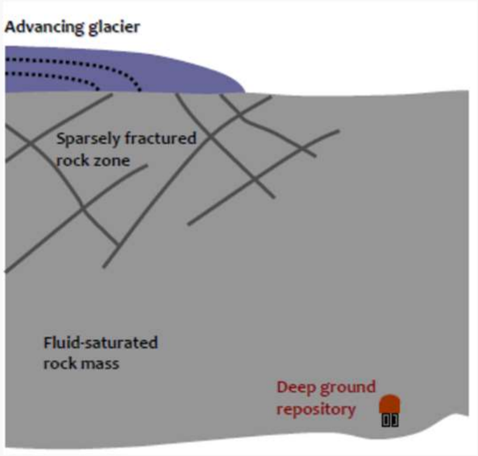

**Geologic Disposal of HL-NFW**




**Geothermal Energy Extraction**



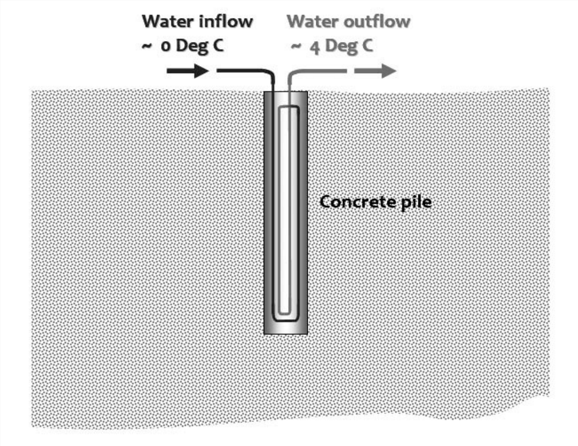

**Heat Generation During Fault Rupture**



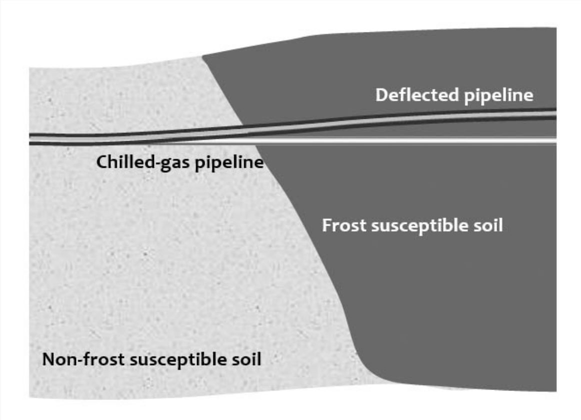

**Glacial Loading of Sequestered sites**

# THM: Areas of Application … contd.

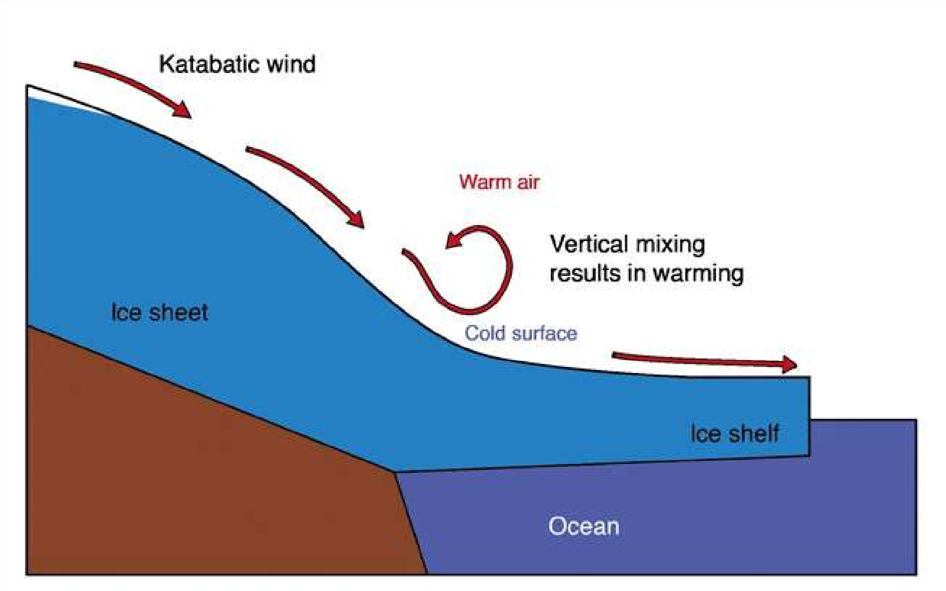
- **THM problems in geo-environmental applications:**




Ground-source heat extraction



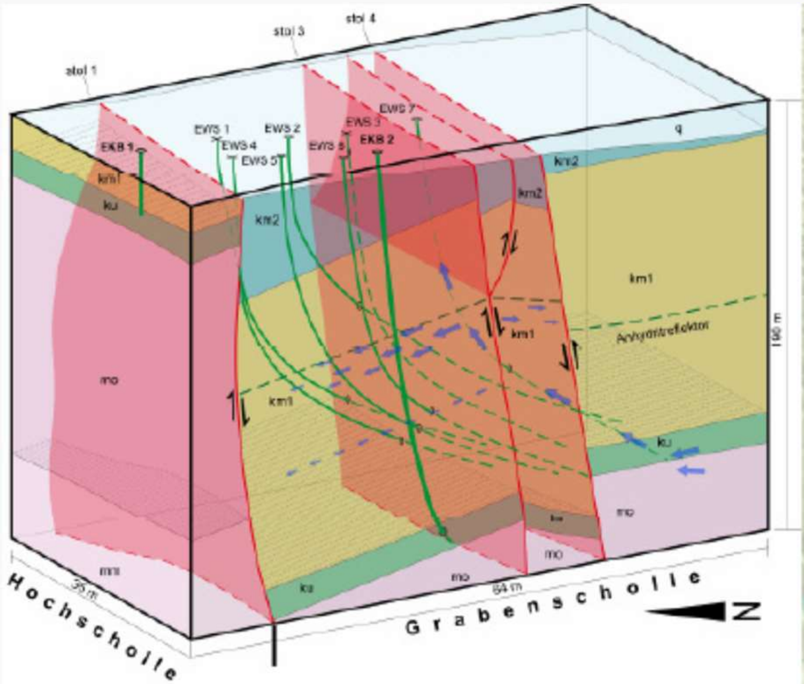

Soil-chilled gas pipeline interaction

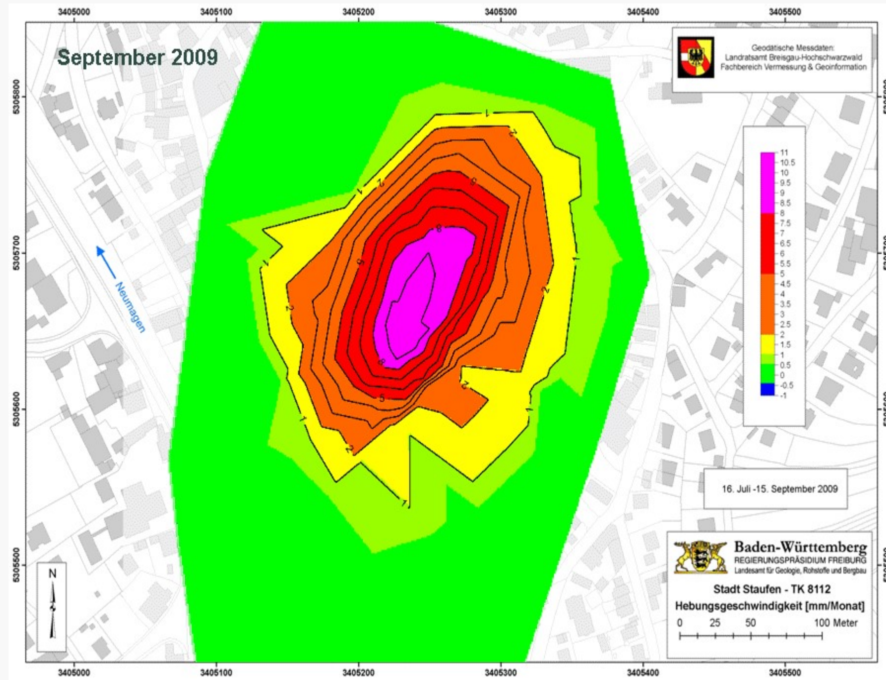



Melting of the Antarctic Ice Sheet- Meltwater Lakes

# THMC: Areas of Application … contd.

- THMC problems in geo-environmental applications:




**Extraction of Geothermal Energy from Deep Groundwater [Staufen im Breisgau, Germany]**

**Ground Heave due to Conversion of Anhydrite to Gypsum**

# THM-Modelling… contd

- The constitutive responses governing the elastic deformations of the porous skeleton, the fluid transport in the porous space and the heat conduction in the system are governed by the Duhamel-Neumann-Biot form of Hooke's law, Darcy's law (relative motion) and Fourier's law:

$$\boldsymbol{\sigma} = G(\nabla \mathbf{u} + \mathbf{u}\nabla) + (\lambda \nabla . \mathbf{u} - \beta K_D)\mathbf{I} + \left(1 - \frac{K_D}{K_s}\right) p \mathbf{I} \quad (1)$$

$$\mathbf{v}_f - \mathbf{v}_s = -\frac{K}{\eta}\left(\nabla p + \rho_f \mathbf{g}\right) \quad (2)$$

$$\mathbf{q} = -\kappa \nabla T \quad (3)$$

- The justification for considering conductive heat transfer is linked to the *Peclet Number* in a particular application:

$$Pe = (Re)(Pr) = \frac{Adv\ Transp\ Rate}{Diff\ Transp\ Rate} = \frac{L\|\mathbf{v}\|}{\alpha}; \ \alpha = \frac{\kappa}{\rho c_p} \quad (4)$$

i.e. $Pe << 1$

# THM-Modelling… contd

- The combination of these constitutive responses with the balance laws gives rise to the following system of weakly coupled partial differential equations governing the dependent variables:

$$\alpha_1 \nabla^2 \mathbf{u} + \alpha_2 \nabla(\nabla.\mathbf{u}) + \alpha_3 \nabla p + \alpha_4 \nabla T = \alpha_5 \mathbf{f} \quad (5)$$

$$\beta_1 \nabla^2 p = \beta_3 \frac{\partial p}{\partial t} + \beta_4 \frac{\partial T}{\partial t} + \beta_5 \frac{\partial}{\partial t}(\nabla.\mathbf{u}) \quad (6)$$

$$\gamma_1 \nabla^2 T = \gamma_2 \frac{\partial T}{\partial t} \quad (7)$$

where $\alpha_n$, $\beta_n$ and $\gamma_n$ are material parameters.

