



# Monitoring of Subsurface Contaminant Remediation at the former Moab Uranium Mill Tailings site by In-Situ Nuclear Magnetic Resonance

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Austin, Tx



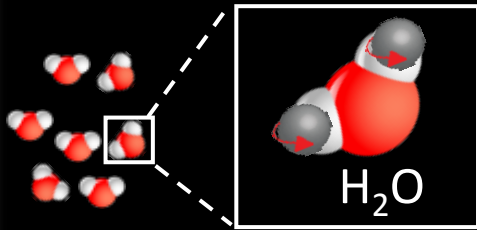
# Introduction:

- ❑ Advancements in remediation engineering have delivered innovative strategies for cleanup incorporating biological, geochemical, and hydrogeologic processes.
- ❑ Efficient and safe monitoring of environmental remediation processes of soil and groundwater is challenging
- ❑ Conventional methods rely largely on direct well fluid sampling and soil coring.
- ❑ The need to measure pore-scale properties of the formation along the remediation process

NMR approaches can be used to efficiently monitor remediation processes in-situ

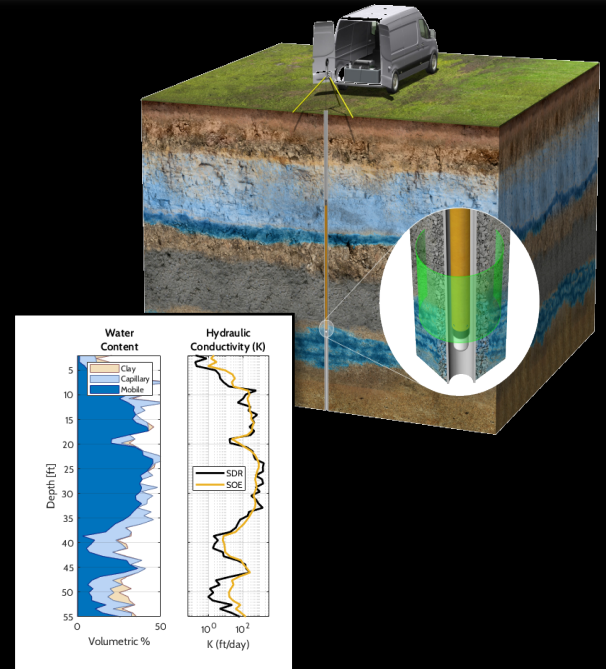


# Nuclear Magnetic Resonance (NMR)



Direct Detection  
of Hydrogen Nuclei

Medical MRI



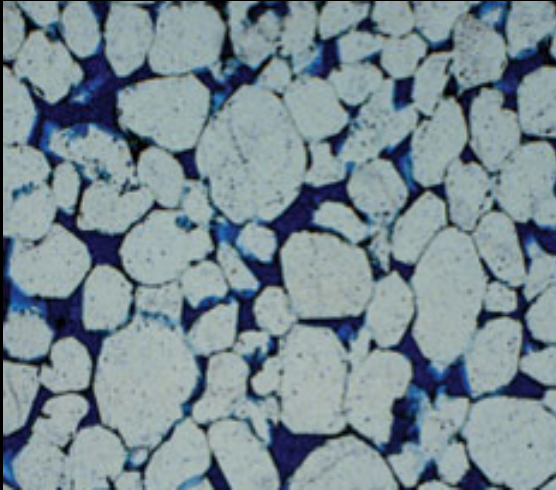
NMR Geophysics



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NMR GEOPHYSICS

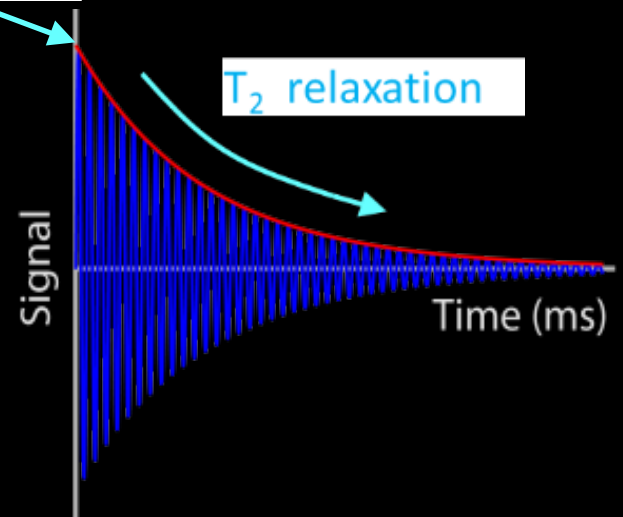
# Hydrologic Properties from NMR

Geologic Material



$A_0 \propto \text{water content}$

NMR Signal



## NMR Directly Measures

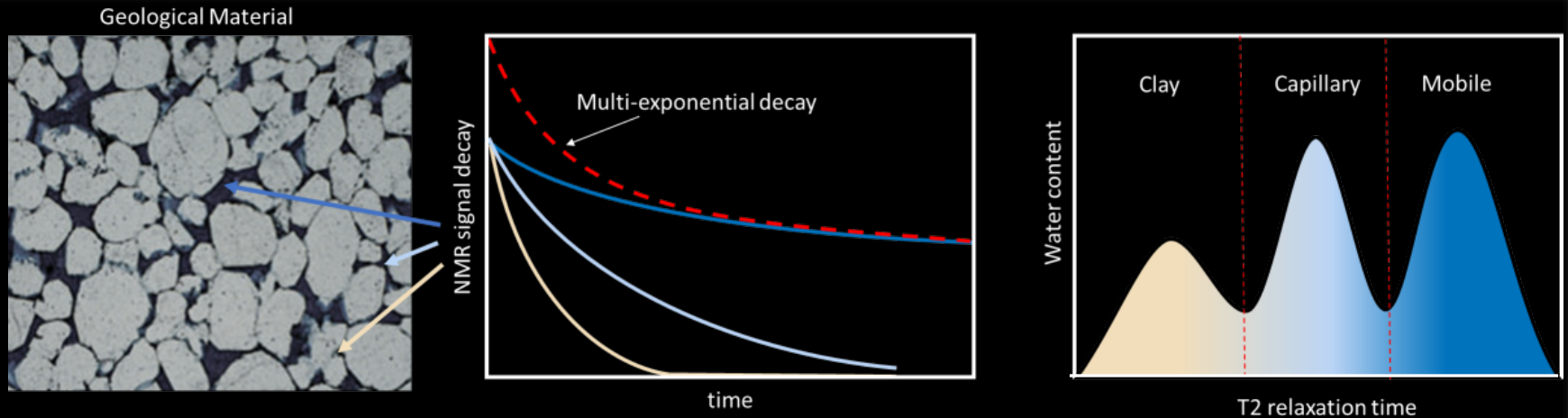
- Water Content, Porosity
- NMR Relaxation Times, Relative pore size



