Hydro-thermal flows in an open fracture:

Important morphology scales ?

Amélie Neuville [1,2],

Renaud Toussaint [2], Eirik Flekkøy [1], Jean Schmittbuhl [2]

(1) AMCS, Fysisk institutt, UiO, Oslo

(2) Institut de physique du Globe, CNRS, UdS, Strasbourg

Geothermal background

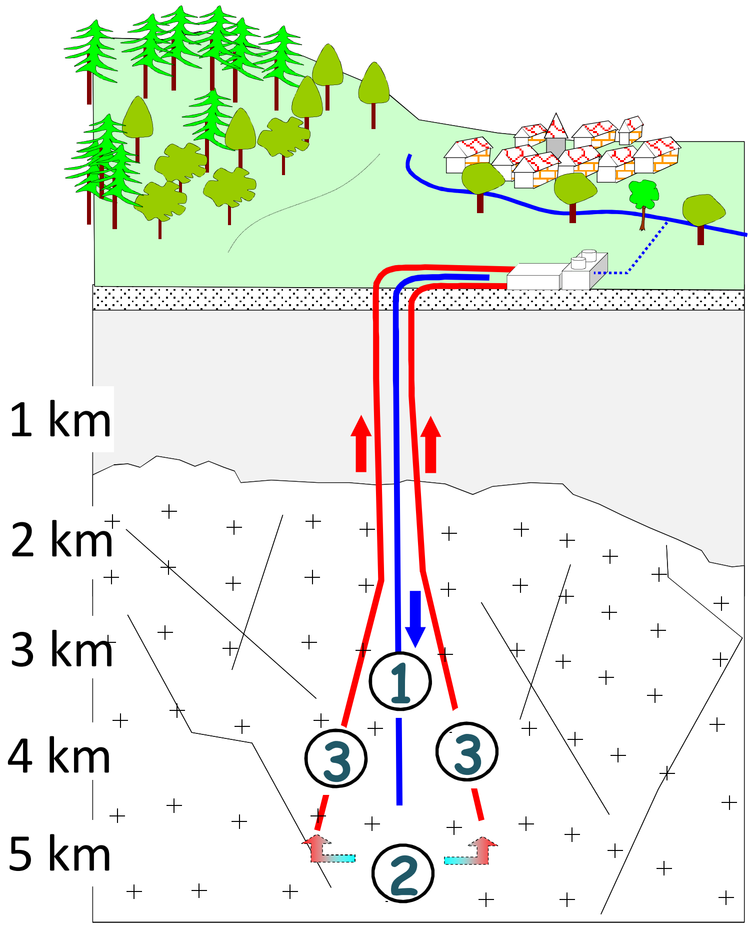
Thermal exchanges between

a hot fractured rock
and a cold fluid

Deep geothermal systems

- "Enhanced Geothermal Systems"
  - Soultz-sous-Forêts (Alsace, France)
  - Cooper Basin (Australia)

- Example of parameters
  - Hydraulic flow : 25 l/s
  - Temperature at injection : 60°C
  - Temperature at pumping : 200°C



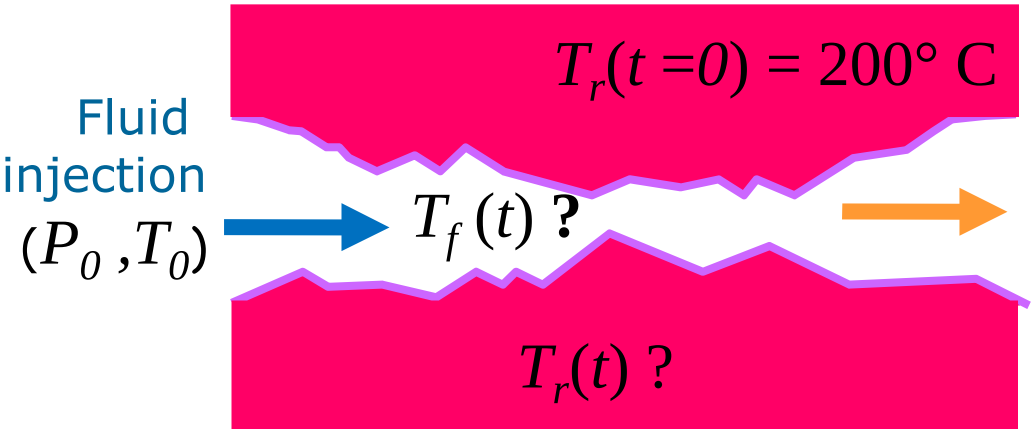
A. Gallien, from AREVA documents

Background and questions

Fracture have a complex morphology

Effect of the morphology of fractures on the

- Hydraulic flow?
- Heat exchange between fluid and rock?



Scale: individual fracture

Modeling

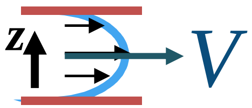
Equations

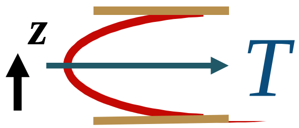
- Navier-Stokes
- Advection-diffusion equation

Depend on
- fluid viscosity η
- pressure gradient $\vec{\nabla} p$
- Rock/fluid thermal diffusivities
- Fracture aperture $a(x,y)$!

