# EFFECTS ON PERMEABILITY OF ROCK FRACTURE GEOMETRY AND FLUID/ROCK TEMPERATURE CONTRAST



Gonçalo Benitez Cunha 15-16/09/2021 Supervisors: Prof. Chris McDermott / Dr. Andrew "Gus" Fraser-Harris

Radioactive Waste Management
THE UNIVERSITY of EDINBURGH
Quintessa

# Overview

- Importance of rock fractures
- Knowns/Unknowns - Fracture permeability influencing factors
- Single fracture characterisation using variograms
- Fracture roughness implications to shear displacement
- Temperature effect on shear displacement

# Why are rock fractures important?

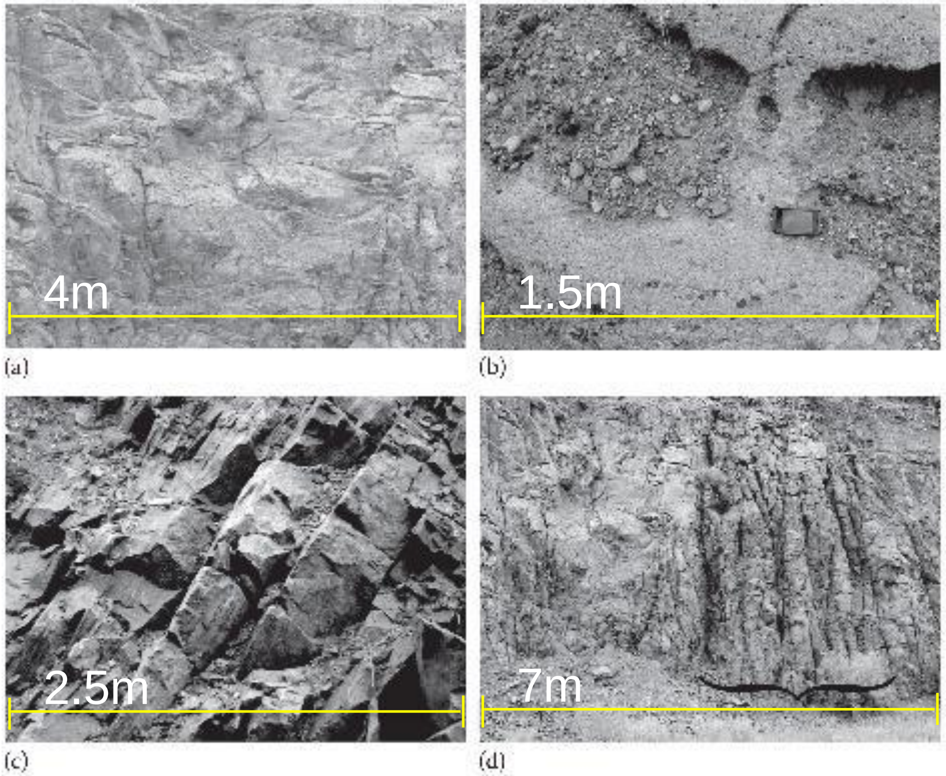



Fig. 1 – Examples of rock types in which geothermal systems occur. (a) Massive, fractured granite. (b) Porous sandstone that is cemented to different degrees. (c) Metamorphic gneisses with parallel, planar fractures. (d) Fault zone in granite. The bracket bounds multiple, parallel, large-scale fractures that dene the fault zone. (Glassley, W.E., 2015).

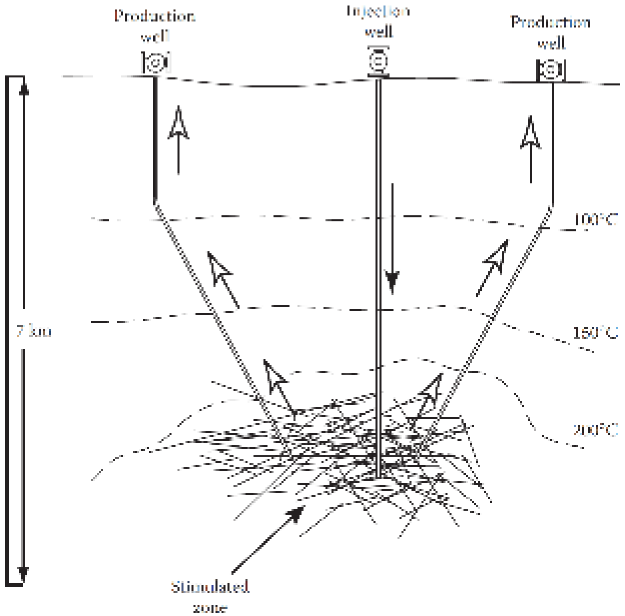



Fig. 2 – Schematic diagram of an enhanced geothermal system (EGS). The injection well is initially used to stimulate a zone in the rock that is at the target temperature. That same well is then used to pump fluid into the stimulated zone. Production wells that have been drilled into the stimulated zone then recover the heated fluid and transfer it to power generating facilities. (Glassley, W.E., 2015).

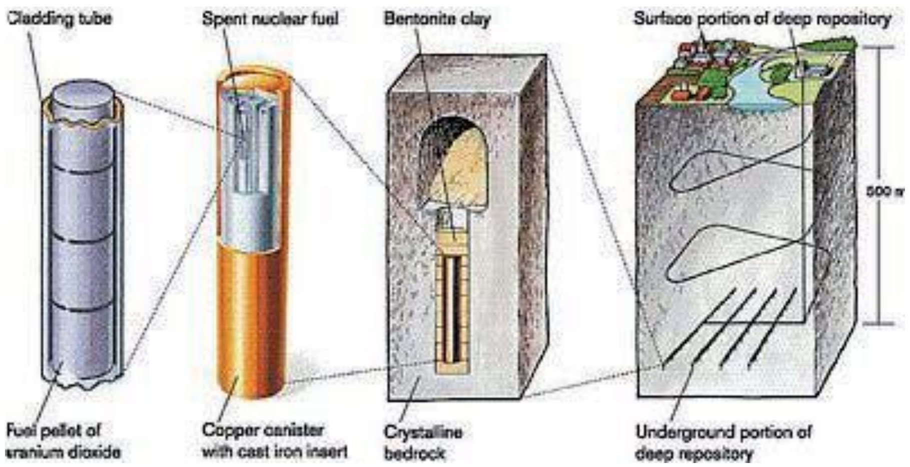



Fig. 3 – Representation of KBS-3 (Swedish) nuclear waste disposal concept (IAEA, 2009).