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# Hydrologic Properties from NMR



Modeling



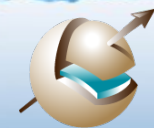
$$K_{SDR} = C_{SDR} T_2^2 S^2 N \quad K_{SOE} = C_{SOE} (\sum_i A_i T_2)^2$$

## NMR Directly Measures

- Water Content, Porosity
- NMR Relaxation Times, Relative pore size

## NMR Estimates

- Pore Size Distribution, Bound/Mobile Porosity
- Hydraulic Conductivity

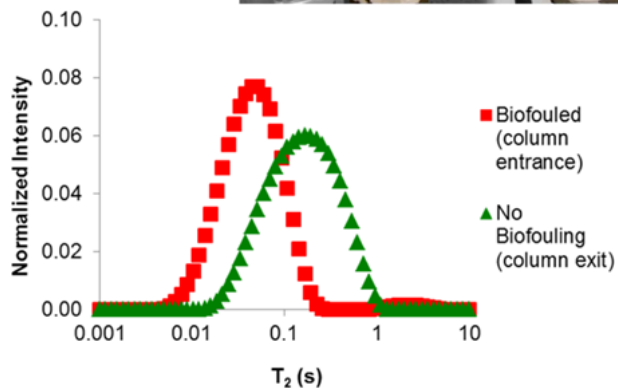
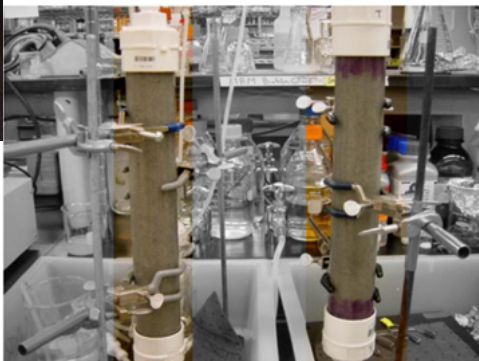


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# Previous work using NMR

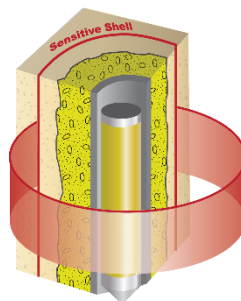
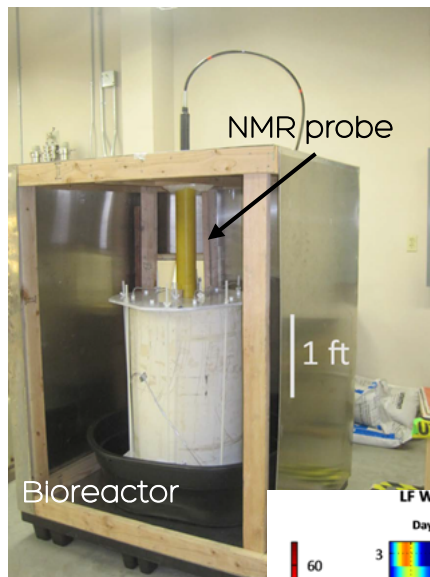
## In-situ detection of biofilm in porous media

### Benchtop NMR sensor

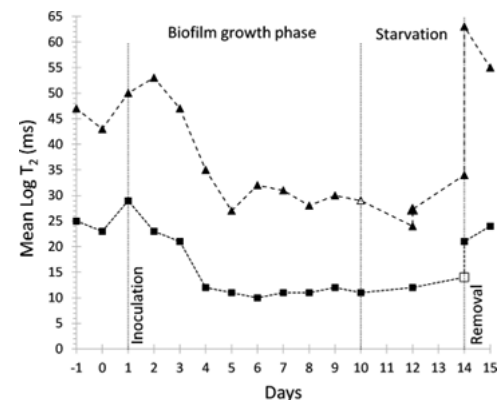


Sanderlin et al, 2013

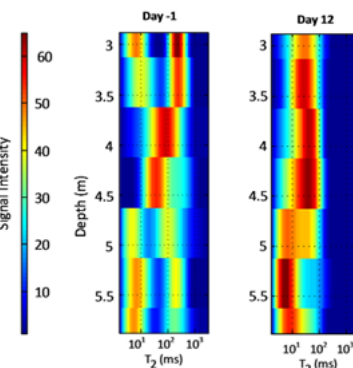
### Borehole NMR logging sensor



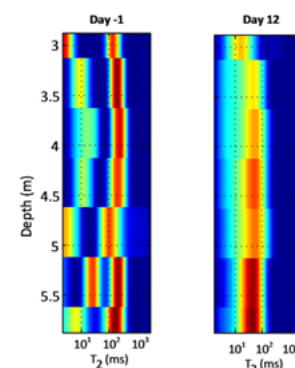
Javelin® NMR  
Deep View Sensitivity



LF Well Profile -  $T_2$  Distribution



HF Well Profile -  $T_2$  Distribution



Kirkland et al. 2015

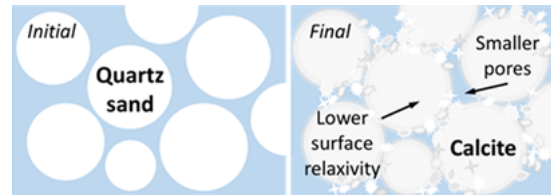
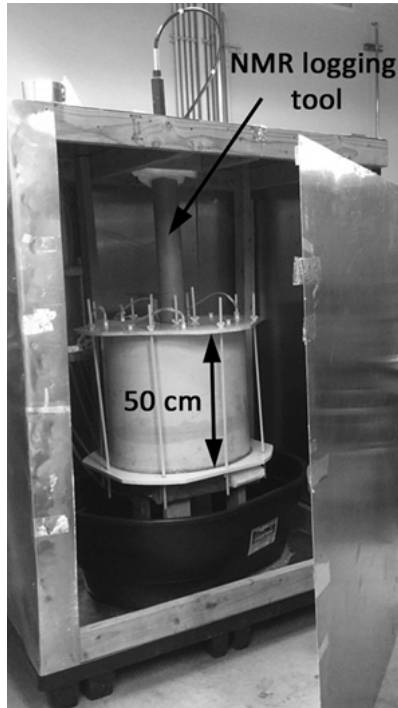


