Cross-borehole electrical resistivity tomography for imaging ZVI amendment spreading at remediation sites

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HydroGeophysics Group
AARHUS UNIVERSITY

Danmarks Tekniske Universitet

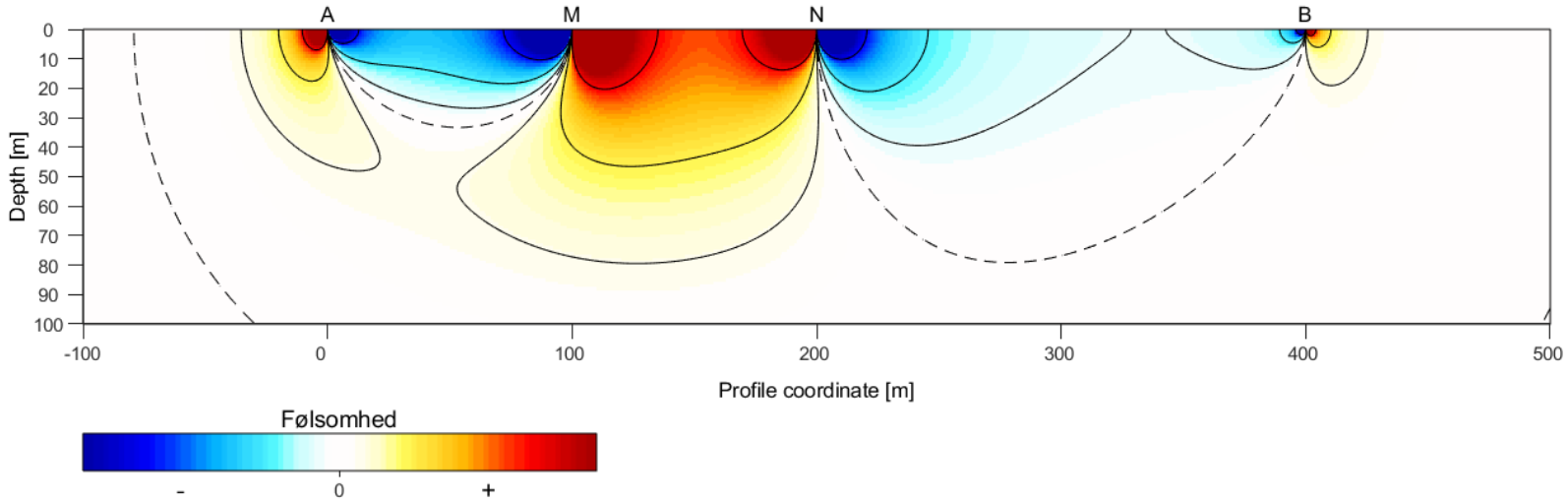
DTU

COWI

REGION

Region Hovedstaden

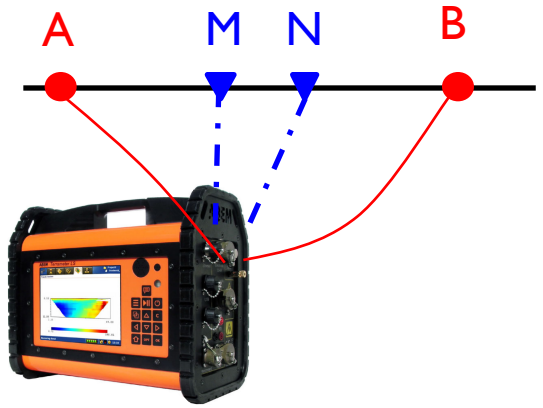
Geophysics provides spatial continuity



Adapted from Christiansen et al., Lecture notes, 2020

■ Current (A-B)

▼ Potential (M-N)

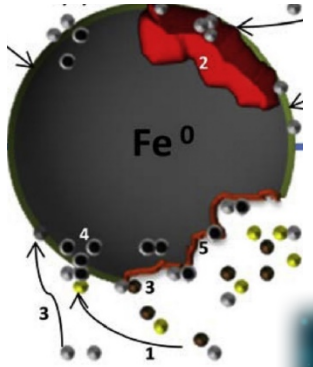


$$\Delta V_{MN} = R \cdot I_{AB}$$

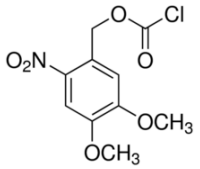
Provect-ZVI injection triggers release of...

Bacteria

Solid iron

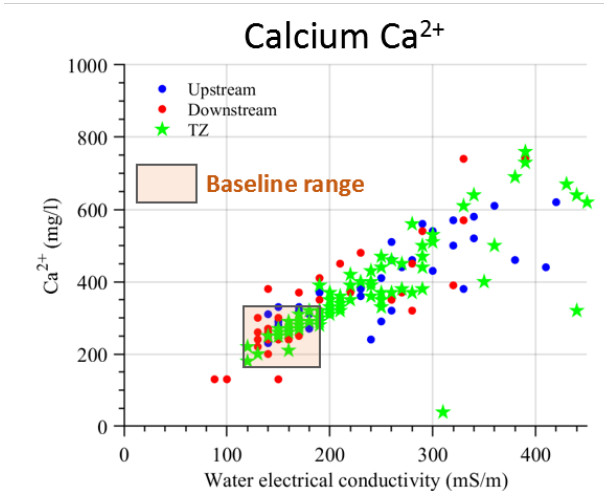


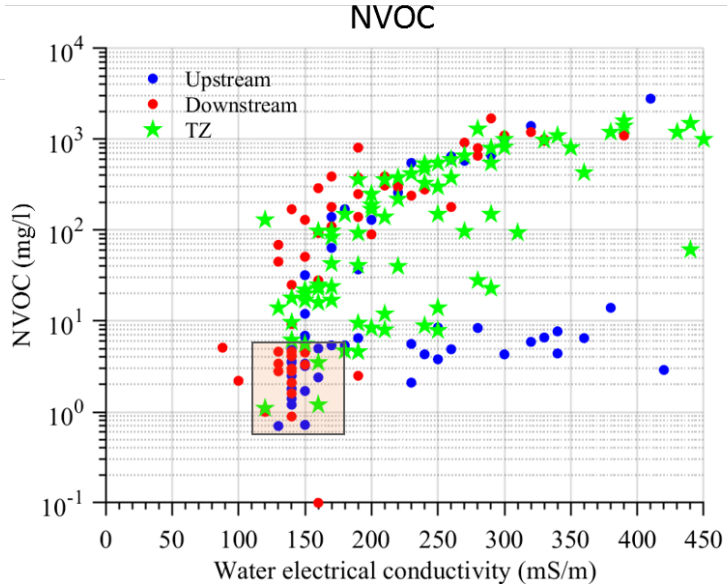
NVOC

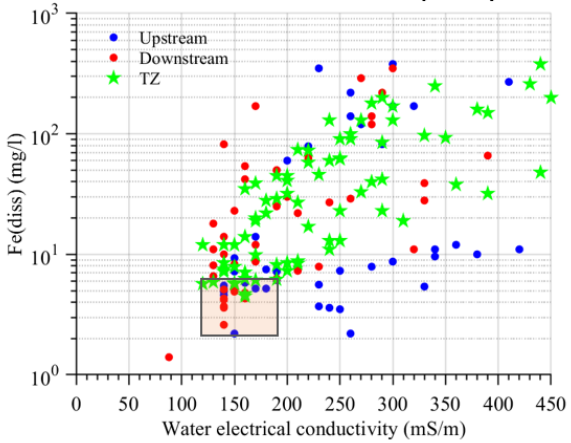


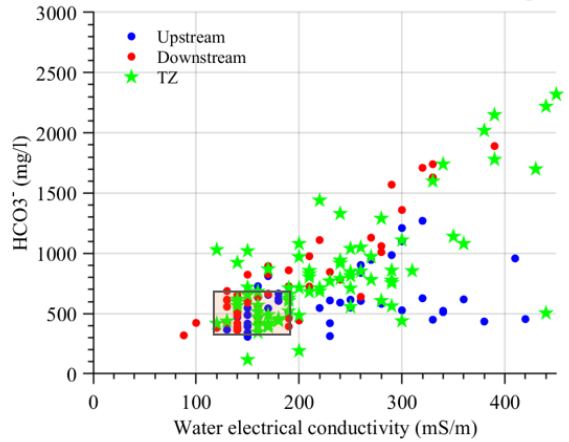
Ionic cloud

Ca^{2+}, Fe^{2+}, Cl^-, HCO_3^-









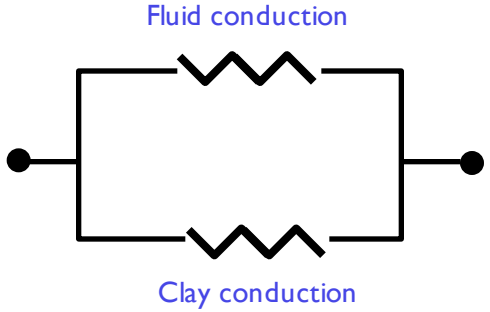
Lévy et al., under review at WRR

Ionic cloud vs resistivity

Theory

Electric charge carrier	Electrical parameter	Environmental parameter
Ions in pore water	ρ or σ	Equivalent ion concentration **ionic cloud**
Ions in/on clay minerals	ρ or σ	Cation Exchange Capacity **clay minerals**

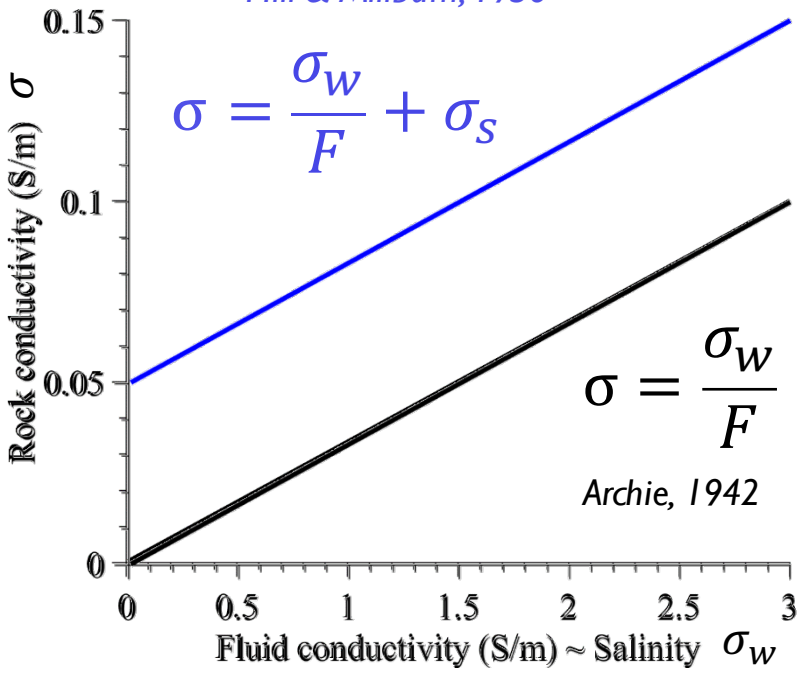
- Added complexity with clays
- But not an issue
  - With Farum's geology
  - When looking at time-variations



$$\rho = \frac{1}{\sigma}$$

ρ = resistivity
σ = conductivity

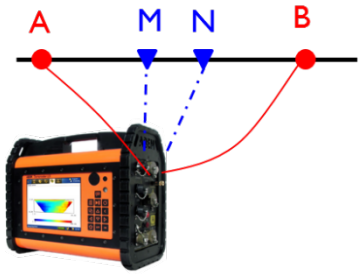
Hill & Millburn, 1956

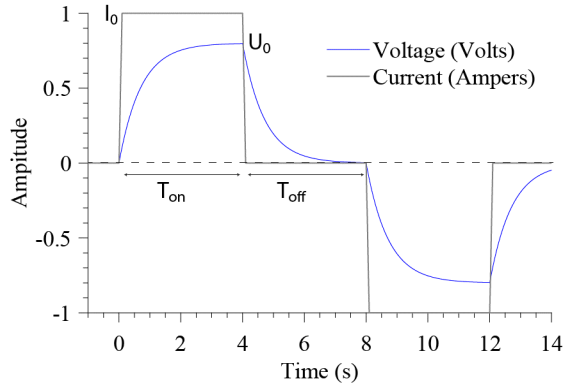


Electrical resistivity tomography (ERT)

■ Current (A-B)

▼ Potential (M-N)





Electrical resistivity tomography (ERT)

■ Current (A-B)

