In-situ NMR measurements to quantify crude oil at National Crude Oil Spill Fate and Natural Attenuation Research site in Pinewood, MN

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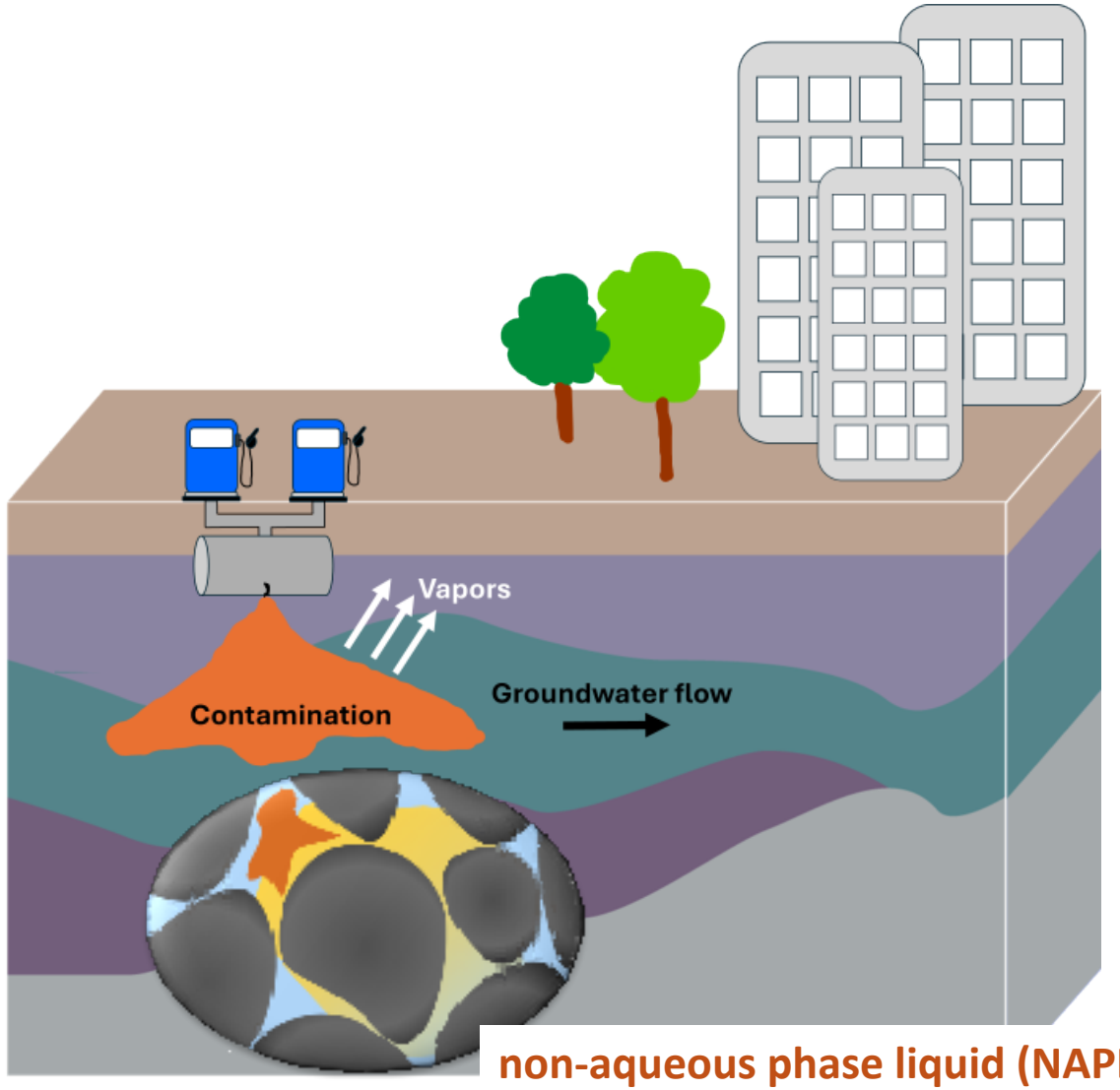
Problem: Hydrocarbon Contamination in Groundwater

- Surface spills, pipeline ruptures, underground tanks leakage
- Contamination due to different types of hydrocarbons: gasoline, diesel, motor oil, creosote, crude oil.
- Hydrocarbon contamination in the formation can be in non-aqueous phase liquid or dissolved phase.



non-aqueous phase liquid (NAPL)
dissolved phase

Characterization approaches: Traditional methods

VISTACLARA NMR GEOPHYSICS

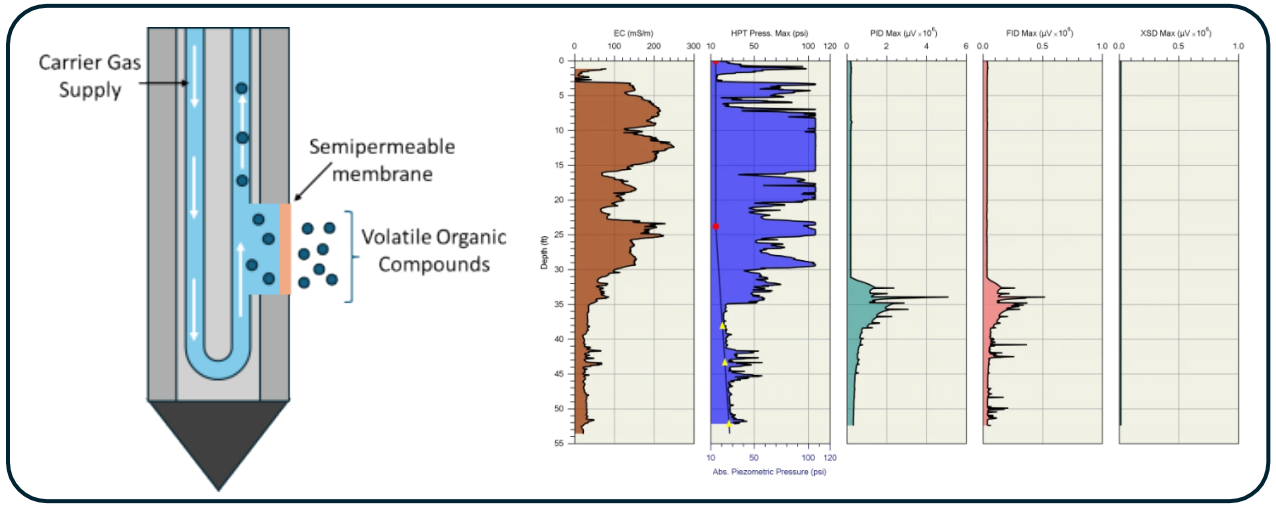
Sample coring and fluid sampling

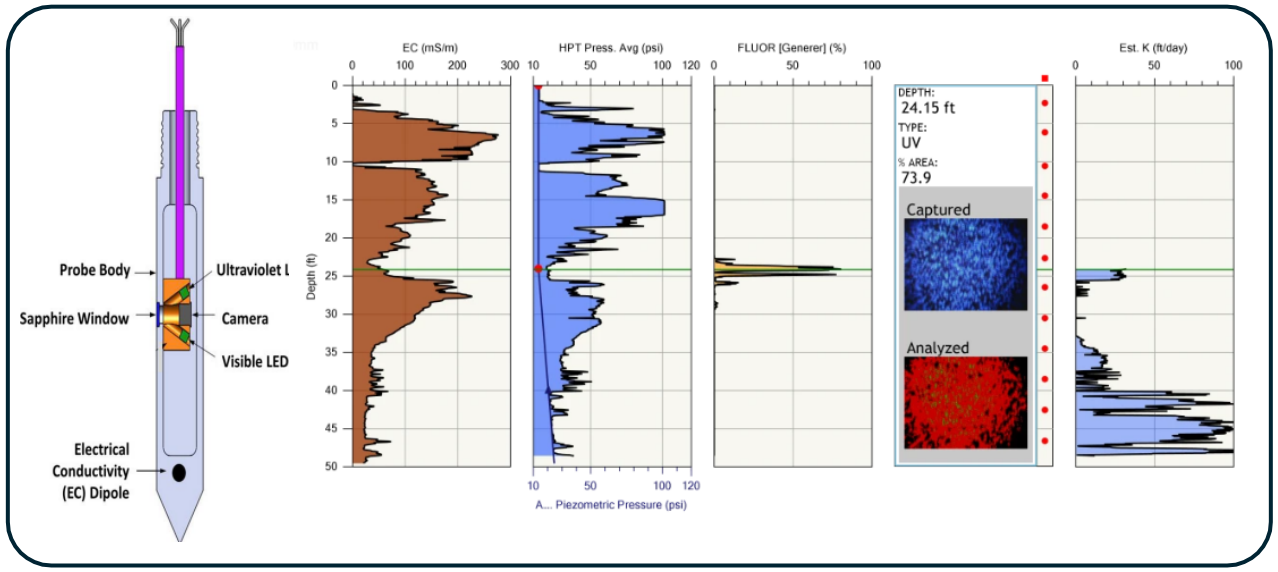
- ❑ Formation disturbance
- ❑ Provides smeared spatial and temporal response
- ❑ Health exposure risks
- ❑ investigation-derived waste disposal

Characterization approaches: In-situ methods

Direct push Membrane Interface Probe (MIP)

The MIP DP detects a volatile organic compounds with depth in soil.





Direct Push Optical Image Profiler (OIP)

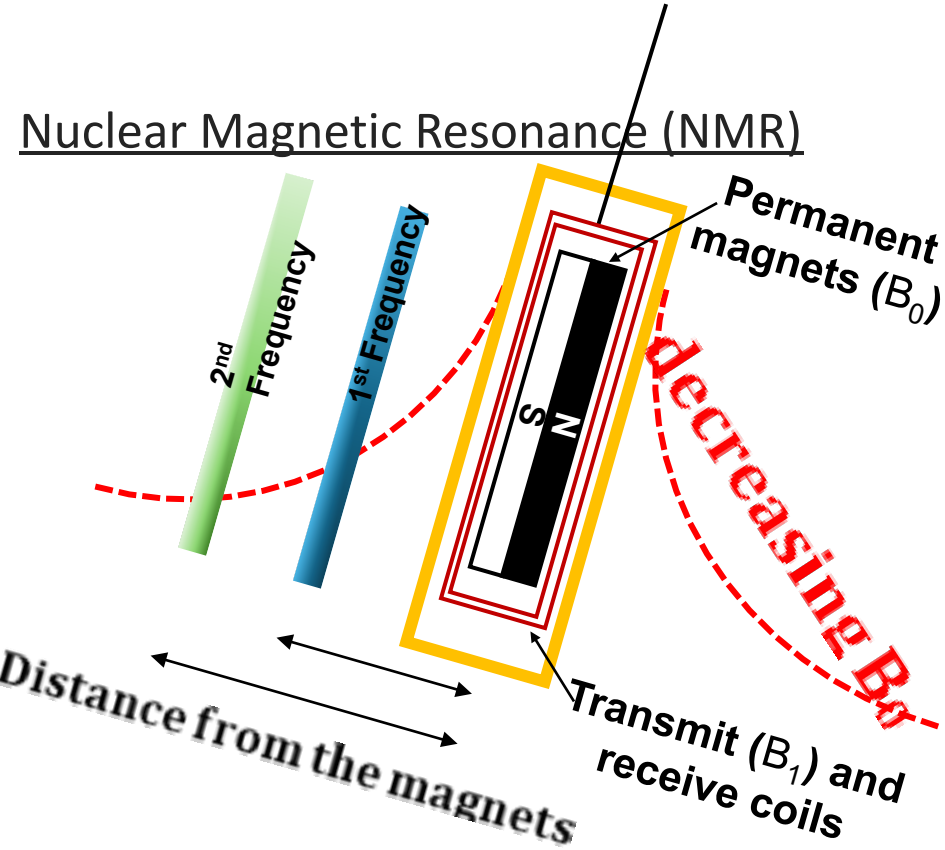
The OIP DP tool uses real time analysis of fluorescence images to detect the non-aqueous phase hydrocarbons.

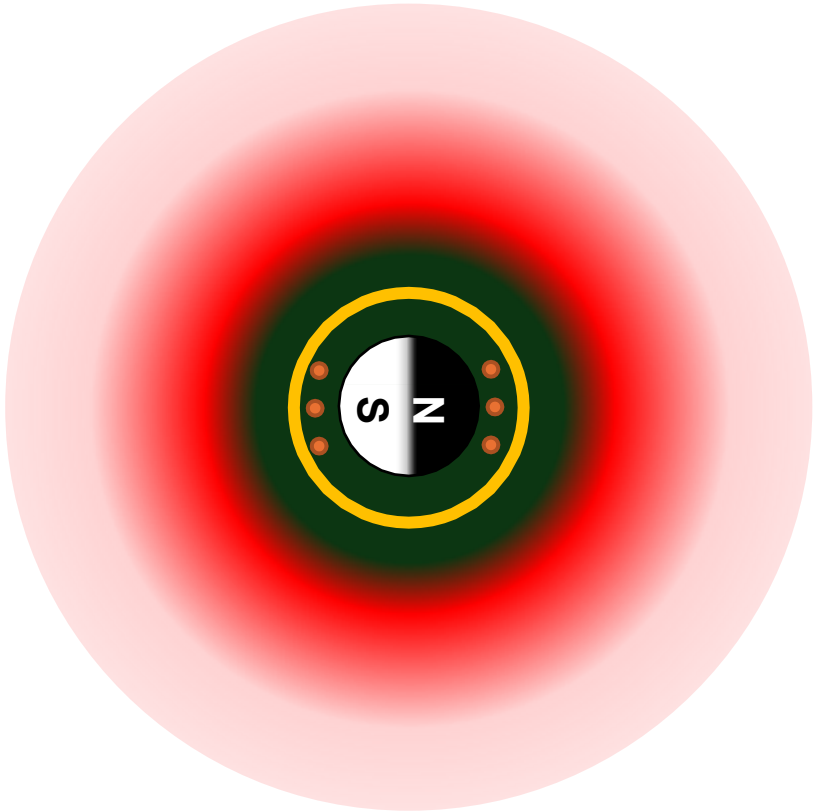
Both methods are not quantitative

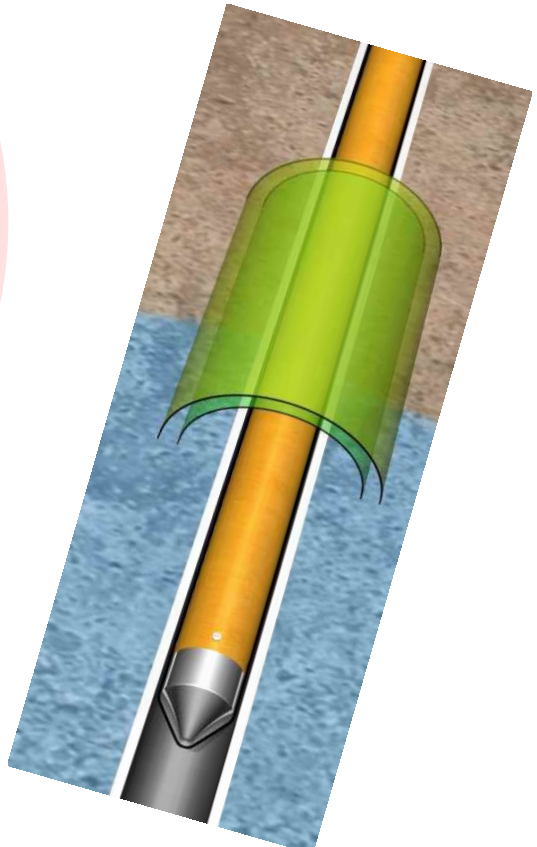
* Courtesy of Geoprobe

Characterization approaches: In-situ methods

Nuclear Magnetic Resonance (NMR)

