Shear Enhanced Permeability In a Utah FORGE Granitoid Fracture

Project: Experimental Determination and Modeling-Informed Analysis of Thermo-poromechanical Response of Fractured Rock for Application to Utah FORGE/5-2615

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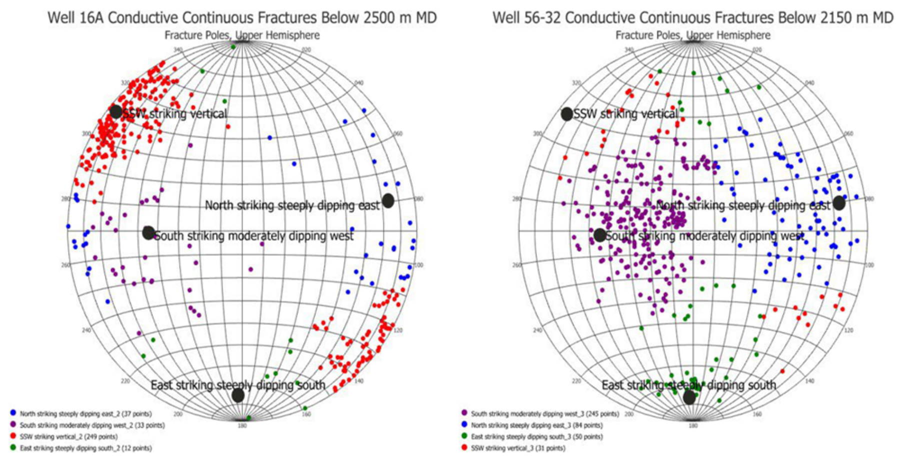
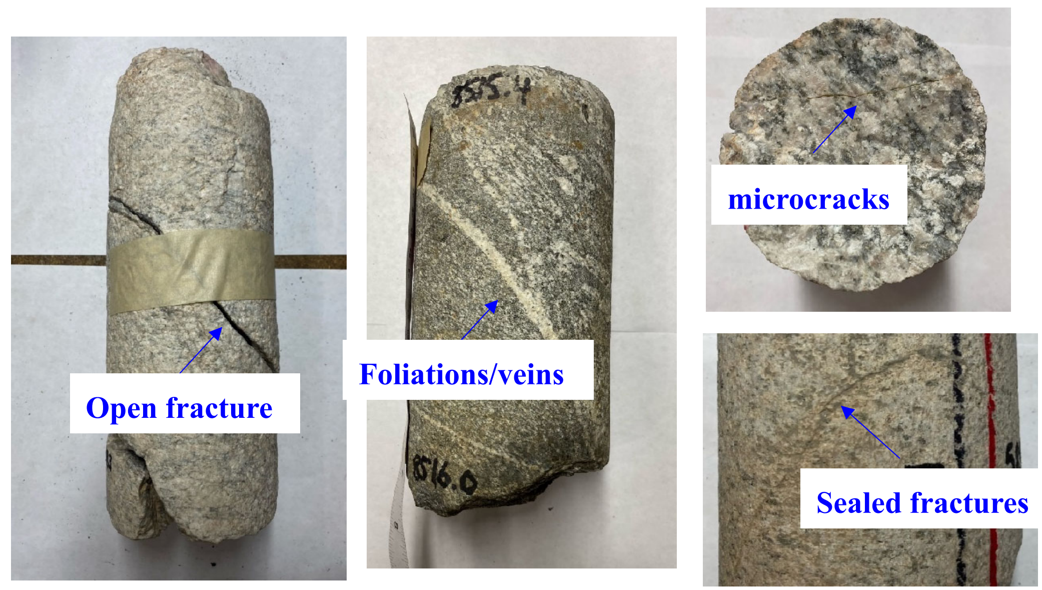
Background

- **Natural Fractures in FORGE**
  - Abundant natural fractures in FORGE EGS reservoir (4 major fracture sets)
  - Different types and scales of natural fractures/discontinuities



		Set 1: South striking moderately dipping west	Set 2: East striking steeply dipping south	Set 3: SSW striking vertical	Set 4: North striking steeply dipping east
Intensity	P_{32}	0.42	0.35	0.19	0.2
	%	36.1	30.1	16.6	17.2
Orientation	Mean Strike [deg]	179	92	221	350
	Mean Dip [deg]	44	77	85	73

