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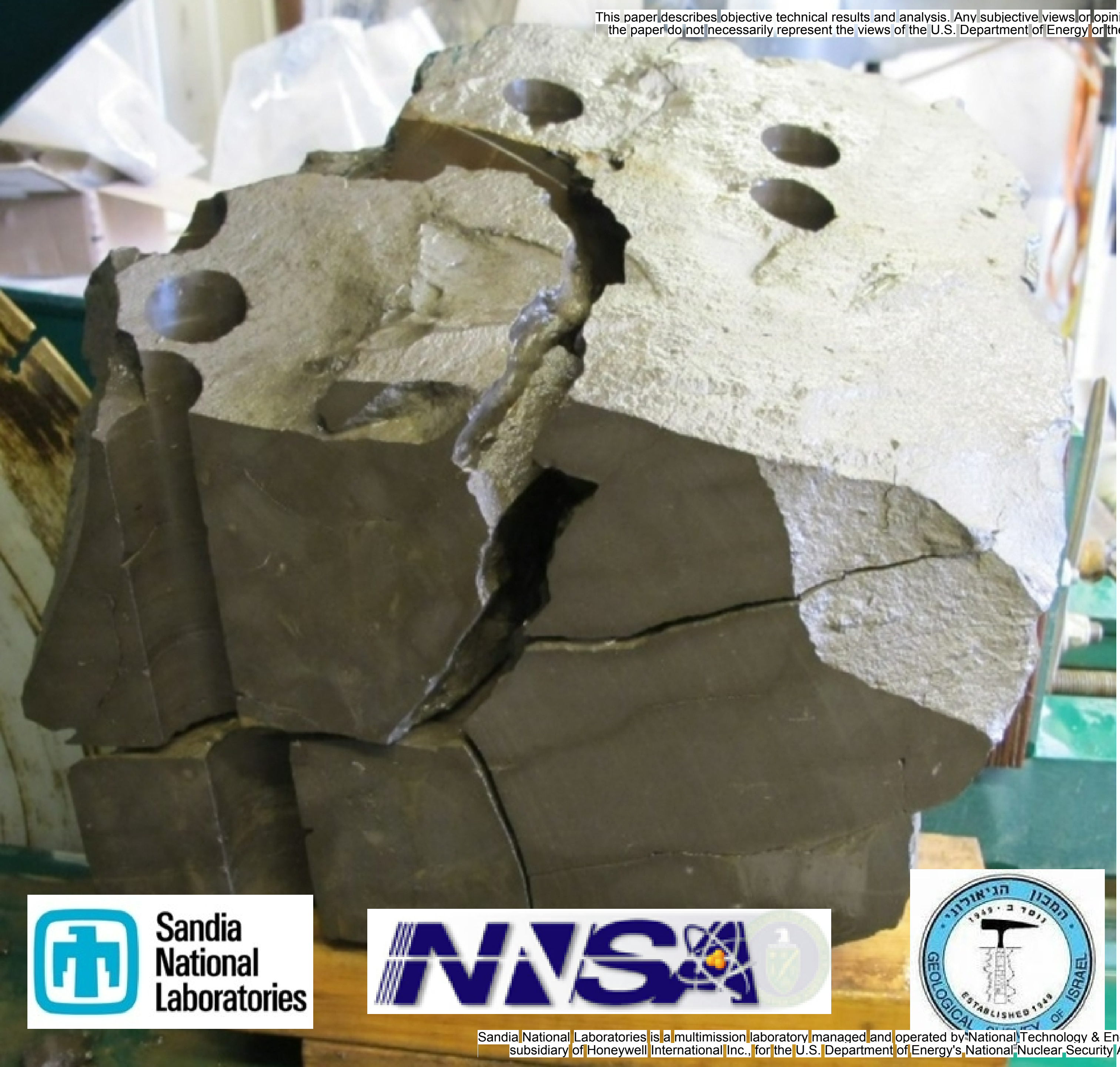

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Thermal-Hydrological-Mechanical Characterization of the Ghareb Formation at Conditions of High-Level Nuclear Waste Disposal