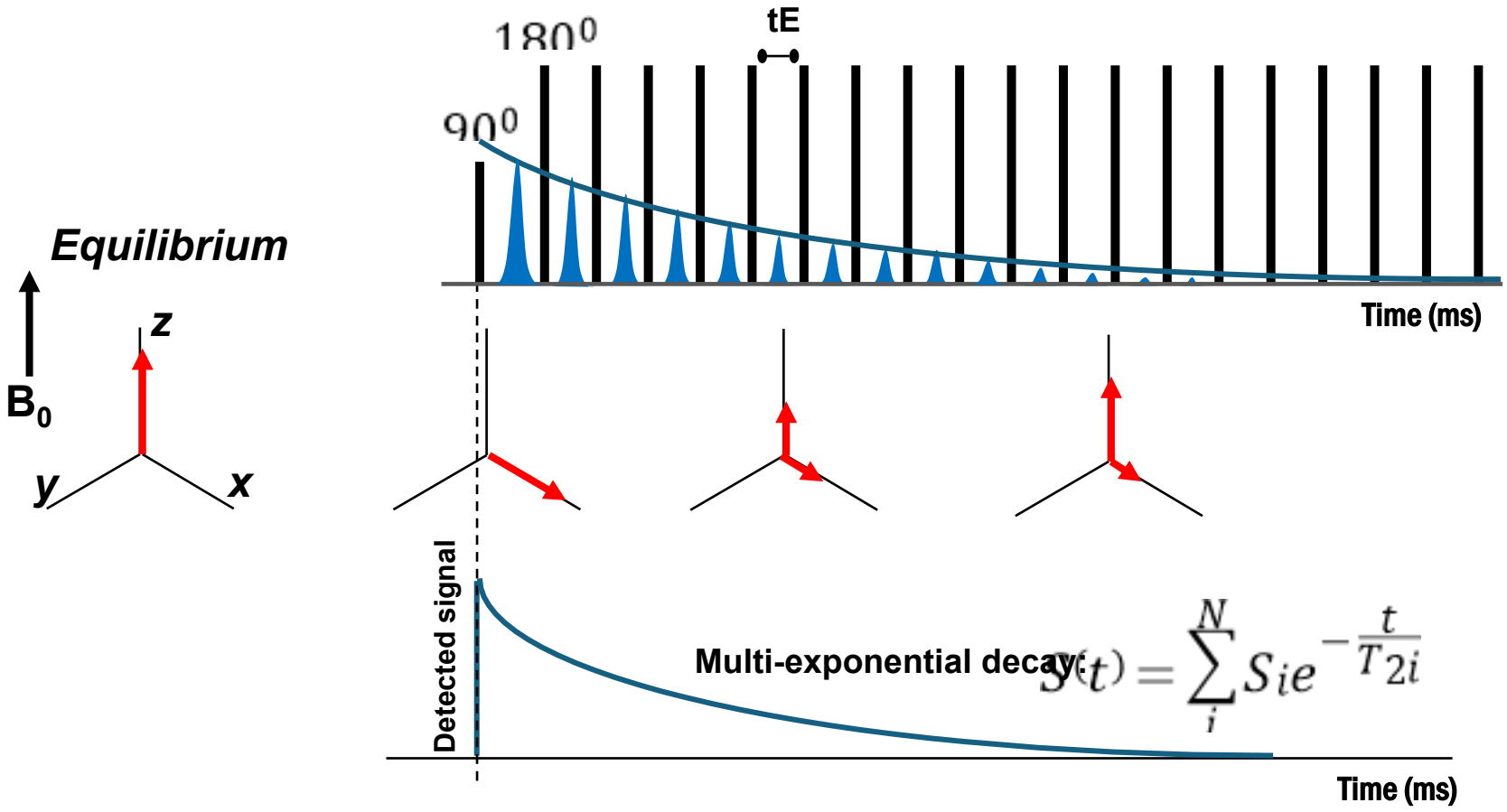


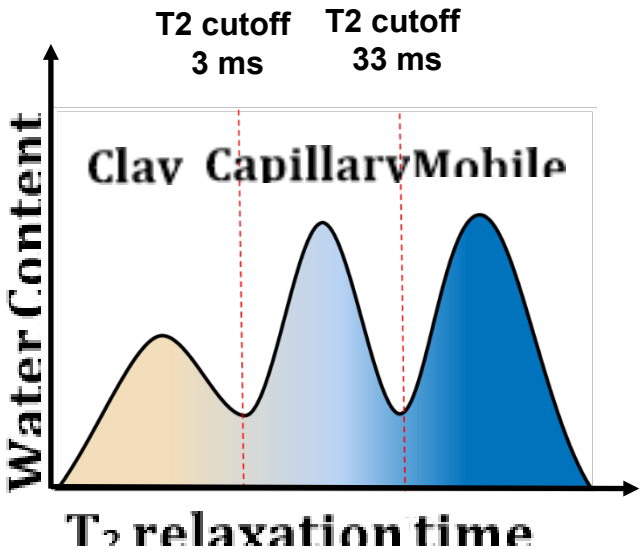




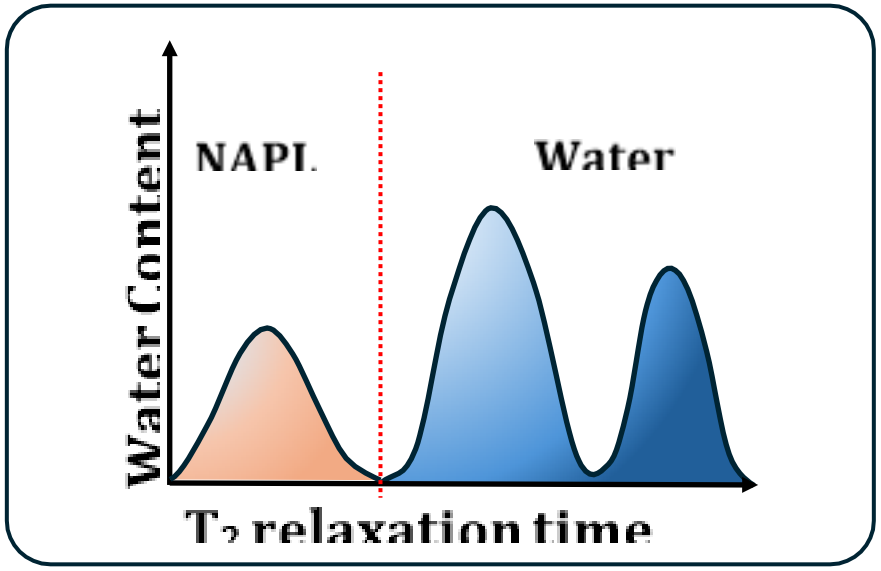
NMR relaxation measurement

CPMG is the most common NMR pulse sequence used in NMR geophysics



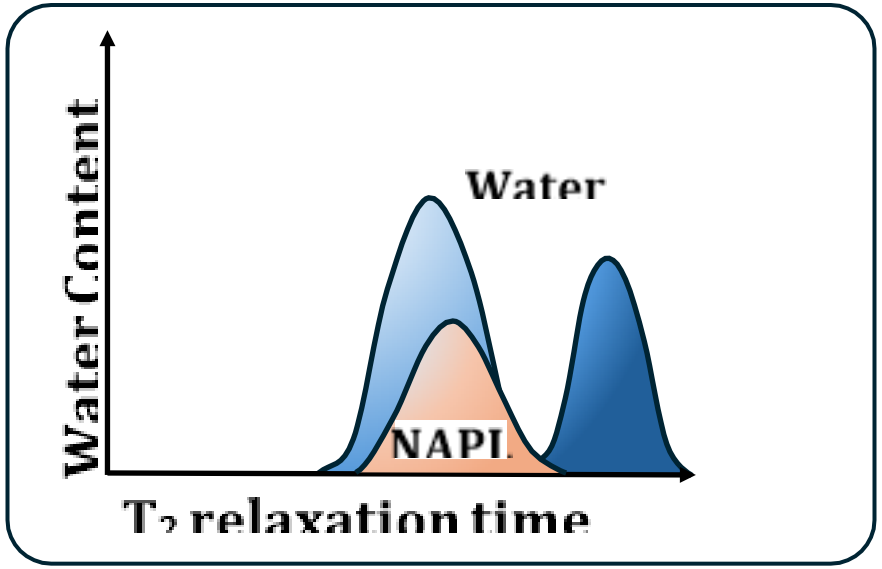


NMR relaxation measurement in multi-fluid system



Fluids with different T2 relaxation properties:

- Different peaks for water and NAPL.
- We can get different peaks for water in different pore sizes.
- Not very reliable.



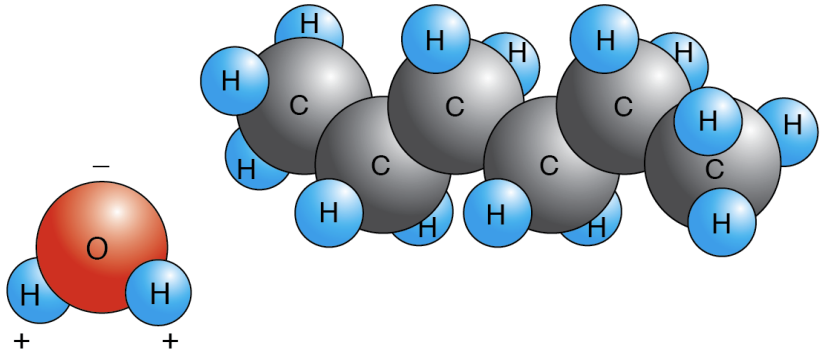
Fluids with overlapping/similar T2 relaxation properties:

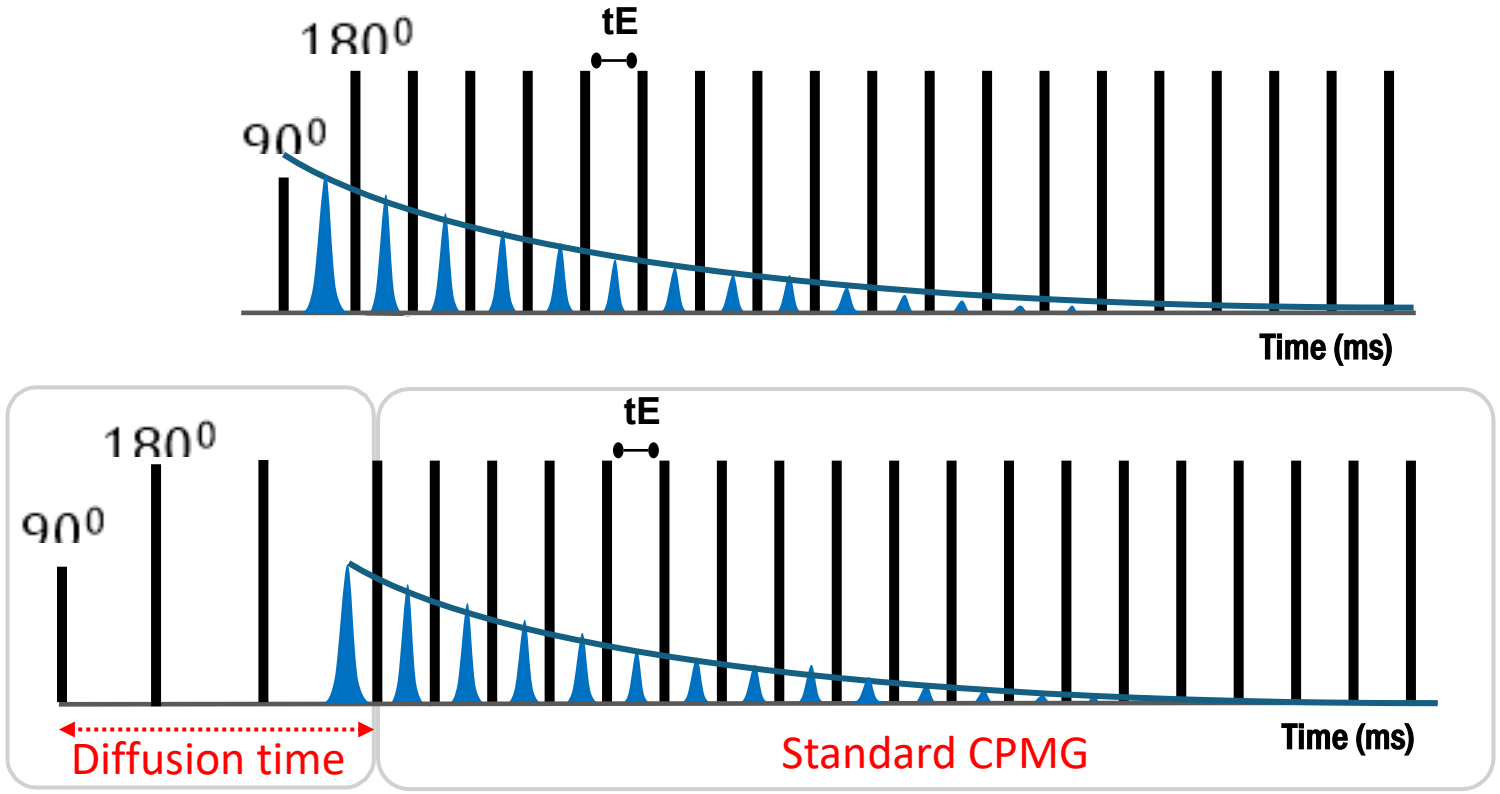
- Peaks are overlapping.
- Not possible to differentiate between different fluid types.

