NMR Technologies for High-Resolution Site Characterization and Monitoring of Environmental Remediation

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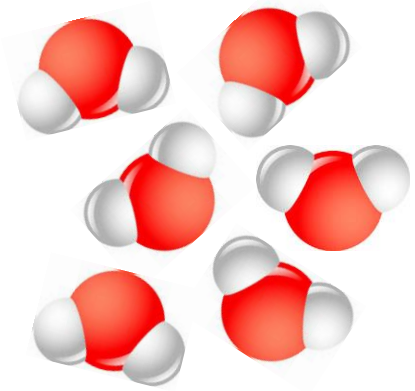
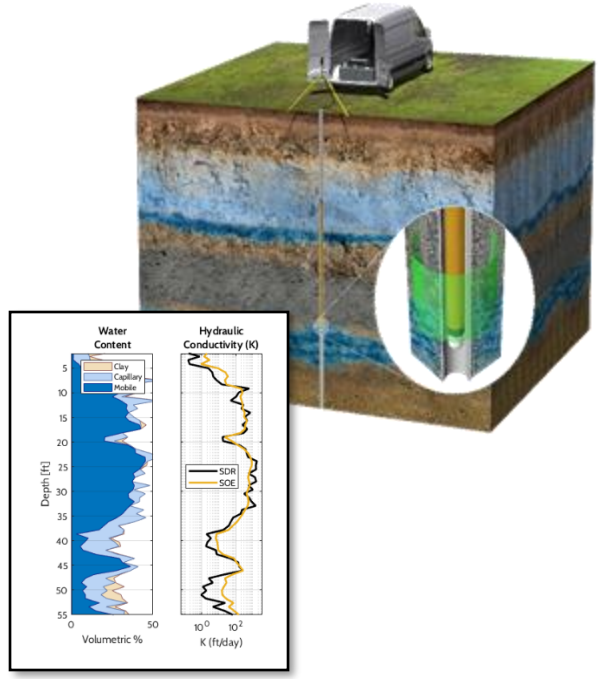
Applications of Nuclear Magnetic Resonance (NMR)

Water molecules



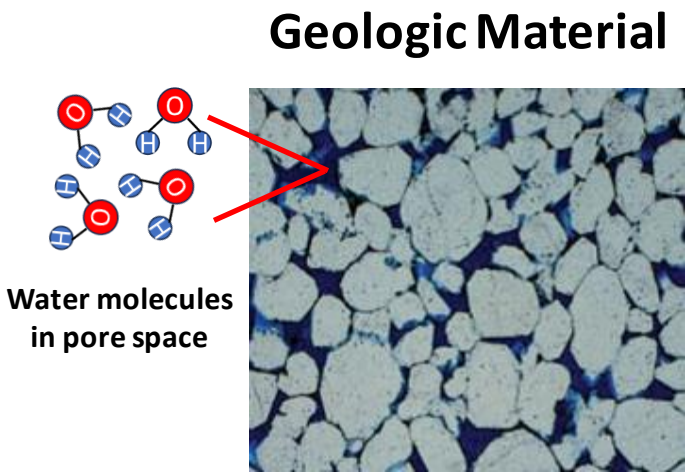
Direct Detection
of Hydrogen Nuclei

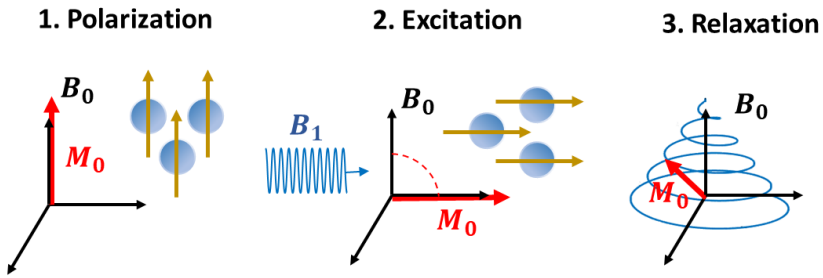
Medical MRI

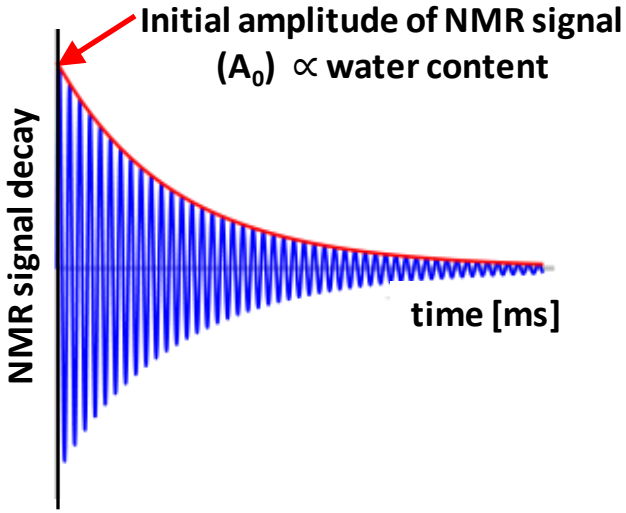


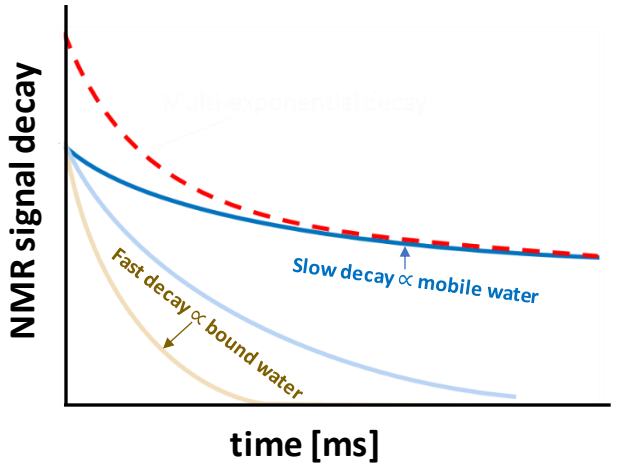
NMR Geophysics

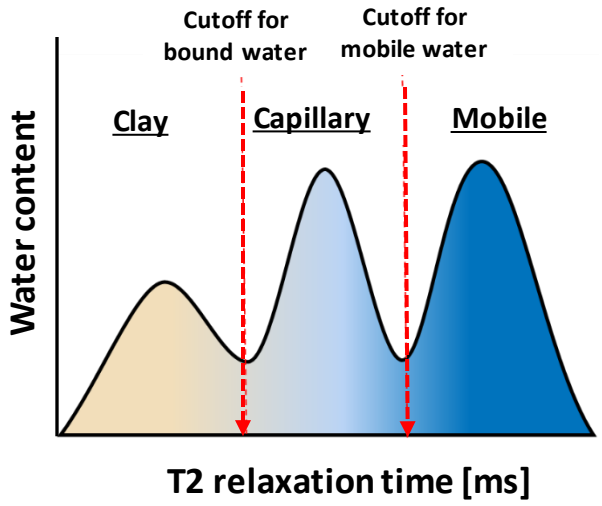
How it works?











Modeling

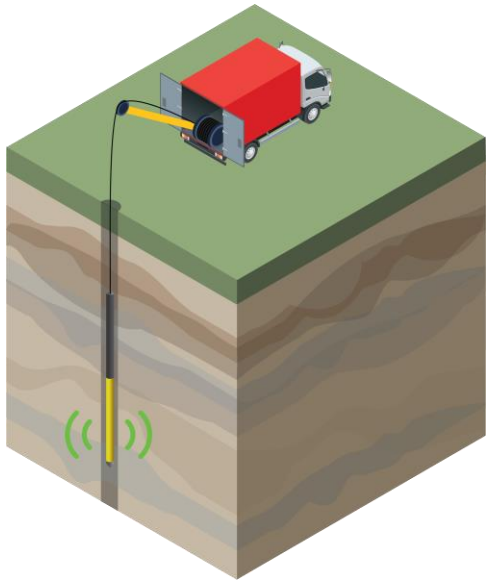
$$K_{TC} = \frac{\phi}{\tau(S/V)^2}$$

$$K_{SDR} = C_{SDR} T_2^2 S_0^N$$

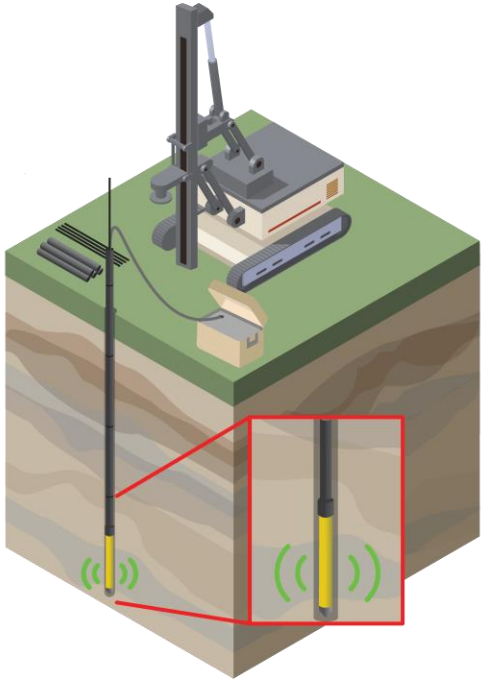
$$K_{SOE} = C_{SOE} (\sum_i A_i T_2)^2$$