# What’s known? – Permeability influencing factors

Aperture

1. Stress field (σ1, σ2, σ3)
2. Fluid pressure
3. Matching degree (τ Δx)
4. Surface roughness
5. Chemical processes

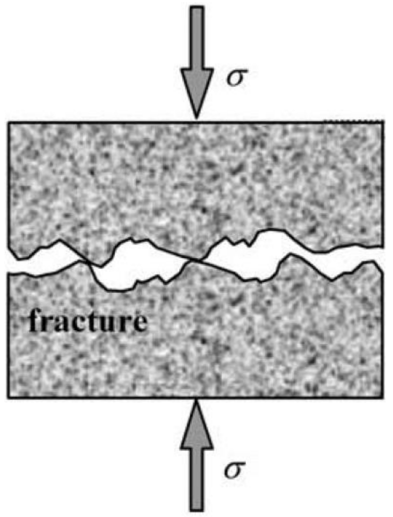



*Figure 4 – Fracture stiffness (Yasuhara and Elsworth, 2004).*

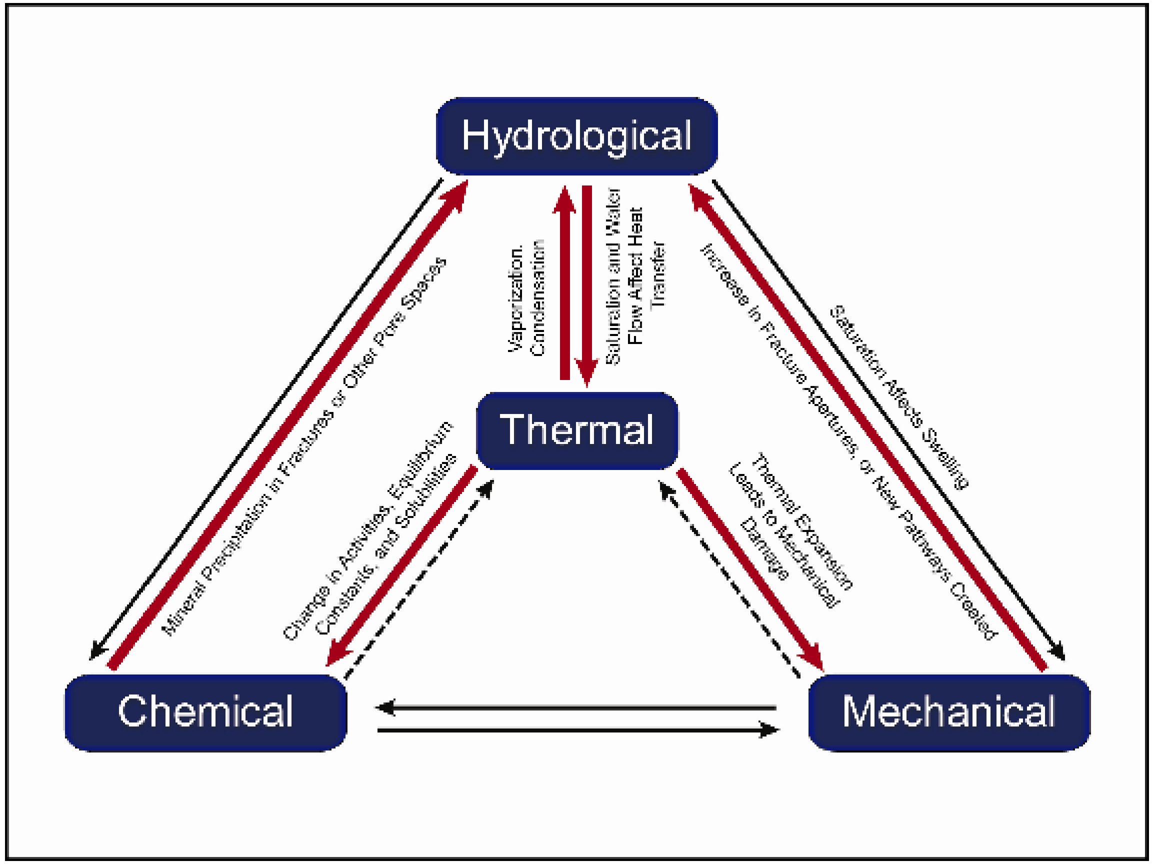



*Figure 5 – Thermal-Hydraulic-Mechanical-Chemical processes coupling.* Manepally et al (2011).