- When these material parameters are functions of the dependent variables themselves, the problem is non-linear: i.e.

$$\alpha_n = \alpha_n(\mathbf{u}, p, T) \quad ; \quad \beta_n = \beta_n(\mathbf{u}, p, T) \quad ; \quad \gamma_n = \gamma_n(\mathbf{u}, p, T) \quad (8)$$

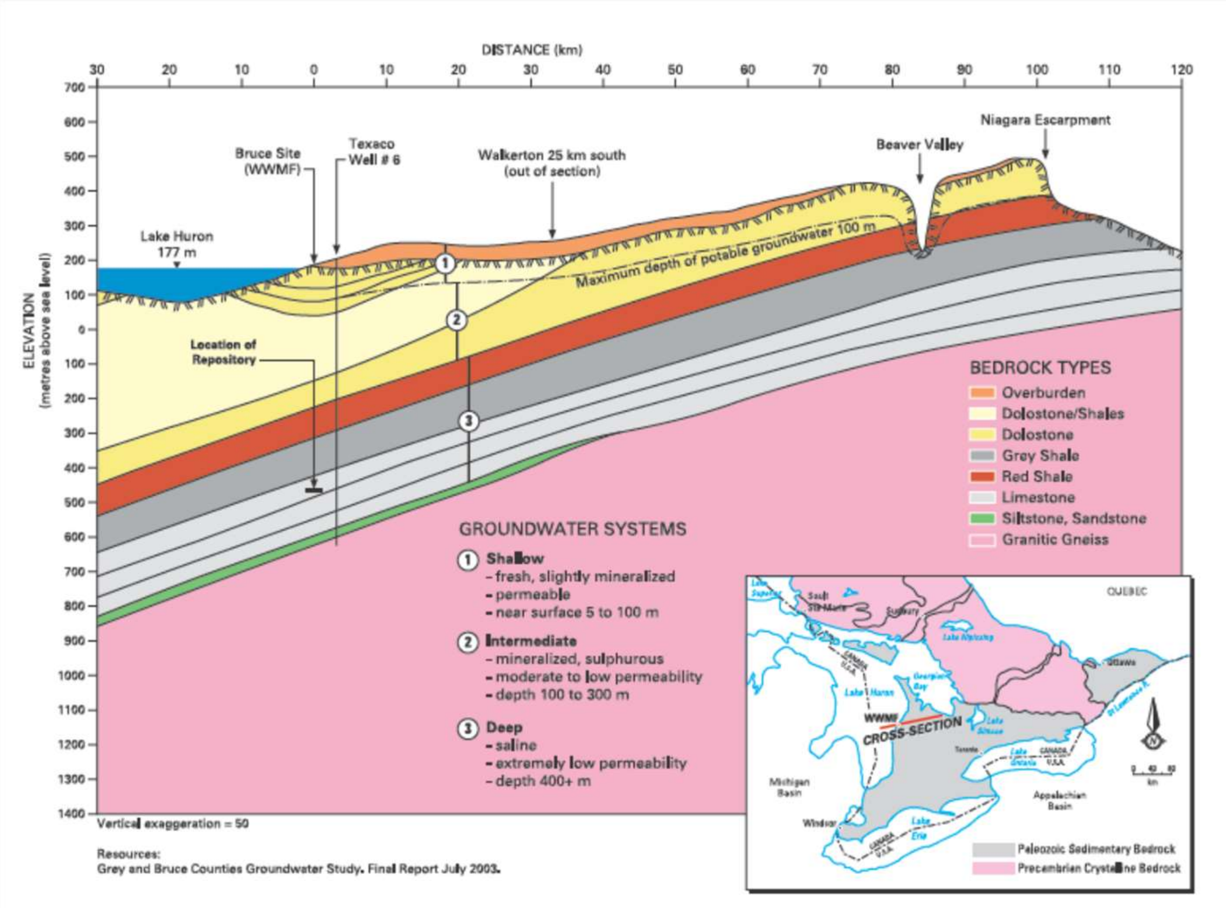
and, in general, there are no assurances of even the existence of a solution.

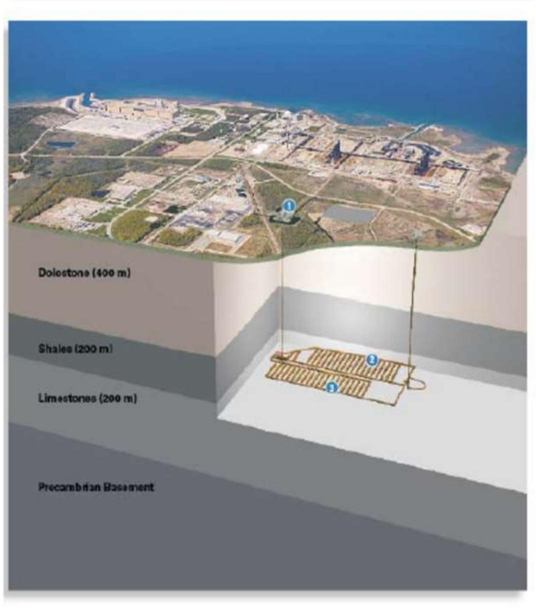
# An Application

- The objective of the THM research was to develop a bench-scale experimental configuration that can be used to assess the predictive capabilities of the weakly coupled THM formulation.
- Heating of a fluid-saturated domain and measurement of temperature fields is non-conclusive (i.e. The process is pure heat conduction.)
- Heating of a fluid saturated medium and measuring deformations of the region is also non-conclusive (i.e. The process is purely thermo-elastic.)
- The only available option is to measure pore fluid generation in the rock, during heating. *This is easier said than done…!* The strategy is to create a "*Fluid Inclusion*" within the rock and to measure its response to heating.

# Relevance of the Application

- **The rock that will be used in the bench-scale THM testing is obtained from the same geological formation that is targeted 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)**



# The Experimental Approach

- The rock is the Cobourg Limestone, which is classified as an argillaceous, dolomitic, calcitic limestone found in the middle Ordovician Limestone of the Paleozoic sequence in southern Ontario, within the Appalachian and Michigan Basins.

- The Lower Cobourg formation consists of a mottled light to dark gray, very fine-to coarse grained, fossiliferous, bluish-grey to grey-brown argillaceous limestone. These features have been observed and are well documented in the literature*.

- The formation has very consistent lateral continuity and in the Appalachian Basin an outcrop of the formation is accessible at the Saint Mary's Cement, Quarry in Bowmanville, ON.

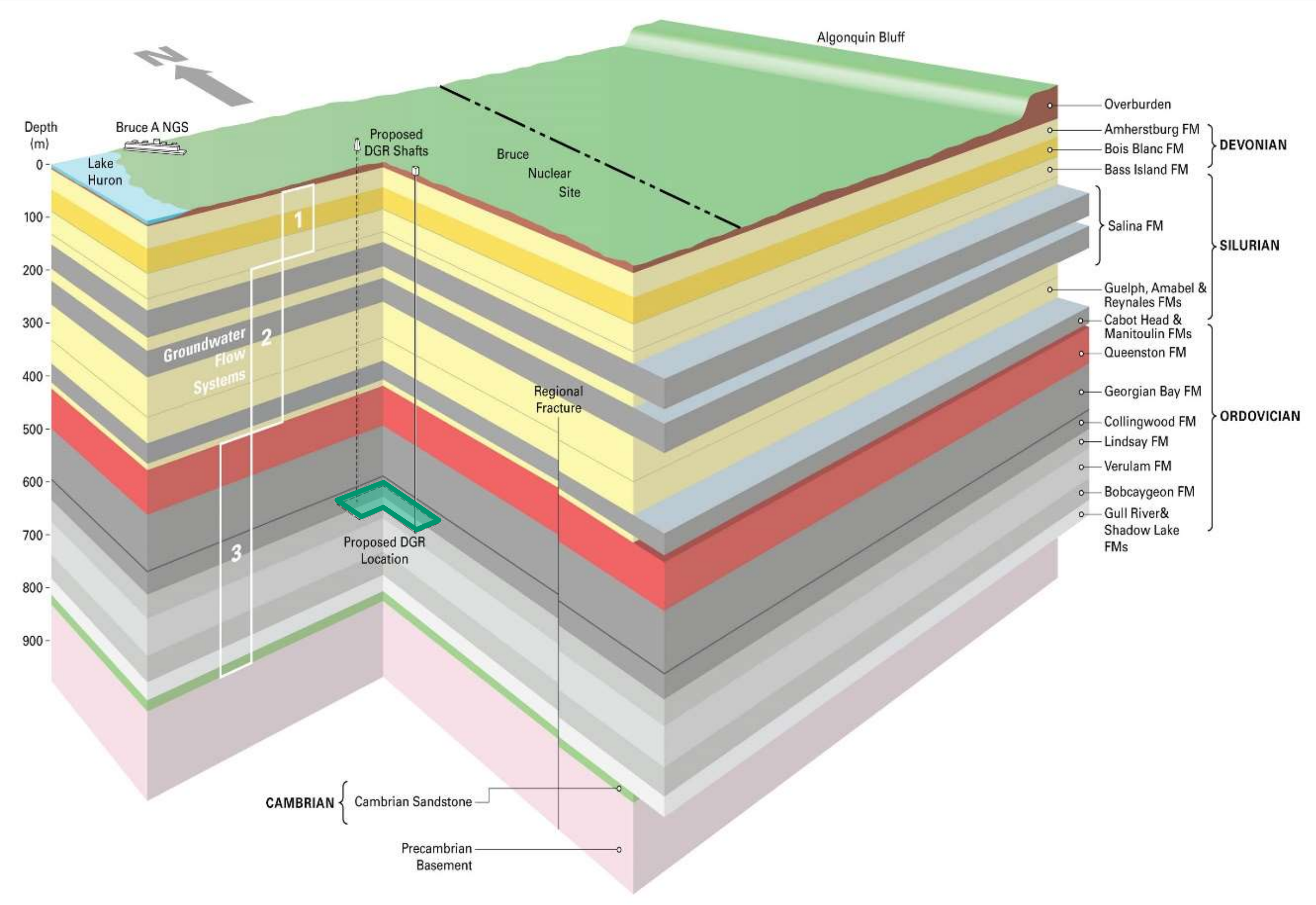
[*Golder Assoc 2003; Mazurek, *TR-Univ Bern*, 2007; Vilks and Miller, *NWMO*, 2007; Lam et al., *OPG Rep*., 2007; Gartner Lee, *OPG Rep*. 2008; APSS et al., *Environ. Earth Sciences*., 2011 ; APSS and Jenner, *Ground Water*, 2012; APSS *NWMO Rep*, 2017]

# Block Sample Retrieval

- **Two cuboidal block samples of the Cobourg Limestone (large block: ~ 2.16m across and ~ 1.016 thick; smaller block: 1 m across and ~0.7 m thick; total weight ~ 11 metric tons).**

# The Choice of the Cobourg Limestone

- **The Cobourg Limestone is encountered at site that is proposed by NWMO for the construction of a Deep Ground Repository for the storage of Low- and Intermediate-Level Nuclear Waste.**



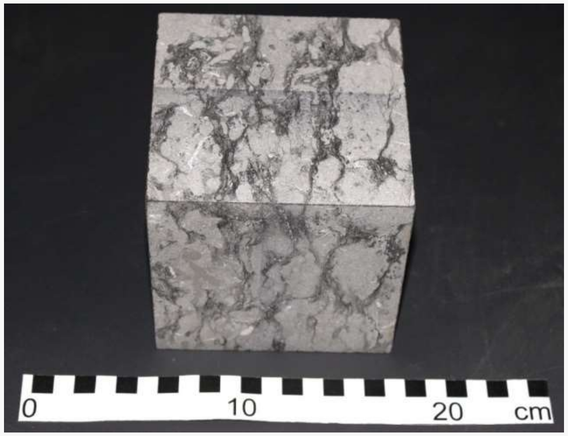
# Fabric, Heterogeneity and Stratification

- The surface fabric of Cobourg Limestone indicates the presence of both heterogeneity and stratification.