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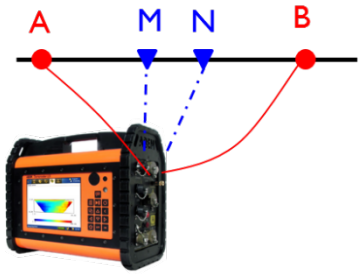
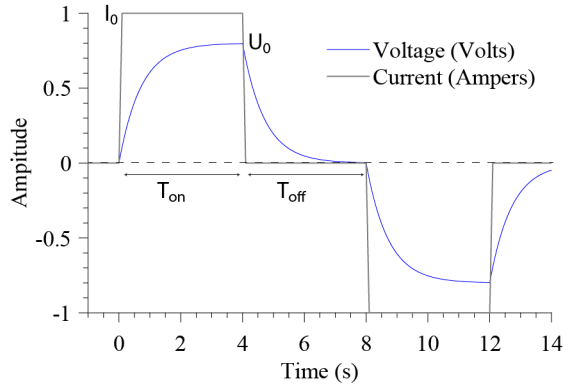
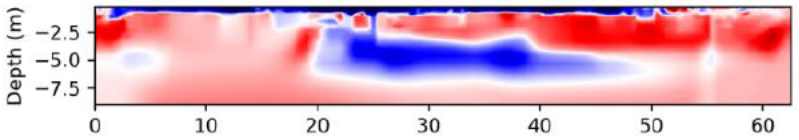