Diffusion NMR measurement

Measurement is done to separate fluids based of their diffusivity

- ❑ Diffusion is the function of viscosity
- ❑ Viscous long chain hydrocarbons have lower diffusivity than water
- ❑ Strong magnetic field gradient is required for diffusion NMR measurement
- ❑ Diffusion NMR experiment is repeated with multiple diffusion times





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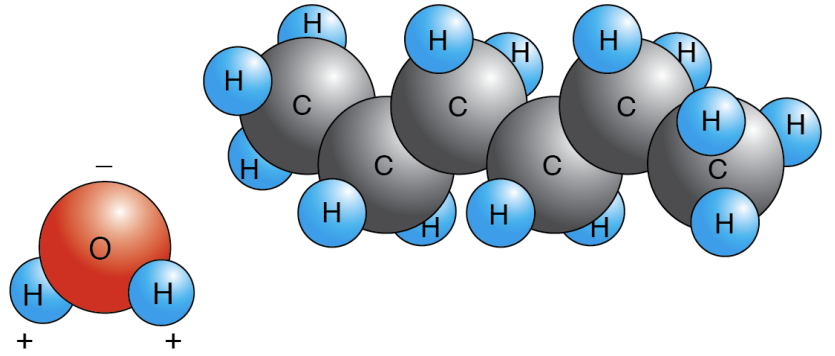

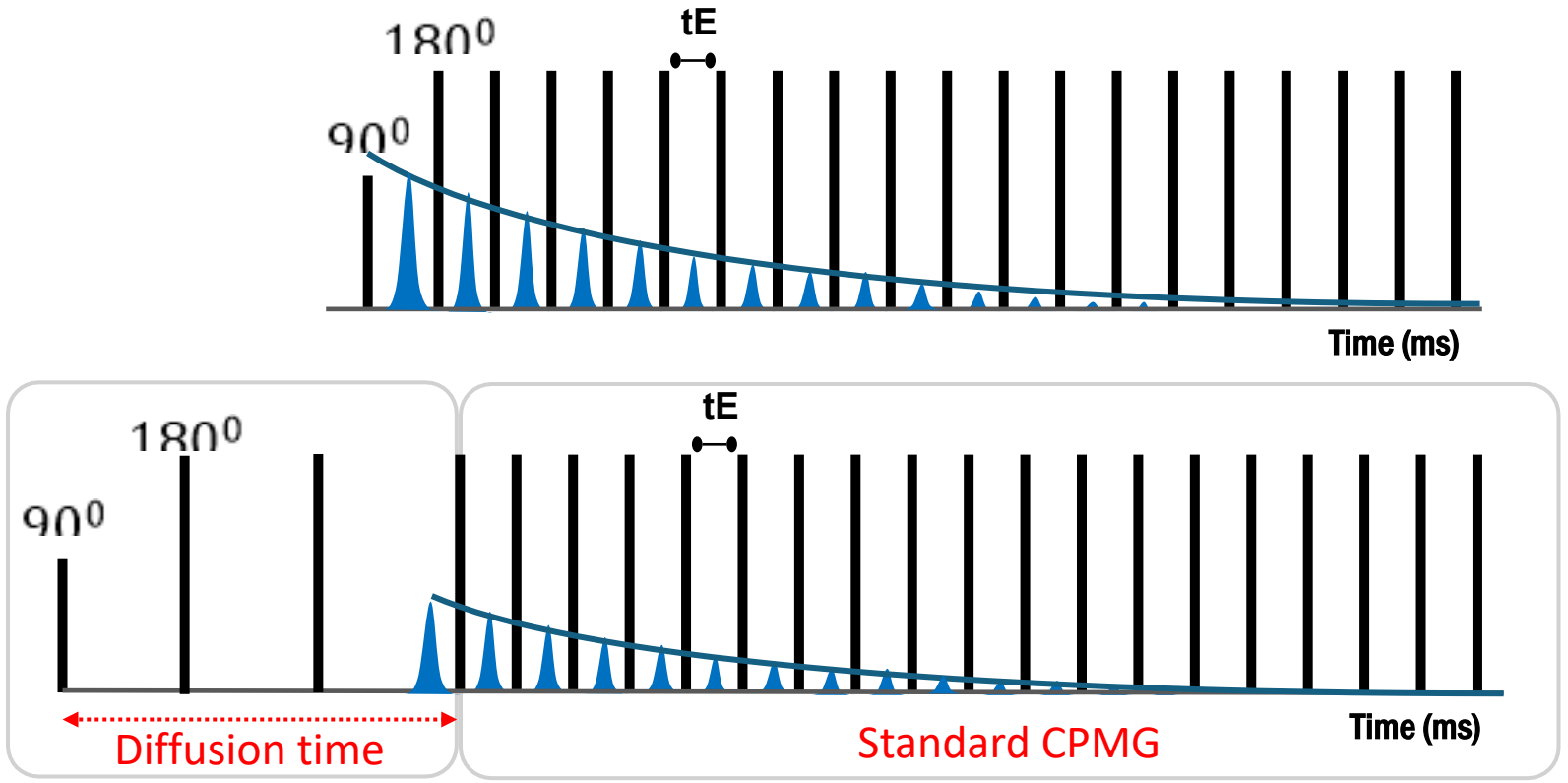

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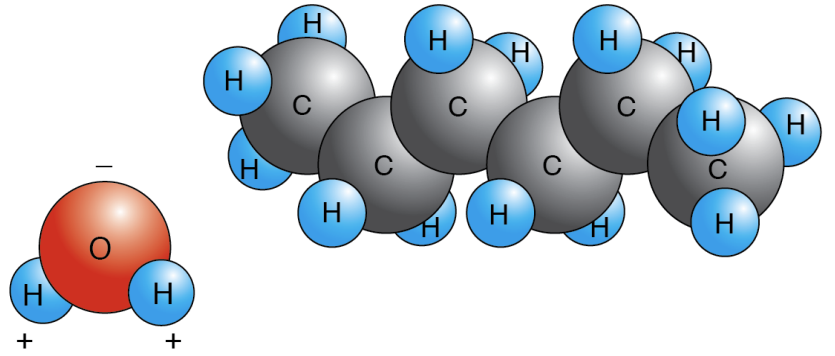
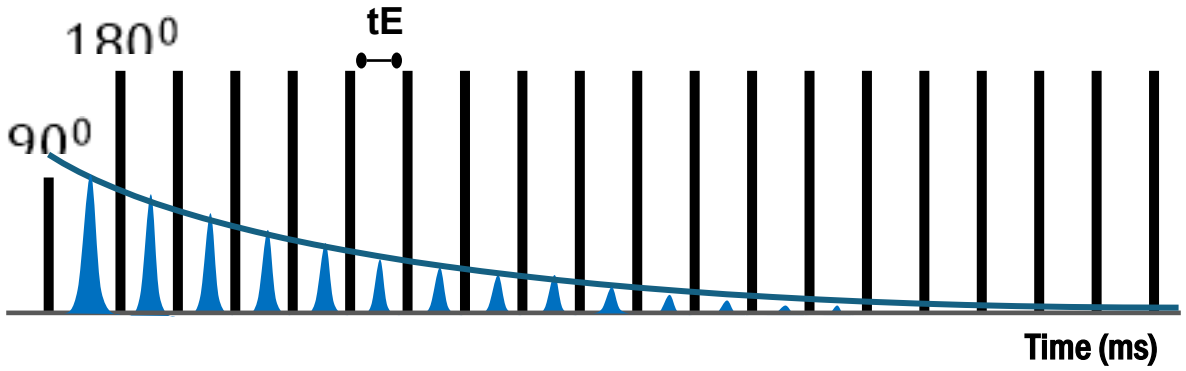
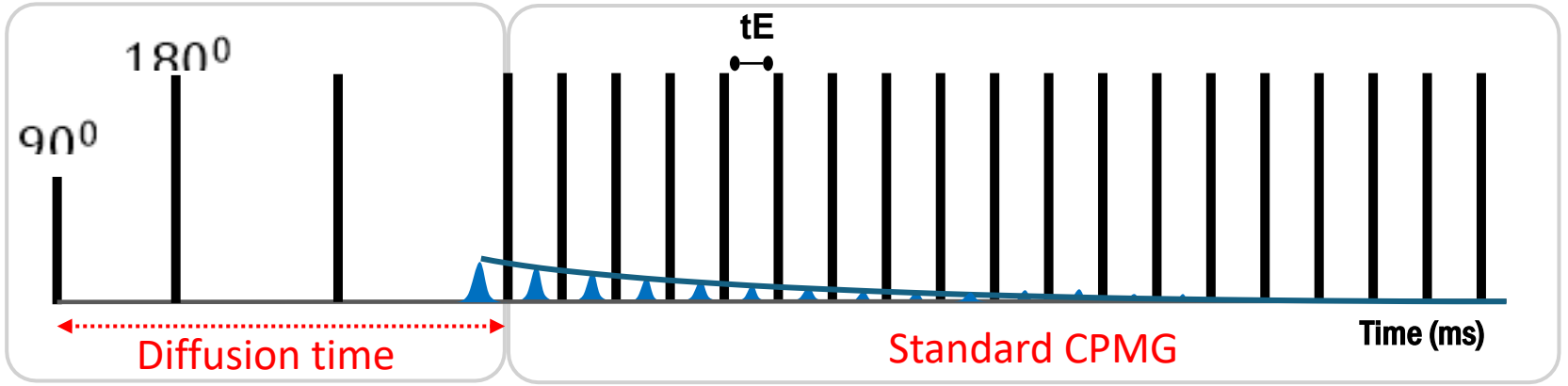


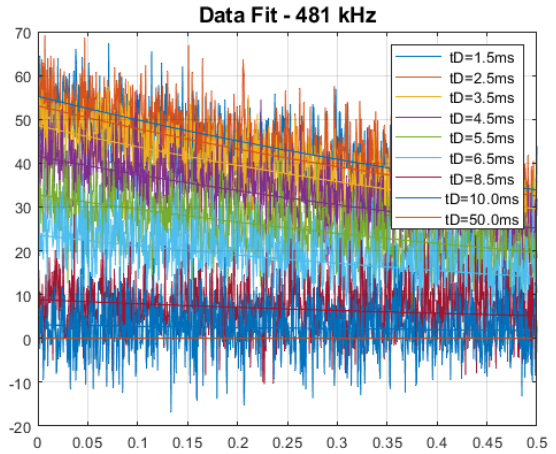


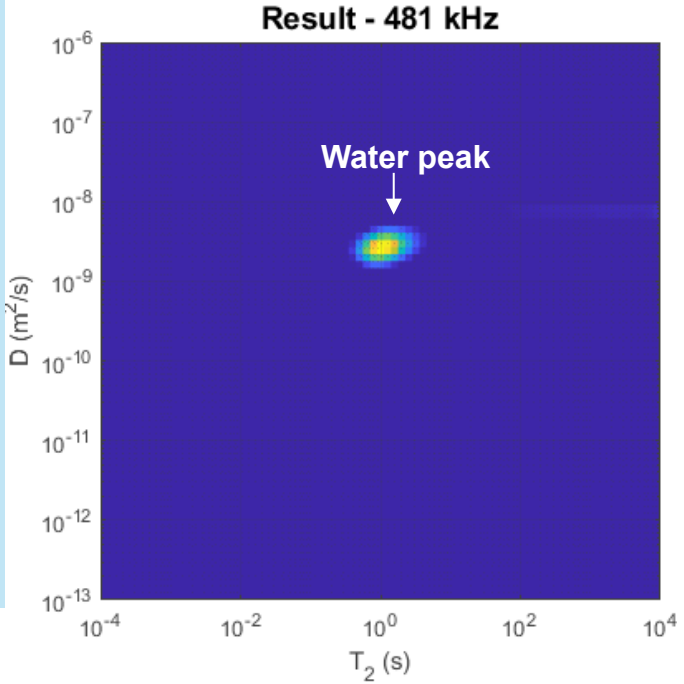


Diffusion NMR measurement

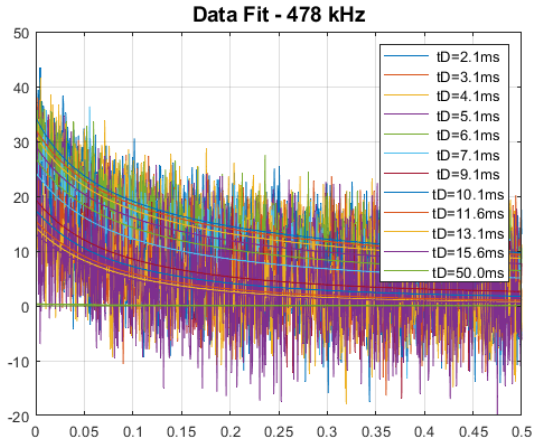
Diffusion NMR experiment is analyzed to obtain diffusion-T2 correlation maps

