Nuclear Magnetic Resonance Geophysical Investigations

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The business of sustainability

ERM

Goal: Improved Conceptual Site Models
Problem: Heterogenaity vs Simplyfing Assumptions
Solution: Resolve & understand the true aquifer fabric and multi-domain groundwater flux, groundwater storage systems

Typical Aquifer Fabric

Lithology	Typical Hydraulic Conductivity	Fluid Mobility	Flow Contribution	Primary Mass Flux Mechanism
Sands and Gravels	10 to 100+ ft/day ($3.5x10^{-3}$ to $3.5x10^{-2}$ cm/sec)	Mobile/Free	90%	Advection/Dispersion
Silt/Clayey Fine Sands	1 to 10 ft/day ($3.5x10^{-4}$ to $3.5x10^{-3}$ cm/sec)	Capillary Bound	up to 10%	Diffusion/Advection
Clay/Silt	< 0.1 ft/day (< $3.5x10^{-5}$ cm/sec)	Clay Bound	<1%	Diffusion

NMR Provides Direct Measurement of Fluid Mobility

NMR builds on other High-Resolution Site Characterization tools

HRSC Tools

- EC lithology
- CPT lithology
- Televiewers (acoustic/optic) lithology
- Heat-Pulse Flow Meter flow contribution
- HPT flow contribution
- MIP contaminant distribution
- LIF contaminant distribution
- ***Traditional Borehole Geophysics***

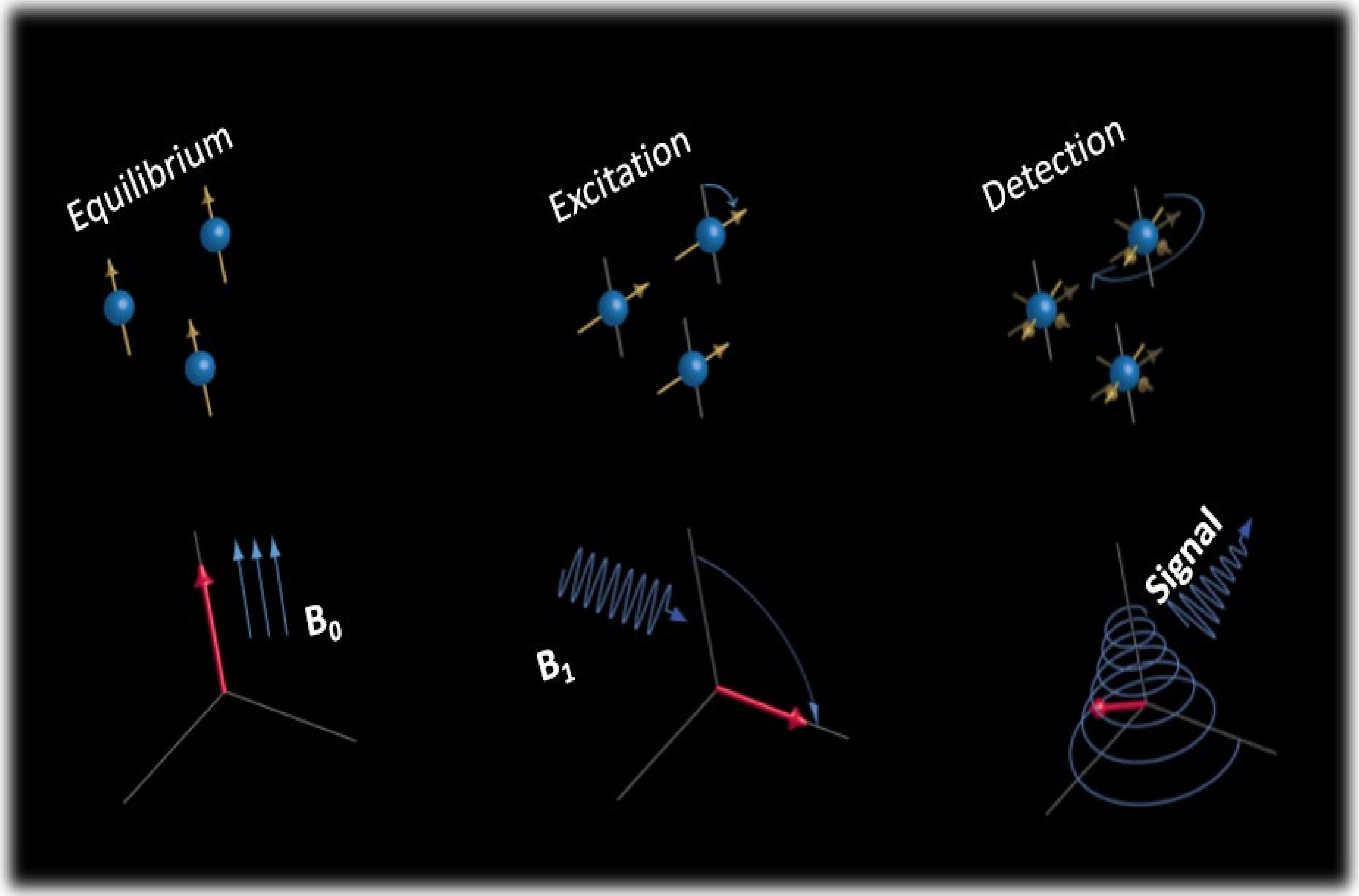
NMR Geophysics Provides:

- Direct Quantification of Water Content and Total Porosity (no equivalent push-tool method)
- Quantification of Mobile versus Bound/Capillary Water Content (no equivalent push-tool method)
- Robust Estimation of Pore Size and Distribution (no equivalent push-tool method)
- Robust Estimation of Hydraulic Conductivity
- LNAPL Detection at Saturations to <5%
- ***Can be Acquired in Existing PVC-cased Wells***

Some Potential Applications:

- ***High Resolution Conceptual Site Model Development:***
  - Perched water characterization
  - Aquifer preferential pathways and storage zones
  - Pore volume estimation
  - Mass flux estimation
- ***Quantification of Changes in Saturation and Hydrogeologic Properties Over Time:***
  - Infiltration/dewatering/residual saturation
  - Biofouling/pore-space reduction
  - LNAPL reduction
- ***Supply/Extraction Well & Remediation System Design***
  - Optimize screen intervals

NMR Measurement Physics



Properties of fluids that effect echo trains:

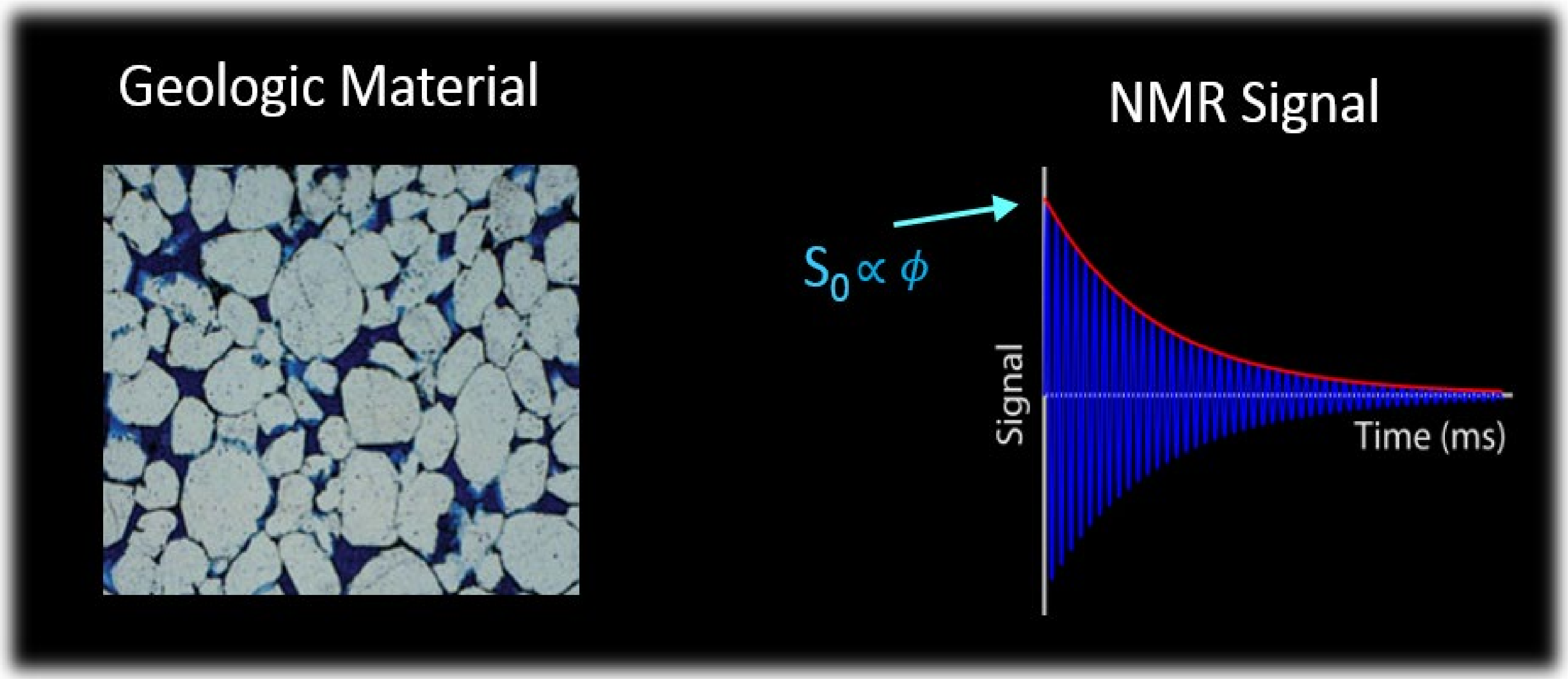
- hydrogen index (HI)
- longitudinal relaxation time (T1)
- transverse relaxation time (T2)
- diffusivity (D, the extent to which molecules move at random in the fluid).

T2 decay is proportional to pore size.

Porosity and pore size can be used to estimate permeability and the free fluid index (moveable fluids)

Figure Courtesy of VistaClara, Inc.

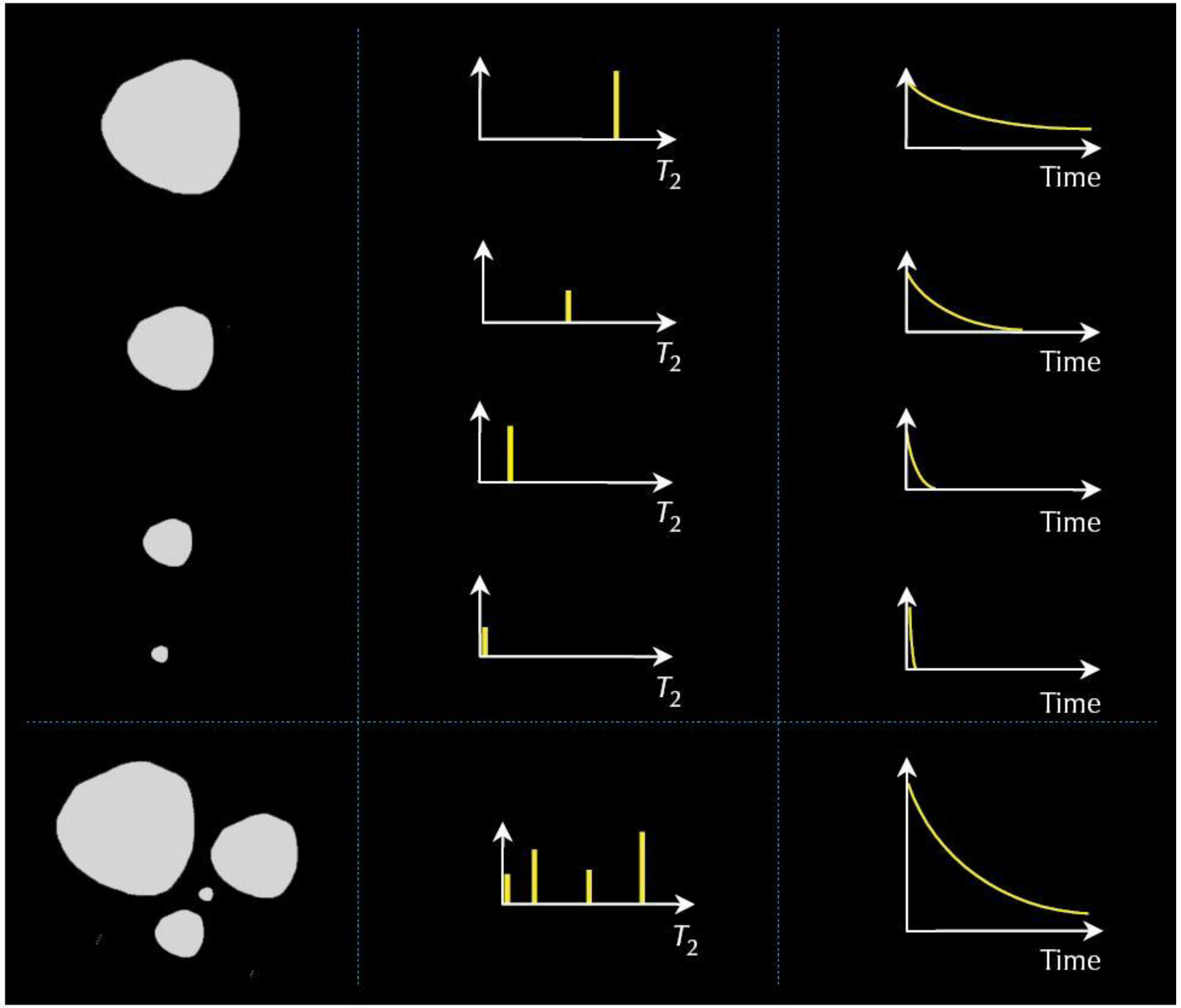
Hydrologic Properties from NMR



- MRI directly measures the density of hydrogen nuclei in fluids
- Since density of hydrogen nuclei in water is known, data can be directly converted to an apparent water-filled porosity
- Can also determine the presence and quantities of different fluids

Figure Courtesy of VistaClara, Inc.

