High-resolution characterization of the induced fracture network around galleries in the Callovo-Oxfordian Clay

using

4-D numerical borehole analysis and pneumatic tomography approaches

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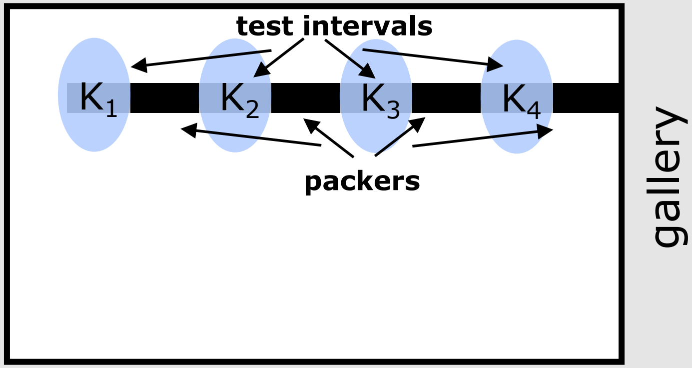
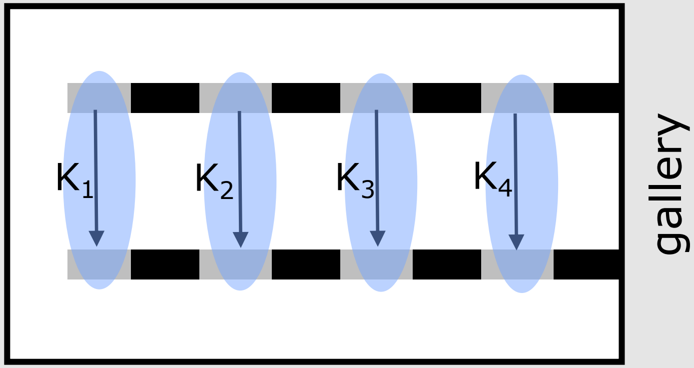
Spatially high rsolution hydraulic testing: Concepts (I)

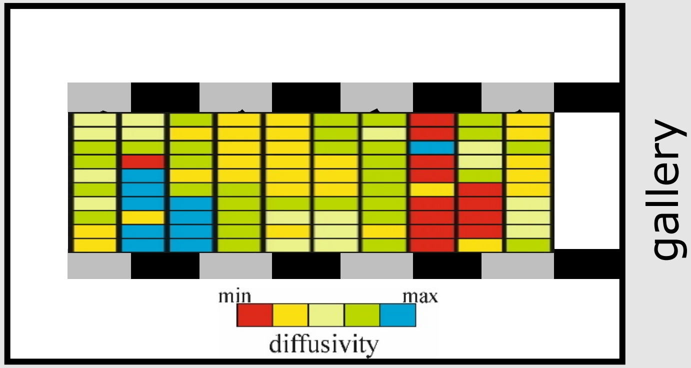
Hydraulic single-well tests



Hydraulic cross-well tests

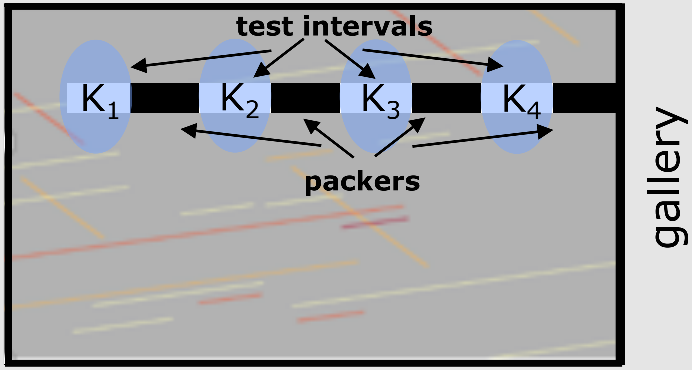


Hydraulic Tomography

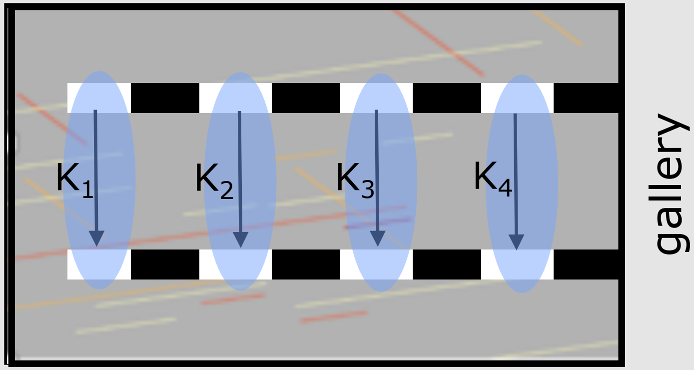


Spatially high rsolution hydraulic testing: Concepts (II)

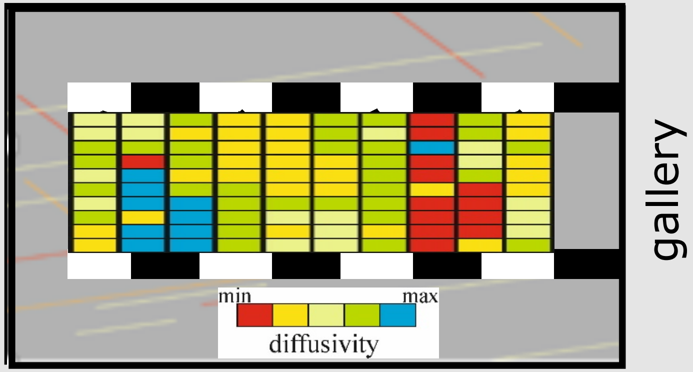
Hydraulic single-well tests



Hydraulic cross-well tests



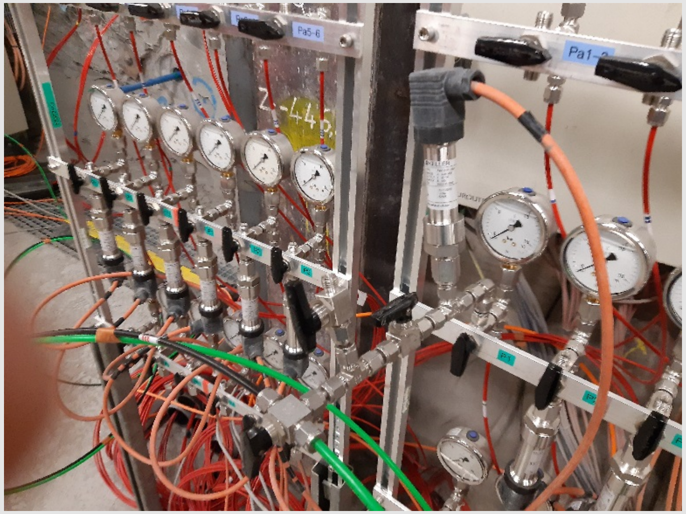
Hydraulic Tomography



Advantages of Hydraulic Tomography:

- Direct measurement
- Proof of hydraulic fracture connectivity
- Spatially high resolution parameter estimates

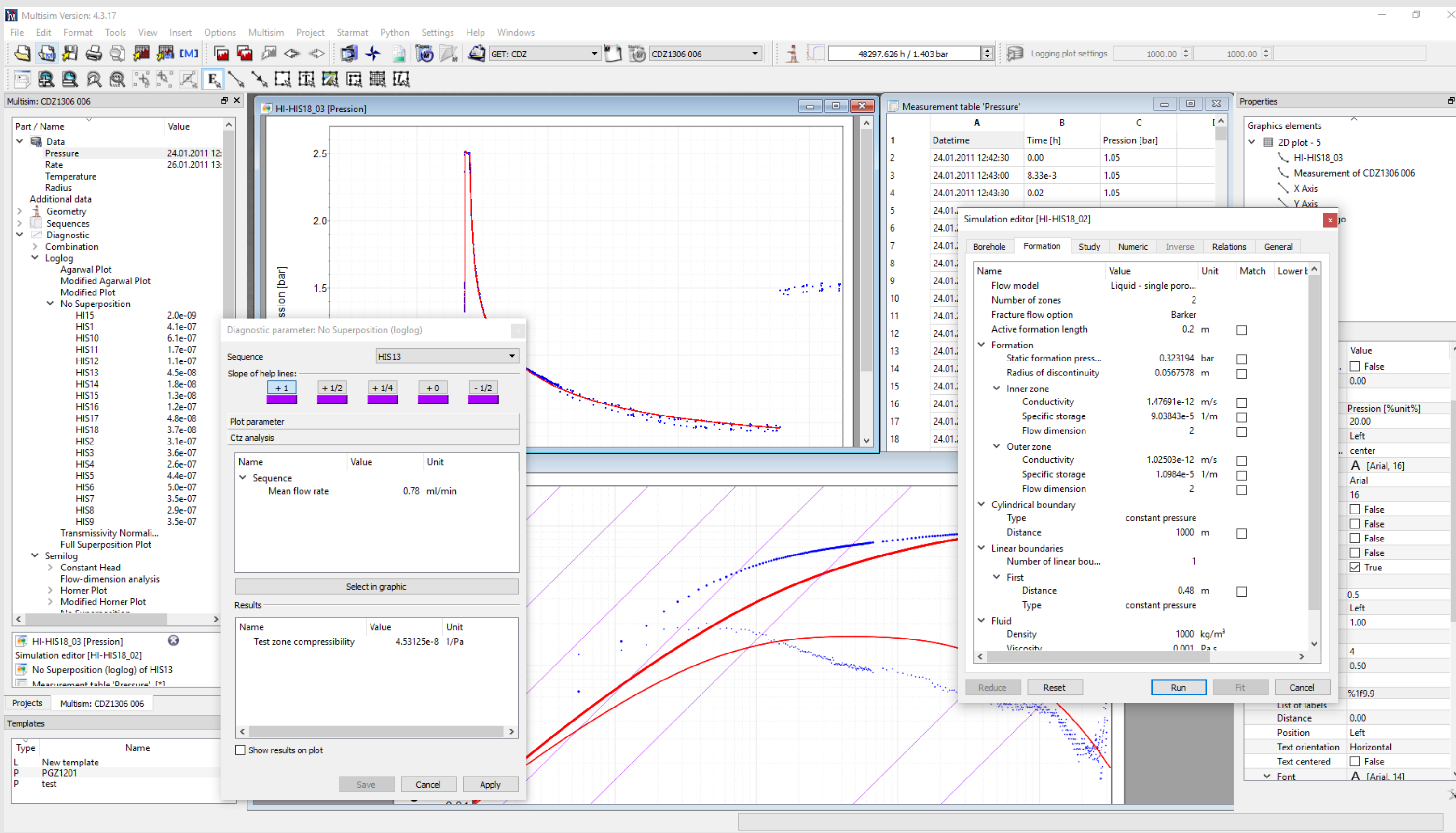
Spatially high resolution hydraulic testing: equipment



