Well-test flow responses of highly heterogeneous porous and fractured media

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Task T3: Well test interpretation in 2D and 3D heterogeneous porous media and in DFN

T3.1: Our first objective is to design an interface between ODE solvers and fast sparse linear solvers. The first target libraries will be SUNDIALS [hindmarsh et al., 2005] and HYPRE [Falgout et al., 2005]. All modules will be integrated in the HYDROLAB development platform. The transient flow solver module will be made generic to porous media, fractured media and porous fractured media.

T3.2: Our second objective is to use the transient module for simulating transient flow in heterogeneous porous media (task T1).

T3.3: We will develop a module for simulating transient flow in DFN (task T2).

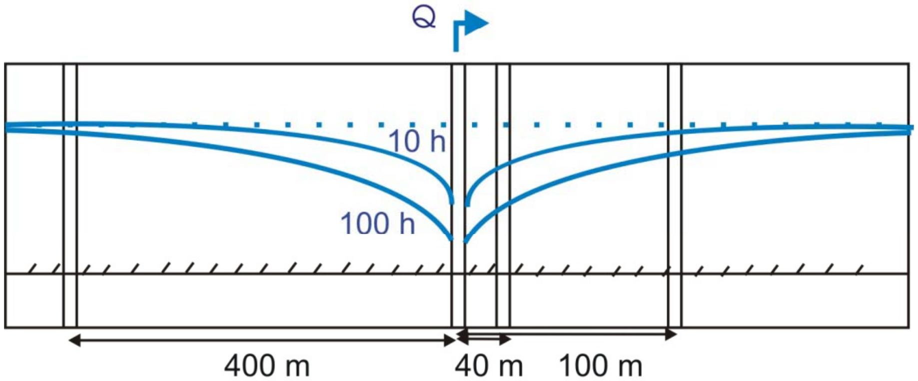
T3.4: We will use the supervisor of Monte-Carlo method and the deployment of simulations on grid architectures to run multiparametric simulations (task T7). The results will be stored in a well structured database which will be available in the free release of the platform. The database will be used for setting up relation between drawdown signals and the medium hydraulic properties.

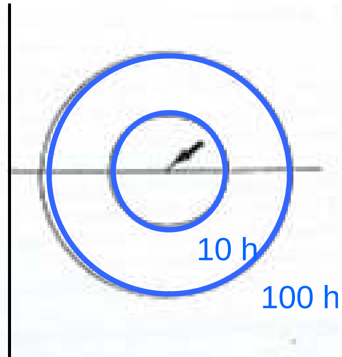
Results will be compared to signals obtained in natural fields and particularly on the site of Ploemeur (Brittany) [*Le Borgne , et al., 2004]. A review of site data is given in [de Dreuzy and Davy, 2007]. This step will be undertaken in strong collaboration with the ERO H+*.

Codes

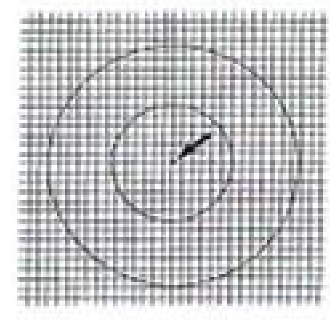
- Modification of SUNDIALS
  - Interface to SUNDIALS
  - Integration within SUNDIALS of an interface to other linear solvers (the same as in steady state)
- Construction of the transient systems dH/dt=A.H
  - Porous media
  - DFN
- Which applications use transient codes?
  - 2D-3D well tests
  - Hydraulic tomography
  - Fracture-Matrix

Well-test interpretation models





D=1



D=2

- Classical flow equation $D = 1, 2 \; or \; 3$

$$S\frac{\partial h}{\partial t} = \frac{T}{r^{D-1}}\frac{\partial}{\partial r}\left(r^{D-1}\frac{\partial h}{\partial r}\right)$$

- Drawdown solution

$$D = 1 \quad h_r(t) \sim \sqrt{t} - 1$$

$$D = 2 \quad h_r(t) \sim \ln(t)$$

$$D = 2 \quad h_r(t) \sim 1 - 1/\sqrt{t}$$

- Generalized flow equation $1 \le D \le 2$

$$S\frac{\partial h}{\partial t} = \frac{T}{r^{D-1}}\frac{\partial}{\partial r}\left(r^{D-1-(d_w-2)}\frac{\partial h}{\partial r}\right)$$

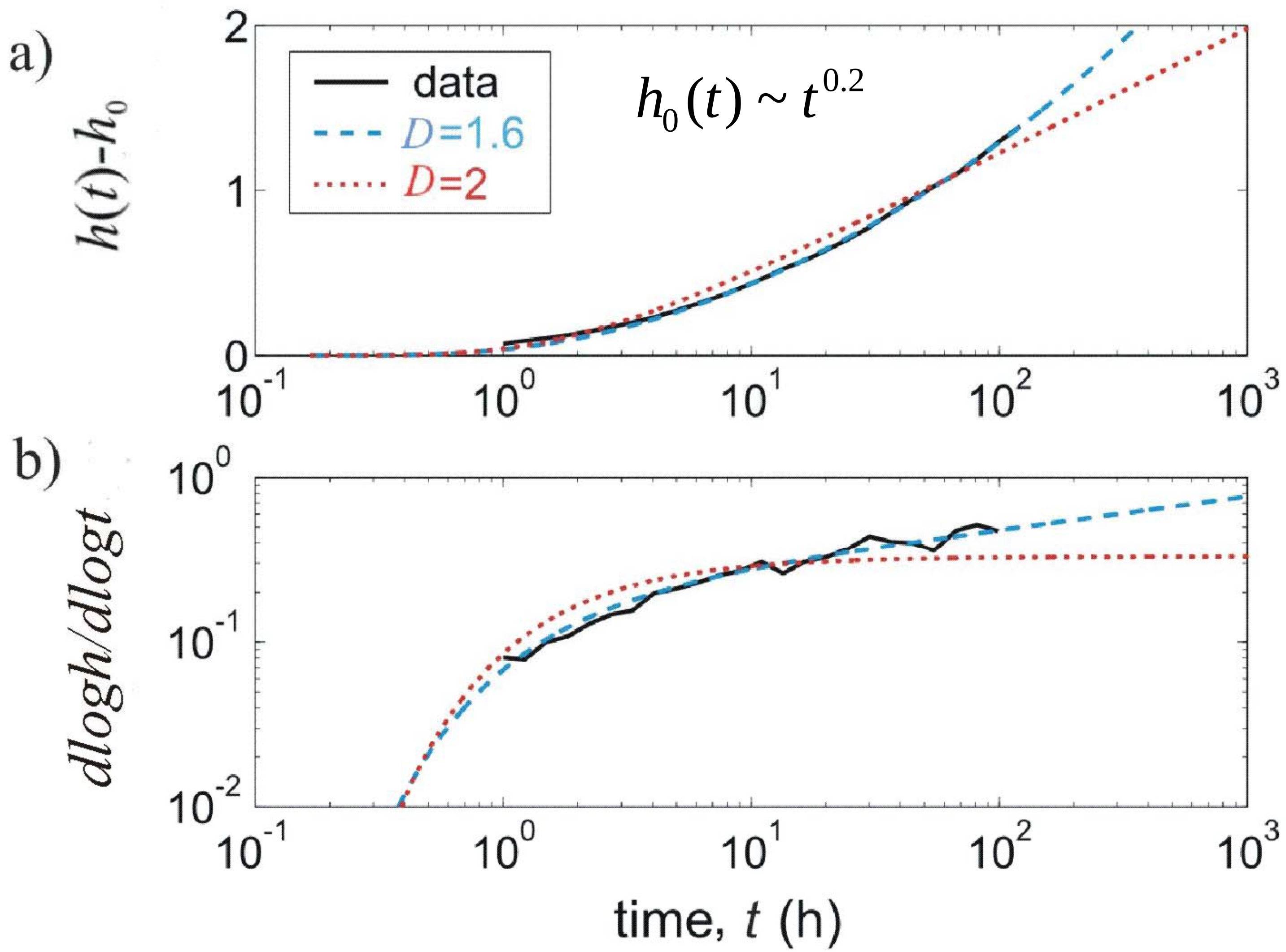
- Generalized drawdown solution

$$h_r(t) \sim \left[\frac{t}{t_c(r)}\right] \wedge \left(-\frac{n}{2}\right) \quad with \quad n = \frac{2 \cdot D}{d_w}$$