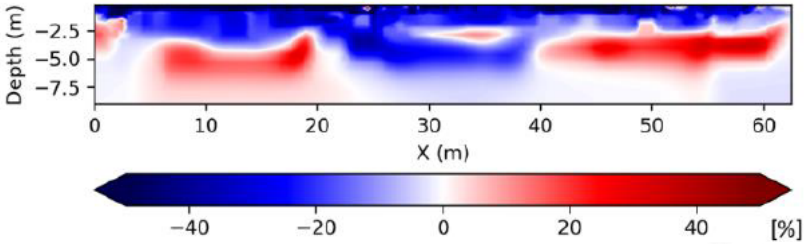


Surface ERT

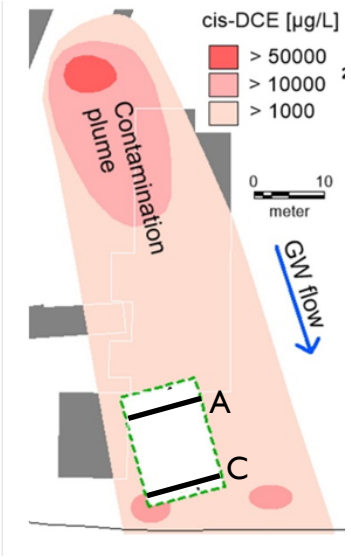
Inj + 11 months

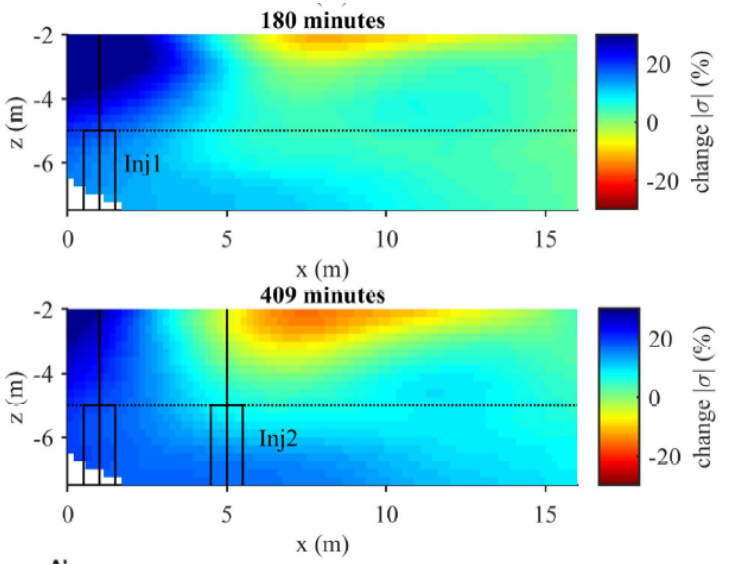


Inj + 14 months



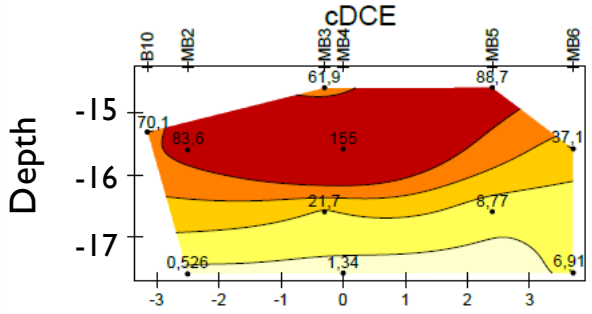
Nivorlis et al. 2019

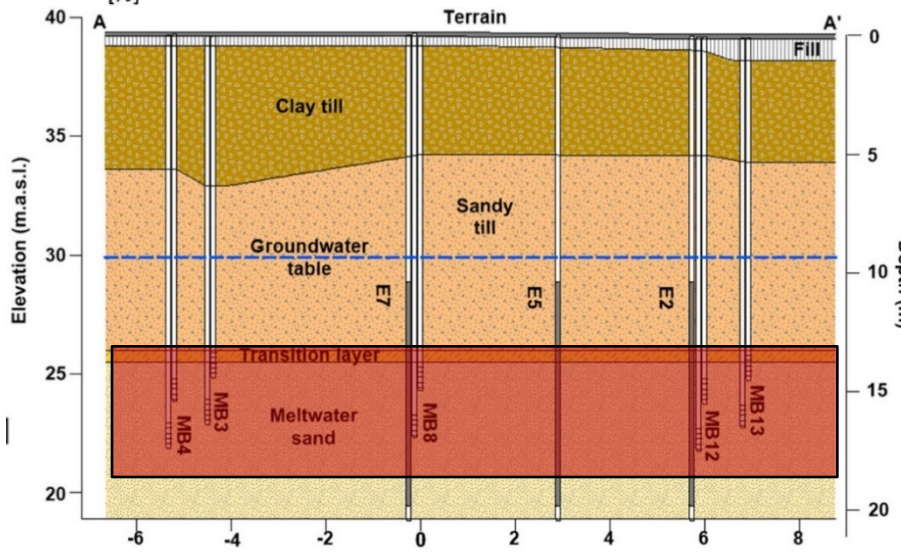




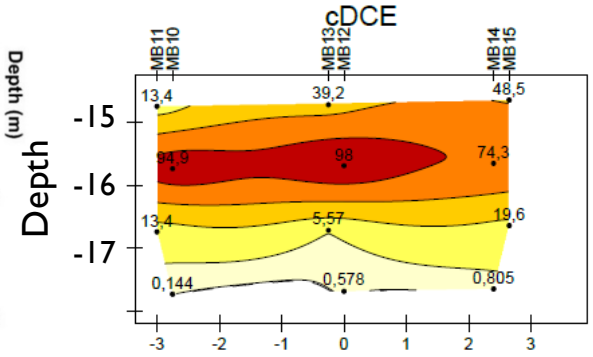
Flores-Orozco et al., 2019

Transect A

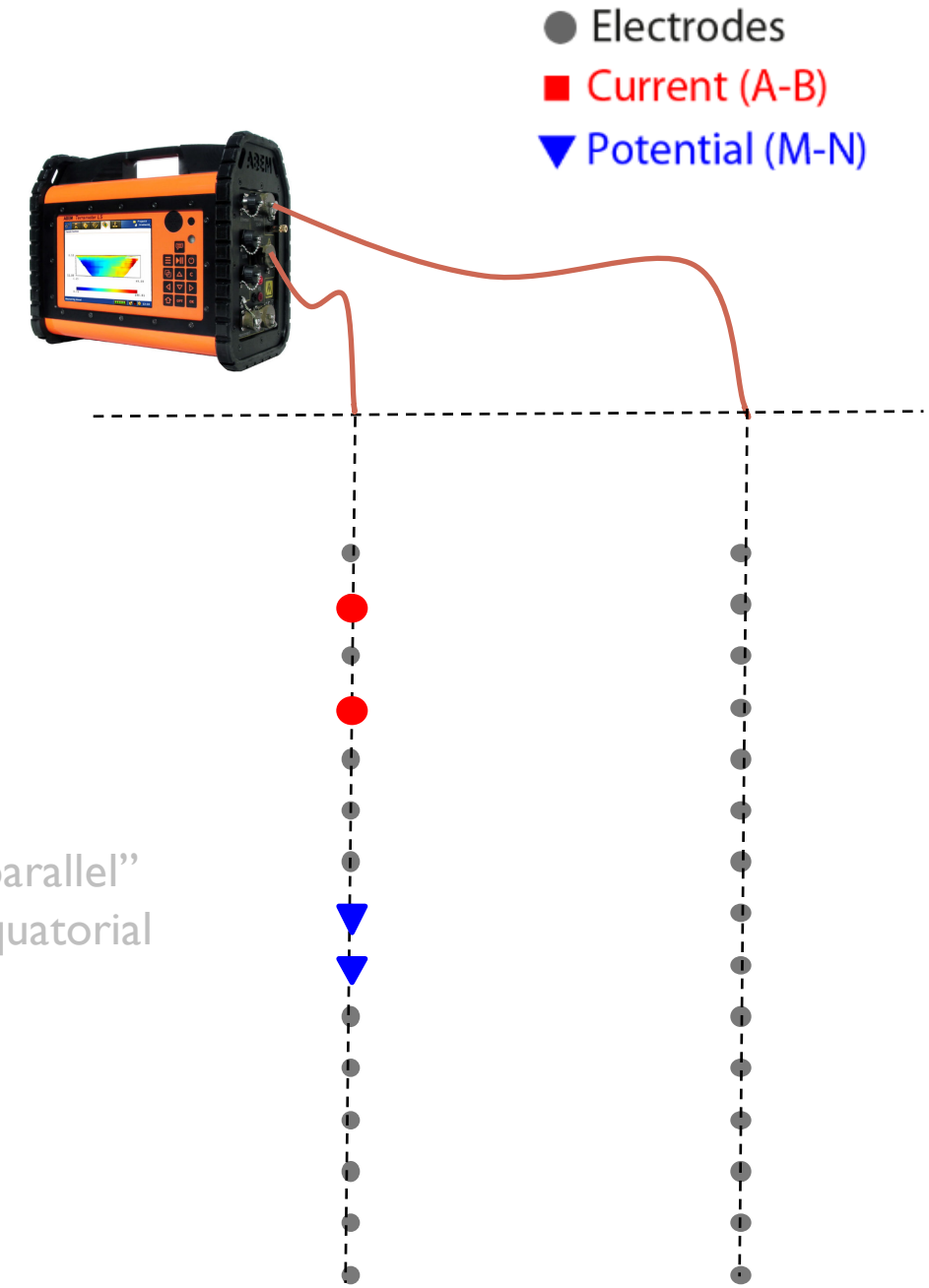




Transect C



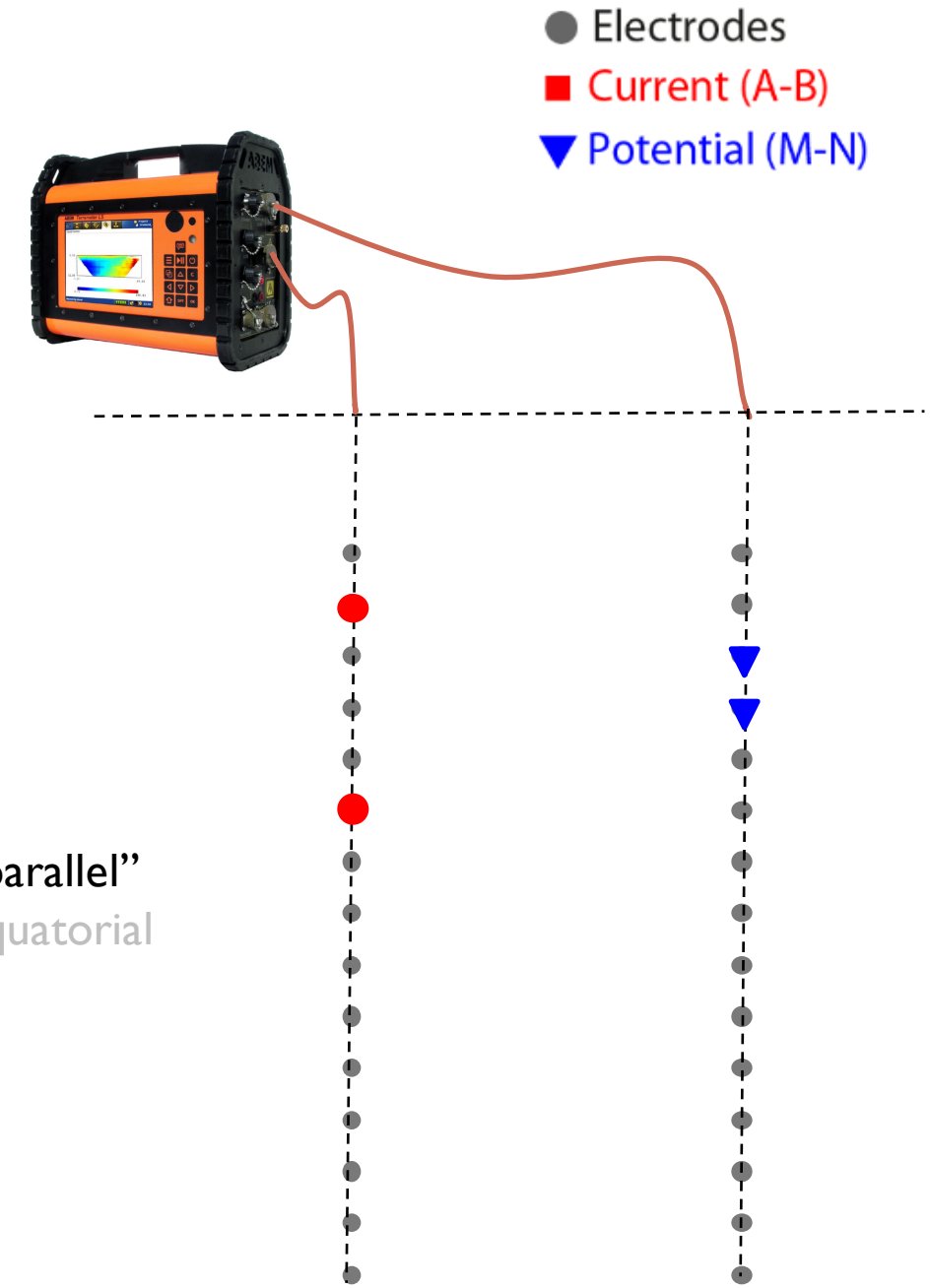
Cross-borehole ERT



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

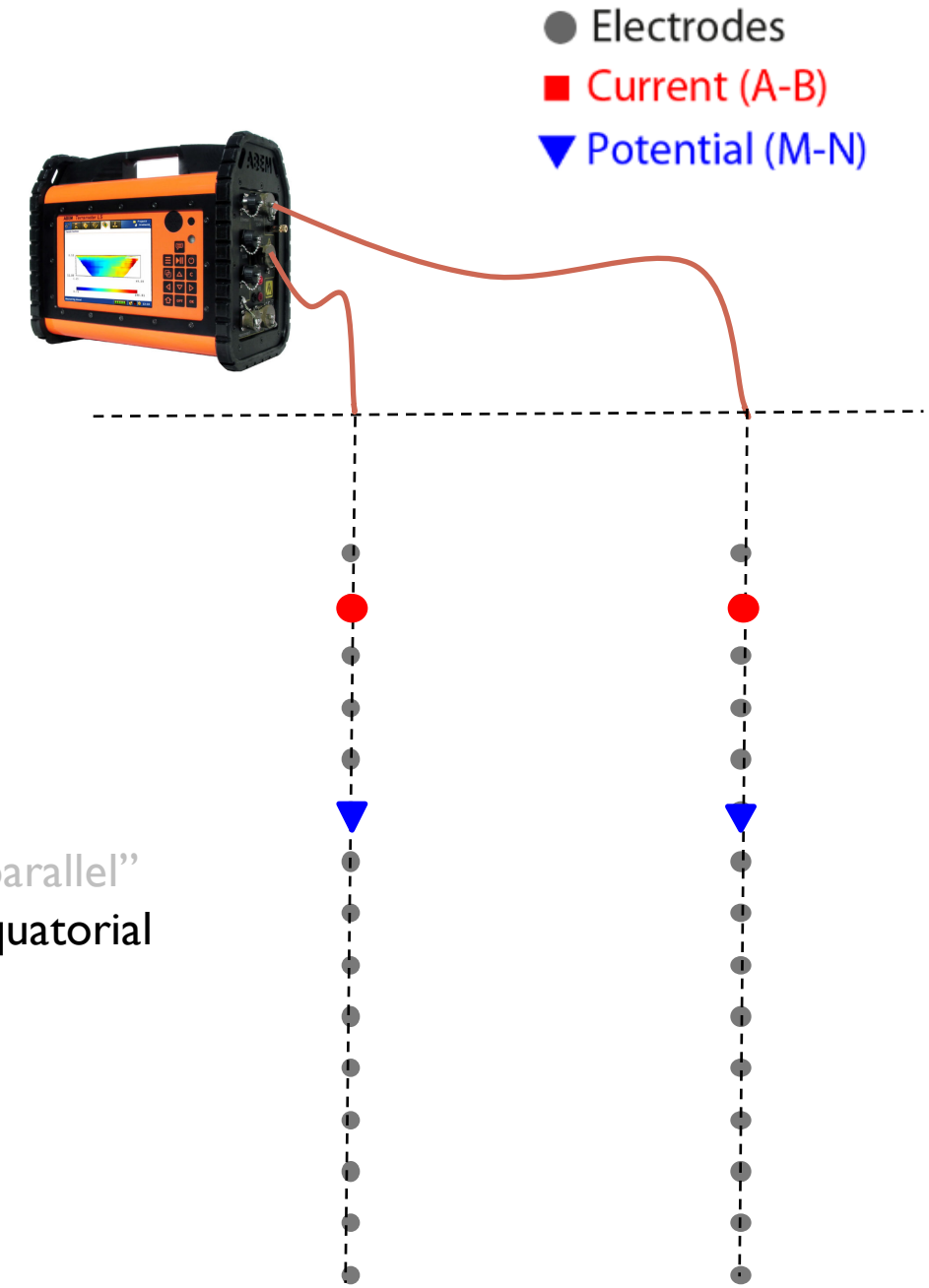
Cross-borehole ERT

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

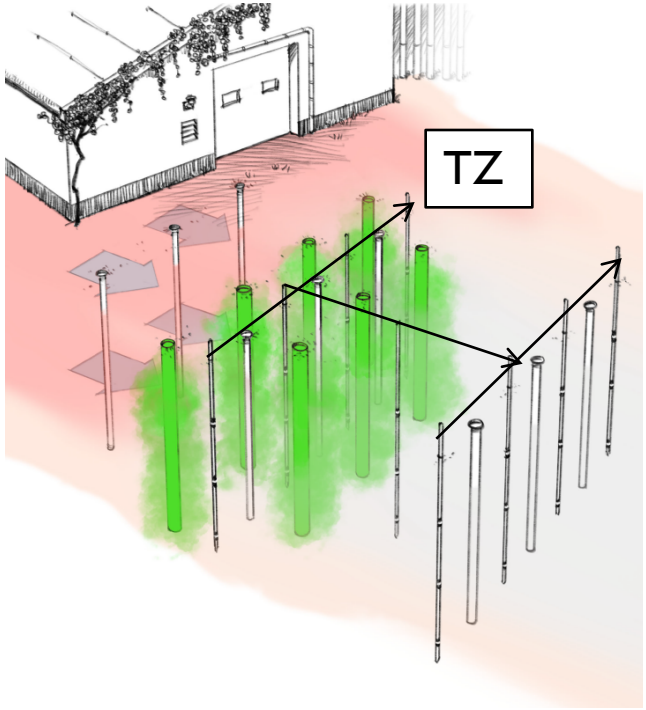


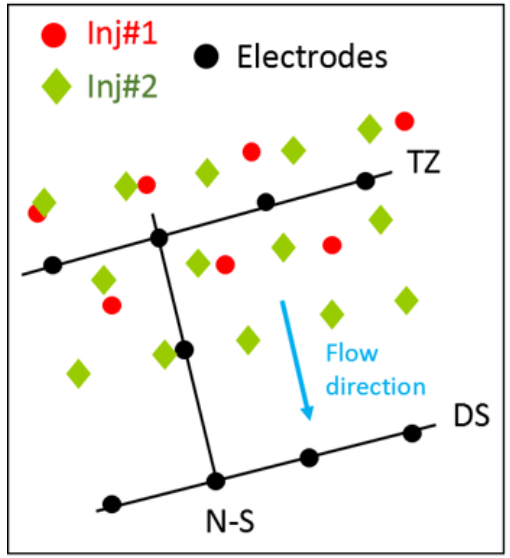
Cross-borehole ERT

