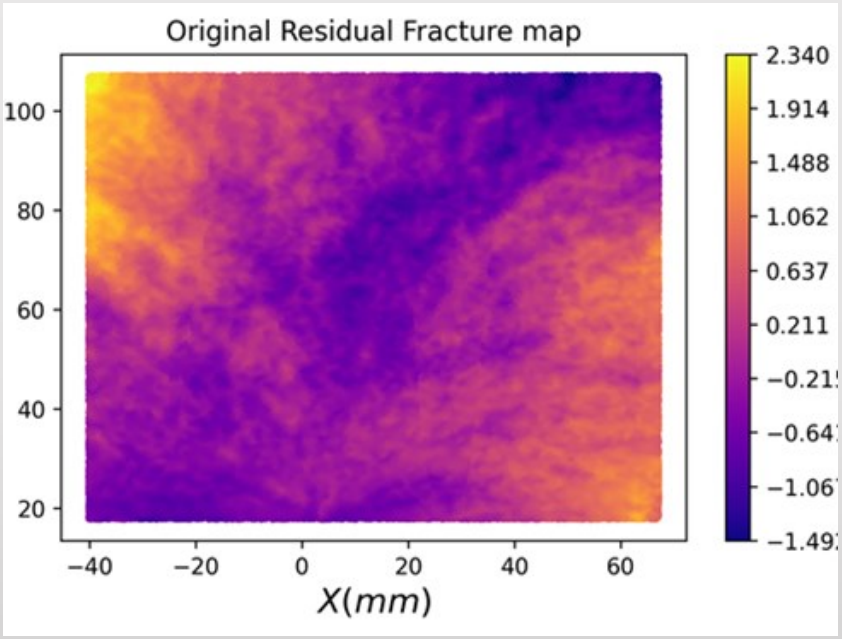
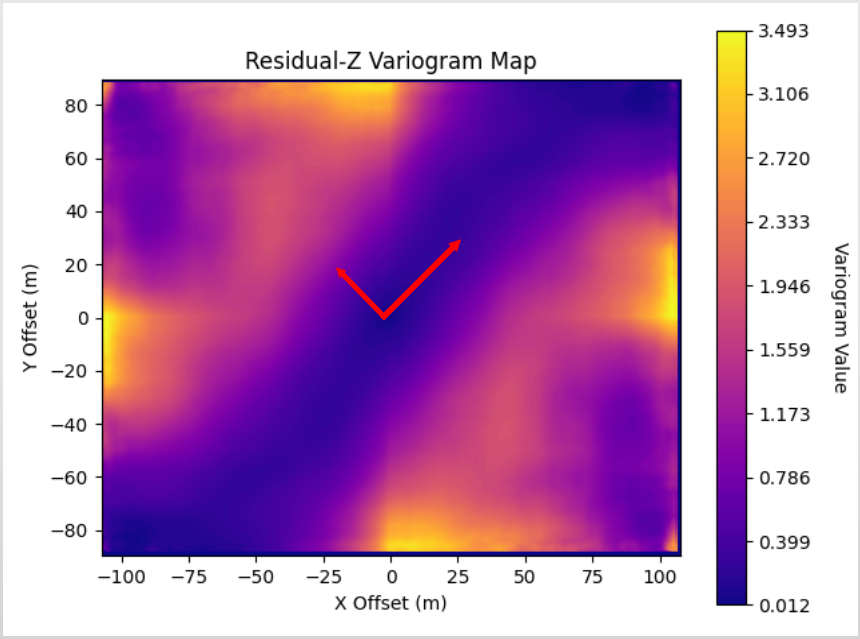
Safety of Nuclear Waste Disposal Symposium 15-09-2023

Characterising a rock fracture rough surface using spatial continuity and kriging: applications to meshing for coupled thermo–hydraulic–mechanical–chemical (THMC) models





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Why are rock fractures important?

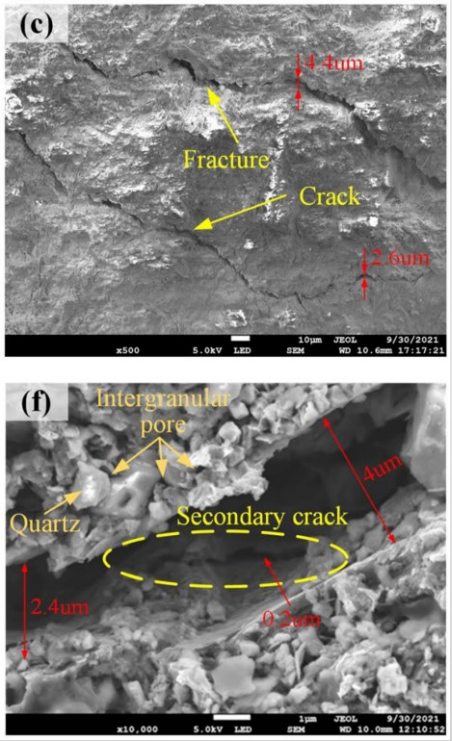


Fig.1 – Qu et al 2022: Characteristics of Complex Fractures by Liquid Nitrogen Fracturing in Brittle Shales. Rock Mechanics and Rock Engineering (2022) 55:1807–1822

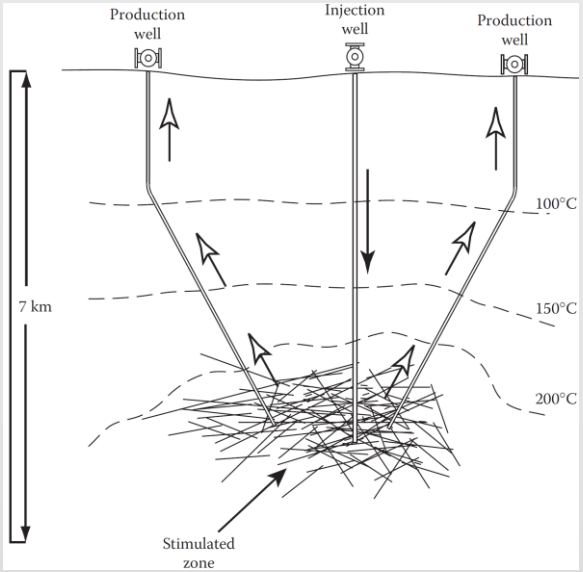


Fig.2 - Schematic diagram of an enhanced geothermal system (EGS). The injection well is initially used to stimulate a zone in the rock that is at the target temperature. That same well is then used to pump fluid into the stimulated zone. Production wells that have been drilled into the stimulated zone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

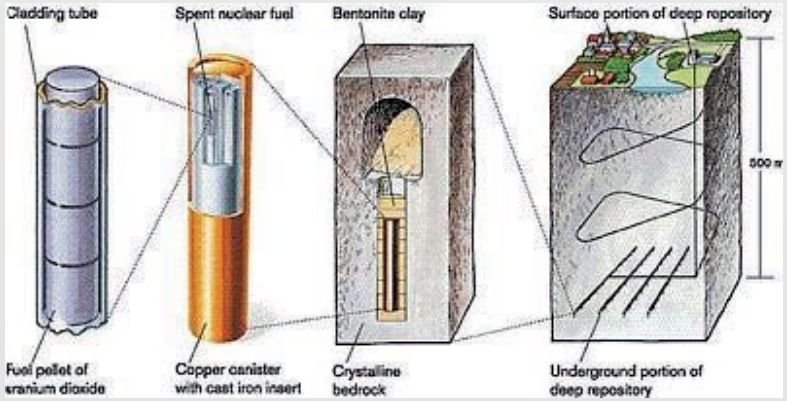


Fig.3 - Representation of KBS-3 (Swedish) nuclear waste disposal concept (IAEA, 2009).

