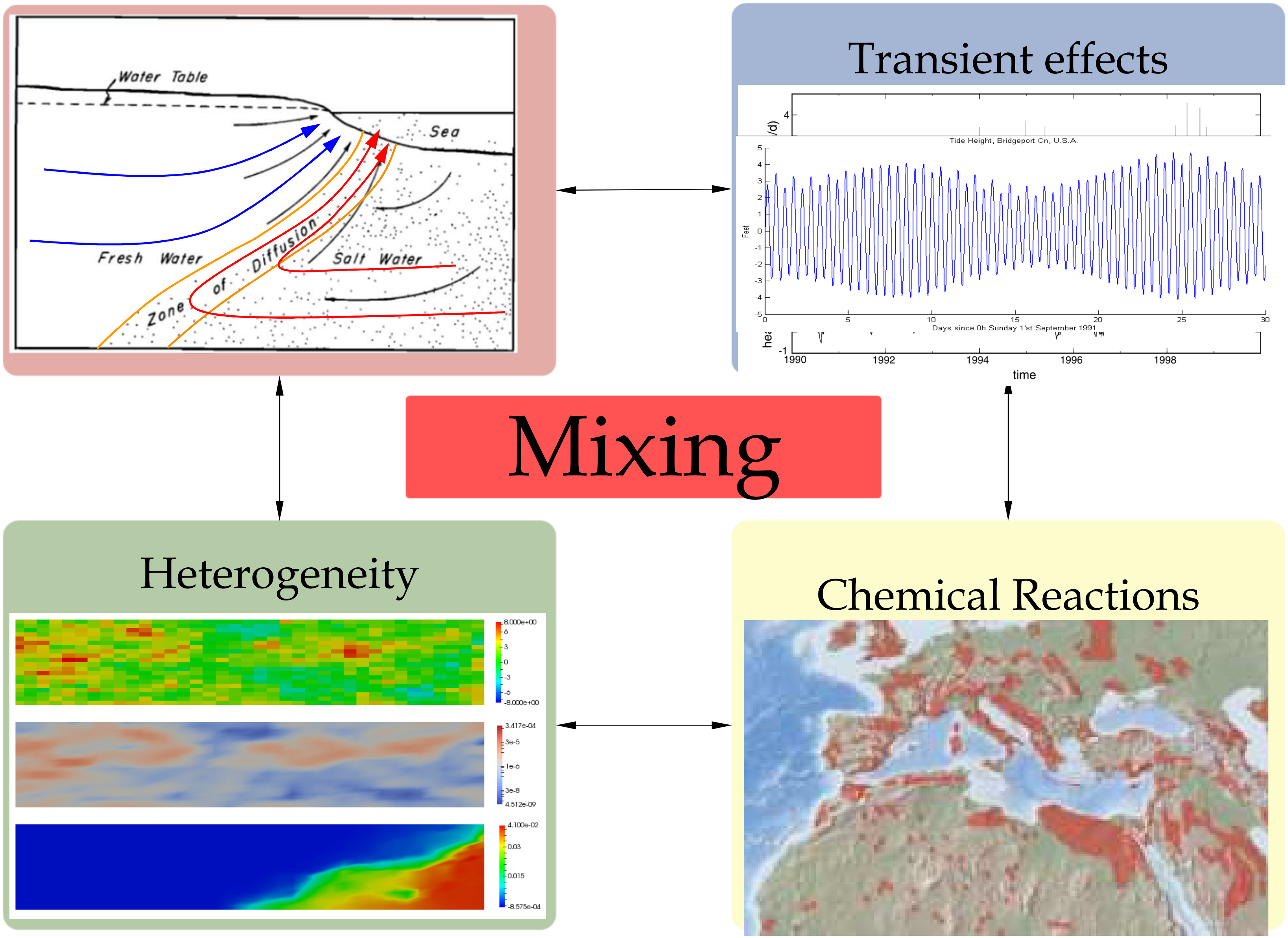
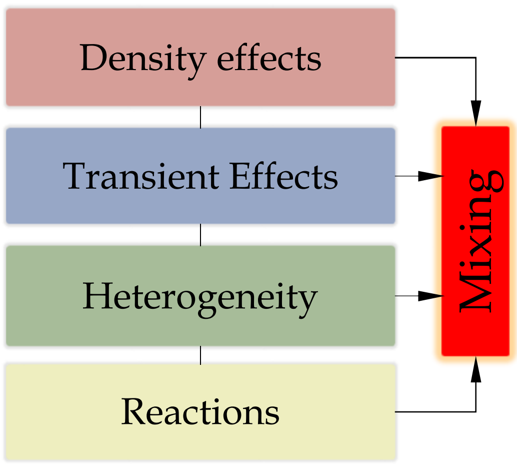
Coastal aquifers



Quantify the impact of the coupling between density effects and temporal and spatial variability on mixing and chemical reactions in coastal aquifers.



Theoretical Approach

Field Experiments:
-Argentona

Numerical Simulations
-2d
-3d

(i) Quantification of flow heterogeneity and fluid deformation

(ii) Identification of flow strain and stress centers, which drive concentration gradients and mixing

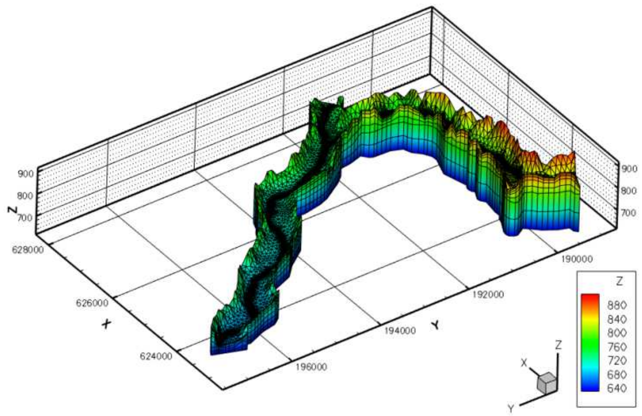
(iii) Development of mixing and reaction diagnostics to explain and predict observed reaction patterns.

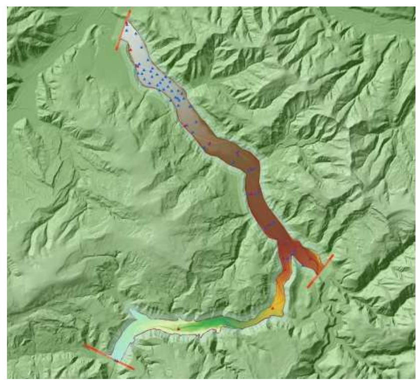
CSIC idæa

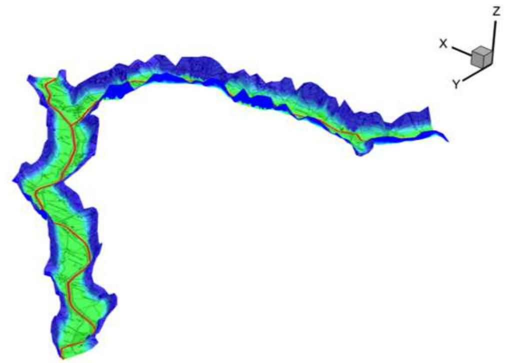
Closing blind spots for surface water groundwater exchanges by integrating novel tracers in numerical models (January, ITN kick-off meeting, Paris)

- CHYN: PHILIP BRUNNER, PHILIPPE RENARD, DANIEL HUNKELER,
- UFZ
- FZJ

Centre d'Hydrogéologie et de Géothermie (**CHYN**)



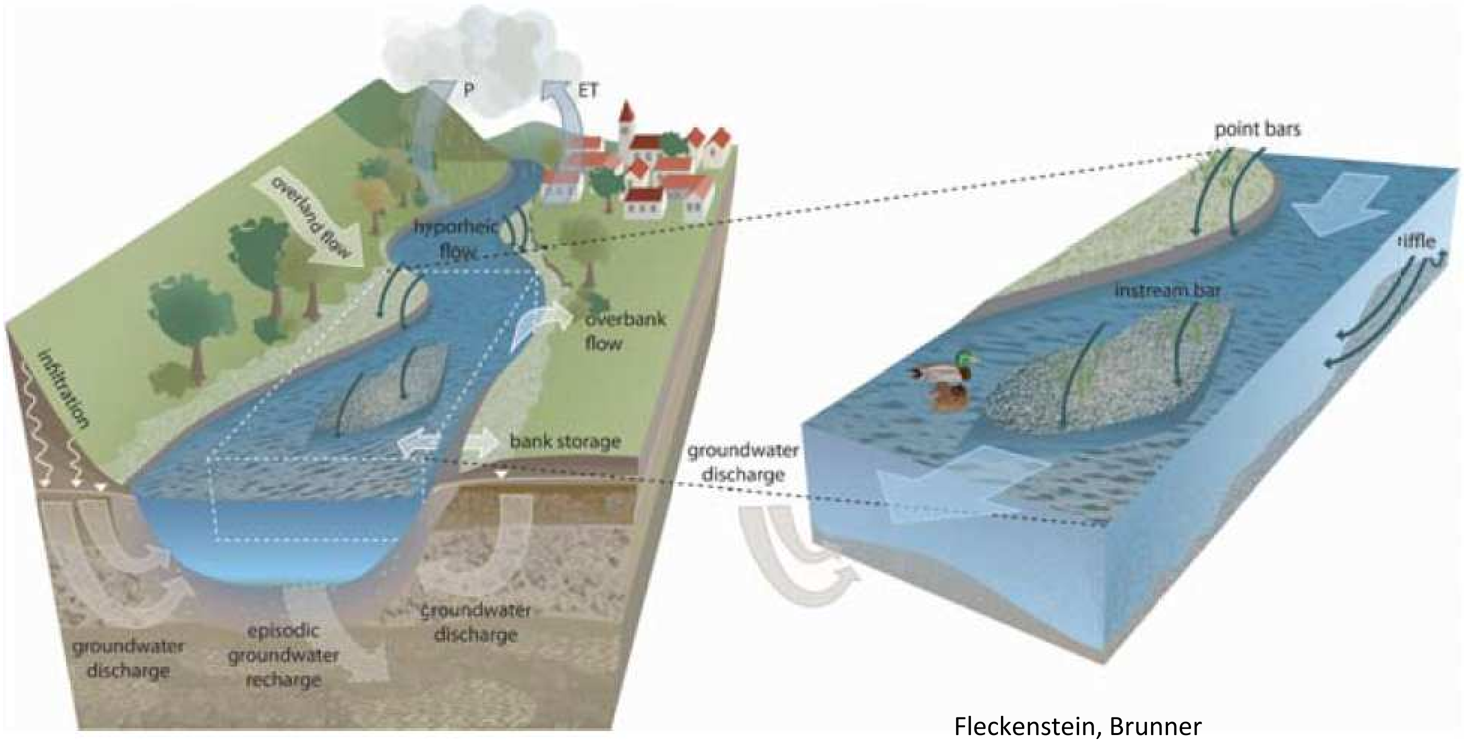




STUDY SITE: UPPER EMME VALLEY

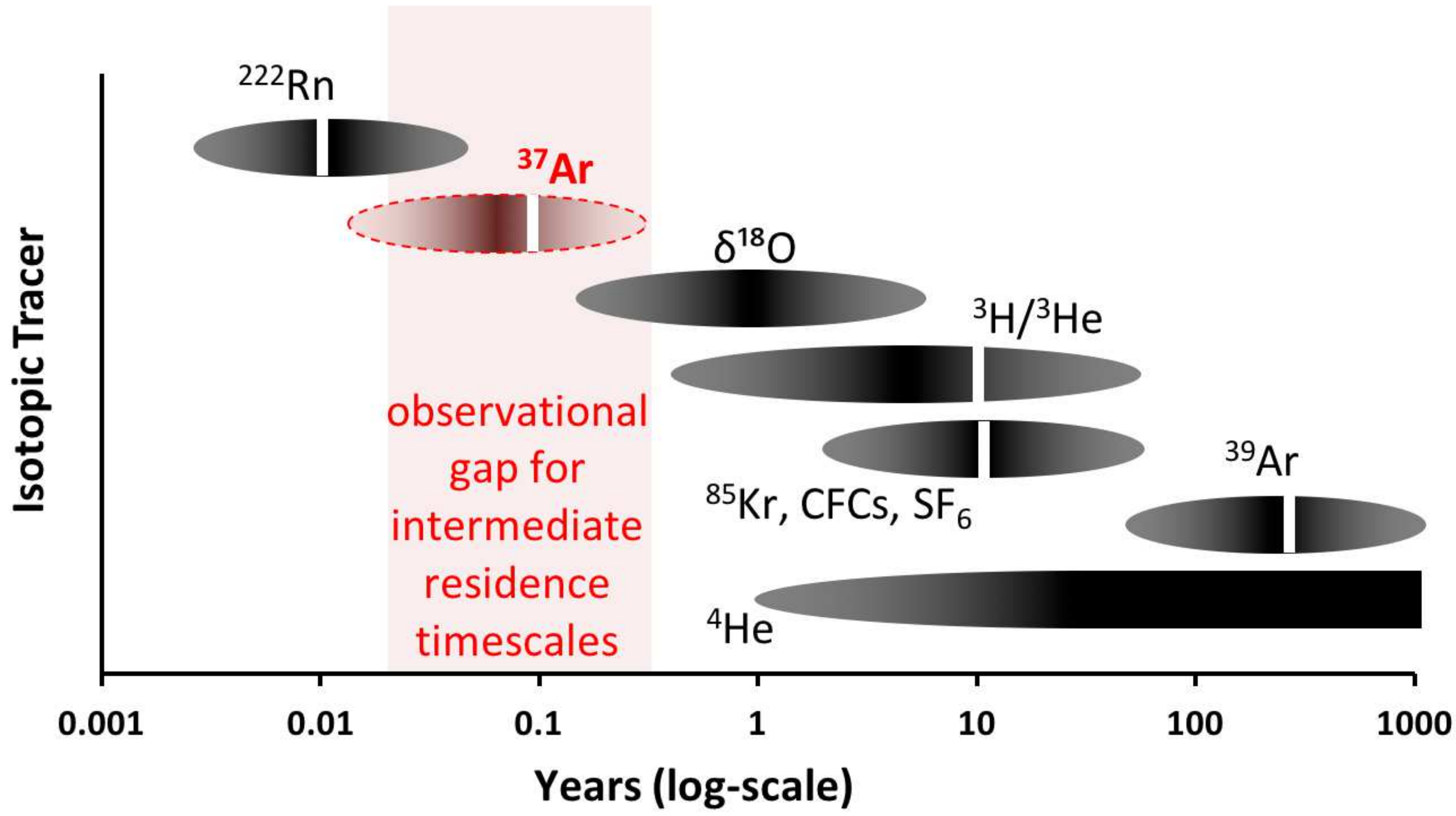
Goals:

- Provide and integrate field and modelling approaches to overcome the conceptual and observational gaps between the hyporheic and meander scale



Fleckenstein, Brunner

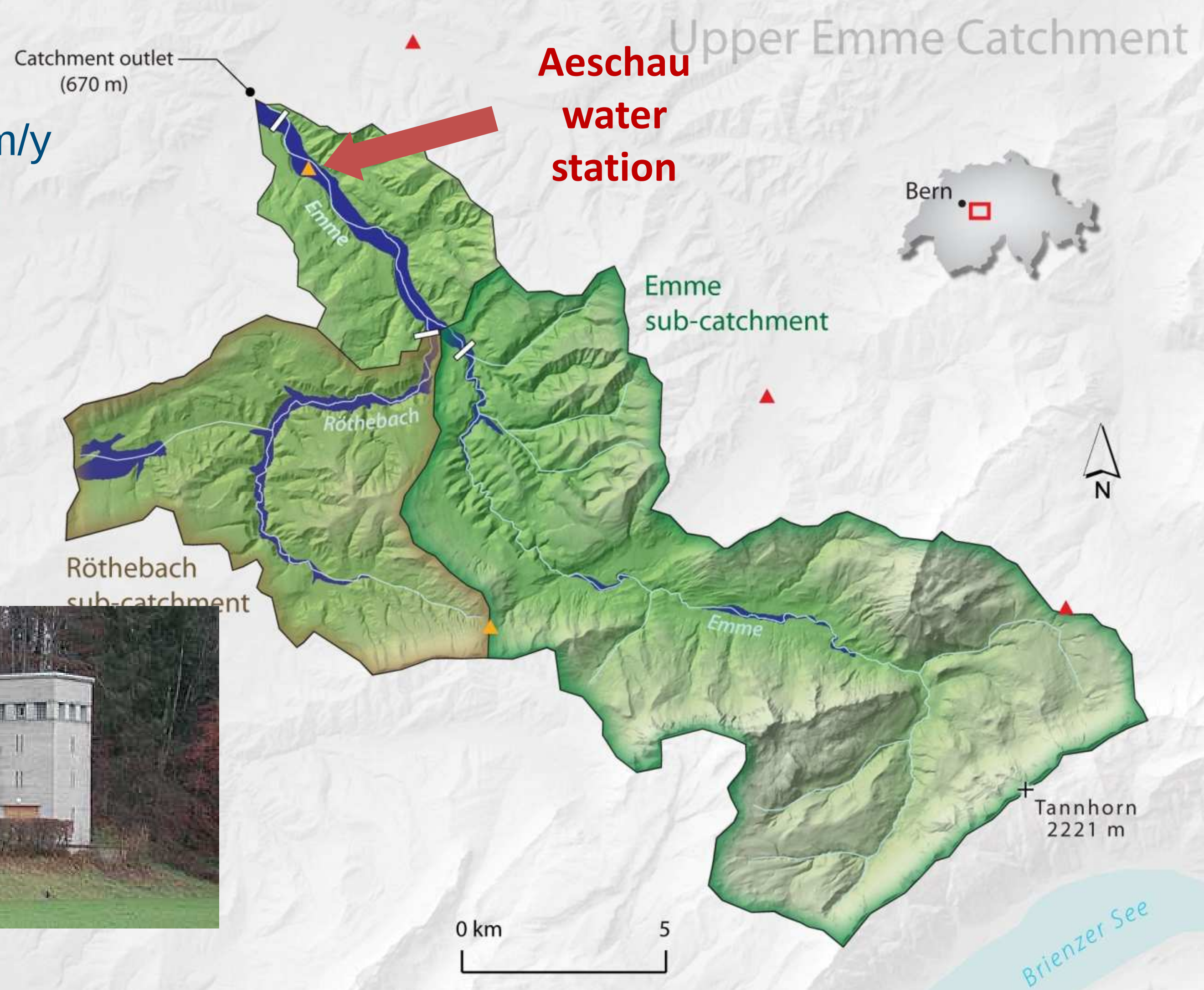
STUDY SITE: WATER BALANCE



STUDY SITE: UPPER EMME VALLEY

Characteristics:

- Precipitation: 1365 mm/y
- Basin: 175 km^2
- Av. runoff: 5.5 m^3/s
- Abstraction: 360 l/s



EXPECTED RESULTS

- **The ESR project aims to provide and integrate field and modelling approaches to overcome the conceptual and observational gaps between the hyporheic and meander scale**

- **The natural tracer Argon 37 (used to detect underground nuclear bomb tests) closes this gap but has so far not been employed in this context.**

- **Numerical models simulating both the hyporheic and meander scale will allow quantifying exchange fluxes and processes across the different spatial and temporal scales.**

- **The models will be based on a high-resolution characterization of the streambed and calibrated with the tracer data.**

- **Streambed characterization and modelling will benefit from other ESRs**

ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data		

ITN Enigma

Motivations

- Fracture networks are multi-scale and complex

  Data are sparse

  No model is satisfactory

- Hydraulic (and mechanical) properties of fractured rock masses are poorly known at scales of 10-100 m

  Relationship between flow characteristics and fracture network properties is an open issue

  Flow is channelled and hardly detectable

  Some important characteristics of flow (fracture intersection, flow in fracture planes, “matrix” structure) are unknown

- Geophysical imagery of decametric fracture domains is a challenge (*no more an issued for large deformation zones*),

  As well as geophysical imagery of flow in fractures

ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2

Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data

ITN Enigma

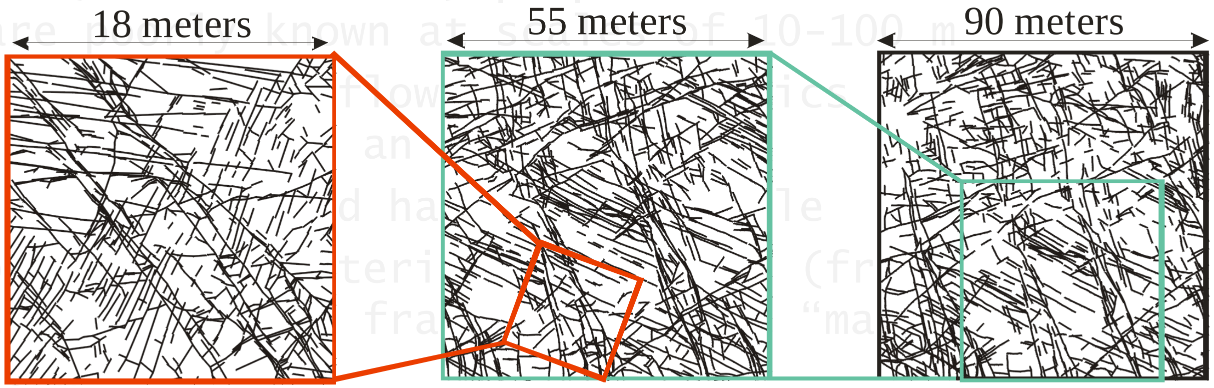
Motivations

- Fracture networks are multi-scale and complex

  Data are sparse

  No model is satisfactory

Scale issue



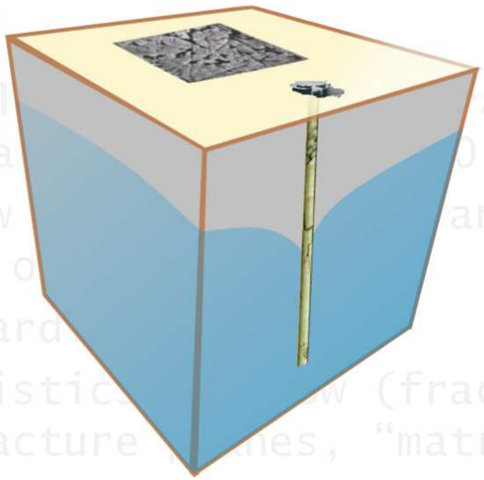
Density variability

ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data		

ITN Enigma

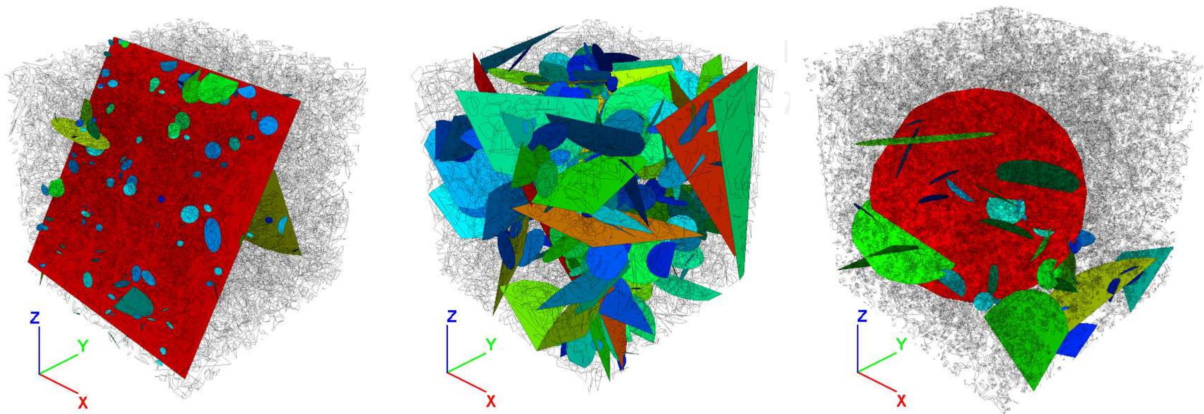
Motivations

- Fracture networks are multi-scale and complex
  Data are sparse
  No model is satisfactory



- Hydraulic (and mechanical … actured rock masses are poorly known a … 0 m
  Relationship between flow … and fracture network properties is an o…
  Flow is channelled and hard…
  Some important characteristic… w (fracture intersection, flow in fracture … nes, "matrix" structure) are unknown

- Geophysi… challenge…),
  As well a…



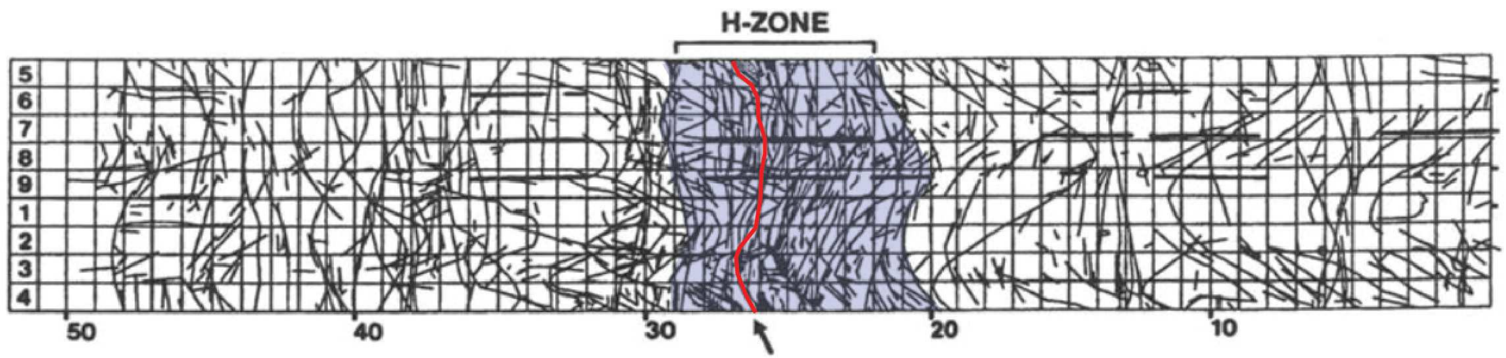
ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data		

ITN Enigma

Motivations

- Fracture networks are multi-scale and complex
  Data are sparse
  No model is satisfactory

- Hydraulic (and mechanical) properties of fractured rock masses are poorly known at scales of 10-100 m
  Relationship between flow characteristics and fracture network properties is an open issue
  Flow is channelled and hardly detectable
  Some important characteristics of flow (fracture intersection, flow in fracture planes, “matrix” structure) are unknown