# What’s not known?

1. Shear effect on permeability (gouge formation vs dilation)

2. Roughness effect on shear

3. Influence of roughness upscaling

4. Influence of temperature in shear behaviour

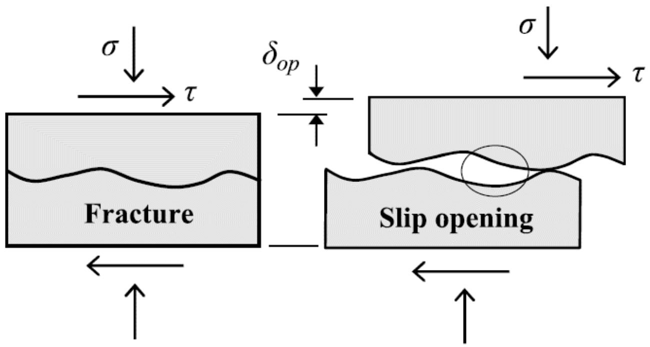



Figure 6 – *Dilation from shear.*

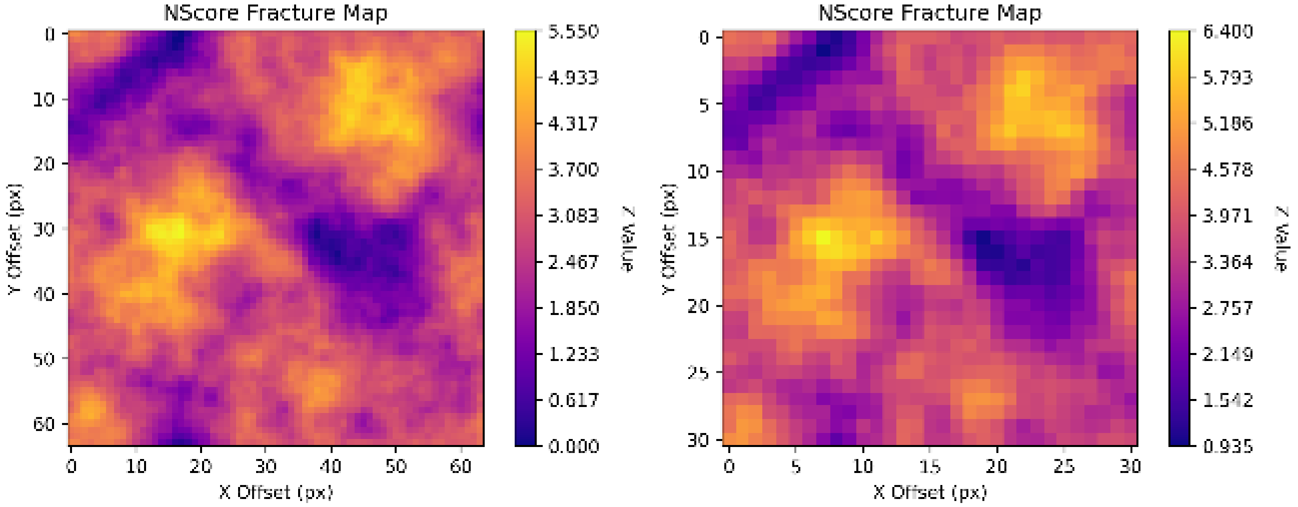



Figure 7 – *Left: Synthetic fracture 64x64 pixels. Right: Upscaled 2x2*

# DECOVALEX (*DEvelopment of COupled models and their VALidation against EXperiments*) – Task G

An international research and model comparison collaboration project for advancing the understanding and modelling of coupled THMC processes in geological systems.

Task G focuses on understanding shear reactivation of fractures and the potential for shear displacement as well as their effect on permeability as a consequence of THMC processes.

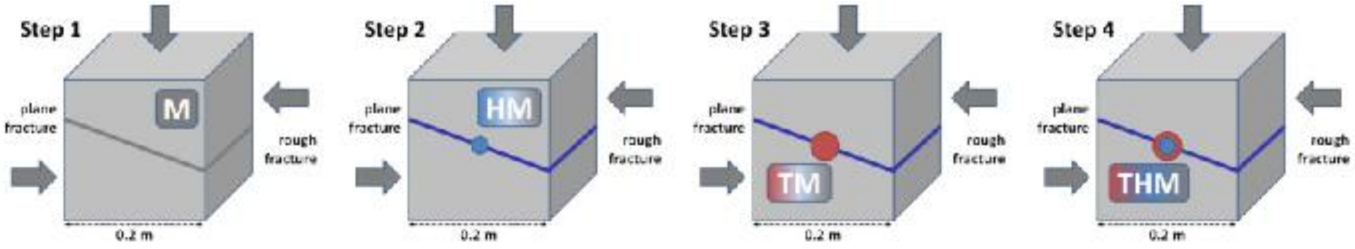



**Figure 2:** Geometric cases (cubes): Step 1 (M) > Step 2 (HM) > Step 3 (TM) > Step 4 (THM)

https://decovalex.org/

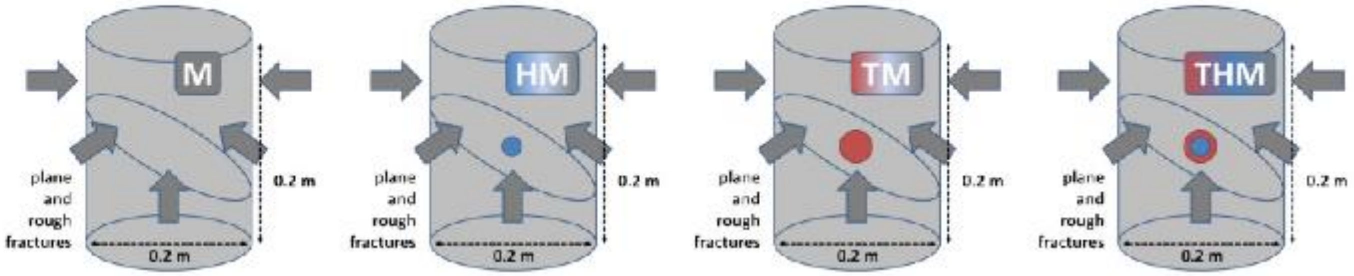



**Figure 3:** Geometric cases (cylinders): Step 1 (M) > Step 2 (HM) > Step 3 (TM) > Step 4 (THM)

*Fig. 8 – Geometric cases (cylinders) for steps M, HM, TM and THM of DECOVALEX 2023's task G. From (DECOVALEX, 2020).*

Radioactive Waste Management

THE UNIVERSITY of EDINBURGH

Quintessa

# Single fracture characterisation using variograms

- **Research question:** Is there a relationship between fracture surface roughness at different scales and what is that relationship? And is there a relationship with anisotropy?

- **Rationale:**
  - Fracture typically described through statistical distributions (McCraw 2016, Zou et al 2015) of roughness topography, deconvolution (Fourier Transform)* of the surface or power spectrum (Brown 1995).
  - Statistical distributions don't account for the heterogeneous 2D distribution, just the overall distribution.
  - The * generally only applied to profiles of rough surfaces.