Multi-packer system **Interval and Packer** **Control unit**

Multisim

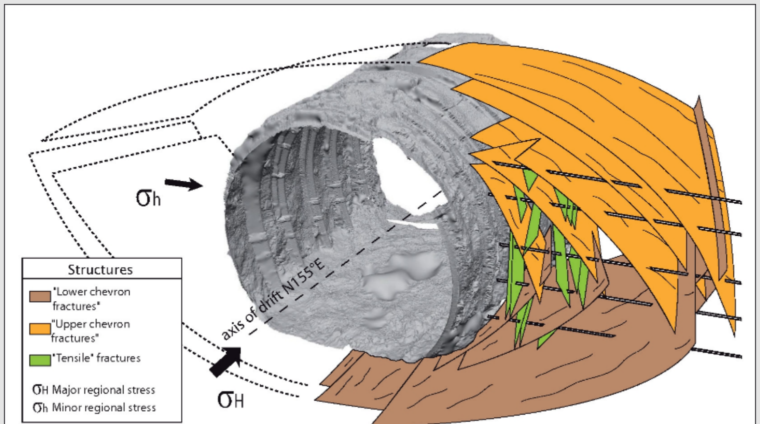
inhouse borehole simulator



Hydraulic/pneumatic tomography:

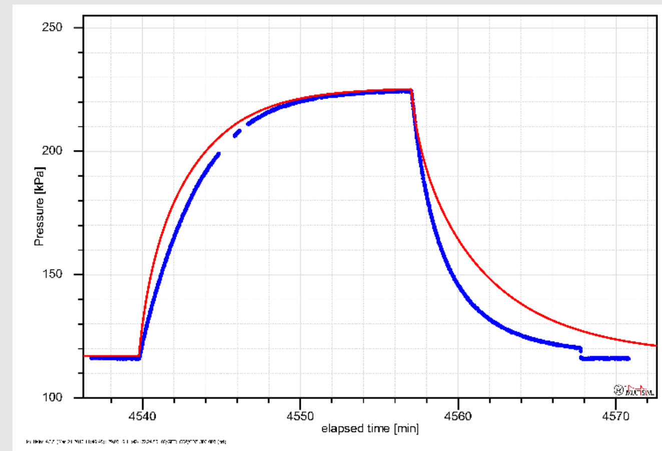
- A useful tool for characterizing the EDZ (evolution)?

Conceptual model of the EDZ

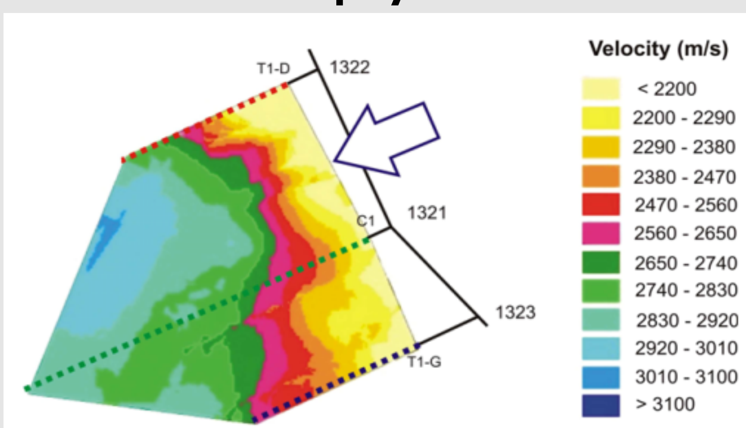


de la Vaissièrre et al., 2015

Conventional hydraulic testing

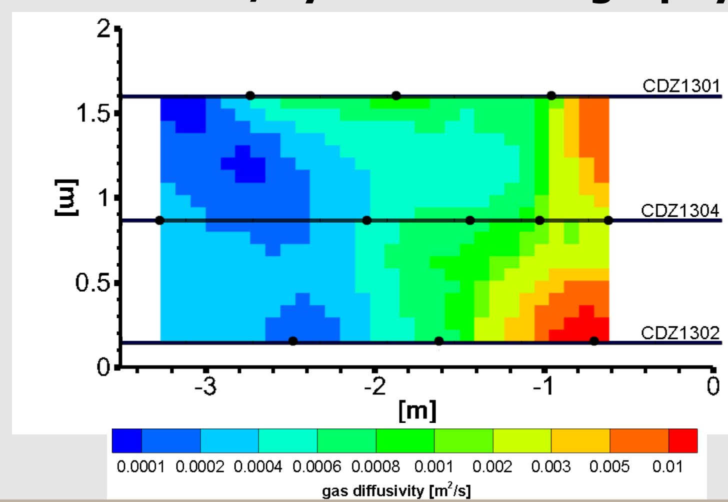


Geophysics

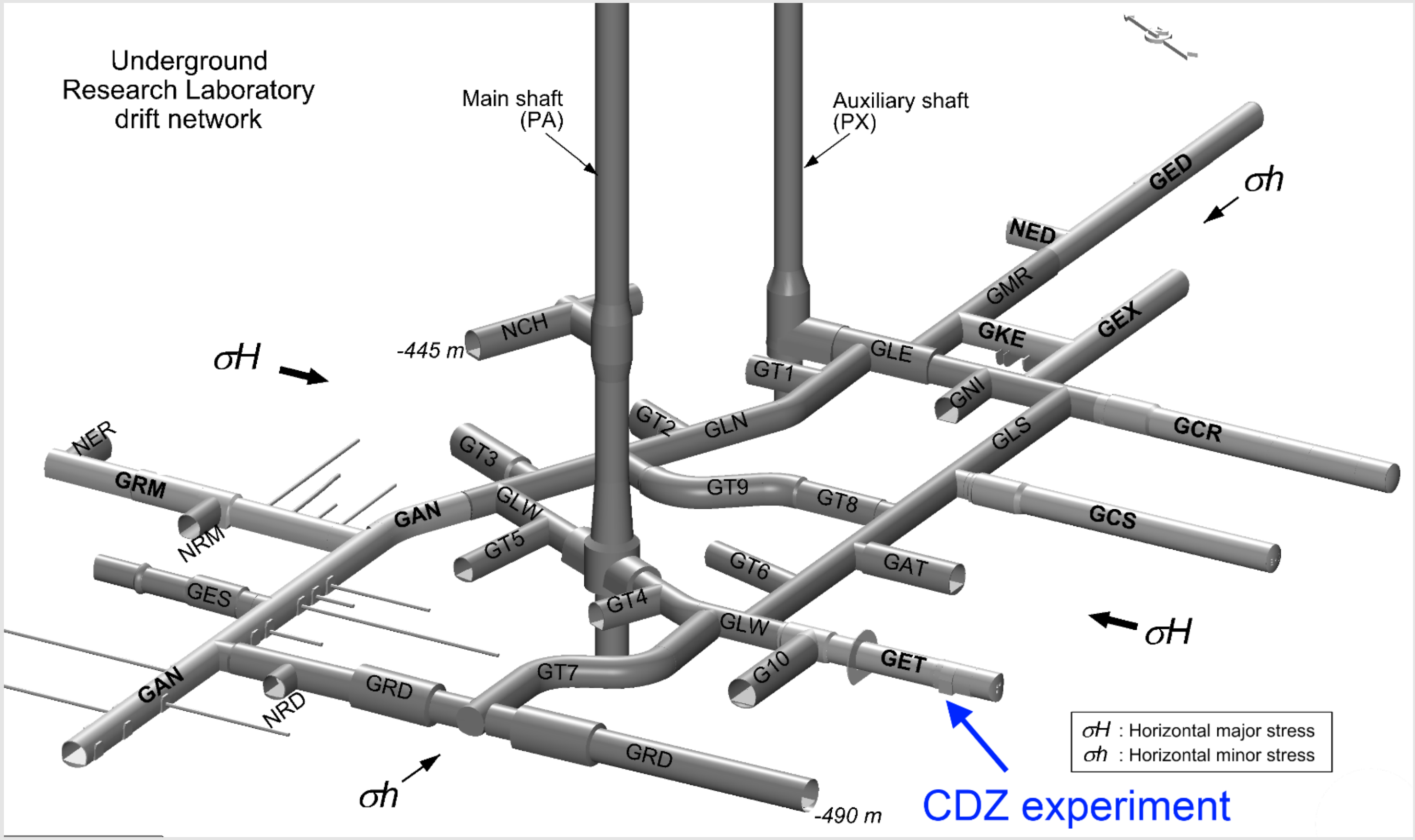


de la Vaissièrre et al., 2014

Pressure/hydraulic tomography



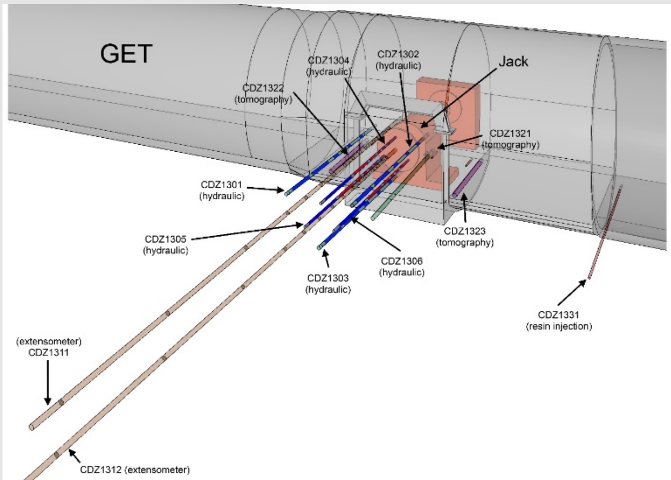
The Meuse /Haute Marne Underground Research Laboratory