Spatial Continuity

- What is it?

It's a variable's spatial dependence (in direction and distance).

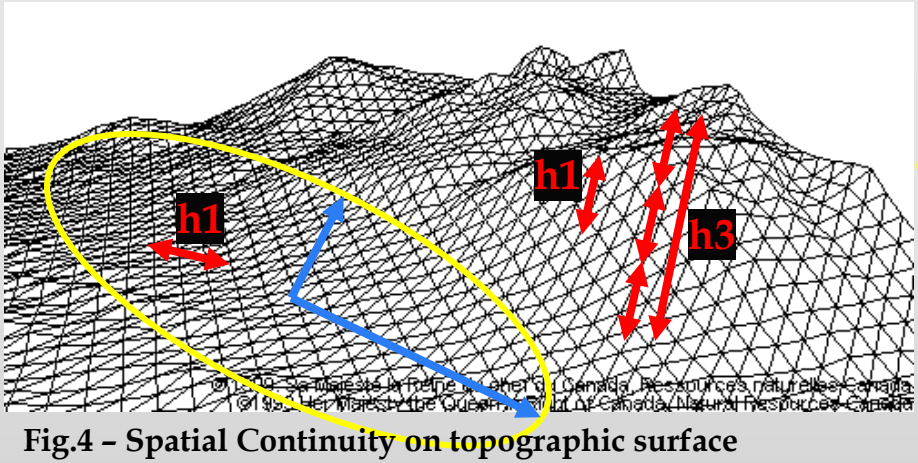
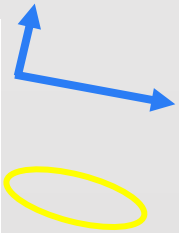


Fig.4 – Spatial Continuity on topographic surface
https://ethz.ch/content/dam/ethz/special-interest/baug/irl/plus-dam/documents/lehrveranstaltungen/msc/MCDA/Lecture3_KRIGING.pdf



Minor and major directions and respective ranges of correlation

Correlation limit area

NOTE: Both the blue vectors and yellow elliptic area should be imagined as flat along the XY-plane.

γ (variance) $is\ a\ function\ of\ (Z_{Si} - Z_{Sj})^2$

Spatial Continuity

- **How is it used?**

In conjunction with kriging, it is used to predict a value at an unknown location

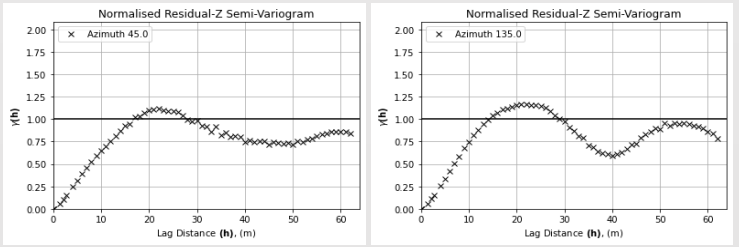


Fig.5 –Bottom: From left to right, semi-variograms for 45 and 135°.

- **What is kriging?**

Kriging is the **BLUE** (**B**est **L**inear **U**nbiased **E**stimator).

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i * z(xi)$$

Best – aims to reduce global σ^2.
Linear – uses Inverse Distance Linear weights
Unbiased – aims at Mean Global Error=0 (i.e. $\sum_{i=1}^{n} \lambda_i$=1)
It uses the variograms' directions and distances with the hard data points to predict the weights (λ) used to predict ($\hat{z}$) the value z at location x_0:

- Unknown value at location
- Known value at location within the bounds of correlation
- Known value at location outside the bounds of correlation
- Vector between unknown and known values' locations

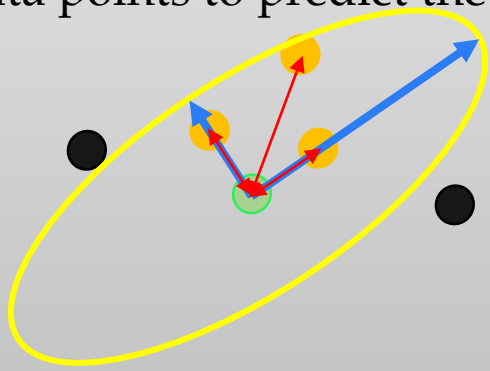


Fig.6 –Kriging schematic.

Spatial Continuity

- **Why use Spatial Continuity (SC)?** A SC understanding might allow us to :

1. lower the computation by finding a Representative Elementary Volume (REV).
2. replicate the fracture's experimental flow behaviour with kriged models (based on raw or REV data).
3. extrapolate the fracture using the its SC.
4. better understand of how the fracture would respond to changes in in-situ conditions, especially shear movement and fluid flow.

- **How to test this?**

1. Find the REV using variograms and build an aperture model
2. Compare the experimental flow data to its OGS model (using aperture model from 1.) with similar experimental conditions
3. Blind predict aperture outside our data
4. Compare flow data with τ at different SC's orientations

Methodology

- The data used was taken from the 4th quadrant area red (square Fig.3). A colour-scaled illustration is depicted in Fig.4.

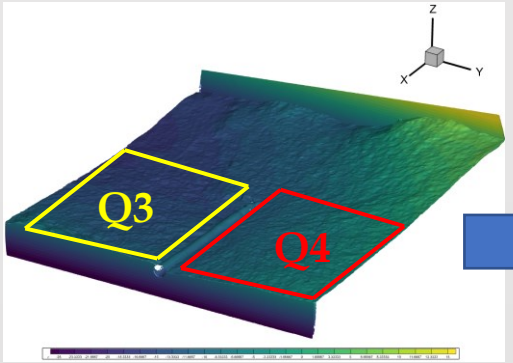


Fig.7 - Original Greywacke data. The red square represents the sub-dataset used in the study.

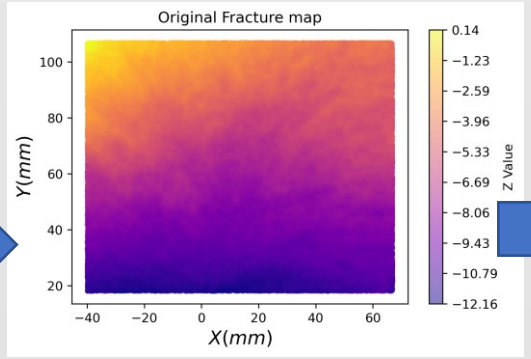


Fig.8 - Colour-scaled quadrant 4 greywacke top surface.