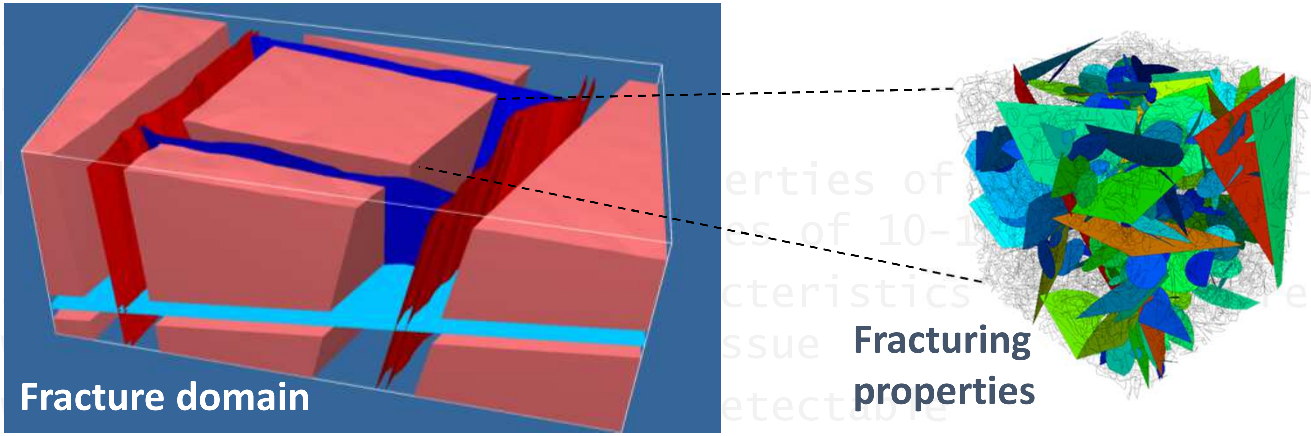


ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data		

ITN Enigma

Motivations

- Fracture networks are multi-scale and complex



Some important characteristics of flow (fracture intersection, flow in fracture planes, “matrix” structure) are unknown

- Geophysical imagery of decametric fracture domains is a challenge (*no more an issued for large deformation zones*),
  As well as geophysical imagery of flow in fractures

ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data		
Planned secondment(s): CNRS Rennes (5 months), UNIL (5 months), SKB (2 month)		

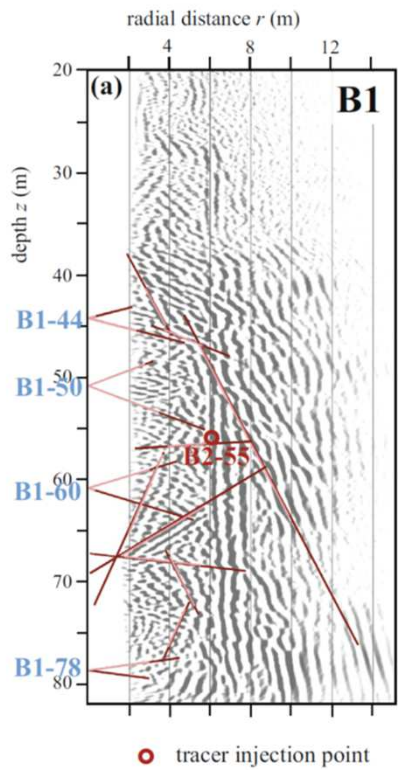
ITN Enigma

Scientific objectives

- Constrain fracture network from geophysical imageries, including time-lapse imagery during flow experiments, and fracture mapping;
- Develop a methodology to DFN conditioning (e.g. [*Davy et al.*, 2013; *Dorn et al.*, 2013])
- Improve our knowledge on the flow in fracture networks: fracture intersection, flow in the fracture planes, dead-ends (“matrix”) structure

Experiments/methods

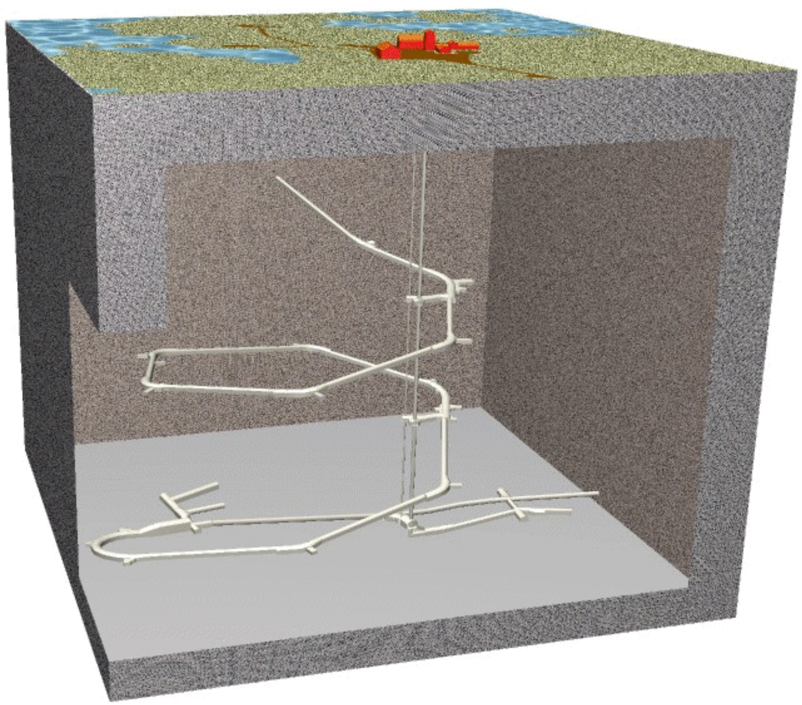
- Experiment in the Äspö tunnel
- Geophysical imagery methods: GPR, seismic tomography (Vp/Vs), fibre optic, others..
- Geomechanical survey: inclinometry, deformation gages, stress measurements
- Fracture mapping: possibility of further excavation?
- Flow experiments with contrast tracers: pumping test (duration, dipole, …), observation boreholes, packers, tracer



C. Dorn et al. / Advances in Water Resources 62 (2013) 79–89

ESR4	Host ITASCA	Main deliverables: 1.2, 1.3, 4.2

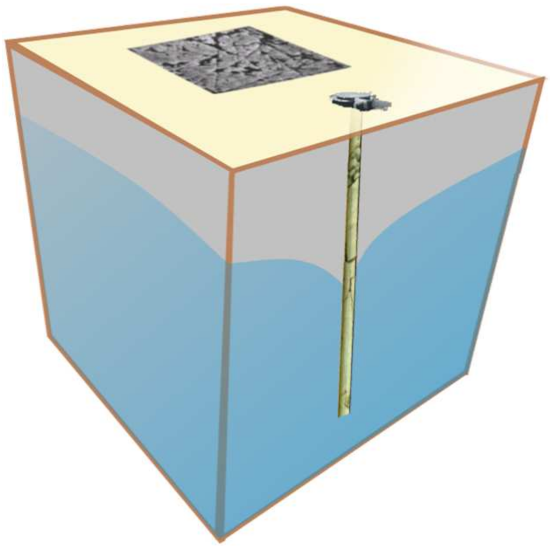
Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data

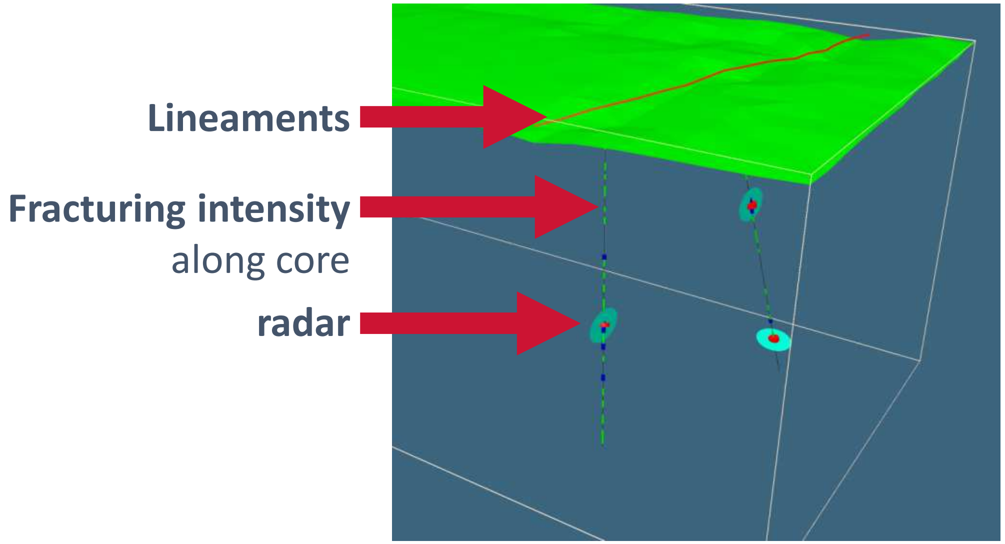


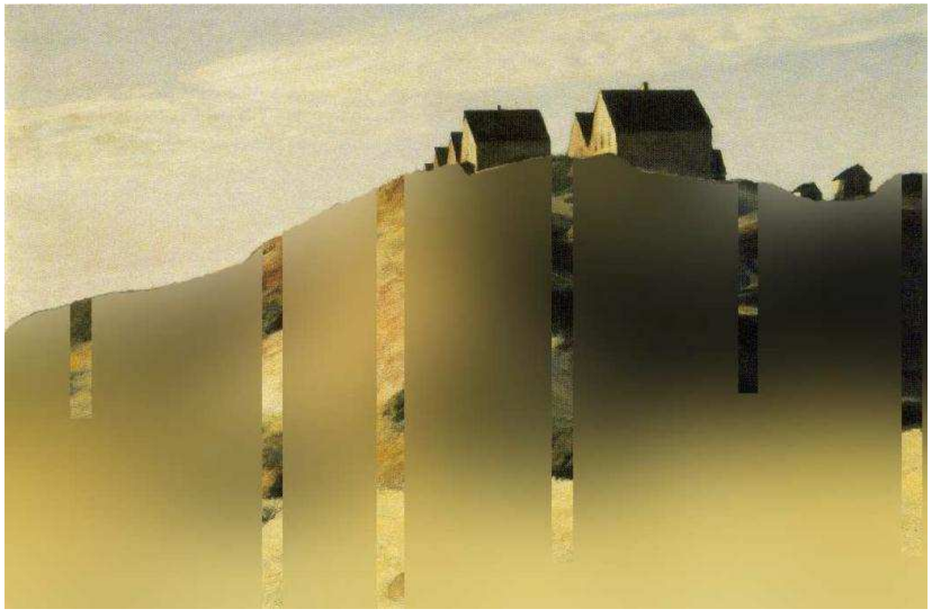
Äspö Hard Rock Laboratory

ITN Enigma

- **Multiscale organization** $10^{-2} - 10^{4}$ m
  density$\sim f(\text{orientation}) * \text{length}^{-a}$
- **Critical range:** $1 - 100$ m







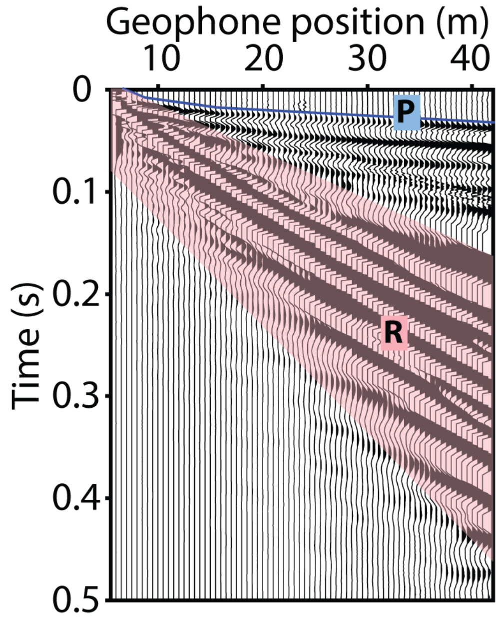
ITN Enigma

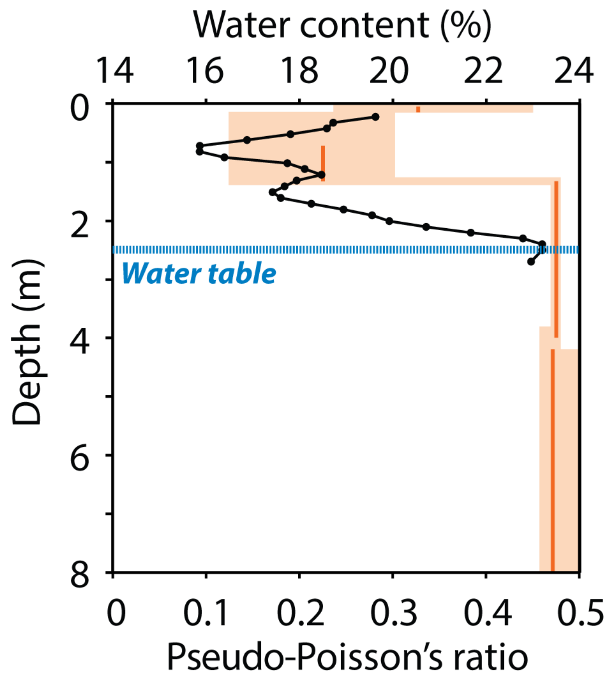
ITN Enigma

PhD #5: Monitoring spatio-temporal water redistribution in the subsurface with seismic methods

Ludovic Bodet, Laurent Longuevergne

<u>CONCEPT</u>: VP/VS or Poison's ratio classically permit imaging fluids in rocks but this strategy remains underused in near-surface applications, hence in hydrogeophysics (e.g. Pride, 2005)!