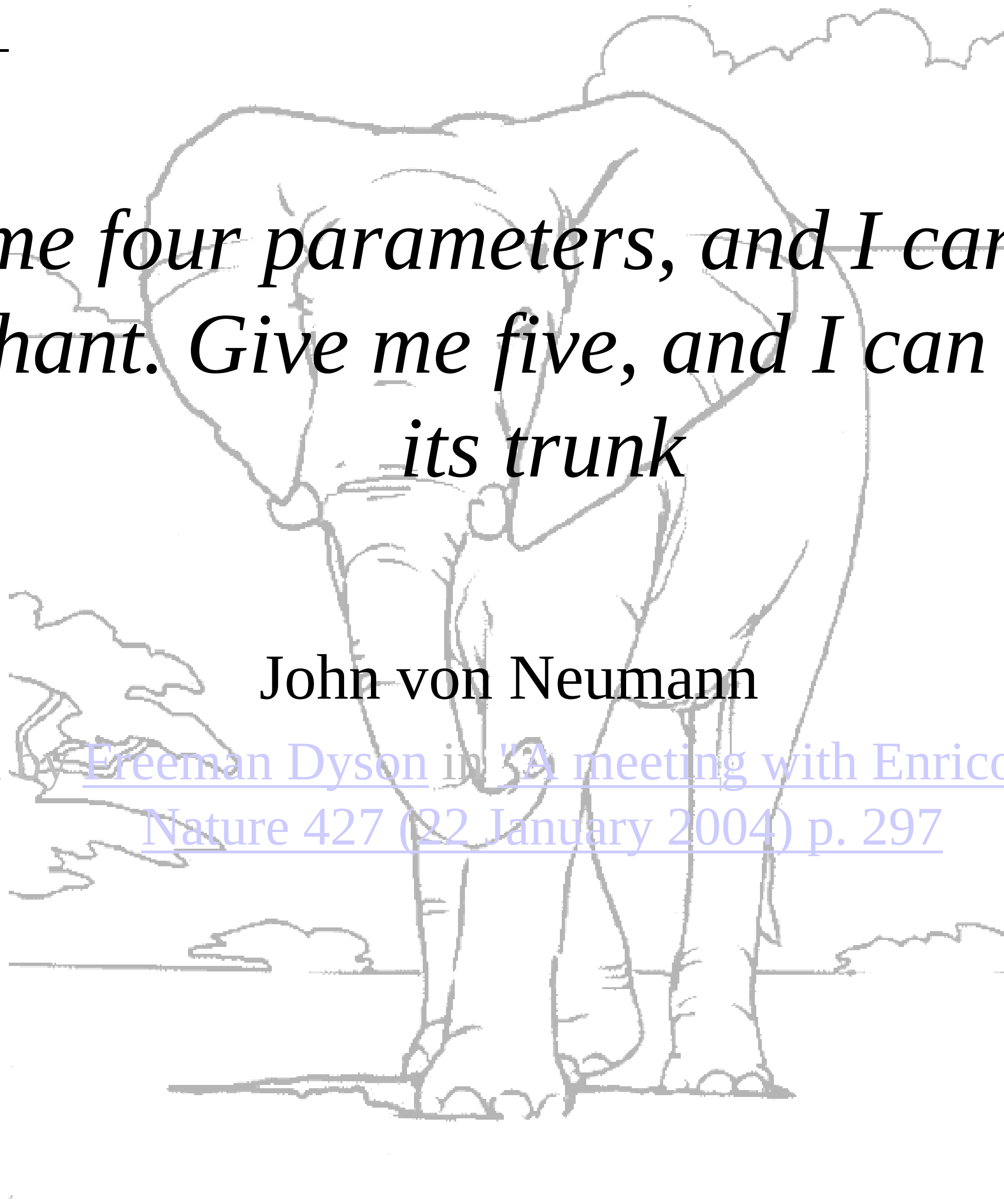
$$t_c(r) \sim r^{d_w} \qquad r^2(t_c) \sim t_c^{\frac{2}{d_w}}$$

Barker [1988], Acuna and Yortsos [1996]

Field test in a fractured aquifer (Ploemeur, France)



Le Borgne et al., *WRR*, 2004, Equivalent mean flow models for fractured aquifers: Insights from a pumping tests scaling interpretation

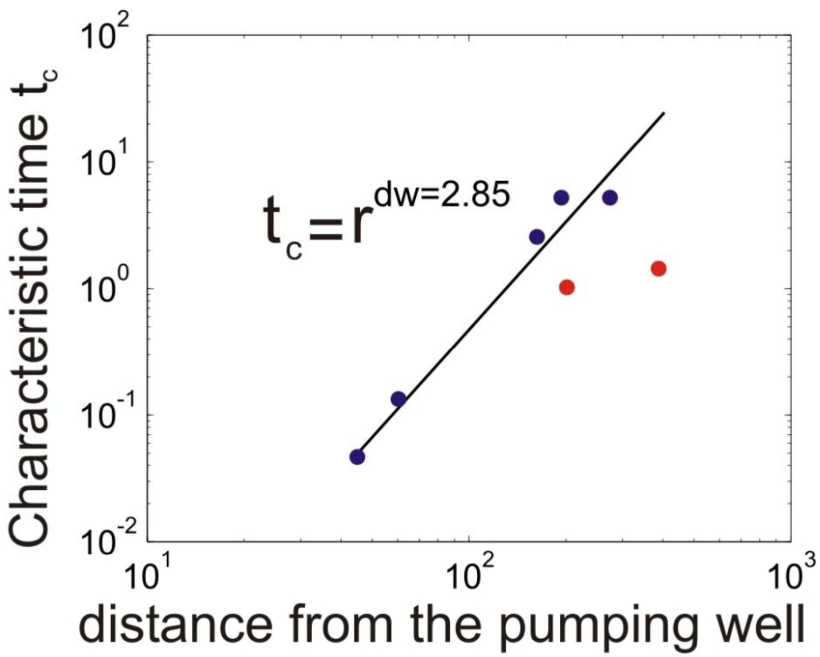


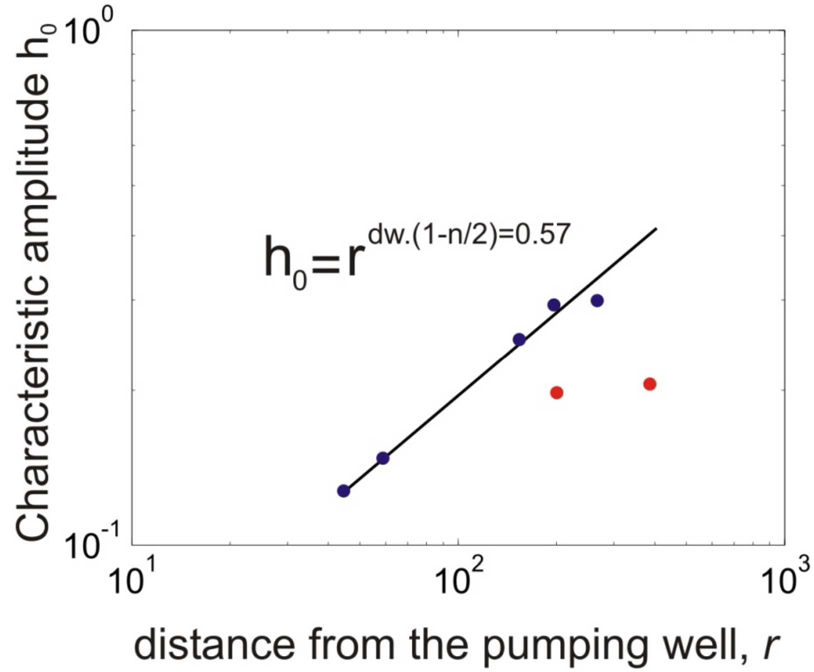
Give me four parameters, and I can fit an elephant. Give me five, and I can wiggle its trunk

John von Neumann

As quoted by Freeman Dyson in "A meeting with Enrico Fermi" in Nature 427 (22 January 2004) p. 297

