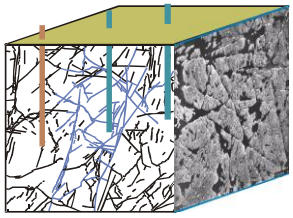
Heat transport in fractured rocks

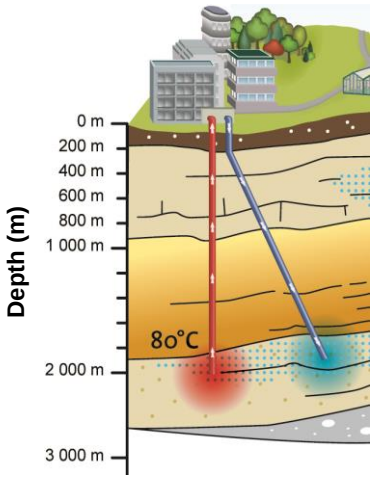


Outline of the lecture :

- Introduction about heat transport in porous media
- Fractured rock hydrogeology
- Use of heat as a groundwater tracer
- Field tracer tests experiments

Olivier Bour, Université Rennes 1, France;

Heat transport in porous media



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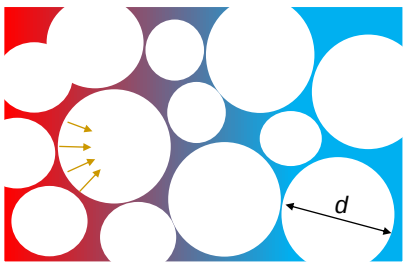
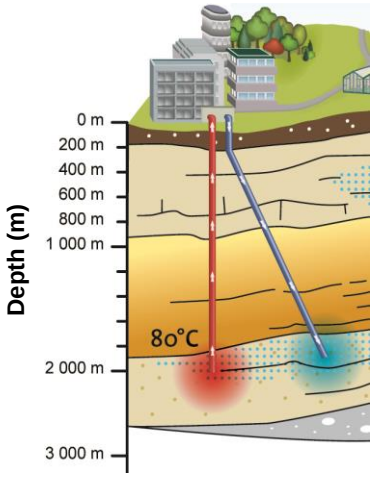
- Conduction in the solid phase
- Heat transport in the fluid phase
- Heat exchanges between the fluid and solid phase



In practice : thermal equilibrium between the temperature in the fluid and in the solid phase is reached almost instantaneously

According to Houpert et al (1967) :
t_{eq} < 1 mn for d ~ 1 mm and < 2h for d~ 10 cm

Heat transport in porous media



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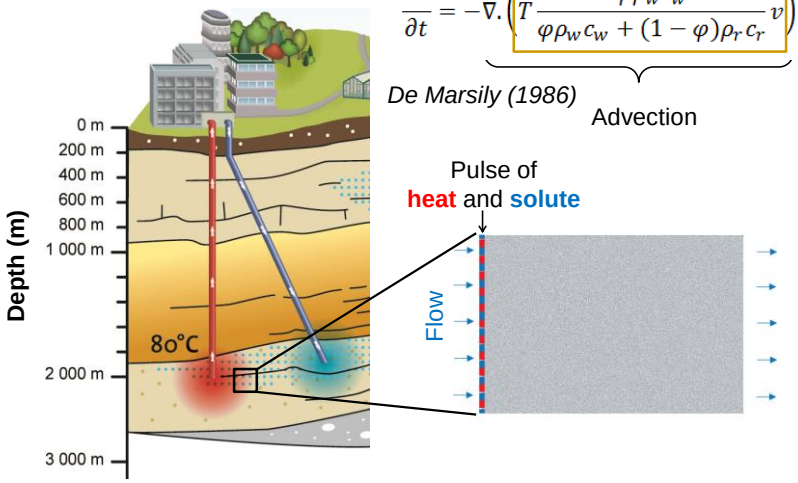
$$\frac{\partial T}{\partial t} = -\nabla.\left(T\frac{\varphi\rho_w c_w}{\varphi\rho_w c_w + (1-\varphi)\rho_r c_r}v\right) + \nabla.[D\nabla T]$$

De Marsily (1986)

Advection

Dispersion + conduction

Heat transport in porous media



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$$\frac{\partial T}{\partial t} = -\nabla.\left(T\frac{\varphi\rho_w c_w}{\varphi\rho_w c_w + (1-\varphi)\rho_r c_r}v\right) + \nabla.[D\nabla T]$$

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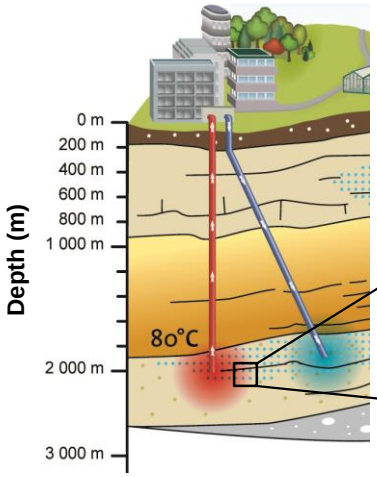
Heat transport in porous media



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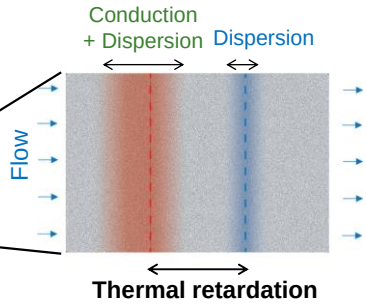
$$\frac{\partial T}{\partial t} = -\nabla.\left(T\frac{\varphi\rho_w c_w}{\varphi\rho_w c_w + (1-\varphi)\rho_r c_r}v\right) + \nabla.[D\nabla T]$$

De Marsily (1986)

Advection

Dispersion + conduction



$$\tau_f = t_T - t_a = \frac{(1-\varphi)\rho_r c_r}{\varphi\rho_w c_w} t_a$$

De Marsily (1986)
Shook (2001)

Free or natural convection (buoyancy-driven flow)

Raleigh number (in porous media) :

$$Ra = \frac{\alpha\rho_w(\rho_w C_w)k}{\mu\lambda} e\Delta T$$

Ra ~ $4\pi^2$ convection/conduction

(Bories and Combarnous, 1975)