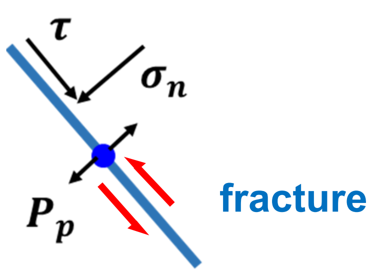
(Finnila et al., 2021)



FORGE core samples (well 78B-32)

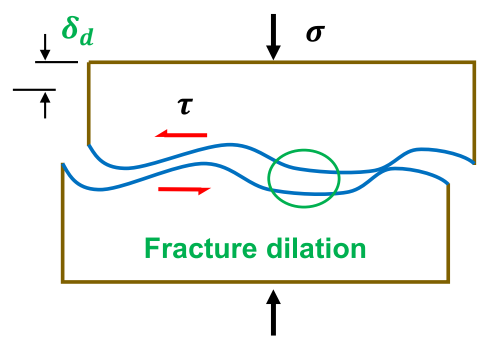
Motivation

- **Natural fractures could play a crucial role in FORGE stimulation [1-8]**
- **Provide reliable data for modeling and analysis**
  - Stress-dependent Permeability
  - Induced Fracture Slip by Injection (hydroshearing conceptual model)



$$\tau = C_0 + \mu(\sigma_n - \alpha P_p)$$

Fracture slip by injection



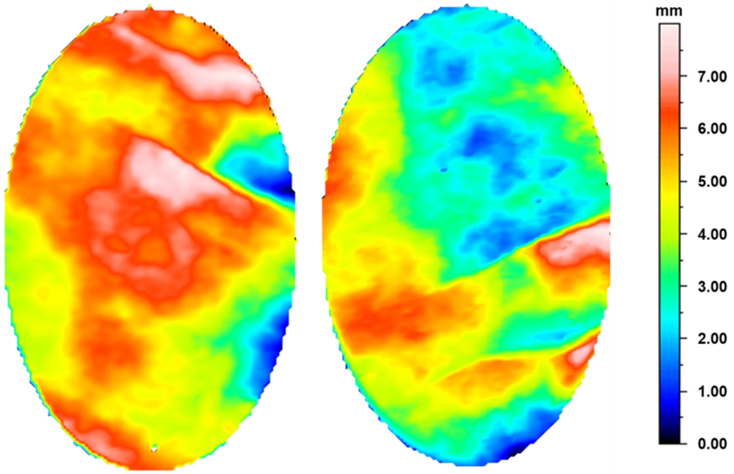
Permeability increase

Sample Preparation and Fracture Geometry

- **FORGE Granitoid Core from 78B-32 Well @8504 ft.**

2-inch diameter sub-coring

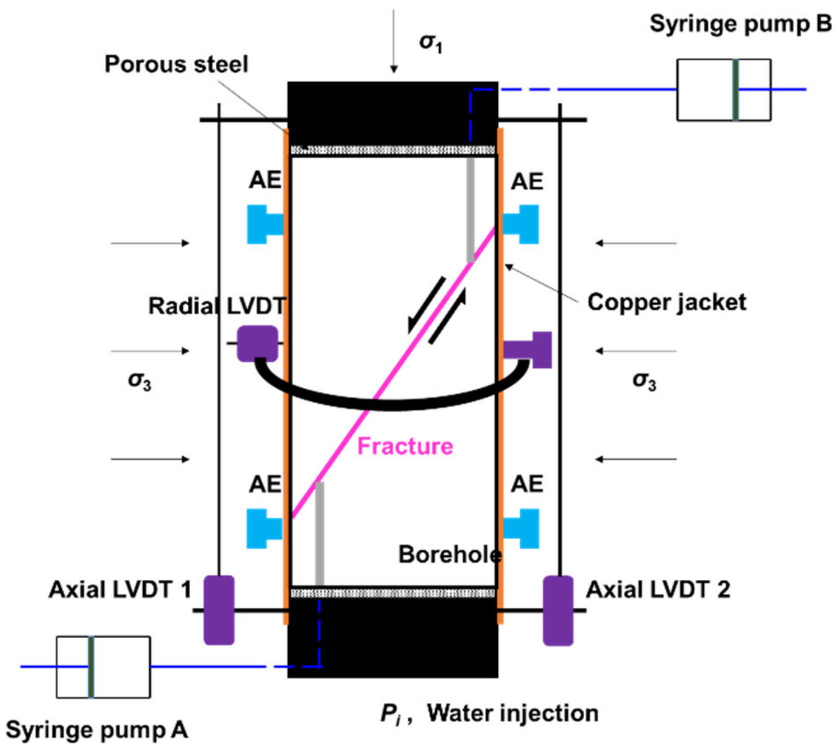
Tensile-induced rough Fracture



Surface scanning contour, JRC = ~16

Experimental Methods

- **Experimental Configuration [5,7]**



Ye and Ghassemi, 2018; 2020

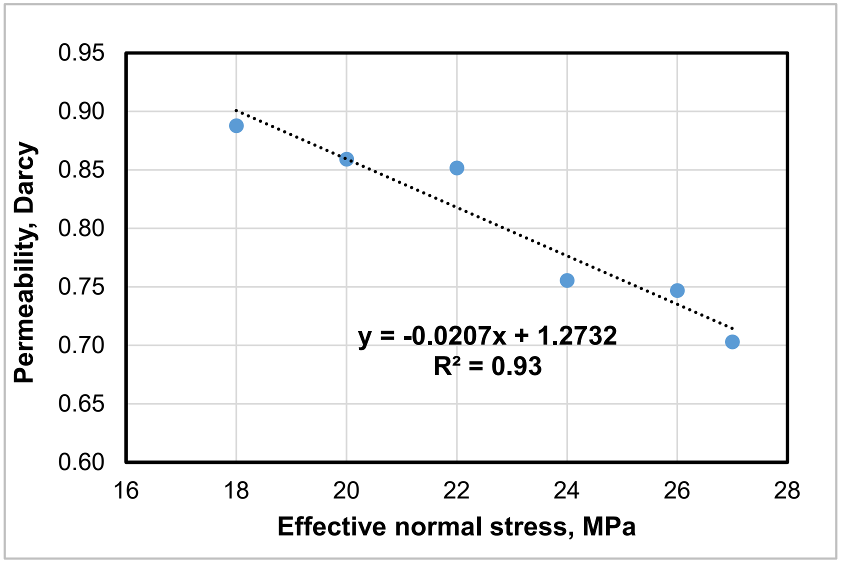
Two Types of Experiments:

- **Stress-dependent Fluid Flow Test**
  - Measure permeability and fracture aperture under different stresses.