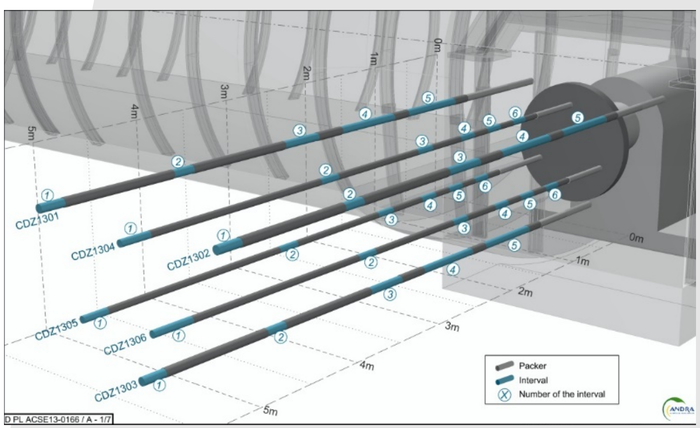
de la Vaissière et al., 2015, J. Hydrol

Experimental set-up

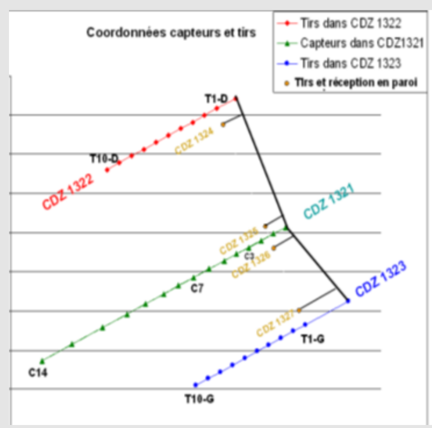
CDZ-Experiment (Compression of the Damage Zone)

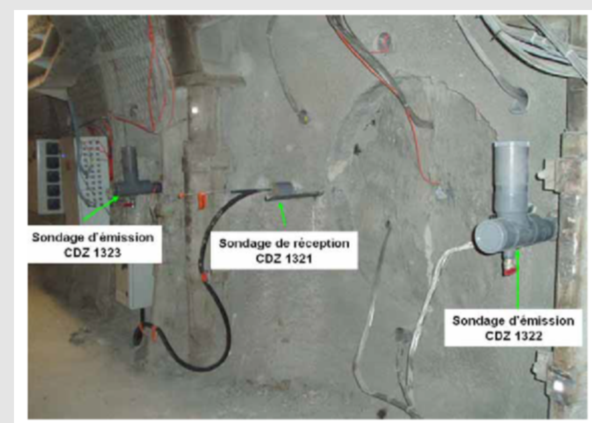


de la Vaissière et al., 2015, J. Hydrol



6 boreholes with multi-packers (3 under the plate the others outside)



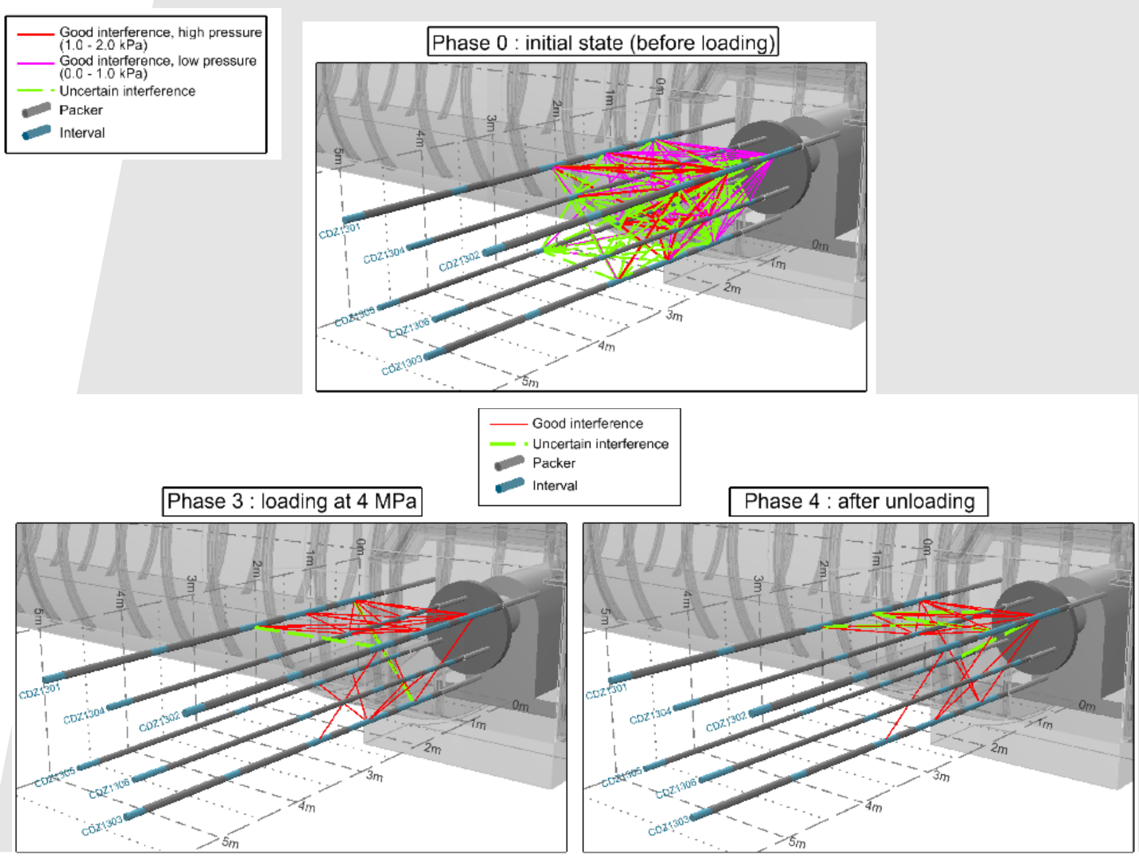


3 boreholes for seismic tomography

Evolution of the damage zone under loading

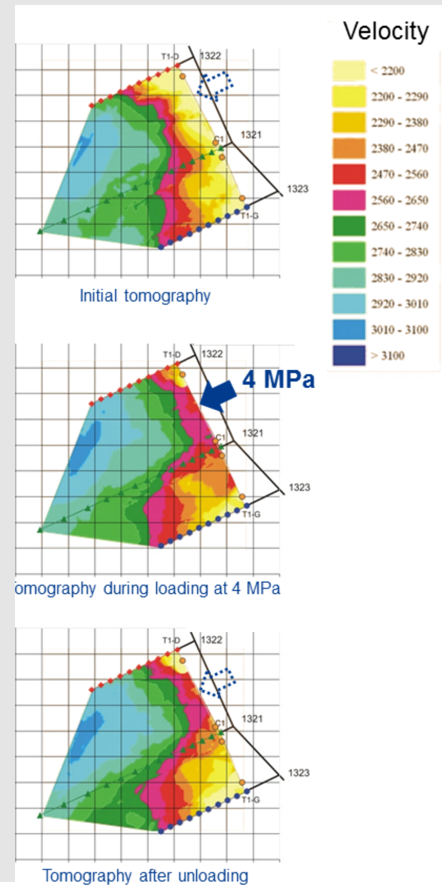
Cross-holes interferences results

- Number of interferences decreases during the loading



Seismic tomography results

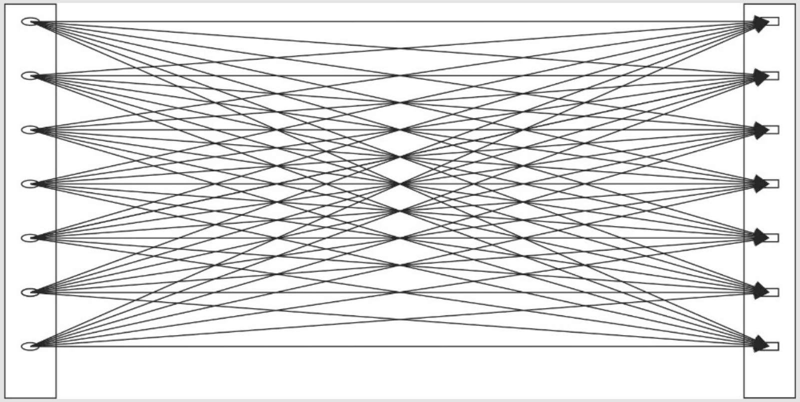
- the velocities increase by several hundreds of m/s below the loading area



de la Vaissière et al., 2015, J. Hydrol

de la Vaissièrre et al., 2014

Inversion technique



line integral (geophysical travel time tomography):

$$t = \int_{x_1}^{x_2} \frac{ds}{v(s)}$$

line integral (hydraulic travel time tomography):