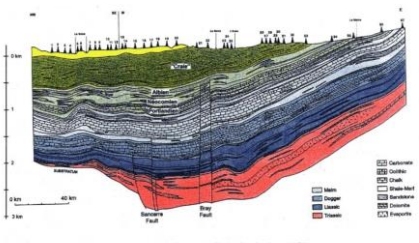
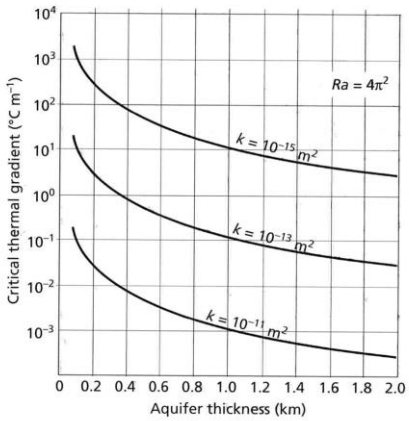
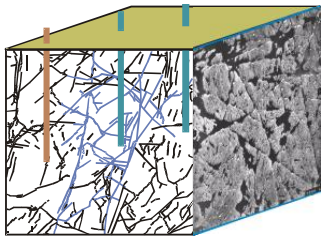


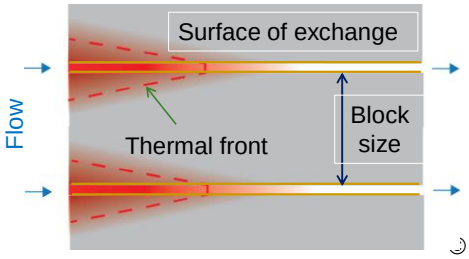
Figure 4 : coupe transversale de Bassin de Paris d'après Goy (1979)



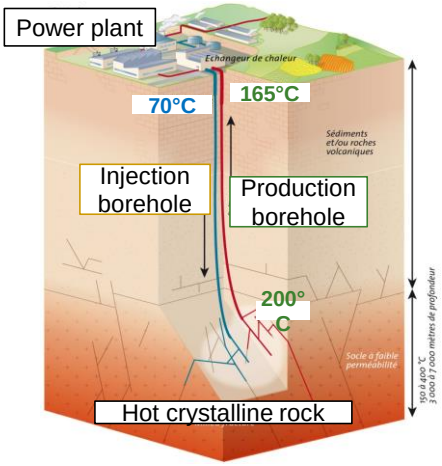
Hiscock and Bense, Hydrogeology: Principles and Practice, 2nd Edition, Wiley, 2014

Heat transport in fractured rocks





Enhanced geothermal system≈ 4000 to 5000 m



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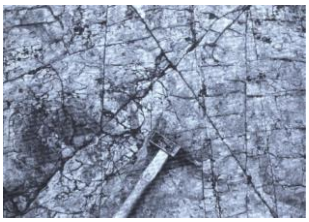
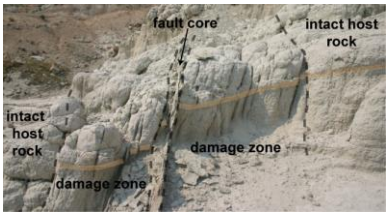
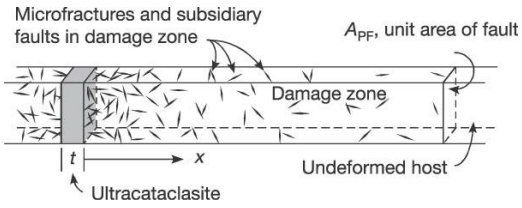
Fractures, faults, joints etc…



Mattauer, 1976

Bense et al., 2013





Chester et al., 2013

Geological model of permeability

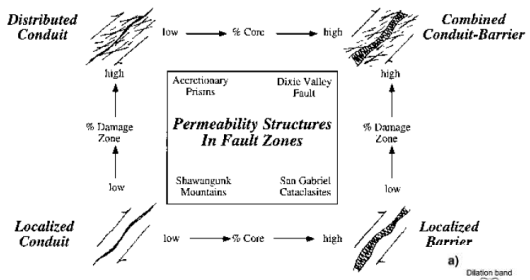
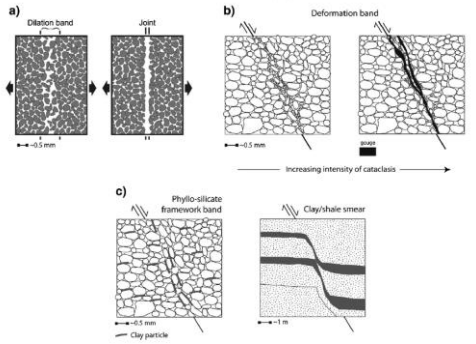


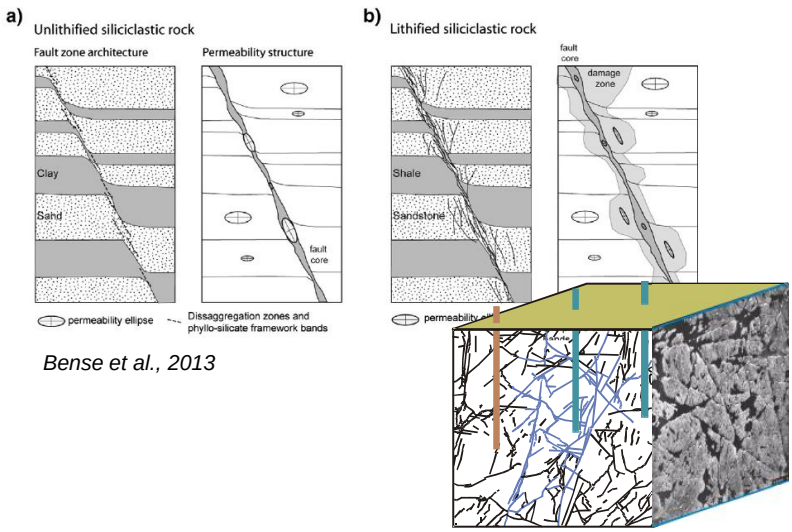
Figure 2. Conceptual scheme for fault-related fluid f

