Institut de Physique du Globe de Strasbourg

Université de Strasbourg

Ecole et Observatoire des Sciences de la Terre

29/06/2010

Soutenance de thèse

Comportement hydro-thermique d'un écoulement de fluide dans une fracture rugueuse :

Modélisation et application à des massifs fracturés

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Directeur de thèse : Jean Schmittbuhl

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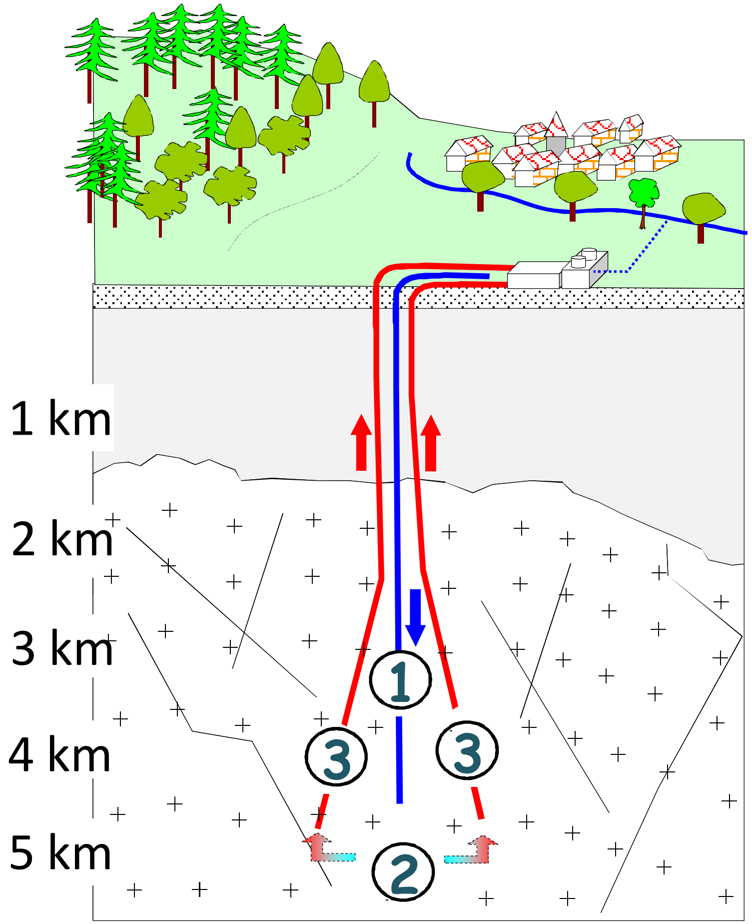
Thèse présentée en vue d'obtenir le grade de : Docteur de l'Université de Strasbourg

Discipline : Sciences de la Terre et de l'Univers
Spécialité : Géophysique

Geothermal background

- Thermal exchanges between
  a hot fractured rock
  and a cold fluid

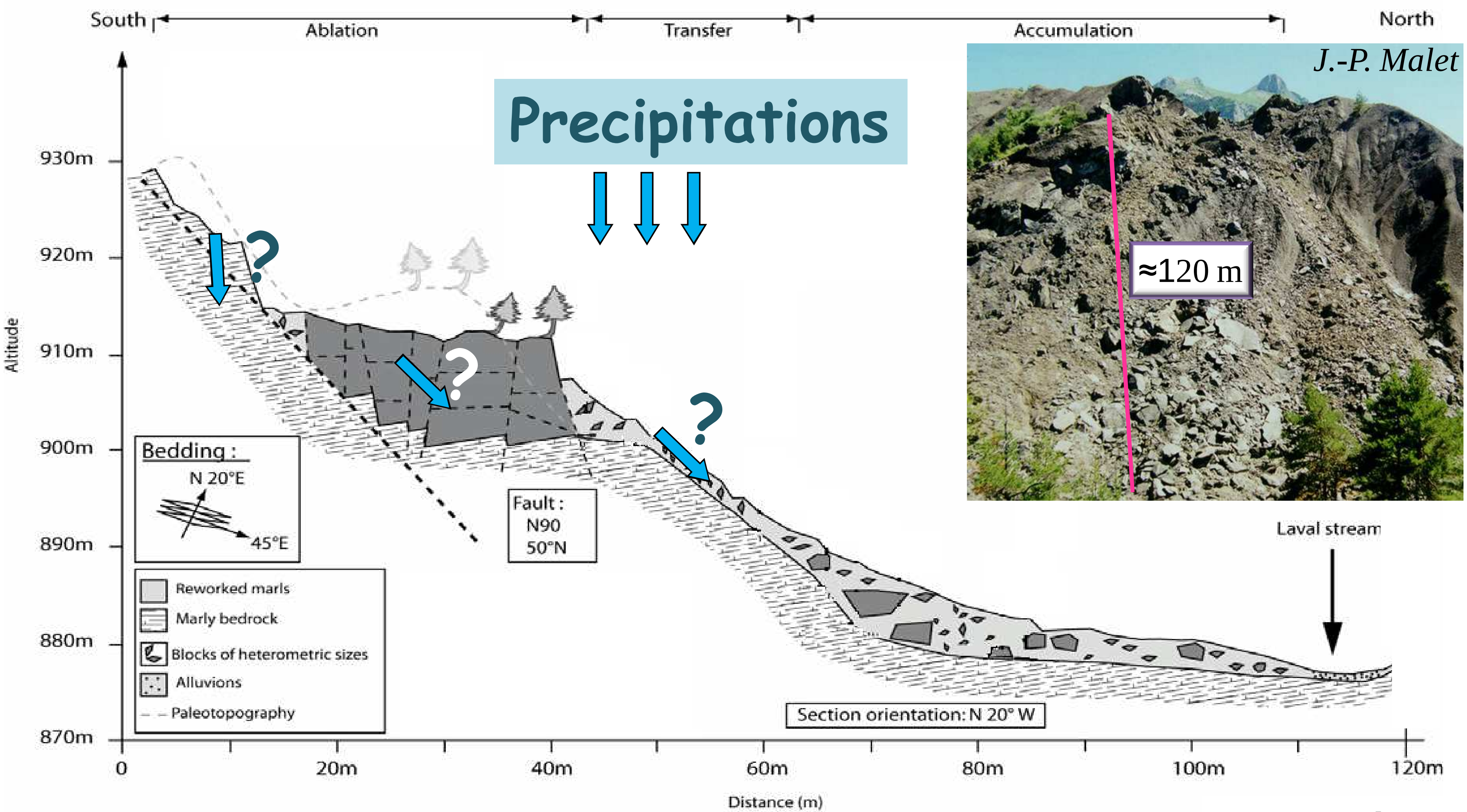
- Deep geothermal systems
  - "Enhanced Geothermal Systems"
    - Soultz-sous-Forêts (Alsace, France)
    - Cooper Basin (Australia)
  - Example of parameters
    - Hydraulic flow : 25 l/s
    - Temperature at injection : 60° C
    - Temperature at pumping : 180° C



A. Gallien, d'après documents AREVA

Landslide background

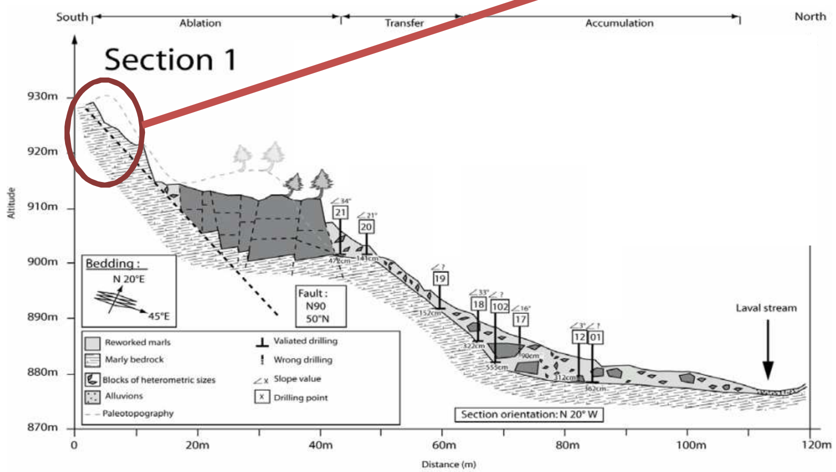
- Influence of water on landslide triggering



M. Fressard, 2009

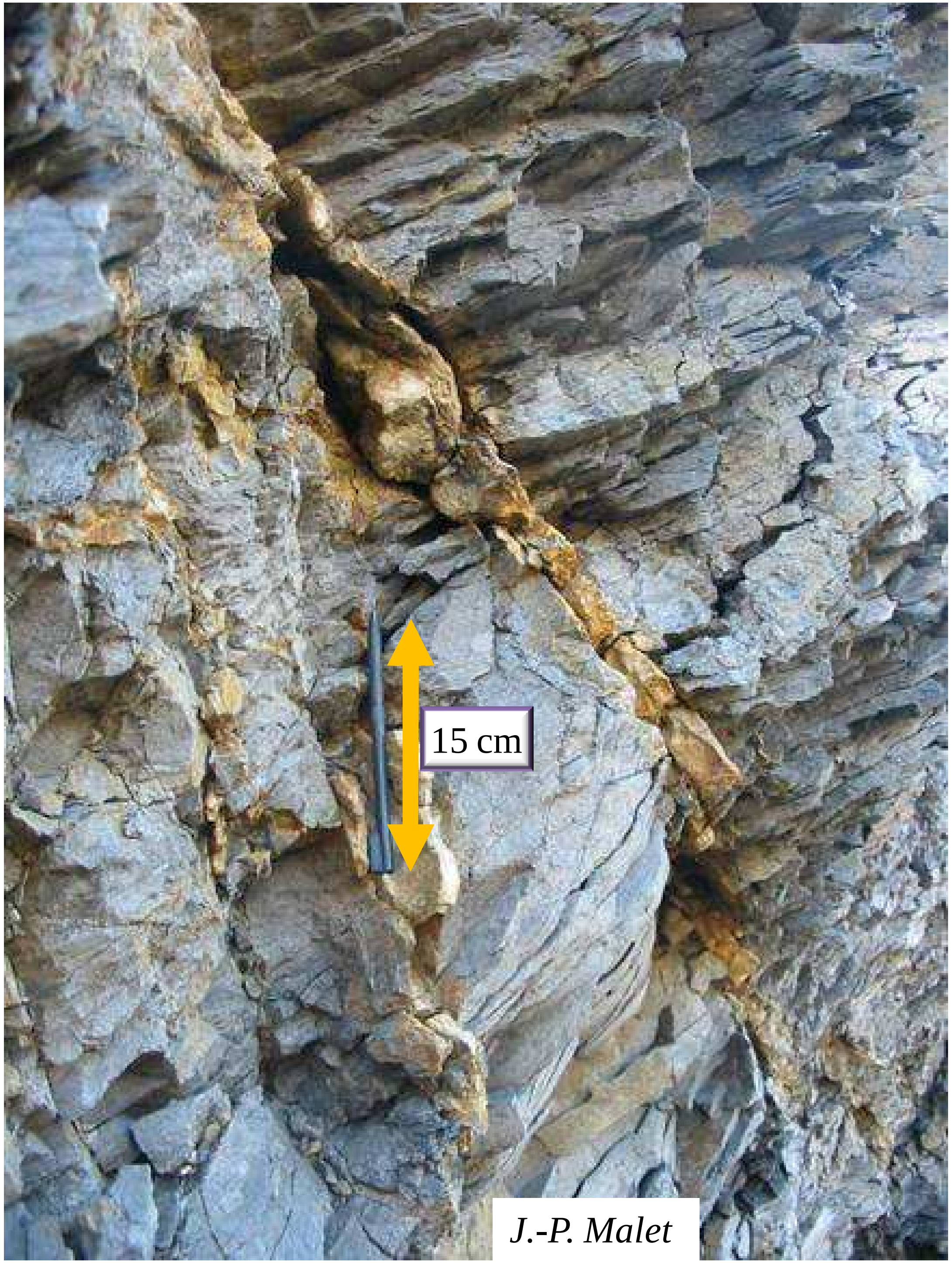
Draix, (Alpes de Haute-Provence, France)

Landslide background



Altered rock

Fluid inside fractures



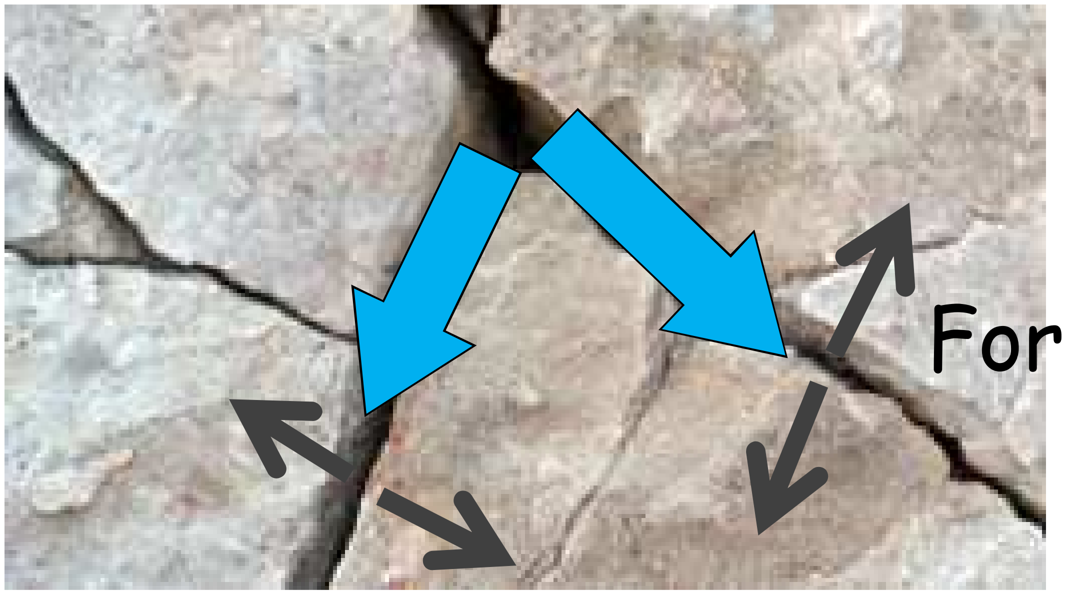
Permeability of Draix bedrock?

Influence of water on landslides triggering

(Not exhaustive)

- Gravity: material full of water is heavier
- Pore pressure
- Chemical processes
  - Rheology/dissolution
  - Sealing of fractures

- Less friction
- More fractures
- Larger fractures

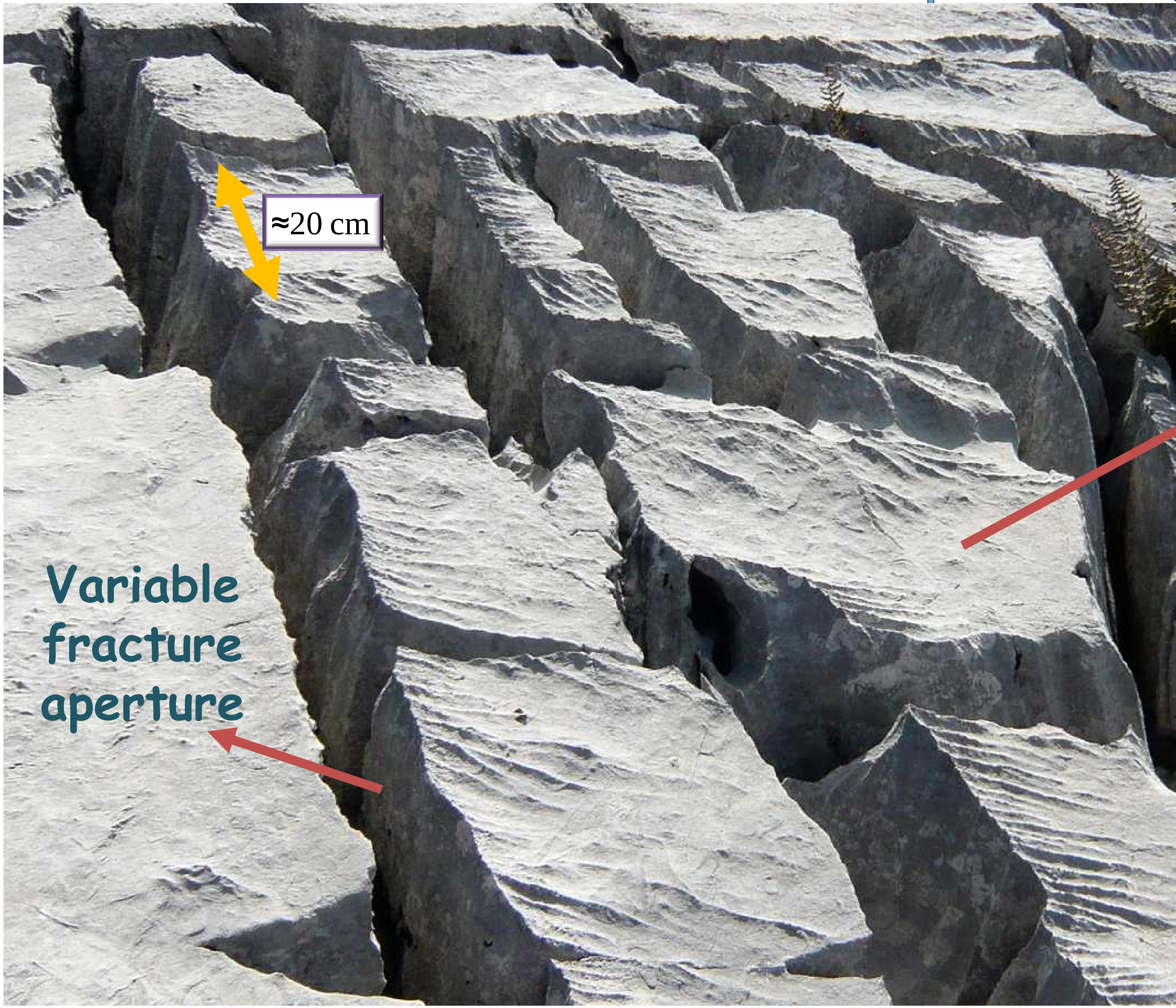


Force increases

Fracture network

D.D. Pollard
Limestone bed, England.