Relaxation rates strongly correlate with pore size

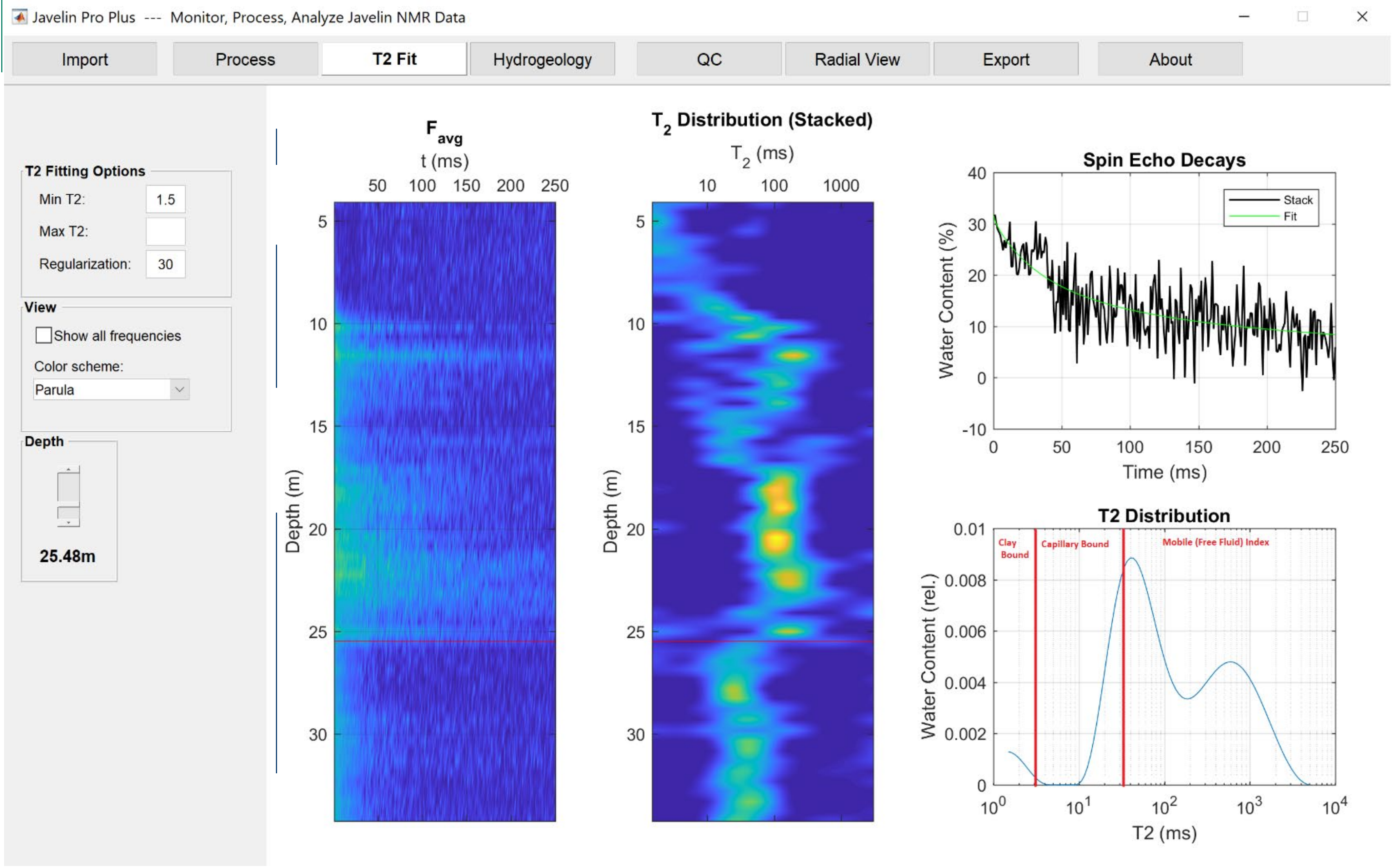


T2 relaxation time increases with pore size

Composite Echo Train

 Figure Courtesy of VistaClara, Inc.

Mobile Versus Immobile Porosity

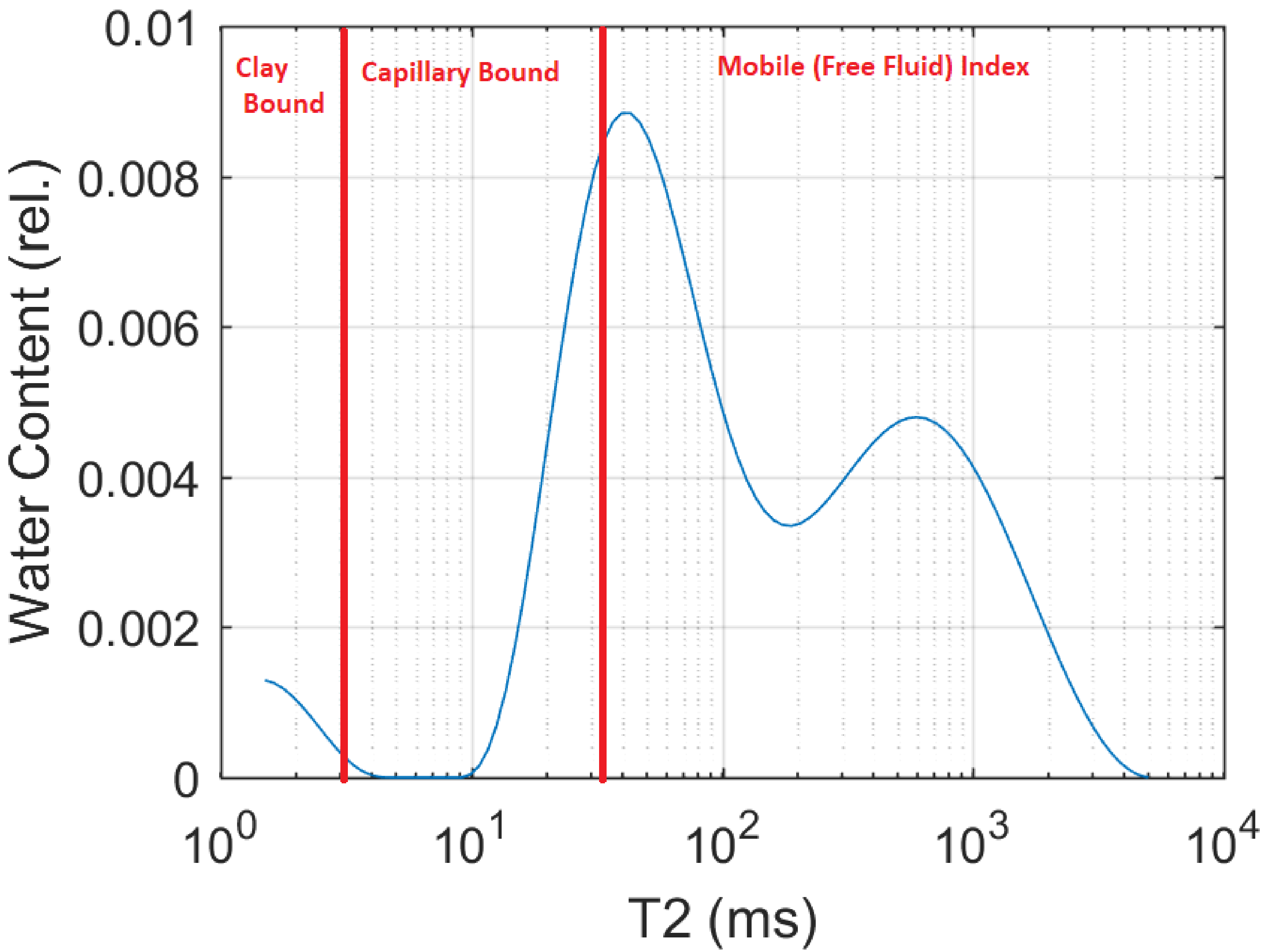


Using inverse modeling, composite echo trains are converted to porosity distributions.

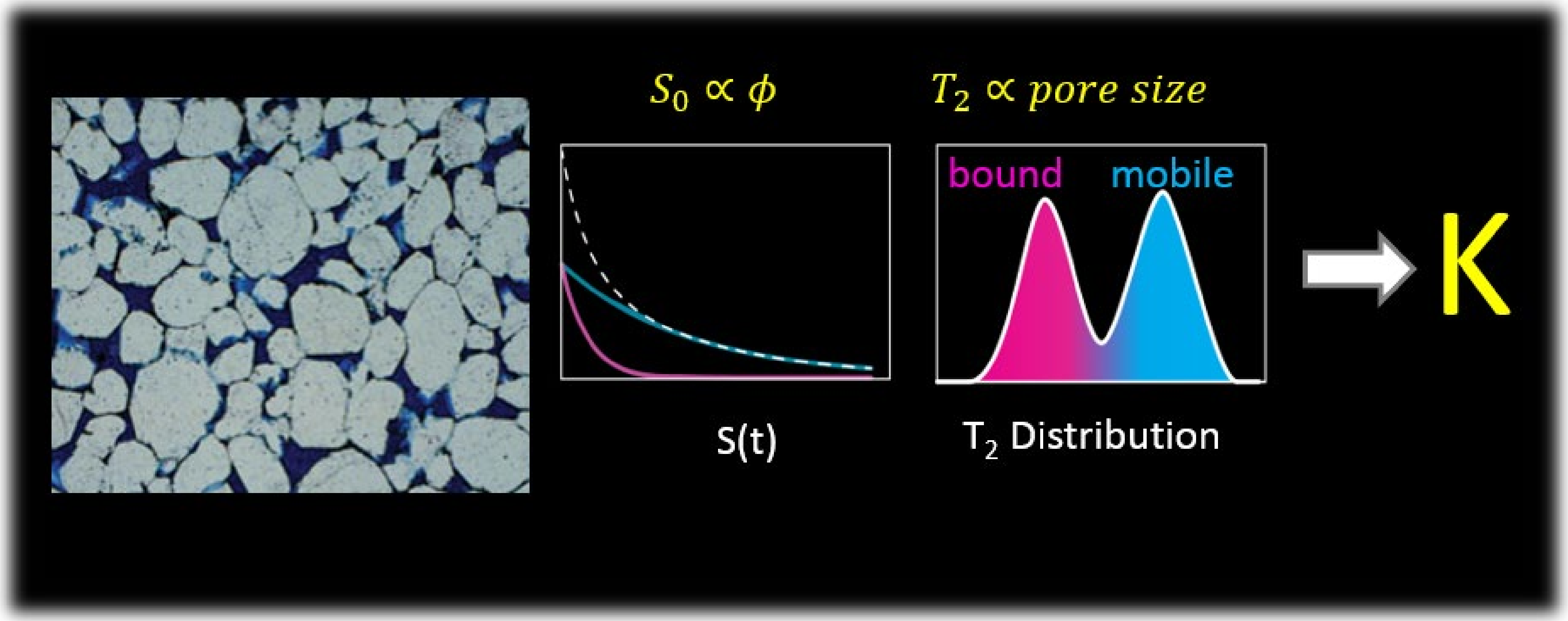
Modeling is based on substantial laboratory calibrations to various soil/rock matrices