Geotechnical Nuclear Magnetic Resonance instruments

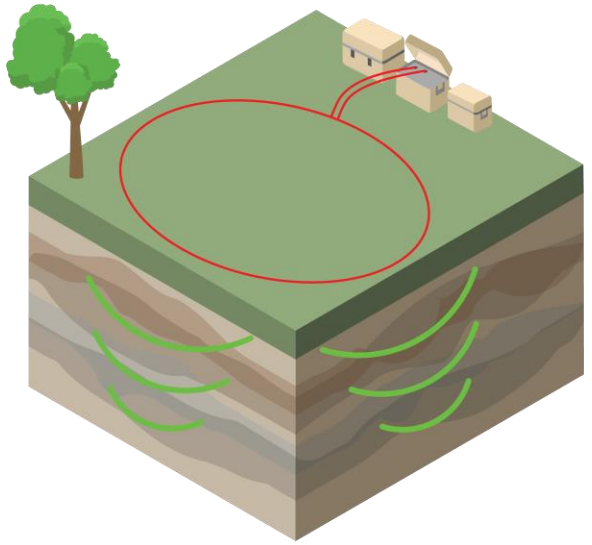
NMR Borehole Logging Tools



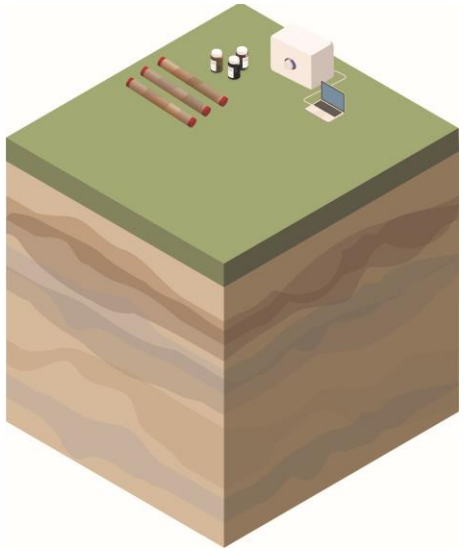
Portable and Direct Push NMR Tools



Surface NMR technology



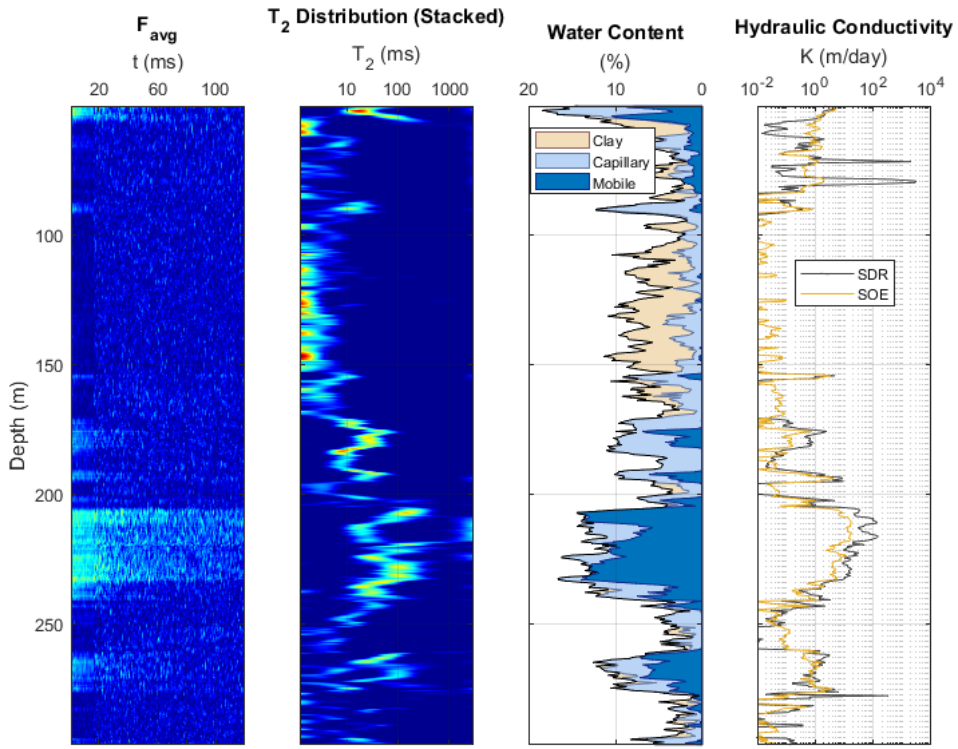
NMR Soil & Core Analyzer

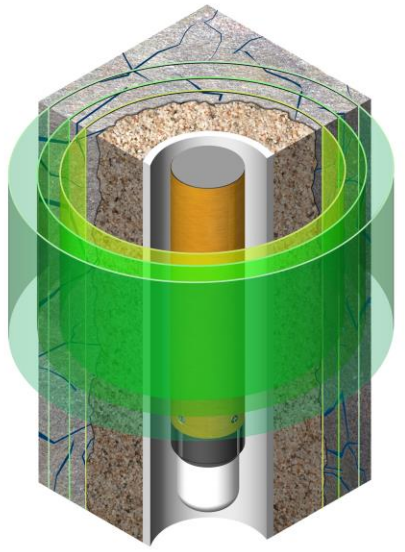


NMR Borehole logging tools:

- The NMR borehole logging tools can be operated in open or plastic-cased holes.
- In-situ measurement of hydrogeologic properties that govern contaminant storage and transport:
  - Porosity
  - Pore size distribution
  - Hydraulic conductivity
- Large diameters of investigation to see past the annular space of the well. The measurement is conducted directly in the formation.
- Multi-frequency operation below the AM broadcast band provides faster logging speeds and immunity to EMI noise.

Moab UMTRA, UT

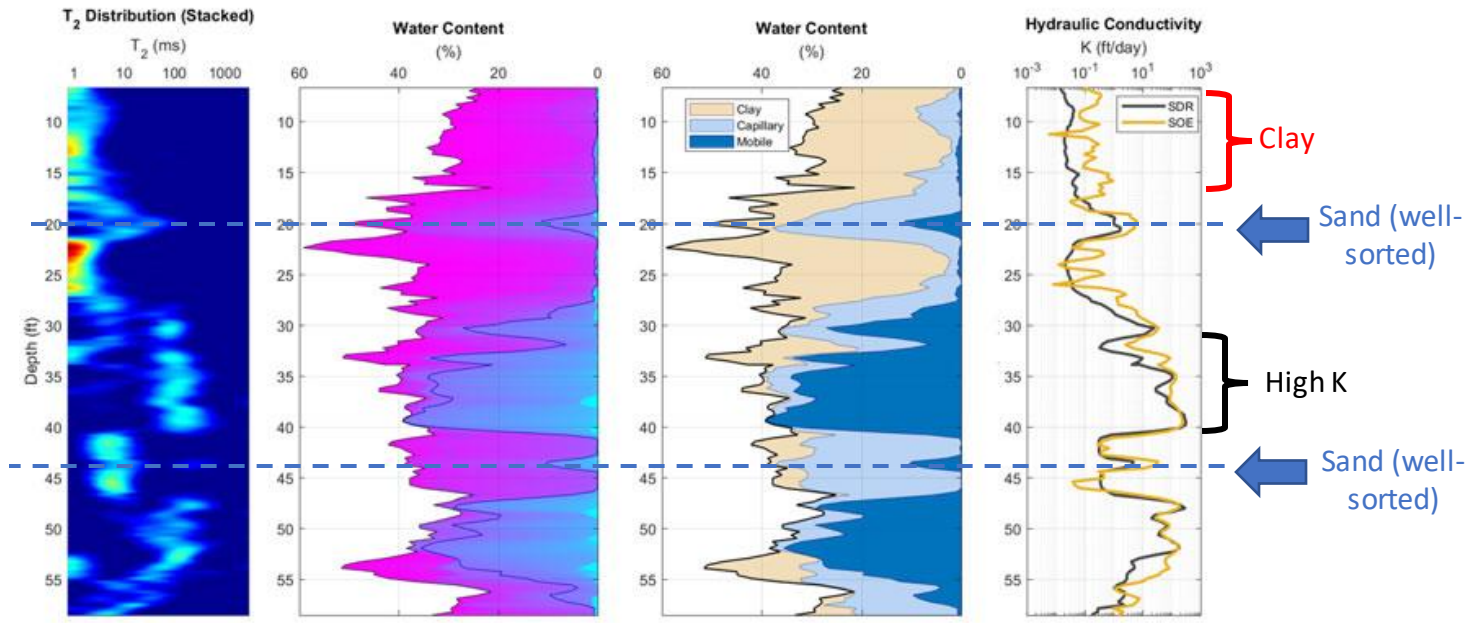




Portable and Direct Push NMR logging tools:

- Portable and light-weight, battery powered
- Very high resolution in-situ NMR measurements
  - Vertical resolution can reach 2 inches
- Measure boreholes up to 10 cm diameter and 60 m deep
- Can be deployed using Direct Push rigs and CPT
- Low impact, no contaminated drilling waste

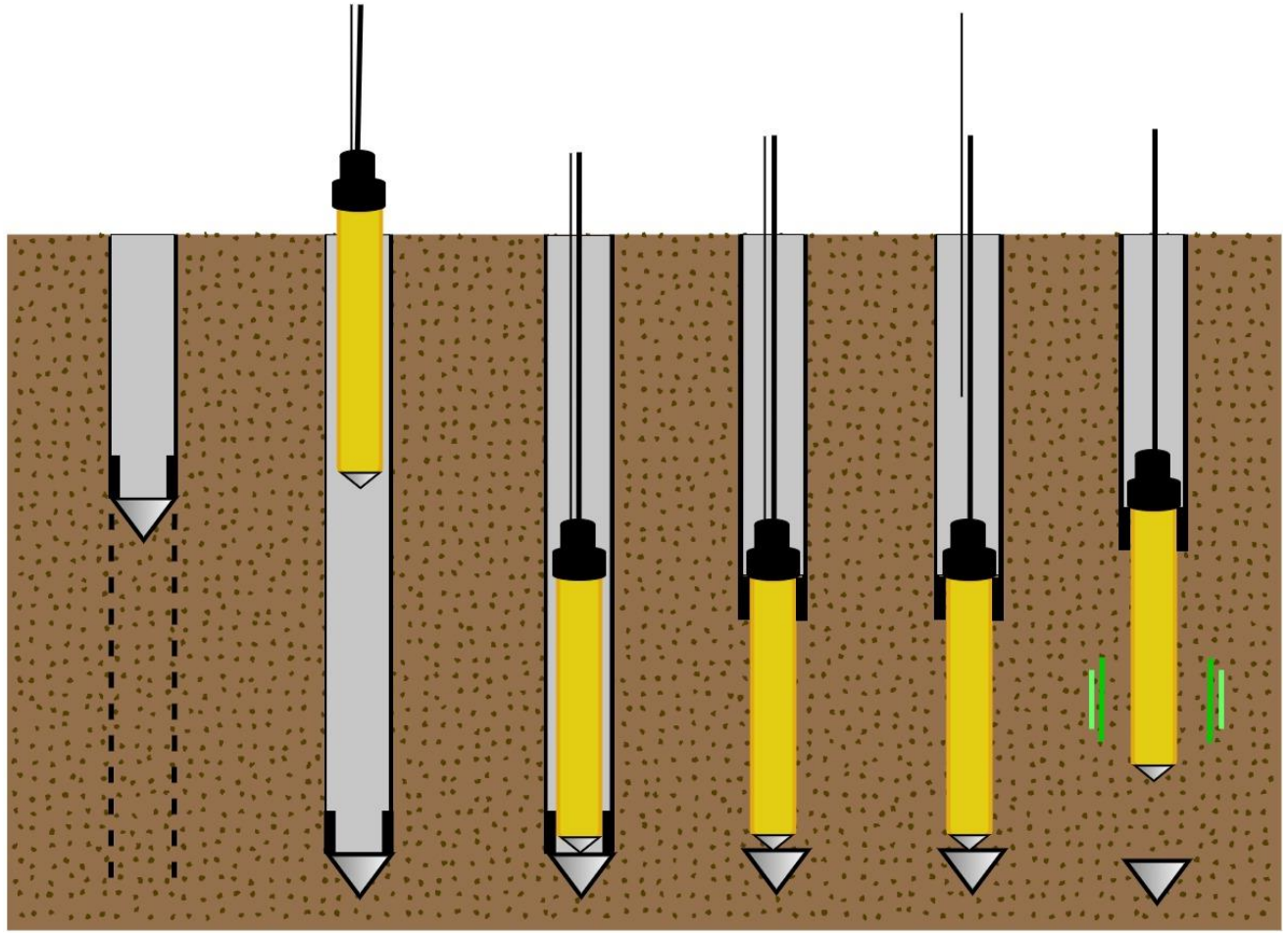
- The DP NMR technology is applicable in many areas of earth sciences such as high-resolution site characterization (HRSC), environmental monitoring, mining, and groundwater resources.