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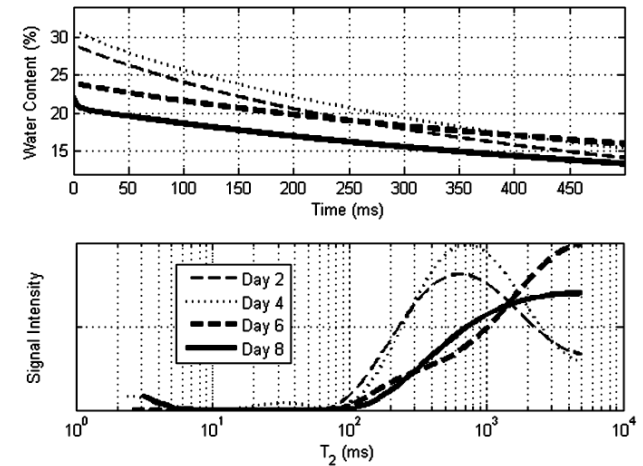
# Previous work using NMR

## In-situ detection of microbially induced calcite

Borehole NMR logging sensor



## NMR monitoring results

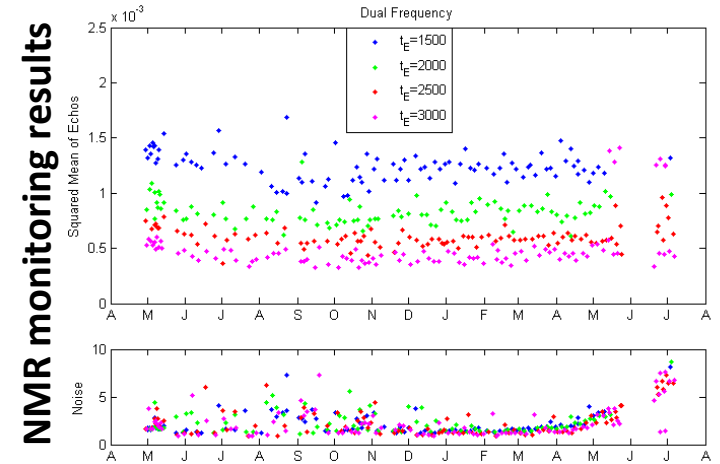


Kirkland et al. 2015

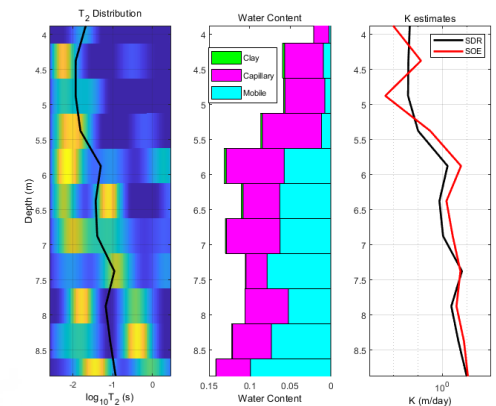
# Previous work using NMR

## NMR Monitoring of Geochemical and Mineralization Changes

- ❑ Hypothesis: Formation of mixed-valence minerals, such as magnetite, over time would reduce the NMR relaxation time decreasing the hydraulic conductivity
- ❑ Unattended NMR logging system for 15 months at Rifel, CO.



- ❑ No change in hydraulic conductivity was detected over time.
- ❑ The data are repeatable and stable (low variance) over the very long 15-month interval.