Eikonal solver

$$\sqrt{t_{peak}(x_2)} = \frac{1}{\sqrt{6}} \int_{x_1}^{x_2} \frac{ds}{\sqrt{D(s)}}$$

$$\sqrt{t_{\alpha,d}} = \frac{1}{\sqrt{6 f_{\alpha,d}}} \int_{x_1}^{x_2} \frac{ds}{\sqrt{D(s)}}$$

Vasco et al., 2000, WRR

Brauchler et al., 2003, 2011 WRR

Data processing (I)

1. Wavelet denoising

$$s(k) = f(k) + \varepsilon * e(k)$$

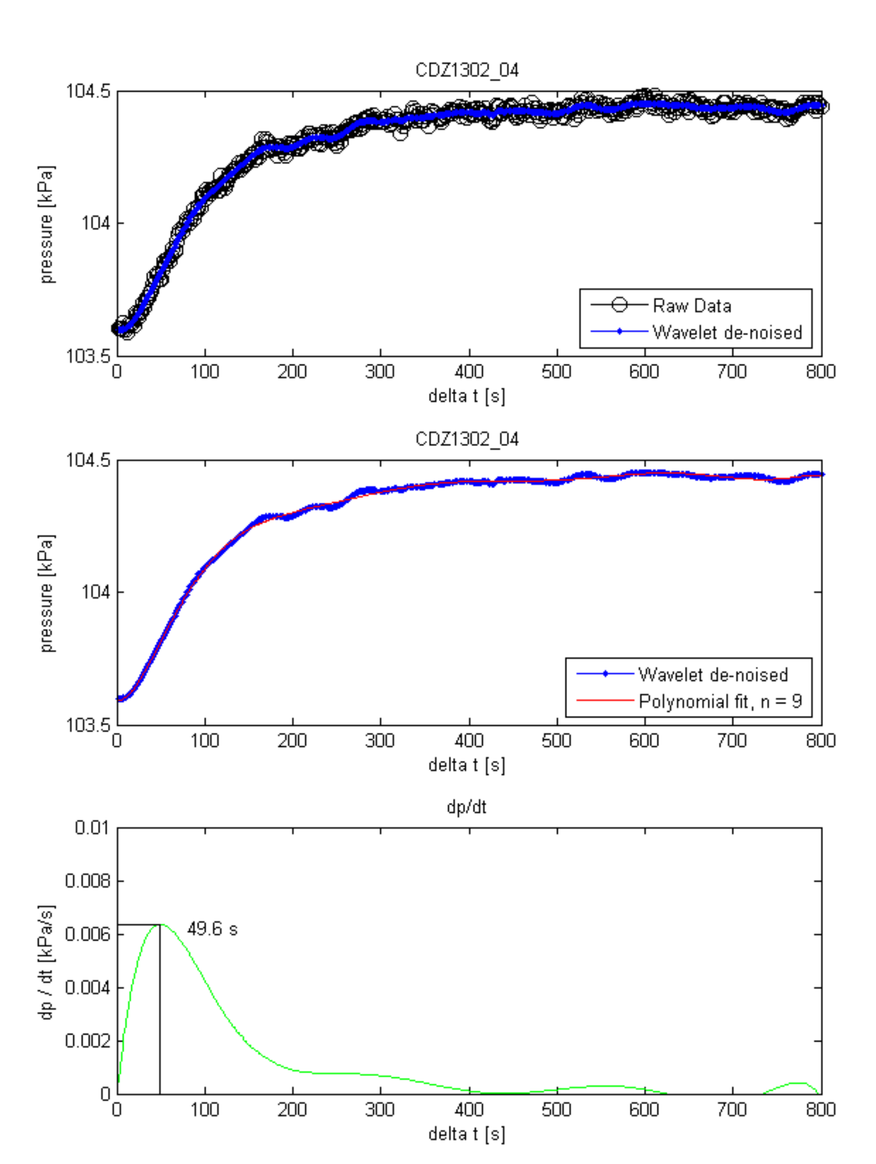
$f(k)$ *de-noised signal*

ε *wavelet coefficient*

$e(k)$ *noise*

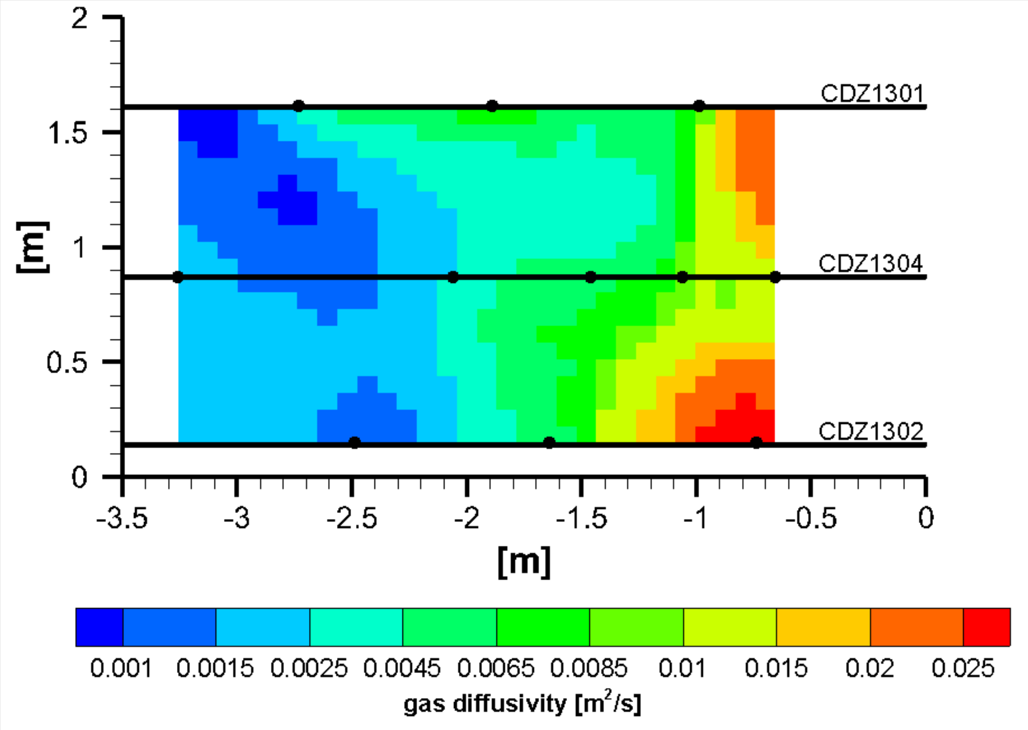
2. Polynomial regression

3. Derivative of the polynomial



Inversion results 2-D

Prior to loading, based on 28 interference signals



Zone 1:

- sub-vertical tensile fractures
- located between 0.6m and 1m away from the drift wall

Zone 2:

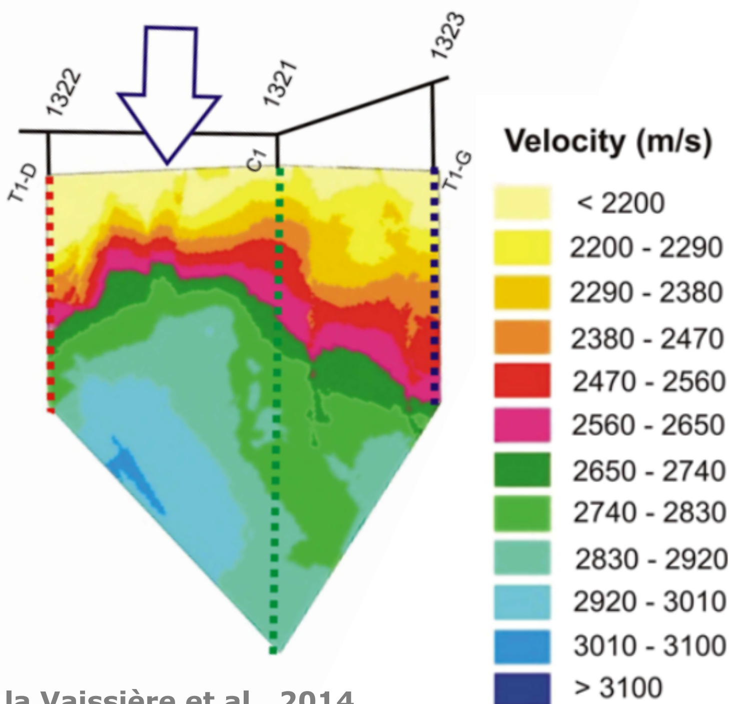
- “impregnated” shear fractures
- located between 1m and 1.5m away from the drift wall

Zone 3:

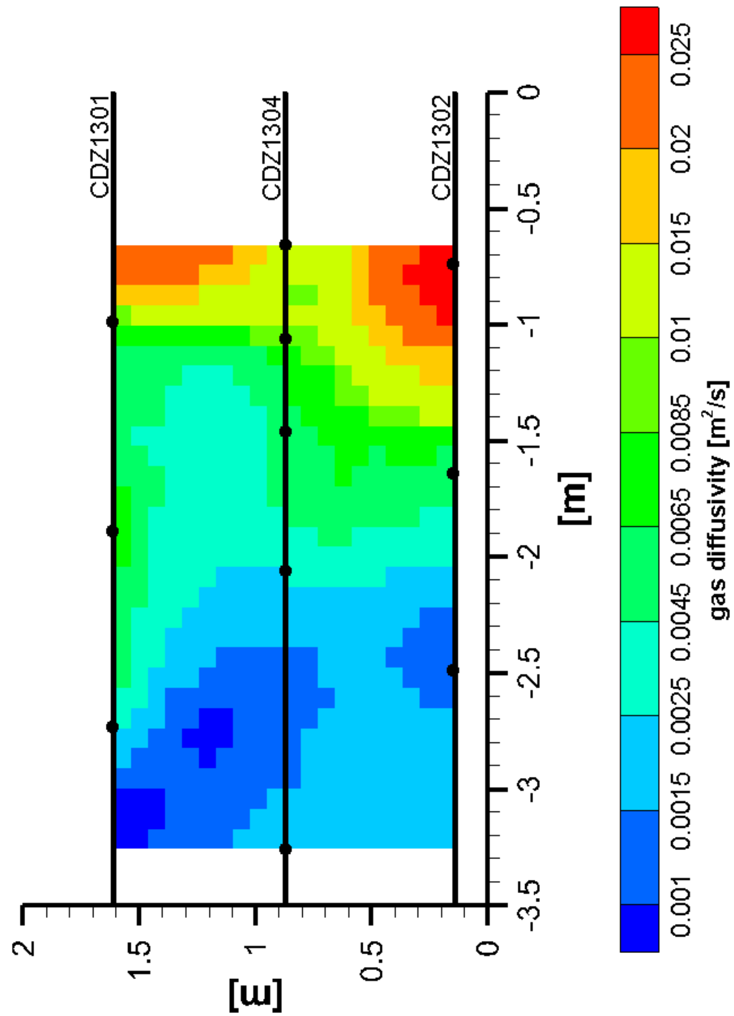
- “non-impregnated” shear fractures
- located more than 2m away from the drift wall

Comparison of seismic and diffusivity tomograms

Qualitative interpretation

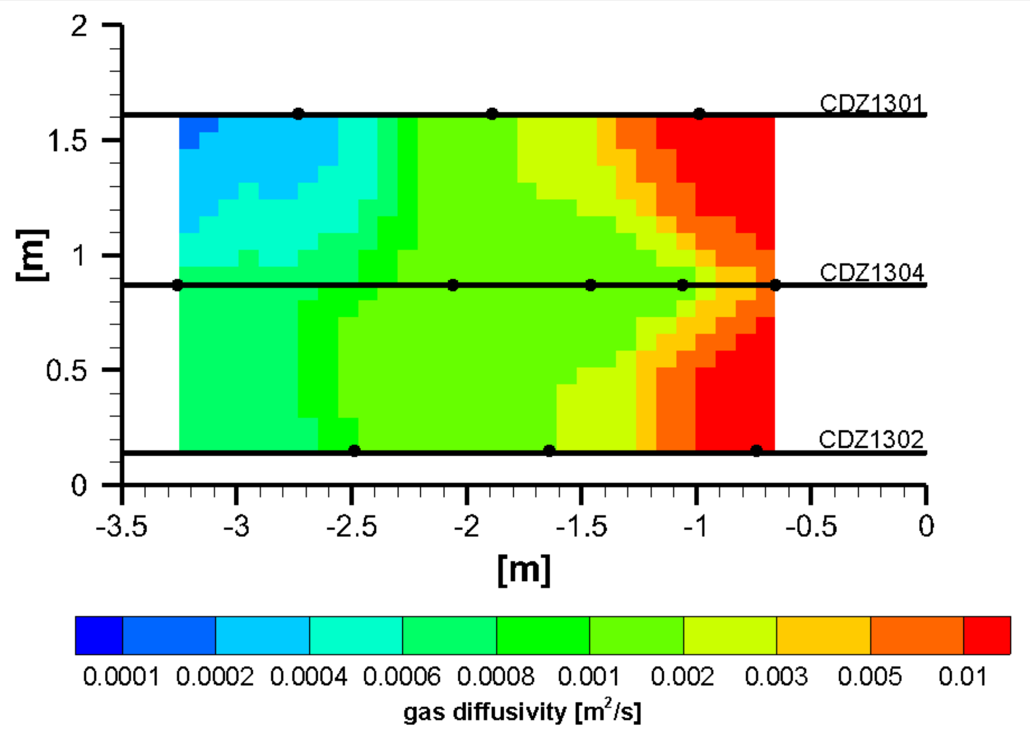


de la Vaissière et al., 2014



Inversion results 2-D

After loading cycle 1 of 2 MPa based on 27 interference signals



Zone 1:

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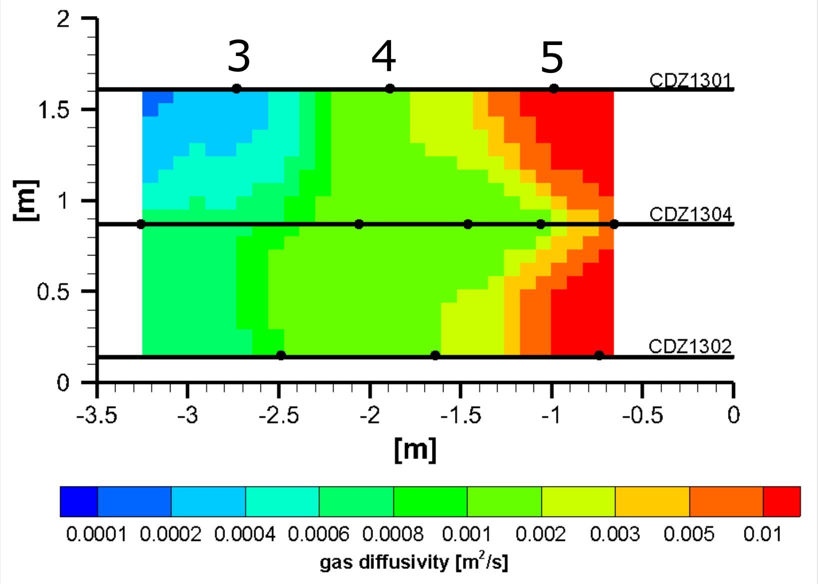
Inversion results 2-D

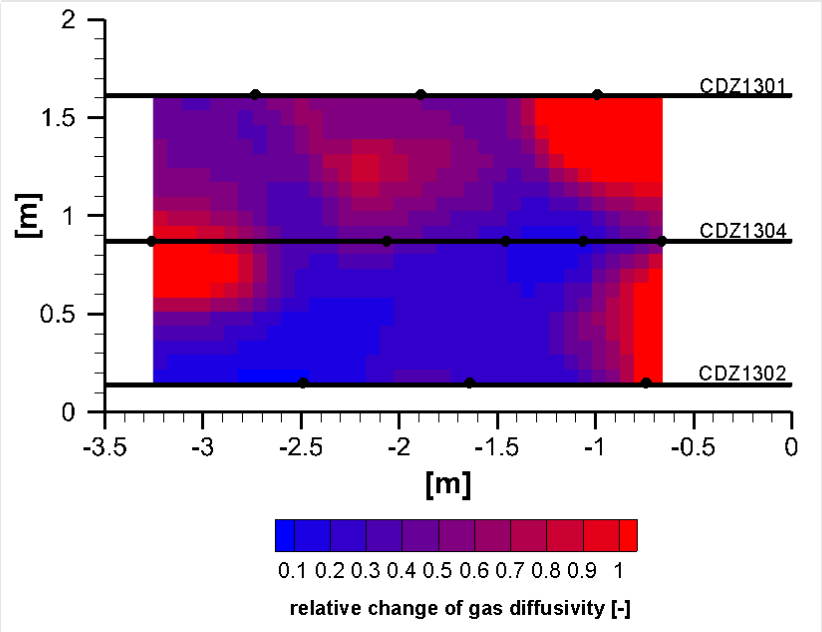
Comparison with single borehole gas tests

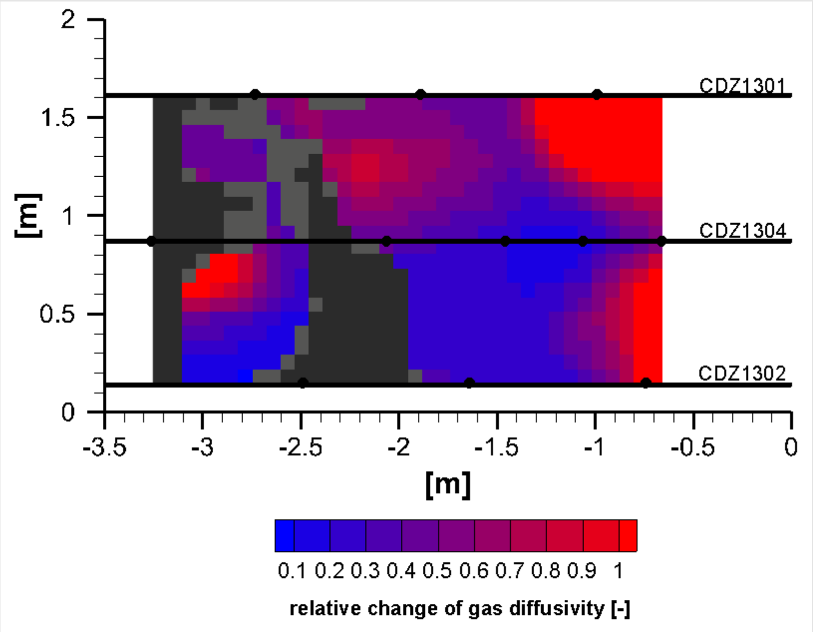


Hydraulic tomography	Permeability [m²]
Minimum value	2.6E-16
Maximum value	2.6E-14