T2 Distribution

T2 Cutoffs:
Clay = 3 ms
Capillary = 33 ms



Hydrologic Properties from NMR

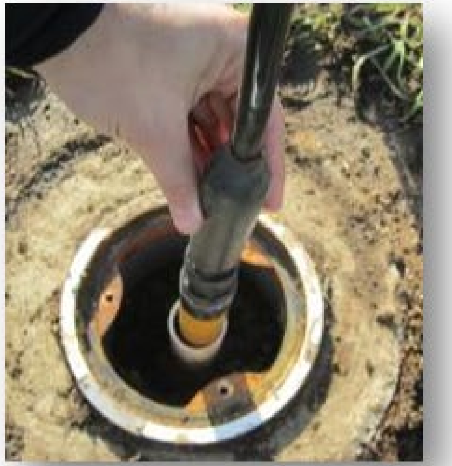


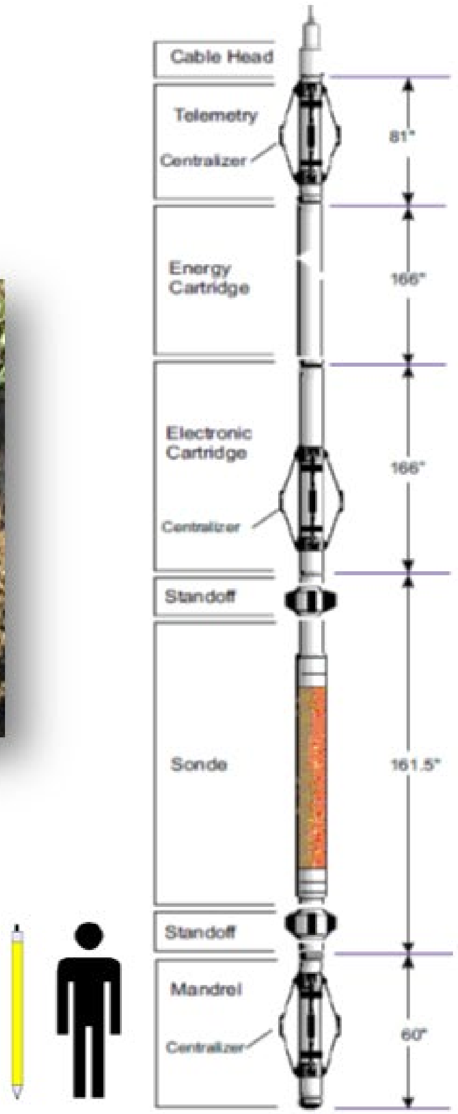
NMR Provides:

- Water Content
- Total Porosity (independent of lithology)
- Pore Size
- Pore Size Distribution
- Relative Amounts of Mobile, Capillary-Bound, and Clay-Bound Porosity
- Estimates of Permeability

Figure Courtesy of VistaClara, Inc.

Downhole NMR Logging



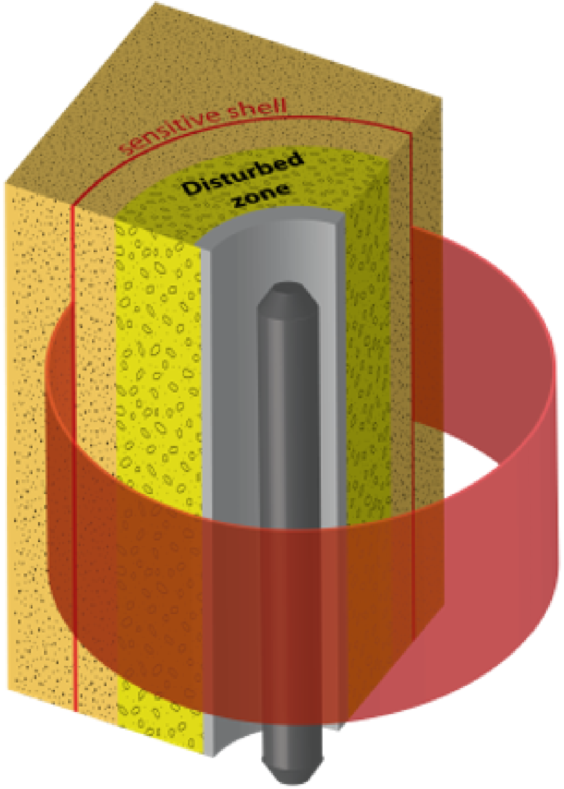


Advanced technology from the oilfield optimized for near-surface applications

Figure Courtesy of VistaClara, Inc.

Downhole NMR Logging

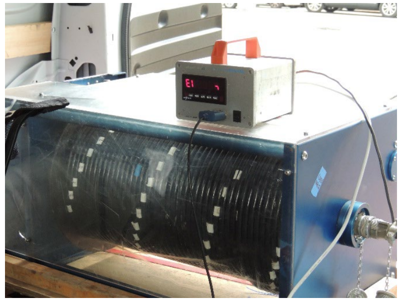
- Operated with PC computer
- Surface station generates high power RF pulses



- Permanent magnets in probe polarize hydrogen
- Coils in probe transmit RF pulses to excite and measure NMR signal
- Sensitive zone is outside zone disturbed by drilling
- Operates in open or PVC-cased holes

Figure Courtesy of VistaClara, Inc.

Javelin System (VistaClara, Inc.)



Javelin System (VistaClara, Inc.)

Features	JP525	JP350	JP238 ★	JP175(B)	JP175D	Dart
Probe Diameter	5.25 in	3.50 in	2.38 in	1.75 in	1.75 in	1.75 in
Sensitive Diameter	20 in	15 in	12 in	8 (10) in	10 in	6 in
Probe Length	5.5 ft	6.3 ft	7.1 ft	7.2 ft	7.2 ft	4.3
Vertical Resolution	1.5 ft	1.5 ft	1.5 ft	3 ft	1.5 ft	9 in
Echo Spacing	0.7 ms	0.7 ms	0.7 ms	0.9 ms	0.9 ms	0.5 ms
Number of Shells	4	4	4	2	2	2
Logging Speed*	200 ft/hr	200 ft/hr	200 ft/hr	75 (50) ft/hr	25 ft/hr	15 ft/hr

