



# Borehole Stability in the Ghareb Formation

**NNSA-IAEC Workshop on Nuclear Waste Management  
and Subsurface Science  
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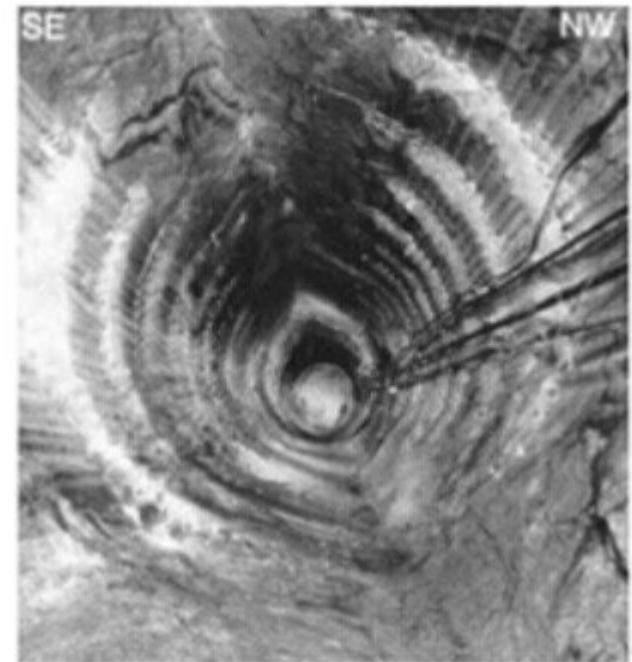
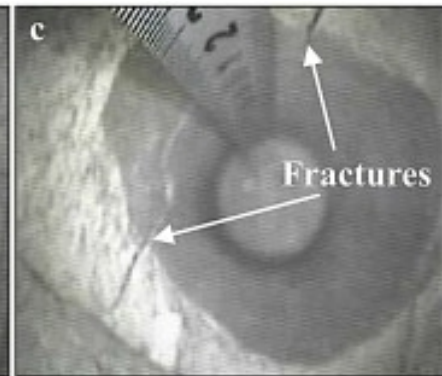
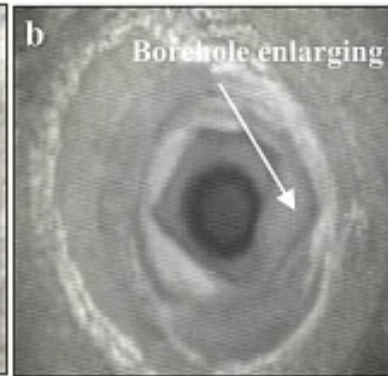
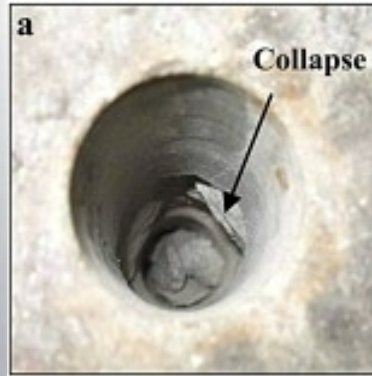
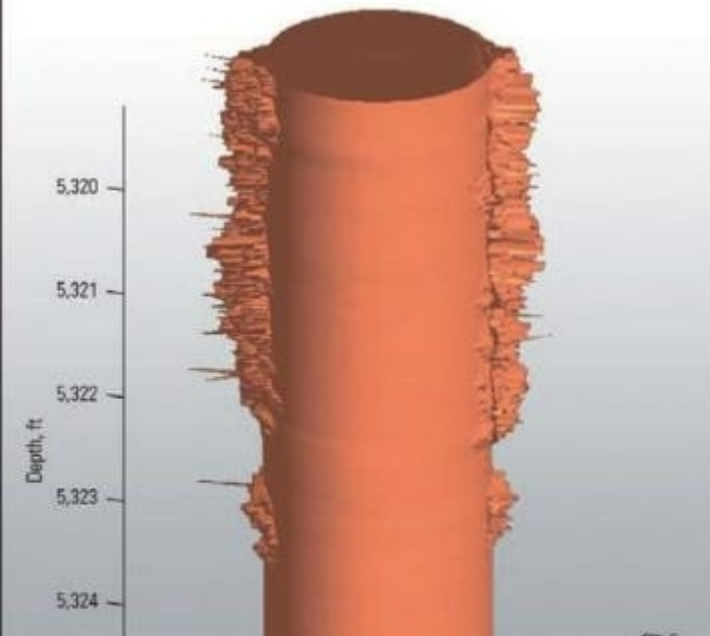
**Lawrence Livermore National Laboratory**

**Eyal Shalev**

**Vladimir Lyakhovsky**



# Borehole deformation in-situ



Eyal

# Geomechanical considerations

- Organic rich carbonate chalk/mud that hasn't been deeply buried
  - High porosity, kerogen content
- Drilling will induce elevated stresses
- Target reservoir in vadose zone, but repository installation could introduce standing fluids
- Carbonate chinks shown to be sensitive to temperature, saturation, fluid chemistry
- Stress-strain behavior necessary to parameterize models

# 2022 Work Completed

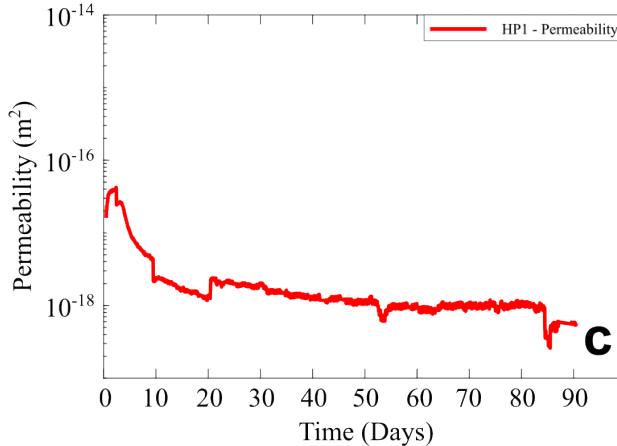
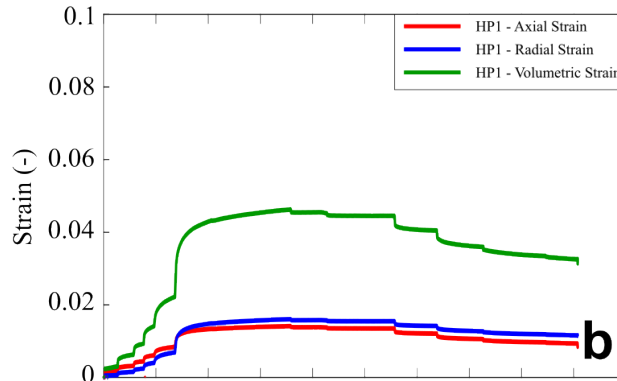
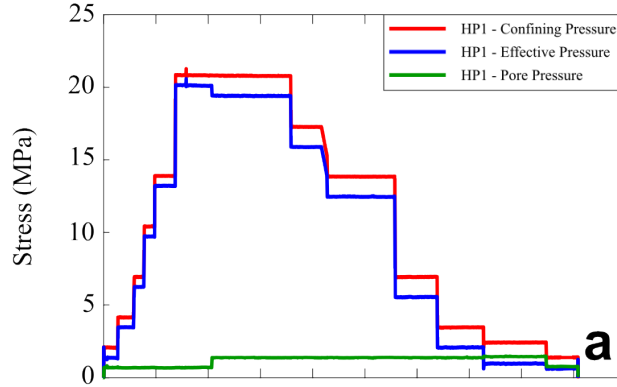
- **3 Hydrostatic Creep-Permeability Tests:**
  - Creep rate increases with increased pressure
  - Above ~10-15 MPa effective pressure deformation anisotropy begins to occur even under isotropic conditions
- **Two Triaxial Creep Tests:**
  - Strain rate produces noticeable divergence in strain behavior prior to failure
  - Increasing temperature to 100 °C induces significant compaction and enhanced creep
- **4 Thermal Property Tests up to 175 °C:**
  - New samples show divergence from previous properties measured with different Ghareb block

# Sample Preparation is a Challenge

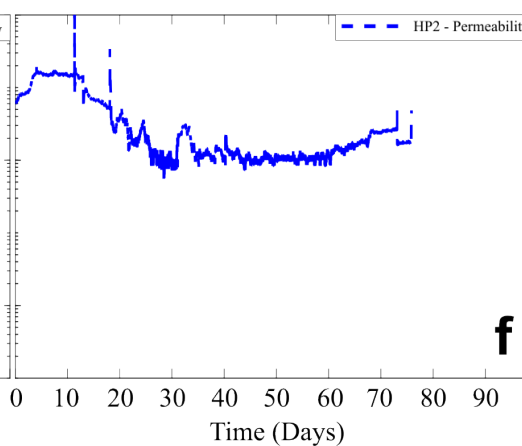
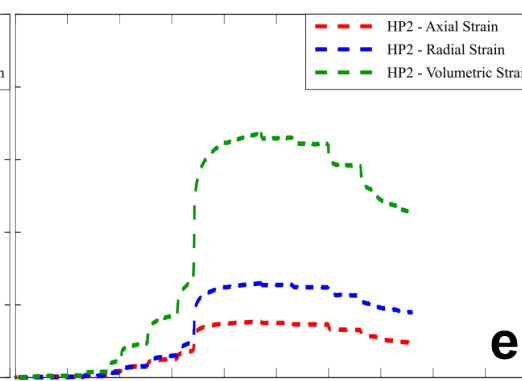
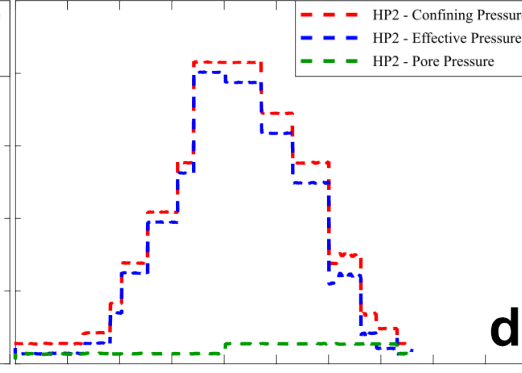


# Long Term Hydrostatic Test

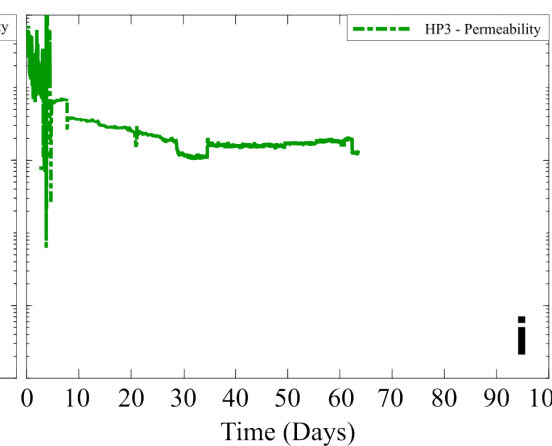
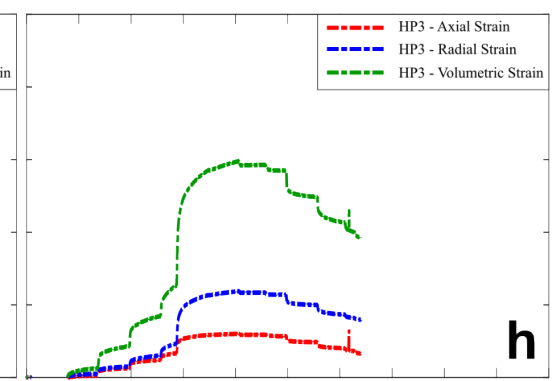
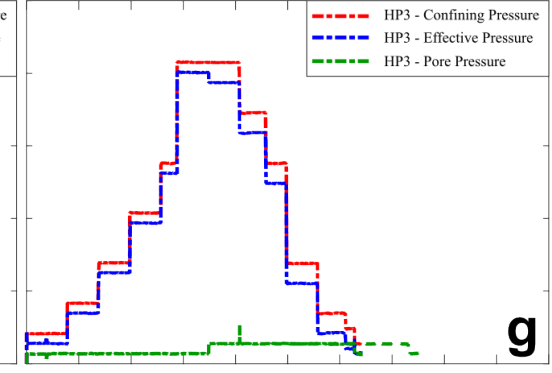
## HP1