Direct Push NMR logging tools:

How it works:

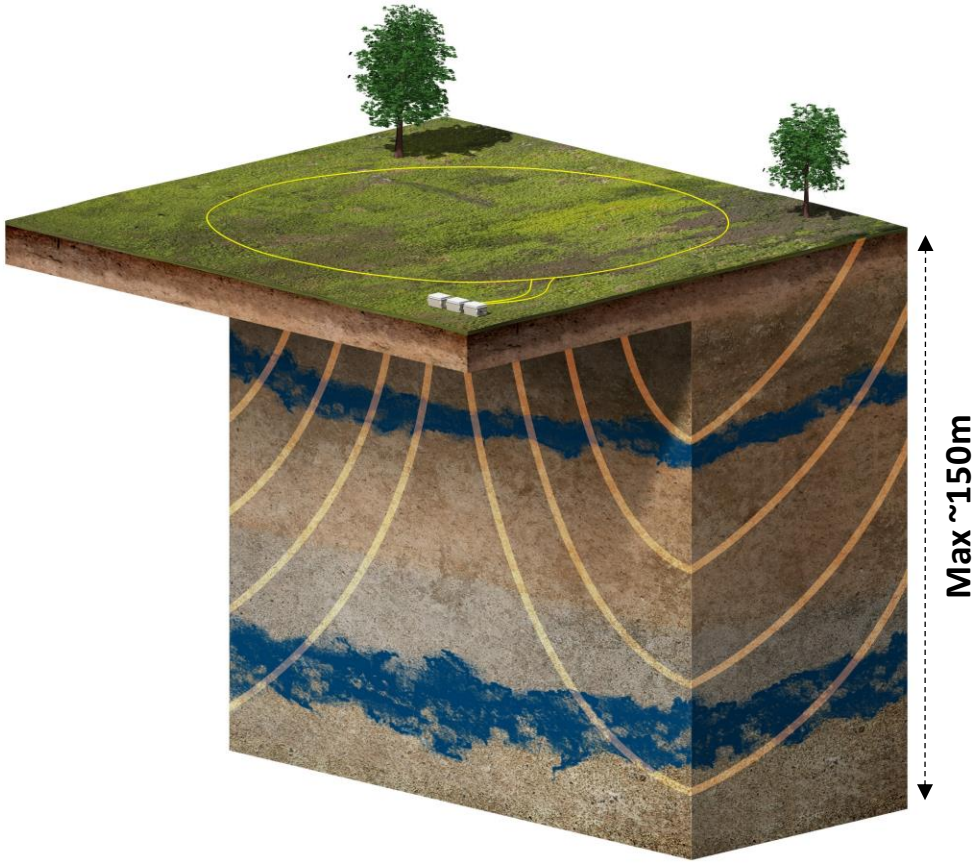
- Same as borehole logging NMR, except smaller more portable instrumentation.
- NMR tool is deployed through drill rods.
- Expendable drill point is pushed out the bottom of the rods exposing the NMR tool to the formation
- NMR measurements performed “on the way up”

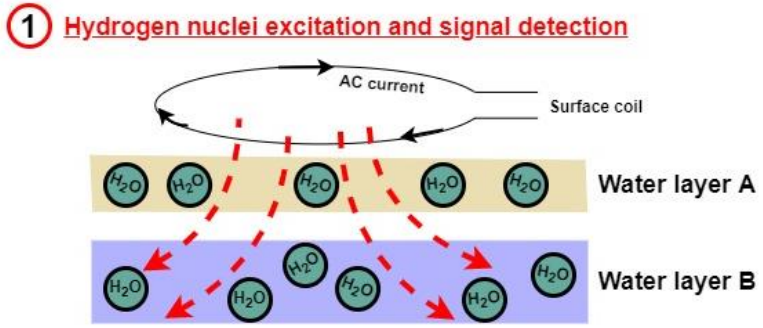


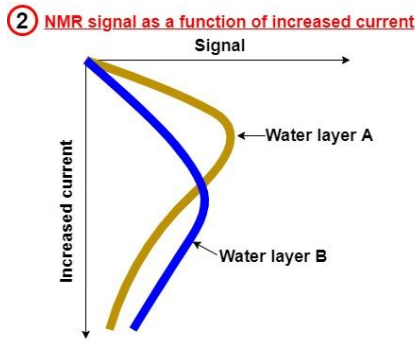
Surface NMR (sNMR) technology

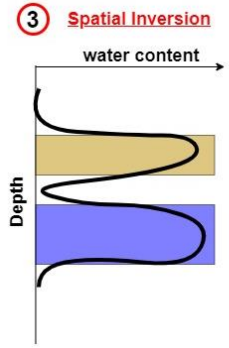
Earth's magnetic field is used as background B_0 field

- Non-Invasive method, no drilling required.
- Quantitative Measurements to estimate water content, effective porosity, and permeability.
- Time-lapse monitoring of subsurface changes to observe variations in groundwater levels, fluid movement, and other dynamic processes.







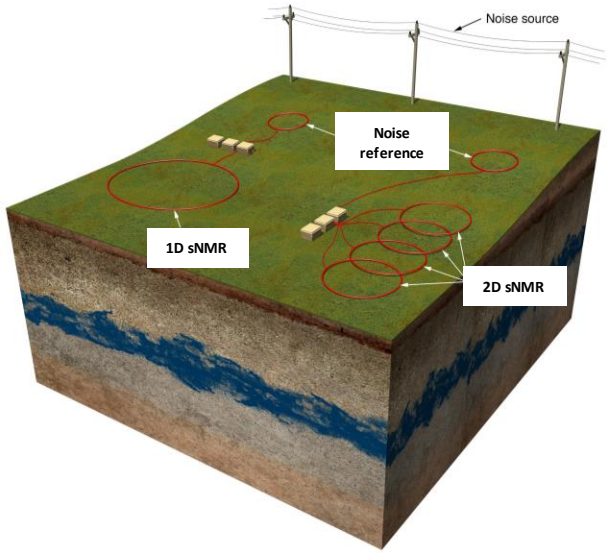


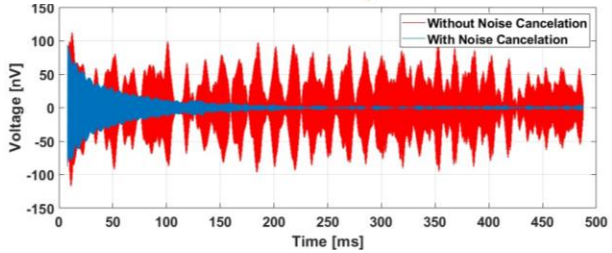
Surface NMR (sNMR) technology

Limitations and Solutions:

Environmental and Cultural Noise

- Multi-coil acquisition with adaptive noise cancelation algorithm is a critical innovation enabling sNMR technology to be used in wider range of environments.

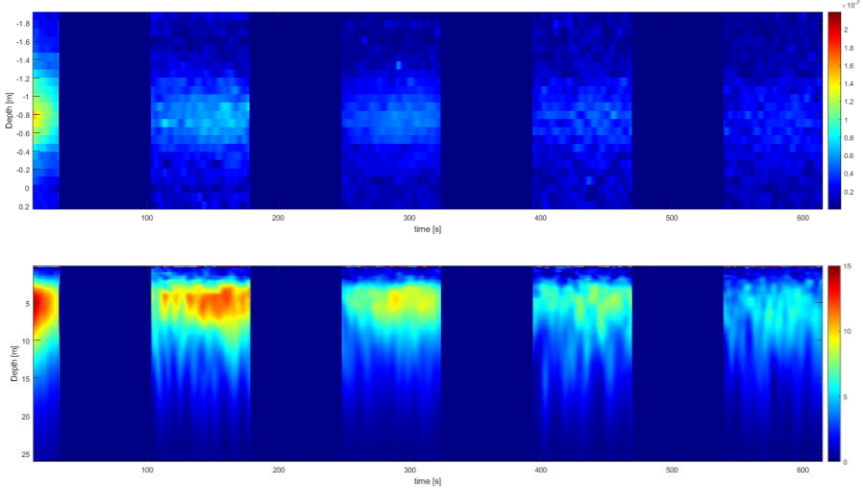




Cancelation of high-level noise

Magnetic Geology

- Spin Echo and CPMG pulse sequences can resolve large pose water in magnetic geology.
- Detection of NMR signal is still challenging in highly magnetic geology.

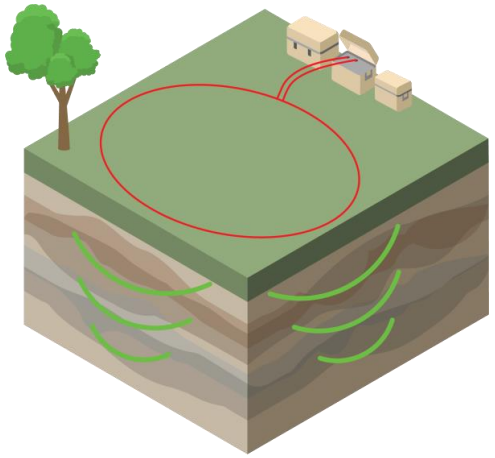


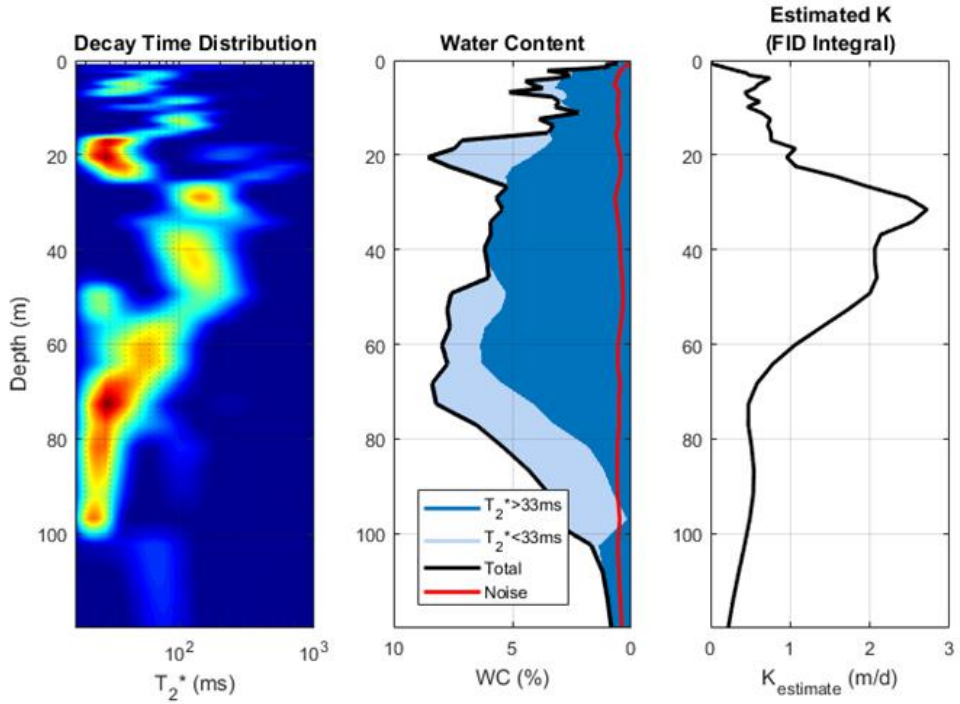
Depth of Investigation

- Depends on:
  - Loop size
  - Ability to generate and manage high voltage and current
  - Electrical conductivity of the subsurface
- High-power sNMR instrumentation is capable to resolve subsurface up to 150m.