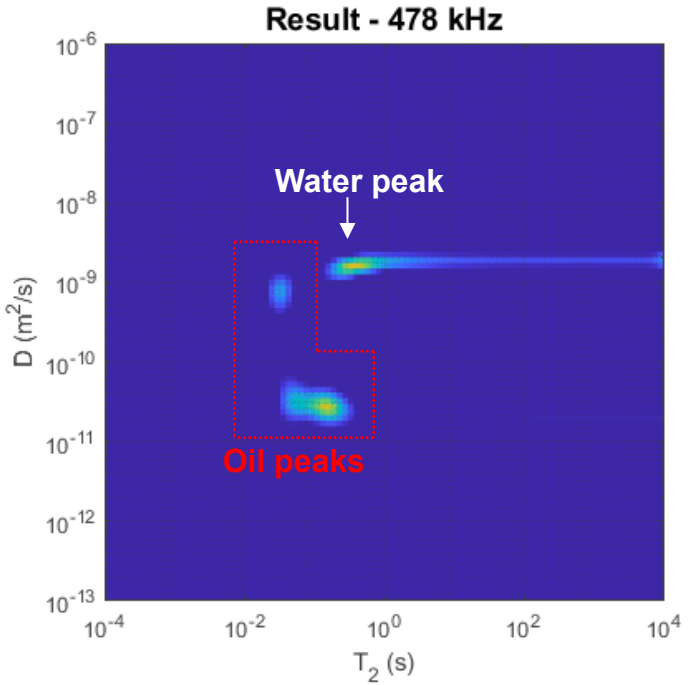
Bulk Water



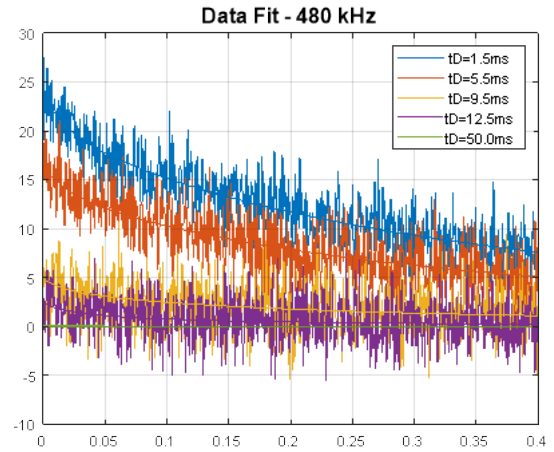


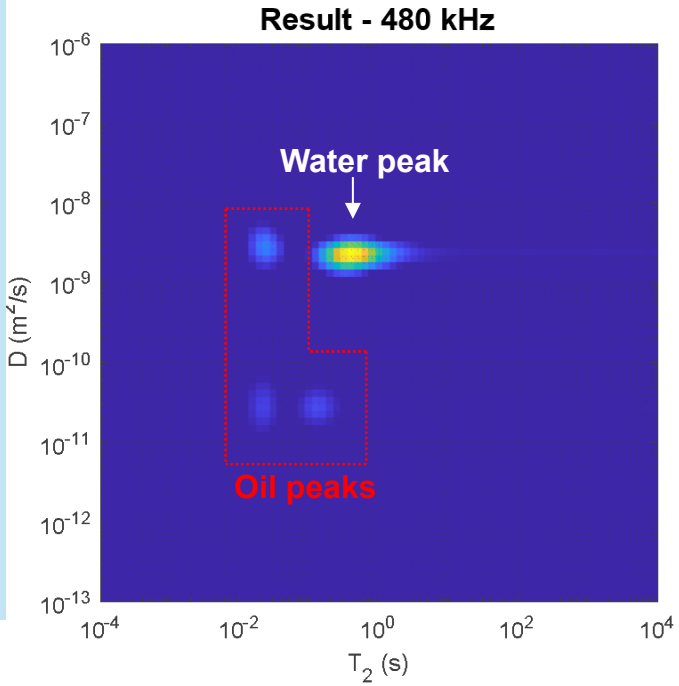
50% Water: 50% Oil





80% Water : 20% Oil





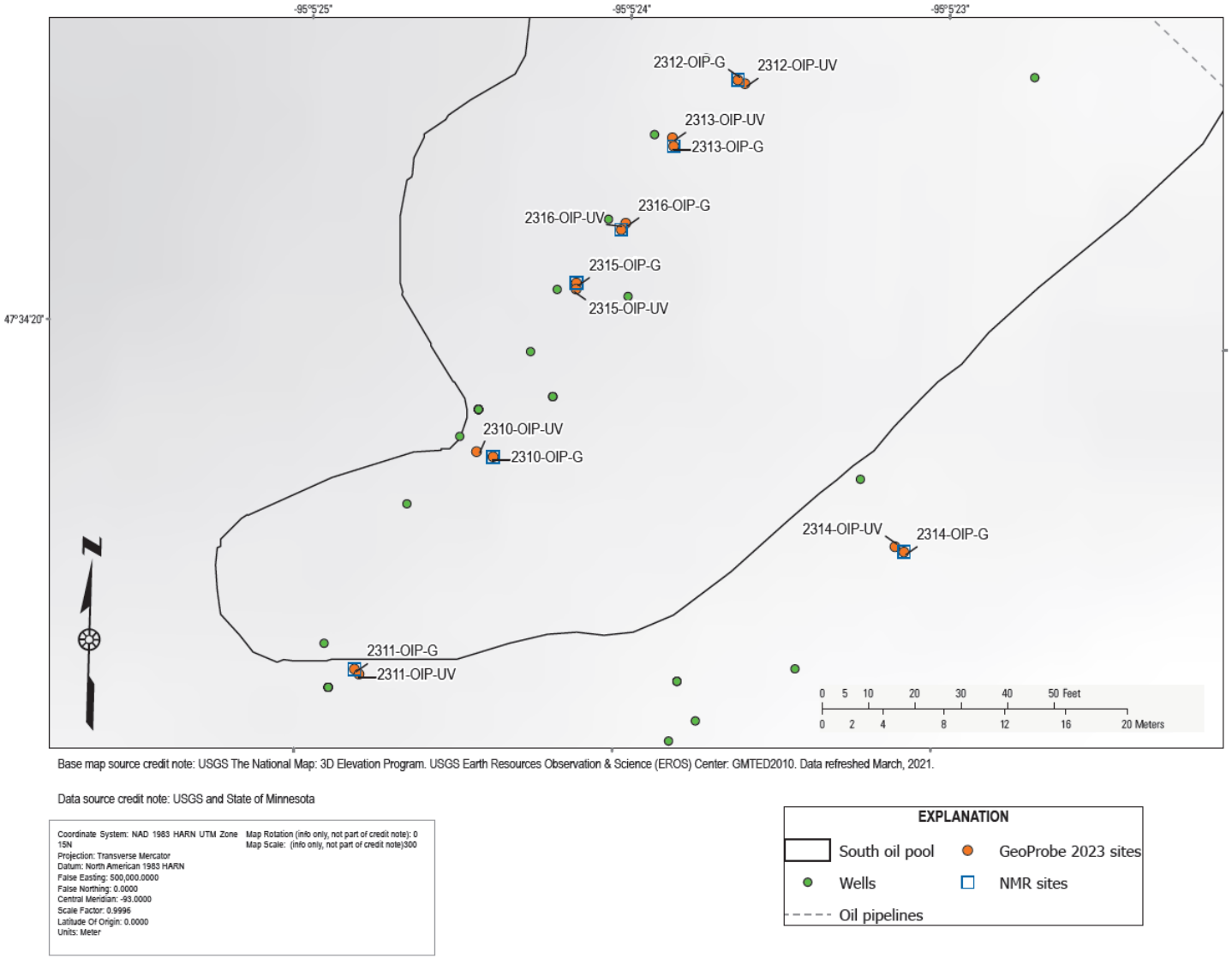
Diffusion NMR investigation at National Crude Oil Spill Fate and Natural Attenuation Research site in Pinewood, MN

Bemidji Investigations: Methods

VISTACLARA NMR GEOPHYSICS

Experiments:

- ❑ Initial logs with OIP-UV (light NAPL fuels and oils) and OIP-G (heavy NAPL fuels, oils, and tars) to identify the presence of NAPL and location for Direct Push (DP) NMR.
- ❑ OIP was combined with Hydraulic Profiling Tool (HPT).
- ❑ DP NMR measurements at each location.



Base map source credit note: USGS The National Map: 3D Elevation Program. USGS Earth Resources Observation & Science (EROS) Center: GMTED2010. Data refreshed March, 2021.

Data source credit note: USGS and State of Minnesota

Coordinate System: NAD 1983 HARN UTM Zone 15N
Projection: Transverse Mercator
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False Northing: 0.0000
Central Meridian: -93.0000
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Units: Meter

Map Rotation (info only, not part of credit note): 0
Map Scale: (info only, not part of credit note)300

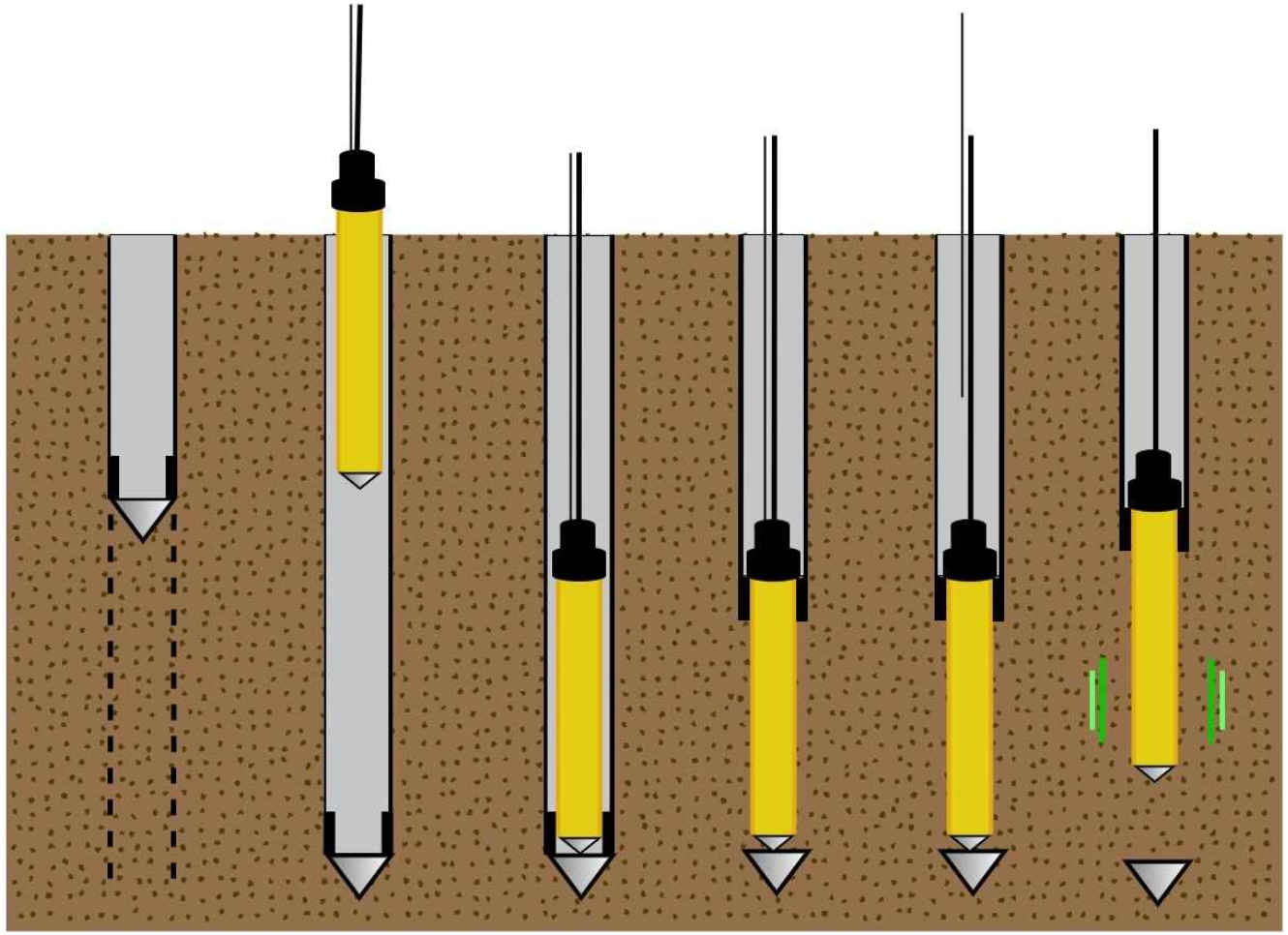
EXPLANATION

- South oil pool
- GeoProbe 2023 sites
- Wells
- NMR sites
- Oil pipelines

Bemidji Investigations: DP NMR tool use

Deployment:

- ❑ Empty 2.25-inch rods are advanced to the desired depth.
- ❑ 1.40-inch ID NMR probe is deployed through the rods using extendable push rods.
- ❑ The drill rods are retracted using the DP machine, while the extendable push rods are used to hold the probe in place.



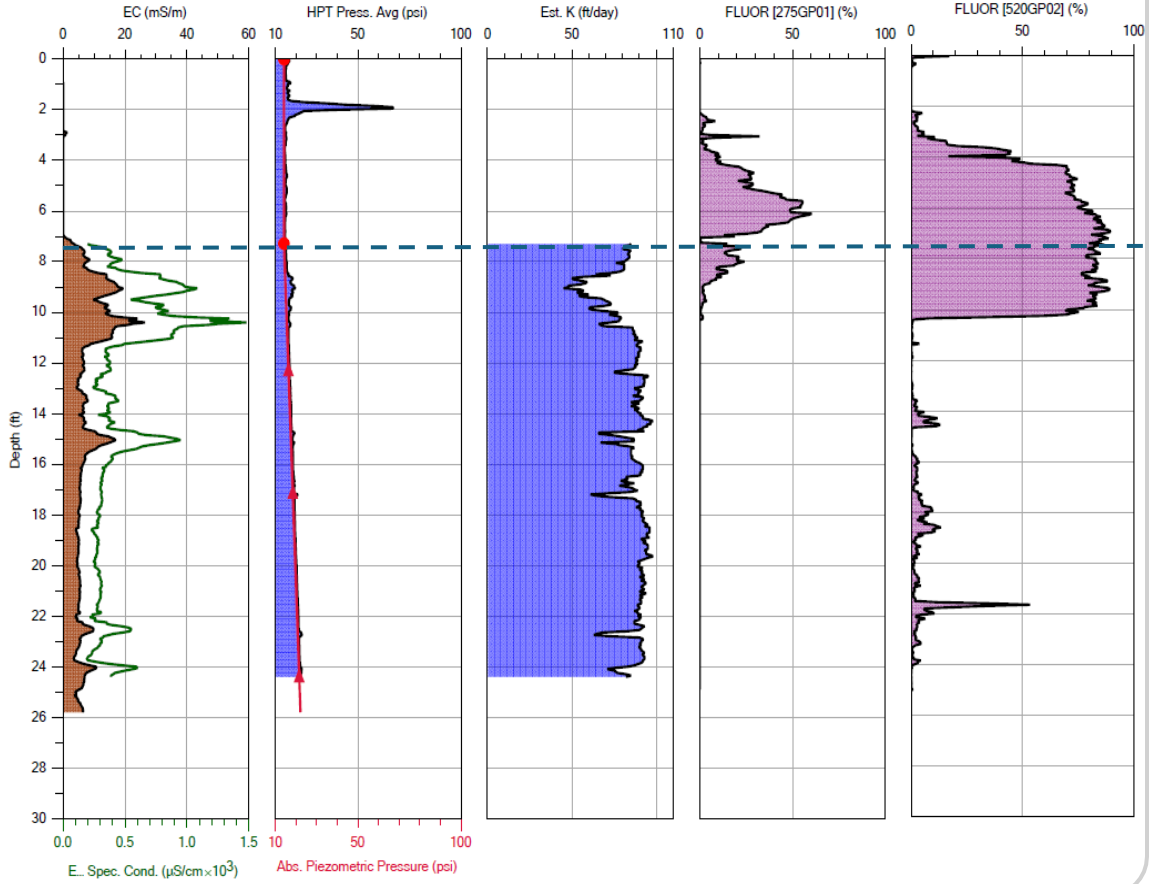
Measurements:

- ❑ NMR measurement is conducted on the way up using stepped mode of 6-inch.
- ❑ CPMG: Along entire log to estimate total water content, relative pore-size distribution, and hydraulic conductivity.
- ❑ Diffusion NMR: At selected locations along the log (limited time)