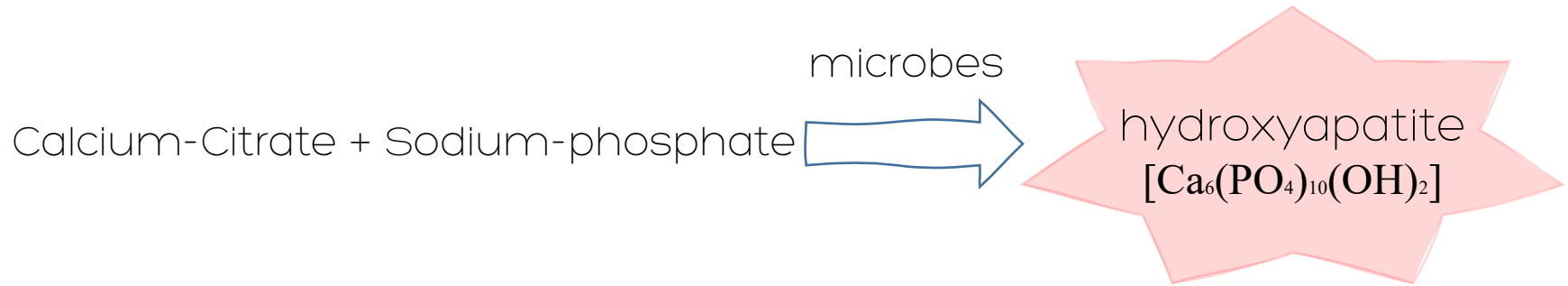




# Moab UMTRA



# Hydroxyapatite precipitation reaction

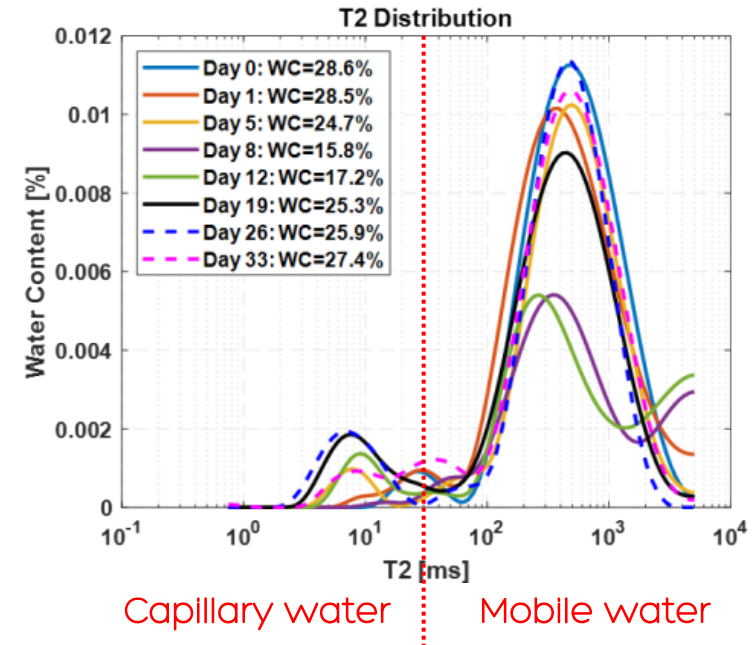
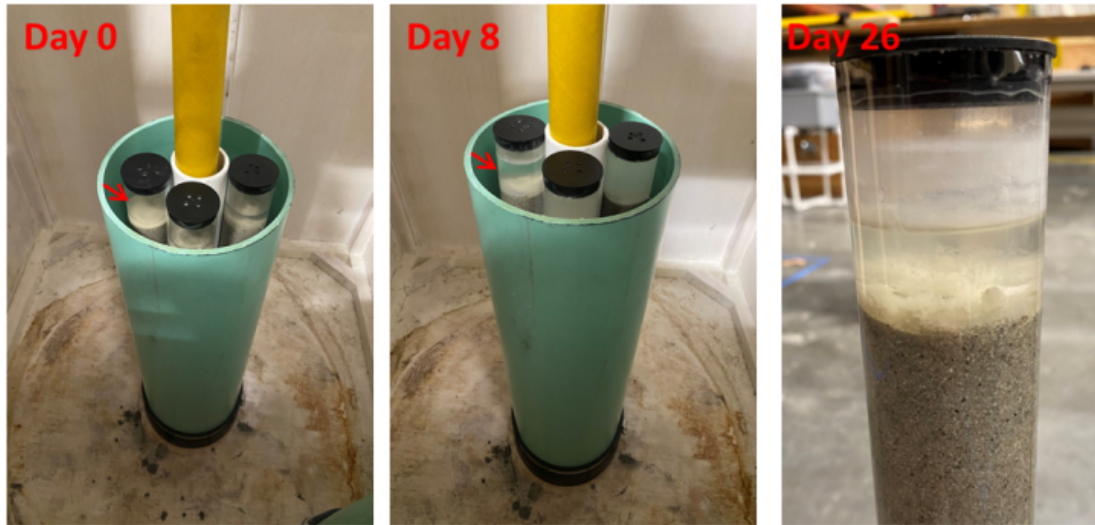


- ❑ Permeable barriers for containment of radioactive contaminants and heavy metals
- ❑ Strongly absorbs uranium, strontium, lead, and selenium
- ❑ Low water solubility
- ❑ High stability under reducing and oxidizing conditions
- ❑ Available and low cost