Hydro-thermal models

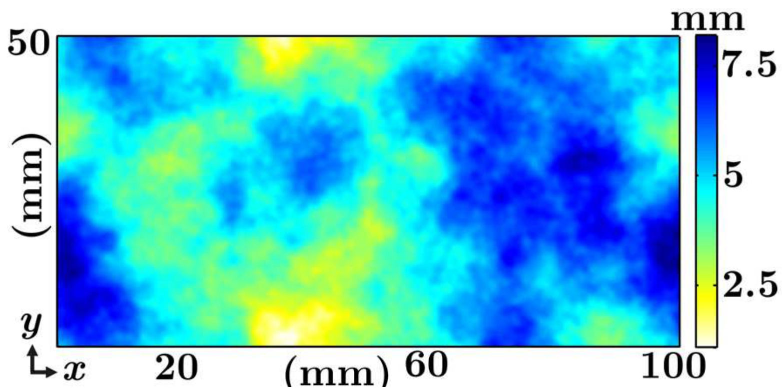
- **Finite differences (FD) model**
  - Lubrications approximations
    = Equations averaged across the aperture
      - Velocity contained in the mean plane (x,y)
      - Diffusive heat flux along z
      - Advective heat flux in the mean plane (x,y)
  - Constant temperature rock
  - Self-affine aperture: "Smooth" roughness



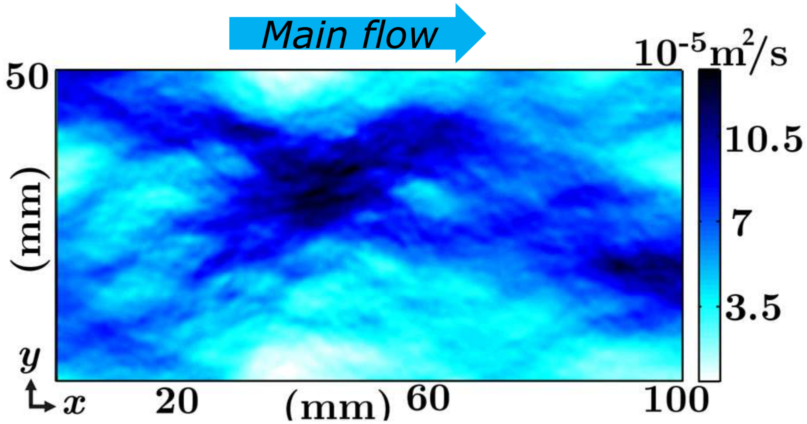


- **Lattice Boltzmann (LB) model**
  - Statistical method
    - Fictitious mass and energy particles
  - No terms discarded in the equations
  - Single asperity with steep slopes, "Sharp" roughness

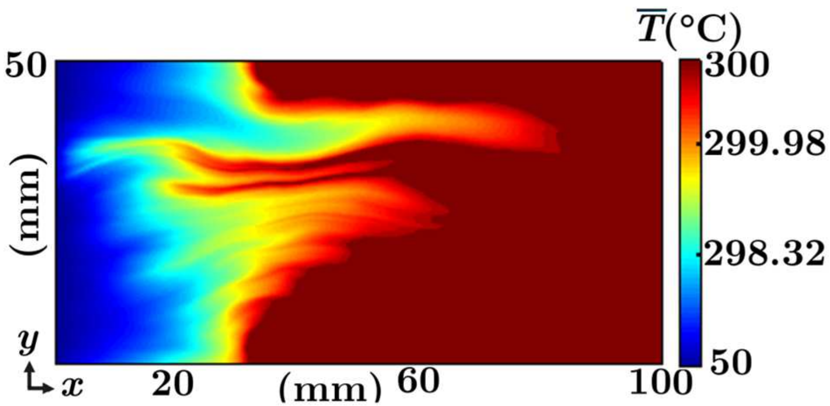
Illustration…hydro-thermal result (FD)



Rough apertures (self-affine) $a(x, y)$



2D-flow norm $\|\vec{q}\,(x, y)\|$



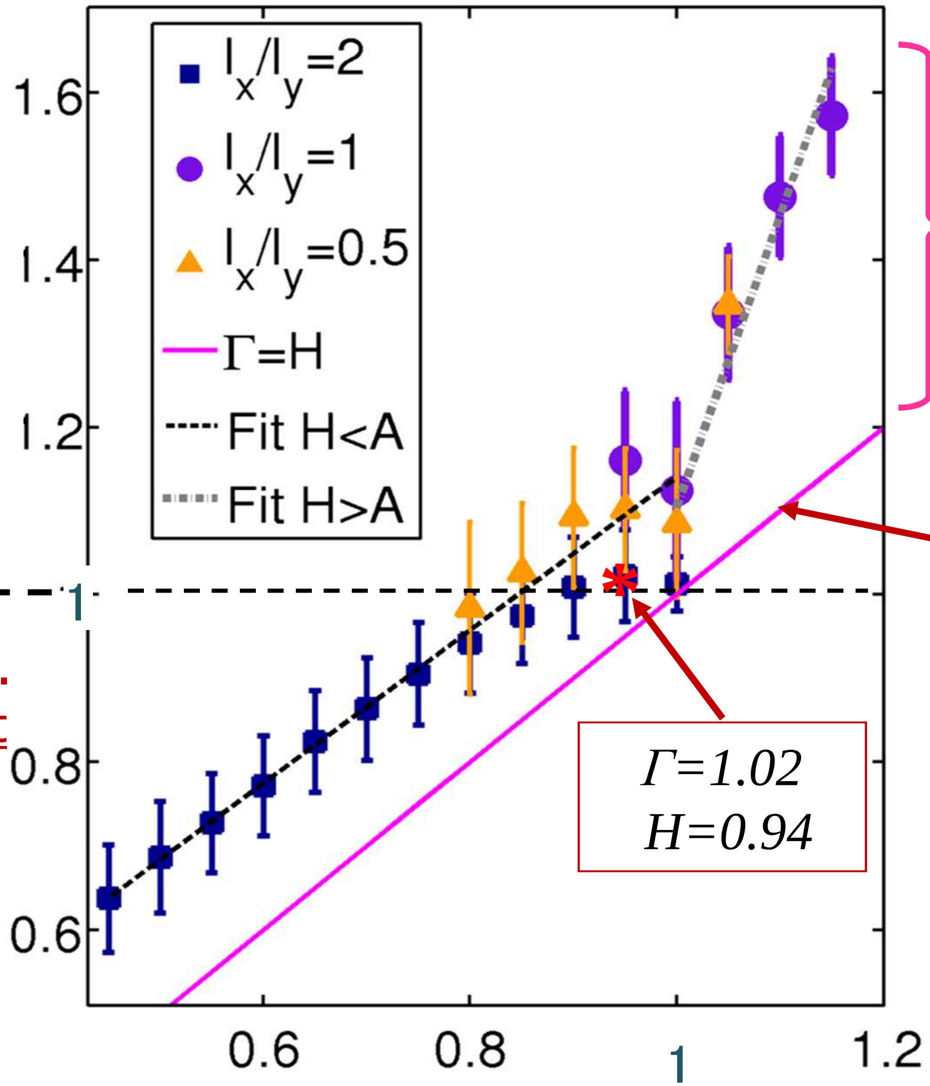
Averaged temperature $$\overline{T}(x, y) = \frac{\int_a V(x, y, z) T(x, y, z) dz}{\int_a V(x, y, z) dz}$$