2-D Relationship Tomogram

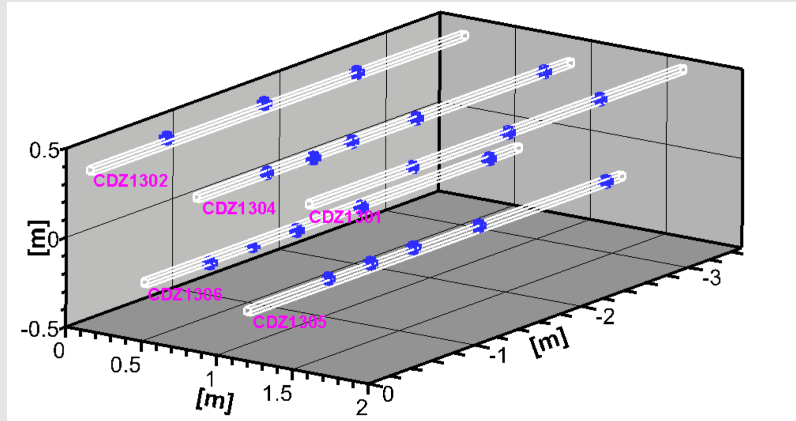
Comparison of the tomograms prior to loading and after loading step 1

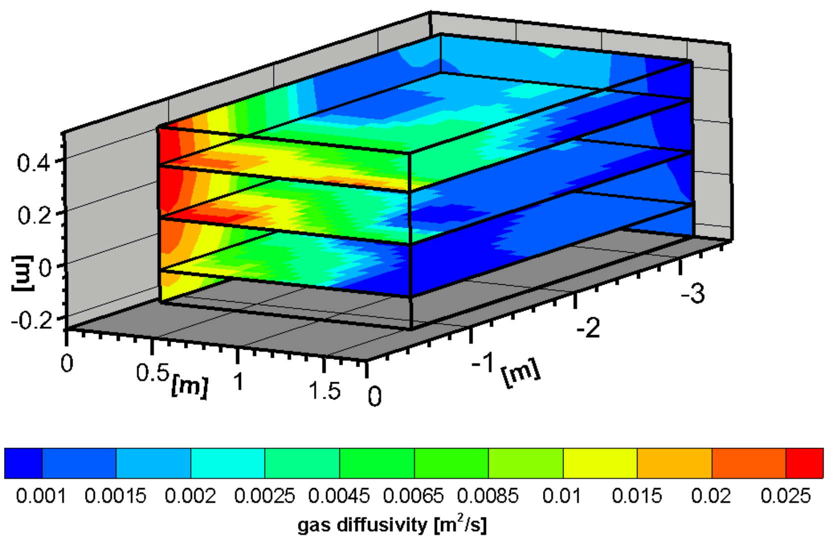




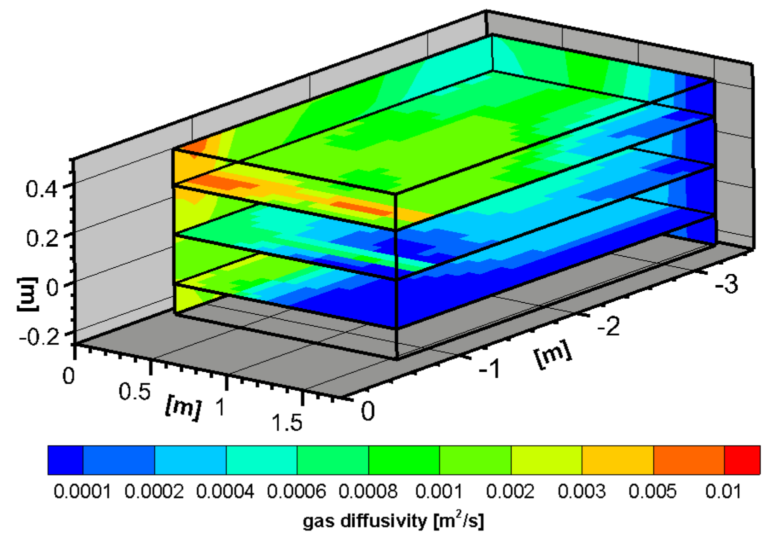
Inversion results 3-D

Prior to loading and after loading of 2 MPa





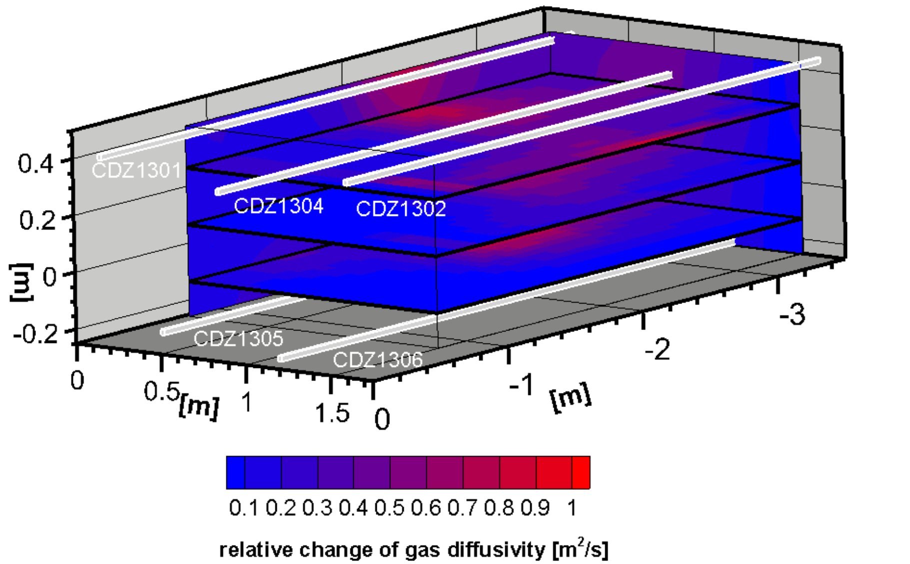
48 interference signals

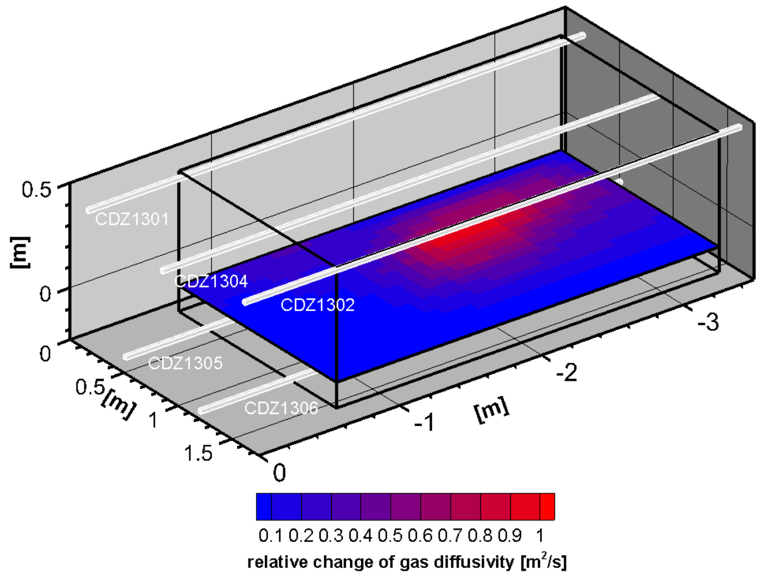


45 interference signals

3-D Relationship Tomogram

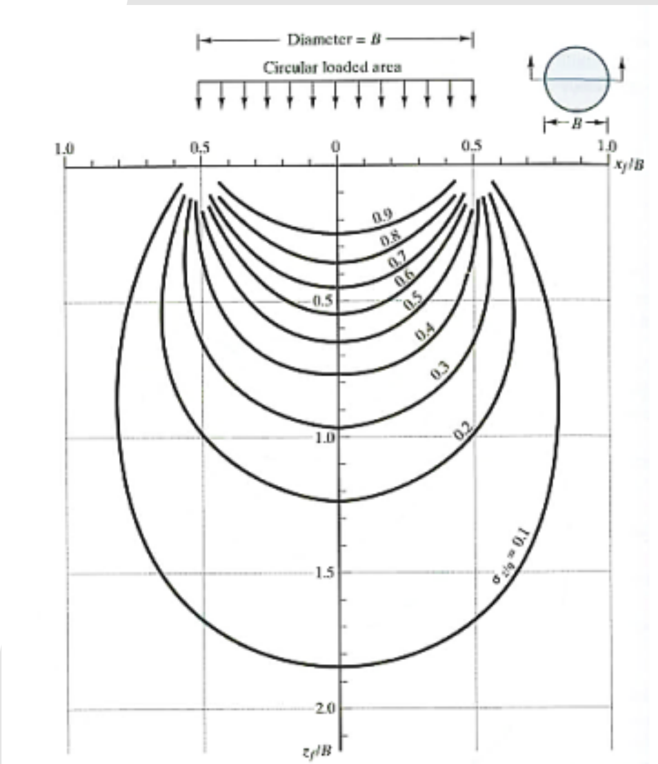
Comparison of the tomograms prior to loading and after loading step 1





3-D Relationship Tomogram

Comparison of the tomograms with the vertical induced stress beneath a circular loaded area, Boussinesq solution