Caine et al., 1996

Bense et al., 2013

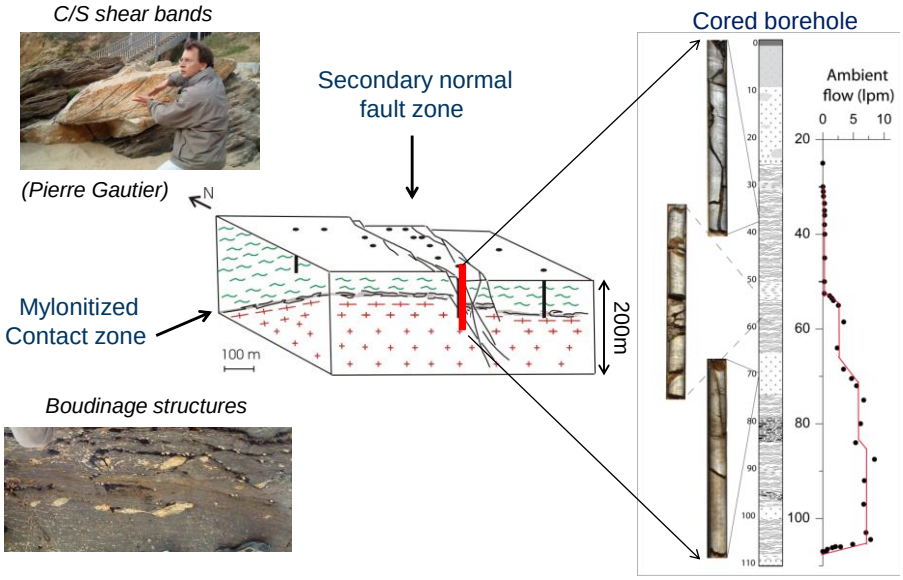


Fault architecture and conceptualized permeability structures

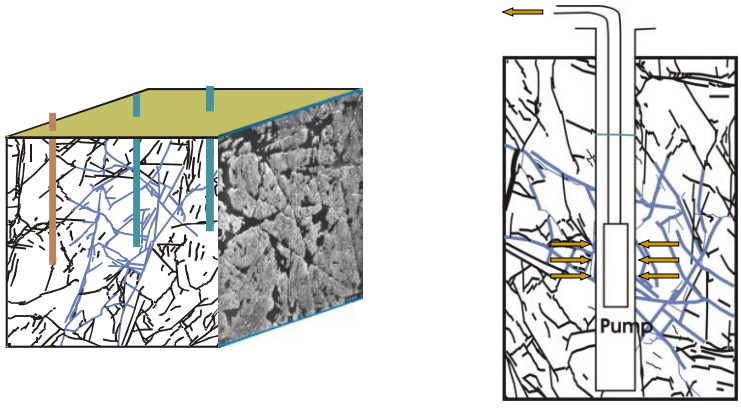


Bense et al., 2013

Complexity of geological structures



Flow characterization in fractured rocks (crystaline rocks)



Diagnostic plots and well test interpretation

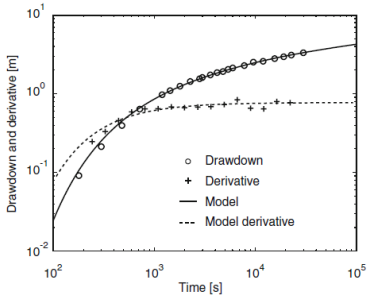


Fig. 3 Example of the diagnostic plot of the Fetter (2001) data superimposed with a fitted Theis model. One can observe that the fit is rather good and that the model reproduces well the main features of the drawdown data and its derivative

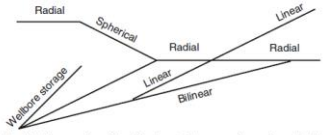


Fig. 8 Flow regime identification tool representing schematically the log-derivative of drawdown as a function of logarithmic time (redrawn from Ehlig-Economides et al. 1994b)

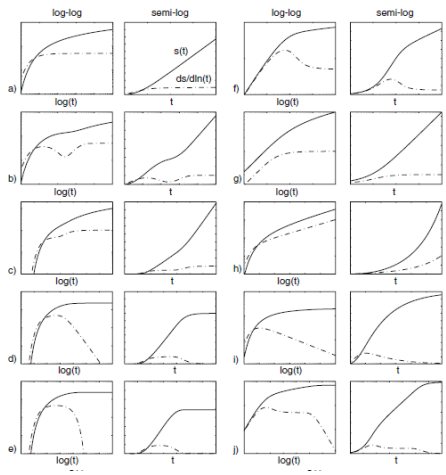


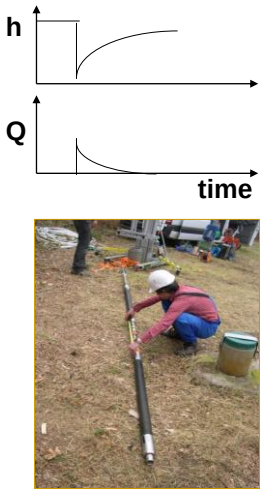
Fig. 2 Most typical diagnostic plots encountered in hydrogeology: **a** Theis model: infinite two-dimensional confined aquifer; **b** double porosity or unconfined aquifer; **c** infinite linear no-flow boundary; **d** infinite linear constant head boundary; **e** leaky aquifer; **f** well-bore storage and skin effect; **g** infinite conductivity vertical fracture; **h** general radial flow—non-integer flow dimension smaller than 2; **i** general radial flow model—non-integer flow dimension larger than 2; **j** combined effect of well bore storage and infinite linear constant head boundary (modified from Renard 2005b)

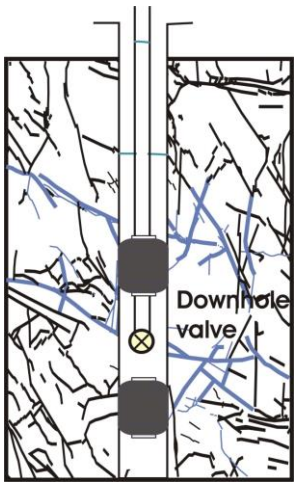
Renard et al., 2008

(See also Bourdet et al, 1983; 1989, Bourdet, 2002)

