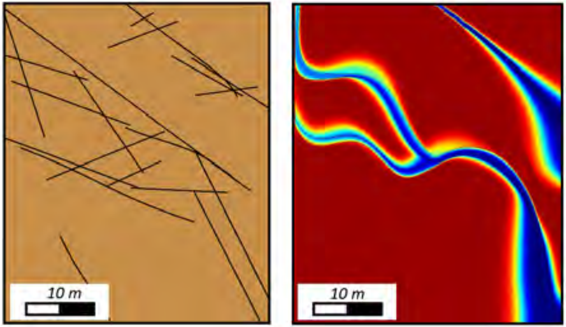
Heat transport in the subsurface:

In situ experiments and modelling

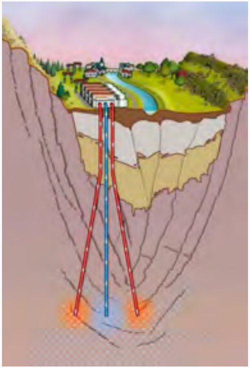
Maria Klepikova

September 26, 2019

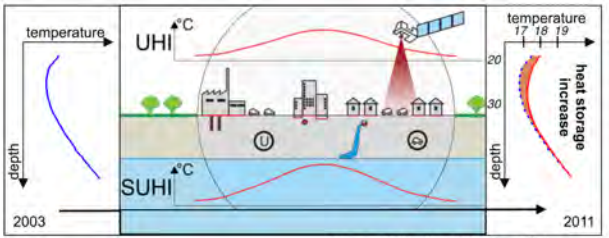


Understanding heat transport processes in the subsurface is central to many environmental, geological and industrial processes

- Energy production in geothermal reservoirs
- Heat storage in the ground
- Near-field thermal effects in radioactive waste disposal

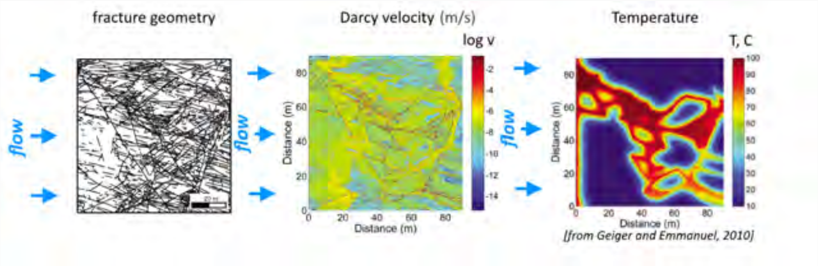


- Subsurface urban heat islands (SUHI)



[Benz et al., Sc. of the Total Env., 2018]

Flow and transport processes in fractured media

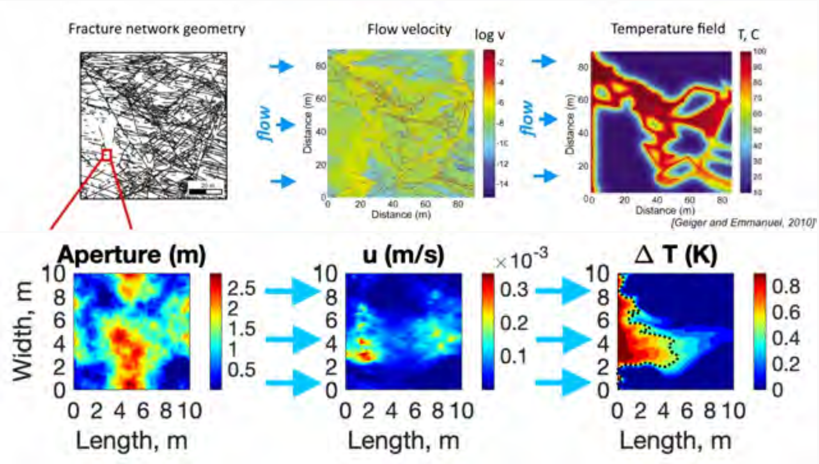


Fracture network-scale heterogeneity influences flow and transport

Hydraulic properties?

Fracture connectivity?

Flow and transport processes in fractured media



Fracture-scale heterogeneity influences flow and transport

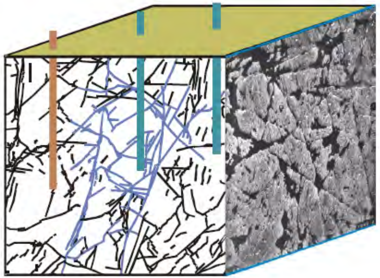
Fracture geometry (fracture apertures field, fracture length)?

Fracture-matrix exchange?