in = inches

ft = feet

ms = milliseconds

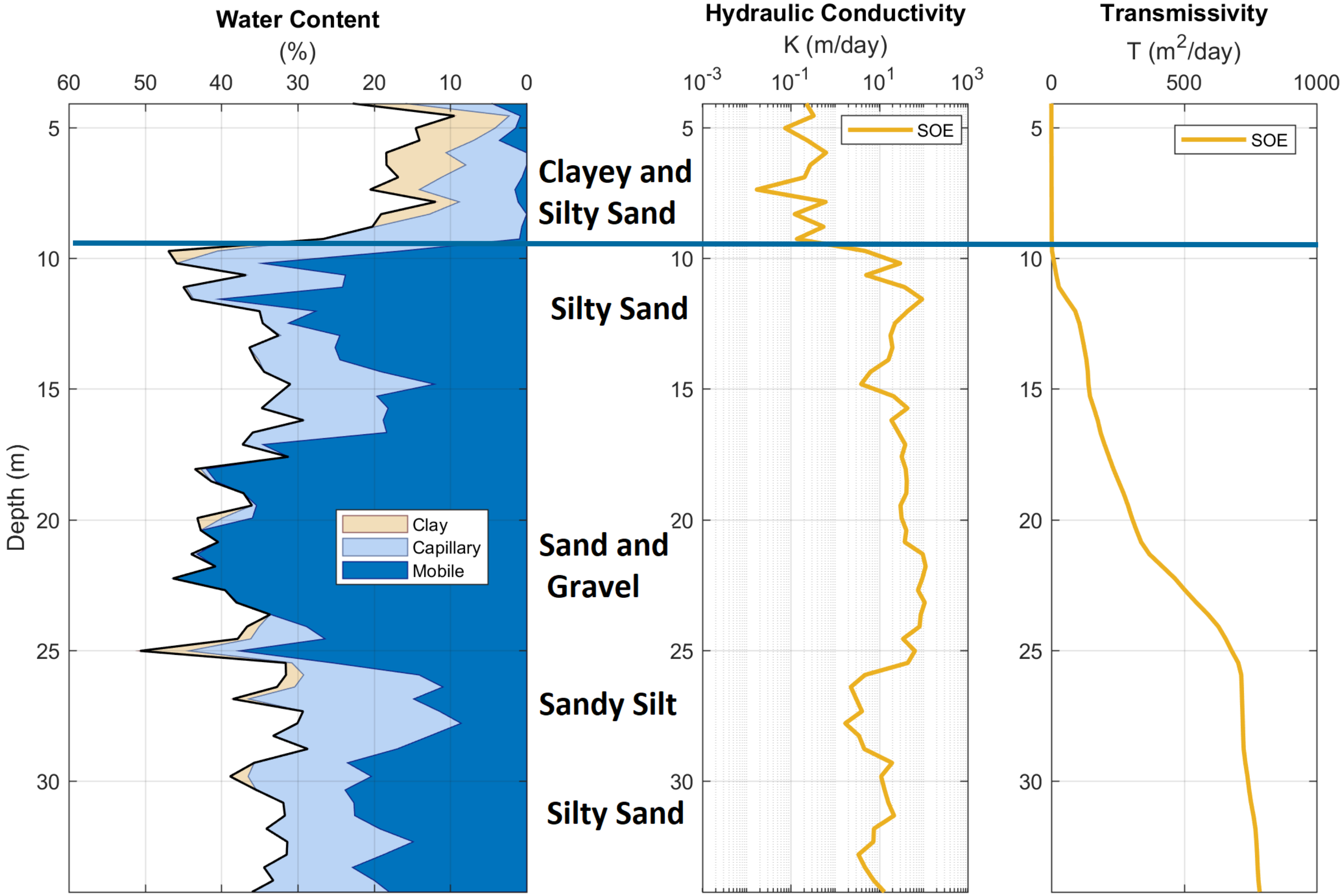
ft/hr = feet per hour

*Logging speed depends on formation type, hole conditions, and desired resolution

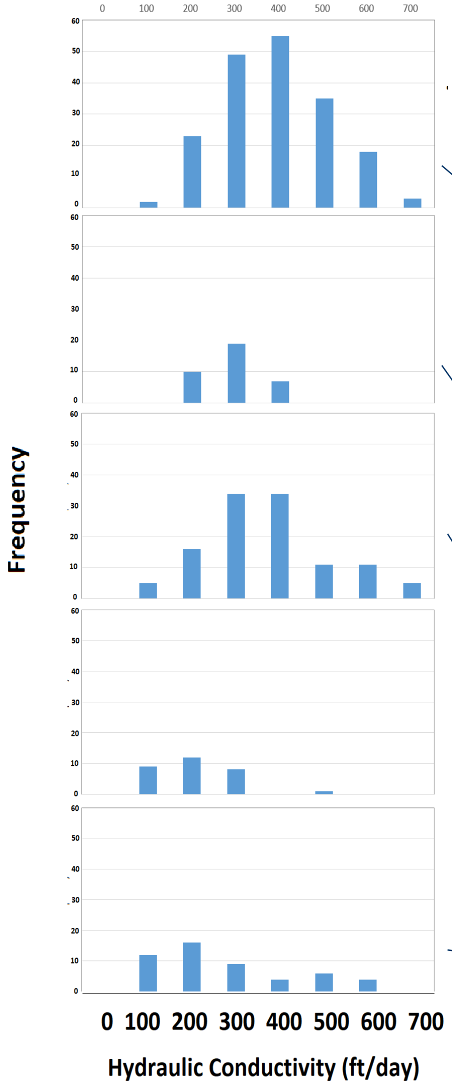
★ Can be deployed with Geoprobe Systems® equipment (direct-push tool)

Straightforward Interpretation

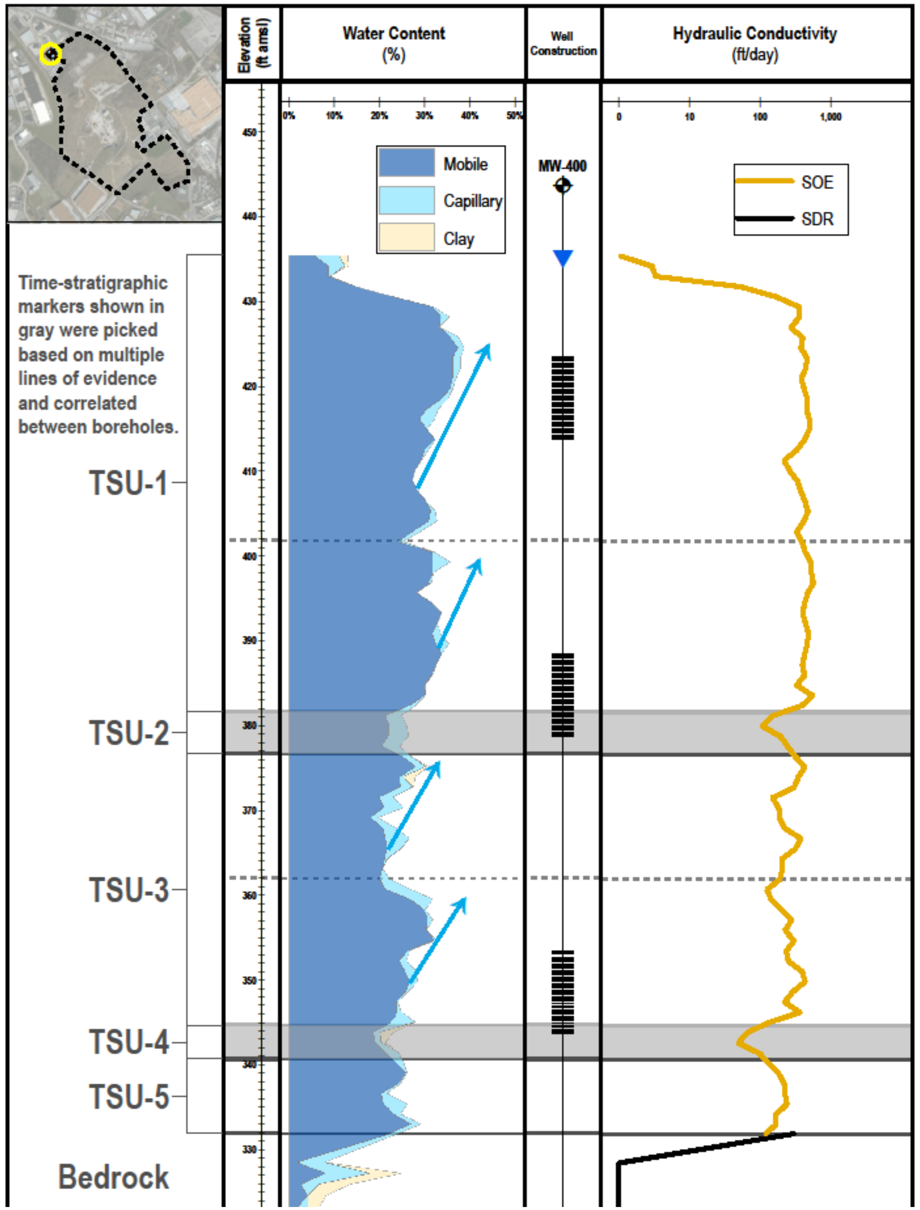
- Vertical resolution determined by length of coil in probe and pore size distribution
- Real-time processing automated in packaged software
- Interpretation yields detailed characterization of aquifer structure and properties (bound/mobile water content, permeability)