Flow characterization : packers testing

- **Slug tests :**



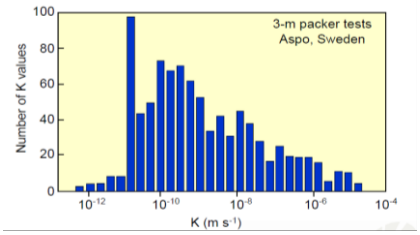


see National Research Council (1996)

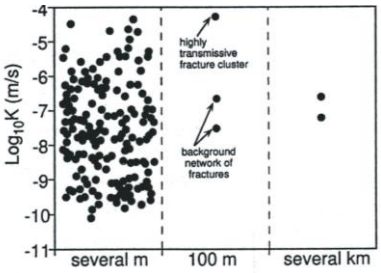
Problems related to fracture networks

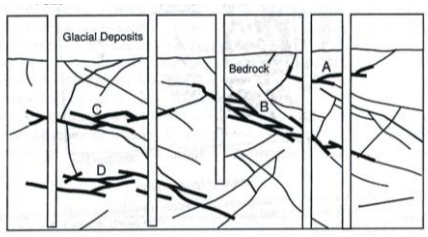
Flow localisation and scale effects

- High variability of permeability :



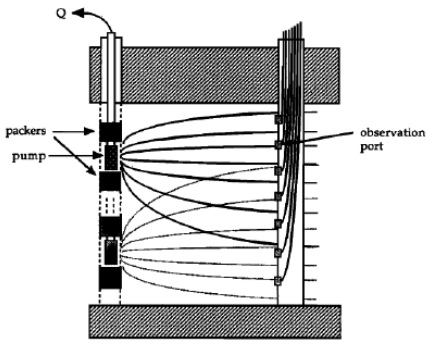
Tsang et al., 1996



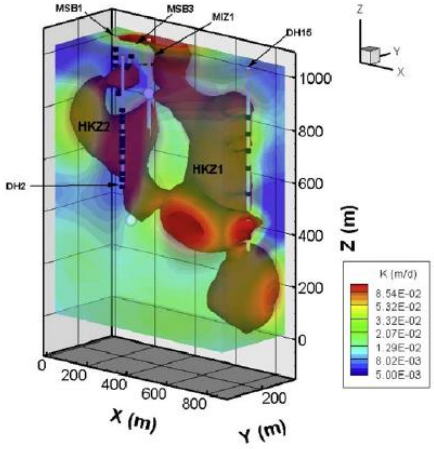


(*Mirror Lake, Hsieh et al., 1999*)

Flow properties : hydraulic tomography



Principle of hydraulic tomography experiment [Butler et al., 1999].

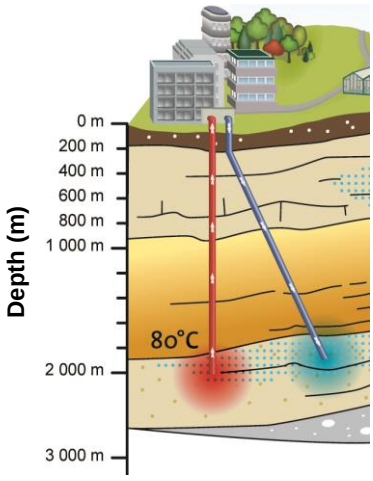


Hydraulic conductivity K tomogram (m/day) obtained from the inversion of cross-hole tests from Illman et al. [2009].

Fractured rock hydrogeology (in crystalline rocks) :

- It is relatively simple to get some permeability estimates even permeability distributions at different scales
- It is also simple to have some ideas about hydraulic connectivity between boreholes as long as permeability allows cross-boreholes testing
- It is much more challenging to image flow paths or to estimate the structure of the permeable fracture networks (only conceptual models)
- Needs of other tools : tracer tests, hydrogeophysical methods …

Heat transport in porous media



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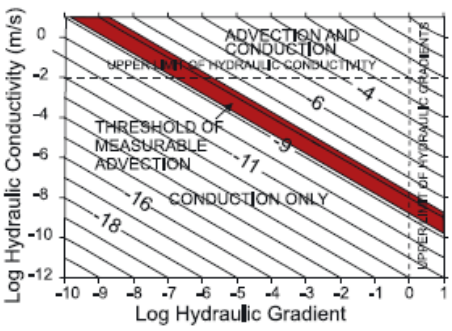
$$\frac{\partial T}{\partial t} = -\nabla.\left(T\frac{\varphi\rho_w c_w}{\varphi\rho_w c_w + (1-\varphi)\rho_r c_r}v\right) + \nabla.[D\nabla T]$$

De Marsily (1986)

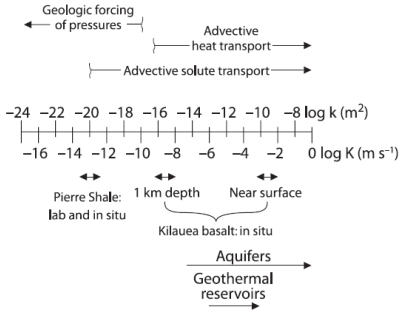
Advection

Dispersion + conduction

Advection versus Conduction

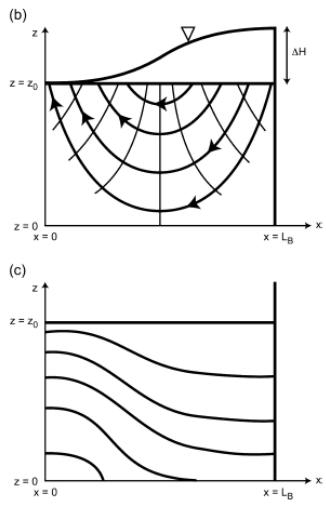


(Ferguson et al., 2006)

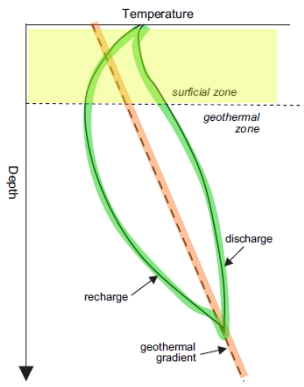


(Rojstaczer et al., 2008)

