RemPlex Seminar

June 3, 2025

Subsurface Sensing: Advancing Electrical Geophysical Techniques for Non-Invasive Characterization and Monitoring at Complex Sites

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Today’s Seminar and Speakers

Subsurface Sensing: Advancing Electrical Geophysical Techniques

Lee Slater
Distinguished Professor
Rutgers University

Adrián Flores-Orozco
Head of the Geophysics Institute
Technical University (TU) Wien

Hilary Emerson
Earth Scientist
Pacific Northwest National Laboratory

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ELECTRICAL GEOPHYSICS: THE SPECTRAL INDUCED POLARIZATION (SIP) METHOD

Lee Slater, Senior Geophysicist

Joint Appointment: Henry Rutgers Professor of Geophysics, Rutgers University Newark

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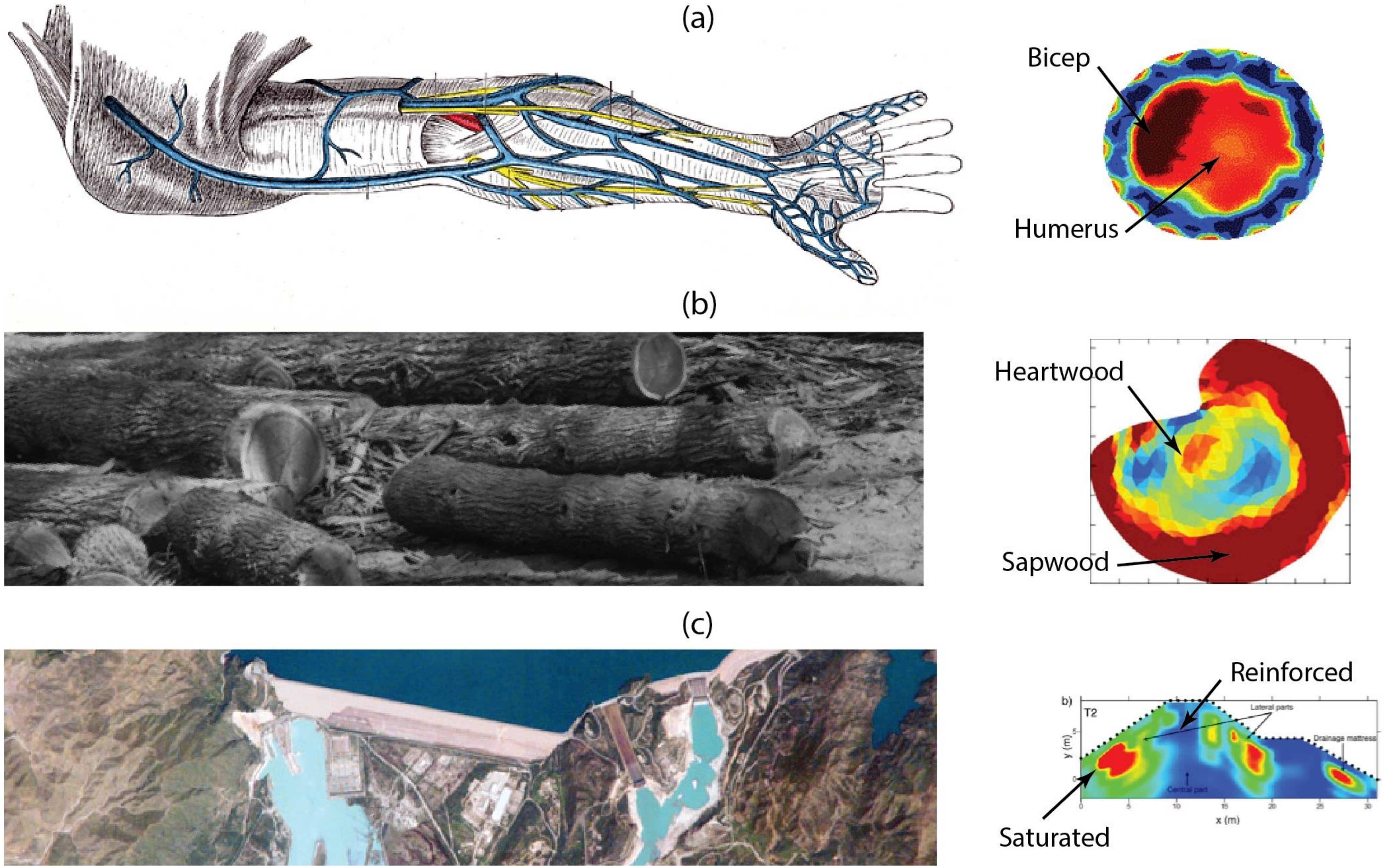
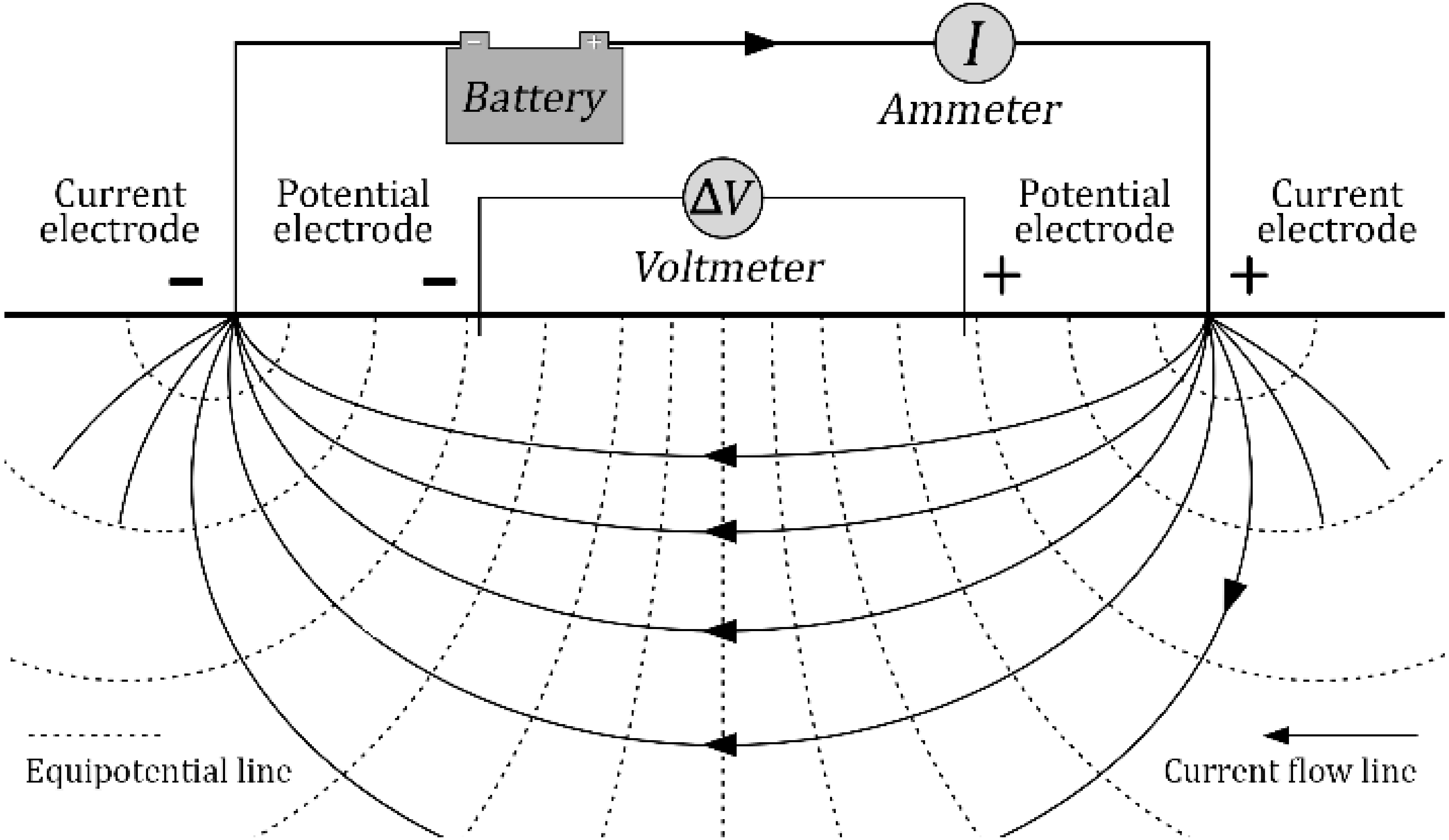
Non-invasive electrical imaging

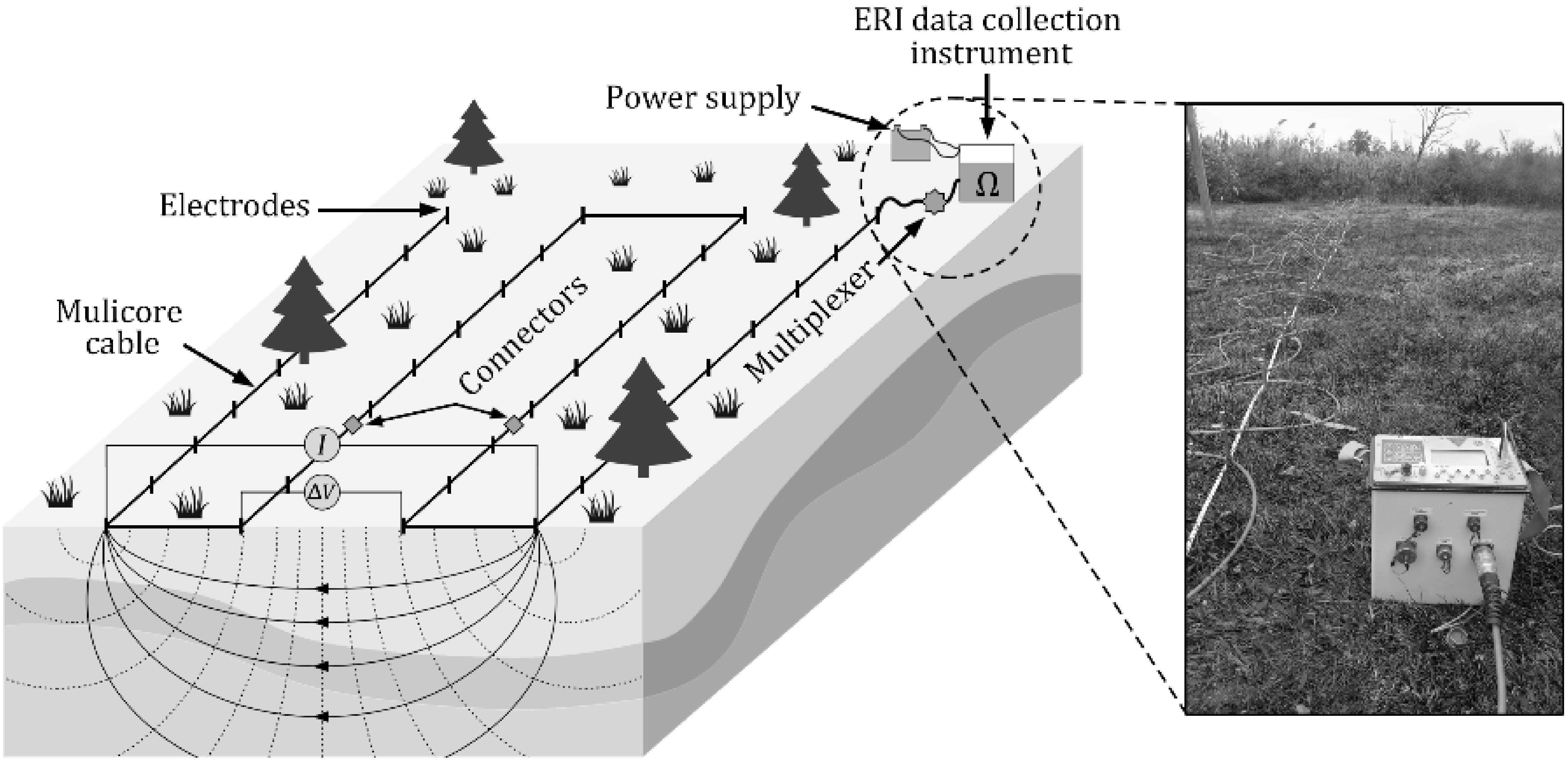


Falzone et al. (2018), Transport in Porous Media

Electrical geophysics



Electrical geophysical imaging



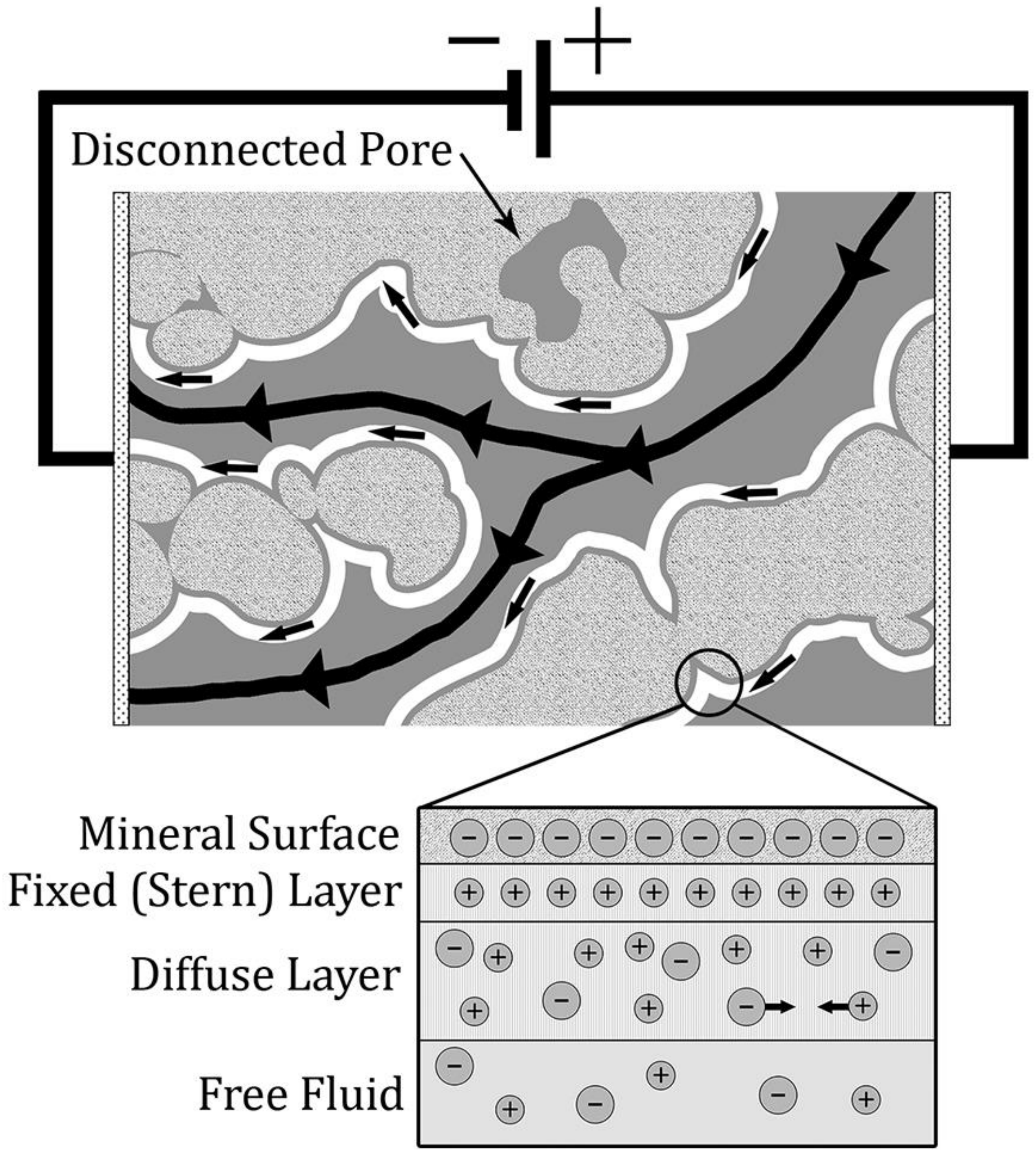
Binley and Slater, 2020, *Resistivity and induced polarization: theory and applications to the near-surface Earth*

Electrical current transport in the Earth

- Conduction: migration of ch… applied electric field

- Earth acts as a resistor

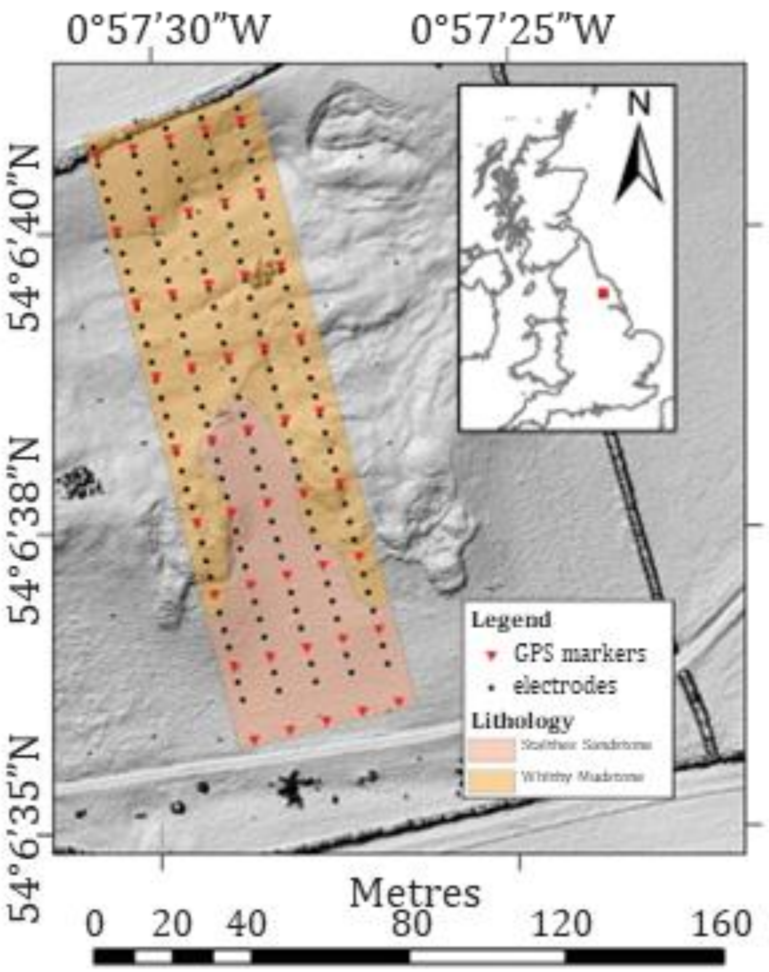
Quantified by <u>electrical conductivity</u> of the Earth

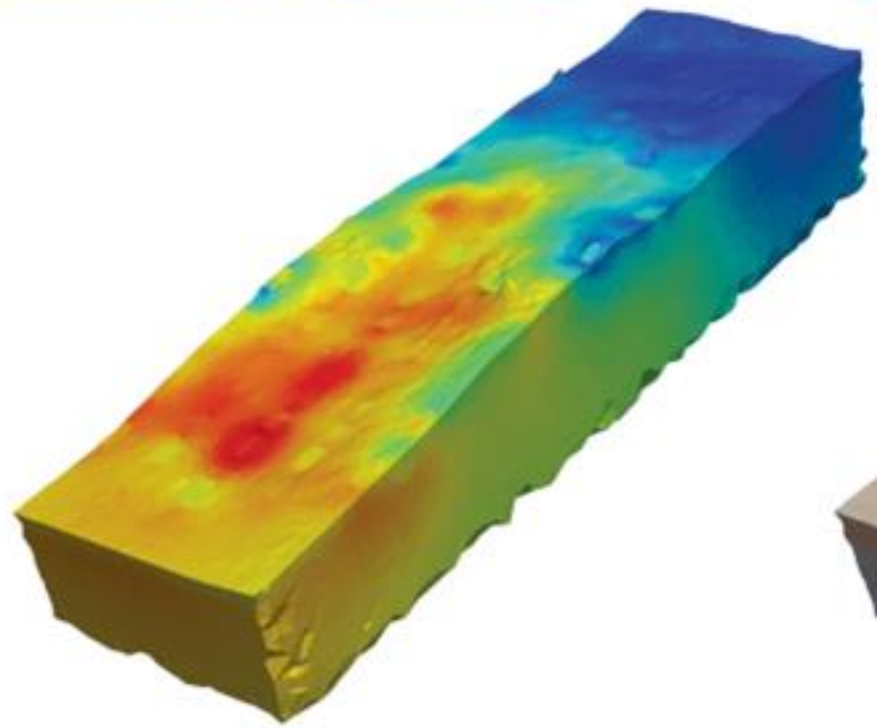


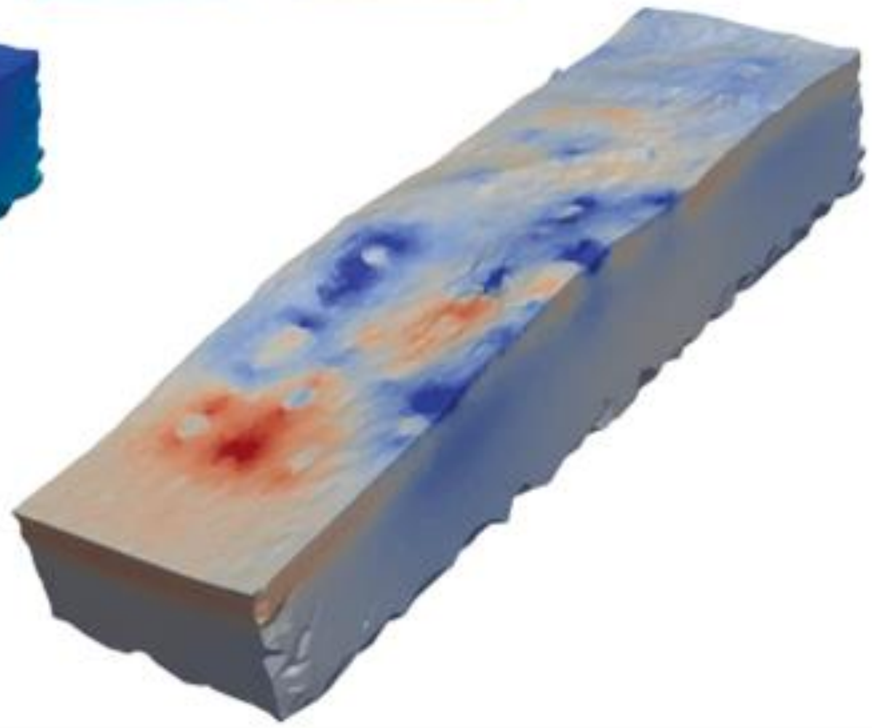
Imaging structures

Hydrogeophysical relationship

Spatial variations in electrical conductivity → Spatial variations in property of interest (e.g. moisture content)

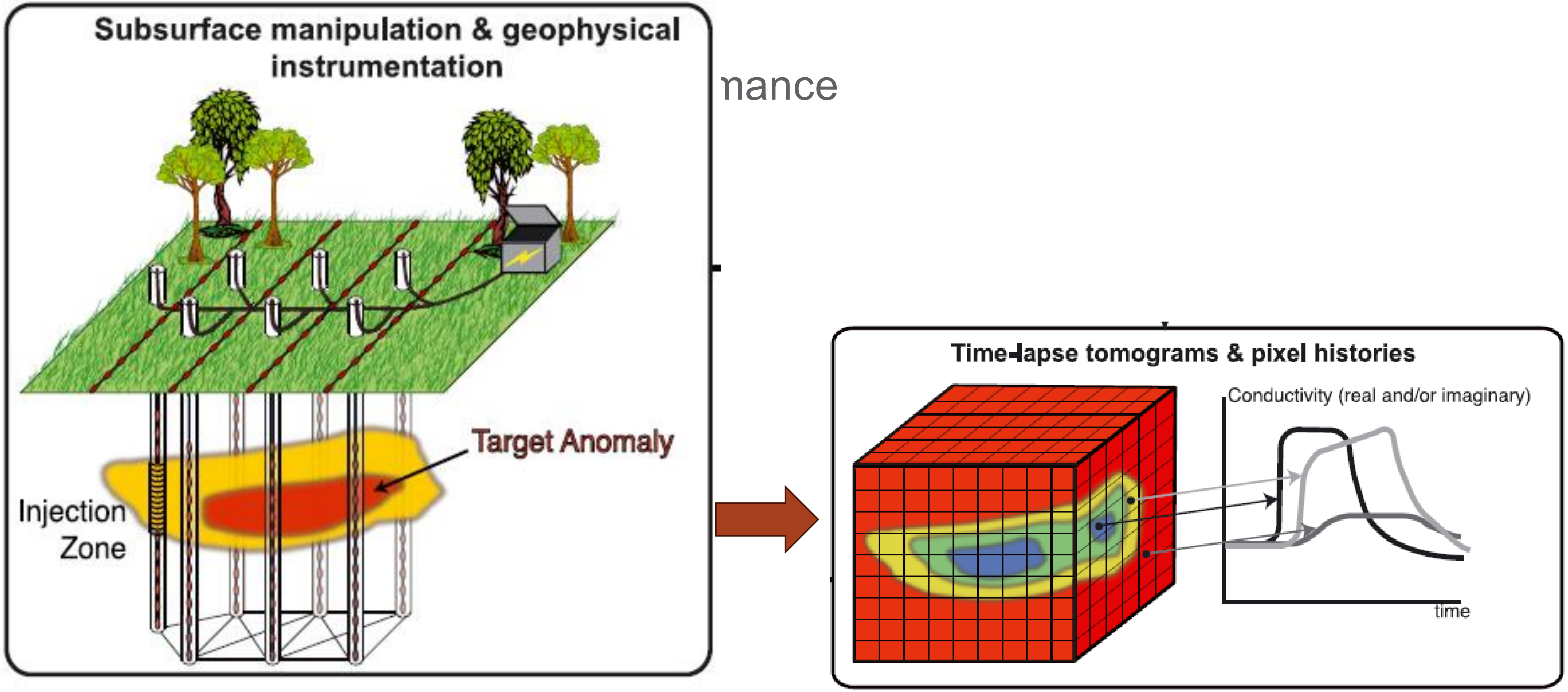






Binley and Slater, 2020, *Resistivity and induced polarization: theory and applications to the near-surface Earth*

Electrical geophysical monitoring of subsurface processes



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Polarization of charge in the Earth: insulating grains

- Polarization: temporary displacement and storage of charge under an applied electric field
- Earth acts as a poor (leaky) capacitor

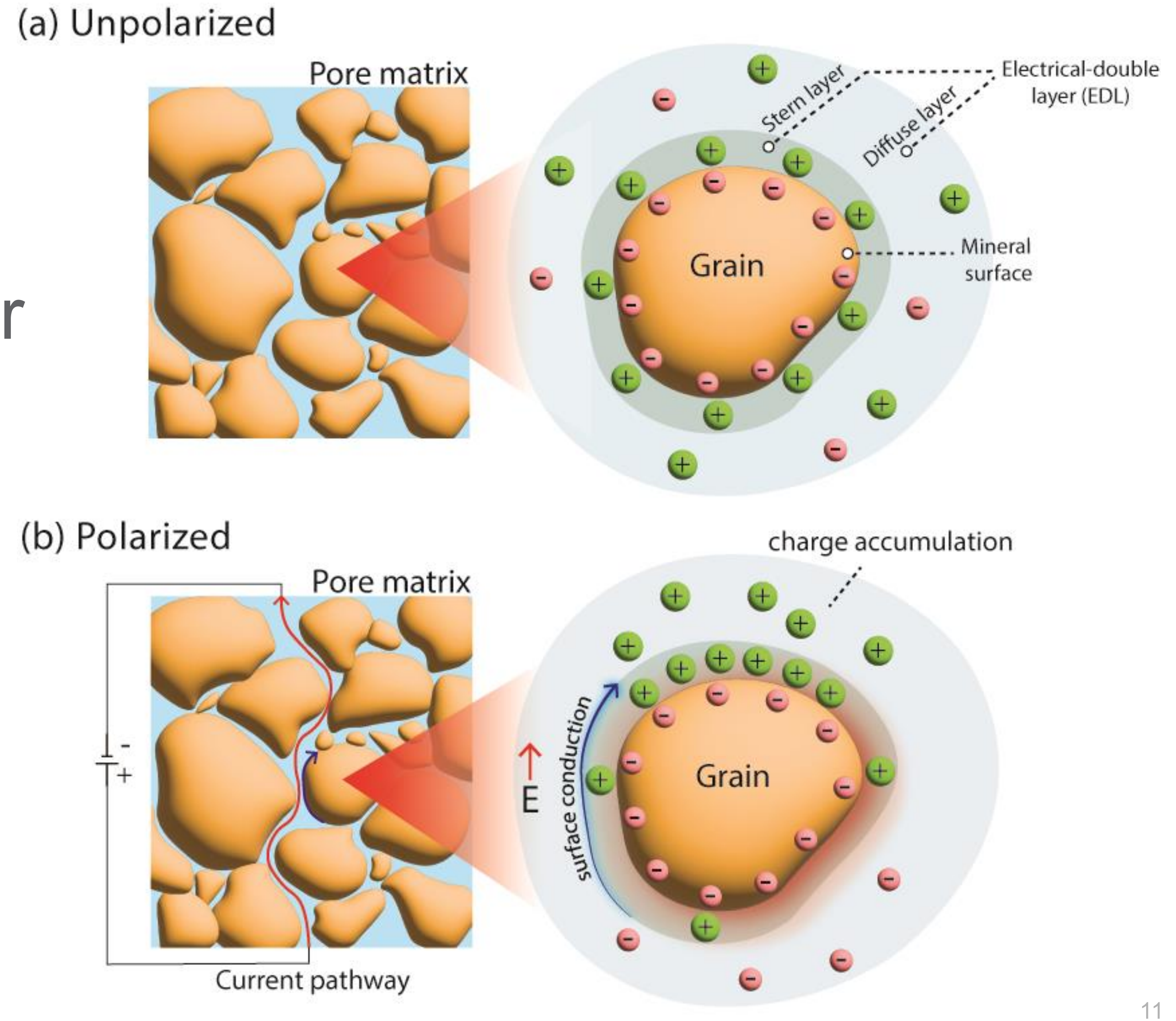
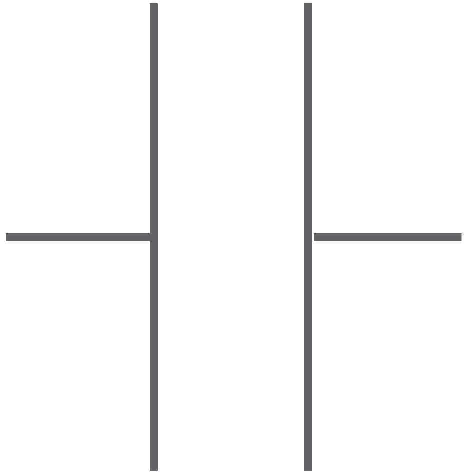


Figure credit: Klaudio Peshtani, Pacific Northwest National Laboratory

Polarization of charge in the Earth: conducting grains

- Electron conductors make the Earth a much better capacitor



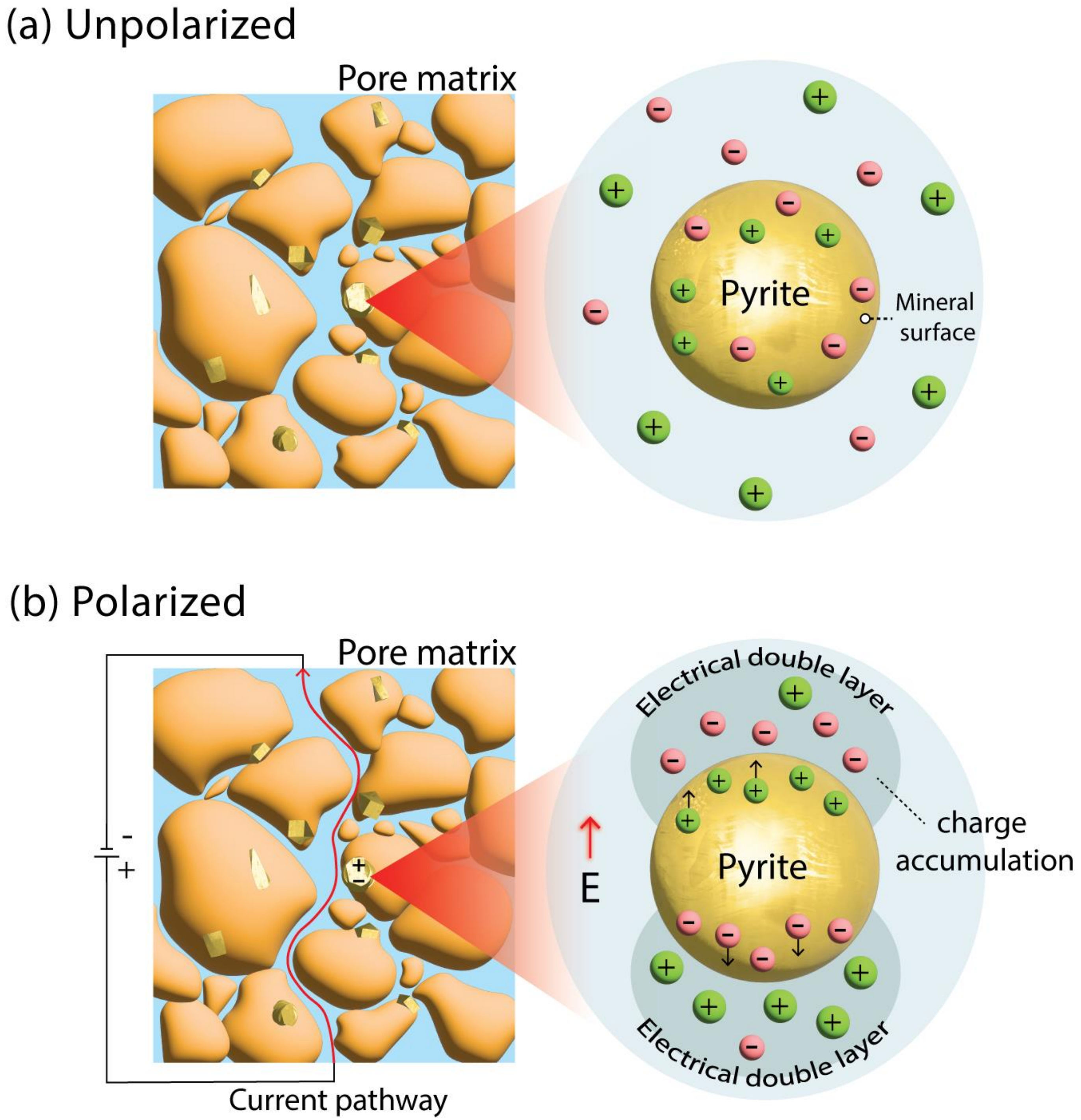
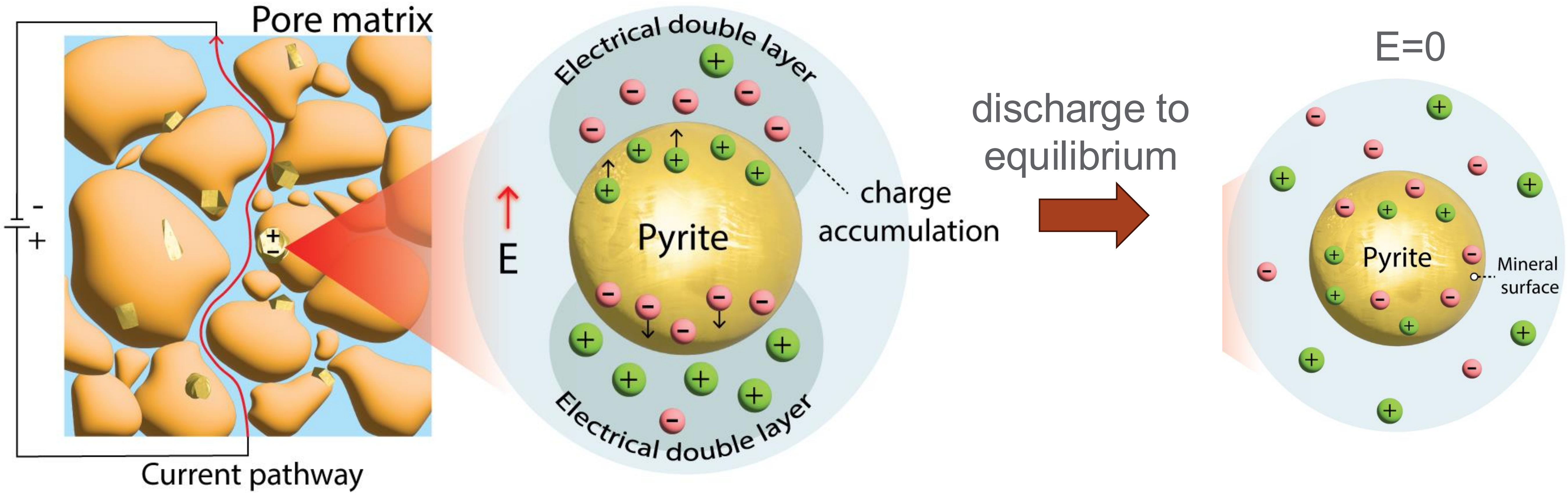