Exponent d_w form the field data of Ploemeur

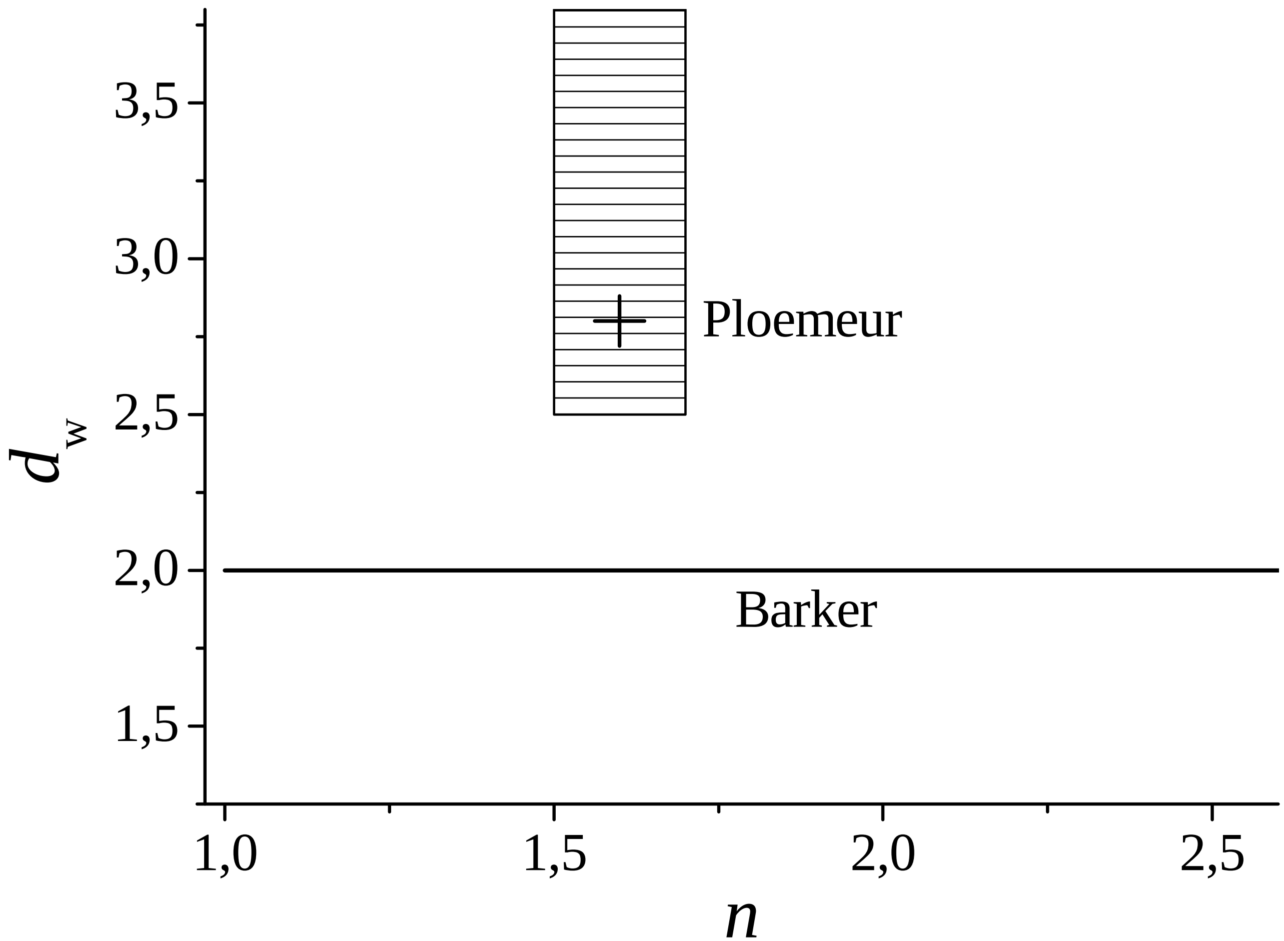




$$d_w = 2.85$$

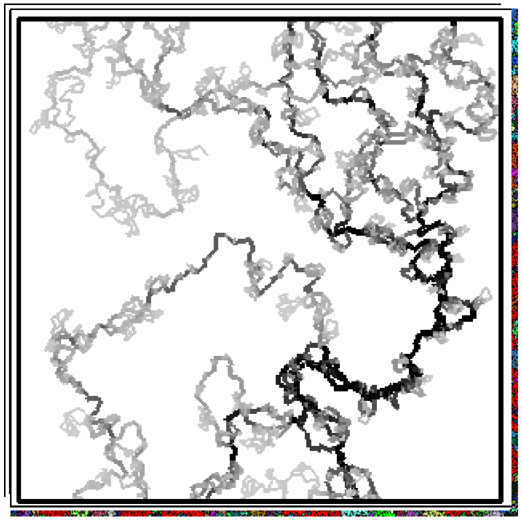
anomalously slow drawdown diffusion

Which permeability structure leads to non-classical drawdown repsonse such as Ploemeur's?



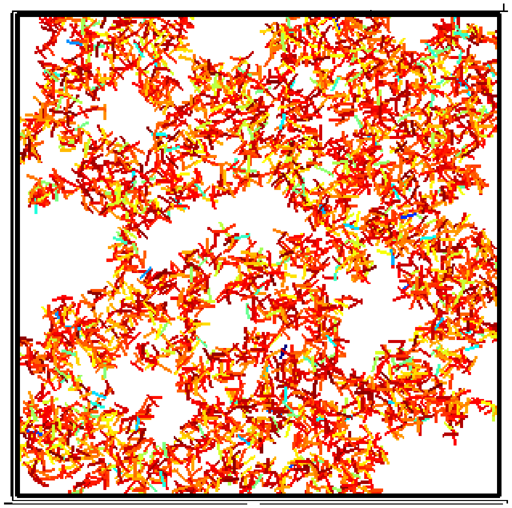
Fractals: Percolation structures d_f=1.86