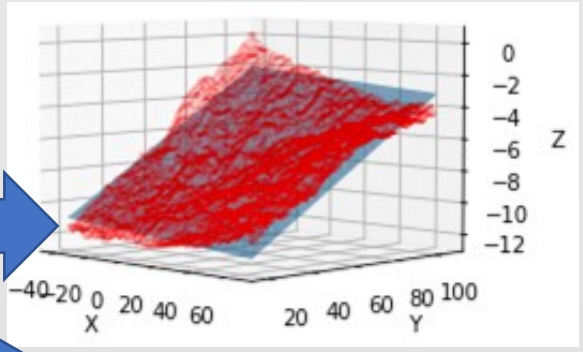


Fig.9 – De-trending process using a fitted plane through the data and subtracting that plane from the data.

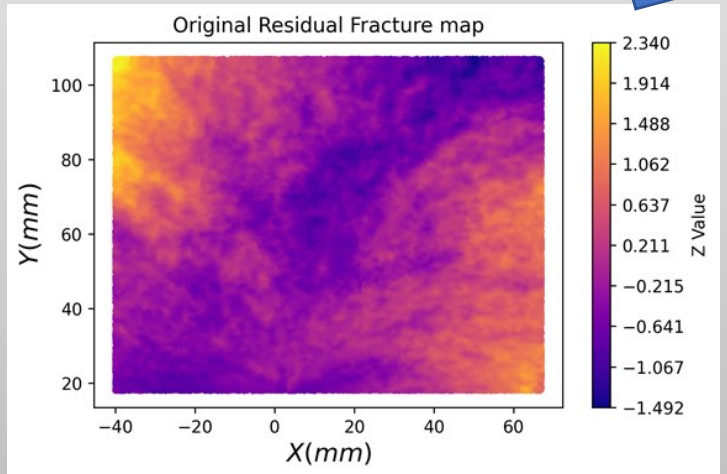
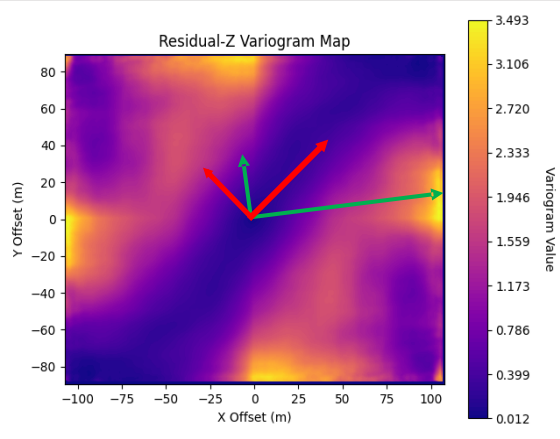


Fig.10 - residuals fracture map.

Methodology

- Fig.8 shows the residuals semi-variogram map and corresponding semi-variograms for the directions of major and minor continuity, respectively, which present a more stable sill.. As expected, the major and minor directions of continuity have changed from the green to the red.



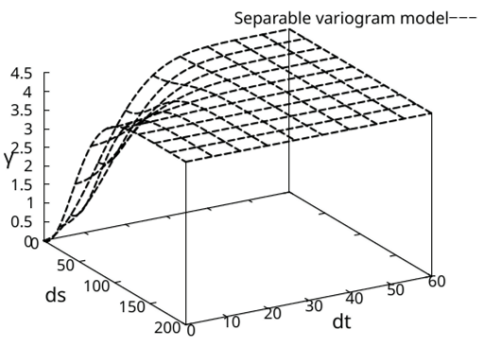
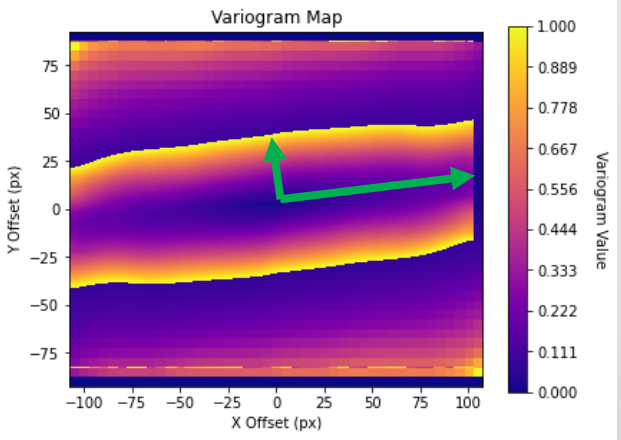


Fig.13 - *https://ebrary.net/133375/management/theoretical_variogram_covariance_function#aftercont*



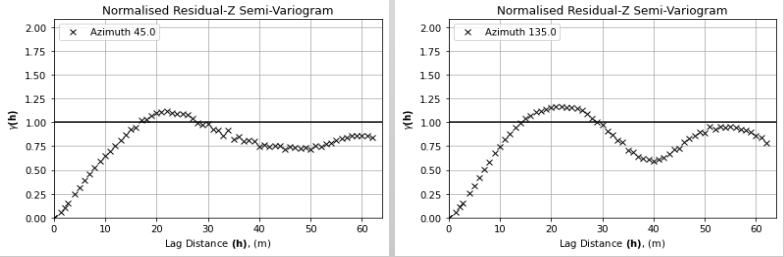


Fig.11 – Top: Residuals semi-variogram map. Green arrows represent the old and red arrows represent the new major and minor directions. **Bottom(Fig.5)**: From left to right, semi-variograms for 45 and 135°.

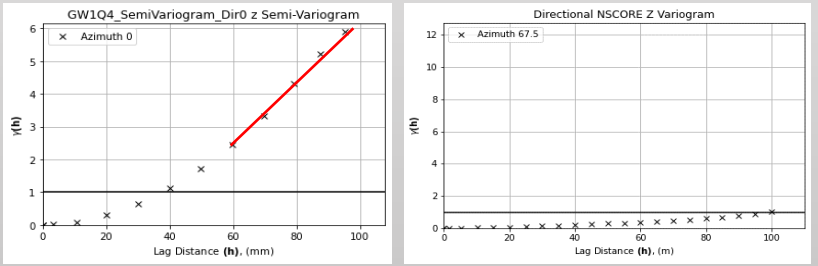


Fig.12 - Top: Semi-variogram map of Original data with lag=5mm. Bottom: From left to right, Semi-variograms for 0° and 67.5°.

Upscaling

- The final input necessary for kriging are some upscaled points. The fracture residuals are then upscaled using a grid fitted through them;
- In each "cell", a plane is fitted and the central point of the plane is taken as the representative value, similar to Fig.5 in de-trending. This avoids clustering and averaging issues.

