Building reliable groundwater transport models at contaminated sites using cross-borehole electrical monitoring

Léa Lévy, Lund University, SWEDEN

Léa Lelimouzin (PhD student), Delphine Roubinet, Cédric Champollion, University of Montpellier (FRANCE)

Chloé Delbet (MSc student), Sorbonne University / Lund University

Line M. Madsen, Aarhus University, DENMARK

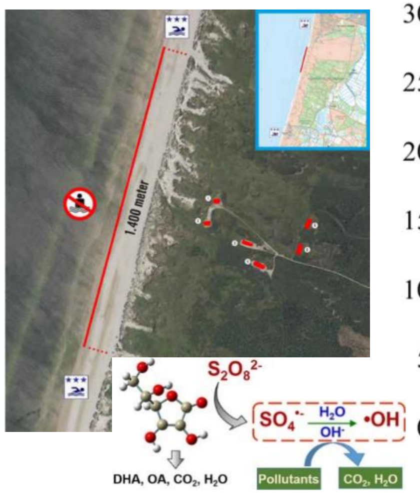
Thomas Günther, Leibniz Institute for Applied Geophysics, GERMANY

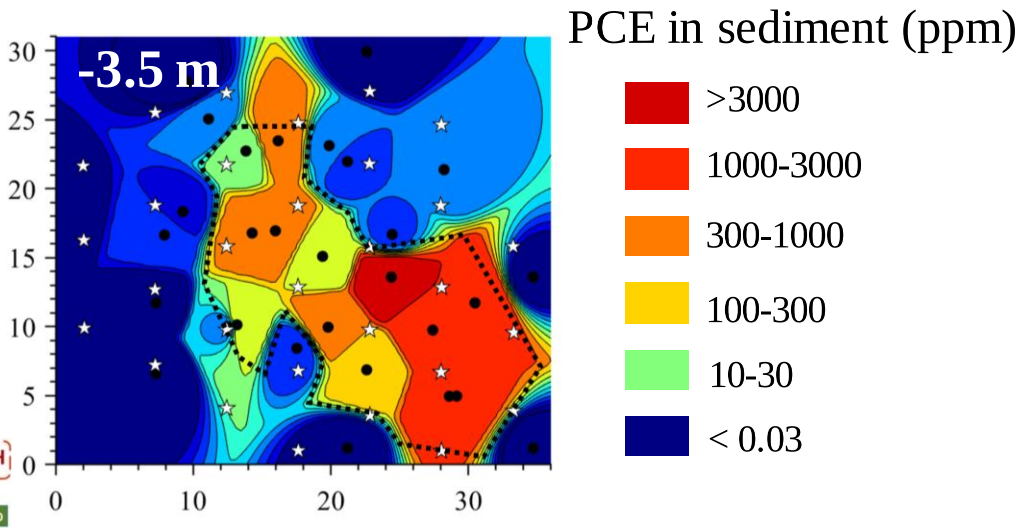
Poul L. Bjerg, Technical University of DENMARK

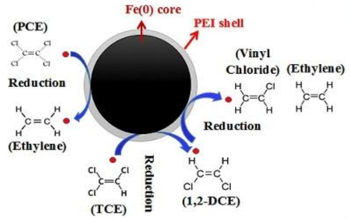
Nina Tuxen, Region Hovedstaden, DENMARK

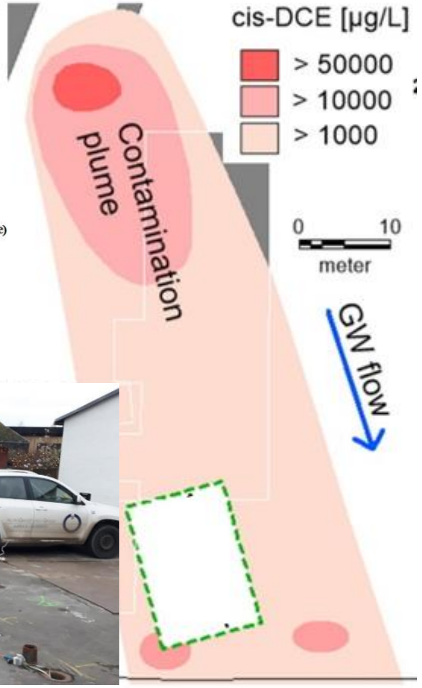
Groundwater contamination

- Main site : Farum "the parking lot"
  - Waste from packaging factory 1959-1989
  - Chlorinated solvents, hydrocarbons
  - In-situ reductive dechlorination: ZVI + carbon substrate + bacteria
- Comparison site: Kærgård "the beach"
  - 280.000 m3 of pharmaceutical waste 1956-1973
  - Chlorinated solvents, hydrocarbons, antibiotic, mercury, cyanide
  - In-situ chemical oxidation: peroxide activated persulfate (free radicals)

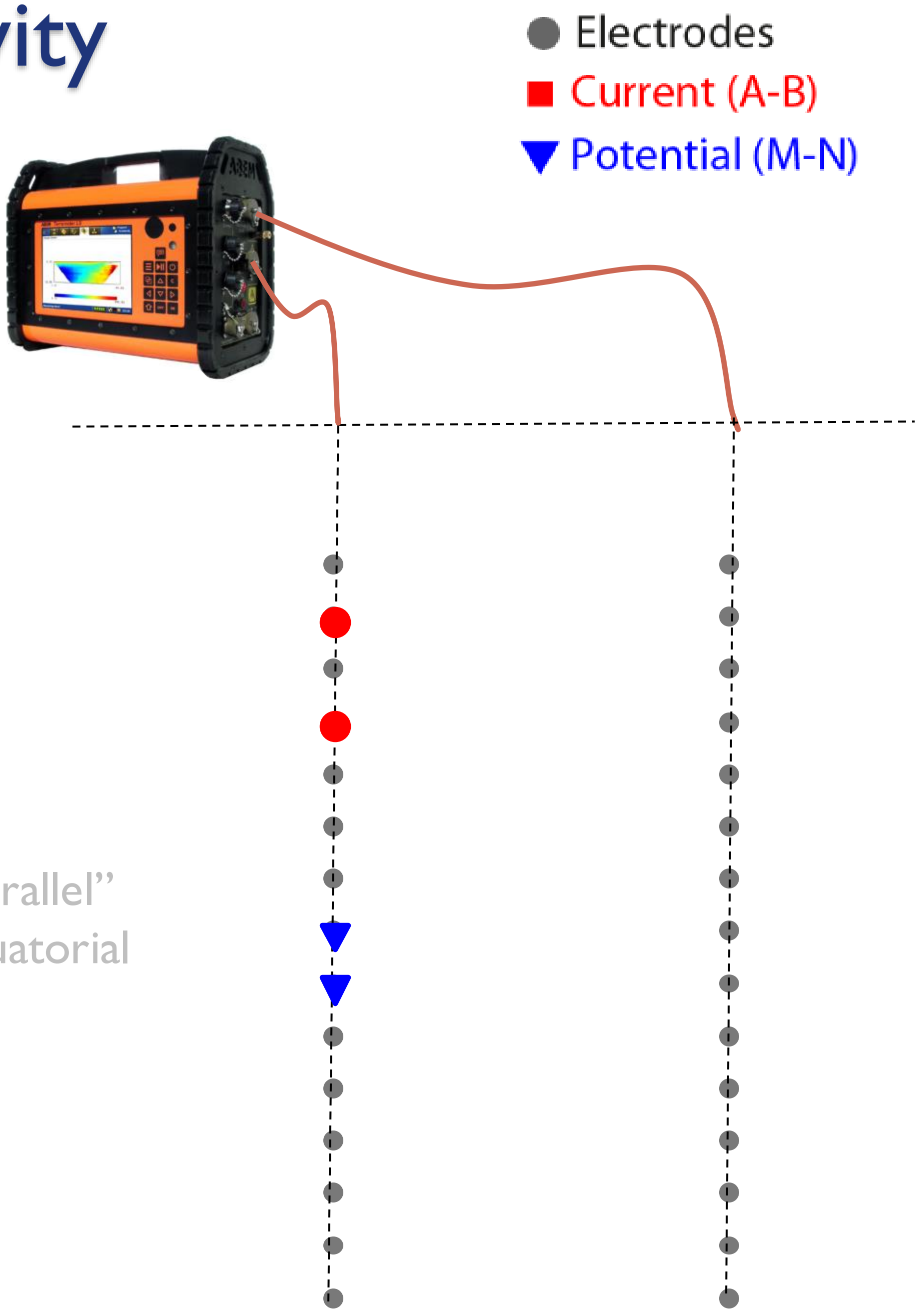








Cross-borehole electrical resistivity tomography (XB-ERT)



1. Single Borehole
2. Cross-borehole "parallel"
3. Cross-borehole equatorial

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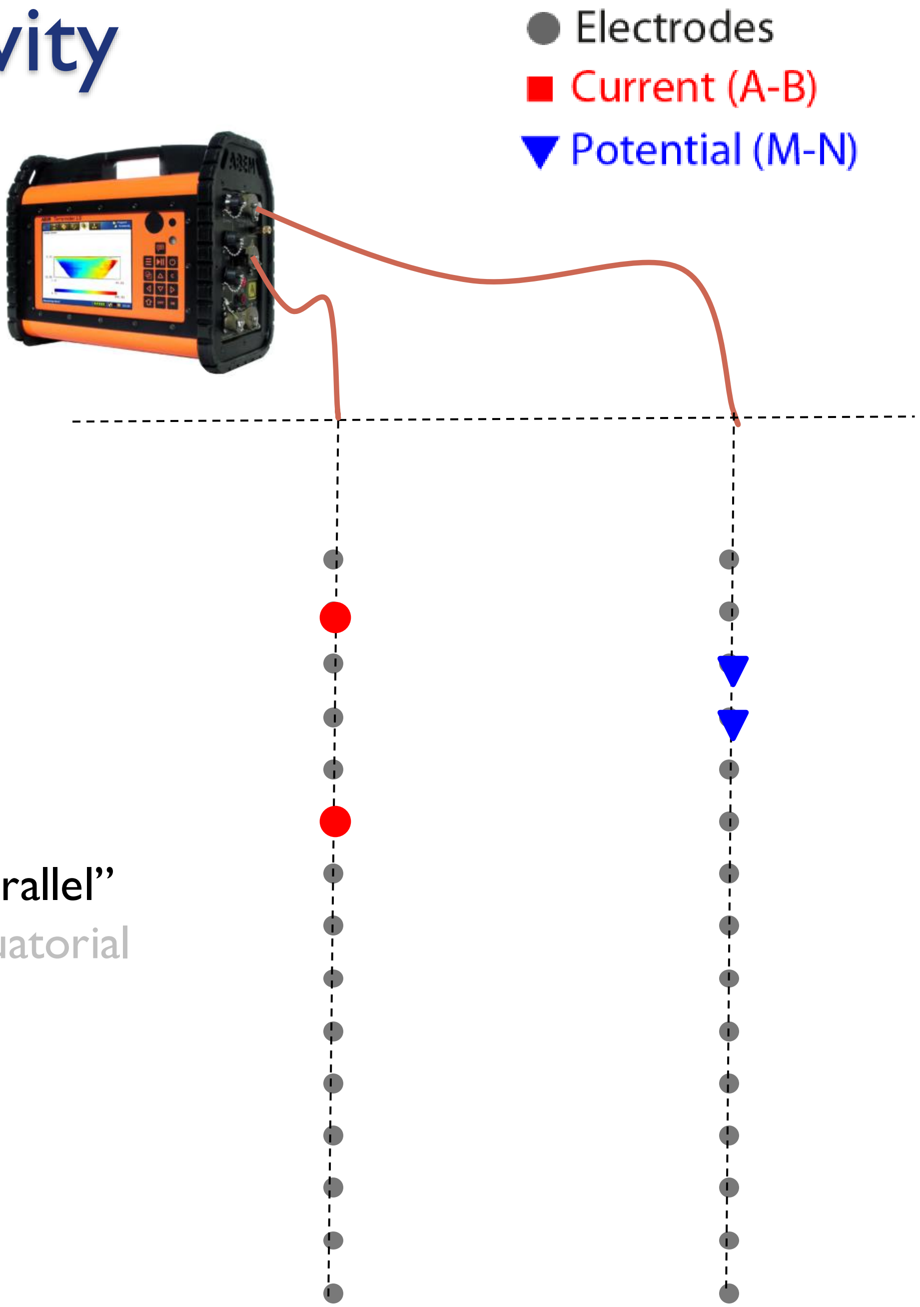