406 mm Cuboidal Sample -Surface Dry

406 mm Cuboidal Sample-Surface Moist

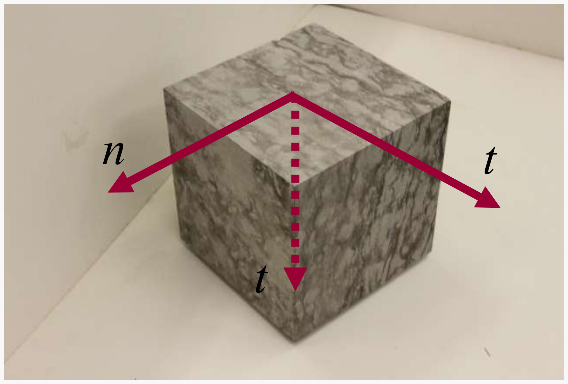

130 mm Cuboidal Sample – 45°




130 mm Cuboidal Sample – 0°

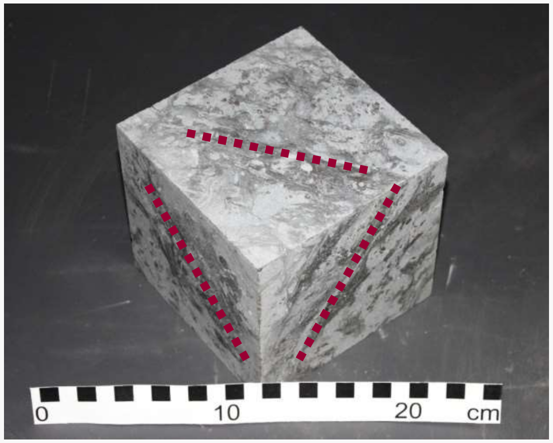
# Fabric, Heterogeneity and Stratification

- The surface fabric of Cobourg Limestone indicates the presence of both heterogeneity and stratification.

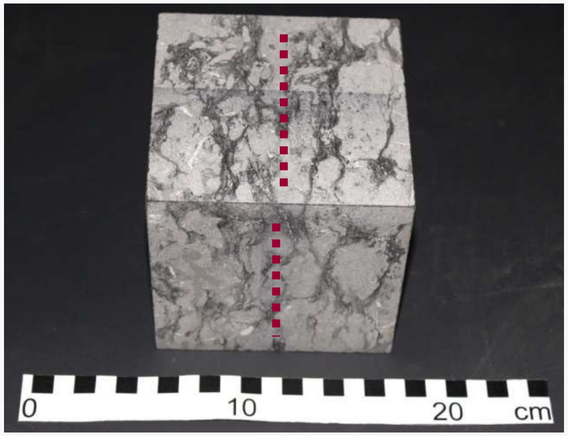



406 mm Cuboidal Sample -Surface Dry

406 mm Cuboidal Sample-Surface Moist




130 mm Cuboidal Sample – $45^{0}$

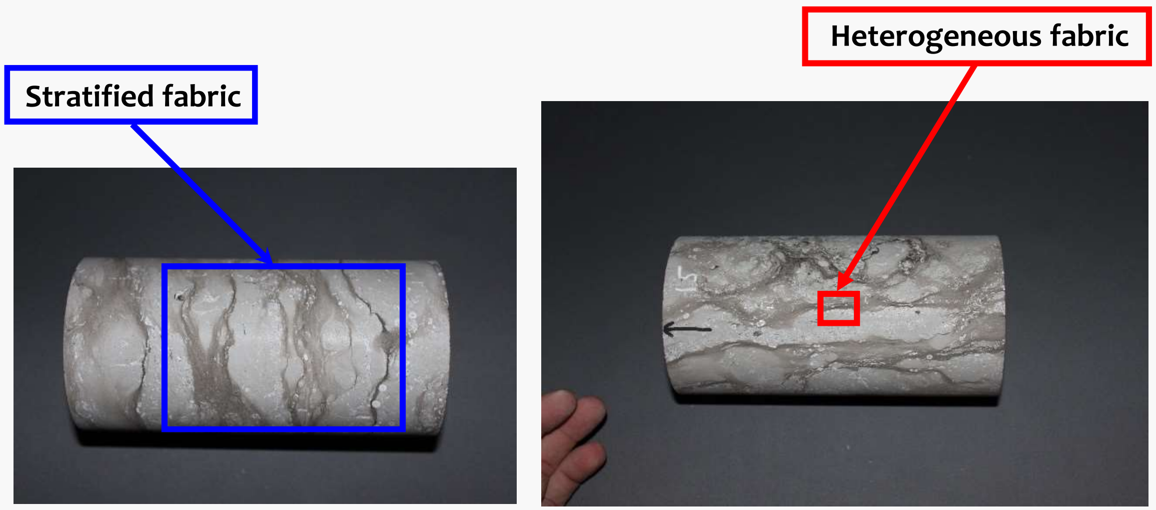



130 mm Cuboidal Sample – $0^{0}$

# Fabric, Heterogeneity and Stratification… .contd.

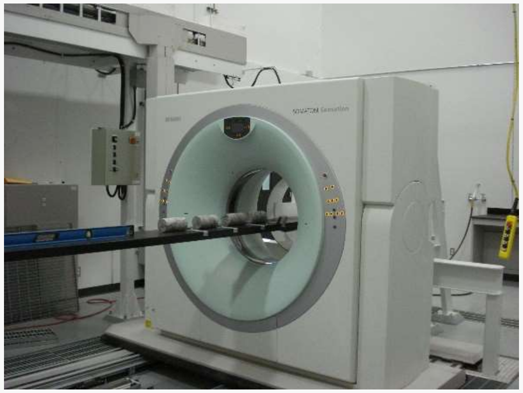
- Any experimentation of a heterogeneous geomaterial has to address the influence of scale in order to interpret the results in a meaningful way.

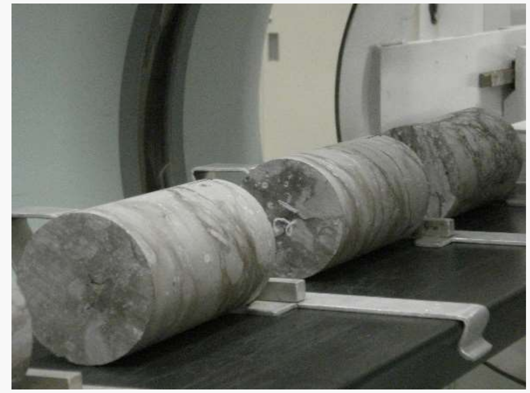
- One approach is to consider sufficiently large Representative Volume Elements so that the influence of the fabric is accounted for within the average estimates (i.e. no scale effects in bench-scale testing).