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

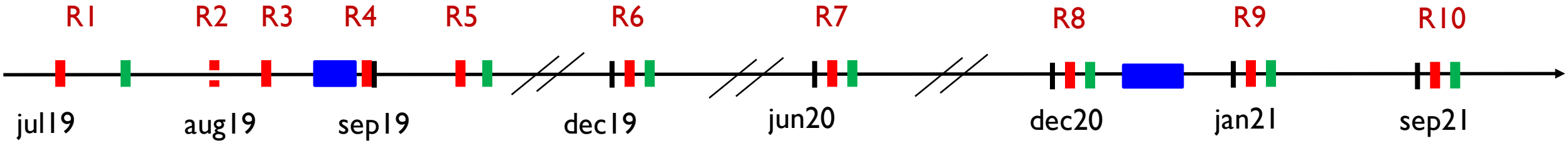


Data acquisition history

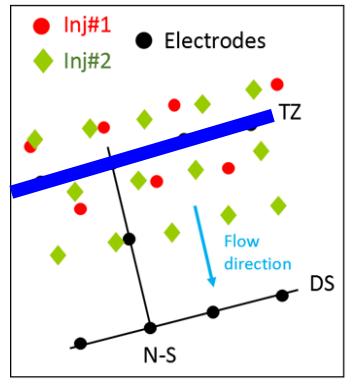


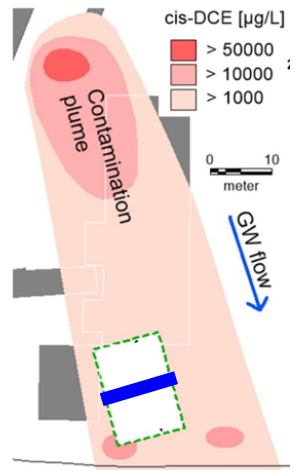


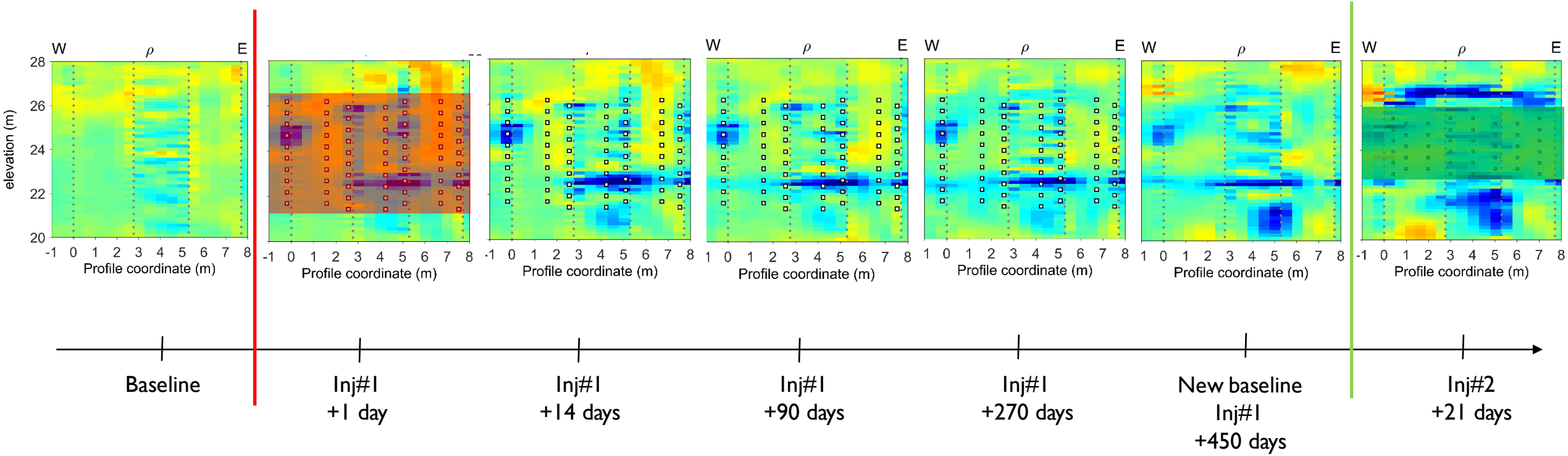
Water samples
XB ERT



Evolution over 2 years



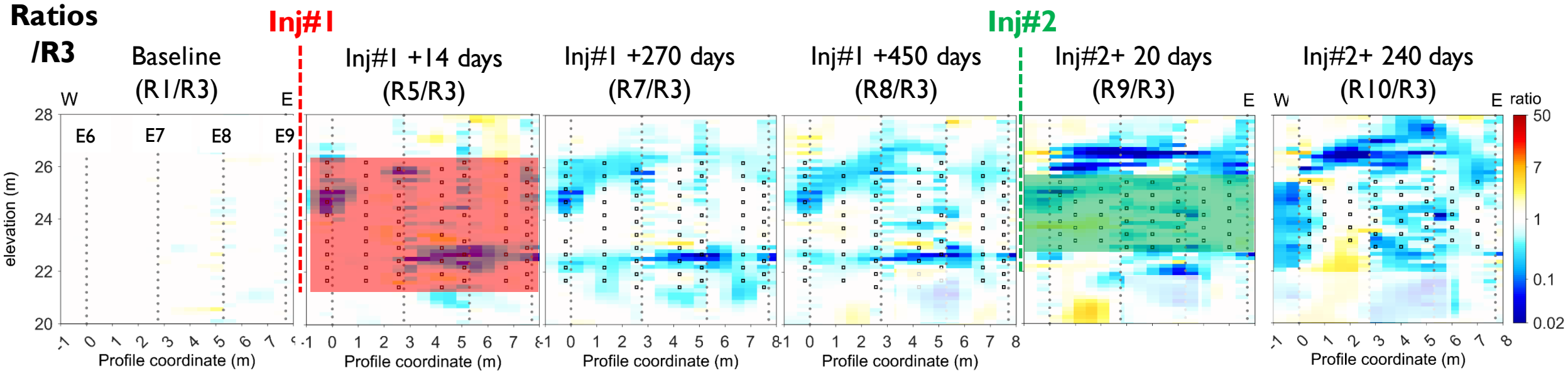


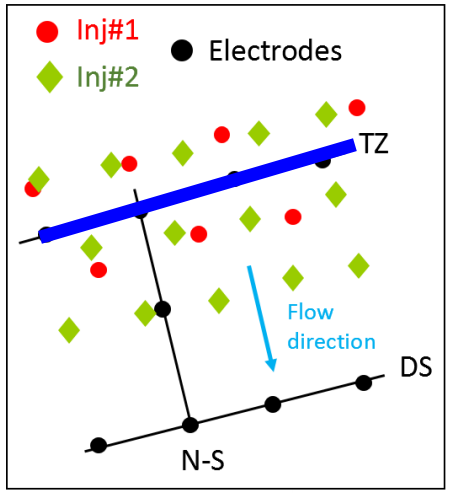


Lévy et al., under review at WRR

Subtracting geology – TZ transect

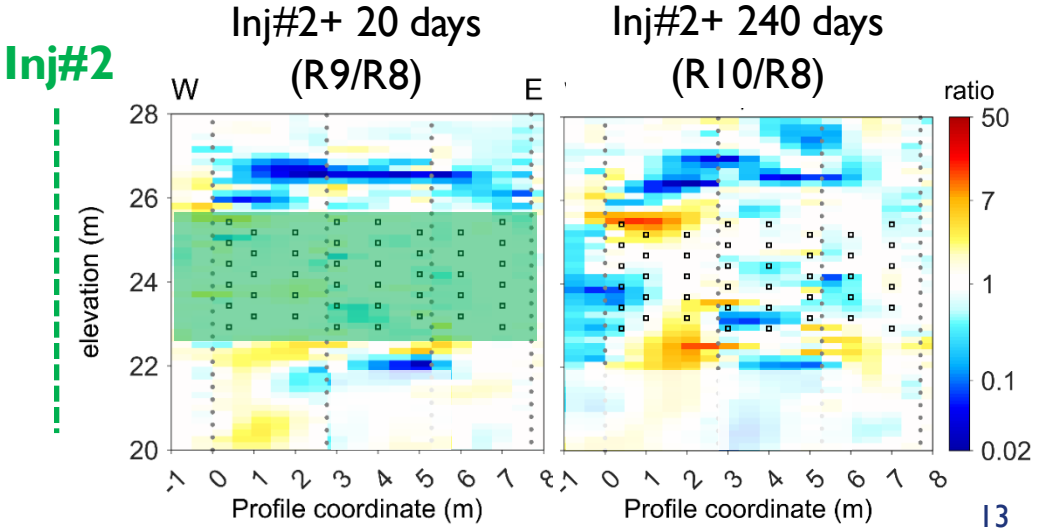
Ratios /R3





Lévy et al., under review at WRR

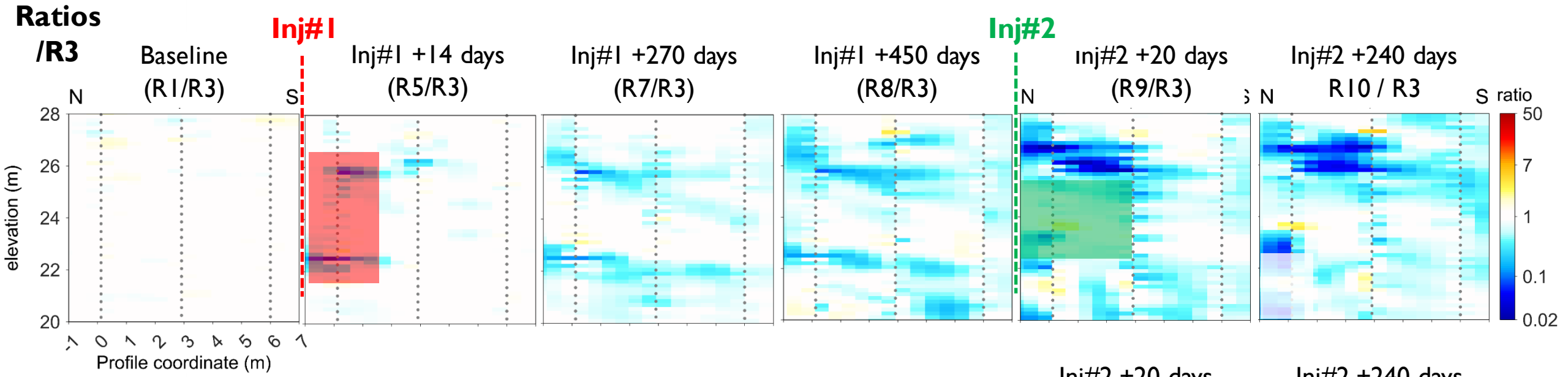
Ratios /R8

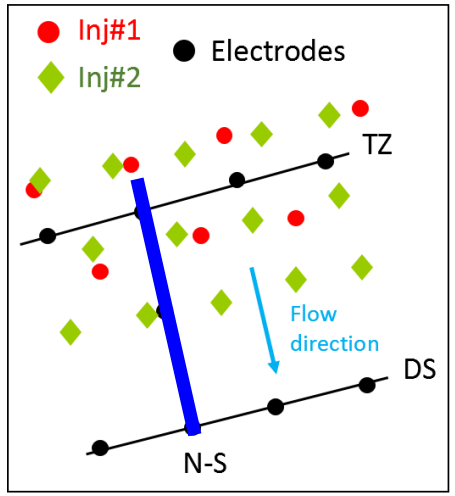


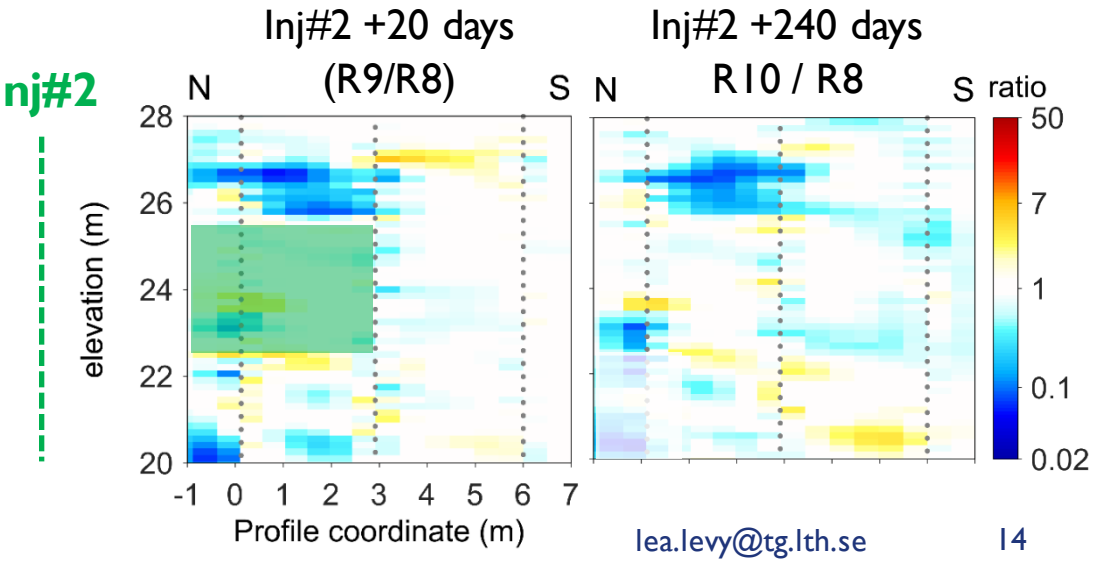
From Kirsten's presentation:

"Det er tydeligt fra NSVP, at NVOC- og jern-konc. er forhøjede over og under den ønskede dybde"