Neuville et Al. *Phys. Rev. E* (2010)

Neuville et Al. *C.R. Geosci.* (2010)

Statistical results using various morphologies

Inverse of the heat exchange Efficiency (Γ)



Thermal exch. less efficient than parallel plates separated by A

Thermal exch. more efficient than parallel plates separated by A

Thermal exch. less efficient than flat model with same permeability

Expected thermal efficiency deduced from the hydraulic efficiency

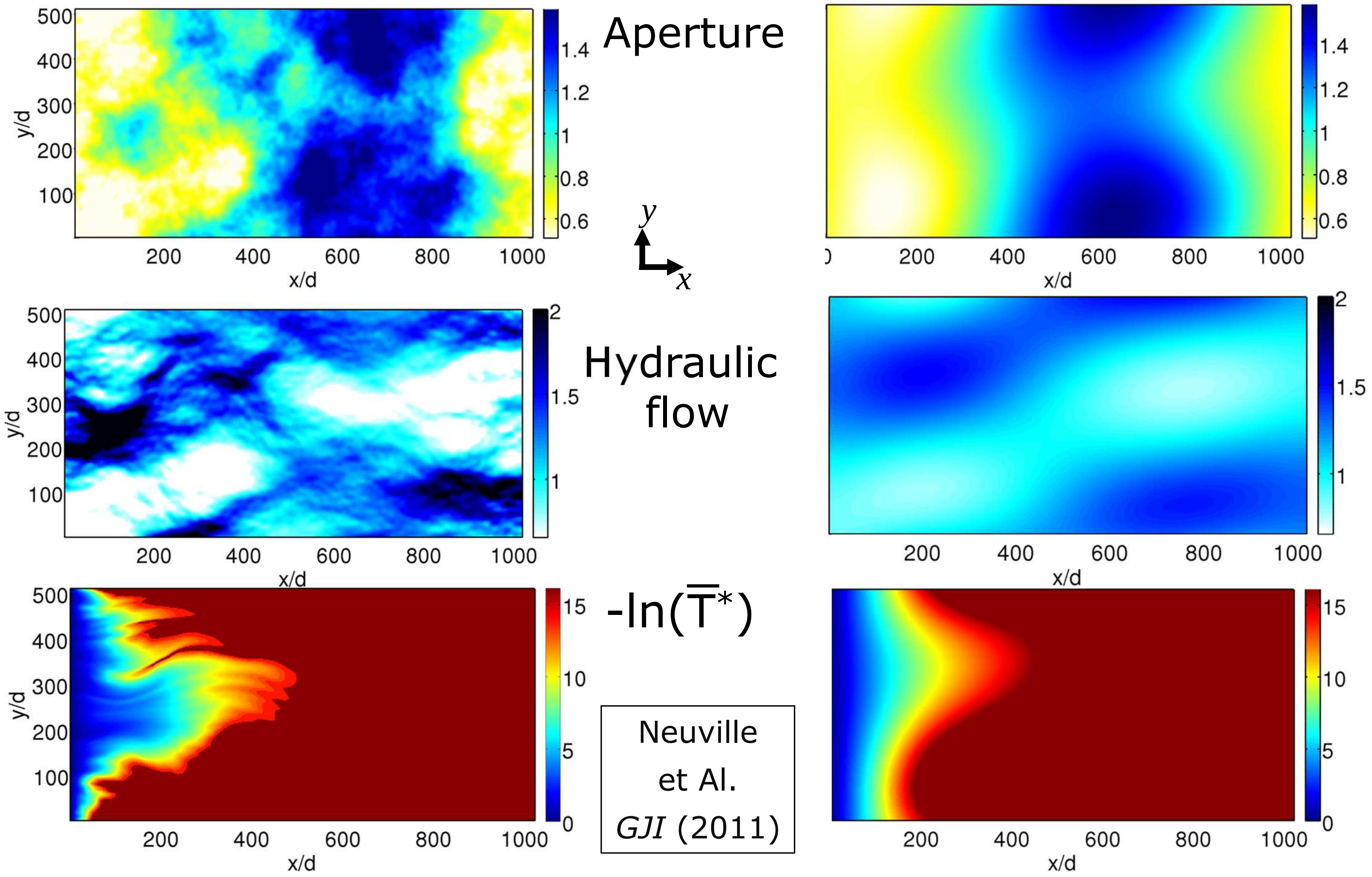
A: mean geometric aperture

Hydraulic exchange efficiency (H)