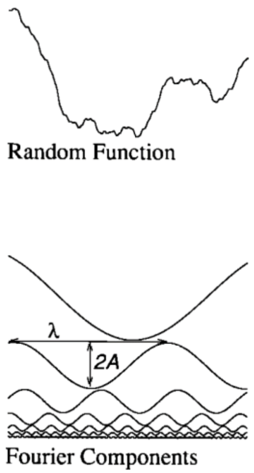



*Figure 10 – Surface profile (top left) and corresponding Fourier components (bottom left) (Brown (1995)).*

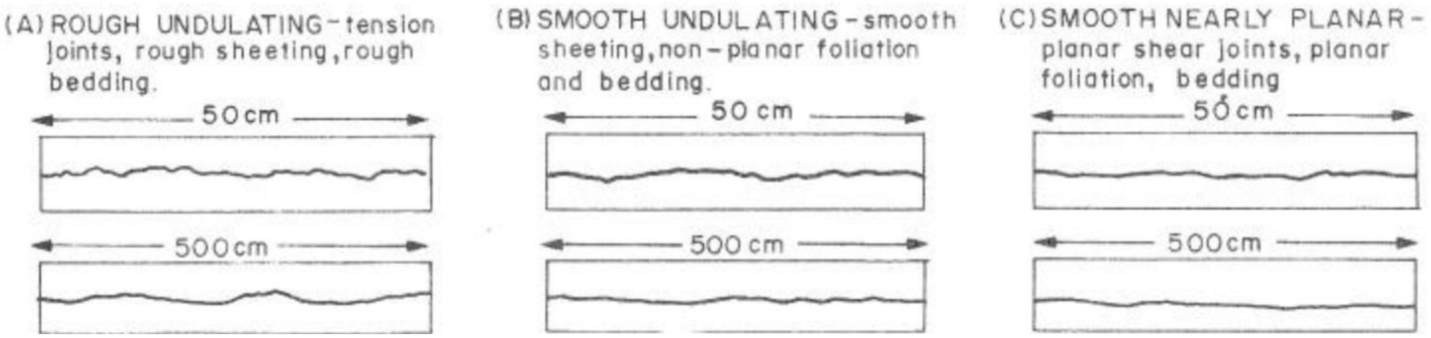



*Figure 9 – Classification of smooth/rough fractures (Bandis, S., Lumsden, A.C. & Barton, N. (1981)).*

# Single fracture characterisation using variograms

- **Aims:**
  - Innovate methodologically using variograms to describe fracture surfaces as opposed to statistical distributions
  - Provide a method that intrinsically demonstrates anisotropy and trends
  - Facilitate upscaling
  - Kriging
- **Applicability:** Applicable to any rough surface hence to different industries (material- and geo-sciences).

# Variogram basics

- Cone geometry parameters:
  - Lag (w)
  - Azimuth (θ)
  - Azimuth tolerance (α)
  - Bandwidth
- Computing experimental variogram
- Computing variogram map

$$y(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left(z(x_i) - z(x_i + h)\right)^2$$

## Structured Data

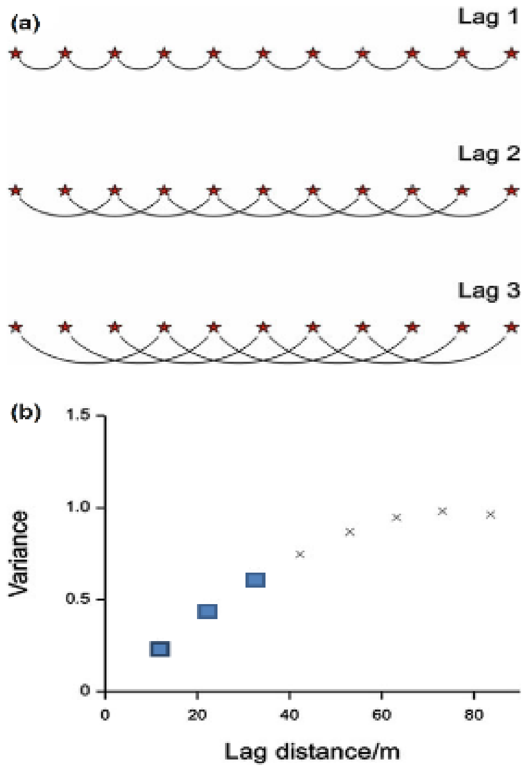



*Figure 13* **a** Comparisons for computing a variogram for three lag intervals from a sample of a regularly spaced population and

**b** Semi-variances plotted against the first three lag intervals to form the sample Variogram – Oliver, M. & Webster, R., 2015.

## Scattered Data

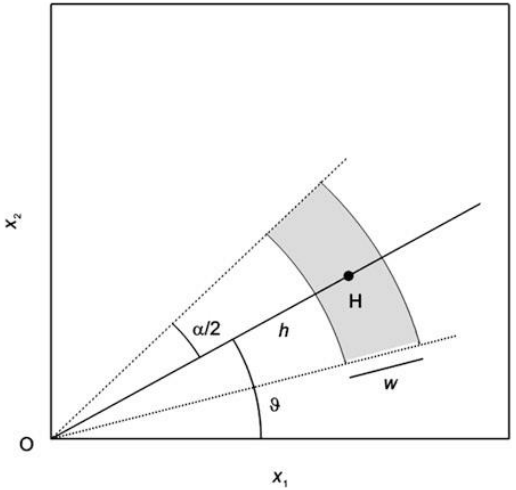



*Figure 11* – Two-dimensional geometry for discretising the lag into bins, by distance and direction – Oliver, M. & Webster, R., 2015.