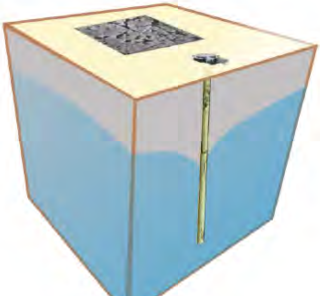
Scientific challenges

Dealing with heterogeneity:

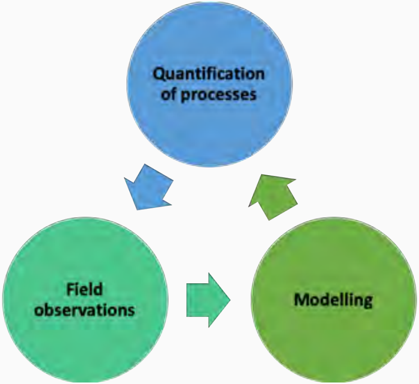
- In the context of highly localized flows



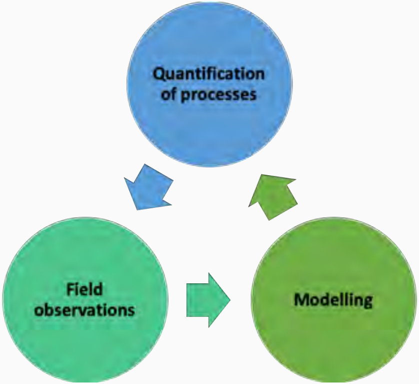
- In the context of undersampled structures



Coupling data, modelling and predictions



Coupling data, modelling and predictions



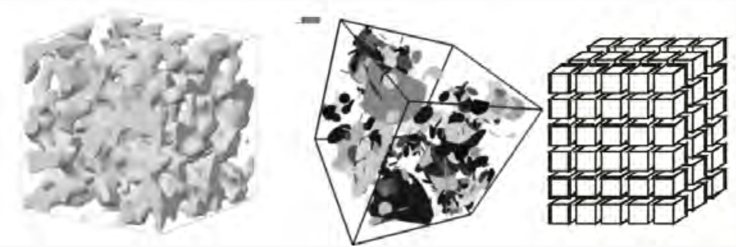
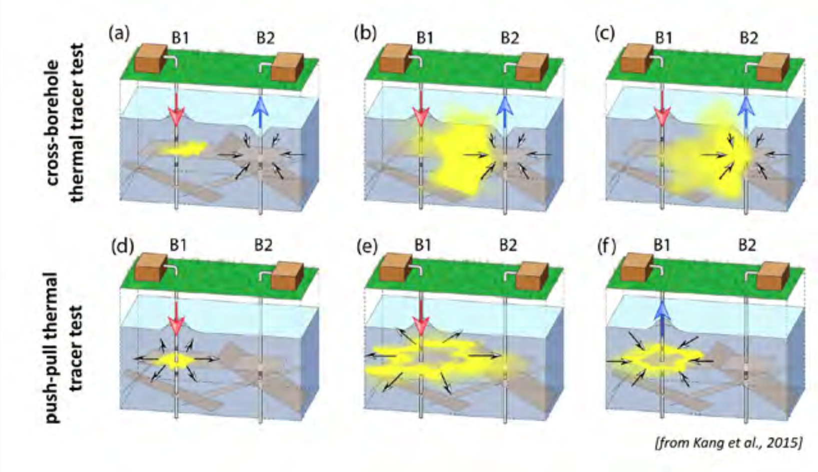


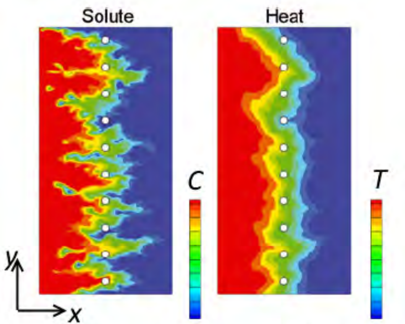
Table of content

Heat tracer tests to understand aquifers as geothermal resources

Tracer test experimental methodology



Why using active thermal tests?



[from Irvine et al., 2015]

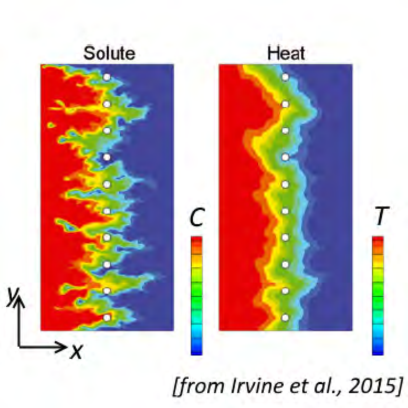
Heat is an ideal tracer:

- Easy to measure
- No toxicity added to the environment
- Distributed Temperature Sensing allows measurements continuous in time (<1min) and in space (∼10 cm)

Different physics:

Heat diffusivity is much larger than solute diffusivity
($\sim 10^2\ cm^2/s$ vs $\sim 10^6\ cm^2/s$).
This allows heat to be transported through lower *K* zones by conduction, whereas solutes flow around low *K* zones

Why using active thermal tests?