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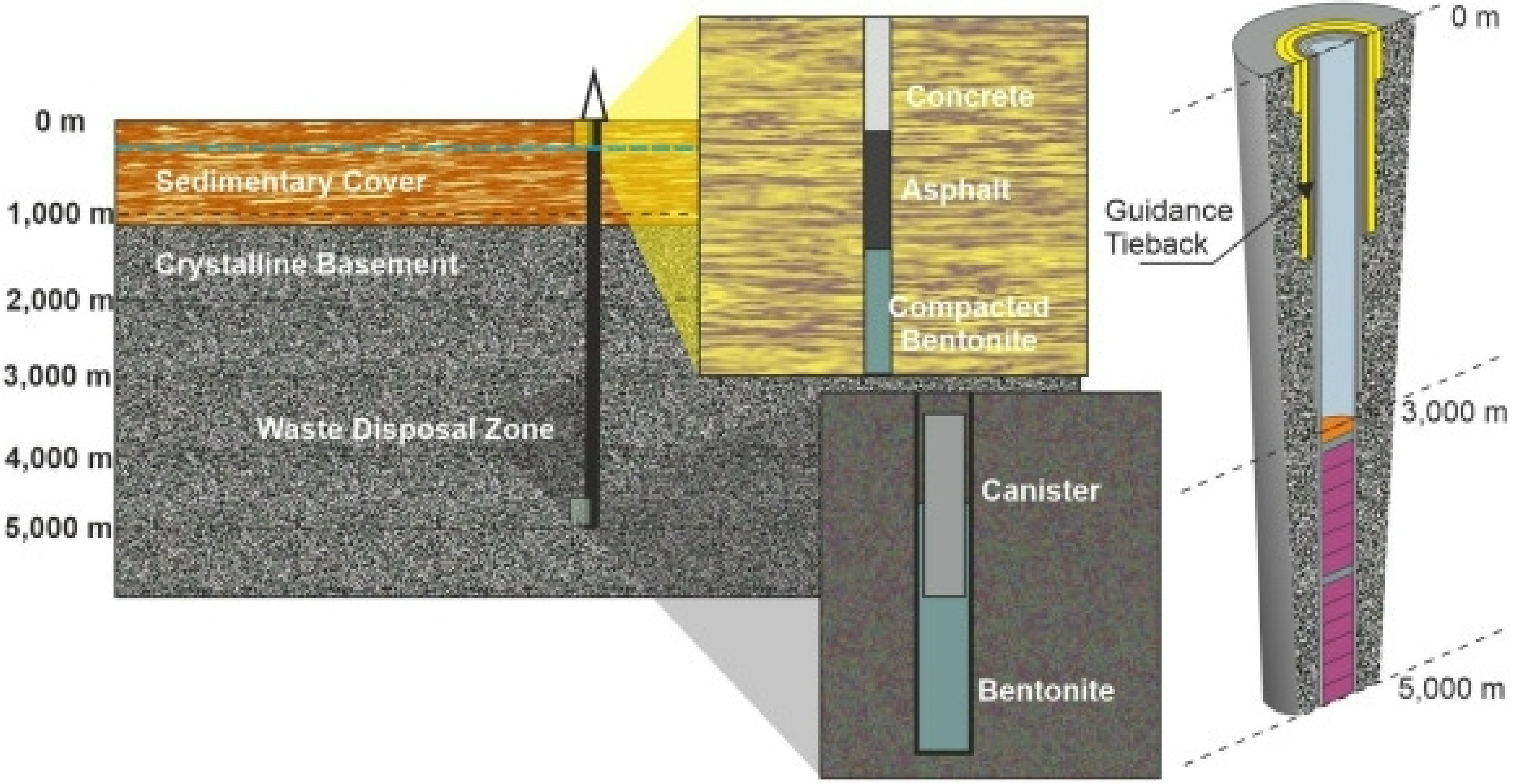
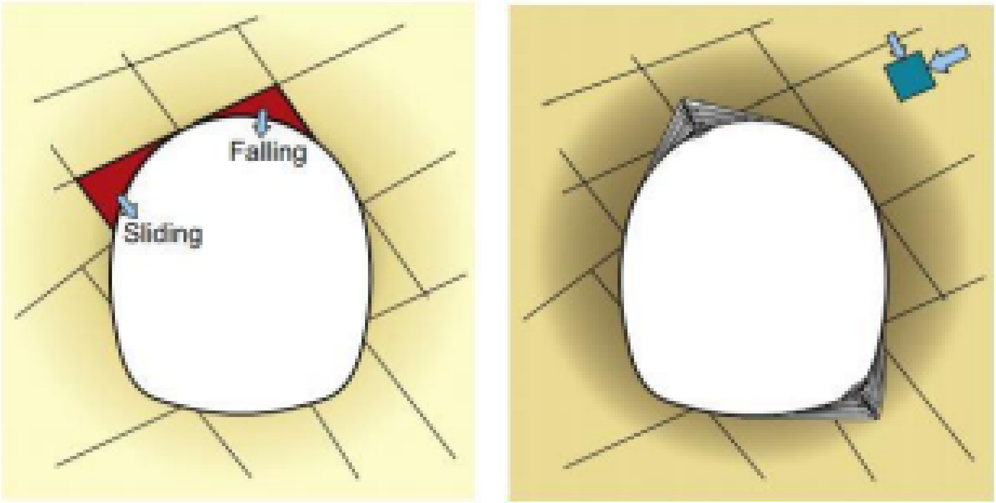
Background

- Disposal of nuclear waste remains ongoing problem worldwide
- One method is subsurface disposal of nuclear waste into geologic repositories
- Despite potential, issues exist that need to be addressed in order to establish the short- and long-term capability of geologic repositories for isolating nuclear waste



Example conceptual model for borehole disposal of nuclear waste from Kochkin et al. (2021)

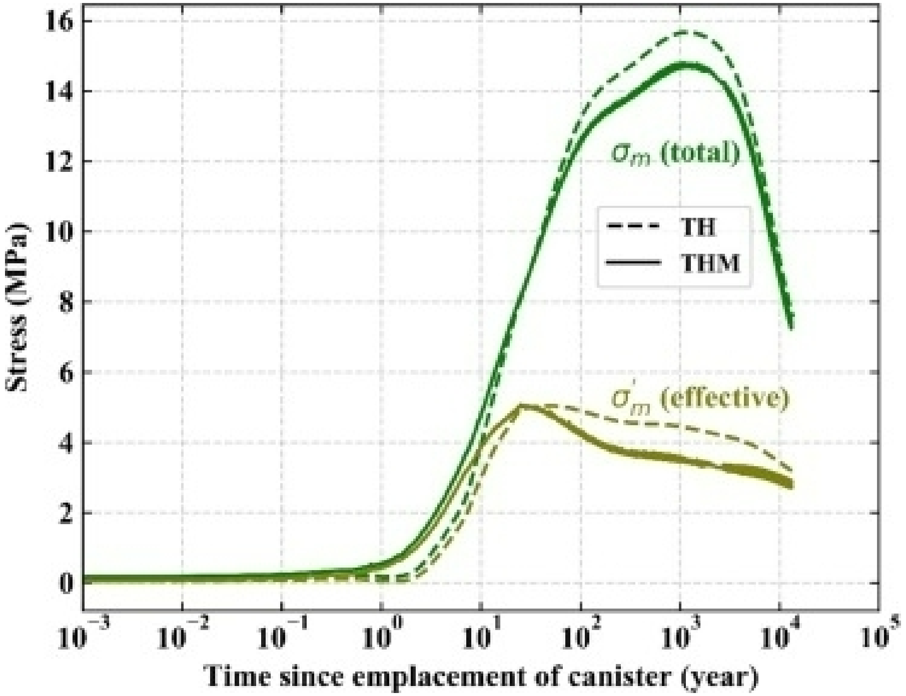
Geomechanical Considerations



Examples of deformation around underground excavation from Martin and Christiansson (2009)

- Rock mass responses to perturbations are coupled thermal-hydrological-mechanical-chemical (THMC) processes
- Deformation can degrade a repository's ability to isolate nuclear waste over time
- To successfully model a repository's behavior during operations, host rock behavior must be adequately quantified to mitigate risk of repository failure