  - Establish empirical correlations under FORGE conditions
  - Fracture slip was not induced
- **Injection-induced Fracture Shear Test**
  - Induce fracture slip by injection
  - Measure permeability evolution along with fracture slip
  - Establish relationship between permeability and shear displacement

Stress-dependent Fracture Permeability

- **Stress-dependent Fluid Flow Test [5,7]**
  - Using the effective mean stress at the reservoir (σ_3 = 30 MPa).
  - Hydrostatic test without inducing fracture slip.
  - Measurements of permeability and fracture aperture under different stresses.
  - Empirical correlations:
    - Permeability (k) vs. effective normal stress (σ'_n).

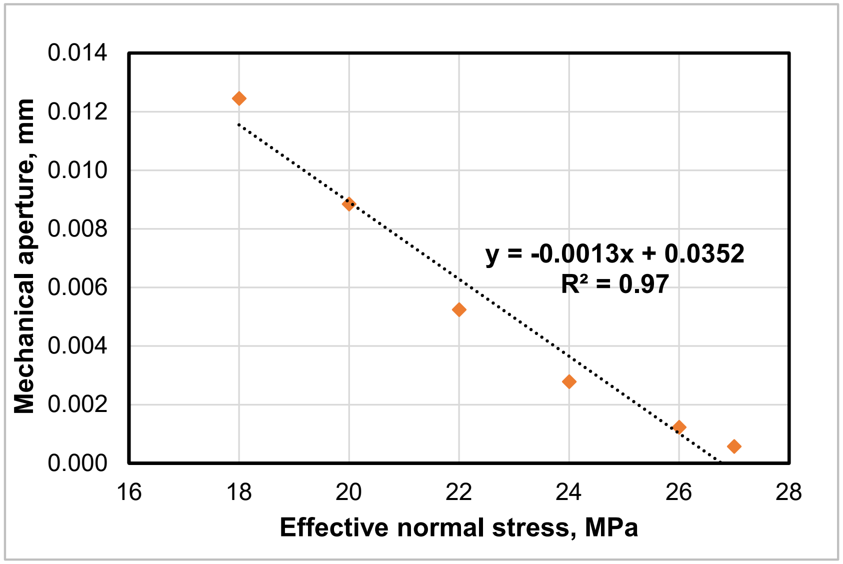
σ_3 (MPa)	P_o (MPa)	P_i (MPa)	σ'_n (MPa)	Q (ml/min)	d_n (mm)	d_h (mm)	k ($\times10^{-12}$ m^2)
30	2	4	27	0.21	0.0006	0.0029	0.70
		6	26	0.46	0.0012	0.0030	0.75
		10	24	0.94	0.0028	0.0030	0.76
		14	22	1.68	0.0052	0.0032	0.85
		18	20	2.27	0.0088	0.0032	0.86
		22	18	2.98	0.0125	0.0033	0.89