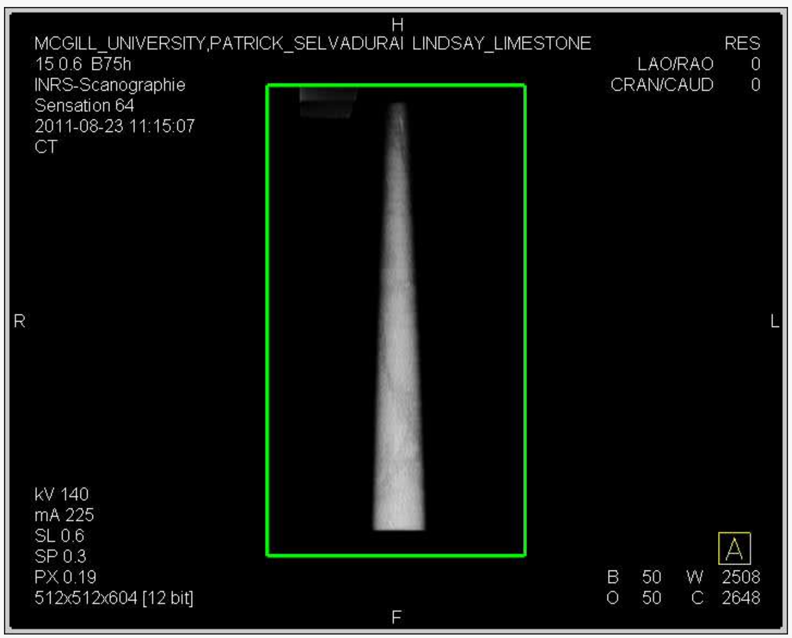


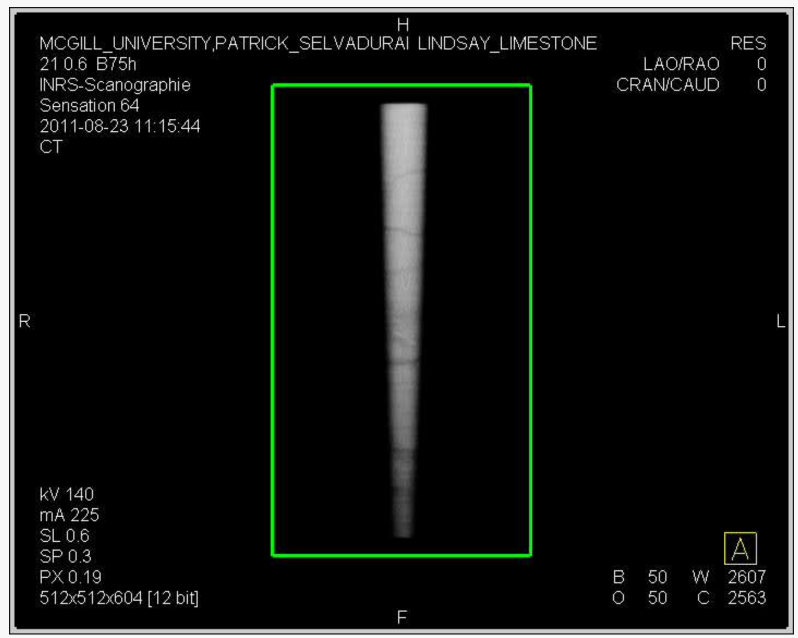

The Cobourg Limestone Cores- 85 mm diameter

# Internal Fabric of the Cobourg Limestone*



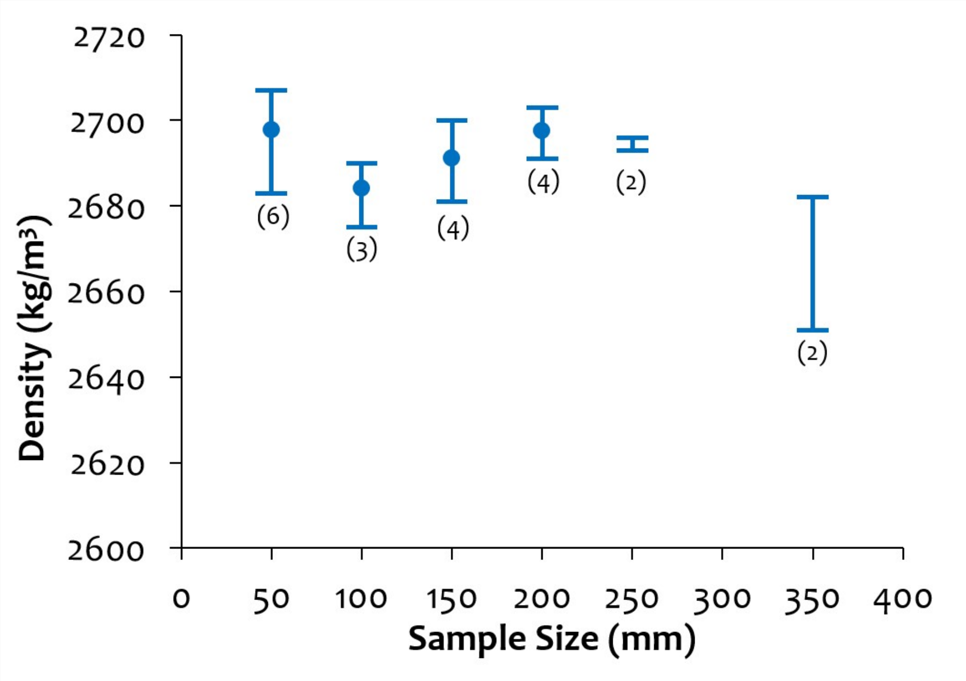


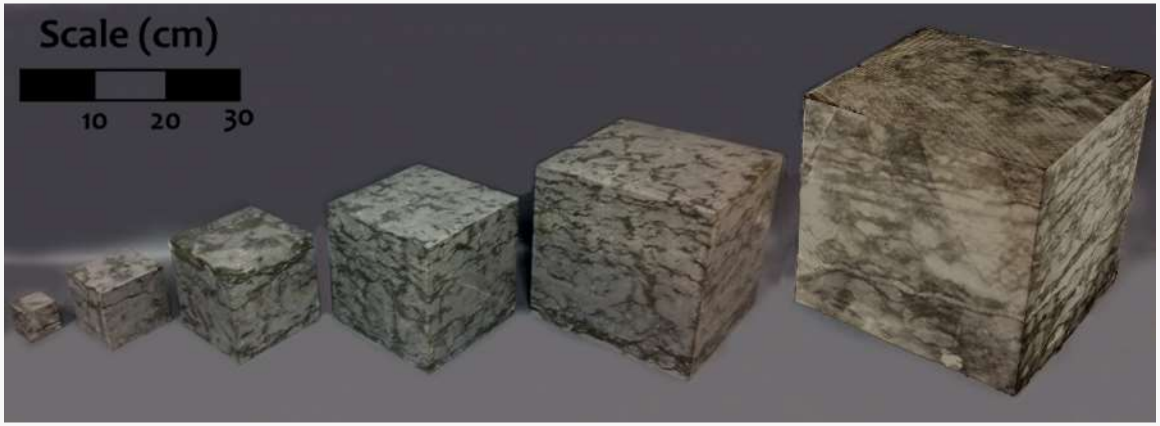


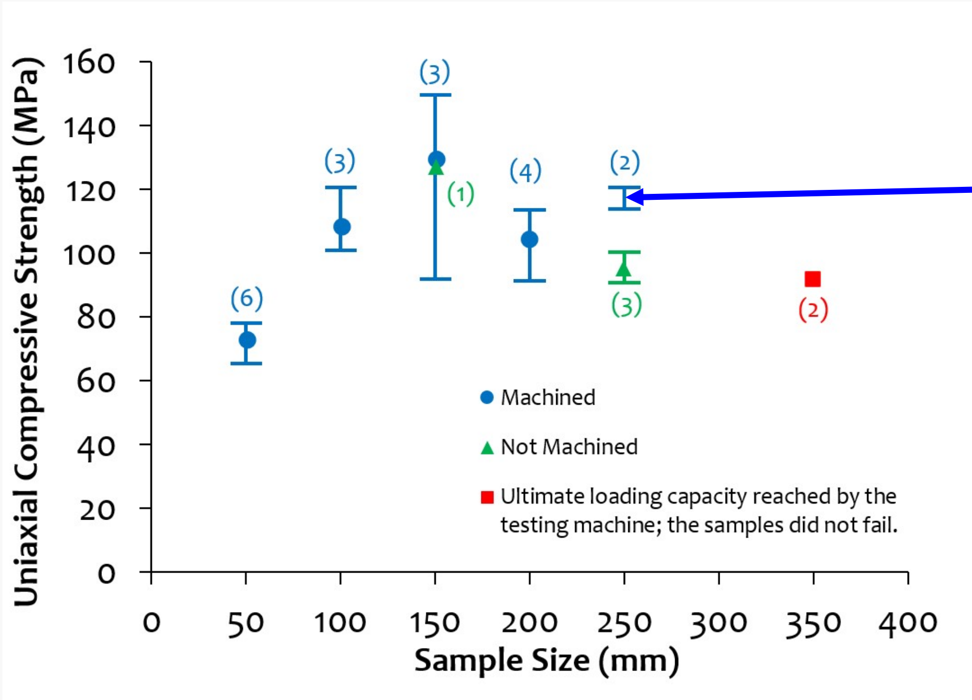

*CT Scans Performed at the Research Facility at INRS-ETE, QC.

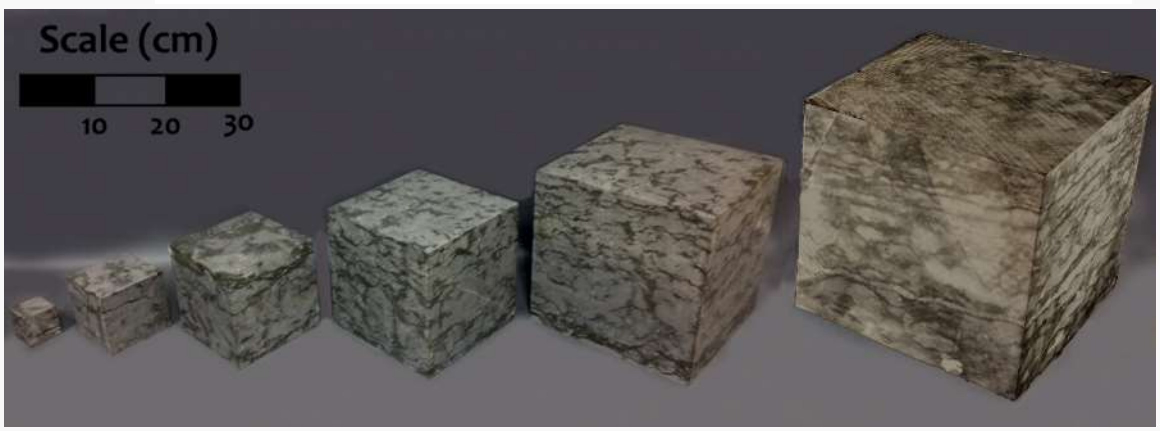
# Influences of Scale: Density of the Cobourg Limestone (May 2015)



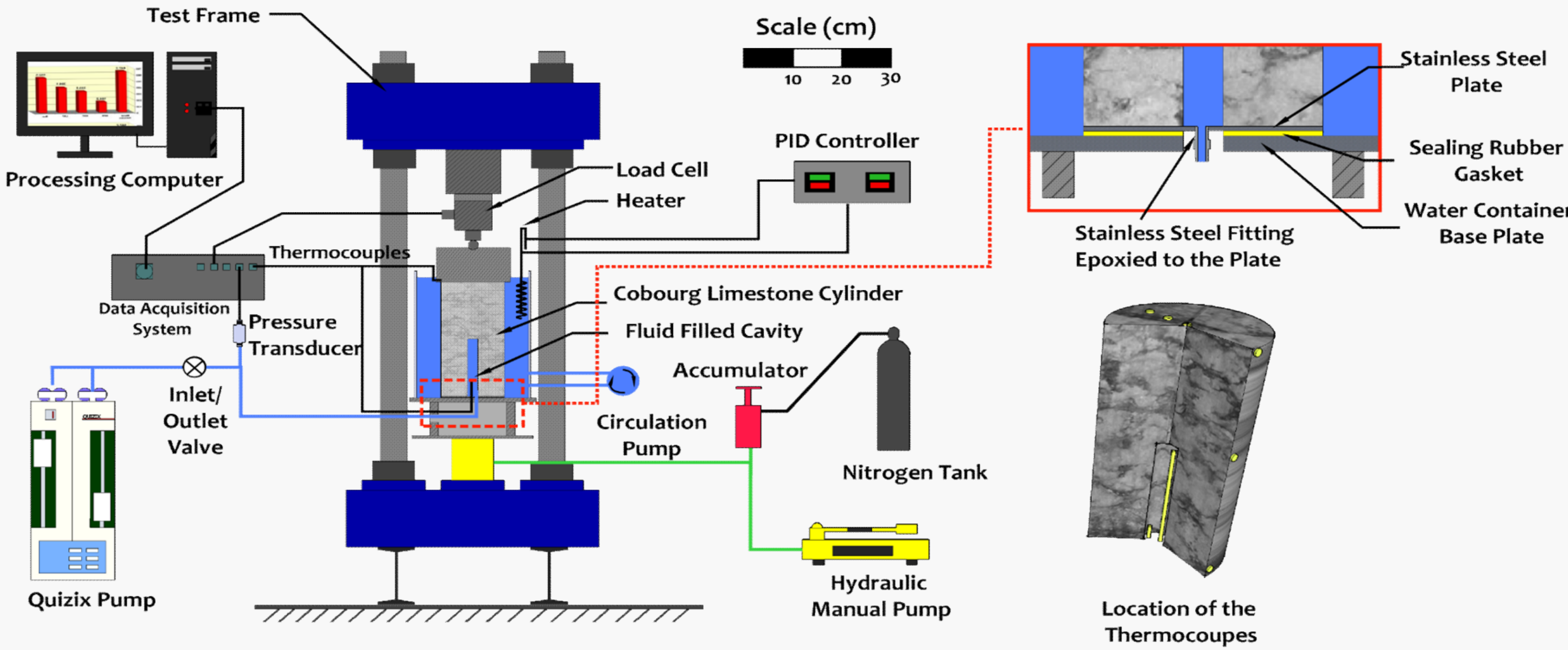
# Influences of Scale: Cube Strength of the Cobourg Limestone (May , 2015)



# Cobourg Limestone THM Experiment

- The Cobourg Limestone sample used in the THM Research Program was 150 mm in diameter and 300 mm in length.
- The axis of the cylinder is NORMAL to the nominal planes of the argillaceous partings.
- The axis of the cylinder contains a *partially drilled cylindrical cavity,* which is fluid-filled .