Pasquet (2011-2015)
Ph.D. Thesis
Pasquet et al. (2015)
Near Surf. Geophys.
Pasquet et al. (2015)
J. of App. Geophys

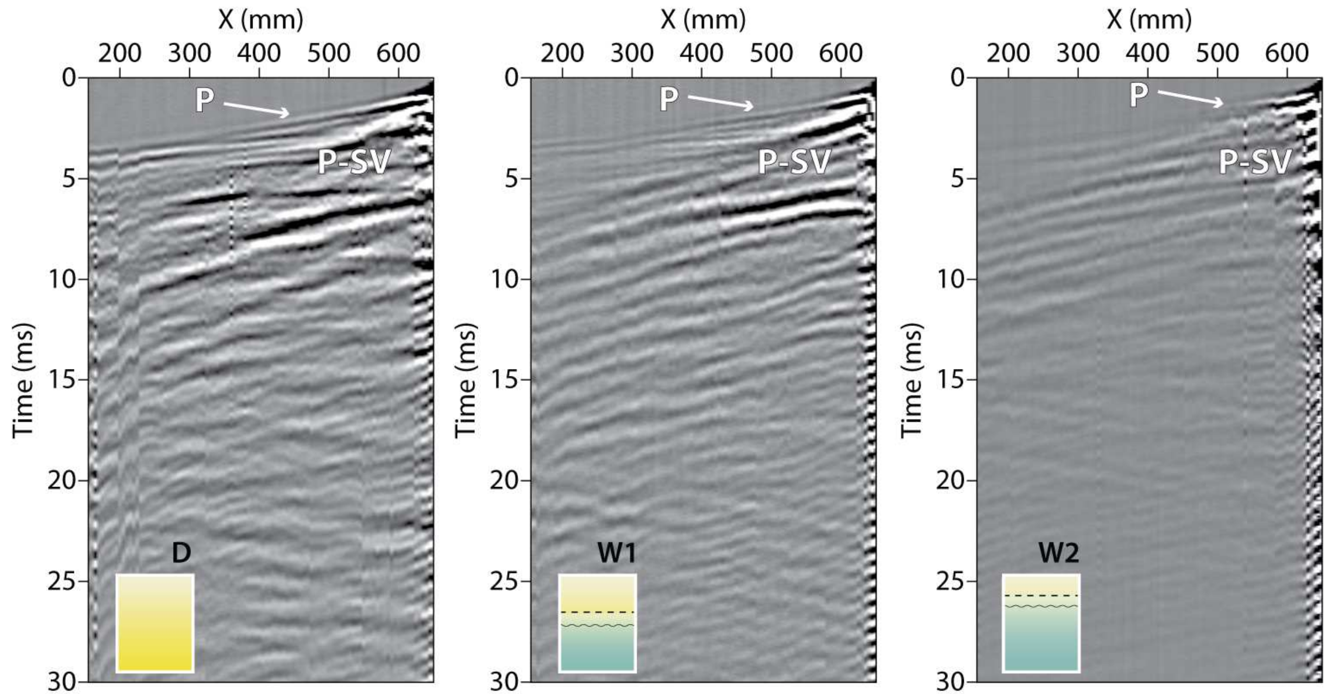
<u>BACKGROUND</u>: VP and VS can be estimated from a **single acquisition** by interpretation of both P- and surface waves . Recently proved to be efficient on various hydrosystems (in 2D as well!).

PhD #5: Monitoring spatio-temporal water redistribution in the subsurface with seismic methods

Ludovic Bodet, Laurent Longuevergne

APPROACH: Exploit the **full wealth** of seismic data for water saturation/pressure monitoring :

1. *Extract information from temporal variations of times/attenuation/dispersion;*
2. *Link changes in seismic properties with hydrodynamic parameters;*
3. *Combine active seismic with scaled seismic noise monitoring.*



Dangeard (2015-2018)
PhD Thesis
Dangeard et al. (2016)
EAGE-NSG
Pasquet et al. (2016)
Vadose Zone J.

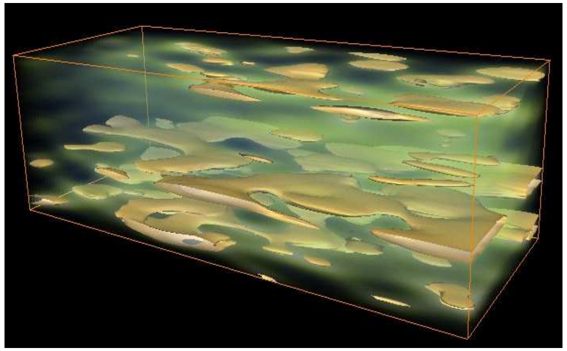
CHALLENGES: **Spatial variability** of "dry" mechanical properties is larger than changes due to water content; Near-surface media are **unconsolidated.**

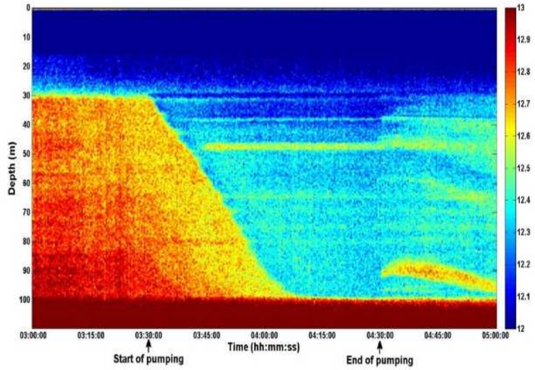
`[we can share a detailed work-plan : ludovic.bodet@upmc.fr ; laurent.longuevergne@univ-rennes1.fr ]`

ESR 6 : Active Fiber-Optic DTS methods to monitor subsurface flow dynamics

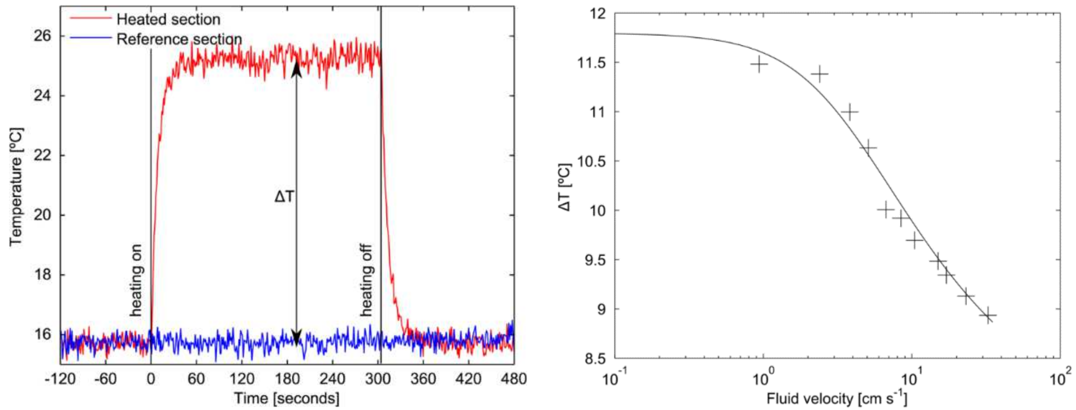
- Passive FO DTS methods allows to locate permeable karst conduits, fracture locations, to quantify borehole flow velocities and to characterize groundwater dynamics or thermal transport.

- Active DTS methods are very complementary for quantifying borehole flows in ambient conditions, or related to pumping and cross-borehole flows. By using either a local thermal source or using the armoring of the cable, active DTS methods are much more sensitive to flow.





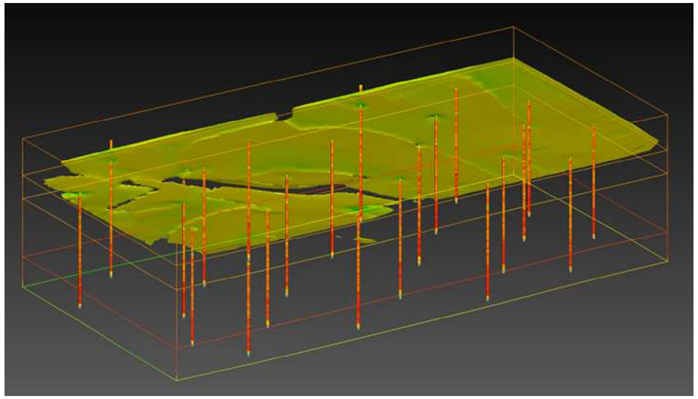
Le Lay et al. (in prep) Characterization of groundwater dynamics in a karst aquifer through Active and Passive Fiber Optic DTS methods



Read et al. (WRR, 2014) Active-Distributed Temperature Sensing to continuously quantify vertical flow in boreholes

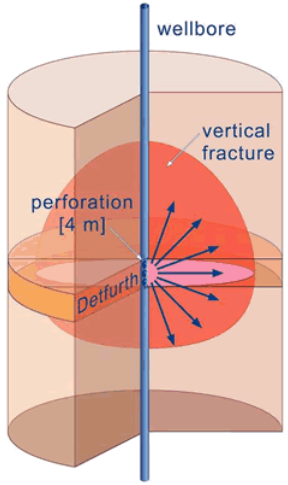
ESR 6 : Active Fiber-Optic DTS methods to monitor subsurface flow dynamics

Main objective : Image flow properties and study hydro-thermo-mechanical processes.



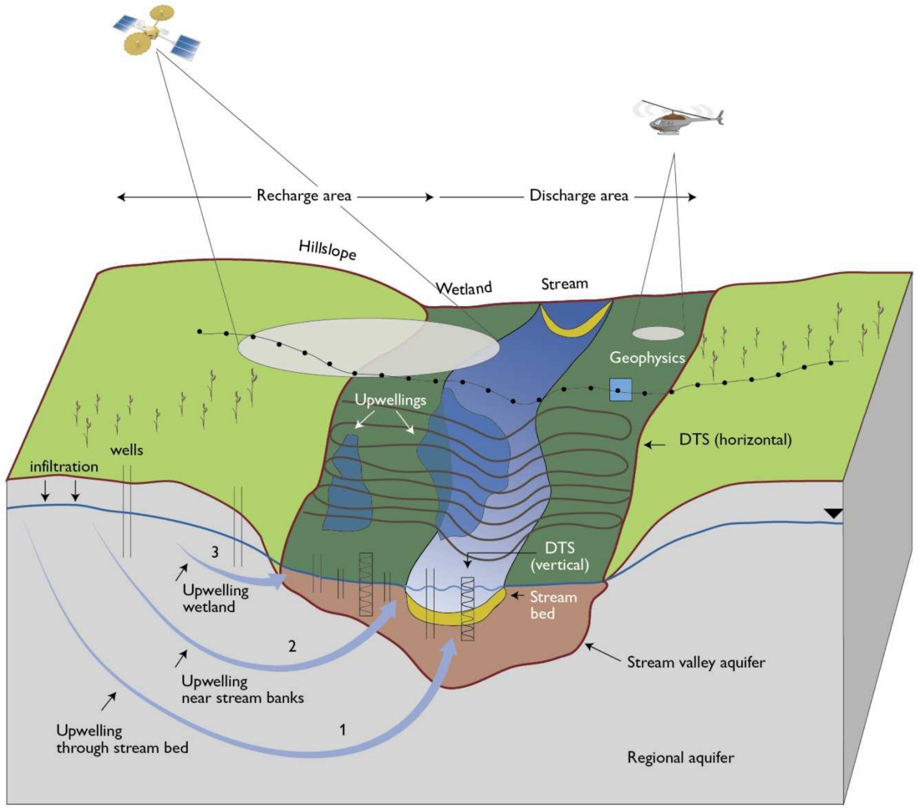
- Adapt passive methods in various hydraulic conditions (cross-borehole interference tests, periodic hydraulic tests and ambient conditions) in fractured media (Ploemeur and Äspö sites)

- Develop active DTS methods in buried cables within saturated porous media in order to quantify in-situ fluxes within sandy aquifers (Hermalle site), saline wedges (Argentona site) with the objective of testing an innovative flow tomography approach (also possible within the hyporheic zones at River Selke site for instance). Development of a model of heat transfer in porous media and a model of inversion of distributed flow data)



- Possible extent : analysis of coupled hydro-(thermo-) mechanical processes in fractured media using Distributed Strain sensing (possible applications at Ploemeur and Äspö sites)

ESR7: Multi-scale thermal imaging of groundwater upwelling in stream valleys



Motivation:

- Streams are natural drainage networks and their efficiency depends on the spatial hydrological connection to the upland
  - Geology/transmissivity
  - Streambed K, temperature effects
- Riparian zone hydrology
  - Flooding/climate
  - Upwelling on land vs stream bed seepage
- Riparian zone ecology
  - "Last line of defence" towards mitigating e.g. agricultural pollution

Objective: (1) Quantify relative contribution of groundwater discharge to stream valleys through either springs and stream bed and (2) Quantify the effects of temperature-controlled hydraulic parameters on discharge

Field site: 1-3 HOBE sites (Hygild, Evi1, Evi2; see poster), all showing various degrees of groundwater upwelling on land and seepage to stream