Figure credit: Klaudio Peshtani, Pacific Northwest National Laboratory

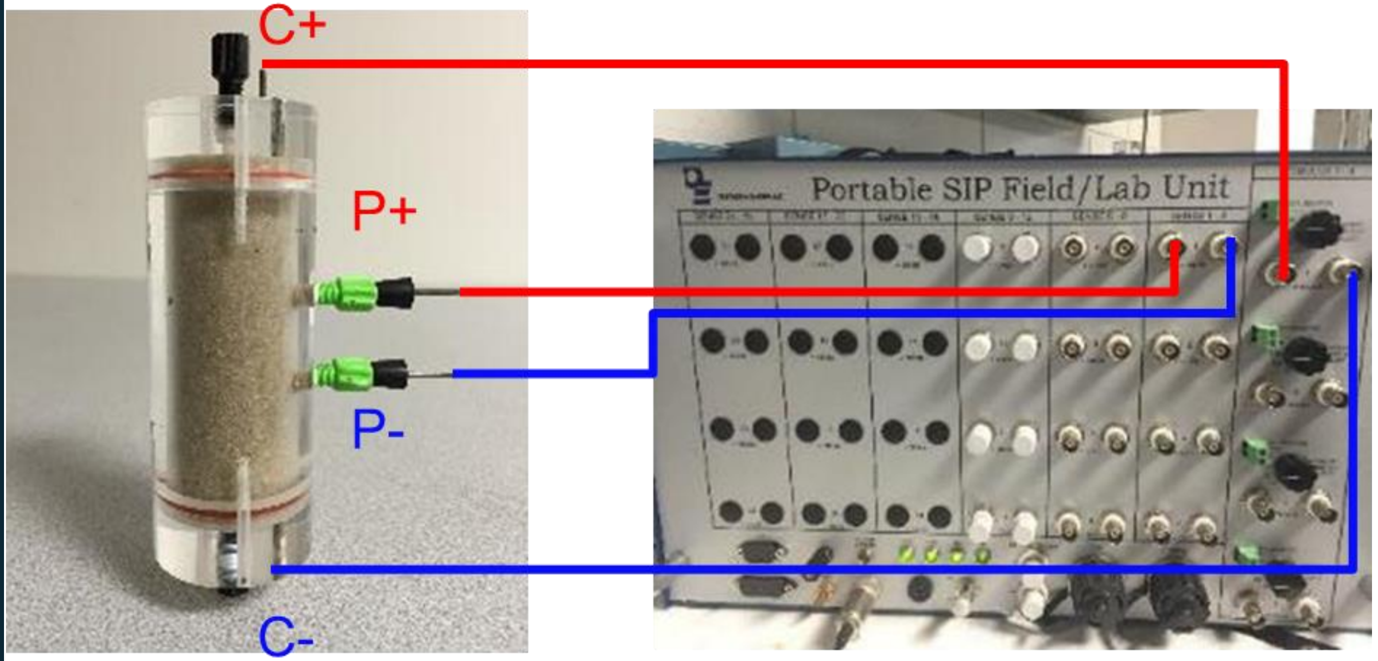
What Spectral Induced Polarization measures

Electrical conduction + Amount of charge displaced (polarization magnitude) + Time to discharge (relaxation time)



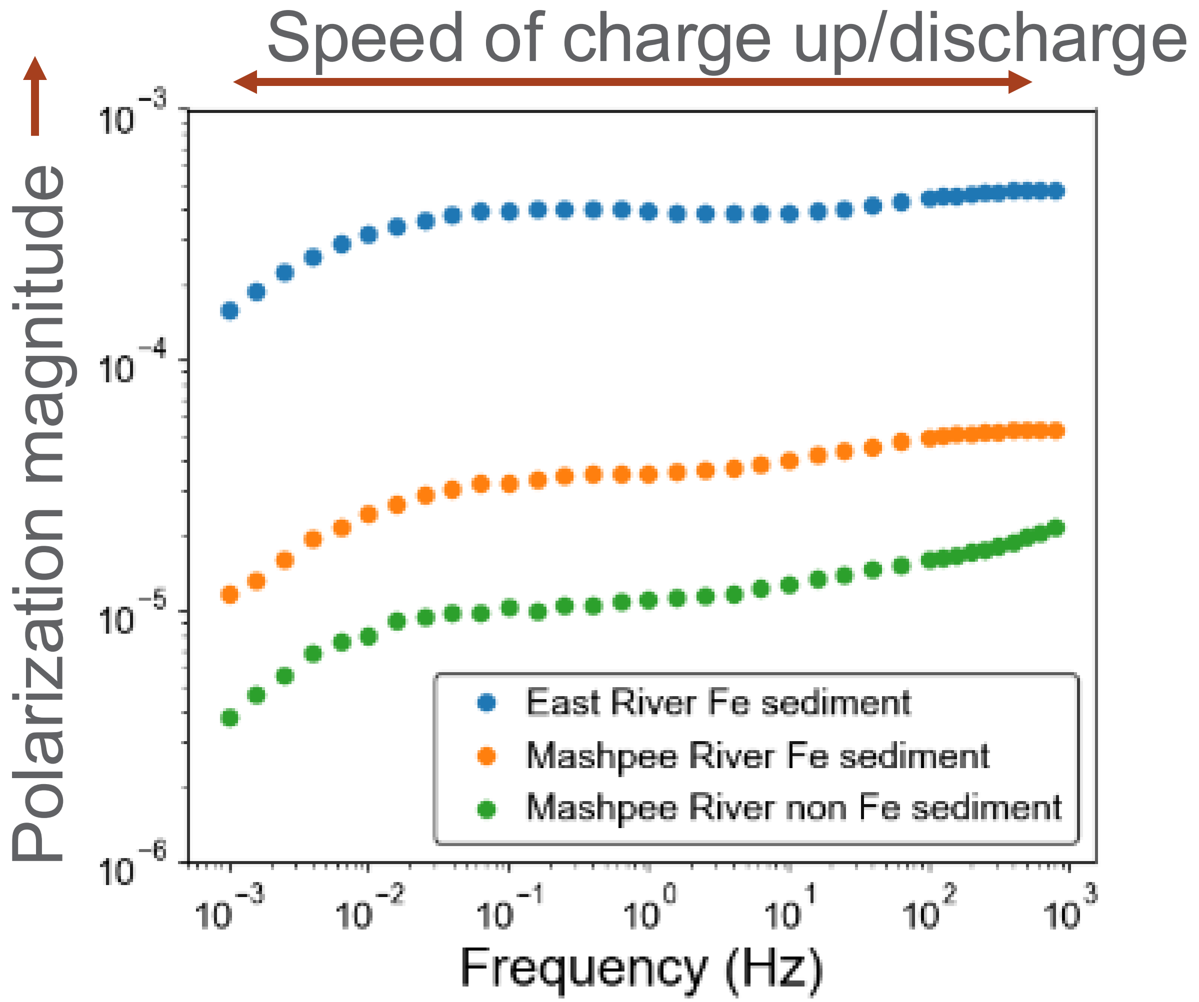
Laboratory Spectral Induced Polarization (SIP) measurements

- Analyzes <u>complex electrical properties</u> as a function of frequency of the applied electric field



Sample

Electronics



Spectral response

Multi-scale applications

EMERSON TALK

FLORES-OROZCO TALK

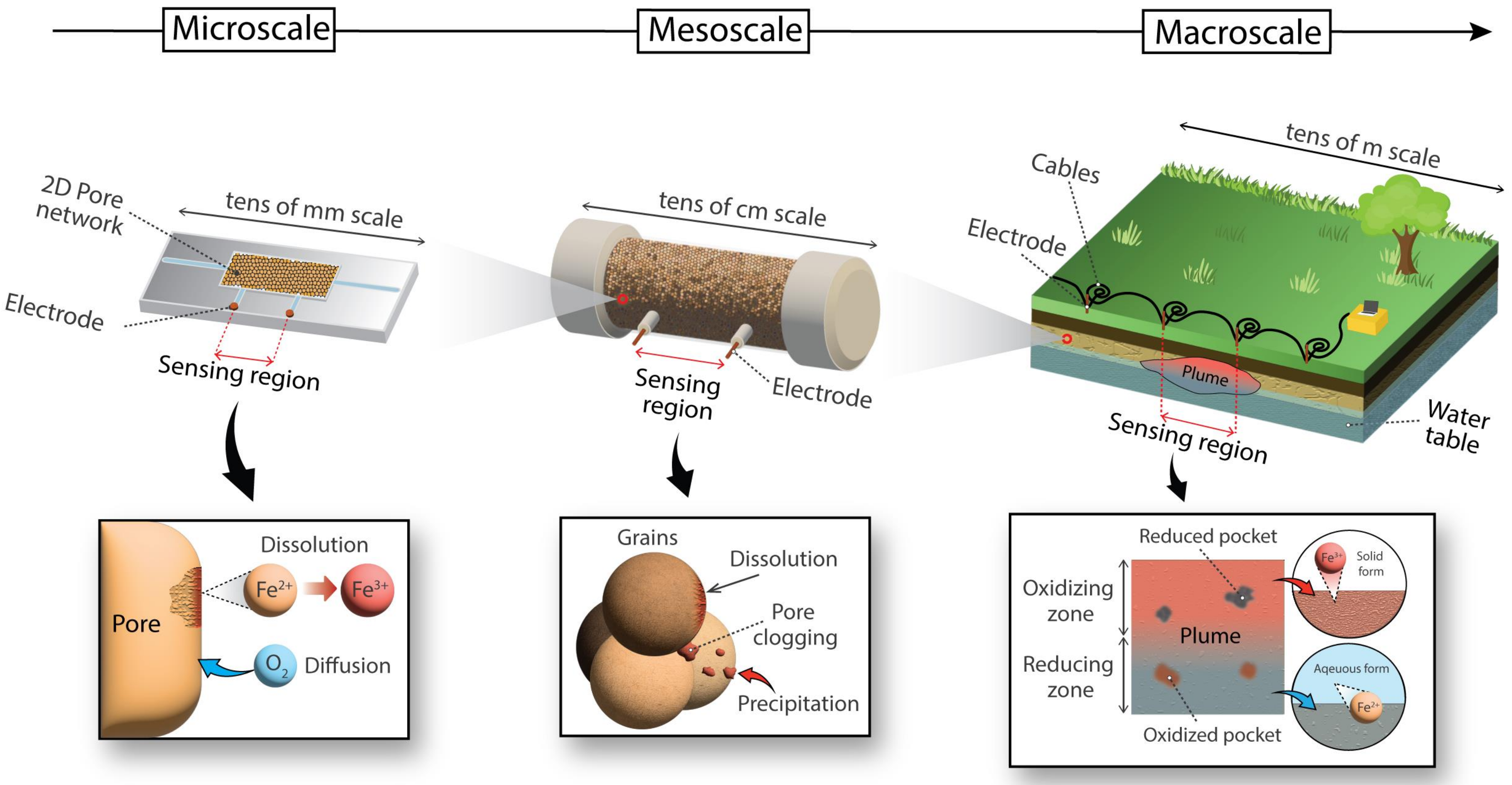


Figure credit: Klaudio Peshtani, Pacific Northwest National Laboratory

Thank you

Geophysical imaging for the design and evaluation of groundwater remediation

Adrián Flores-Orozco

Research Unit of Geophysics
Department of Geodesy and Geoinformation

Objective and hypothesis

- ❑ What are the advantages of using the Induced Polarization (IP) imaging method for the characterization and monitoring of contaminated sites?

- ➢ We propose that IP investigations can be used at the field-scale to improve the design of remediation strategies by identifying the source-zone and plume of contaminants, the extension of contaminant plumes, lithological changes, etc.

- ➢ IP monitoring can help to improve the efficiency of the remediation by informing in quasi-real-time regarding the delivery of remediation agents, changes in the subsurface properties

Outline

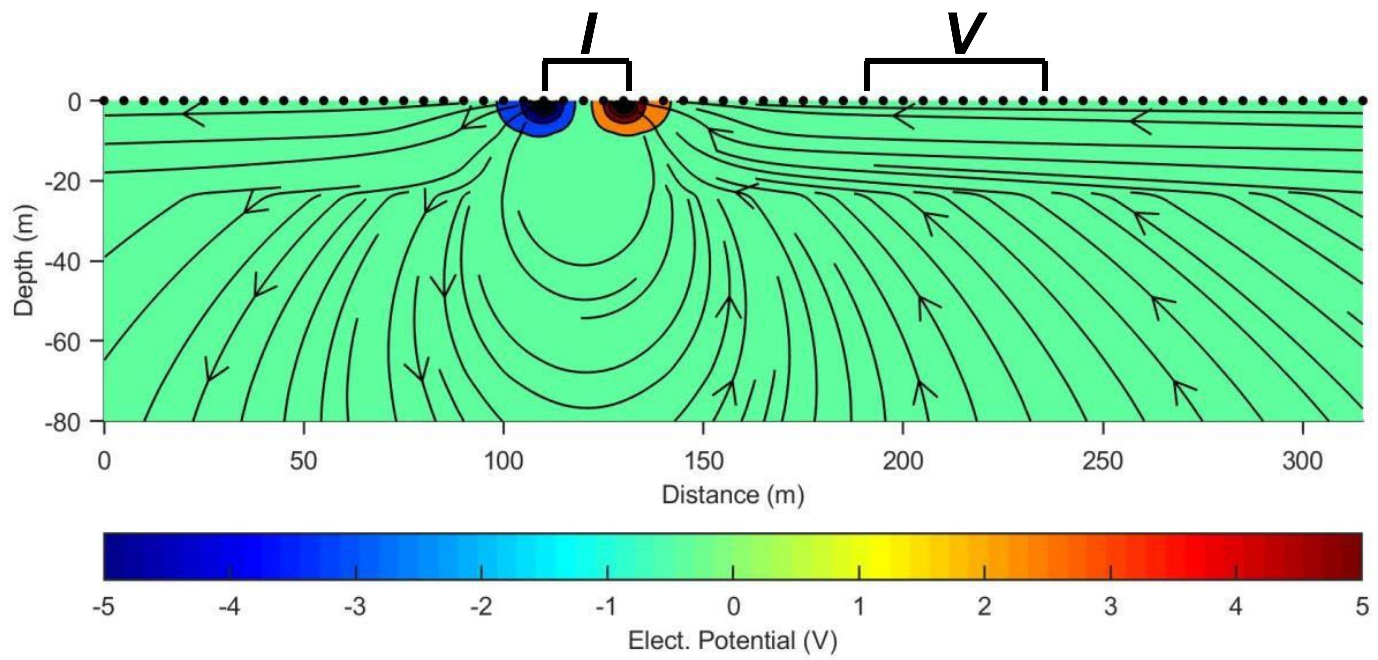
- Distortions in IP imaging due to anthropogenic structures
- Comparison between different measuring techniques in IP
- The frequency-dependence of IP in hydrocarbon contaminant plumes
- Discriminating between the source zone and the plume of contaminants

- Induced Polarization along nanoparticles injection

- Monitoring the efficiency of groundwater remediation strategies

Electrical imaging methods

- Imaging methods aim at resolving change sin the electrical properties
  - 10 – 100’s electrodes
  - 100 – 1000’s of quadrupoles

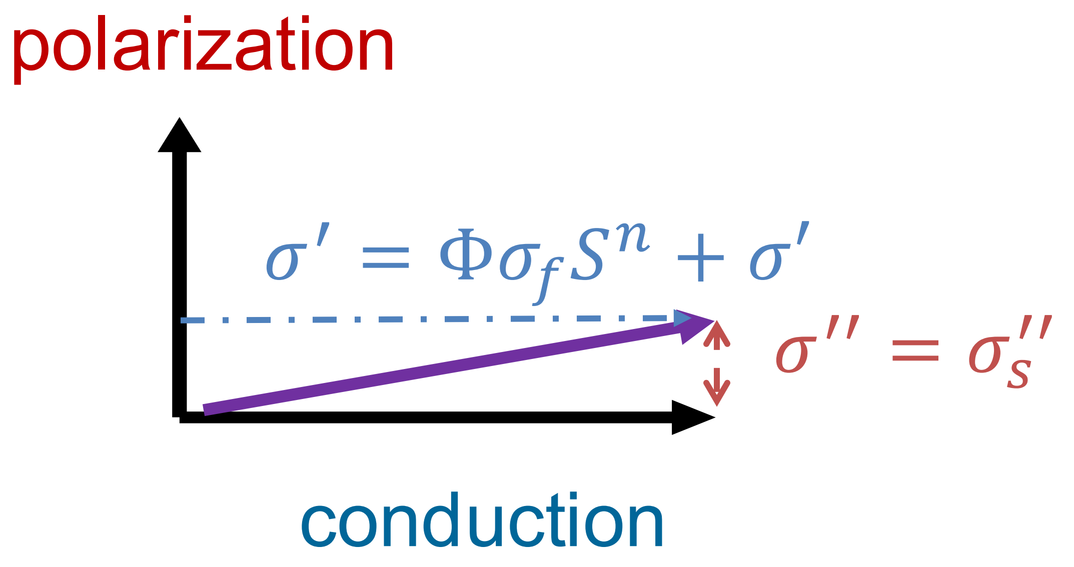


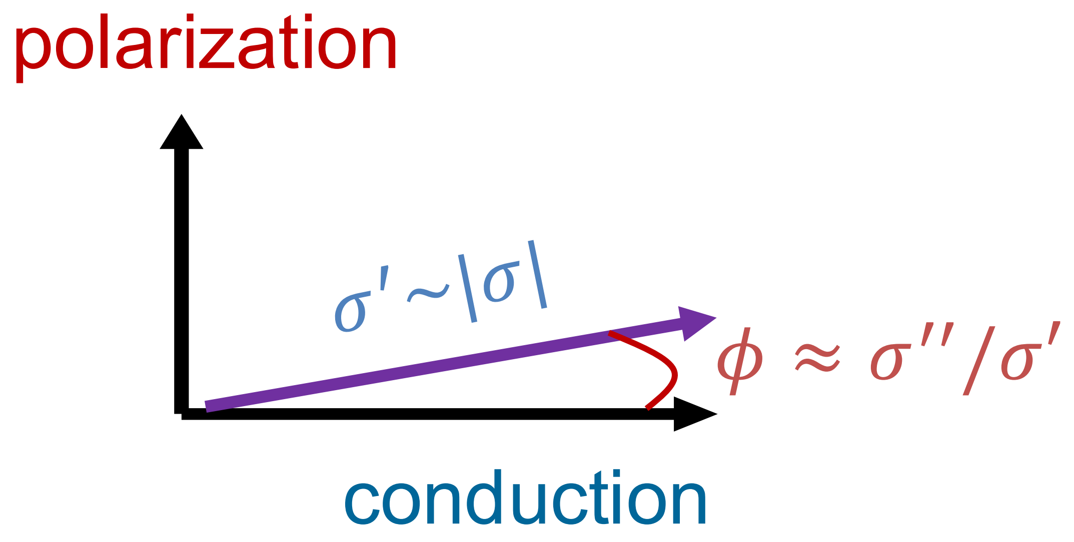
Complex conductivity

- Two electrical properties simultaneously measured
- We use a complex- conductivity (σ^*) to represent both properties:
  - Conductivity (σ')
  - Capacitive (σ'') - or induced polarization effect

$$\sigma^* = \sigma' + i\sigma''$$

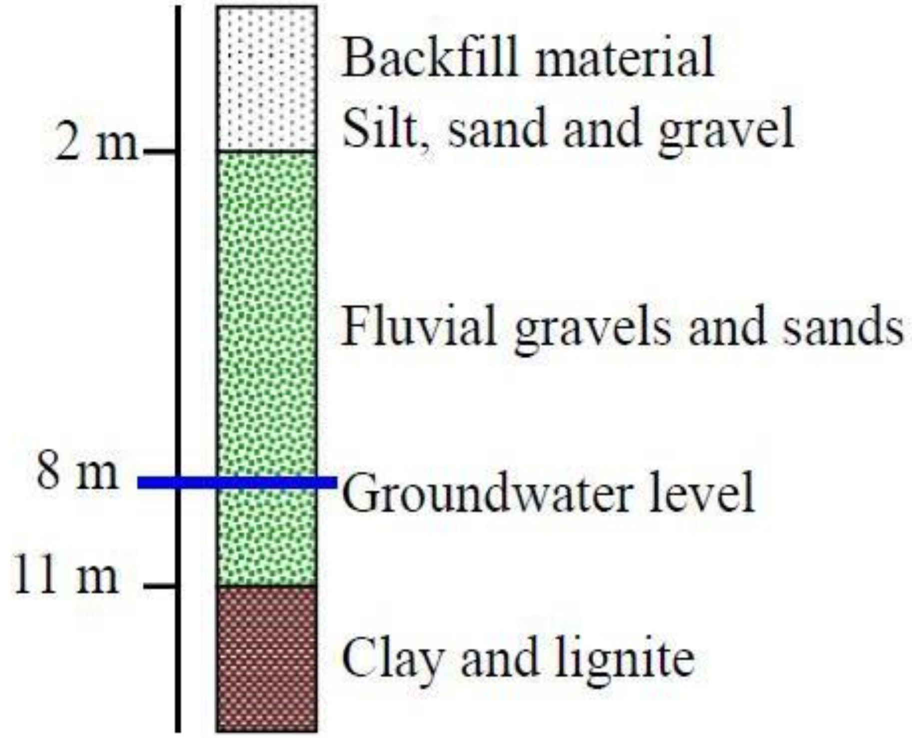
$$\sigma^* = |\sigma| + e^{i\phi}$$





Case study | Zeitz site

- ❑ Former hydrogenation plant
- ❑ BTEX contaminants: Benzene, Toluene, Ethylbenzene, Xylene
- ❑ Groundwater located at 8m depth
- ❑ High Benzene concentrations in groundwater



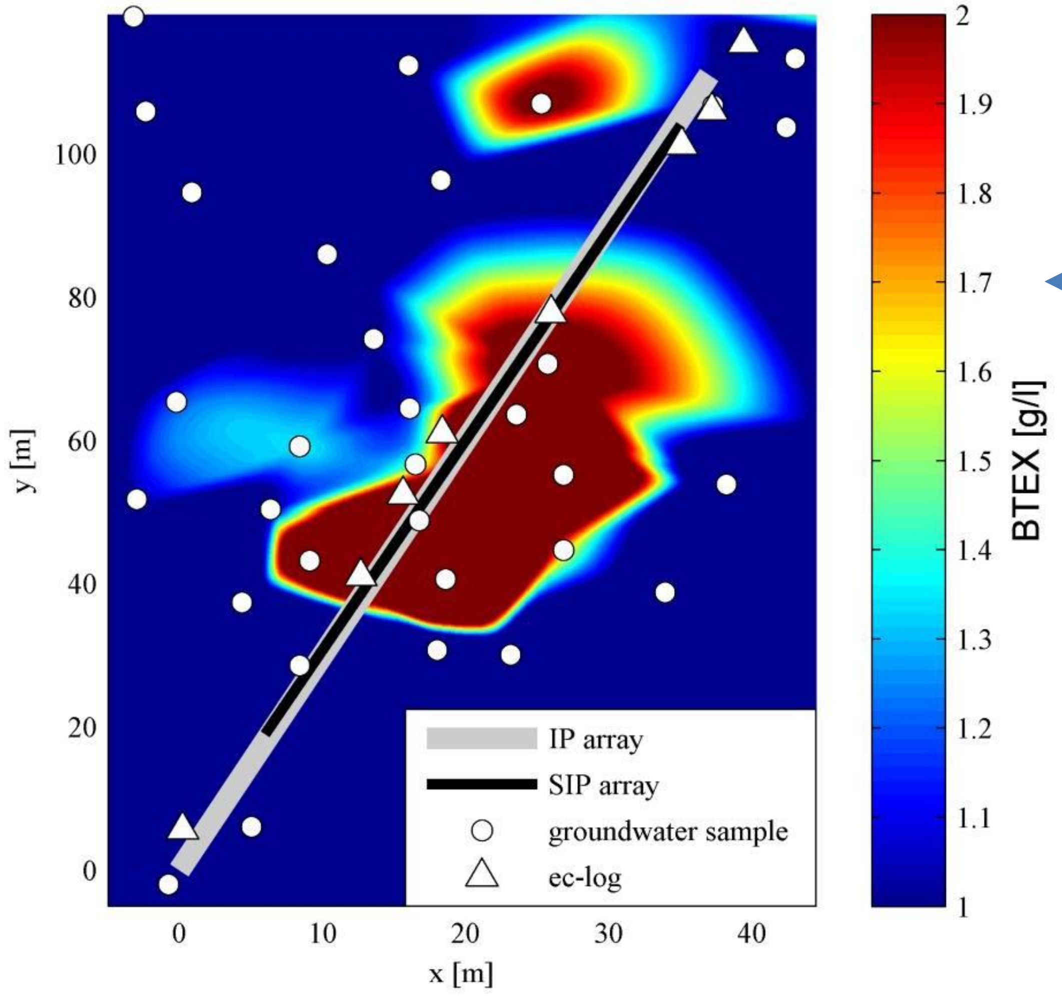
Flores Orozco, A, Kemna, A., Oberdörster, C., Zschornack, L., Leven, C., Dietrich, P. and Weiss, H., 2012. Delineation of subsurface hydrocarbon contamination at a former hydrogenation plant using spectral induced polarization imaging. Journal of contaminant hydrology, 136, pp.131-144
https://doi.org/10.1016/j.jconhyd.2012.06.001

Measurements set-up

- The electrical image should be centered at the area with the highest contaminant concentrations

- Time-domain (TDIP)
- 48 electrodes – 2.5 m spacing
- 2s pulse length (240 – 1840 ms)

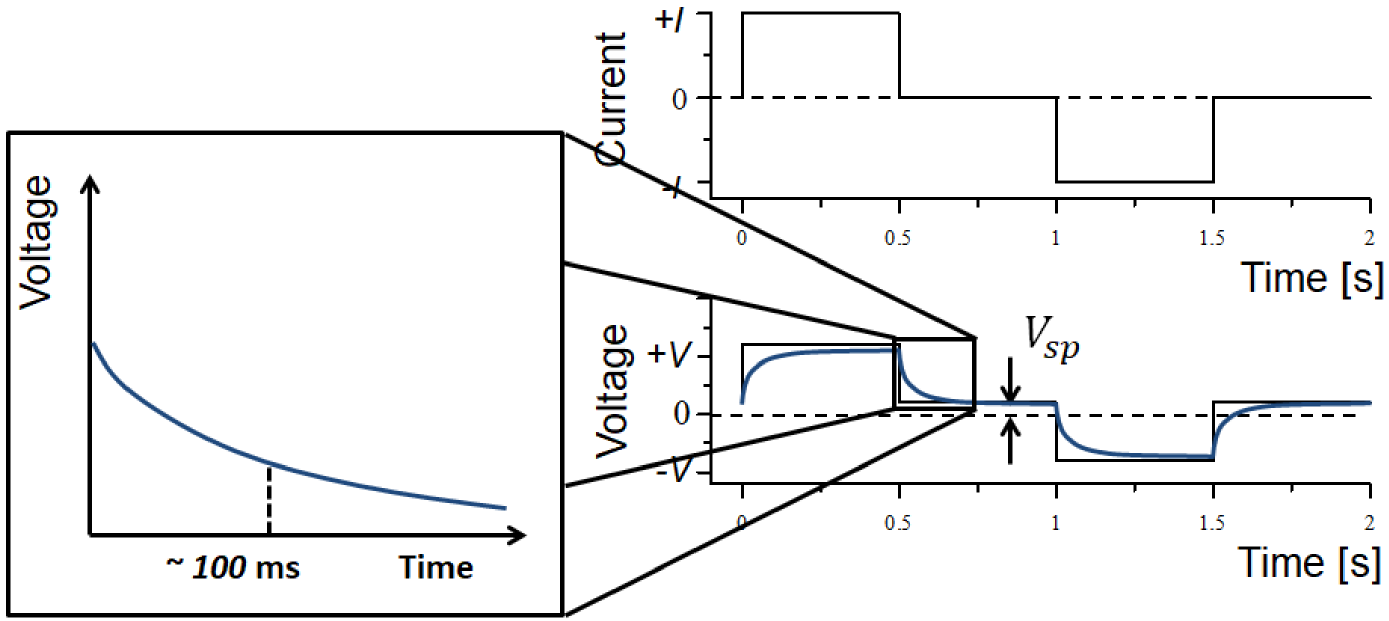
- Frequency-domain IP (FDIP)
- 36 electrodes – 2.3 m spacing
- SIP between 0.07 and 1000 Hz

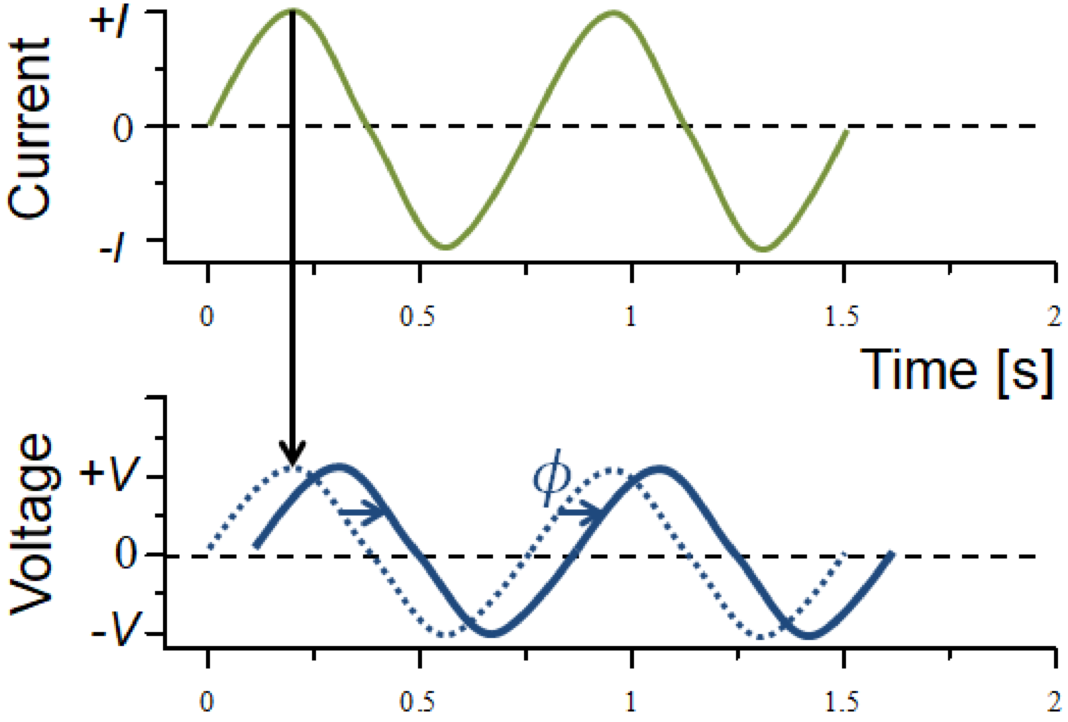


Saturation concentration of Benzene is 1.7 g/l

Induced Polarization measurements

- The capacitive properties of the subsurface reflects as:
  - A slow decay in the voltage after switching the current off (discharging curve) for measurements using direct-current (time-domain IP)
  - A phase-shift (ϕ) between the injected current and measured voltage when using alternating current (frequency-domain IP)



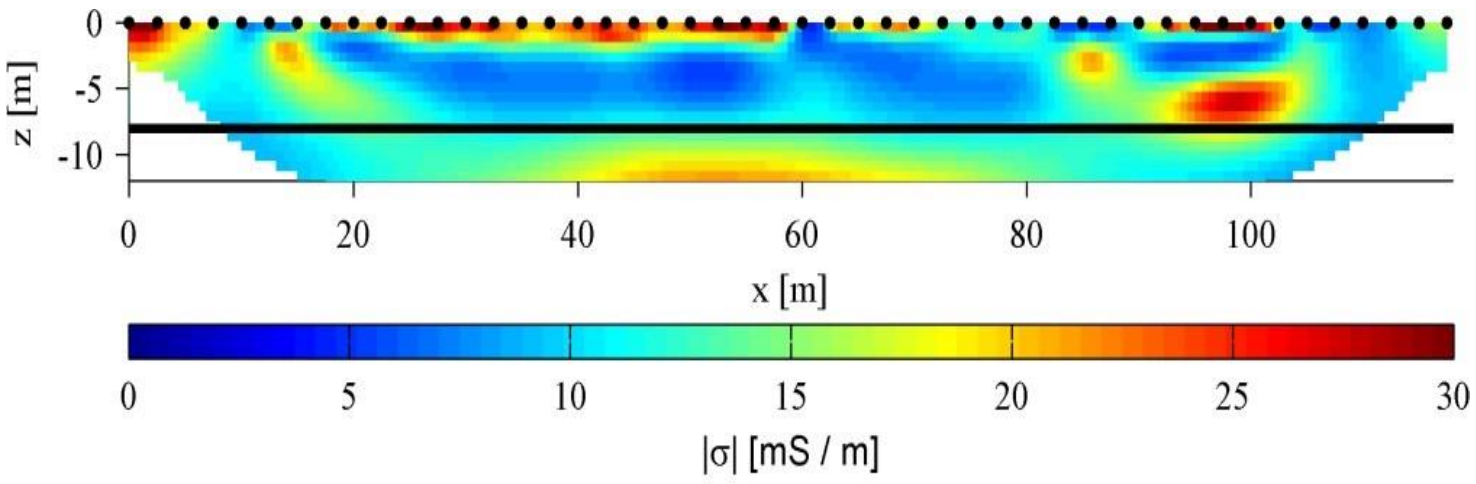


Initial time-domain (TDIP) results

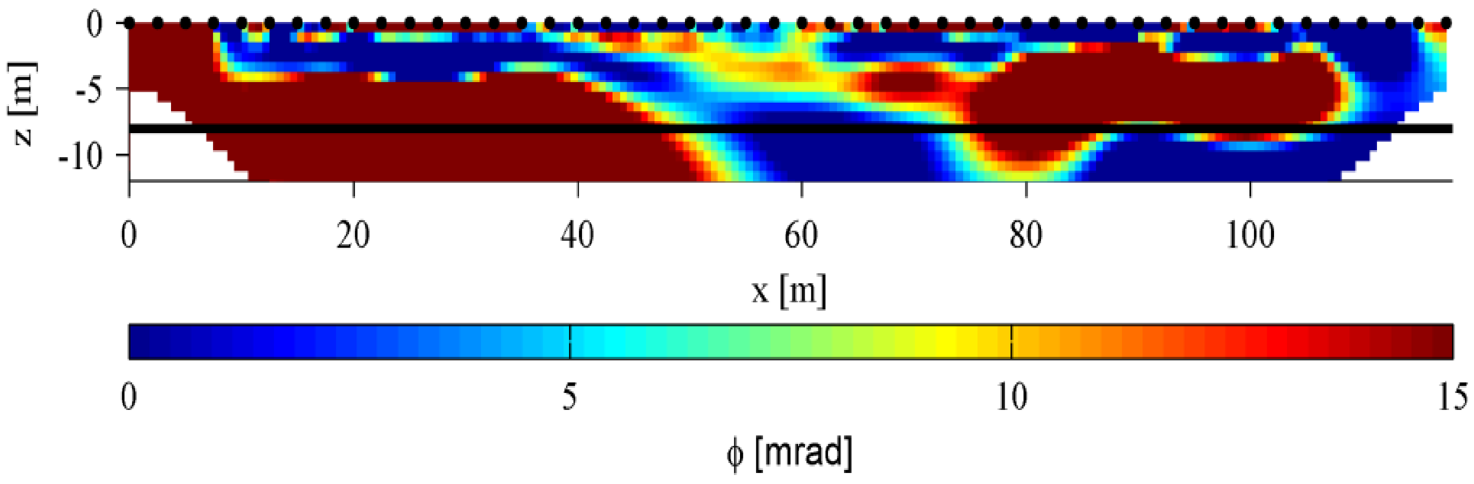
- Initial results for TDIP measurements reveal significant changes along the profile

- Is the high conductivity and low polarization response in the middle due to the presence of buried infrastructure?