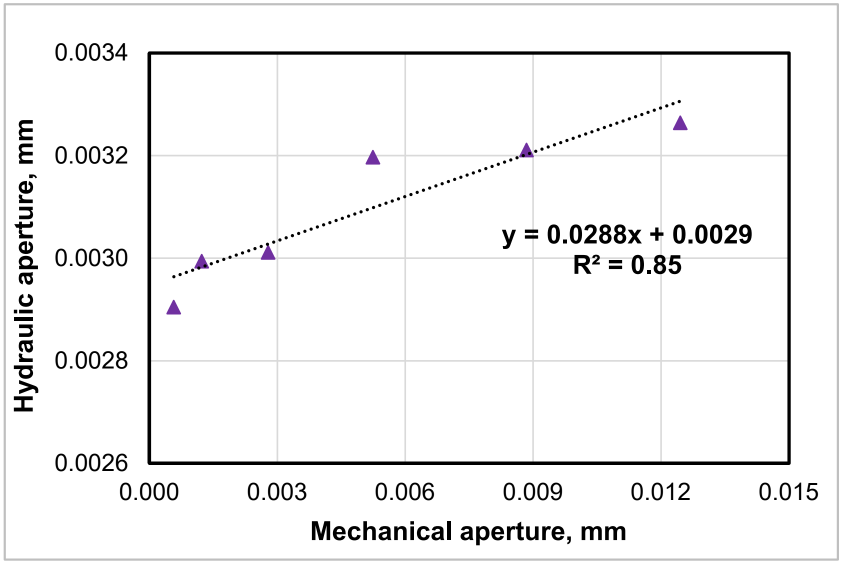


$$k = k_o - A\sigma'_n = 1.273 - 0.207\sigma'_n$$

Stress-dependent Fracture Permeability

- **Stress-dependent Fluid Flow Test [5,7]**
  - Empirical correlations:
    - Mechanical aperture (d_n) vs. effective normal stress (σ_n').
    - Mechanical aperture (d_n) vs. hydraulic aperture (d_h).