## HP2

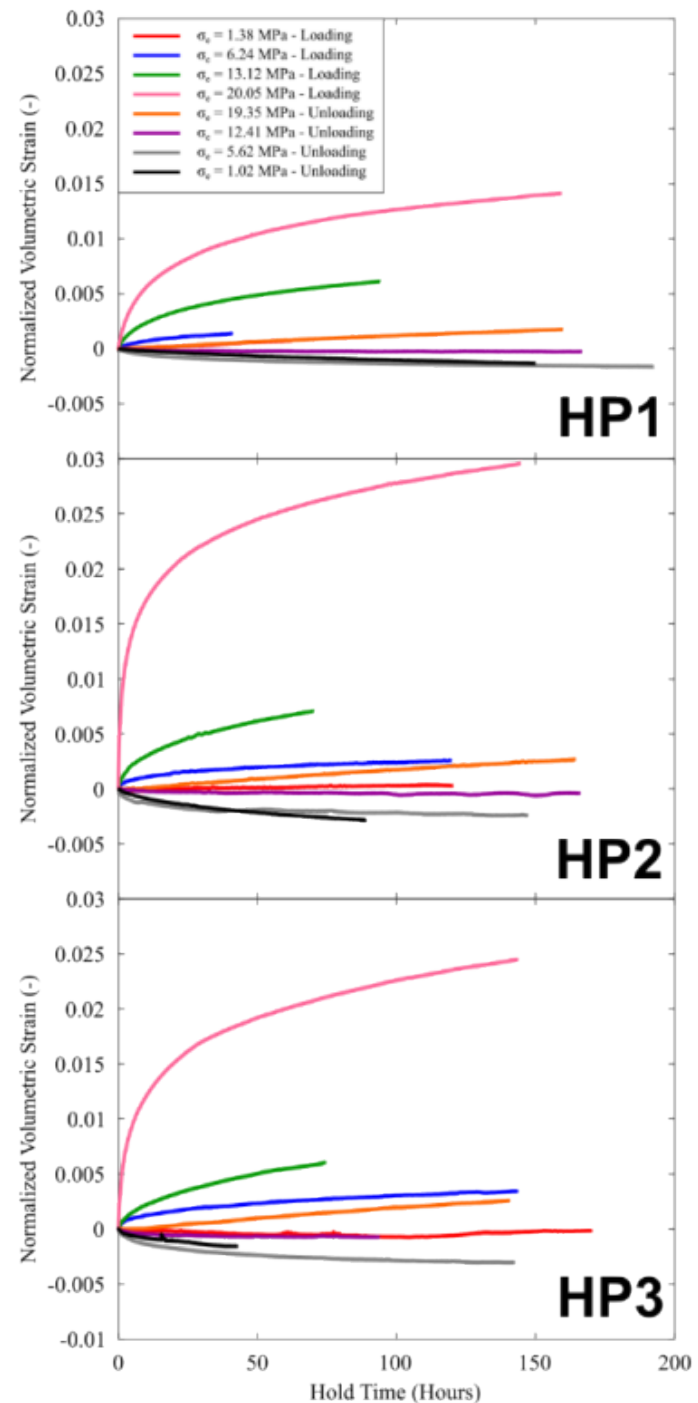
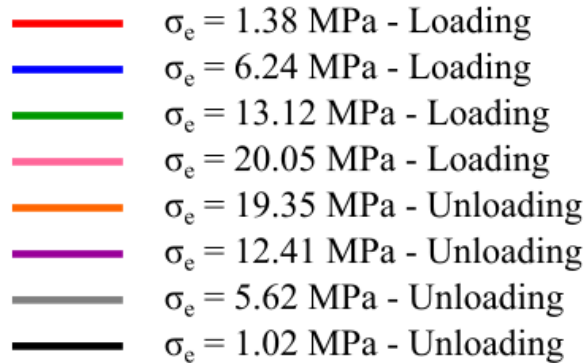


## HP3



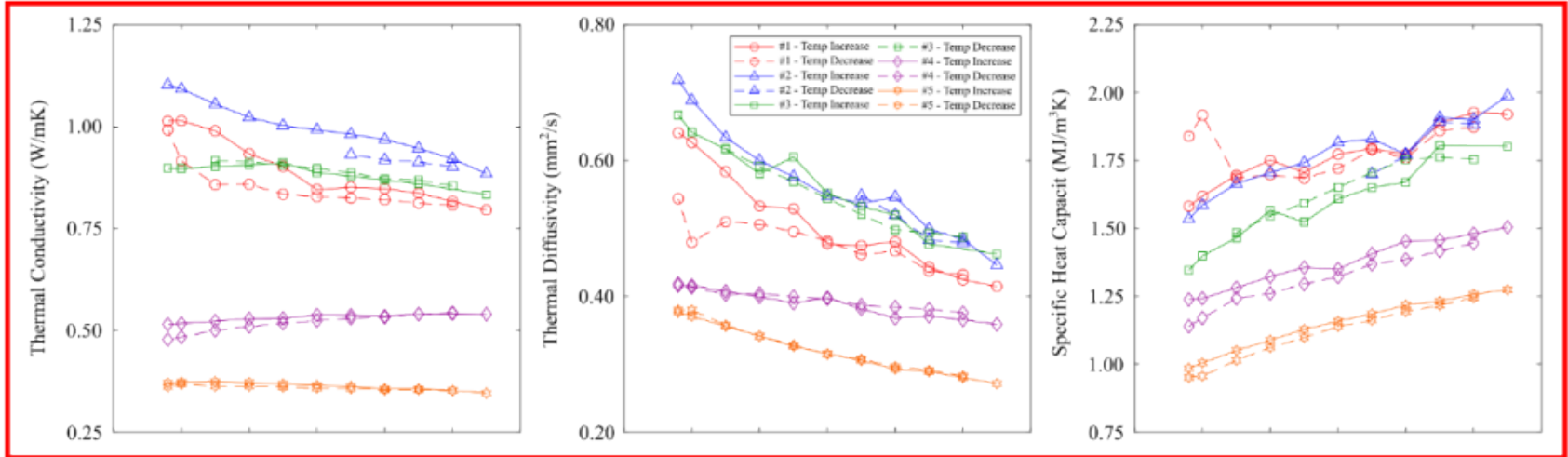
# Time-Dependent Behavior

- Rate of creep increases with effective pressure
- Increasing pressure from 13.12 to 20.05 MPa, there is a significant jump in compaction
- Ghareb behavior is viscoplastic, or nonrecoverable and time-dependent, and pressure-dependent