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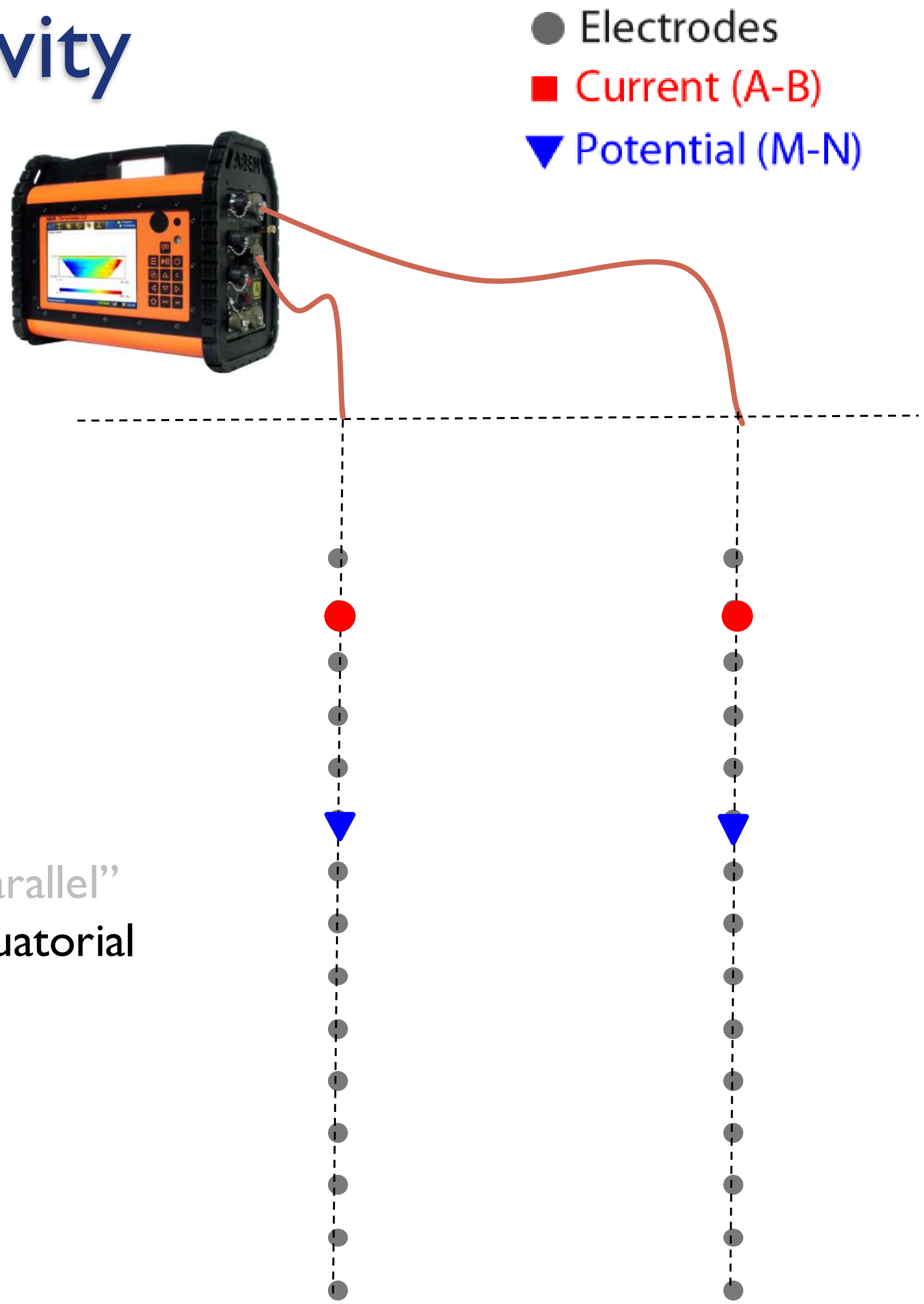
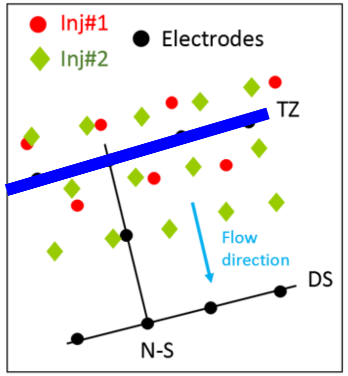
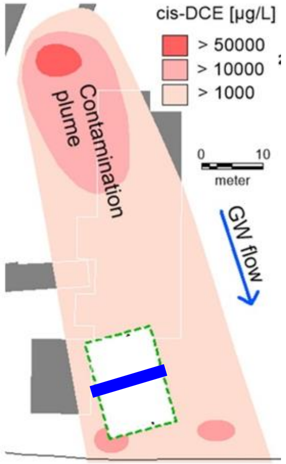
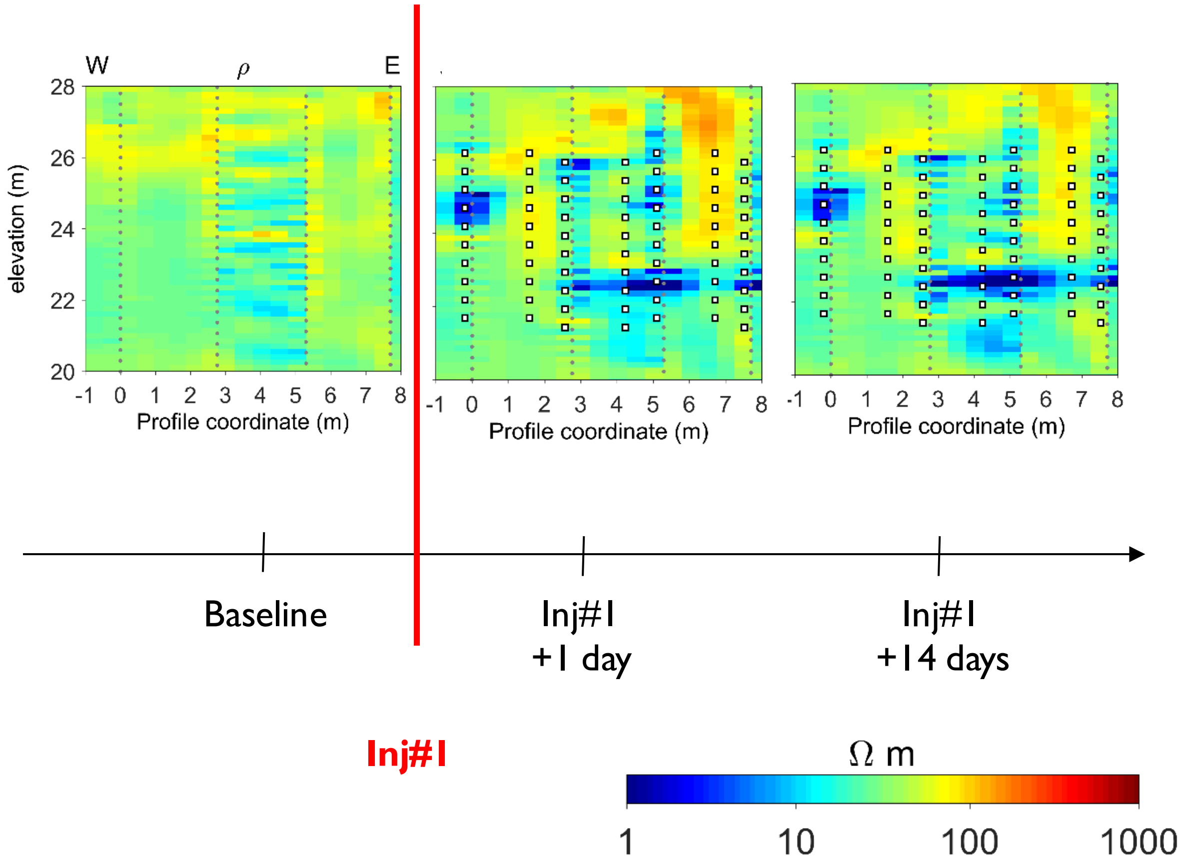
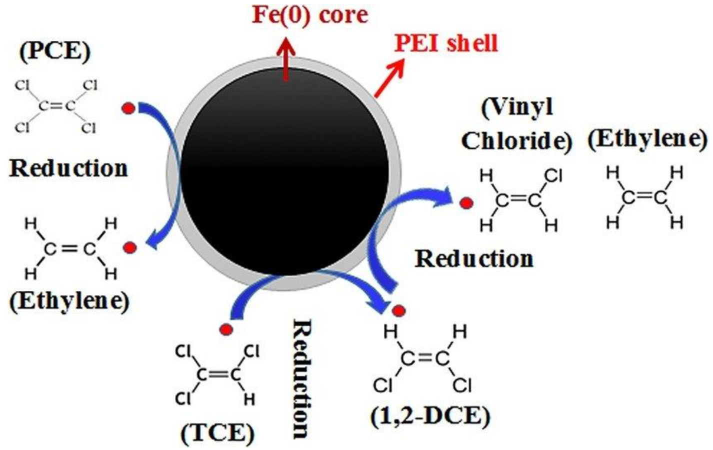