Surface NMR (sNMR) technology

Surveys Water Well Drilling Locations (Chile)





Non-invasive surface NMR shows shallow water and highly permeable aquifer from 25 m to 50 m deep.

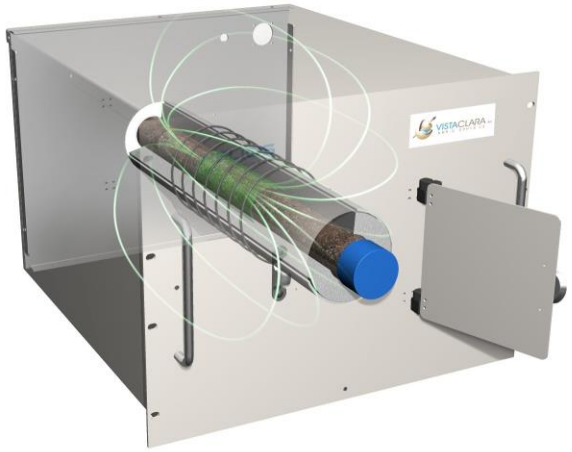
NMR Soil & Core Analysis for groundwater investigations

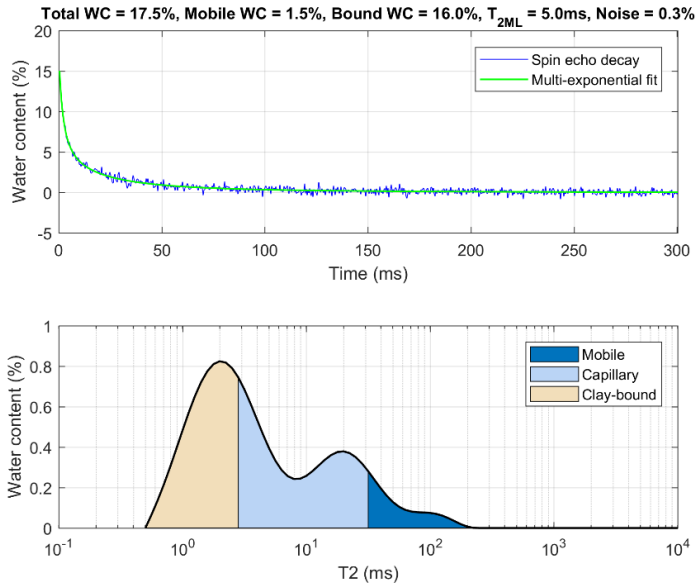
Laboratory or field measurement of fluid content and hydrogeological properties from:

- Core samples
- Soil samples
- Drill cuttings

Specific applications:

- Formation-specific calibration of NMR hydrogeologic models for NMR logging:
  - Hydraulic conductivity
  - T_2 cutoffs for NMR-based estimation of bound/mobile porosity
- Residual water content in ore
- Monitoring of bioremediation processes

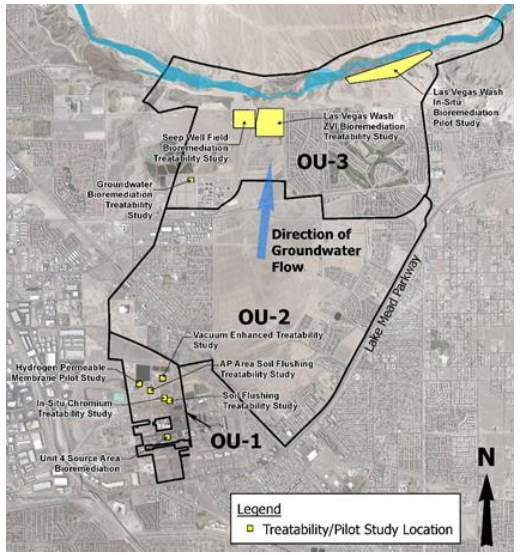




Applications: High-resolution site characterization

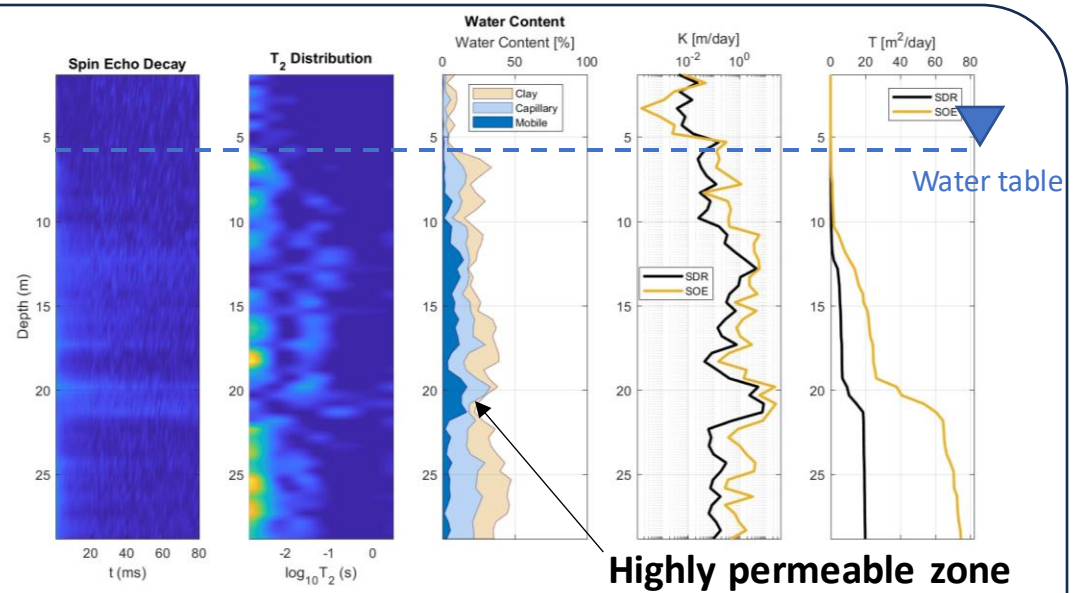
NMR borehole logging for conceptual site models of groundwater flow at NERT/PEPCON site

