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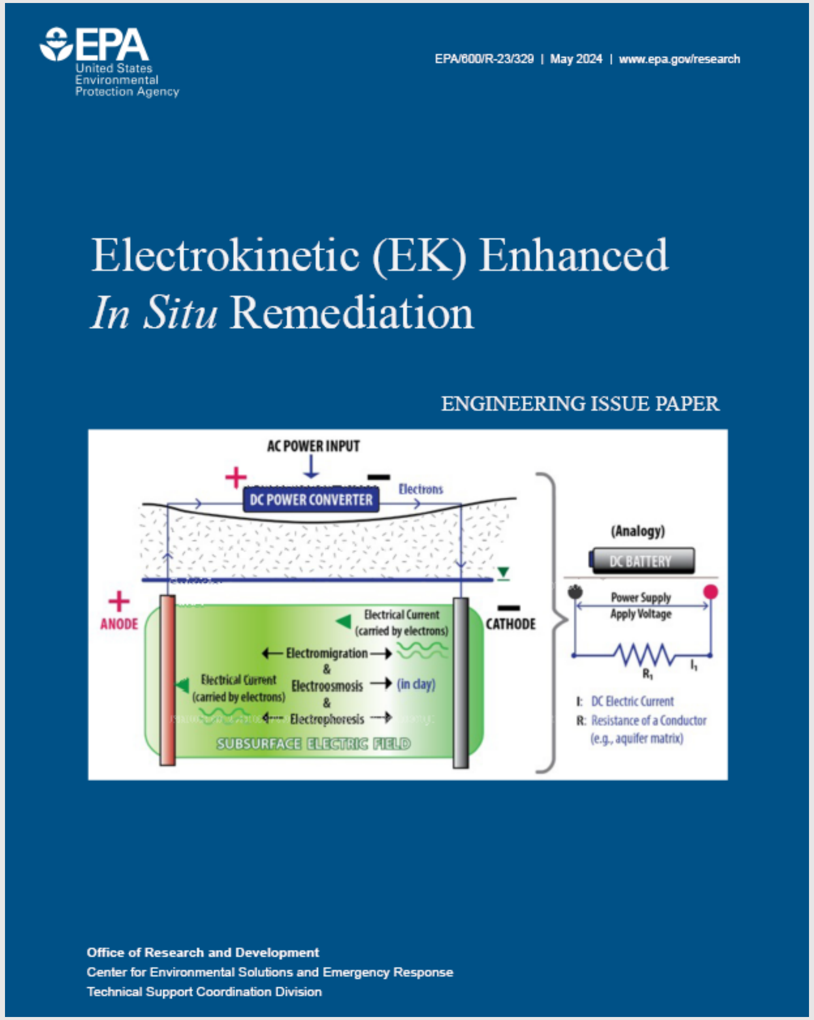
Technology Development from Concept to Field Implementation
EK Enhanced Amendment Delivery for In Situ Remediation
in Low-Permeability Materials



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June 2024

Outline

- Challenges & Motivation
- EK Fundamentals for *In Situ* Remediation Applications
- USEPA Engineering Issue Paper
- Example Cases – EK-BIO and EK-ISCO [Bench, Pilot, Full-Scale]
- Take Away Messages

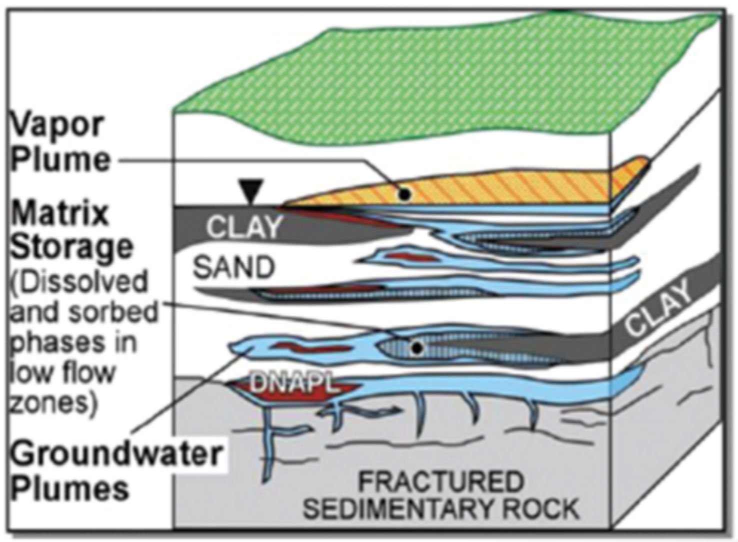
Challenges and Motivation

Contaminants diffused into low permeability (low-k) materials serve as secondary sources (back diffusion) lasting for decades

EISB and ISCO / ISCR are effective technologies, but amendment distribution is poor in low-k and heterogeneous materials

Delivery & **Contact**

Better & fundamentally improved amendment delivery techniques are required for low-k sites



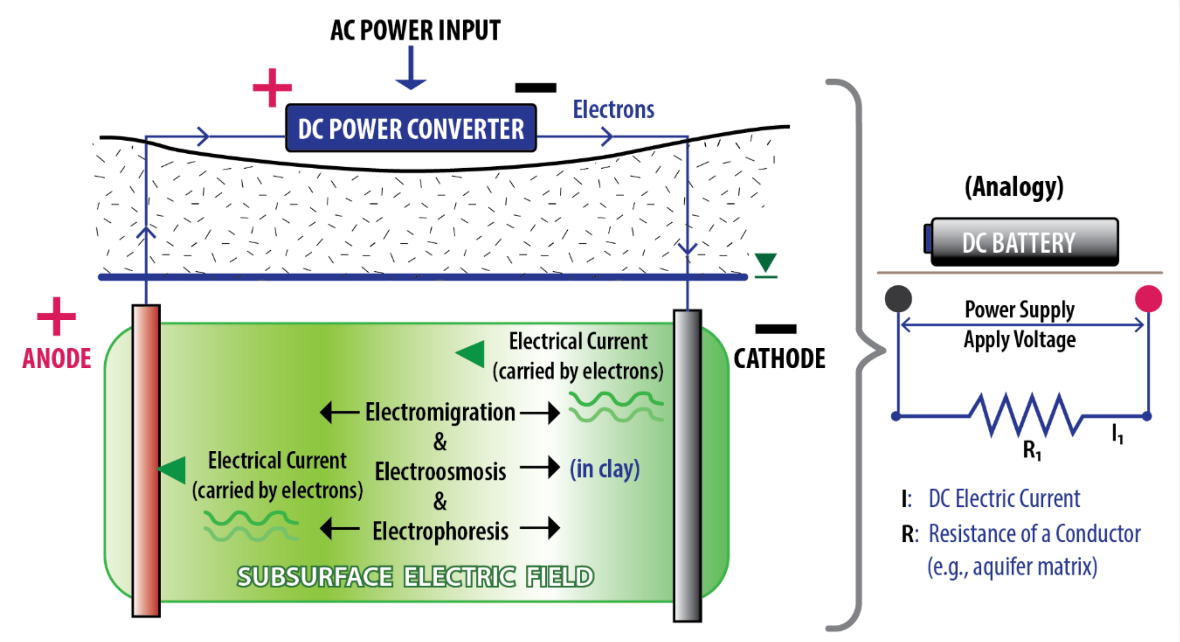
From ESTCP, ER-200530

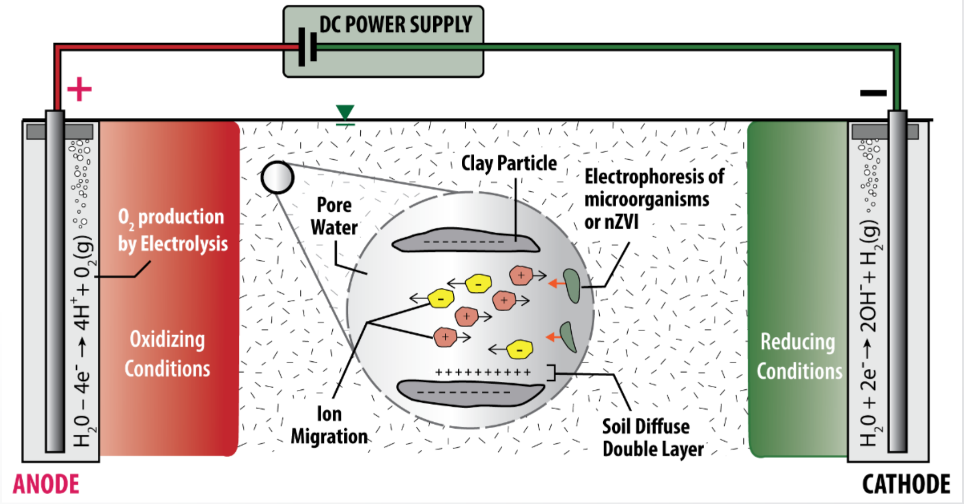
Electrokinetic (EK) Fundamentals

- Application of direct current (***DC***) to saturated formation to create a subsurface electric field