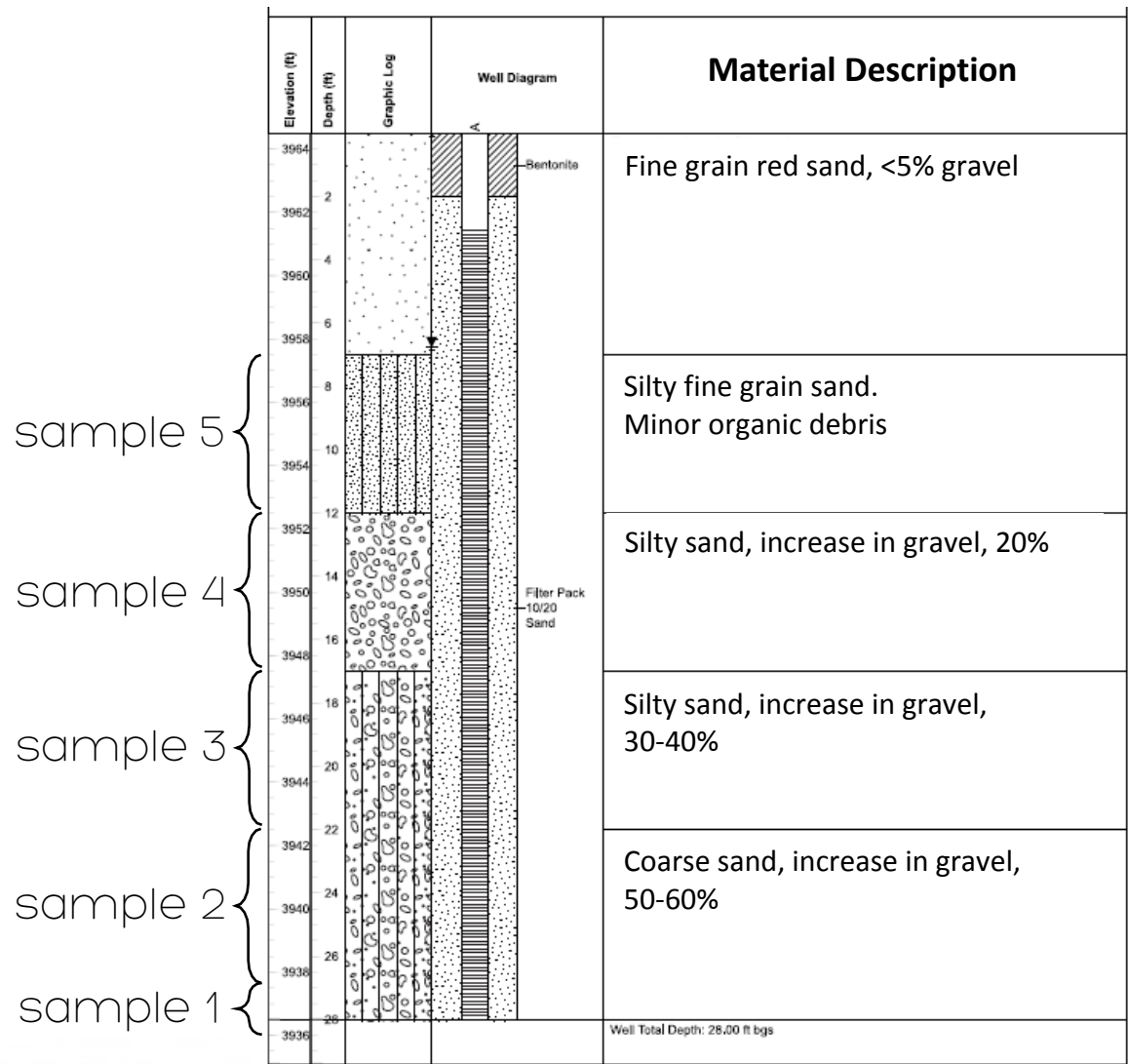


# Lab experiments with silica sand

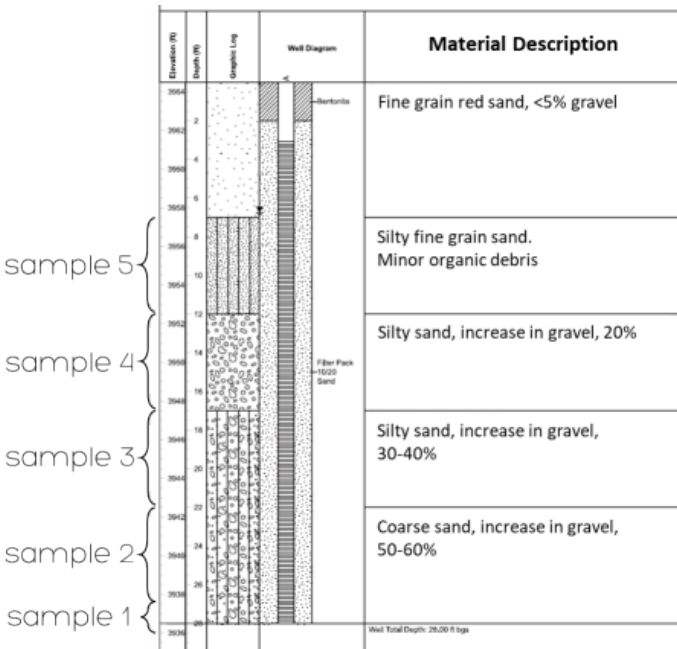


- ☐ Dart NMR probe was used for NMR monitoring
- ☐ Significant change in water layer above the silica sand during the first week, due to massive gas formation
- ☐ Mobile water content decreasing and capillary water increasing over time
- ☐ White precipitation is observed between and on top of the silica sand after three weeks into the monitoring

# Lab experiments with Moab UMTRA core samples



# Lab experiments with Moab UMTRA core samples



**Day 0**



**Day 8**



**Day 15**



**Day 29**



Iron sulfide minerals

- ❑ Massive gas ( $\text{CO}_2$ ) build up during the first week of monitoring
- ❑ Hydroxyapatite and iron sulfide ( $\text{FeS}$ ) minerals precipitations happen simultaneously over time



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# Lab experiments with Moab UMTRA core samples

**Day 0**



**Day 8**



**Day 15**



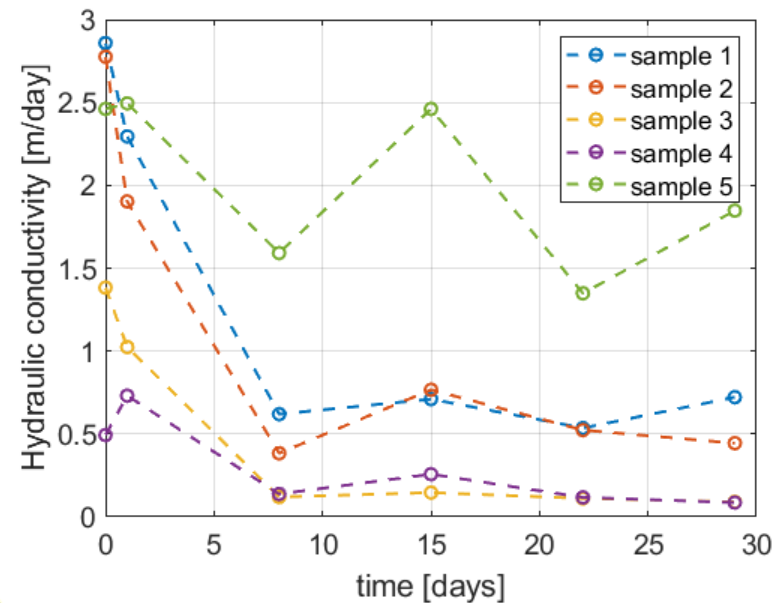
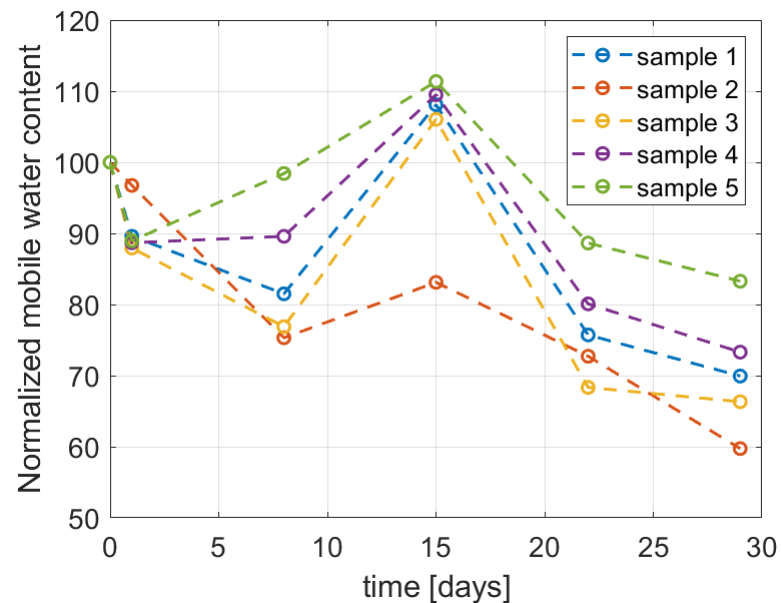
**Day 29**



- ❑ Massive gas ( $\text{CO}_2$ ) build up during the first week of monitoring
- ❑ Hydroxyapatite and iron sulfide ( $\text{FeS}$ ) minerals precipitations happen simultaneously over time



# Lab experiments with Moab UMTRA core samples



- ❑ Helios NMR core analyzer was used for monitoring
- ❑ Mobile water content decreasing and capillary water increasing over time, associated with apatite formation
- ❑ Significant drop in hydraulic conductivity during the first week



# Remote NMR Monitoring System Overview





# Remote NMR Monitoring System Overview

The screenshot displays the Javelin Remote Monitoring Dashboard. At the top, the title 'Javelin Remote Monitoring Dashboard' is on the left, and the date and time '26/04/2023 11:42:04' are on the right. Below the title bar, a status bar shows 'Network Status: Connected' and 'Tool Status: Winch 1 direction set to uphole'. A left-hand sidebar contains a list of navigation items: System Overview, Battery Voltage, Solar Charger, Laptop Charger, System Power, Probe Selection, Winch 1 Controls (which is highlighted with a blue bar), and Winch 2 Controls. The main content area is divided into several panels. The 'Winch 1 - Connect to Ports' panel includes input fields for 'Depth COM:' (value 9) and 'Tension COM:' (value 7), with 'Connect' and 'Disconnect' buttons below. The 'Winch 1 - Meter Readings' panel shows 'DEPTH: 4.35 m' and 'TENSION: 34'. The 'Winch 1 - Meter Setting' panel has a 'Set Winch 1 Depth (m):' input field with the value '0.00' and a 'Set Depth' button. The 'Winch 1 - Trigger Settings' panel features a 'Trigger Length (s)' slider ranging from 0.5 to 3, a 'Winch Direction' toggle set to 'Up' (with 'Down' and 'Up' options), and an 'Auto-trigger Winch' section with a toggle set to 'On'. A red notification box in the auto-trigger section states 'Auto-trigger finished' and provides instructions: 'Press and hold any Shift key, then click trigger below. Releasing Shift will stop the winch.' A 'Trigger' button is located at the bottom of this panel.