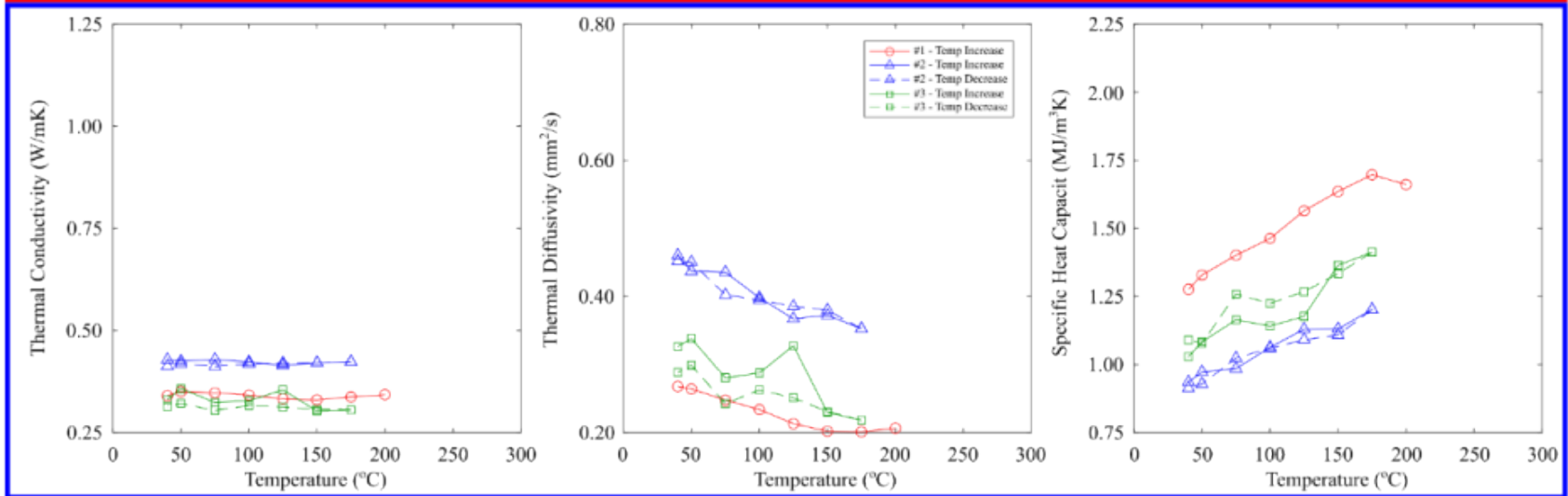


# Thermal Properties of Dry Ghareb Rocks

Set #1

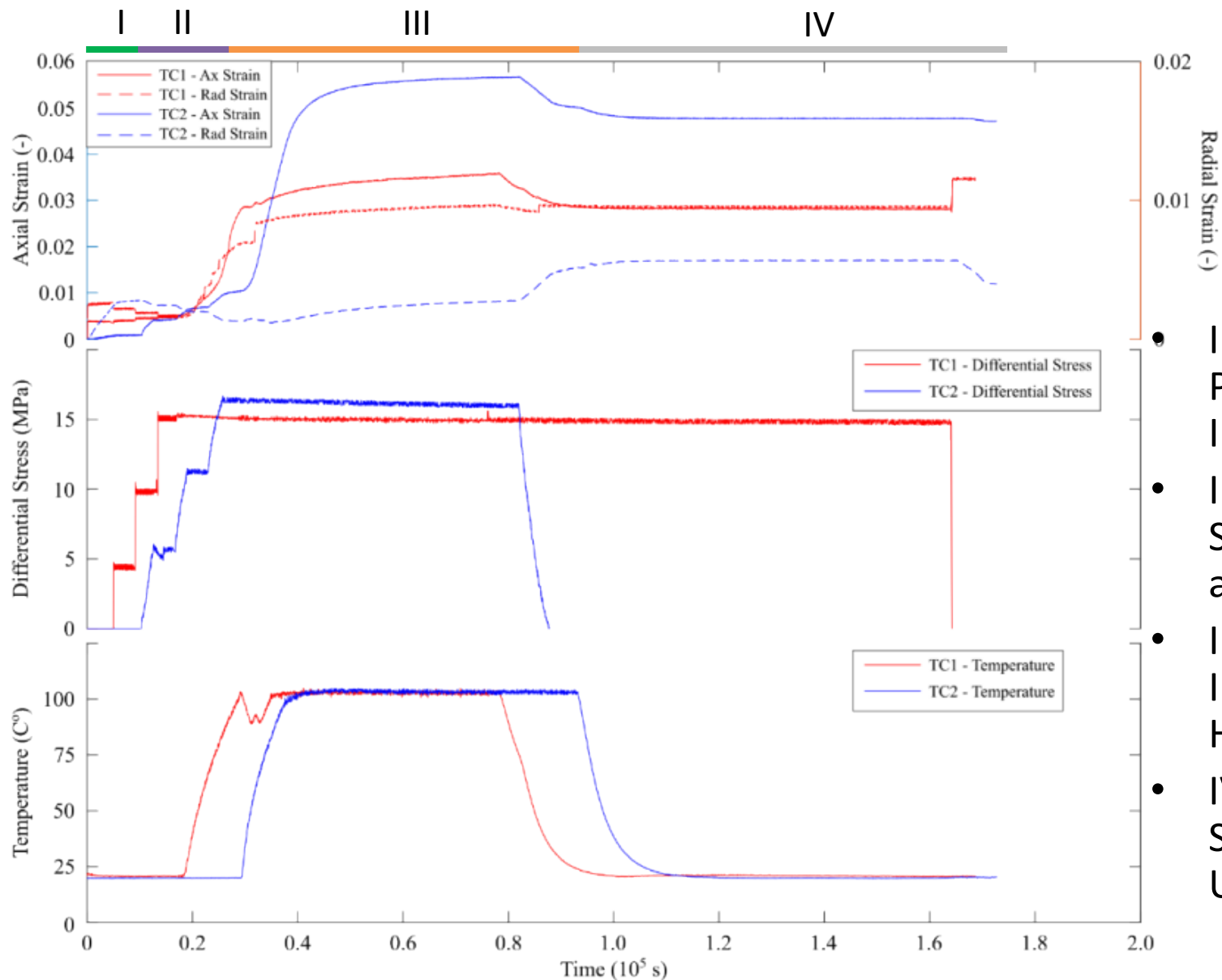


Set #2



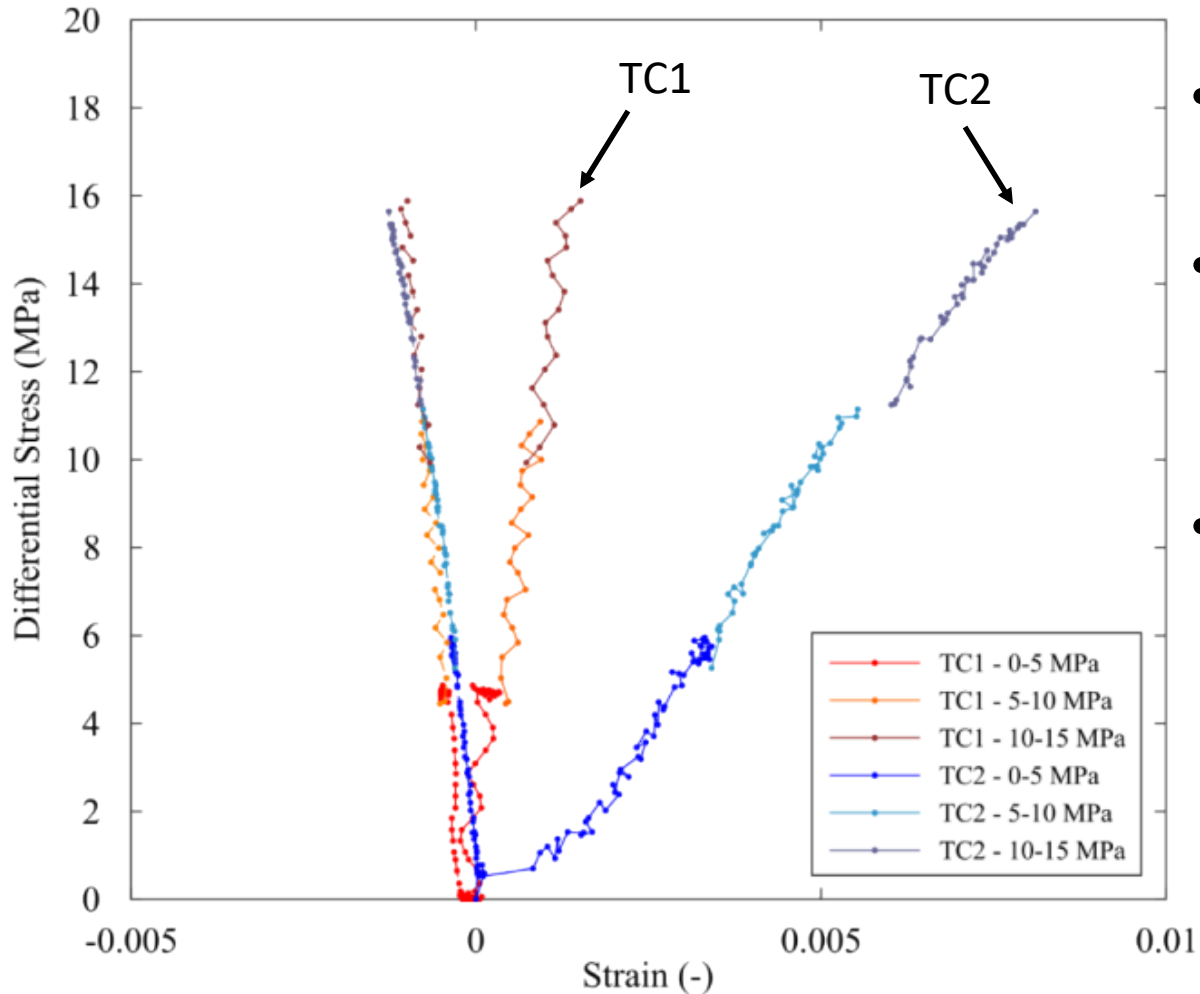
- Thermal conductivity, thermal diffusivity, and specific heat capacity

# Triaxial Creep and Thermal Loading Tests



- I: Confining Pressure Increase
- II: Differential Stress Loading and Holds
- III: Temperature Increase and Holds
- IV: Differential Stress Unloading

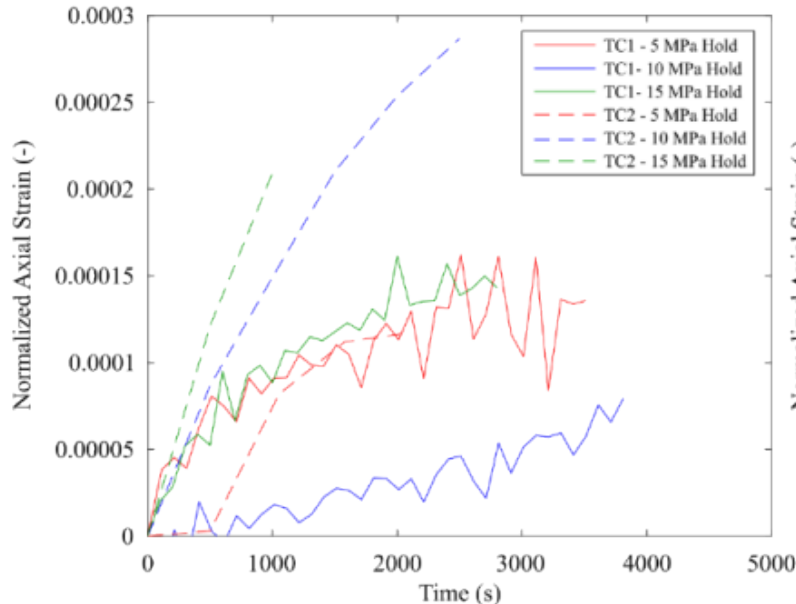
# Effect of Loading Rate



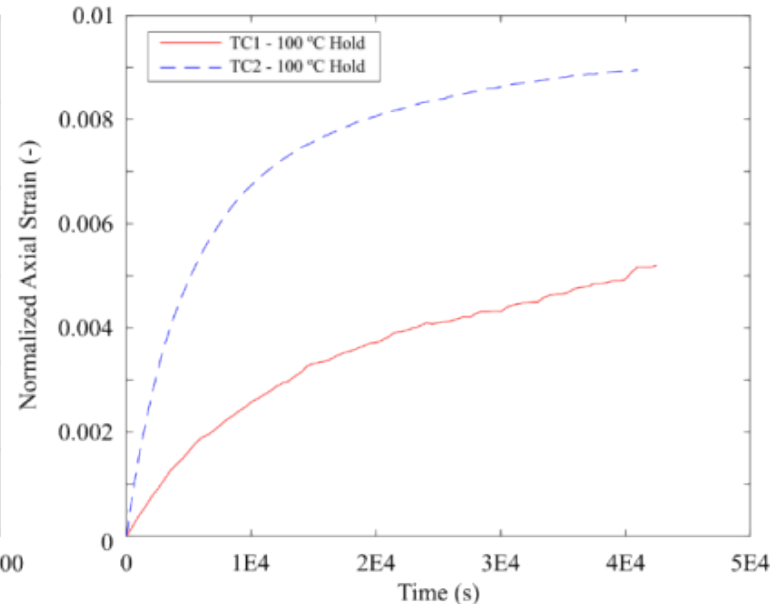
- TC1 Strain Rate  $\sim 10^{-4} \text{ s}^{-1}$
- TC2 Strain Rate  $\sim 10^{-6} \text{ s}^{-1}$
- Slower rate induces more axial strain for the same stress – time-dependent deformation

# Effect of Temperature and Creep Behavior

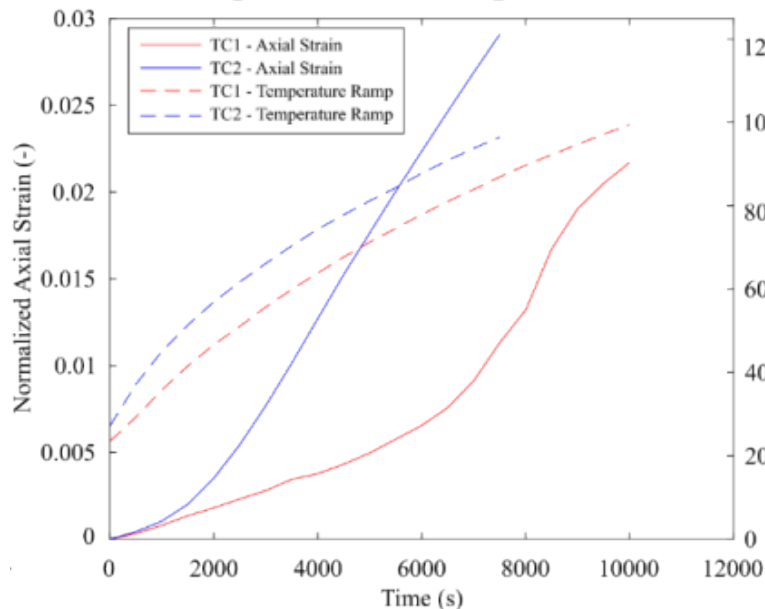
## Differential Stress Holds



## Hold at 15 MPa and 100 °C



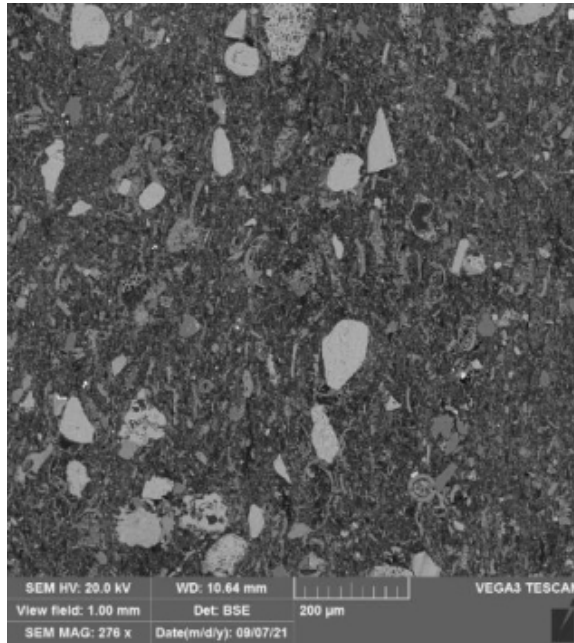
## Temperature Loading at 15 MPa



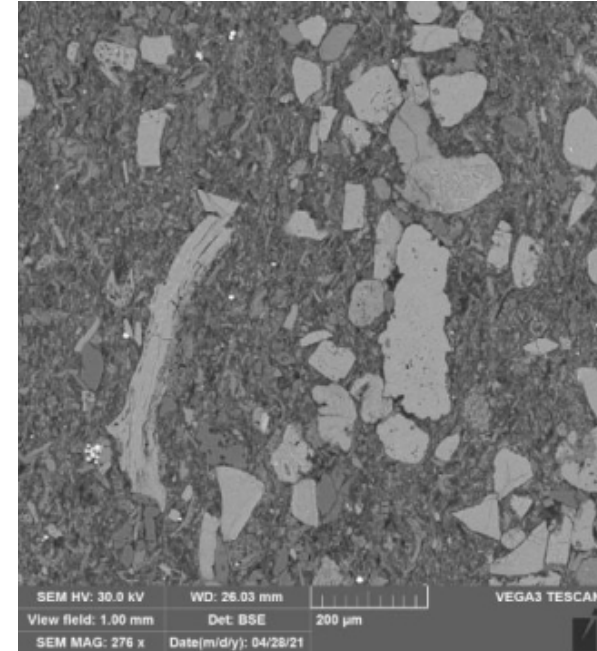
- Low strain under holds at room temperature
- Strain rate at 100 °C much higher than at room temp
- Increasing temperature to 100 °C leads to significant axial strain due to increased plasticity