Field methods: Multi-scale thermal imaging; (1) air-borne (in-house access to UAV with TIR camera, (2) DTS (in-house access), (3) point temperature profiles. Compare with traditional methods (e.g. wells, seepage)

Modelling: (1) Develop statistical methods/metrics for analysis of temperature signals and (2) develop surface-subsurface flow and heat transport model to simulate spatio-temporal thermal and flow heterogeneity

Secondments: UNINE: geostatistics, UFZ: heat modeling

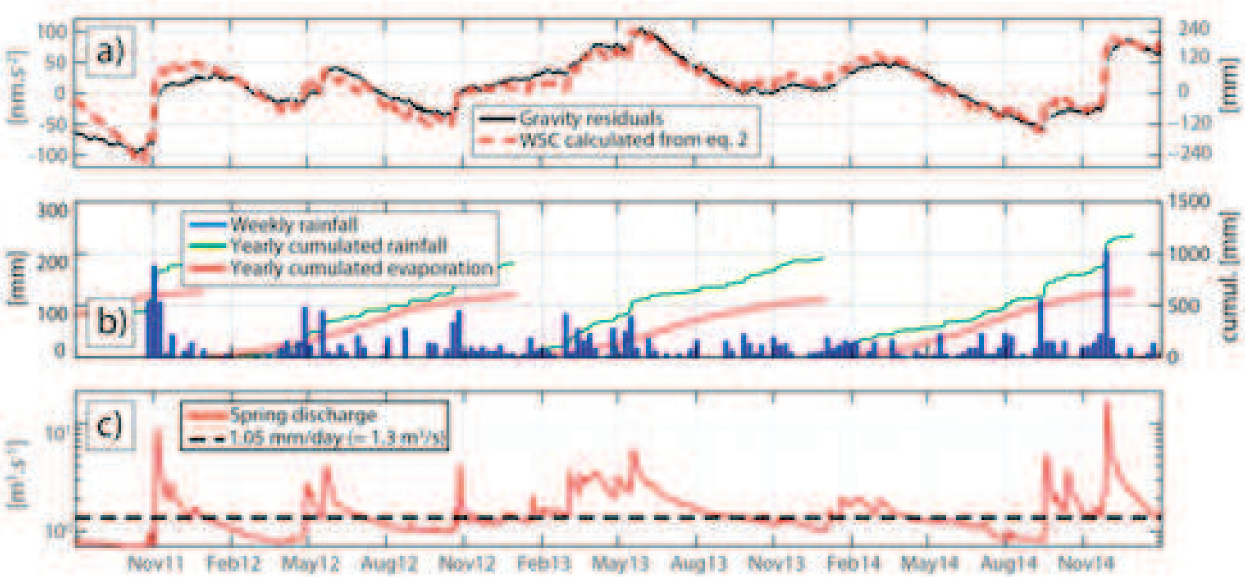
ESR 8 (Champollion, Desruelle)
Kick-off Enigma 30/01/2017, Paris

ESR 8: Monitoring water storage changes with a new portable absolute quantum gravimeter

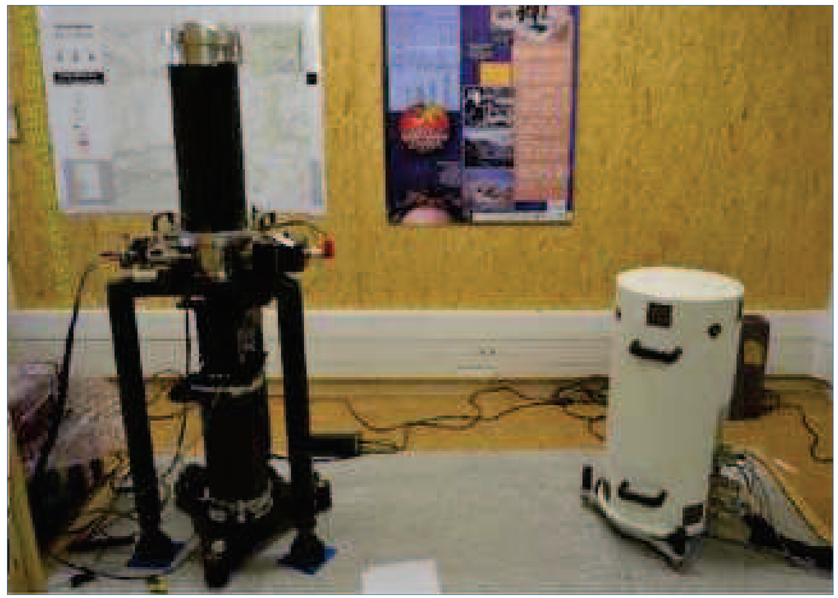
Bruno Desruelle, Muquans, Bordeaux, France
C. Champollion, GEK H+ observatory coordinator, Lab. Géosciences Montpellier, UM, France

ESR 8 (Champollion, Desruelle)
Kick-off Enigma 30/01/2017, Paris

- Gravity allows monitoring water storage in vadose zone with a large volume investigated
- Need of a new accurate and field dedicated instrument

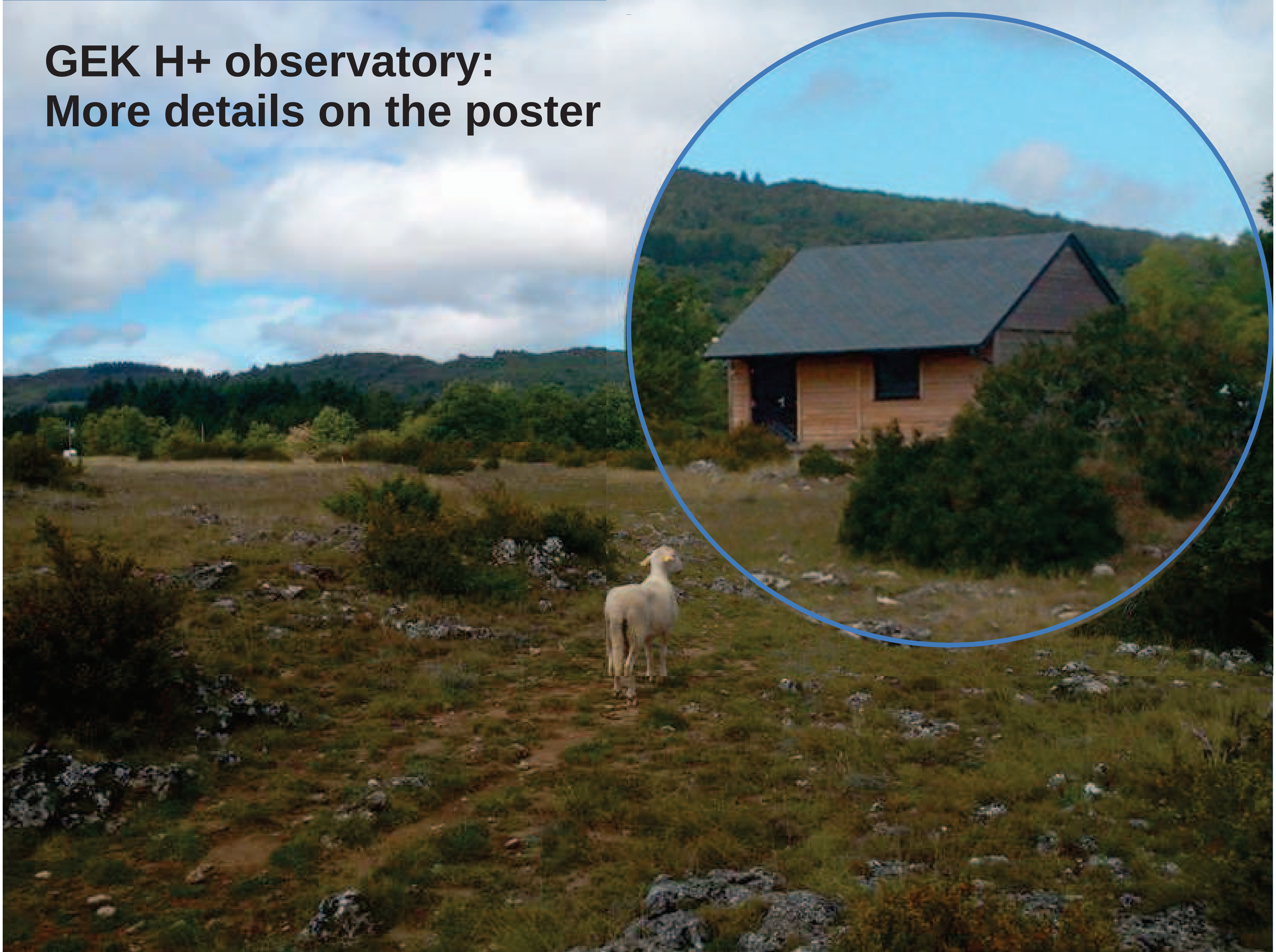


Gravity, meteorological and hydrological observations on the GEK H+ observatory since May 2011



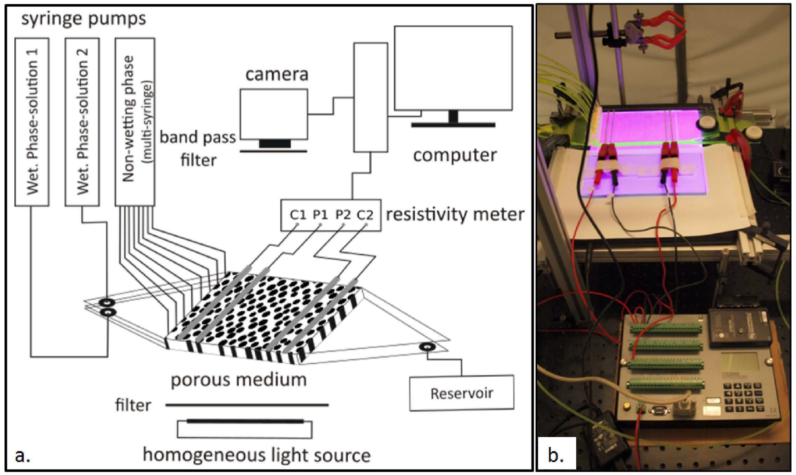
"Old" FG5 (left) and new AQG (right) in the GEK observatory

- Two parts (equal importance) in the PhD:
  - First comparison and validation of the new gravimeter “on the field”
    - GEK H+ observatory, existing gravity references, evapo-transpiration monitoring and hydrological models
  - Then experimentations on at least two sites:
    - LSBB H+, deep karstic vadose zone, MRS and boreholes complementary observations
    - HOBE, shallow vadose zone, soil moisture and cosmic ray complementary observations
    - Others sites can be discussed


GEK H+ observatory:
More details on the poster

ESR 9: Geophysical signatures of spreading and mixing

Set-up

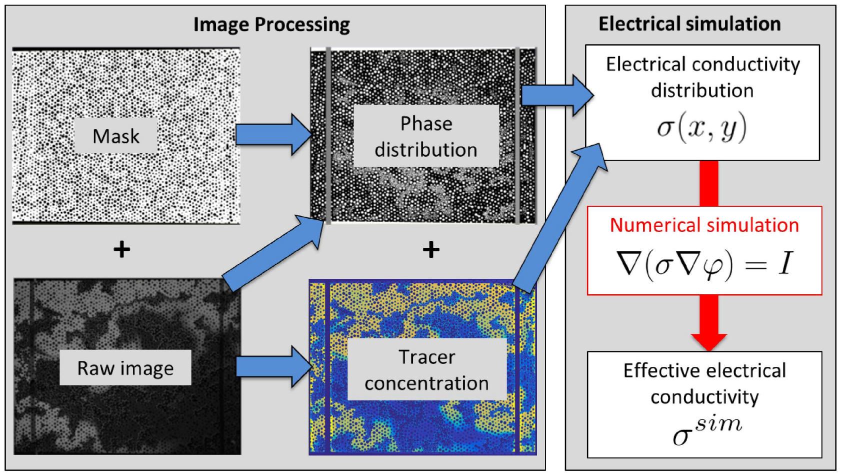


Host: University of Lausanne (Linde)

Primary ENIGMA collaborators

- CNRS (Jougnot, Le Borgne, Meheust)
- CSIC (Dentz, Carrera)
- Jühlich (Huisman)

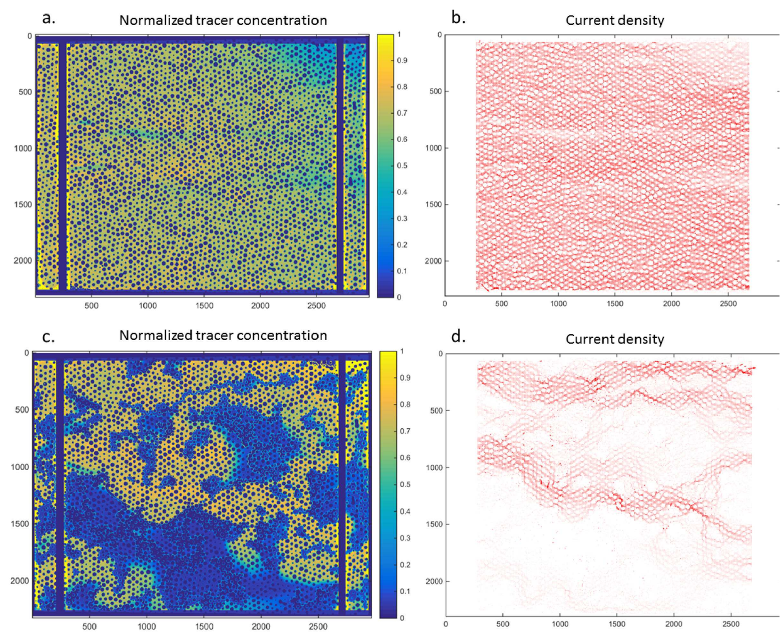
Processing



Figures from Jougnot et al. (in prep.)