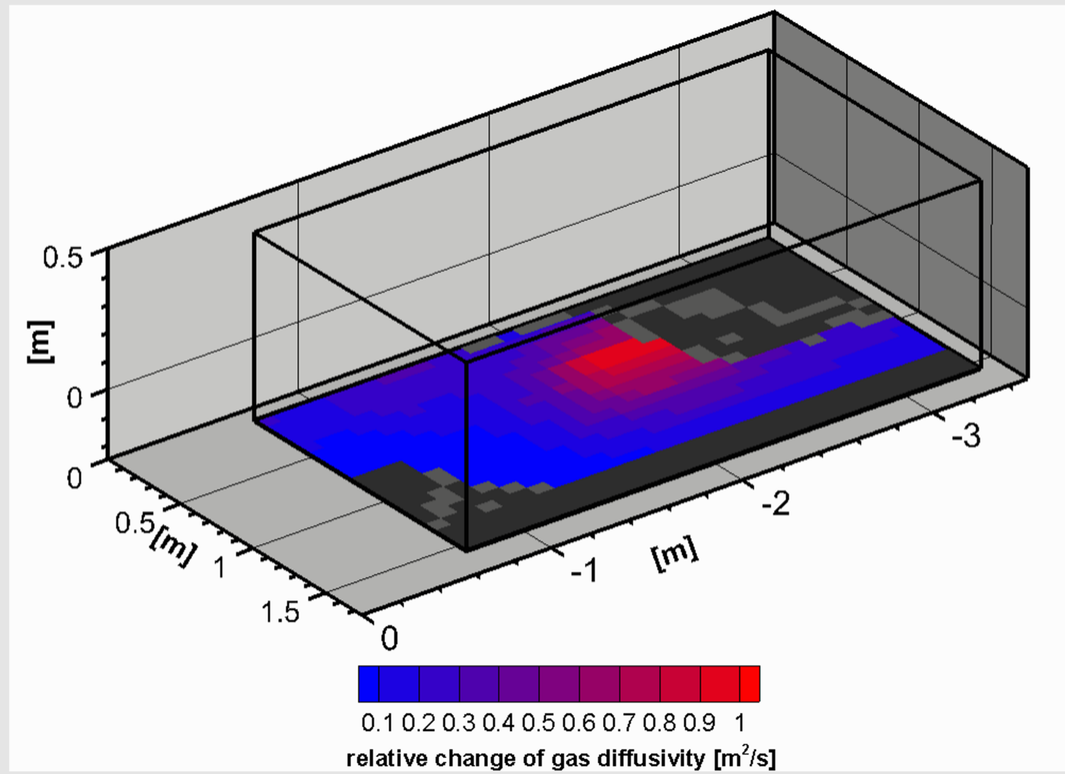


Figure 10.10, page 330 in Coduto [1999]

Summary

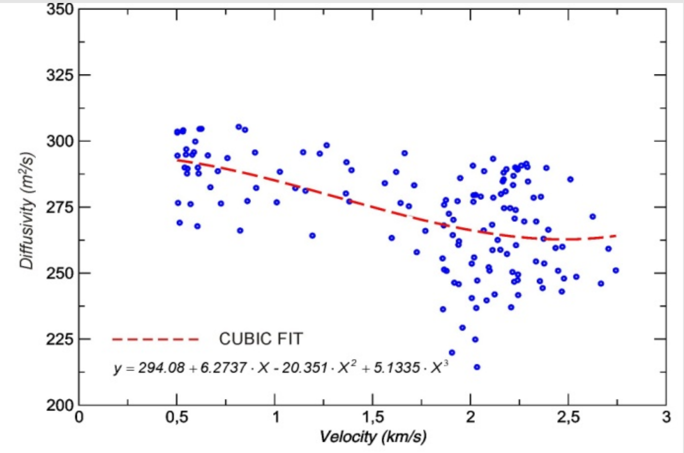
- **Hydraulic/pneumatic tomography: A useful tool for characterizing the EDZ (evolution)?** **YES**
  - reconstruction of hydraulic **changes orthogonal and parallel** to the drift wall with a **high spatial resolution**
  - the reconstructed diffusivity values are in accordance with numerical single-borehole analysis performed with the borehole simulator **Multisim**
  - the obtained diffusivity tomograms depicts **three different zones** of the **excavation-induced fracture network, which are in accordance with** the conceptual model

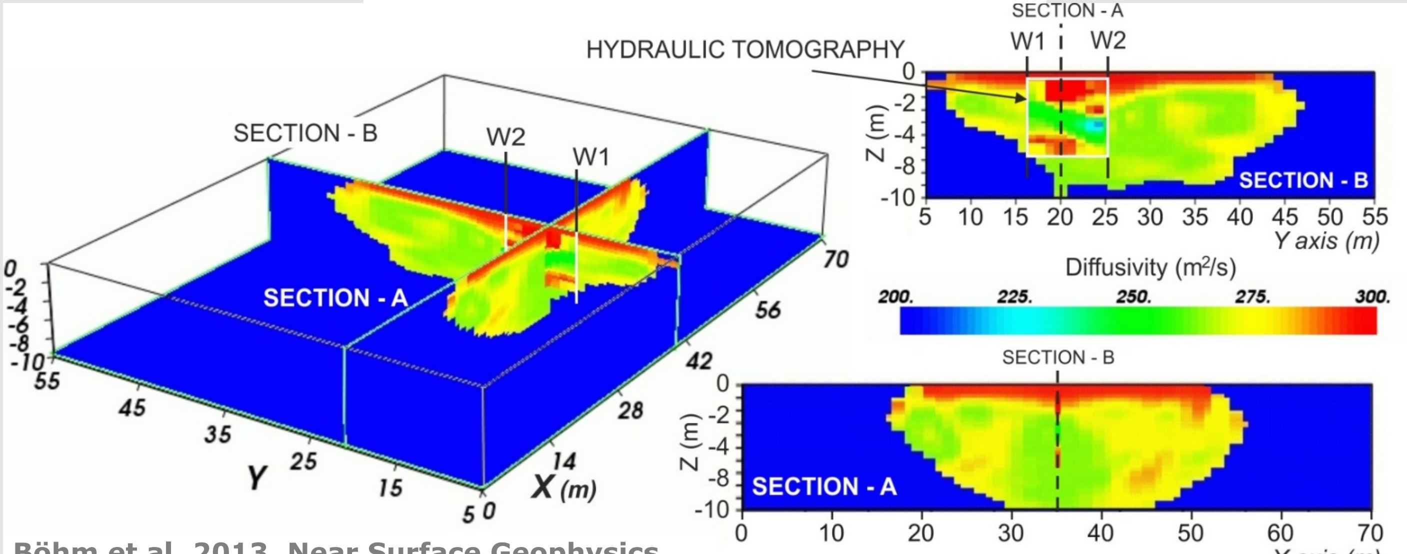
- **Relationship tomograms** show a **similar pattern** as the **vertical induced stress** beneath a circular loaded area **(Boussinesq solution)**

- **Strong positive correlation** between the reconstructed **diffusivity distribution and p-wave velocity**

Outlook

Site specific relationship: p-wave velocity - diffusivity





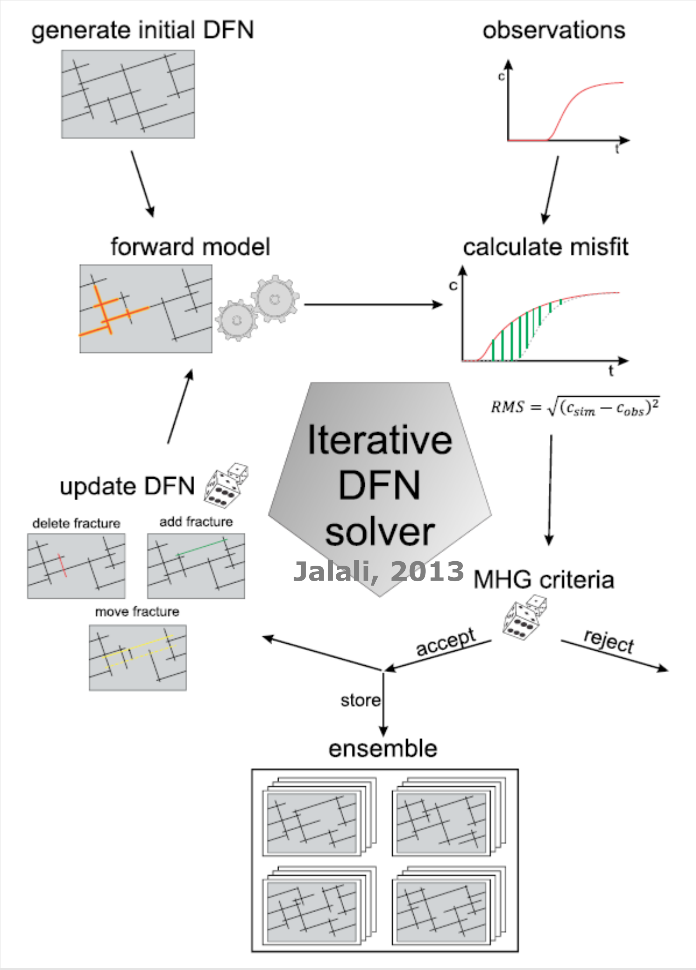
Böhm et al.,2013, Near Surface Geophysics

Outlook (II)

Discrete fracture inversion -Theory

- The inversion procedure is initiated by randomly generating a DFN realization based on the following **a priori information**:
  - The results of the **travel time based inversion**, derivation of potential positions of fractures and appraisal of the hydraulic properties
  - Statistical information: e.g. fracture length distribution, minimum fracture length, fracture orientation