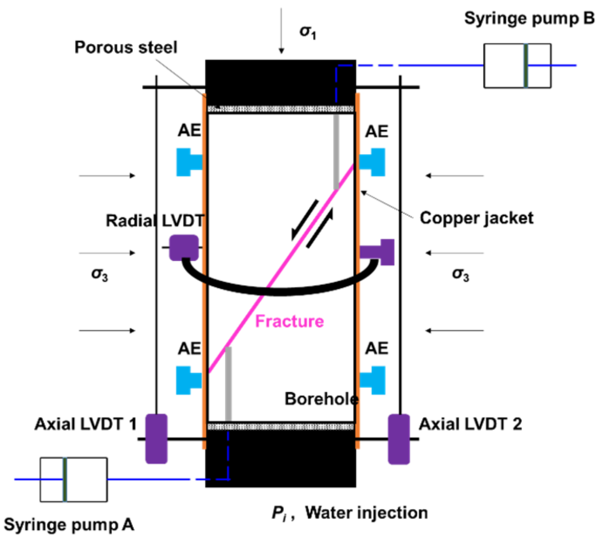


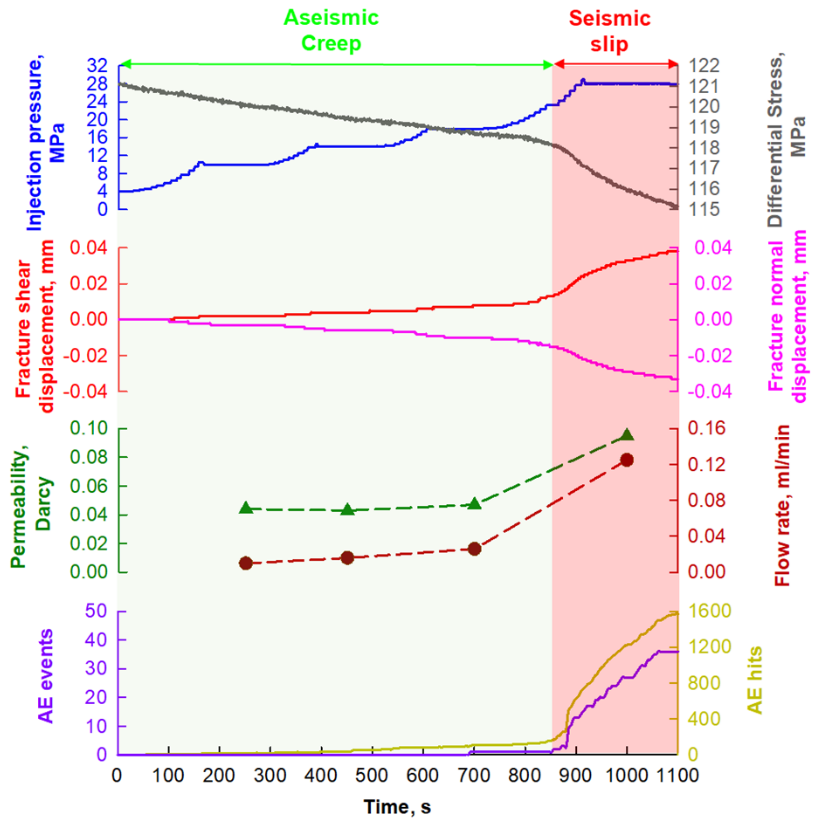
$$d_n = d_{n0} - B\sigma_n' = 0.0352 - 0.0013\sigma_n'$$

$$d_h = d_{h0} + Cd_n = 0.0029 + 0.0288d_n$$

Induced Fracture Slip by Injection

- **Injection-induced Fracture Shear Test**
  - $\sigma_d = 120$ MPa (~65% critical stress) simulating fractures under sub-critical stress state
  - Increase injection pressure to induce fracture slip

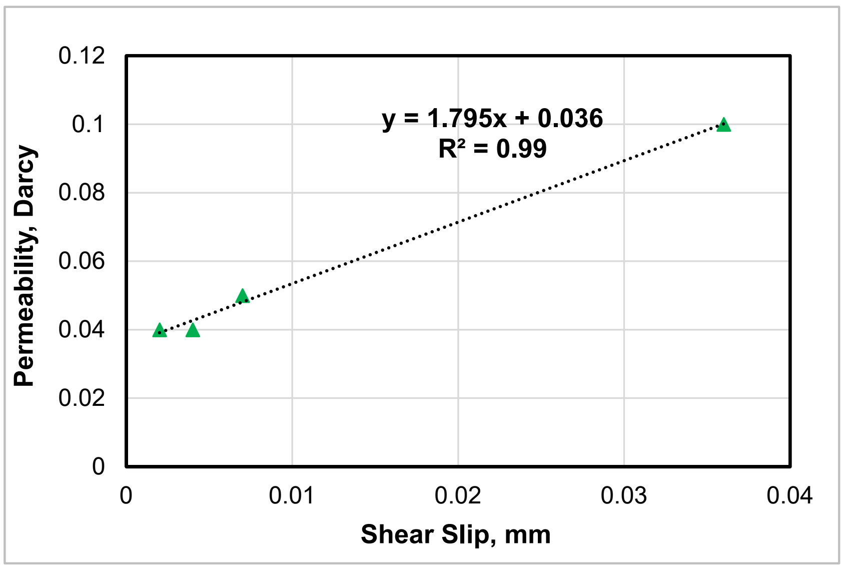




- Due to the relatively low stress, large slip/shear failure was not induced
- 0.04 mm slip, 0.03 normal dilation, 8 MPa stress drop
- Fluid rate increased from 0.01 to 0.13 ml/min
- Permeability enhanced from 0.04 to 0.10 Darcy
- The small slip induced significant flow enhancement
- Two phases: aseismic creep and seismic slip.