Model Discretization



		MW-400	443.74	1.21
	elevation	depth	freef	Ksoe
443.74	436	8.2306	6%	0.750947
443.74	434	9.4357	9%	2.94501
443.74	433	10.6408	9%	3.333014
443.74	432	11.8459	15%	51.73054
443.74	431	13.051	23%	170.1752
443.74	429	14.2561	32%	357.2296
443.74	428	15.4612	34%	357.4305
443.74	427	16.6663	33%	269.9161
443.74	426	17.8714	36%	400.3129
443.74	425	19.0765	37%	377.3567
443.74	423	20.2816	36%	461.8747
443.74	422	21.4867	36%	438.4383
443.74	421	22.6918	36%	379.178
443.74	420	23.8969	36%	416.67
443.74	419	25.102	34%	462.6727
443.74	417	26.3071	30%	453.5252
443.74	416	27.5122	29%	497.0538
443.74	415	28.7173	30%	491.0672
443.74	414	29.9224	32%	421.5758
443.74	413	31.1275	30%	327.0553
443.74	411	32.3326	29%	217.1617
443.74	410	33.5377	28%	261.4209
443.74	409	34.7428	27%	335.0117
443.74	408	35.9479	28%	374.4351
443.74	407	37.153	30%	429.8629
443.74	405	38.3581	31%	471.4722
443.74	404	39.5632	31%	412.6355
443.74	403	40.7683	27%	329.9234
443.74	402	41.9734	24%	393.6686
443.74	401	43.1785	32%	435.2676
443.74	399	44.3836	32%	524.767
443.74	398	45.5887	32%	532.0197
443.74	397	46.7938	31%	563.3232
443.74	396	47.9989	28%	470.6862
443.74	395	49.204	32%	422.9988
443.74	393	50.4091	34%	398.6667
443.74	392	51.6142	33%	441.0255
443.74	391	52.8193	32%	483.1798
443.74	390	54.0244	32%	459.8488
443.74	389	55.2295	34%	423.6371
443.74	387	56.4346	32%	394.6662
443.74	386	57.6397	32%	424.7077
443.74	385	58.8448	30%	329.033
443.74	384	60.0499	30%	553.0809
443.74	382	61.255	27%	387.5384
443.74	381	62.4601	21%	149.0355
443.74	380	63.6652	22%	106.9336
443.74	379	64.8703	22%	193.8402
443.74	378	66.0754	20%	246.1382
443.74	376	67.2805	25%	316.8982
443.74	375	68.4856	28%	427.8226
443.74	374	69.6907	25%	344.7538
443.74	373	70.8958	25%	301.3047
443.74	372	72.1009	20%	148.9579
443.74	370	73.306	21%	183.7122
443.74	369	74.5111	18%	187.1039
443.74	368	75.7162	21%	221.7408
443.74	367	76.9213	21%	376.2966
443.74	366	78.1264	22%	314.9491
443.74	364	79.3315	21%	203.7215
443.74	363	80.5366	21%	206.297
443.74	362	81.7417	20%	188.9454
443.74	361	82.9468	21%	124.2535
443.74	360	84.1519	27%	144.5659
443.74	358	85.357	30%	205.4669
443.74	357	86.5621	31%	276.2836
443.74	356	87.7672	30%	225.1398
443.74	355	88.9723	32%	300.5439
443.74	354	90.1774	26%	231.935
443.74	352	91.3825	24%	251.274
443.74	351	92.5876	26%	391.4999
443.74	350	93.7927	27%	433.5072
443.74	349	94.9978	26%	286.9038
443.74	348	96.2029	24%	222.4906
443.74	346	97.408	24%	364.085
443.74	345	98.6131	23%	132.7319
443.74	344	99.8182	19%	65.70149
443.74	343	101.0233	19%	49.2594
443.74	342	102.2284	21%	96.76372
443.74	340	103.4335	24%	133.4144
443.74	339	104.6386	26%	181.7772
443.74	338	105.8437	24%	219.071
443.74	337	107.0488	20%	215.858
443.74	335	108.2539	21%	238.3616
443.74	334	109.459	23%	164.5491
443.74	333	110.6641	27%	163.3103
443.74	332	111.8692	22%	114.3009
443.74	331	113.0743	8%	27.79698
443.74	329	114.2794	3%	2.230146
443.74	328	115.4845	7%	10.89687
443.74	327	116.6896	4%	9.089211