Variable fracture morphology

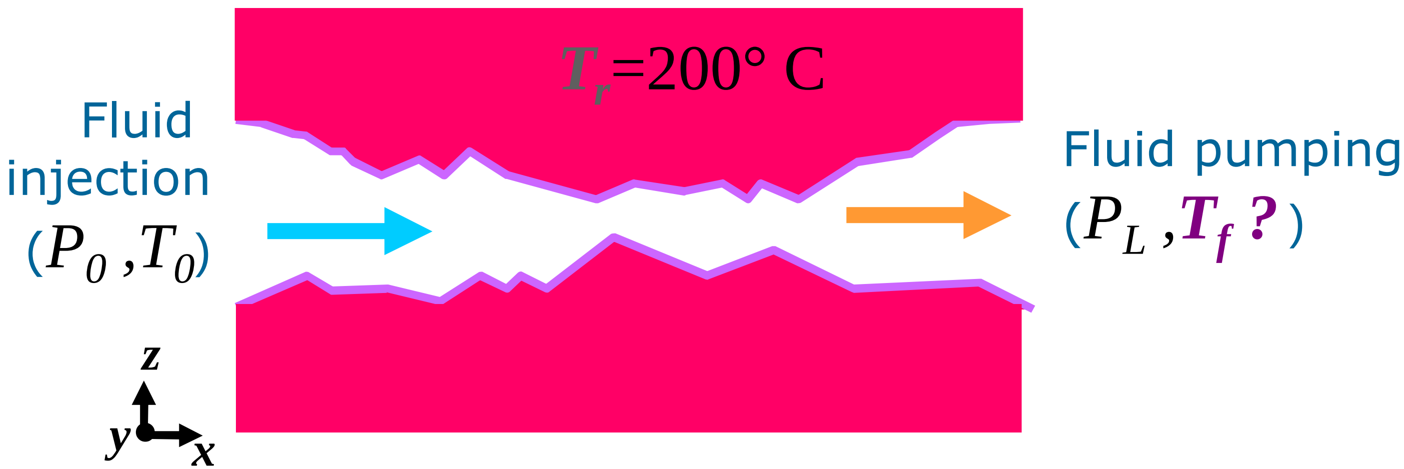


Impermeable bulk

S. Näff, Swiss Speleological Society.

Questions

- Morphology of fractures?
- Effect of the morphology of fractures on the
  - Hydraulic flow?
  - Heat exchange between fluid and rock?



Scale: individual fracture

Outline

Morphology

- Measured on natural fractures (Draix borehole cores)
- Characterization
- Synthetic fractures

Hydraulic models

- Finite differences (methode 1)
  - Hypotheses
  - Results
  - Application to Draix
  - Limits
- Lattice Boltzmann (methode 2)
  - Bases
  - Implementation

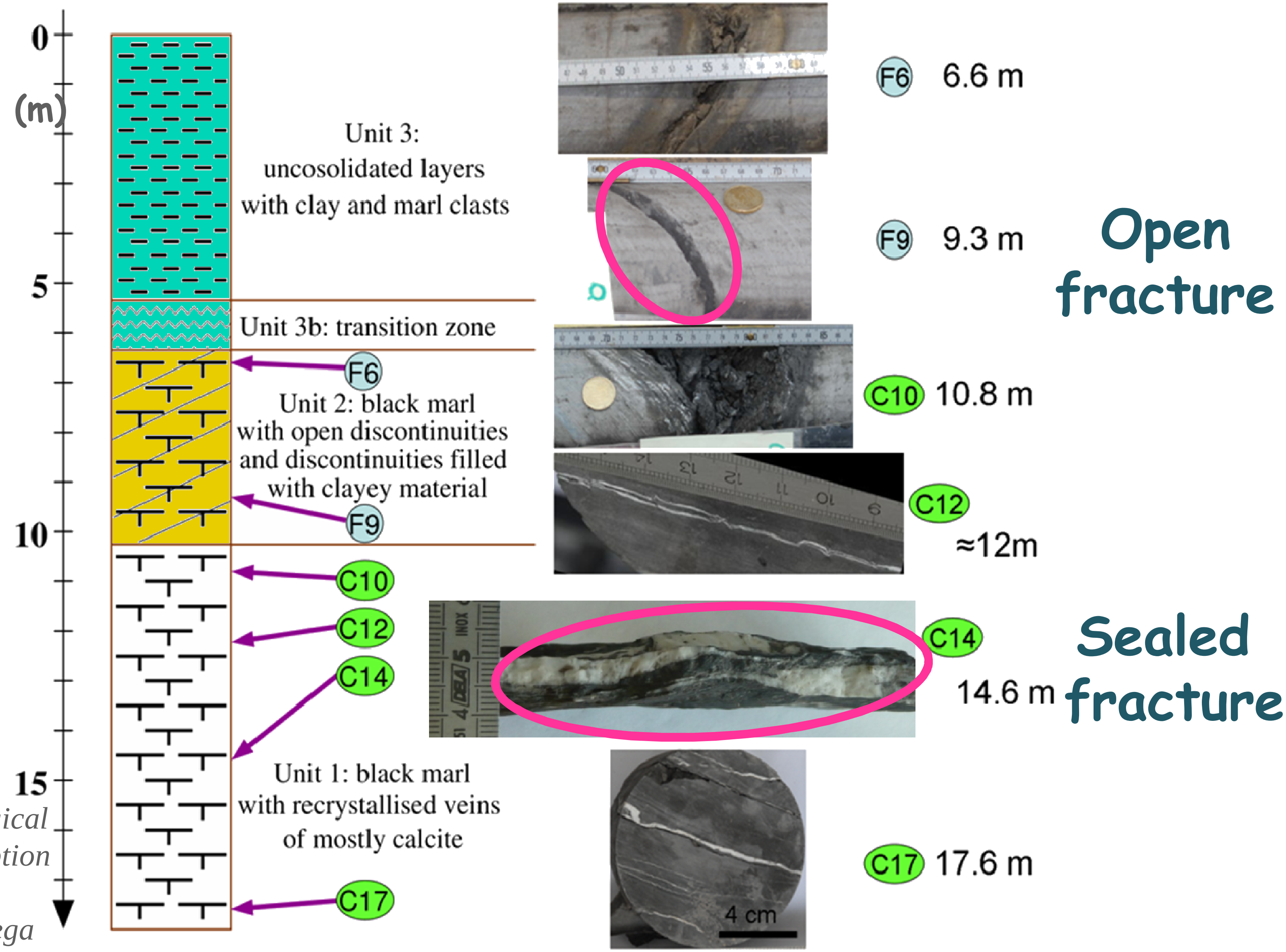
Hydro-thermal models

- Finite differences model
  - Hypotheses
  - Results
  - Limits
- Lattice Boltzmann (LB) model
  - Bases
  - Implementation


Core extracted at Draix
(Alpes de Haute-Provence, France)
30 m
Example of landslide
(150m) further
Borehole cores
Top of a stable zone

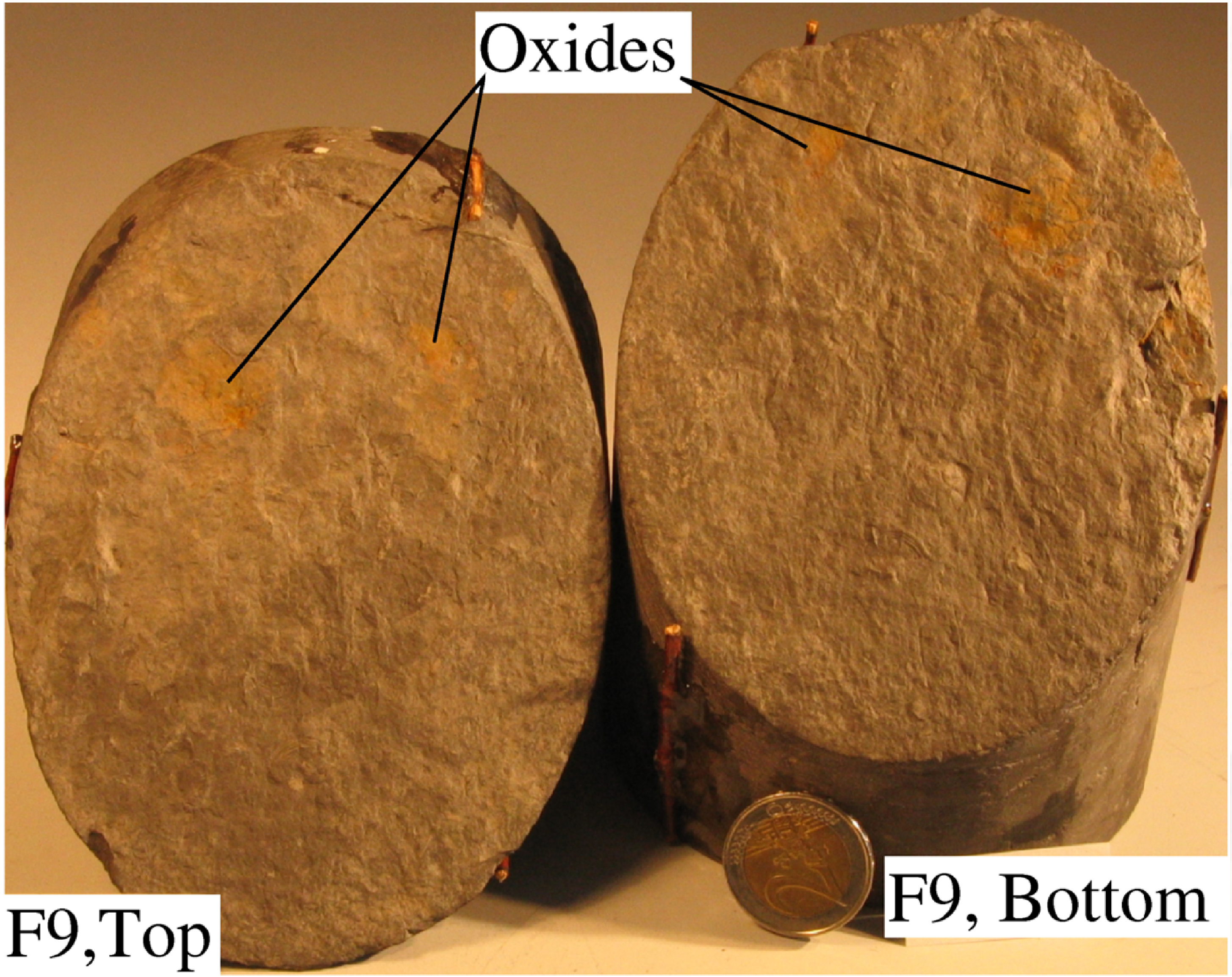
J.-P. Malet

Data: Drilled core



Geological description From J. Ortega

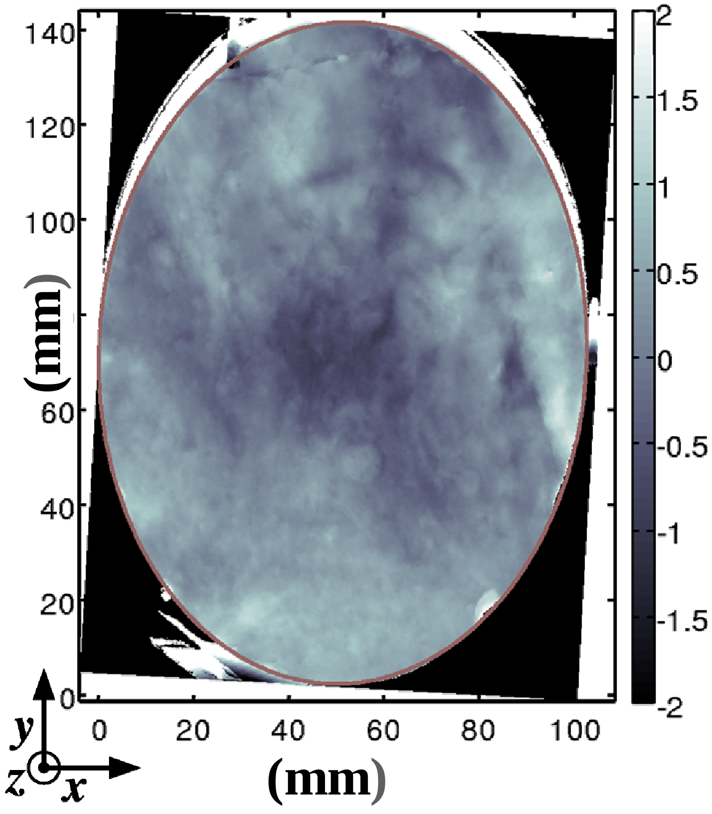
Open fracture



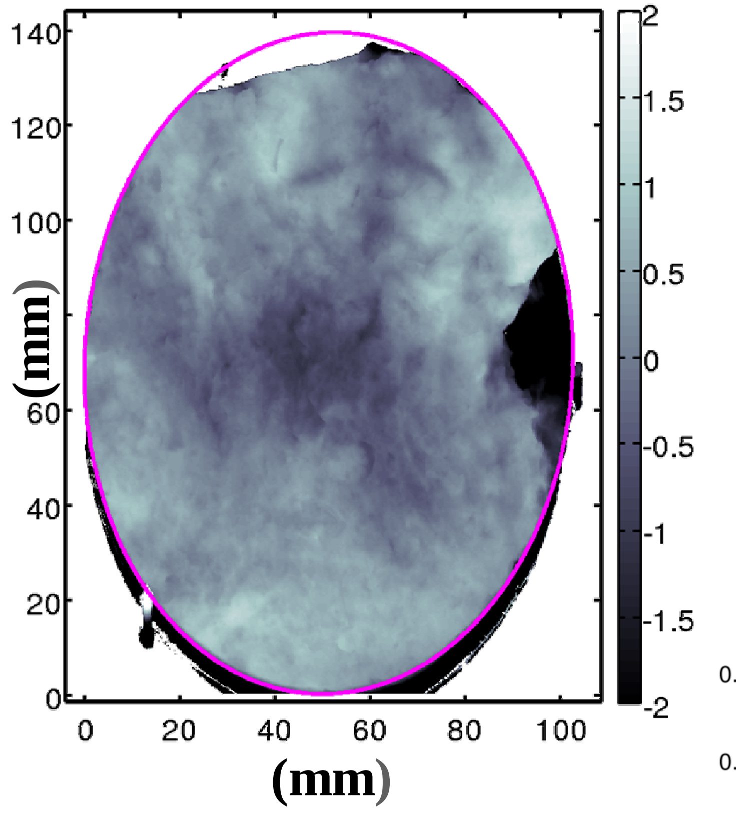
Roughness of the topography

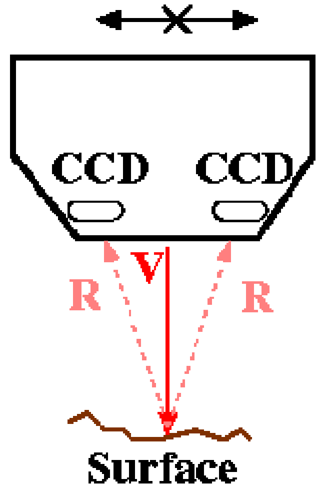
- Optical profiler (vertical precision ~ 1µm)

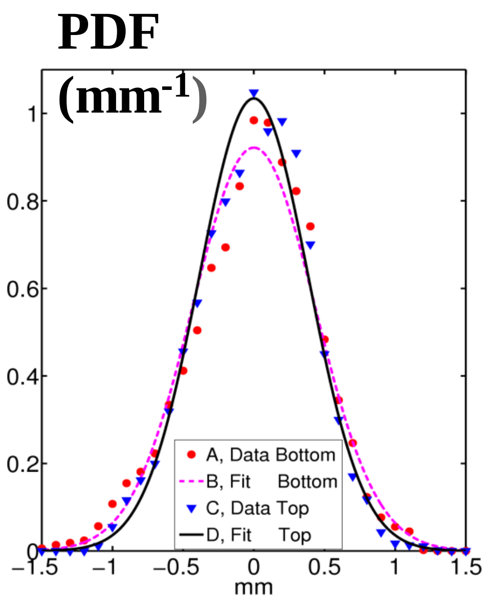
Top (mm)



Bottom (mm)







<u>Topography RMS :</u> σ = **0.4** mm for both surfaces

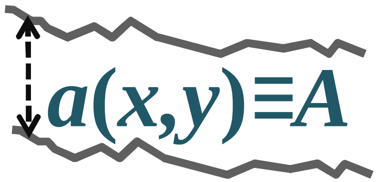
Gaussian distributions of the topography

How opened are the fractures?

- Contact ? Mean aperture A ?
- Variability of the aperture ?
- Scale properties of the surfaces
  - Independence of both surfaces?

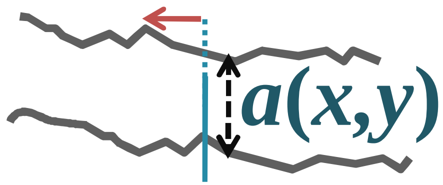
Correlated surfaces

Identical surfaces
Mode I



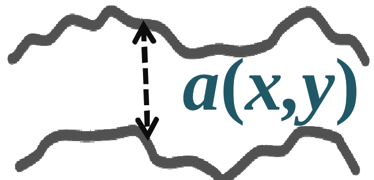
A: **constant**

Identical surfaces
Mode I+II



Anisotropic aperture

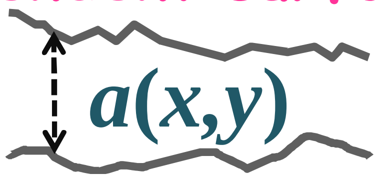
~ Identical surfaces
Small scale noise
Mode I



Isotropic aperture

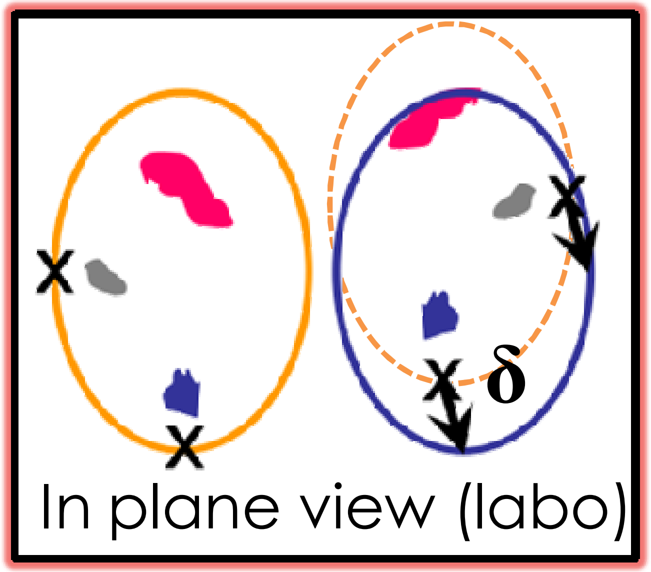
- *Correlated surfaces at large scales*
- *Independent surfaces at small scales*