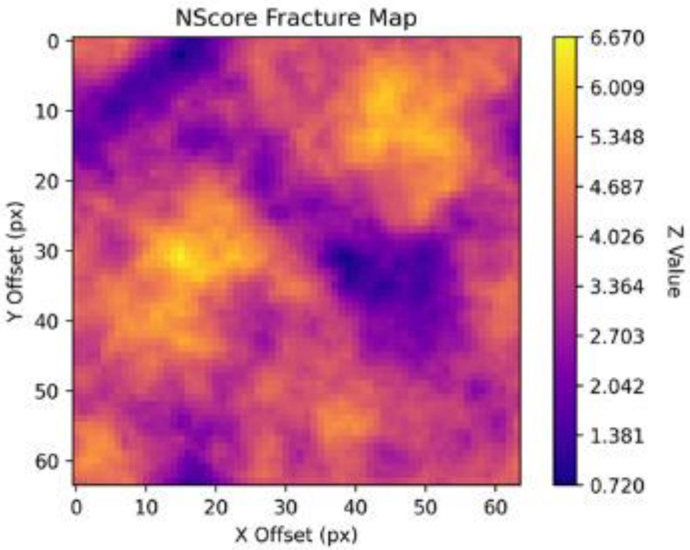



*Figure 12* – 64x64 Normalised Synthetic Fracture map

# Greywacke_Q4 – Variogram map & semi-variograms (lag=5)

- Trends visible on semi-variograms

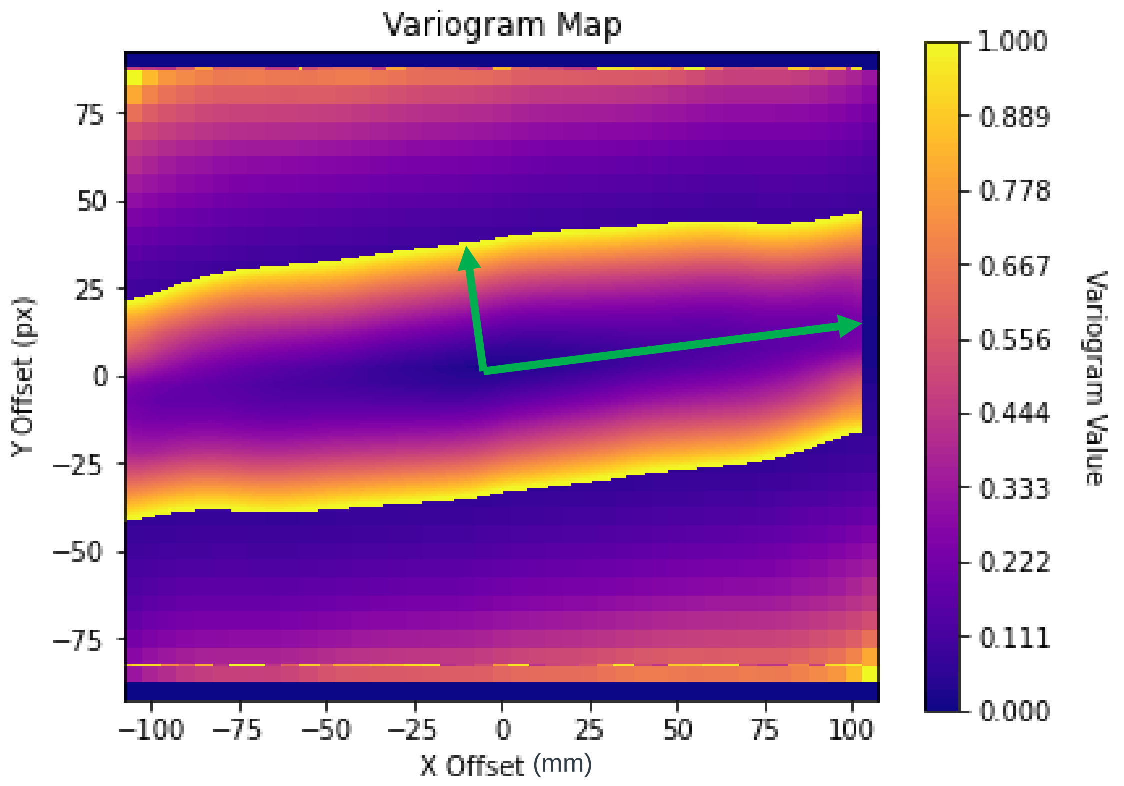



*Figure 14* – Greywacke Quadrant 4 variogram map. Short continuity (minor) in the ~350° and longer continuity (major) in the ~80° directions.

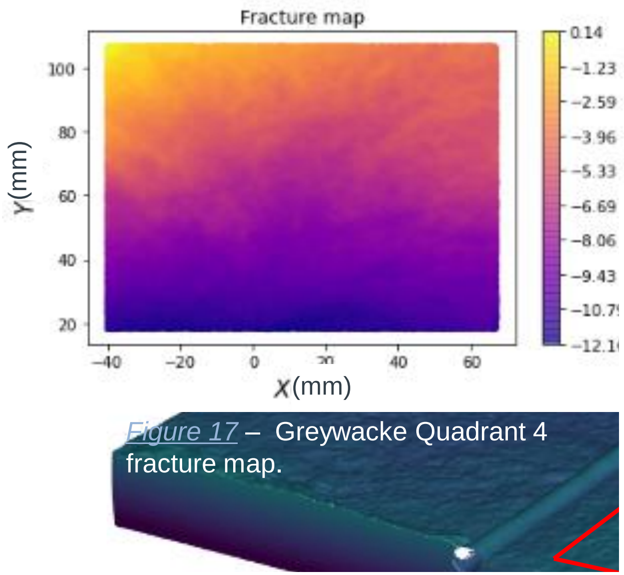
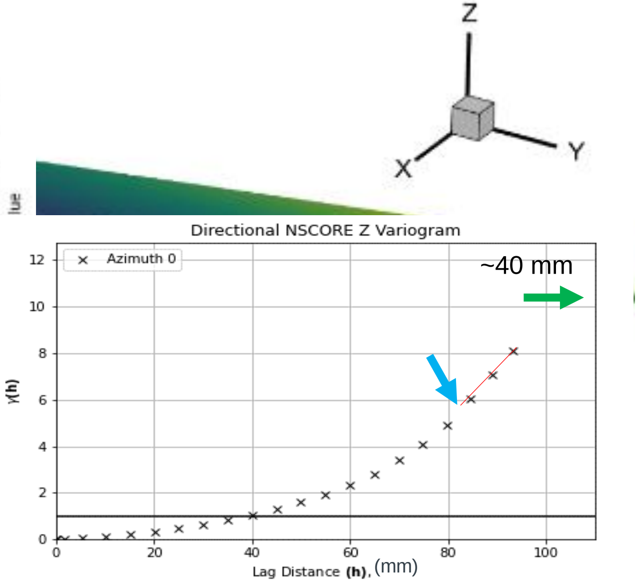



*Figure 17* – Greywacke Quadrant 4 fracture map.