Classical percolation



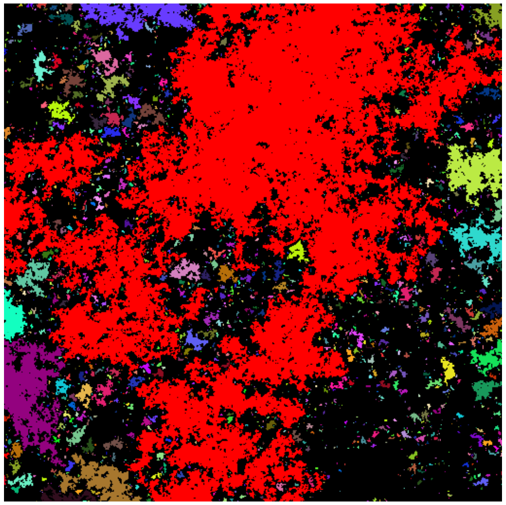
d_w~2.9

Continuum percolation
Permeability distribution



d_w>2.9

Correlated percolation



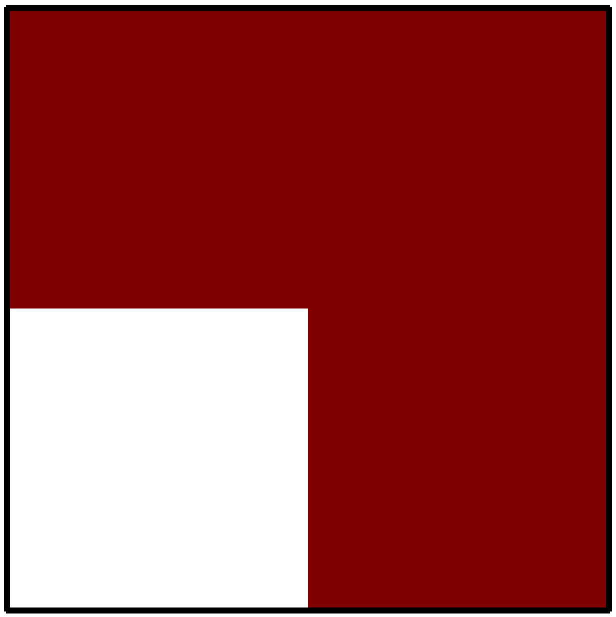
Makse

$2.3<d_w<2.9$

All structures have the same fractal dimension

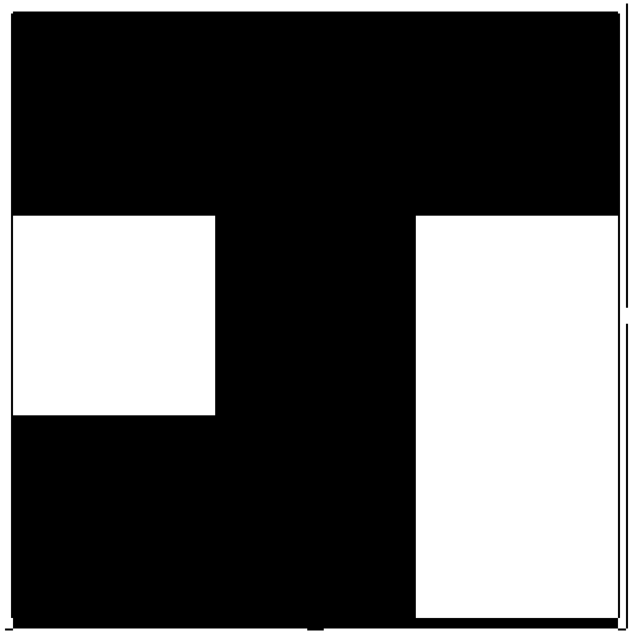
Fractals: Sierpinskis

Sierpinski gasket
d_f~1.6



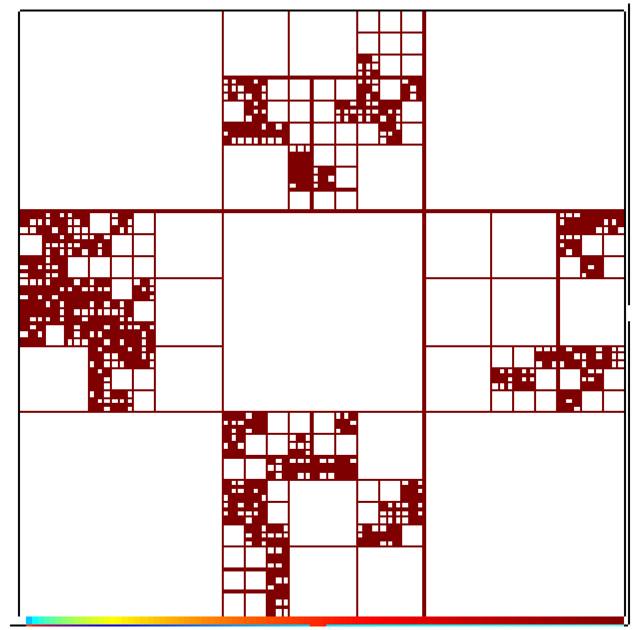
d_w~2.3

Genralized Sierpinski
1.3<d_f<2



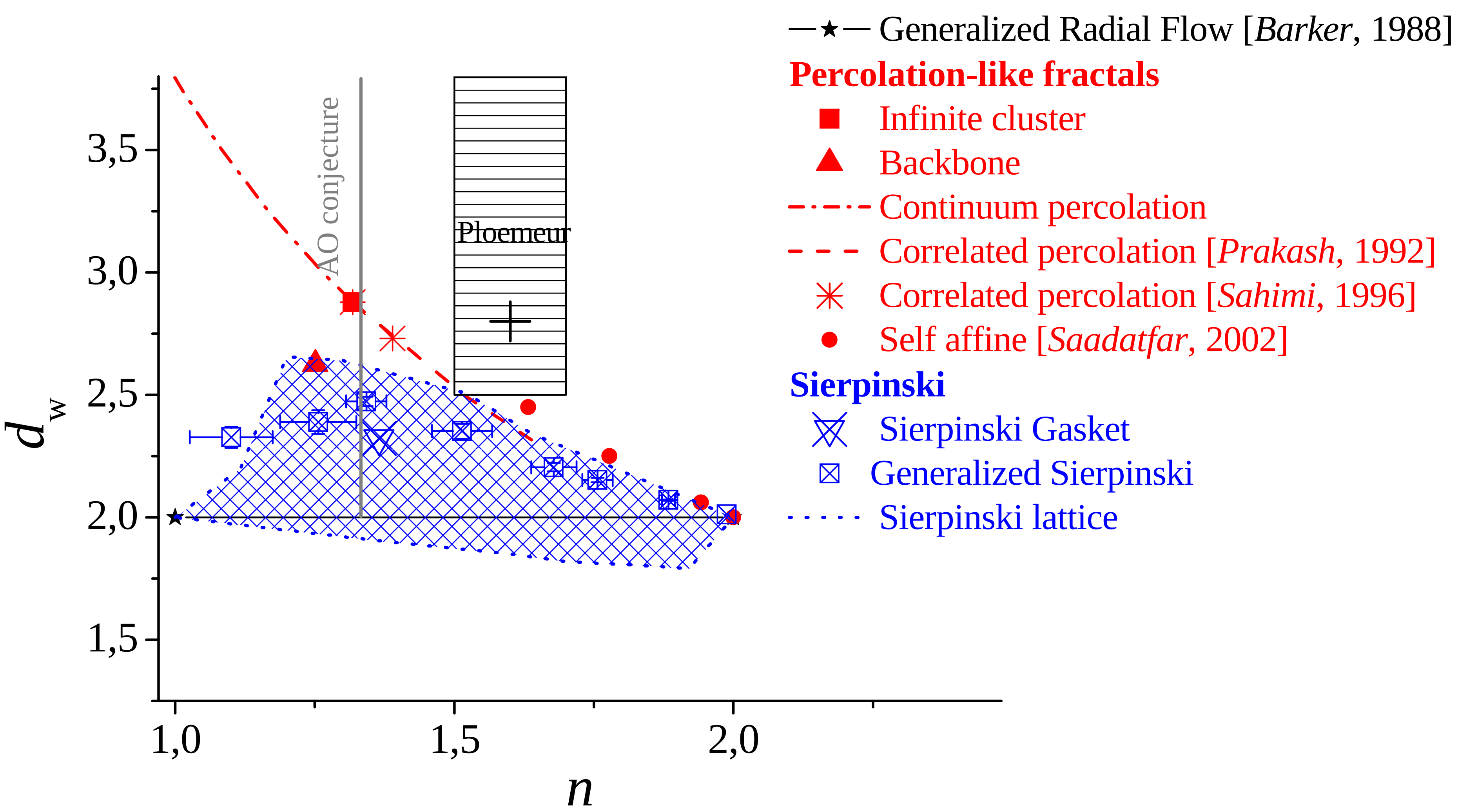
Regular multifractals with d_f<2 become disconnected with increasing scale

Sierpinski lattice
1.3<d_f<2

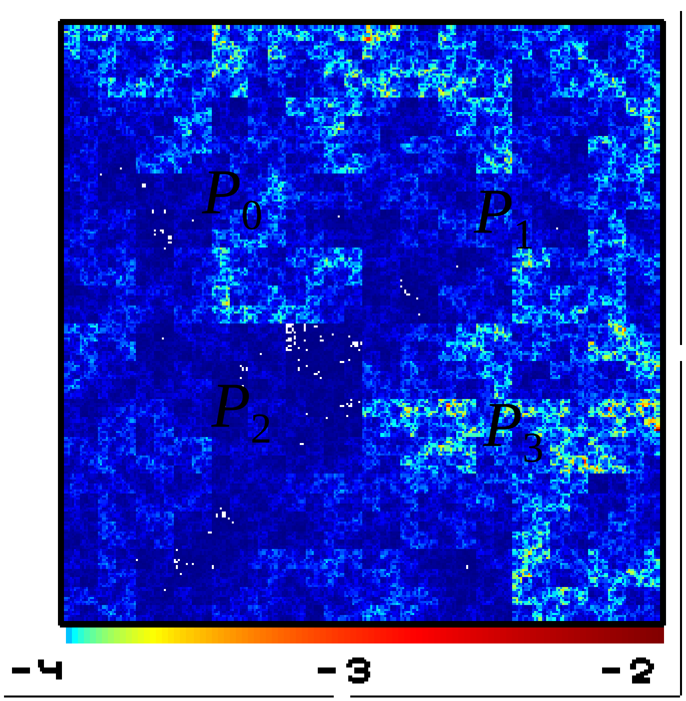


2<d_w<2.5

Which permeability structure leads to non-classical drawdown repsonse such as Ploemeur's?



From fractal structure to long-range correlated permeability fields
Continuous multifractals (d_f=2)



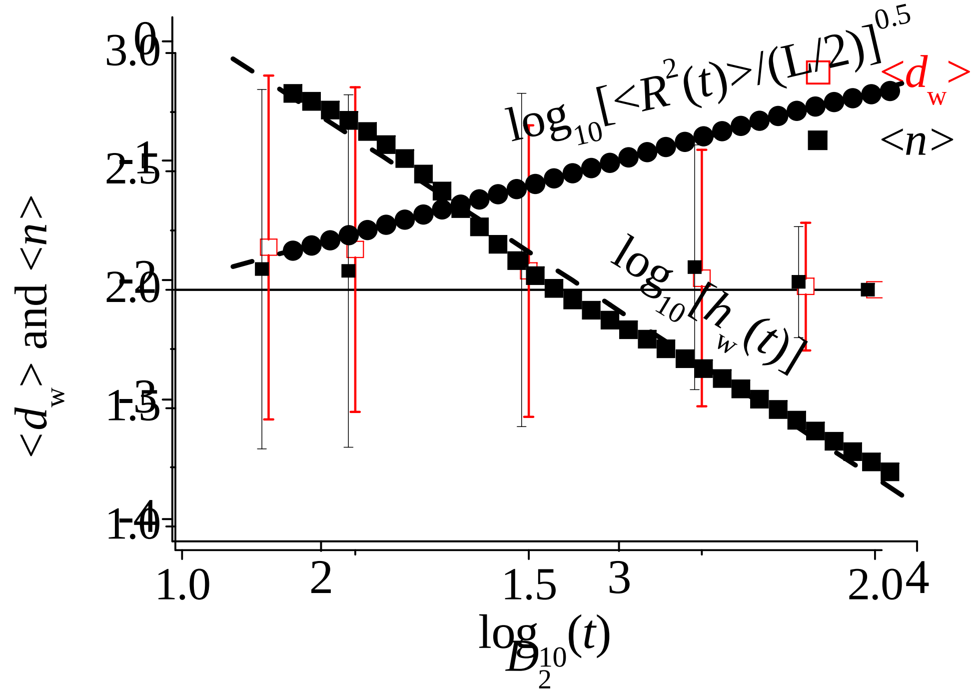
de Dreuzy et al., Physical Review E, 2004