On the use of heat as a groundwater tracer



Domenico and Palciauskas, 1973



M. Anderson (2005), Heat as a groundwater tracer, Ground water, modified from Taniguchi et al, 1999

First 10 m:
- Seasonal temperature variations

Geothermal gradient:
- The geothermal heat flux;
- Conductive heat transfer properties

Perturbed by GW flow:
- Regional flow velocity

Heat Flow and subsurface temperature as evidence for basin-scale ground-water flow (Deming et al., 1992)

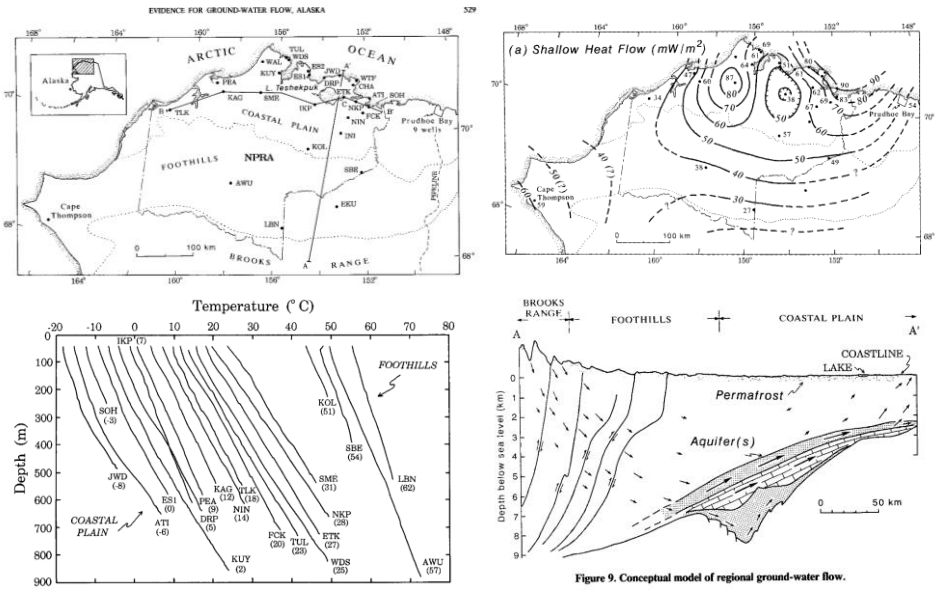
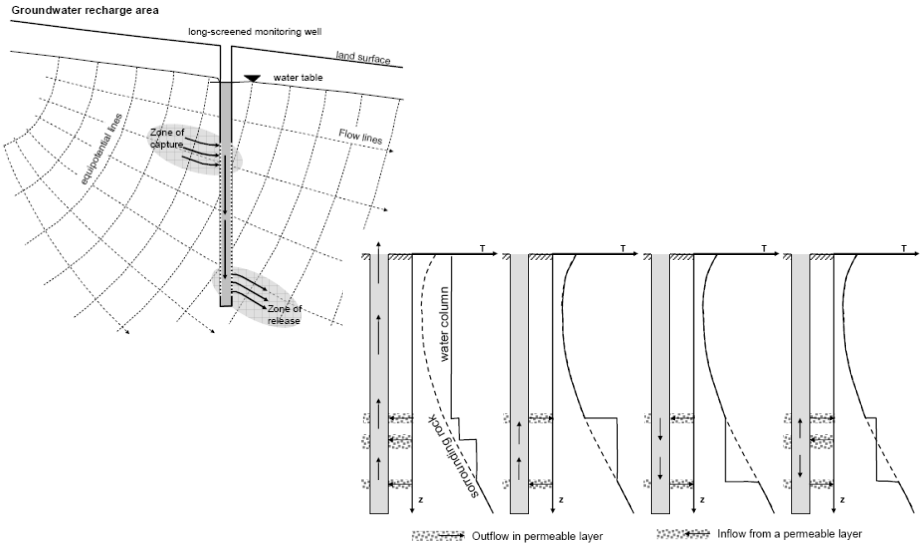


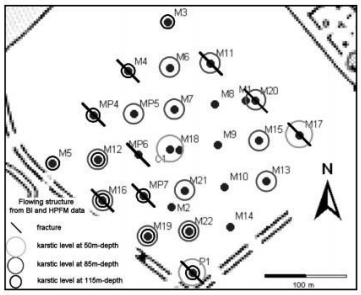
Figure 9. Conceptual model of regional ground-water flow.

Borehole flows in open or screened boreholes

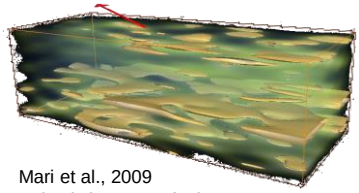


Frank Börner, Susann Berthold (2009), Groundwater Geophysics.

On the use of heat in a karst system
(coll. J. Bodin, G. Porel Univ Poitiers)

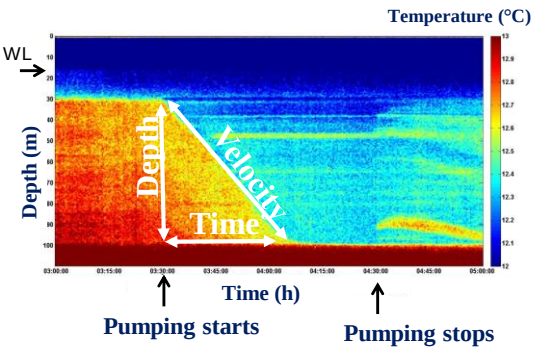


Chatelier et al., 2011



Mari et al., 2009
Seismic imagery of a karst system

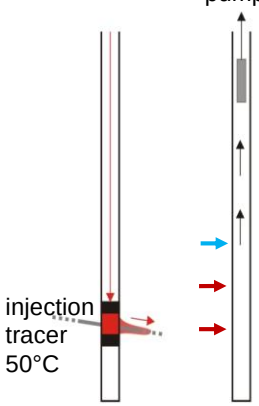
Temperature monitoring with FO DTS



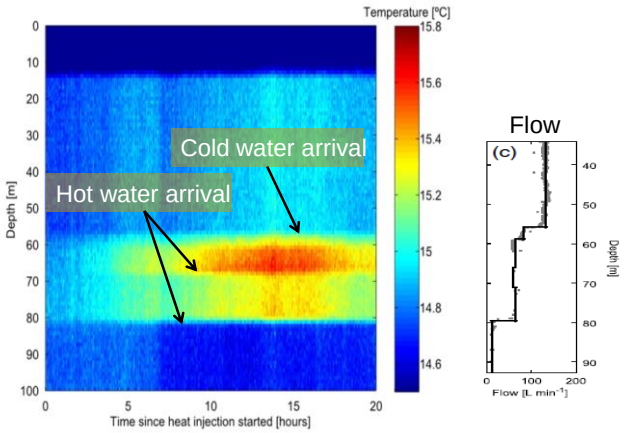
Fiber optic monitoring of active thermal tracer tests