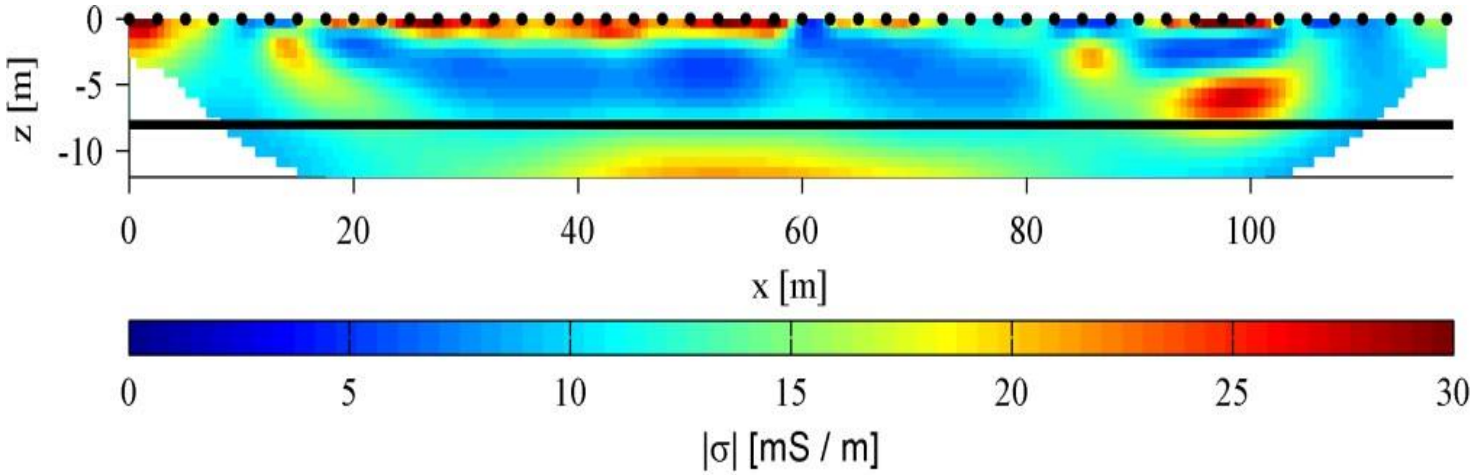
Electrical conductivity (σ')

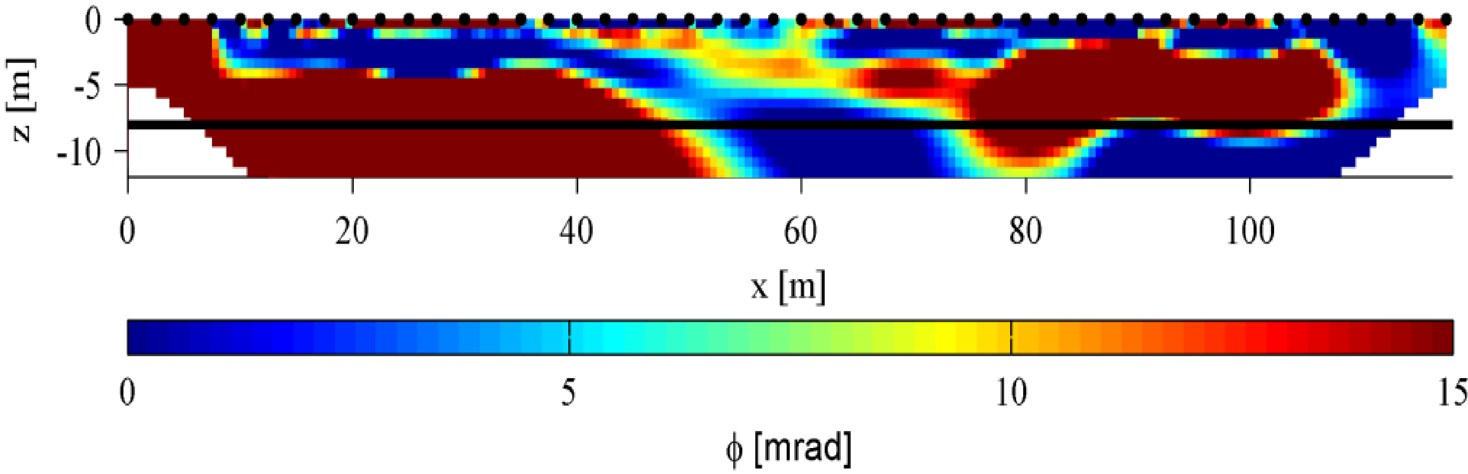


Induced Polarization (ϕ)

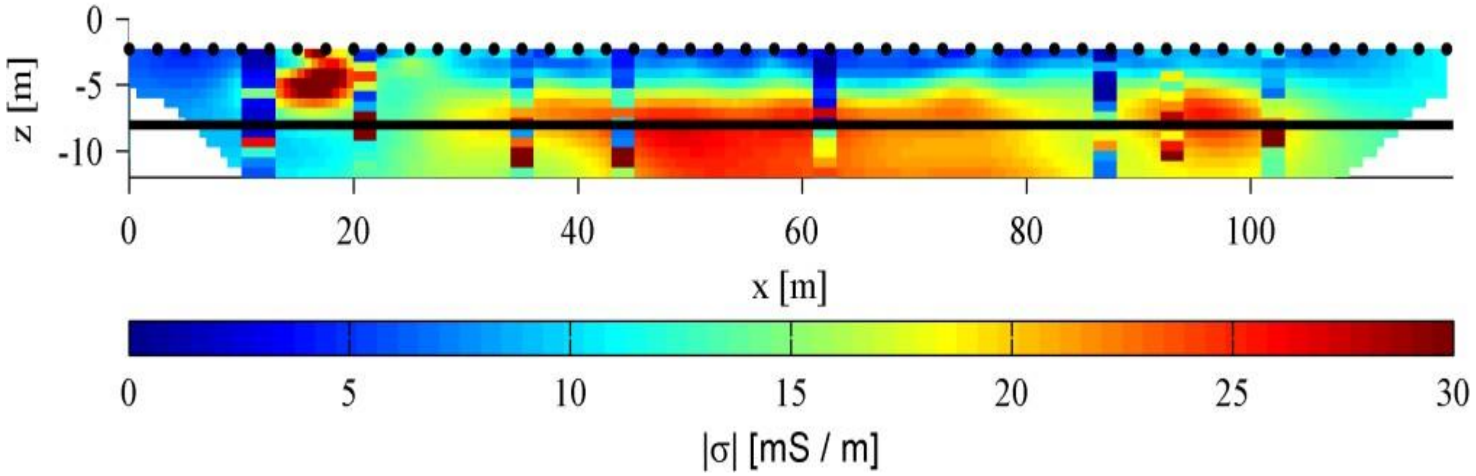


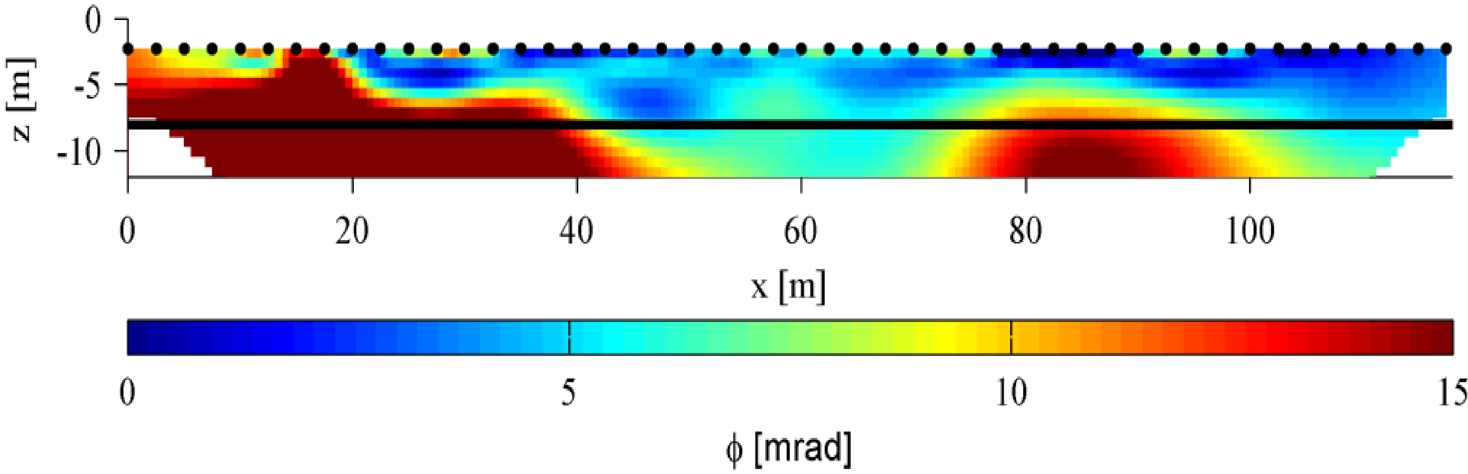
TDIP results 1: the effect of anthropogenic noise





After excavation of the trench



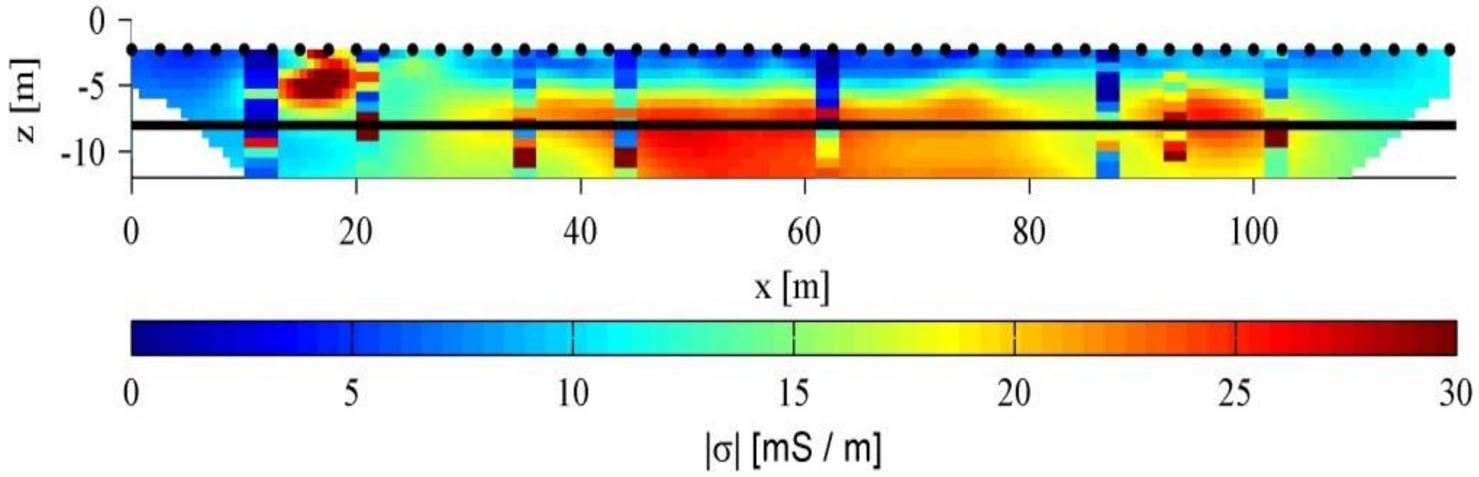


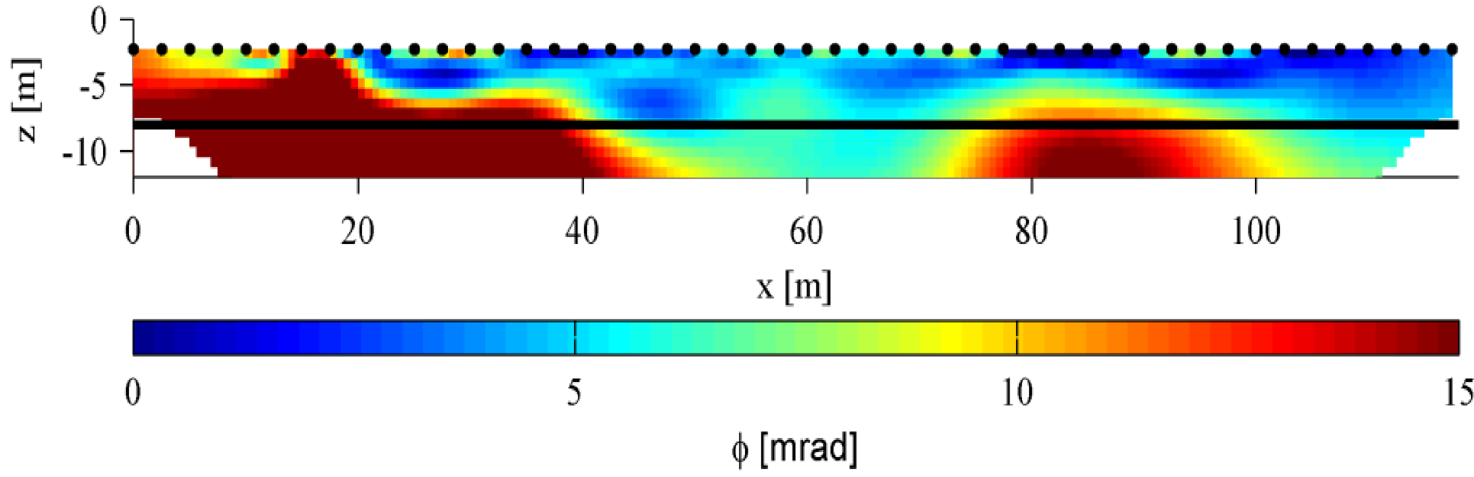
TDIP results 1: the effect of anthropogenic noise

- Initial results reveal similar structures at depth for data collected before and after the excavation of a trench

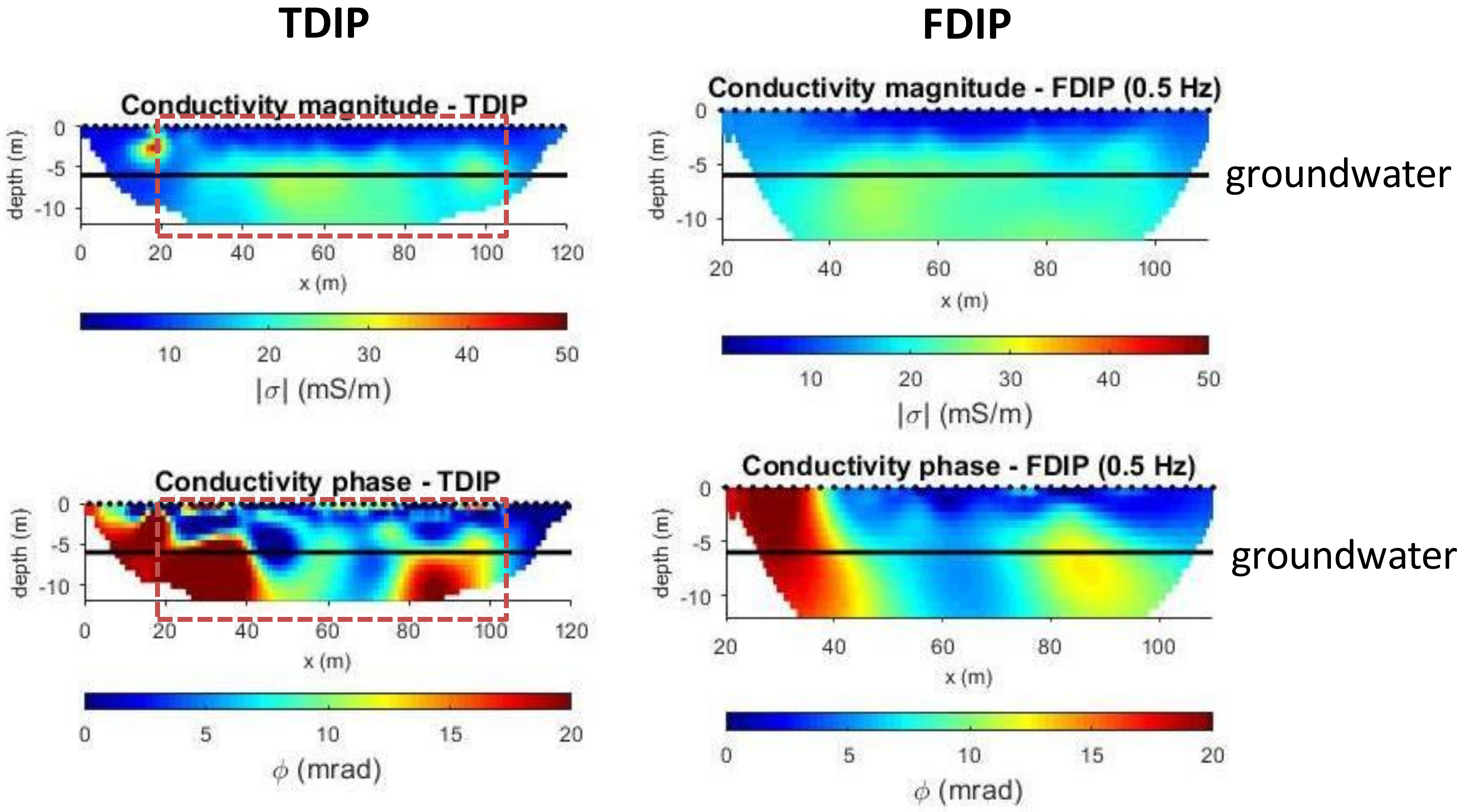
- Seems that structures resolved with IP imaging might still be acceptable even if data is collected in urban environments

After excavation of the trench



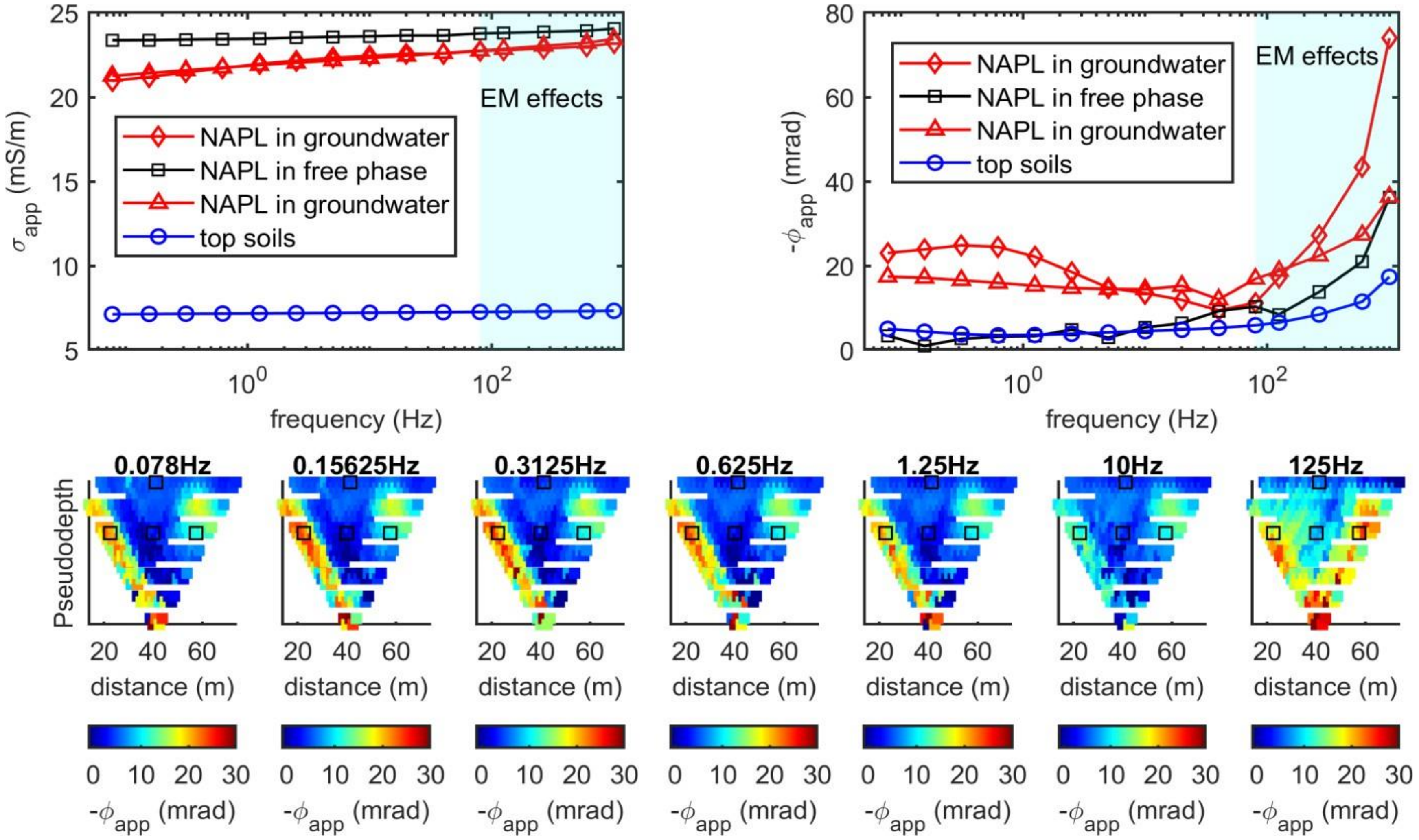


How comparable are different IP techniques



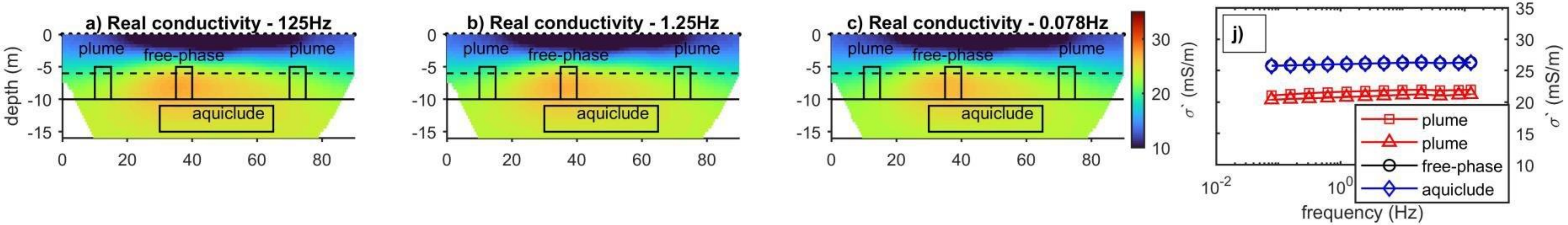
Why spectral IP (SIP)?

- Frequency-dependence of the measured IP data
- Measurements are re-collected between 0.1 and 500 Hz
- Low frequencies are limited by the acquisition time
- High frequencies are affected due to parasitic electromagnetic (EM) effects



SIP signatures in BTEX contaminant plumes

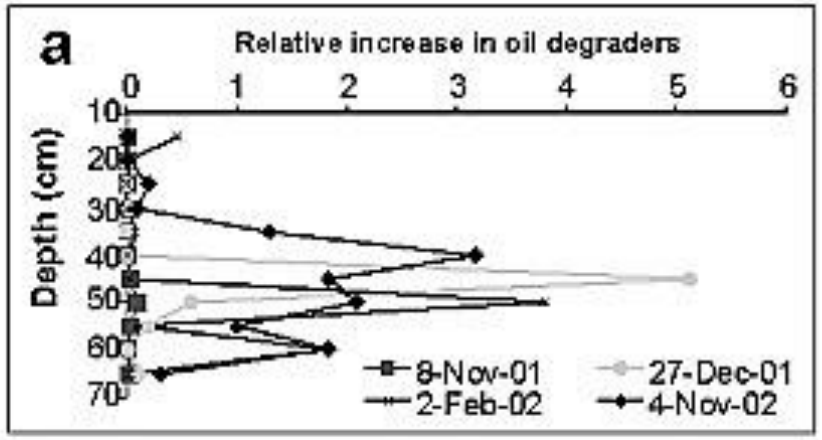
- Negligible frequency-dependence in conductivity
- The highest electrical conductivity (σ') is observed where higher BTEX concentrations are observed (free-phase)

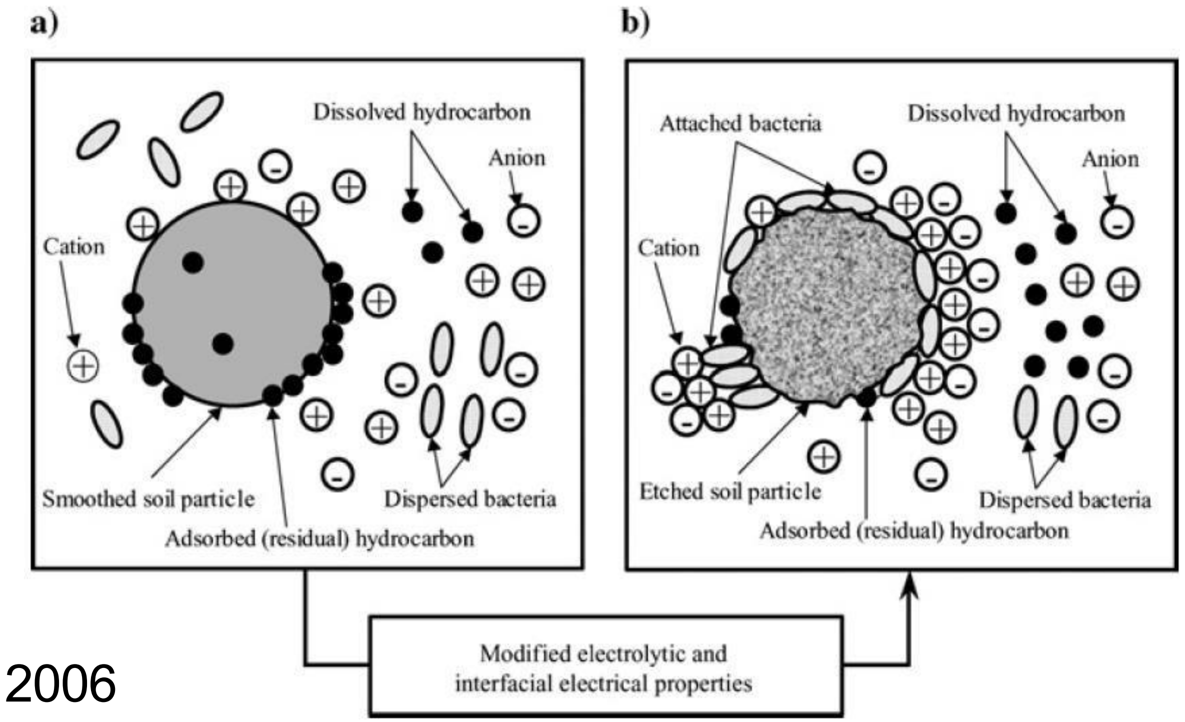


High conductivity of hydrocarbon contaminant plumes

Increase in the electrical conductivity due to mature oil plumes

- Fresh hydrocarbon plumes: high electrical resistivity
- Aged hydrocarbon plumes: enhance microbial activity, which in turns results in the accumulation of organic acids and metabolic products increasing the fluid conductivity

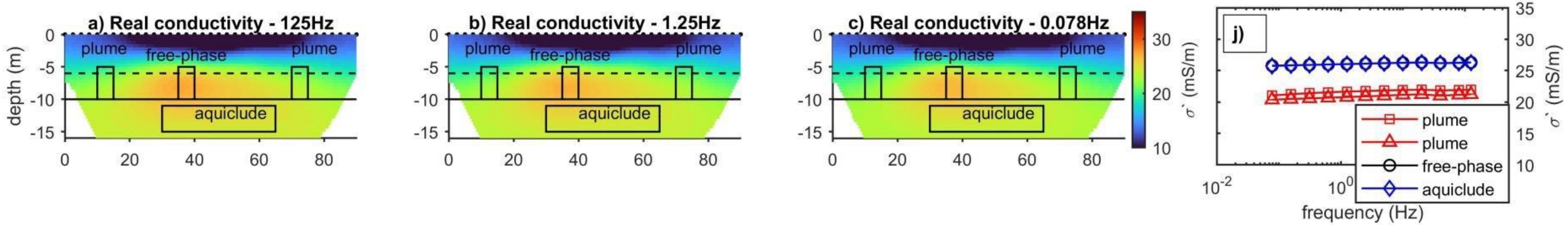




Abdel Aal et al., GRL, 2006

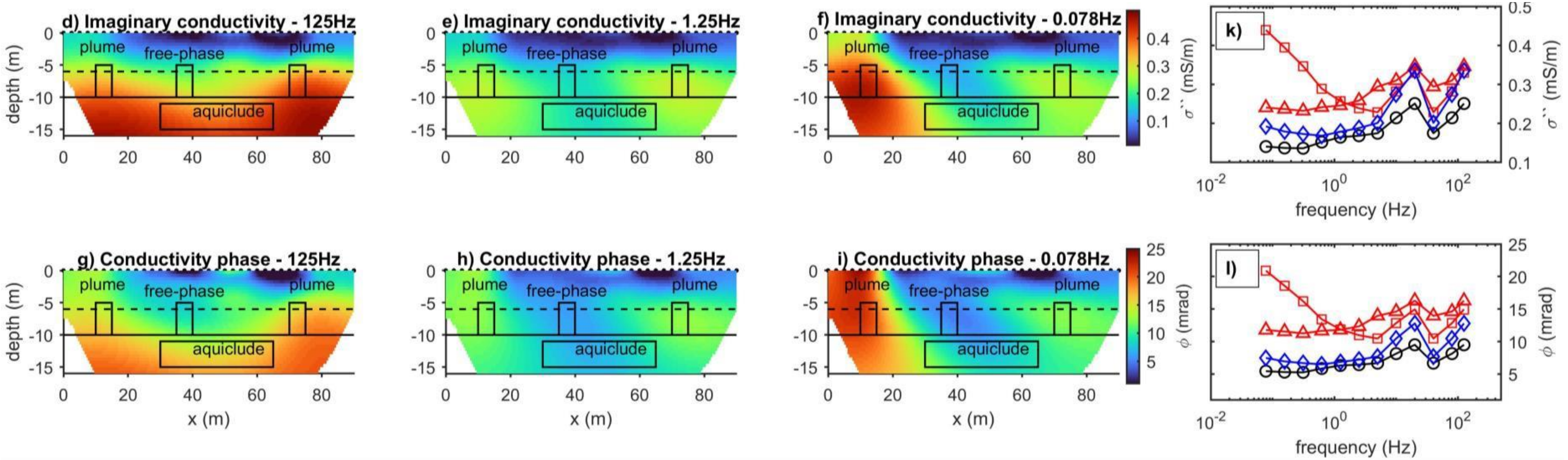
SIP signatures in BTEX contaminant plumes

- The highest electrical conductivity (σ') is observed where higher BTEX concentrations are observed (free-phase)
- The high conductivity is expected for a mature contaminant plume, due to high ionic strength in pore water accompanying microbial activity
- The higher the BTEX concentrations the higher the degradation?



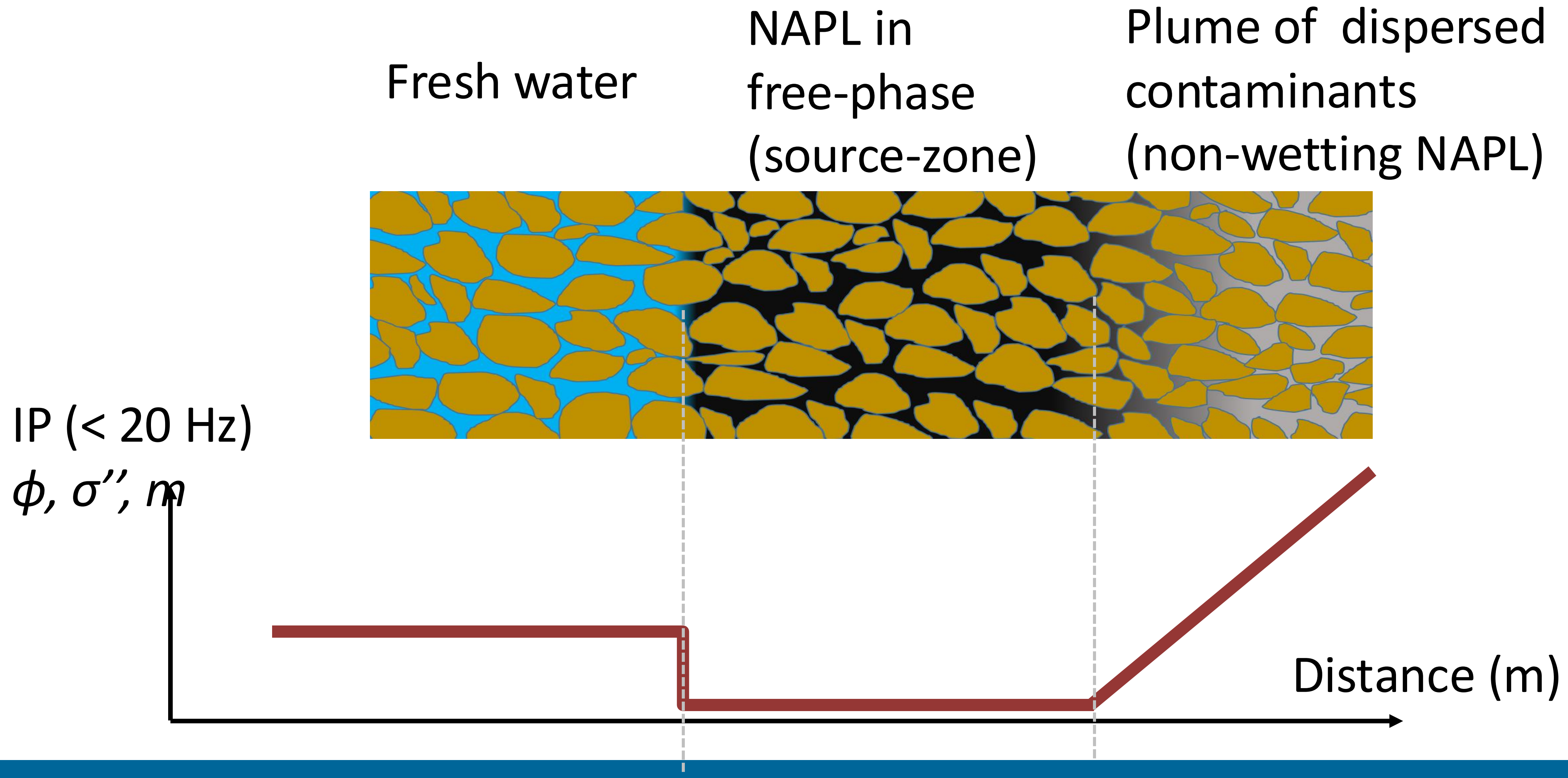
The polarization imaging results

- The polarization (σ'' or ϕ) images show high values at intermediate BTEX concentrations and negligible response in the middle of the profile, at the highest BTEX concentrations



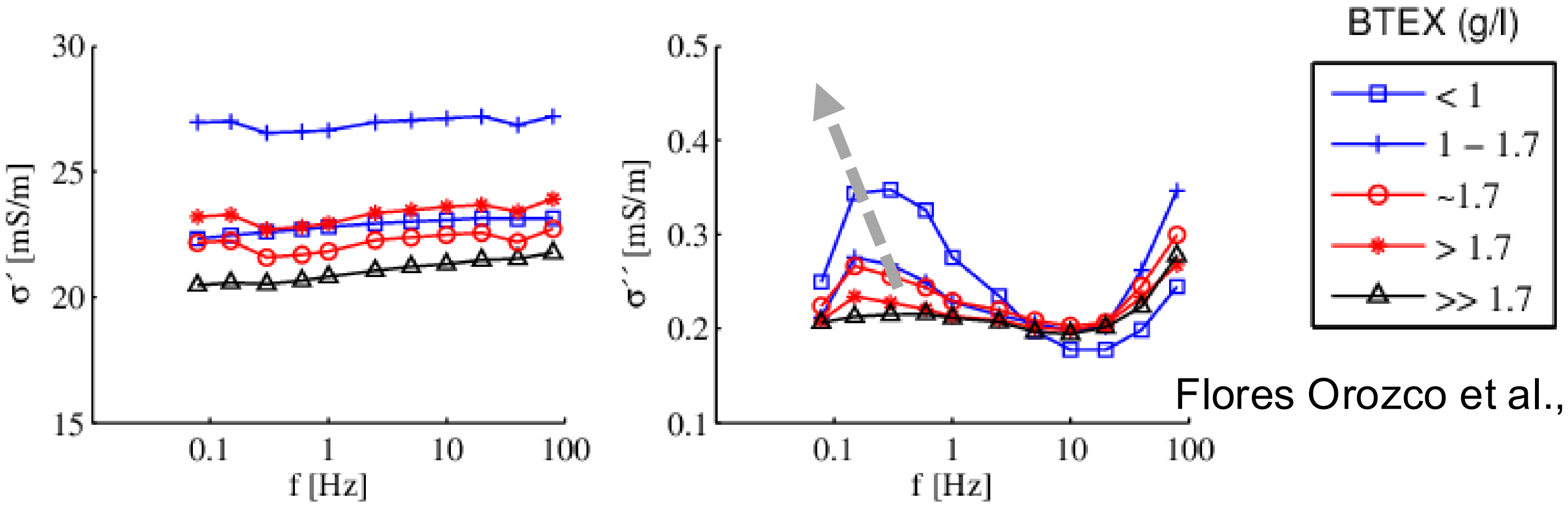
Design of a remediation strategy

- IP permits to discriminate between the source-zone (contaminants in free-phase) and the plume of dispersed contaminants