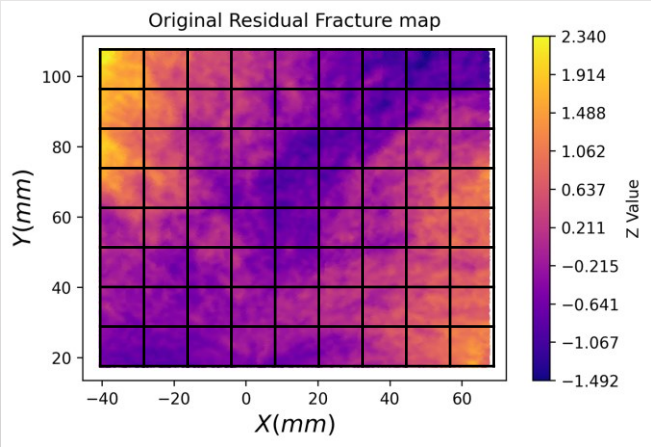
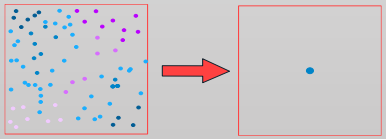


Fig.6 - Residuals fracture map.



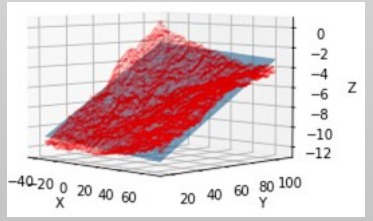


Fig.14 – Fitting a plane through the cell's data and keeping the central point for averaging.

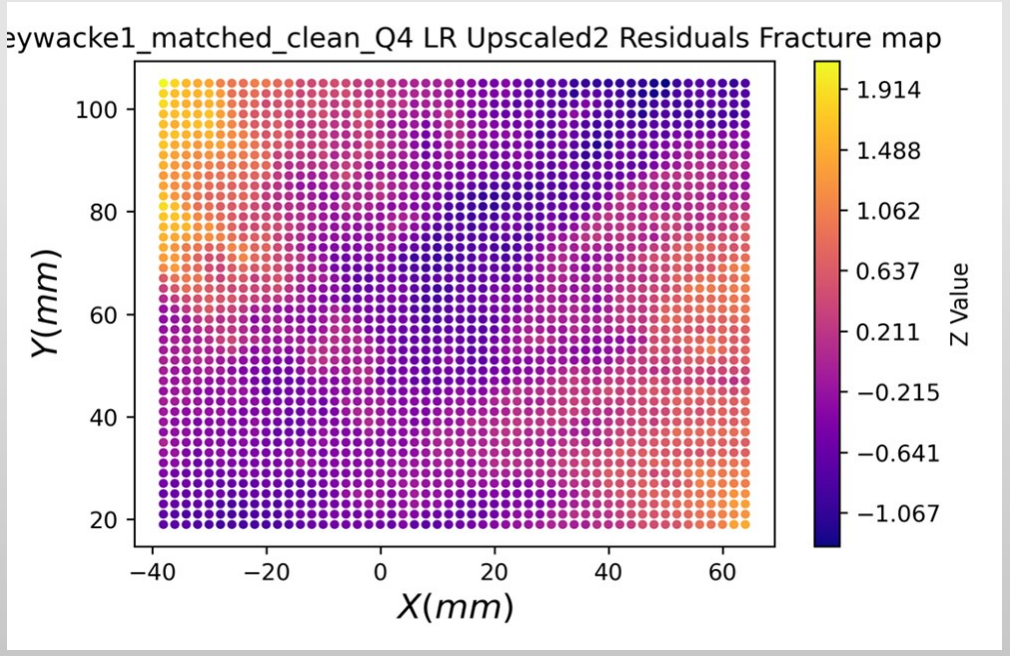


Fig.15 – Upscaled results of 2x minimum "cell" size.

Results

- A reasonable match between the kriged and original surfaces is achieved.
- The data is transformed from scatter to structured.
- If the data is normalised, the absolute values are lost (unless the initial distribution is kept).
- The number of data points are reduced to less than 90%, or more depending on the level of upscaling.

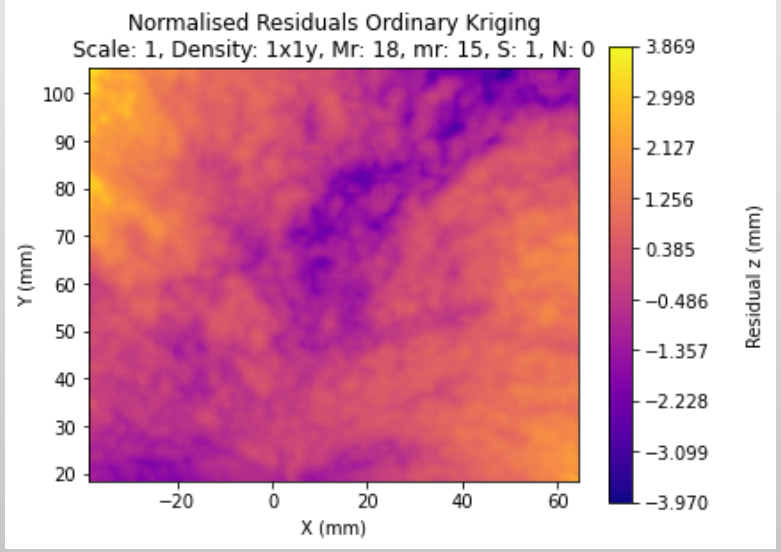


Fig.16 – Ordinary Kriging results (9,000 points).

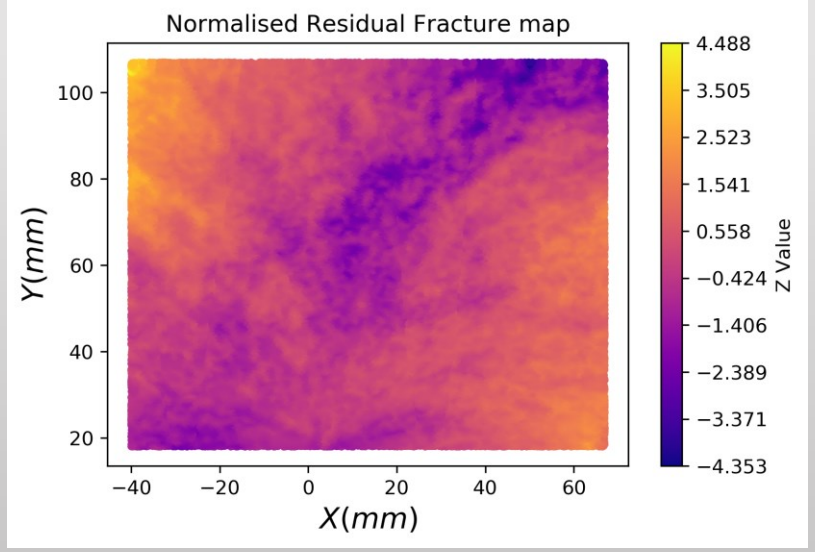


Fig.17 - Normalised residuals fracture map (Normalised Fig.7) (130,000 points).