# SEM observations

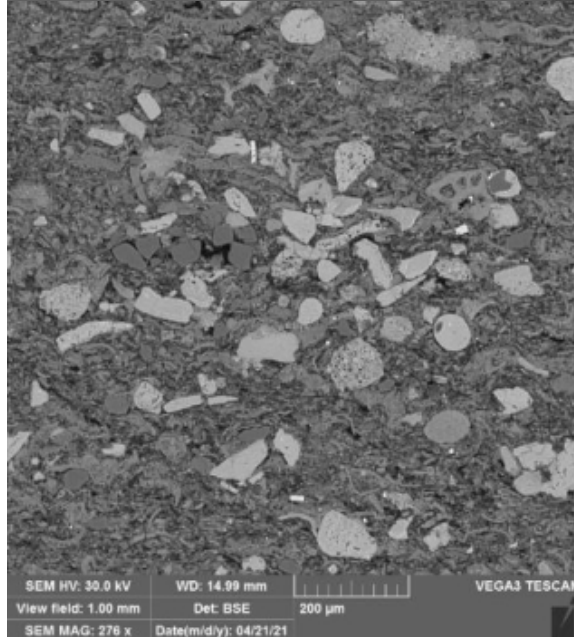
Undeformed



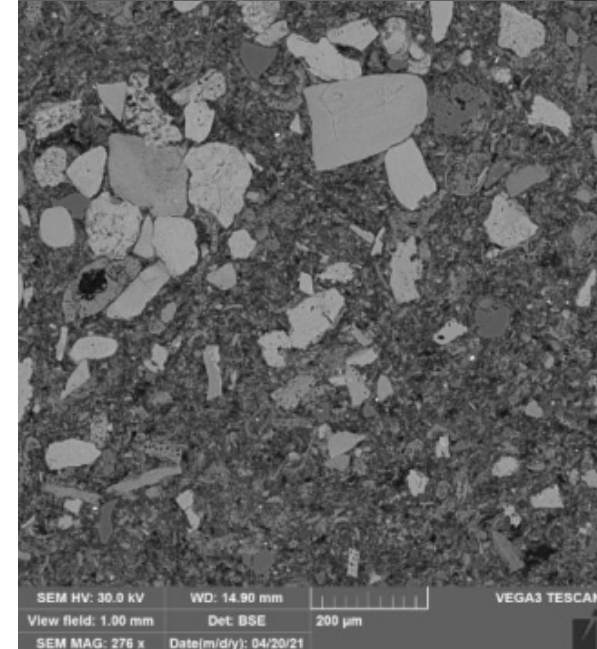
Hydrostatic  
compaction



Dry  
creep



Wet  
creep



Charles?

# Conclusions

- Ghareb deformation is time-dependent
- Increasing stress is can reduce permeability by 1-2 orders of magnitude in Ghareb
- Ghareb thermal properties are highly variable
- Rate of stress change affects rock deformation
- Minor creep strain occurs at pressure, but largest strains occur by increasing temperature up to 100 °C

# Effect of heat

## Conductive heat transfer, no advection

q-values:

Heat equation, cylindrical coordinates

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C_p} \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$

Energy balance for r=0 (boundary condition with heat production)

$$\frac{\partial T}{\partial t} = \left( \frac{q}{\pi R^2} - \lambda \frac{2}{R} \frac{\partial T}{\partial r} \right) / \rho C_p$$

Watt/m									Years
#9	#8	#7	#6	#5	#4	#3	#2	#1	cooling time
1978	989	198	98.9	39.6	19.8	13.8	1.98	0.20	40
1582	791	158	79.1	31.6	15.8	11.1	1.58	0.16	50
514	257	51.4	25.7	10.3	5.14	3.60	0.51	0.05	100
158	79.1	15.8	7.91	3.16	1.58	1.11	0.16	0.02	150
55.4	27.7	5.54	2.77	1.11	0.55	0.39	0.06	0.01	200
31.6	15.8	3.16	1.58	0.63	0.32	0.22	0.03	0.003	250
15.8	7.91	1.58	0.79	0.32	0.16	0.11	0.02	0.002	300
4.35	2.18	0.44	0.22	0.09	0.04	0.03	0.004	0.0004	500
2.77	1.38	0.28	0.14	0.06	0.03	0.02	0.003	0.0003	700
1.98	0.99	0.20	0.10	0.04	0.02	0.01	0.002	0.0002	1000
1.42	0.71	0.14	0.07	0.03	0.01	0.01	0.001	0.0001	2000
1.19	0.59	0.12	0.06	0.02	0.01	0.01	0.001	0.0001	3000
1.19	0.59	0.12	0.06	0.02	0.01	0.01	0.001	0.0001	4000
1.19	0.59	0.12	0.06	0.02	0.01	0.01	0.001	0.0001	5000
1.19	0.59	0.12	0.06	0.02	0.01	0.01	0.001	0.0001	10000

ARMA 21- 1662

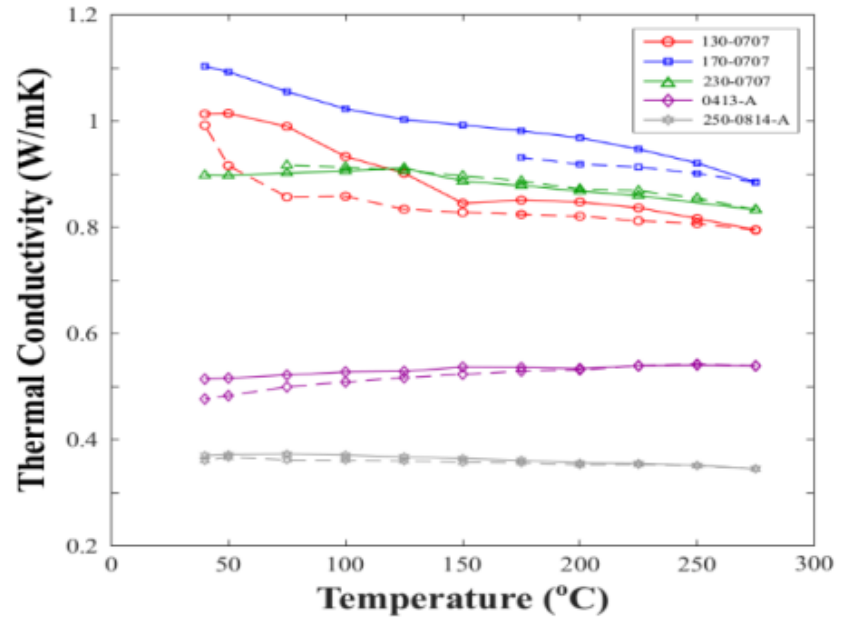
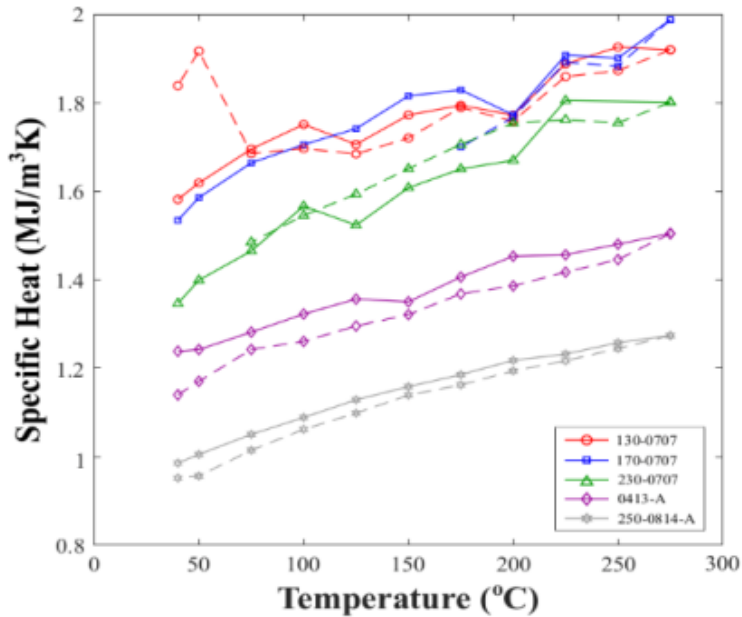
# Characterization and borehole analysis of the Ghareb Formation for nuclear waste disposal

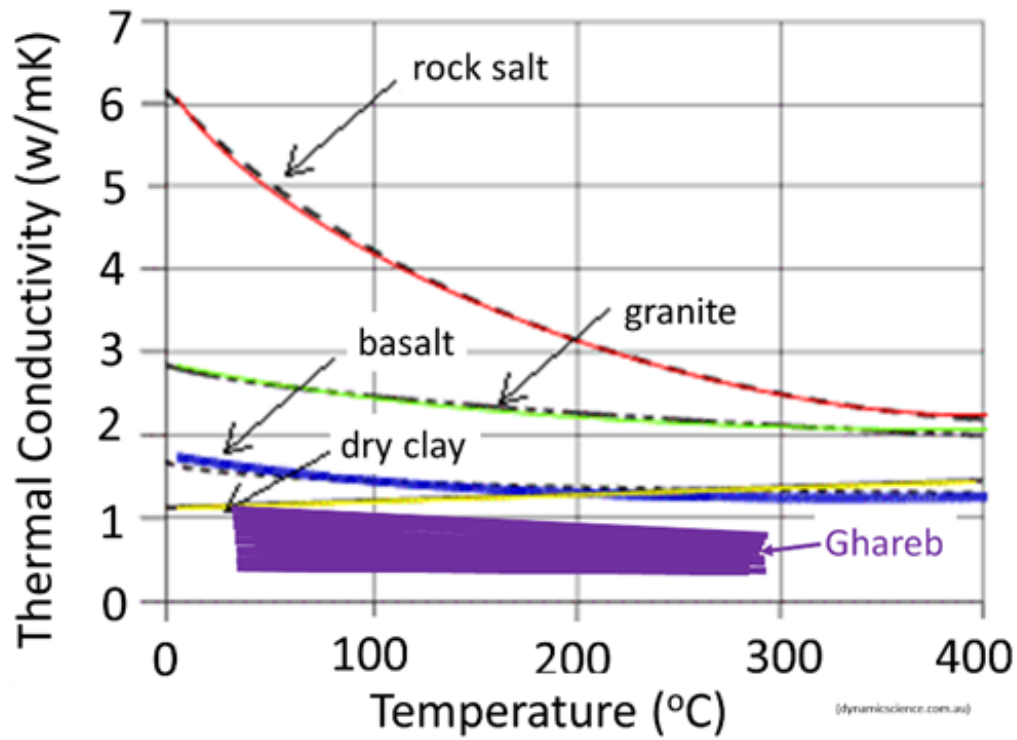
Bauer, S., Choens, C., and Kibikas, W.

Sandia National Laboratories, Albuquerque, NM, USA

Shalev, E., and Lyakhovsky, V.

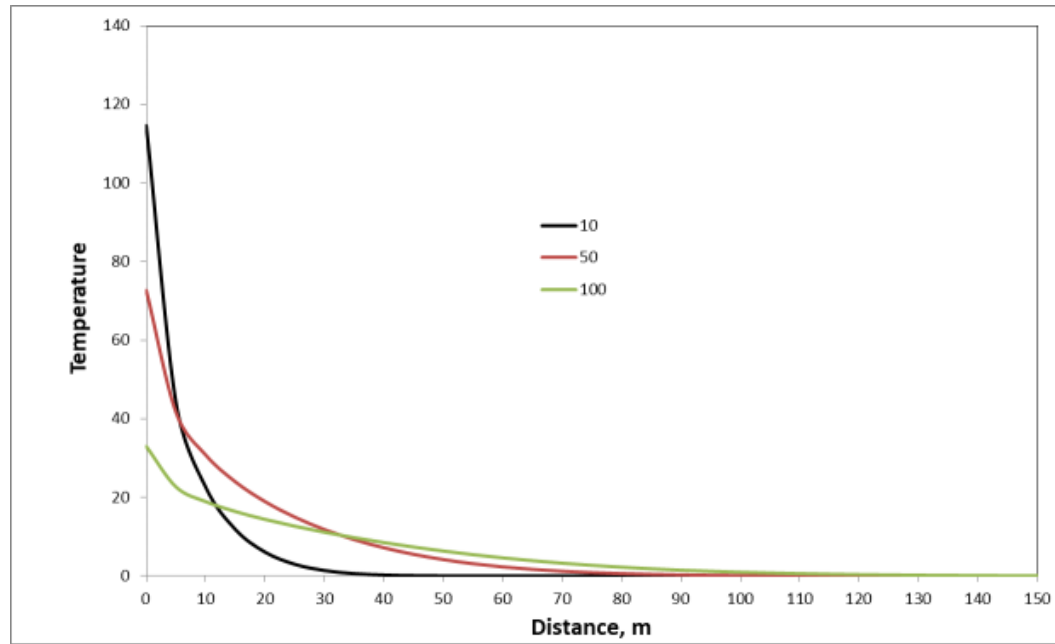
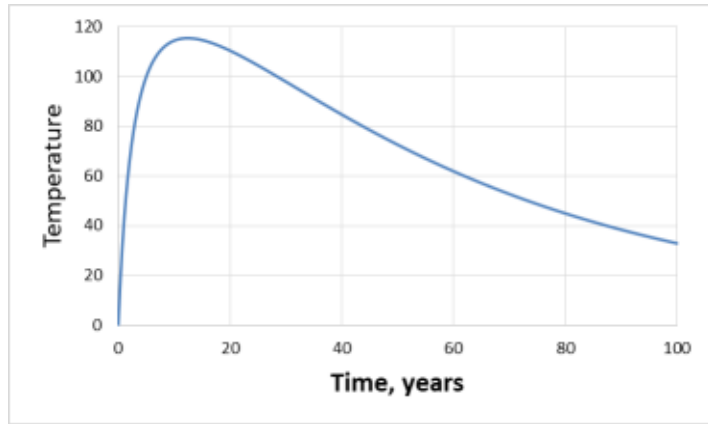
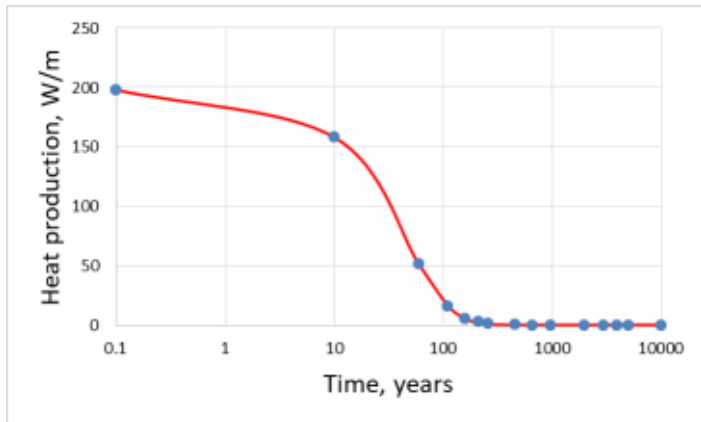
Geological Survey Israel, Jerusalem, Israel