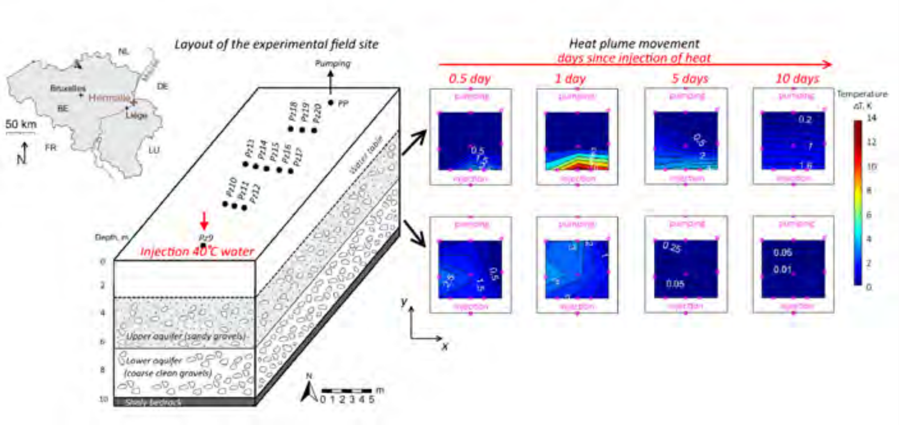
Heat is an ideal tracer:

- Easy to measure
- No toxicity added to the environment
- Distributed Temperature Sensing allows measurements continuous in time (<1min) and in space ($\sim$10 cm)

Research questions:

- Can we characterize heterogeneities of alluvial aquifers by performing active heat tracer tests?
- Can we provide input data for an inverse problem?

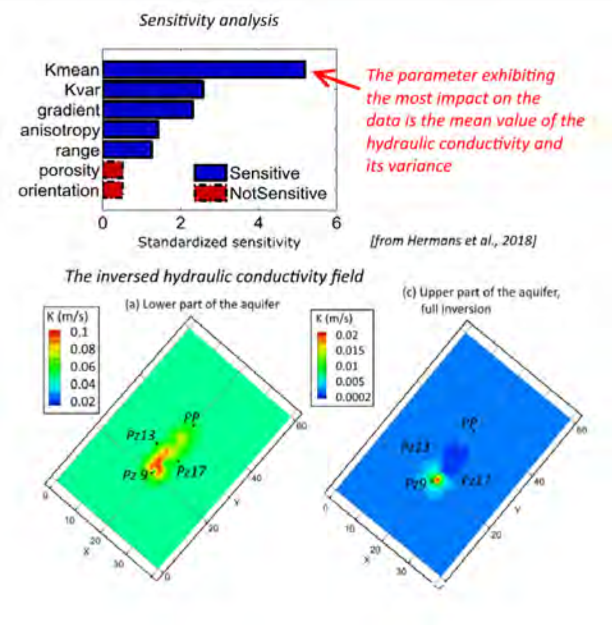
Heat tracer tests in alluvial aquifers, experiment



☐ The space-filling arrangement of monitoring wells allowed detailed assessments of the 3D spreading of the heat plume.

☐ BTCs showed complex behaviour of the thermal plume spreading.

Heat tracer tests in alluvial aquifers, modelling

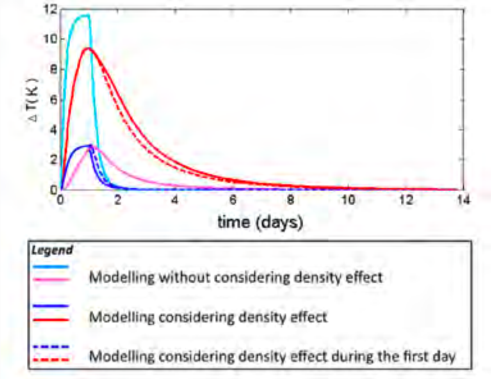


☐ Thermal response of the aquifer is strongly controlled by the hydraulic conductivity field.

☐ By inversion of temperature breakthrough curves measured in observation boreholes, the main preferential flow paths were characterized

Heat tracer tests in alluvial aquifers, modelling

Temperature profiles
in the middle of the first panel:
Upper layer and Down layer



☐ The density effect has a strong impact on temperature variations.

☐ Vertical distribution of heat due to injection of hot water influences then temperature distribution in all boreholes.

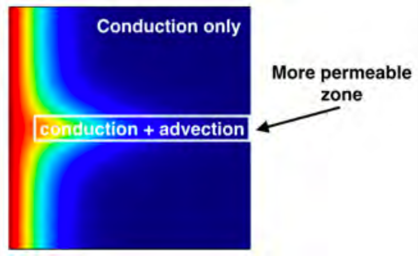
☐ Density effect plays a significant role only during the first day.

Heat tracer tests in alluvial aquifers, conclusions (1/4)

- Our results indicate that the actual efficiency of geothermal projects is strongly affected by the heterogeneity of the K-field. *[Klepikova et al., JoH, 2016].*
- Due to high injection temperatures during the field experiment a temperature-induced fluid density effect on heat transport may occur, and this effect should be considered by a model.
- *Hermans et al, WRR, 2018* showed that heat tracer tests could be a useful approach to estimate the heat storage capacity of an alluvial aquifer and, thus to design a geothermal systems.