Independent surfaces

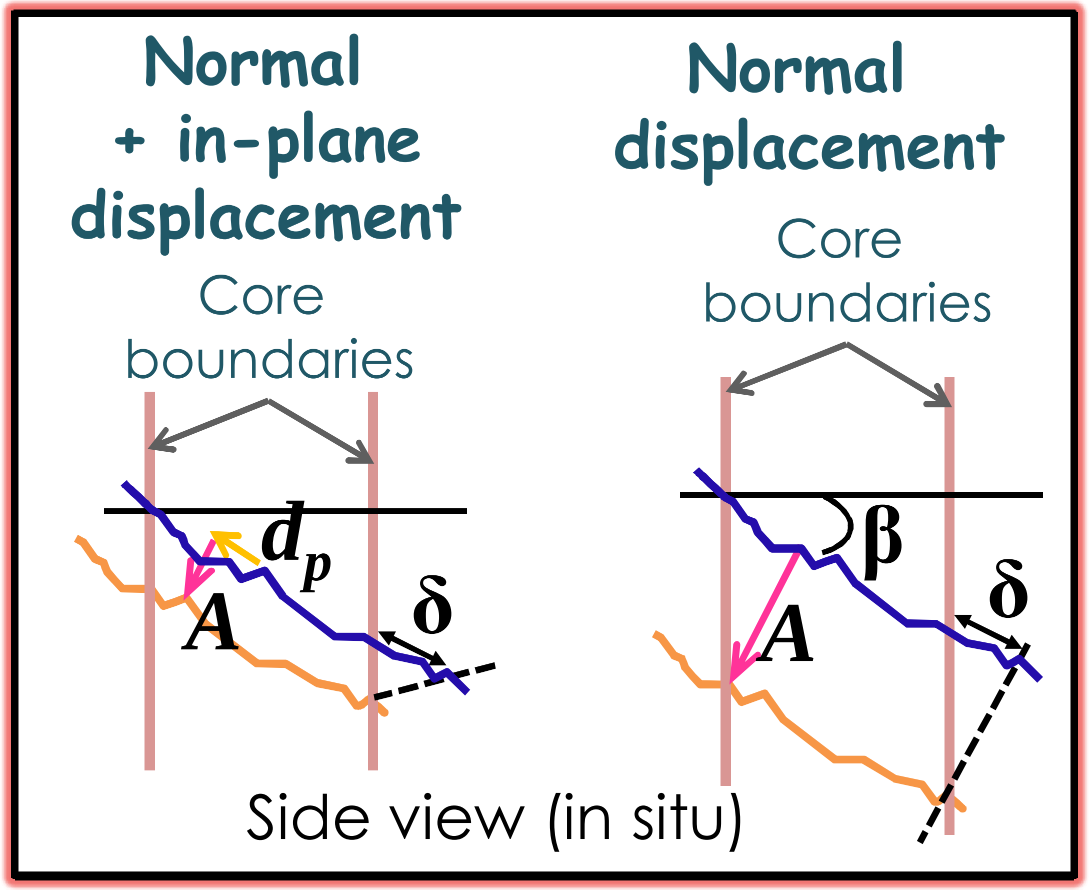


Reconstruction of aperture: open discontinuity

- Similarities of the sides → δ obtained
- Assumptions about the displacement:



$$\delta = A.\tan(\beta) + d_p$$

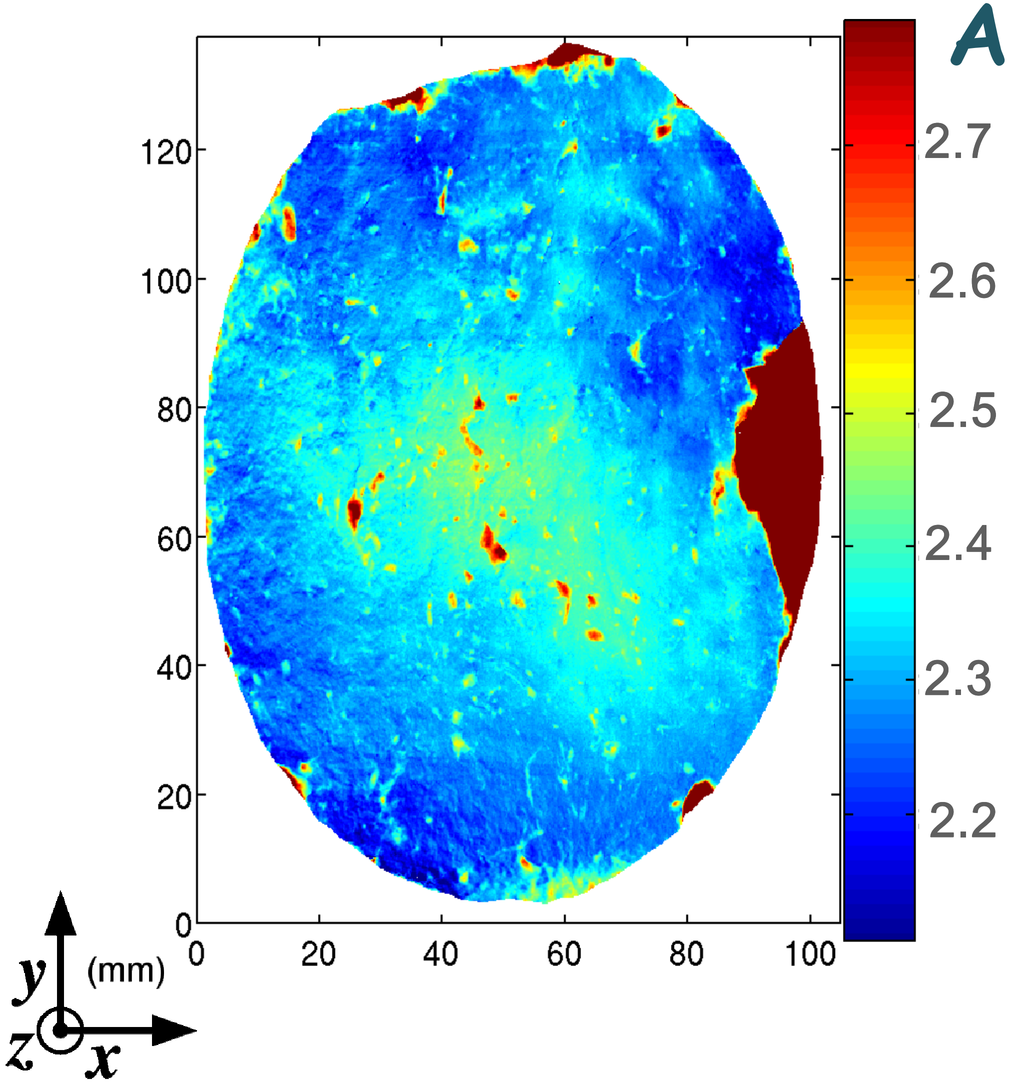


- Pure in-plane displacement → A = 0; $d_p = \delta$
- Pure normal displacement → $A = \delta/\tan(\beta) \approx 2.3$ mm ; $d_p = 0$

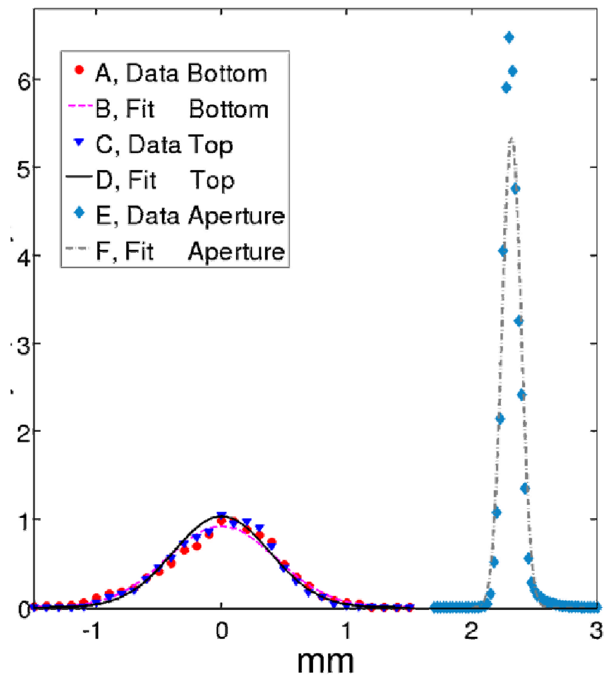
Reconstruction of aperture: open discontinuity

Hypothesis: normal displacement

Aperture (mm)



PDF (mm^{-1})

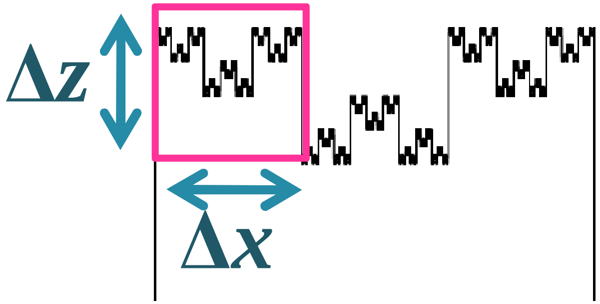


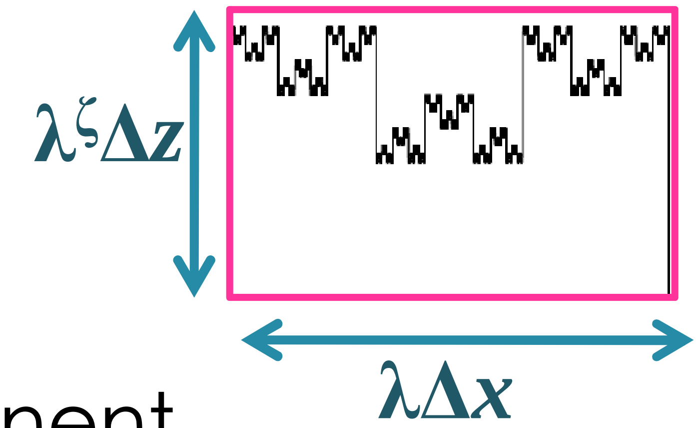
RMS:

- Aperture:
  $\sigma = 0.08$ mm
- Top and Bottom:
  $\sigma = 0.4$ mm

Self affine topography

- Spatial property:
  - Statistical spatial correlation
  - Anisotropic fractal
  - Statistically invariant under:
    - $\Delta x \longrightarrow \lambda \Delta x$
    - $\Delta y \longrightarrow \lambda \Delta y$
    - $\Delta z \longrightarrow \lambda^{\zeta} \Delta z$ *(for any λ)*

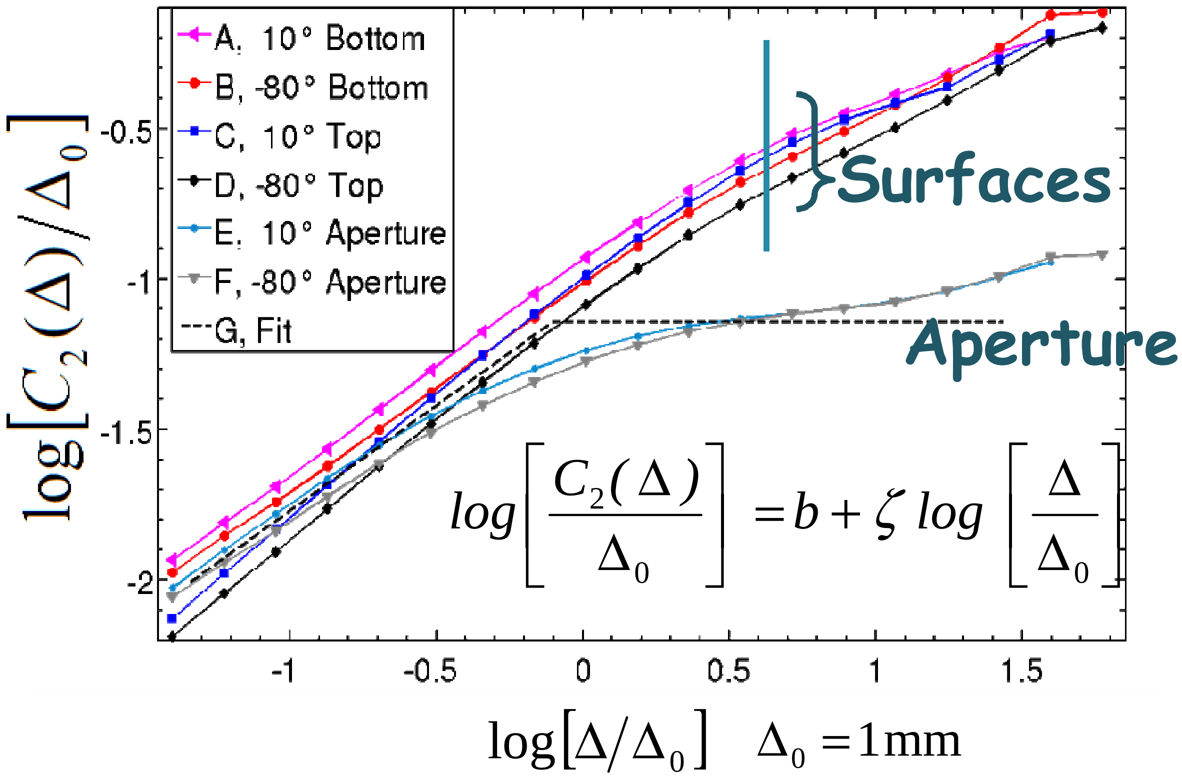


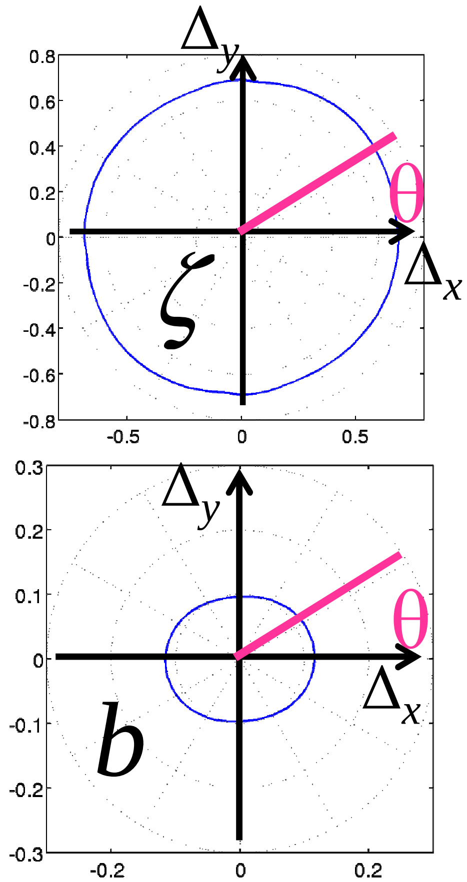


- Roughness (or Hurst) exponent

  $\zeta \approx 0.7 - 0.8$

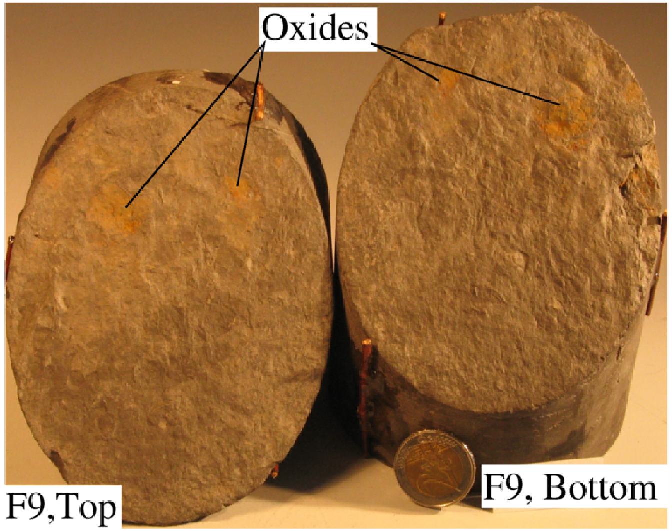
Autocorrelation C_2 of the topography/aperture

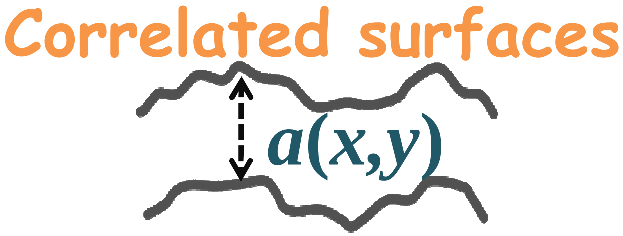




- Bottom and top topographies
  - Self affine from 0.06 to 7 mm
  - $\zeta \approx 0.70$ (bottom)
  - $\zeta \approx 0.75$ (top)
- Aperture
  - More or less self-affine if $\Delta < 1$ mm
  - $\zeta \approx 0.6 - 0.7$
  - More or less Uncorrelated if $\Delta > 1$ mm

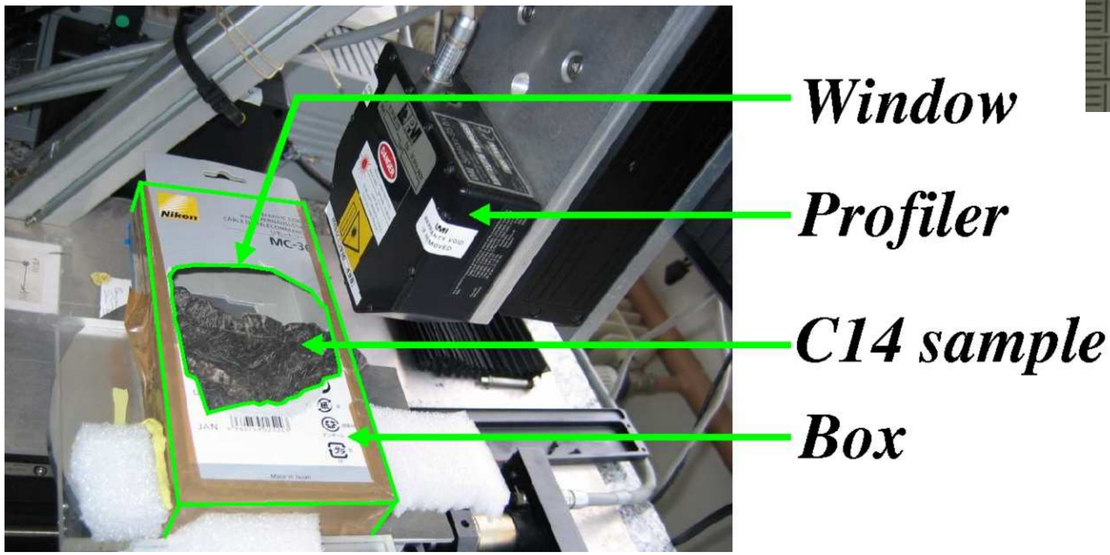
Open fracture
Aperture measurement

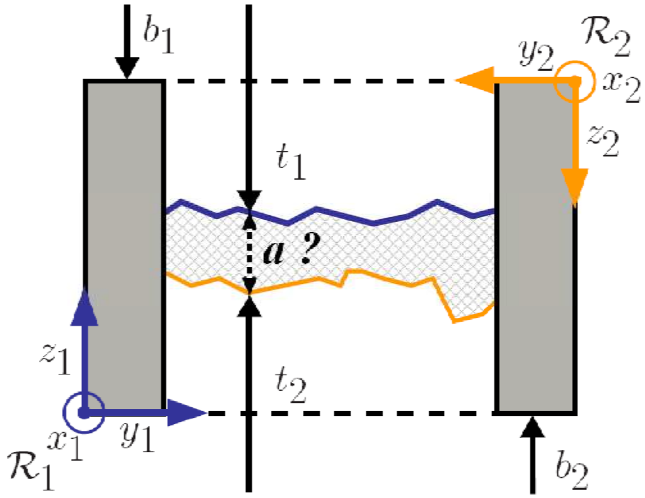


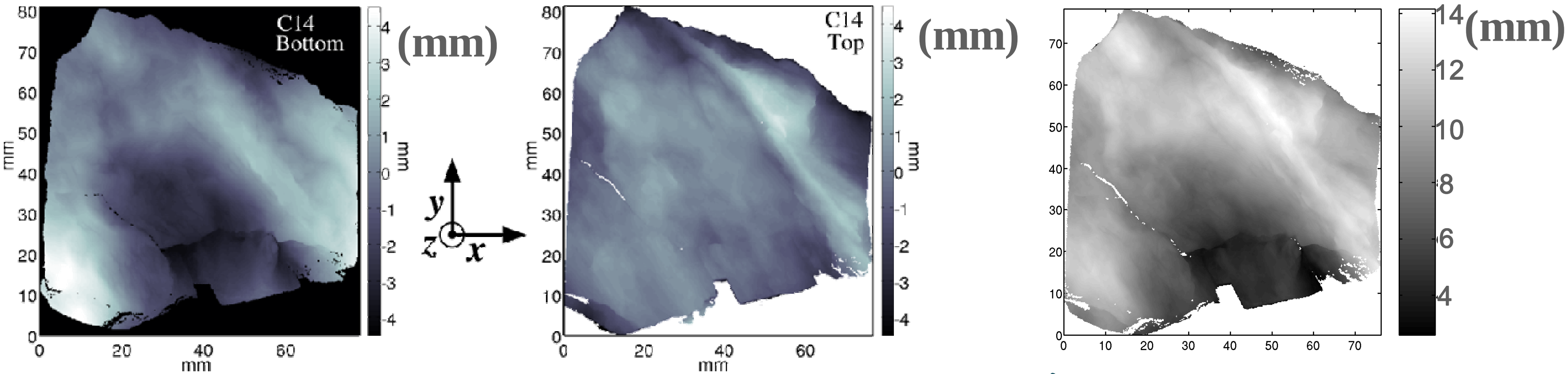


- No anisotropy of
  - the surfaces
  - the aperture
- Correlated surfaces at large scales
- Independent surfaces at small scales
- Self affine model of the aperture at small scales