- "Powered" by the electric field, select amendments move through clays and silts via:

  - **Electro-migration (EM)** – movement of charged ions
  - **Electro-osmosis (EO)** – bulk movement of water
  - Electrophoresis (EP) – the movement of charged solid particles (e.g., colloids)





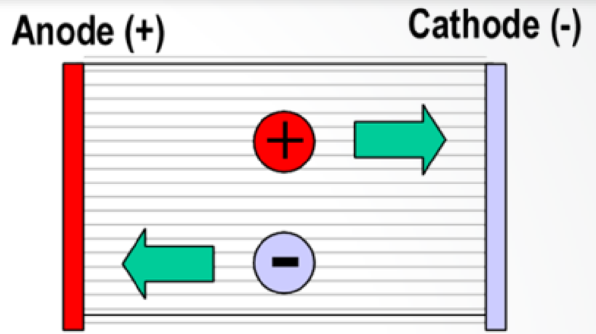
USEPA EIP (2024)

Electrokinetic (EK) for Amendment Transport

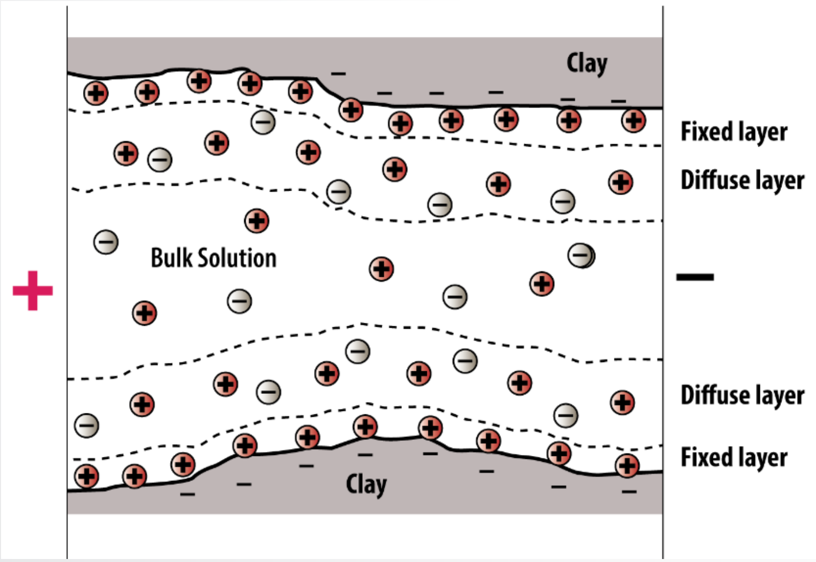
- **Electromigration** is the movement of ions in an electric field. Ions are attracted to the electrode of opposite polarity/

Voltage Gradient

$$J_i = -D_i^* \frac{\partial c_i}{\partial x} - u_i^* c_i \frac{\partial \phi}{\partial x} + qc_i$$



Anions: negatively charged ions
Cations: positively charged ions
Anode: Positively charged electrode
Cathode: Negatively charged electrode

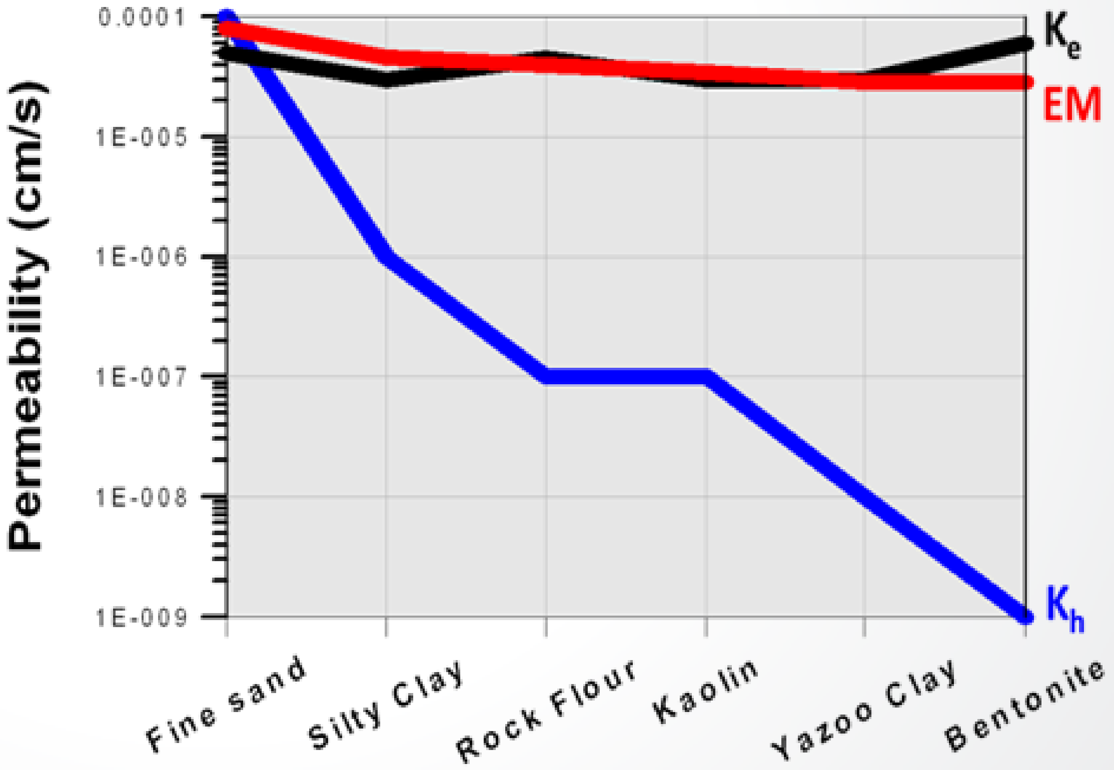


- **Electroosmosis** is the movement of pore fluid and, thus, dissolved constituents induced by a voltage gradient.

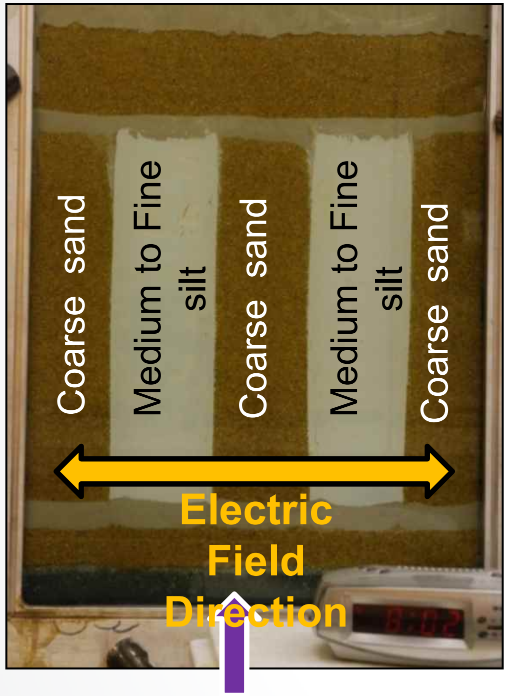
EK Transport is Fundamentally Different

Why will EK work in low-k formations where conventional hydraulic injection techniques often face challenges?