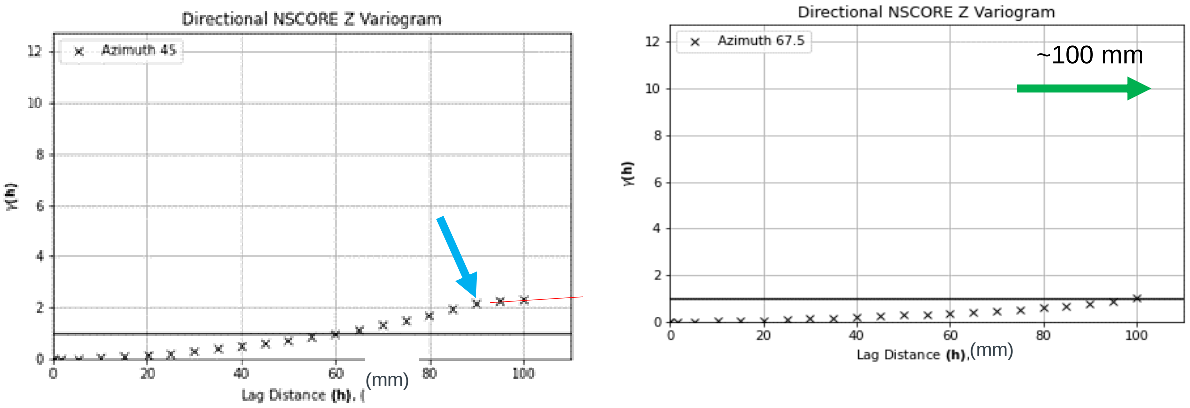




*Figure 15 – Greywacke quadrant 4 s*emi-variograms for 0°, 45° and 67.5°.

Radioactive Waste Management

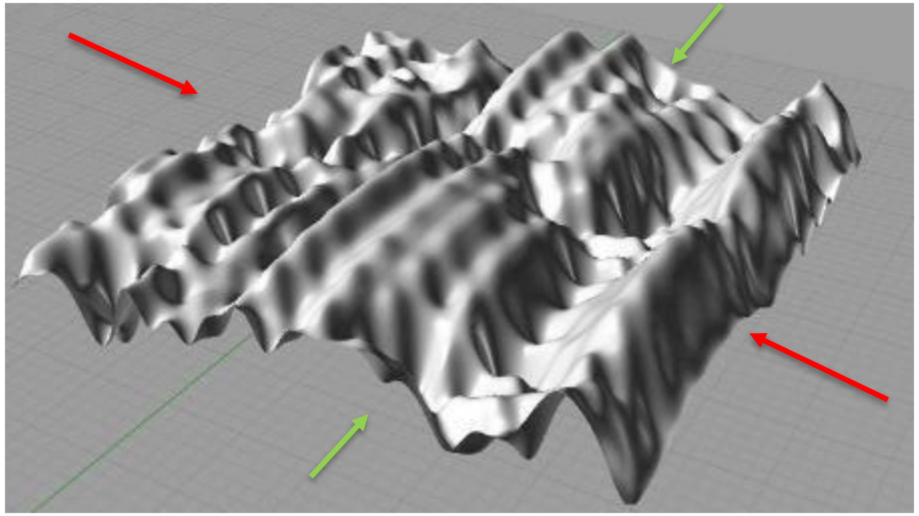
THE UNIVERSITY of EDINBURGH

Quintessa

# Fracture roughness implications to shear displacement

- **Research question:** How does the fracture surface roughness at different scales impact the effective stresses necessary in order to observe shear displacement?

- **Rationale**:
  - Shear models usually rely on JRC (Joint Roughness Coefficient - experimental parameter) and on generalised geometry descriptions (neglect spatial distribution and nature of roughness and stress field direction)



S. Bandis, A. C. Lumsden and N. R. Barton

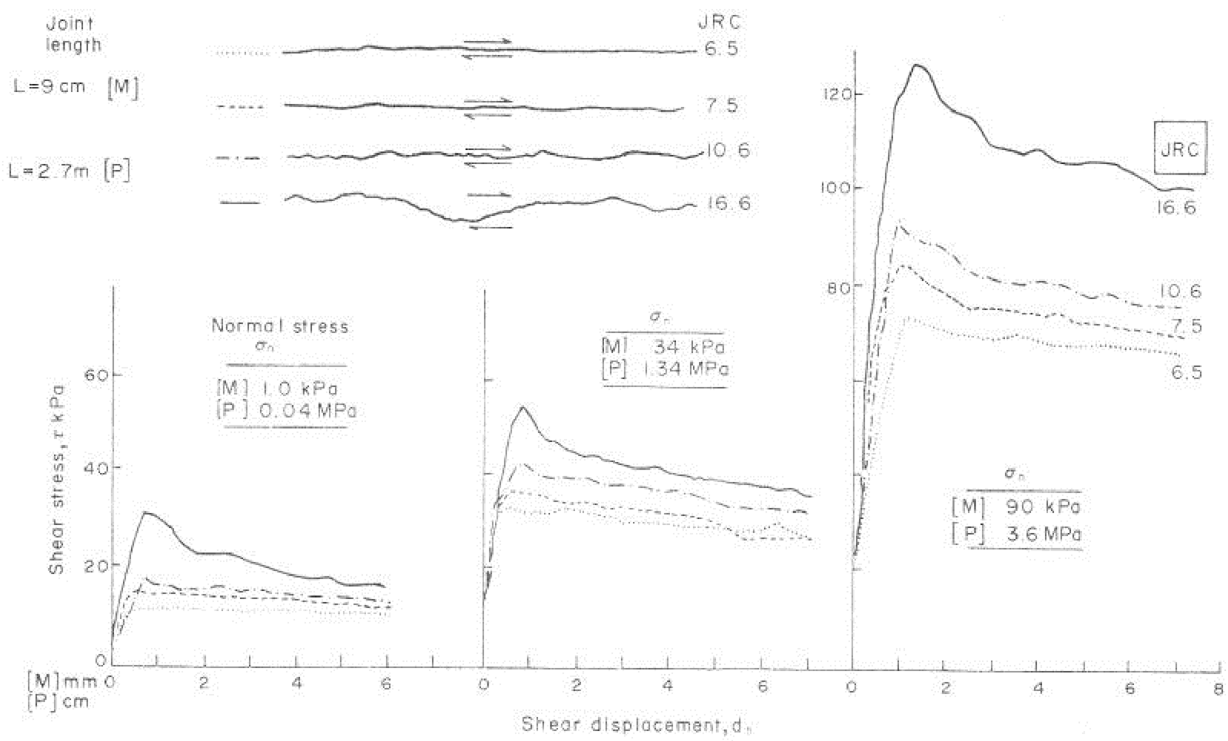



Fig. 4. Shear stress—shear displacement behaviour of model joints with different surface roughness, tested under three levels of normal stress. [M] = model, [P] = prototype.