Aperture reconstruction
Sealed discontinuity

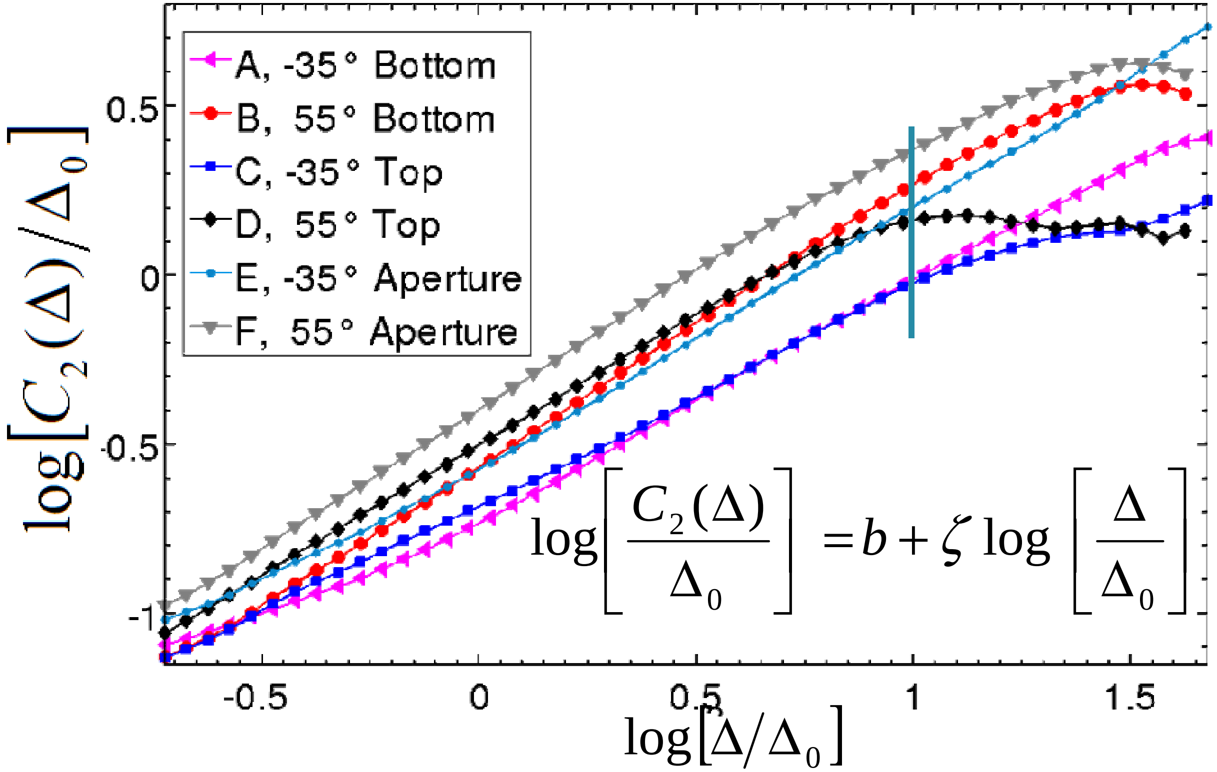


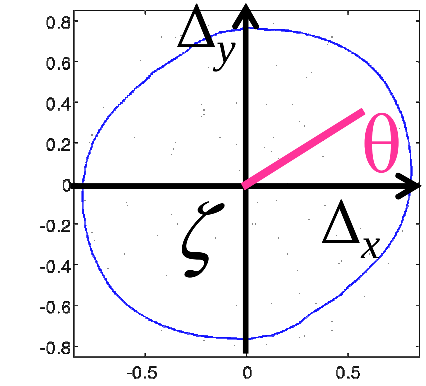


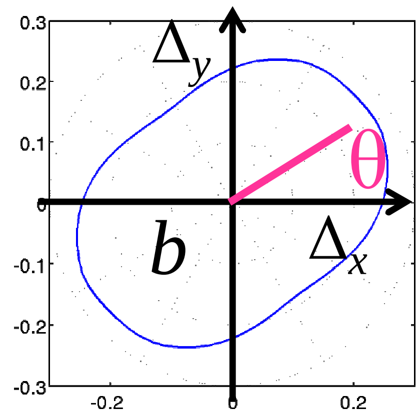


Bottom **Top** **Aperture** σ /A>0.45

Autocorrelation C_2 - Sealed fracture







$\Delta_0 = 1\,\mathrm{mm}$

Bottom, top and aperture:

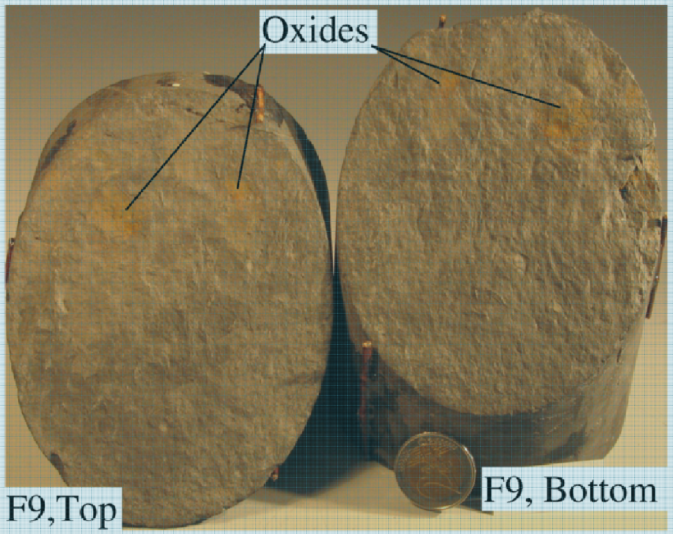
› Self affine from 0.3 to 10 mm

› Anisotropy of b and ζ (visible despite errors bars)

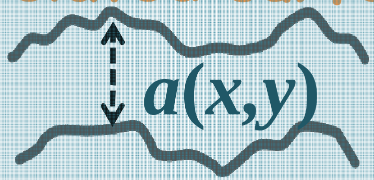
- $\zeta \approx 0.65 - 0.8$ (top)
- $\zeta \approx 0.7 - 0.85$ (bottom)
- $\zeta \approx 0.7 - 0.85$ (Aperture)

Aperture measurements

- Open fracture



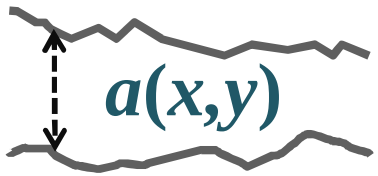
Correlated surfaces



- No anisotropy of the surfaces
- No anisotropy of the aperture
- Correlated surfaces at large scales
- Independent surfaces at small scales

- Sealed fracture

Independent surfaces

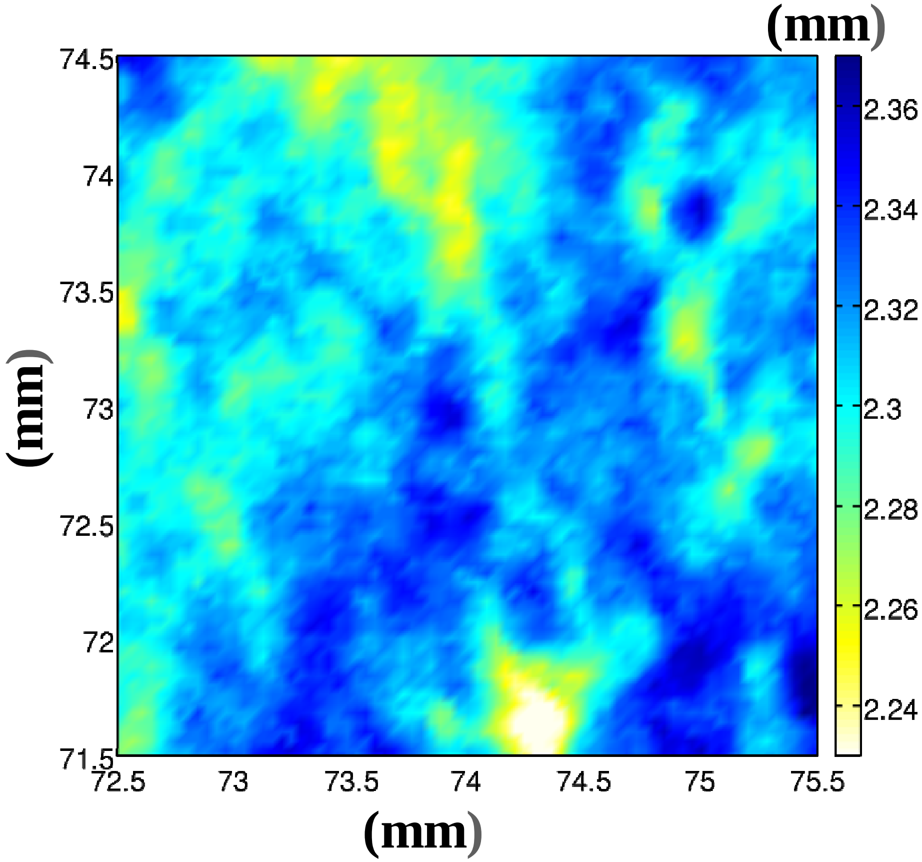


- Anisotropy of the surfaces
- Anisotropy of the aperture
- Independent surfaces

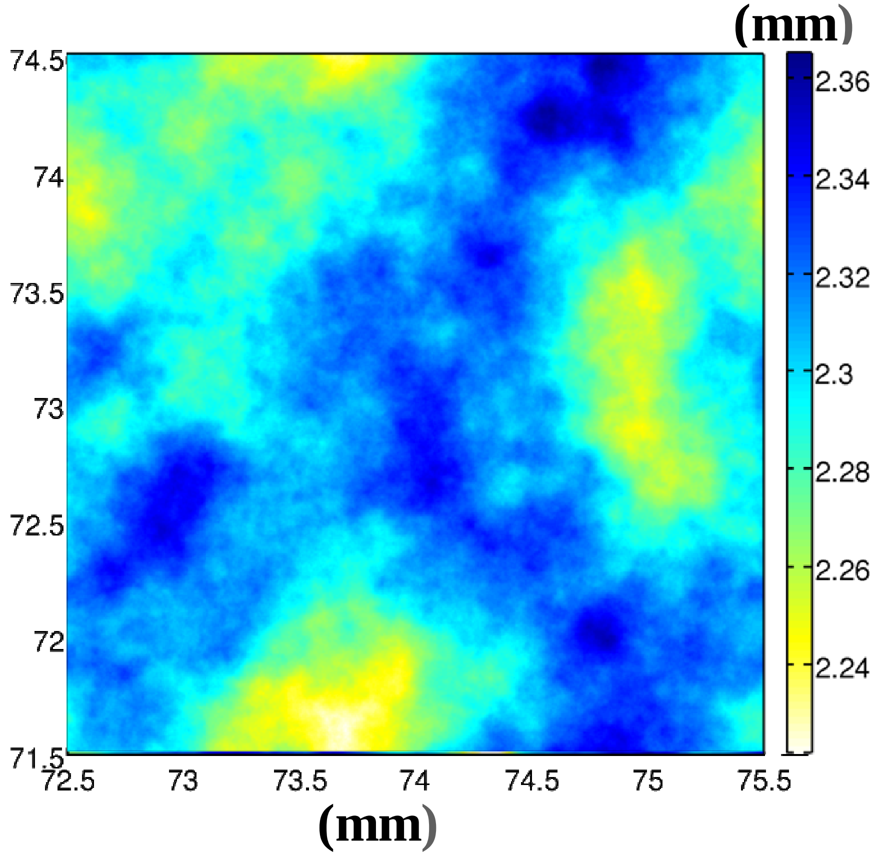
Both are self-affine at small scales

Aperture model

- Natural aperture



- Self-affine aperture



$$\zeta = 0.8$$

Hydraulic flow - meth.1: finite differences

- $\rho\left(\frac{\partial \vec{v}}{\partial t}+\vec{v}.\vec{\nabla}\vec{v}\right)=-\vec{\nabla}p+\eta\Delta\vec{v}$

Hyp.

Permanent Laminar

- Stokes $\vec{\nabla}p=\eta\Delta\vec{v}$

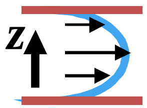
Hyp.

Hydraulic lubrication

$v_z(x,y,z)=0$

- Parabolic profile:

$$\vec{v}(x,y,z)=\frac{\vec{\nabla}p}{2}\cdot(z-z_1)\cdot(z-z_2)$$



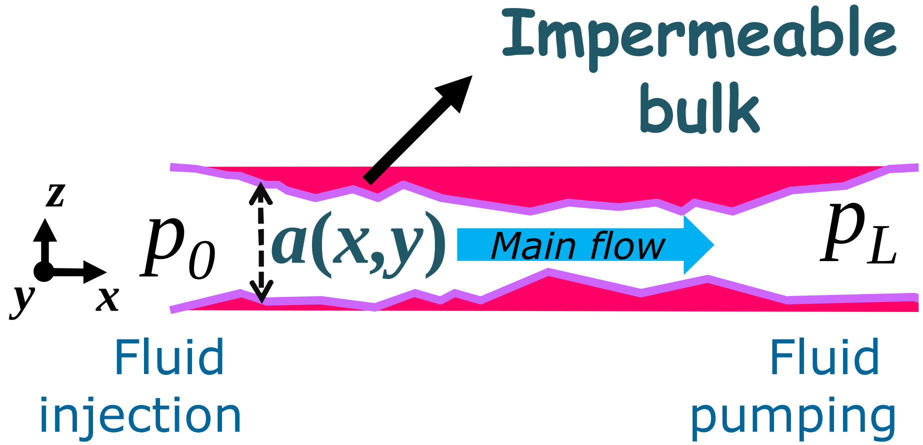
Hyp.