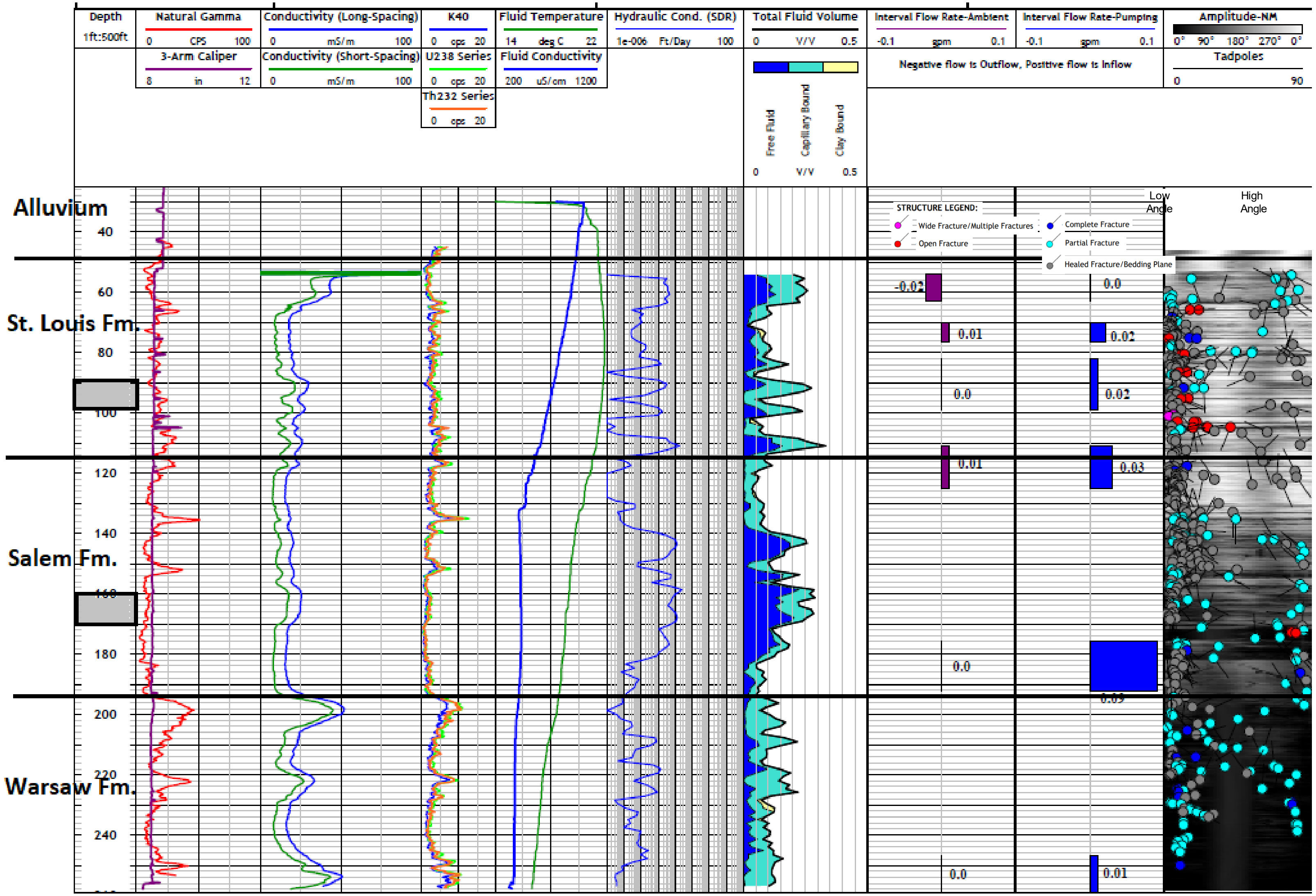


Bedrock Stratigraphy - Geophysical Logs

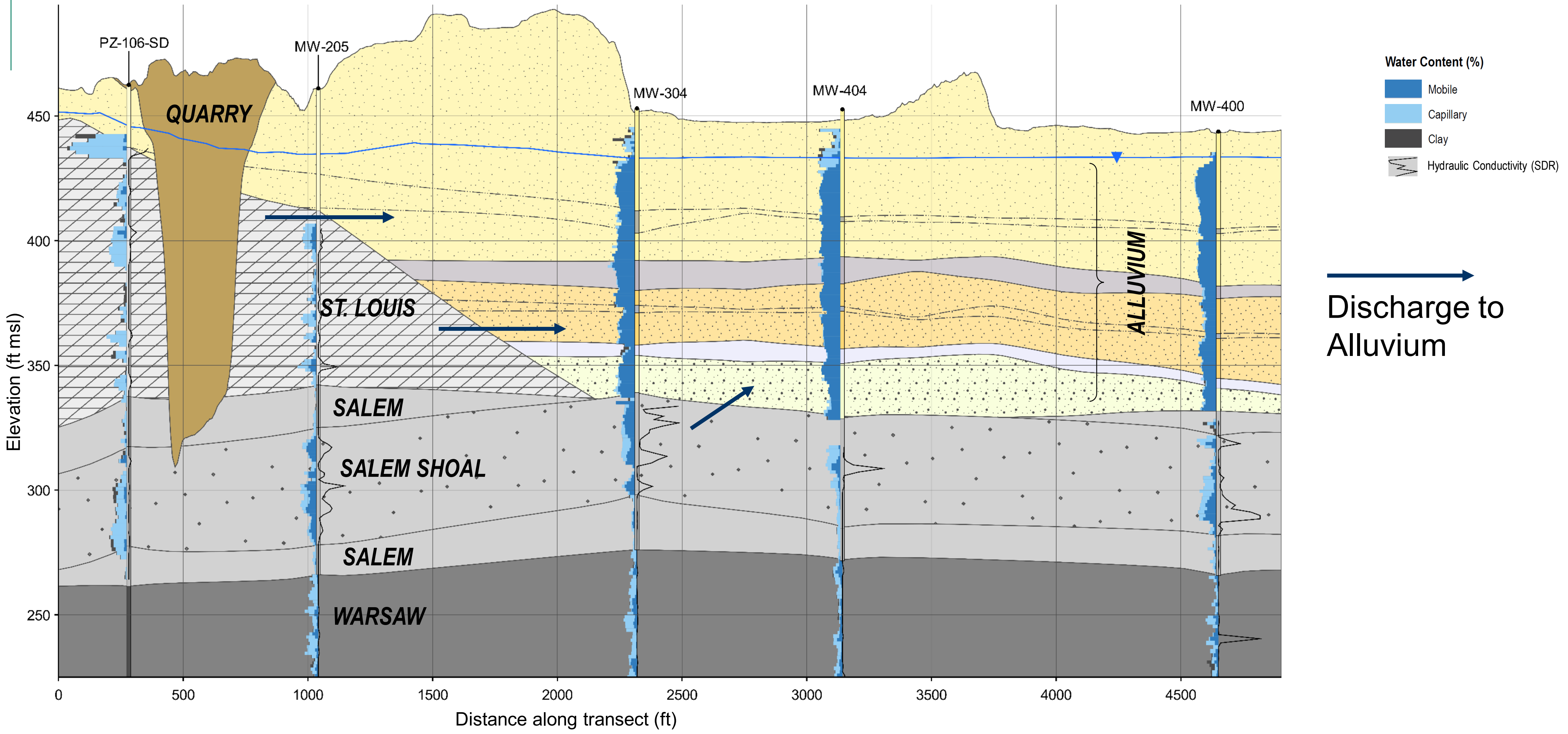
St. Louis Formation dominated by fracture porosity (low angle)

Salem Formation dominated by matrix porosity

Warsaw primarily bound water porosity (claystone/shale)



Bedrock Alluvium Interaction



Discharge to Alluvium

Multi-Phase Porosity Distribution

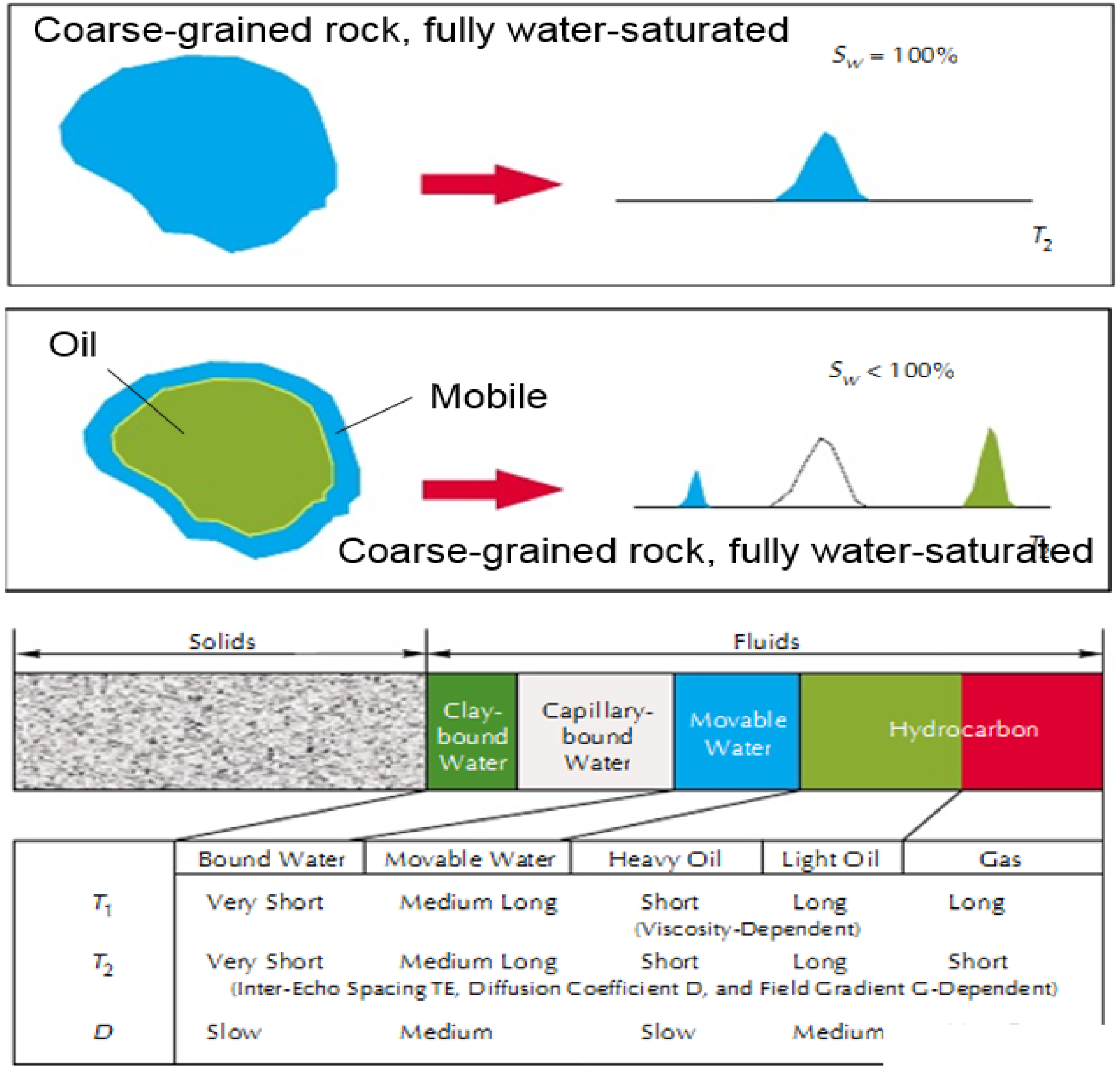
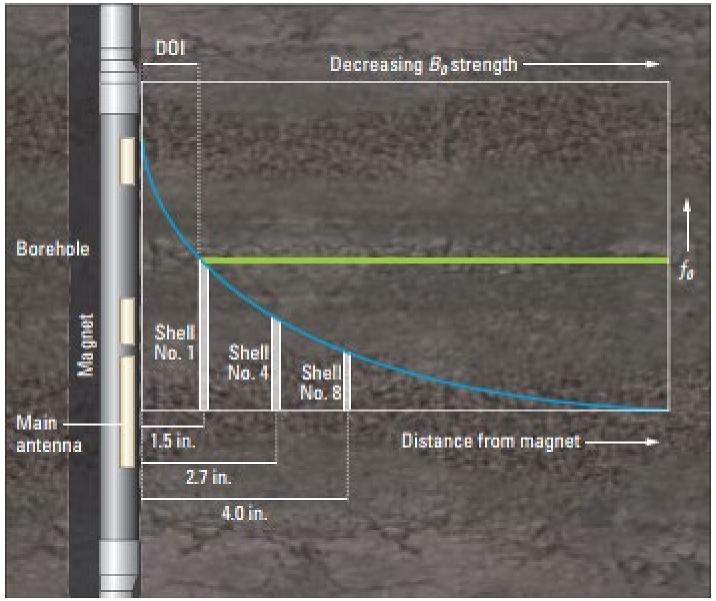