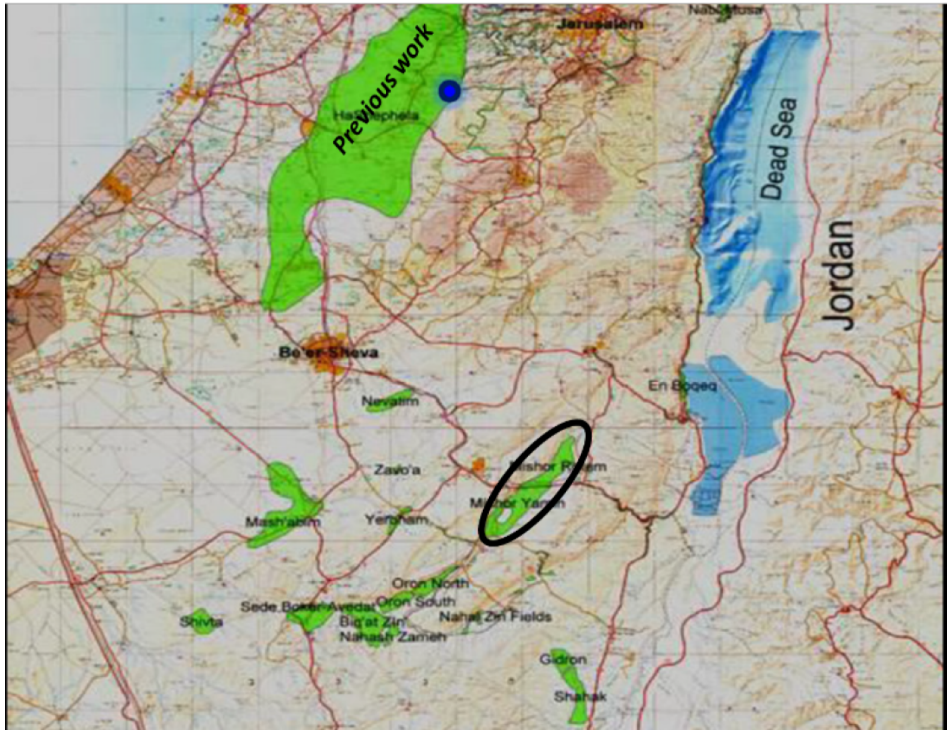
- During construction and operation act ivies of a repository, host rock will be subjected to perturbations of the in-situ stress, temperature, and hydraulic pressure, such as:
  - Thermal stressing generated by waste
  - Pore pressure fluctuations
  - Excavation of underground areas



Modelling effect of mechanical, hydraulic and thermal loading from waste emplacement from Sasaki and Rutqvist (2021)

Ghareb Formation

- Ghareb formation is investigated for potential as nuclear waste repository



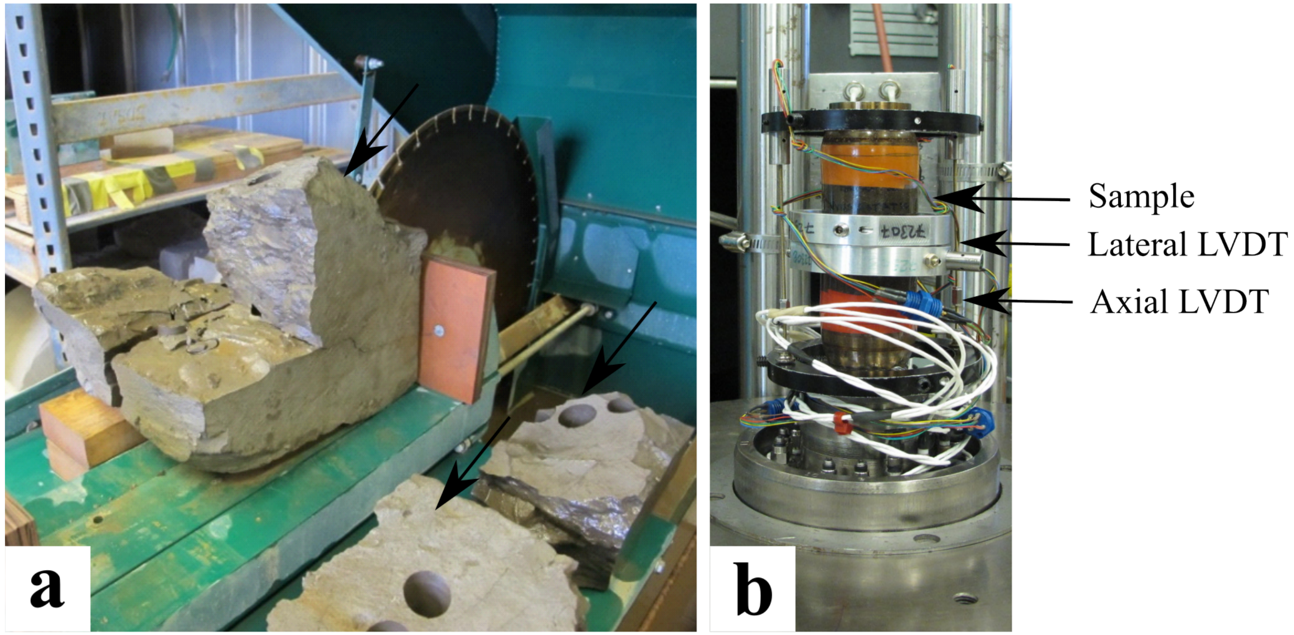
Map showing location potential disposal location in southern Israel

Quarried formation material procured for laboratory testing

- Organic-rich carbonate chalk/mud
- Depth: ~500 m
- Porosity: 20-40 %
- High sulfur and kerogen content

Methodology

- Expand on previous geomechanical work (Bauer et al., 2019; Bauer and Choens, 2020; Bauer et al., 2021)
- Three types of tests:
  1. Triaxial deformation tests with dry and wet samples measuring permeability during testing
  2. Triaxial deformation tests with wet samples at 100 C°
  3. Hydrostatic creep tests measuring permeability



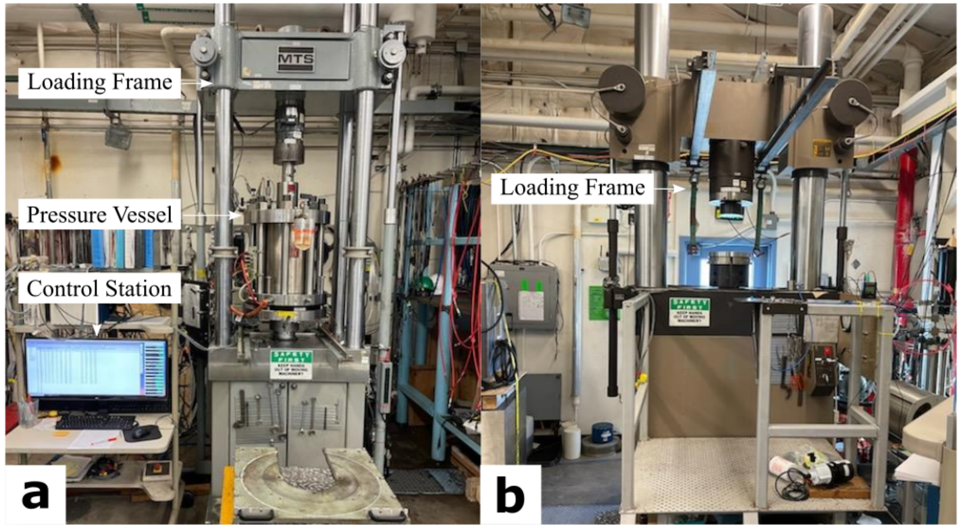
Methodology

Triaxial tests at 23 C°

- Confining Pressures: 3.5-20.7 MPa
- Pore Pressures: 0.6 MPa
- Dry and water-saturated samples tested
- Differential stress was unloaded to 0 MPa at intervals for 1 hour to measure permeability change
- Load-unload cycles were used to determine elastic moduli of samples
- Deformed until failure or uniform deformation behavior was occurring