Klepikova, M. V., S. Wildemeersch, T. Hermans, P. Jamin, Ph. Orban, F. Nguyen, S. Brouyère, A. Dassargues (2016), Heat tracer test in an alluvial aquifer: Field experiment and inverse modelling, *Journal of Hydrology*.
Hermans, T., Nguyen, F., Klepikova, M. V., Dassargues, A., and Caers, J. (2018), Uncertainty quantification of medium-term heat storage from short-term geophysical experiments using bayesian evidential learning, *Water Resources Research*.

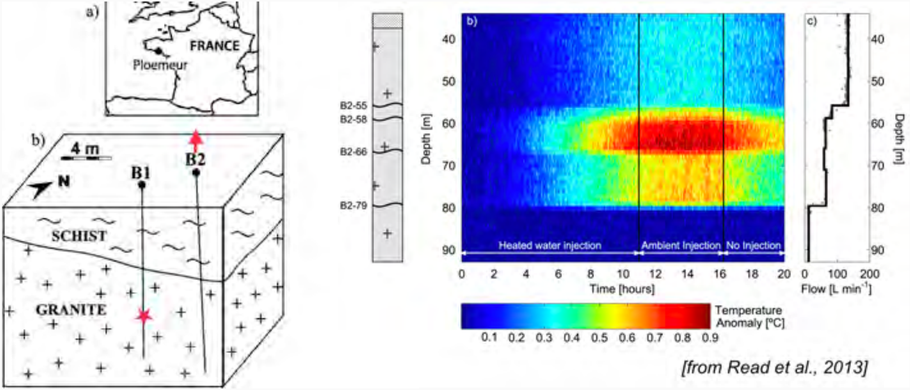
Heat tracer tests in fractured crystalline aquifers



Research questions:

- Which type of information can be obtained from heat tracer tests in a fractured aquifer?
- What test configuration should be chosen to extract relevant information?

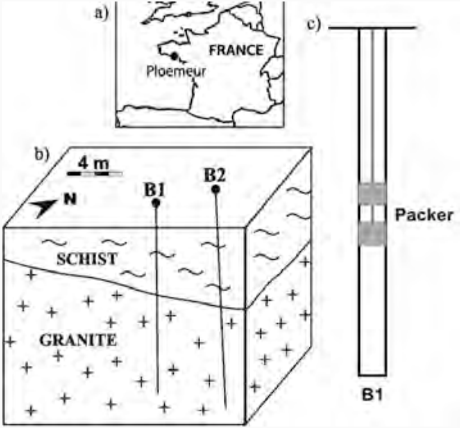
Cross-borehole heat tracer test, Ploemeur, France

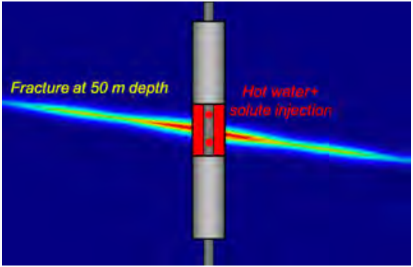


Compared to salt tracer test:

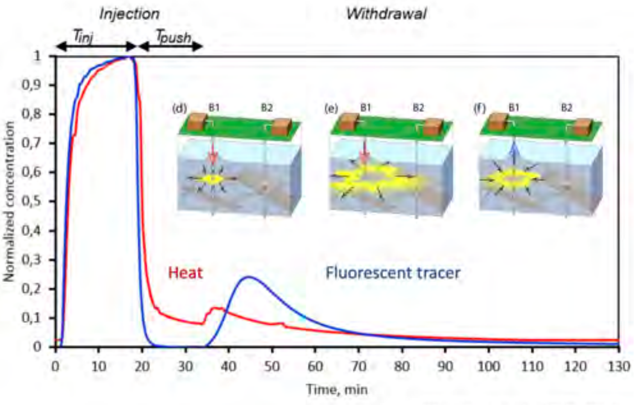
☐ The thermal BTC is strongly attenuated.
☐ Different BTC locations is different.

Push-pull heat tracer test, Ploemeur





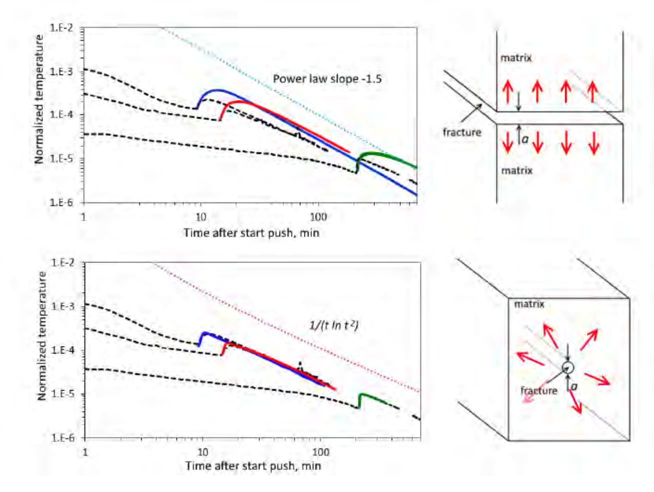
Push-pull heat tracer test, Ploemeur



[Klepikova et al., WRR, 2016]