Less permeable than parallel plates separated by A

More permeable than parallel plates separated by A

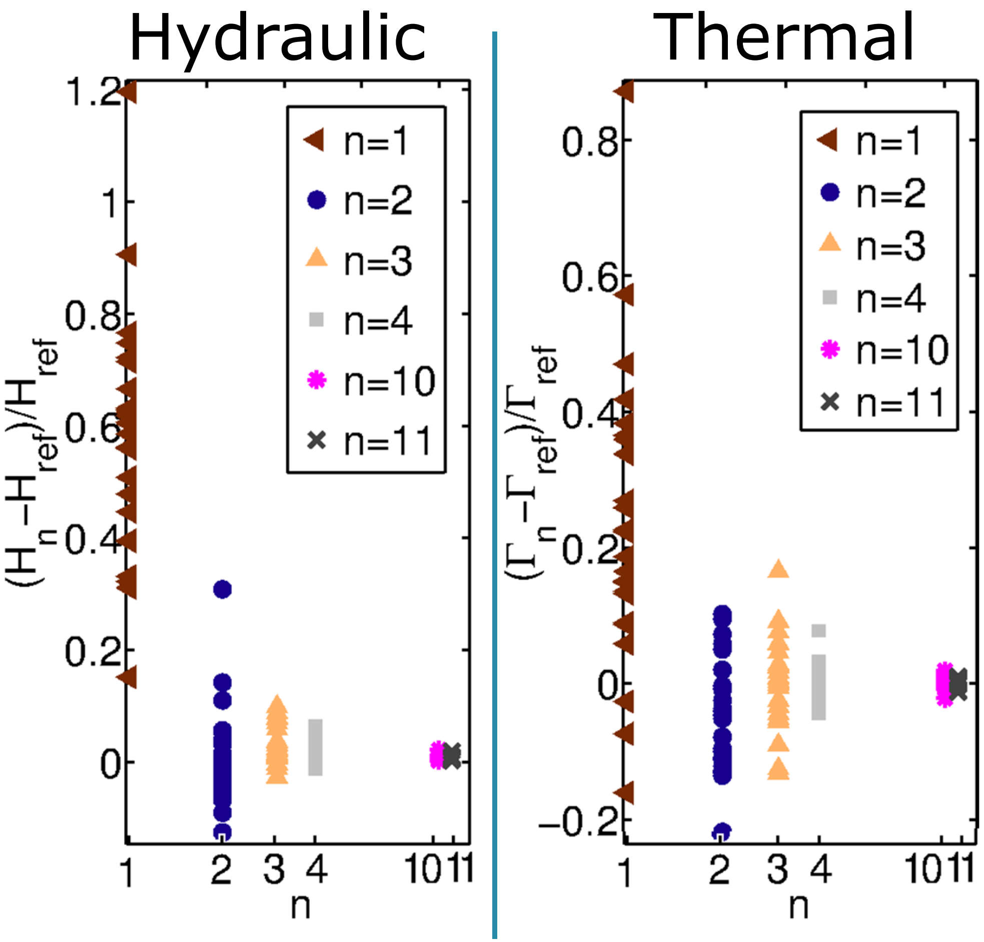
Control of the large scales modes on the hydro-thermal variations



Quantification: importance of the large scales

Fourier filtering of the aperture $a(x,y)$:

$$\begin{cases} \left(\frac{k_x L_x}{2\pi}\right)^2 + \left(\frac{k_y L_y}{2\pi}\right)^2 \geq n^2 & \rightarrow \left\|\tilde{a}_n\left(k_x, k_y\right)^2\right\| = 0 \\ \left(\frac{k_x L_x}{2\pi}\right)^2 + \left(\frac{k_y L_y}{2\pi}\right)^2 < n^2 & \rightarrow \left\|\tilde{a}_n\left(k_x, k_y\right)^2\right\| = \left\|\tilde{a}\left(k_x, k_y\right)^2\right\| \end{cases}$$



$(H_n - H_{ref})/H_{ref}$ and $(\Gamma_n - \Gamma_{ref})/\Gamma_{ref}$:

Difference between the efficiencies
in the filtered (H_n, Γ_n)
and
in the fully rough geometries
(H_{ref}, Γ_{ref})