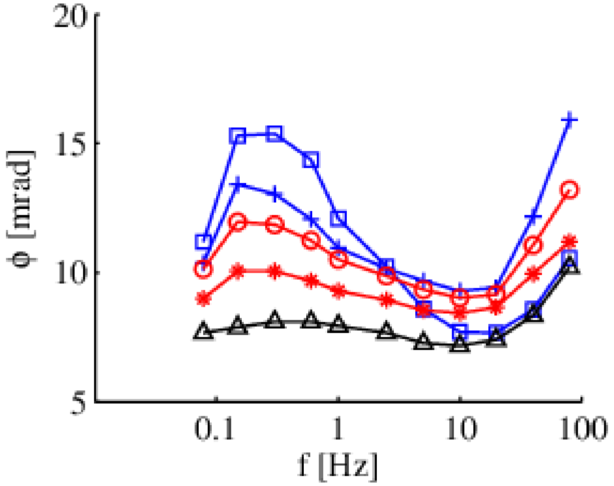


The SIP response of hydrocarbon contaminants

- Increasing the polarization (σ'' or ϕ) with increasing the hydrocarbon concentrations (< 1.7 g/l)
- Negligible polarization for contaminants in free-phase (concentration above 1.7 g/l)



Flores Orozco et al., JCH 2012



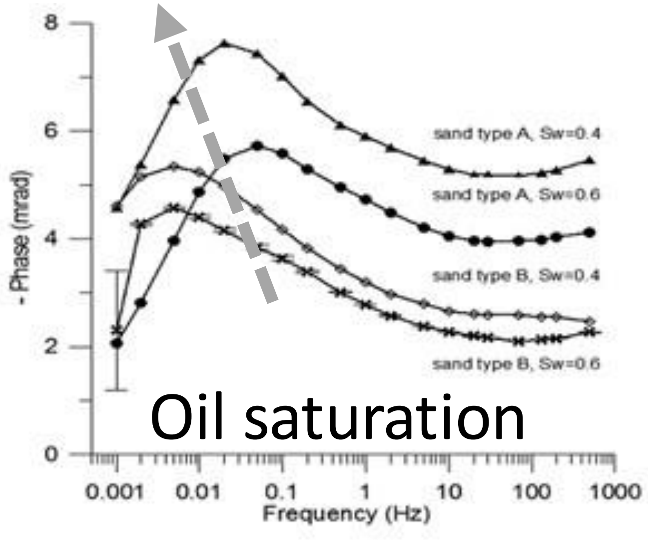
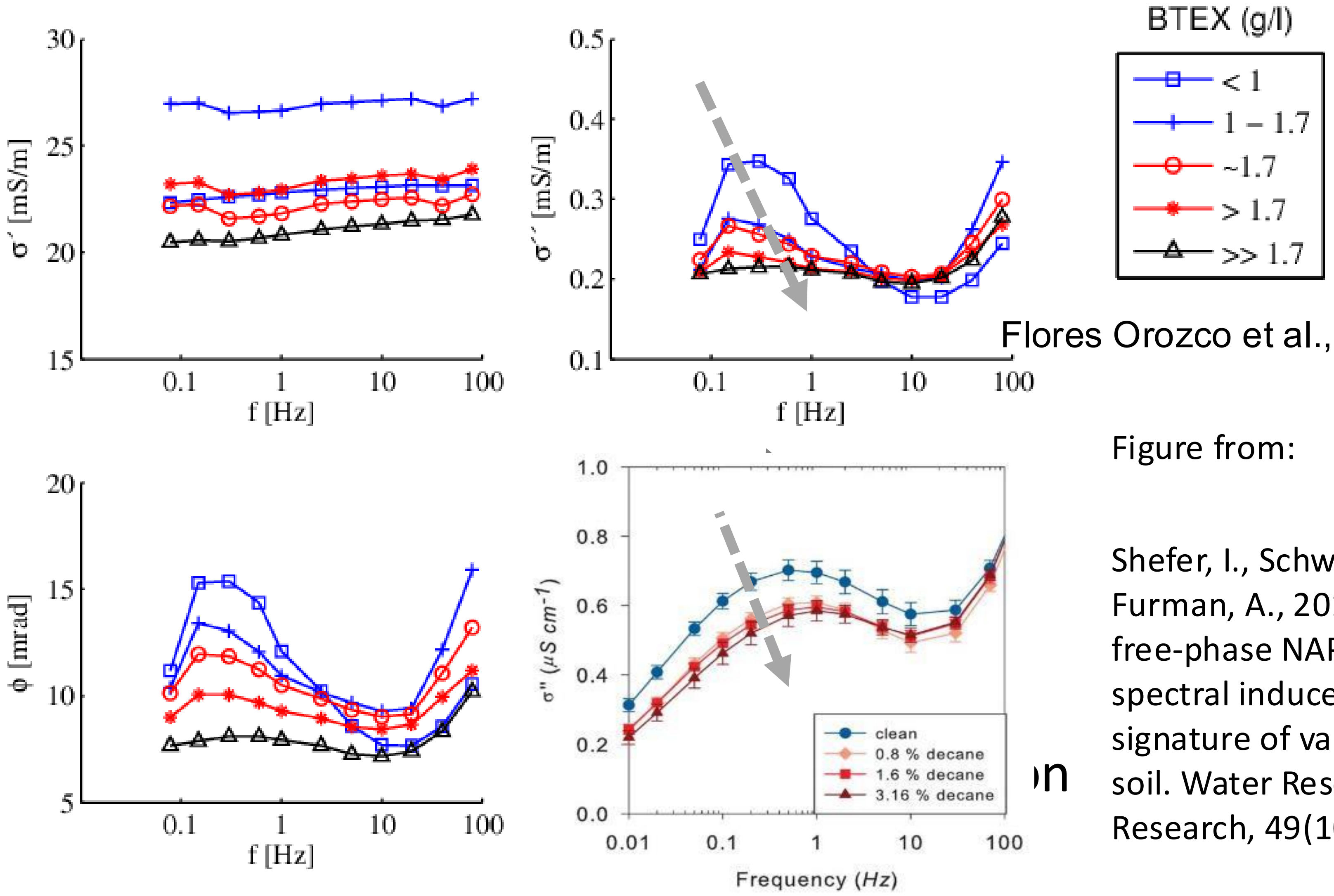


Figure from:

Schmutz et al., 2010. Influence of oil saturation upon spectral induced polarization of oil- bearing sands. Geophysical Journal International, 183(1)

The SIP response of hydrocarbon contaminants

- Decrease In the polarization with increasing contaminant concentration has also been reported for laboratory measurements by Shefer et al. (2013)



Flores Orozco et al., JCH 2012

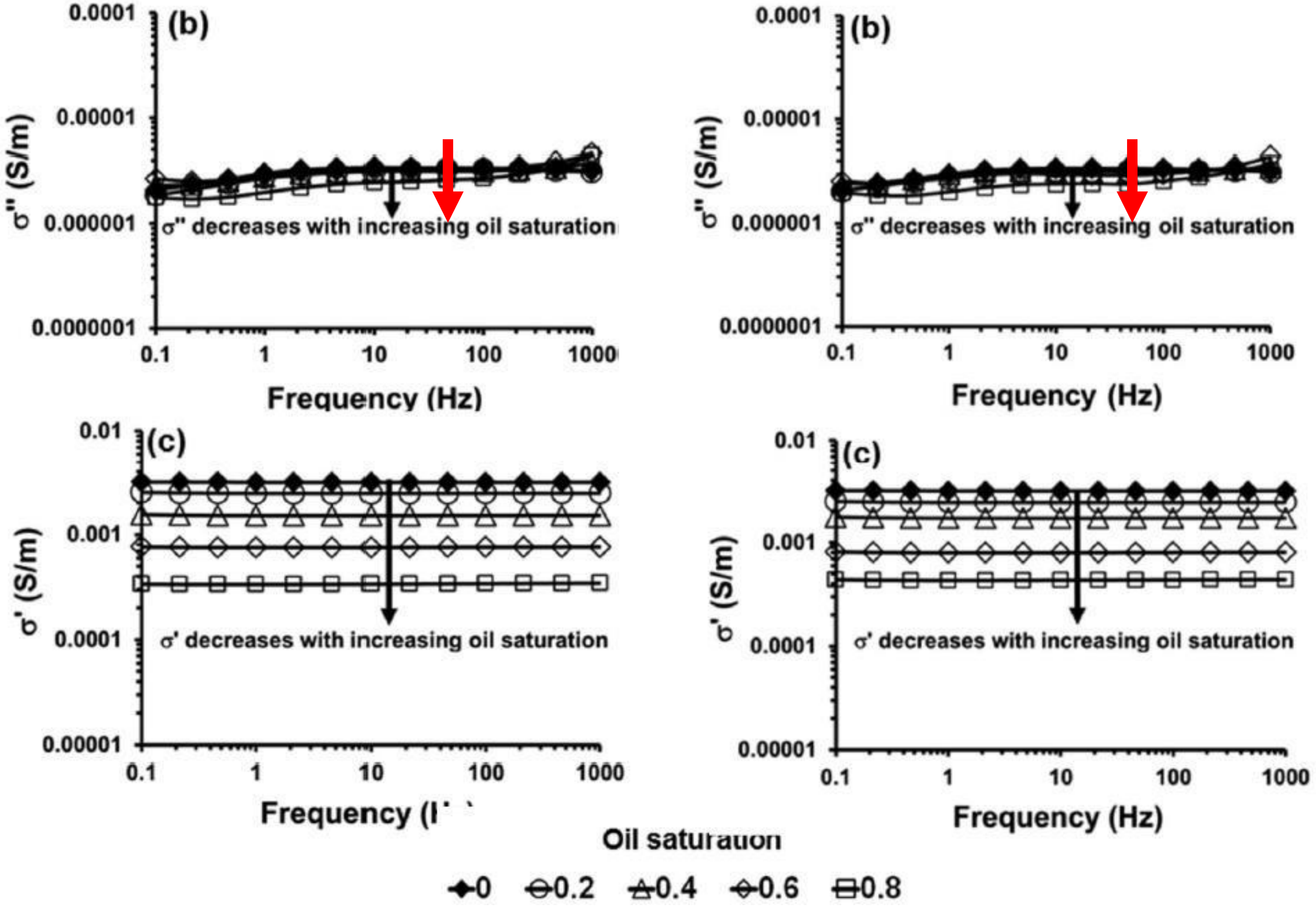
Figure from:

Shefer, I., Schwartz, N. And Furman, A., 2013. The effect of free-phase NAPL on the spectral induced polarization signature of variably saturated soil. Water Resources Research, 49(10),

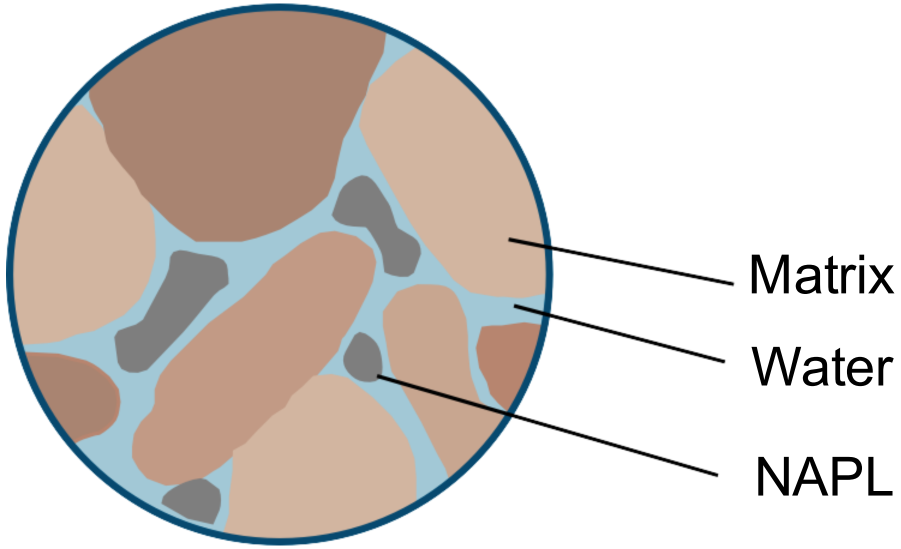
SIP signatures for water-wetting oils

Fresh oil (water-wetting) and sand mixture

Degraded oil (water-wetting) and sand mixture



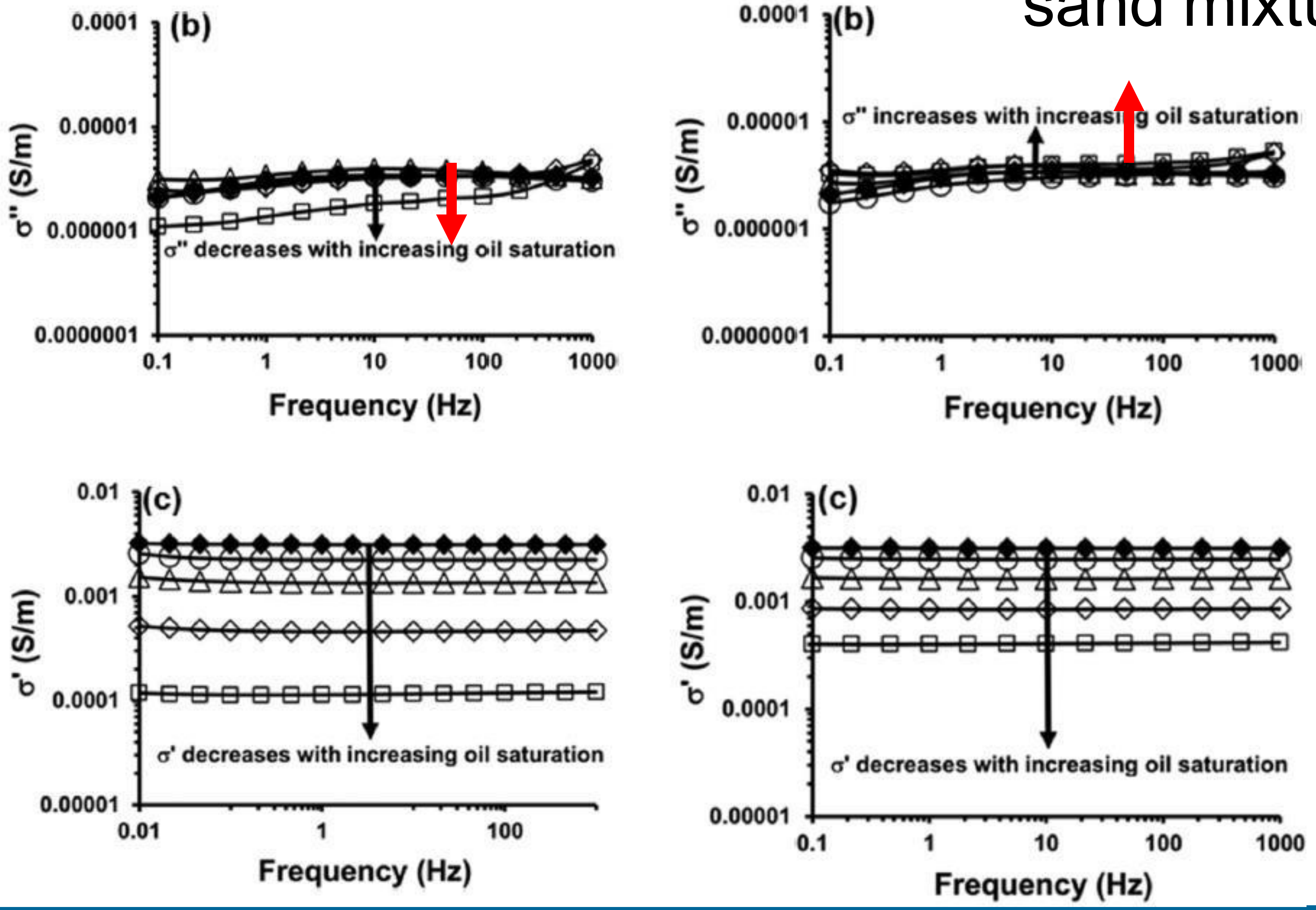
From: Abdel Aal, G.Z. And Atekwana, E.A., 2014. Spectral induced polarization (SIP) response of biodegraded oil in porous media. Geophysical Journal International, 196(2)



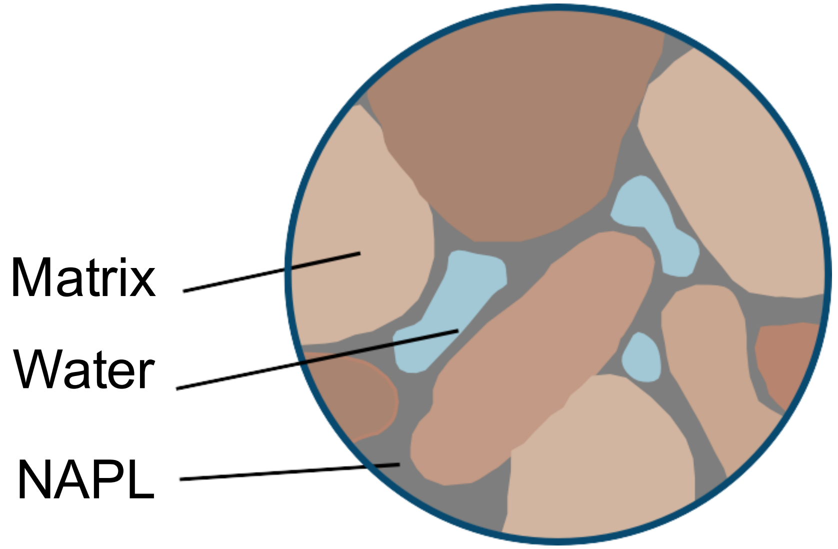
SIP signatures for oil-wetting oils

Fresh (wetting-) oil and sand mixture

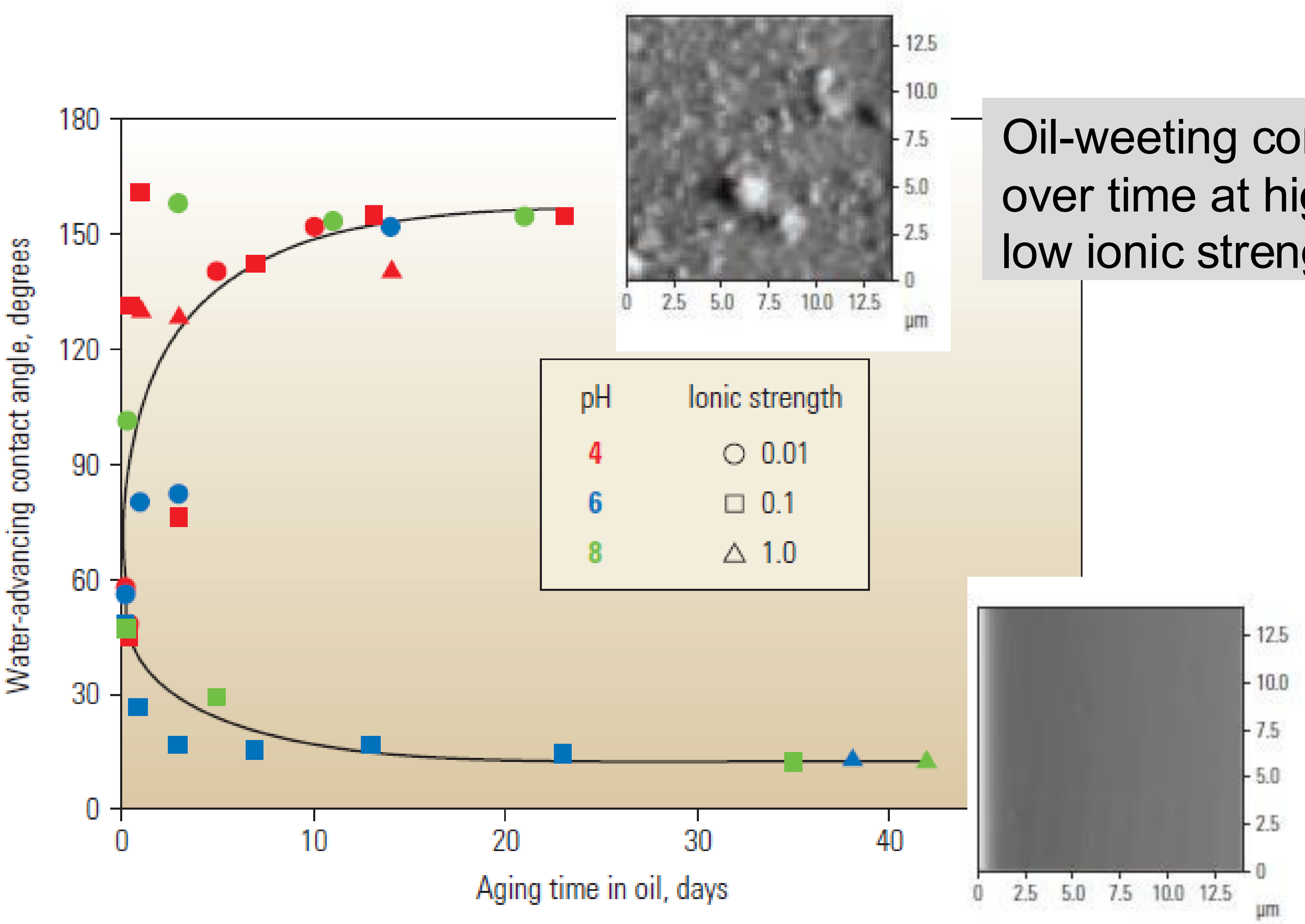
Degraded (wetting-) oil and sand mixture



From: Abdel Aal, G.Z. And Atekwana, E.A., 2014. Spectral induced polarization (SIP) response of biodegraded oil in porous media. Geophysical Journal International, 196(2)



Aged plumes - wettability



Oil-weeting conditions given over time at high acidic pH and low ionic strength

A glass surface covered with water (varying concentrations of NaCl) in crude oil

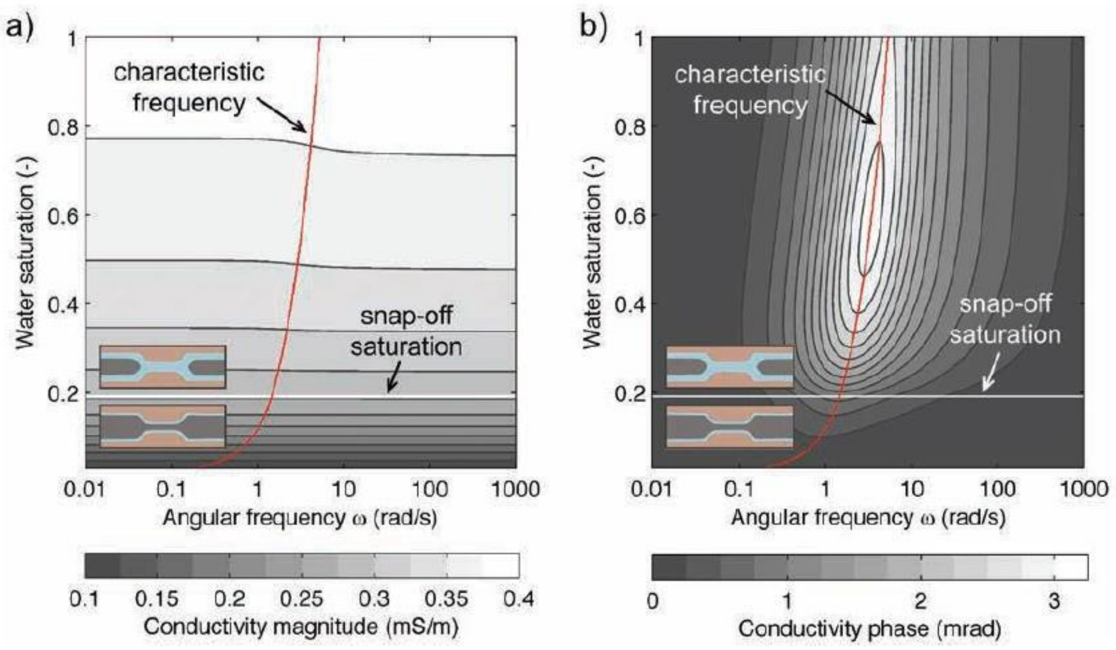
Figure from: Abdallah et al., 1986. Fundamentals of wettability. *Technology*, *38*(1125-1144)

Controls on the SIP signatures of hydrocarbon contaminants

- ❐ Concentration
- ❐ Wettability

- ❐ Maturation
- ❐ Biogeochemical transformations
- Wettability
- Fluid conductivity
- Weathering of grains – porosity
- Accumulation of microbial cells

Water-wet oil with a ζ-potential of -25 mV



Water-wet oil with a ζ-potential of -125 mV

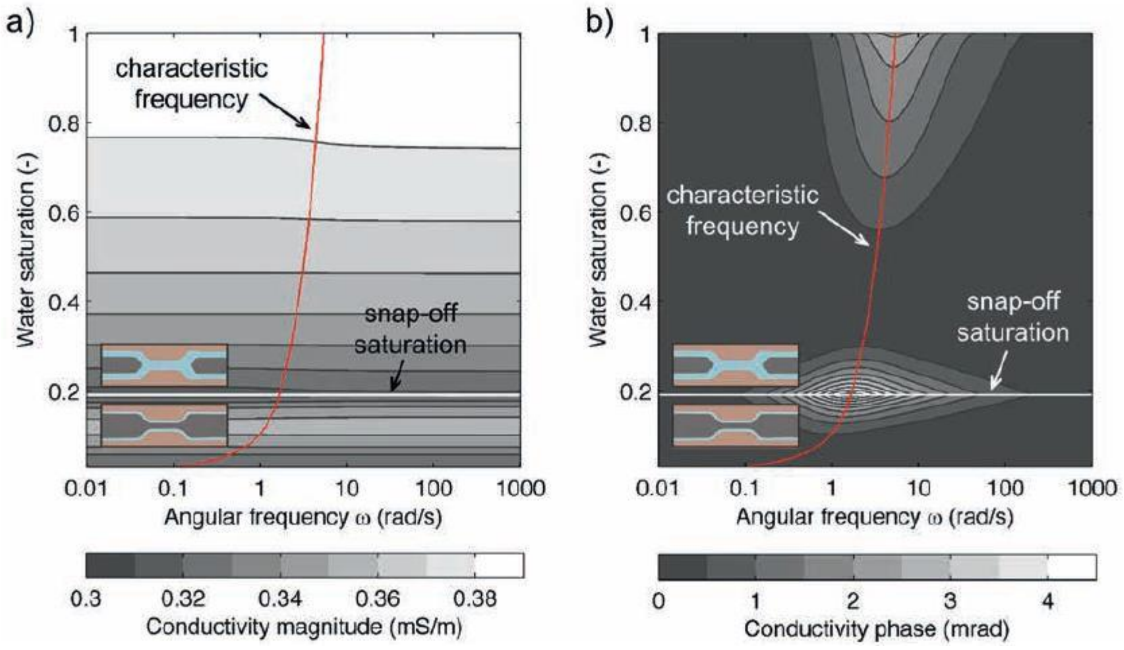


Figure from: Bücker et al., NSG 2017
https://doi.org/10.3997/1873-0604.2017051

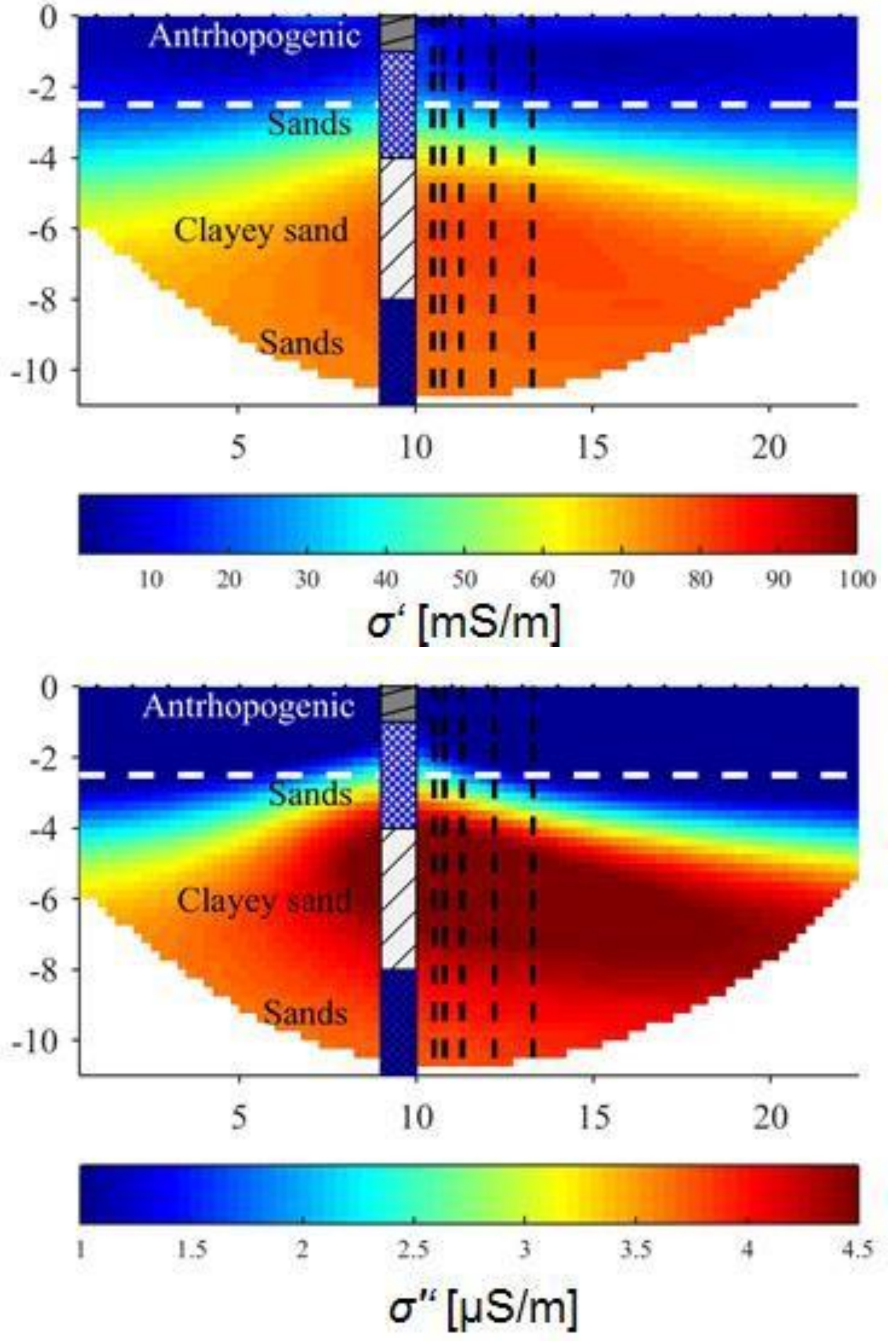
Monitoring of remediation strategies

IP imaging results | lithology

- Chlorinated solvents

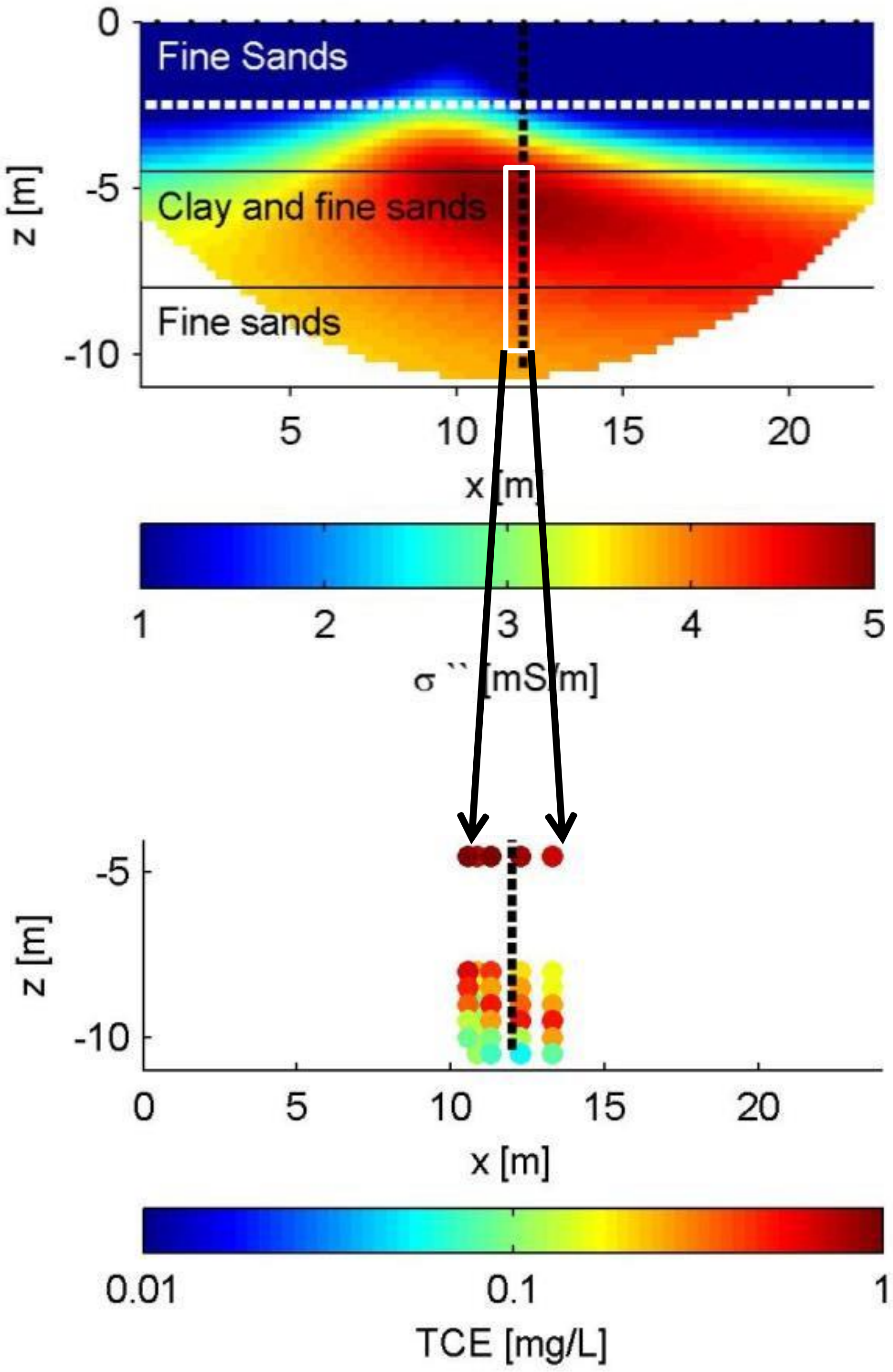
- Sallow aquifer: between 2 and 4 m depth
- Deep aquifer: below 8 m depth
- Groundwater found at 2.5 m depth

- Electrical images prior to any remediation reveal changes related to lithology



IP imaging results | contaminant

- ❑ Increase in the polarization effect (σ'') with increasing concentrations of trichloroethene (TCE)
- ❑ Large spatial coverage in IP images than borehole data
- ❑ Information from areas not accessible for water samples