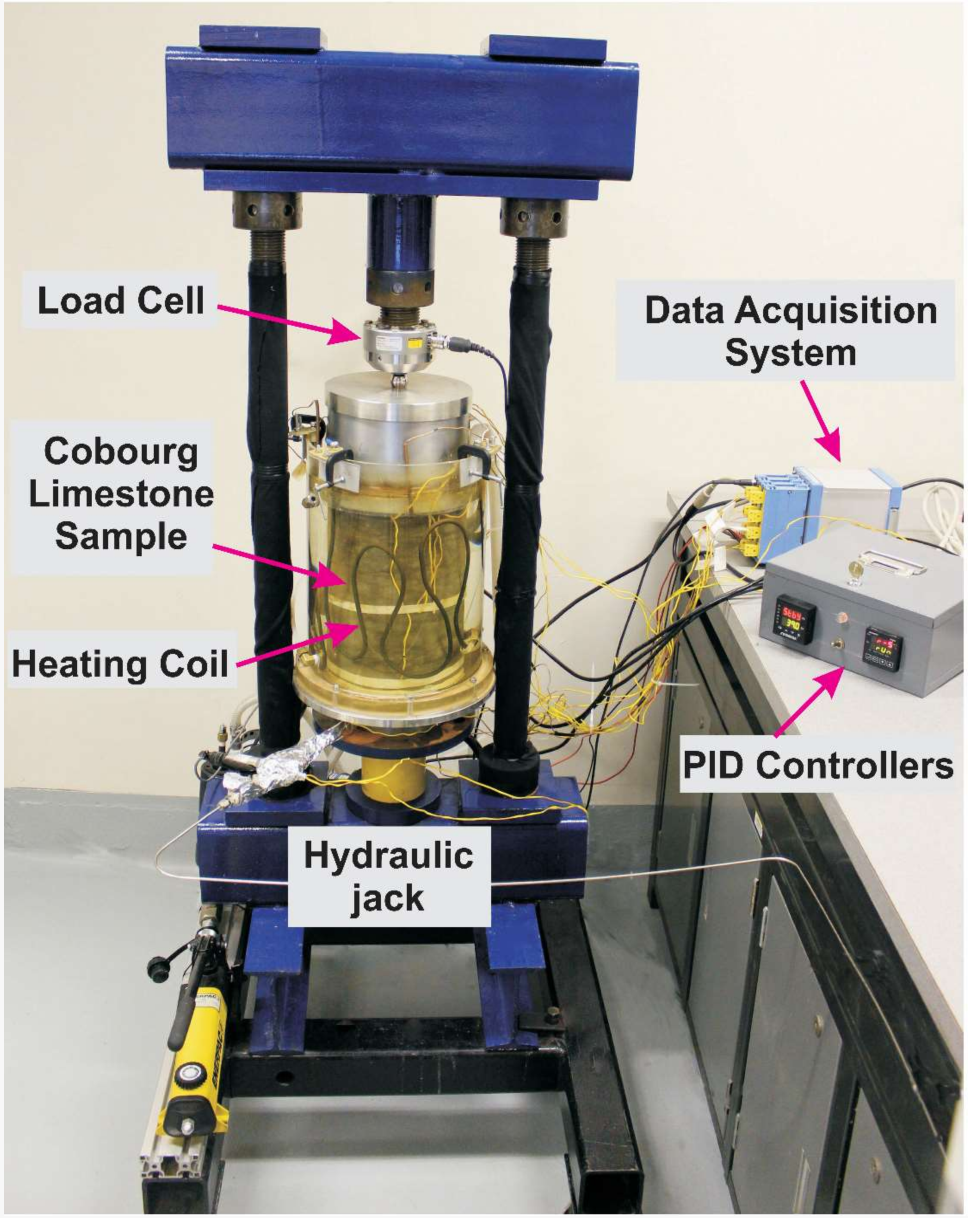
# Cobourg Limestone THM Experiment… contd.

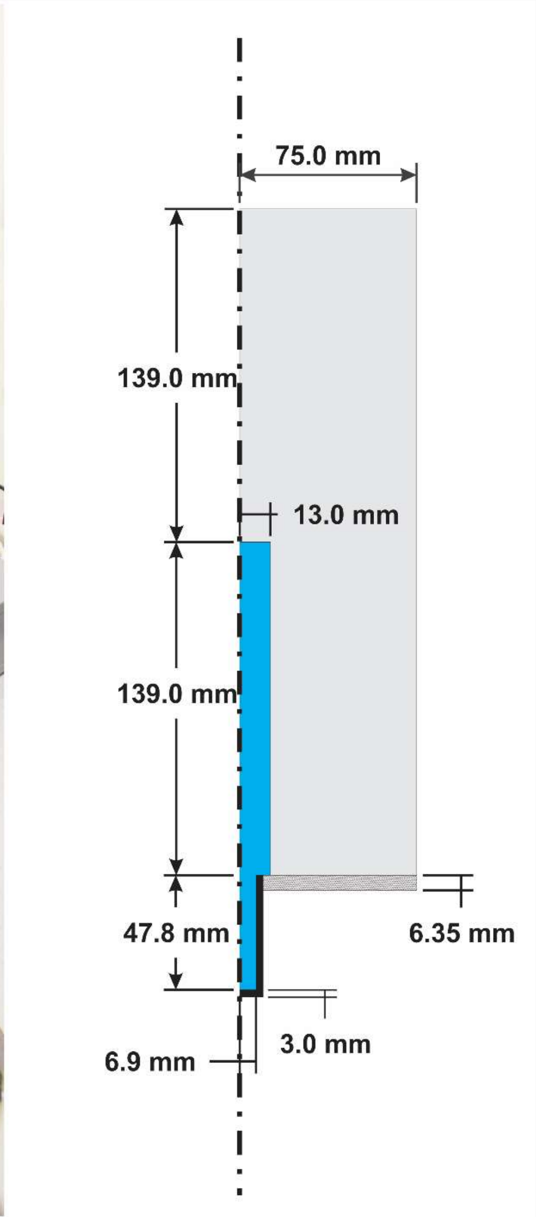
- **Four views of the fabric of the Cobourg Limestone cylinder cored NORMAL to the nominal planes of stratification. (Diameter of cylinder is 150 mm and length 300 mm)**

# Cobourg Limestone THM Experiment … contd.

- **Four views of the fabric of the Cobourg Limestone cylinder cored ALONG the nominal planes of stratification. (Diameter of cylinder is 150 mm and length 300 mm)**

# Cobourg Limestone THM Experiment… contd.



# THM-Modelling: Fluid-Saturated Porous Medium

- **The system of weakly coupled non-linear partial differential equations governing the dependent variables, apllicable to the fluid-saturated rock can be written as**

$$\left(K_D + \frac{G_D}{3}\right)\nabla(\nabla.\mathbf{u}) + G_D\nabla^2\mathbf{u} - \alpha\nabla p - K_D\beta_s\nabla T = \mathbf{0} \qquad (9)$$

$$S\frac{\partial p}{\partial t} + \nabla.\left[-\frac{\mathbf{K}}{\mu(T)}\nabla p\right] + \alpha\frac{\partial(\nabla.\mathbf{u})}{\partial t} - \left[n\beta_f(T) + (\alpha - n)\beta_s\right]\frac{\partial T}{\partial t} = 0 \qquad (10)$$

$$c_p^*(T)\frac{\partial T}{\partial t} - k_c^*\nabla^2 T = 0 \qquad (11)$$

- **The *specific storage term*, the *effective thermal conductivity* and *effective specific heat* are defined by**

$$S = nC_w + (\alpha - n)C_s\,; \quad k_c^* = nk_{cf} + (1-n)k_{cs}$$
$$c_p^*(T) = n\rho_f(T)c_f + (1-n)\rho_s c_s \qquad (12)$$

**The *Voigt Upper Bound*, which gives results consistent with the *Hashin-Shtrikman* estimate is used to define the effective property.**

# THM-Modelling: Fluid-Filled Cavity

- **The fluid-filled cavity can be modelled by appeal to properties of a pure fluid region or as an equivalent porous medium where THM and physical parameters , such as $n$, $K_{eff}$ , etc., are chosen to ensure uniform temperature and fluid pressure in the cavity region:**

$$(K_D + \frac{G_D}{3})\nabla(\nabla.\mathbf{u}) + G_D\nabla^2\mathbf{u} - K_D\beta_s\nabla T = \mathbf{0} \qquad \textbf{(13)}$$

$$C_{eq}(p)\frac{\partial p}{\partial t} + \nabla.\left[-\frac{K}{\mu(T)}\nabla p\right] + \frac{\partial(\nabla.\mathbf{u})}{\partial t} - \beta_f(T)\frac{\partial T}{\partial t} = 0 \qquad \textbf{(14)}$$

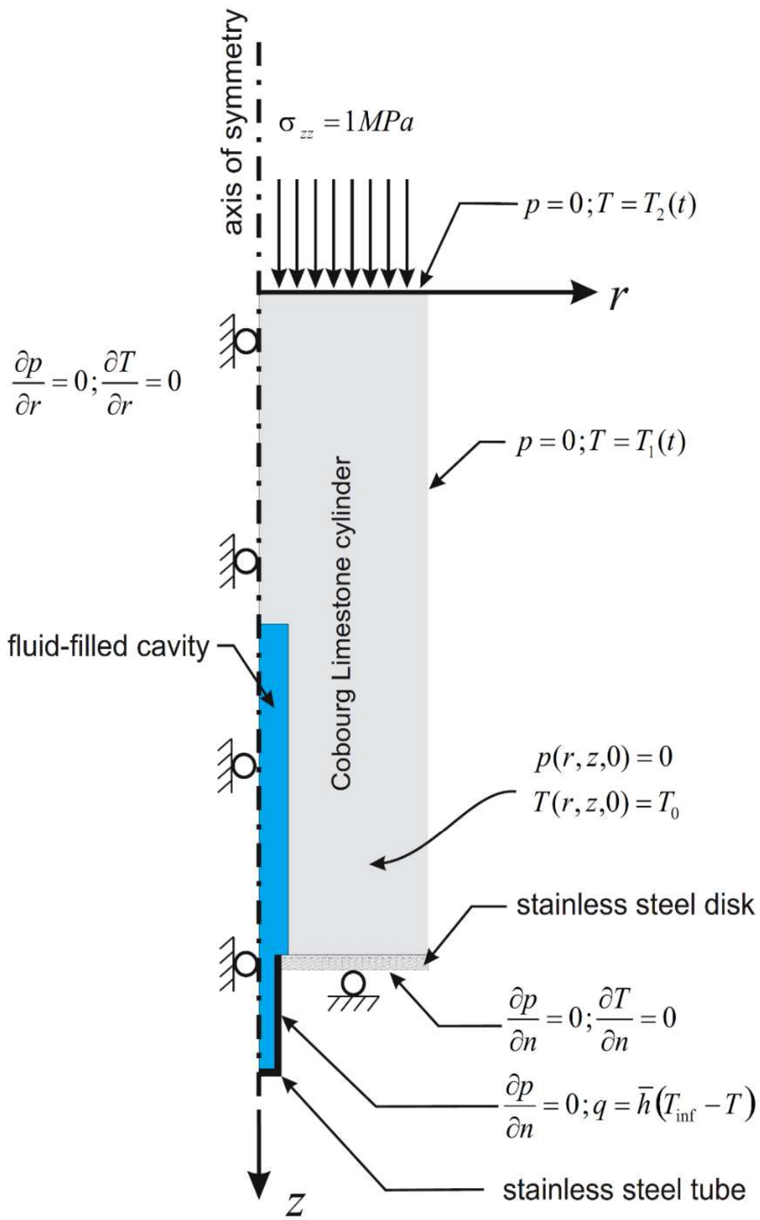
$$c_p^*(T)\frac{\partial T}{\partial t} - k_c^*\nabla^2 T = 0 \qquad \textbf{(15)}$$