Farum – parking lot ZVI remediation









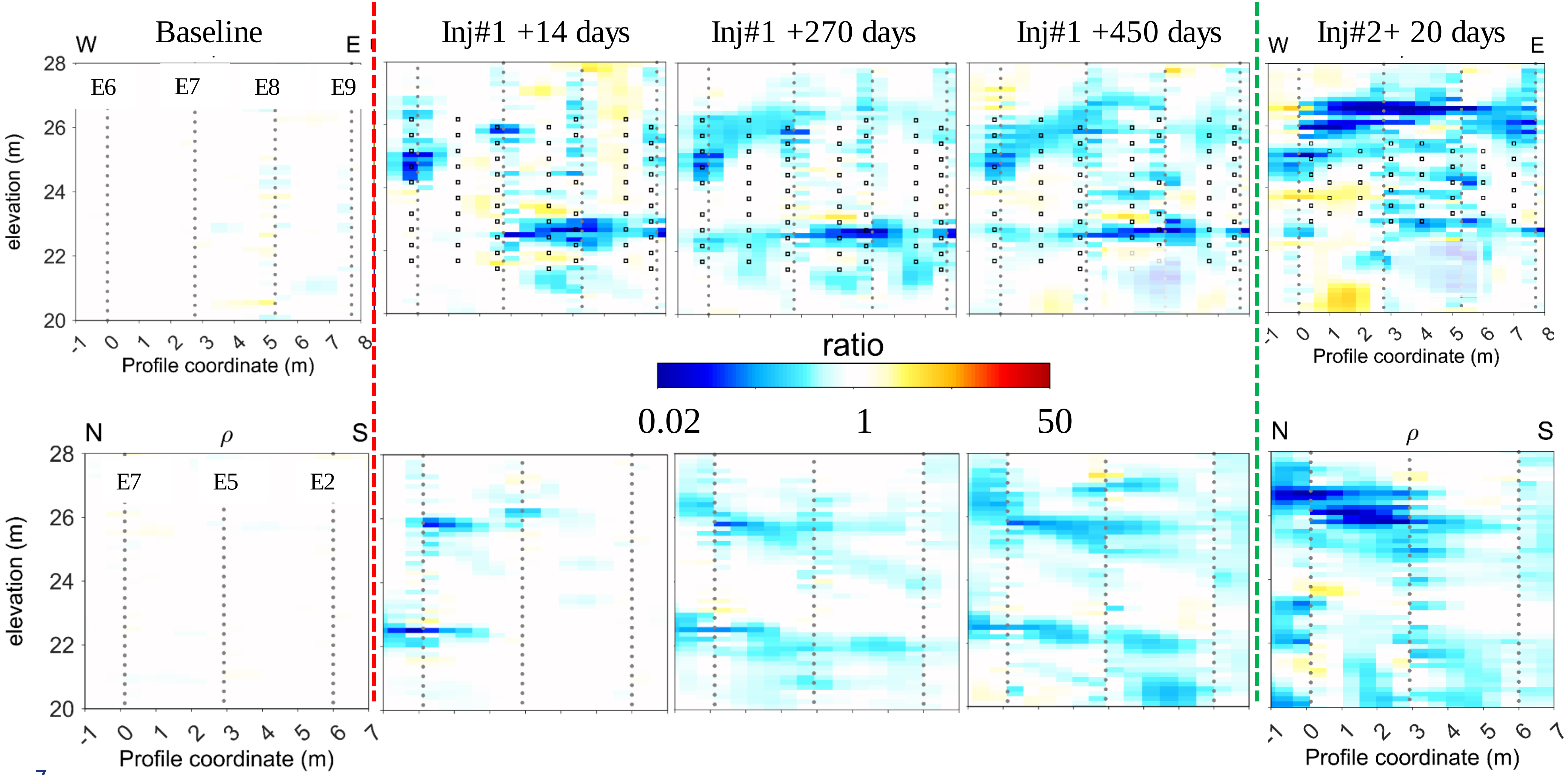
In-situ remediation campaigns with ZVI in 2019 and 2020

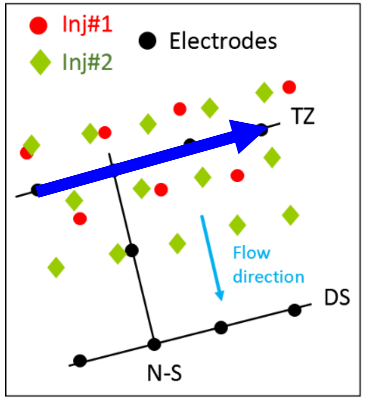
7-14 injection wells – 1-3 days

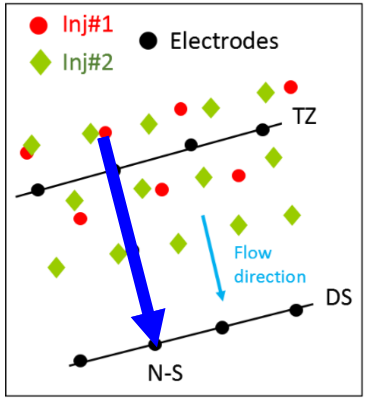
Lévy et al., 2022 (WRR)

Farum - Subtracting geology

Ratios / baseline



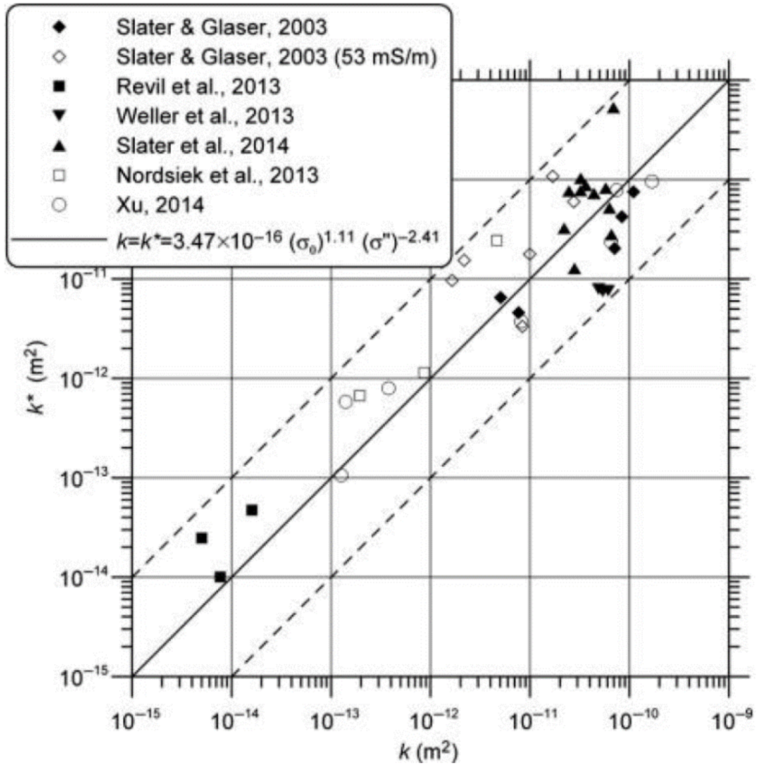




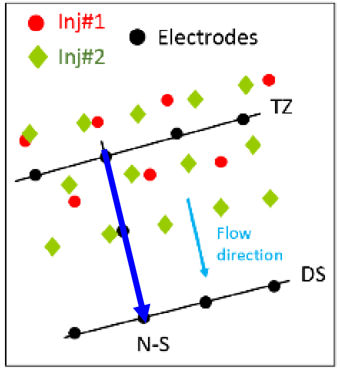
Lévy et al., 2022 (WRR)

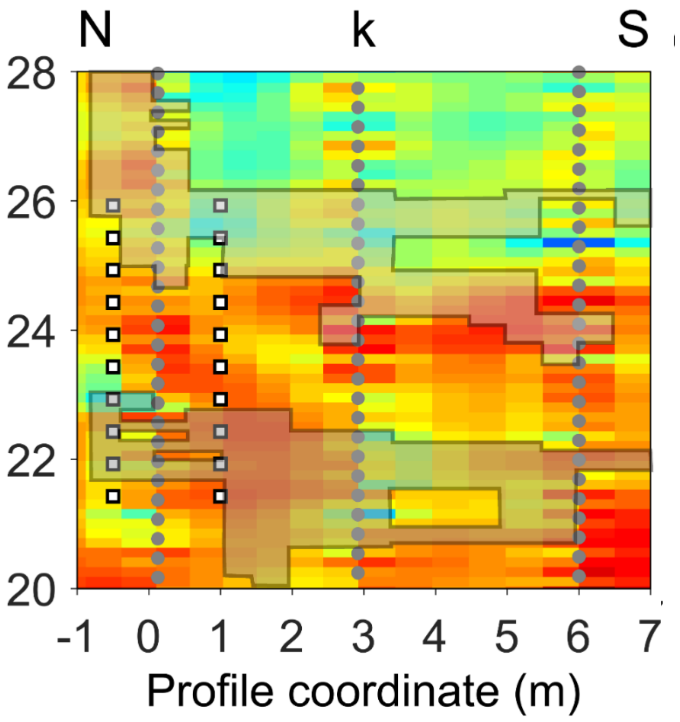
k-field estimations from XB-ERT/IP

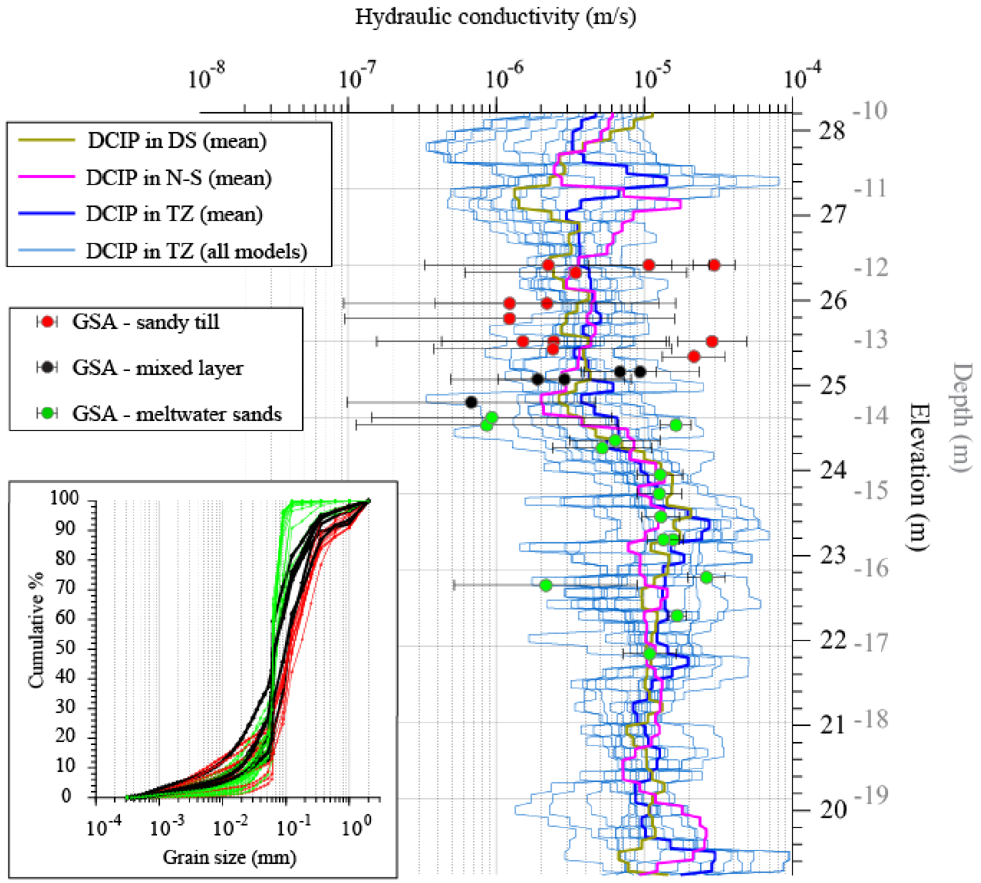
$$k^* = \frac{3.47 \times 10^{-16} \sigma_0^{1.11}}{\sigma''^{2.41}}$$