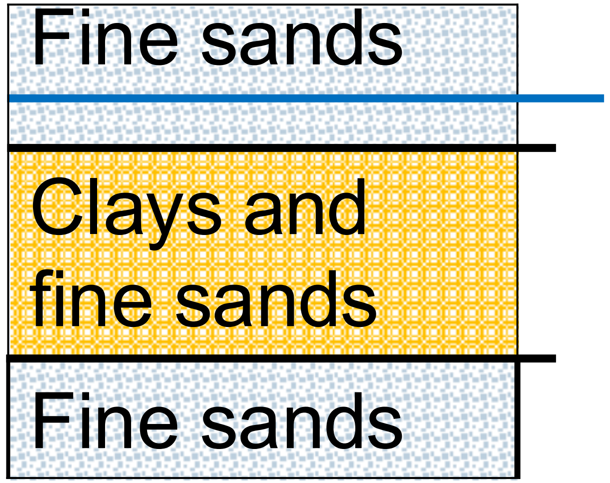


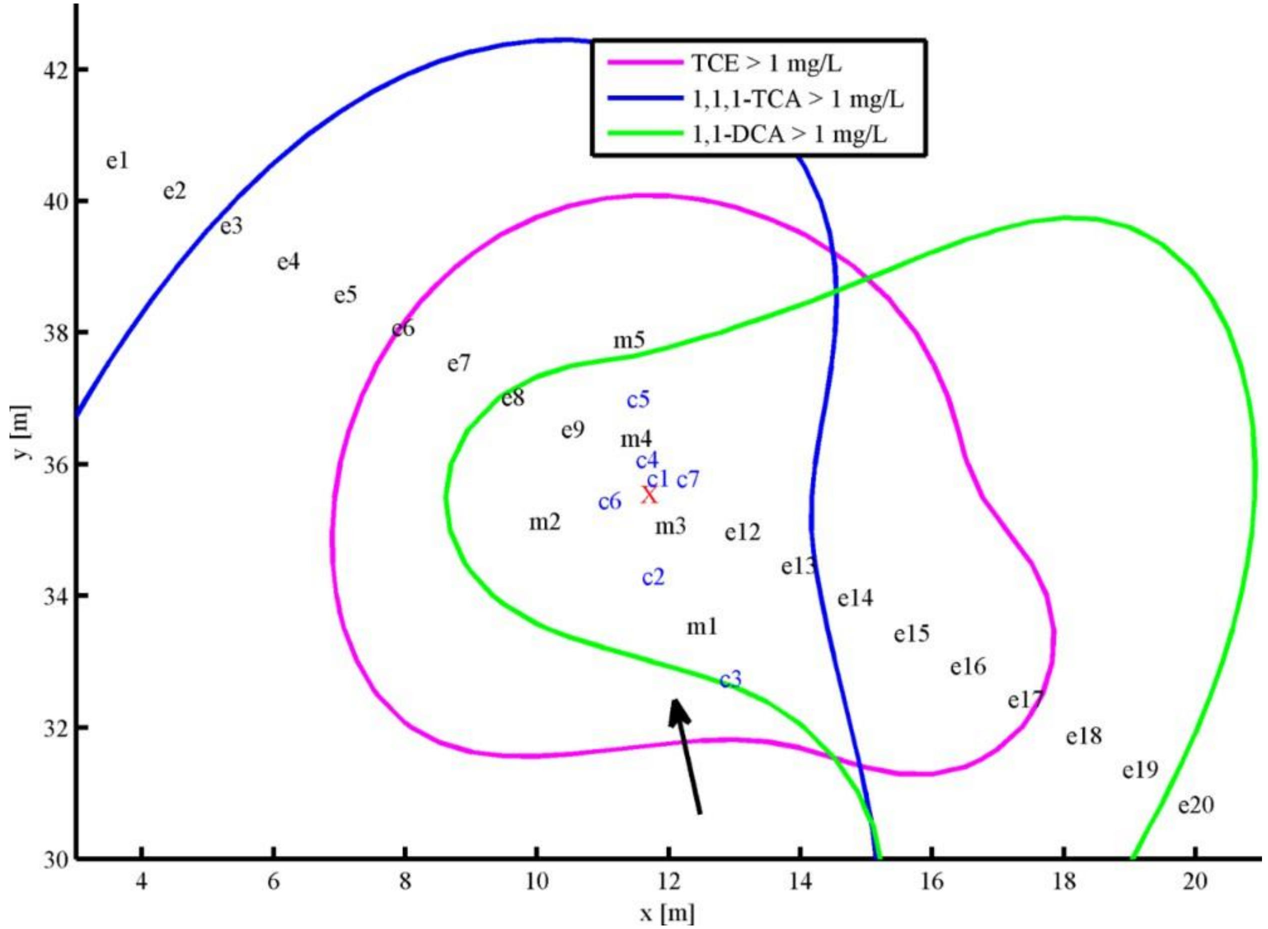
Injection of micro-scale ZVI particles

- Target: deep aquifer

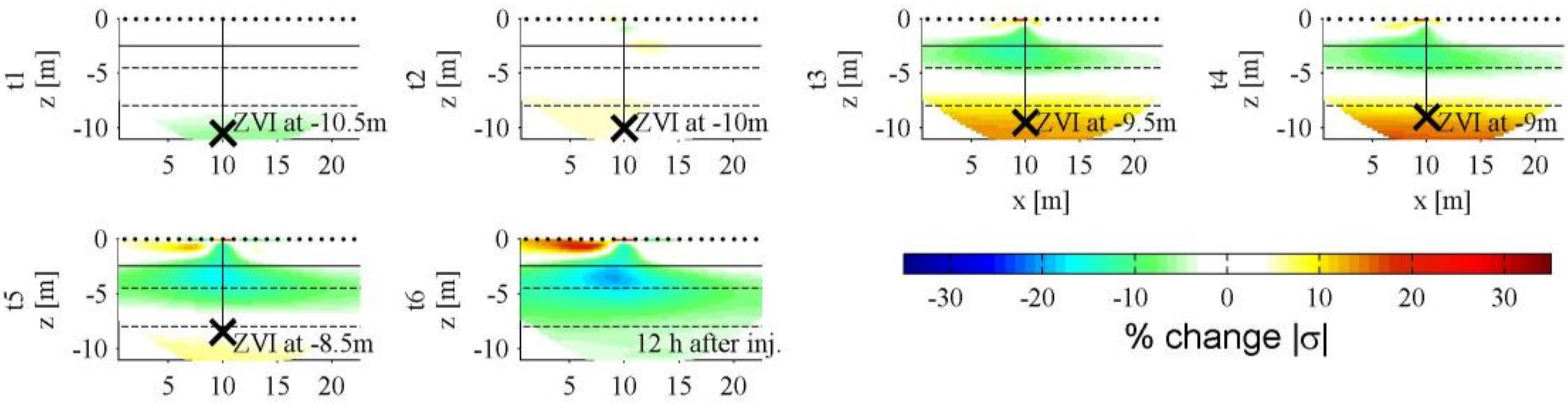
- Injections of ~21 kg of mZVI (d_{50} = 56 µm) coated with biopolymer solution
- Injection at 10.5, 10, 9.5, 9, 8.5 m depth
- Final amendment of enzymes to removing the coating

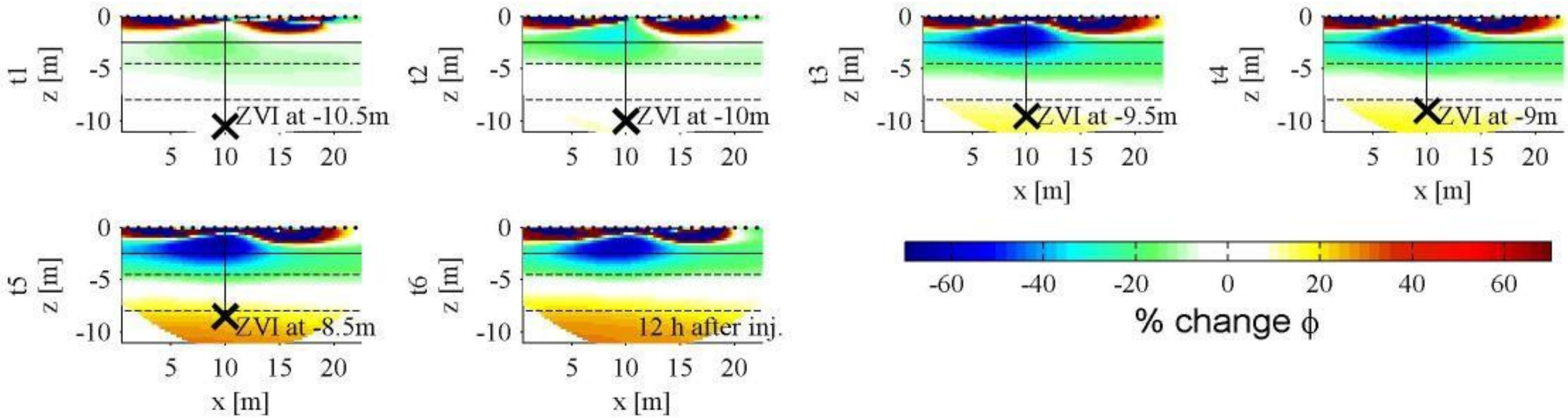
- 15 minutes injection – 15 minutes to move the pump to the new position
- IP data collection < 15 minutes





Monitoring | electrical conductivity

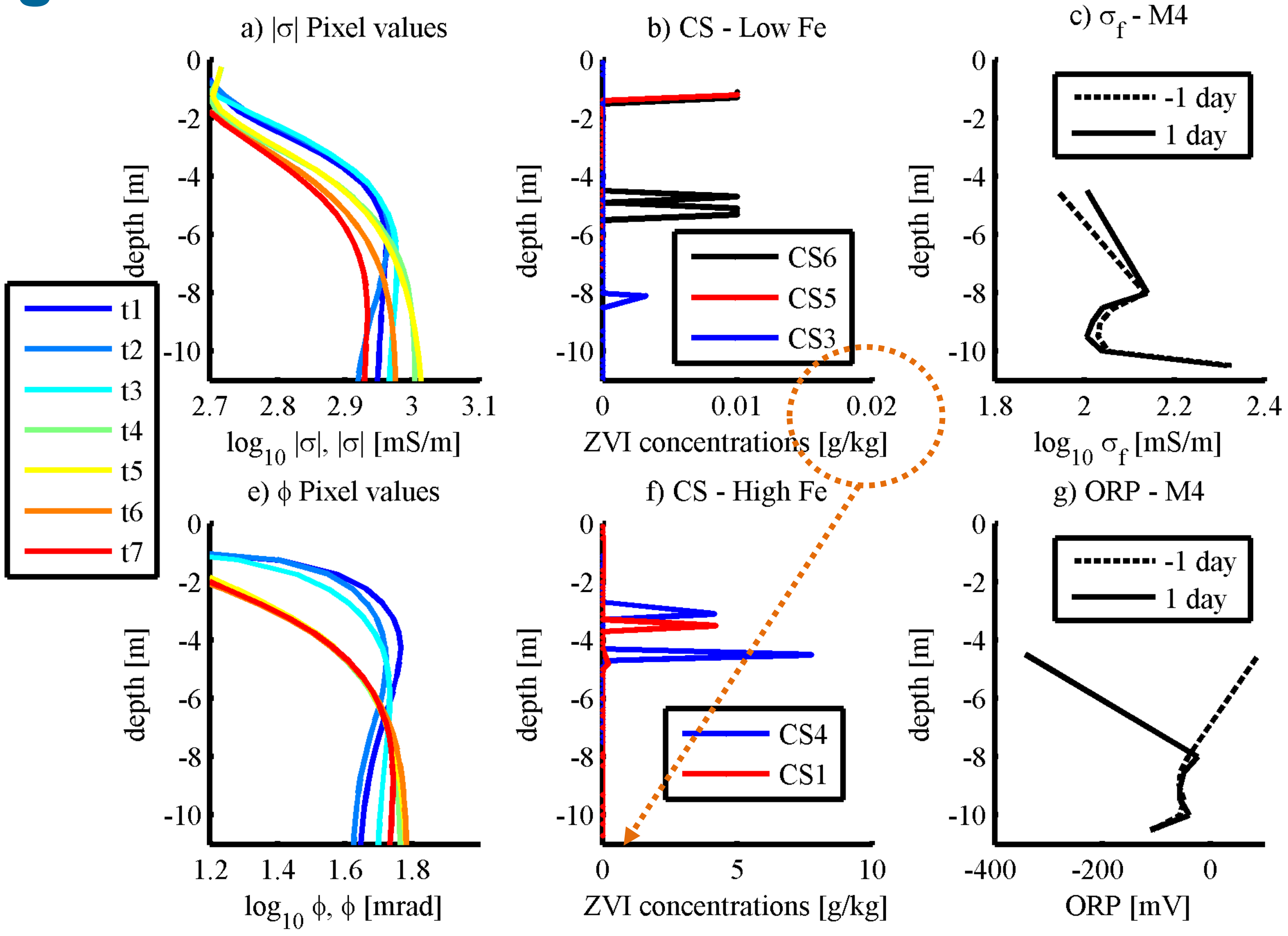



t1
z [m]
ZVI at -10.5m
t2
ZVI at -10m
t3
ZVI at -9.5m
t4
ZVI at -9m
t5
ZVI at -8.5m
t6
12 h after inj.
x [m]
% change ϕ

What controls the IP signatures

- IP imaging reveals the incorrect delivery of the particles

- Information can be gained on real-time to adjust the remediation strategy

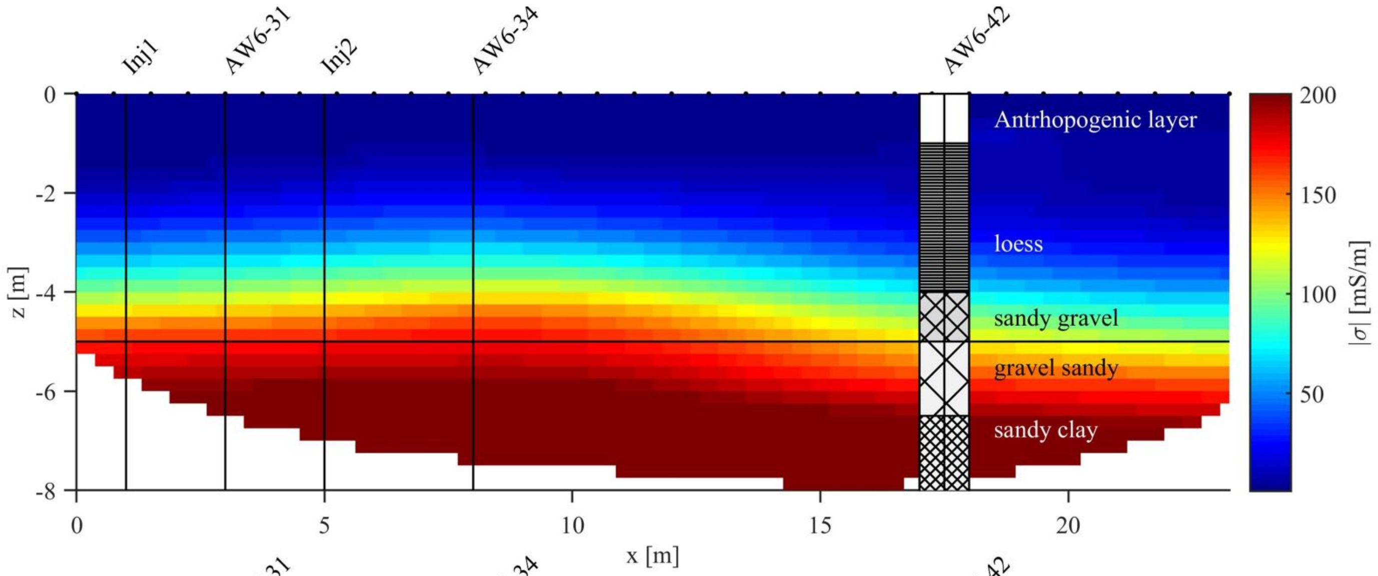


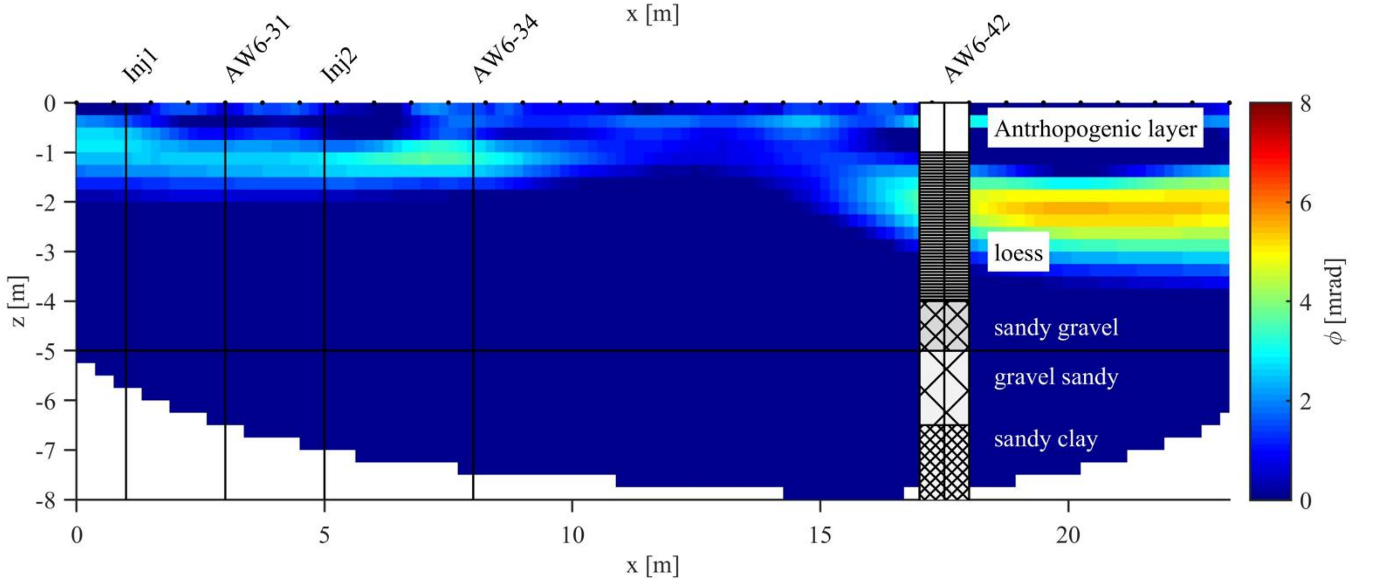
Flores Orozco et al., ES&T 2015
https://pubs.acs.org/doi/abs/10.1021/acs.est.5b00208

Injection of nano-Goethite particles

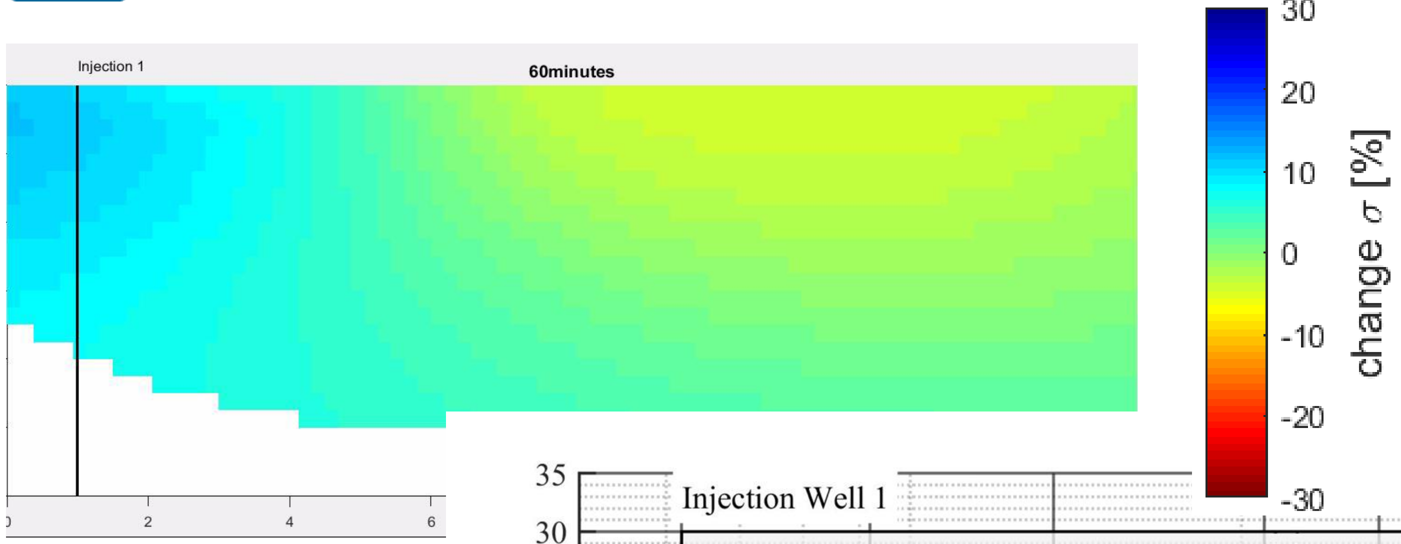
- Benzene contaminated site
- Groundwater table at 5m depth (gravel sandy aquifer)
- Injections using nano-scale FeOx particles (iron oxides)

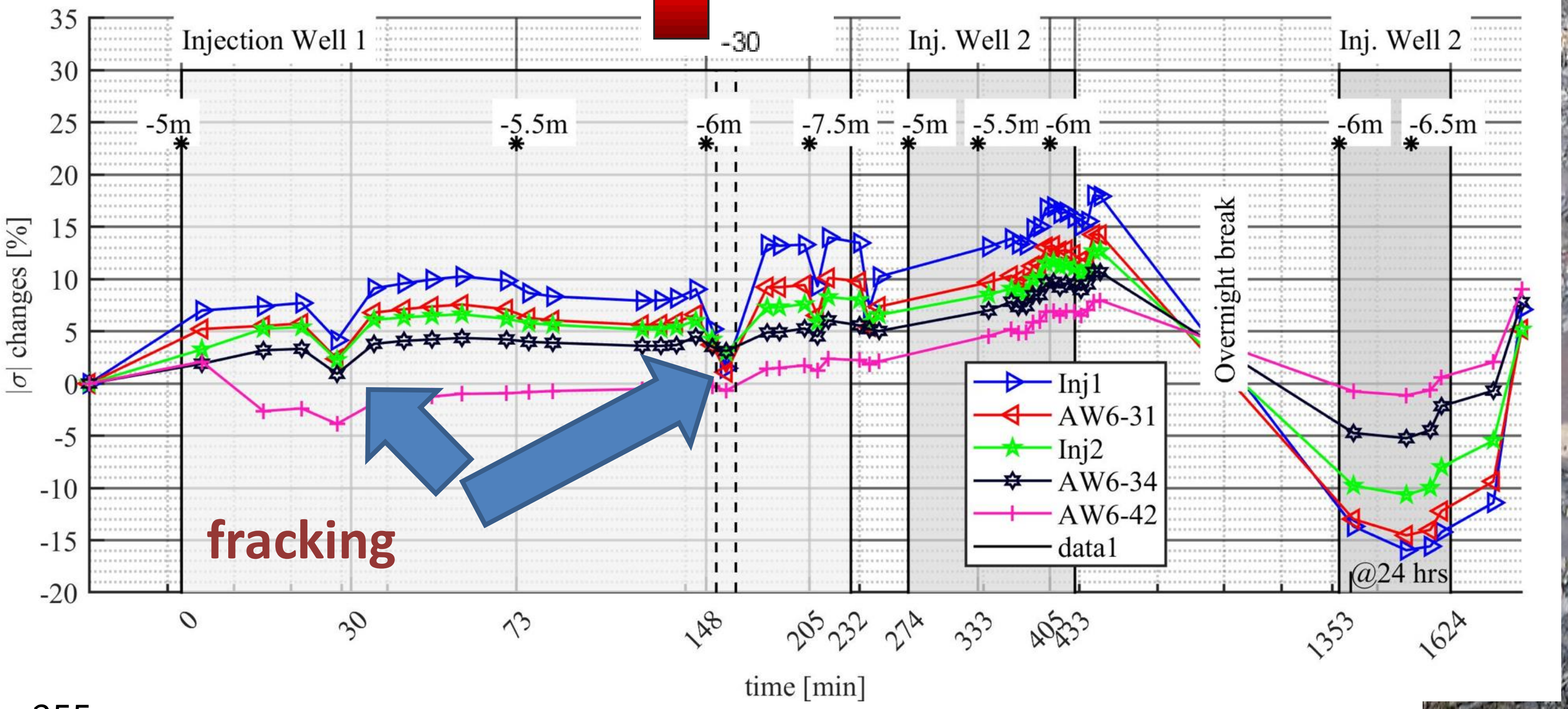
  → 300 kg iron (60 m^3) in a solution of 5 g/l (Humic acids)
- Injection between 5 and 7 m depth



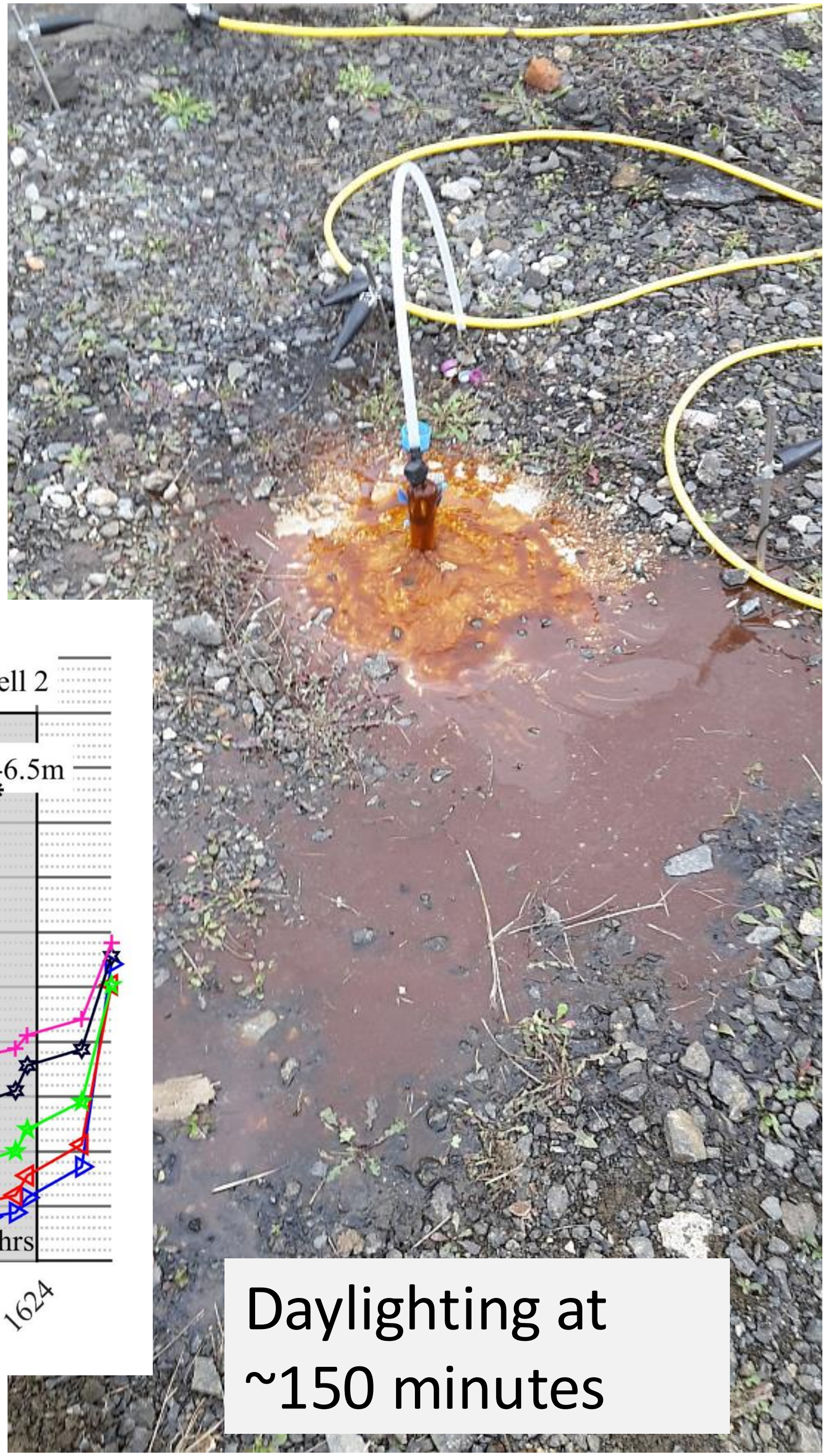


Monitoring results | conductivity





Flores Orozco et al., GJI 2019
https://doi.org/10.1093/gji/ggz255



Daylighting at
~150 minutes

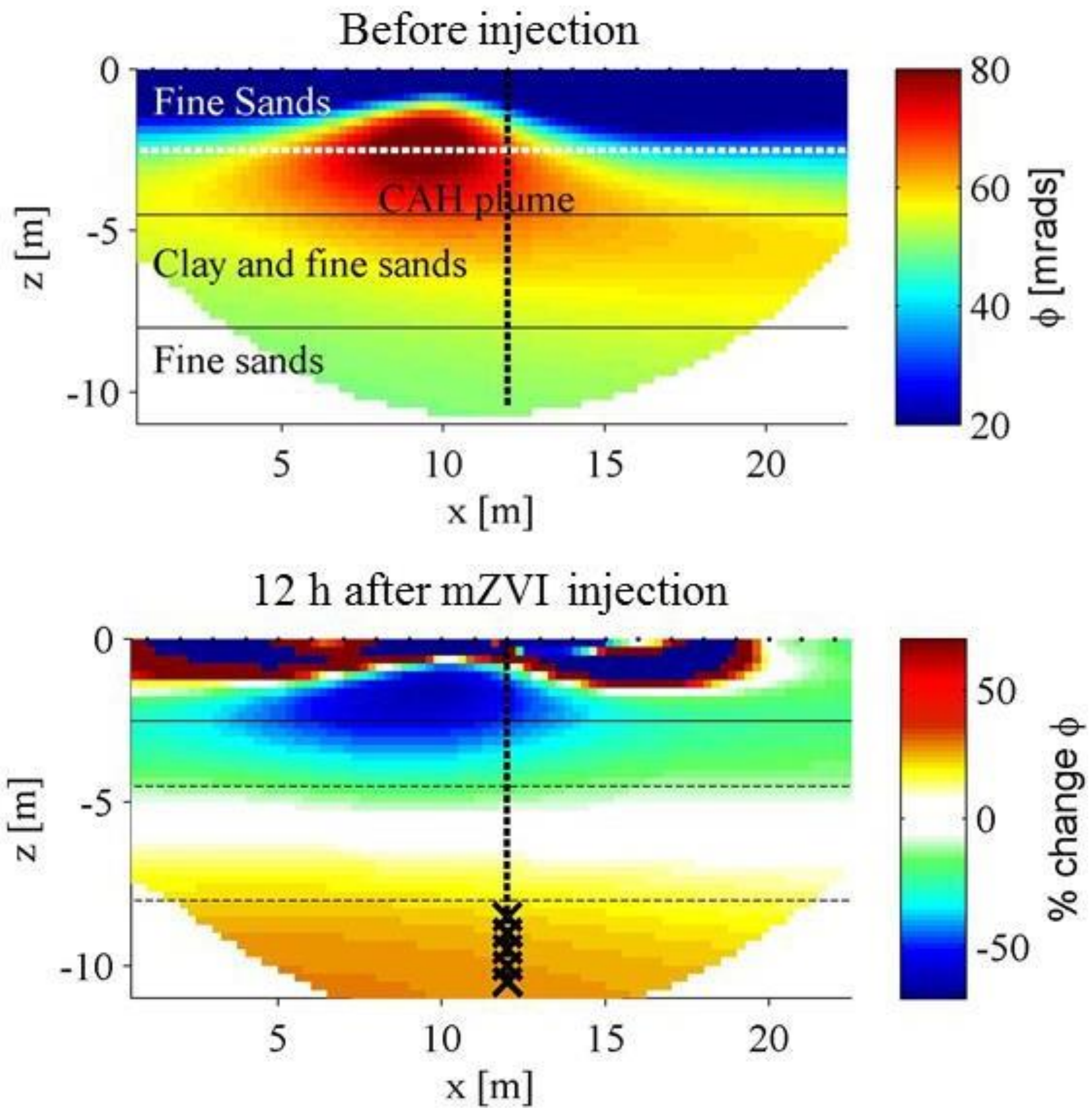
Improving the efficiency of remediation strategies

- IP imaging can be useful to design and evaluate the efficiency of remediation strategies

- Identify the geometry of the source-zone and the plume of dissolved contaminants
- This information can be used to better design the remediation approach

Evaluating the efficiency of remediation strategies

- IP monitoring can provide real-time information in the subsurface critical to adjust the remediation approach
  - Changes in pore-space geometry such as loss of permeability, fracking, etc.
  - Changes in the properties of the contaminant, such as wettability
  - Increase in the conductivity associated to enhanced microbial activity



Aged oil plumes

Aged hydrocarbon plumes

- Phyiscal and chemical changes into the grains, the pollutants will also change the properties of the pore water

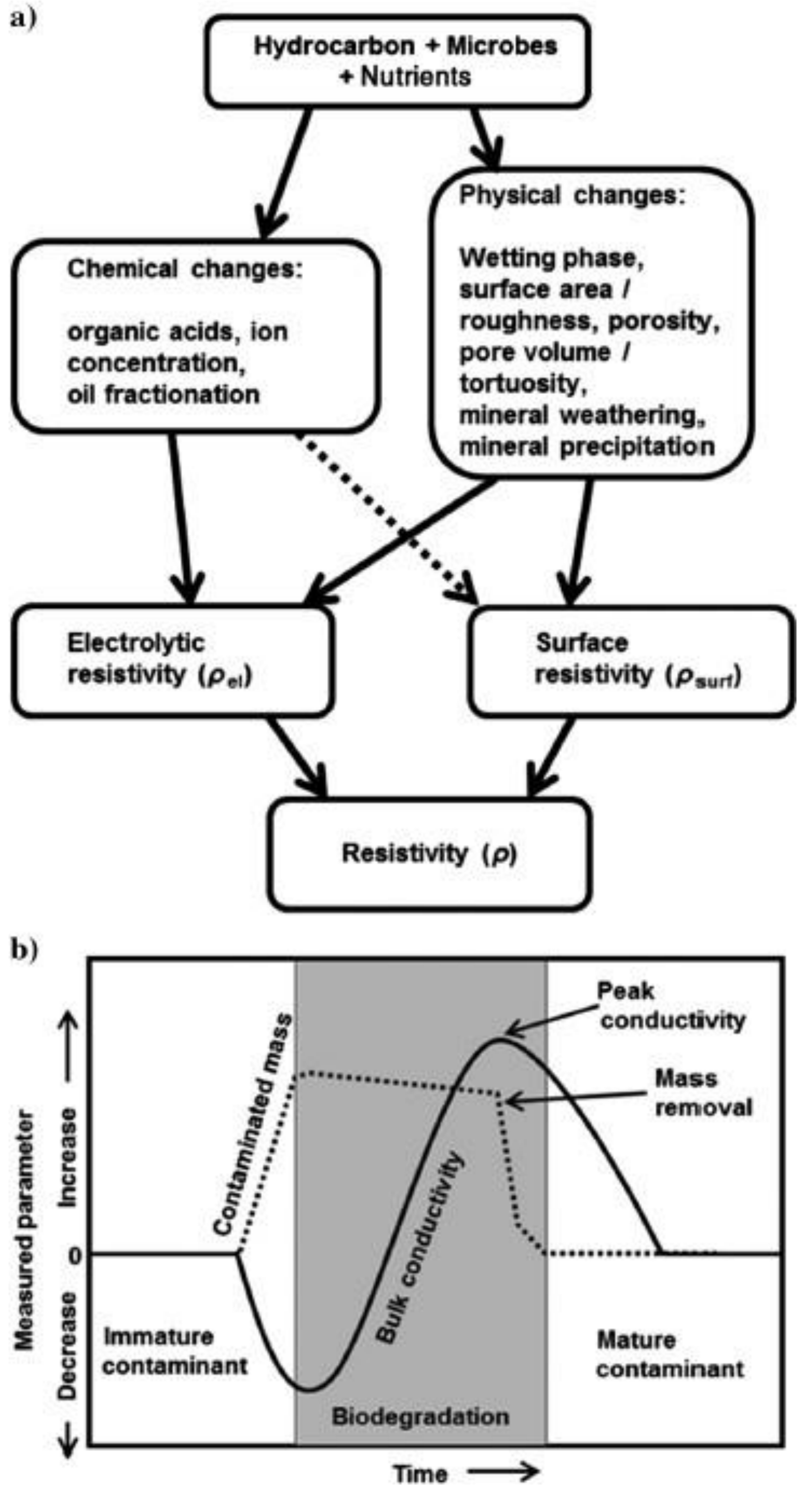
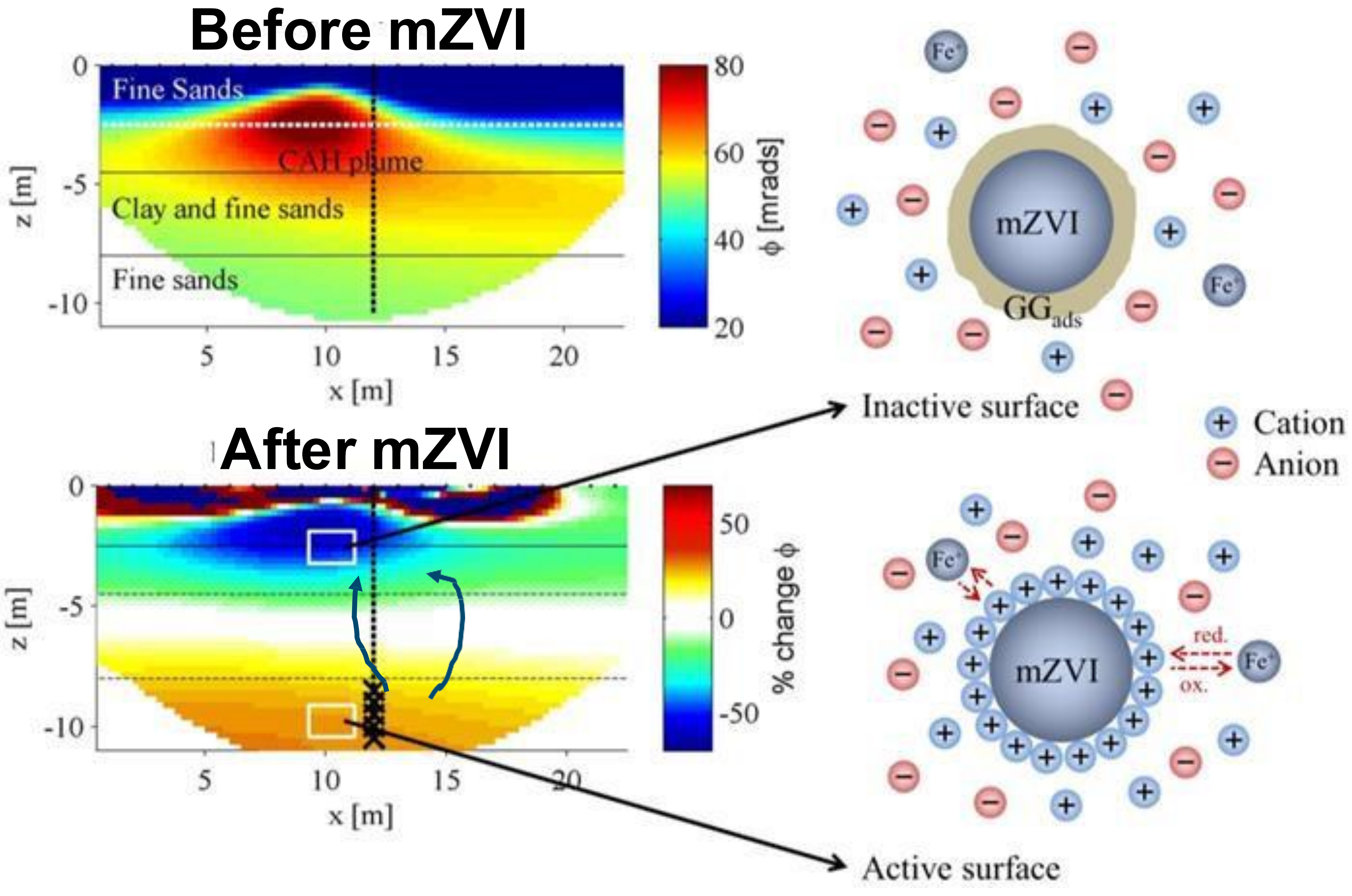