Subtracting geology – N-S transect

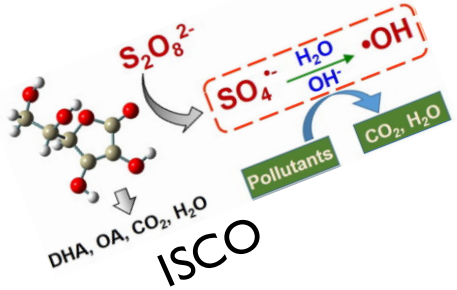




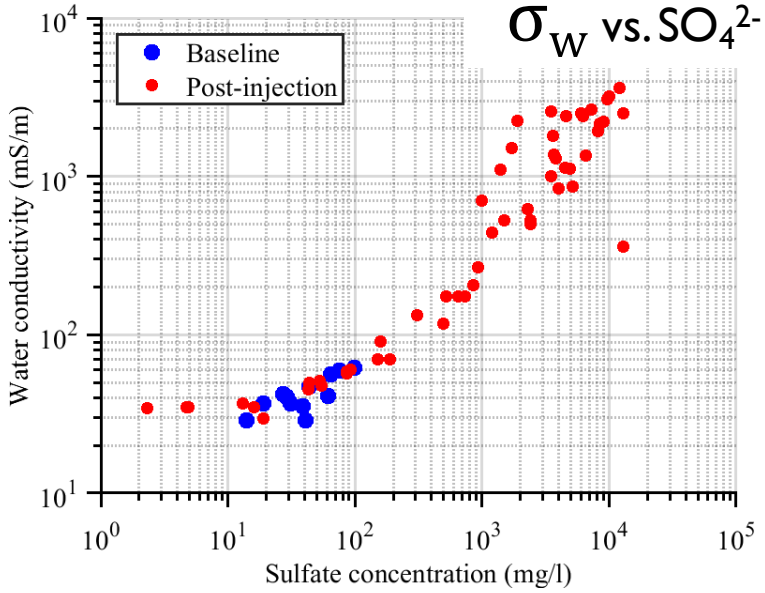


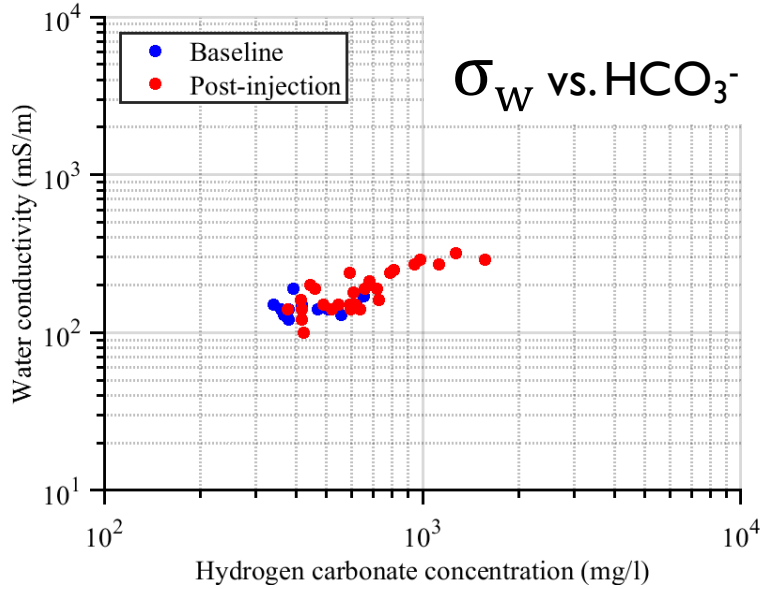
Lévy et al., under review at WRR

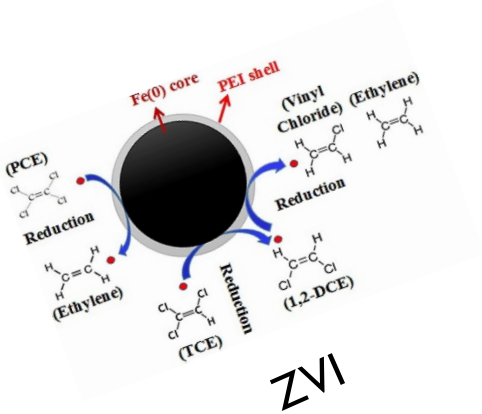
Comparison ISCO / ZVI



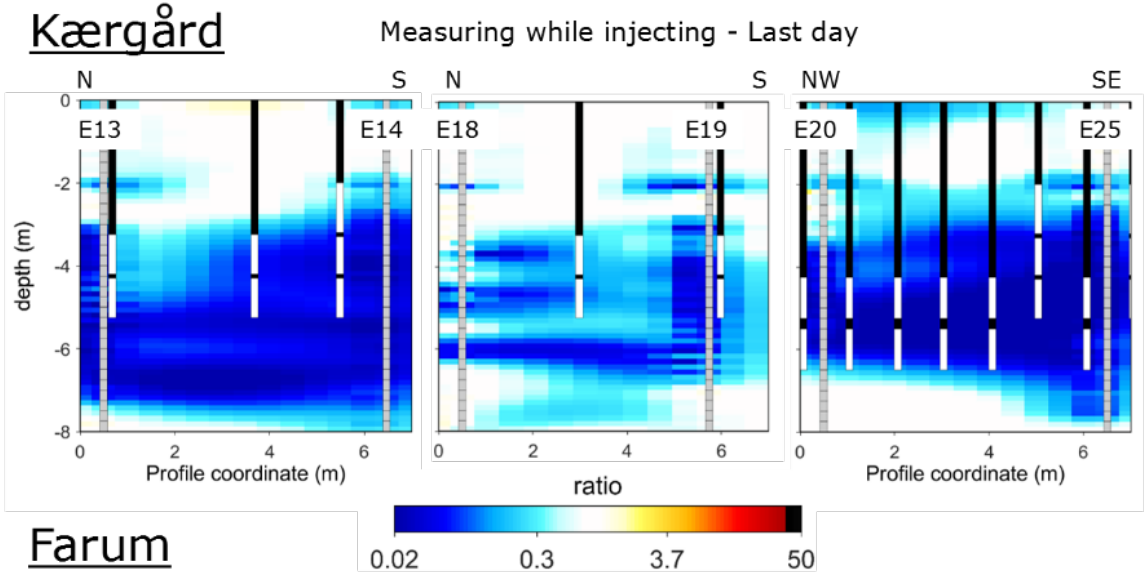
ISCO

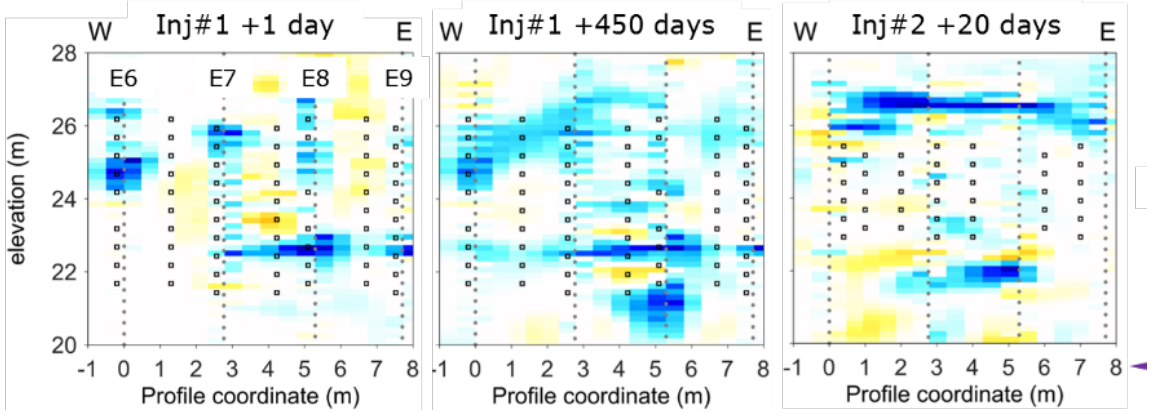




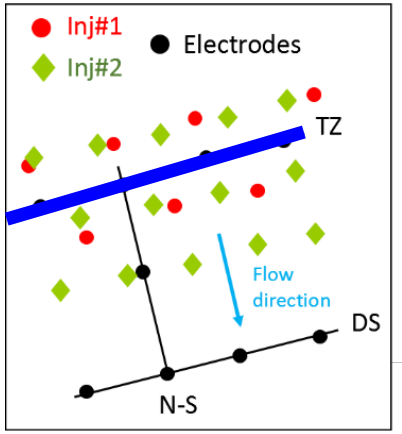


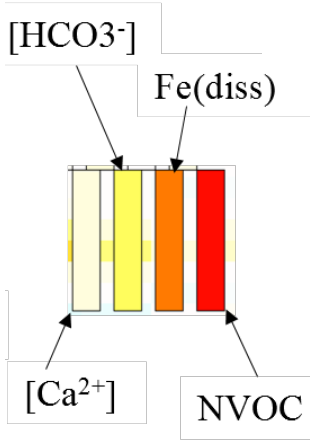
ZVI

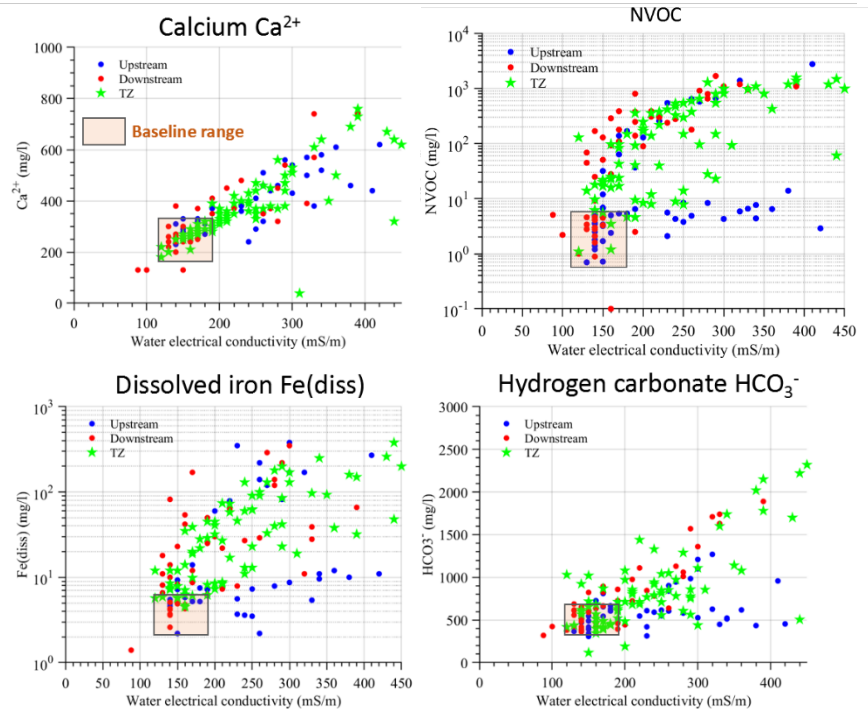


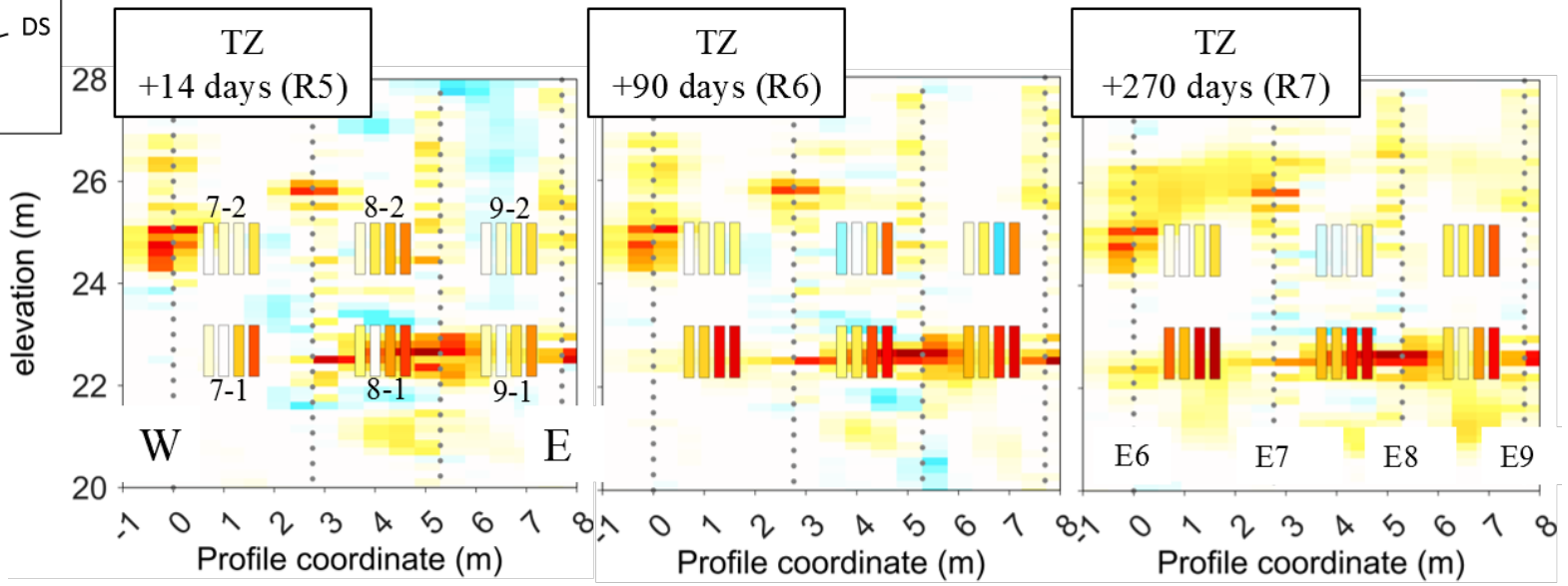


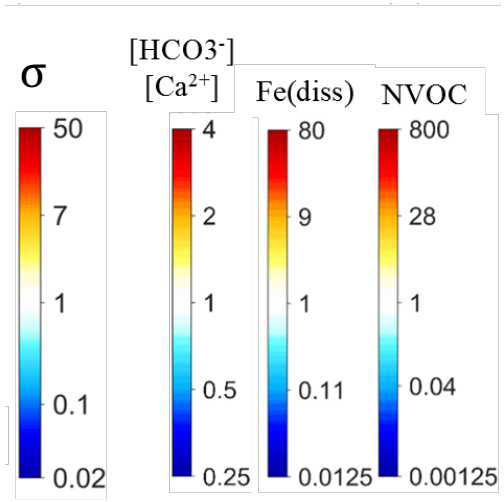
Qualitative comparison with chemistry











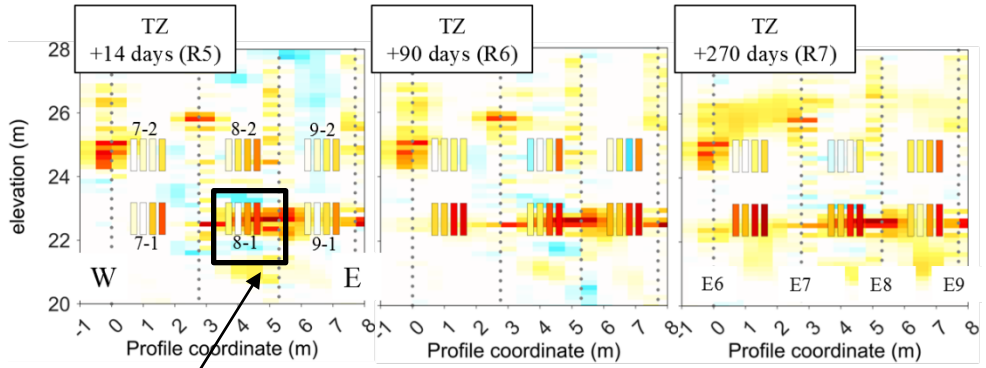
Lévy et al., under review at WRR

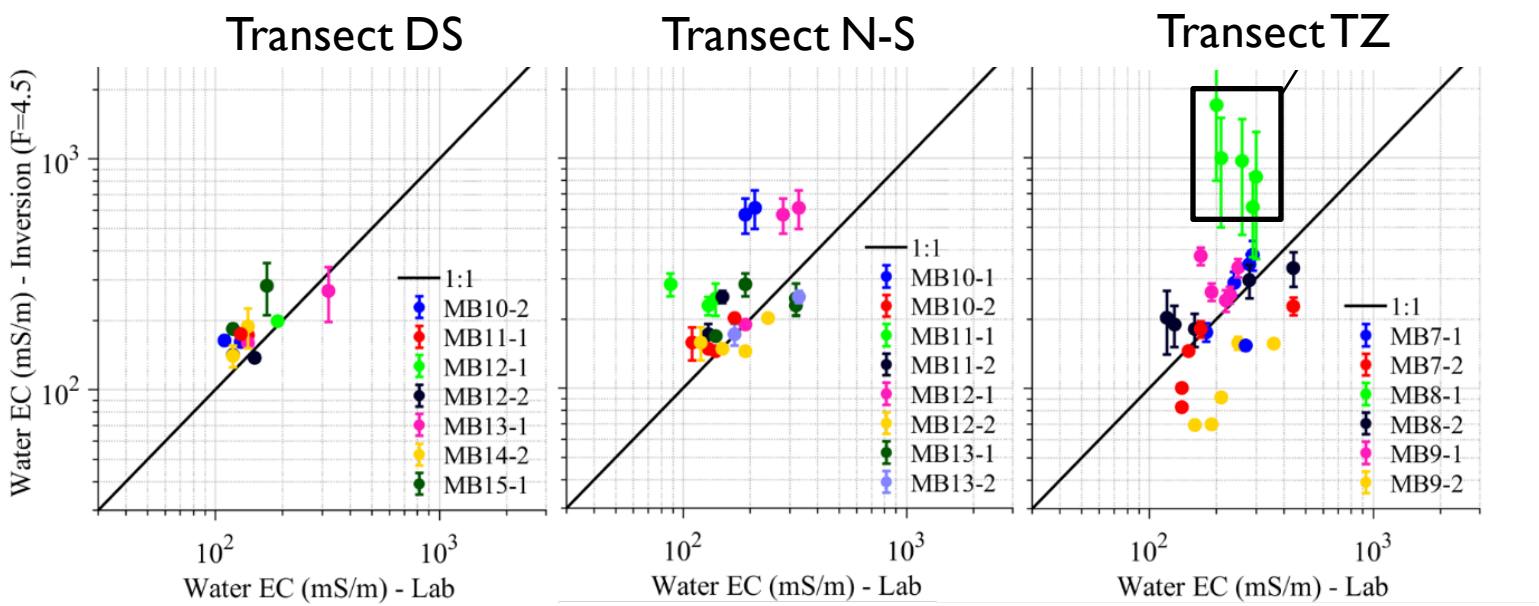
Can we be quantitative?