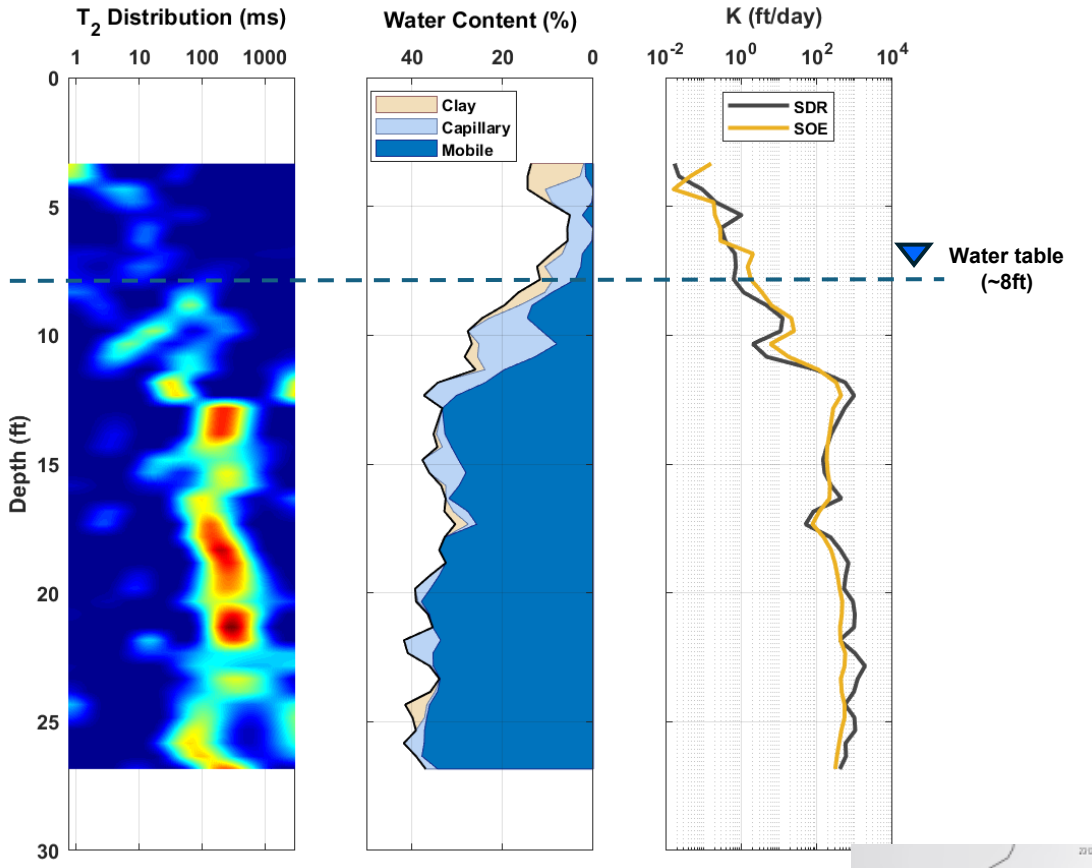
Bemidji Investigations: Within the South Plume-Location #1

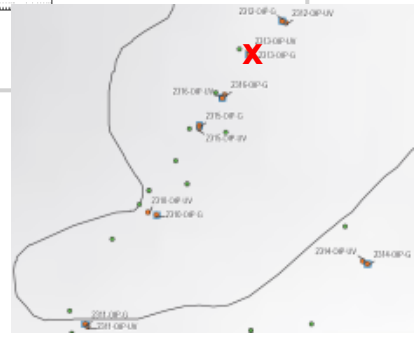
VISTACLARA NMR GEOPHYSICS

OIP



Direct Push NMR

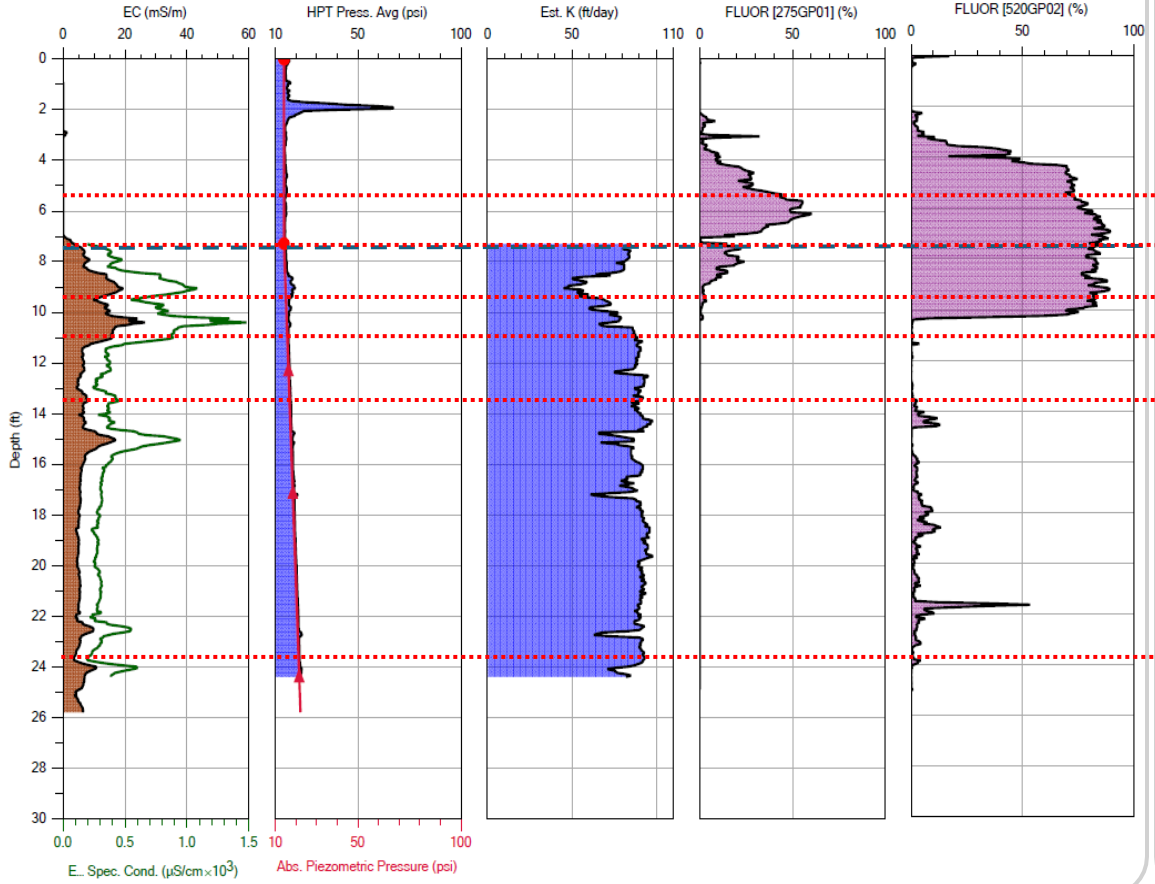




Bemidji Investigations: Within the South Plume-Location #1

VISTACLARA NMR GEOPHYSICS

OIP



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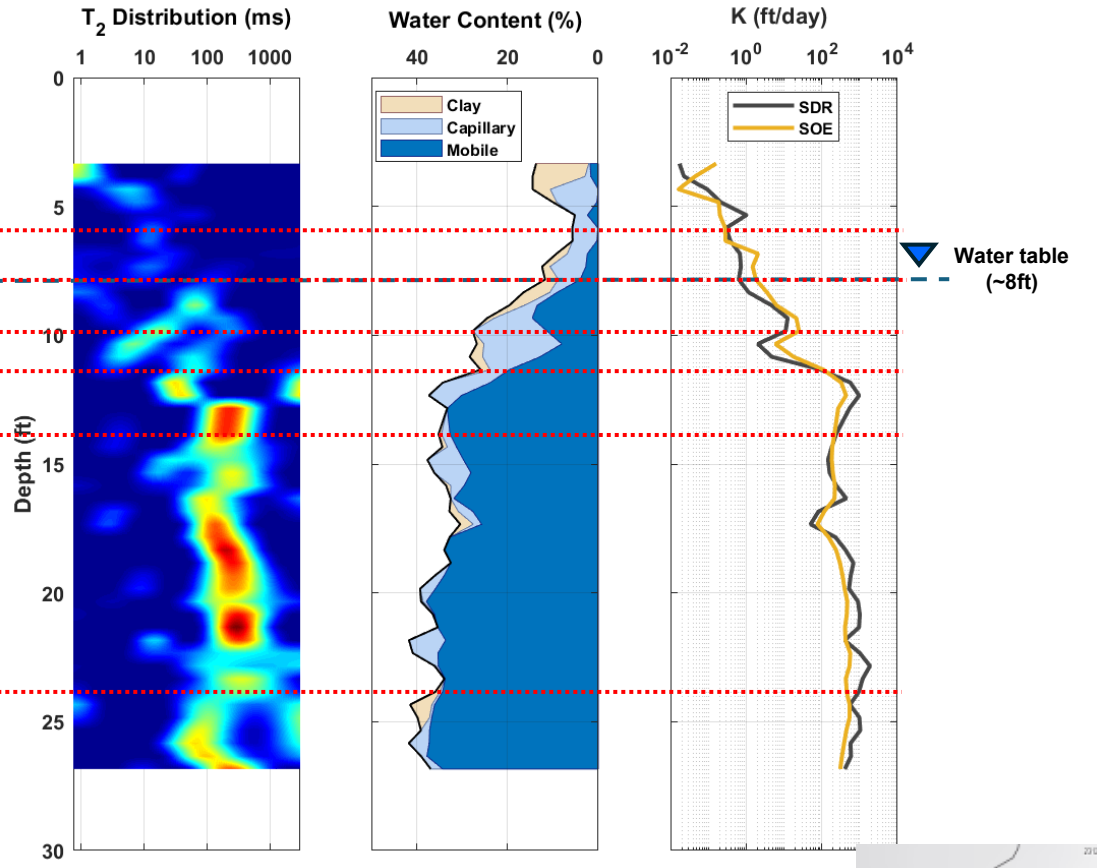
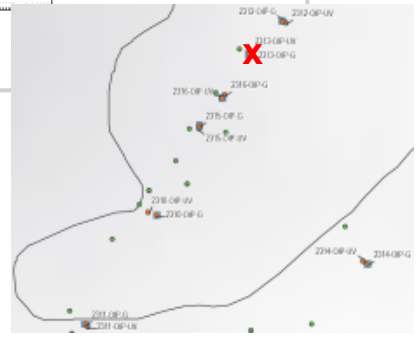
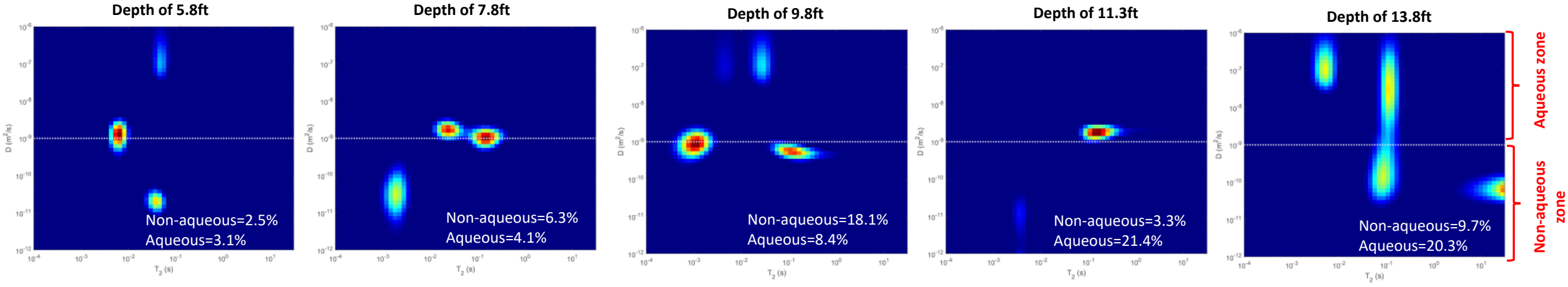


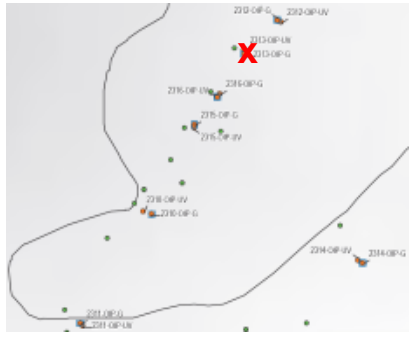


Bemidji Investigations: Within the South Plume-Location #1

Diffusion NMR: Diffusion-T2 correlation maps are estimated to differentiate and quantify fluid types in the formation.



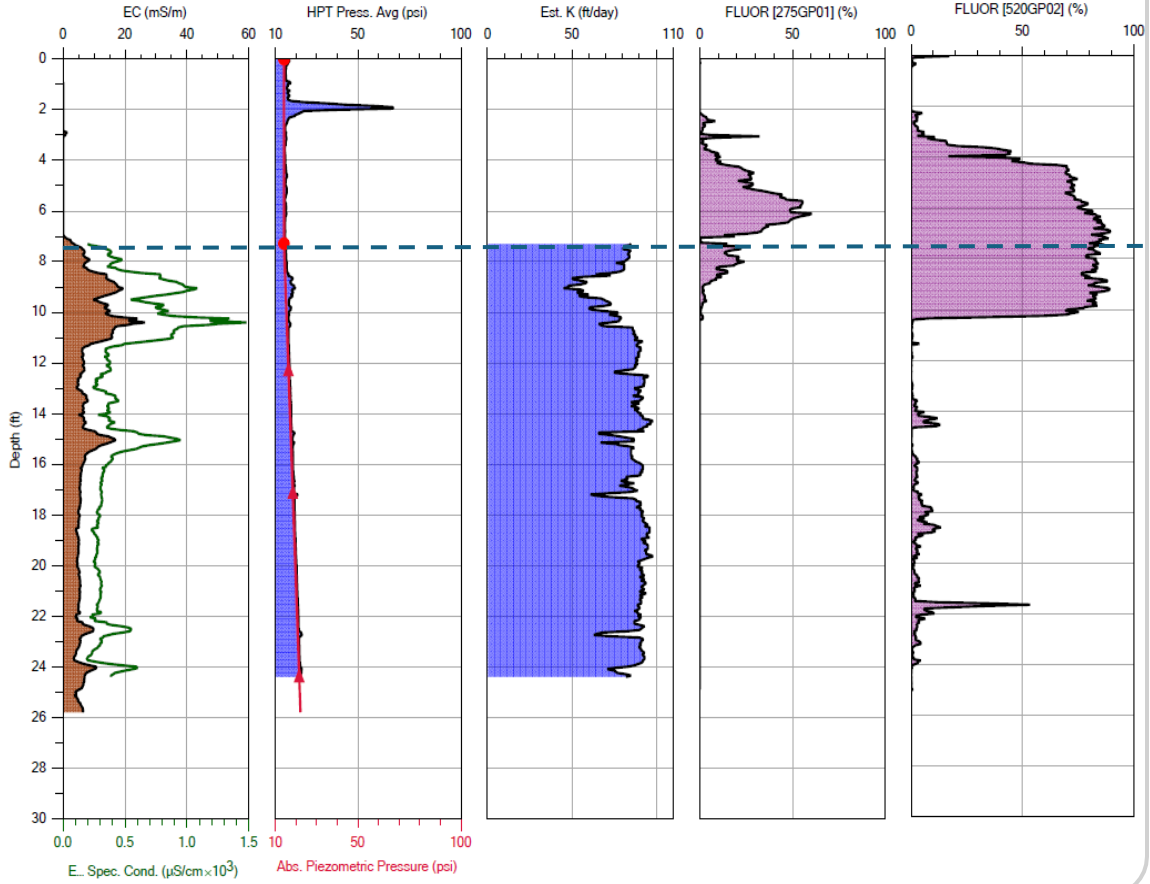
Water has faster diffusivity (D) as compared to crude oil.