Dimensions

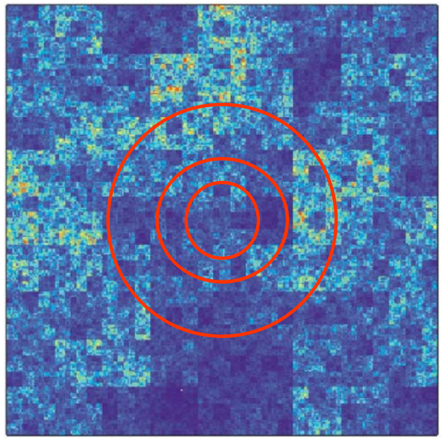
P_0	P_1
P_2	P_3

$$D_q = -\frac{\ln\left(\sum_i P_i^q\right)}{(q-1)\cdot\ln(l)}$$

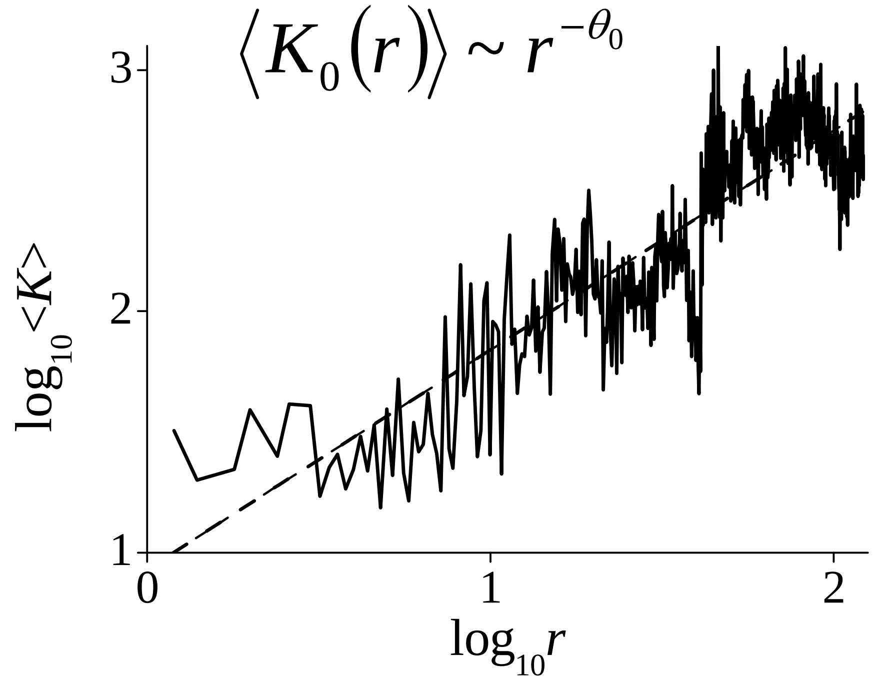
$$d_f = D_0 = 2$$



d_w related to the permeability scaling



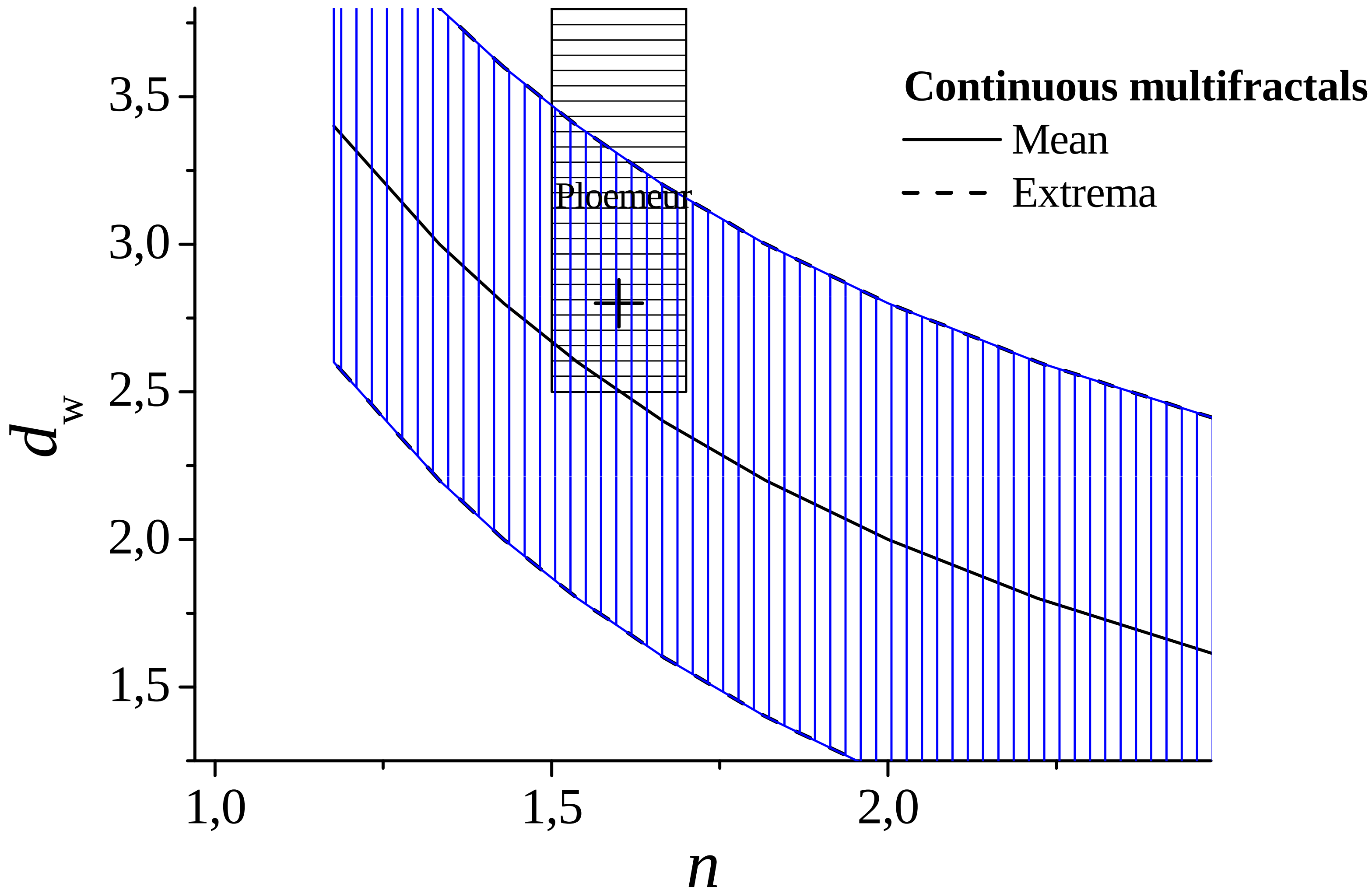
$<K_0(r)>$, the annular average



$$d_w = 2 + \theta_0 + 2 - D_2$$

- d_w is given by purely geometrical exponents
- D_2 induces an increase of d_w by $(2-D_2)$ when compared to the annular case
- Through θ_0, d_w depends on a local property : the permeability at the well

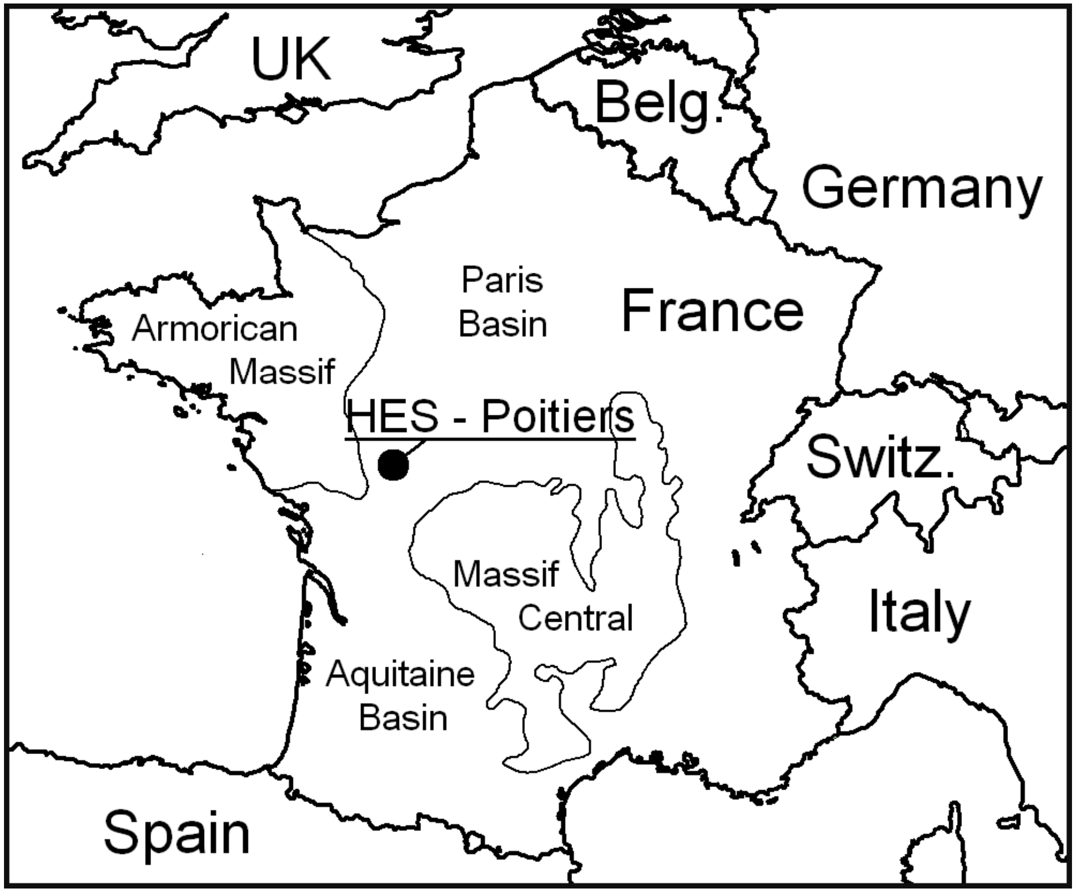
Which permeability structure leads to non-classical drawdown repsonse such as Ploemeur's?