- EK transport relies on electrical properties of aquifer matrix (not hydraulic)
- Soil electrical properties ≈ between sand and clay
- As K_h decreases, EK becomes the more efficient delivery method



Effective Amendment Delivery by EK in Low-k



T = 6 hr (MnO_4^- flushing; No EK)

T = 12 hr (MnO_4^- flushing; No EK)

T = 6 hr w/ 2-hr EK (MnO_4^- flushing with EK)

T = 12 hr w/ 8-hr EK (MnO_4^- flushing with EK)

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EK Applications for *In Situ* Remediation

- Remember – **EK is** a remediation reagent **delivery** technology

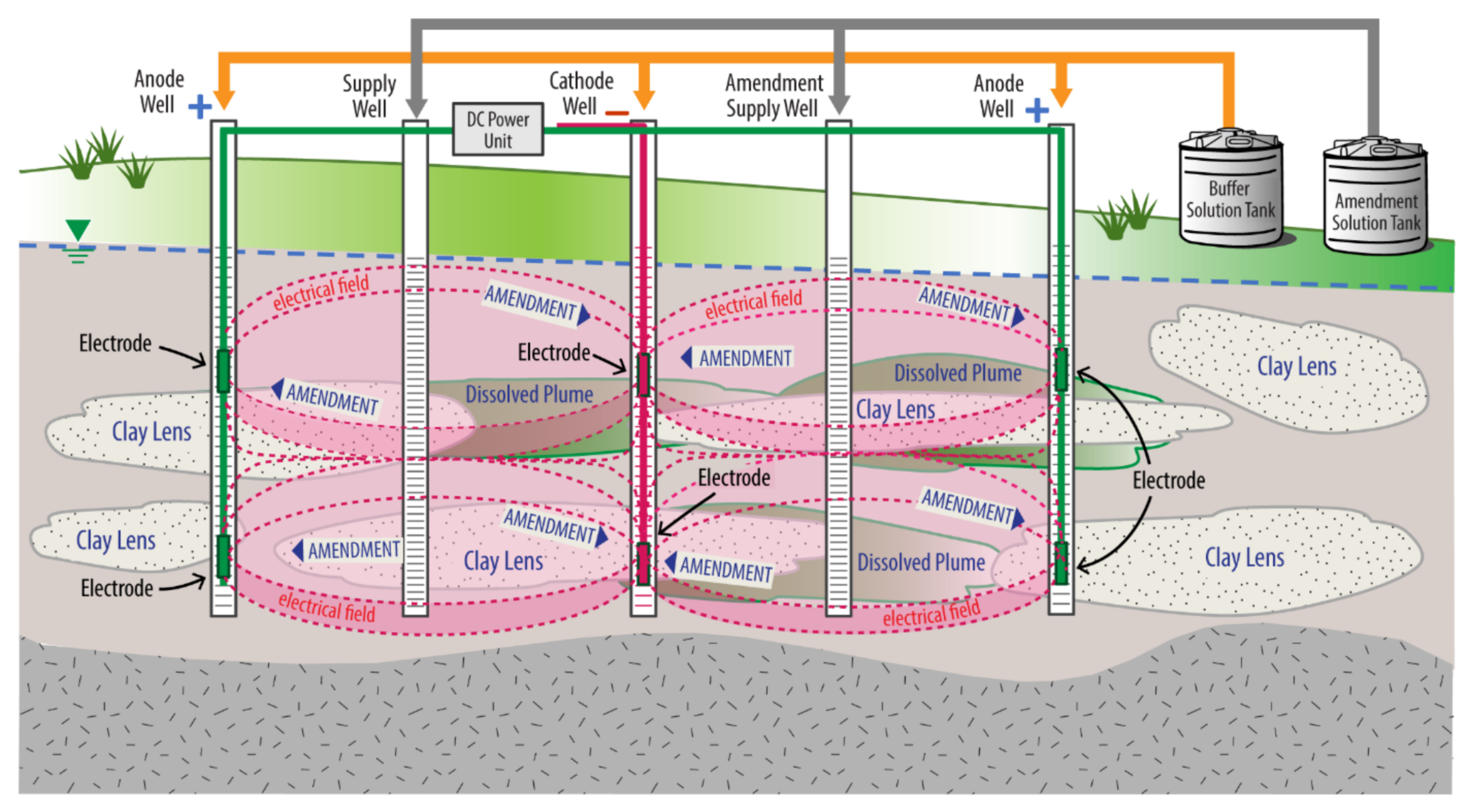
- <u>For *In Situ* Bioremediation</u>

- **EK-BIO** : Distribution of electron donors (lactate) or electron acceptors (sulfate, nitrate) and/or microorganisms (*Dehalococcoides, Dehalobacter*) to promote biodegradation

- <u>For *In Situ* Chemical Oxidation Remediation</u>

- **EK-ISCO** : Distribution of permanganate (MnO_4^-) or persulfate ($S_2O_8^{2-}$) to promote oxidation

Implement EK-enhanced *In Situ* Remediation



USEPA ORD Engineering Issue Paper

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Available in Summer 2024

EIP Structure –

- Technology fundamentals;
- Stepwise process of evaluating, developing, and ultimately implementing the EK technology;

  Screening/evaluation generally follows the CERCLA FS and RD framework

Criteria	EK-enhanced Remediation and Project-Specific Considerations
THRESHOLD CRITERIA	
BALANCING CRITERIA	
Long-Term	This criterion considers the ability of an alternative to maintain protection of human health and the environment over time.
MODIFYING CRITERIA	
State Acceptance	Acceptance will be based on regulatory stakeholder review of the proposed plan during the required community involvement period

- Provides select case studies

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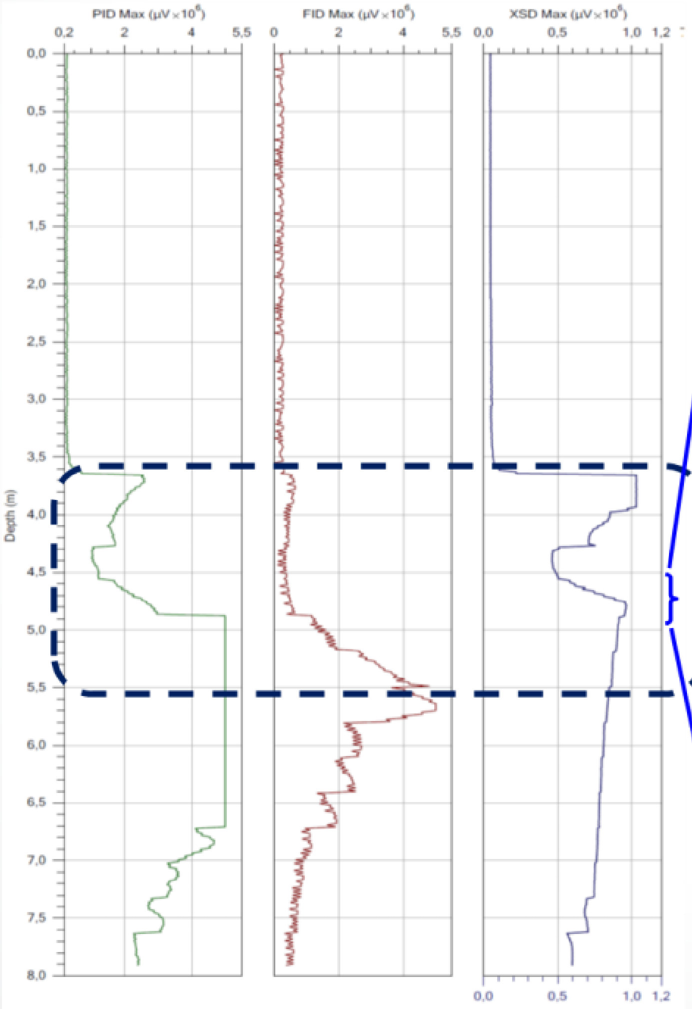
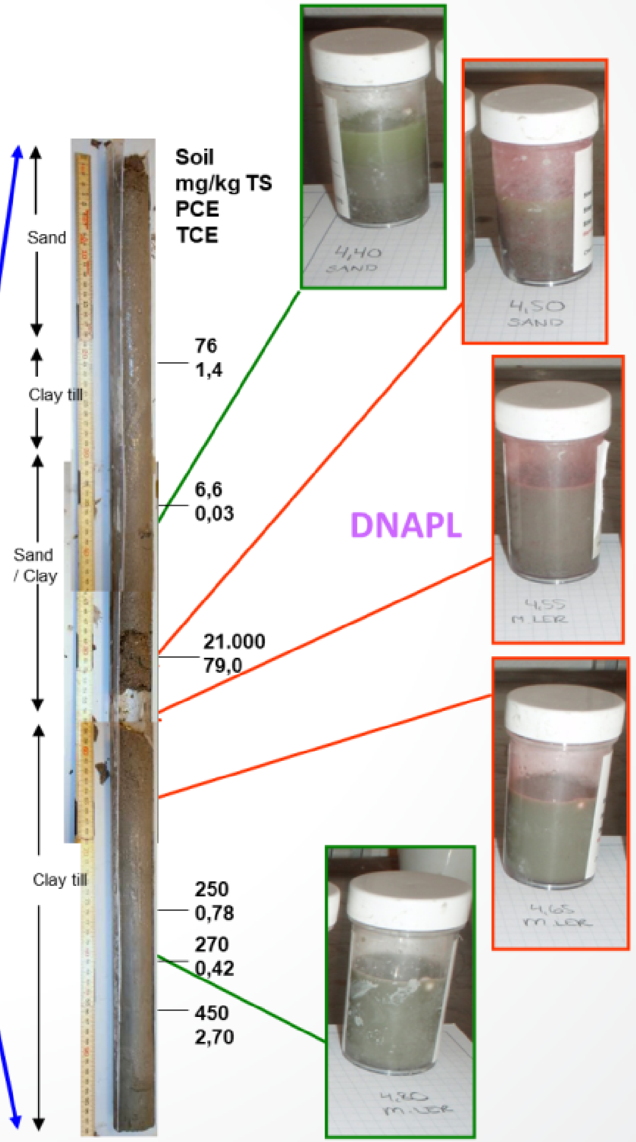
EK-BIO From Bench to Full-Scale, Skuldelev, DK