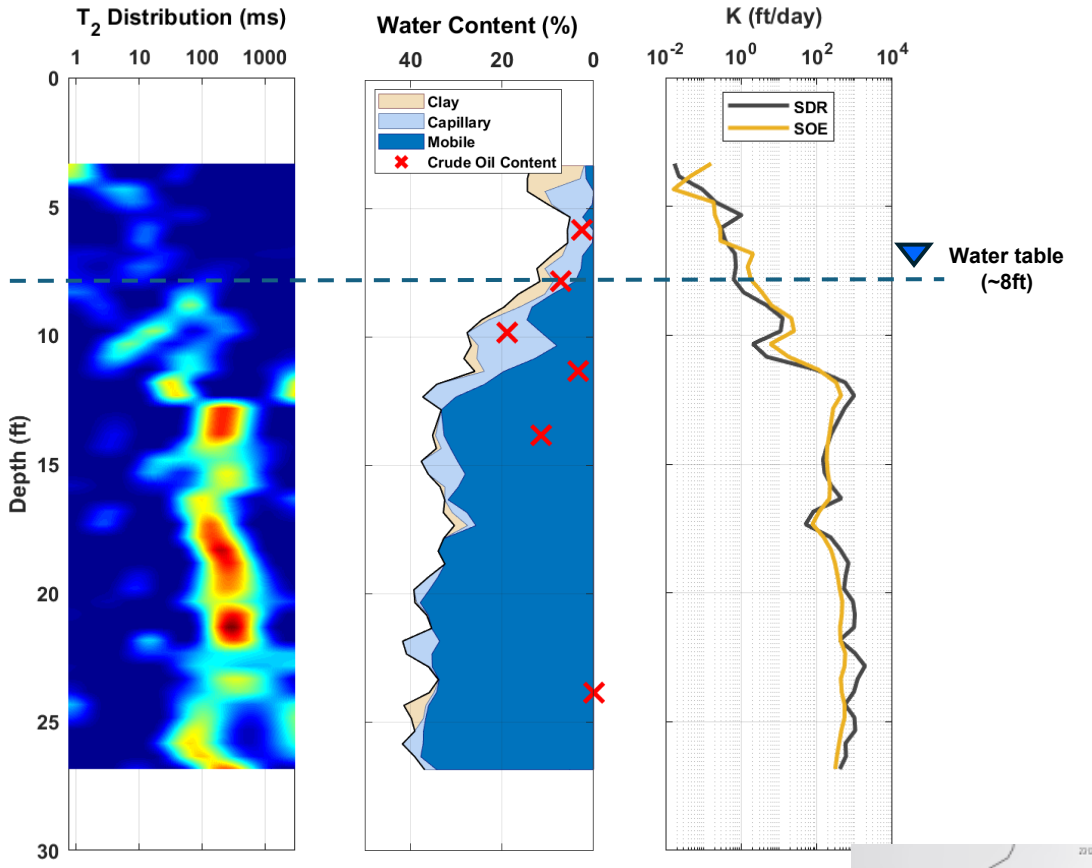
Bemidji Investigations: Within the South Plume-Location #1

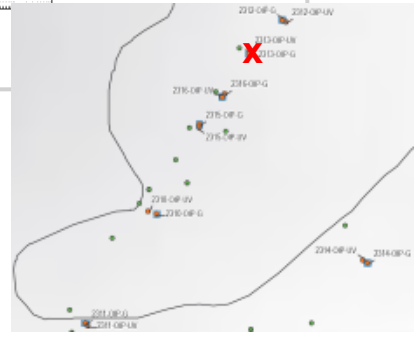
VISTACLARA NMR GEOPHYSICS

OIP



Direct Push NMR





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VISTACLARA NMR GEOPHYSICS

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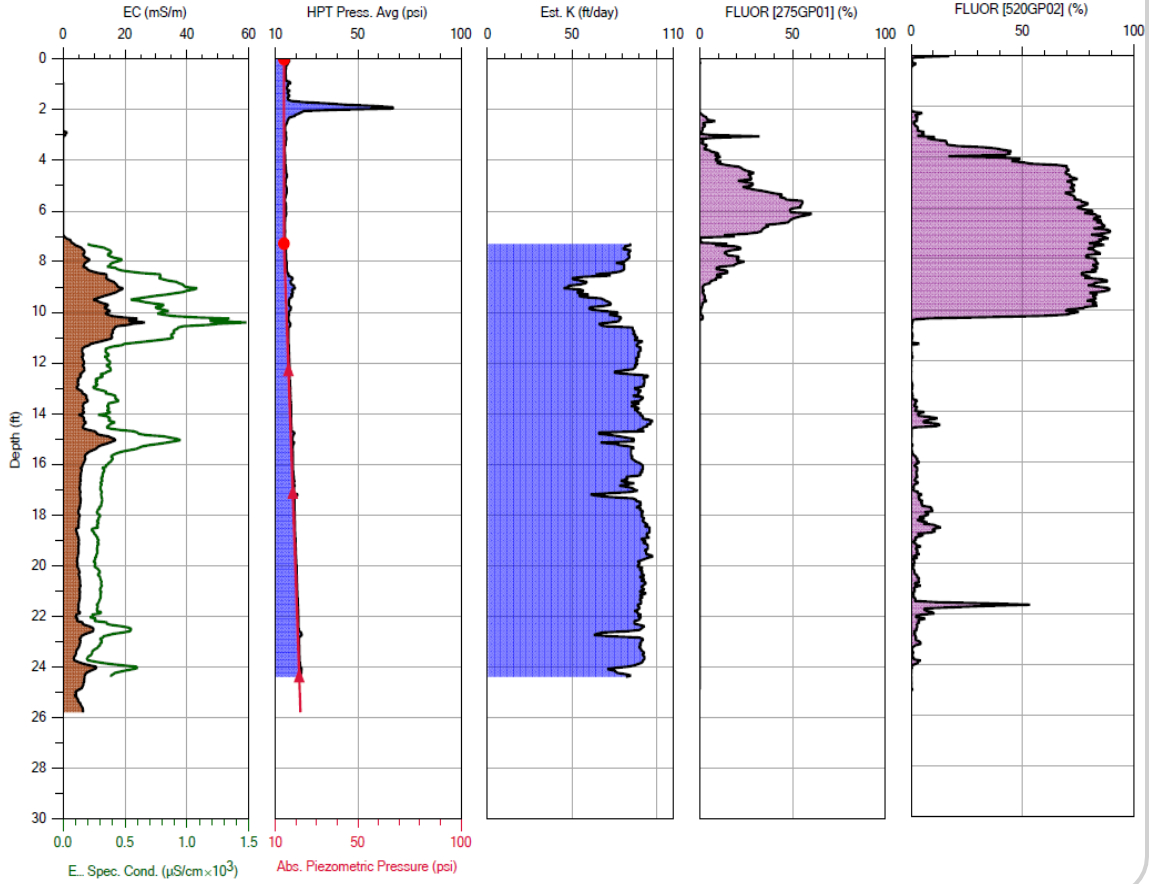

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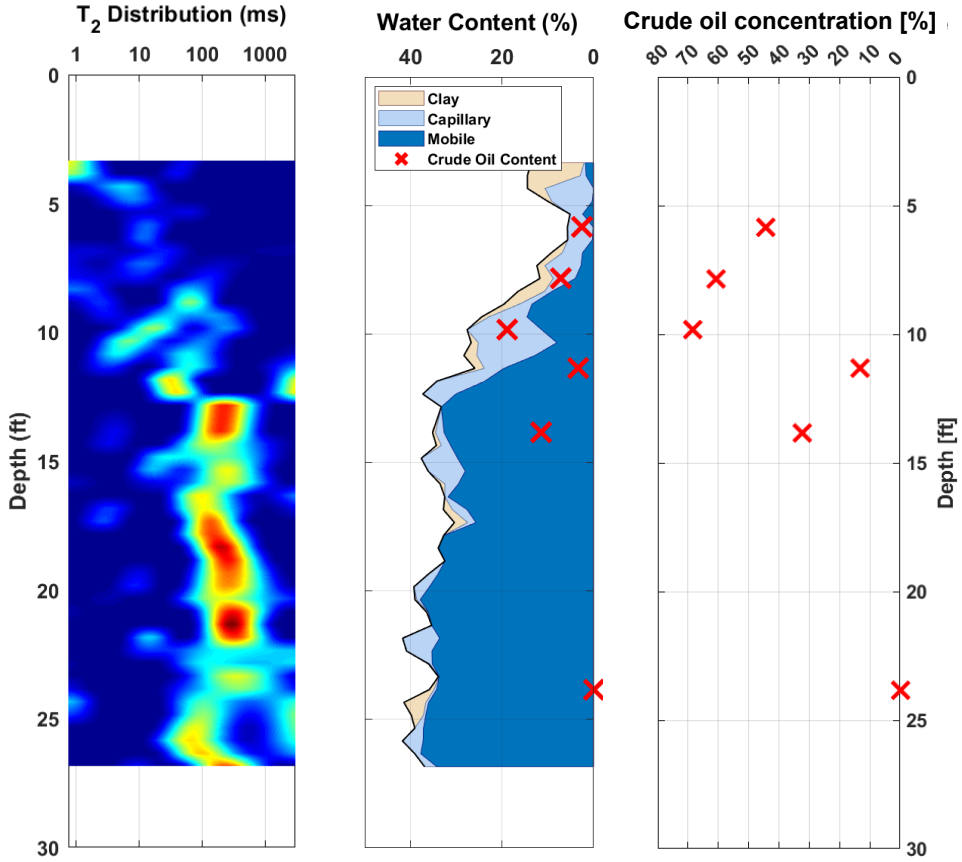

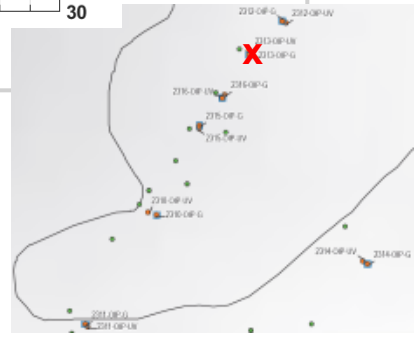

Bemidji Investigations: Within the South Plume-Location #2

VISTACLARA NMR GEOPHYSICS

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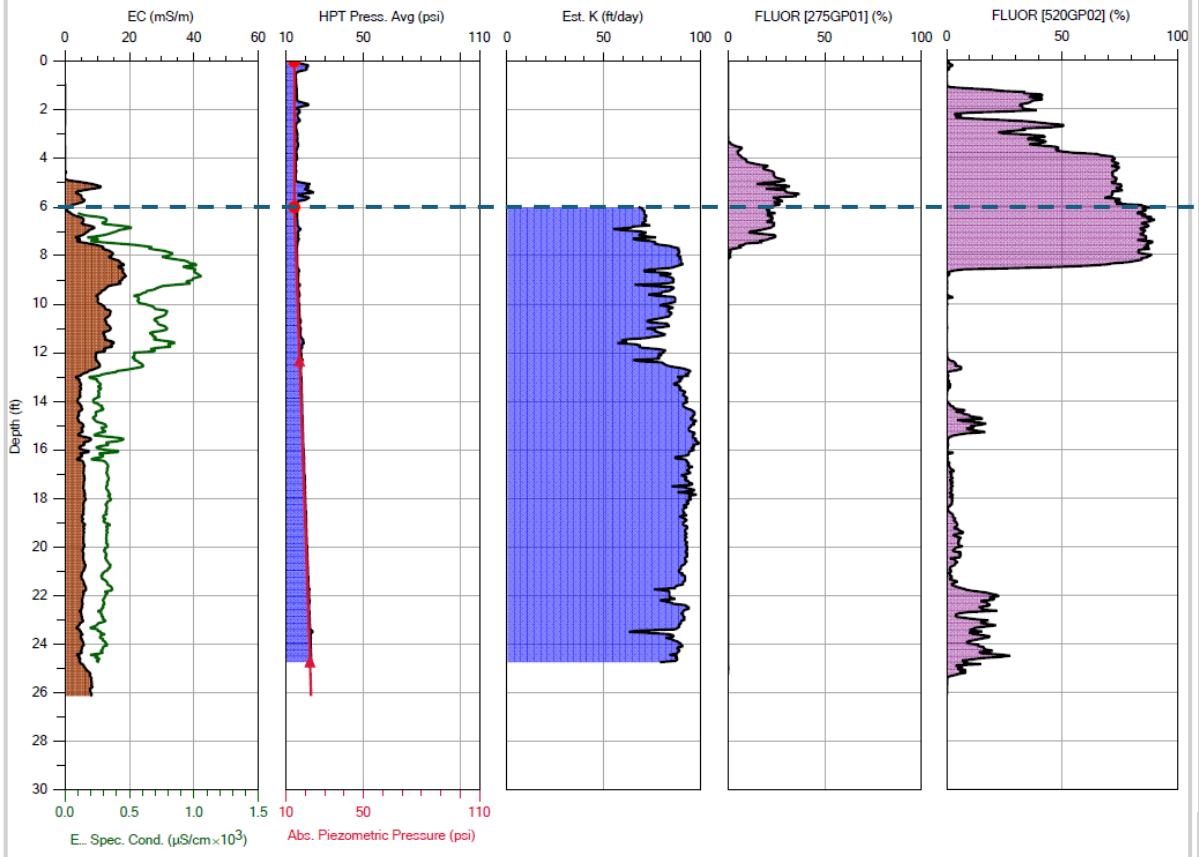