1988- catastrophic fire and explosions

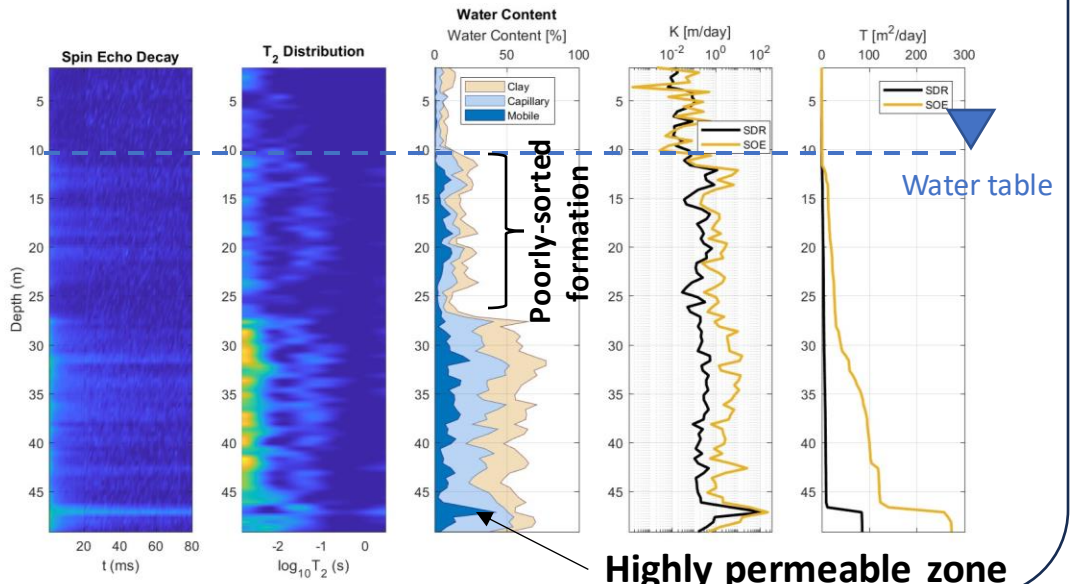


Study Area site

Location 1: 2-inch PVC well

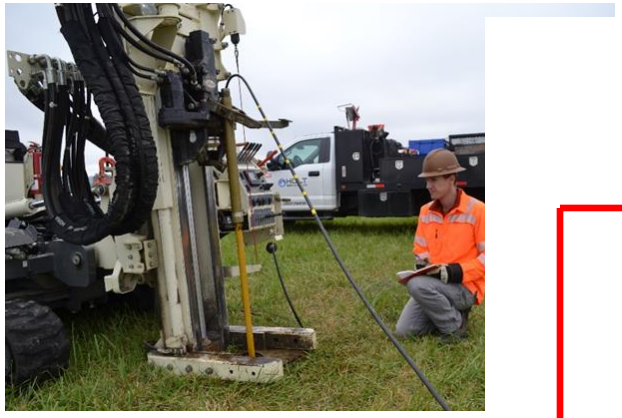


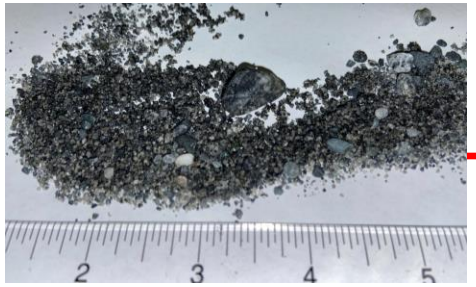
Location 2: 4-inch PVC well

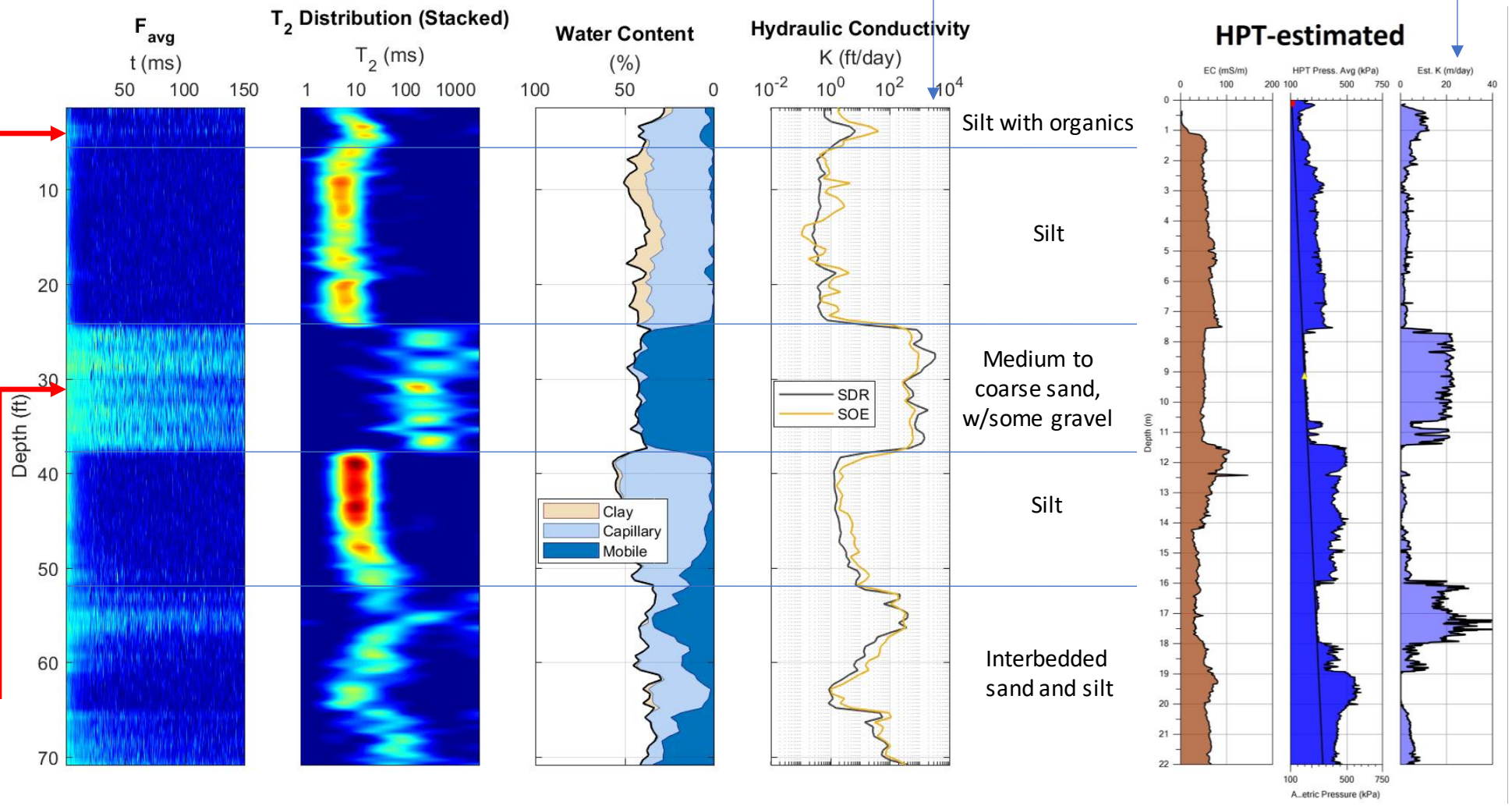


Applications: High-resolution site characterization

DP-NMR: Ebey Island, Washington

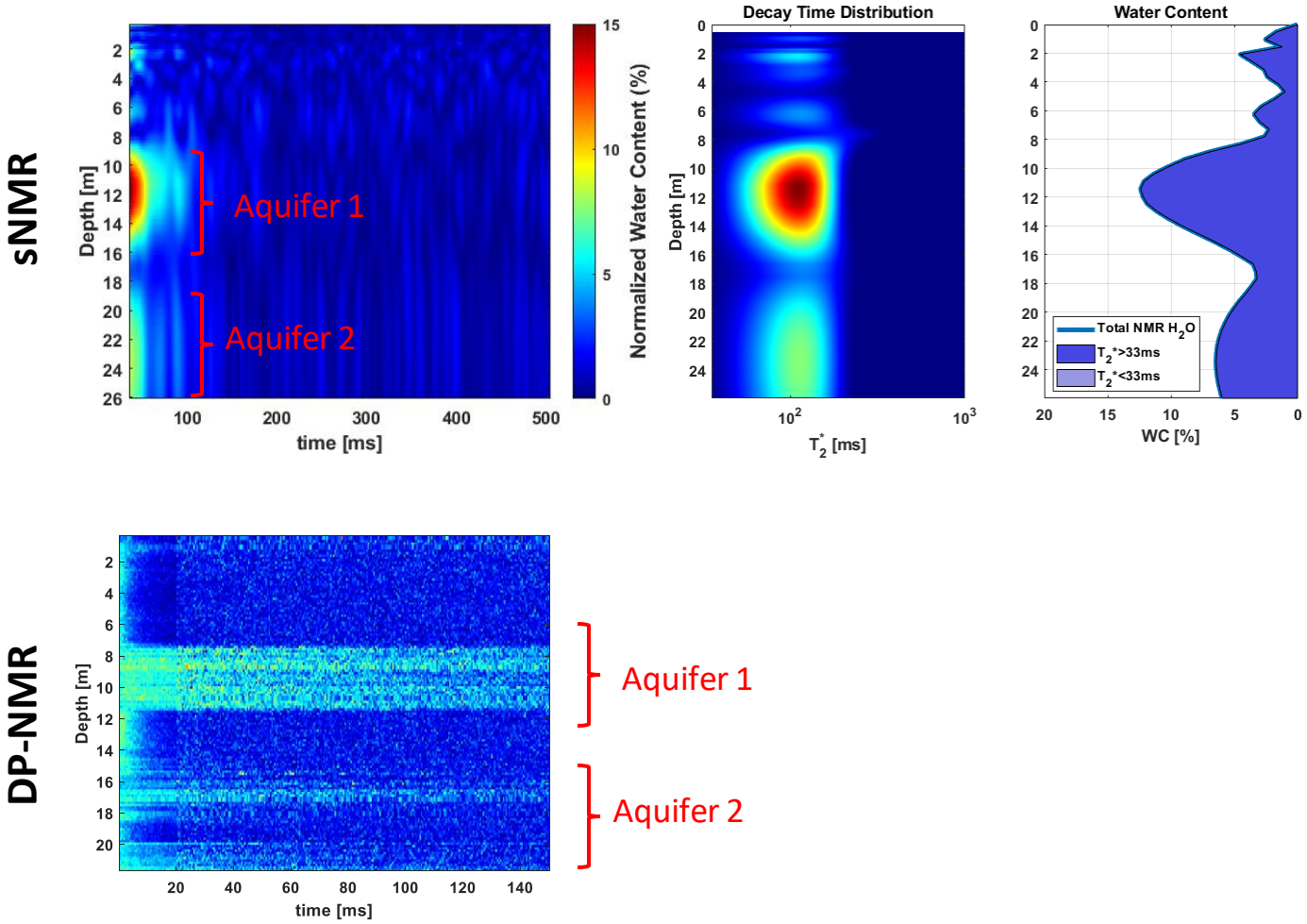






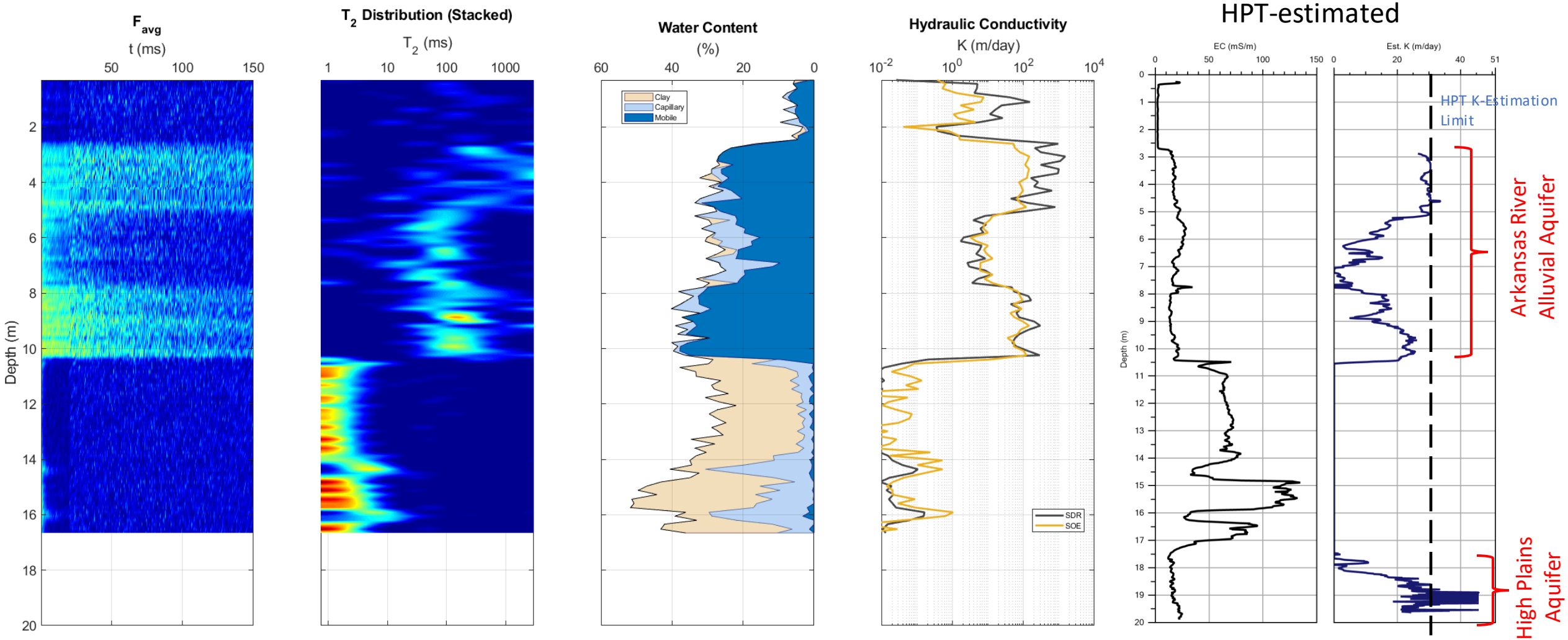
Applications: High-resolution site characterization