Targeting PCE DNAPL in Clay Till

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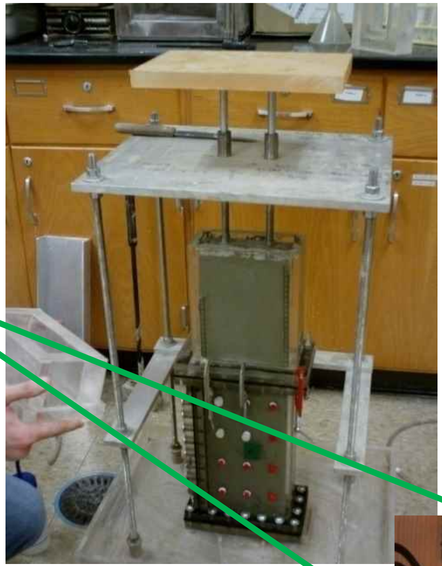
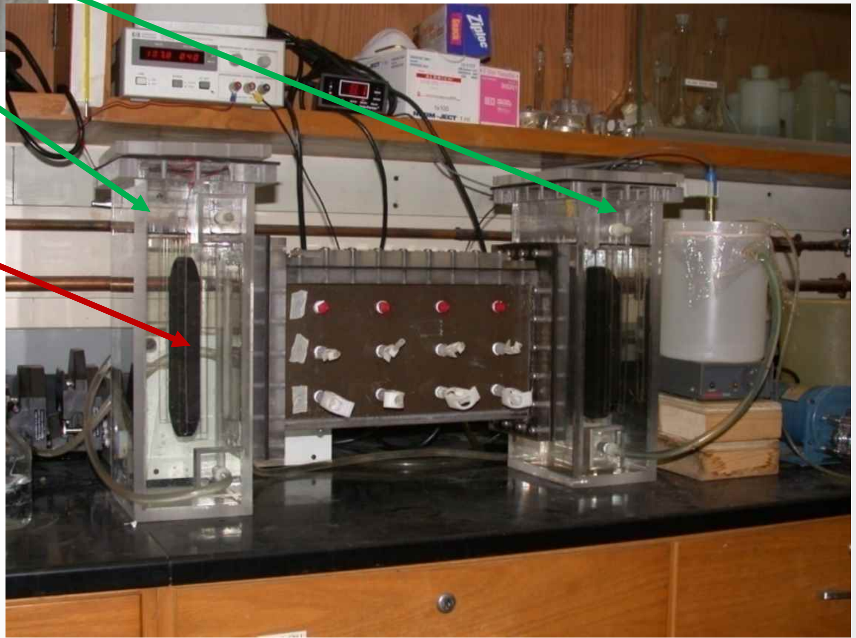
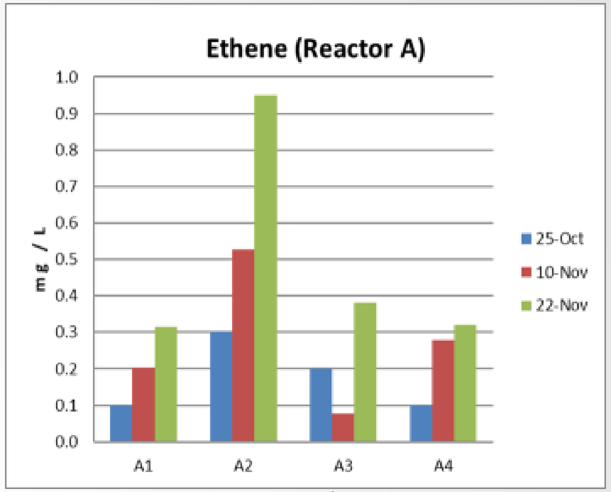
EK-BIO Bench-Scale Treatability Test

- **Bench Scale EK Reactor (40 cm x 15 cm x 5 cm test cell)**
- **Two 5-Liter electrode chambers: with cross-circulation & gas vent**
- **Electrodes : graphite plates**
- **DC power supply and control**
- **Interior pore-water sampling ports to track the transport progress**





Complete dechlorination to ethene



Interior Sampling Ports

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Flexible Electrific Field Orientations

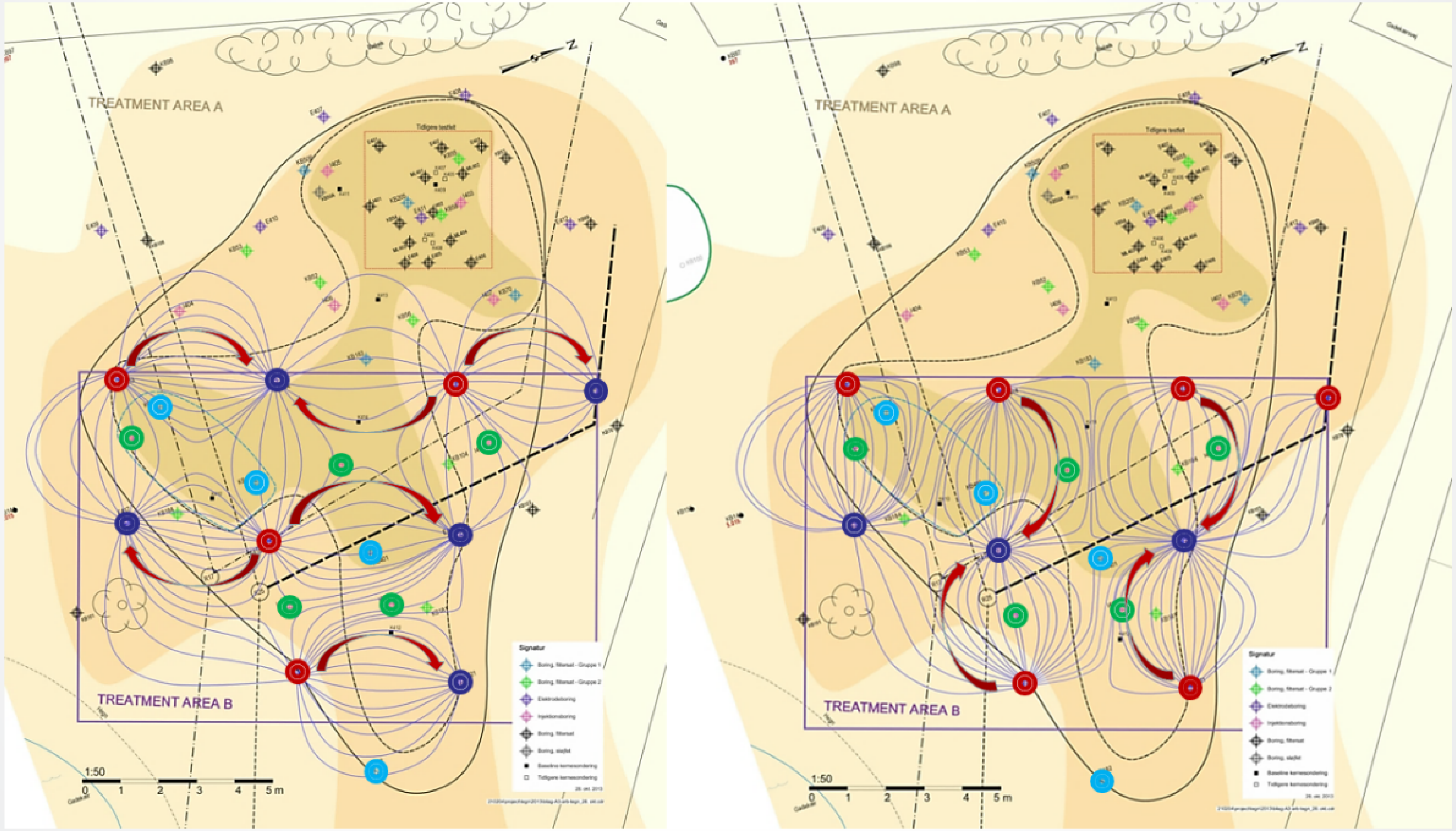
Anodes (+)