Conclusions

- Structure and hydraulic heterogeneity have a strong influence on transient exponents n and d_w (Percolation induces slower diffusion than Sierpinski).
- Transient exponents n and d_w depend both on **global** properties (fractal dimension) and on **local** characteristics (local permeability scaling).
- Several well tests performed from different pumping wells are necessary to find the global properties (fractal dimension, correlation dimension, …)

Limestone aquifer example (SEH)



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LARGE NUMBER OF WELLS

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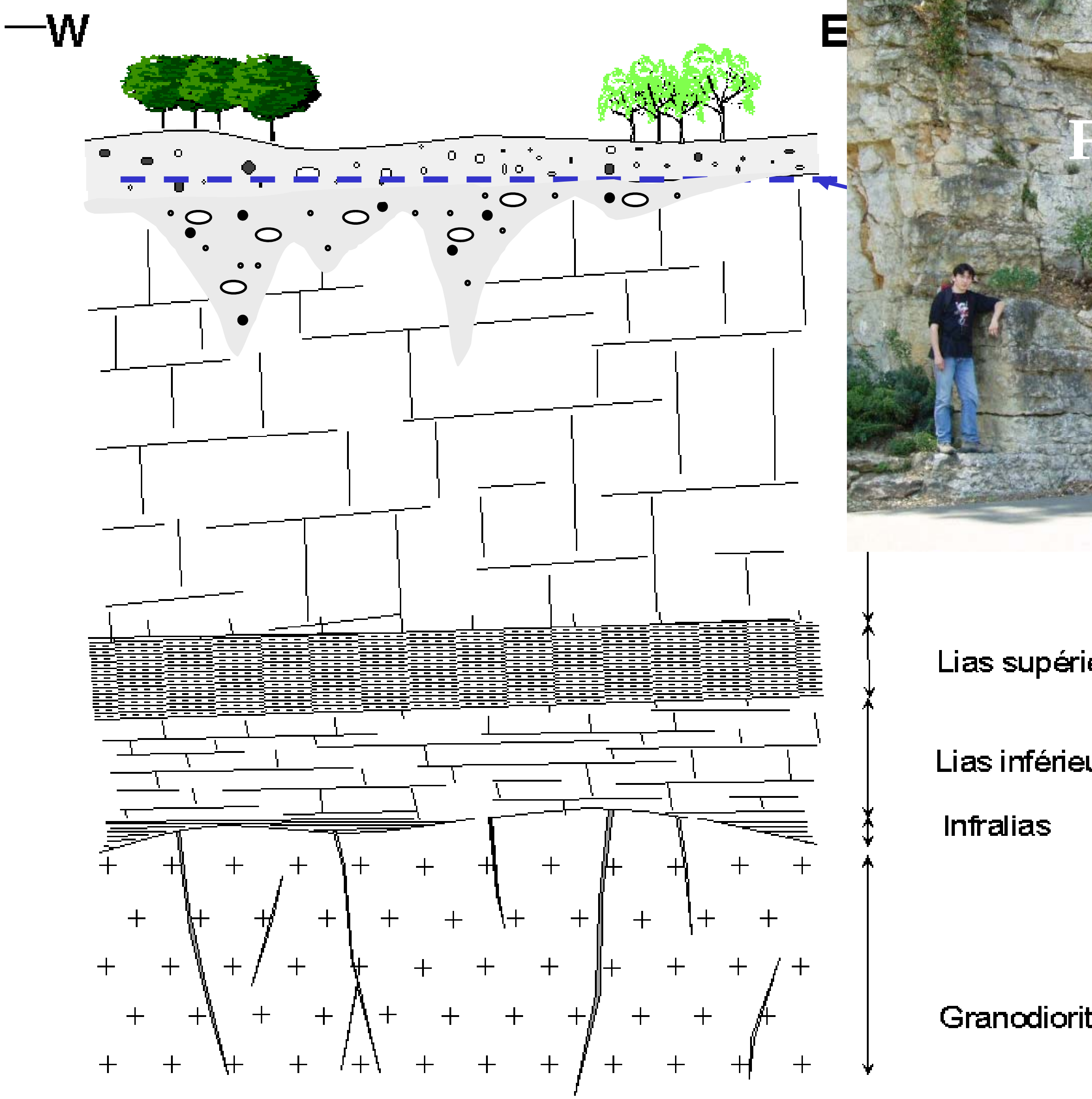
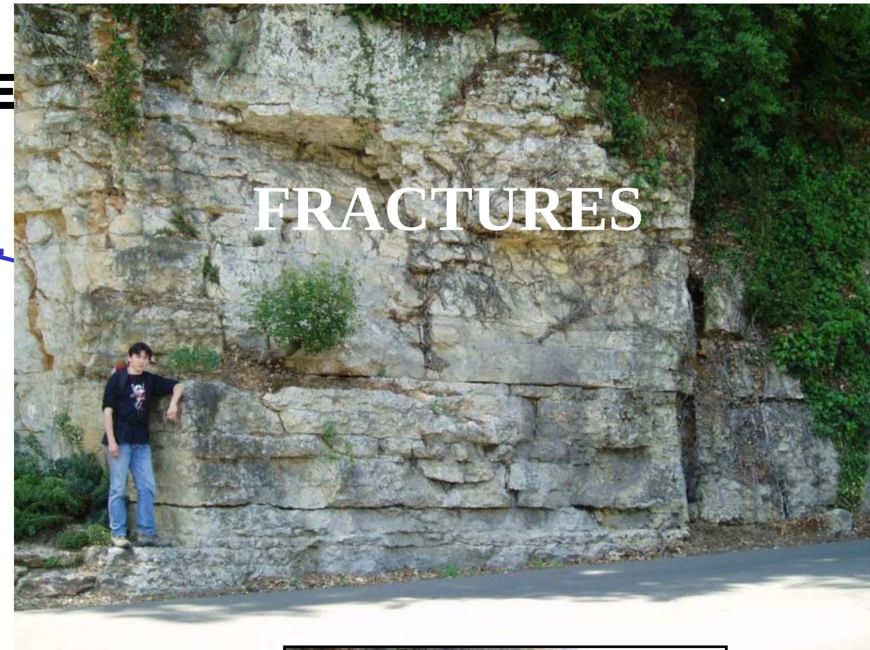
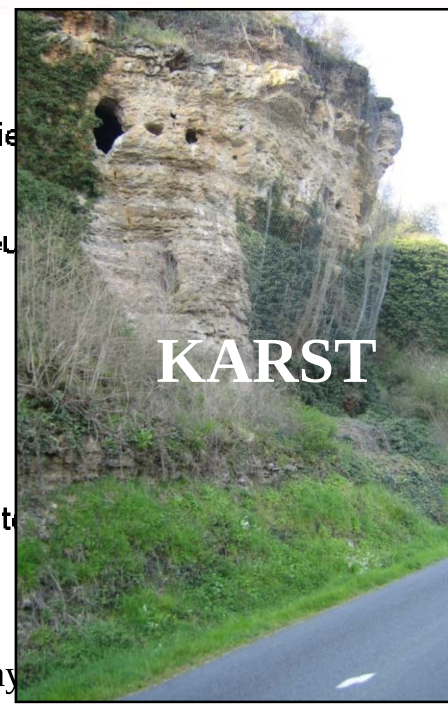

W
E
30 m
34 m
Lias supérie
Lias inférieu
Infralias
Granodiorit
m
m
m


FRACTURES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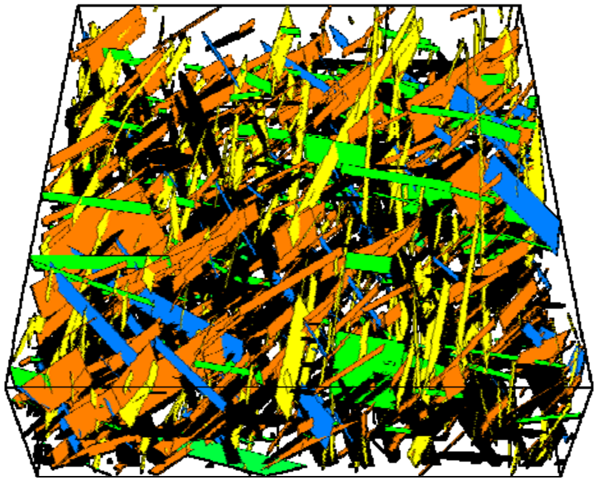
Determination of the appropriate modeling approach?