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

Scale effects in thermal recovery



- The channel model fits well the data
- This questions the relevance of the classical parallel plate model *[Klepikova et al., WRR, 2016]*

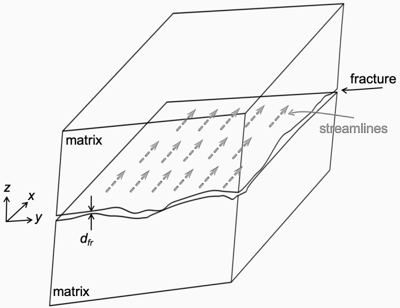
Heat tracer tests in fractured aquifers, conclusions (2/4)

- Flow channeling has a crucial impact on heat transport. It controls not only the breakthrough times but also the physics of heat transport and heat exchanges.
- Thermal push-pull tracer tests are shown to provide valuable insights on fracture geometry and fracture aperture.
- In the field, experiments at different scales are really useful to constrain the underlying physical processes.
- Heat tracer test is an excellent approach for characterizing heterogeneities in fractured and in sedimentary rocks and for the design of efficient geothermal systems.

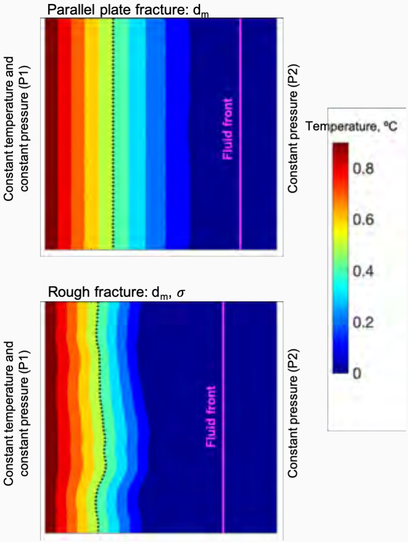
Klepikova, M. V., Le Borgne, T., Bour, O., Dentz, M., Hochreutener, R., and Lavenant, N. (2016), Heat as a tracer for understanding transport processes in fractured media: Theory and field assessment from multiscale thermal push?pull tracer tests, Water Resour. Res.

Influence of a single fracture heterogeneity on heat transport

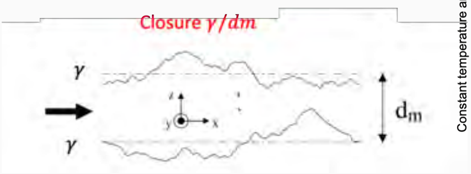
Heat transport in a rough fracture



What are geometrical parameters of fractures that control the fracture-matrix heat exchange and advection along the fracture?



Heat transport in a rough fracture



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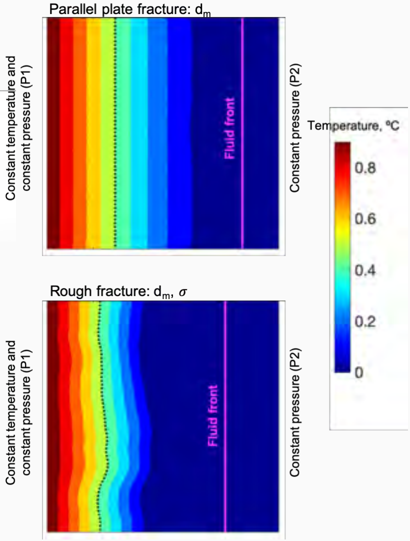
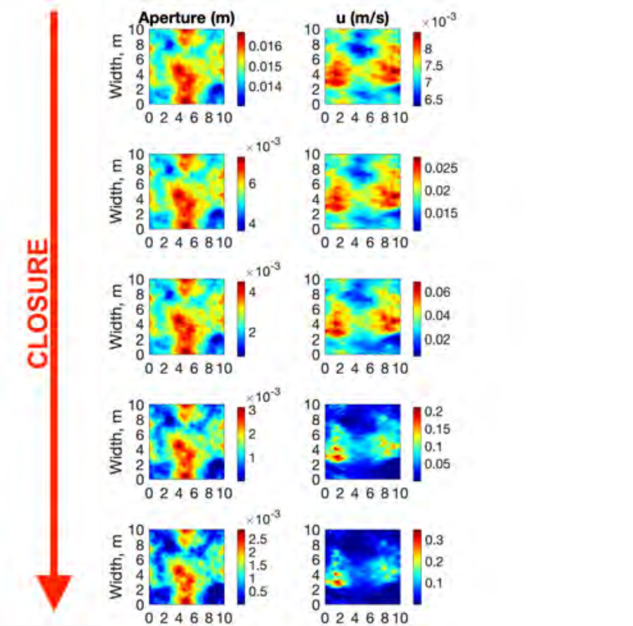
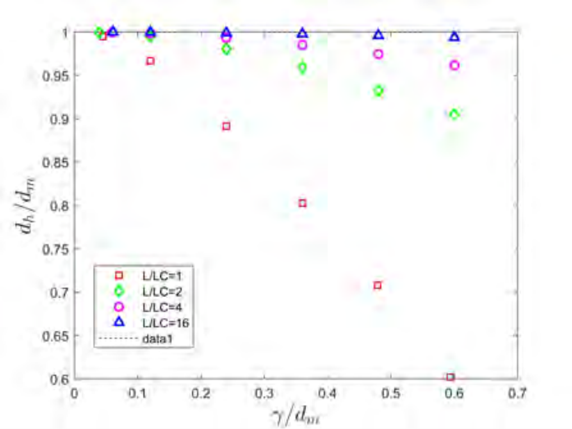


