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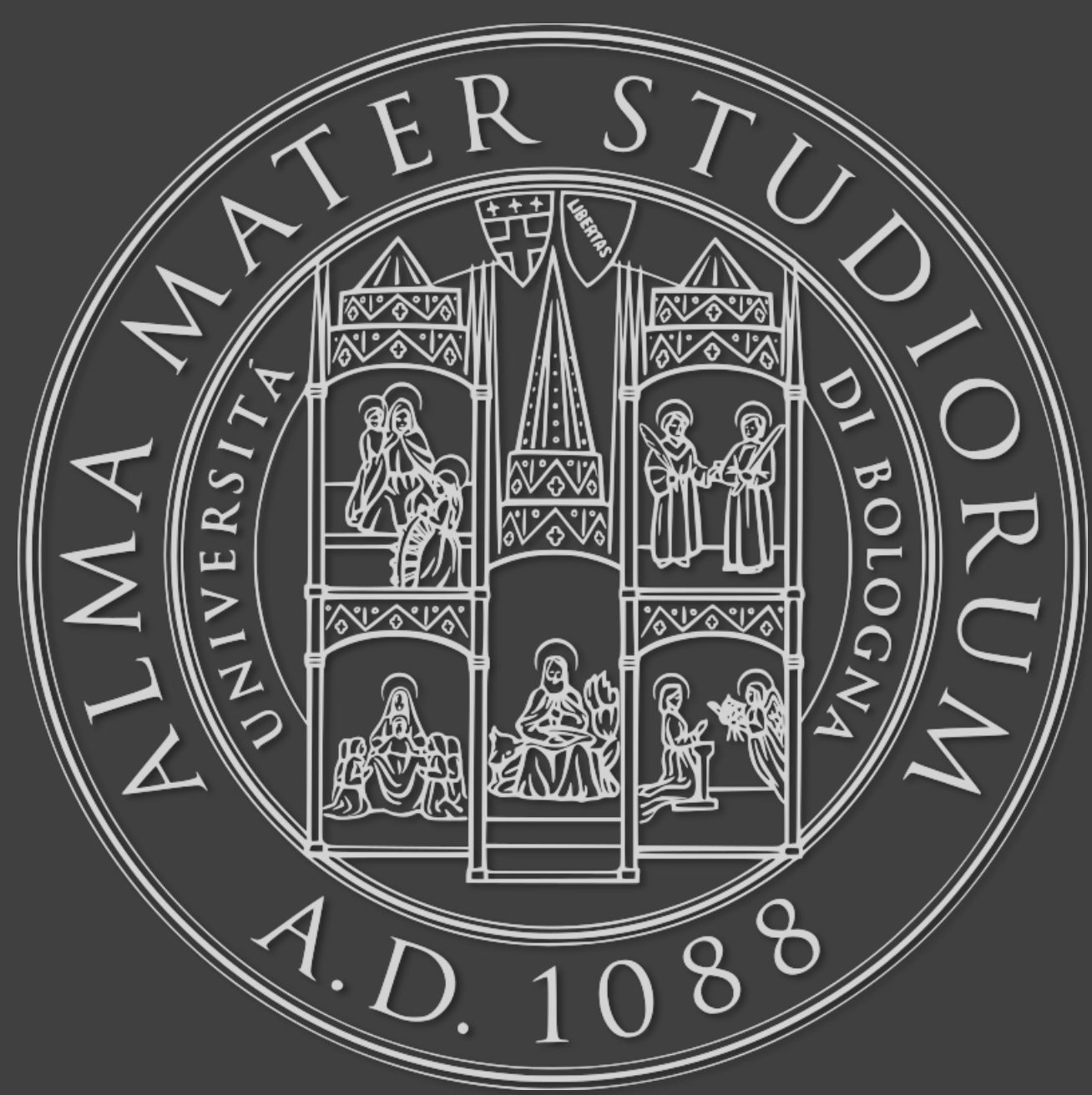
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## A STOCHASTIC ANALYSIS OF THE NON-NEWTONIAN HYDRAULIC BEHAVIOUR OF ROUGH FRACTURES

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### FLOW OF SHEAR-THINNING FLUIDS IN GEOLOGICAL FRACTURES

The **hydraulic behavior of geological formations** is mainly governed by **fractures connectivity** and **permeability**, whose heterogeneity strongly affects flow and transport, with fluid rheology playing an important role often oversimplified.

- Typically, unconventional and deep geothermal reservoirs present both **low-porosity** and **low-permeability**
- Activities in gas shale or hot rock requires **hydraulic stimulation** to enhances productivity and become cost effective
- Fluid viscosity is strictly linked with the activity effectiveness (e.g., proppant transport or stimulation fluid recovery).

**Fluids** involved in subsurface industrial activities present a **shear-thinning behaviour** at **continuum scale**, due to their complex make-up.