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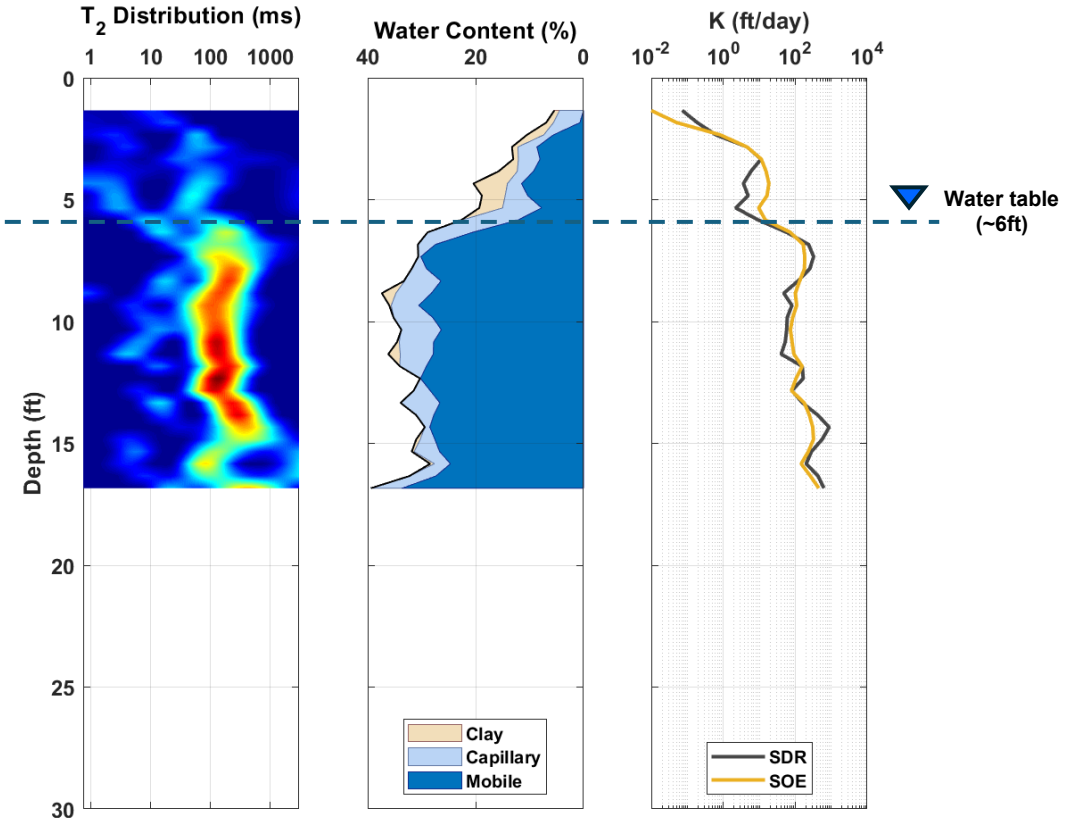

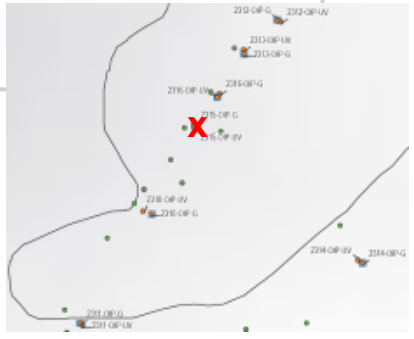

Bemidji Investigations: Within the South Plume-Location #2

VISTACLARA NMR GEOPHYSICS

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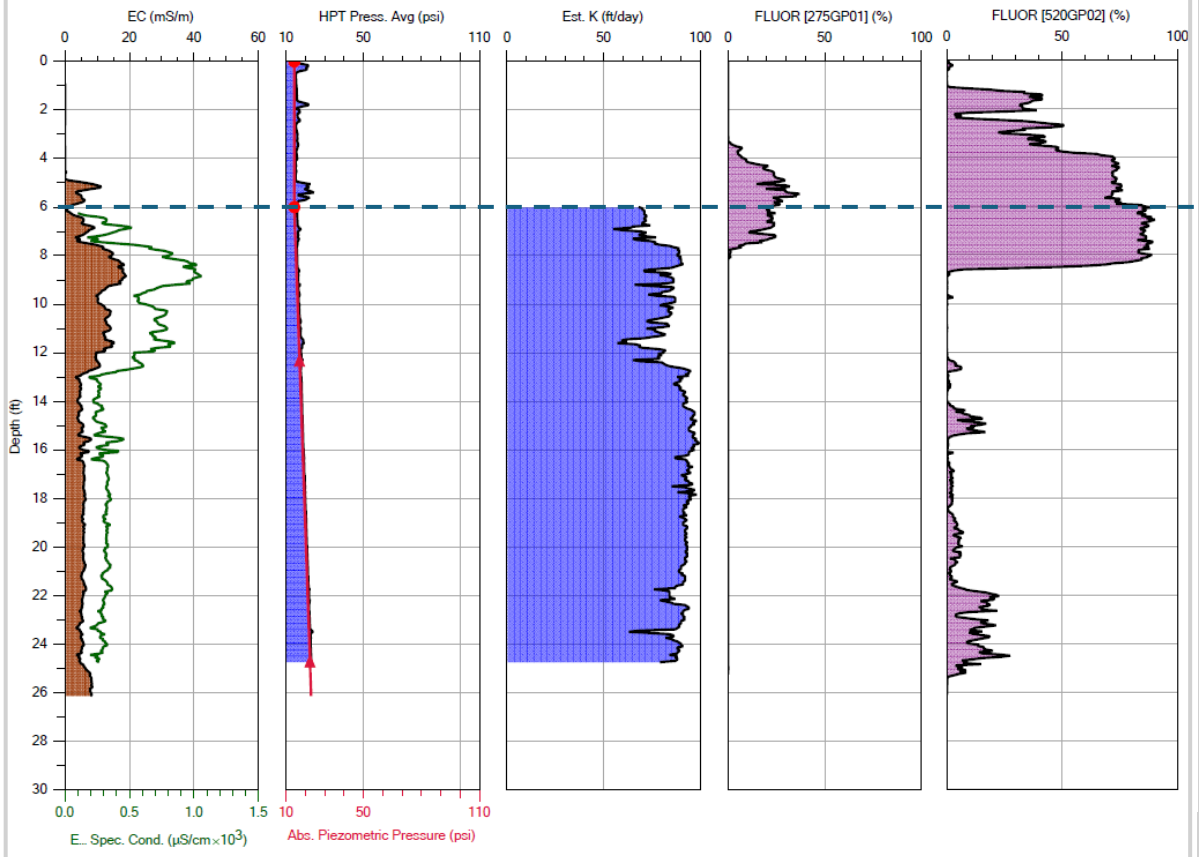

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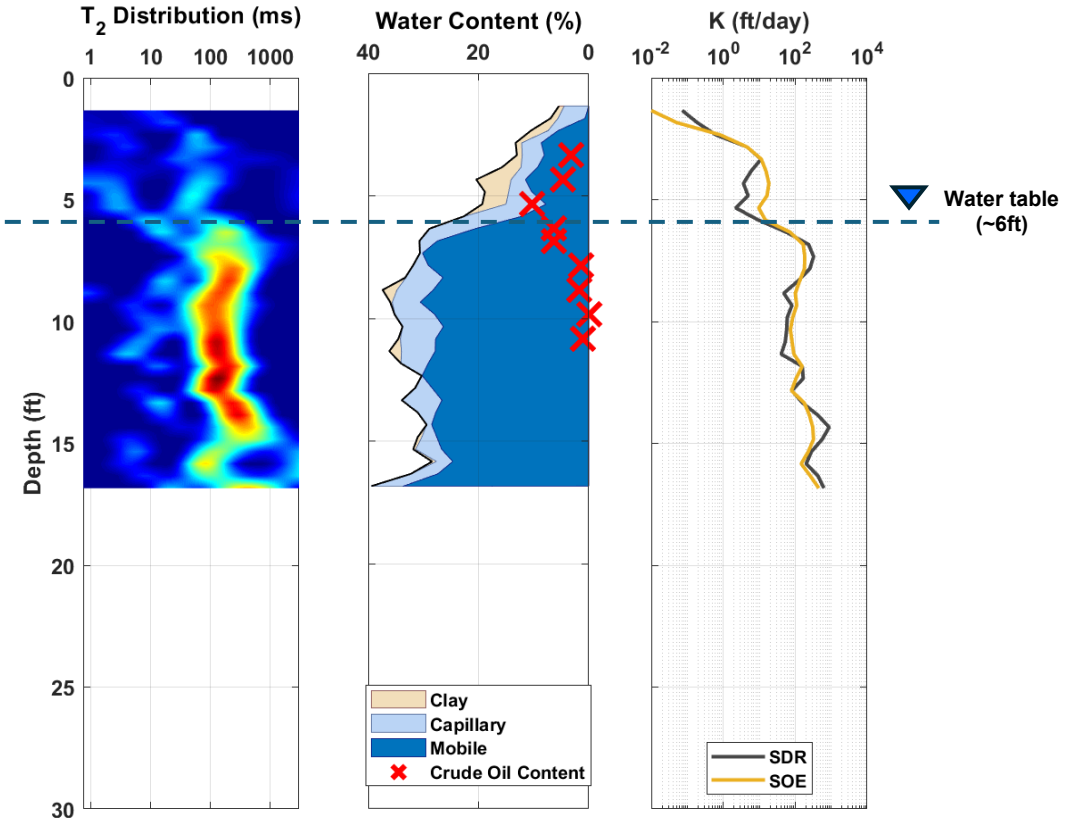

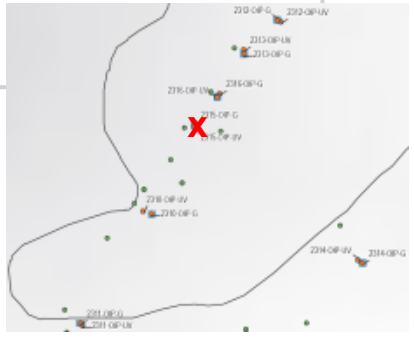

Bemidji Investigations: Within the South Plume-Location #2

VISTACLARA NMR GEOPHYSICS

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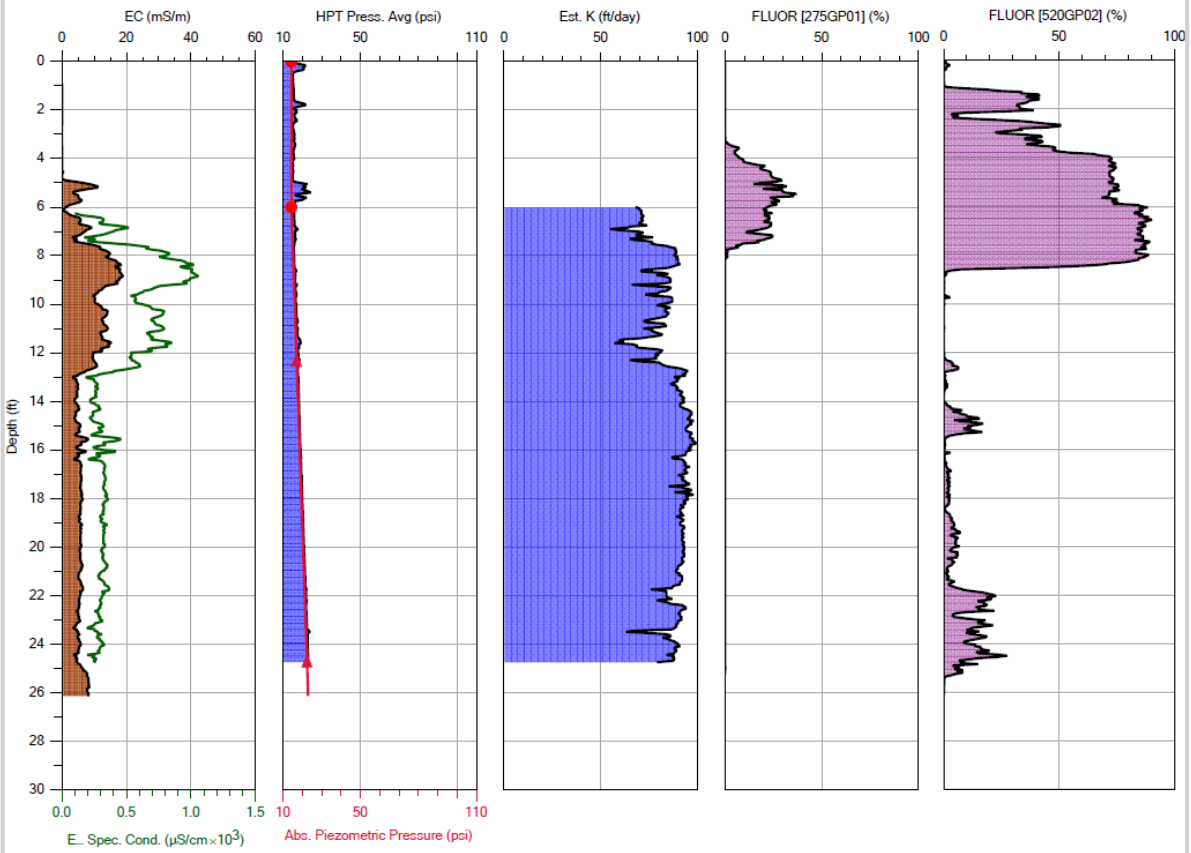
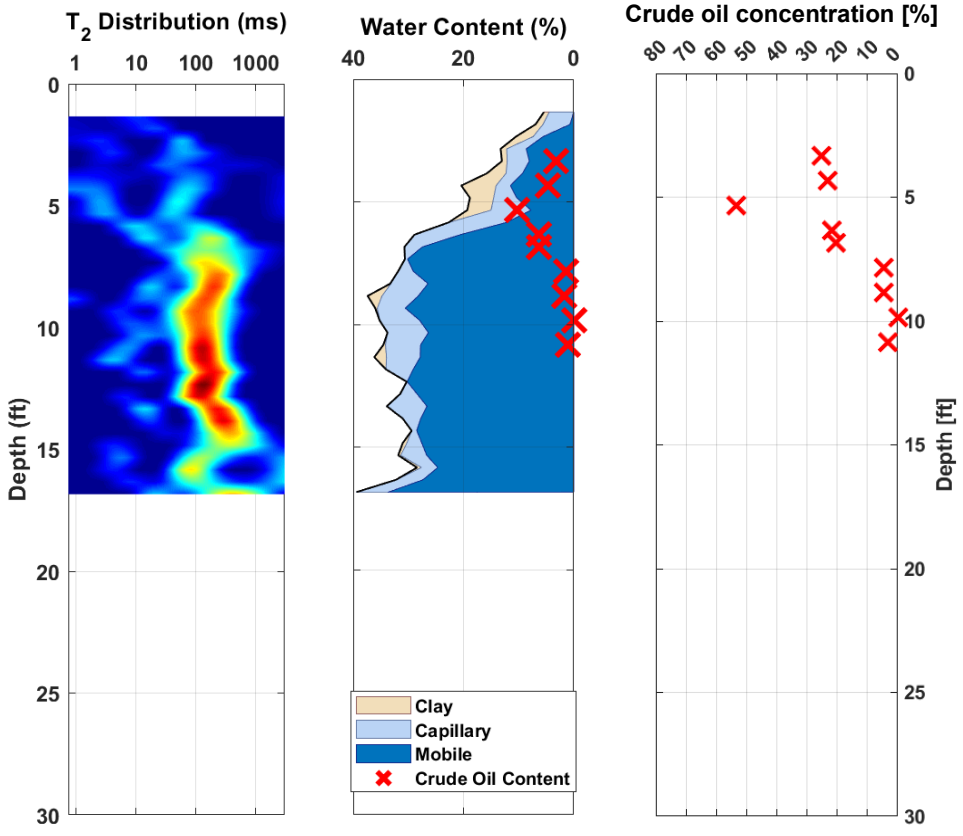
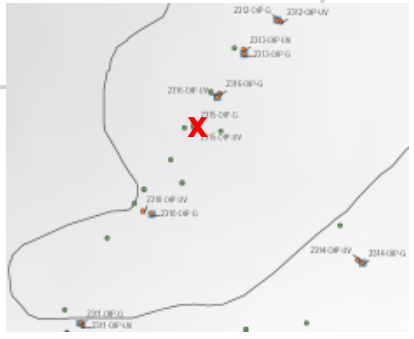