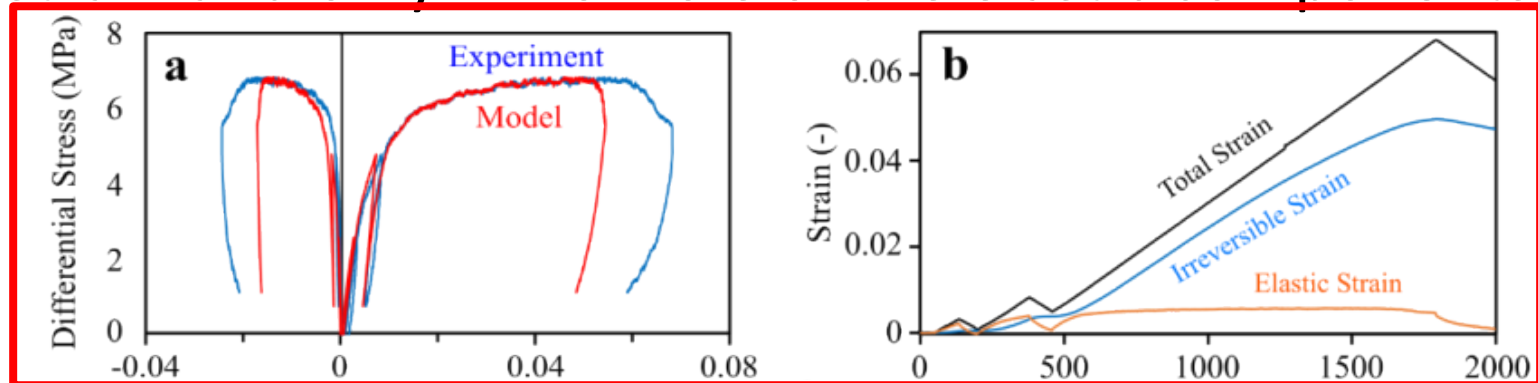
Specific heat 1.5 MJ / m<sup>3</sup> K  
Thermal conductivity 0.7 W / m K

Case 7

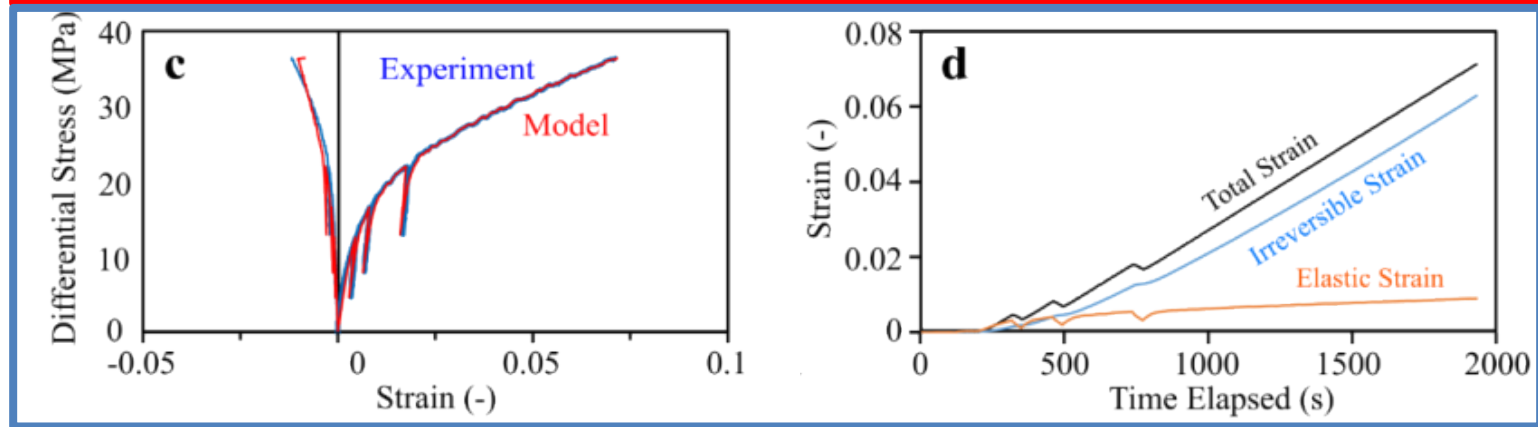


Previous analysis revealed the dominant role of the irreversible strain and only minor role of the elastic components

TT7

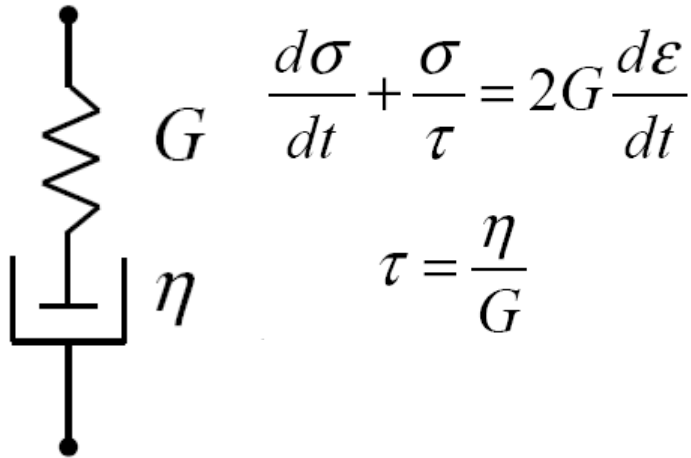


TT9



- Numerical models of low and high pressure tests fit experimental data fairly well (a and c), especially at high pressures
- Strain components derived from experimental data (b and d)

Stress relaxation: Maxwell element



$$\frac{d\sigma}{dt} + \frac{\sigma}{\tau} = 2G \frac{d\varepsilon}{dt}$$

$$\tau = \frac{\eta}{G}$$

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{irr}$$

Earth Science:

Weertman power law

Material Science and Engineering:

Norton's creep power law

$$\frac{d\varepsilon_{irr}}{dt} = A_0 \left( \frac{\sigma}{\sigma_{ref}} \right)^n \exp \left( -\frac{Q}{RT} \right)$$