- muds
- foams
- water-based suspensions

**Subsurface industrial activities:**

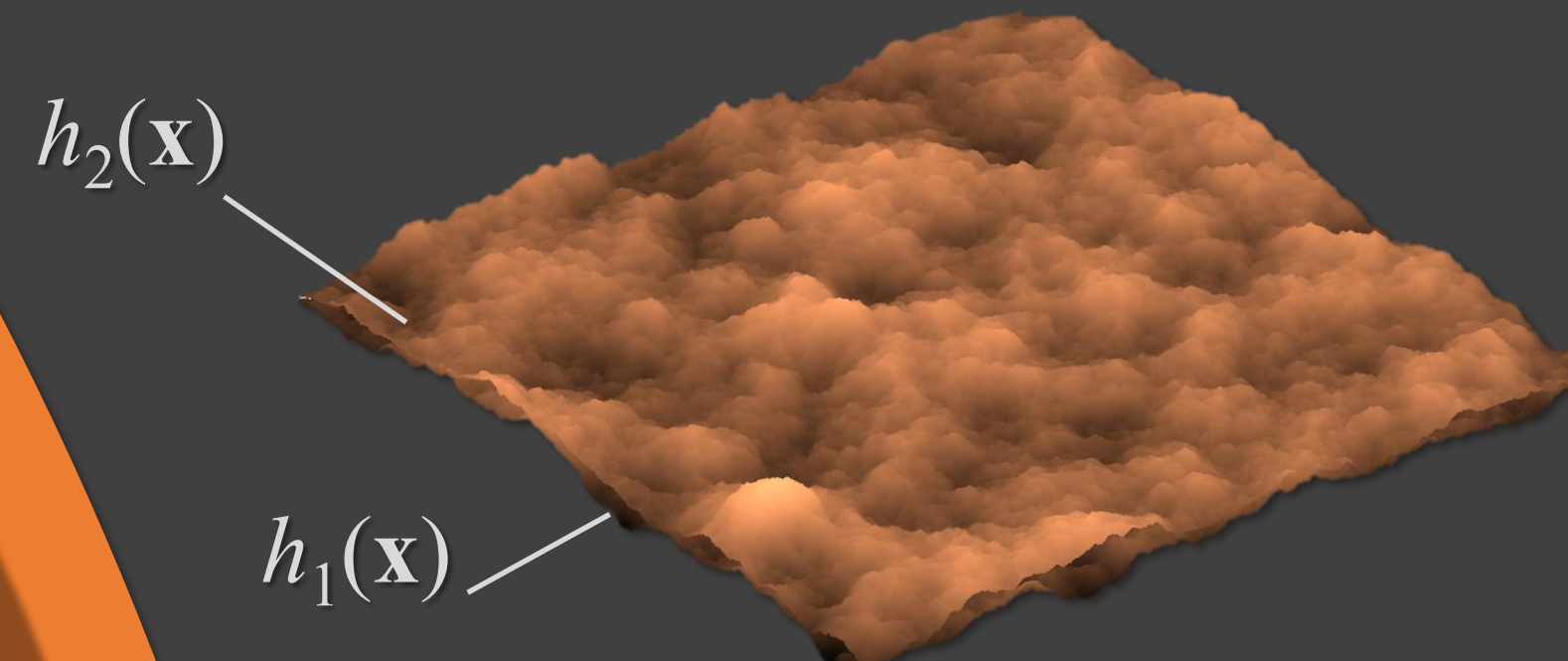
- Enhanced Oil Recovery (EOR)
- Enhanced Geothermal Systems (EGS)
- Carbon sequestration
- Lost circulation of drilling fluids

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### NUMERICAL MODELING

#### 2.1 Synthetic fracture generator

A synthetic aperture field is estimated by mating two **isotropic self-affine surfaces**  $h_i(\mathbf{x})$



$$w(\mathbf{x}) = h_1(\mathbf{x}) - h_2(\mathbf{x}) + \langle w \rangle$$

A rough surface can be generated as a 2D white noises and introducing spatial correlation: multiplying the modulus of the Fourier transform by the modulus of the wave numbers