Triaxial tests at 100 C°

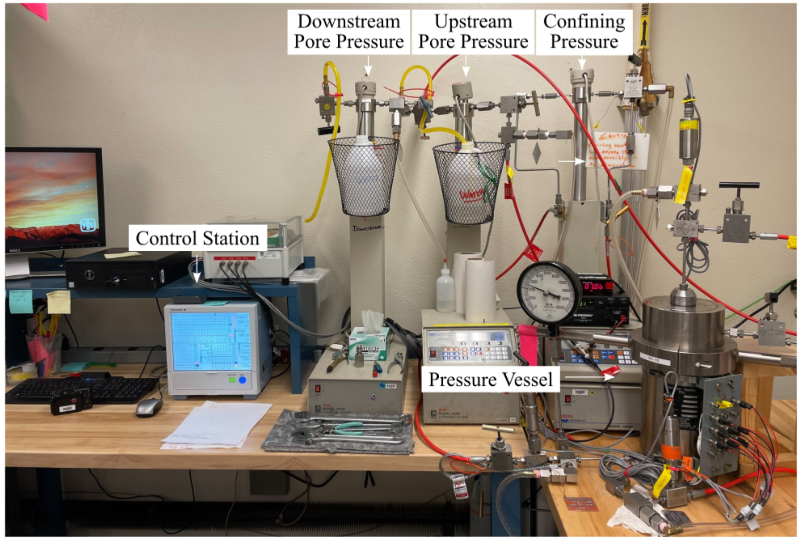
- Confining Pressures: 1.4-20.7 MPa
- Pore Pressures: 0.6 MPa
- Water-saturated samples
- Load-unload cycles were used to determine elastic moduli of samples
- Deformed until failure or uniform deformation behavior was achieved



Triaxial apparatus for deformation tests at 23 C° (a) and 100 C° (b)