$\varepsilon_{irr}$  – differential irreversible strain

$\sigma$  – differential stress

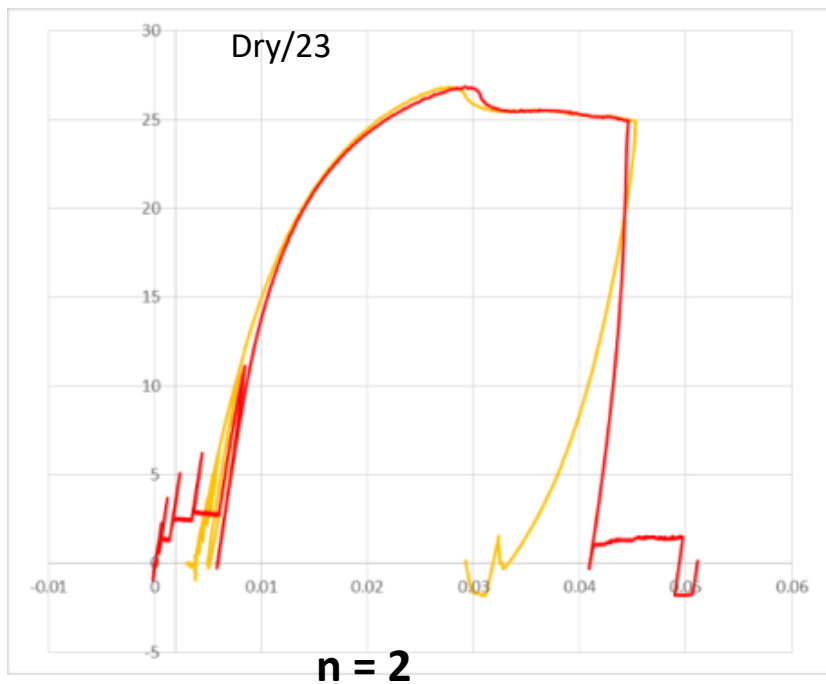
n - power index

Q - activation energy

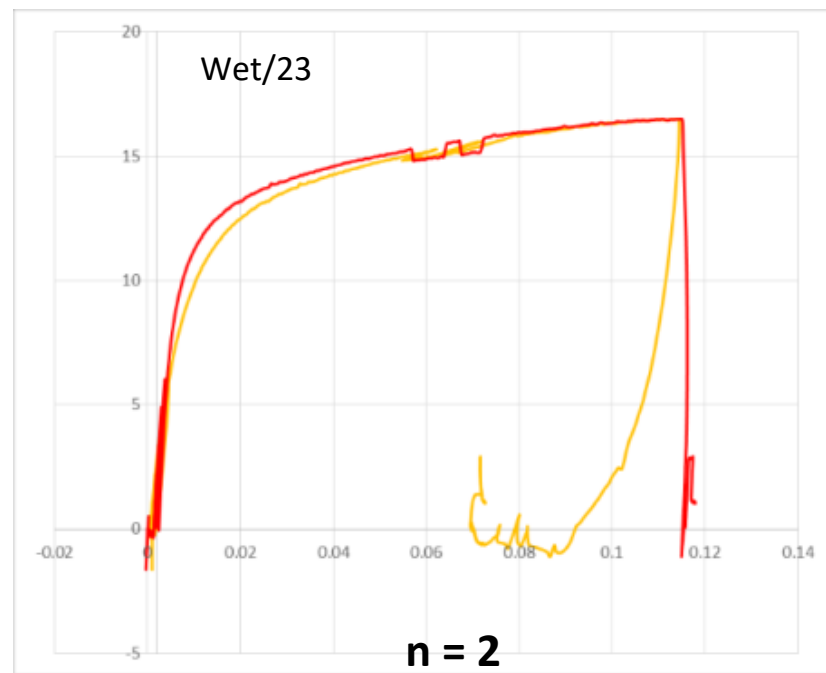
R - gas constant

T - temperature

TP2



TP4



Differential stress

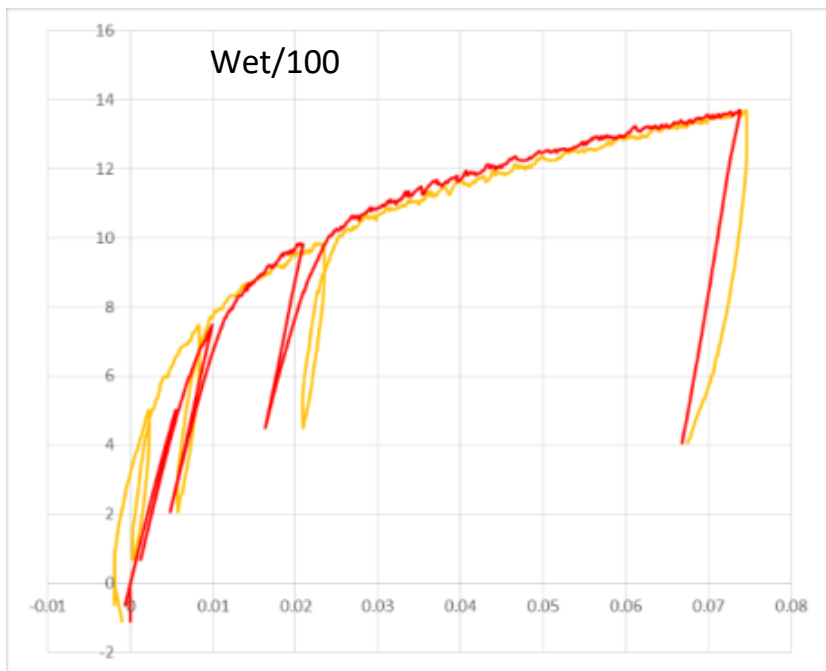
Differential strain

$$A_0 \exp\left(-\frac{Q}{RT}\right) \approx 9e-8 / \text{sec}$$

$$A_0 \exp\left(-\frac{Q}{RT}\right) \approx 1.0e-7 / \text{sec}$$

Similar values

TT5



$n = 2$

$$A_0 \exp\left(-\frac{Q}{RT}\right) \approx 3.5e-7 / \text{sec}$$

Differential strain

TT7



$n = 2$

$$A_0 \exp\left(-\frac{Q}{RT}\right) \approx 1.6e-6 / \text{sec}$$

Values differ by order of magnitude

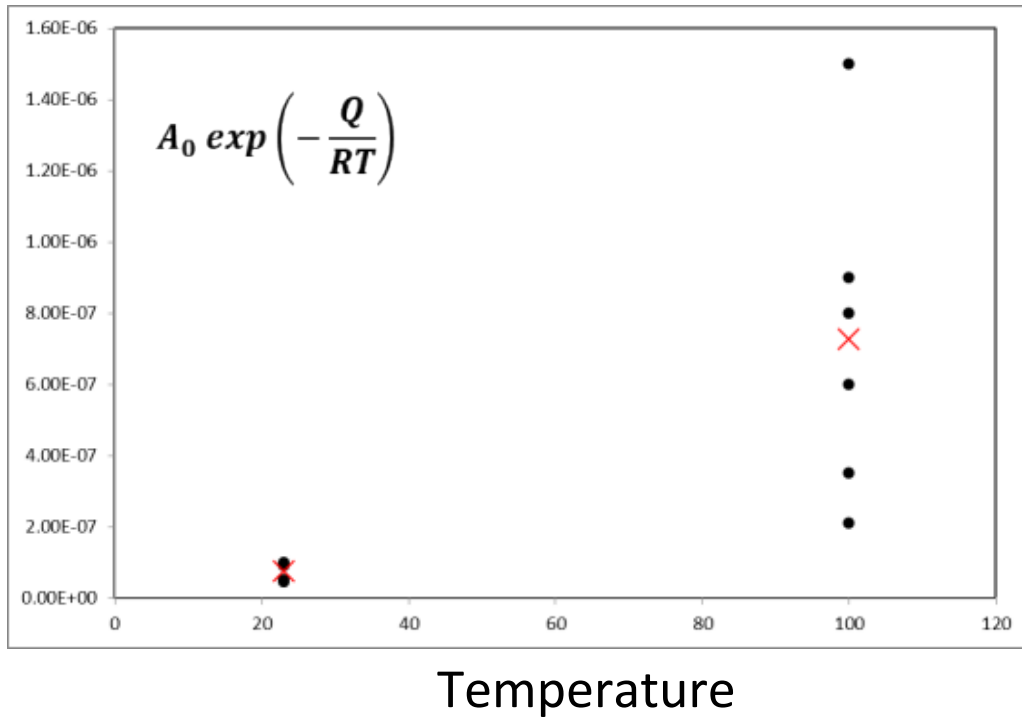
Name		Pconf (MPa)	Pfluid (MPa)	Mu (MPa)	Poisson	$A_0 \exp\left(-\frac{Q}{RT}\right)$ (MPa) <sup>-2</sup> sec <sup>-1</sup>	n
TT1	Wet/100	10	0.7	300	0.2	6.0e-7	2
TT4	Wet/100	10	1	800	0.2	2.1e-7	2
TT5	Wet/100	7	1	500	0.2	3.5e-7	2
TT6	Wet/100	3.4	1	300	0.2	9.0e-7	2
TT7	Wet/100	1.4	0.7	300	0.2	1.5e-6	2
TT9	Wet/100	20	1	1000	0.2	6.0e-8	2
TP1	Dry/23	20.66	0.589	2000	0.2	4.5e-8	2
TP2	Dry/23	3.475	0.584	2000	0.2	9.0e-8	2
TP3	Dry/23	6.9	0.6	2000	0.2	5.0e-8	2
TP4	Wet/23	3.498	0.594	2000	0.2	1.0e-7	2
TP5	Wet/23	20.743	0.588	2000	0.2	9.0e-8	2

## Power law parameters:

$$n = 2$$

$$A_0 = 4.5E-3 \text{ 1/sec}$$

$$Q = 27 \text{ kJ/mol}$$



## Relaxation time scale

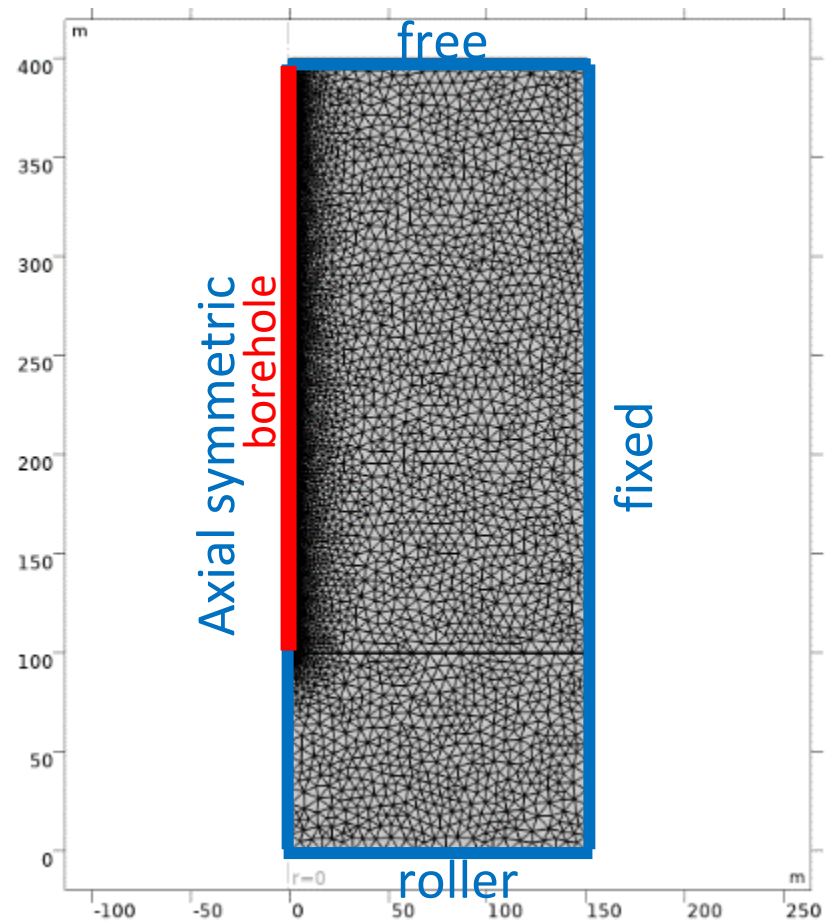
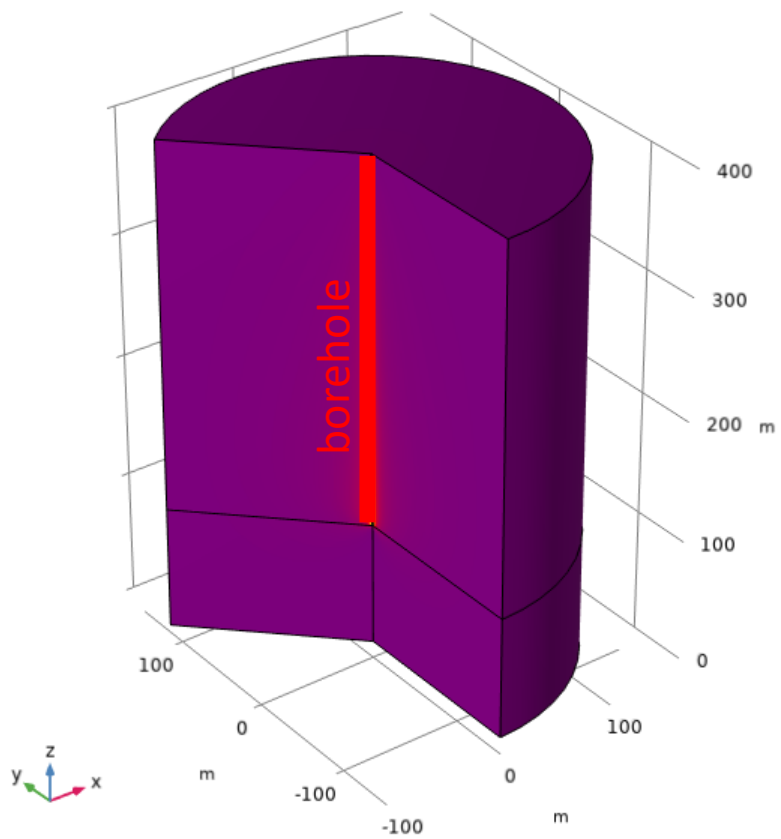
$$\frac{d\varepsilon_{irr}}{dt} = A_0 \left( \frac{\sigma}{\sigma_{ref}} \right)^2 \exp\left(-\frac{Q}{RT}\right) \quad \varepsilon_{elast} = \frac{\sigma}{2\mu}$$

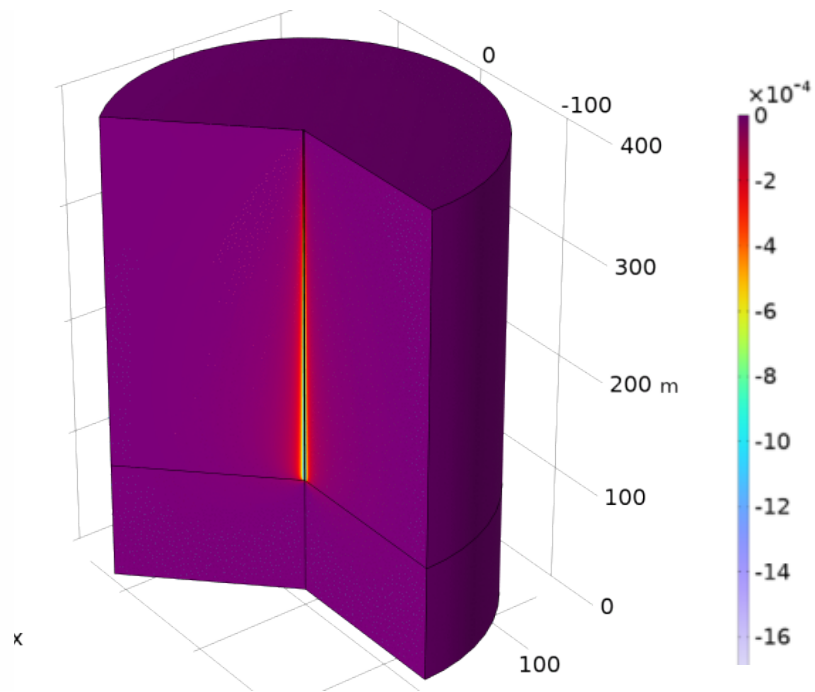
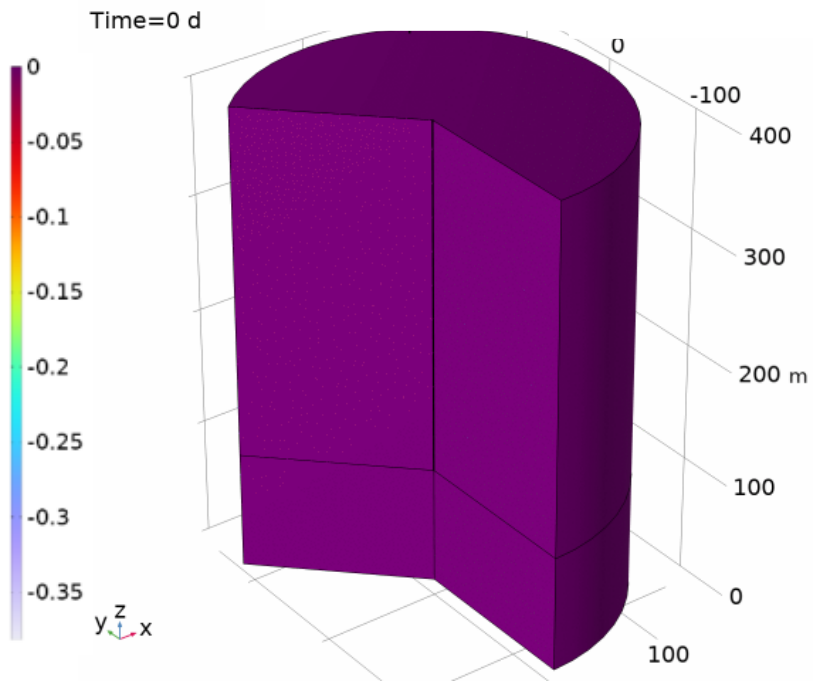
$$\frac{d\varepsilon_{total}}{dt} = \frac{d\varepsilon_{irr}}{dt} + \frac{d\varepsilon_{elast}}{dt} = \frac{1}{2\mu} \frac{d\sigma}{dt} + A_0 \left( \frac{\sigma}{\sigma_{ref}} \right)^2 \exp\left(-\frac{Q}{RT}\right) = 0$$