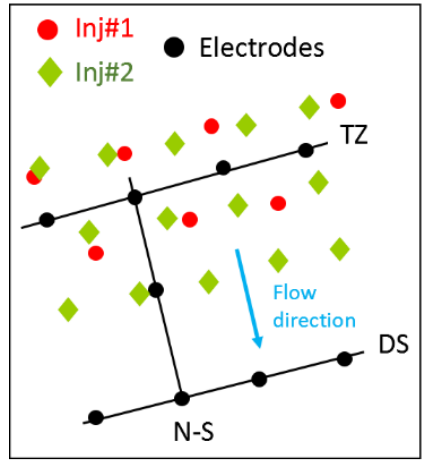
Correlation assuming only dissolved ions contribute to electrical conduction... Is there something else?

Archie, 1942

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

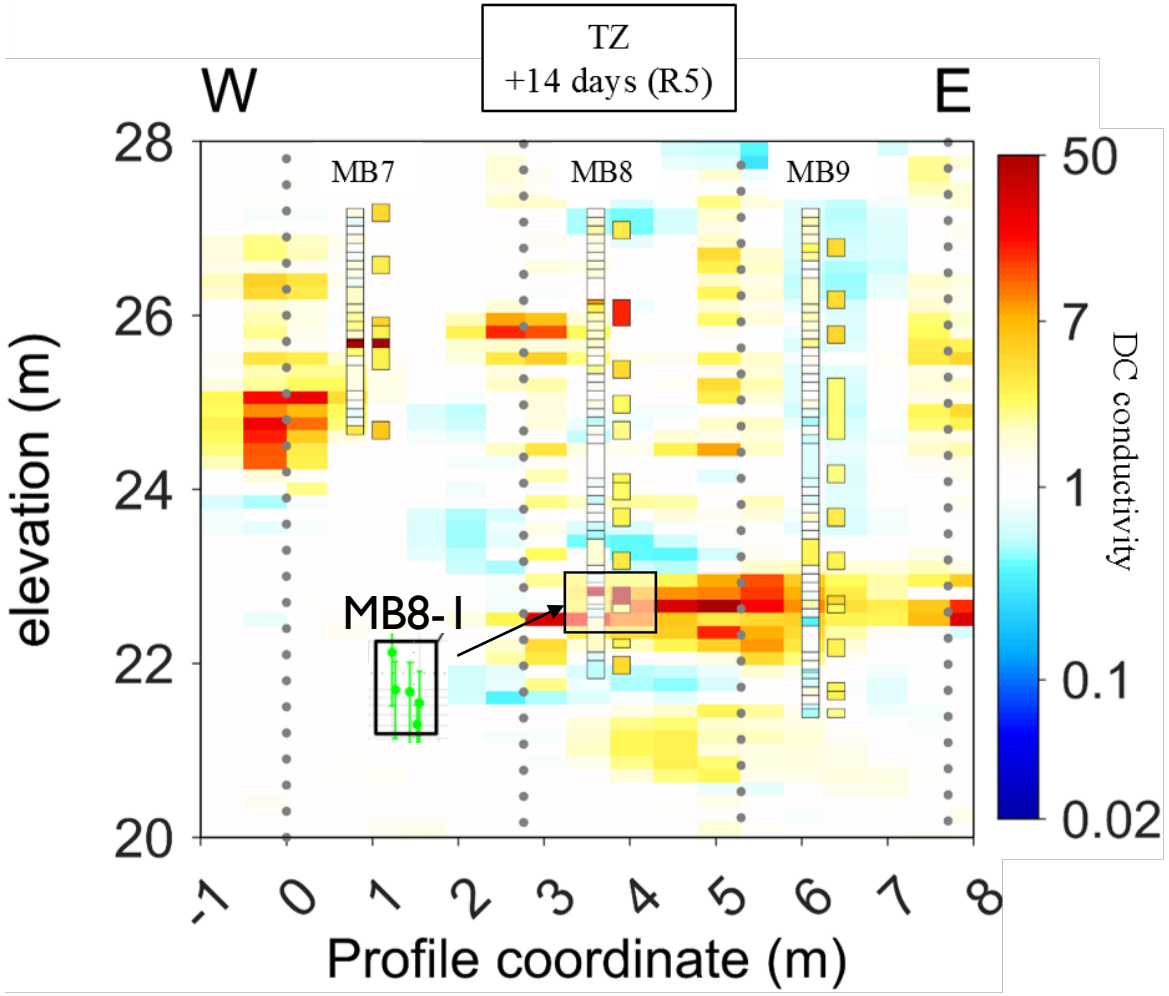




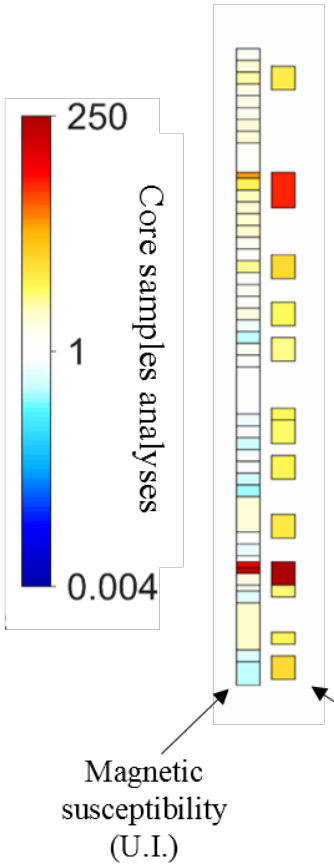


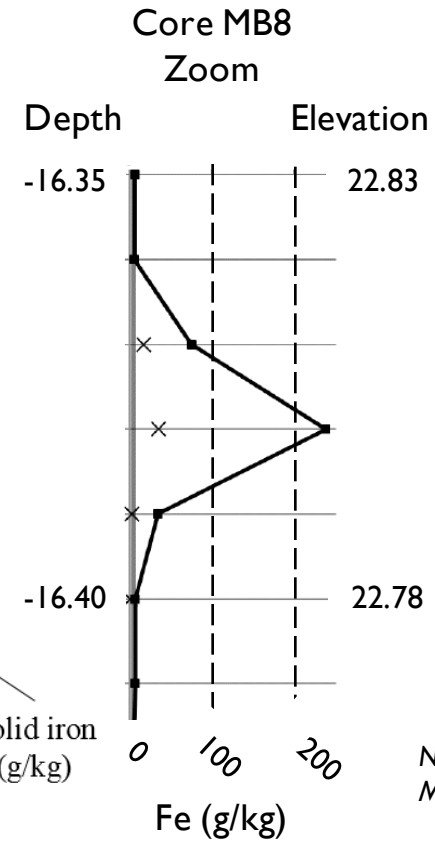
Lévy et al., under review at WRR

What happens at the outlier screen?



Peak : 240 g/kg of Fe(solid) !



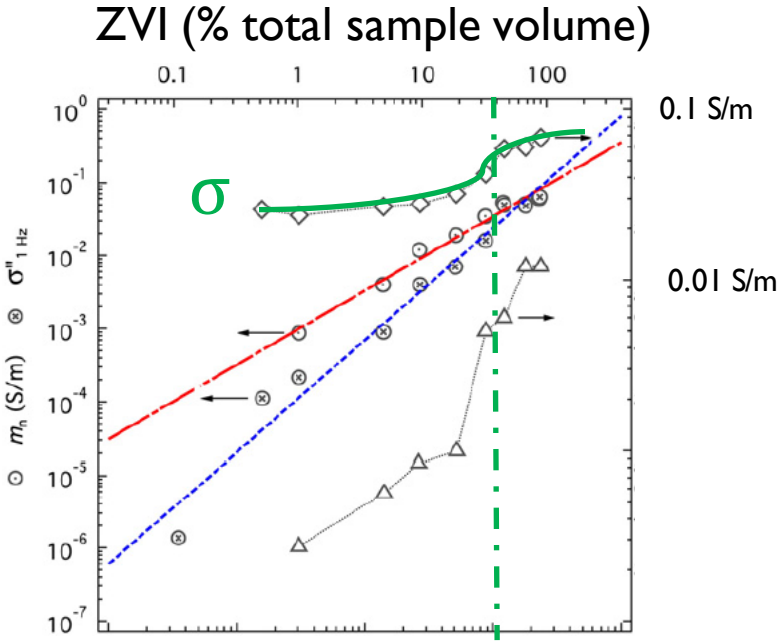


N. M. Christensen, MSc thesis, 2020

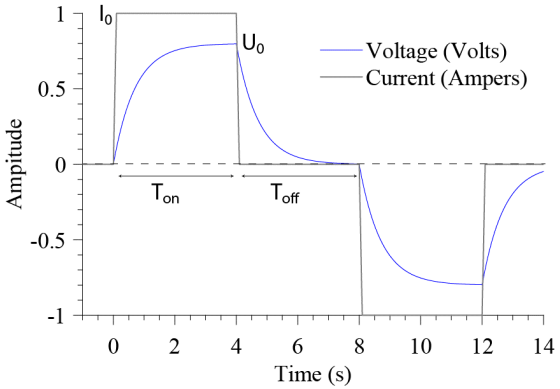
Lévy et al., under review at WRR

Electrical properties of ZVI

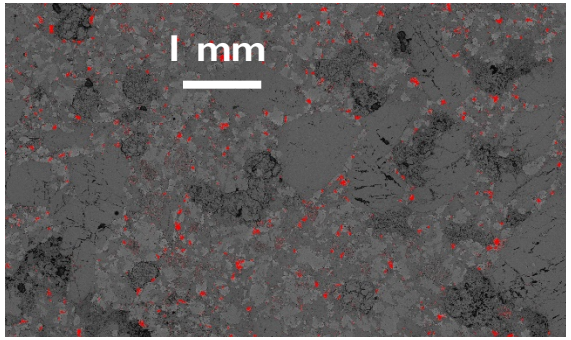
Electric charge carrier	Electrical parameter	Environmental parameter
Ions in pore water	ρ or σ	Equivalent ion concentration **ionic cloud**
Ions in/on clay minerals	ρ or σ	Cation Exchange Capacity **clay minerals**
Electrons in connected metallic particles	ρ or σ	Volume of metallic particles **sulfides, ZVI**
Electrons in disseminated metallic particles	Φ_{max}	Volume of metallic particles **sulfides, iron-oxides, ZVI**
Ions in pore water and adsorbed at solid surface	Φ_{max}	Pore surface area **hydraulic conductivity**



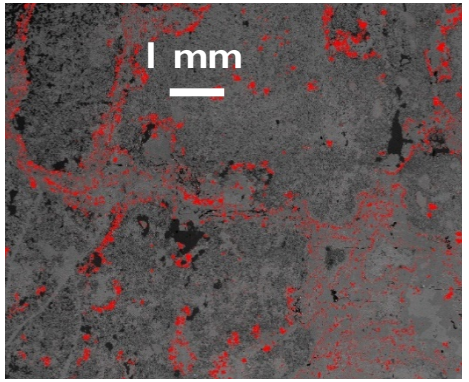
Slater et al., 2005



Connected iron particles.
© alamy.com



Disseminated magnetite particles in fresh basalt.