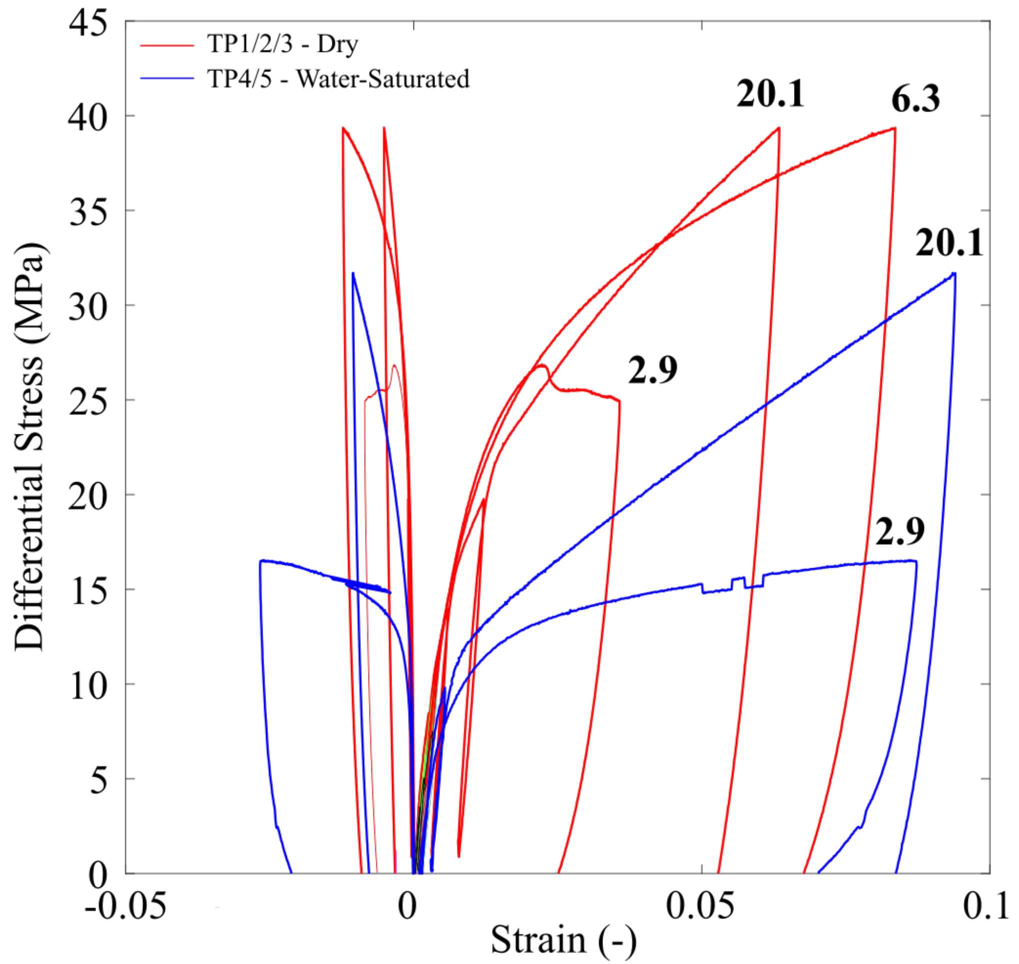
Hydrostatic Creep Tests

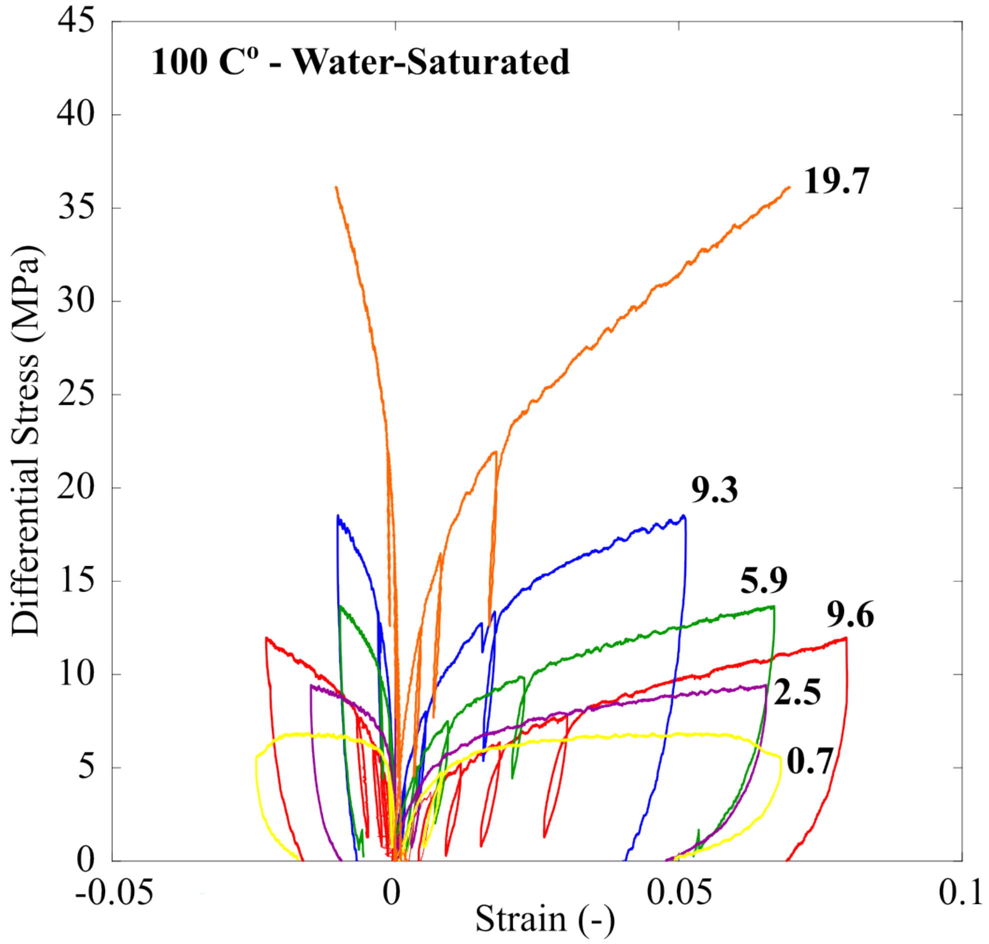
- Confining pressure was incrementally increased to 20 MPa, then to 0 MPa
- Pressure increments held for 1-4 days, then pressure increased or decreased
- Differential pore pressure maintained between sample ends to measure permeability during testing



Pressure vessel for hydrostatic creep tests

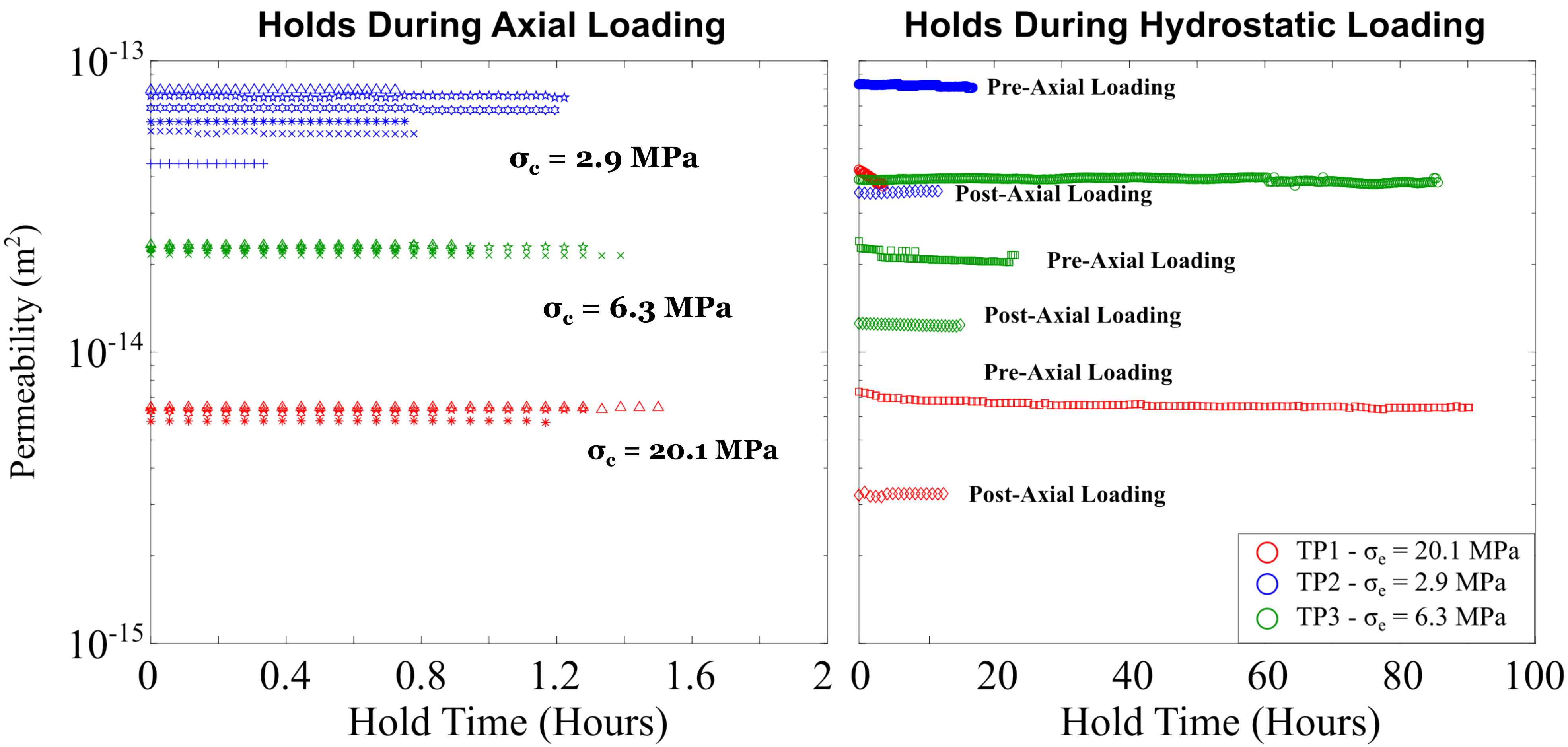
Results: Triaxial Tests





- Rocks are not macroscopically brittle, failure only occurs for dry conditions at room temperature and lowest pressure conditions
- Water and temperature both degrade rock strength response to increased loading compared to dry conditions