Figure from:
Heenan, J., Slater, L.D., Ntarlagiannis, D., Atekwana, E.A., Fathepure, B.Z., Dalvi, S., Ross, C., Werkema, D.D. and Atekwana, E.A., 2015. Electrical resistivity imaging for long-term autonomous monitoring of hydrocarbon degradation: Lessons from the Deepwater Horizon oil spill. *Geophysics*, *80*(1)

Surface properties control the IP response

- Brush layer – adsorbed biopolymers to the surface of the metallic particles prevent charge transfer mechanisms between the electrolyte and the ZVI surface

- Bare particles (after degradation of the brush layer) corresponds to electrode polarization



Pacific Northwest
NATIONAL LABORATORY

Advancing Subsurface Monitoring:

Spectral induced polarization for detecting remedial amendment delivery and reactivity

Hilary P. Emerson

Z Vincent, JN Thomle, K Peshtani,
JE Szecsody, NP Qafoku, J Robinson, L Slater,
and RD Mackley

U.S. DEPARTMENT OF ENERGY BATTELLE

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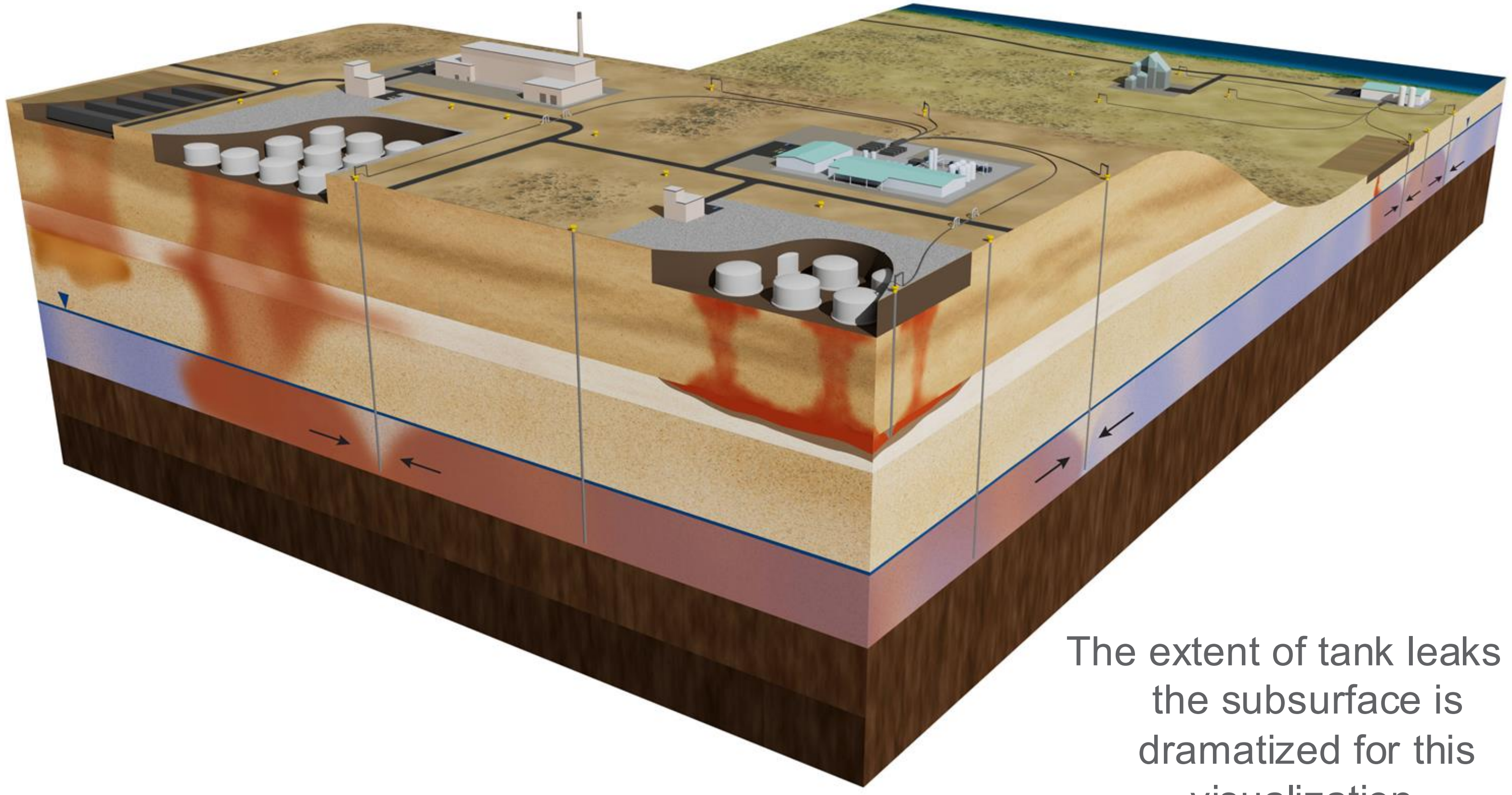
PNNL-SA-211510

Talk Preview

Electrical geophysics for understanding reactions at the solid-water interface during subsurface remediation

- What is spectral induced polarization (SIP) and how does it relate to commonly used geophysical techniques?
- How can we use SIP to understand mineralogy and interfacial chemistry?
- Can we monitor apatite formation in sediments with SIP?
- Can we characterize iron transformations in sediments with SIP?

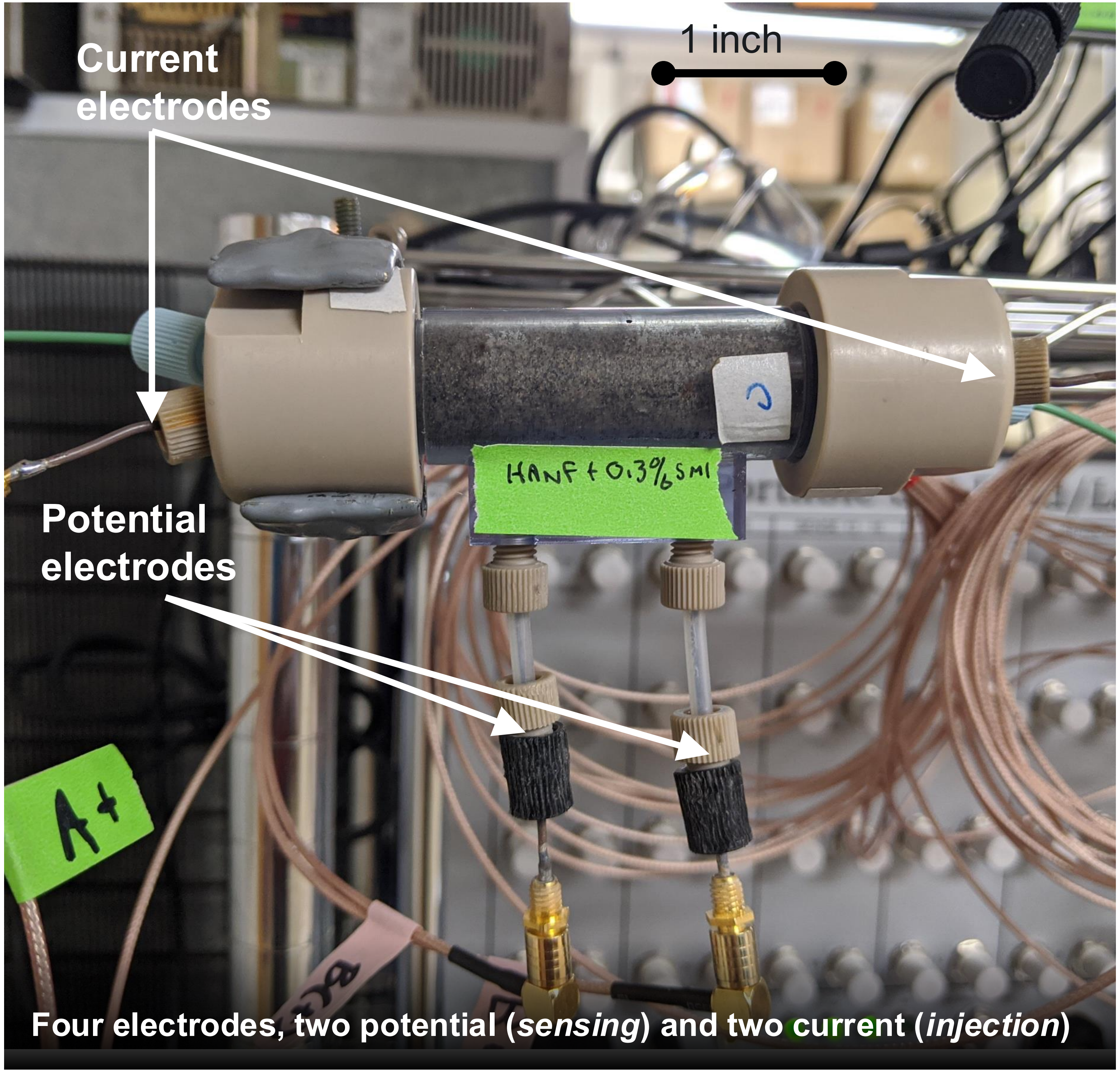


The extent of tank leaks to the subsurface is dramatized for this visualization.

What is Spectral Induced Polarization?

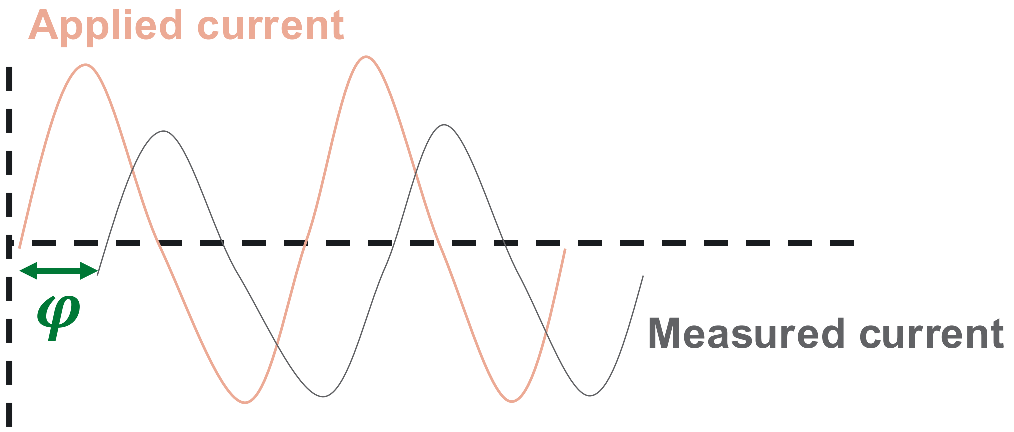
A geophysical technique that applies low alternating electrical current across a pair of electrodes (*current*) and measures a response across sensing (*potential*) electrodes in-between the current electrodes

Collects both *resistivity* (inverse is conductivity) and *phase shifts*



Four electrodes, two potential (*sensing*) and two current (*injection*)

Comparison to Conventional Geophysical Techniques



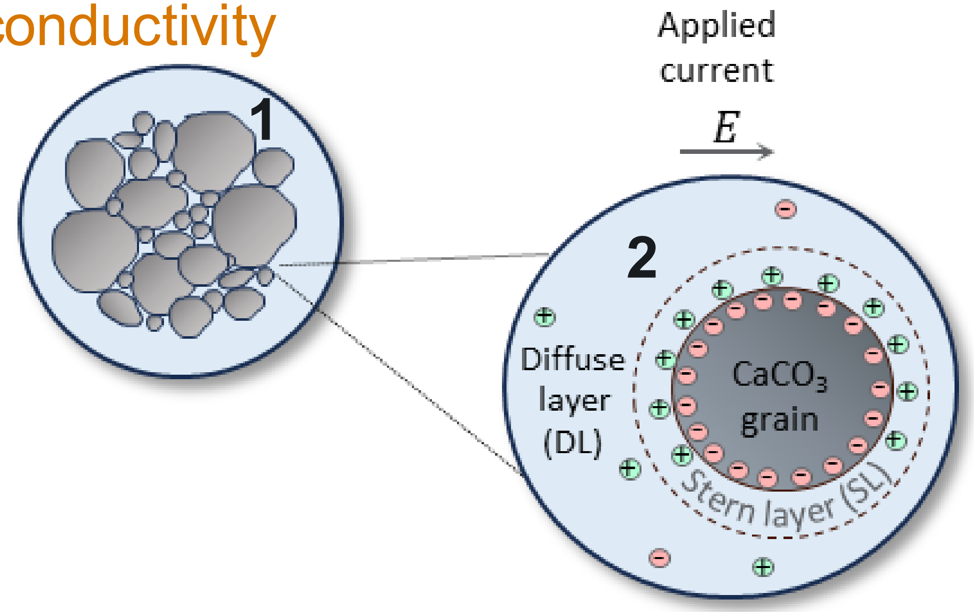
- Electrical resistivity, ER
  - Commonly used in the field
  - ER does not allow separation of electrolytic (1 – via the fluid-filled pores) and interfacial (2 – via the EDL) charge transport processes
- Spectral induced polarization, SIP
  - Being developed for field, limited use to date
  - SIP measures complex conductivity and phase, φ
  - Allows separation and provides high sensitivity to processes impacting interfacial charge transport mechanisms

$$Complex = Real + [i \times Imaginary]$$

$$\sigma = \sigma' + i\sigma'' = |\sigma| e^{-i\varphi}$$

complex conductivity

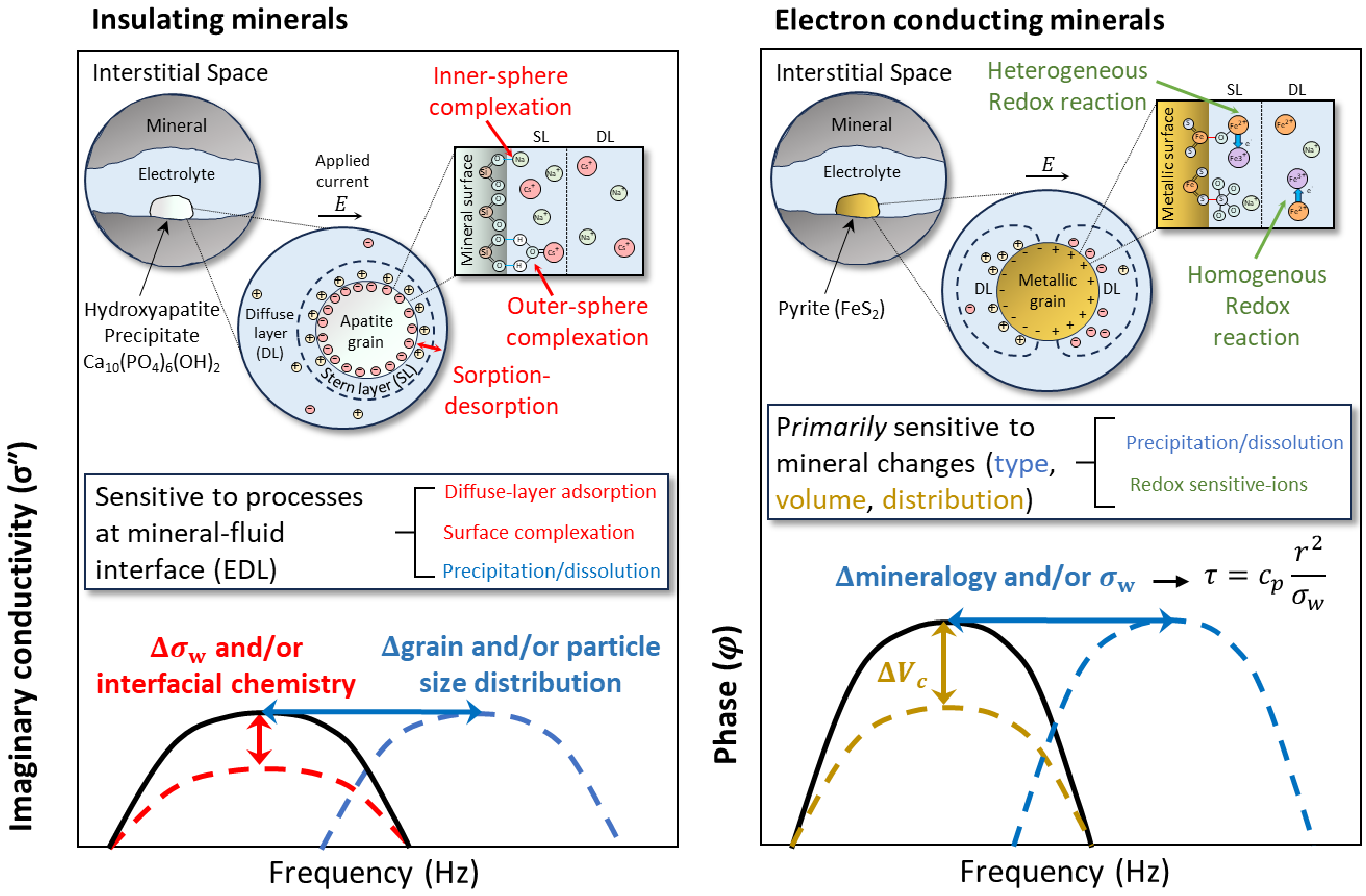
phase



*Measured values in orange and green

Conceptual Model of SIP

- Significantly different response for *insulating* versus *electron conducting* minerals
- Shifts expected in both *frequency* and *magnitude* of response
- *Physical* and *geochemical* changes impact response

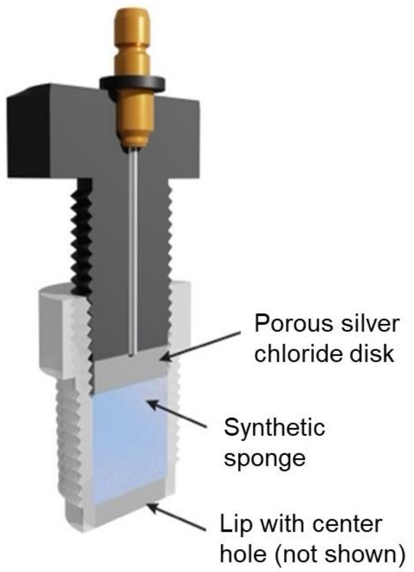


Δ refers to change, σ_w is fluid conductivity, SSA is specific surface area, V_c is volume content (including particle size) of electron conducting minerals, τ is relaxation time, c_p is specific polarizability, arrows delineate change from baseline peak (*black solid line*) after geochemical reaction (*dashed line*)

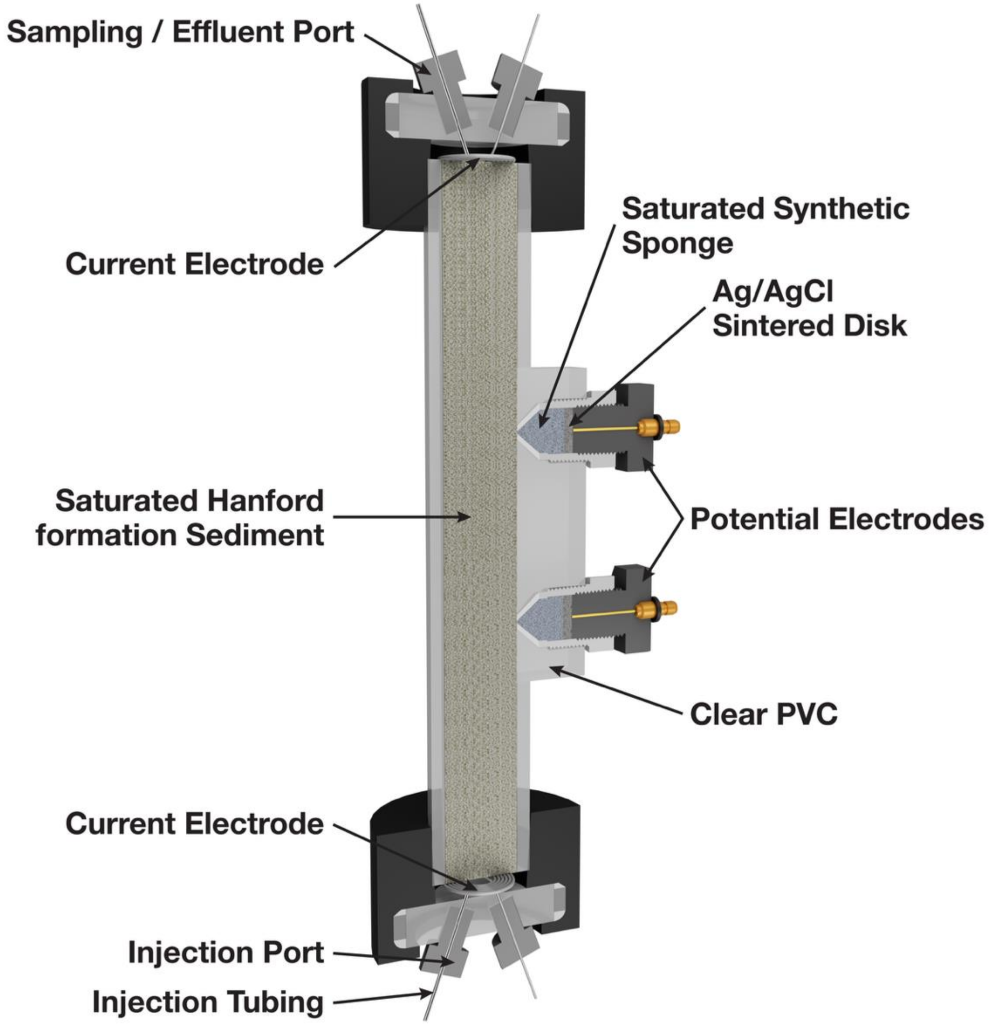
Approach

Objective: Evaluate SIP response for non-intrusively monitoring remediation in the subsurface (including both delivery and subsequent transformations)

1. Determine SIP response during remediation
   - During treatment with particulate zero valent iron or liquid apatite-forming amendments
   - Following groundwater flushing of injected solutions
2. Identify signatures associated with SIP response, if possible
   - Characterize column sediments to quantify physical and geochemical changes



SIP potential electrode



Experimental scale – one-dimensional columns

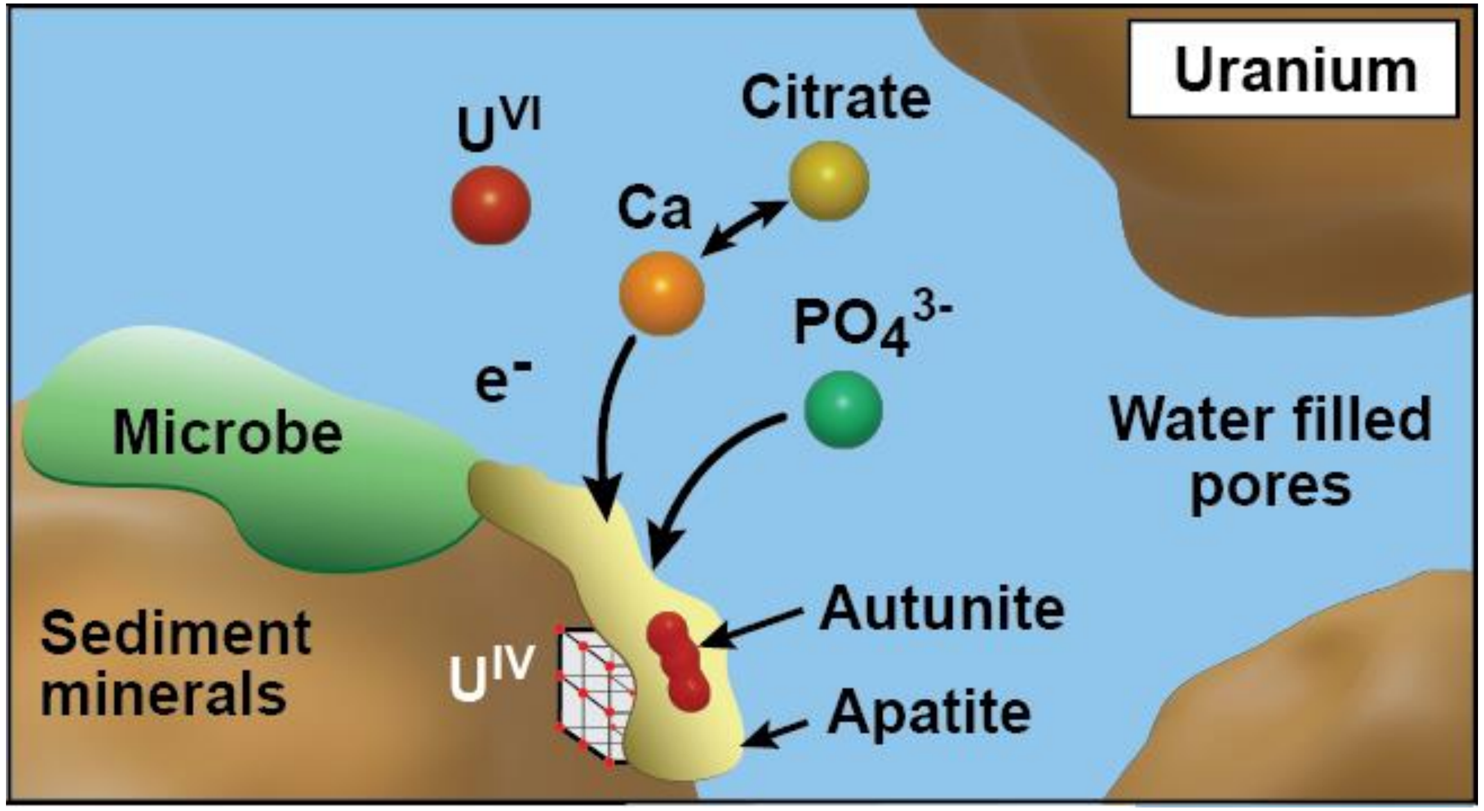
What Happens During Liquid PO_4 Injection?

High ionic strength injection solution fills pore spaces

Ca^{+2} and PO_4^{-3} become available in solution

Apatite $Ca_{10}(PO_4)_6(OH)_2$ precipitates on sediment particles

Conceptual diagram of delivery of calcium citrate PO_4 solutions into pore space with subsequent precipitation of apatite and contaminant-specific precipitates (e.g., autunite)



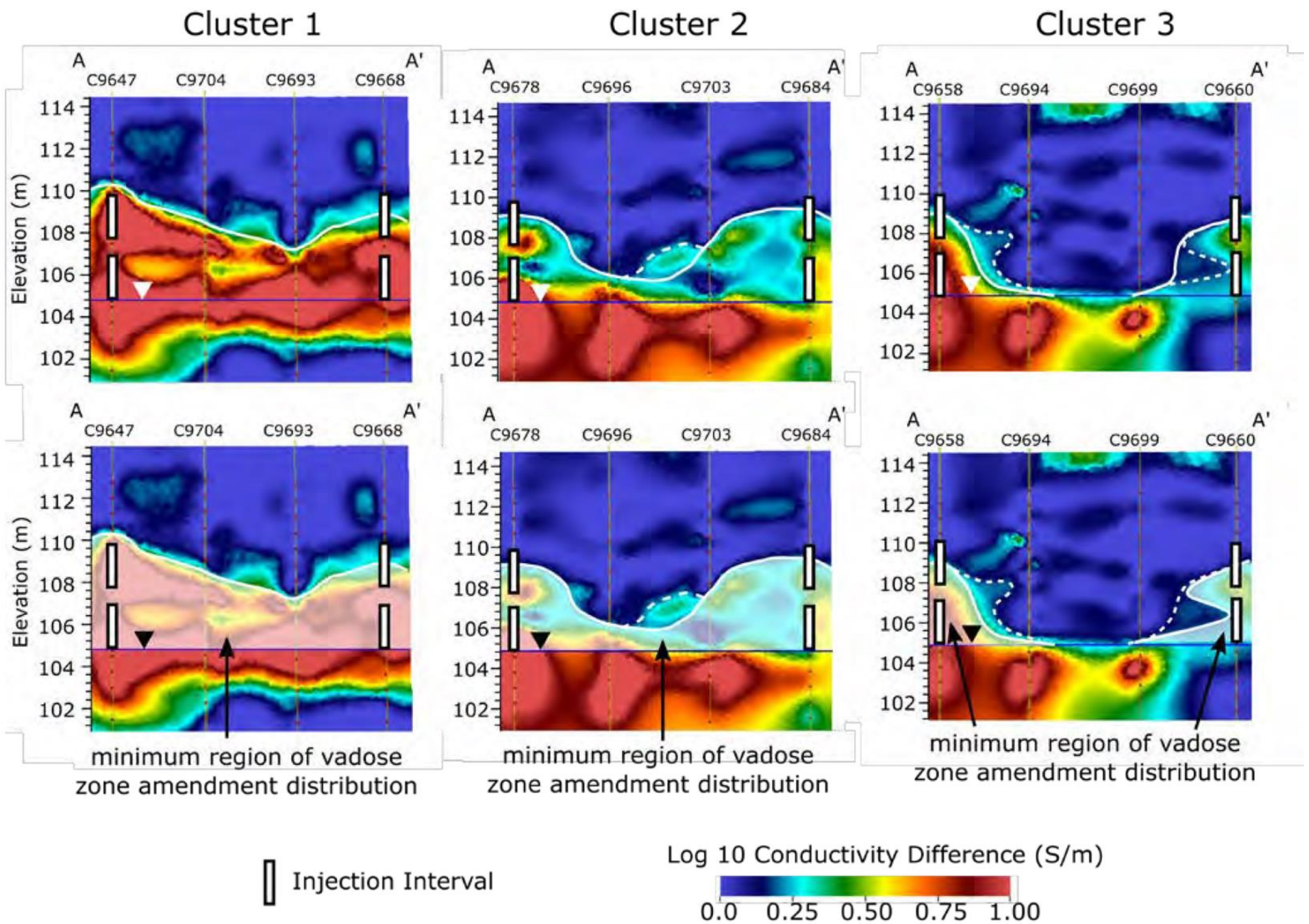
Can we identify when and where apatite is forming?

What Happens During Injection?
Stage B Injection at 300 Area of Hanford Site

High ionic strength injection solution fills pore spaces

Poly-PO_4 chains slowly break apart, Ca^{+2} exchanges into solution

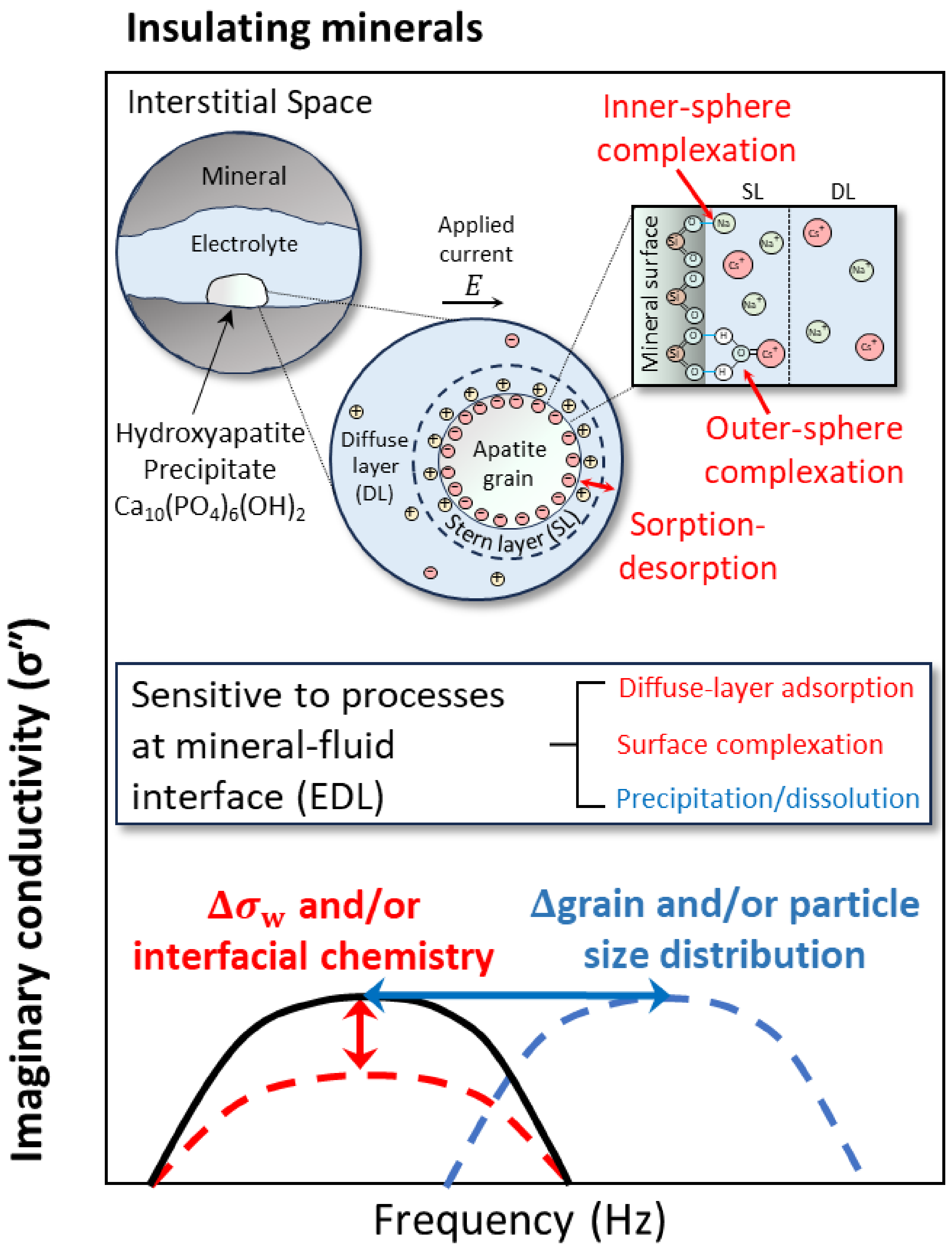
Apatite $Ca_{10}(PO_4)_6(OH)_2$ precipitates on sediment particles



Electrical resistivity shows where injection solutions are delivered but cannot indicate where amendment is precipitating (Johnson et al. 2019 PNNL-28619)

Conceptual Model of Liquid PO_4 for SIP

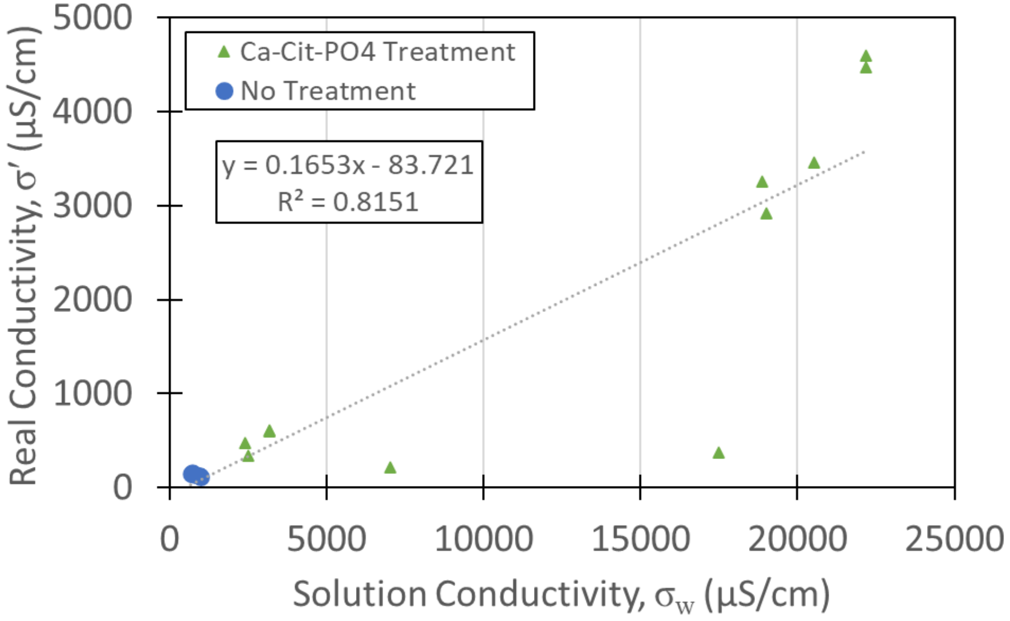
- Initial injection
  - $\uparrow \sigma_w$ contributes to $\uparrow \sigma'$ and $\downarrow \varphi$
  - $\uparrow \sigma''$ from ion exchange, adsorption, and/or initial Ca-PO_4 precipitation
- Post injection
  - $\downarrow \sigma_w$ back to natural conditions $\uparrow \varphi$
  - $\uparrow \sigma''$ from ion exchange, adsorption, and/or initial Ca-PO_4 precipitation
  - Shift in τ (peak frequency) due to pore blocking or particle size changes