Q4 Aperture

- Aperture map of Q4 of the Greywacke hydraulic fracture and corresponding variogram map and major/minor directions' semi-variograms.

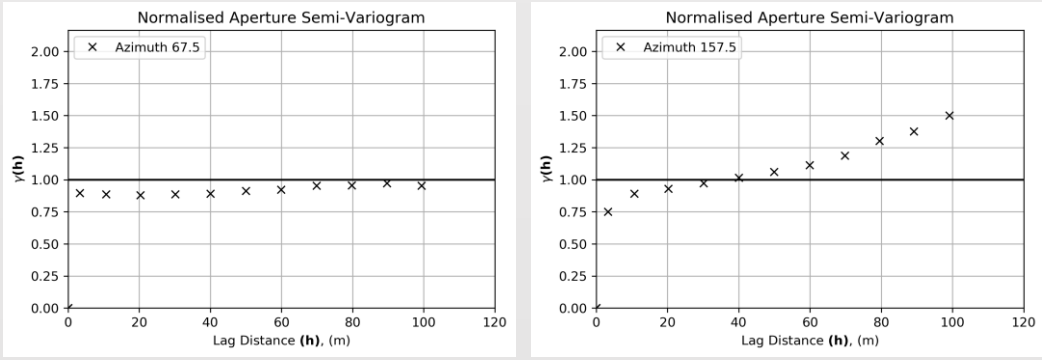


Fig.19 – Aperture major direction (67.5°) (left) and minor direction (157.5°) (right) variograms.

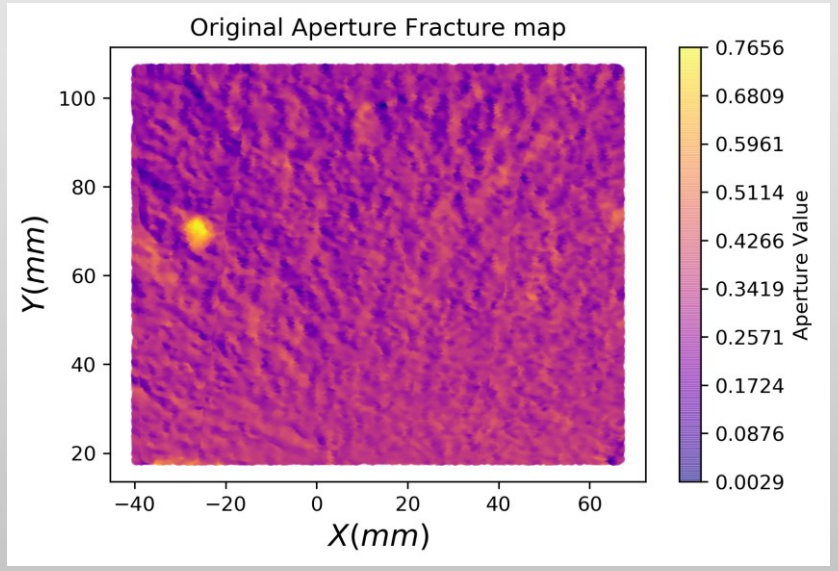


Fig.18 – Aperture map.

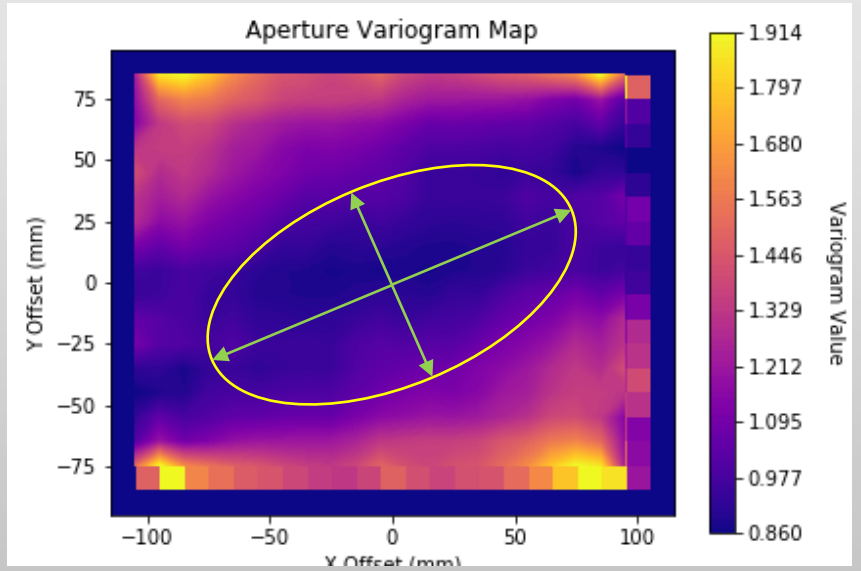


Fig.20 – Aperture variogram map

Variograms on Q4 upscaled22 aperture data vs Q4 original aperture data

- No satisfactory spatial continuity analysis results.

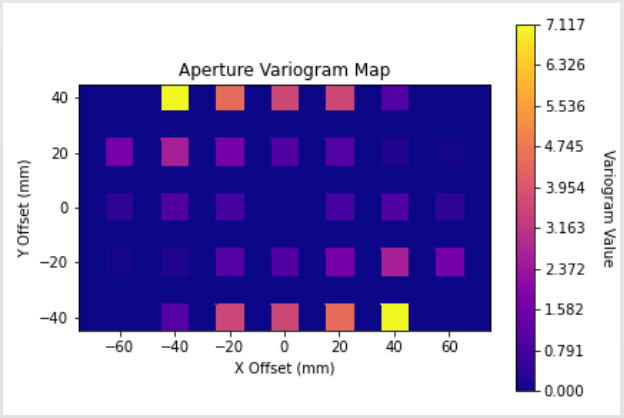


Fig.22 – Scale22 aperture variogram map.

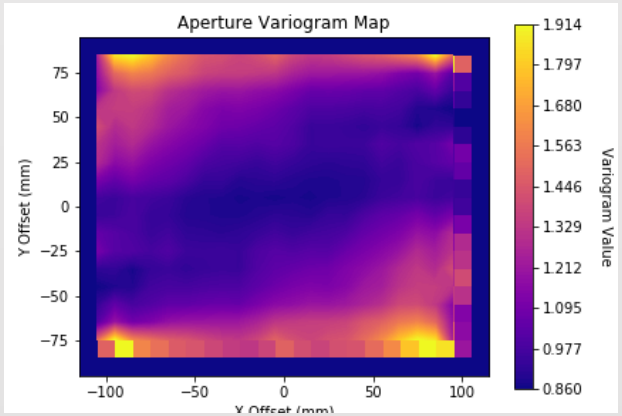


Fig.20 – Q4 lag10 original aperture variogram map.