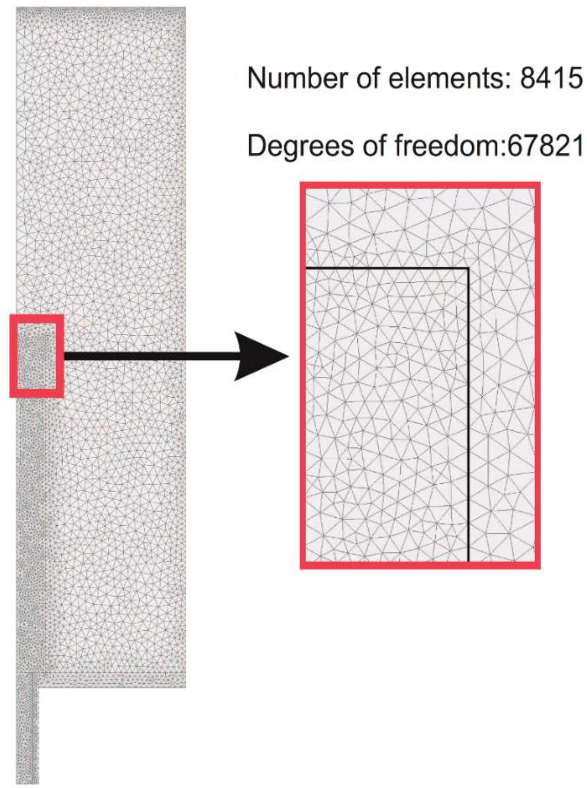
- **The formulation (13) to (15) can also account for the air fraction the fluid, which can influence the compressibility of the fluid and alter the pressure decay (APSS and Najari, *Geotechnique*, 2015): e.g.**

$$C_{eq} = \varphi C_a + (1-\varphi)C_w \qquad \textbf{(16)}$$

**where, $\varphi$ is the air fraction.**

# THM-Computational Modelling



# THM-Computational Modelling…..

- The computational accuracy of the Multiphysics Code used in the study has been verified by *NSERC* and *NWMO Sponsored Research* and documented in several publications:

  APSS and Selvadurai (2010) *Proc Roy Soc Math Phys A*

  APSS and Suvorov (2012) *Proc Roy Soc Math Phys A*

  APSS and Suvorov (2014) *Proc Roy Soc Math Phys A*

  Selvadurai and APSS (2014) *Phil Mag*

  APSS and Najari (2014) *Adv Water Res*

  Najari and APSS (2015) *Env Earth Sci*

  APSS and Najari (2015) *Geotechnique*

  APSS et al. (2015) *Geosci Model Development*

  APSS and Kim (2016) *Proc Roy Soc Math Phys A*

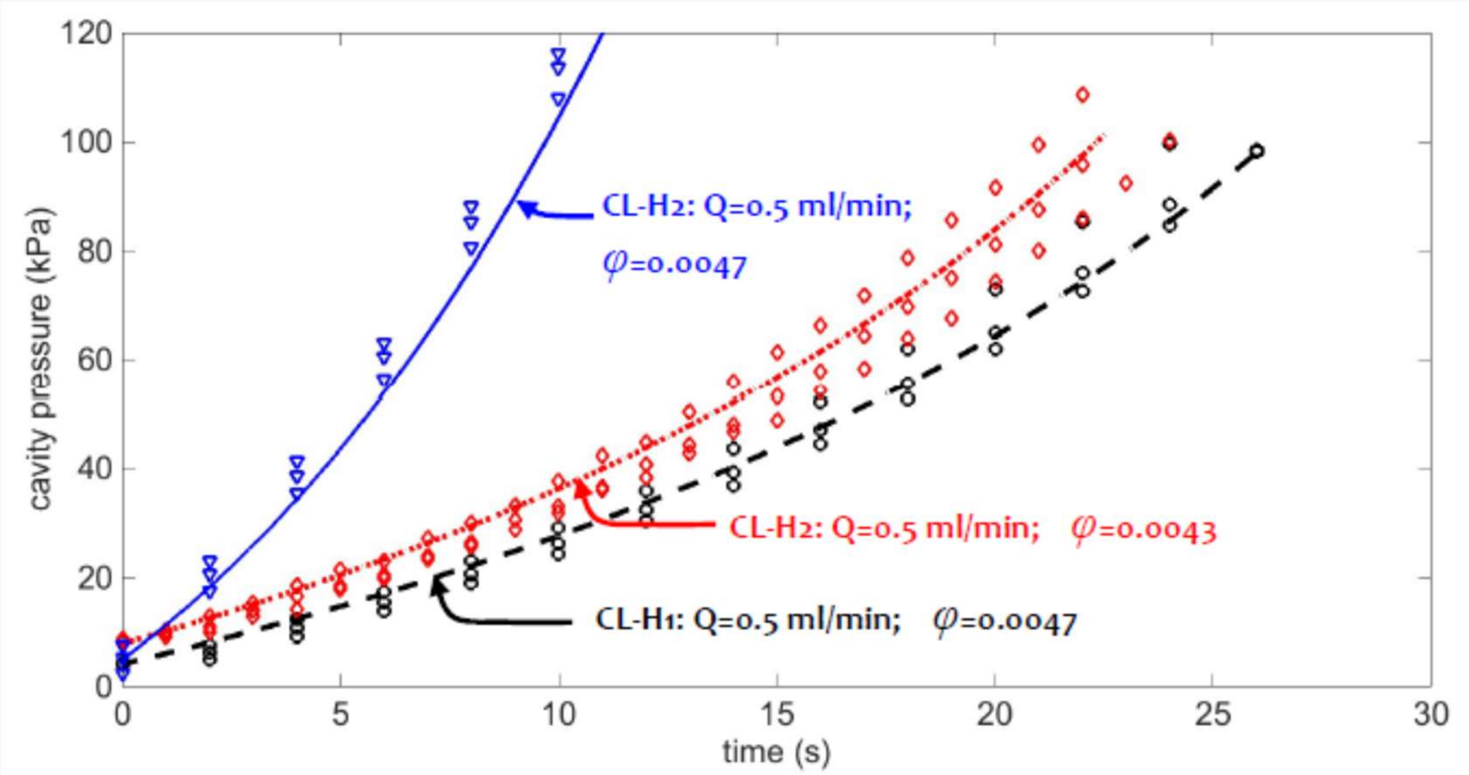
  APSS and Suvorov (2016) *Thermo-Poroelasticity and Geomechanics,* Cambridge University Press.

- ALL these publications also carry the following disclaimer

  *"The use of the computational Code XX is only for demonstration purposes only. The authors neither advocate nor recommend the use of the Code without conducting suitable validation procedures to test the accuracy of the code in a rigorous fashion."*

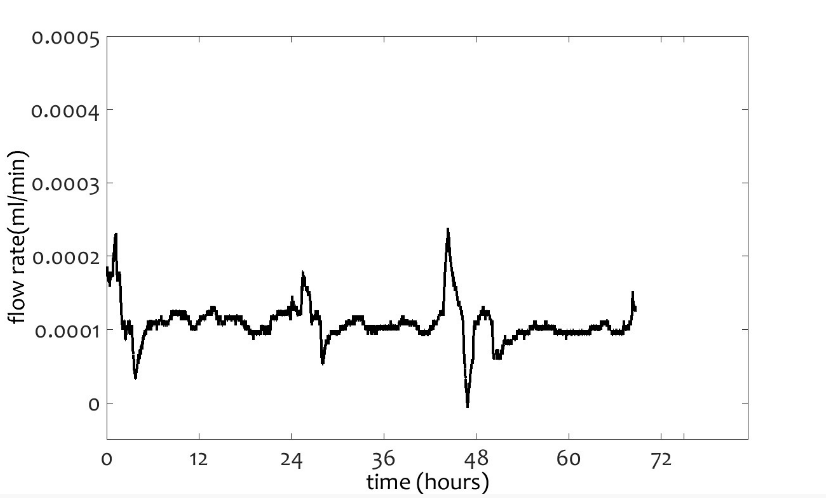
# Cavity Pressurization Tests

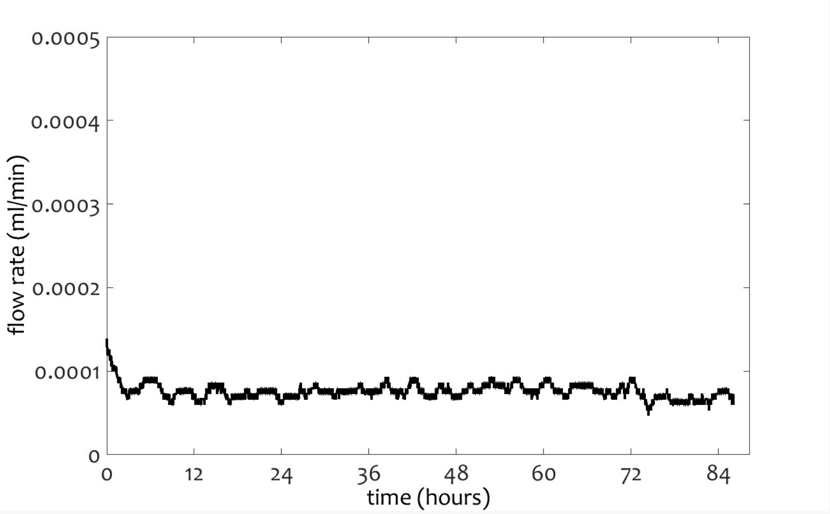
- **These tests can be used to estimate, computationally, the air fraction $\varphi$ in the fluid-filled cavity and the connections.**
- **The work of APSS and Najari (*Geotechnique* 2015) shows the influence of $\varphi$ in contributing to the mis-match between steady state tests and transient hydraulic pulse tests.**
- **The Cobourg Limestone has a permeability transverse isotropy of an order of magnitude.**



# Permeability Measurement

- Prior to performing the THM experiments, the permeability of the Cobourg Limestone sample was measured by conducting *constant pressure steady state tests*.
- The water pressure in the central cavity was kept at 100 kPa using a Quizix precision pump and the changes in the flow rate were recorded. Fluid used was regular tap water.
- The results were analysed using the Multiphysics code and the permeability was estimated to be (2 to 3.6)×$10^{-20}$ $m^2$. [1 Darcy~$10^{-12}$ $m^2$; 1 nan0-Darcy~$10^{-21}$ $m^2$; 1 micro-Darcy~$10^{-18}$ $m^2$; 1 milli-Darcy~$10^{-15}$ $m^2$ ]



# The THM Experiment

- Three consecutive heating stages were performed on the sample by changing the water temperature at the boundary of the cylinder.
- The water temperature was initially increased from 25°C to 40 °C and kept constant for 24 hours; the temperature was then raised from to 40°C to 55 °C and kept constant for a further 24 hours; the temperature was finally raised from to 55°C to 70 °C and kept constant for another 24 hours.
- The time history of the fluid pressure generated within the sealed cavity was recorded. As the temperature pulse reaches the cavity, the thermal expansion THM mis-match between the Cobourg Limestone and the water raises the pressure, which dissipates with time.