Connected pyrite particles in altered basalt.
Lévy et al., 2019

Cross-borehole ERT: strengths

- 2D continuous visualization tool
- High-resolution in the target volume
- Resistivity changes reflect ionic content
  - Ca^{2+}, Fe^{2+}, Cl^{-}, HCO_3^{-} (Kærgård : SO_4^{2-})
  - We also follow NVOC
  - We may also see solid iron (if conc. >20%)
  - Resistivity ratios subtract the geology
- Practical impact
  - Adds spatial information to chemical monitoring
  - Preferred pathways of ZVI reagent mapped at two injection rounds

Current limits and perspectives

- Injected product should decrease the resistivity
  - Background resistivity shall not be too low
- Only tested down to 20 m so far
- Electrode installation could be cheaper and more robust
  - depends on depth and geology
- Data acquisition could be faster and more user-friendly
- Outlier detection could be more accessible to end-users
- Uncertainty could be estimated in a more systematic manner
- 2D vs 3D inversion
- Interpretation could be pushed further
  - E.g. fracture networks

Tak!

Contact info:
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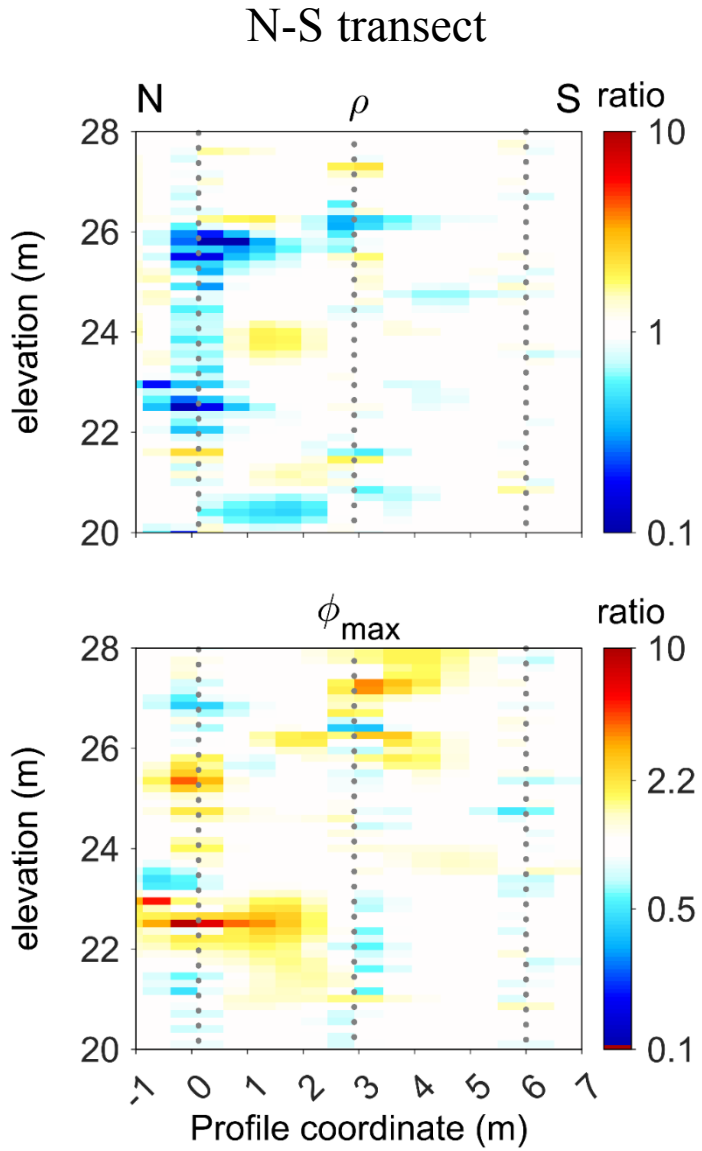
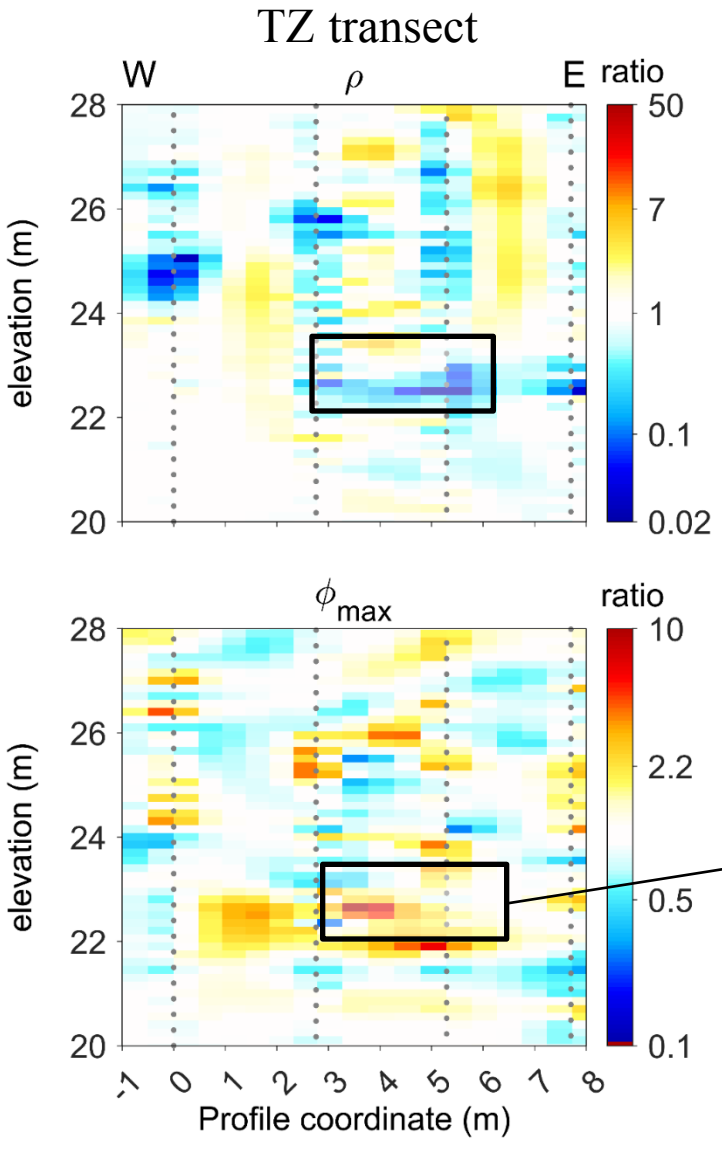
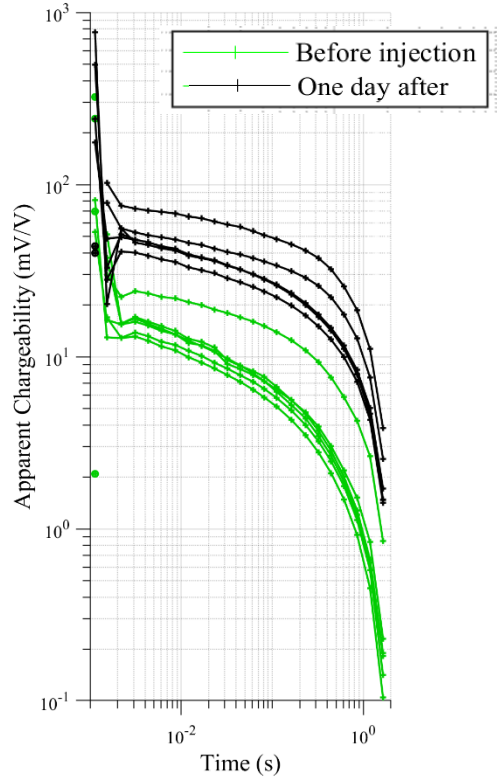
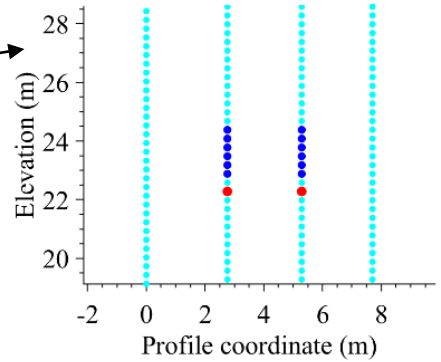
DRAFTS

Increase of polarization at Inj+1d



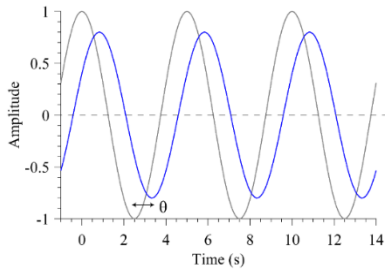


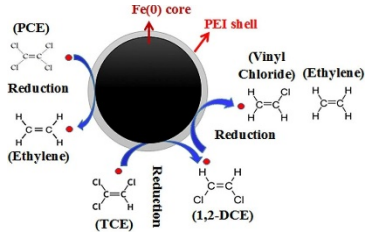




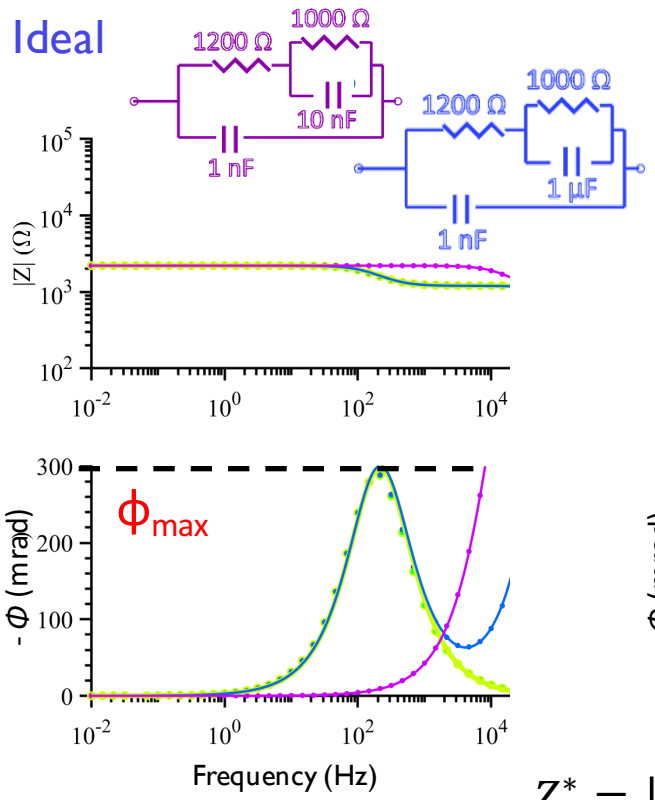
ZVI vs polarization (IP)

Electric charge carrier	DCIP parameter	Environmental parameter
Ions in pore water	ρ or σ	Equivalent ion concentration **ionic cloud**
Ions in/on clay minerals	ρ or σ	Cation Exchange Capacity **clay minerals**
Electrons in connected metallic particles	ρ or σ	Volume of metallic particles **sulfides, ZVI**
Electrons in disseminated metallic particles	Φ_{max}	Volume of metallic particles **sulfides, ZVI**