Incompressibility

- Reynolds equation:

$$\vec{\nabla}.(a(x,y)^3\vec{\nabla}p)=0$$

in 2D



Notations:

Fluid density: ρ

Dynamic viscosity: η

*Velocity: **v**(x,y,z)*

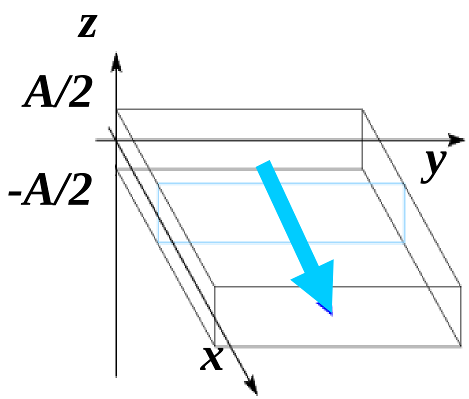
Pressure: p(x,y,z)

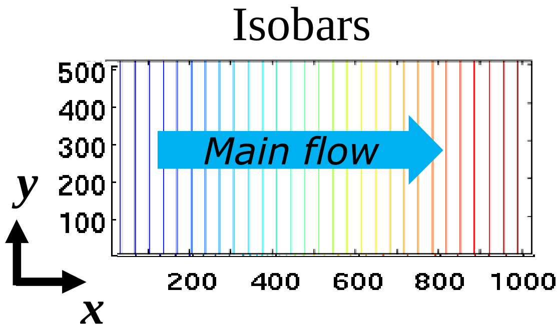
Solving: Finite differences + biconjugate gradient method

Hydraulic aperture *H*

- Parallel plates

➤ ***Analytic solution***



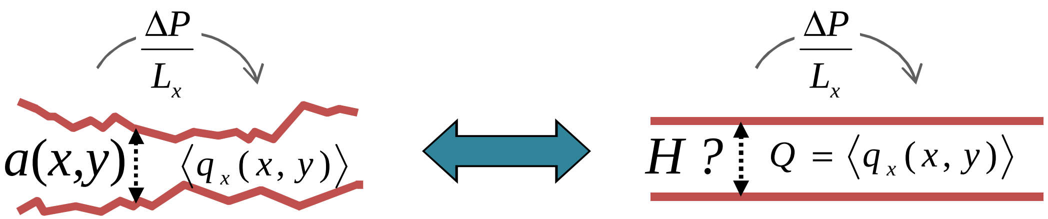


Hydraulic flow

$$\vec{q}_{//}(x,y) = -\frac{\Delta P}{L_x}\frac{A^3}{12\eta}\hat{x}$$

$$\vec{q}(x,y) = \int_a \vec{v}(x,y,z)dz = -\frac{a^3}{12\eta}\vec{\nabla}_2 p$$

- Variable aperture



Geometrical aperture:

$$A = \langle a(x,y) \rangle$$

$$Q = -\frac{\Delta P}{L_x}\frac{H^3}{12\eta}$$

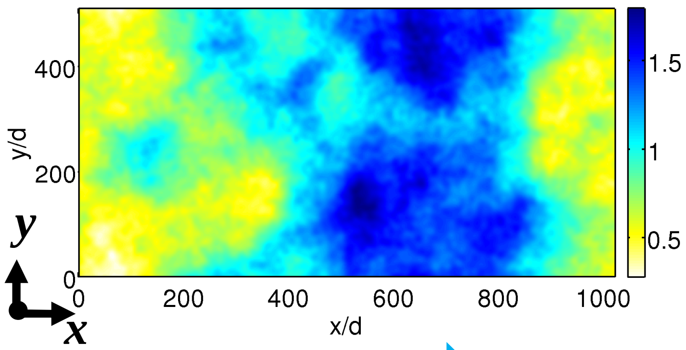
Hydraulic aperture:

$$H = \left[-Q\,12\,\eta\,\frac{l_x}{\Delta P}\right]^{1/3}$$

$$\boldsymbol{H \neq A}$$

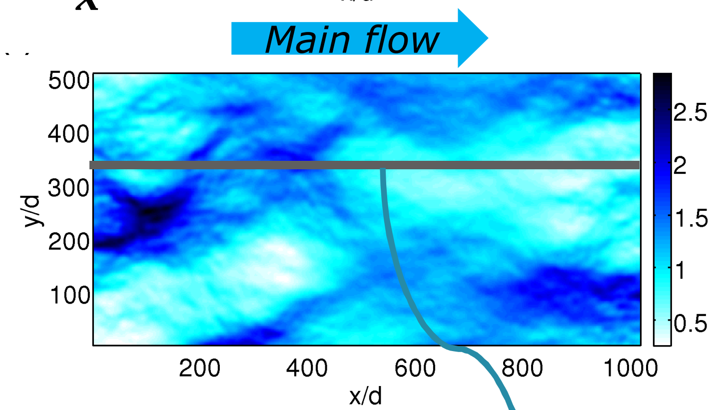
$$\langle a^{-3} \rangle^{(-1/3)} < H < \langle a^3 \rangle^{(1/3)}$$

Illustration...hydraulic result



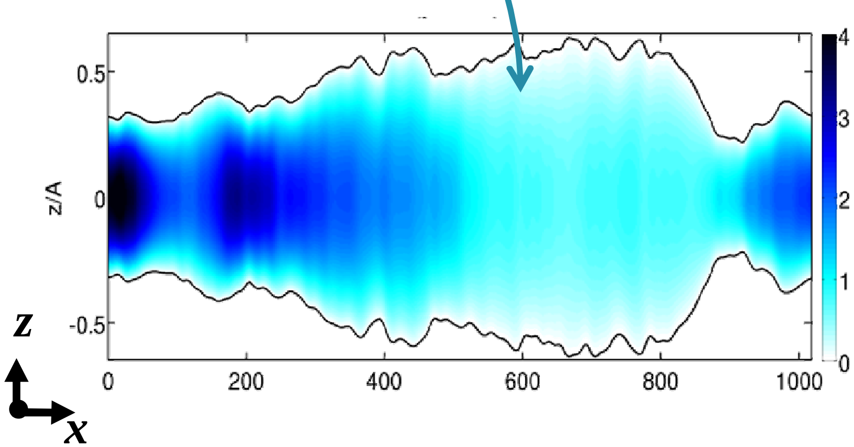
Rough apertures

$$a^*(x,y) = \frac{a(x,y)}{A}$$



2D-flow norm

$$\left\|\vec{q}^*(x,y)\right\| = \frac{12\eta\, L_x \left\|\vec{q}(x,y)\right\|}{\Delta P\, A^3}$$



Velocity

$v^*(y/d=302)$

Example

A	**1 mm**
σ	**0.35 mm**
$L_x \times L_y$	**1 x 0.5 m²**

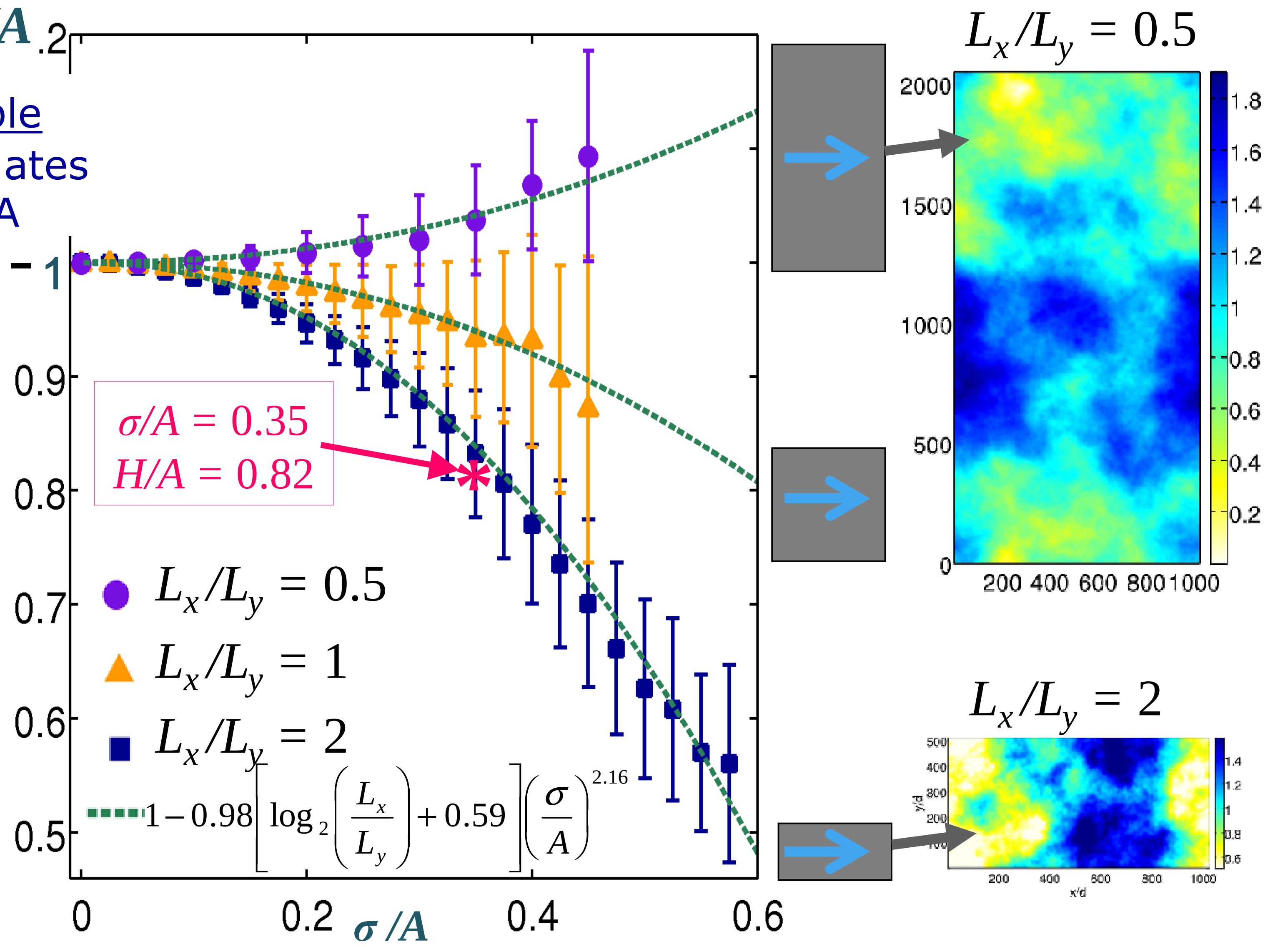
*Dyn. visc. **η*** *(10 bar; 100°C)*	**3.10⁻⁴ Pa.s**
∂p/∂x	**250 Pa/m**
H	**0.82 mm**
$q^* = 1$	$q = 7\ 10^{-5}\ m^2/s$
$v^* = 1$	$v = 7\ 10^{-2}\ m/s$

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = 0.23$$

Statistical results: hydraulic apertures H

More permeable than parallel plates separated by A

Less permeable than parallel plates separated by A



Roughness amplitude

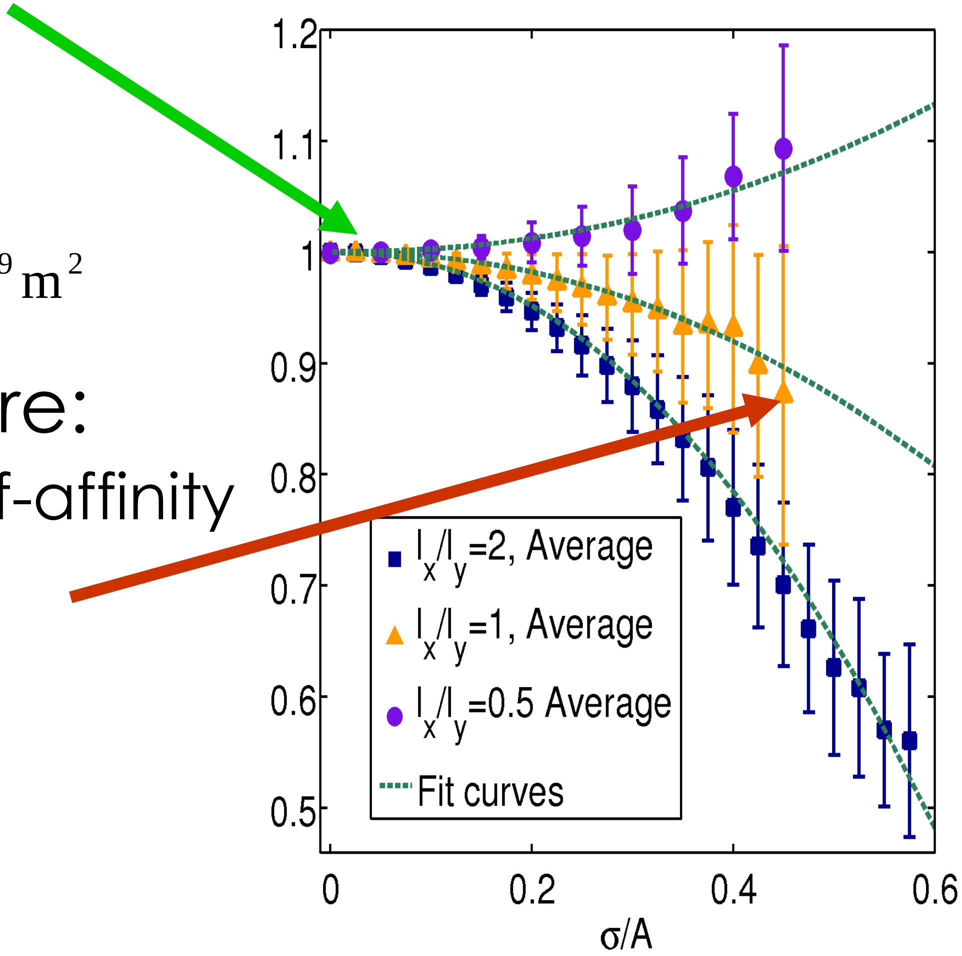
Permeability of the Draix fractures

- Like the open aperture:
  - About flat aperture : σ /A<0.04
  - H = A = 2.3 mm
  - Permeability:

$$k = \frac{H^3}{12} = 1.10^{-9}\,\mathrm{m}^2$$

- Like the sealed aperture:
  - At observed scales : self-affinity
    - σ /A>0.45
    - A ≈ 1 cm
    - H'/A≈ 0.9 => H'≈ 0.9 cm
  - Permeability:

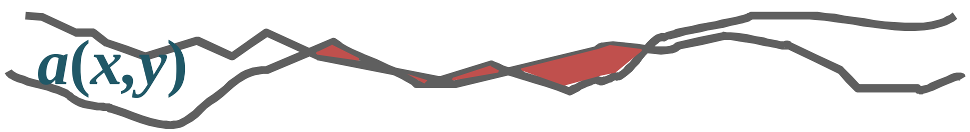
$$k' = \frac{H'^3}{12} = 6.10^{-8}\,m^2$$



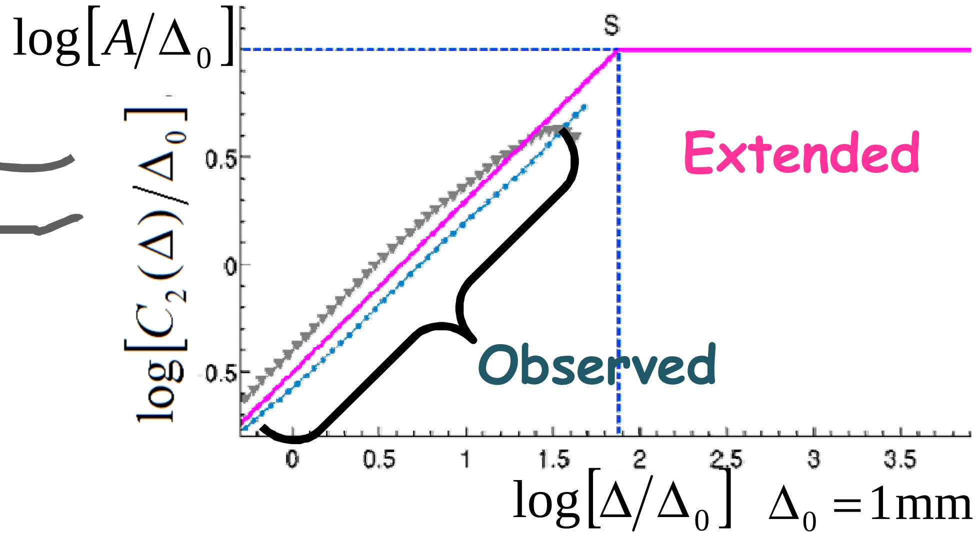
Permeability of Draix bedrock

How to extend fracture models at large scales ?

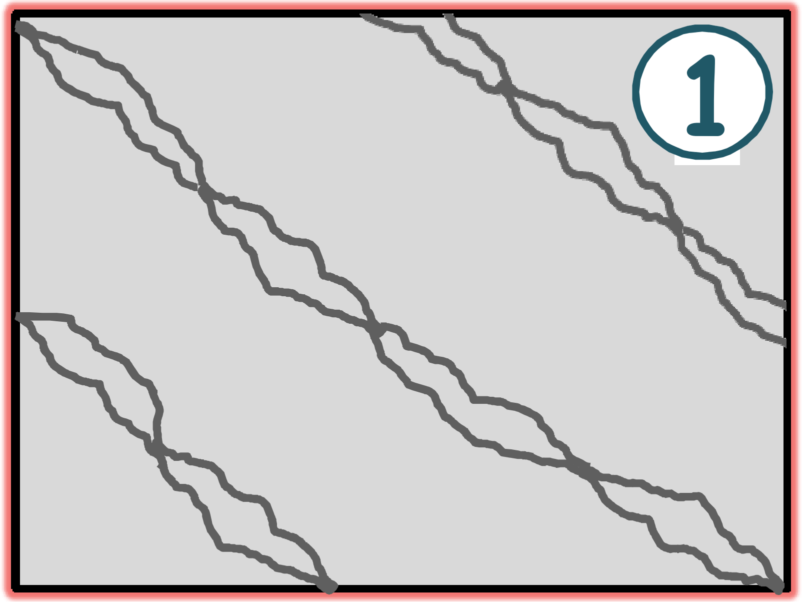
- Linear density fractures
  - Open fracture: 1 per m (core observation)
  - Sealed fracture which will reopen
    - Chemical conditions ??
- Extension of the scaling law
  - What we know:
    - Self-affinity can't be valid at very large scales

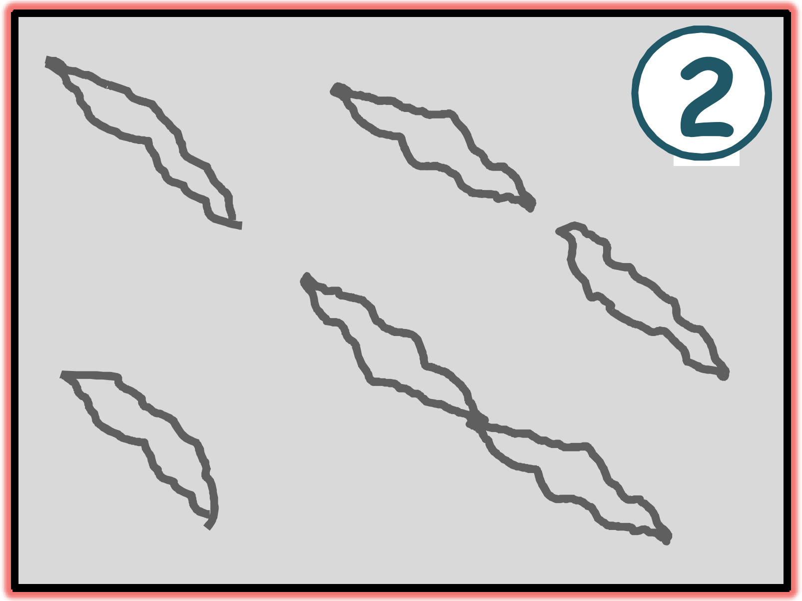


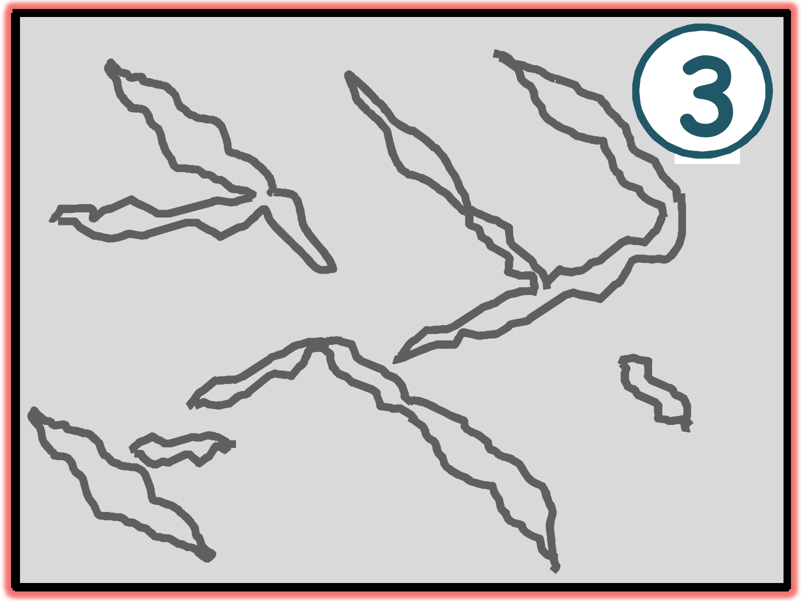
Interpenetration
Not physical !