Weller et al. (2015)



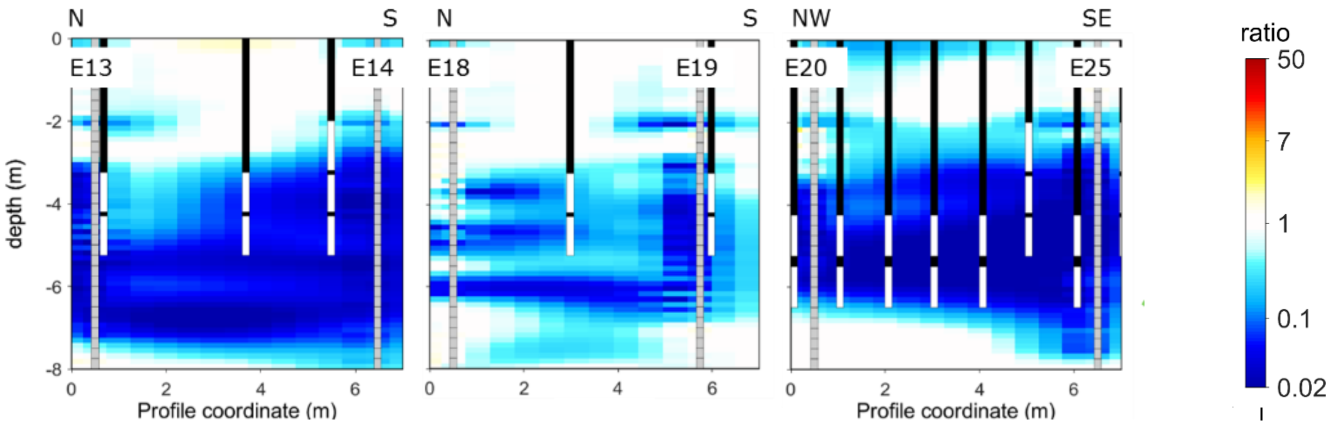


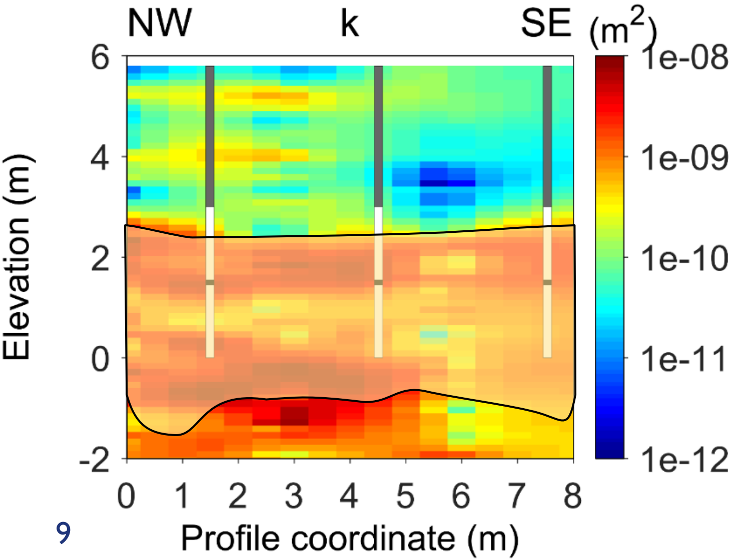


Lévy et al., 2022 (WRR)

Comparison both sites

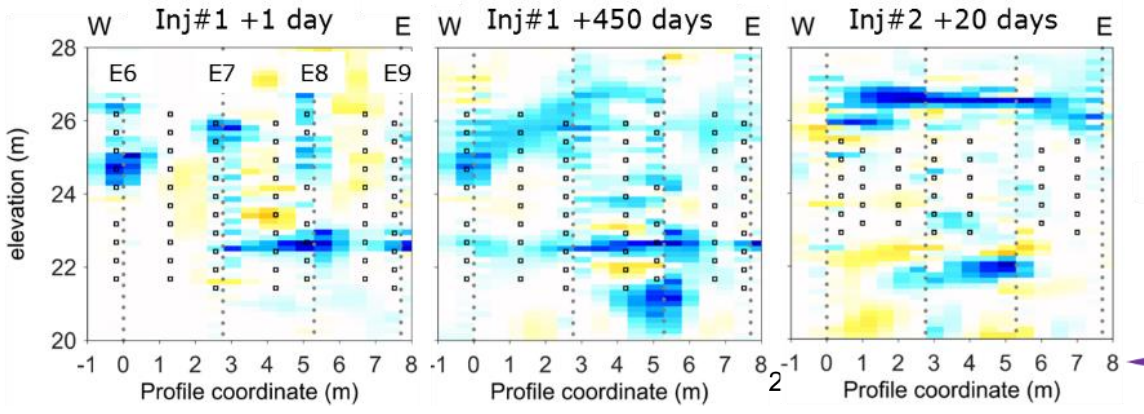
Kærgård "the beach"

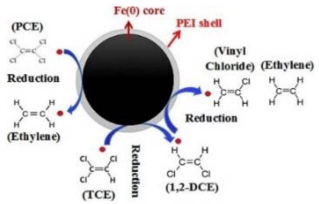




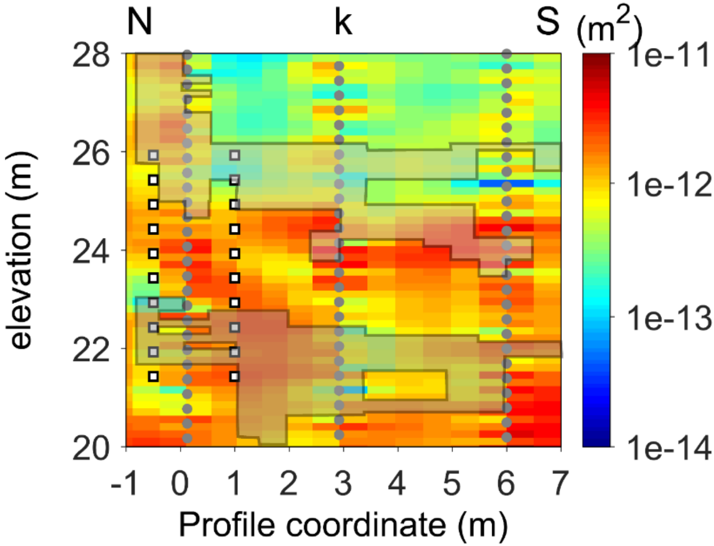
- Sulfate (low viscosity)
- Near-uniform spreading
- High permeability

Farum "the parking lot"



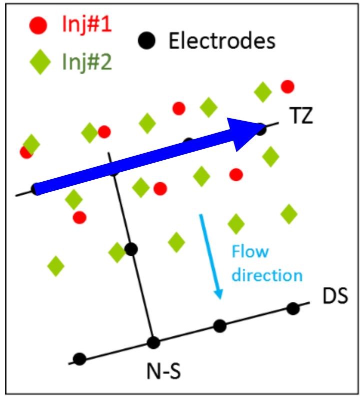


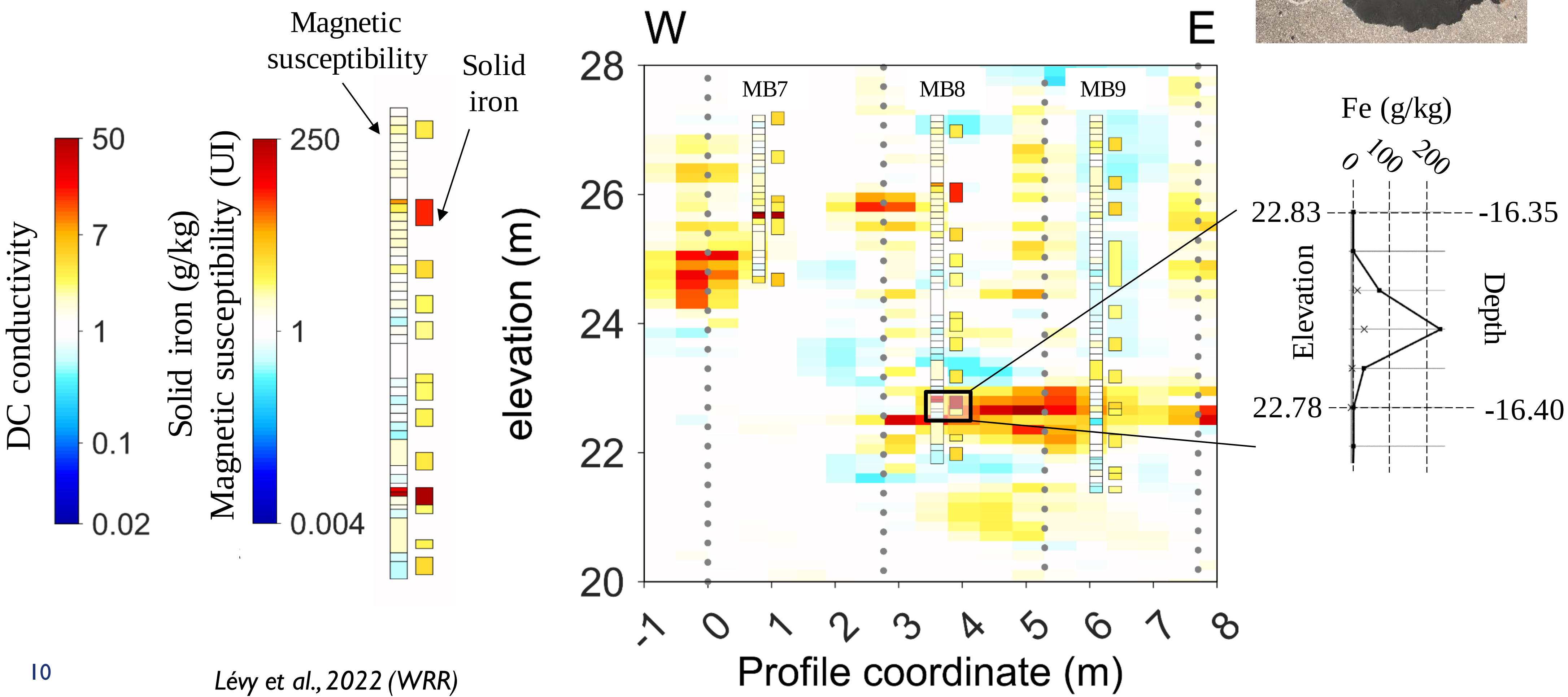
- ZVI (high viscosity)
- Heterogeneous spreading
- Intermediate permeability
- **Preferential flowpaths**



Lévy et al., 2021 (NSG-EAGE Proceedings)

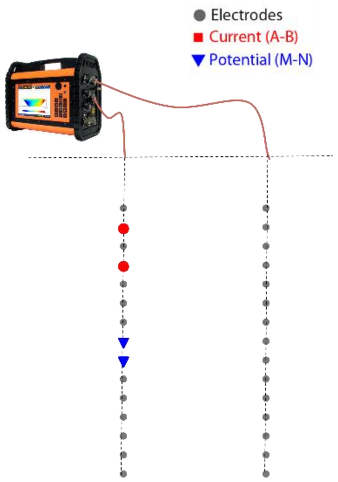
High-pressure injection
Engineered flowpaths?