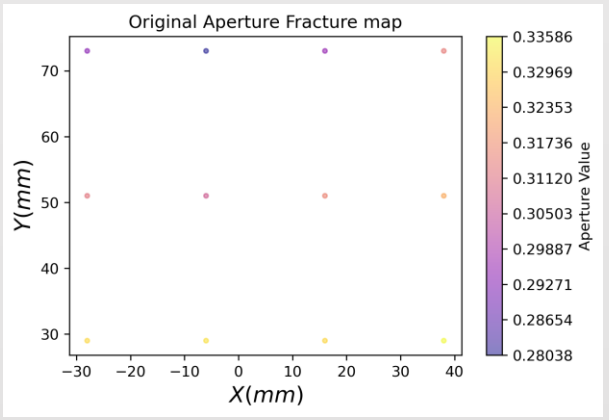
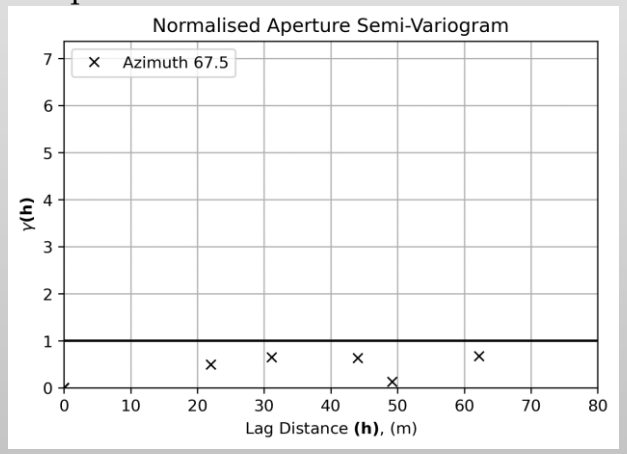


Fig.21 – Scale 22 Aperture map.



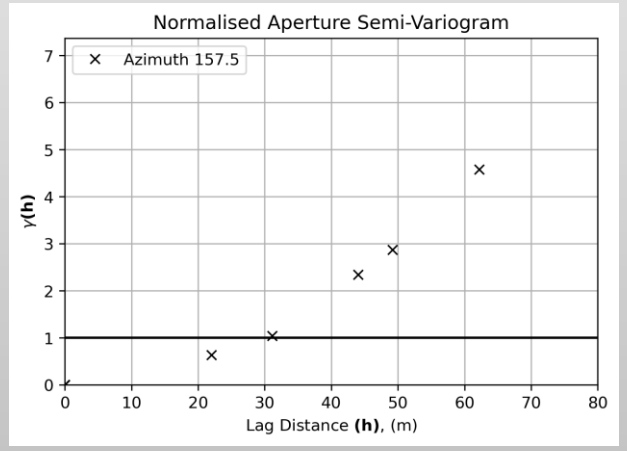
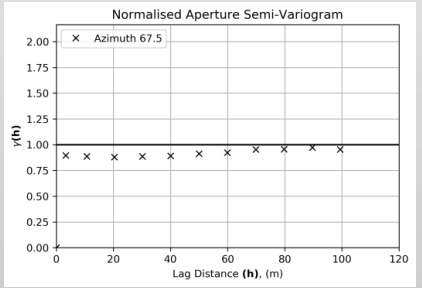


Fig.28 – Q4 Scale22 Semi-variograms.



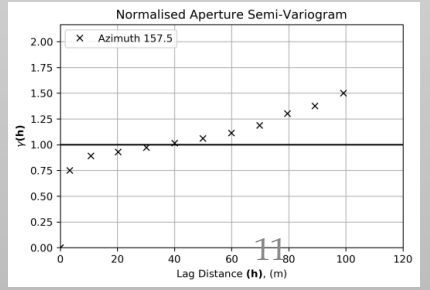


Fig.19 – Q4 Aperture major direction (67.5°) (top) and minor direction (157.5°) (bottom) variograms.

Variograms on Q4 scaled9 vs Q4 original aperture data

- Scale 9 could be interpreted as the REV scale to work with for Q4 aperture

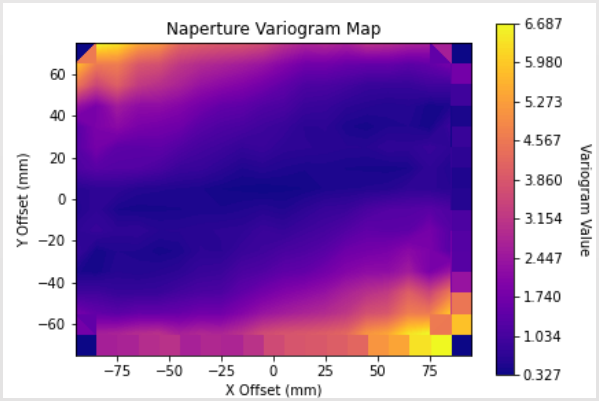


Fig.24 – Q4 scale9 lag10 aperture variogram map.

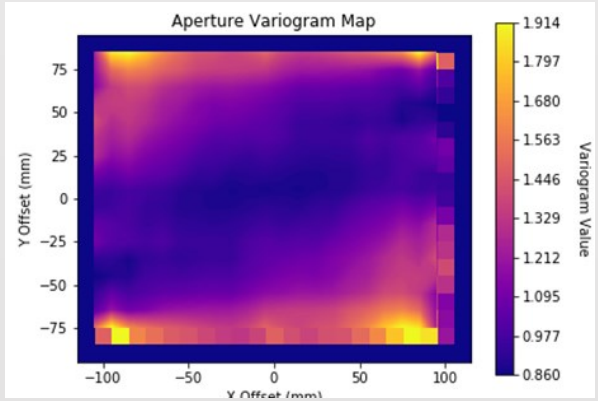


Fig.20 – Q4 lag10 original aperture variogram map.

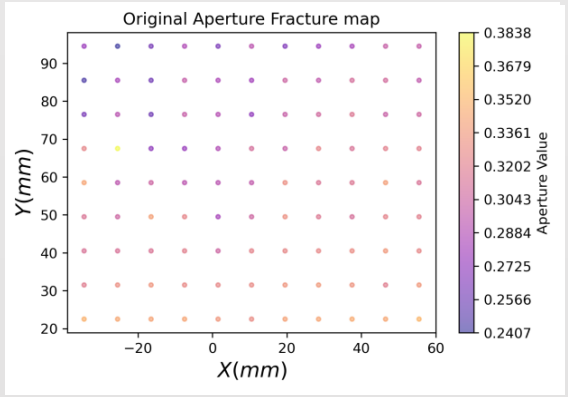
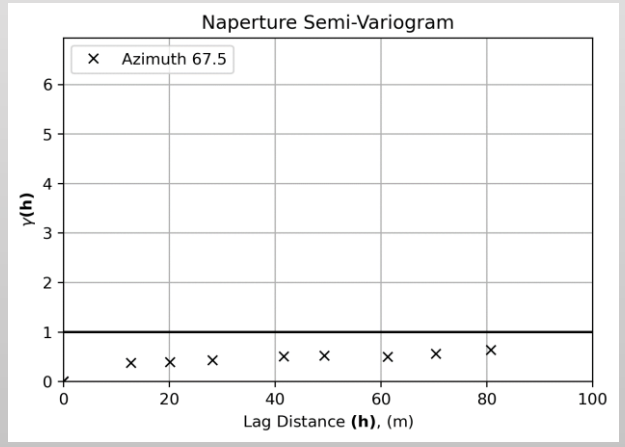


Fig.23 – Q4 scale9 Aperture map.