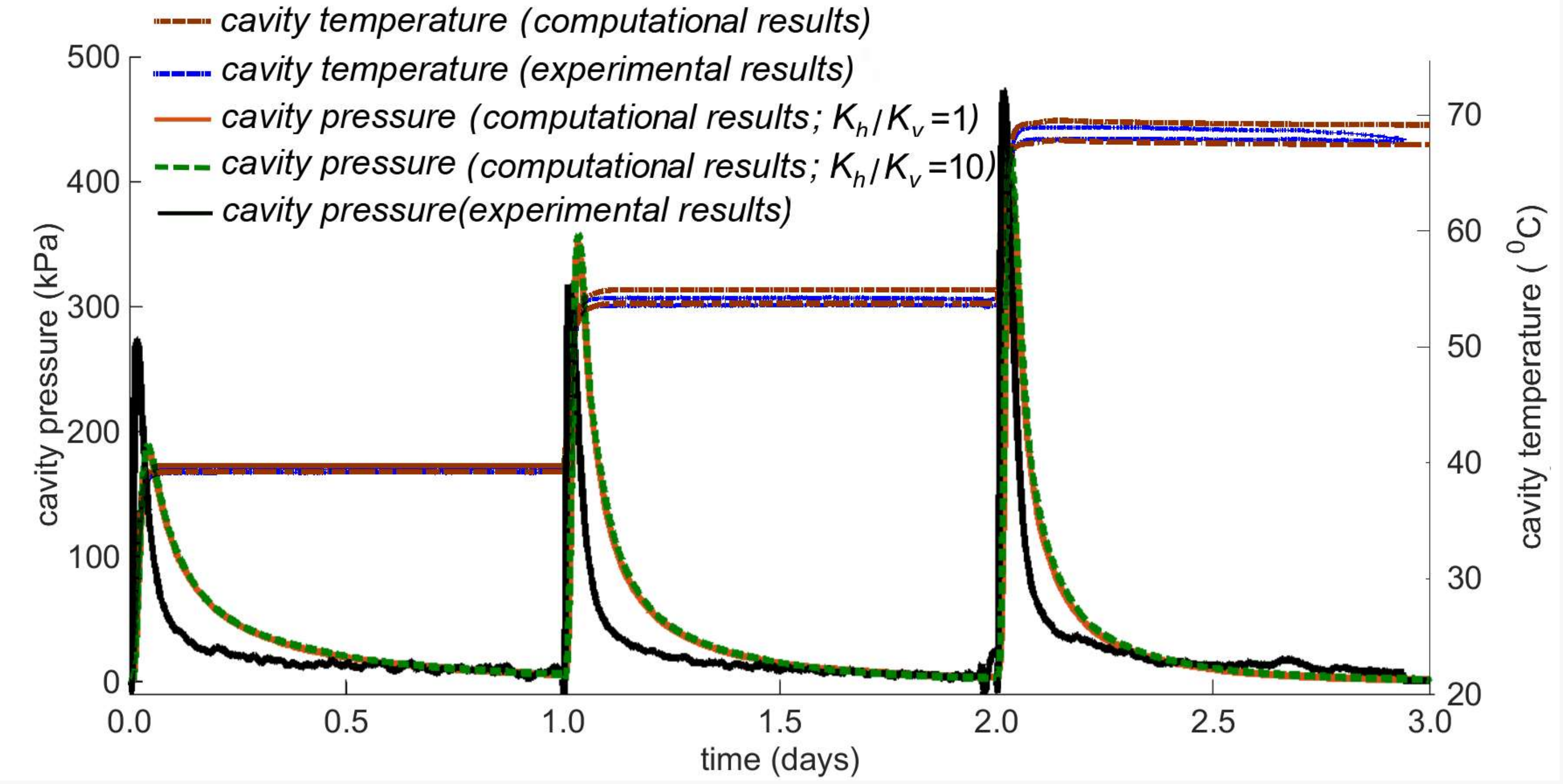
# THM-Computational Modelling-Material Parameters

| Parameter | Cobourg Limestone | Water | Stainless Steel |
|---|---|---|---|
| Young's modulus (GPa) | 21 [a] | - | 200 [b] |
| Poisson's ratio | 0.25 [a] | 0.49 | 0.3 [b] |
| porosity (%) | 1-4 [a] | 100 | - |
| Biot coefficient | 0.7 [c] | - | - |
| permeability ($m^2$) | $1.4 \times 10^{-19}$ | - | - |
| volumetric thermal expansion coefficient ($^oC^{-1}$) | $2.0 \times 10^{-5}$ [d] | $\beta_f(T)$ [e] | $4.9 \times 10^{-5}$ [b] |
| thermal conductivity ($W.m^{-1}.{}^oC^{-1}$) | 2.5 [f] | 0.58 [e] | 16.5 [b] |
| specific heat capacity ($J.kg^{-1}.{}^oC^{-1}$) | 770 [f] | 4187 [e] | 480 [b] |

a. Selvadurai et al. (2011)
b. McGuire (2008)
c. Wang (2000)
d. AECL (2010)
e. Holzbecher (1998)
f. AECL (2011)

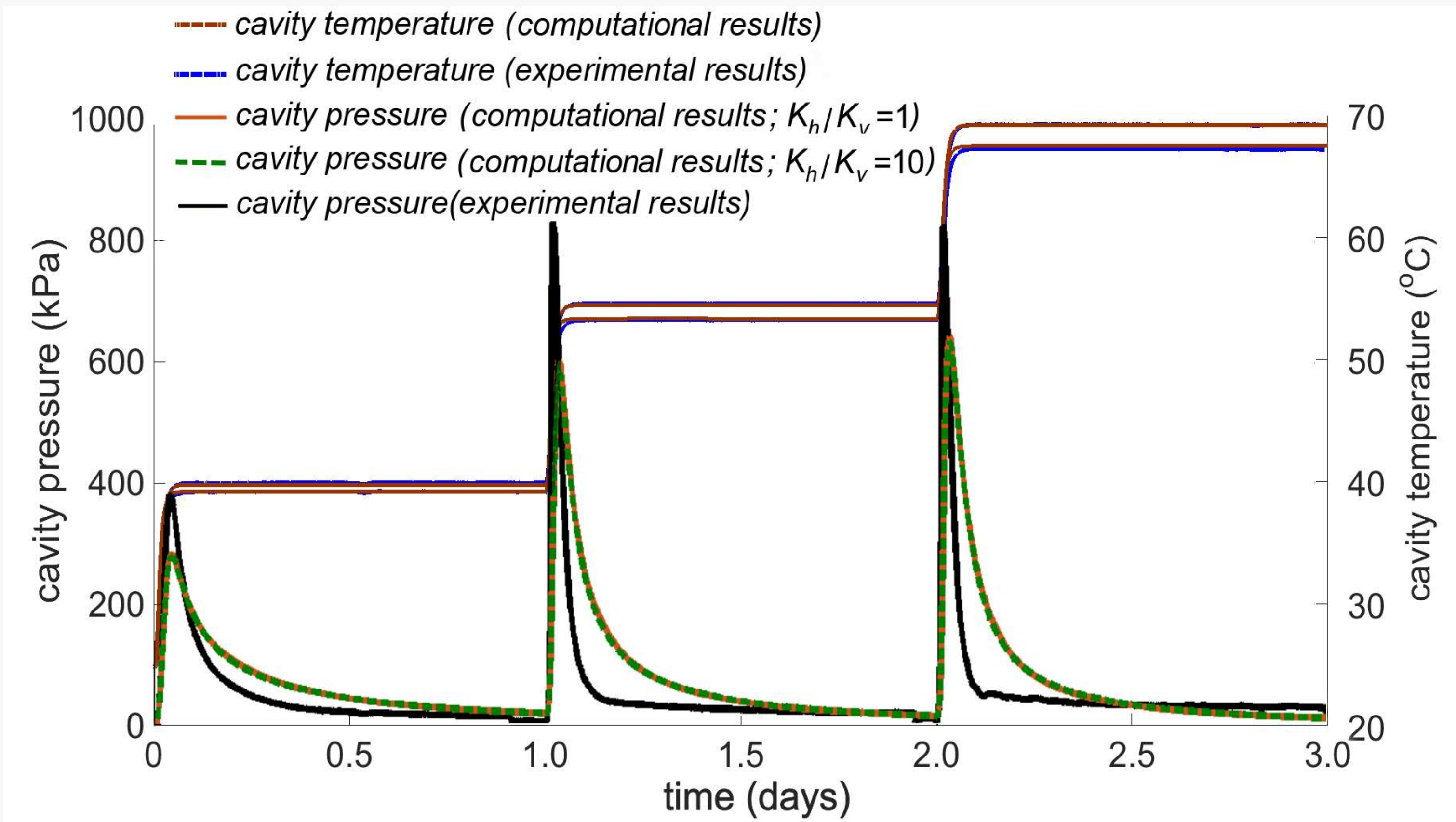
# Comparison of Experimental Results and Computational Estimates

- **Central cavity is oriented NORMAL to the nominal stratifications identified by the argillaceous partings.**
- **Comparisons are made with temperatures and fluid pressure within the cavity. [Sample Ref. CL-H1]**