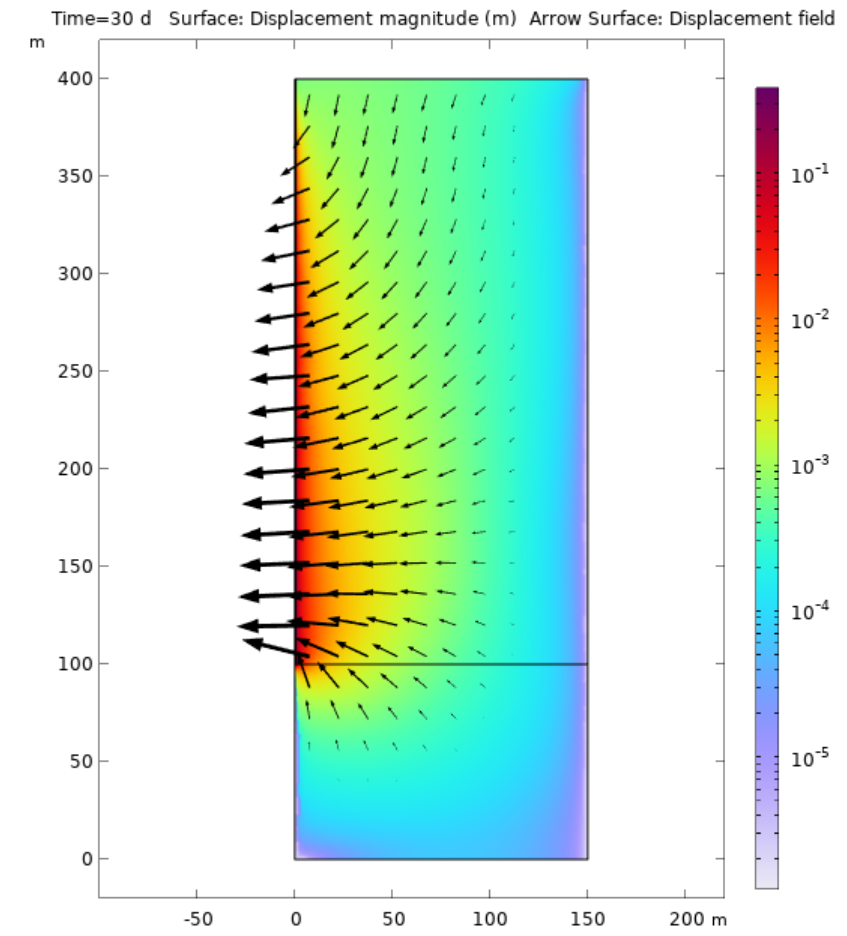
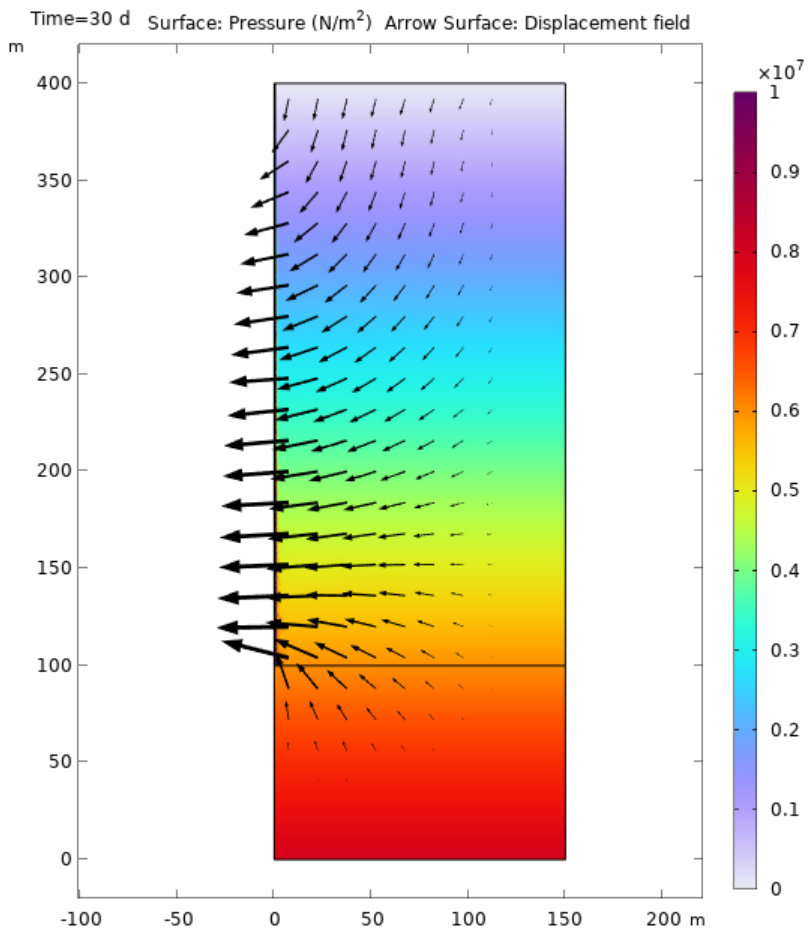
Solution:  $\frac{\sigma(t)}{\sigma_{ref}} \sim \frac{\sigma_{ref}}{2\mu A_0 \exp\left(-\frac{Q}{RT}\right)} \frac{1}{\text{time}}$

time scale

Relaxation time scale at 23°C ~ ten days  
 at 100°C it reduces to days

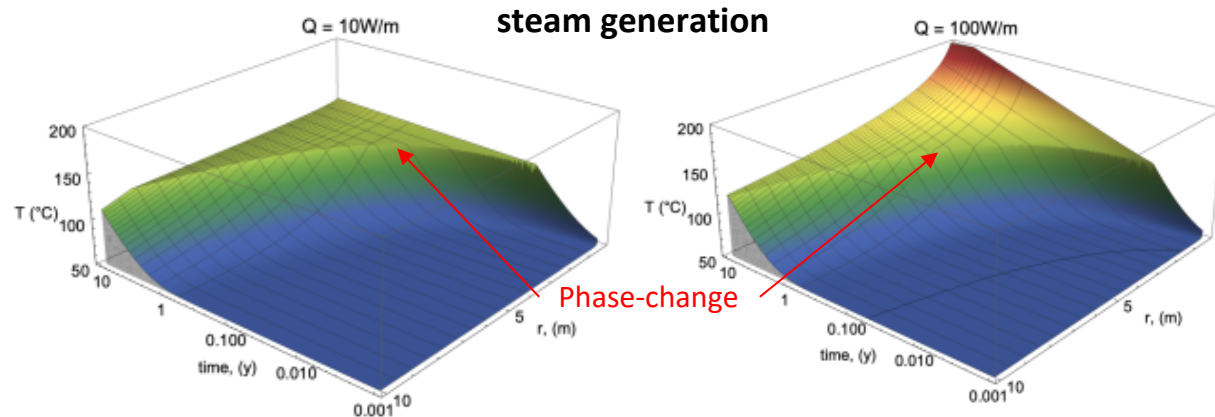
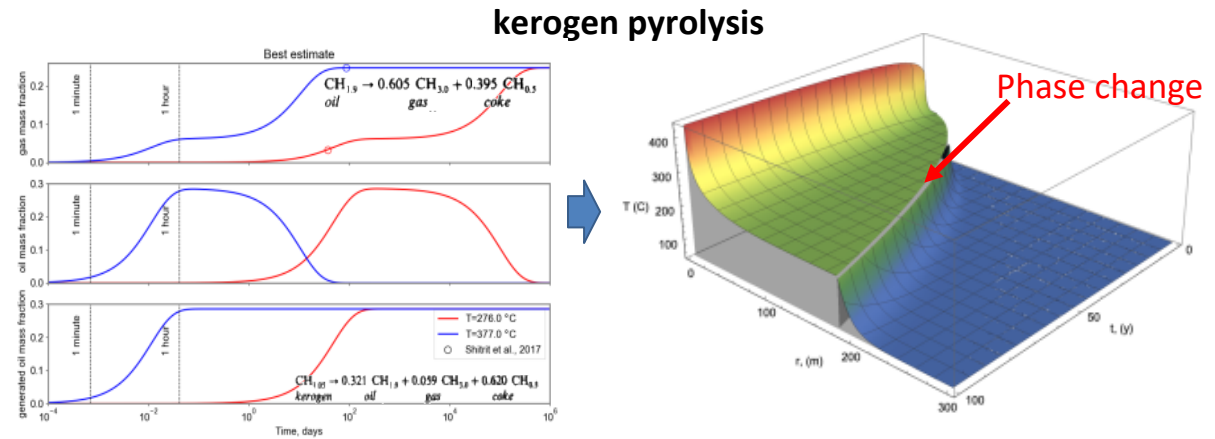






# Thermal Considerations

- Previously we showed that kerogen decomposition is significant in the 200-400C range.
- If the goal is “no emissions” including steam during emplacement – this will significantly limit the allowable heat generation (i.e. storage capacity) per borehole, due to the extremely low thermal conductivity of the rock.
- Simple thermal models show even a low-power heat source will lead to steam generation at the borehole surface in a short time-scale
- Wellbore casing will mitigate steam effects, with steam generation forming at the casing-rock interface.
- Maximizing heat capacity of the waste package may increase time-scales for steam generation.



Steam generation at the formation borehole surface will occur at short time-scales. Further analysis is needed to asses options for containing this steam during emplacement

# Uncertainty Quantification Framework

## Challenges:

- Formation mechanical response shows complicated dependency on temperature, rate, pore pressure, and chemistry.
- There may be differences in the in-situ rock response vs. that measured in the lab for available samples.
- Models with sufficient complexity to capture the full response of the rock will have non-unique parameterizations that are equally well fit to available data

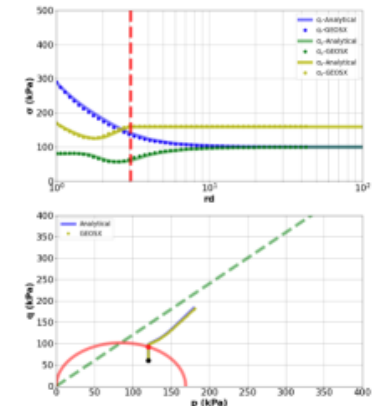
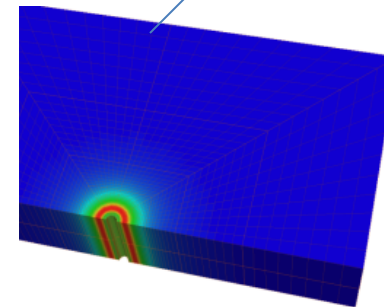
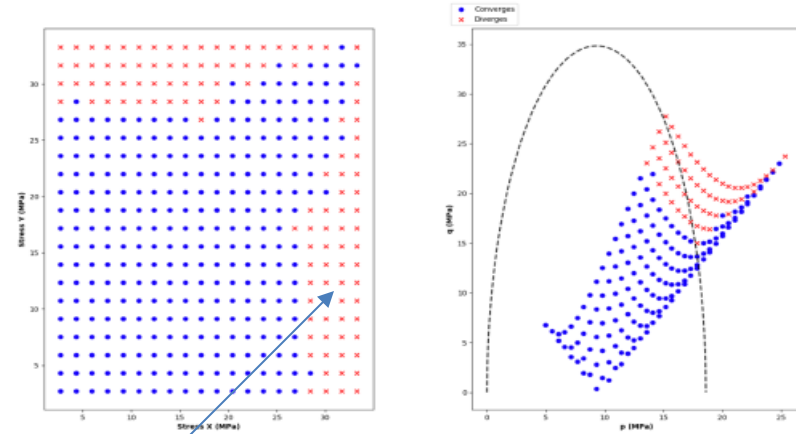
## UQ approach:

- For any plausible model form, we derive an ensemble of parameter sets that equally fit the available experimental data.
- For each model/realization we assess the region of borehole stability (formation stress, pore pressure, temperature, etc.)