**Javelin Remote Monitoring Dashboard** 26/04/2023 11:42:04

**Network Status:** Connected

**Tool Status:** Winch 1 direction set to uphole

**System Overview**

- Battery Voltage
- Solar Charger
- Laptop Charger
- System Power
- Probe Selection
- Winch 1 Controls**
- Winch 2 Controls

**Winch 1 - Connect to Ports**

Depth COM: 9

Tension COM: 7

Connect Disconnect

**Winch 1 - Meter Readings**

DEPTH: 4.35 m

TENSION: 34

**Winch 1 - Meter Setting**

Set Winch 1 Depth (m): 0.00

Set Depth

**Winch 1 - Trigger Settings**

Trigger Length (s)

0.5 1 1.5 2 2.5 3

Winch Direction

Down Up

Auto-trigger Winch

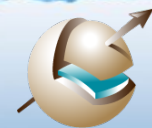
Off On

**Auto-trigger finished**

Press and hold any Shift key,  
then click trigger below.  
Releasing Shift will stop the winch.

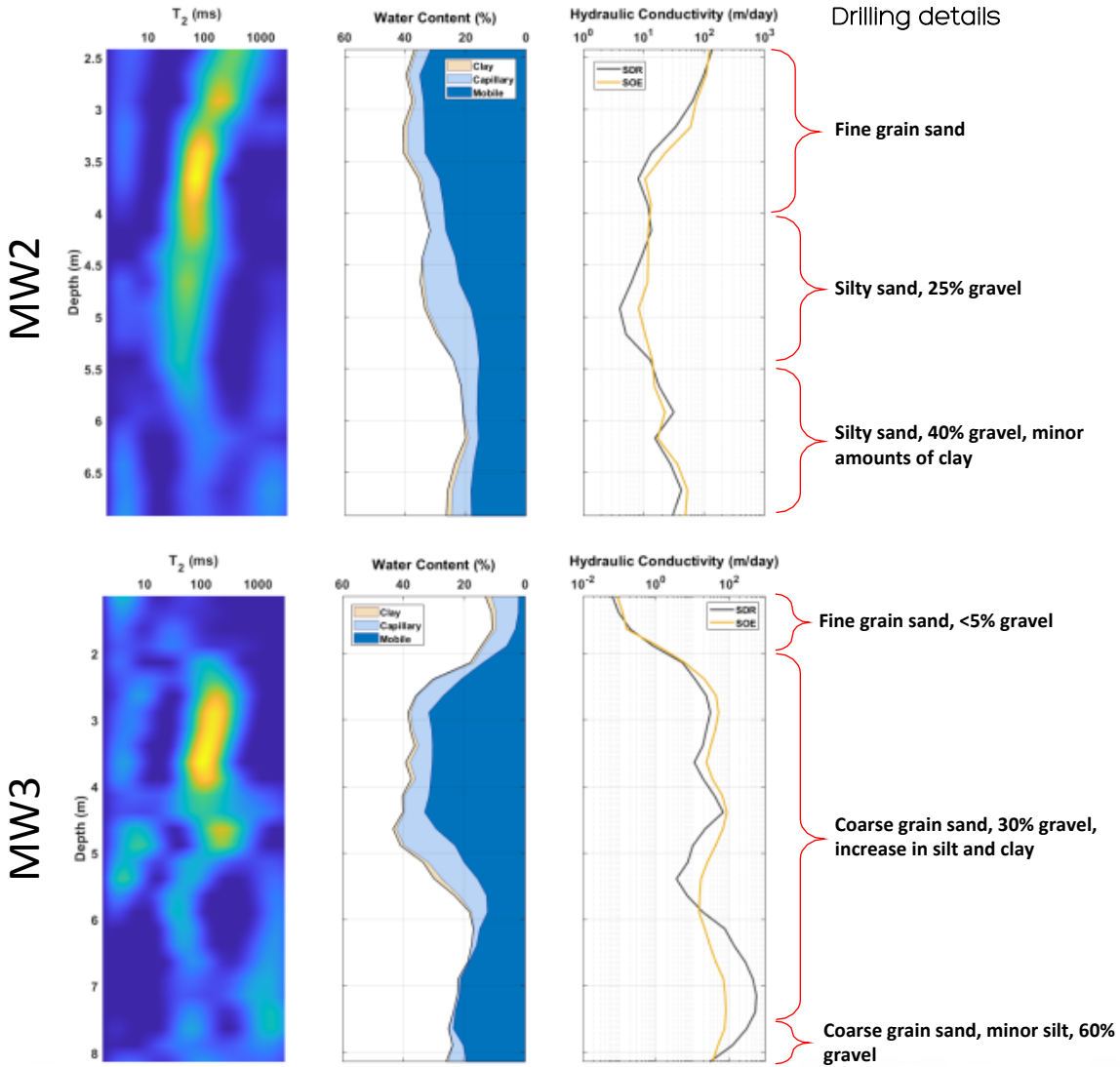
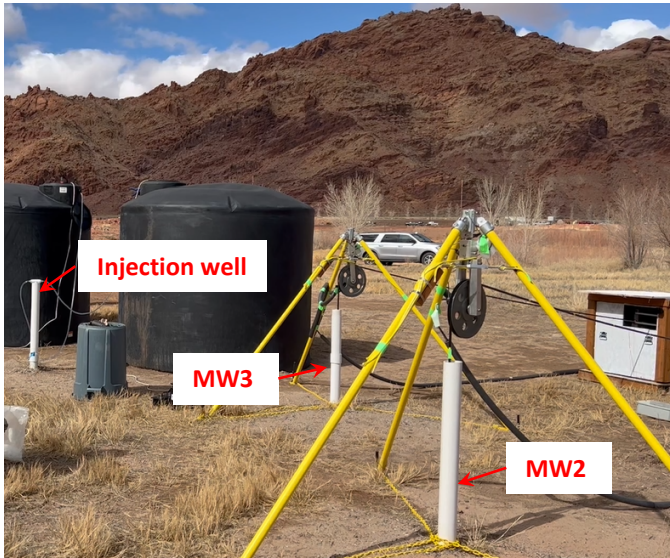
Trigger