*Figure 15 – Shear stress vs Shear displacement of model joints with different JRCs and under different normal stress.*

# Temperature effect on shear displacement

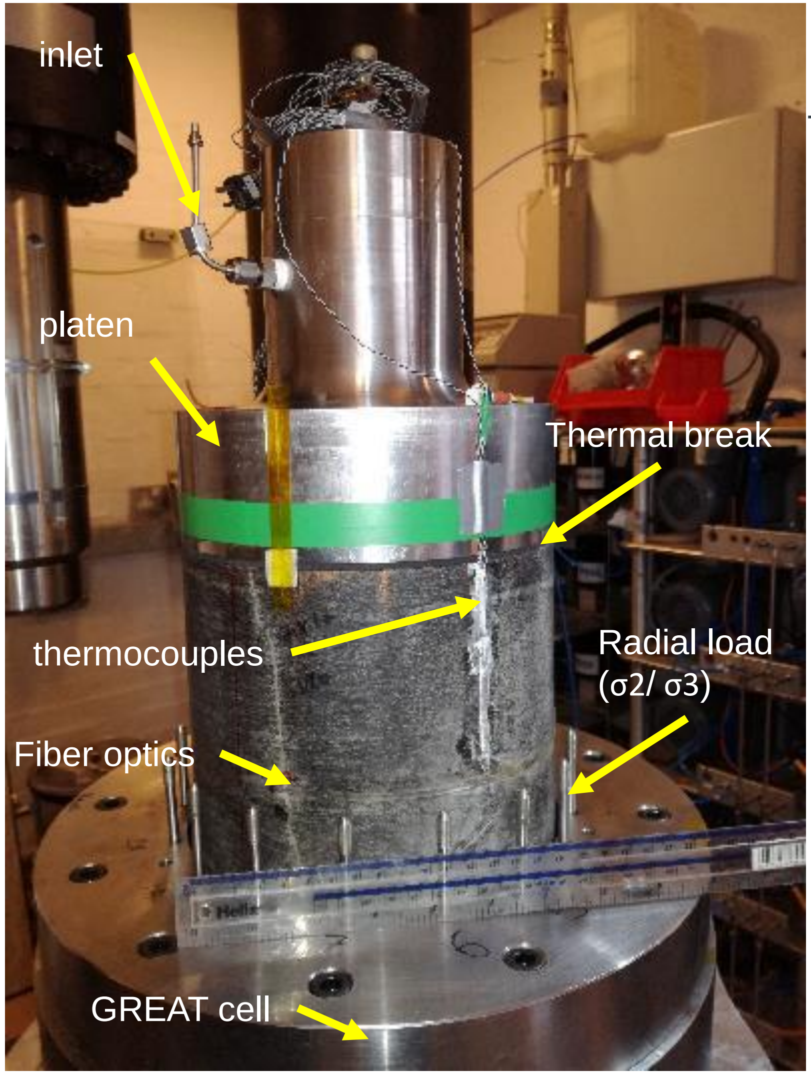
- **Research question:** How does temperature influence shear displacement?

- **Rationale:** Rock temperature increase has several consequences such as:
  - Aperture closure due to mineral dilation
  - Fracture tip propagation
  - Fracture roughness increases & toughness decreases with temperature (very high temperatures) (Zhang et al 2001)
  - Change in Young's Modulus (very high temperatures) (Zhang et al 2001)
  - Fluid pressure increases – potentially inducing shear to occur

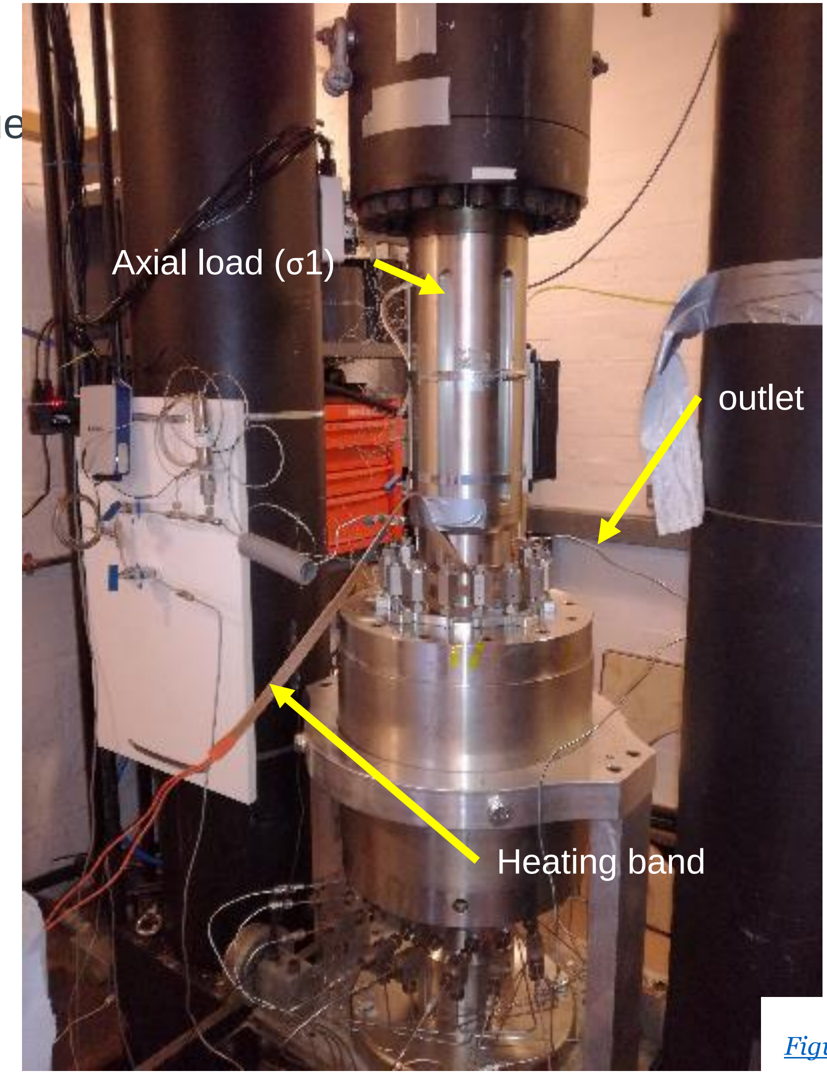
- **Aim:** Through experimentation and modelling, understand fluid flow through fractures up/downstream of radioactive waste crystalline repositories.