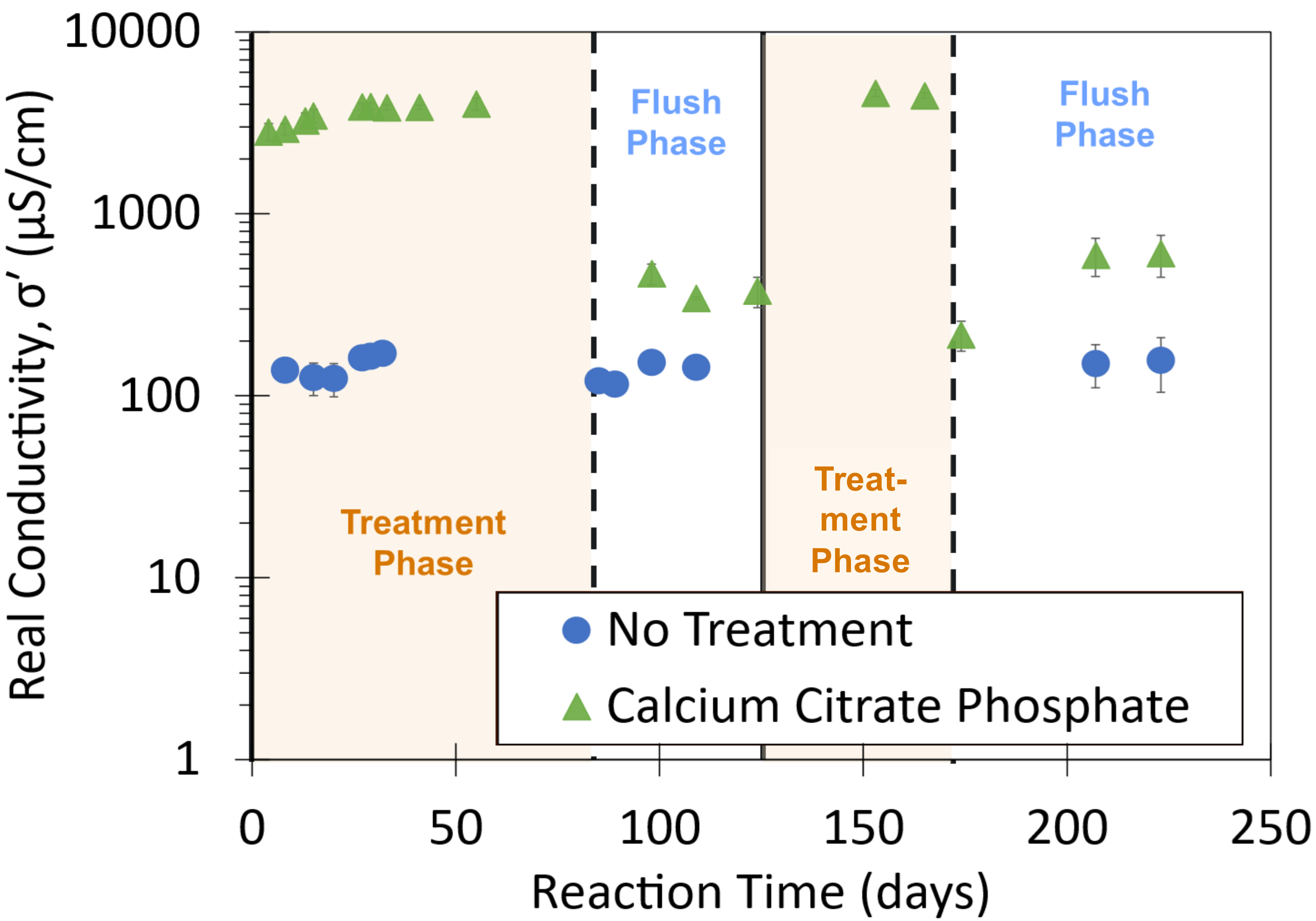


Results: Liquid PO_4 Amendments Column Testing

Significant increase in real conductivity, σ′, only during treatment with apatite-forming solutions

- Similar to ER response
- Correlates with solution conductivity increases

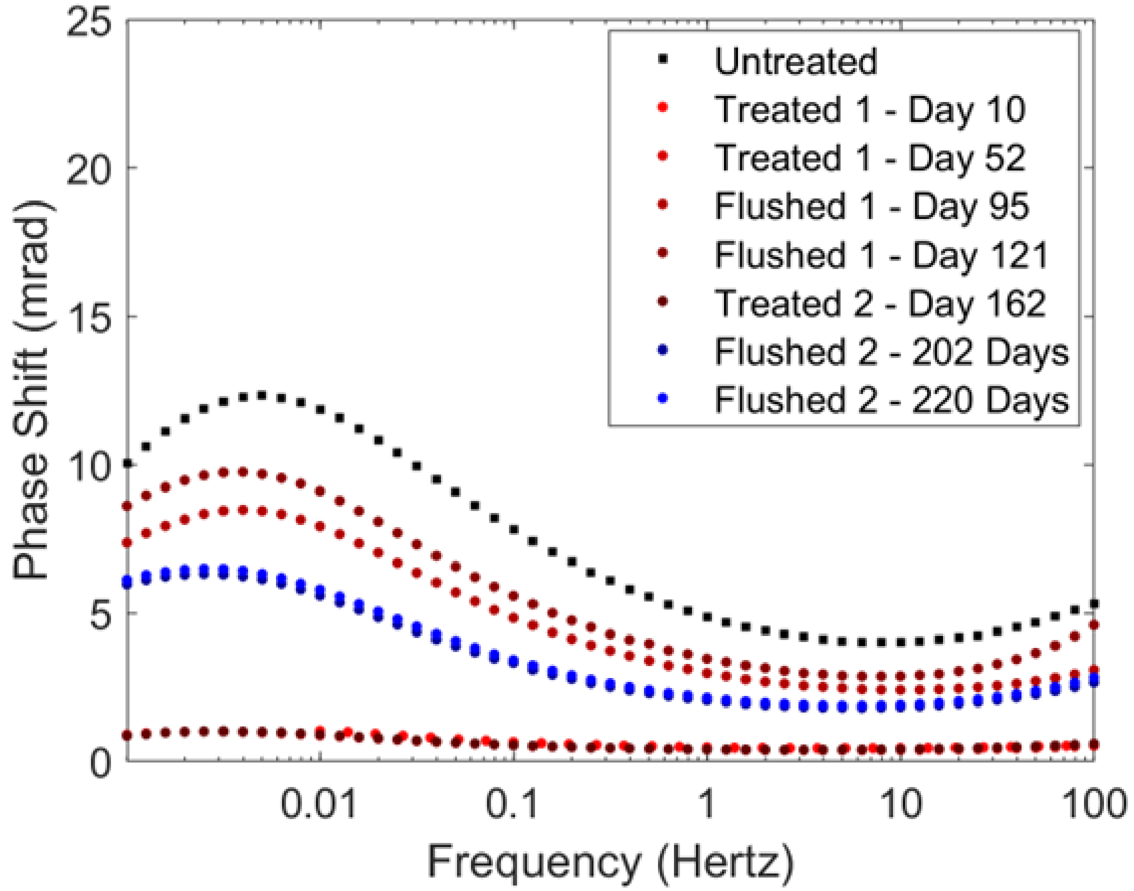


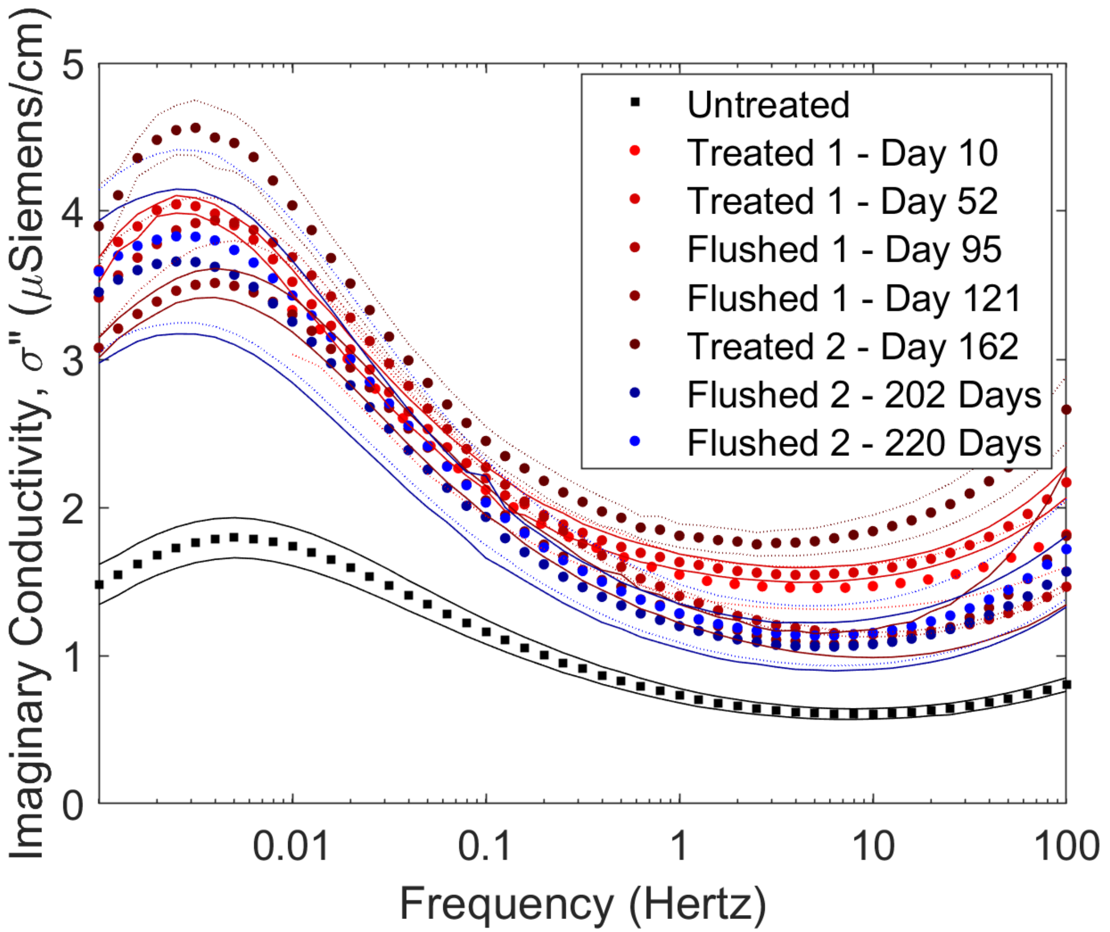


Results: Liquid PO_4 Amendments Column Testing

Increase in imaginary conductivity (σ''), following treatment and after flushing

- Increase consistent after flushing, not impacted by solution ionic strength
- Frequency-specific response (peak at 0.005 Hz)
- Suggests impacts to particle surfaces from precipitation

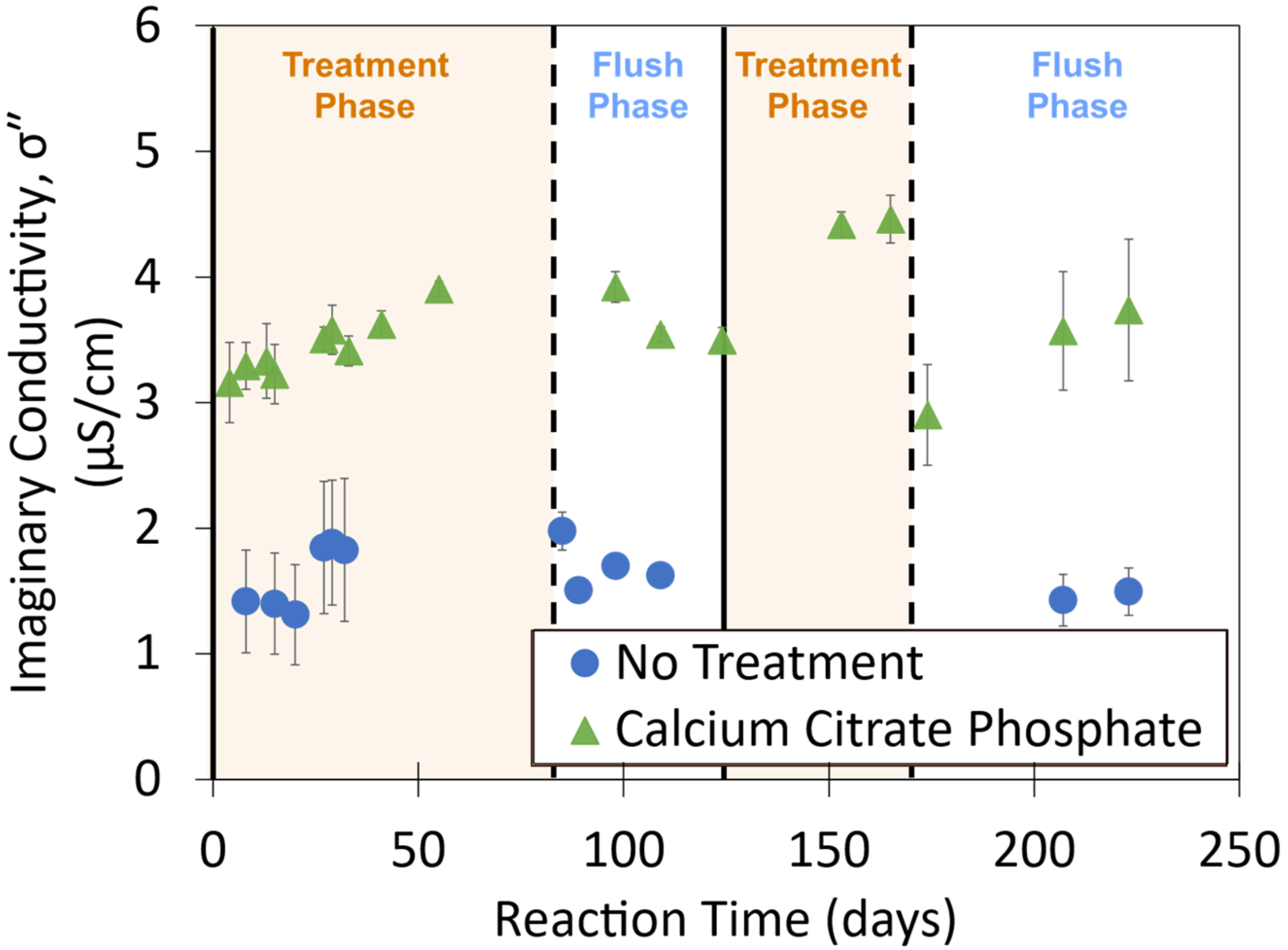




Results: Liquid PO_4 Amendments Column Testing

Increase in imaginary conductivity (at 0.005 Hz), σ″, following treatment and after flushing

- Increase consistent after flushing, not impacted by solution
- Frequency-specific response (τ at 0.005 Hz)
- Suggests impacts to particle surfaces and interface
- SIP provides additional information not possible with ER



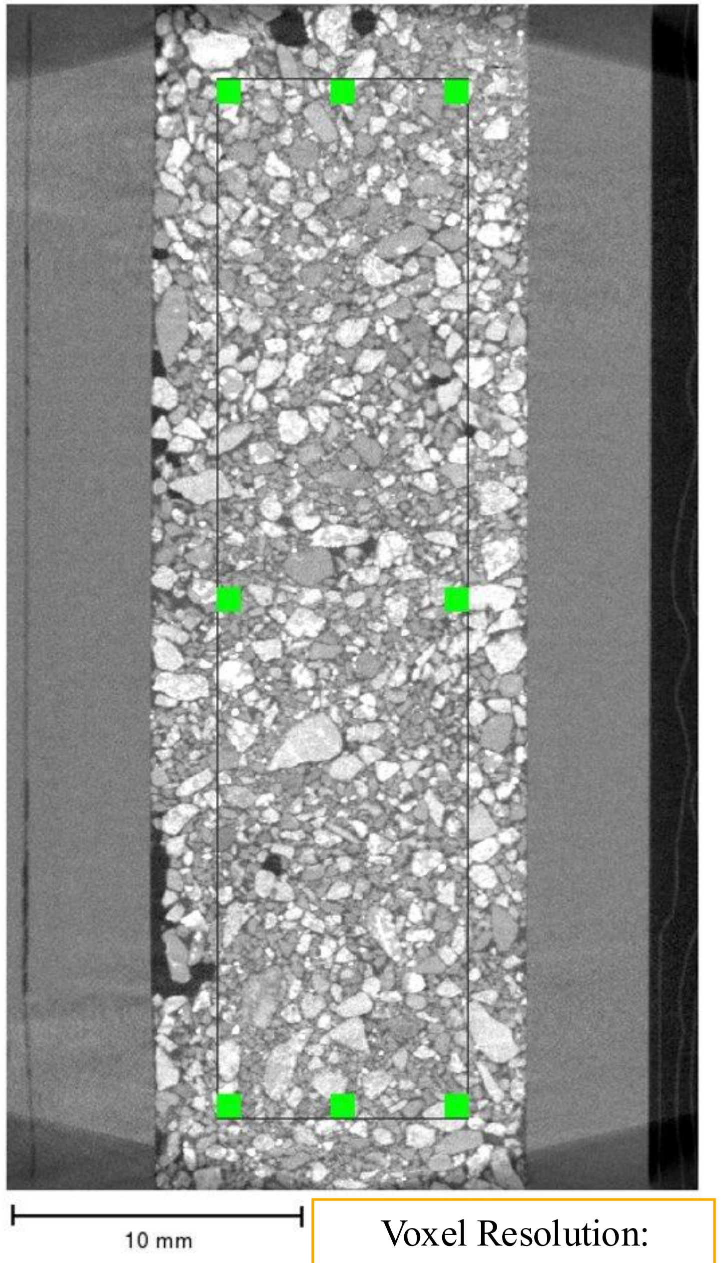
Results: Liquid PO_4 Amendments Post Characterization

Condition	BET Surface Area (m^2/g)
Untreated	7.7 ± 1.6
Before first flush	8.2 ± 0.1
After first flush	10.2 ± 0.6
After second flush	8.4 ± 0.3

Average 2-4 samples from a single column

Sample	Porosity		
	Inject #1	Flush #1	Flush #2
Treated	0.30	0.32	0.33
	0.33	0.31	0.36
	0.30	0.32	NM
	0.31	NM	NM
	0.32	NM	NM
Control	0.33	0.33	0.38
	0.31	0.26	0.29

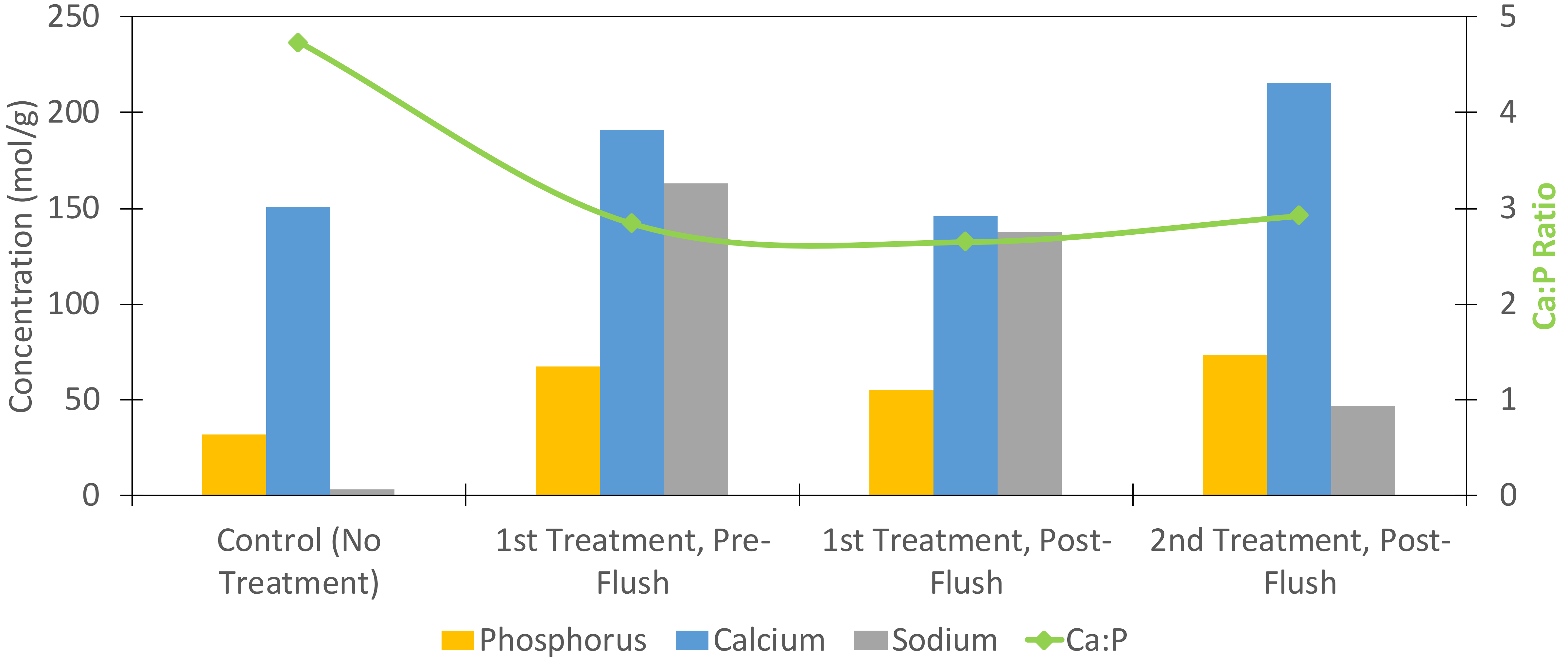
Showing replicates over time; NM = not measured



Voxel Resolution: 0.0205 mm

- No significant change in surface area as measured by BET
- No consistent change in porosity, pore connectivity, or pore size as shown by XCT

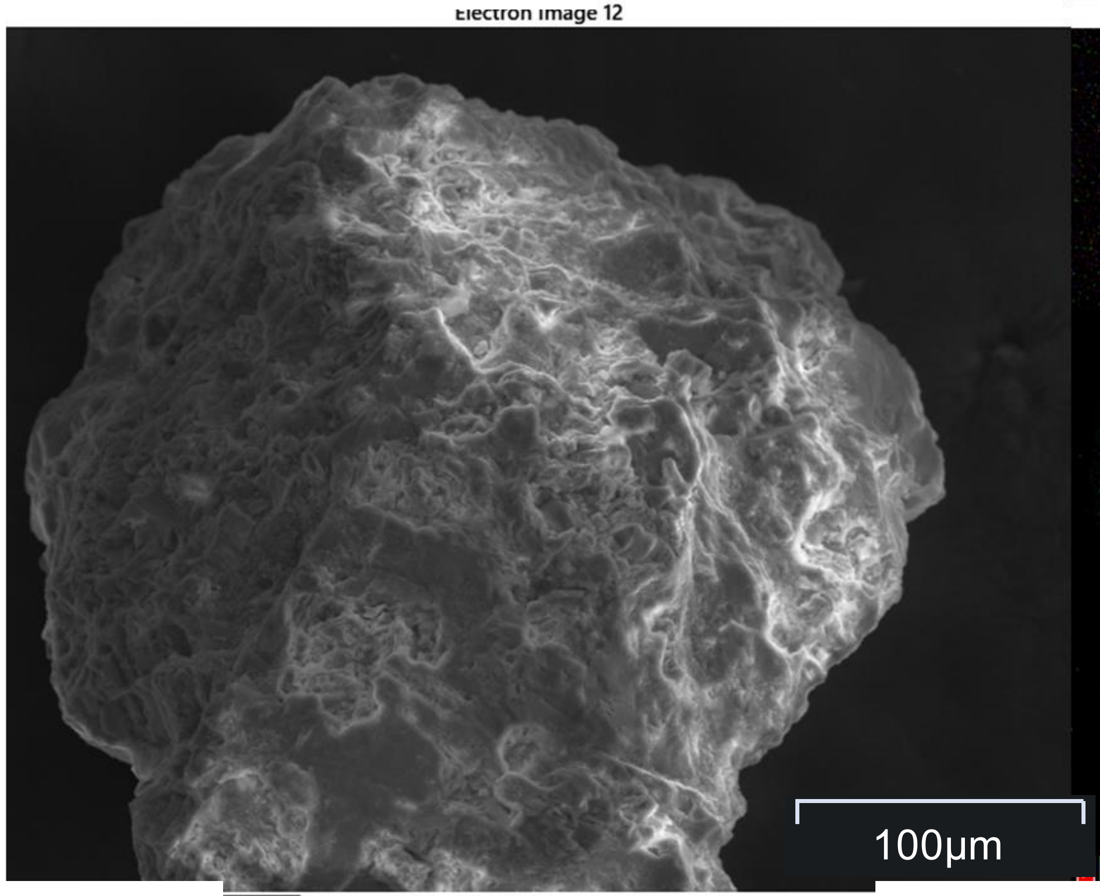
Results: Liquid PO_4 Amendments Post Characterization



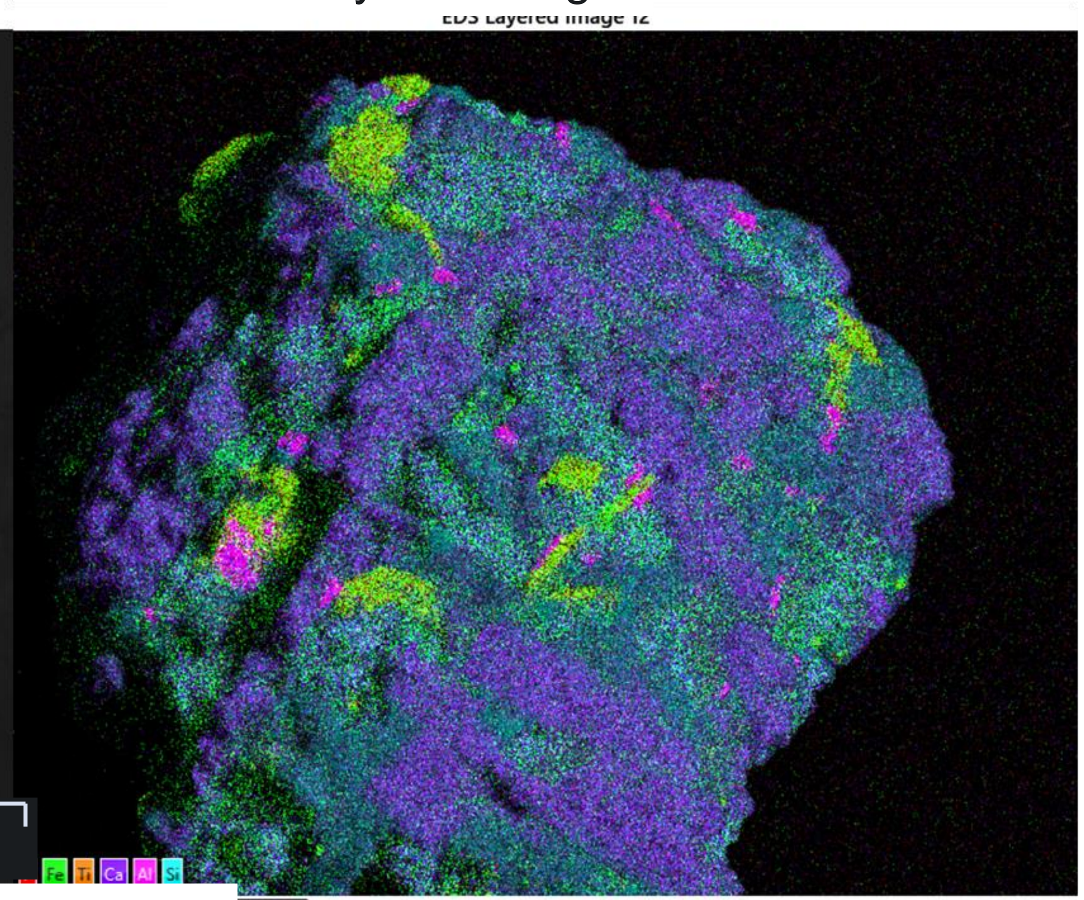
- Significant increase in solid phase phosphorus
- Ca:P ratio moving closer to apatite (1.25), likely significant $CaCO_3$ in sediments

Results: Liquid PO_4 Amendments Post Characterization

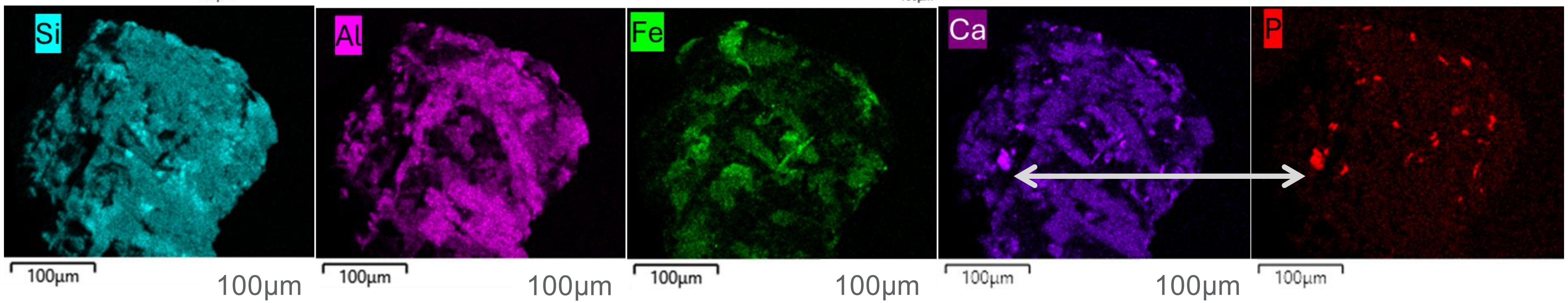
Electron Image



EDS Layered Image



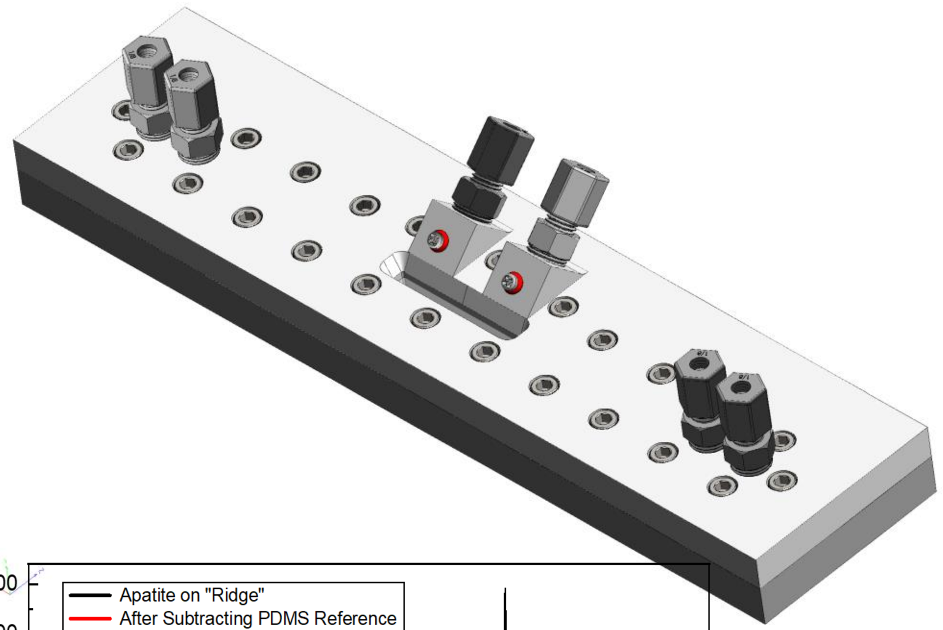
Note: Co-association of Ca and P, potentially $Ca_{10}(PO_4)_6(OH)_2$

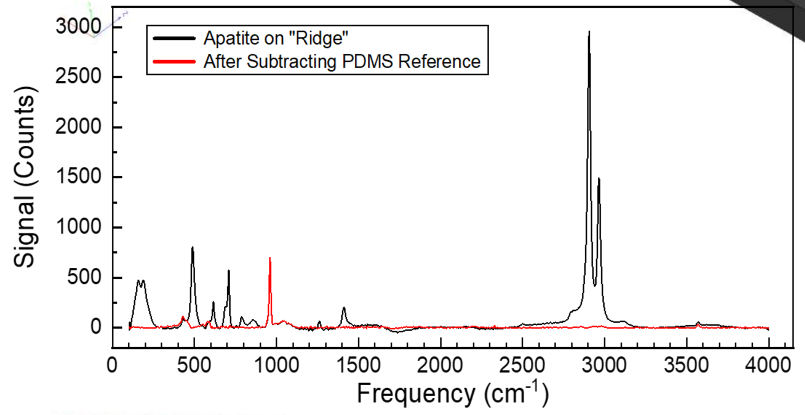


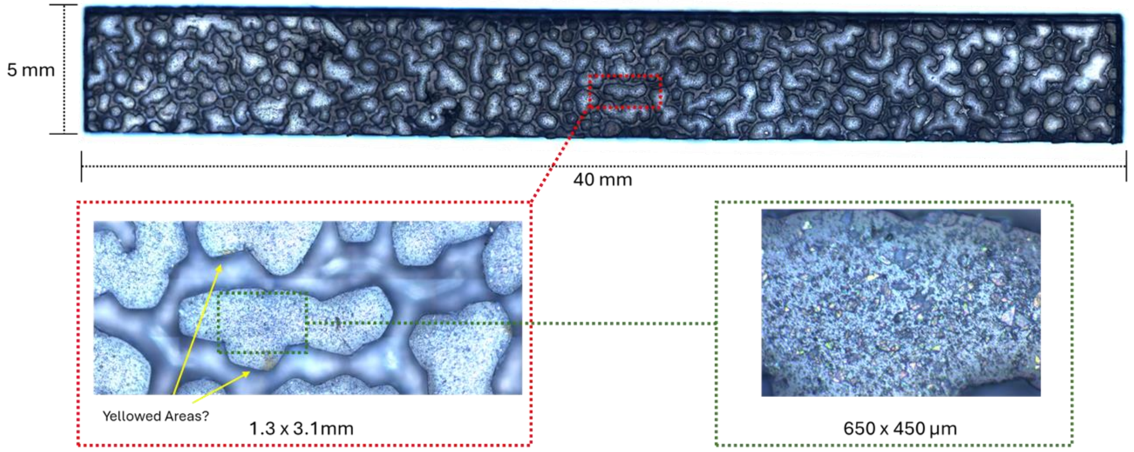
100µm 100µm 100µm 100µm 100µm

Conclusions and Future Work
Liquid PO_4

- Real conductivity, σ′ (similar to ER, delivery indicator)
  - Dominated by changes in fluid conductivity
  - Results show where liquid PO_4 was *delivered*
- Imaginary conductivity, σ″ (apatite formation indicator)
  - ↑ as surface of minerals changed, *independent of solution conductivity*
  - Δ likely due to ion exchange, adsorption, apatite precipitation, and coating
- Results show promise for SIP for monitoring both <u>delivery</u> of solutions and <u>formation</u> of apatite coatings
- Future work: Decrease scale to confirm controlling mechanisms via microfluidics







What Happens with Zero Valent Iron?