injection of hot water (50 °C) at 80 m depth

pumping

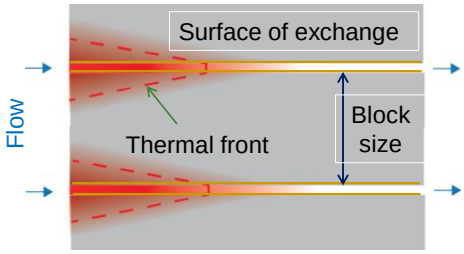


Temporal evolution of the temperature profiles in the pumping well with fiber optic

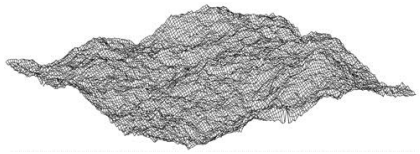


Read et al. (GRL, 2013) Characterizing groundwater flow and heat transport in fractured rock using Fibre-Optic Distributed Temperature Sensing

Heat transport in fractured media

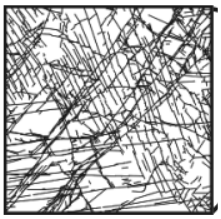


Fracture scale



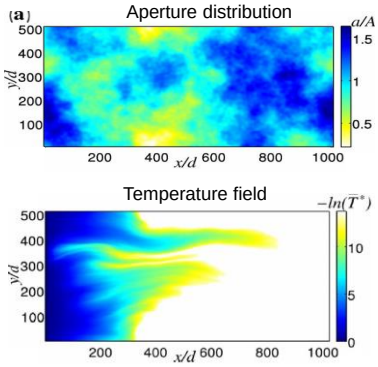
Oron, A. P., and B. Berkowitz, 1998
(see also Meheust and Schmittbuhl, 2000 and others)

Network scale

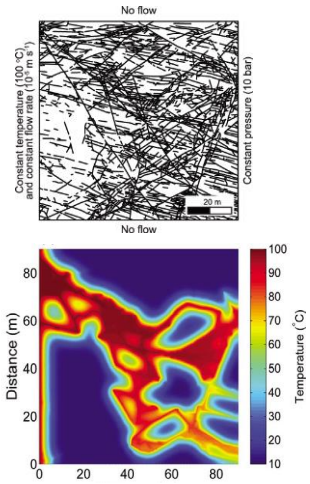


Odling, 1997

Effect of flow channeling on heat transport

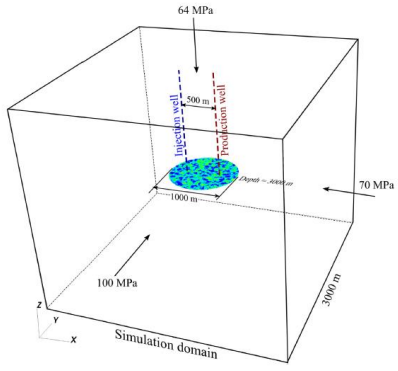


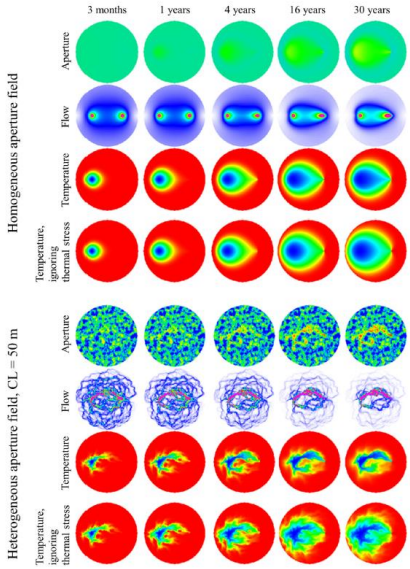
Neuville et al. (2010)



Geiger and Emmanuel (2010)

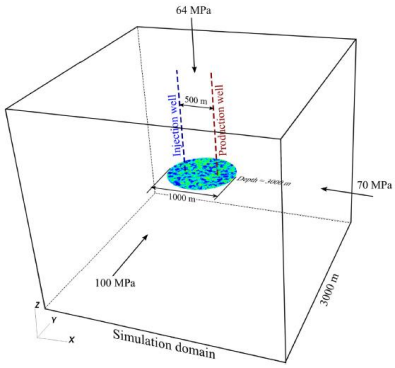
Effect of flow channeling on heat transport

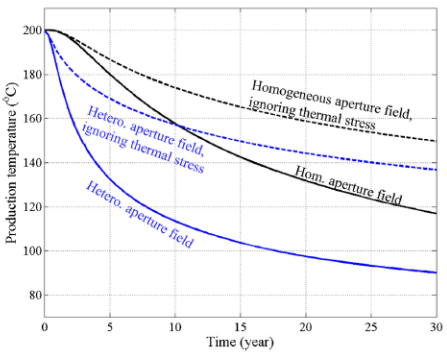




Guo et al. (2016)

Effect of flow channeling on heat transport

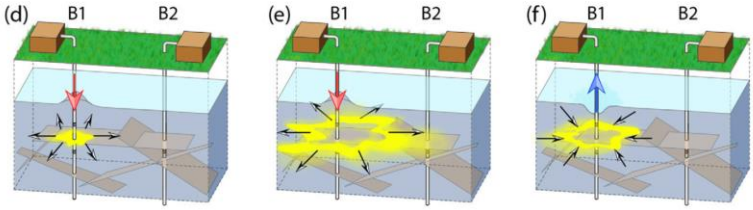




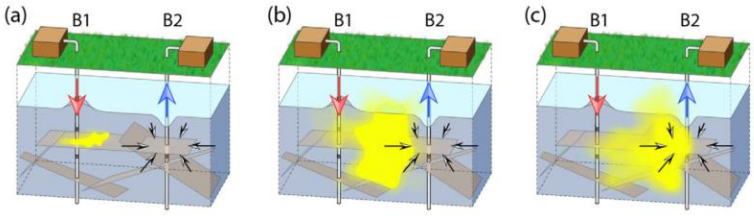
Guo et al. (2016)