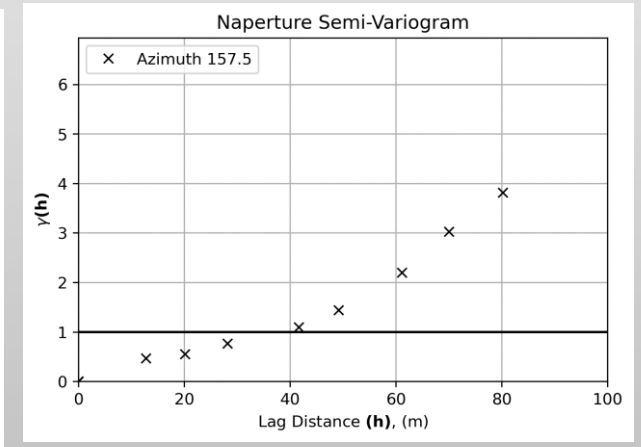
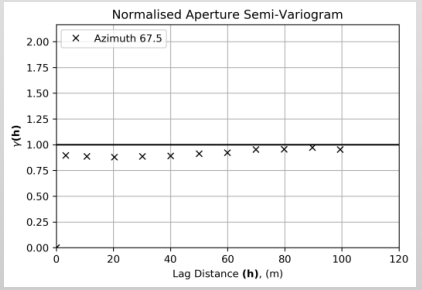
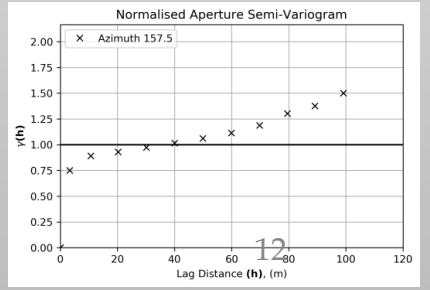


Fig.32 – Q4 scale9 Aperture major direction (67.5°) (top) and minor direction (157.5°) (bottom) variograms

Fig.19 – Q4 Aperture major direction (67.5°) (top) and minor direction (157.5°) (bottom) variograms.





Q4 Aperture – Extrapolation area

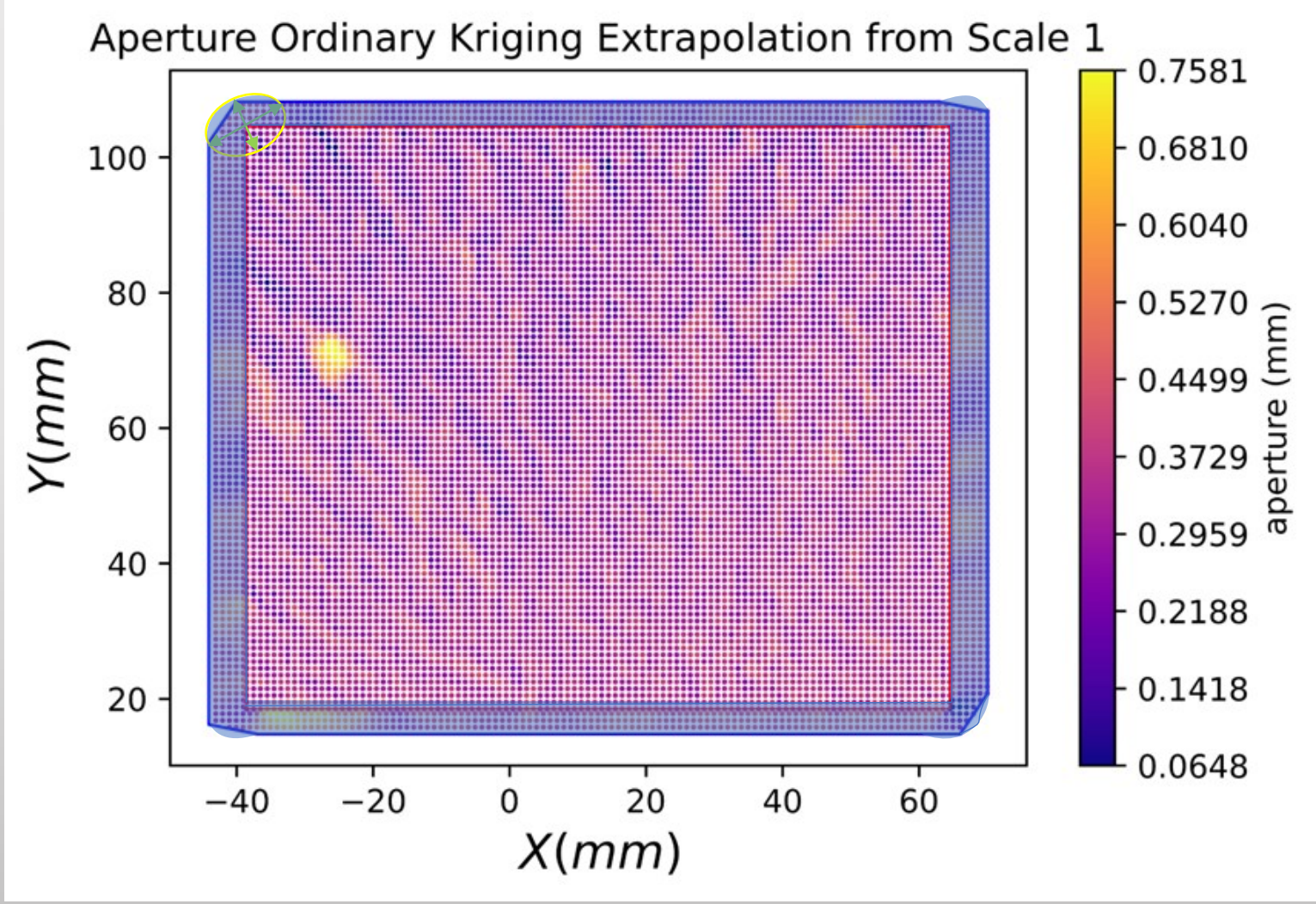


Fig.27 – Aperture map.