Evolution of the heat transport behavior



Simulated flow velocity fields for different values of fracture closure while the Peclet number *Pe* is set to 80.

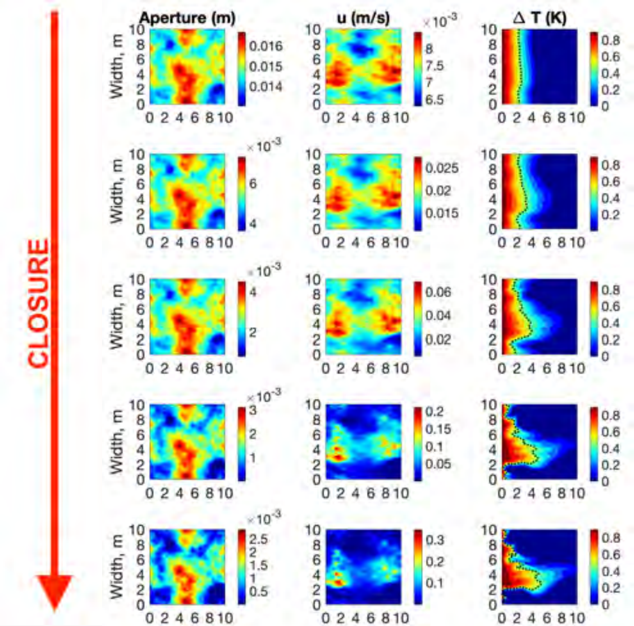


closure

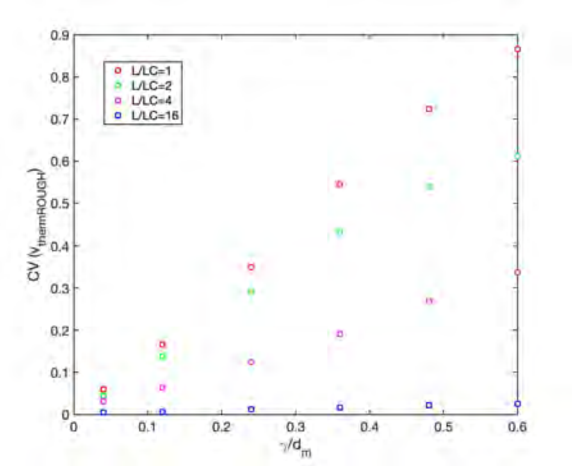
☐ The hydraulic behaviour of the rough fracture deviates from the idealized parallel plate fracture model as fracture closure increases.

☐ The deviation from the cubic law decreases as L_c is decreased.

Evolution of the heat transport behavior



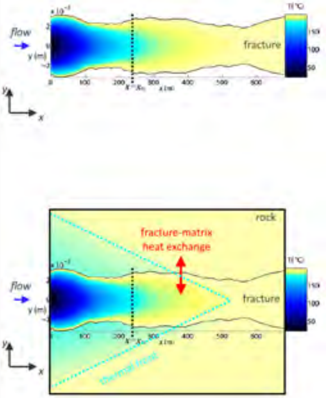
Simulated temperature fields for different values of fracture closure while the Peclet number *Pe* is set to 80.



closure

Standard deviations of the velocity of the thermal front.