Cathodes (-)

Injection wells

Monitoring wells

Electromigra-tion: Donor transport



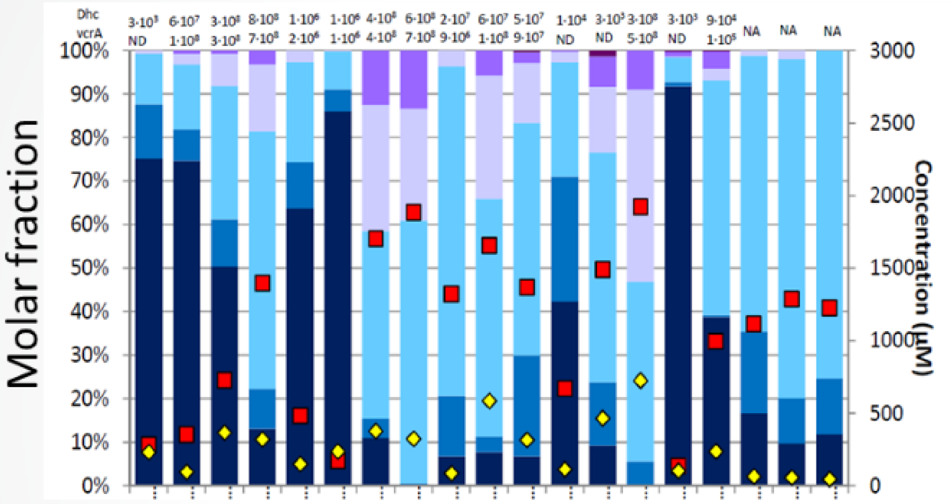
(More details in Riis, C. et al., Groundwater Monitoring & Remediation, 2023)

Full-Scale EK-BIO : PCE Reductive Dechlorination to Ethene in Glacial Clay

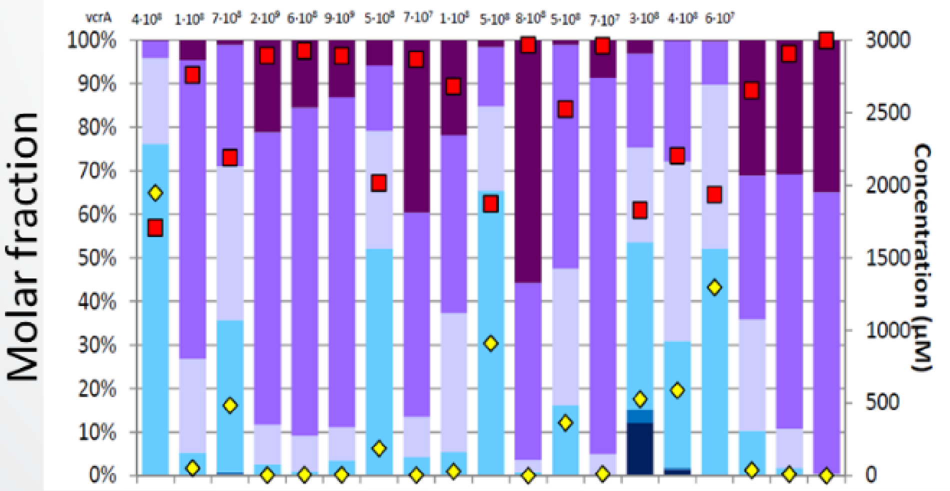
GW Quality "Signature"

- PCE
- TCE
- cis-DCE
- VC
- Ethene

BASELINE



YEAR 2



Biodegraded 285 kg of PCE in the treatment zone (>98% of the estimated pre-remedy total).

Rebound testing 6 months after cessation of EK-BIO operation confirmed sustained microbial dechlorination activities (degree of dechlorination increased) and compliance with the remedial goals.

Capital Region of Denmark: No Furth Action for Source Remediation → GW MNA

(More details in Riis, C. et al., Groundwater Monitoring & Remediation, 2023)

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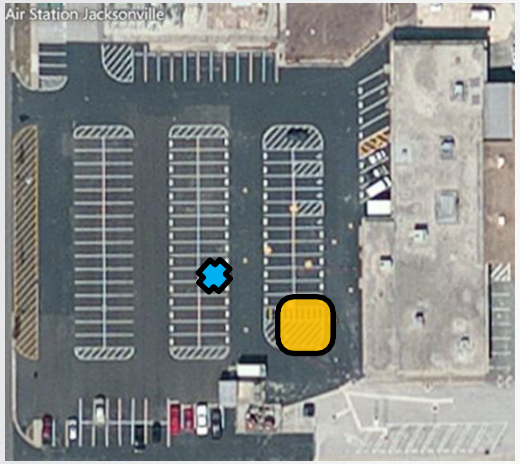
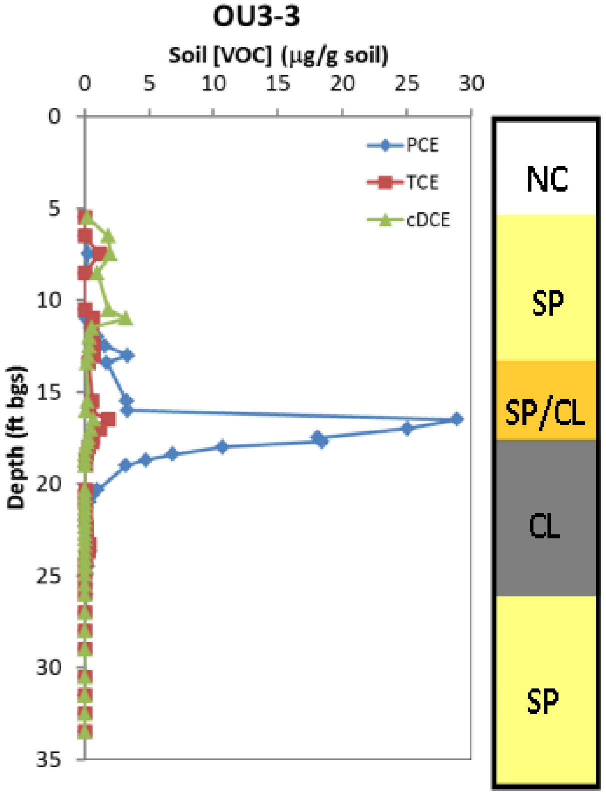
EK-BIO Field Demonstration at Naval Air Station Jacksonville, Florida



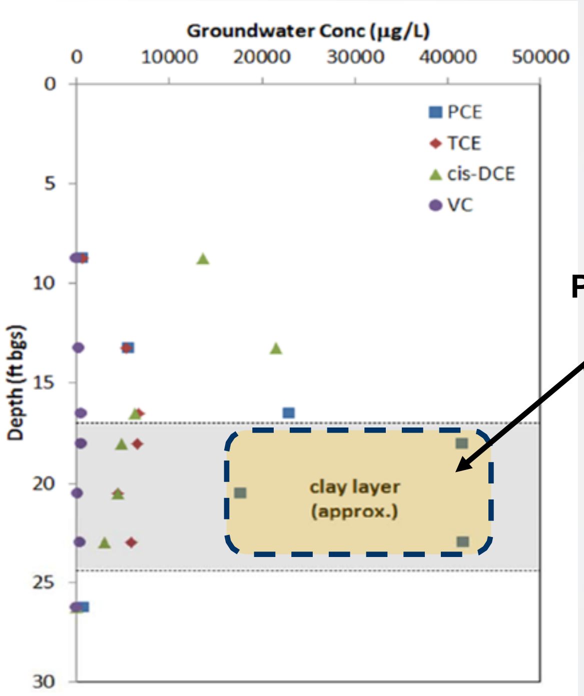
- Former dry cleaner
- Source for a large dissolved plume
- Source area now under an active parking lot
- Many existing subsurface utilities

Classic example of contaminant mass diffused into low-K materials.