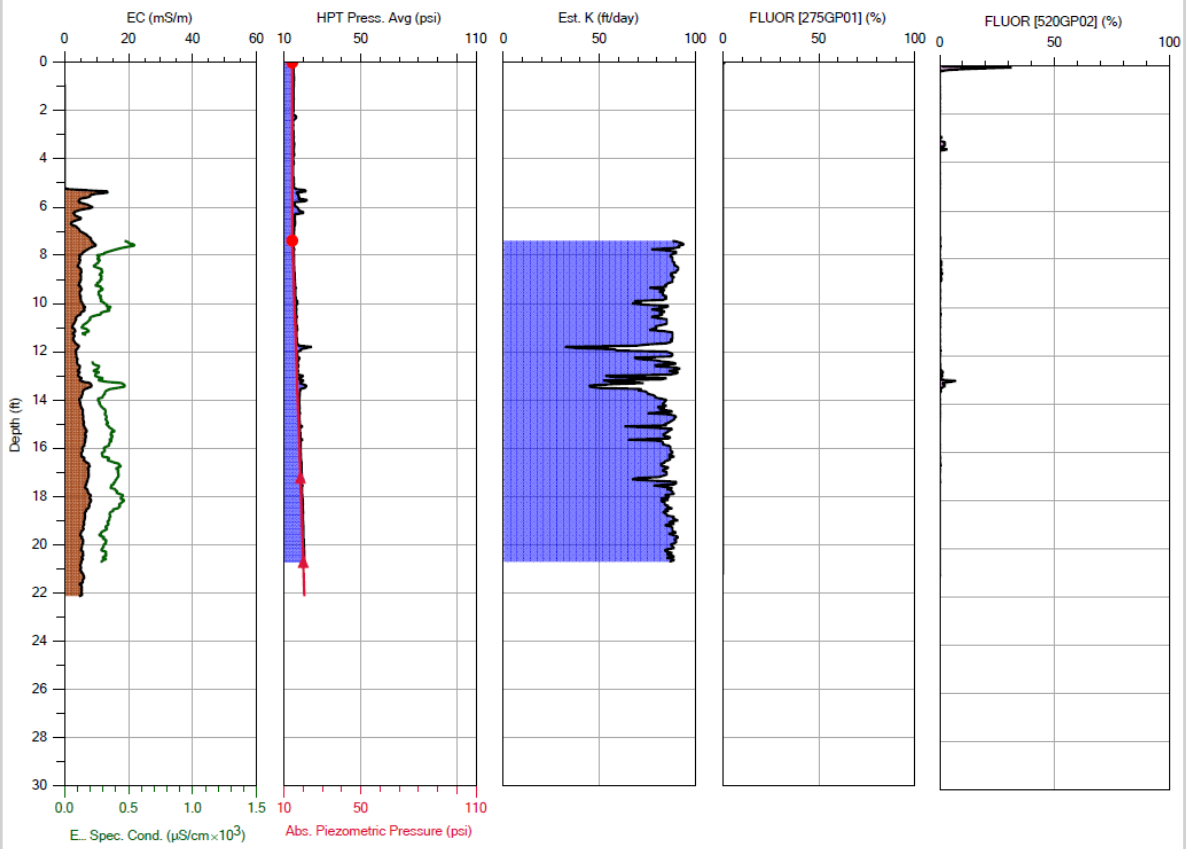
Direct Push NMR



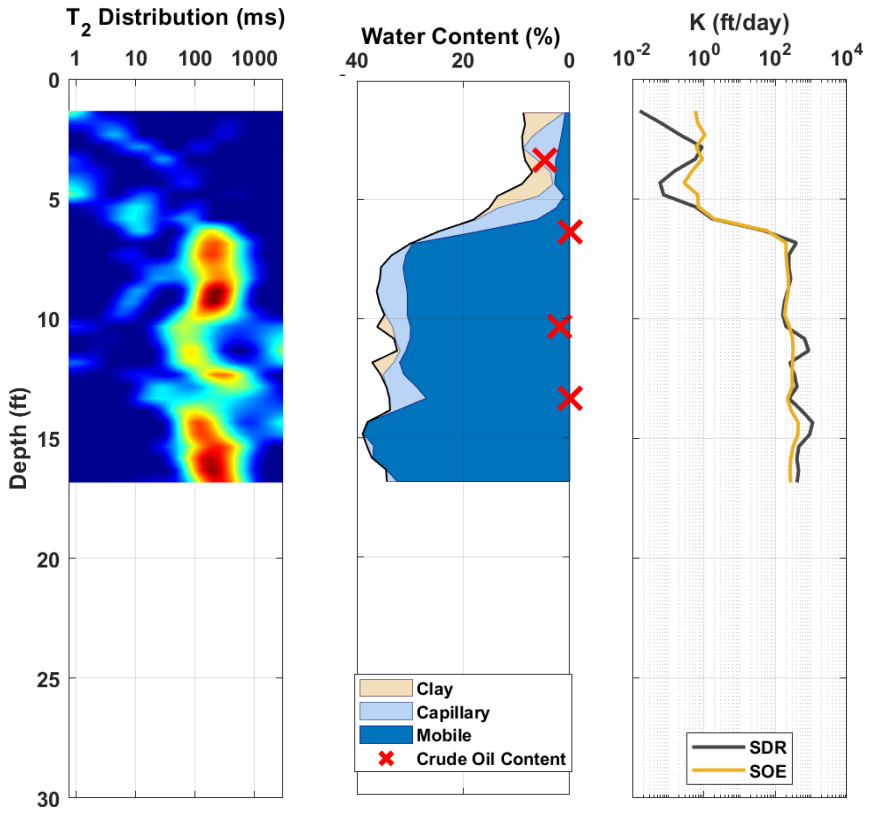


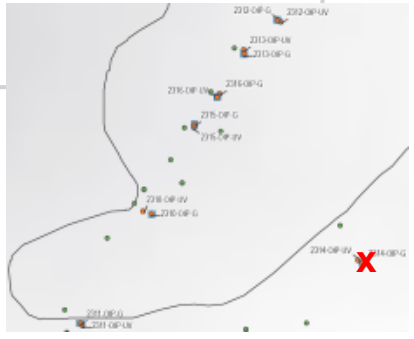
Bemidji Investigations: Outside the South Plume

OIP



Direct Push NMR

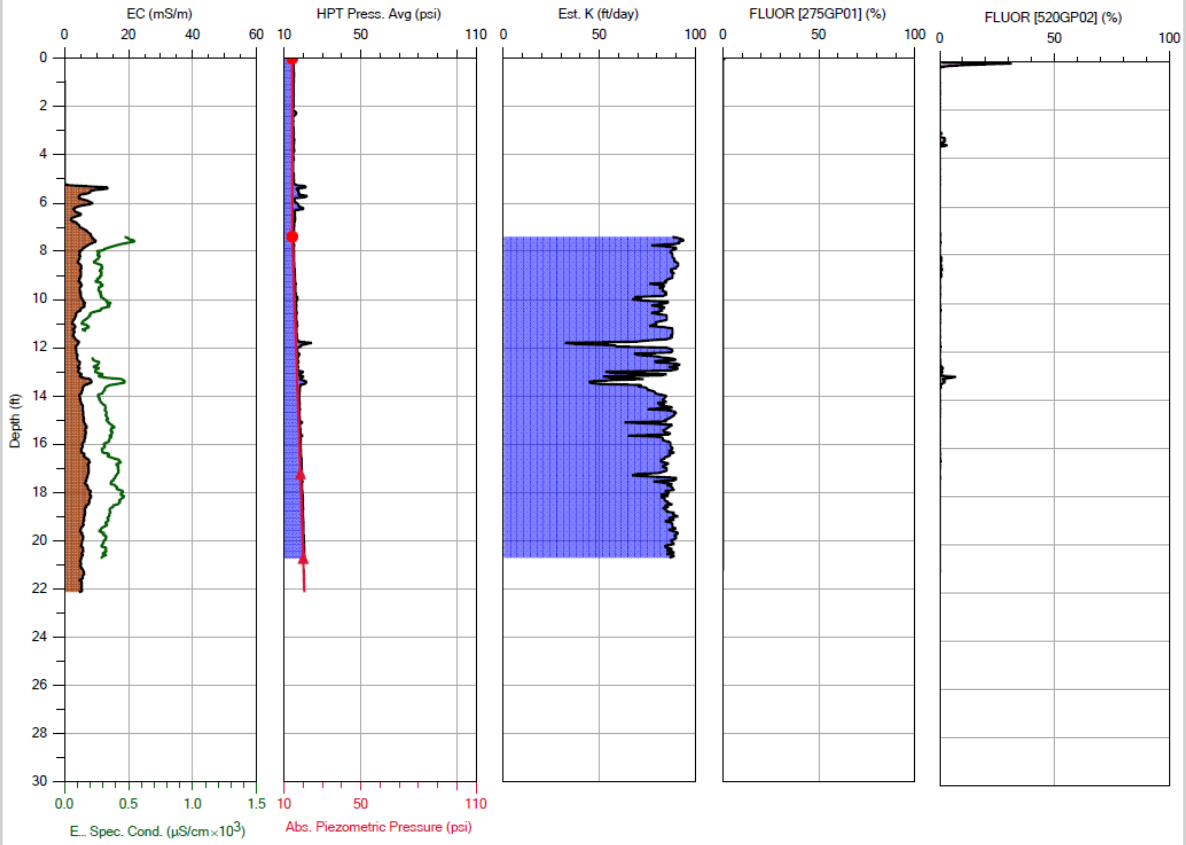




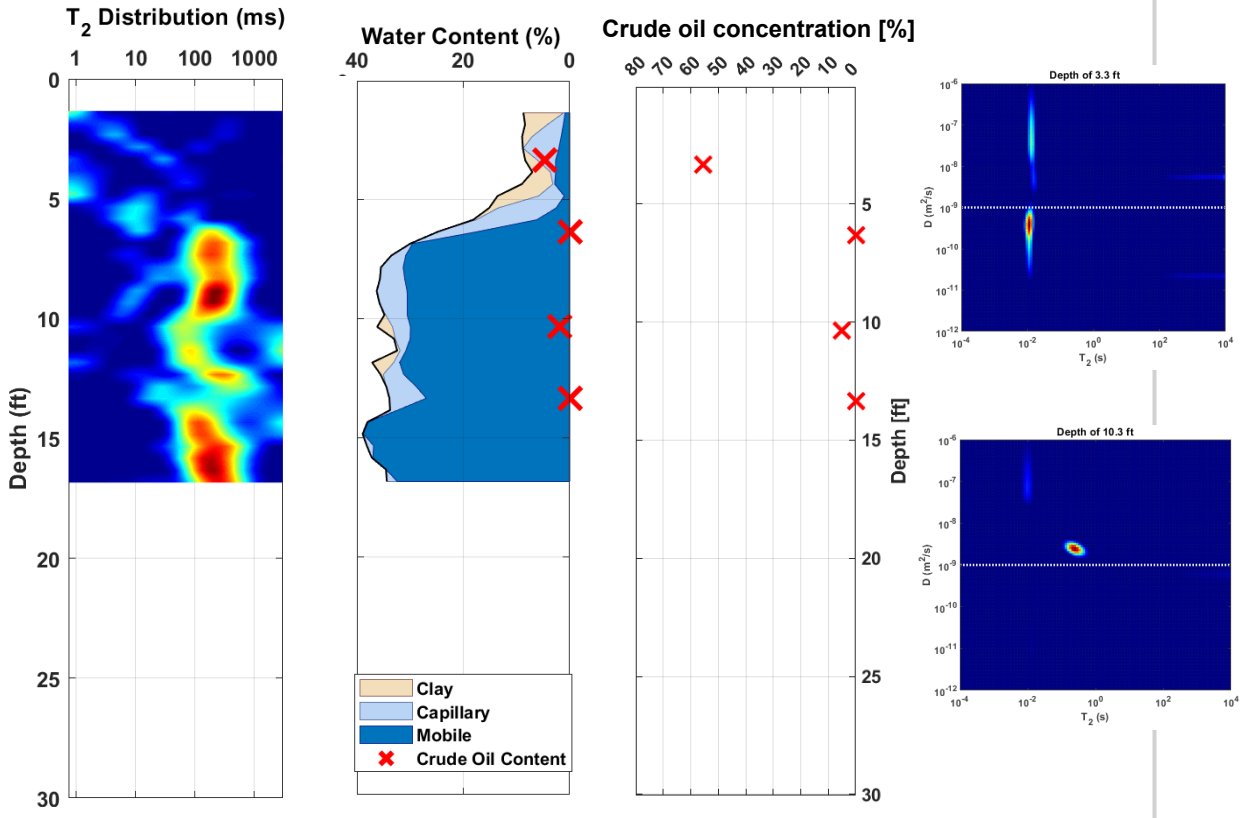
Bemidji Investigations: Outside the South Plume

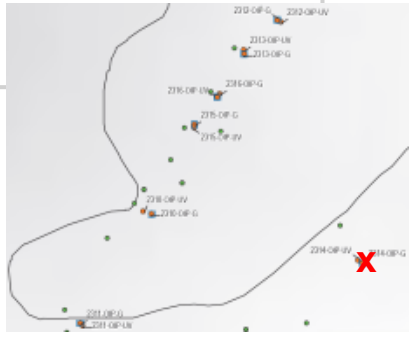
VISTACLARA NMR GEOPHYSICS

OIP



Direct Push NMR





Conclusions

VISTACLARA NMR GEOPHYSICS

This study shows:

- ❑ Good correlation between OIP and NMR measurement was observed.
- ❑ OIP could detect and locate crude oil based on fluorescence emitted from the hydrocarbons.
- ❑ Diffusion NMR represents a promising method for direct quantification of crude oil content directly within the formation.
- ❑ The method can be used with all borehole logging NMR tools and measure NAPL content in already existing monitoring wells.

The main limitation of diffusion-based NMR:

- ❑ The current acquisition protocol required long acquisition times.
- ❑ The measurement is done only at stationary location- continuous log is currently unavailable.

Thank you

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