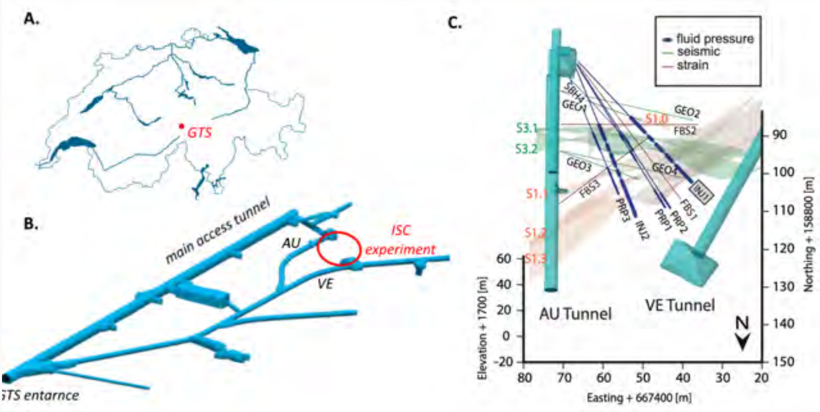
- Flow channeling at the scale of a single fracture has a crucial impact on heat transport
- Taking the itemperature evolution of the hosting rock into account significantly modifies transport behaviour
- Compared to flat fractures with equivalent permeability, for a rough aperture, the heat exchange is more efficient.
- The heat transport behavior of a rough fracture is highly variable. The variability significantly increases as the fracture is closed. It is also controlled by the spatial correlations of the aperture fluctuations.



[modified from Neuville et a., 2010]

Heat transport in a network of fractures

In-situ Stimulation and Circulation (ISC) Experiment, Grimsel site

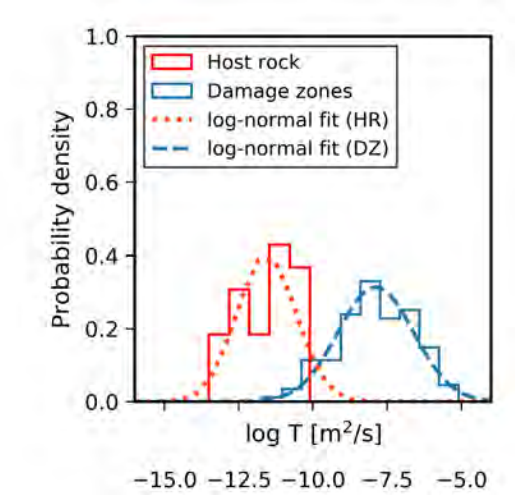


- Geothermal system prototype
- Dekameter scale
- A dense network of sensors *[Amann et al., 2018]*

Objective: characterize heat transport efficiency of a fracture network

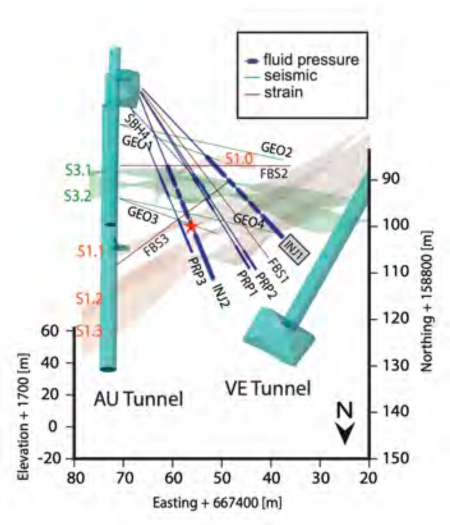
Packer test experimental methodology

Inferred hydraulic properties



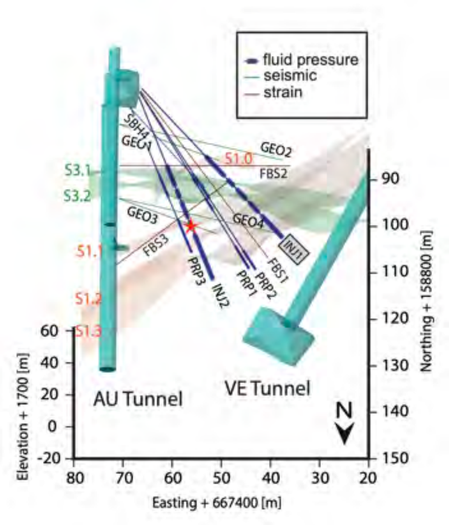
Long term cross-borehole heat tracer test, Grimsel test site

Injection of hot water (50°C) into the packed off fracture at 24 m depth

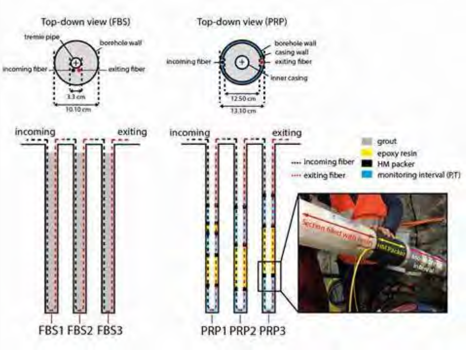


Temperature monitoring with fiber optics in the surrounding boreholes

Injection of hot water (50°C) into the packed off fracture at 24 m depth



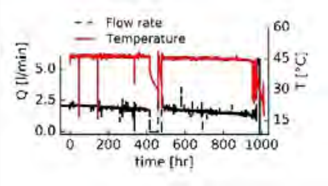
Temperature monitoring with fiber optics in the surrounding boreholes