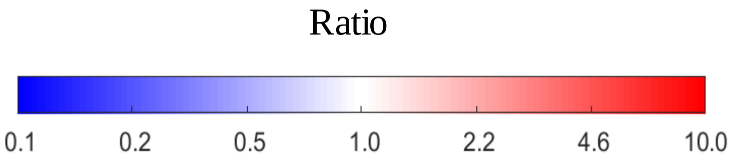




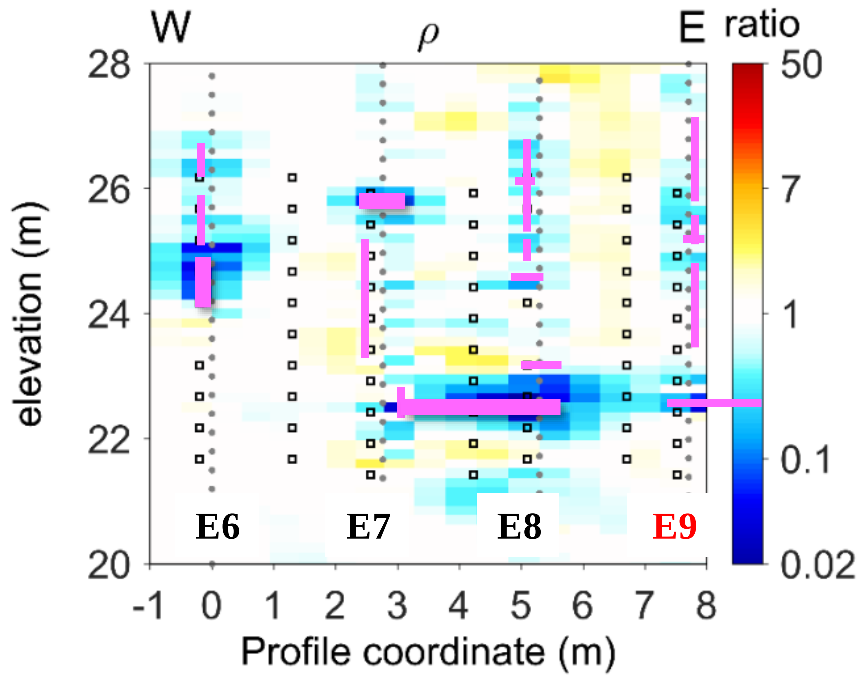
Lévy et al., 2022 (WRR)

Inversion of discrete fractures
3 and 18 fractures

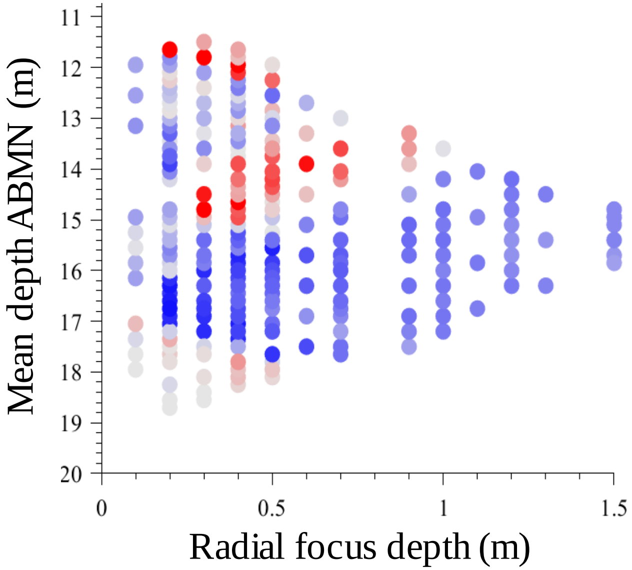




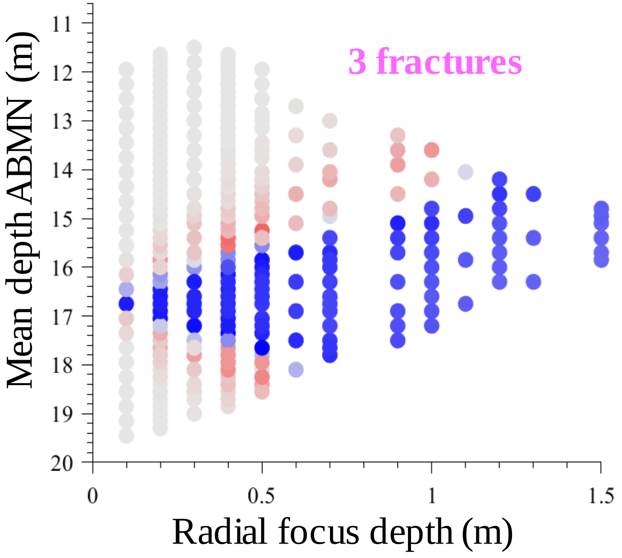
Ratio model (AarhusInv)
{after injection}/{before injection}

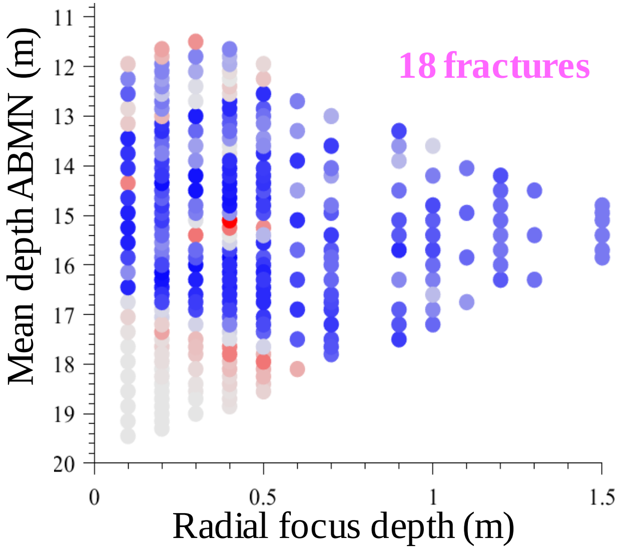


Ratio measured data (SB E9)
{after injection}/{before injection}



Ratio simulated data (SB E9)
{with DFN}/{Matrix only}





Inverting time-lapse dataset with {DFN+matrix}
One horizontal fracture – Five parameters

$$\chi = \frac{1}{N}\Sigma\left(\frac{\rho_{a,DFN} - \rho_{a,EPM}}{\rho_{a,EPM}} - \frac{\rho_{a,+1day} - \rho_{a,baseline}}{\rho_{a,baseline}}\right)^2$$