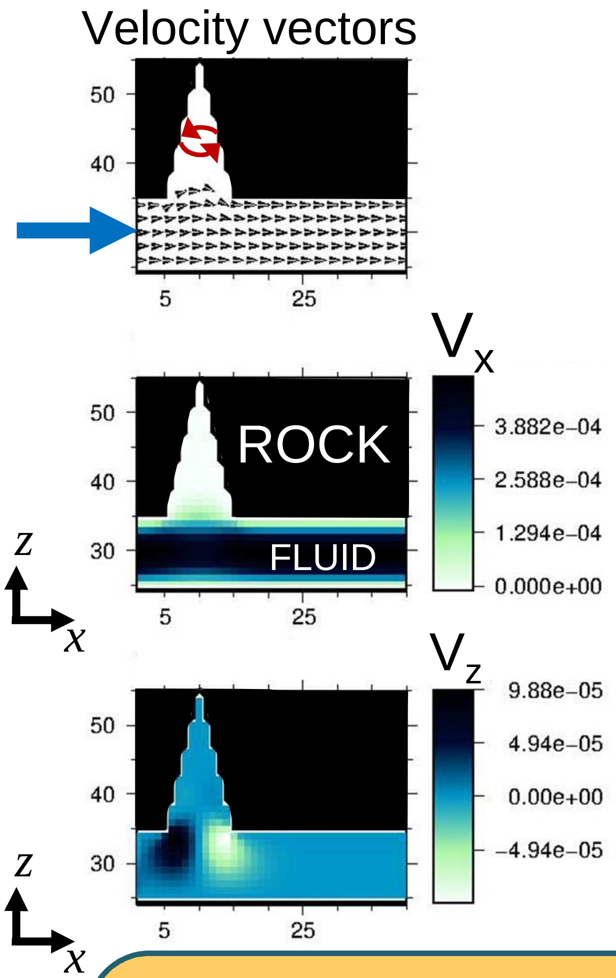
n = 1

- Average aperture kept
- Parallel case

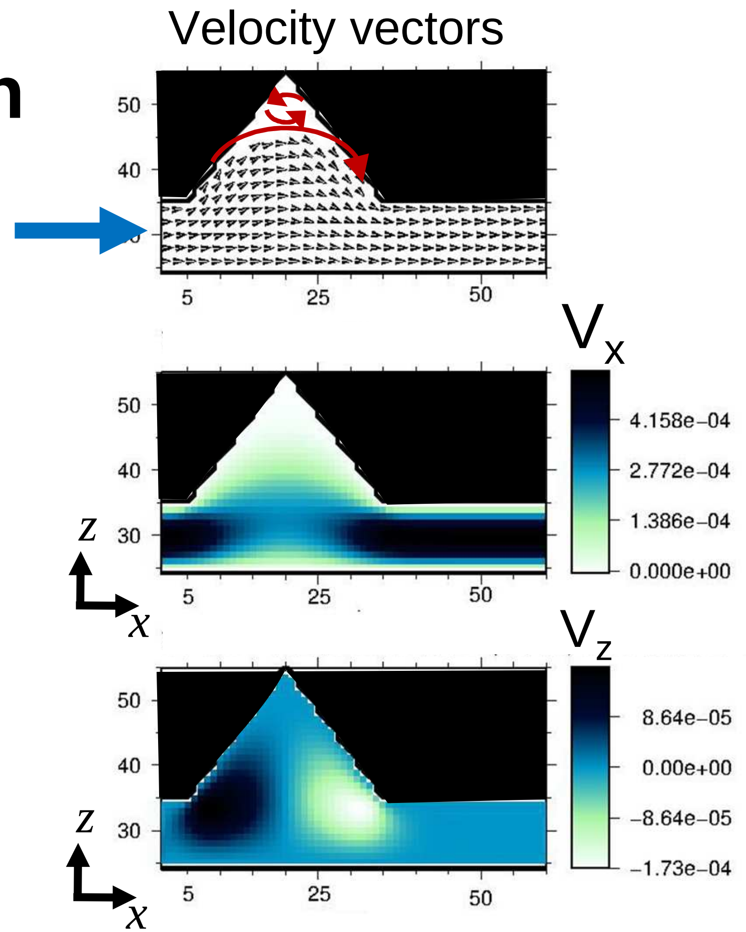
n ↗

- Morphology is better described
- H_n converge towards H_{ref}
- Γ_n converge towards Γ_{ref}

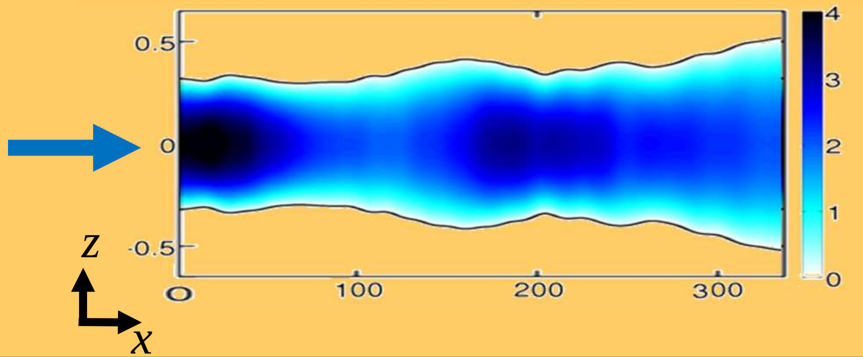
Simulations with LB methods



Recirculation at small Reynolds number (Re ≈ 0.003)