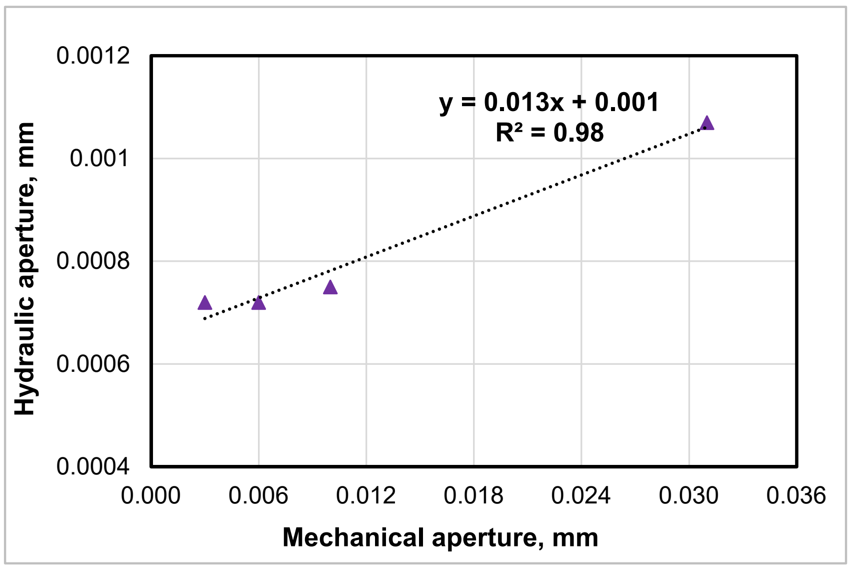
Induced Fracture Slip by Injection

- **Injection-induced Fracture Shear Test**
  - Positive correlation between permeability and fracture slip (described as a linear model)
  - Mechanical aperture is larger than hydraulic aperture (resistance to flow by asperities)