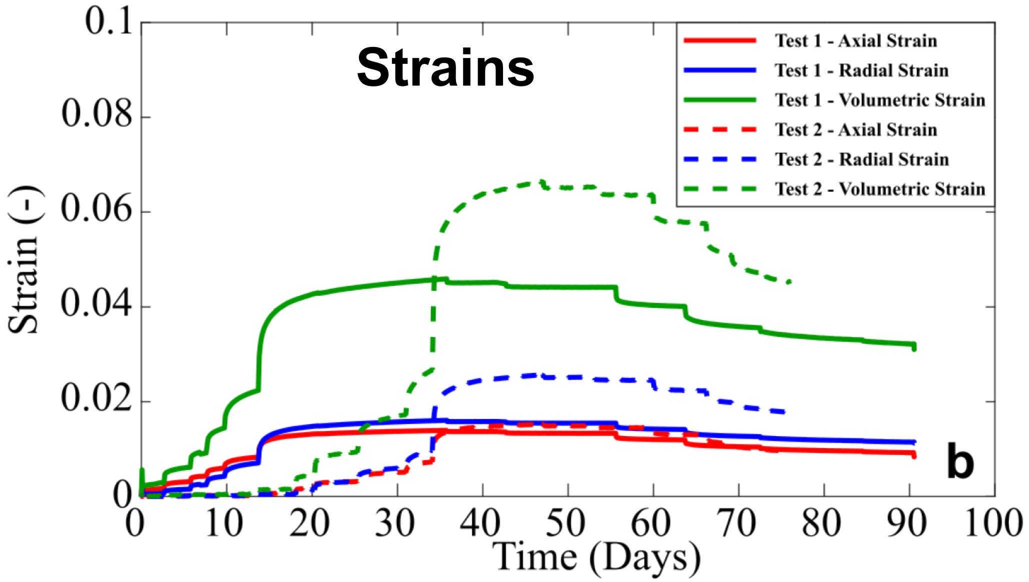
Results: Triaxial Tests - Permeability

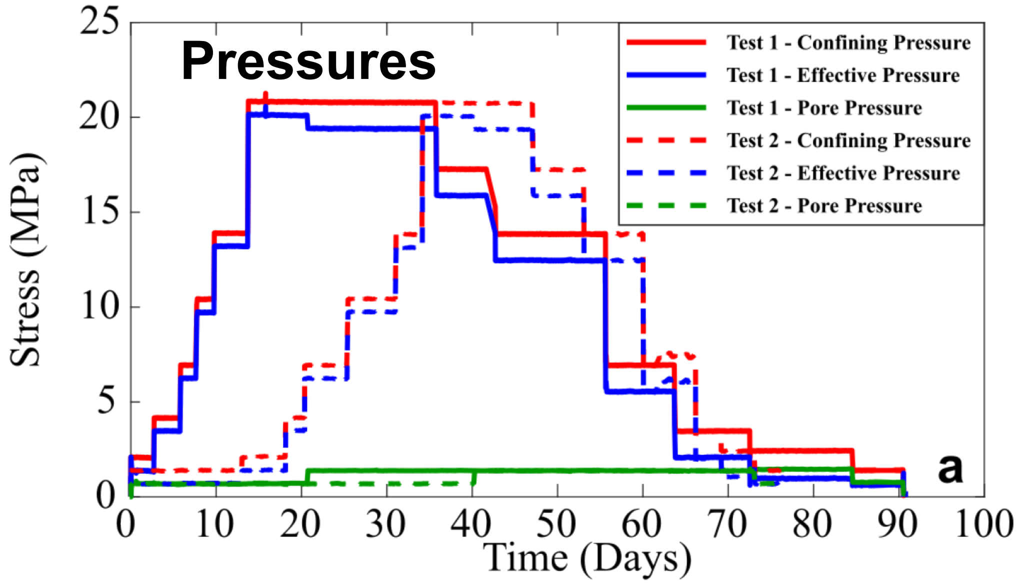


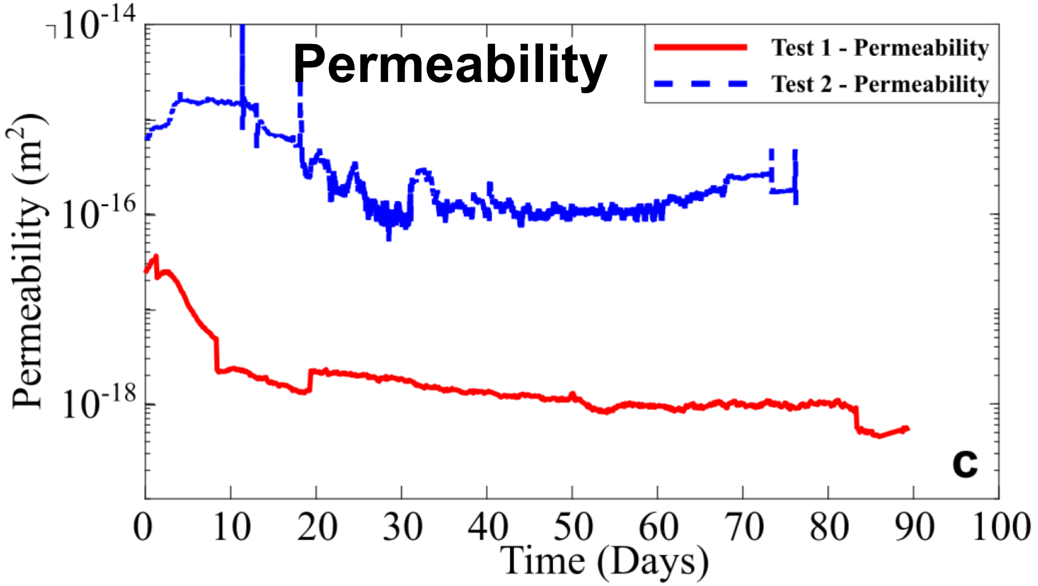
- Permeability decreases with each subsequent unload of differential stress, but change is greater at lower confining pressures
- Permeability reduced by 40-55% after axial loading is ended in all tests