EPM = equivalent porous media (matrix)
DFN = discrete fracture network

<u>Inverted parameters</u>

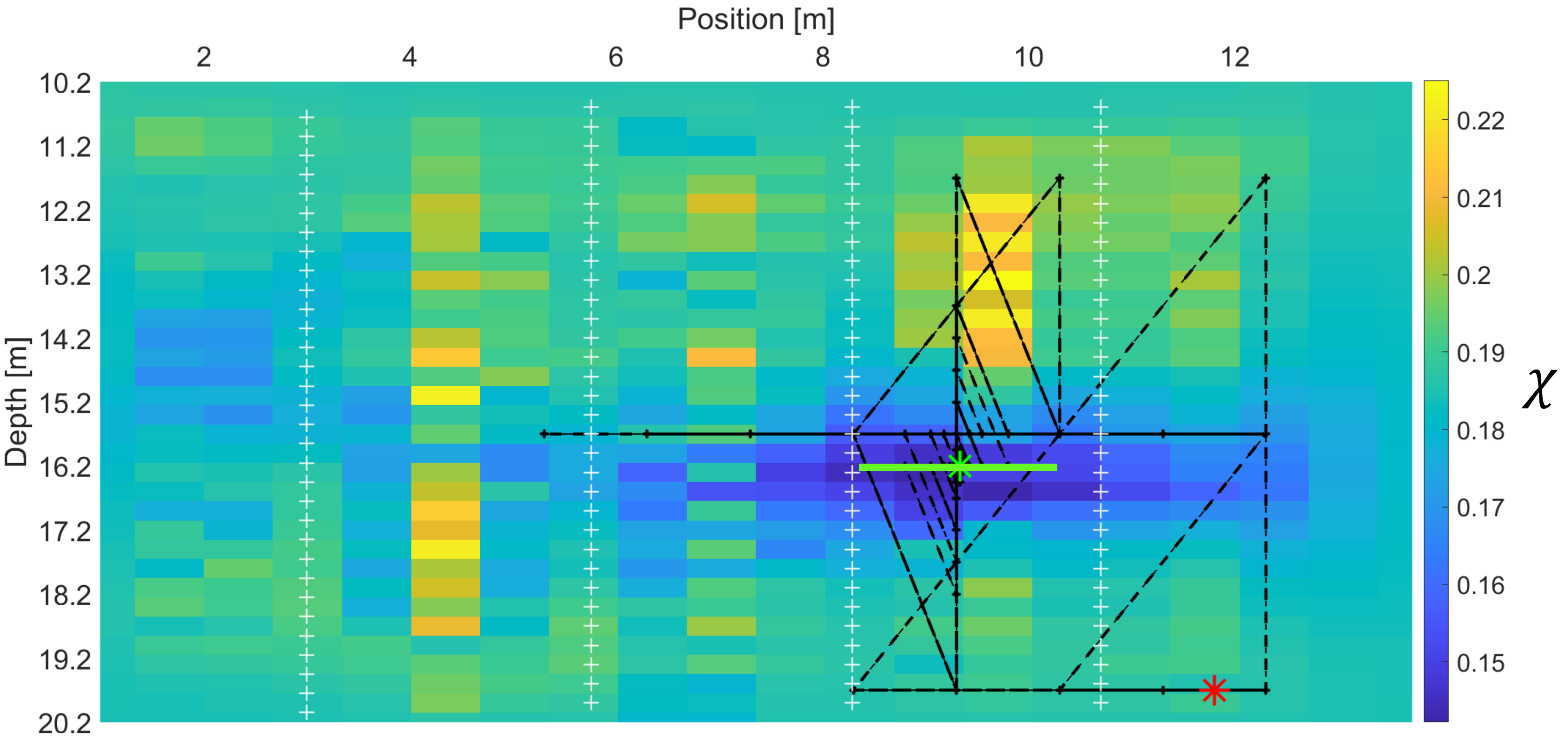
Depth = 16.2 m

X_left = 8.426 m

X_right = 10.24 m

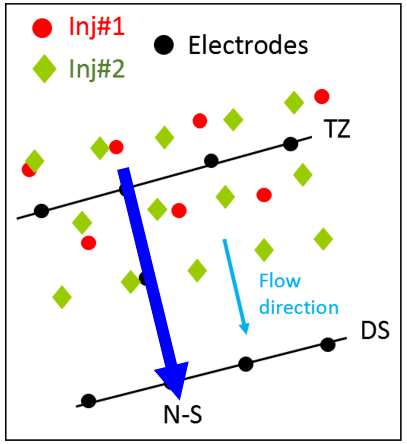
Aperture = 0.099 m

σ_{frac} = 20.96 S/m



Work by PhD student Léa Lelimouzin

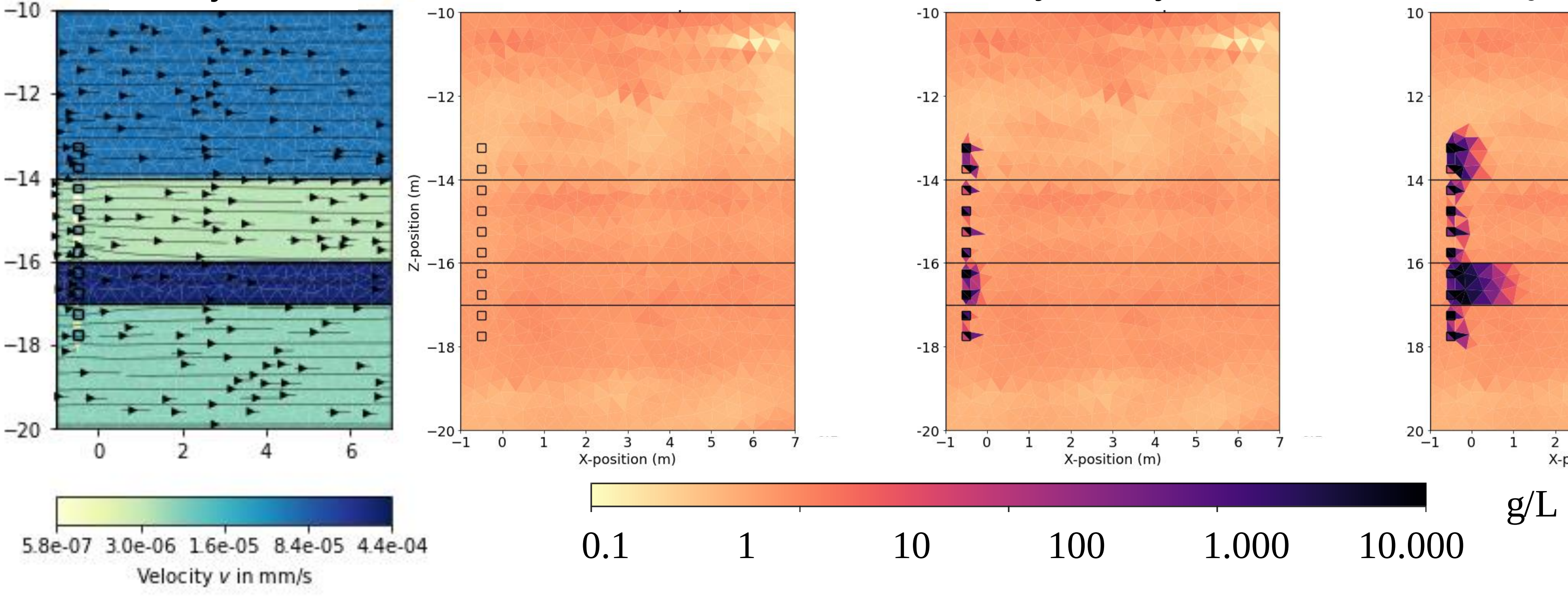
Hydrogeophysical modelling
Synthetic analysis



Permeability - flow model

Solute concentration - transport model

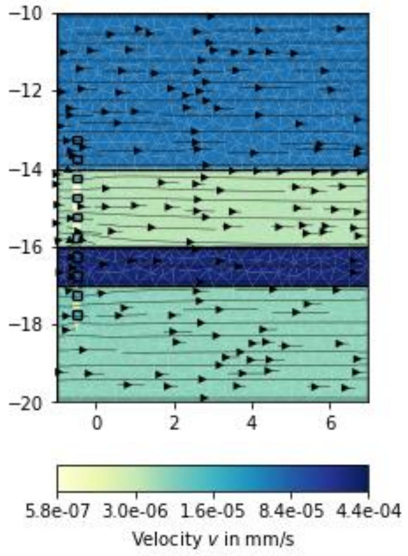
Steady-state | Baseline | Inj + 1 day | Inj + 14 days

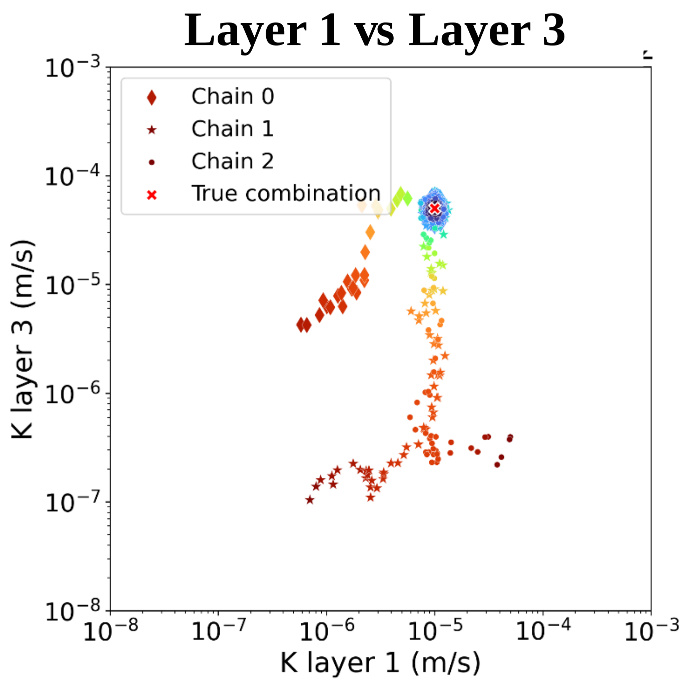


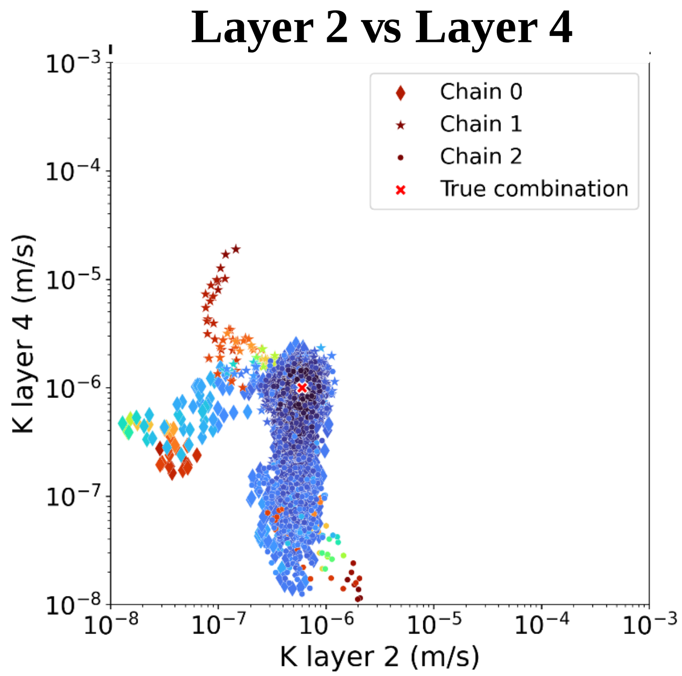
$$v = -K * grad(\Delta P) \longrightarrow \frac{\partial C}{\partial t} = \nabla(D\nabla C) - \boldsymbol{v}.\nabla C + S \longrightarrow \sigma_f(t) = \frac{C(t)}{6.66} \longrightarrow \sigma_b(t) = \sigma_f(t) * F$$

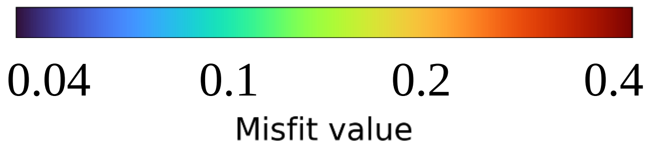
MCMC inversion of 1D K-field

- Synthetic XB data
  - 3 boreholes, 96 electrodes
  - Same sequence as measured data
  - 3 time-steps
  - 3% noise added
- Inversion of synthetic data
  - Metropolis-Hastings procedure
  - 3 MCMC chains
  - 3000 iterations / chain
  - 1 iteration ~ 4.4 sec
- Layers 2 and 4 less well determined