Permeability vs. fracture slip

$$k = k_i - Dd_s = 0.036 + 1.795d_s$$

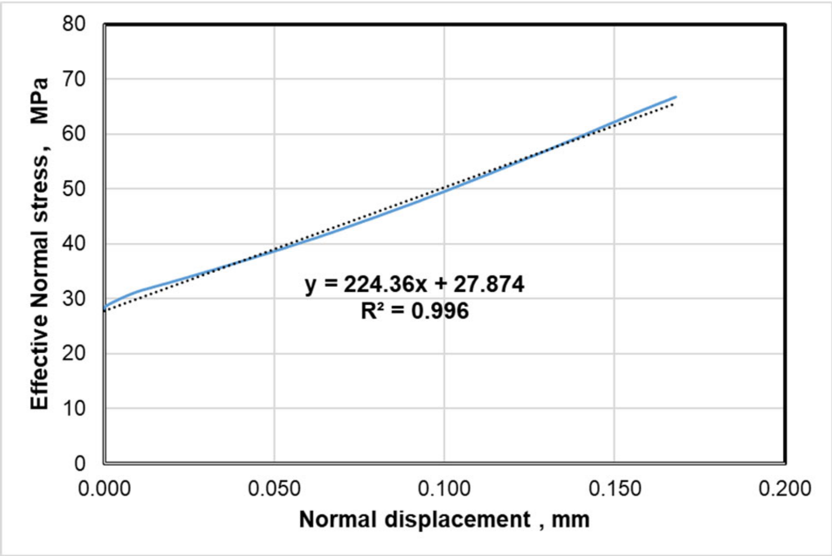


Mechanical aperture vs. hydraulic aperture

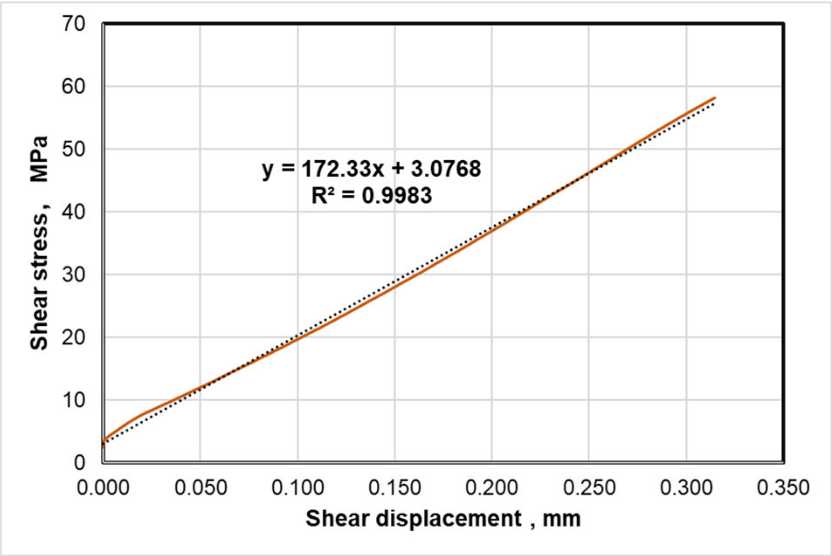
$$d_h = d_{h0} + Cd_n = 0.001 + 0.013d_n$$

Fracture Stiffness

- The displacement during loading stage was used to determine fracture stiffness
- **Norman stiffness**: 224 MPa/mm
- **Shear stiffness**: 172 MPa/mm



K_n = 224 MPa/mm



K_s = 172 MPa/mm

Summary

- **Stress-dependent Permeability In a FORGE Granitoid Fracture**
  - Established empirical correlations between permeability, stress, and fracture aperture
  - The hydraulic aperture is not zero even when the mechanical aperture is zero, indicating that a mechanically closed fracture retains some permeability
  - The mechanical aperture is generally larger than the hydraulic aperture. This difference suggests that the resistance of contacted asperities affects fluid flow in a rough fracture
- **Fracture Slip on Permeability**
  - Shear slip likely enhances permeability (even a small slip) for granite rocks of FORGE, provided the slip displacement isn't overly large, which could create gouge materials and clog the fracture
    - *Large shear slip is unlikely to occur due to stress relaxation along with fracture slip, this is also evidenced by the low magnitudes of induced seismicity at FORGE (maximum M0.5 to date)*
  - Slip can help create a fracture network (inducing fracture propagation and reactivating secondary fractures) [9]

References

1. Kelkar, S., Wolde Gabriel, G., Rehfeldt, K. 2016. Lessons learned from the pioneering Hot Dry Rock project at Fenton Hill, USA. Geothermics, 63, 5-14.
2. Richards, H.G. et al. 1994. The performance and characteristics of the experimental Hot Dry Rock Geothermal Reservoir at Rosemanowes, Cornwall (1985-1988). Geothermics, 23(2), 73-109.
3. Warpinski, N.R. , Wolhart, S.L., Wright, C.A. 2001. Analysis and Prediction of Microseismicity Induced by Hydraulic Fracturing. SPE 71649.
4. Huang, K., Cheng, Q., Ghassemi, A., Bauer, A., 2019. Evaluation of shear slip in fractured rock using a 3D coupled thermo–poromechanical FEM. Int. J. Rock Mech. 120, 68-81.
5. Ye, Z., Ghassemi, A. 2018. Injection-induced shear slip and permeability enhancement in granite fractures. J. Geoph. Res. Solid Earth, 123, 24 p.
6. Ye, Z., Ghassemi, A. 2020. Heterogeneous fracture slip and aseismic-seismic transition in a triaxial injection test. Geophysical Research Letters, 47(14).
7. Ye, Z., Ghassemi, A. 2022. Laboratory Insights into the Potential of Shear Stimulation at Utah FORGE, GRC Transactions, Vol. 46.
8. Safari, R., Ghassemi, A. 2015. Three-dimensional thermo-poroelastic analysis of fracture network deformation and induced microseismicity in enhanced geothermal systems. Geothermics, 58, 1-14.
9. Kamali, A., Ghassemi, A., 2018. Analysis of injection-induced shear slip and fracture propagation in geothermal reservoir stimulation. Geothermics, 76, 93-105.

- **Experimental work by: Zhi Ye**