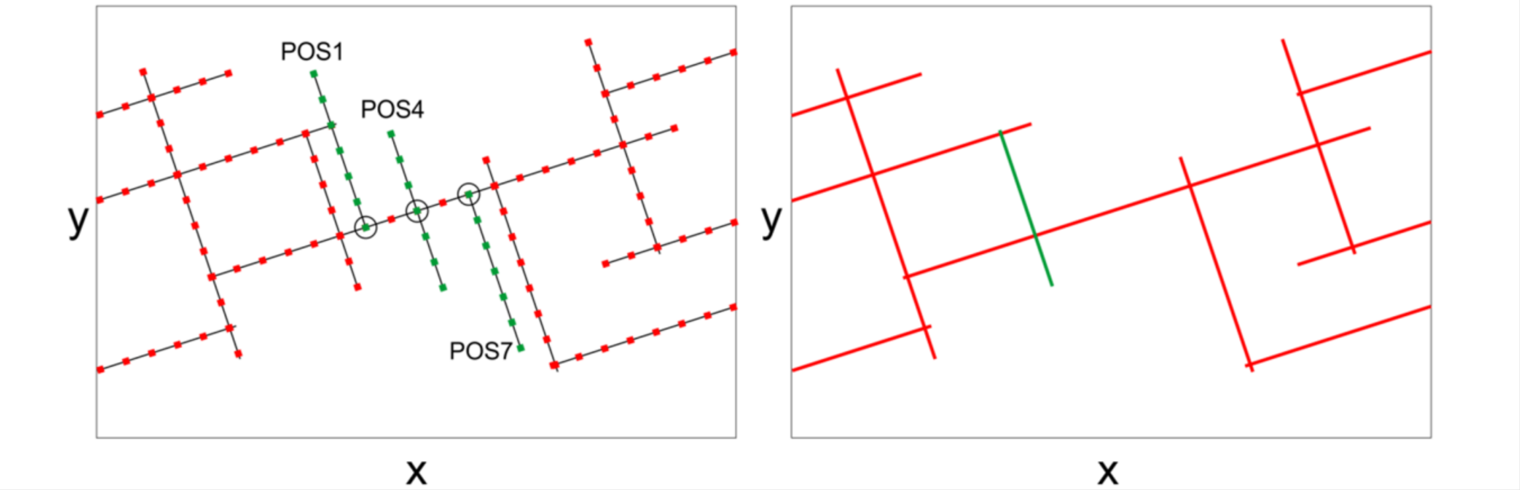
➢ The transdimensional reversible jump Markov Chain Monte Carlo (rjMCMC) is a unique variant of MCMC, in which the **number of parameters can vary among subsequent iterations** during the inversion process



Somogyvári et al., 2017 WRR

Outlook (III)

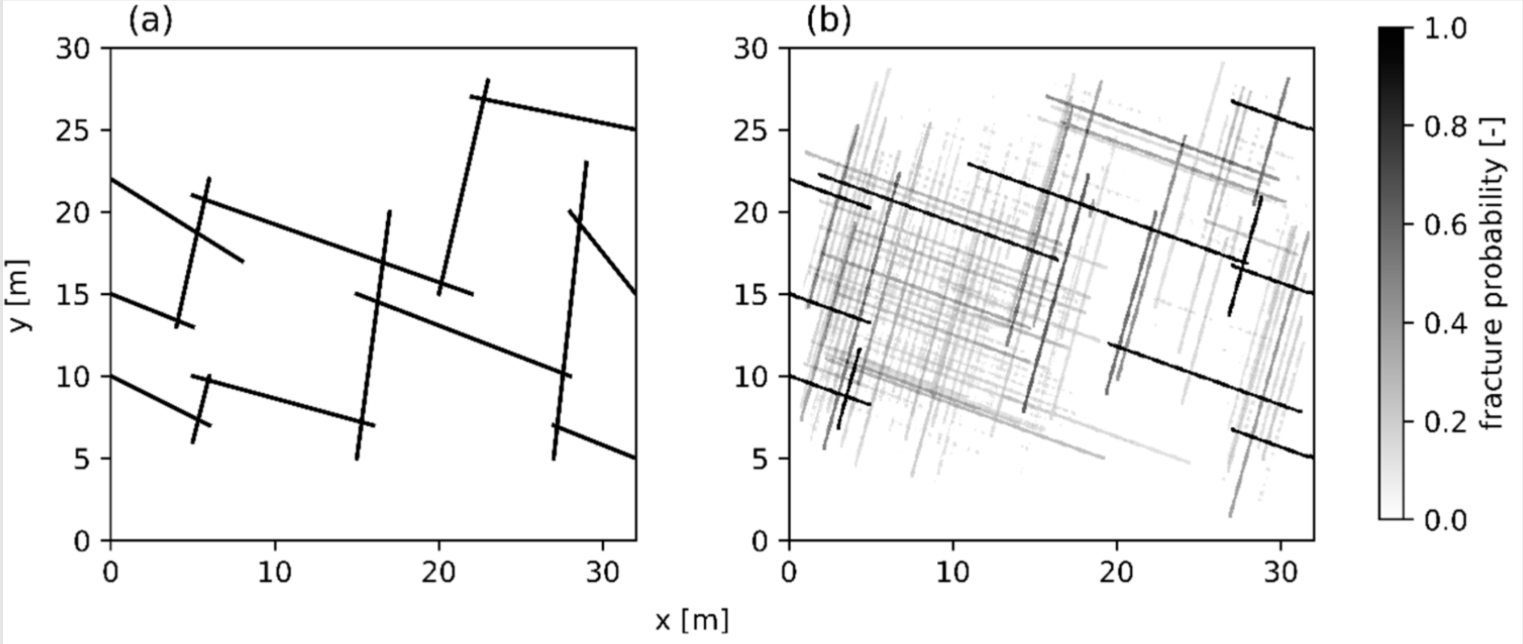
Transdimensional reversible jump Markov Chain Monte Carlo (rjMCMC) inversion



Somogyvári et al., 2017 WRR

Outlook (IV)

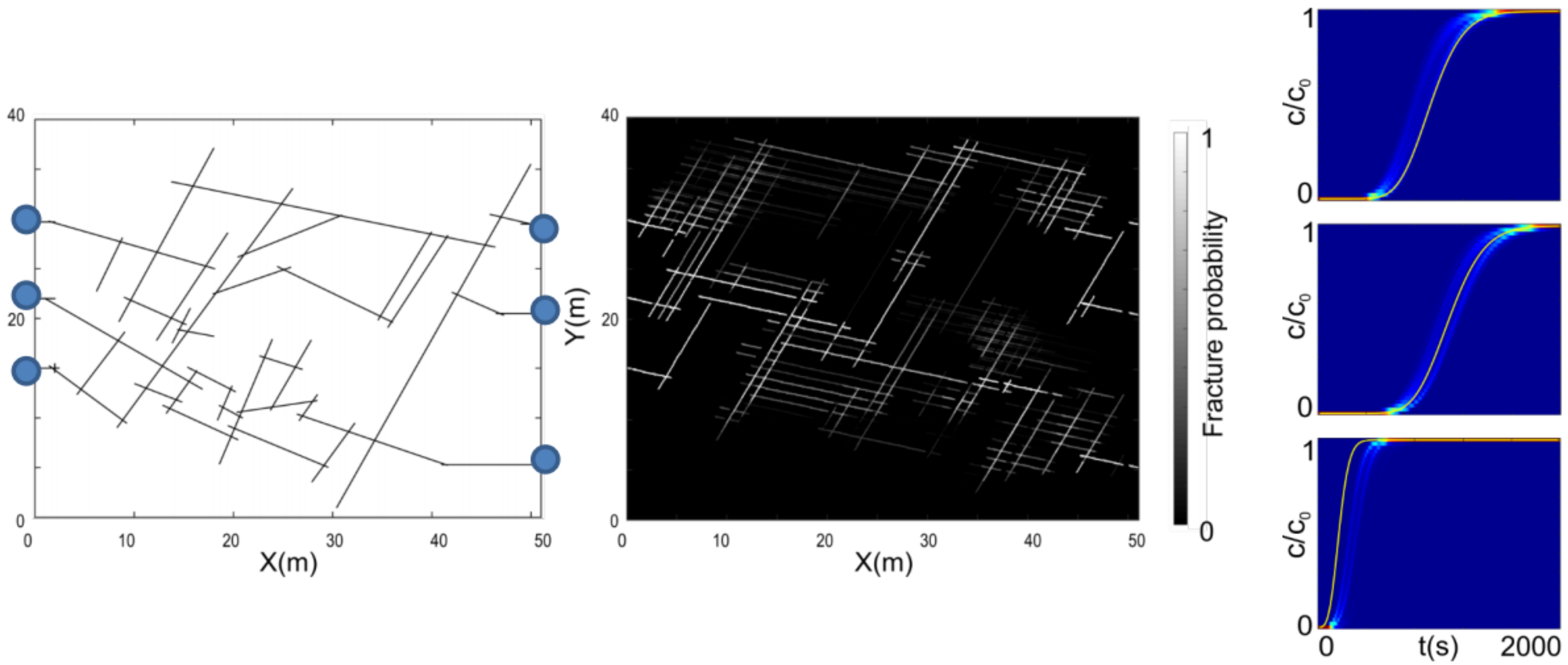
Discrete fracture inversion – pressure data



Ringel et al., 2019, Geoscieneces

Outlook (V)

Discrete fracture inversion – Tracer data



Somogyvári et al., 2017 WRR

Own selected references related to hydraulic tomography

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