Results: Hydrostatic Creep Tests

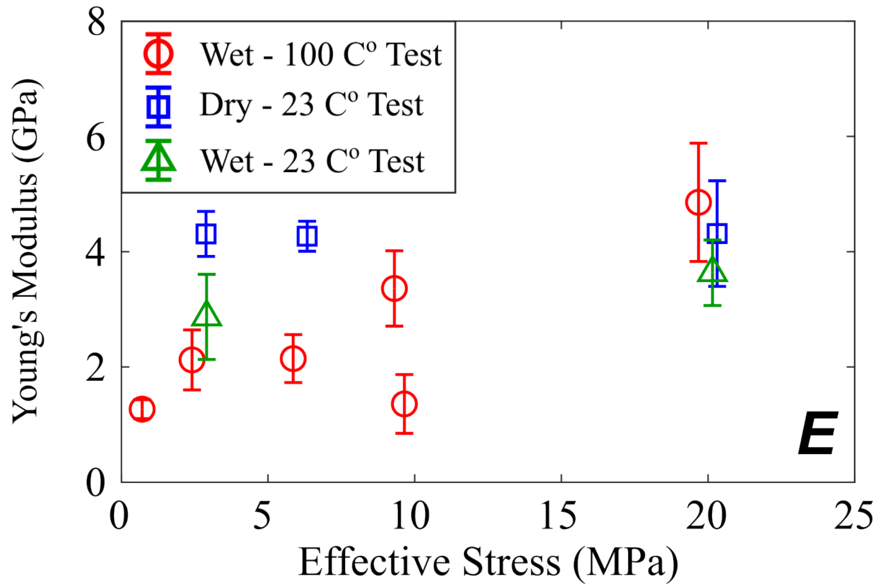
- 2 Tests
- Creep results in .5-1 magnitude of permanent permeability loss
- At 15-20 MPa, radial strain exceeds axial strain and remains higher for remaining test

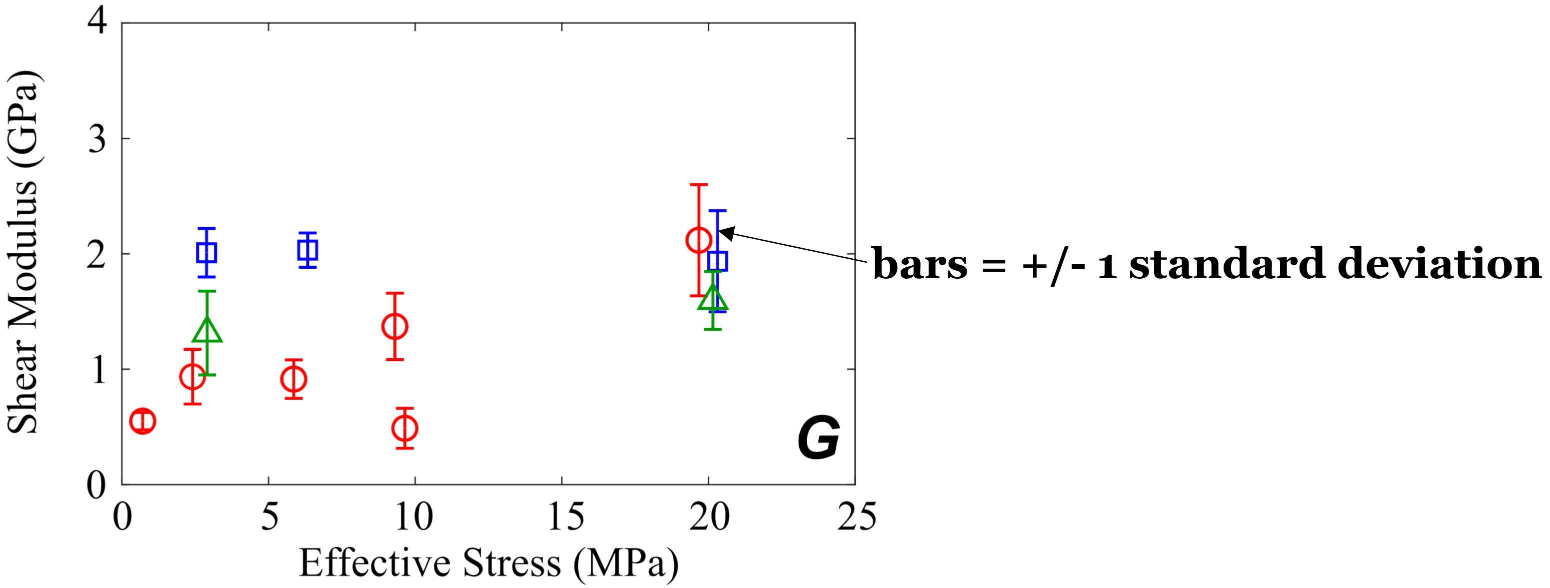


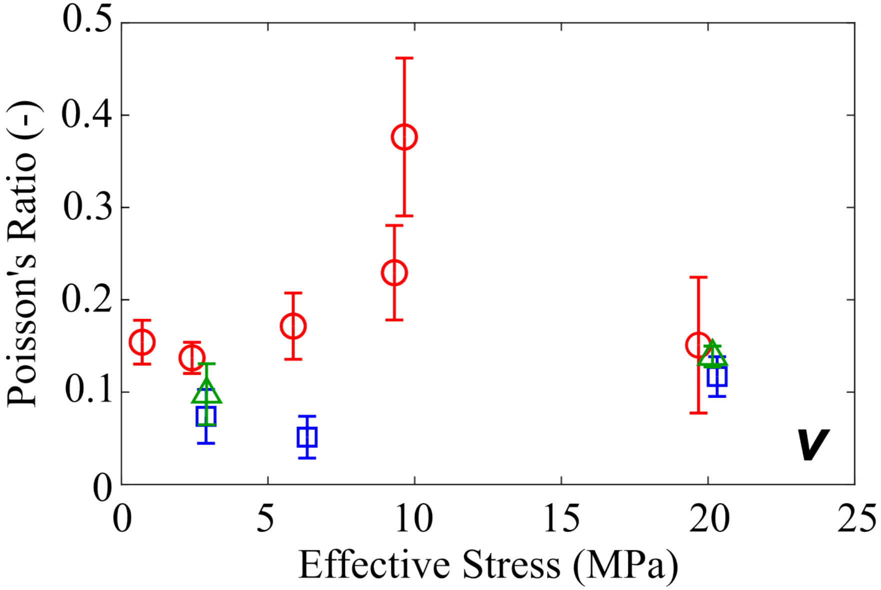




Analysis: Elastic Properties







- Young's and shear modulus increase with effective pressure applied
- Poisson's ratio is more variable, but does not significantly vary from 0.1-0.2 at all conditions
- Water and temperature reduce elasticity at lower pressures (lower *E/G*, higher *v*), but at higher pressure (>10 MPa) values the differences are reduced