# Injection of calcium-citrate and sodium-phosphate



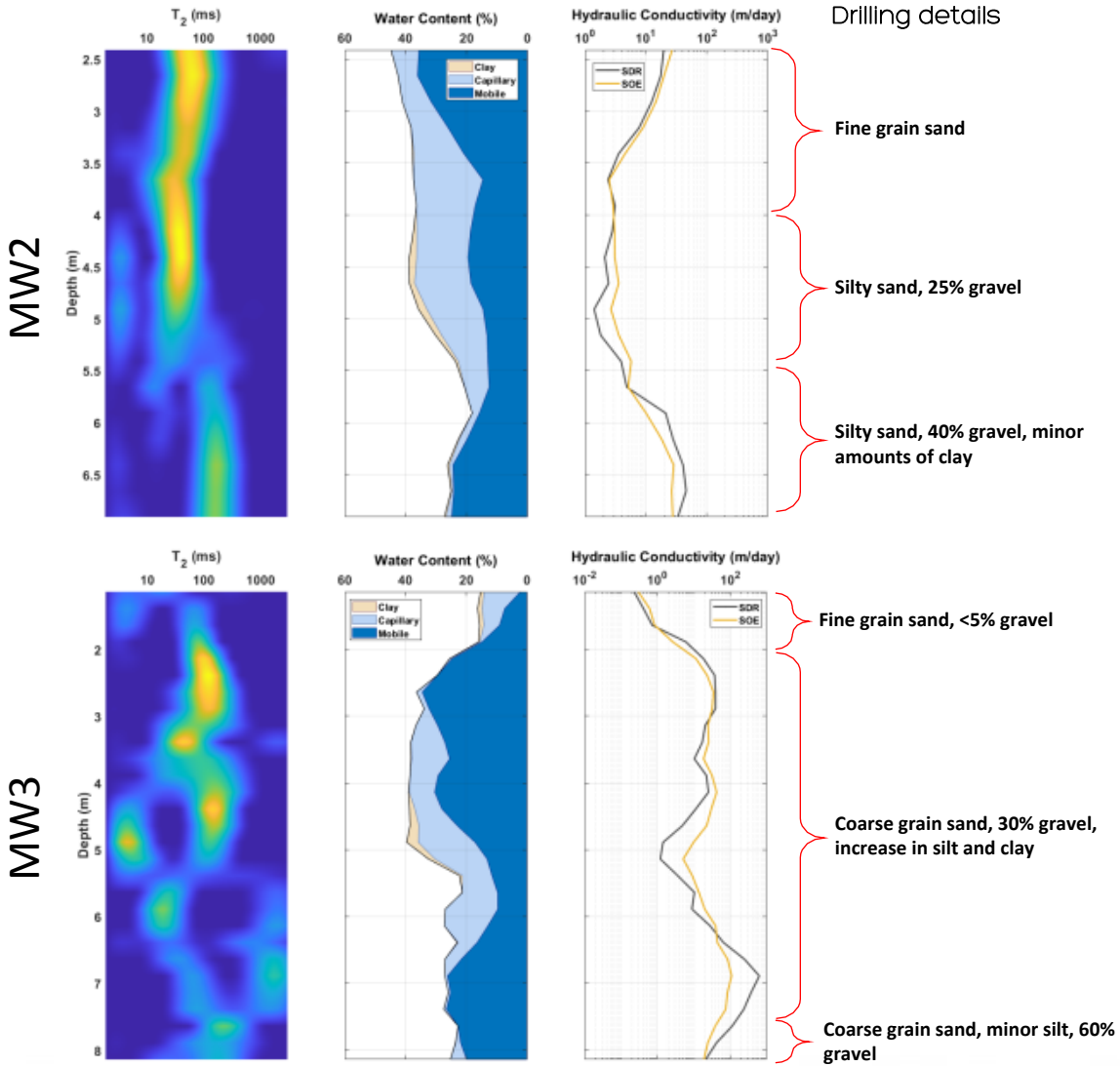
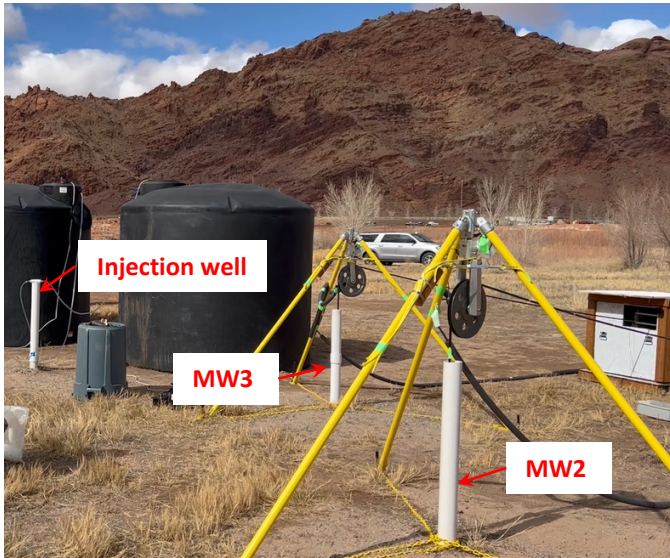
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# Results of Remote NMR monitoring-before injections