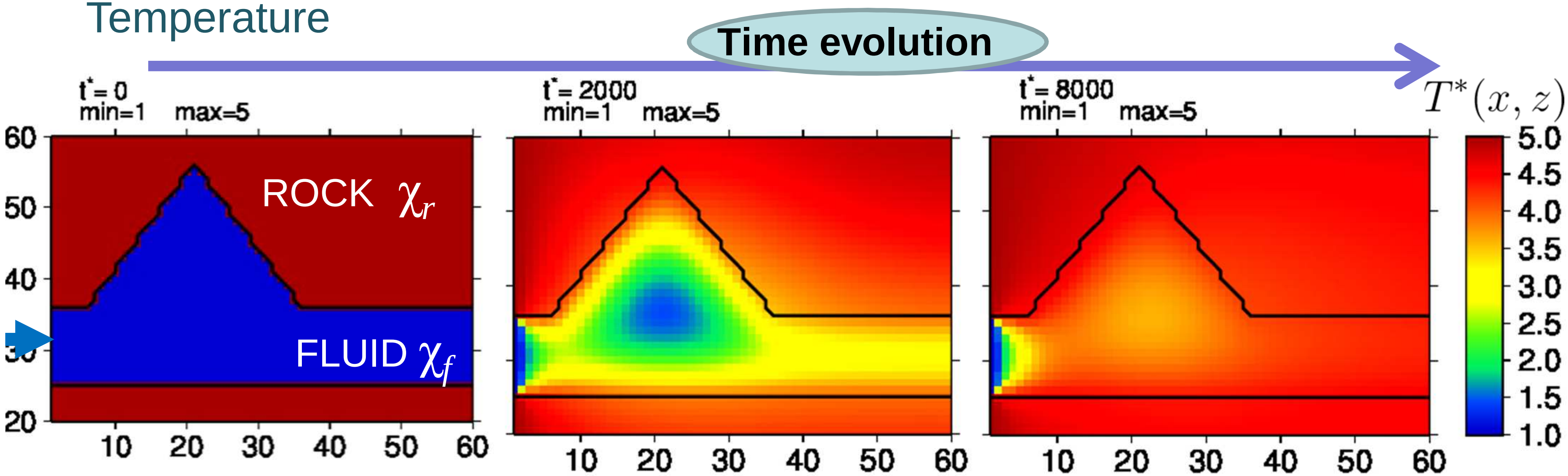


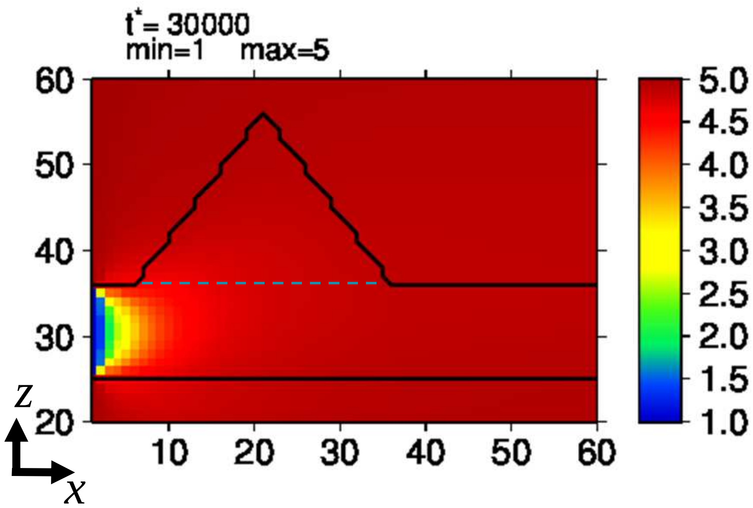
Compared to velocity obtained in FD with lubrication approximation



Simulations with LB methods

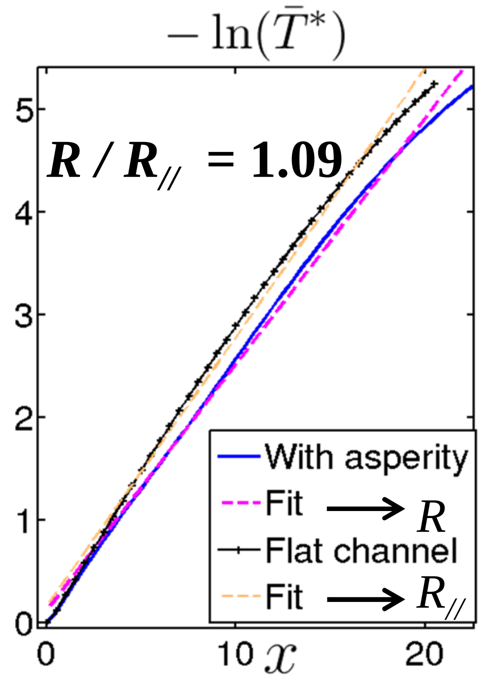
Temperature





$$\bar{T}^*(x) \propto \frac{\int_{a(x)} v_x(x,z)[T^*(x,z) - T^*_{\mathrm{ref}}(x)]dz}{\int_{a(x)} v_x(x,z)dz}$$