Network connectivity





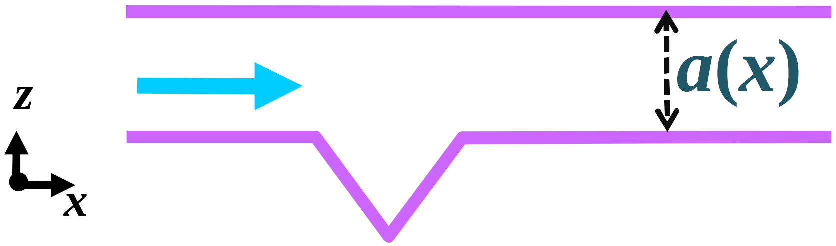


- **Are the observed fractures representative of the large scale permeability ?**

1. Connected network
   Local contact ⇨yes
2. Disconnected network
   Bulk permeability ?
3. Complicated network ! ⇨No

Off lubrication regime ?

- Effect of sharp morphology ?
  - Effect of contact zones ?
  - Corner



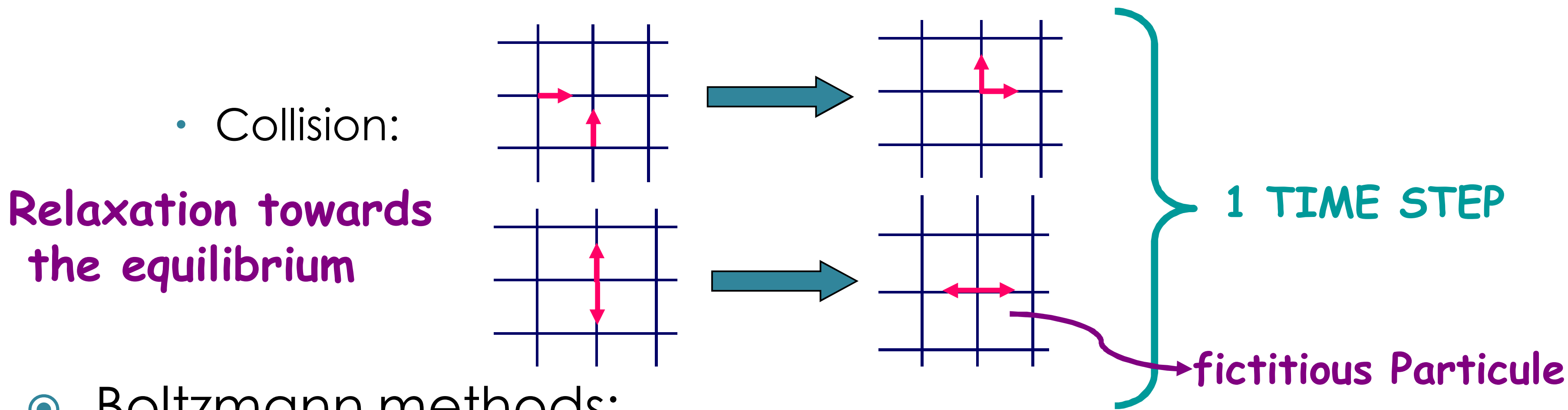
- Higher velocities
- Full Navier Stokes equation

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}.\vec{\nabla}\vec{v}\right)=-\vec{\nabla}p+\eta\Delta\vec{v}$$

- Lattice Boltzmann (LB) methods
- Transient regime
- Equation to be solved in 3D

Some principles of the LB methods

- Comes from Lattice gas methods:
  - Space discretized with a lattice
  - Discrete time, discrete velocity directions
  - Fictitious particles, 1 particle/node in a given direction
    - Streaming:
    - Collision:



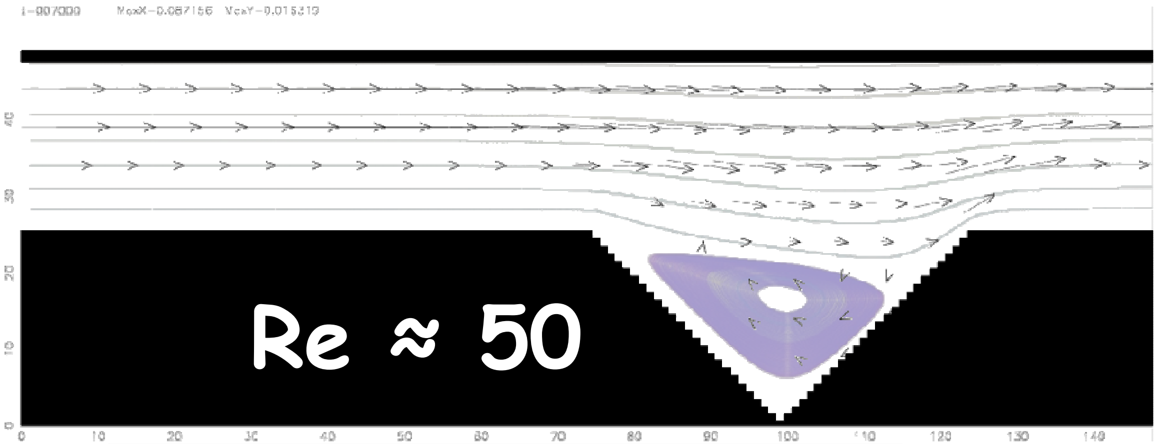
- Boltzmann methods:
  - Average in a mesoscopic volume of particles occupation in a given direction
  - Use of particles distributions : here, mass
  - Conservation of mass and momentum

Flow Recirculation in a corner

Turbulence:

At large Re

Asymmetric



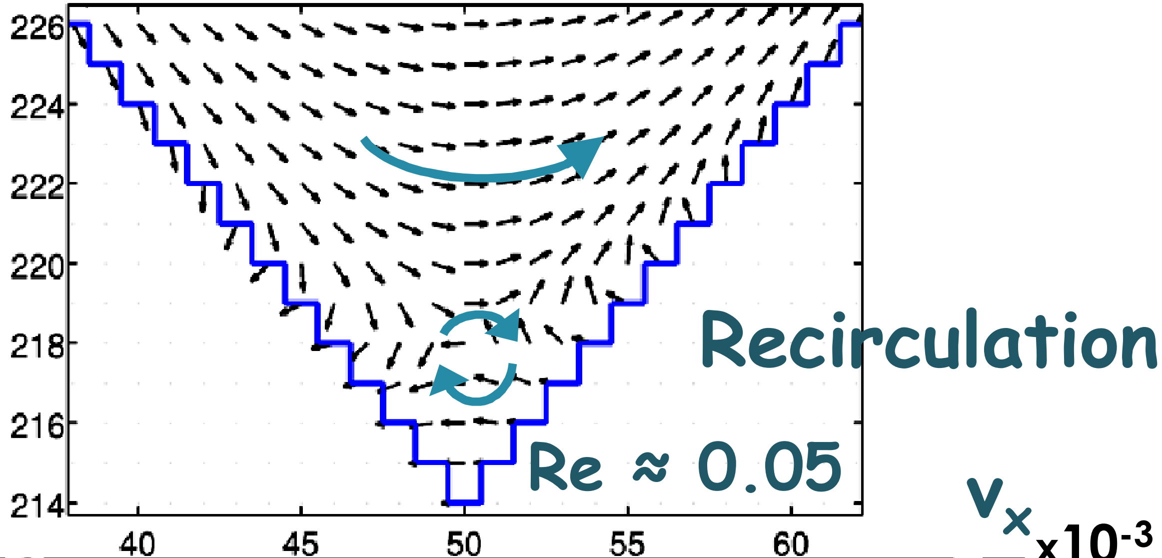
Moffat eddies:

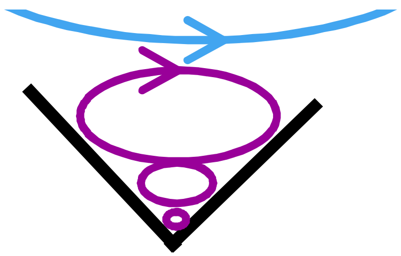
At small Re

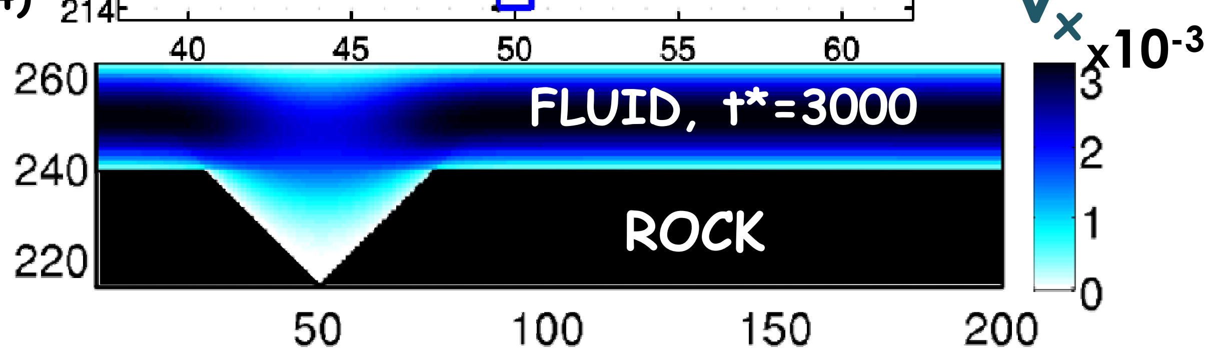
For angle<146°

Symmetric

Moffat, J. Fluid Mech. (1964)







Hydro-thermal flows – meth. 1 Finite differences

- Reynolds equation

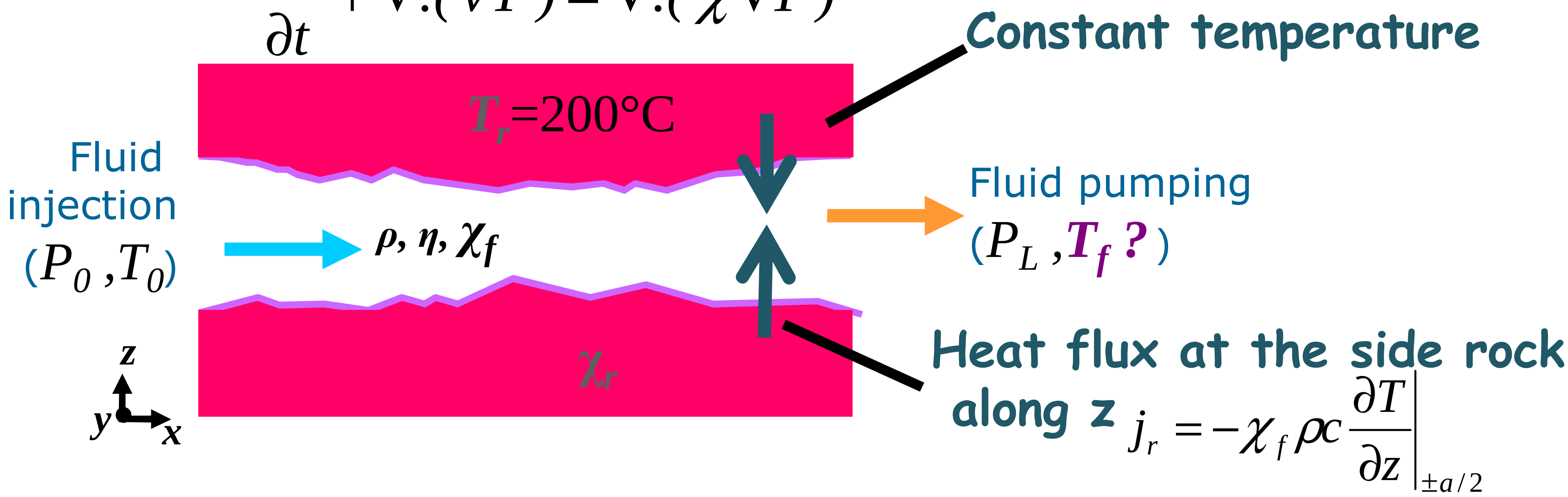
$$\vec{\nabla}.(a(x,y)^3\vec{\nabla}p) = 0$$

- Heat diffusion-advection equation

$$\frac{\partial T}{\partial t} + \vec{\nabla}.(\vec{v}T) = \vec{\nabla}.(\chi\vec{\nabla}T)$$

Notations:

Fluid density: ρ
Dynamic viscosity: η
Fluid thermal diffusivity: χ_f
Rock thermal diffusivity: χ_r
Velocity: $\mathbf{v}(x,y,z)$
Averaged velocity: $\mathbf{u}(x,z)$
Pressure: $p(x,y,z)$



Hypotheses – Meth1

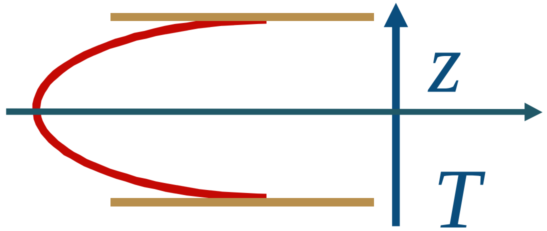
- Internal energy flux averaged across the fracture:

$$\vec{f} = \int_{a(x,y)} \left[E_0 + \rho c(T - T_0)\right] \vec{v}\, dz$$

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

Notations (for the fluid):
- *Density:* ρ
- *Dynamic viscosity:* η
- *Thermal diffusivity:* χ_f
- *Specific heat capacity :* c
- *Velocity:* $\mathbf{v}(x,y,z)$

- Hyp: $q_x \frac{\partial T}{\partial x} + q_y \frac{\partial T}{\partial y} = g(x,y)$
- Quartic profile: $T - T_r = -\frac{g}{32a^3\chi_f}(4z^2 - a^2)(4z^2 - 5a^2)$



Thermal lubrication approximation

- Flux balance: $\vec{\nabla}\,\vec{f} + 2\,j_r = 0$ **with** $j_r = -\chi_f \rho c \left.\frac{\partial T}{\partial z}\right|_{\pm a/2}$
- 2D temperature equation

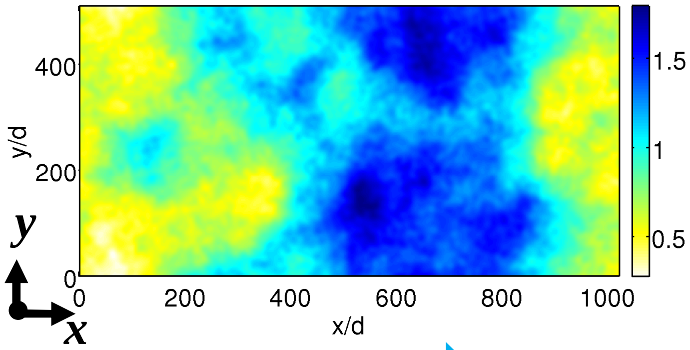
$$\vec{q}(x,y).\vec{\nabla}\overline{T} + \frac{2\chi}{a(x,y)} Nu(\overline{T} - T_r) = 0$$

$$Nu = \frac{j_r}{j_{macro}} = \frac{70}{17}$$

Solving : Finite differences
+ biconjugate gradient method

Illustration…hydro-thermal result

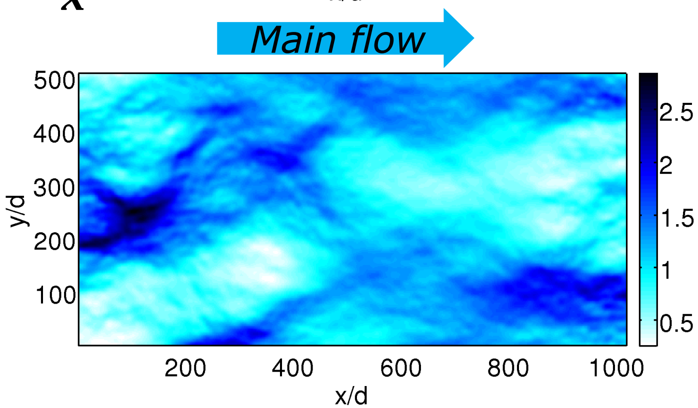
Example



Rough apertures

$$a^*(x,y) = \frac{a(x,y)}{A}$$

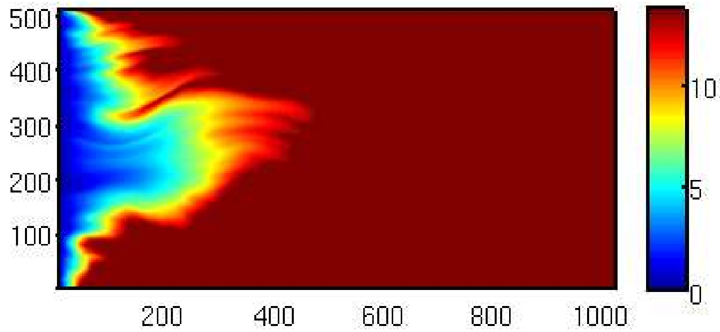
A	**1 mm**
σ	**0.35 mm**
$L_x \times L_y$	**1 x 0.5 m²**



2D-flow norm

$$\left\|\vec{q}^*(x,y)\right\| = \frac{12\eta\, L_x \left\|\vec{q}(x,y)\right\|}{\Delta P\, A^3}$$

Dyn. visc. ***η*** *(10 bar; 100°C)*	**3.10⁻⁴ Pa.s**
∂p/∂x	**250 Pa/m**
H	**0.82 mm**