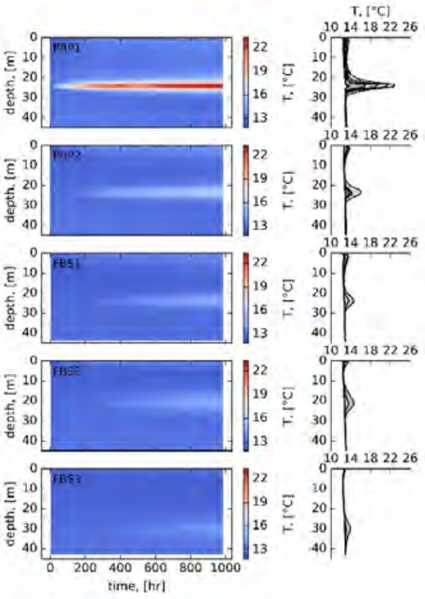
[Brixel et al., in preparartion]

Long term cross-borehole heat tracer test, Grimsel test site

Injection interval



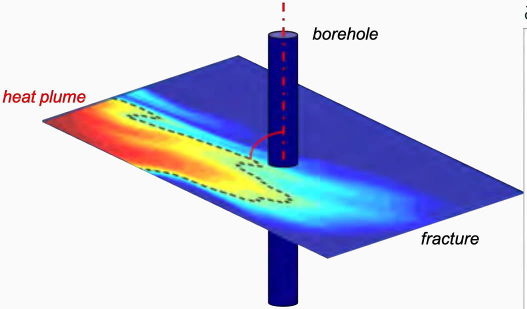
Observation boreholes



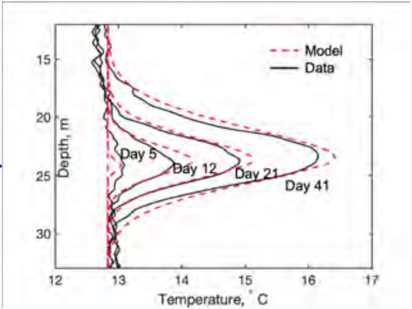
☐ Direct distances:
4.7-7.2 m
☐ First arrival times:
2 *hours*-20 *days*

[Brixel et al., in preparartion]

Long term cross-borehole heat tracer test, Grimsel test site



Several boreholes exhibit asymmetric T profiles



The details of the thermal gradient can be measured, thus enhancing the characterization of heat transport in fractures.

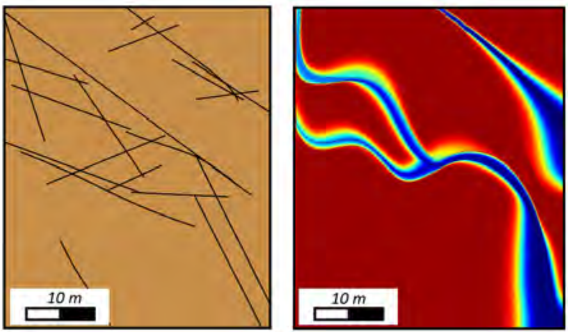
Cross-borehole heat tracer test, conclusions 5/5

- Valuable insights in the 3D characteristics of the heat transport mechanisms in a relatively intact granite were obtained.
- Flow channeling at the network scale has a crucial impact on heat transport
- FO-DTS is a significant advance over traditional point temperature sensors which enables thermal tracer tests to be monitored accurately and efficiently in both time and space.

Conclusions

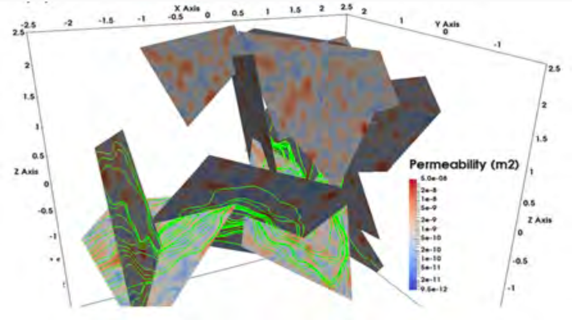
Conclusions

- Channeling in heterogeneous media at multiple scales, implies that fluid flow and heat advection occur mainly through preferential paths which overwhelmingly governs heat transport behavior.
- Predictions based on simplified conceptual models (parallel plate, zonation etc.) may significantly differ from field observations



Future steps

- Development of new models to analyse flow and heat transport in fracture networks to understand the link between heat transport behaviour and the geometric and hydrological characteristics of the structure supporting the flow
- Development of new in situ approaches using heat as a tracer to infer parameters critical for geothermal application



[from Hyman et al., WRR, 2019]

Collaborations

- Olivier Bour, Tanguy Le Borgne, Yves Meheust (Université de Rennes 1)
- Niklas Linde (UNIL)
- Thomas Hermans, Allain Dassargues, Serge Bruyere (Université de Liege)
- Bernard Brixel, Reza Jalali, Clement Roques (ETH Zurich)


Hydraulic tests in Ploemeur, France

Questions?


DTS deployment in Mels, Switzerland