Analysis: Numerical Modelling

$$\varphi_{eq}(P) = \varphi_f + A\exp\left(-\frac{P}{B}\right)$$

$$\Phi_{ij}^{(eq)} = A\left[\delta_{ij} - \exp\left(-\frac{P}{B_1}\delta_{ij} - \frac{\tau_{ij}}{B_2}\right)\right]$$

$$\frac{d\Phi_{ij}}{dt} = C * P\left(\Phi_{ij}^{(eq)} - \Phi_{ij}\right)$$

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{d} + \Phi_{ij}$$

$$\Phi_a^{(eq)} = A\left[1 - \exp\left(-\frac{P}{B_1} - \frac{\tau_a}{B_2}\right)\right]$$

$$\Phi_t^{(eq)} = A\left[1 - \exp\left(-\frac{P}{B_1} - \frac{\tau_b}{B_2}\right)\right]$$

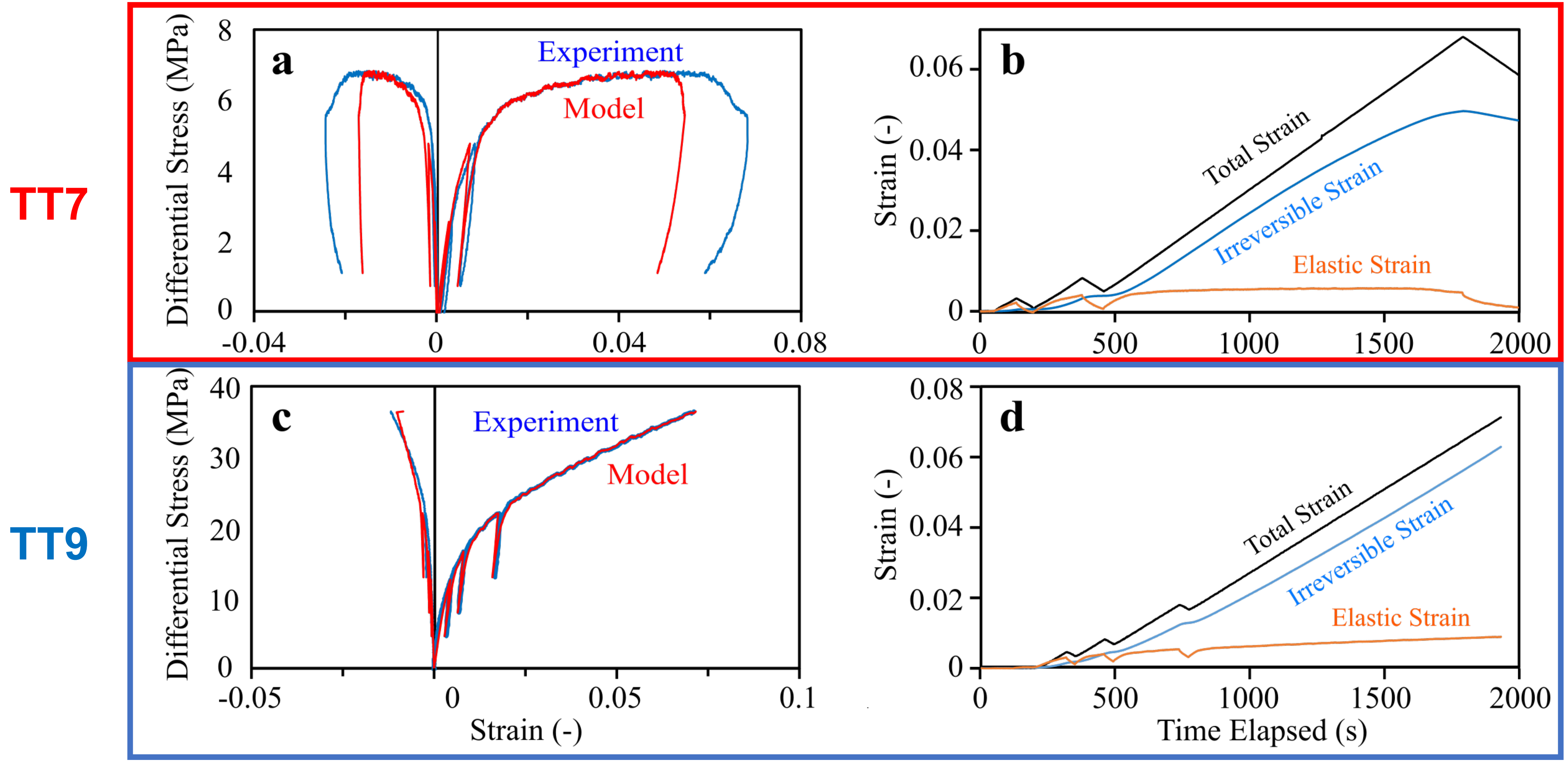
$$\frac{d\Phi_a}{dt} = C_a P\left(\Phi_a^{(eq)} - \Phi_a\right)$$

$$\frac{d\Phi_t}{dt} = C_t P\left(\Phi_t^{(eq)} - \Phi_t\right)$$

Name	Condition	T	G	v	A	B_1/B_2	C_a/C_t
		C˚	MPa	-	%	MPa	$\%*(MPa*s)^{-1}$
TP1	Dry	23	1700	0.2	20	50/40	0.0053/0.005
TP2	Dry	23	1700	0.2	20	50/40	0.006/0.02
TP3	Dry	23	1700	0.2	20	50/40	0.0048/0.01
TP4	Wet	23	1200	0.2	30	50/30	0.017/0.02
TP5	Wet	23	1000	0.2	20	50/30	0.011/0.0045
TT1	Wet	100	600	0.2	20	50/20	0.0057/0.008
TT4	Wet	100	1000	0.2	15	70/20	0.005/0.0012
TT5	Wet	100	800	0.2	25	50/15	0.0055/0.0015
TT6	Wet	100	1000	0.2	20	50/15	0.025/0.01
TT7	**Wet**	**100**	**800**	**0.2**	**30**	**50/10**	**0.022/0.01**
TT9	**Wet**	**100**	**1000**	**0.2**	**20**	**50/20**	**0.0012/0.00035**

Triaxial tests and model parameters

Analysis: Numerical Modelling



- 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)

Concluding Remarks and Future Work

- The coupling of THMC processes in the Ghareb formation was shown through experimental deformation tests
- The potential repository rock was shown to be mechanically soft/weak material
- The variance of rock properties in samples was demonstrated based on potential changes to in-situ conditions induced during waste disposal operations
- Water saturation and elevated temperatures further weaken material
- Short- and long-term permeability alterations were shown to be heavily dependent on the initial porosity and permeability, and the material displays deformation anisotropy
- Numerical modelling of experiments reasonably approximated observations, demonstrating viability for future modelling of repository behavior
- Future work will evaluate the effects of loading rate, permeability, and time into modelling Ghareb deformation during operations

Acknowledgements

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This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.