OpenGeoSys HM Model Validation Against Experiment

- A Finite Element Method coupled Hydro-Mechanical model

Compare modelling results with UoE poliaxial GREAT cell experiment (Fraser-Harris et al. 2020)

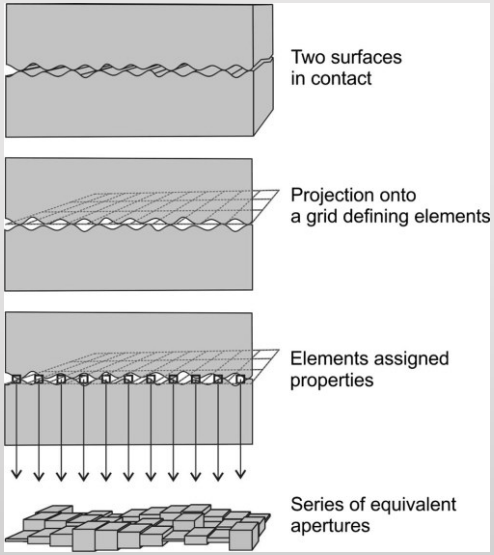


Fig.25 – Aperture distribution mapped to a mesh representing the fracture plane (McDermott et al 2015).

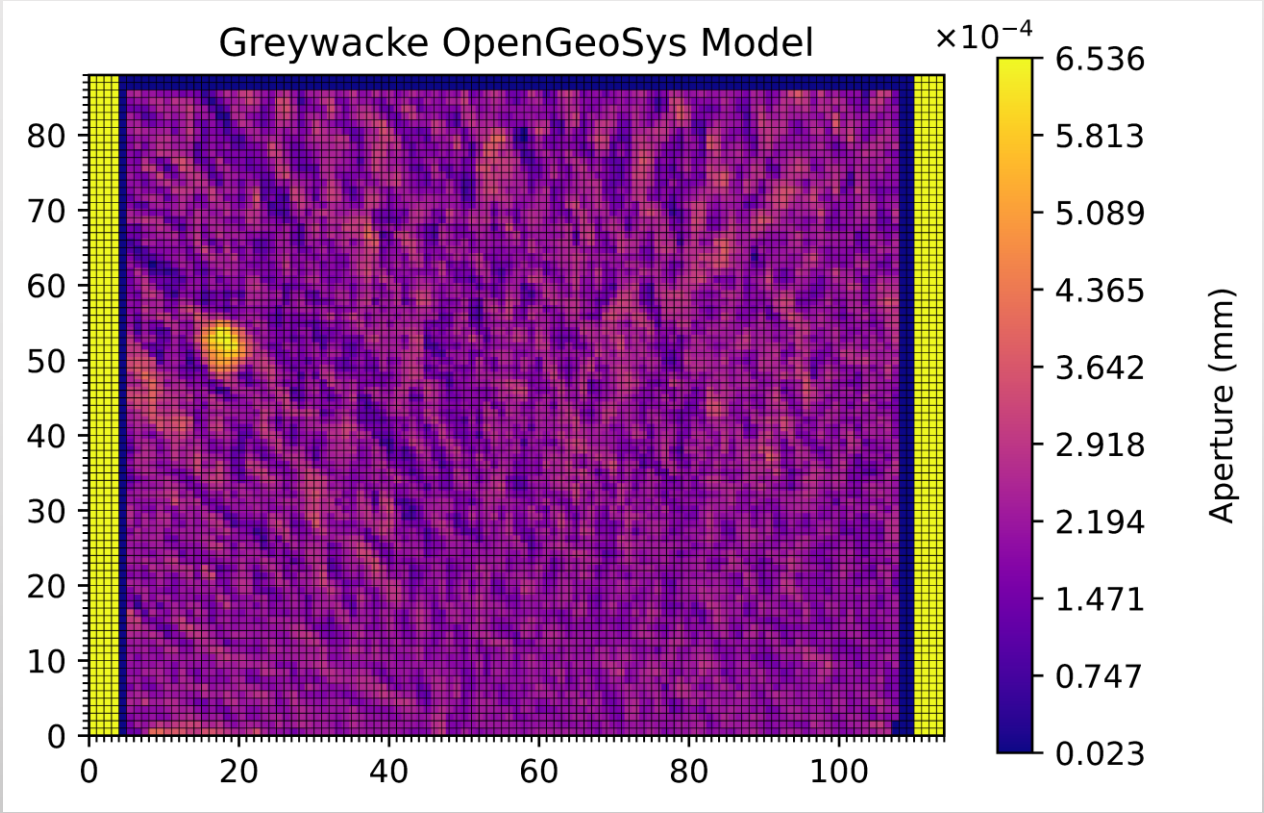
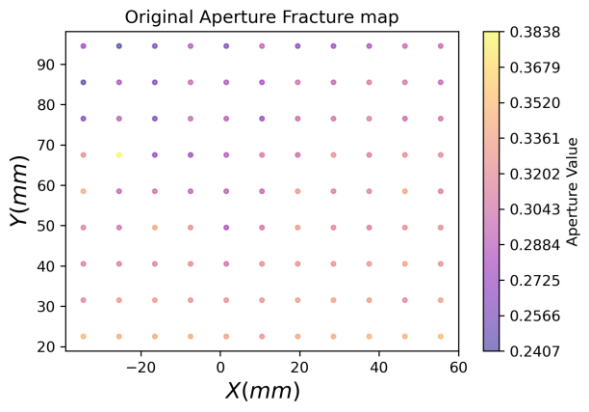
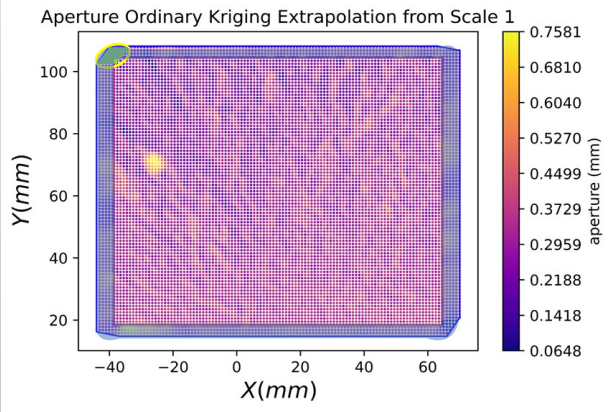


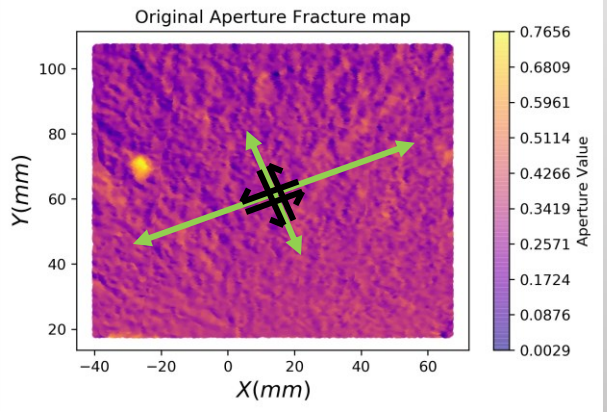
Fig.26 – Greywacke aperture distribution averaged and mapped to a mesh representing the fracture plane.

Next steps

1. Find the REV using variograms and build an aperture model ☑
2. Compare the experimental flow data to its OGS model (using aperture model from 1.) with similar experimental conditions — In Progress
3. Blind predict aperture outside our data ☑
4. Compare flow data with τ at different SC's orientations ☒







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