$$|k| = (k_x^2 + k_y^2)^{1/2} \text{ to the power } -1-H$$

$$|h(\mathbf{k})| \rightarrow |k|^{-1-H} |h(\mathbf{k})|$$

#### 2.2 Fluid Rheology: Ellis model

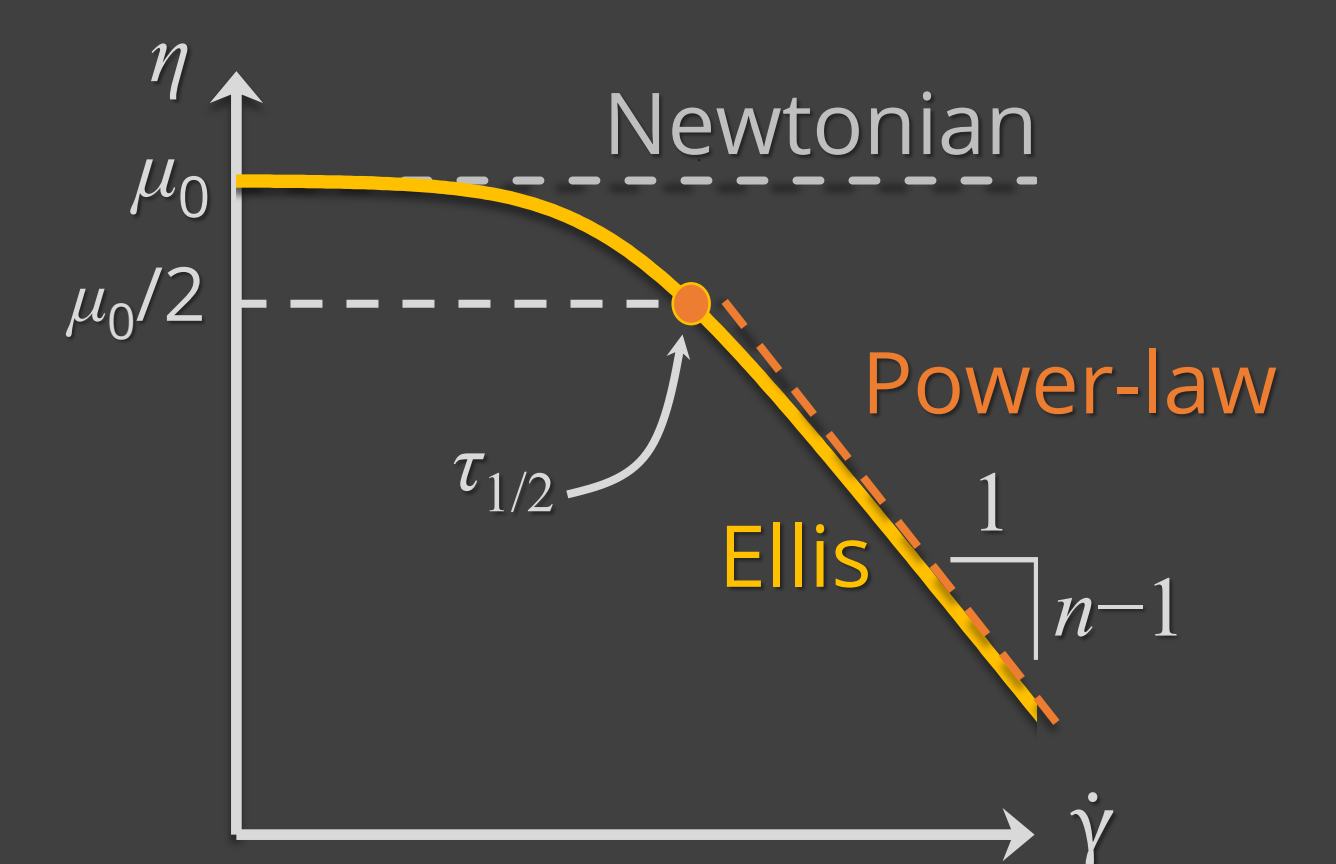
The Ellis model is a **three-parameter generalized Newtonian rheology**

$$\eta = \frac{\mu_0}{1 + \left( \frac{\tau_{xz}}{\tau_{1/2}} \right)^{\frac{1}{n-1}}}$$

$\mu_0$  low-shear rate viscosity ( $\eta \rightarrow \mu_0$  for  $\dot{\gamma} \rightarrow 0$ )

$n$  shear-thinning index

$\tau_{1/2}$  characteristic shear stress:  $\eta(\tau_{1/2}) = \mu_0/2$



#### 2.3 Generalized Non-linear Reynolds Equation

• **Lubrication theory** holds ( $\nabla w \ll 1$  and  $Re \ll 1$ )

$$-\nabla \cdot \left[ \frac{w(\mathbf{x})^3}{12\mu_0} + \frac{n}{(2n+1)} \left( \frac{1}{2^{1+n}\mu_0^n\tau_{1/2}^{1-n}} \right)^{\frac{1}{n}} w(\mathbf{x})^{\frac{2n+1}{n}} |\nabla P|^{\frac{1}{n}-1} \right] \nabla P = 0$$

Numerical modeling via finite volume method:

- The non-linear system of equations is solve via **inexact Newton-Krylov** method
- **Variable-fill-in Cholesky preconditioned conjugate gradient** → linear problem
- A **parameters continuation strategy** is adopted to handle strongly non-linear cases