High ionic strength injection solution fills pores spaces with ZVI or SMI particles

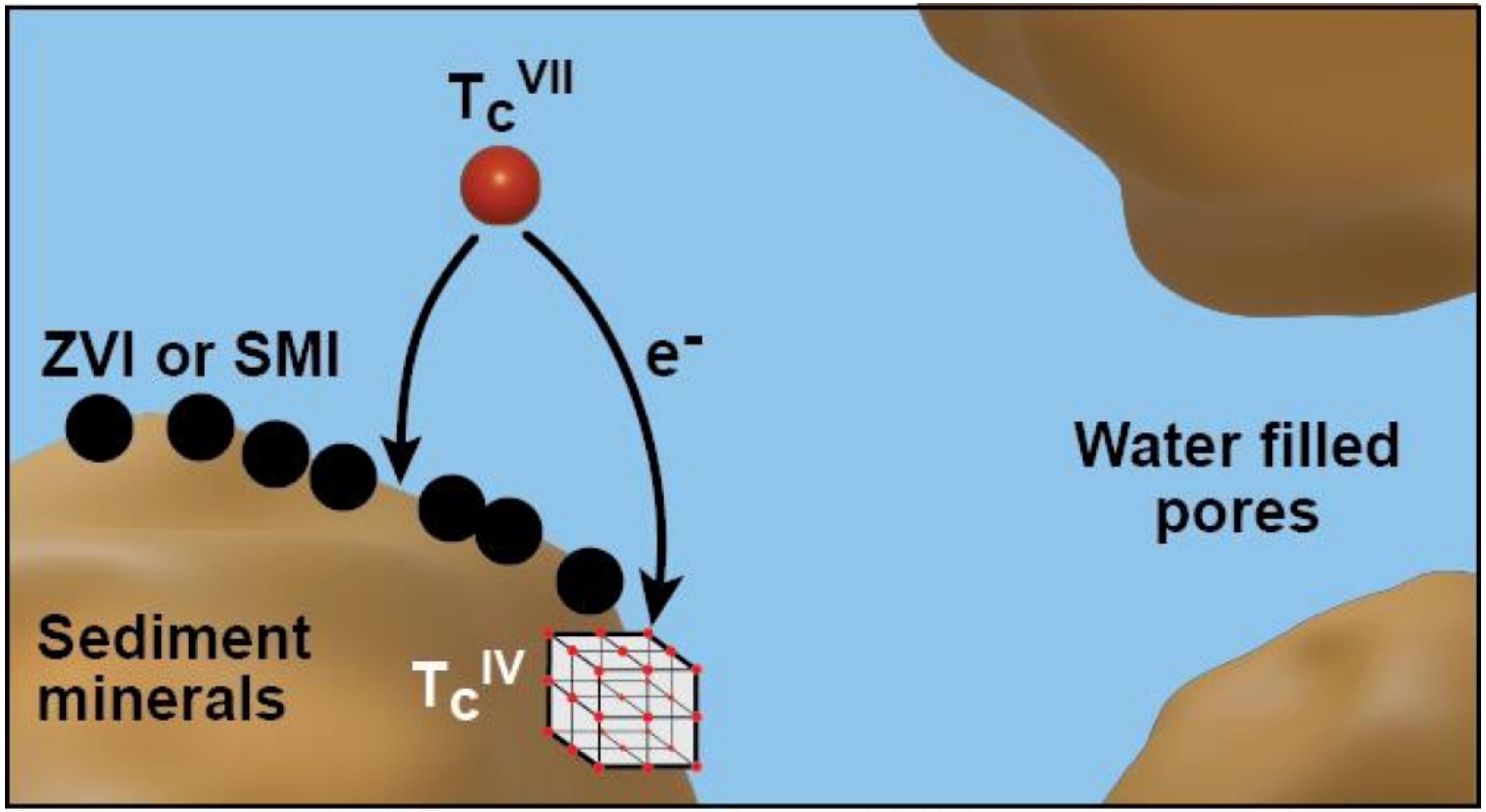
↓

Reducing conditions generated impacting mobility of contaminants

↓

ZVI or SMI corrosion: reduction capacity consumed, iron dissolution, and secondary precipitation

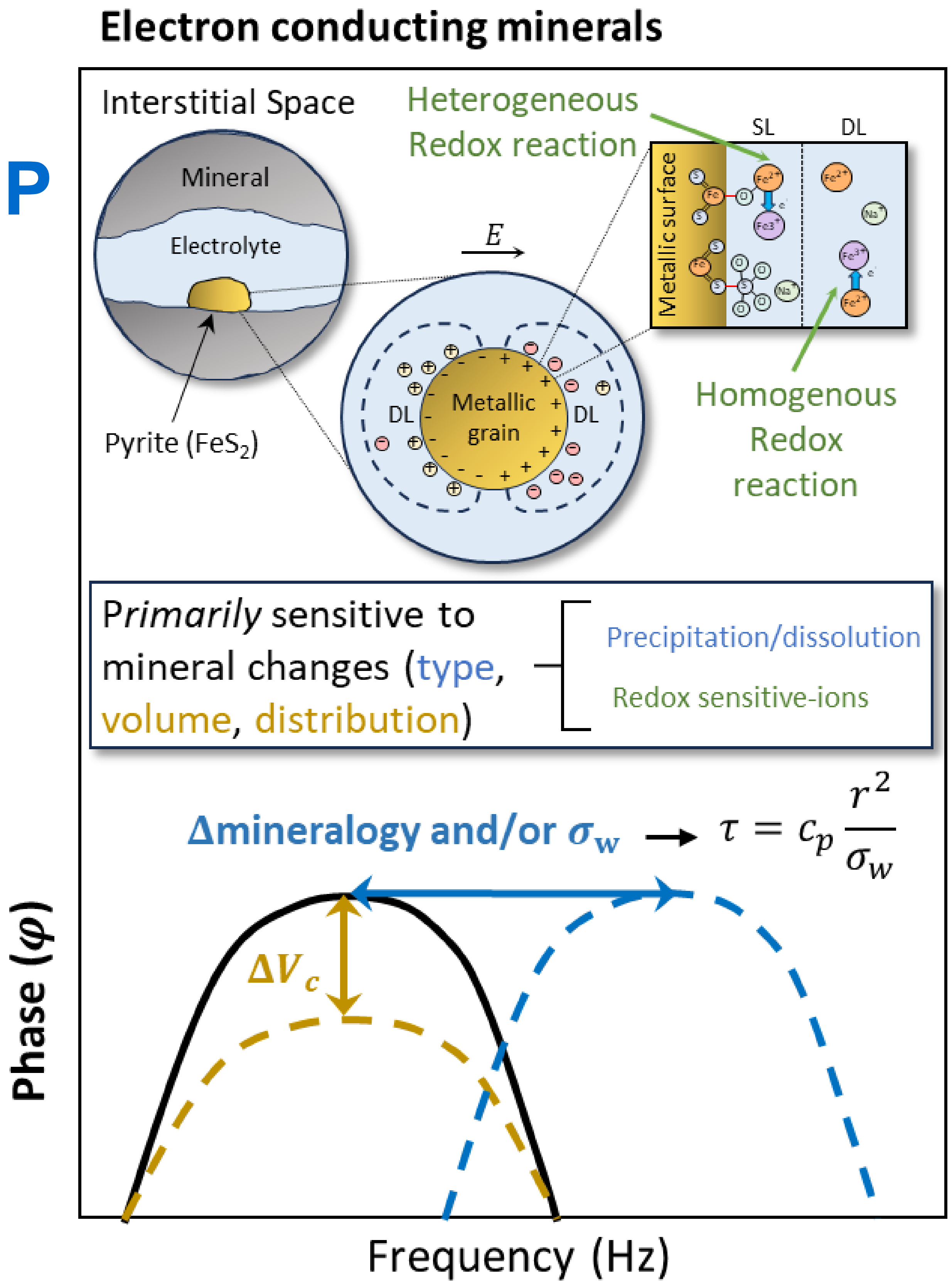
Conceptual diagram of delivery of zero valent iron (ZVI) or sulfur modified iron (SMI) into pore space with subsequent reductive precipitation of contaminants (e.g., TcO_4^-).



Can we predict the point of failure for iron reductants?

Conceptual Model of Iron Amendments for SIP

- Initial injection
  - ↑ σ_w contributes to ↑ σ′ and shift in φ peak
  - ↑ φ coincident with ↑ volume fraction of ZVI or SMI
- Post injection
  - ↓ σ_w back to natural conditions
  - Δφ dependent on volume content of secondary minerals that are polarizable (e.g., magnetite)
  - Shifts in φ peak due to pore blocking or particle size changes

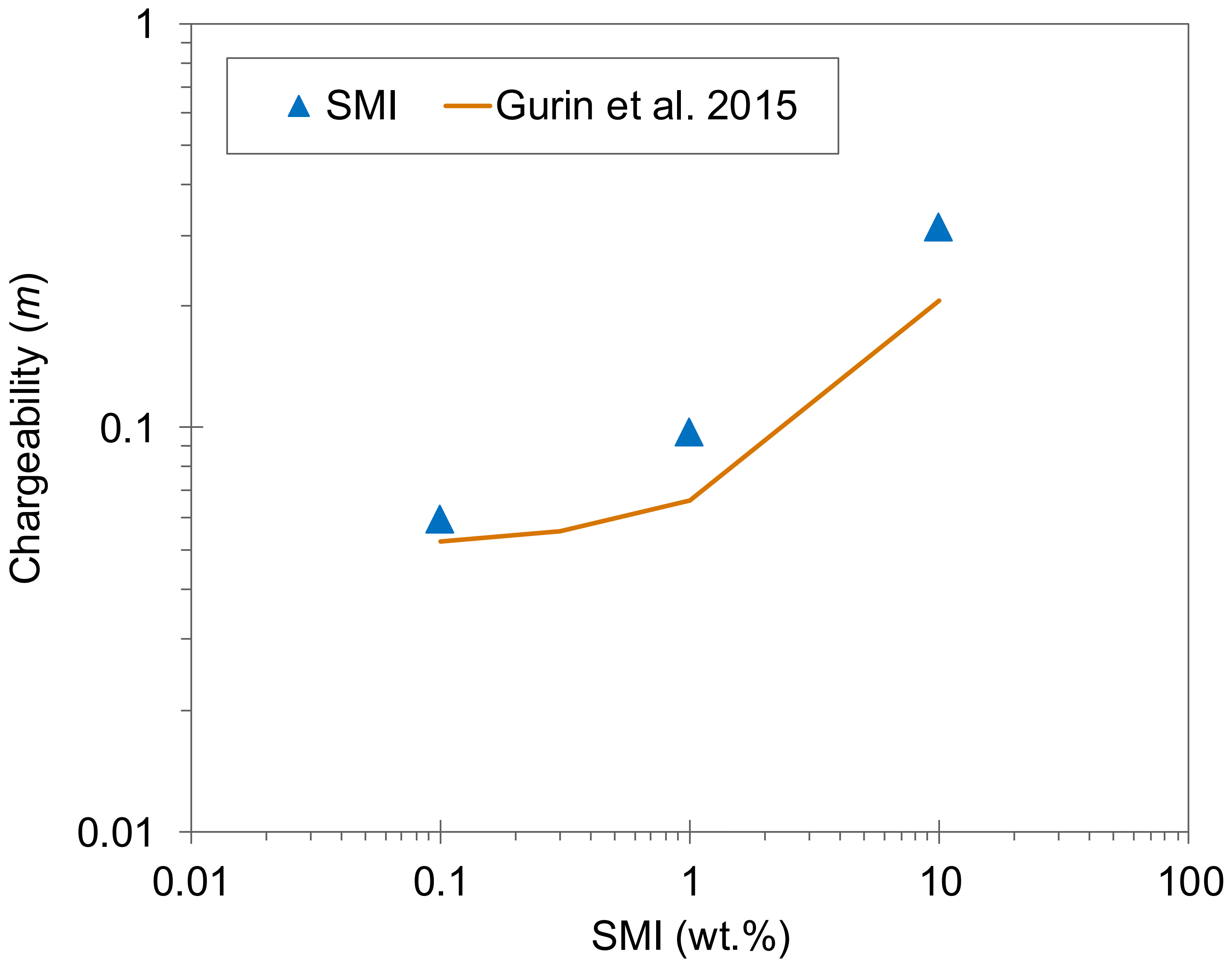


Results: ZVI and SMI Amendments Column Testing

- Volume content strongly correlated with φ and chargeability (*m*)
  - Background sediment polarization corrected based on previous literature

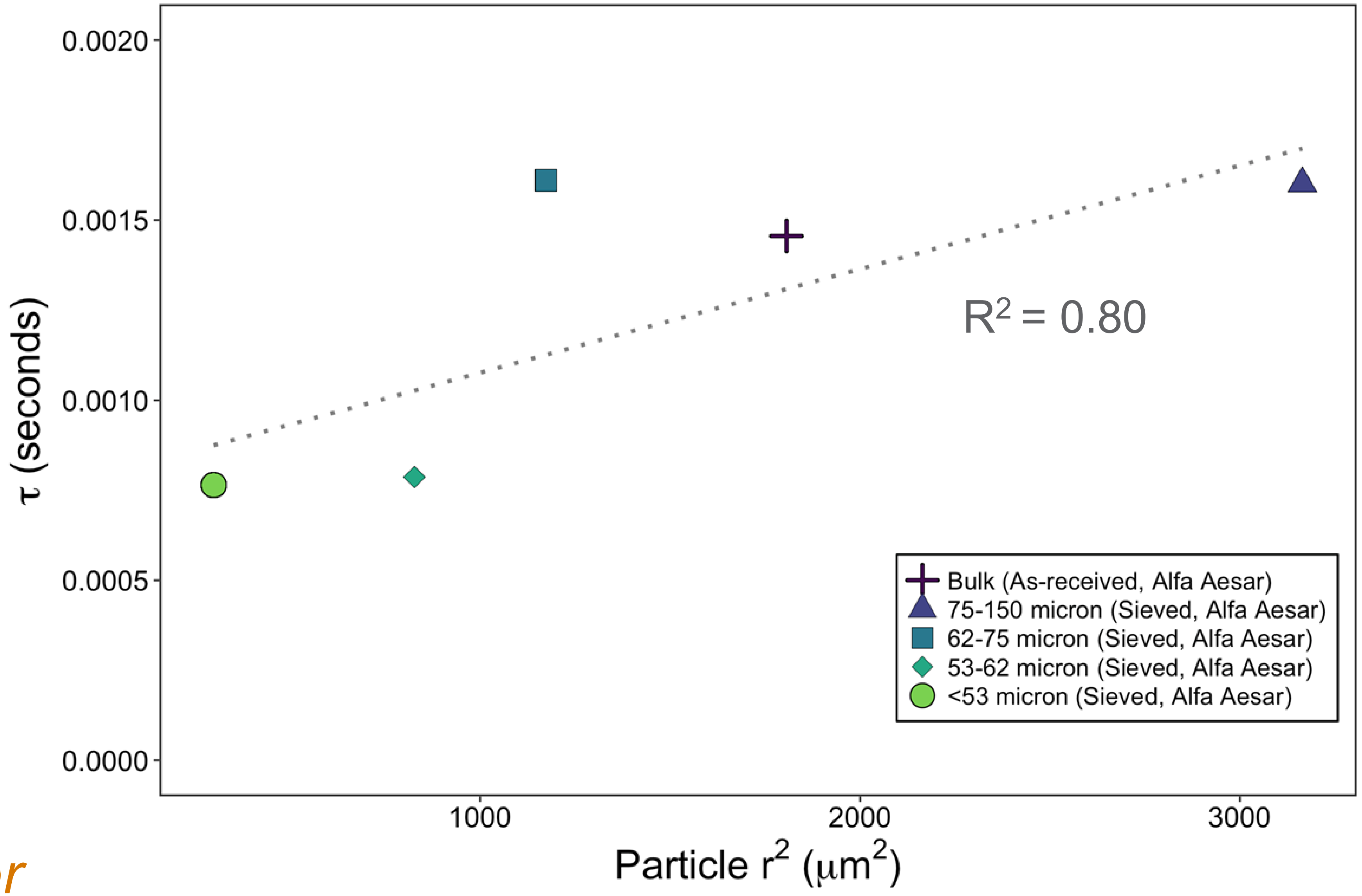
$$m = 1 - (1 - m_b)\frac{2(1-v)^2}{(2+v)(1+2v)}$$

Gurin et al. (2015) Geophys J Int 200
Emerson et al. (2024) J Contam Hydrol 264



Results: ZVI and SMI Amendments Column Testing

- Sieved ZVI materials to isolate different size fractions
- Particle size strongly correlated with τ
  - Consistent with literature
  - Mineral-dependent

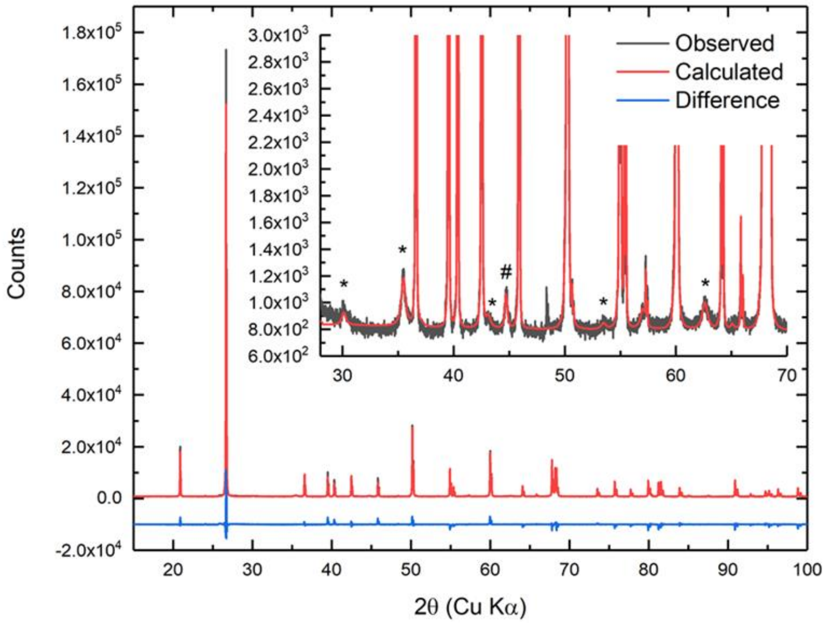


What about changes over time due to corrosion?

Results: ZVI and SMI Amendments Iron Corrosion Testing

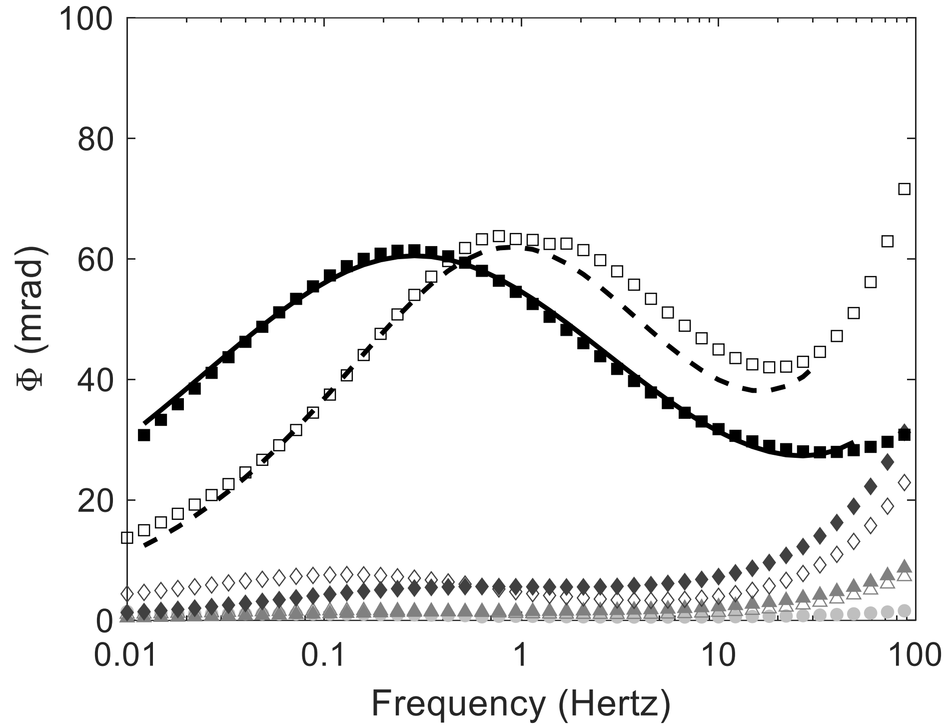
SMI corrosion in silica sand

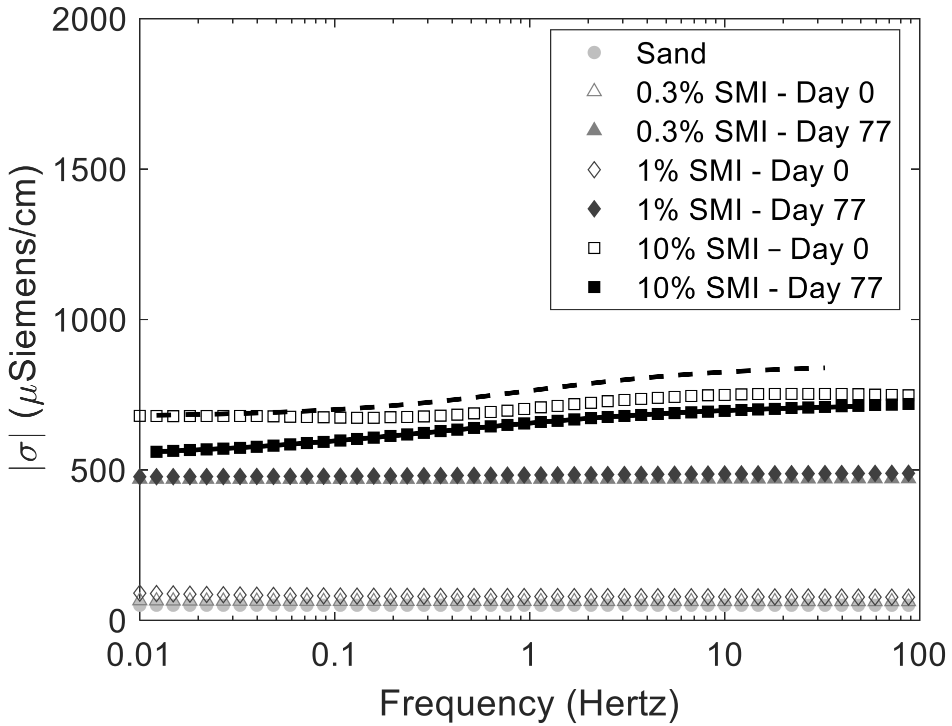
- Significant shifts in τ over time, unclear which mechanisms are controlling response
  - Δ in particle size (via BET)
  - Δ in mineralogy (via XRD)
- No change in the magnitude of φ
  - No *significant* Δ in volume content



Emerson et al. (2024) J Contam Hydrol 264

* magnetite
# zero valent iron

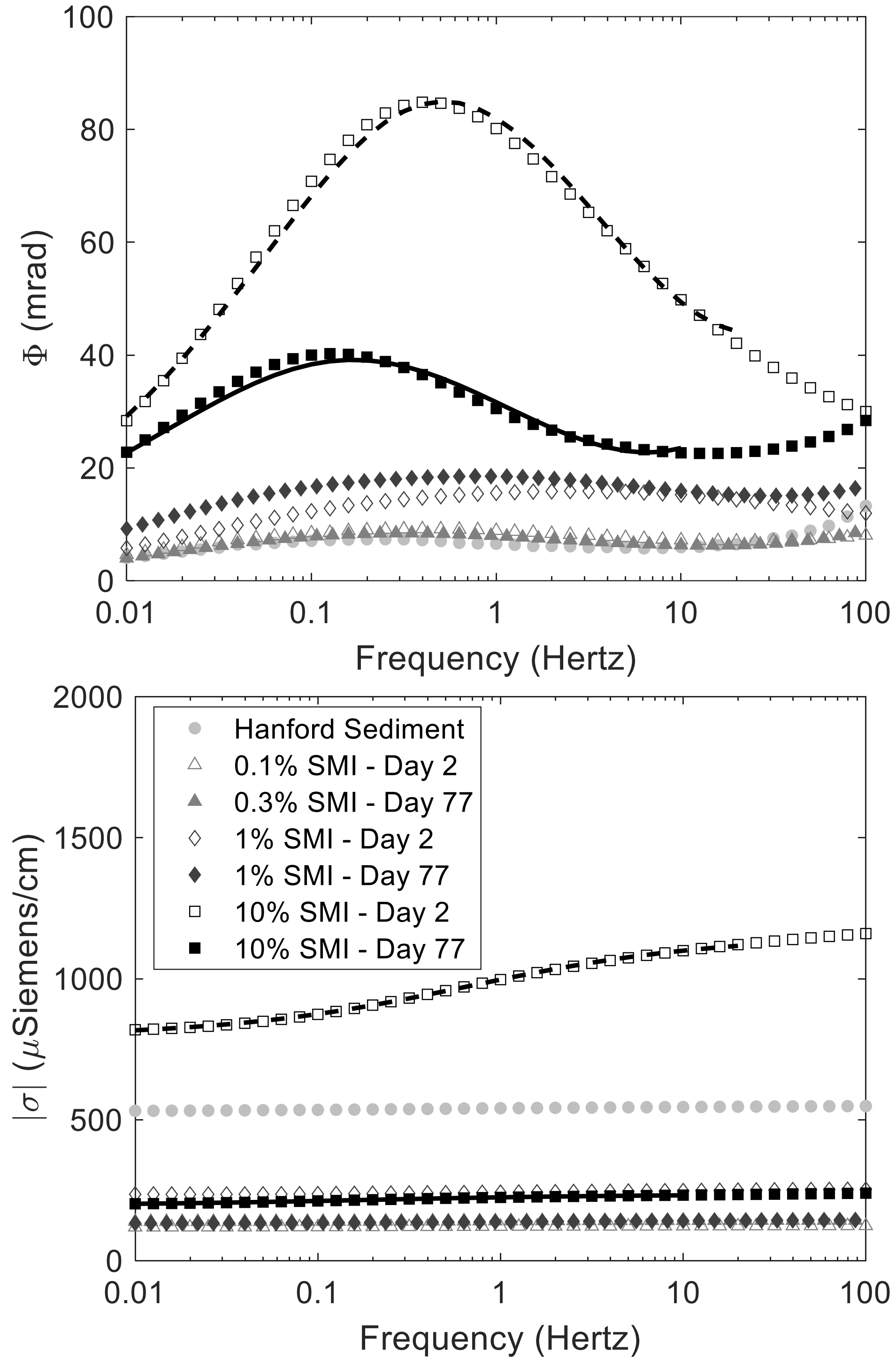




Results: ZVI and SMI Amendments Iron Corrosion Testing

SMI corrosion in Hanford formation sediments

- Significant shifts in τ over time
  - Δ in particle size (via BET)
  - Δ in solution conductivity ($Fe^{+2/+3}$ dissolution)
- Significant shift in the magnitude of φ
- What are the primary mechanisms impacting polarization magnitude and frequency?



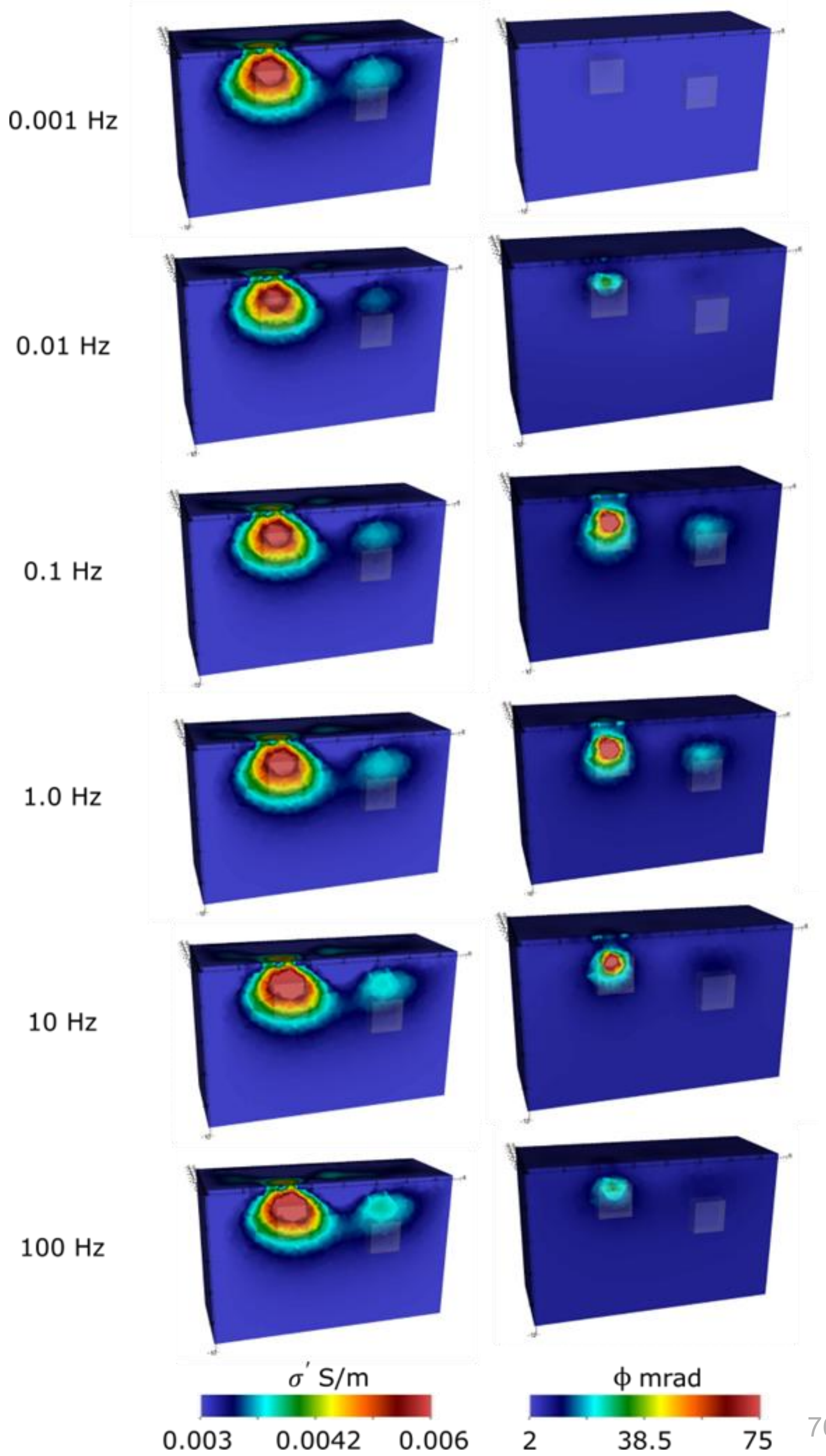
*Contribution from Δ in mineralogy inconclusive (not detected via XRD but redox condition changed over time, potentially moving to Fe^{+3} oxides)

Emerson et al. (2024) J Contam Hydrol 264

Conclusions and Future Work
Iron Amendments

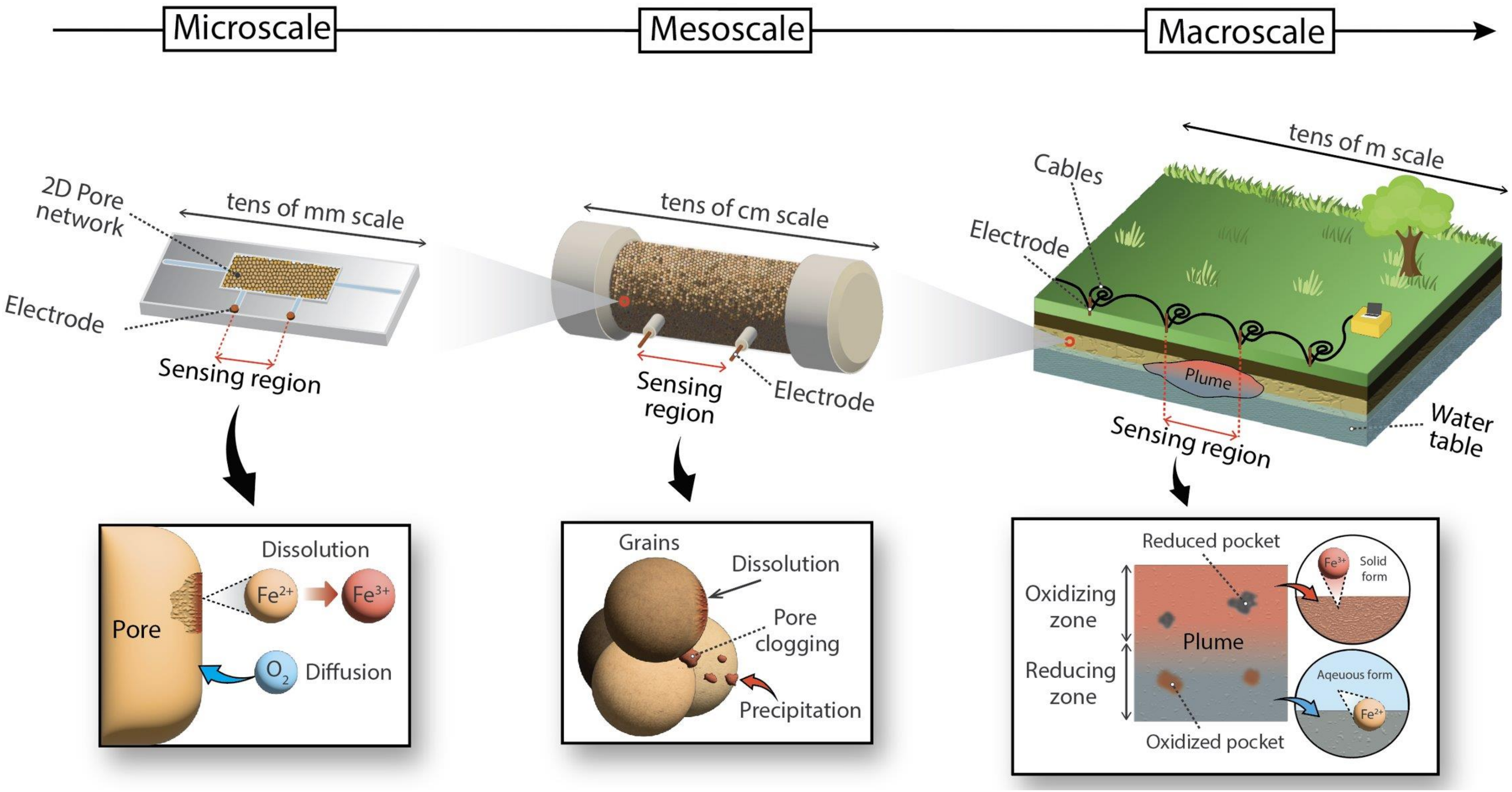
- Real conductivity, σ'
  - Dominated by changes in fluid conductivity
  - Results show where ZVI was *delivered*
- Phase, φ
  - ↑ with volume content
  - Shifts in τ due to Δ in σ_w and particle size
- Results show promise for SIP for monitoring both <u>delivery</u> of solutions and <u>formation</u> of apatite coatings

Future work: Improve real-time characterization to identify controlling mechanisms during corrosion



E4D inversion for SMI using two blocks model

Conclusions



Potential to monitor amendment delivery and transformation with SIP via φ, σ″, and τ depending on material and alteration

Environmental Significance

Promising technology for monitoring source zones during remediation – including potential to confirm injection solution delivery and amendment precipitation

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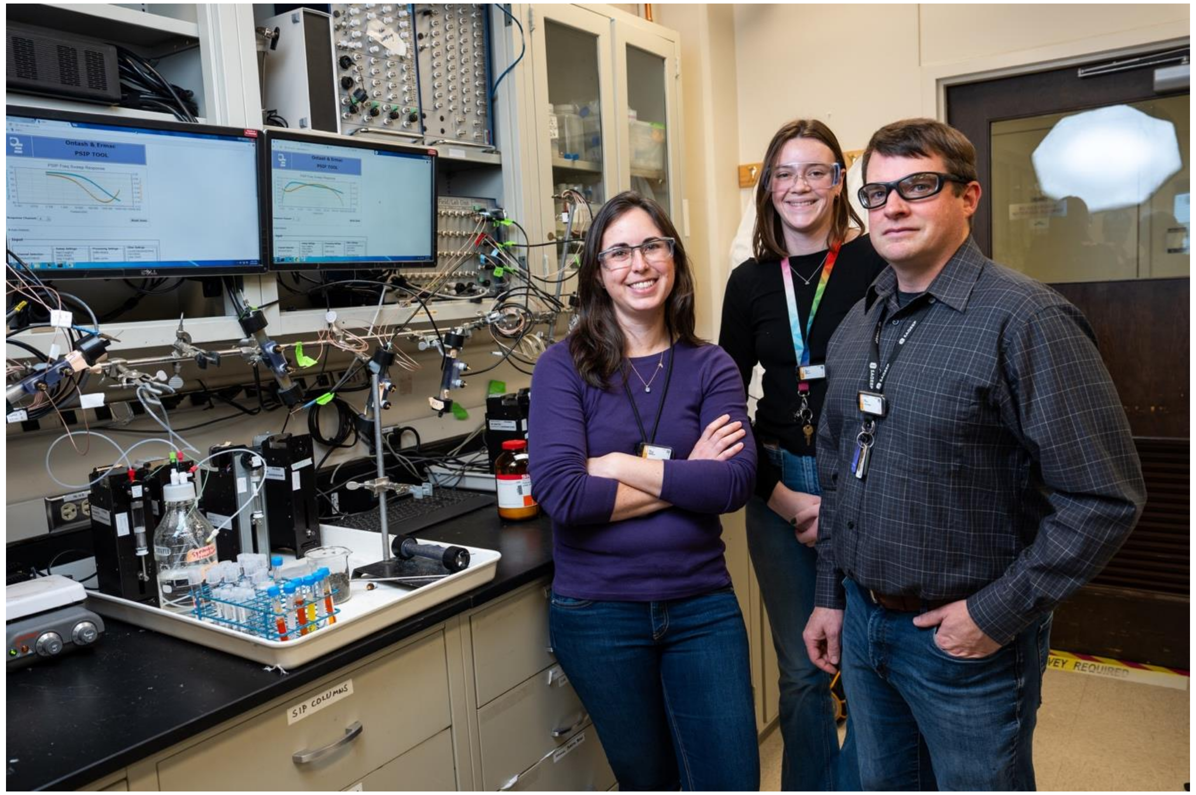

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Thank you

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