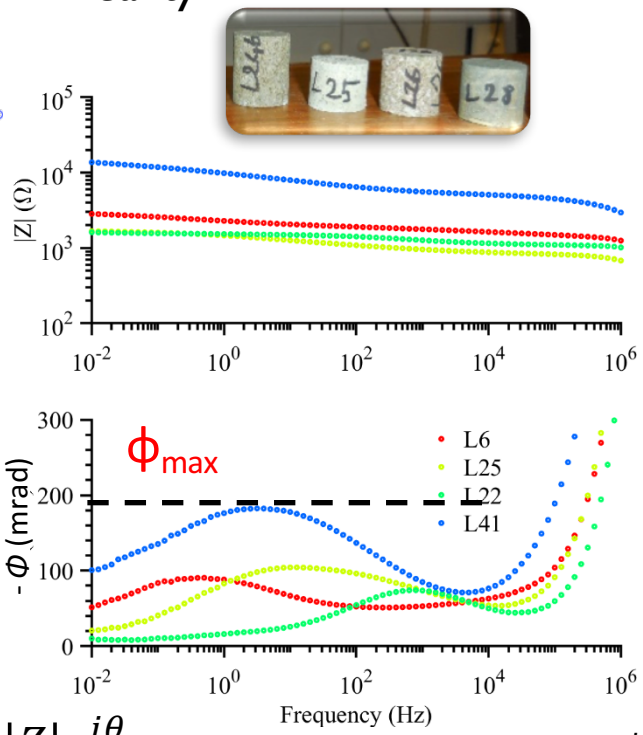


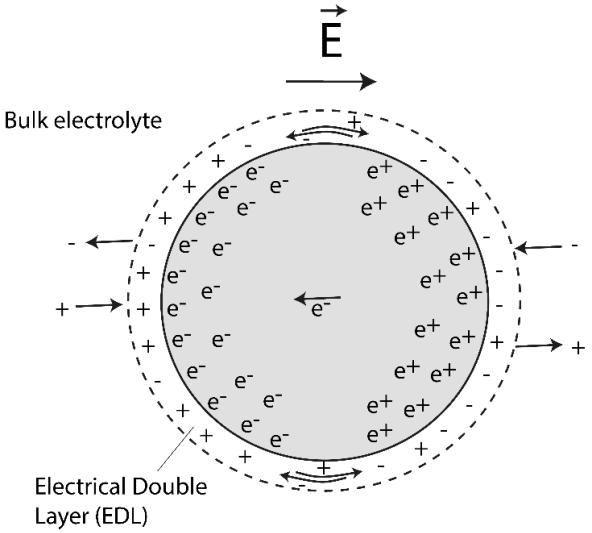


Ideal



Reality





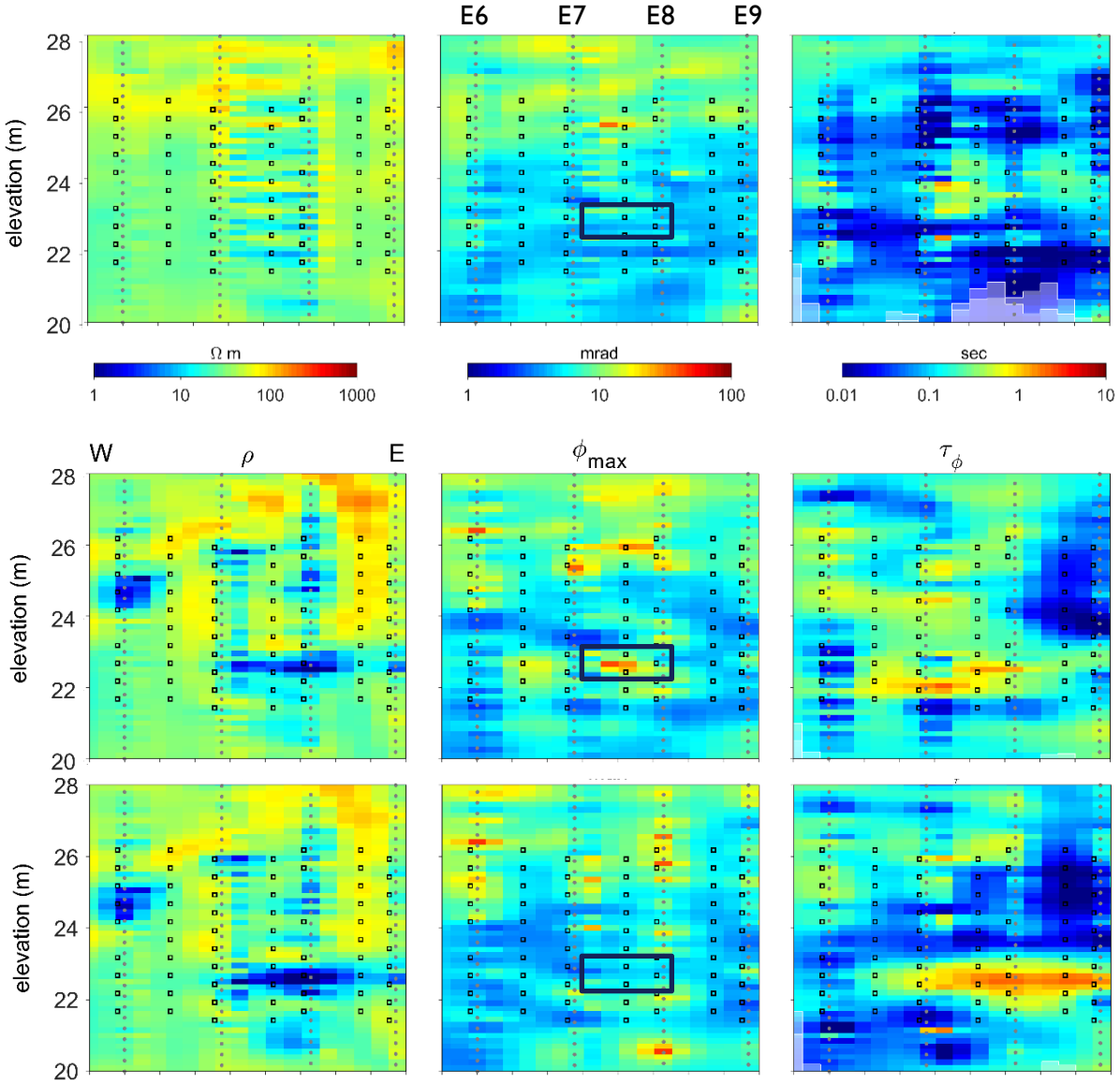
Metallic particle (e.g. ZVI)

$$Z^* = |Z|e^{i\theta}$$

Provect

Compound	%	Source
m-ZVI	5-90	Manufacturer
Calcium dipropionate	2-12	Manufacturer
Yeast extracts	< 2.5	Manufacturer
Guar gum	< 2.5	Manufacturer
Sodium sulfite	< 2.5	Manufacturer
m-ZVI	45	This study
Total (Ca+K+Mg+Na+S)	2.5	This study
Total carbon	19.5	This study
Unknown	34	This study

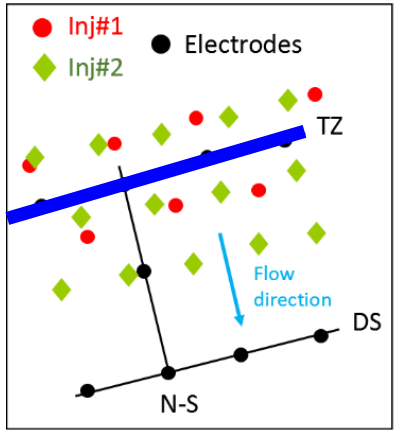
No polarization remaining afterwards



Baseline

+1 day (R4)

+14 days (R5)



But Tau + conduction anomaly suggests > 10% ZVI

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Electrons in disseminated metallic particles	Φ_{max}	Volume of metallic particles **sulfides, ZVI**
Ions in pore water and adsorbed at solid surface	Φ_{max}	Pore surface area **hydraulic conductivity**

Electric charge carrier	DCIP parameter	Environmental parameter
Ions in pore water	ρ or σ	Equivalent ion concentration **ionic cloud**

Electric charge carrier	DCIP parameter	Environmental parameter
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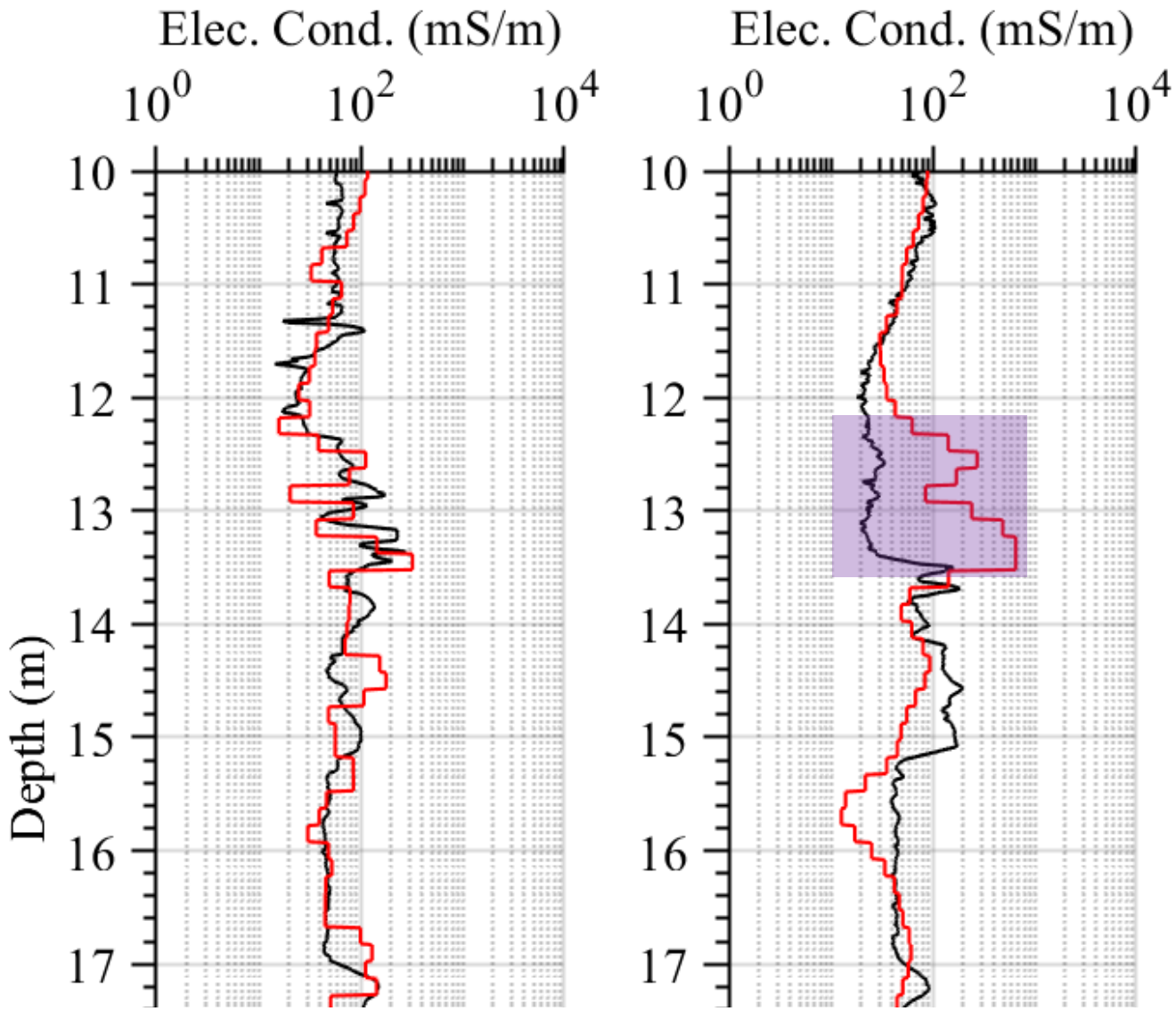
Comparison to MIP

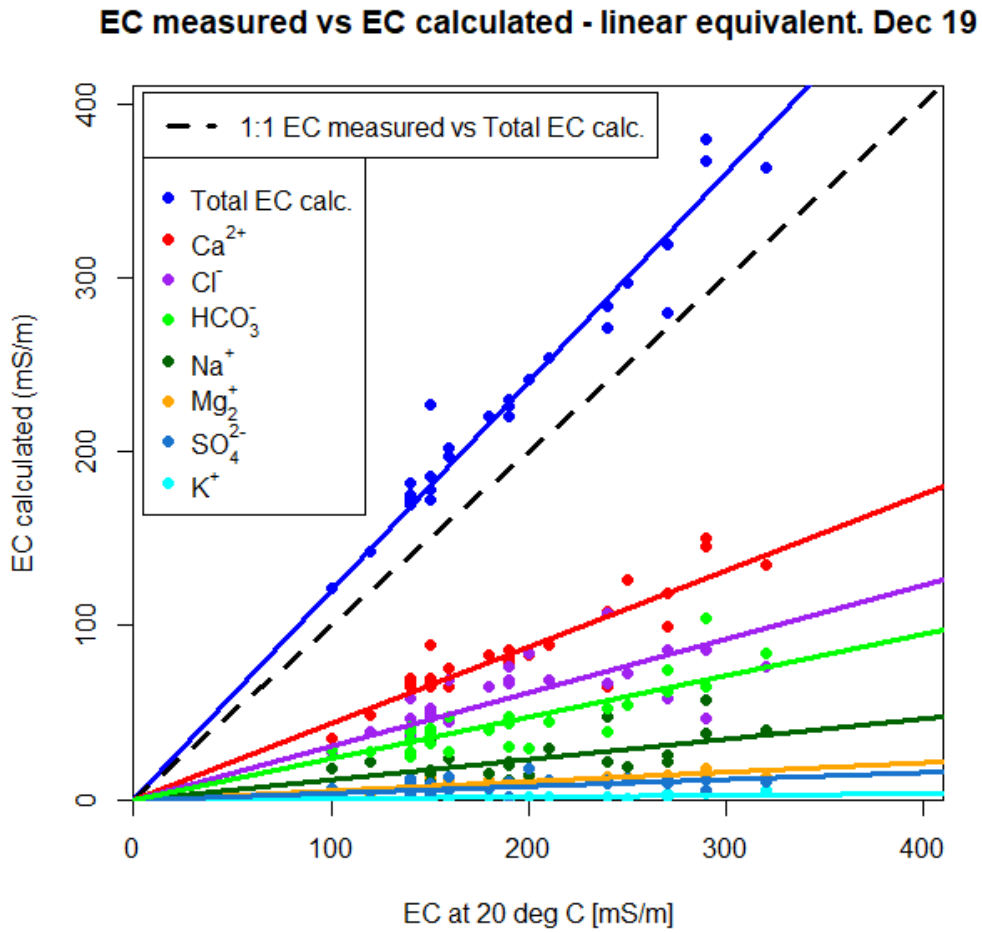


MIP6

DC
(near E5)

MIP1

DC
(between E5-E7)


EC measured vs EC calculated - linear equivalent. Dec 19
1:1 EC measured vs Total EC calc.
Total EC calc.
Ca2+
Cl-
HCO3-
Na+
Mg2+
SO42-
K+
EC calculated (mS/m)
EC at 20 deg C [mS/m]
0
100
200
300
400