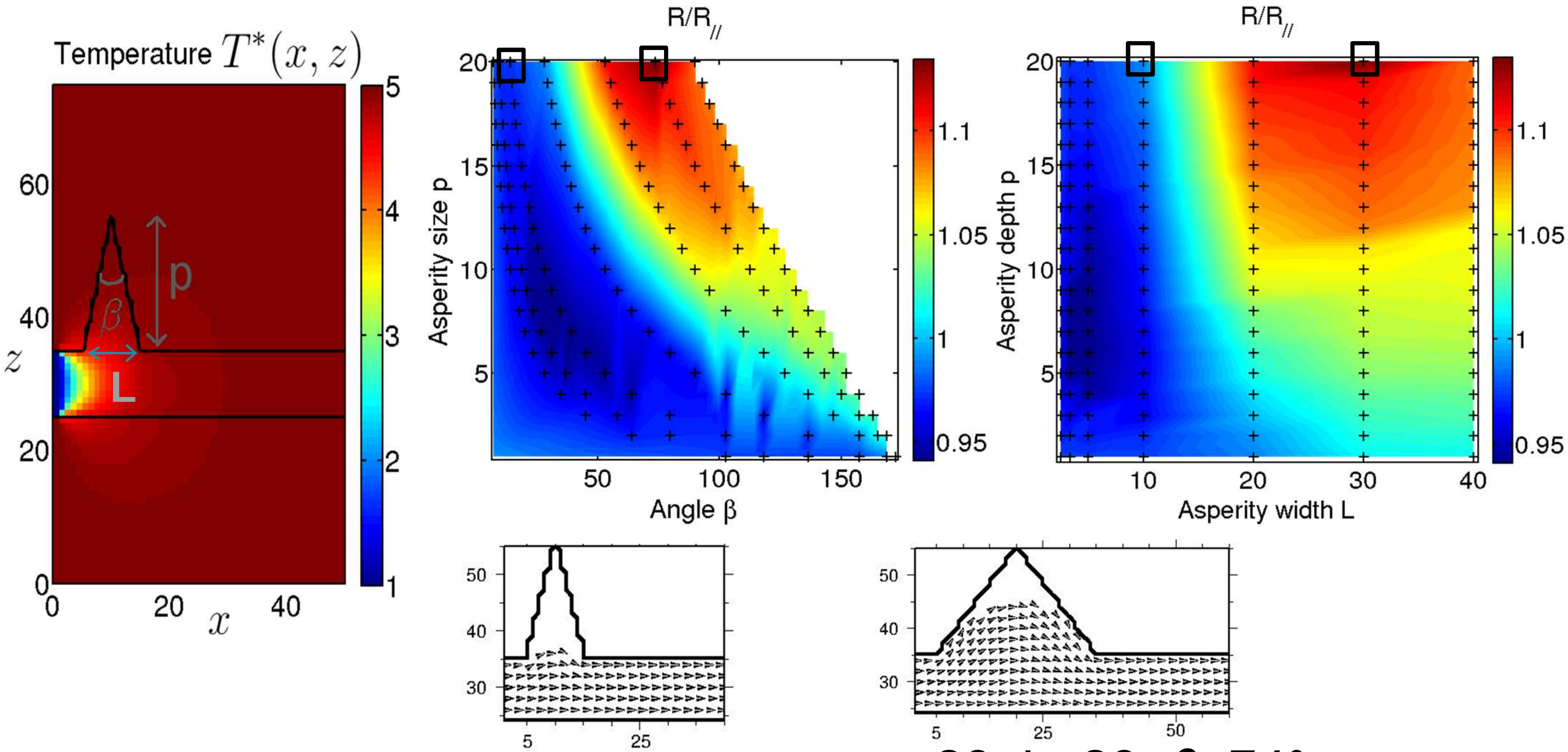
$$\bar{T} \propto \exp(-x/R)$$



Reynolds number: 0.003

Péclet number: 0.5

Thermal length vs asperity shape



p=20, L=10, *β*=28°   p=20, L=30, *β*=74°

At small Pe: thermal exchange slighlty less good with the asperity

Qualitative behavior consistent with the lubrication approximation

Conclusion and perspectives

"Smooth" roughness

Due to roughness, channeling of
- Hydraulic flow
- Temperature (energy)

Large scale variations are important

Thermal exchange less efficient than flat model with same permeability

"Sharp" roughness (cavities)

Inside the asperity with steep slopes:
- Recirculation → Fluid trapped
- Few advective thermal exchanges

How to stimulate these asperities?
- Oscillating pressure gradient?
- Change the Peclet number?

} → On going simulations using LB methods…

Conclusion and perspectives

Hydro-thermal modeling using LB methods

Advantages

- Full hydraulic and heat equation solved in 3D
- Fluid recirculation

Other questions which could be addressed with LB methods:

- Long term behavior of geothermal systems
  - Diffusion in the rock and liquid
- Chemical effects ?
  - Advection-diffusion equation:
    also holds for the chemical species concentration
  - Crystallization/dissolution

Coupling the pressure variations in space and time with mechanical effects ?

Thanks for your attention !

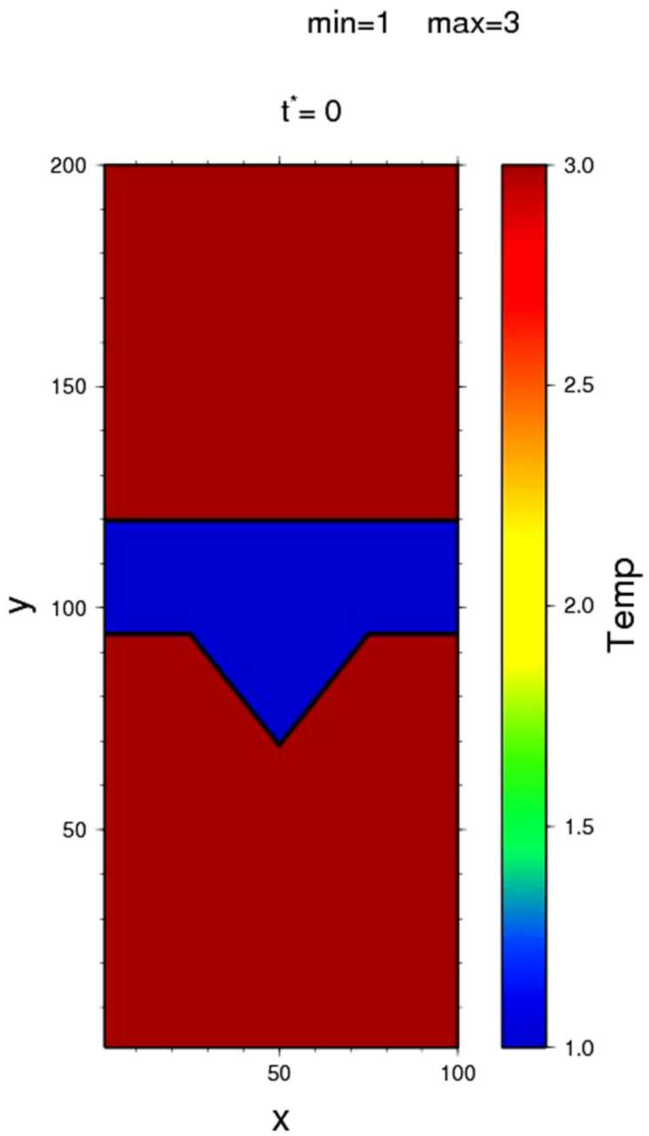
More references:

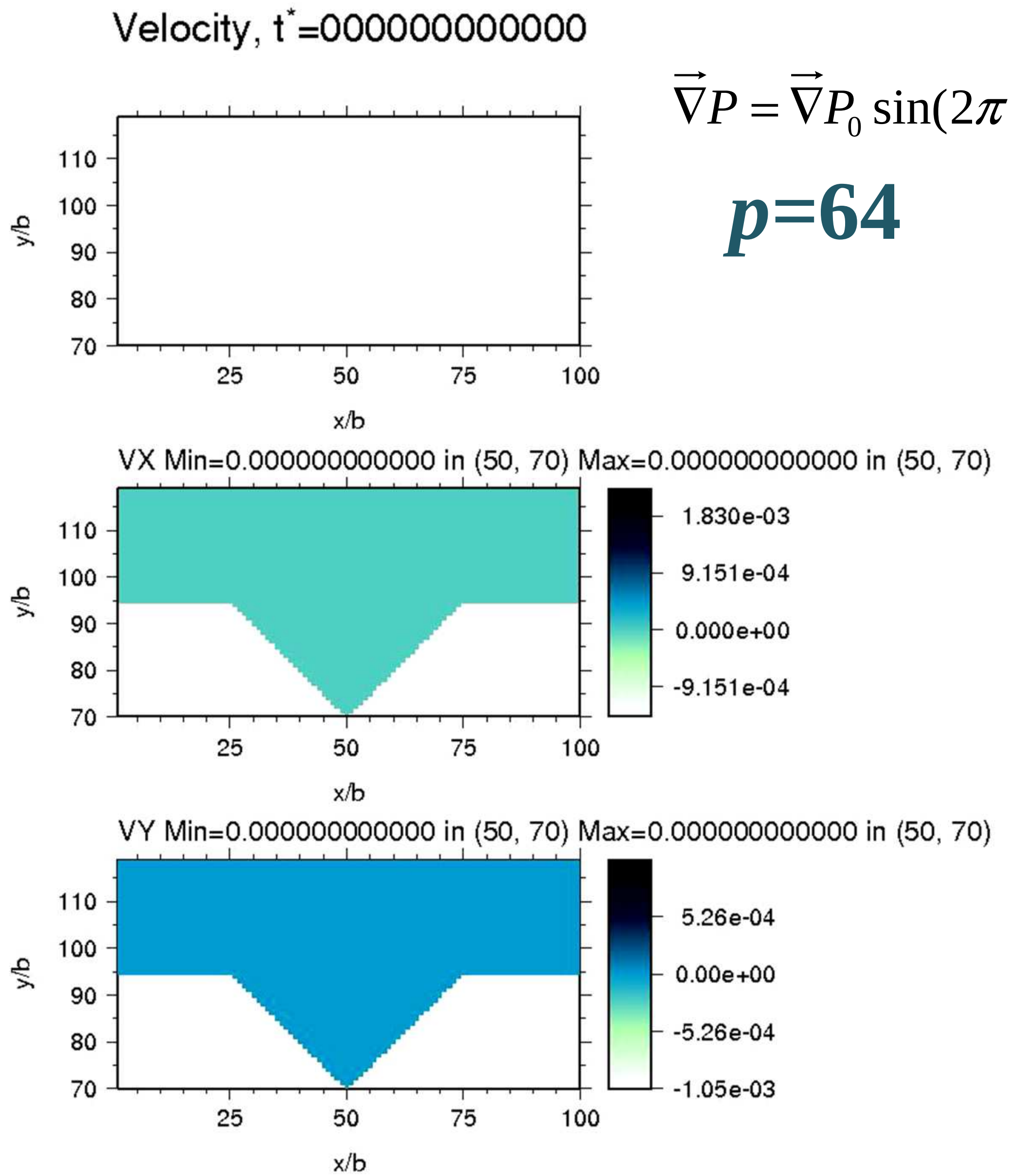
✓ **A. Neuville, R. Toussaint and J. Schmittbuhl (2010)**
Fracture roughness and thermal exchange: A case study at Soultz-sous-Forêts.
Comptes Rendus Geoscience, 347(7-8):616-625

✓ **A. Neuville, R. Toussaint and J. Schmittbuhl (2010)**
***Hydro-thermal flows in a self-affine rough fracture*, Physical Review E, 82, 036317**

✓ **A. Neuville, R. Toussaint and J. Schmittbuhl (2011)**
***Hydraulic transmissivity and heat exchange efficiency of rough fractures: a spectral approach.* Geophysical Journal International**

Oscillating pressure gradient





$$\vec{\nabla}P = \vec{\nabla}P_0 \sin(2\pi t^* / p)$$

***p*=64**