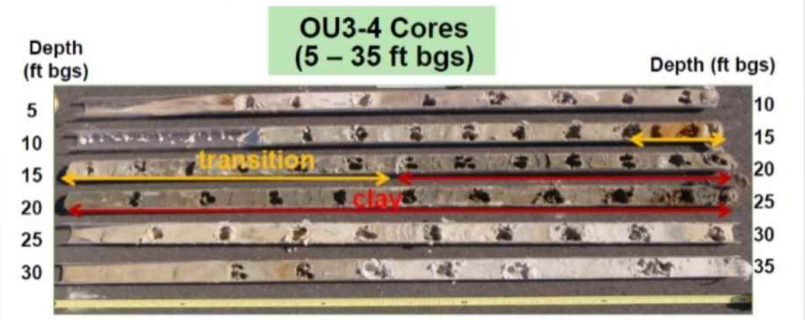
Long-term source for the shallow sand aquifer plume



NC – not characterized; SP – sand; CL – clay



PCE at 15 – 40 mg/L in clay (long term source)



ESTCP ER-201325

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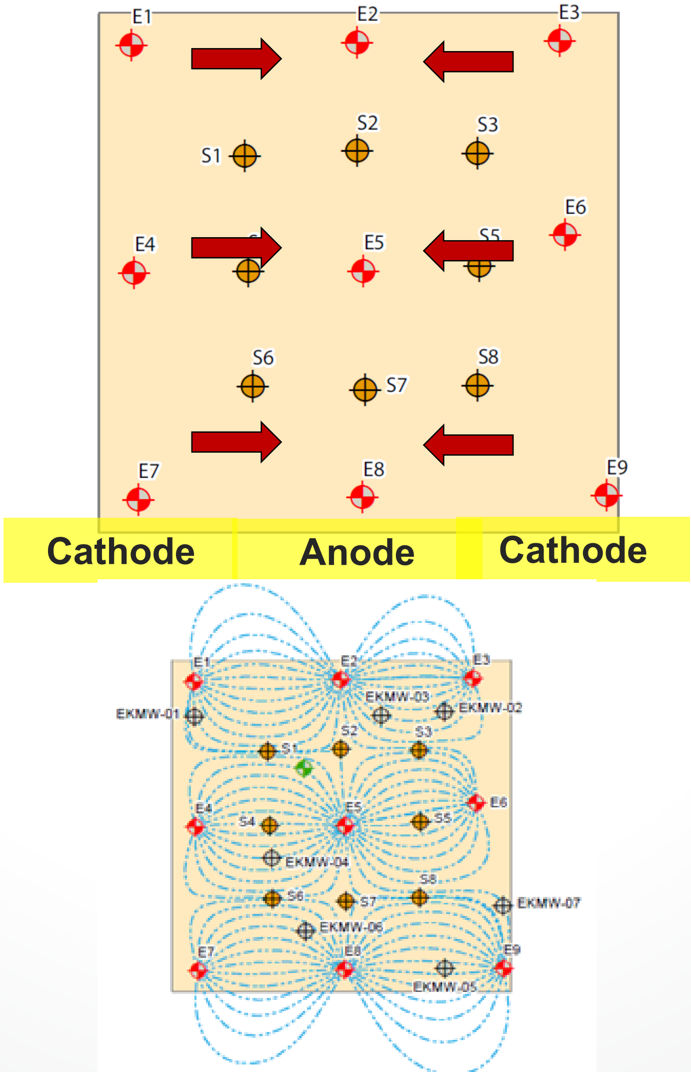
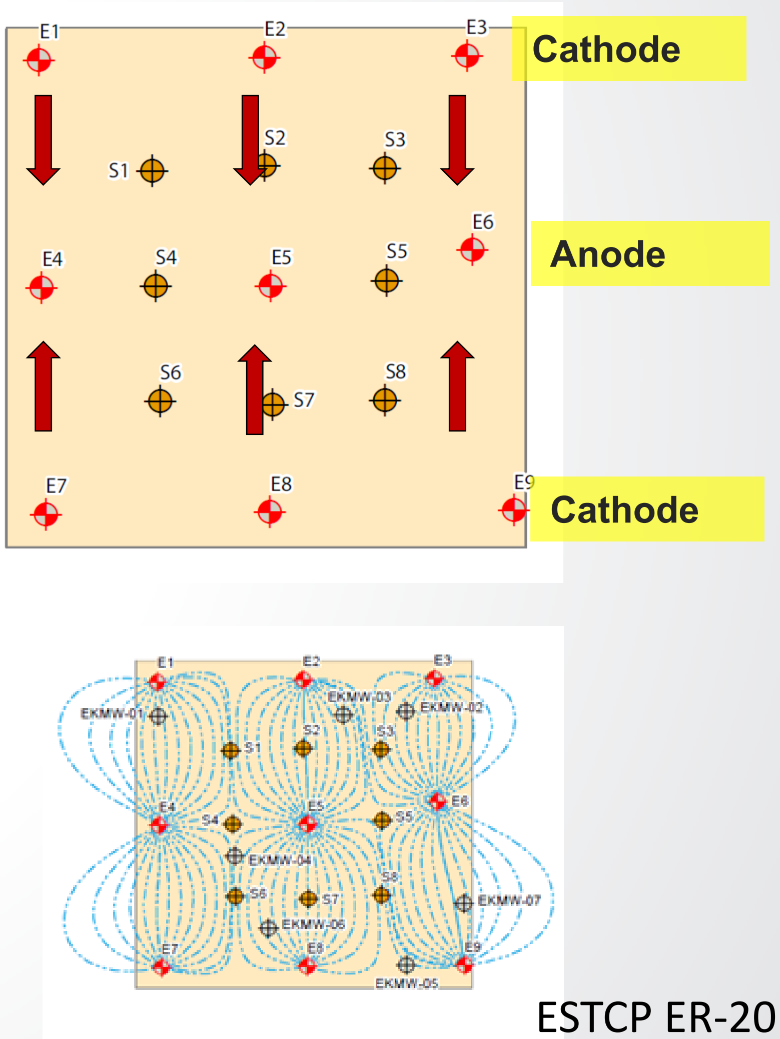
EK-BIO Remediation Operation

- Two stages, each stage = 5 months active operation
- Electrical Power – **8 A to 9 A; 22 to 31 V**
- Total power ~ **1,500 kW-hr** (~ **two 100-W lightbulbs** for the same duration)
- Lactate & Buffer Amendment Supply
- Bioaugmentation at Supply Wells & Electrode wells
- No overpressure injection

Stage 1 Operation



Stage 2 Operation



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EK-BIO Remedy Construction / Installation

Parking lot in use during demonstration

EK System Center

w/ Bioaugmentation of Dechlorination Culture

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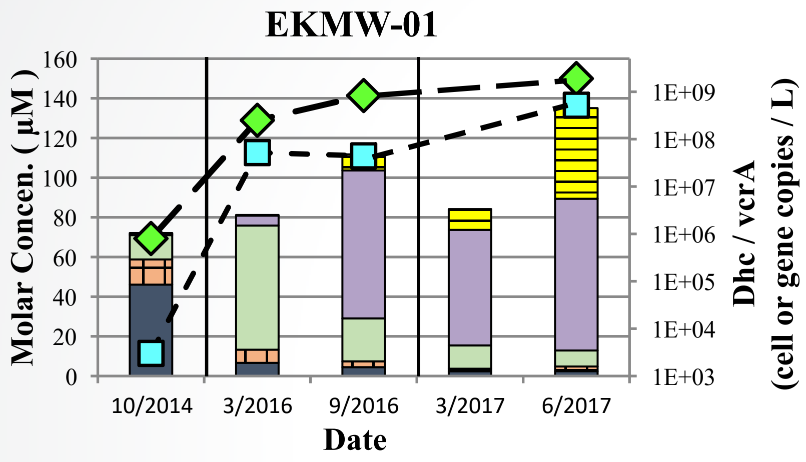
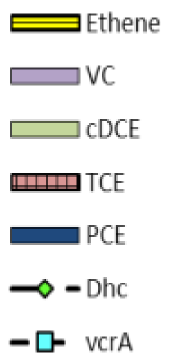
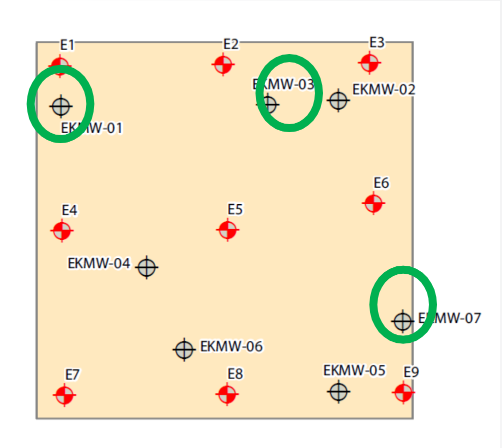
Groundwater Monitoring Within Clay – VOCs and Biomarkers