- **Planned experiments**:
  - Hot fluid into ambient rock, across a range of temperatures (20℃ to 50 ℃).
  - Ambient fluid into hot rock across a range of temperatures (20℃ to 50 ℃).
  - Isothermal at different temperatures

# Temperature effect on shear displacement (experiments)




flue



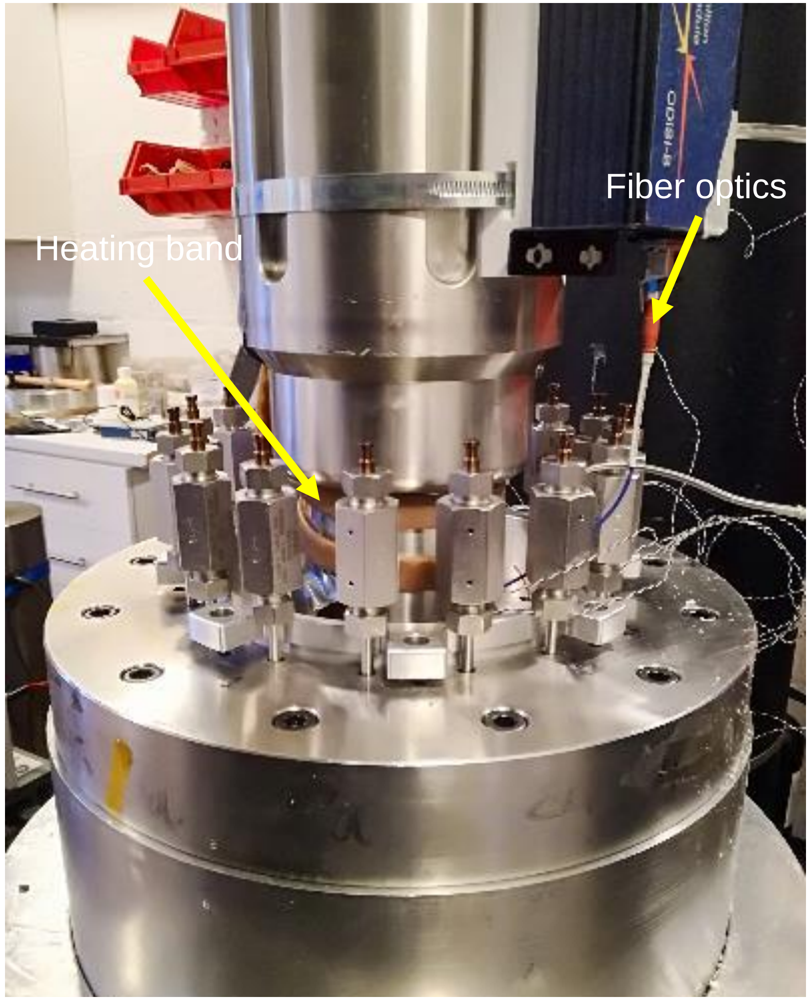




*Figure 16 – Experimental setup of hot fluid into ambient rock experiment.*

# References


- Bandis, S., Lumsden, A.C. & Barton, N. (1981). Experimental Studies of Scale Effects on the Shear Behaviour of Rock Joints. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 18. 1-21. 10.1016/0148-9062(81)90262-X.
- Brown, Stephen R, 1995. Simple mathematical model of a rough fracture. *Journal of Geophysical Research: Solid Earth*, 100(B4), pp.5941–5952.
- Glassley, W.E., (2015). *Geothermal Energy: Renewable Energy and the Environment*. 2nd edition Boca Raton. CRC Press. ISBN: 13: 978-1-4822-2175-6.
- International Atomic Energy Agency, 2009. IAEA Nuclear Series No. NW-T-1.19. *Geological disposal of radioactive waste: technological implications for retrievability*. Vienna, Austria. ISBN 978–92–0–100109–2.
- Kolditz, O et al., 2012. OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. *Environmental earth sciences*, 67(2), pp.589–599.
- Kotousov, Andrei & Bortolan Neto, Luiz & Rahman, Sheik. (2011). Theoretical model for roughness induced opening of cracks subjected to compression and shear loading. International Journal of Fracture. 172. 10.1007/s10704-011-9642-6.
- Manepally et al (2011). *Coupled processes workshop report*. US Nuclear Regulatory Commission Contract NRC-02-07-006.
- McDermott, C.I., Bond, A., Fraser Harris, A.P., Chittenden, N., Thatcher, K., 2015, Application of hybrid numerical and analytical solutions for the simulation of coupled thermal, hydraulic, mechanical and chemical processes during fluid flow through a fractured rock: Environmental Earth Sciences, v. 74, no. 12, p. 7837-7854.
- Oliver, A. M., & Webster, R. (2015). *Basic Steps in Geostatistics:The Variogram and Kriging*. 1 ed. London: Springer Briefs in Agriculture.
- Hideaki Yasuhara, Derek Elsworth & Amir Polak, 2004. Evolution of permeability in a natural fracture: Significant role of pressure solution. *Journal of Geophysical Research - Solid Earth*, 109(B3), pp.B03204-n/a.
- Zou, L., Jing, L., & Cvetkovic, V. (2015). Roughness decomposition and nonlinear fluid flow in a single rock fracture. *International Journal of Rock Mechanics and Mining Sciences*, *75*, 102–118. https://doi.org/10.1016/j.ijrmms.2015.01.016