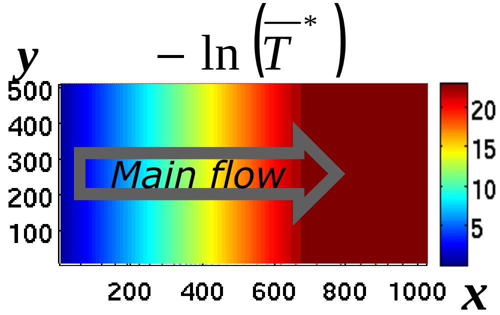


$-\ln(\overline{T}^*)$

$$\overline{T}^* = \frac{\overline{T} - T_0}{\Delta T}$$

Density ***ρ***	**1.10³ kg/m³**
ΔT	**120° C**
Fluid diffusivity χ	**0.17 mm²/s**

Reference case: Parallel plates

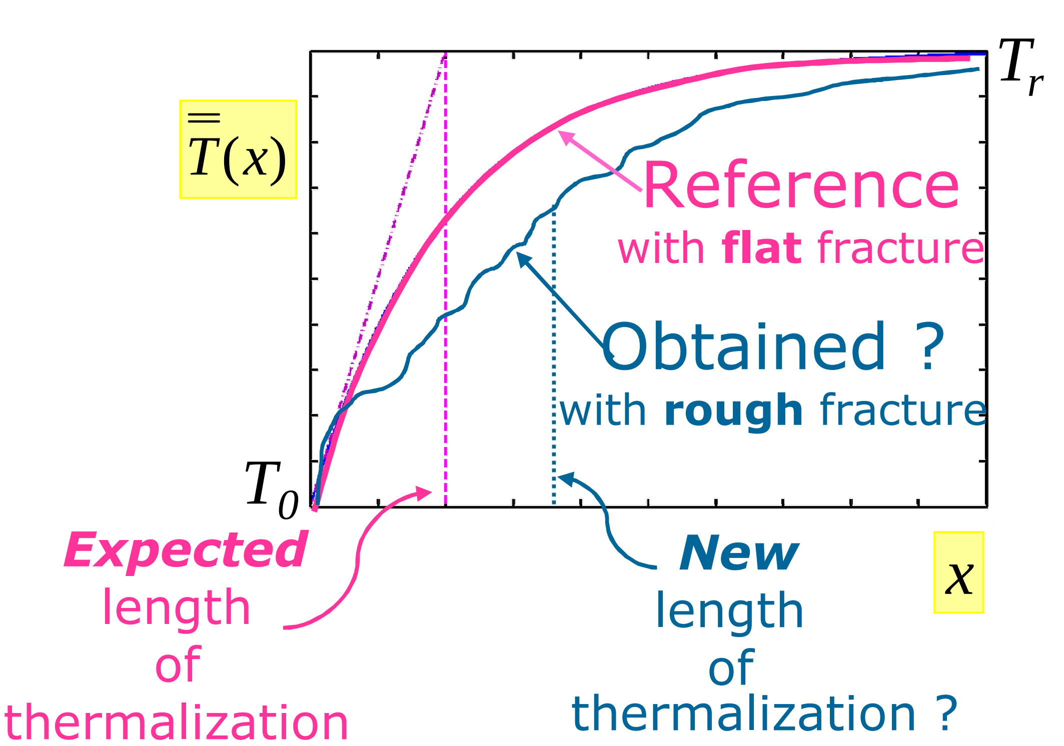


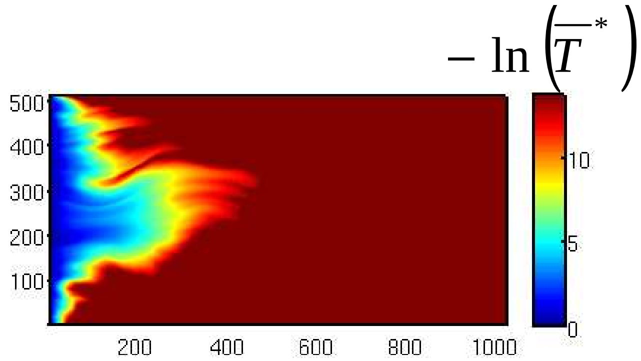
➢ ***Analytic solution***

$$\overline{T}_{//} - T_r = (T_0 - T_r)\exp\left(-\frac{x}{R_{//}}\right)$$

$$R_{//} = \frac{A^2 \left\| \vec{q}_{//} \right\|}{2\,Nu\,\chi_f}$$

- Temperature in 1D



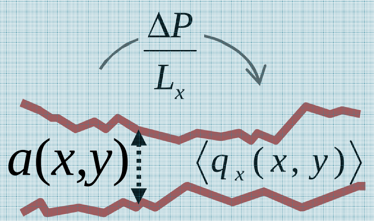


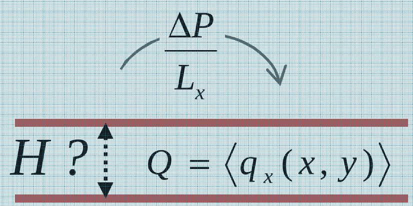
$$\overline{\overline{T}}(x) = \frac{\int_{l_y} u_x(x,y)\,\overline{T}(x,y)\,dy}{\int_{l_y} u_x(x,y)\,dy}$$

$$u_x = \int_a v(x,y,z)\,dz \Big/ a(x,y)$$

Equivalent aperture definitions

› Hydraulic aperture H





$$\vec{q}(x,y) = \int_a \vec{v}(x,y,z)dy = -\frac{a^3}{12\eta}\vec{\nabla}_2 p$$

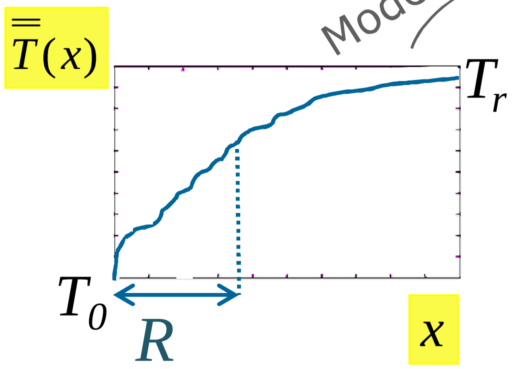
$$H^3 = -\langle q_x(x,y)\rangle 12\eta \frac{l_x}{\Delta P}$$

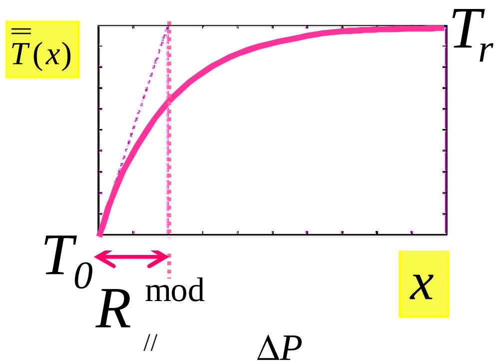
› Thermal aperture Γ

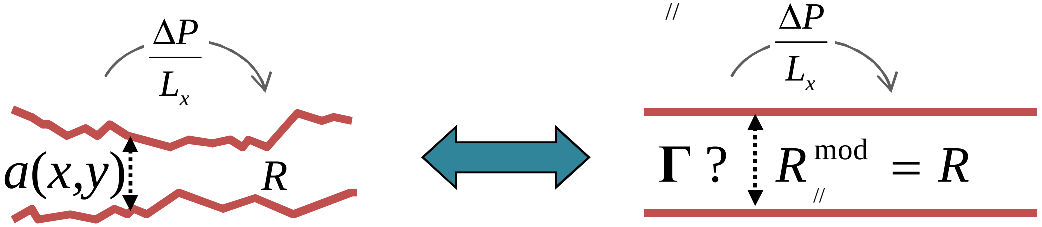
Parallel plates solution

Modeled with

$$\overline{\overline{T}}_{//}^{\text{mod}} - T_r = (T_0 - T_r)\exp\left(-\frac{x}{R_{//}^{\text{mod}}}\right)$$





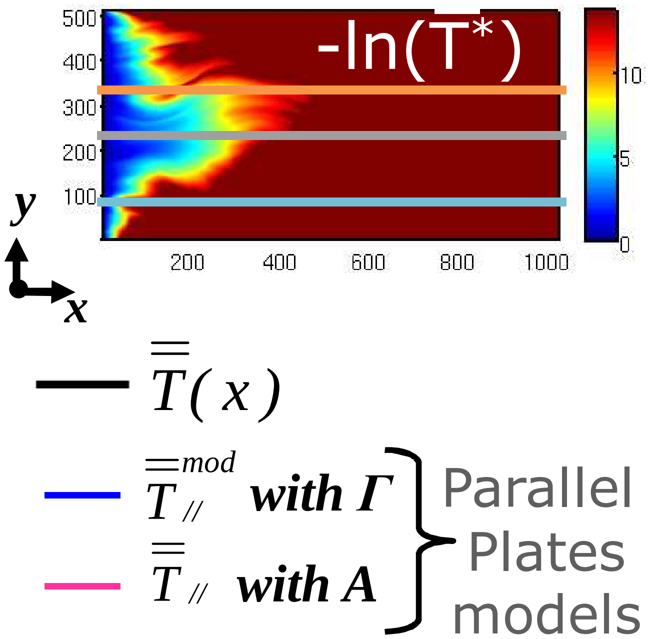


$$\Gamma \propto \left(R_{//}^{\text{mod}}\right)^{1/4}$$

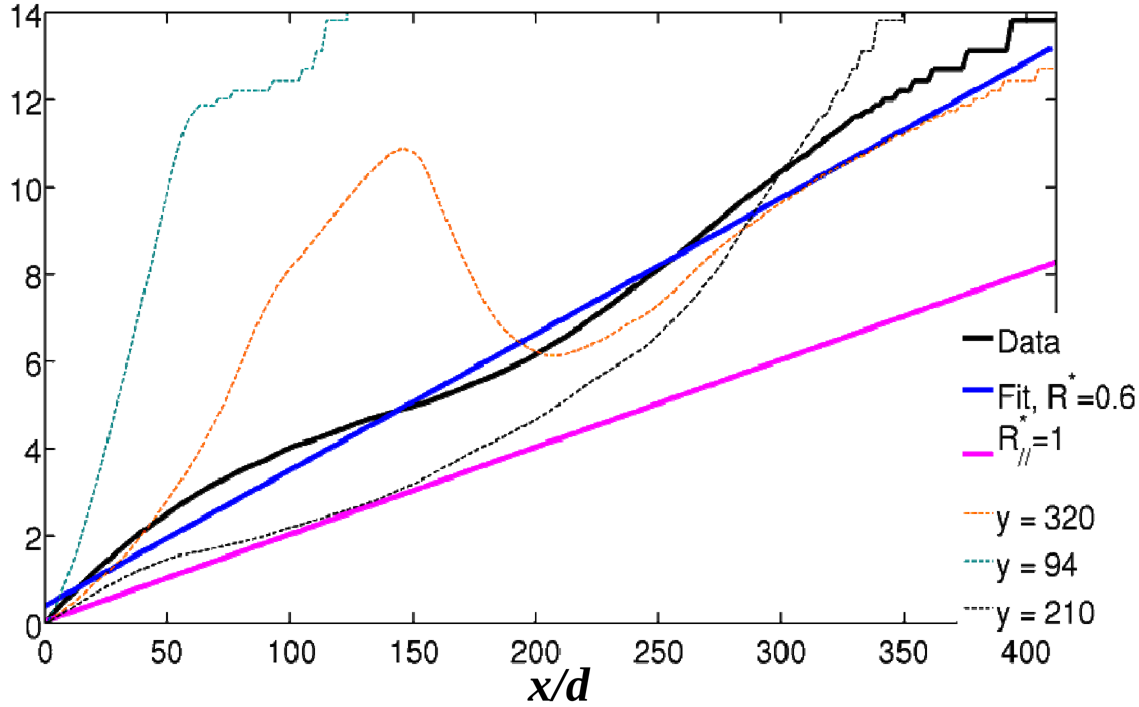
$R_{//}^{\text{mod}}$: Suitable thermal length

Illustration…thermal characterization

2D Temperatures



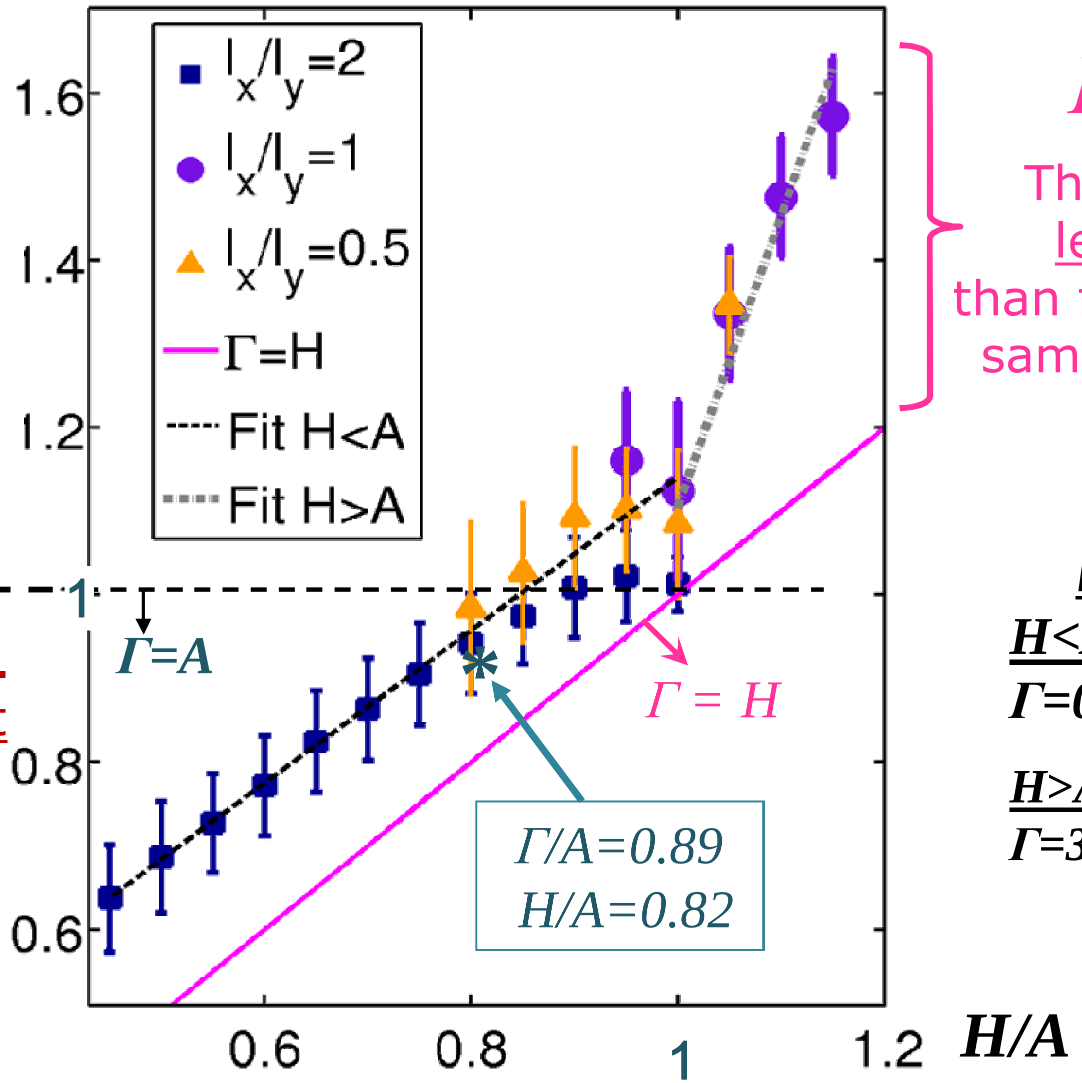
1D Temperatures $-\ln(\overline{\overline{T}}^*)$



- Thermal aperture : $\Gamma = 0.89\text{ mm}\ldots < A = 1\text{ mm}$

Enhanced thermal behavior

Statistical results for thermal apertures



Thermal exch. less efficient than parallel plates separated by A

Thermal exch. more efficient than parallel plates separated by A

Γ >H

Thermal exch. less efficient than flat model with same permeability

Model Fit

H<A :
Γ=0.9H+0.2A

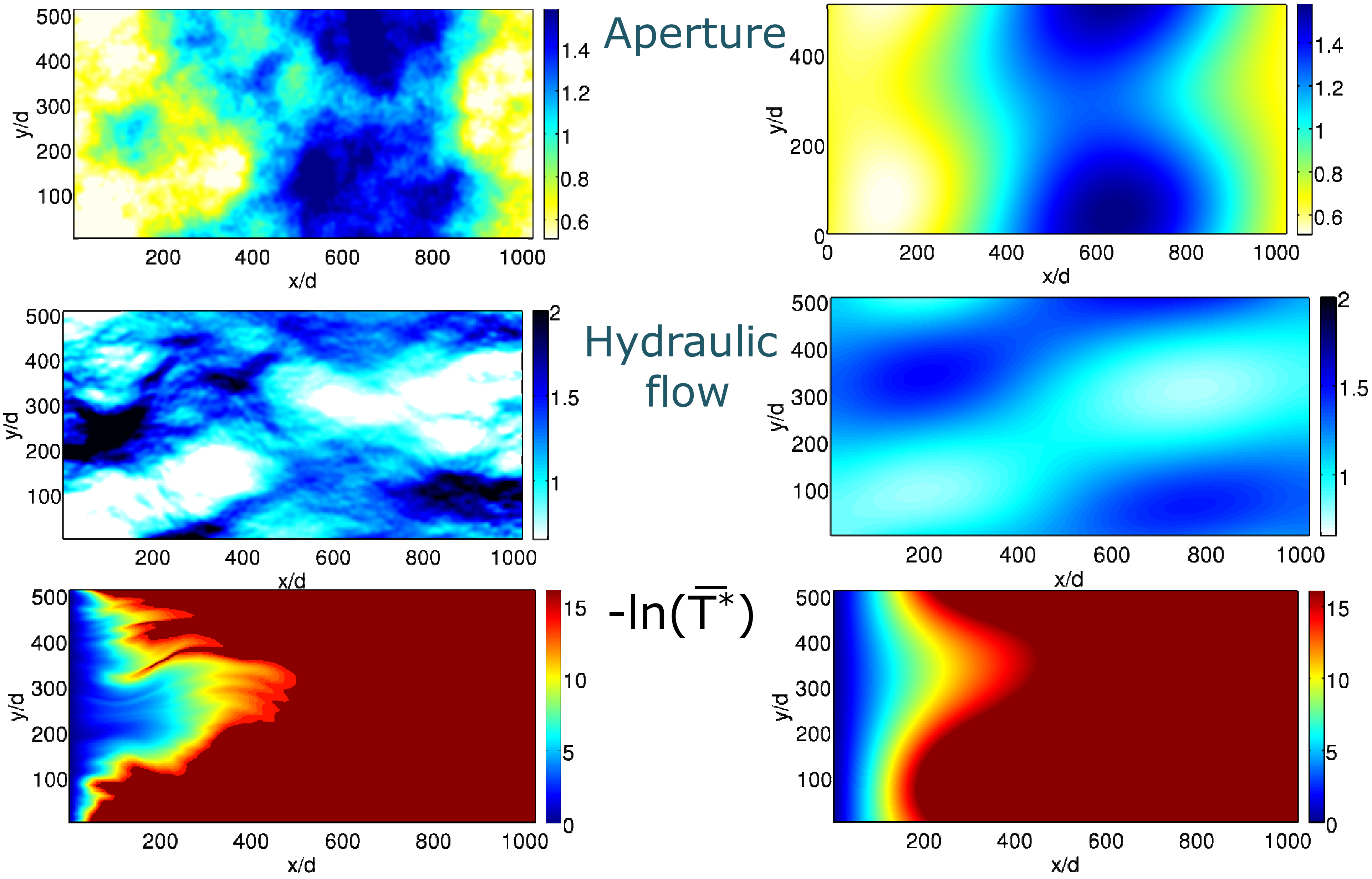
H>A :
Γ=3.5H+2.4A

Normalized hydraulic aperture

Less permeable than parallel plates separated by A

More permeable than parallel plates separated by A

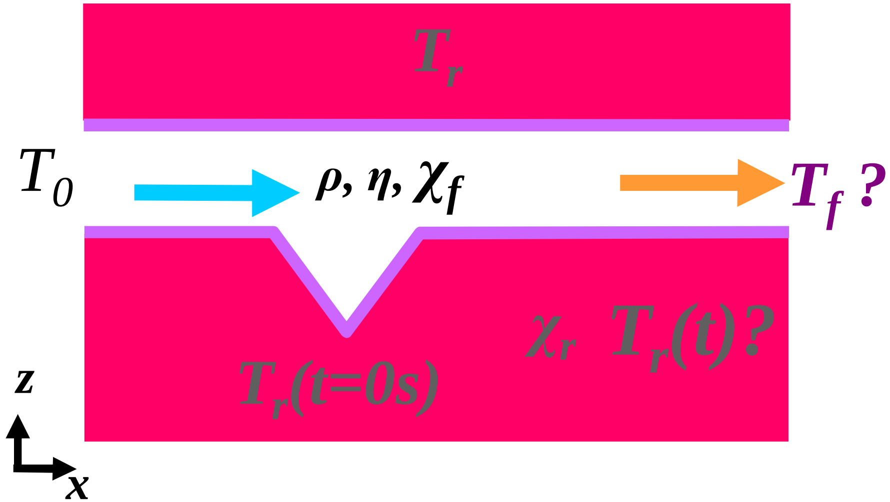
Control of the large scales modes on the hydro-thermal variations



Hydro-thermal equations (Meth 2)

- Off lubrication regime:

ρ: density; χ: Thermal diffusivity; η: Viscosity



Effect of a sharp morphology on

- the fuid temperature ?
- the rock temperature ?