sNMR: Ebey Island, Washington



Applications: High-resolution site characterization

DP-NMR: Larned, Kansas

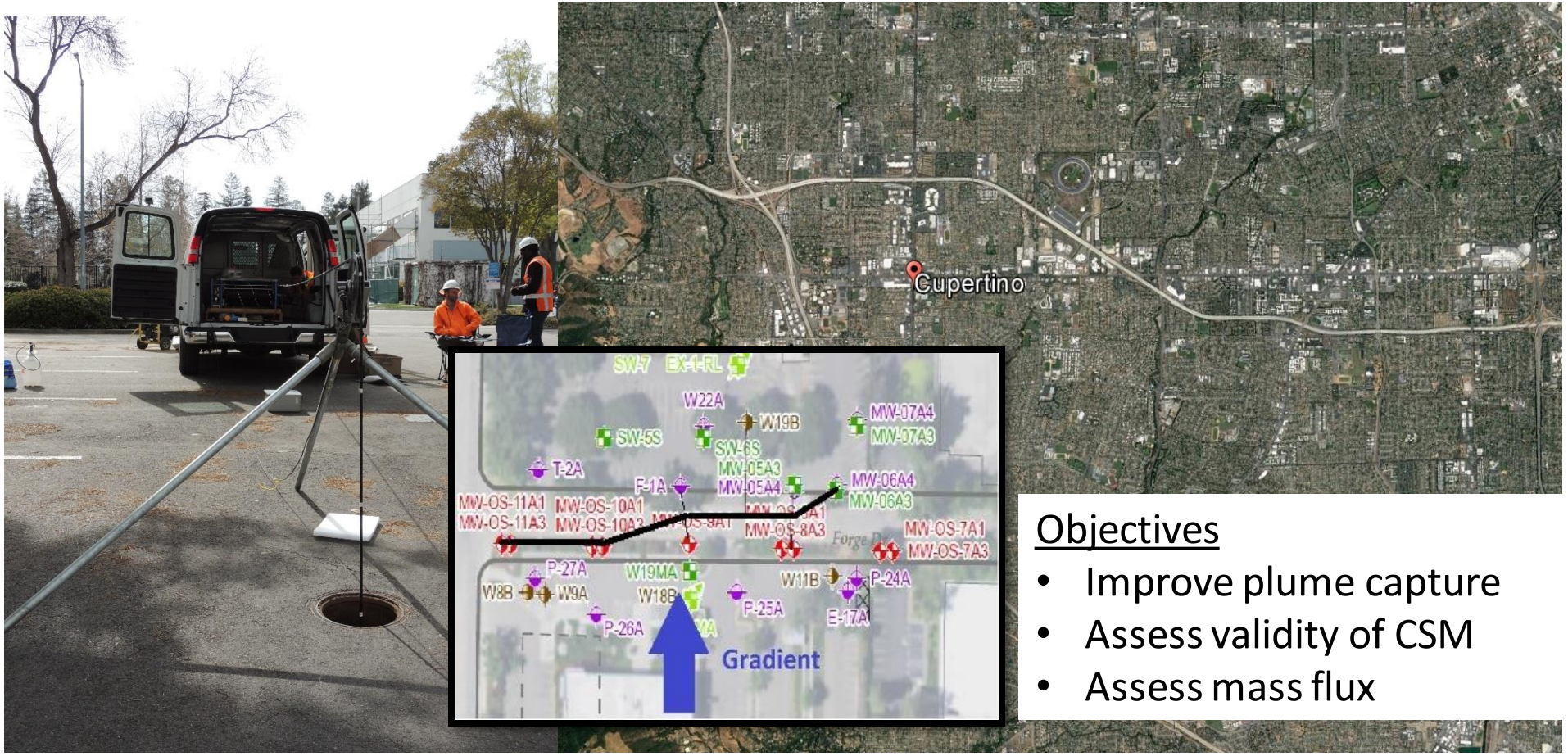


Groundwater Remediation – Chlorinated Solvents

Former Electronics Manufacturing Facility, California

Brad Cross

ERM

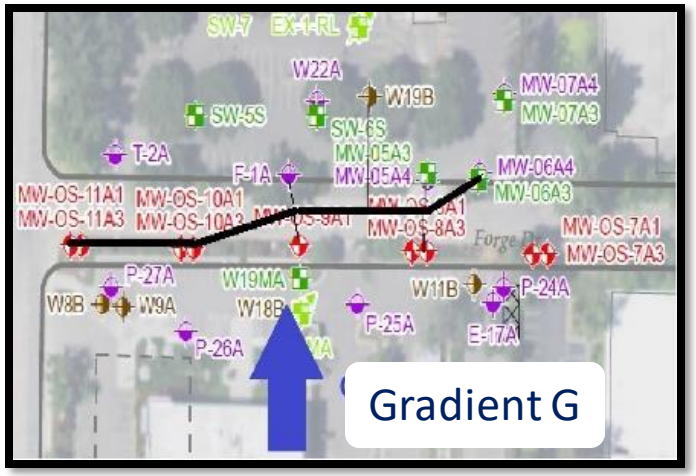


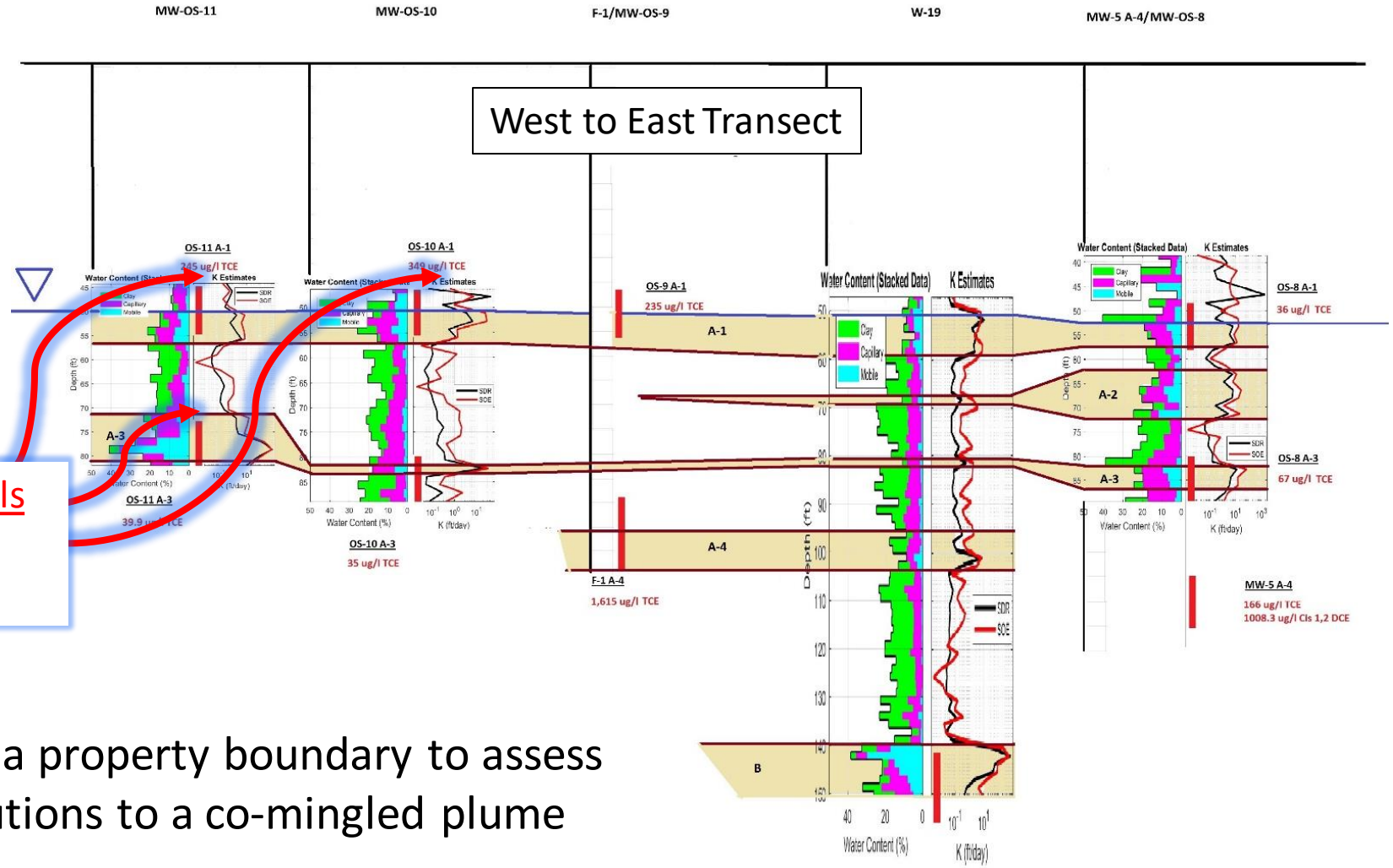
Objectives

- Improve plume capture
- Assess validity of CSM
- Assess mass flux

Study from Brad Cross

Contaminant Mass Flux Analysis





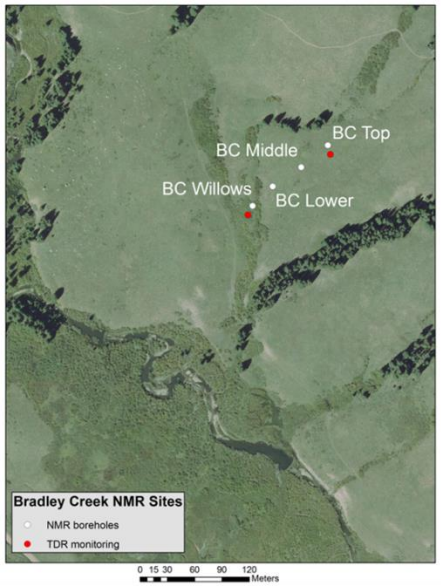
Screen Intervals
K_{NMR} (ft/day)
TCE (µg/L)

Estimated Mass Flux across a property boundary to assess individual source contributions to a co-mingled plume