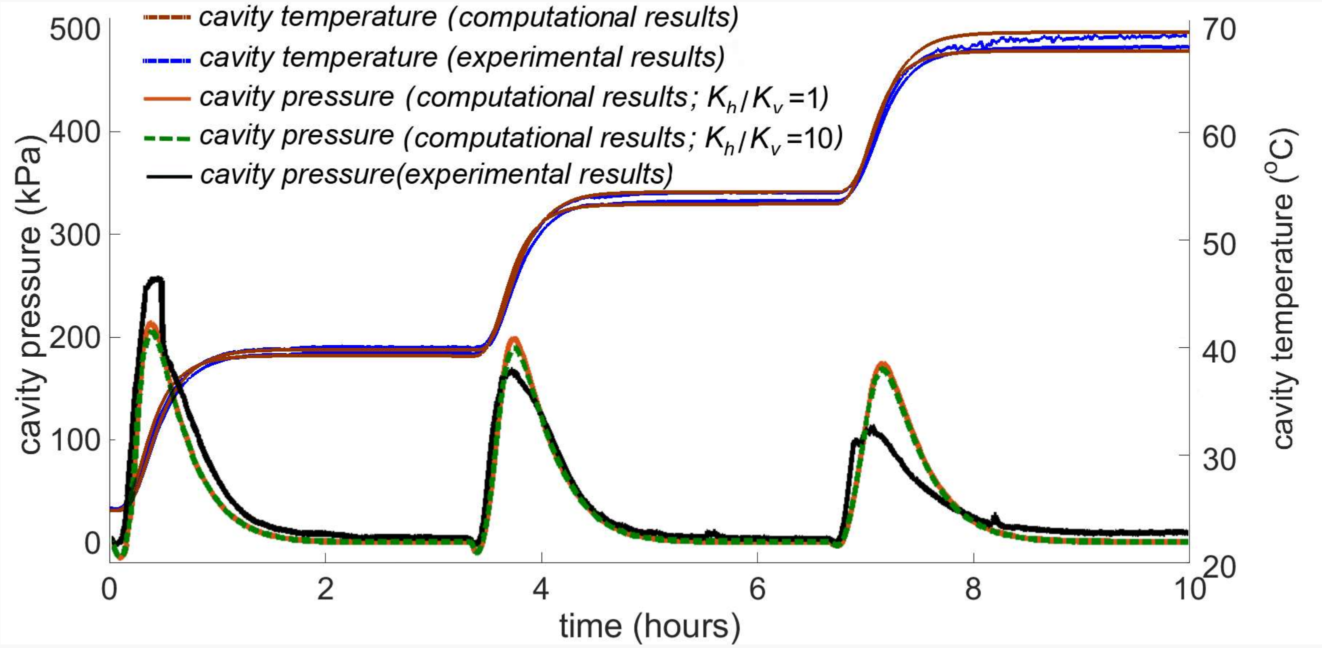
# Comparison of Experimental Results and Computational Estimates

- **Central cavity is oriented NORMAL to the nominal stratifications identified by the argillaceous partings.**
- **Comparisons are made with temperatures and fluid pressure within the cavity. [Sample Ref. CL-H2]**



# Comparison of Experimental Results and Computational Estimates

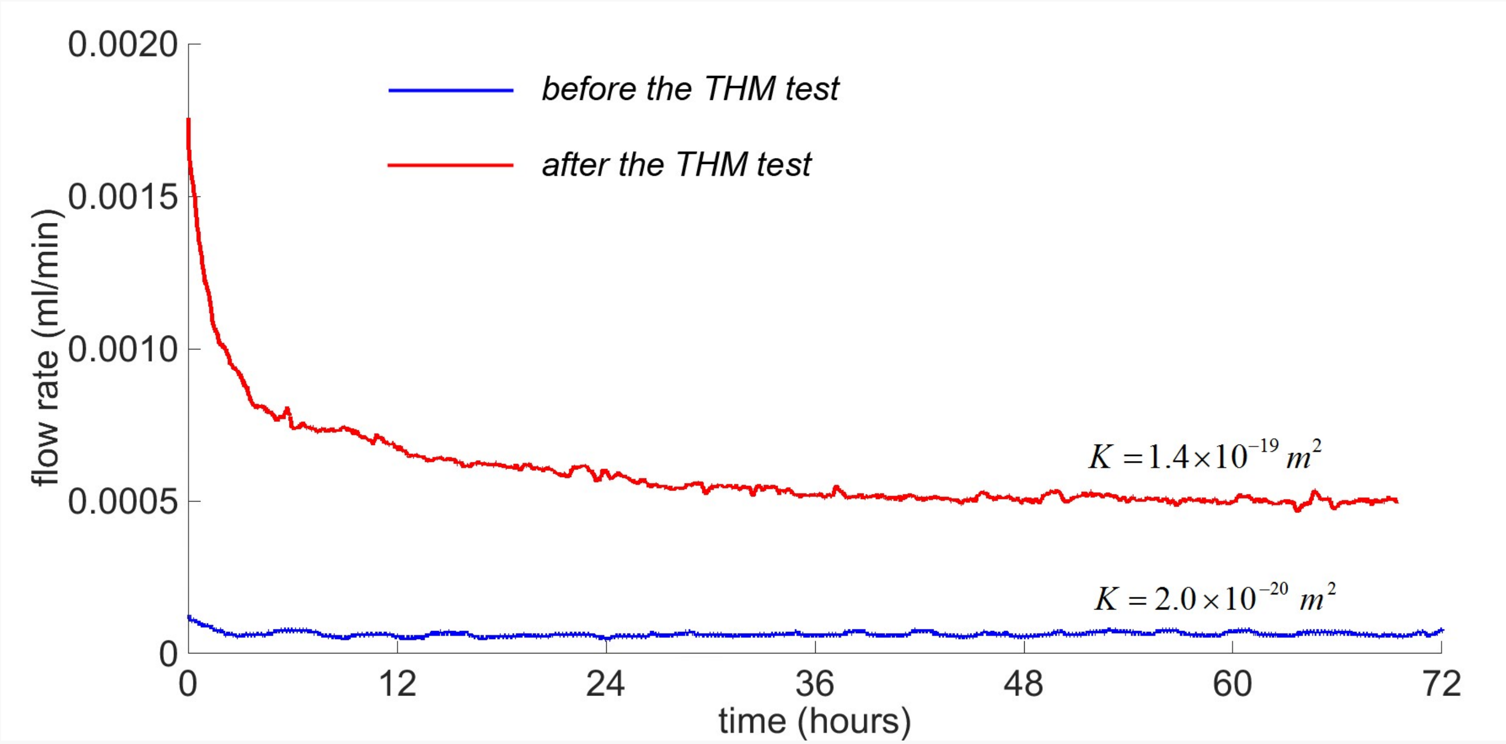
- **Central cavity is oriented ALONG the nominal stratifications identified by the argillaceous partings.**
- **Comparisons are made with temperatures and fluid pressure within the cavity. [Sample Ref. CL-V1]**



# Post THM Experiment Permeability Measurement

- **After the THM test, the sample was allowed to cool down and steady state permeability tests were conducted to determine any alterations to the permeability due to the staged temperature increases.**

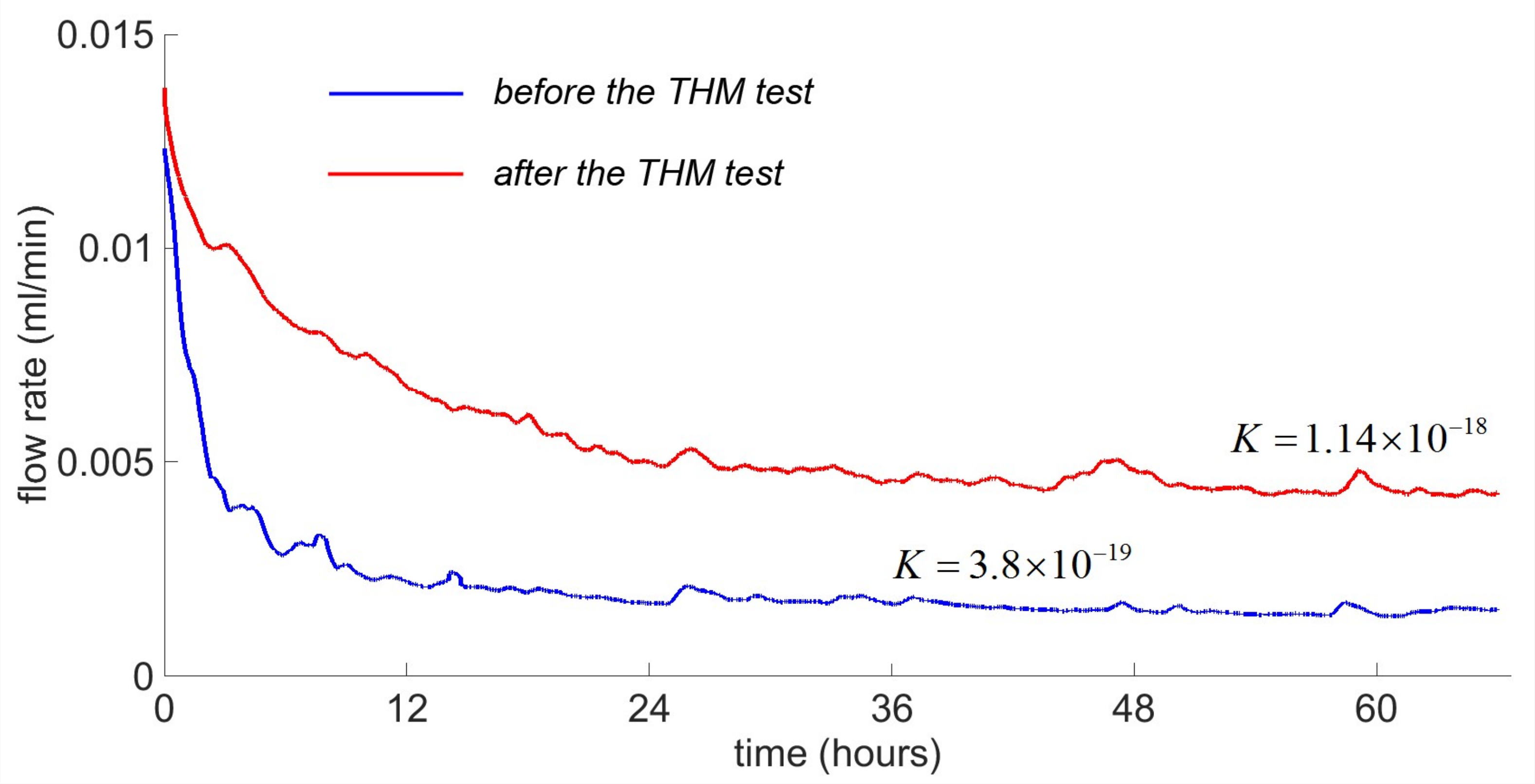
- **Cavity NORMAL to the nominal stratifications.**



# Post THM Experiment Permeability Measurement

- **After the THM test the sample was allowed to cool down and steady state permeability tests were conducted to determine any alterations to the permeability due to the staged temperature increase.**

- **Cavity ALONG to the nominal stratifications.**



# Concluding Remarks

- The Cobourg Limestone displays a dominant internal fabric. This would suggest that the fabric could influence the overall THM behaviour.
- The design of a THM experiment should address quantities that can be measured accurately without the measuring device introducing an anomalous effect (e.g. rock stresses)
- Thermal measurements (e.g. expansion) are possible but do not address the influences of coupling.
- The pore fluid pressure response during a THM excursion offers a plausible option. Again, introducing pore pressure transducers within a THM regime creates its own problems.
- The THM behaviour of a fluid inclusion is a possible way of overcoming the obstacles and criticisms.
- The results of the THM experiments conducted to date indicate that THM models with reduced coupling are able to provide reasonable (not perfect!) correlations.

# Acknowledgements

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