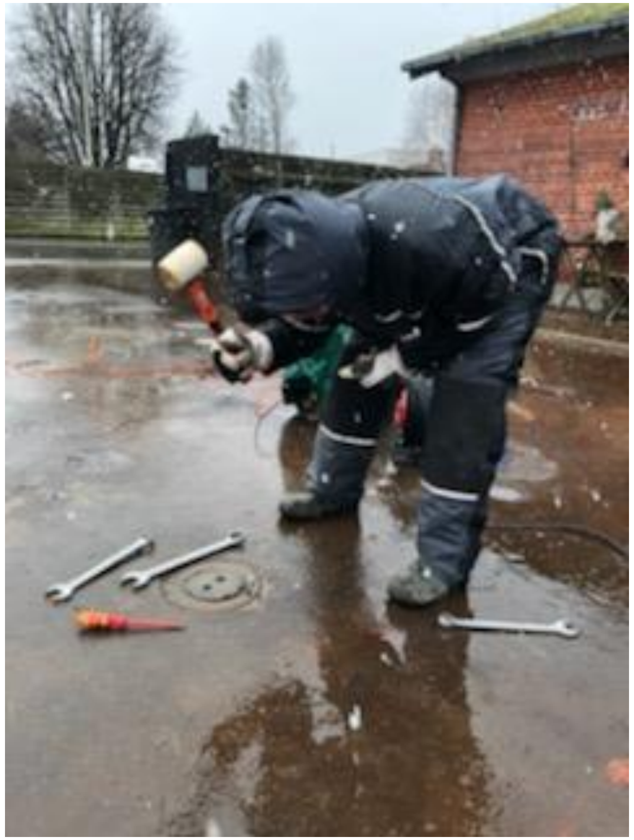


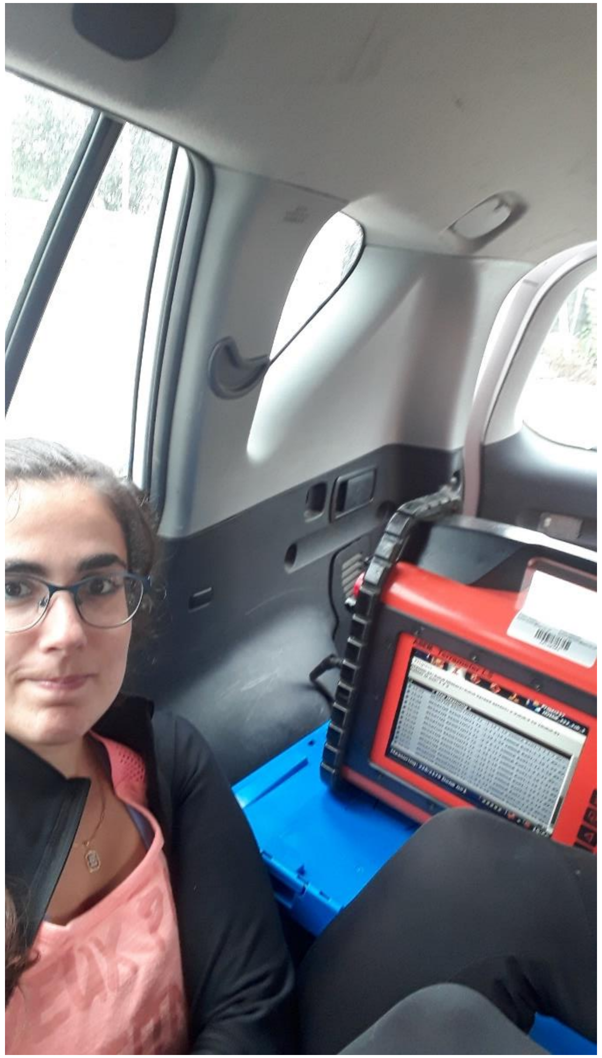


Work by MSc student
Chloé Delbet

Building groundwater transport models at remediation sites

- In-situ groundwater remediation in unconsolidated sediments
- Monitoring spatial distribution of reagent with time-lapse XB-ERT
    - mZVI remediation: prefetential flowpaths, limited distribution
    - ISCO remediation: uniform distribution
    - Transport properties depend both on geology and reagent
- Method 1: Imaging permeability field with XB-ERT/IP data
    - Consistent with grain size analyses, slug tests, HPT
    - Does not explain flowpaths when injection of mZVI under pressure
    - Importance of small-scale heterogeneities and engineered flowpaths
- Method 2: Inversion of discrete fracture networks
    - 1D elements are inverted instead of pixels
    - Next step: solute transport modelling with particle tracking
- Method 3: Joint transport and time-lapse XB-ERT inversion
    - Using reagent as a saline tracer
    - Map the ”true” permeability field based on XB-ERT monitoring data
    - Next steps: invert measured data and move to 2D K-distributions

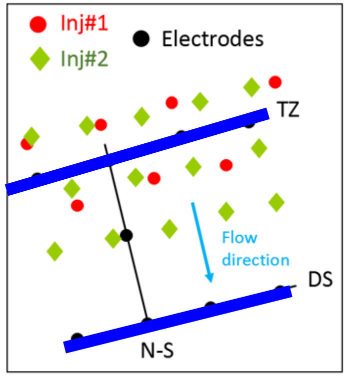


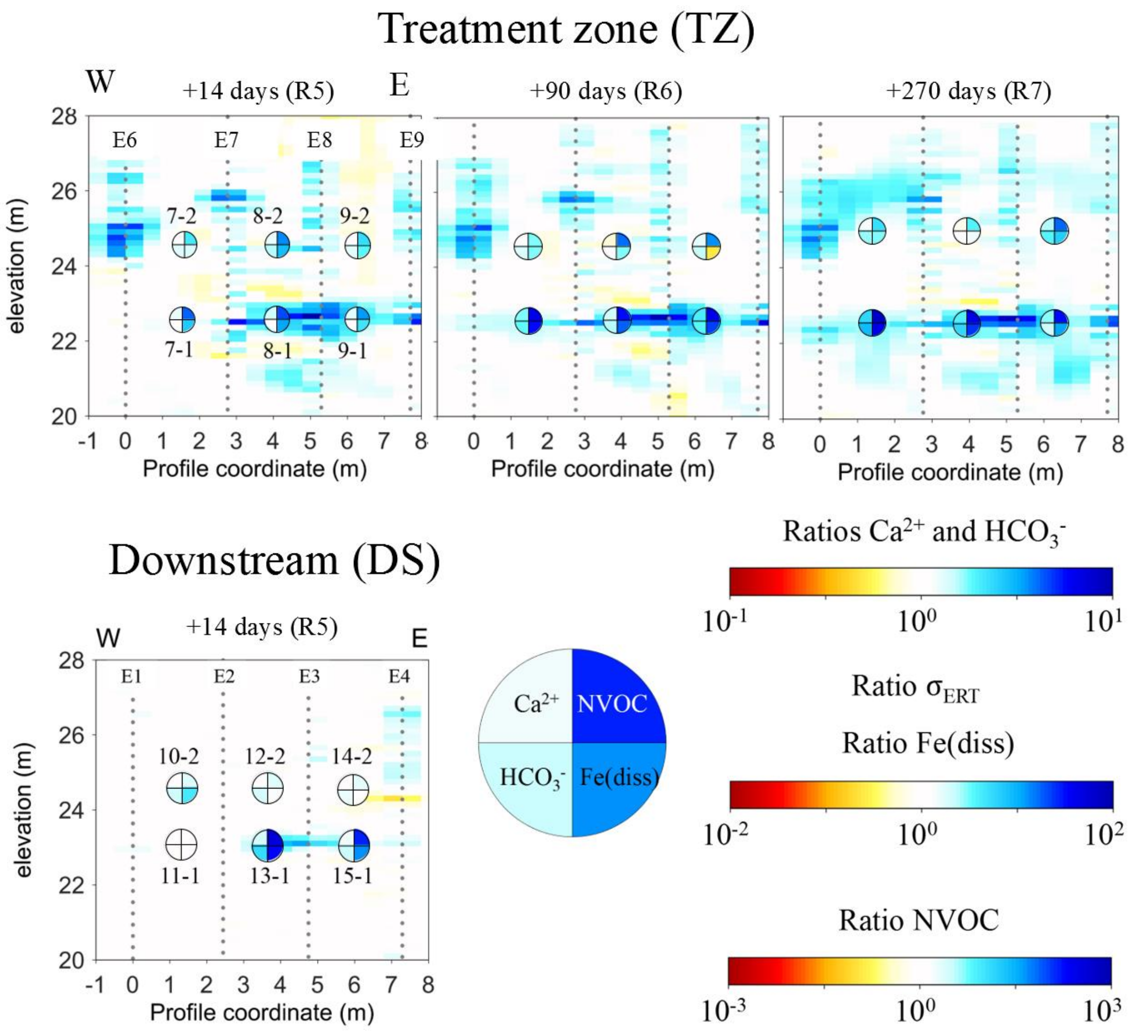


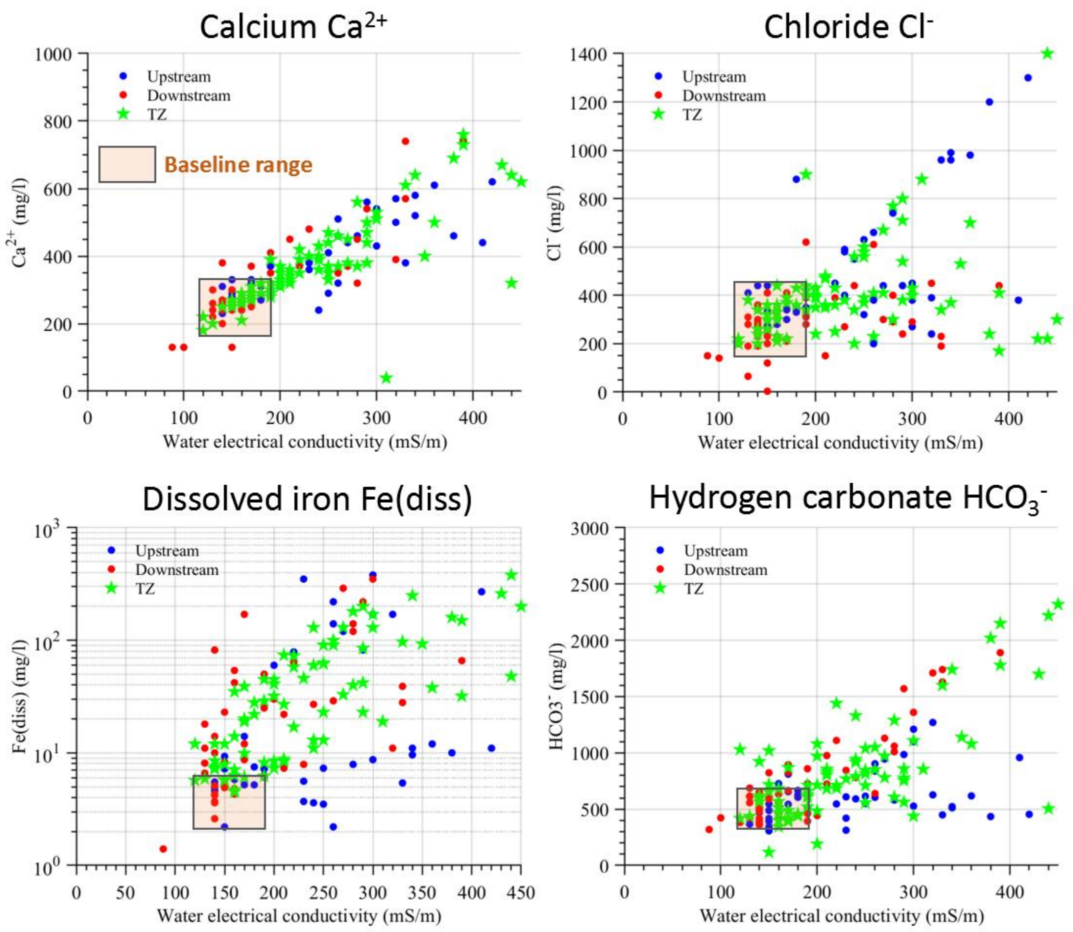
Thank you!

lea.levy@tg.lth.se

Farum: what ions are we looking at?