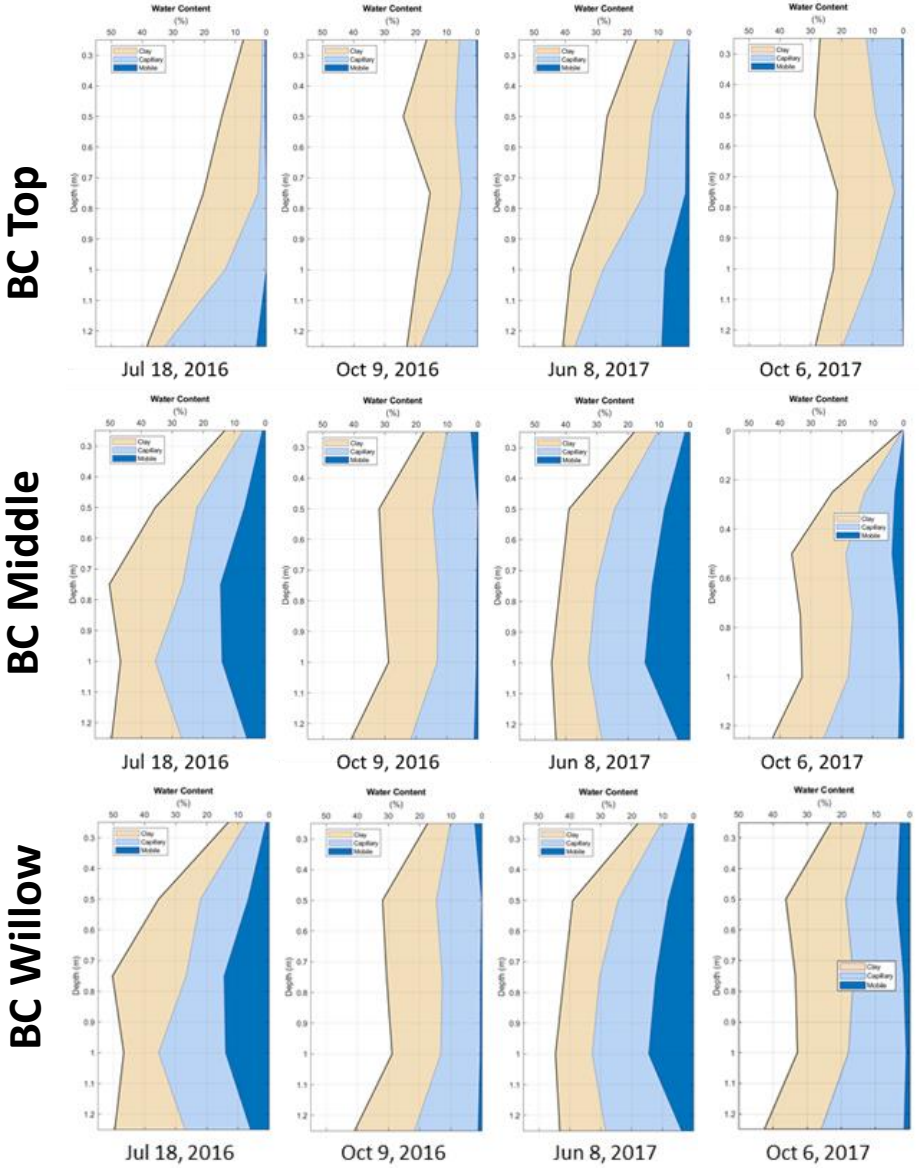
Study from Brad Cross

Applications: Monitoring of Natural Runoff

Bradley Creek Seasonal Soil Moisture Monitoring

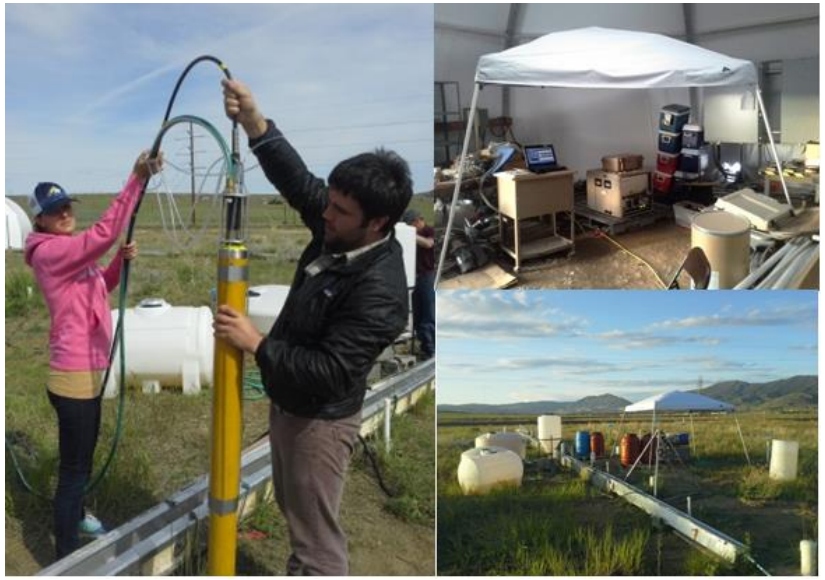


Time-lapse NMR logging measurements showed that near surface soil water content responds differently to snowmelt and precipitation events at different locations on the hillslope.

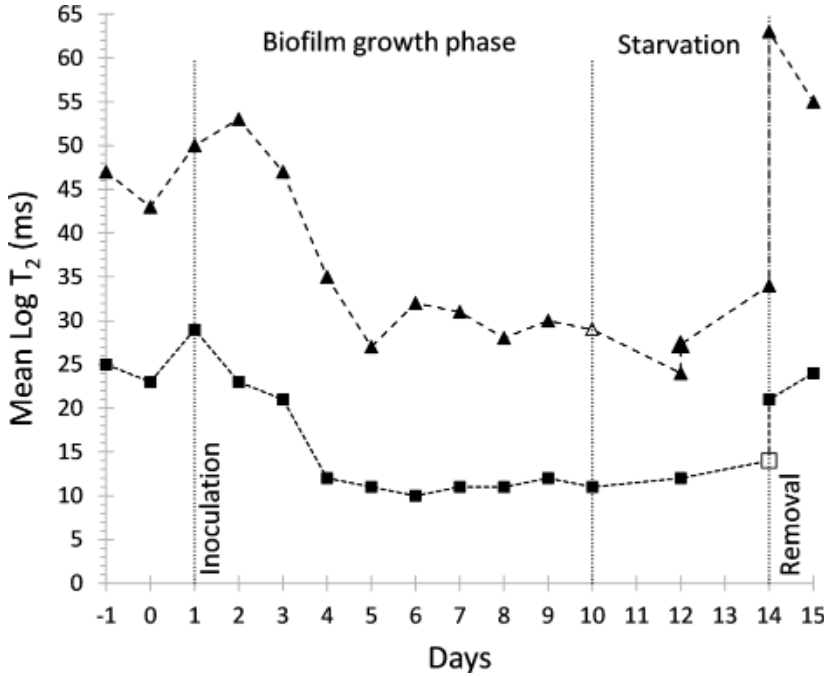


Applications: Monitoring of Remediation processes

In-situ detection of biofilm formation



- Borehole NMR logging tools were used to monitor biofilm formation in-situ.
- Nutrients and selected bacteria injected via tubing into monitoring wells.
- Over time, large pore spaces were clogger with biomatter, increasing surface relaxation associated with faster T2 relaxation which is relatively easy to detect via NMR.
- In the end of study, the wells were injected with bleach solution, removing biofouling and restoring baseline T2 relaxation values.



Kirkland et al. Environmental Science and Technology, 2015

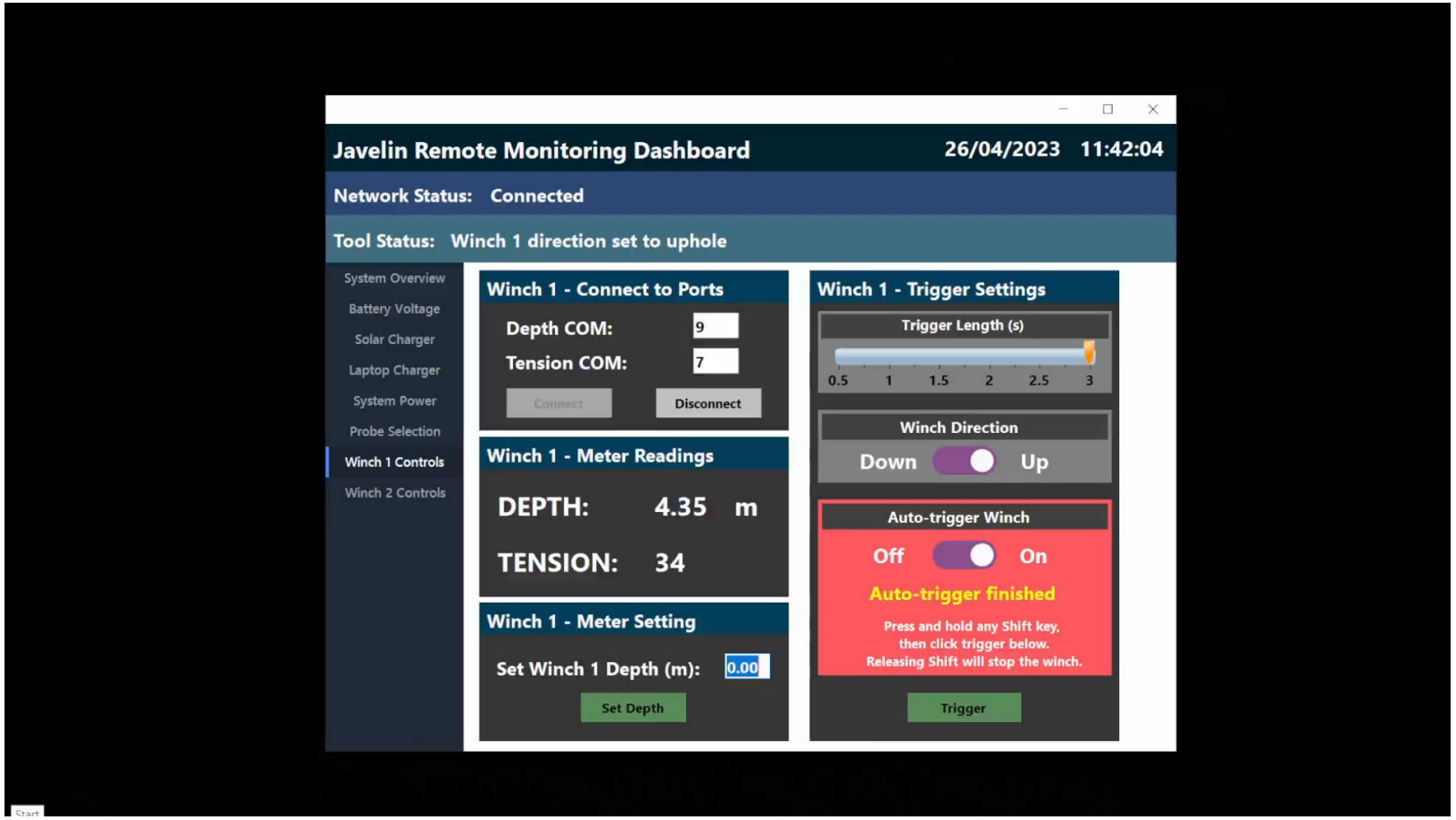
Applications: Monitoring of Remediation processes

Hydroxyapatite precipitation to decrease the mobility of uranium at Moab UMTRA:

Applications: Monitoring of Remediation processes

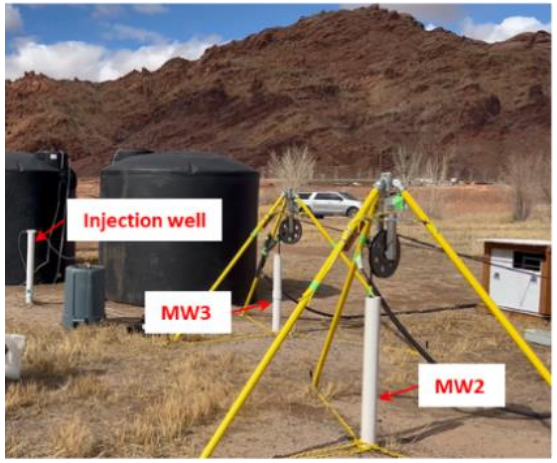
Hydroxyapatite precipitation to decrease the mobility of uranium at Moab UMTRA:

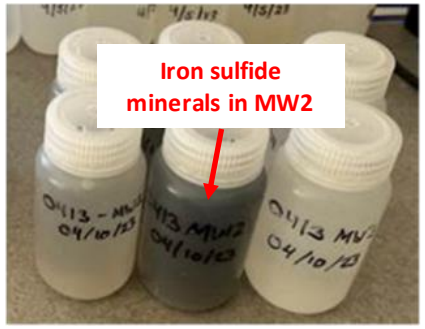
Remote monitoring system overview:

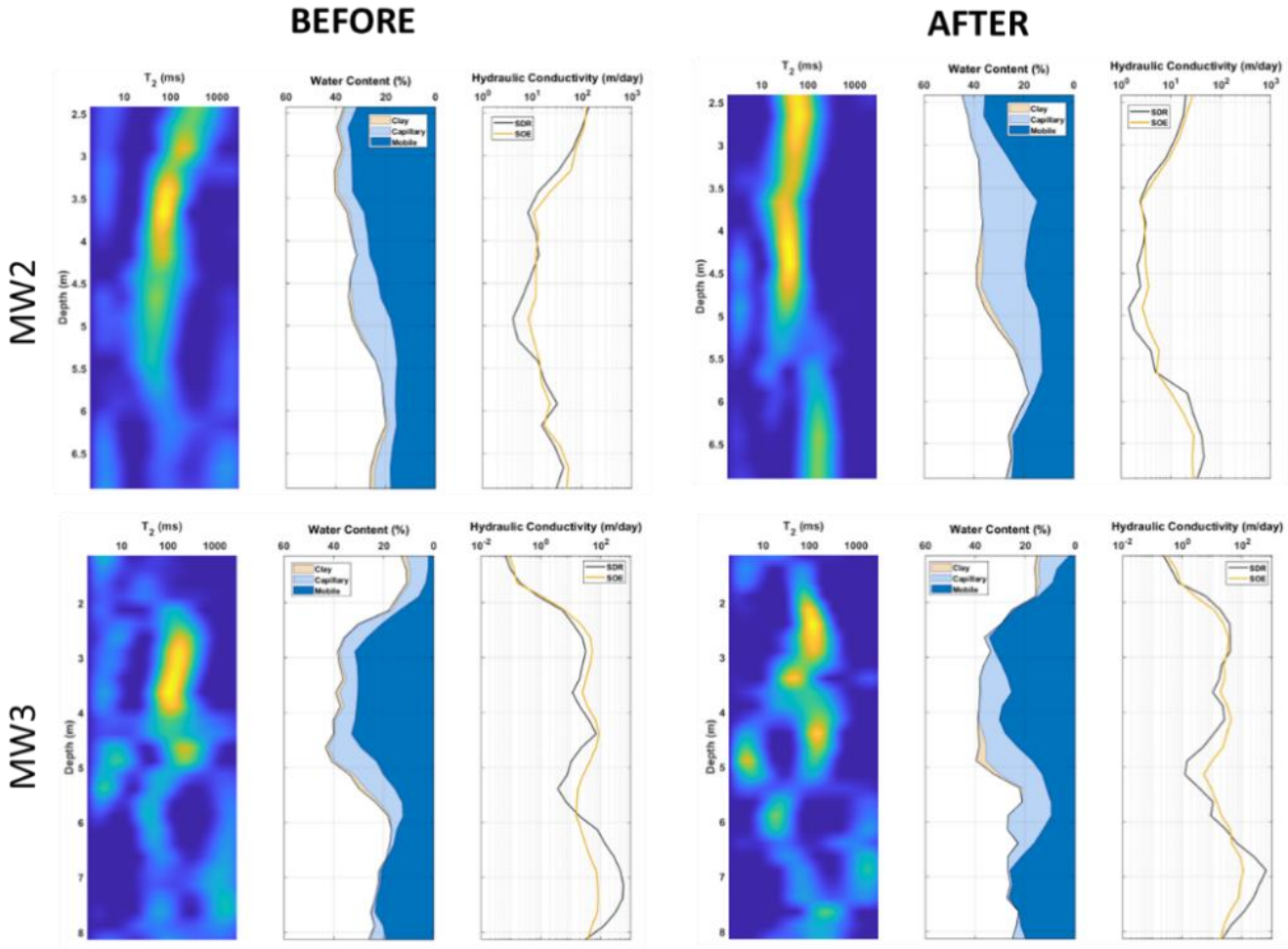


Applications: Monitoring of Remediation processes

Hydroxyapatite precipitation to decrease the mobility of uranium at Moab UMTRA:



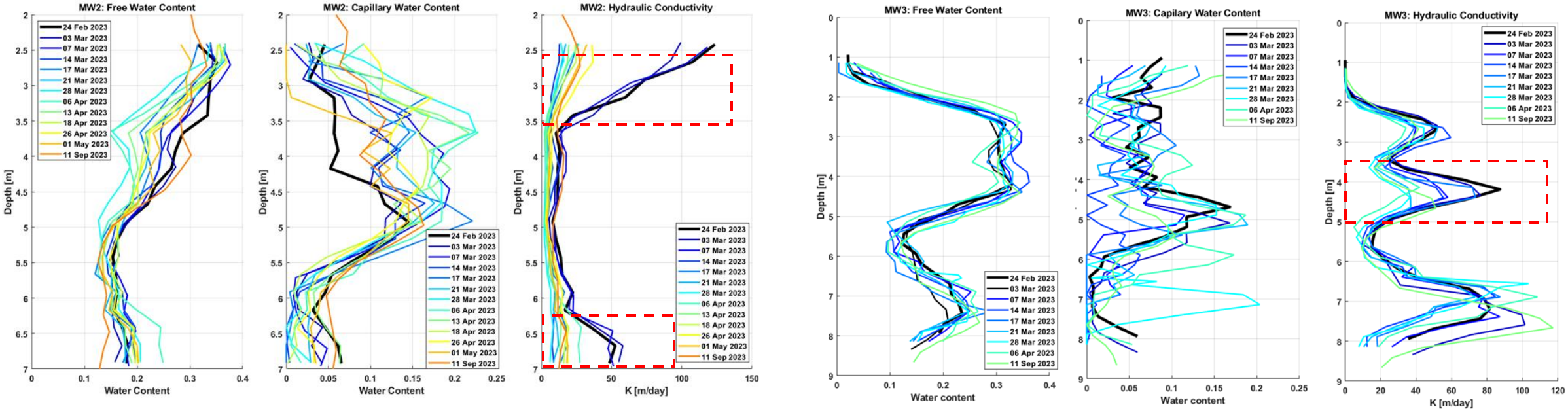




- Before injections, larger hydraulic conductivity values in MW2 vs. MW3.
- A significant decrease in mobile water content and increase in capillary water content over time in MW2 between 2.5 to 3.5 m.

Applications: Monitoring of Remediation processes

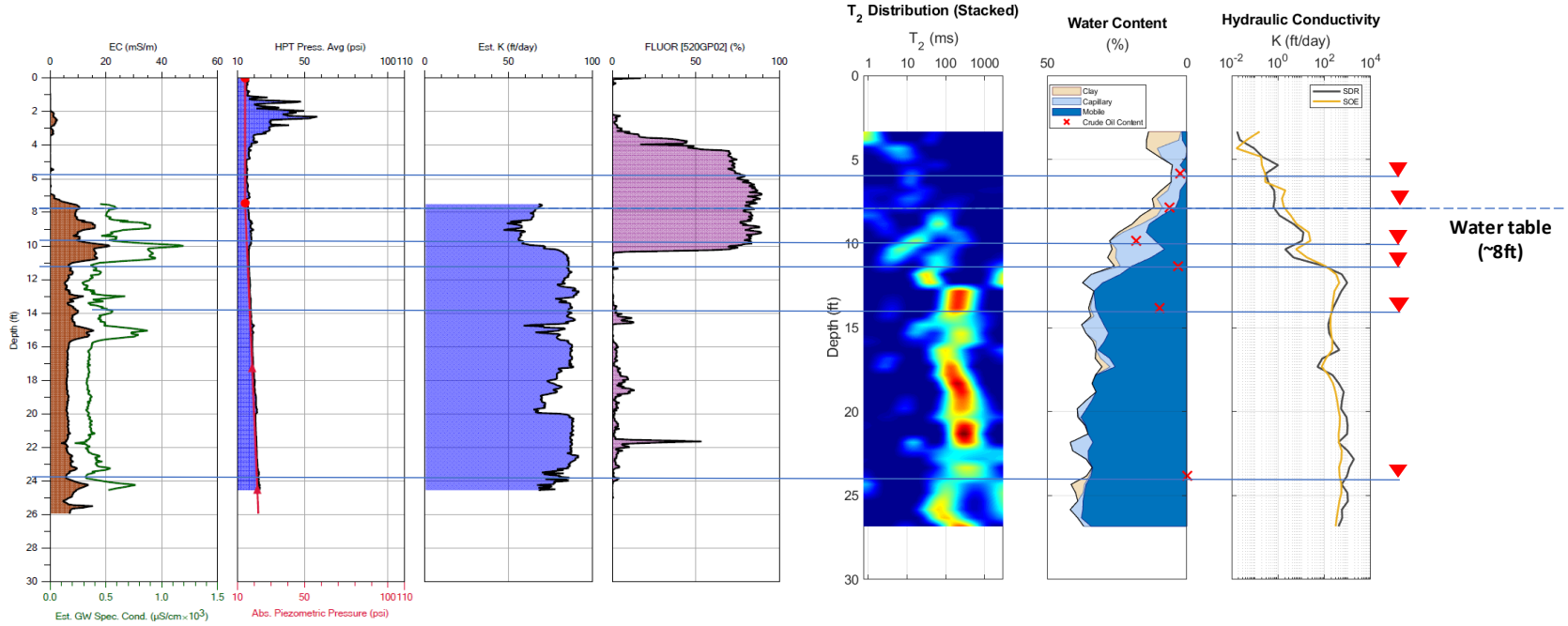
Hydroxyapatite precipitation to decrease the mobility of uranium at Moab UMTRA:

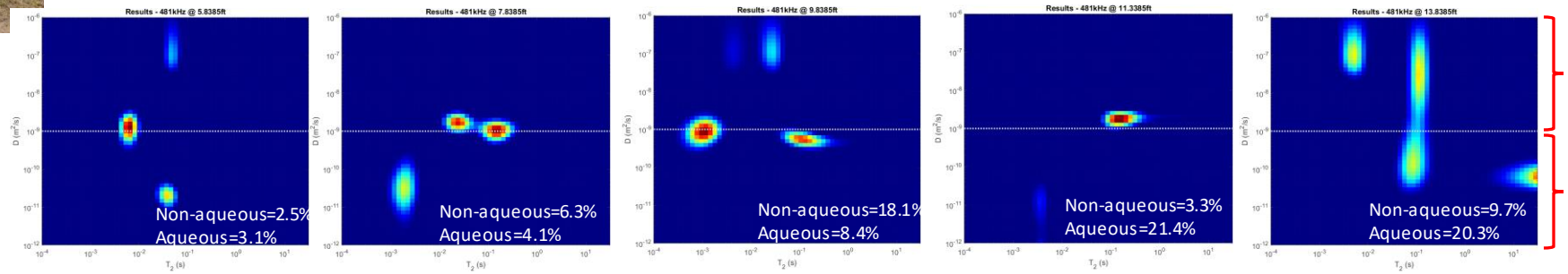


- A dramatic change in hydraulic conductivity was detected over time in MW2 between 2.5 and 3.5m and 6.26 and 7m, associated with formation of hydroxyapatite in pore-space media.
- Smaller changes in NMR-based hydraulic conductivity were detected in MW3 between 3.5 to 5 m.
- The formation of permeable reactive barrier is stable over time (April/May 2023 vs. September 2023).

Applications: NAPL Detection

Crude oil spill site investigations: Bemidji, Minnesota (June 2023)





In-situ quantification of crude oil content in the formation

Summary

Hydrogeological NMR measurements provide unambiguous information on hydrogeological properties:

- Direct detection and measurement of water content in the formation
- Porosity and relative pore size distribution
- Bound and mobile water fractions
- Estimation of hydraulic conductivity and transmissivity

NMR logging technology can provide:

- High-resolution site characterization
  - More robust and accurate conceptual site model
- Efficient monitoring of remediation processes in-situ; remote monitoring is an option
- Soil moisture monitoring
- Improve project outcomes and reduce personnel exposure to radioactive materials
- Reliable and accurate monitoring of remediation processes in-situ within existing PVC wells

Thank you

Acknowledgements:
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