Project: Modélisation des Aquifères Calcaires Hétérogènes (MACH) J. Bodin

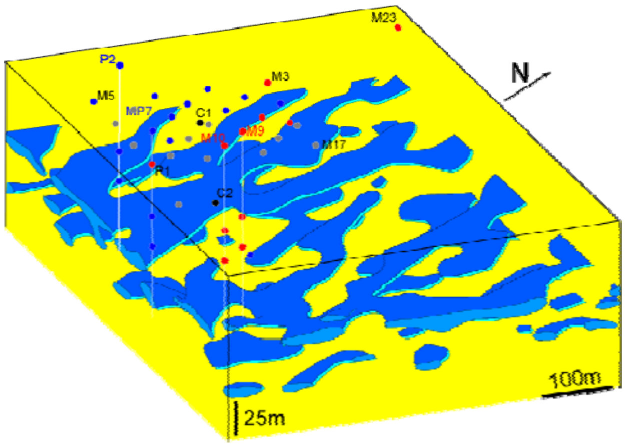


Fracture networks

close to

GEOLOGY

J. Bodin, O. Audoin

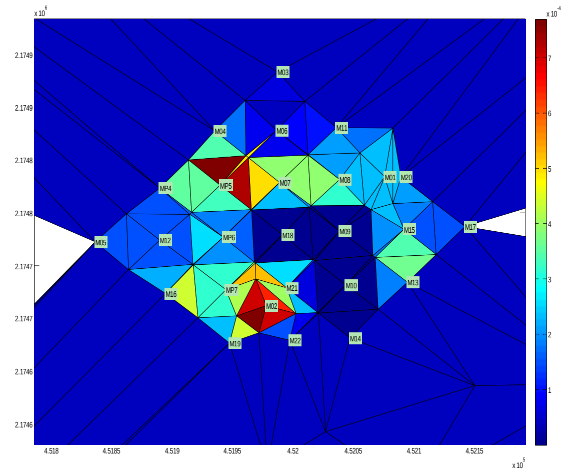


Flow channels

close to

FLOW

H. Pourpak, B. Bourbiaux, IFP



2D permeability field

close to

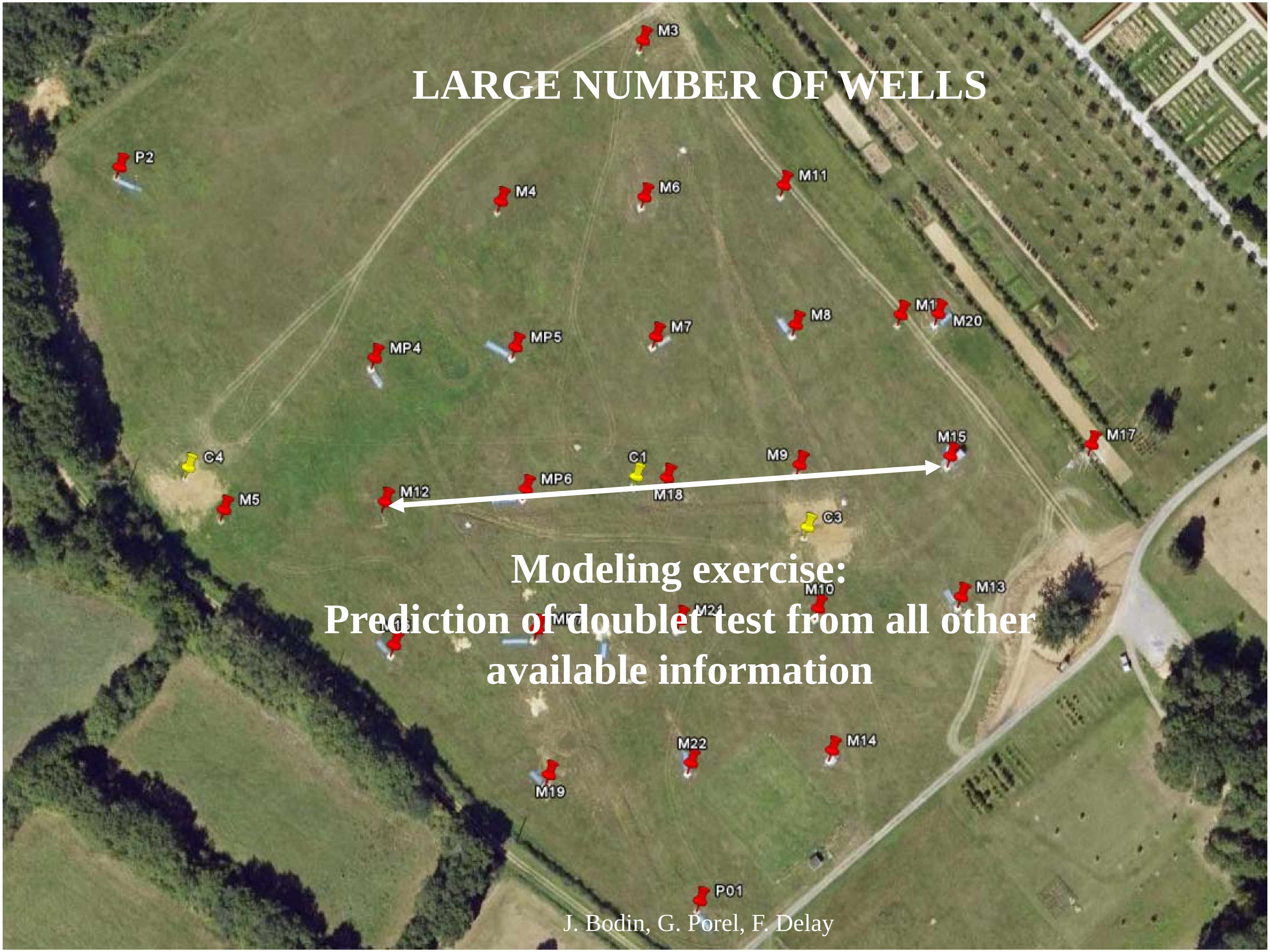
DATA

A. Boisson, J.-R. de Dreuzy, GR

Parameters parsimony

Decreasing modeling complexity

LARGE NUMBER OF WELLS



Modeling exercise:
Prediction of doublet test from all other available information

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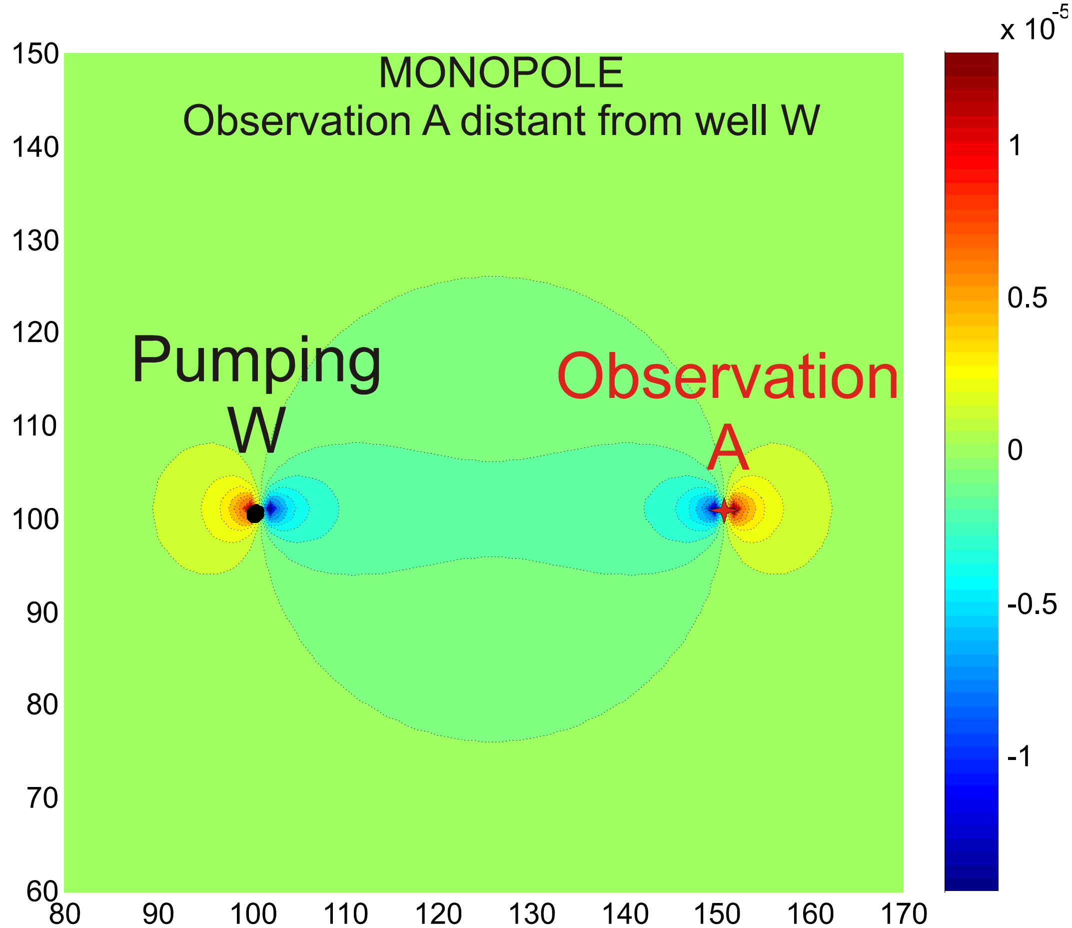
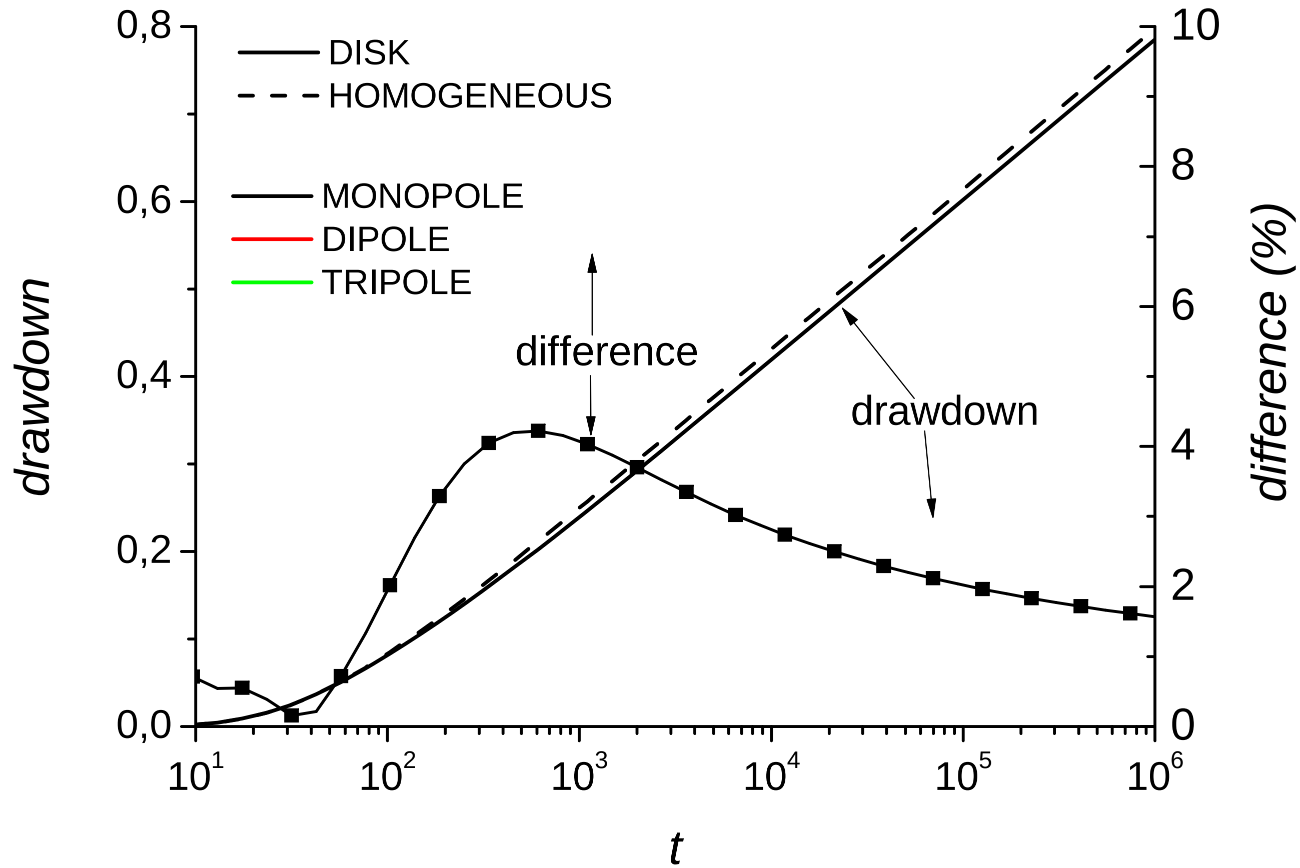
Well tests