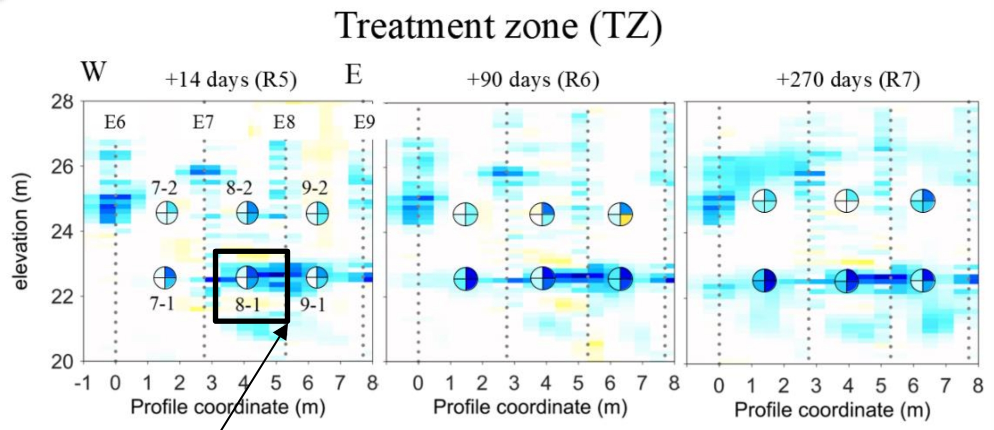
Lévy et al 2022(WRR)

Can we be quantitative?

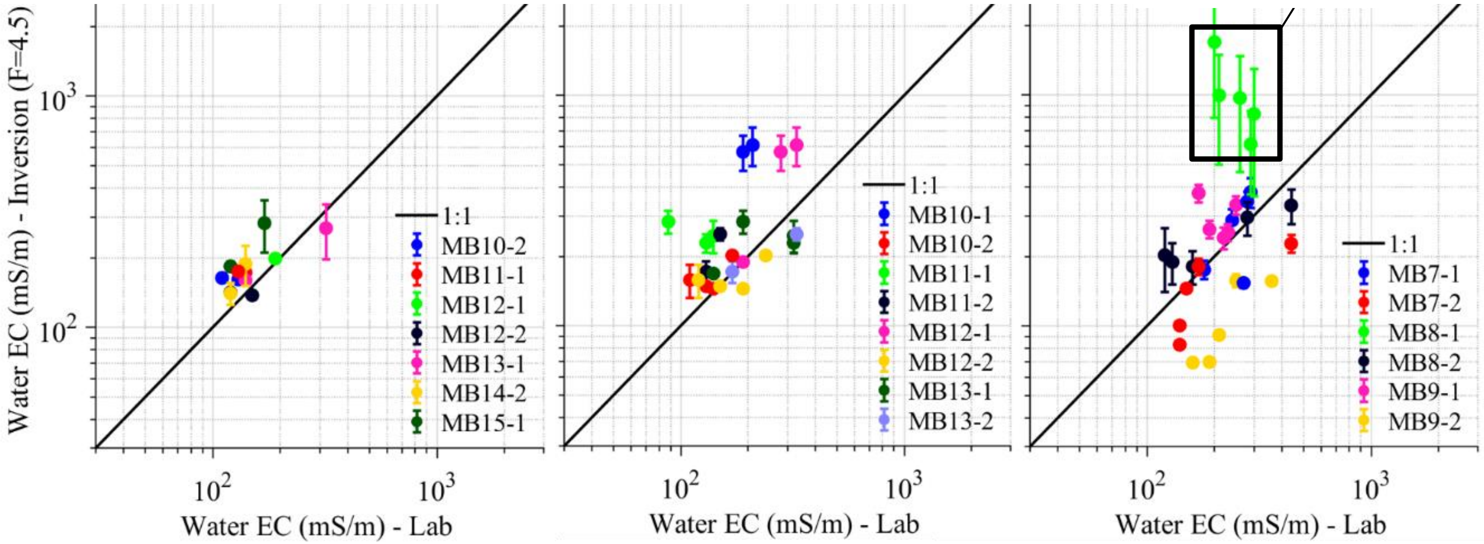
Archie, 1942

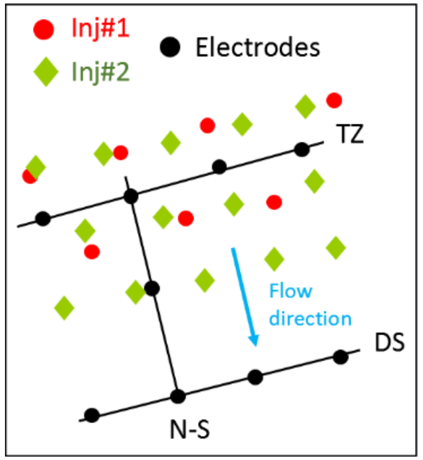
$$\sigma_0 = \frac{\sigma_w}{F}$$

Correlation assuming only dissolved ions contribute to electrical conduction…



Transect DS
Transect N-S
Transect TZ





Lévy et al., WRR, 2022

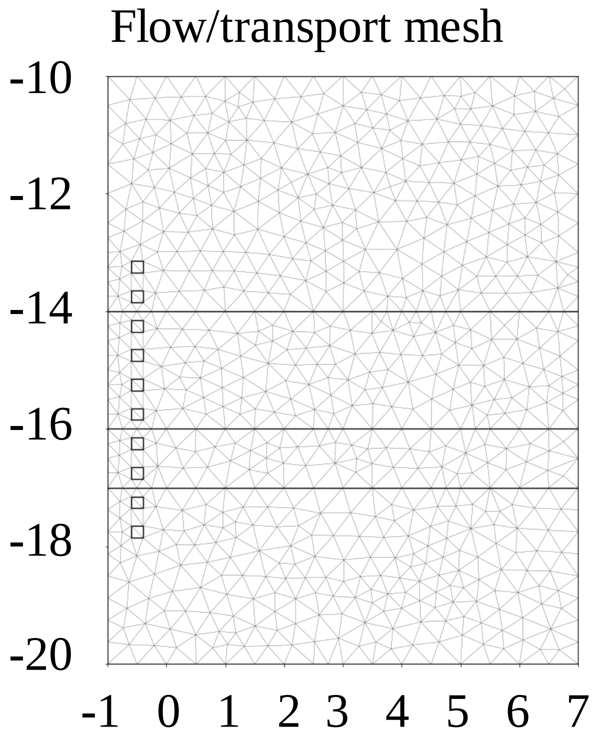
MCMC inversion of 1D K-field

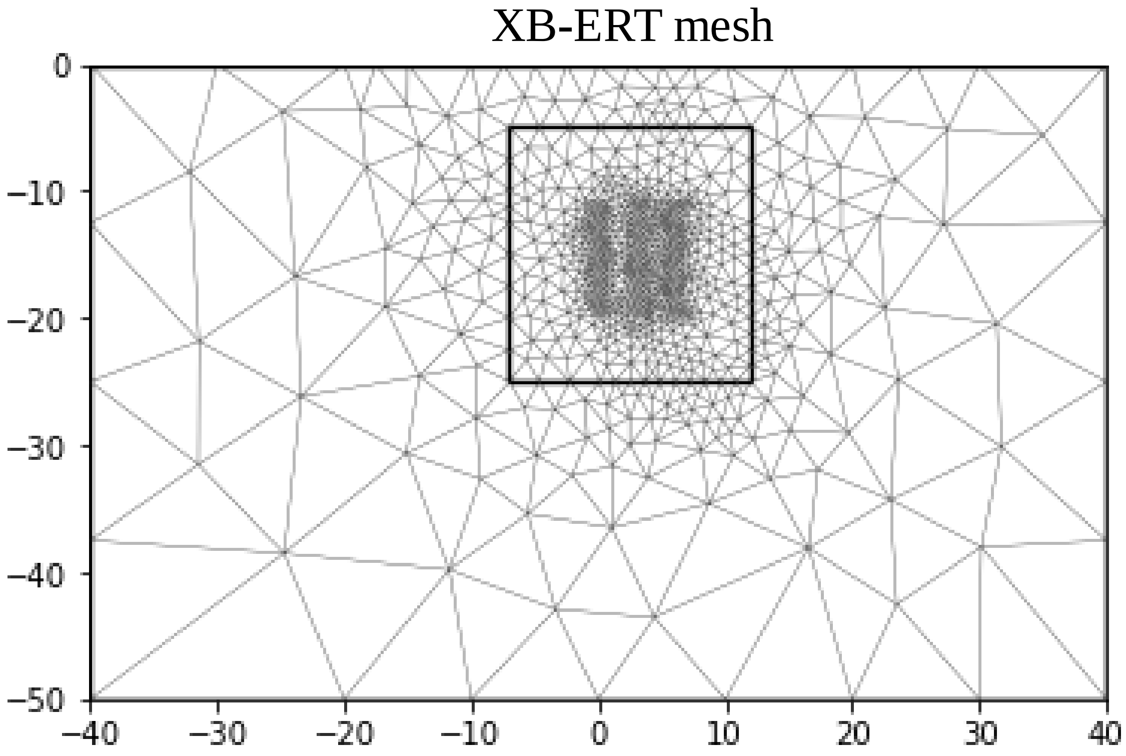
- Synthetic XB data
  - 3 boreholes, 96 electrodes, same sequence as measured data
  - 3 time-steps
  - 3% noise added
- Initial model $K_{i,\ i=1..4}$ randomly drawn and accepted
  - New model: $K_{i,new}=K_{i,old}+\varepsilon$
- Misfit χ predicted vs observed data
- Metropolis-Hastings procedure
  - If new misfit < old misfit →new model accepted
  - Else, likelihood ratio *L* calculated
    - If L>rand[0..1] → new model accepted
    - Else, rejected
  - STD and ε are key to maintain acceptance rate ~20%

$$\chi = \sqrt{\frac{1}{N}\,\Sigma\big(d_i - f(m_i)\big)^2}$$

$$L = exp\left(-\frac{(\chi_{old} - \chi_{new})^2}{STD(d_i)^2}\right)$$

From solute transport to XB-ERT





$$\sigma_b(t) = \sigma_f(t) * F$$

F = 4.5 (fitted in Farum)

$$\sigma_f(t) = \frac{C(t)}{6.66}$$

Coeff 6.66 $g.L^{-1}.m.S^{-1}$ fitted to baseline in Farum