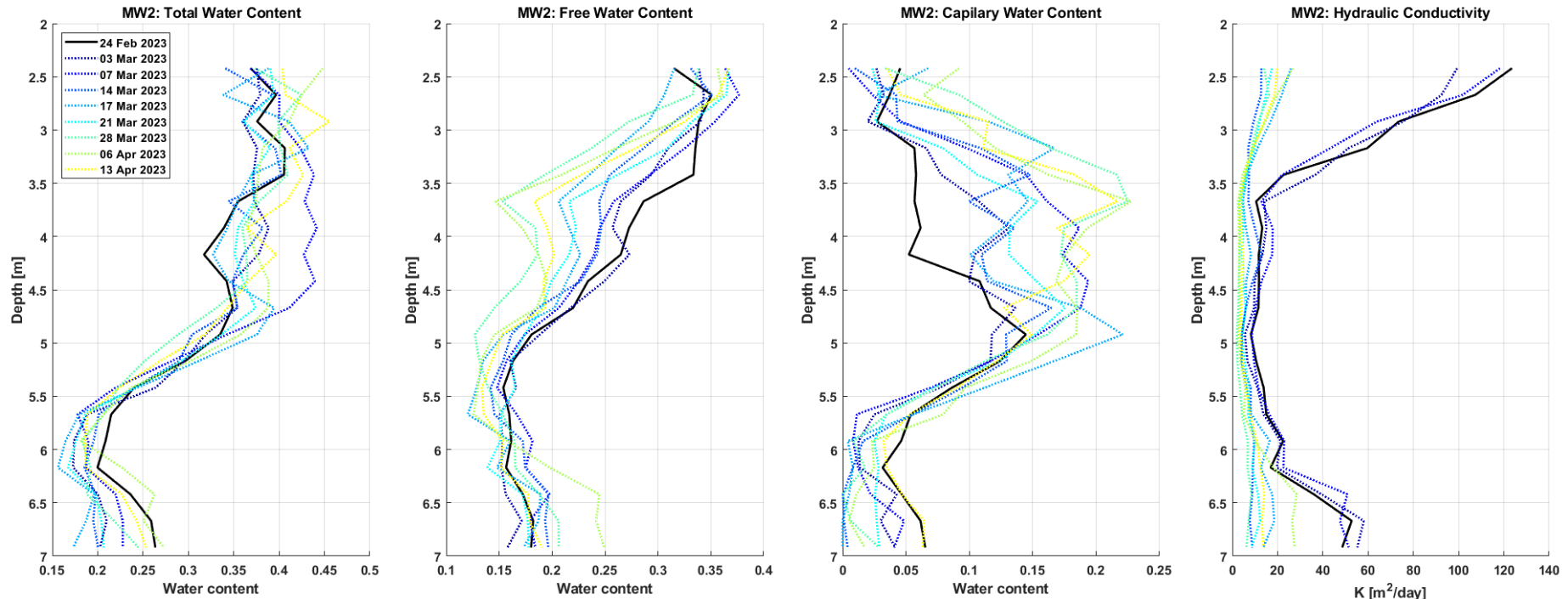


# Results of Remote NMR monitoring-After injections



# Results of Remote NMR monitoring MW2

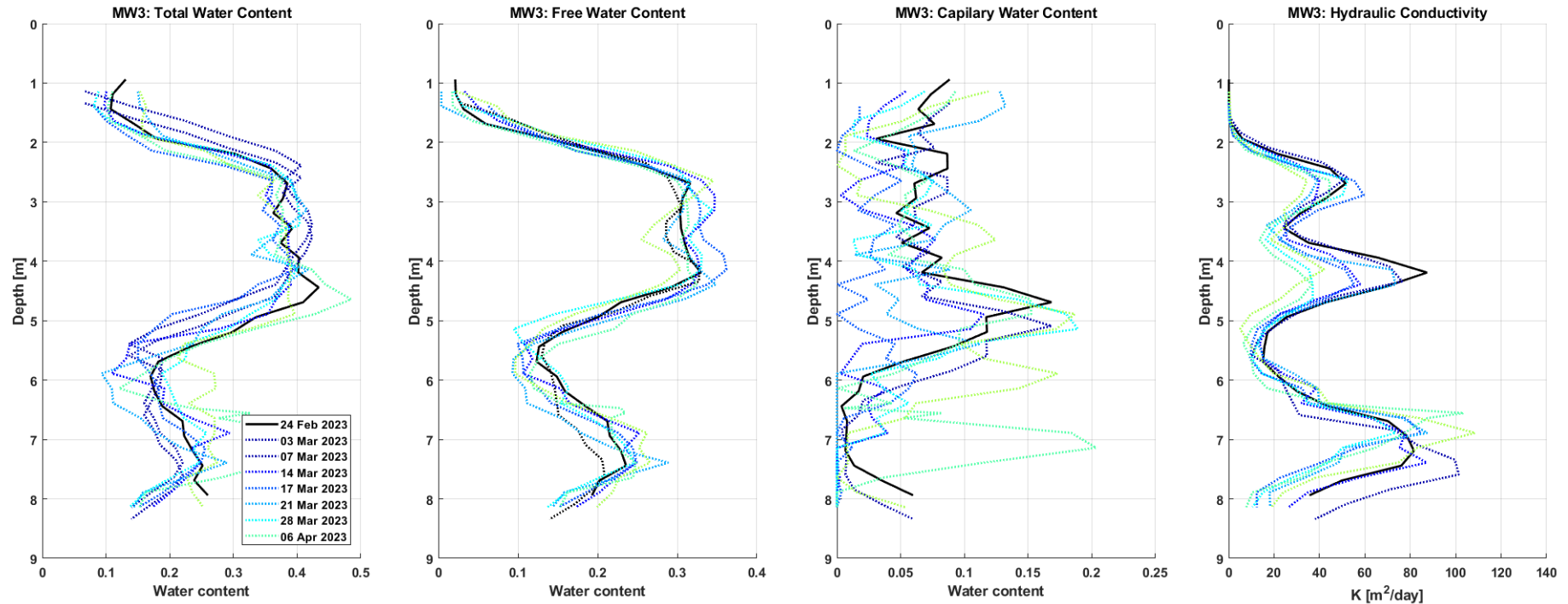
24 Feb 2023 - baseline  
02 Mar 2023 - 1st injection  
16 Mar 2023 - 2nd injection  
05 Apr 2023 - 3rd injection



- ❑ Significant decrease in mobile water content over time
- ❑ Significant increase in capillary water content over time
- ❑ Dramatic decrease in hydraulic conductivity

# Results of Remote NMR monitoring MW3

24 Feb 2023 - baseline  
02 Mar 2023 - 1st injection  
16 Mar 2023 - 2nd injection  
05 Apr 2023 - 3rd injection



□ No significant changes were observed over time in this well



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# Remote NMR Monitoring System Evacuation

May 2nd, 2023  
Evacuation day



May 3rd, 2023  
Flooding, 2 feet water around the wells



# Conclusions

Hydrogeological NMR measurements provide unambiguous information on hydrogeological properties:

- Direct detection and measurement of water content
- Relative pore size distribution
- Bound and mobile water fractions
- Estimation of hydraulic conductivity and transmissivity

NMR logging technology can provide:

- High resolution site characterization
- Efficient monitoring of remediation processes in-situ
- Remote, unattended long-term monitoring provides a very large cost savings when compared with repeated physical mobilizations to the site

# Thank you!

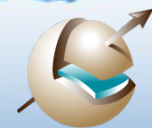
## Acknowledgements

This work was supported by US Department of Energy Grant Number DE-SC0020798.. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the US Department of Energy.

## Special thanks to:

- Moab UMTRA personnel

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