Thermal tracer tests experiments (John's approach)

Push-pull thermal tracer tests



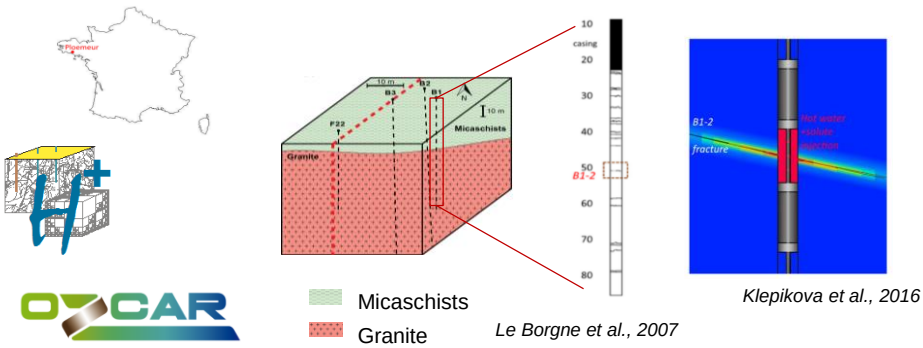
Cross-boreholes thermal tracer tests



Kang et al. (2015)

Ploemeur field site

360° view of a tracer test experimental set up on the Ploemeur site (H+)

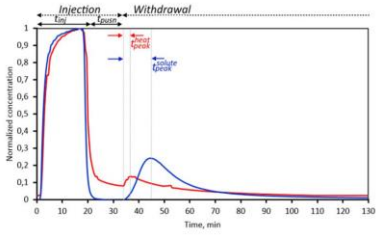


Le Borgne et al., 2007

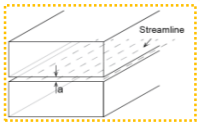
Klepikova et al., 2016

Push-pull tracer tests experiments (Klepikova et al., WRR 2016)

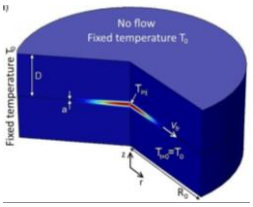
- Several thermal push-pulls with different injection durations

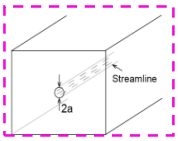


- Theoretical development of the late-time scaling of thermal recovery for different geometries

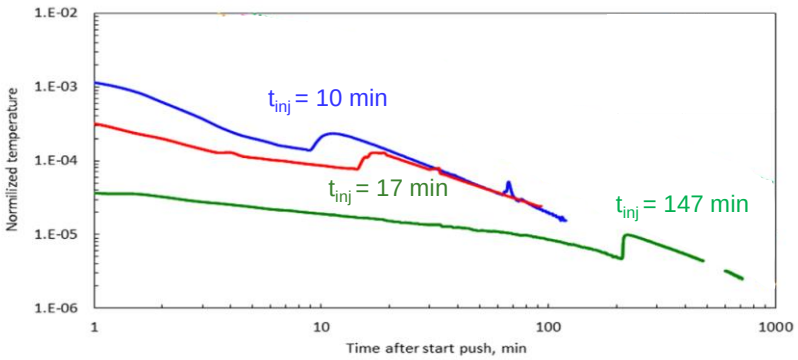


- Numerical modeling



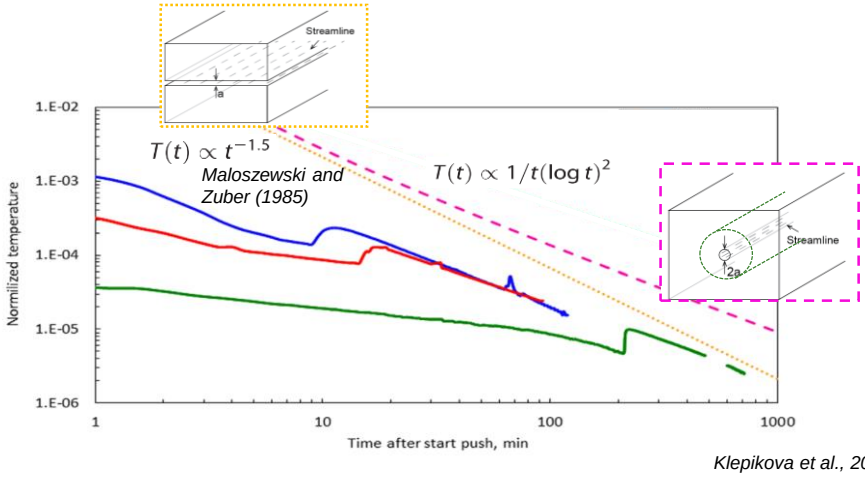


Thermal breakthroughs



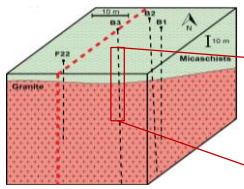
Klepikova et al., 2016

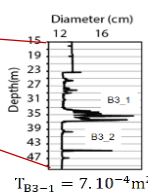
Thermal breakthroughs : late-time scaling