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### STOCHASTIC ANALYSIS

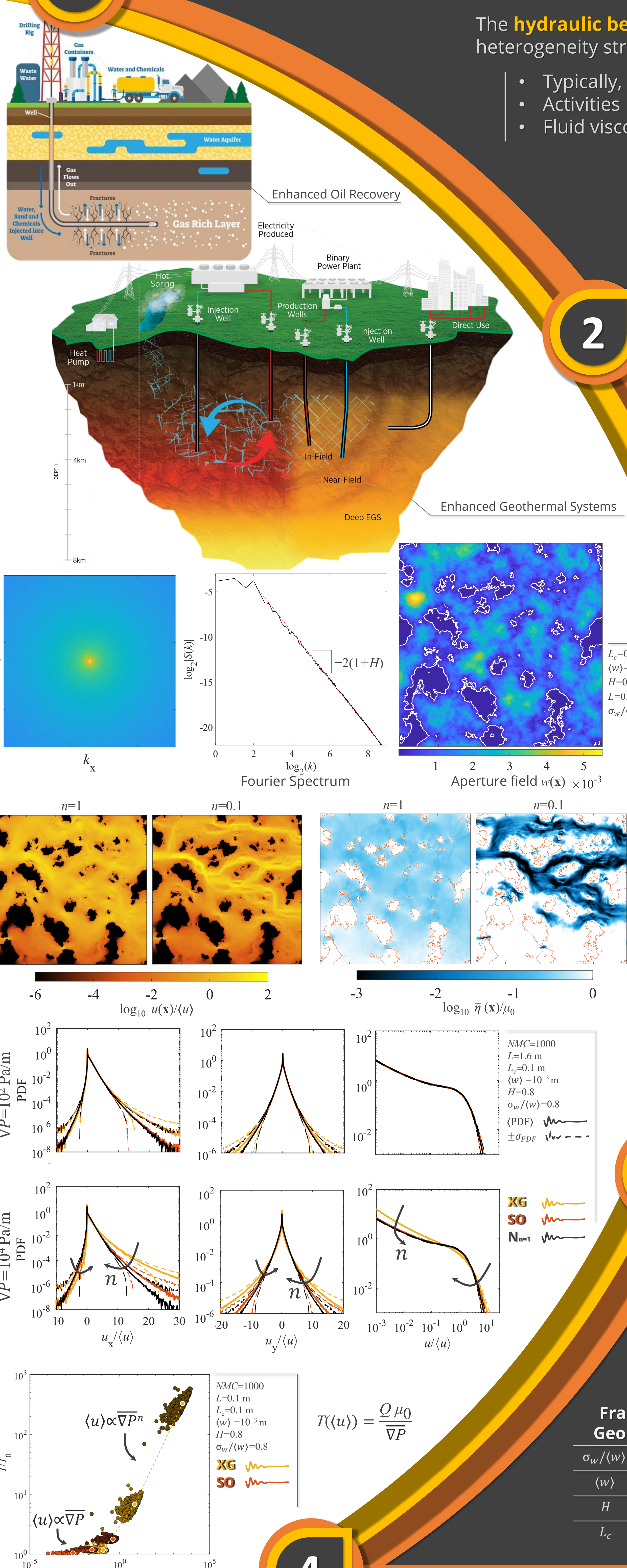
A **Monte Carlo Framework** is adopted to study the impact of:

- **Pressure gradient** ( $\overline{\nabla P}$ ) → Flow regime
- **Shear-thinning behaviour** ( $n$ ) → Fluid rheology
- **Fracture dimension** ( $L$ ) → Scale

For each combination of the parameters (12 in total), the flow is solved considering a set of **1000 fracture realizations**.

Eventually, ensemble statistics are then analysed for:

- **Velocity** components and magnitude ( $u_x, u_y, u$ )
- **Apparent Transmissivity** ( $T$ )



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### CONCLUSION AND PERSPECTIVES

#### 4.1 Conclusion

- Velocity components displays narrow PDFs with nearly exponential decay
- High  $\overline{\nabla P}$  and low  $n$  increase shear-thinning behaviour, favouring flow localization
- QoIs PDFs of the smaller fracture length present higher dispersion
- Shear-thinning behaviour enhances fracture transmissivity, leading to non-darcian flow regime  $\langle u \rangle \propto \overline{\nabla P}^n$

#### 4.2 Perspectives

Flow localization impacts the effectiveness of any subsurface activities

- **High velocities** magnitude PDFs → **channeling metrics**
- **Low velocities** magnitude PDFs → **anomalous transport**

Mèheust, Y., Schmittbuhl, J. (2000) Flow enhancement of rough fracture. *Geophys. Res. Lett.*, 27(18), 2989-2992. doi: 10.1029/1888gl1008464

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