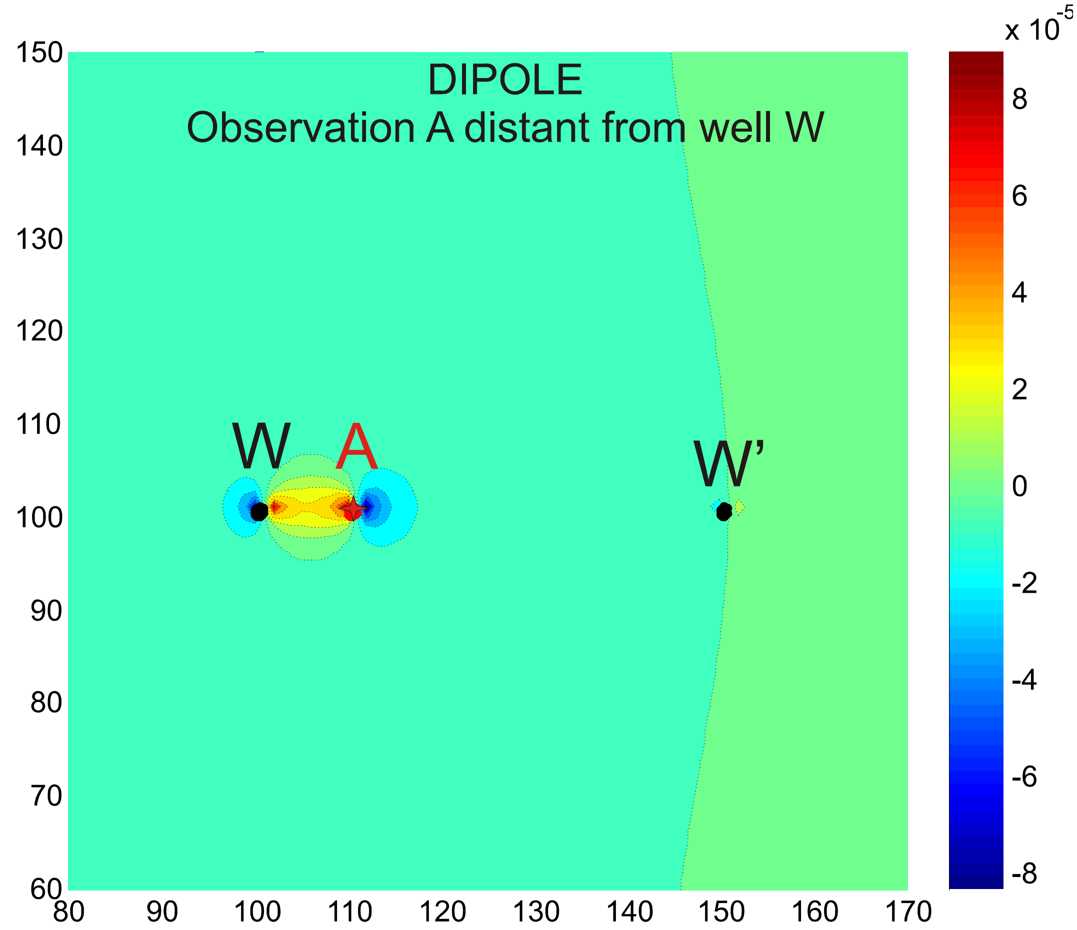


Influence localized between the well and the piezometer

Relative drawdown

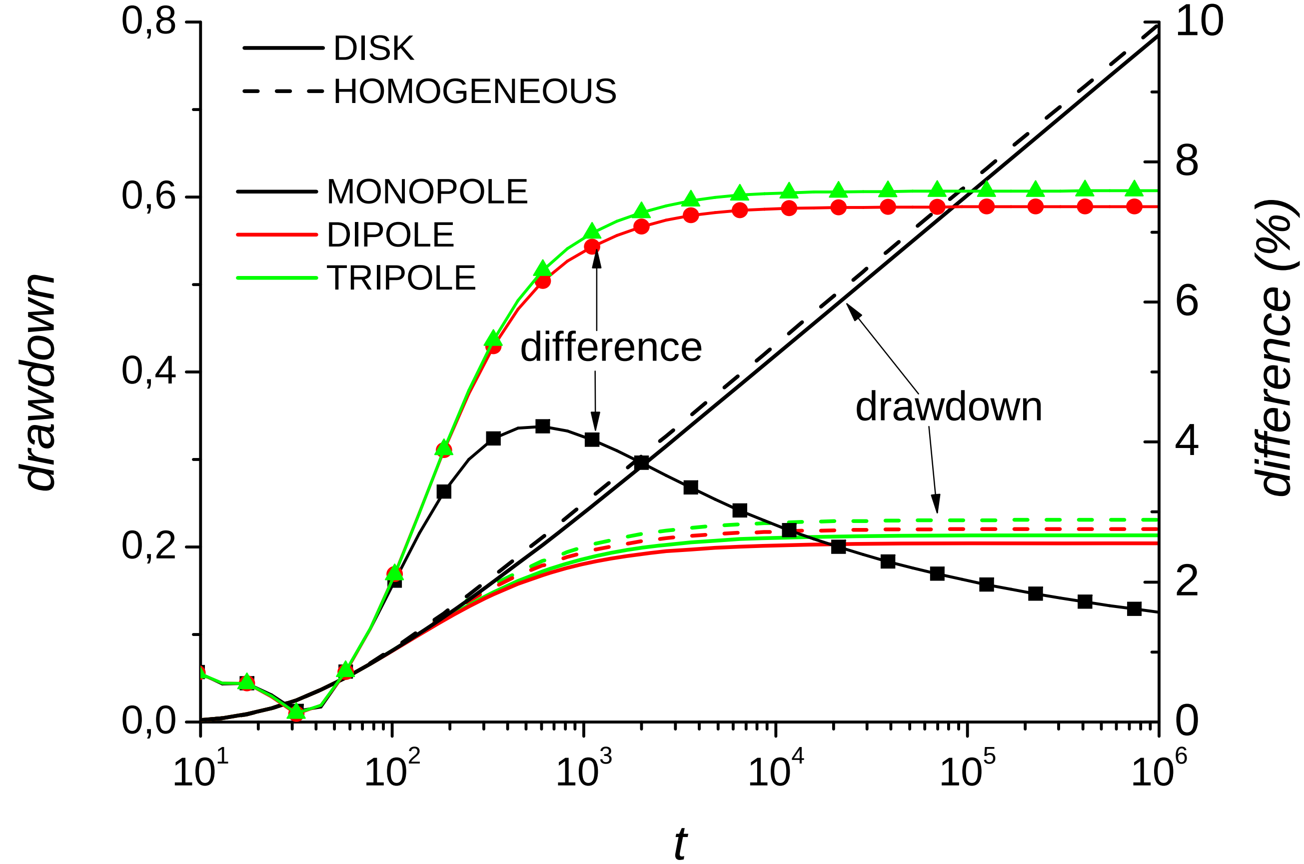


Doublet test



Smaller influence zone
but higher sensitivity

Relative drawdown



Perspectives

- Find structures for the largest range of mean transient exponents *n* and $d_{w..}$ Are they impossible values?
- Cumulated influence of hydraulic and geometrical heterogeneities.
- Beyond models, what are the generic key structure and permeability characteristics for fixed *n* and $d_{w..}$ values?
- Influence of other kind of heterogeneities (3D, fractured media)