Klepikova et al., 2016

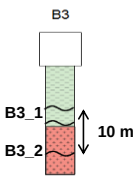
Single well thermal tracer tests





$T_{B3-1} = 7.10^{-4} m^2/s$

$T_{B3-2} = 2,4.10^{-3} m^2/s$



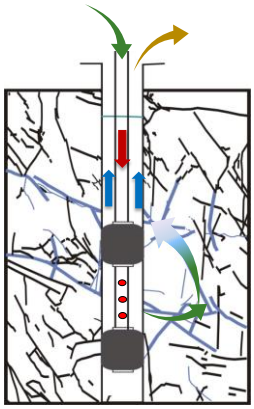
Micaschists

Granite

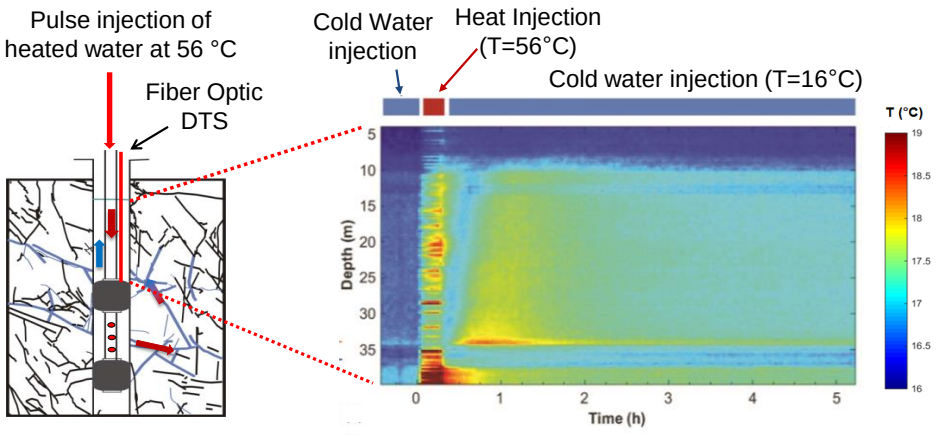
Single well thermal tracer tests

- Develop a new experimental setup for single well thermal tracer tests
- Analytical developments of the expression of thermal retardation and decay for simple fracture geometries
- Achieve tracer tests experiments to compare solute vs thermal tracer tests.

Heat + **solute**



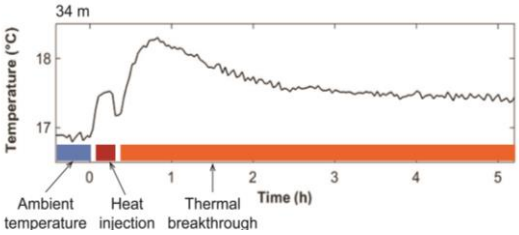
Example of thermal tracer test (FO-DTS Temperature monitoring)

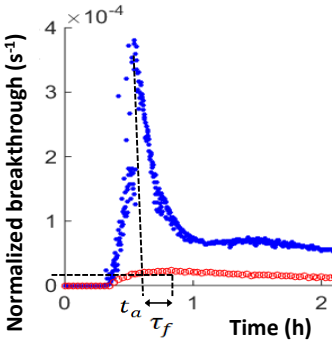


De La Bernardie et al., submitted

Thermal retardation and peak amplitude

Temperature signal



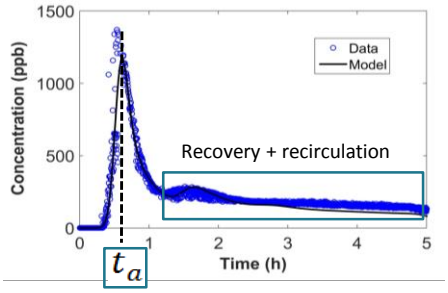


14 min

De La Bernardie et al., submitted

Modeling solute and heat transport in a fracture plane

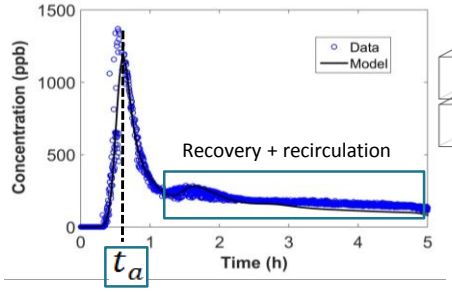
Solute transport modeling

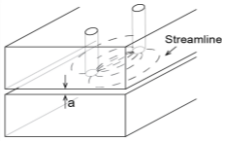


Fracture aperture, a = 3.3 mm

Modeling solute and heat transport in a fracture plane

Solute transport modeling



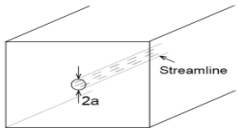


Fracture aperture, a = 3.3 mm

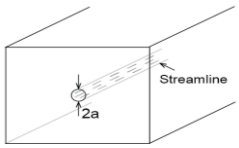
Theoretical thermal retardation

18 hours

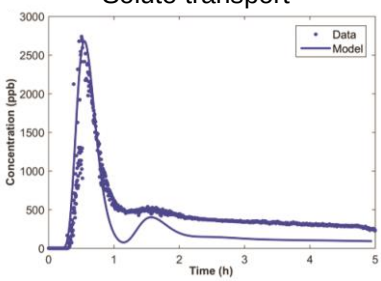
FLOW CHANNELING ?



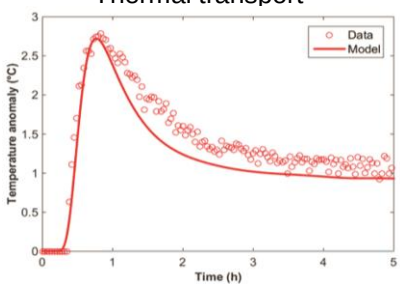
Modeling solute and heat transport in a channel



Solute transport



Thermal transport



De La Bernardie et al., submitted

Concluding remarks

- Flow channeling may really be an issue when considering heat transport in fractured rock. It controls not only the breakthrough times but also the physics of heat transport and heat exchanges.
- Heterogeneities really matters when considering heat transport in fractured rock. Heat may be an excellent tracer for characterizing heterogeneities, not only in fractured rocks but also in sedimentary rocks.
- In the field, experiments at different scales are really useful to constrain the underlying physical processes (like in the lab).
- To do fieldwork, you need a combination of John's enthusiasm and Niklas well defined objectives. Think about the fisherman's who always need to have a strategy and to adapt his strategy

Thank you for your attention

Many thanks to

Maria Klepikova

Jérôme de la Bernardie

And many others, including Tanguy Le Borgne, Nicolas Guihéneuf, Marco Dentz, Marie-Françoise Gérard, Rebecca Hochreutener, Hugo Le Lay, Nicolas Lavenant, Eliot Chatton, Thierry Labasque …