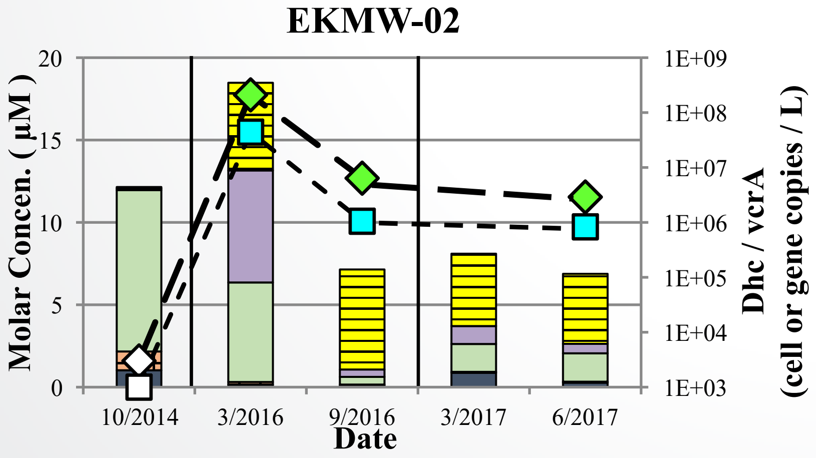
ESTCP ER-201325

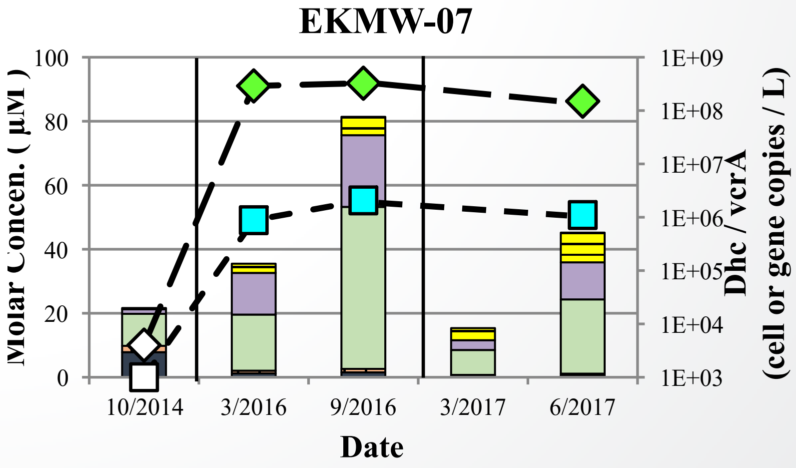






Apparent and significant increases of dechlorination end products and microbial genetic biomarkers





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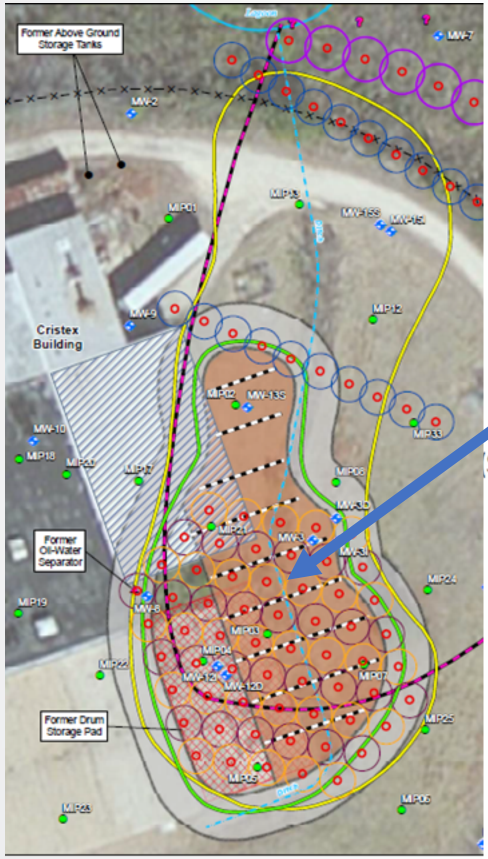
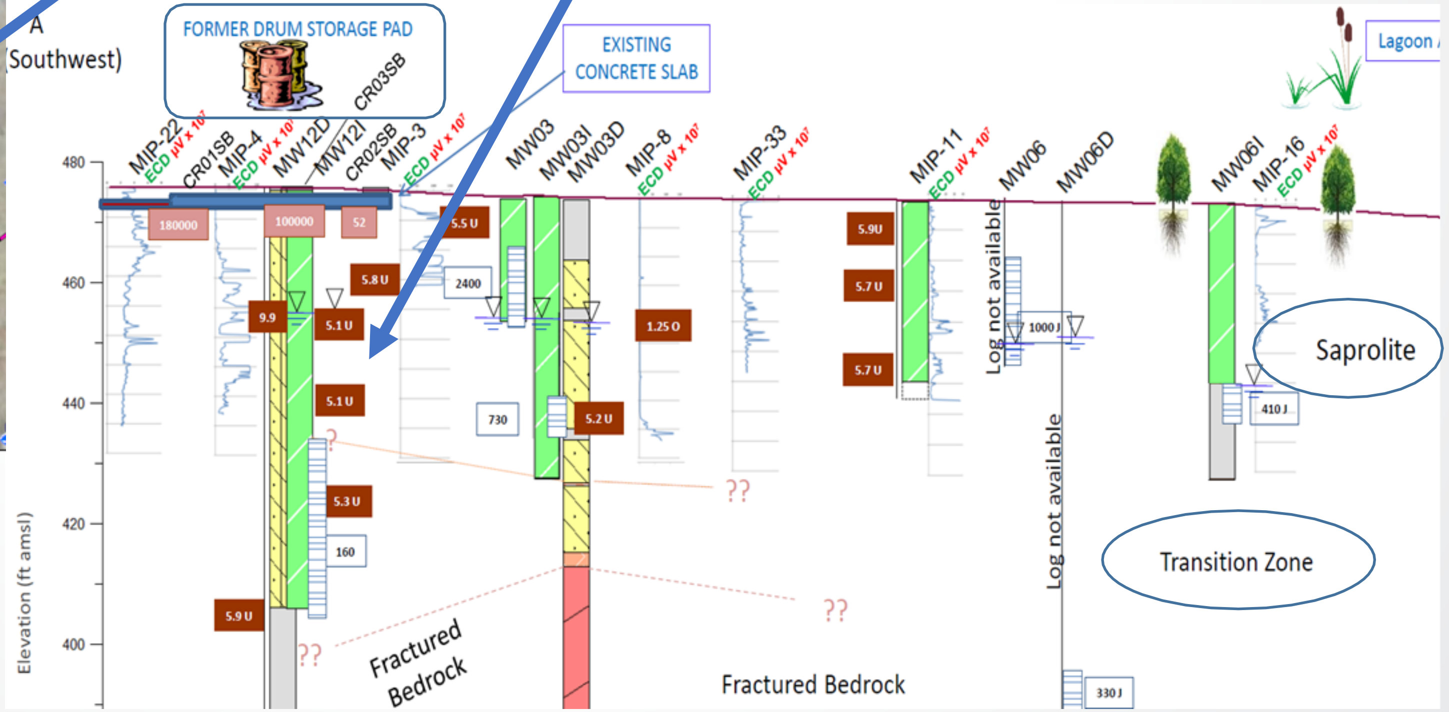
EK-ISCO Pilot at Cristex Drum Superfund Site Oxford, North Carolina

Objective – Pilot test EK-ISCO for remediation of **PCE sources in** the **saprolite** formation