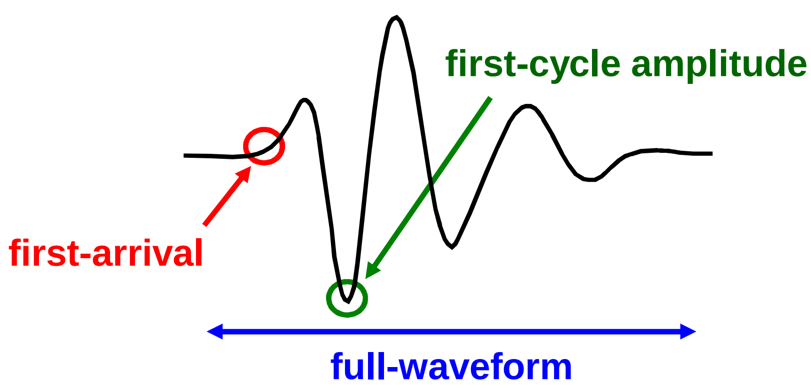
Initial results

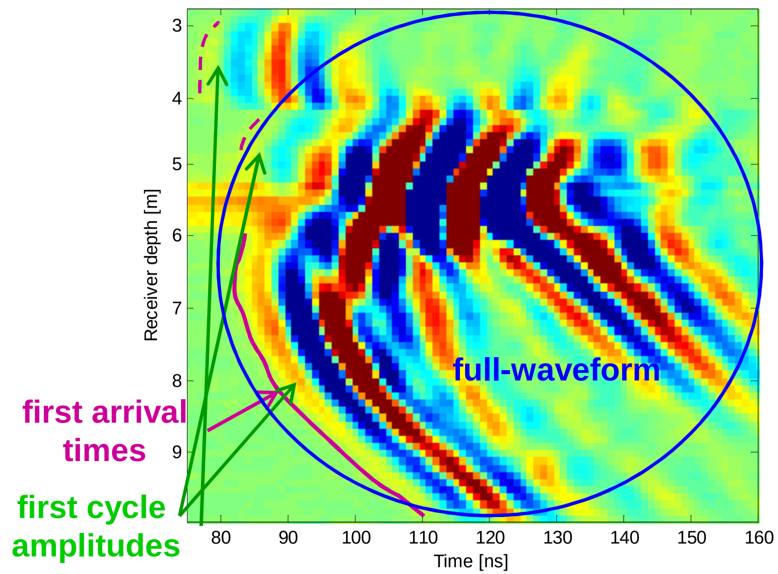
Salinity | Electric current



- **Scientific objective:** To what extent can upscaled/effective properties sensitive to salinity inform us about statistics of spreading and mixing below the averaging-scale?
- **Experimental approach:** Use 2-D millifluidic experiments that provide high-resolution images of pore space, water phase and salinity coupled with geophysical monitoring (electrical, self-potential, spectral induced polarization);
- **Theoretical development:** Upscaling models and link to anomalous transport theory;
- **Outlook:** Turn inadequacies of hydrogeophysical inversion methods (e.g., apparent mass loss) into predictive variables that inform on processes below the resolution limit of geophysical tomograms.

ESR 10: High resolution aquifer imaging with GPR Full-waveform inversion





Ray-based inversion

⇨ **coarse structures**

Full-waveform inversion

⇨ **detailed sub-wavelength structures**

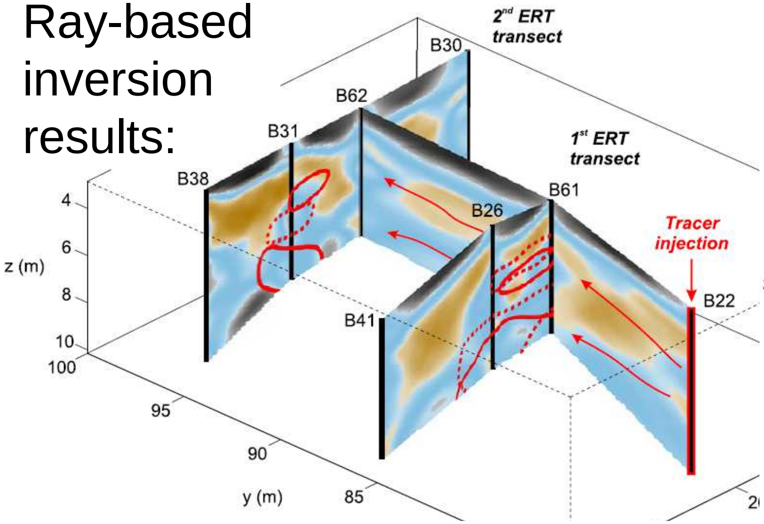
Objectives:

Develop and adapt GPR full-waveform inversion to

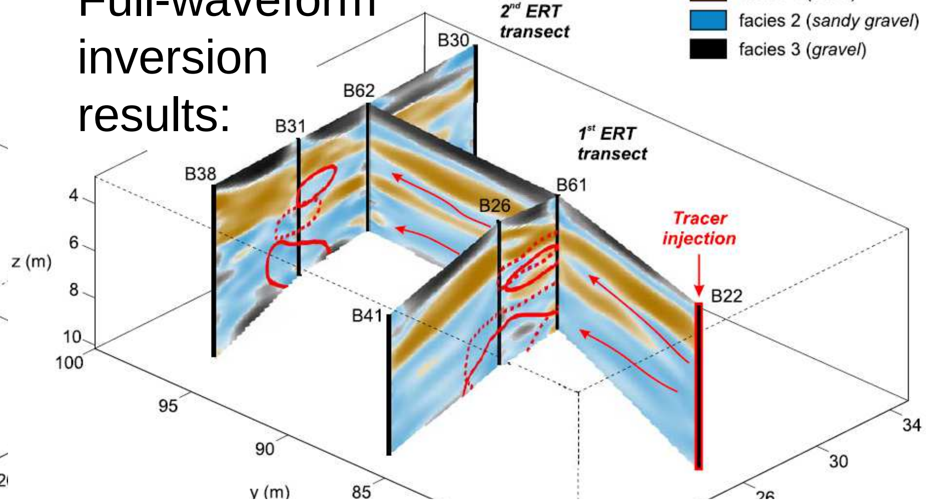
- image tracer front distributions using time-lapse measurements at the Krauthausen test site (alluvial aquifer)
- image and characterise fracture networks at H+ Ploemeur site (fractured aquifer)

Krauthausen Plume splitting explained by GPR full-waveform inversion

Ray-based inversion results:



Full-waveform inversion results:



The obtained inversion results will be compared and combined with data obtained by ESR 2, 3, 4, 5, 6, 9 & 13.

Planned secondments:

- CNRS (2 months, measurements & joint analysis of Ploemeur site results)
- UNIL (2 months, joint analysis of Krauthausen & Ploemeur inversion results),

ESR11 & ESR15

University of Liège, University of Mons, BRGM

ITN Enigma

MARIE SKLODOWSKA-CURIE ACTIONS
ENIGMA Innovative Training Networks -2017

ESR11: Joint heat and solute tracer test inversion for imaging preferential pathways

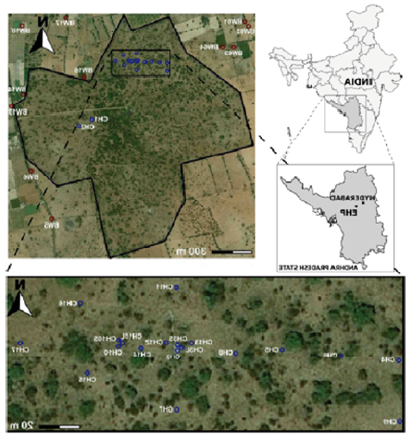
- Rationale

- **Improving prediction methods** of e.g. design and impact for **heat storage systems**, **impact** and **remediation** for solute contamination
- **heat** and **solute** have different (complementary) transport behaviors (i.e. with respect to matrix diffusion, dispersion, conduction) and **new geophysical techniques** provide detailed 2D and 3D images

- Key tasks

- **Co-inversion techniques and prediction-focused approach** (PFA*) (Hermans et al 2016 WRR)
- **Test tracers** with **different diffusion coefficients** in a matrix – fractured media at the fracture to well scales (site UMONS)

ITN Enigma



Materials & methods

Data

4D **ERT and SIP, GPR and DTS** data contains information on transport processes and preferential flow paths

Tracer tests

Sites

Alluvial sediments **(HSA)** and fractured chalk and fractured bedrock overlaid by weathered rocks in India (H+ **Hyderabad** site BRGM)

Interactions

DTS technology **ESR6**;

Model comparison for spreading and mixing **ESR9**;

Hydrogeophysical methods GPR (**ESR10**) and SIP (**ESR12**).

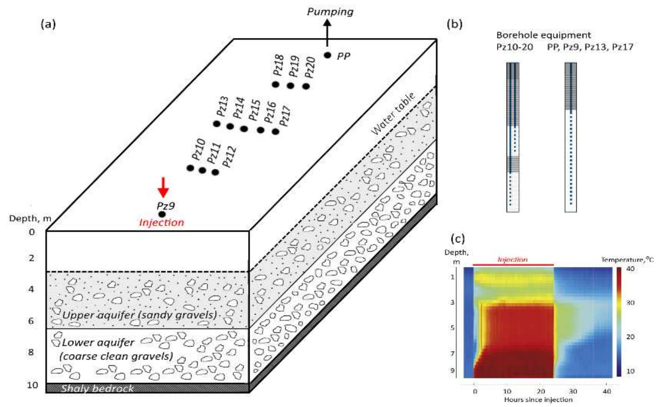
Supervisors:

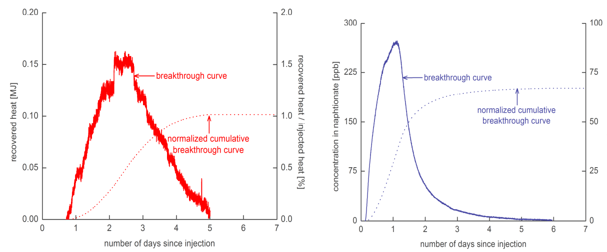
Principal supervisor is : **Prof. Alain Dassargues**, Hydrogeology and Environmental Geology, ULg

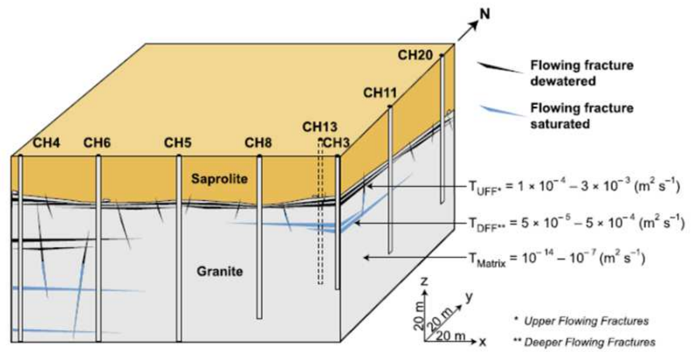
Other supervisor: **Prof. Pascal Goderniaux**, Hydrogeology, UMons

Secondments:

BRGM (Hyderabad)

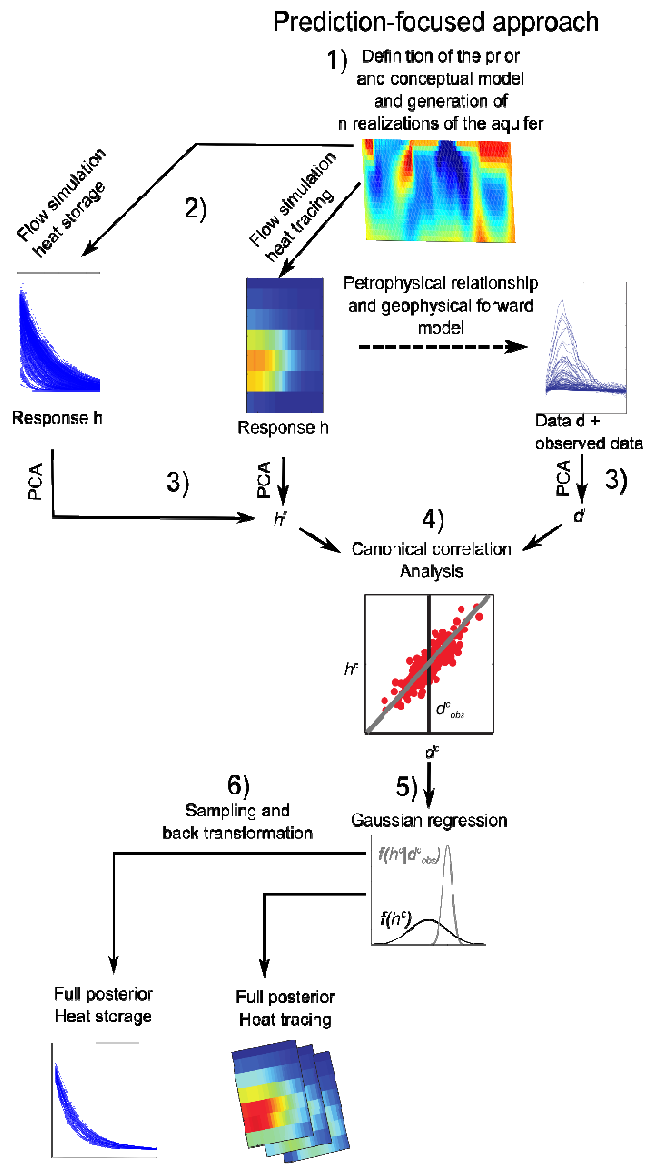






ESR15: Integration of dynamical hydrogeophysical data in a multiple-point geostatistical framework

- Rationale
  - **Integrate 4D spatially distributed data**, with a high temporal resolution, to give **new insights** on transport processes.
- Key tasks:
  - Consider prior scenarios **validation/falsification** using **4D** hydrogeophysical monitoring data of transport processes.
  - Develop a new framework -**PFA/PPM-** to integrate dynamical hydrogeophysical data sets in multiple-point geostatistical framework



Materials & methods

Data

4D **ERT and SIP** data contains information on transport processes and preferential flow paths that can help discriminate between various scenarios better than static images.