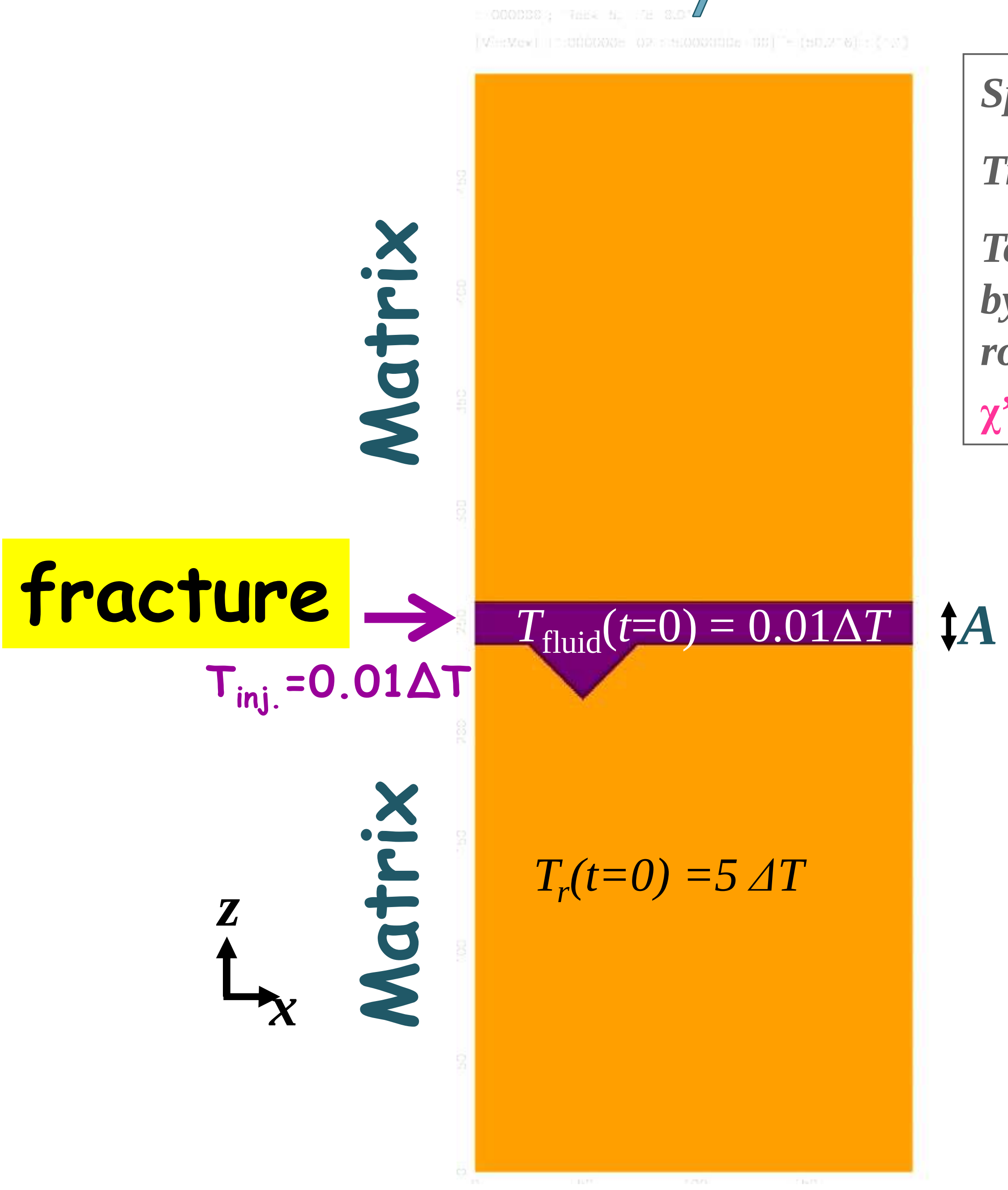
- Rock temperature variable in space and time

$$\frac{\partial T}{\partial t} + \vec{\nabla}.(\vec{v}T) = \vec{\nabla}.(\chi\vec{\nabla}T)$$

Solved in fluid and rock (Thermal diffusivity χ_f and χ_r)

- Use of a second distribution particles with LB methods
- Conservation of internal energy and energy flux

Moderate Reynolds number



Space unit : A/20

Time unit Δt: $[A/(20)]^2 .(1/\chi_r)$

Temperature unit: arbitrary (fixed by fluid injection temperature and rock temperature)

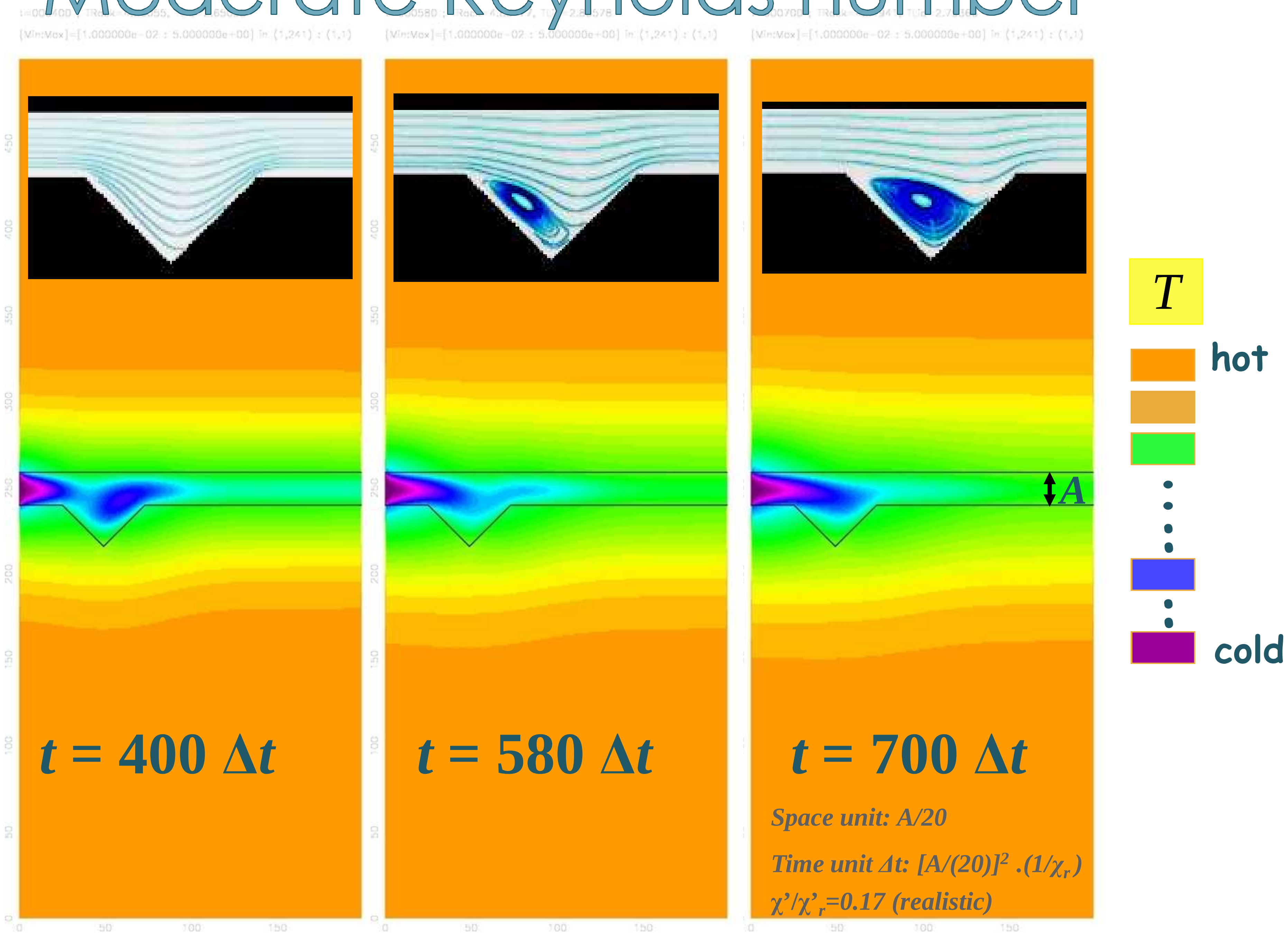
$\chi'/\chi'_r = 0.17$ *(realistic)*

Peclet=45 = $\frac{\text{Convection}}{\text{Conduction}}$

Colorscale:

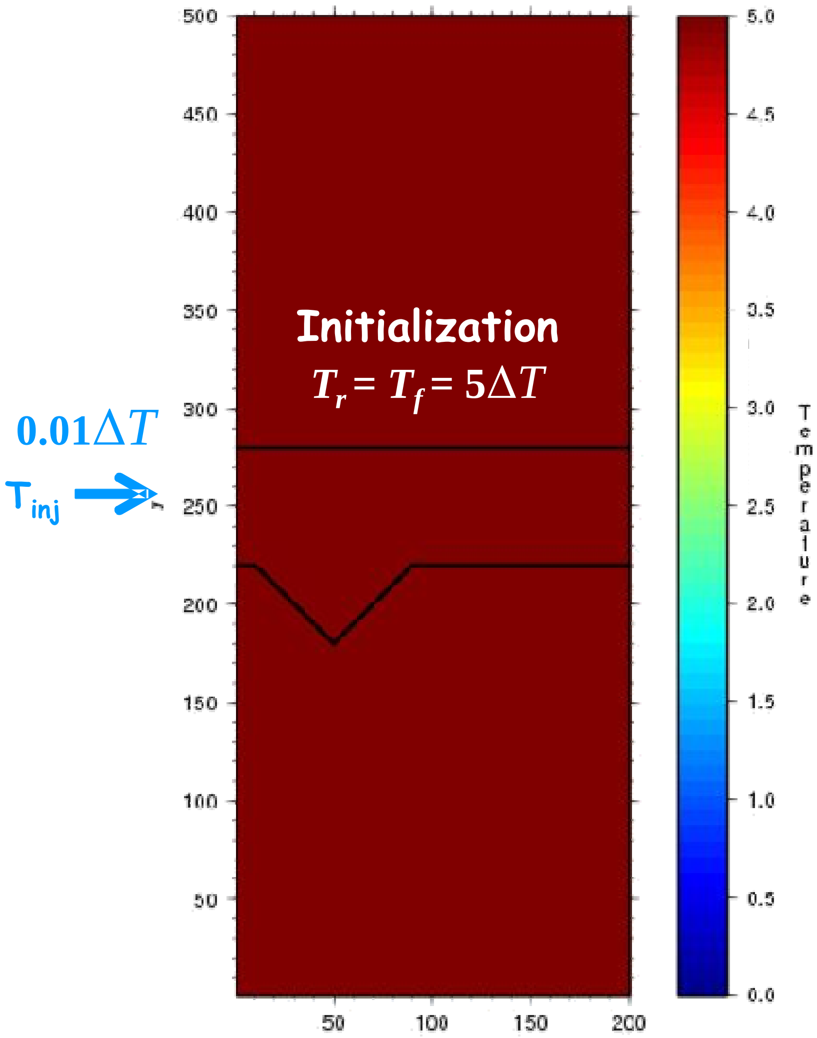
- T=5 ΔT (hot)
- T=4 ΔT
- T=2 ΔT
- T=0.01 ΔT(cold)

Moderate Reynolds number



Large channel perturbed by a corner

- Initialization
  - Channel of 200Δx x 120Δx perturbed by a corner, inside rock
  - Whole system size: 200Δx x 500Δx



Space unit Δx : A/120

Time unit Δt: $[A/(120)]^2 .(1/\chi_r)$

Temperature unit: arbitrary (fixed by fluid injection temperature and rock temperature)

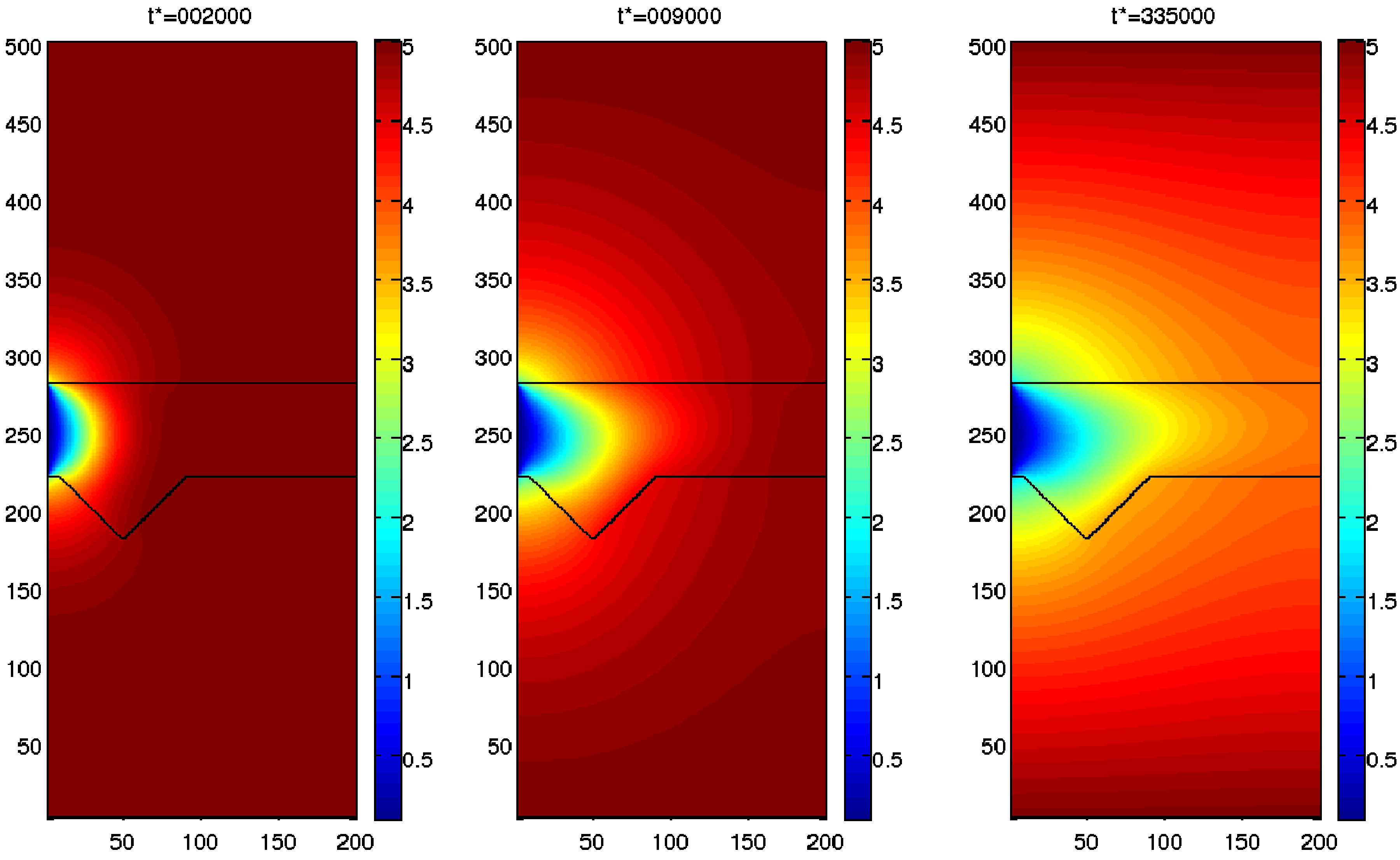
$\chi_f'/\chi'_r = 0.17$ *(realistic)*

T uniform at t=0, equal to rock temperature everywhere ($T_r = T_f = 5\Delta T$)

Pressure gradient imposed so that Reynolds number is about 0.3 at quasi-stationary regime (small Re)

Max(*a*)/Min(*a*) = 145/120 = 1.2
Where a is the fracture aperture

Long term temperature field

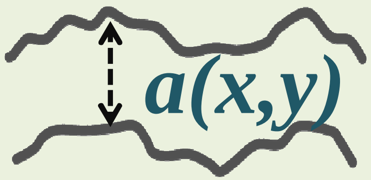


Conclusion and perpectives

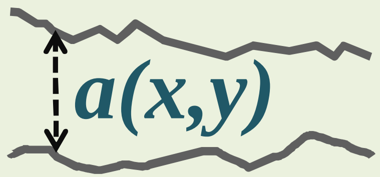
Draix cores and Draix permeability

- Methods developed to reconstruct fracture apertures from borehole core
- Characterization of
  - surfaces
  - Apertures
- Two models of aperture observed

Correlated isotropic surfaces



Indepedant anisotropic surfaces



- Permeability at core scale ($10^{-9}m^2$)
- Some larger scale hydraulic data are expected for comparison

Conclusion and perpectives

Hydro-thermal behavior under lubrication approx.:

- Due to roughness, channeling of
  - Hydraulic flow
  - Temperature (energy)
- Study of the aspect ratio L_x/L_y
- Large scale variations seems relevant
- Coarse grained behavior :
  - Mechanical aperture A
  - Hydraulic aperture H
  - Thermal aperture Γ
- Thermal exchange less efficient than flat model with same permeability
- Laws proposed about H/A, Γ/A
- Integration in network modeling ?

Conclusion and perspectives

Hydro-thermal modeling with LB method

- Advantages
  - Full hydraulic and heat equation solved in 3D
  - Off lubrication regime
  - Diffusion in the rock and liquid
- Long term behavior of geothermal systems
- How does
  - Sharp morphology
  - Moderate velocity

  } **change the thermal field ?**
- Need to explore more parameters to draw a conclusion about the influence of an asperity with steep slopes !
- Characteristic length of scale of the recirculation ?
- Integrate more complex/realistic morphology for the rock