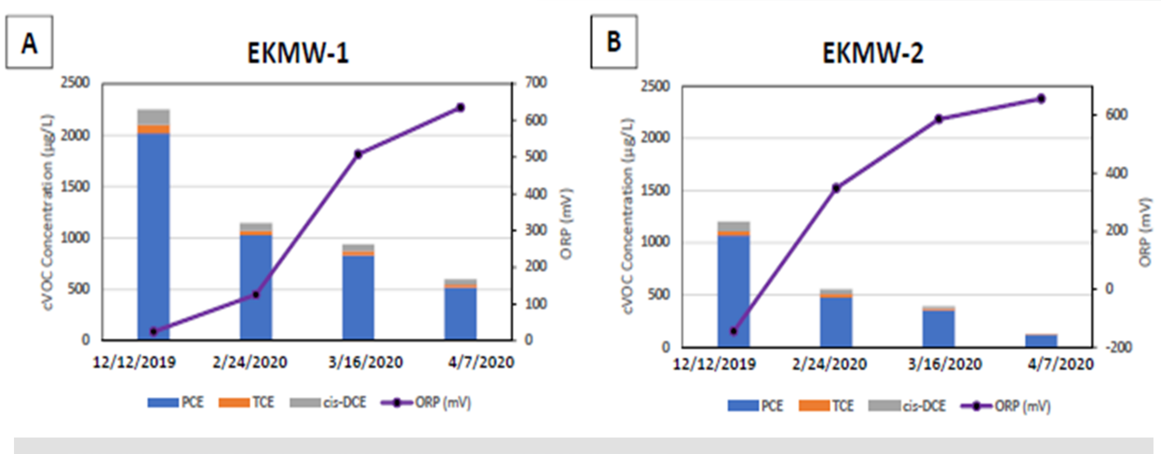
Saprolite – relatively low-permeability, highly heterogeneous

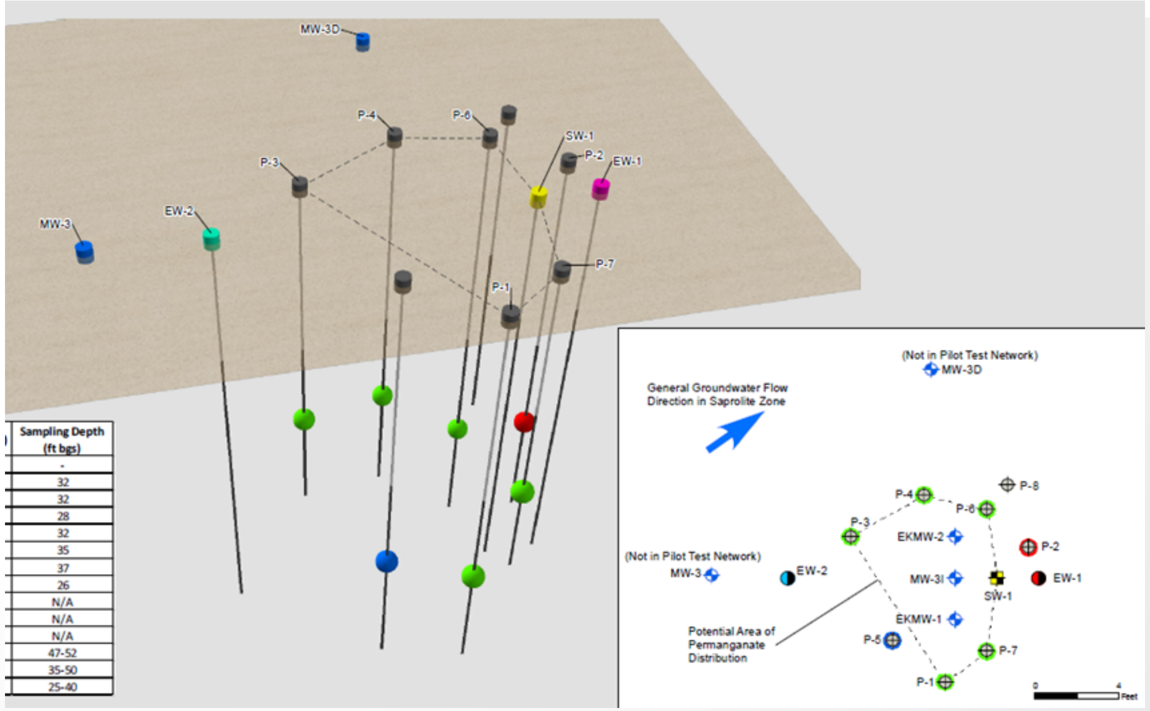


EK-ISCO Pilot at Cristex Drum Superfund Site Oxford, North Carolina

- EK Transport of **permanganate** within pilot test area (57 days; Jan. – Mar. 2020)
  - Decreases in CVOC concentrations coupled with Increases in ORP
  - Distribution detected cross-gradient and upgradient from supply well (up to 7.3 ft upgradient)
  - EK "net" transport rate for permanganate of **1.3 to 4.1 ft / month in saprolite**
  - 152 kW-hr used over 57 days (low electrical energy utilized)

EK Pilot Test System Trailer





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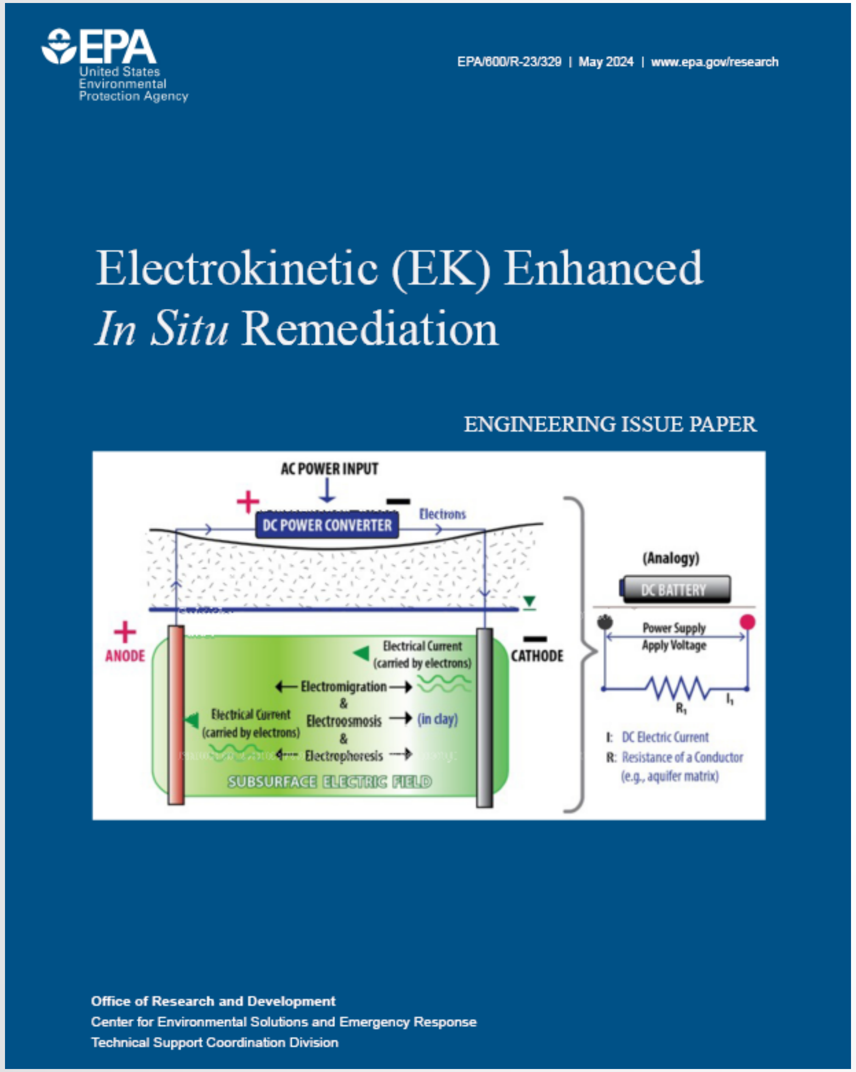
EK-Enhanced *In Situ* Remediation in Low-k Geology Key Takeaway Messages

- **In Situ Remediation Needs Delivery** !
- Achieved **treatment within clay** materials
- Low energy demand [e.g., DC amperage & voltage less than 10A, 35V]
- A **fundamentally different** solution to a vexing problem
- Technology screening / evaluation / selection through treatability study and pilot test
- More technology development ongoing

Engineering Issue Paper Team



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