GPR and DTS provides time-lapse images with a higher spatial resolution than ERT or SIP

Sites

HSA and/or **Krauthausen**, **Ploemeur**

Interactions

Collaborations with **ESRs 13** (UT) and **14** (CSIC) from a methodological point of view.

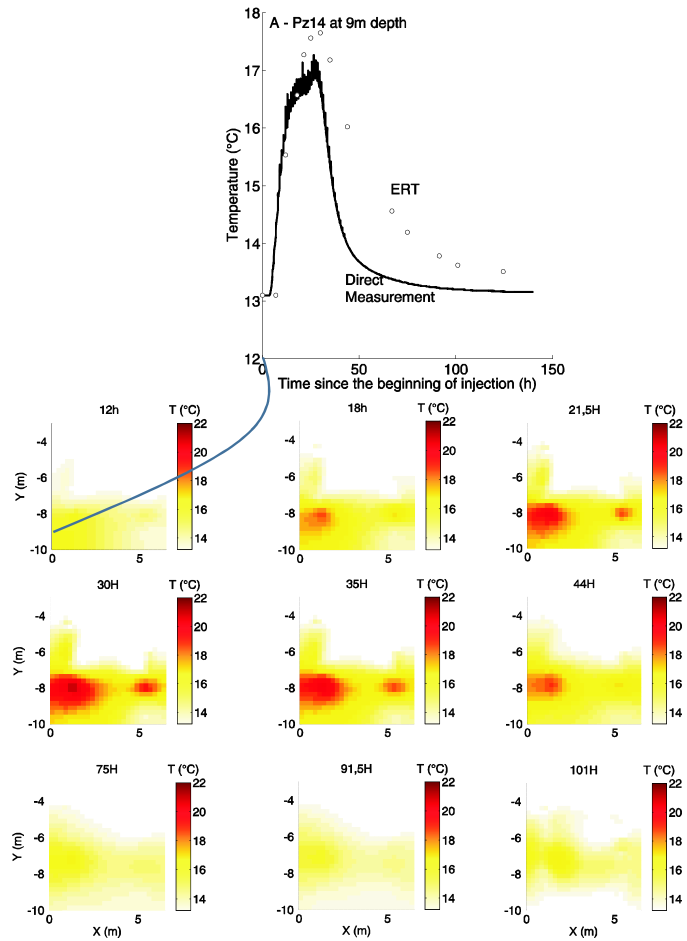
Datasets of **ESR6** (DTS) and **ESR10** (GPR) will be integrated.

Supervisors:

F. NGUYEN (ULg) and T. HERMANS (ULg)

Secondments:

CSIC (joint inversion), **AQUA** (technology transfer)



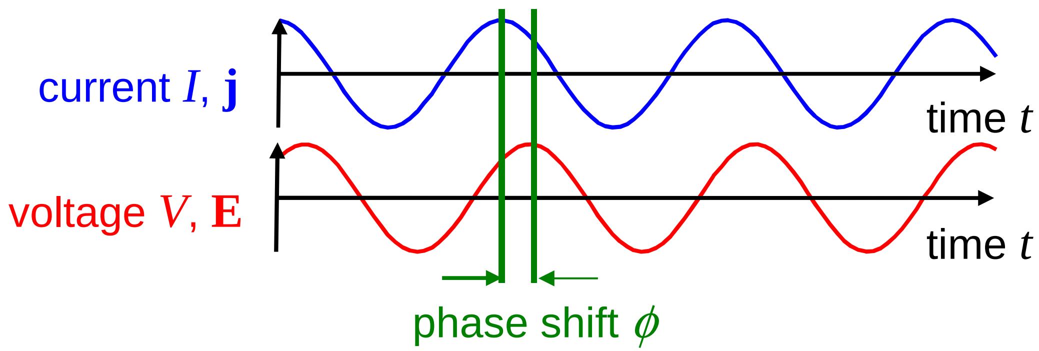
JÜLICH
FORSCHUNGSZENTRUM

ESR12: Spectral induced polarization monitoring for in-situ quantification of biochemical reactions

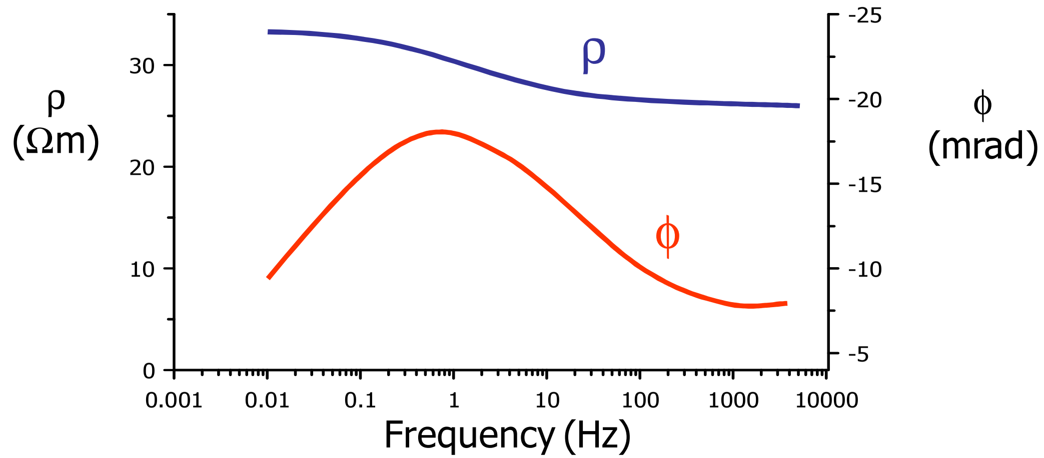
J. A. Huisman, E. Zimmermann, J. Vanderborght
T. Le Borgne, N. Linde, D. Jougnot,
U. Ghosh, Y. Meheust

Spectral Induced Polarization (SIP)

- Electrical polarization under influence of electric field

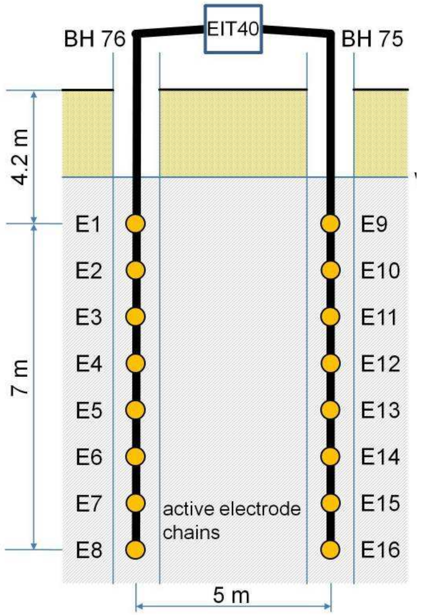


- Description by complex, frequency-dependent electrical resistivity



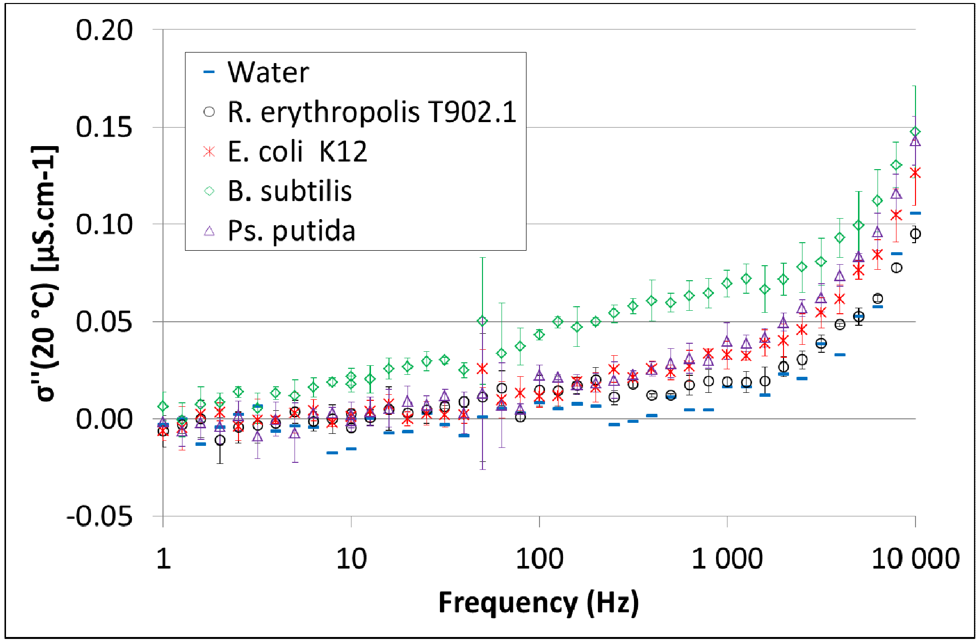
Laboratory SIP and field EIT

n



Biofilms and biochemical reactions

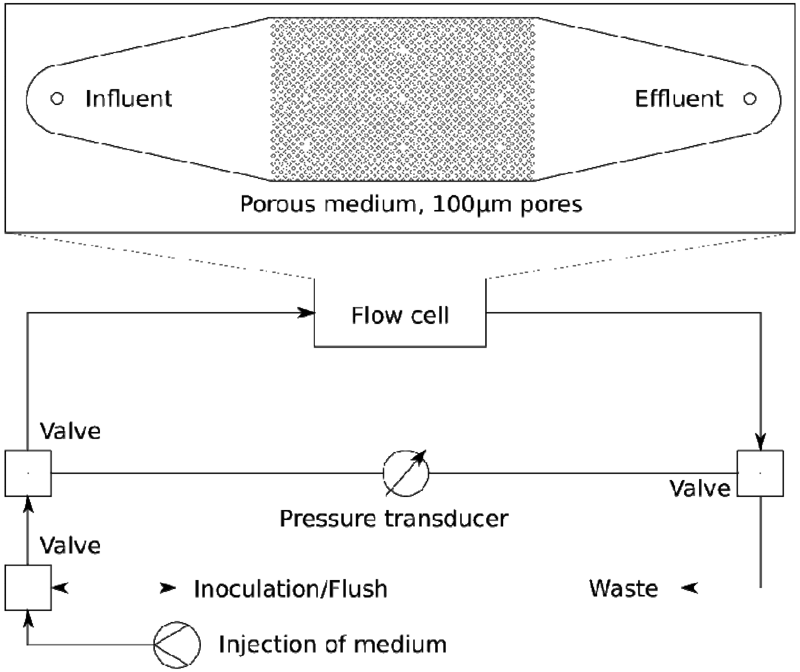
- Direct effects of biofilm on SIP signature

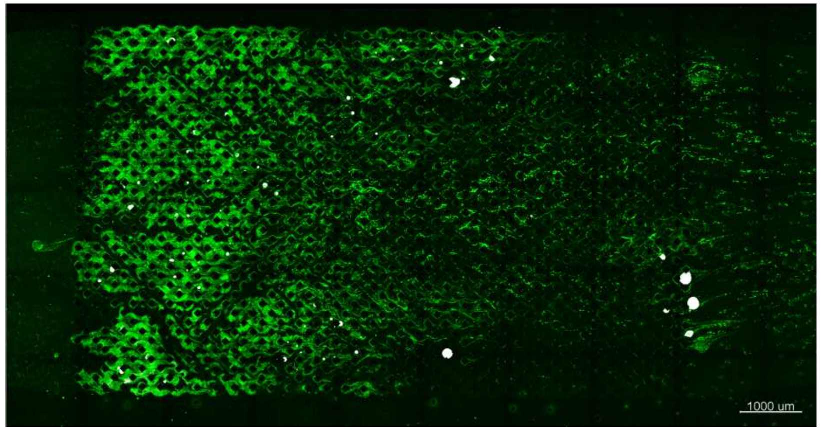


Pilawski et al. (2016)

- Indirect effects of biofilms on SIP signature
  - Changes in porosity
  - SIP signature of mineral precipitates
  - (Bio-)chemical reactions

Experimental approach





Connolly (2015)

- Millifluidic experiments
  - Ability to observe biofilm distribution, mineral precipitates, and perhaps even biochemical reactions and relate this to changes in SIP signature and permeability.

- Time-lapse EIT measurements at Ploemeur site, where zones with abundant biofilm activity has been observed in boreholes.