## Implementation:

- The GEOSX platform allows finite-element simulations of borehole stability, accounting for multi-phase flow, poro-elasticity, and surface/fracture interactions.
- GPU-acceleration of the assembly and linear solve give GEOSX approach the efficiency needed for UQ in a high-dimensional parameter space.
- Current studies use simplified constitutive models (mod. Cam clay, Drucker-Prager, etc.) but workflow is automated to allow automated fitting and UQ studies as new model forms and data are derived.

Borehole stability envelope for a simple cam-clay material

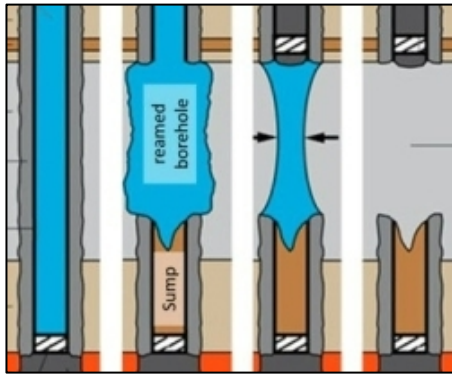


GEOSX borehole stability calculation and verification of plasticity solution

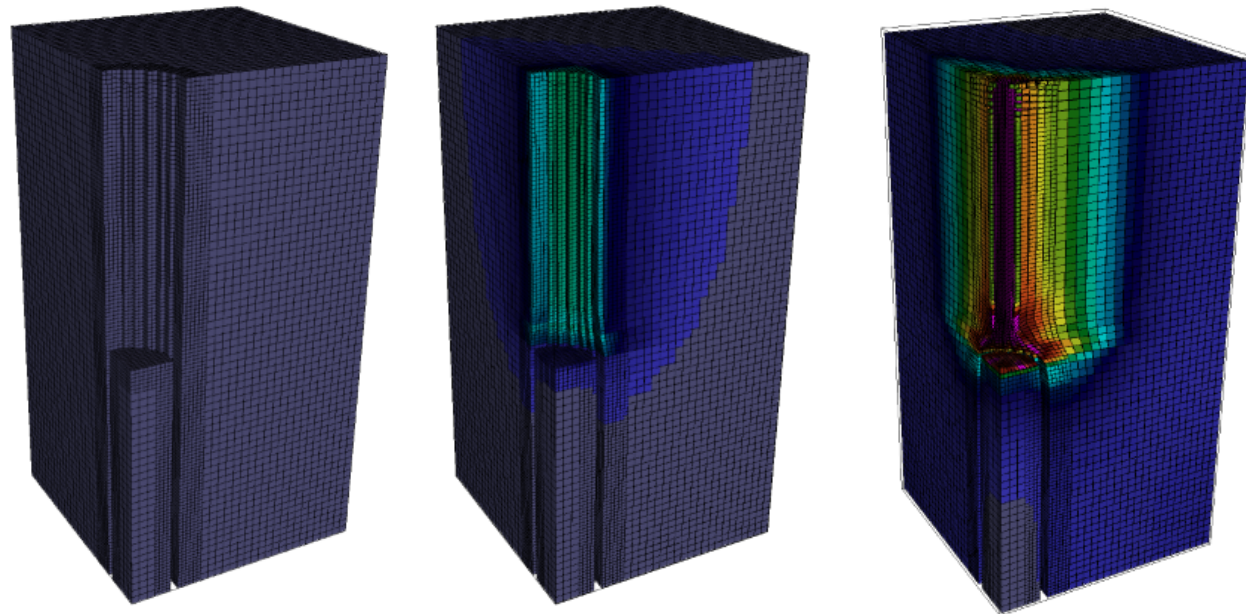
We have developed an automated workflow for model-fitting and parameterized borehole stability analysis in GEOSX towards Uncertainty Quantification of Stability Calculations

# MPM approach for Large-deformation

- Rate-dependent creep deformation of the kerogeneous chalk has motivated a transition from explicit time-integration (suitable for brittle fracture) to implicit FEM solution methods
- Creep events at free surfaces may produce significant local deformation and mesh tangling in Lagrangian FEA codes: lack-of-convergence does not necessarily imply physical instability
- Material Point Method (MPM) provides a robust framework for large-deformation solutions, allowing for analysis of transients of wellbore collapse for prediction of time-scales and loads during these events.



Conceptual Illustration of Creep Collapse

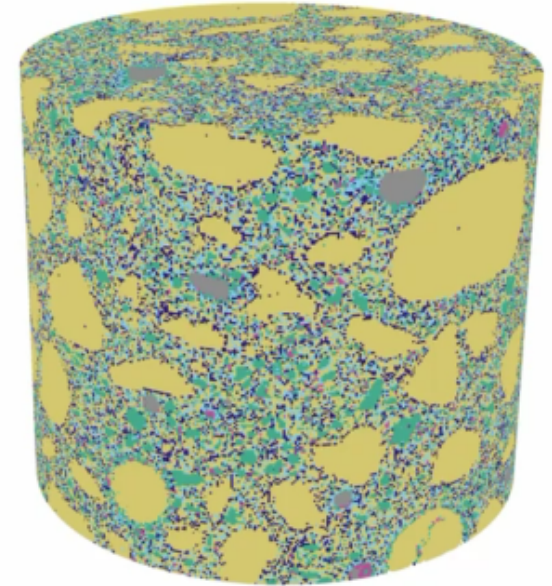


GEOS-MPM Simulation of Wellbore Collapse

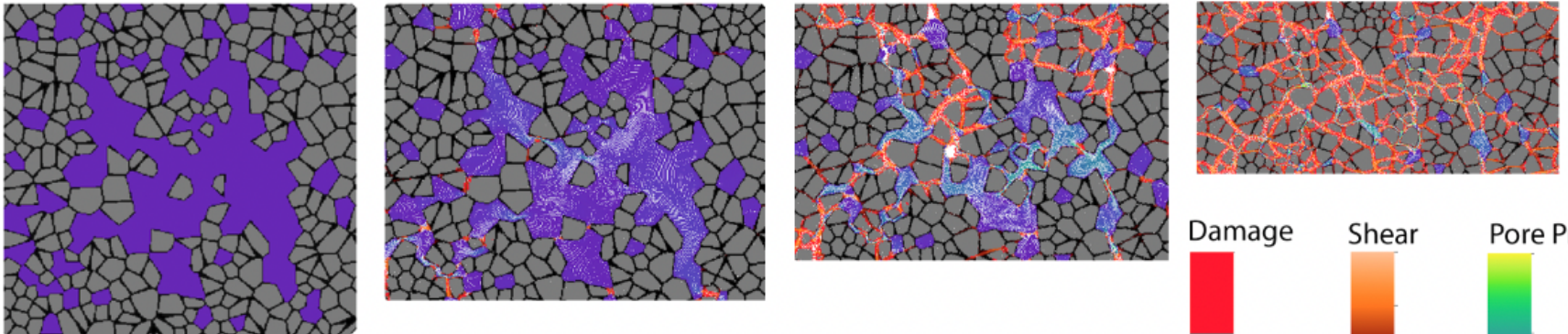
MPM Capability lets us assess the loads on a waste package due to creep collapse of a wellbore

# Mesoscale Simulation

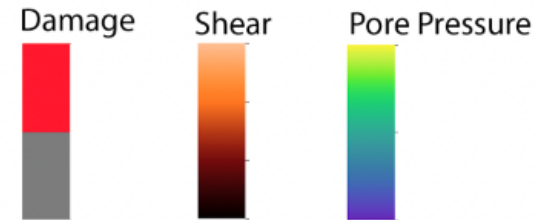
- With limited experimental data, mesoscale modeling can inform understanding of thermal, pore-pressure, and rate effects.
- Recent advances in our multi-physics GEOS-MPM (material point method) code allow mesoscale simulations of compaction and strength testing of heterogeneous materials comprising a brittle crystal, viscoplastic binder, and pore gas/fluid.



3-D GEOS-MPM Mesoscale Simulation



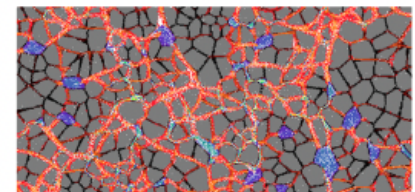
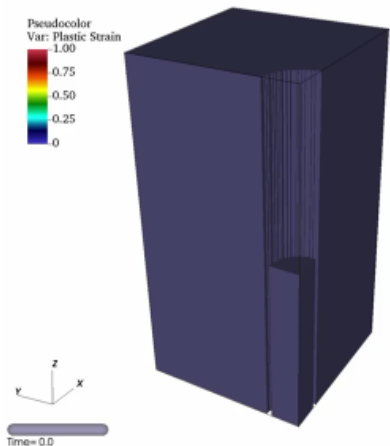
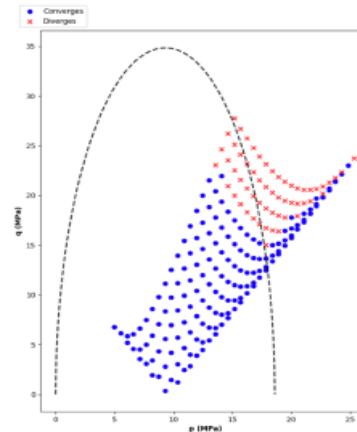
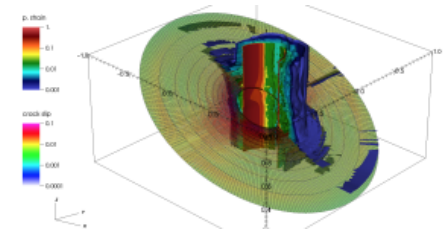
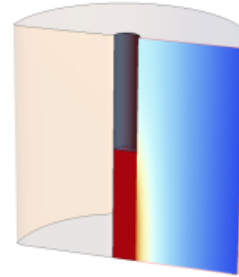
Mesoscale detail showing: Multi-phase, Brittle Damage, and Large-Deformation Plasticity



New simulation capability allows mesoscale modeling of kerogeneous chalk

# Summary: LLNL

- Steam generation at the formation borehole surface is likely in all cases – but containment during emplacement may be possible with sealed casing
- New GEOSX FEM modeling workflow lets us automatically fit material data as it becomes available, and efficiently conduct massive parameter studies to assess stability envelope.
- Material Point Method capability in GEOSX provides a robust capability for numerically-challenging analysis
  - Large-deformation creep response, transient simulation of collapse
  - mesoscale simulation kerogen chalk (phase change, deformation history, and temperature affects)



LLNL has developed workflow and new simulation capability to address uncertainties in predicting borehole stability and thermal-effects

# 2023 Plan

1. Hydrostatic creep tests
2. Prepare borehole samples for analyzing Ghareb properties
3. Test rock properties of borehole samples at low pressures and high temperatures
4. Test thermal properties of different core sections of borehole

# Test Matrix

Quarried Rocks				
Test Type	Confining Pressure (MPa)	Temperature (°C)	Saturation State	Permeability
Triax Creep (fast)	10	100	Dry	No
Triax Creep (slow)	10	100	Dry	No
Hydrostatic Creep	8	20-100	Dry	No
Hydrostatic Creep	8	20-100	Wet	Yes
Hydrostatic Creep	8	20-100	Wet-Undrained	No
Borehole Rocks				
Test Type	Confining Pressure (MPa)	Temperature (°C)	Saturation State	Permeability
Hydrostatic	0-400	20	Dry	No
Triax	2,6,10	20	Dry	No
Triax	2,6,10	20	Wet	No
Triax	2,6,10	100	Dry	No
Hydrostatic Perm	8	20	Wet	Yes
Therm Properties	Ambient	20-275	Dry/Wet	No

Concluding comments/questions?

# Acknowledgements

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