ESR13: Fully Coupled Hydrogeophysical Inversion of 3-D Tracer Tomography using Temporal Moments and Ensemble Kalman Filtering

Olaf A. Cirpka & Carsten Leven

University of Tübingen · Center for Applied Geoscience

Electrical Resistivity Tomography (ERT) Monitoring of Salt-Tracer Tests

- Test site Lauswiesen with several pumping & many observation wells
- Forced-gradient tracer tests
- NaCl + fluorescein as tracer
- Direct observation of fluorescein & heads
- Indirect observation of NaCl by cross-borehole ERT

1. Groundwater Flow Equation

$$S\frac{\partial h}{\partial t} - \nabla\cdot\left(K\nabla h\right) = \sum_{i=1}^{n_w} Q_i^{(w)}\delta\left(\mathbf{x}-\mathbf{x}_i^{(w)}\right)$$

2. Advection-Dispersion Equation

$$\theta\frac{\partial c}{\partial t} + \mathbf{q}\cdot\nabla c - \nabla\cdot\left(\theta\mathbf{D}\nabla c\right) = 0$$

3. Archie‘s Law

$$\sigma = a^{-1}\sigma_w S^n \vartheta^m = \sigma_0 + \kappa c$$

4. Poisson Equation

$$\nabla\cdot\left(\sigma\nabla\varphi\right) = I\left(\delta\left(\mathbf{x}-\mathbf{x}_o\right) - \delta\left(\mathbf{x}-\mathbf{x}_i\right)\right)$$

Insights from Preceding Studies

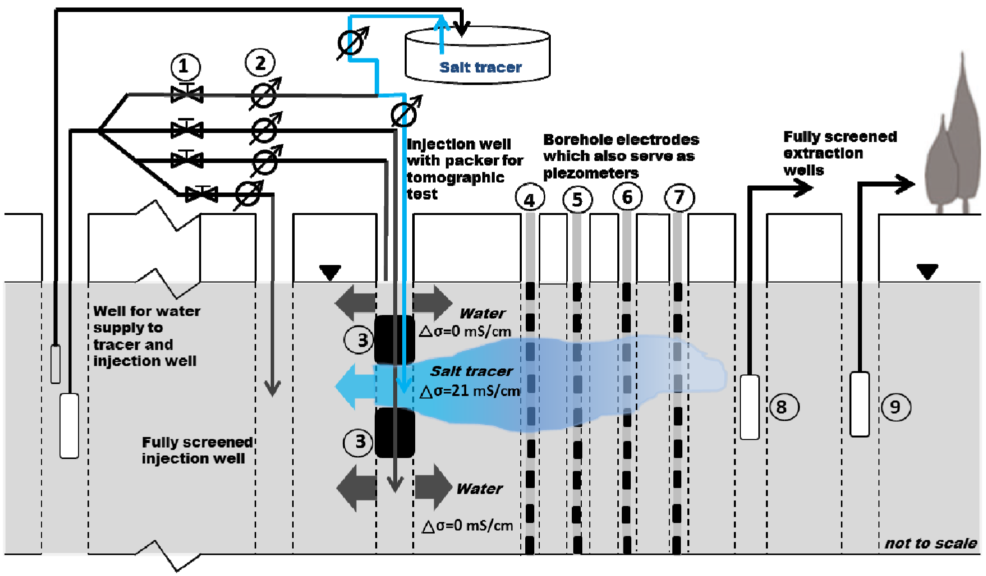
- Analyze mean arrival time rather than time series of ERT signals
  - ⇨ Condensation of data
  - ⇨ High sensitivity w.r.t. hydraulic conductivity
  - ⇨ Low sensitivity w.r.t. formation factor in Archie's law
- Temporal moment-generating equations
- Geostatistical regularization
- Gauss-Newton method

- Moment-generating equations require steady-state flow
  - – Works in the lab, less so in the field
- Gauss-Newton method requires sensitivity of all measurements w.r.t. all parameters
  - ⇨ Many adjoint equations
  - ⇨ Cumbersome programing

☝ Compute temporal moments in transient flow and use EnKF for its inversion

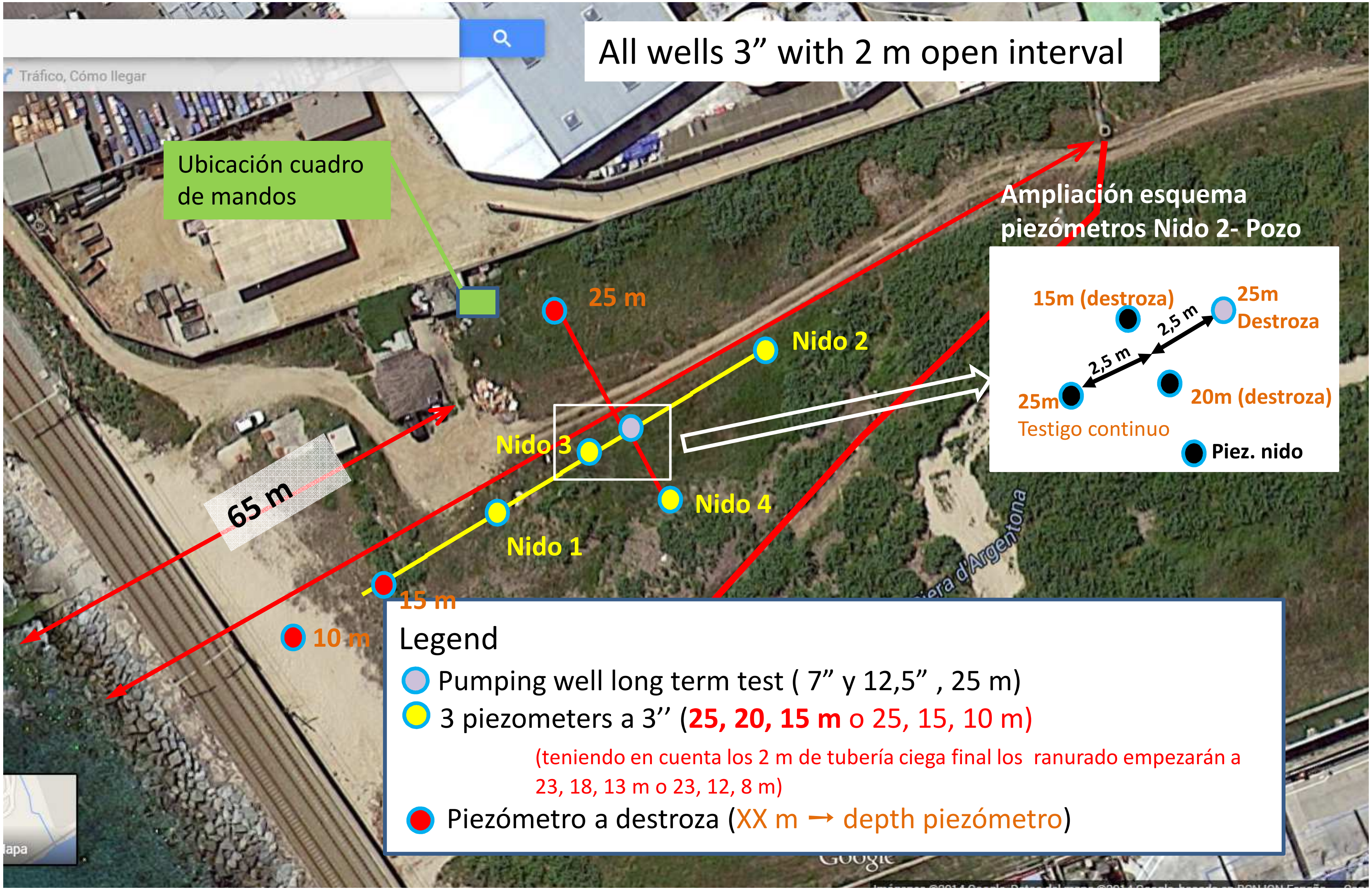
Work Program

- Perform pumping and tracer tests in tomographic setups
- Many issues of field work are resolved



- Adapt EnKF codes to suit the type of measurements
- Various variants of EnKF and data handling (e.g., with temporal moments or full signals)
- Comparison to inversion using 4D-VAR techniques (nonlinear conjugate gradient methods) at University of Heidelberg

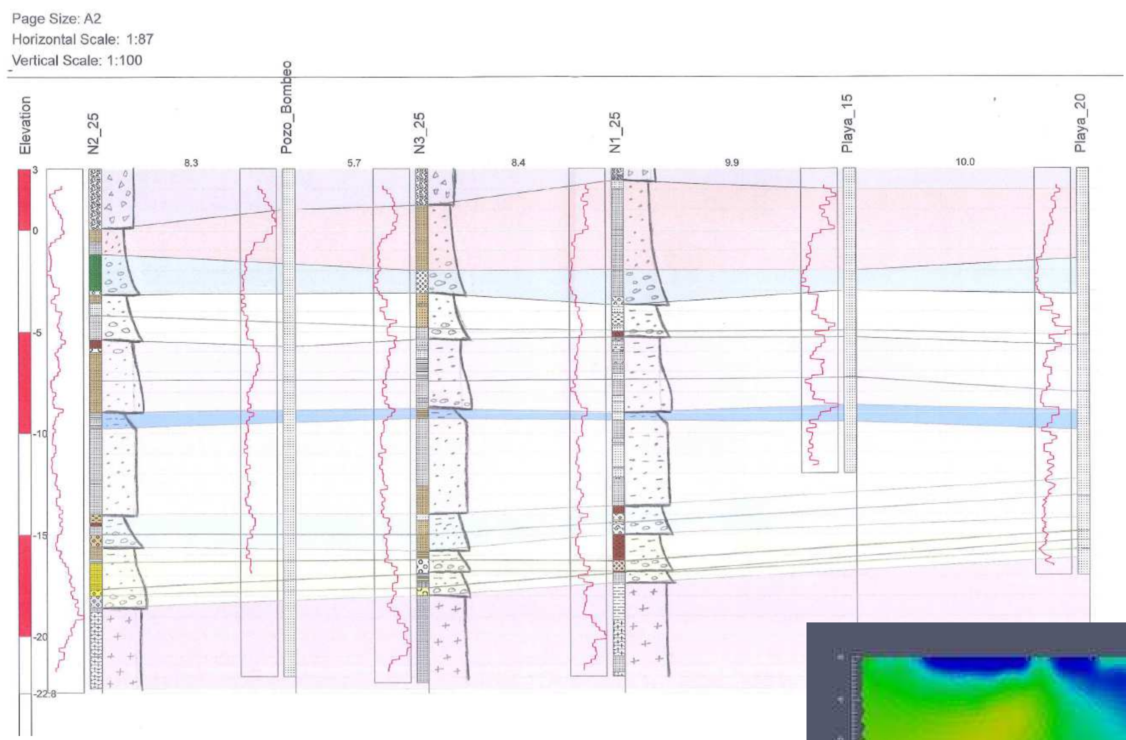
The Argentona site (some 40 km NE of BCN)



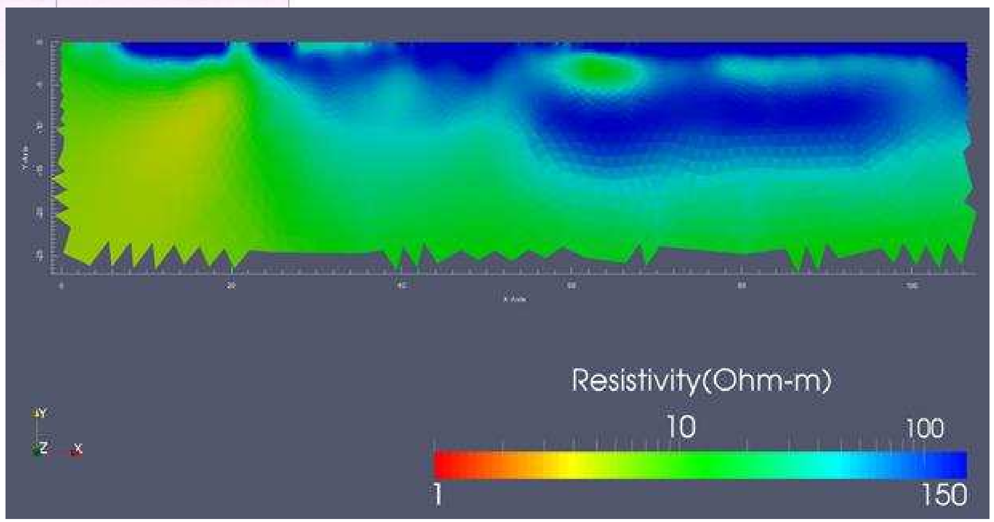


DROMADAIRE


Typical coastal sedimens geology



Prelim ERT



Geologically constrained joint inversion of hydraulic, tracer and ERT data for process visualization

- Effective integration of geological understanding into model inversion remains the single most challenging hurdle for reliable groundwater inversion.
- Including sequential stratigraphy concepts. Inversion will be based on optimizing model fit to hard data on state variables (T, h, C, V), of fields conditioned to categorical data (textural information from boreholes) and sequential stratigraphy concepts on continuity and orientation of layers.
- This will allow testing the validity of geological assumptions. The inversion should provide a detailed visualisation of the actual processes occurring in the field, which would allow us to gain understanding on these processes.
- The methodology of joint inversion will be developed in collaboration with ESRs 13 and 15.

- Pool et al. (2016). A comparison of deterministic and stochastic approaches for regional scale inverse modelling. Application to the Mar del Plata aquifer. J. of Hydrol.