Figure modified from Coates, Xiao, & Prammer; Halliburton Energy Services Publication H02308

Oil Field 2D Diffusion T2 NMR for Fluid Typing
Originally developed by Schlumberger in early 2000s

Static Gradient in Tool Field



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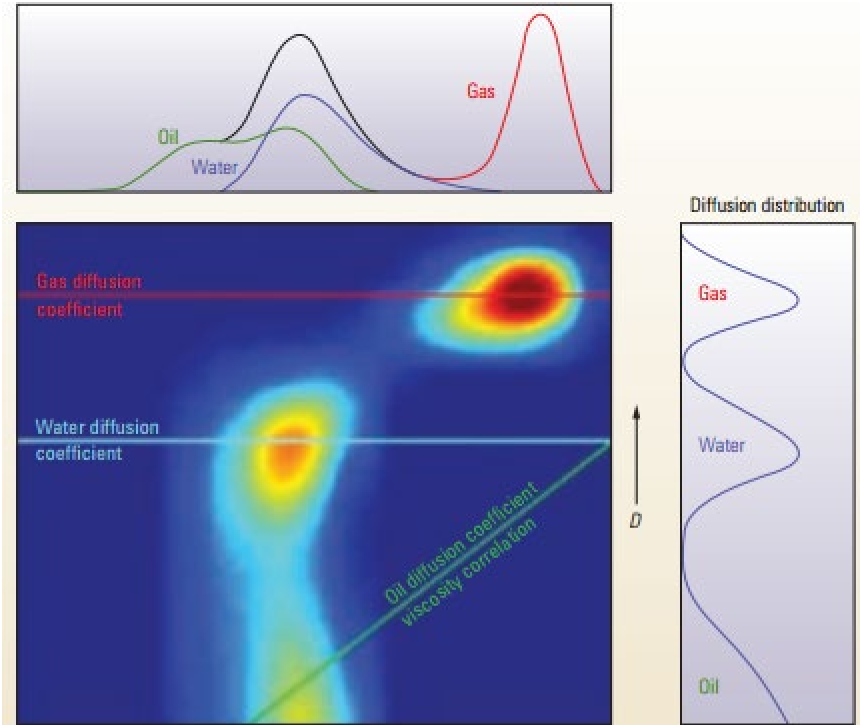


T2

Figures modified from Akkurt et al. 2009

Test Cell Sampling

Bulk Fluid

#1

Water

#2

Diesel

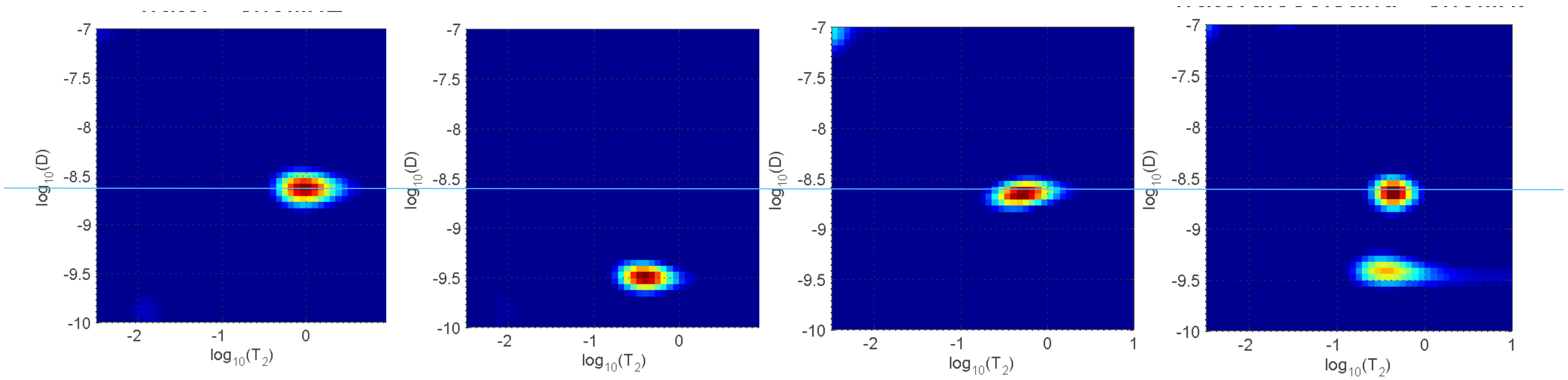
Coarse Quartz Sand

#3

S_W 100%

#4

S_W 60% S_D 40%

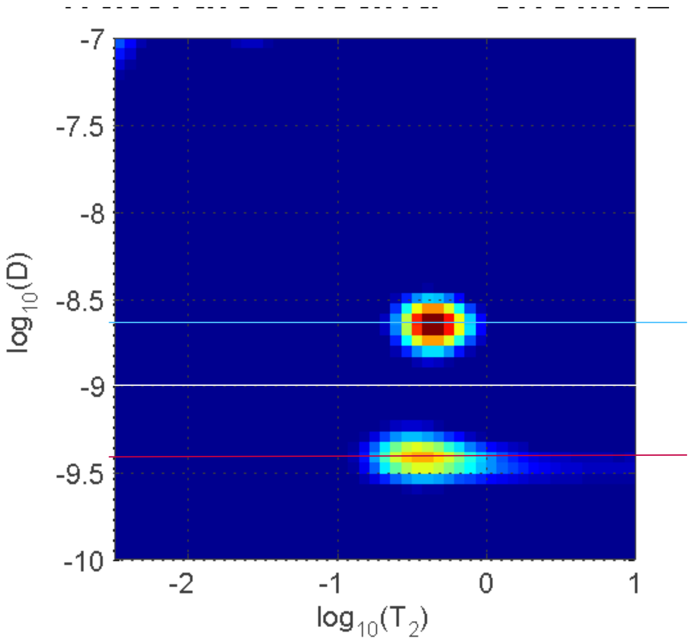


1.58 x 10^{-9} m^2/s

Bench scale NMR Logging Results

Sand with

S_{water}=60% S_{diesel}=40%



∑ = 17.5% vol

∑ = 13.2% vol

57%$_{water}$

43%$_{diesel}$

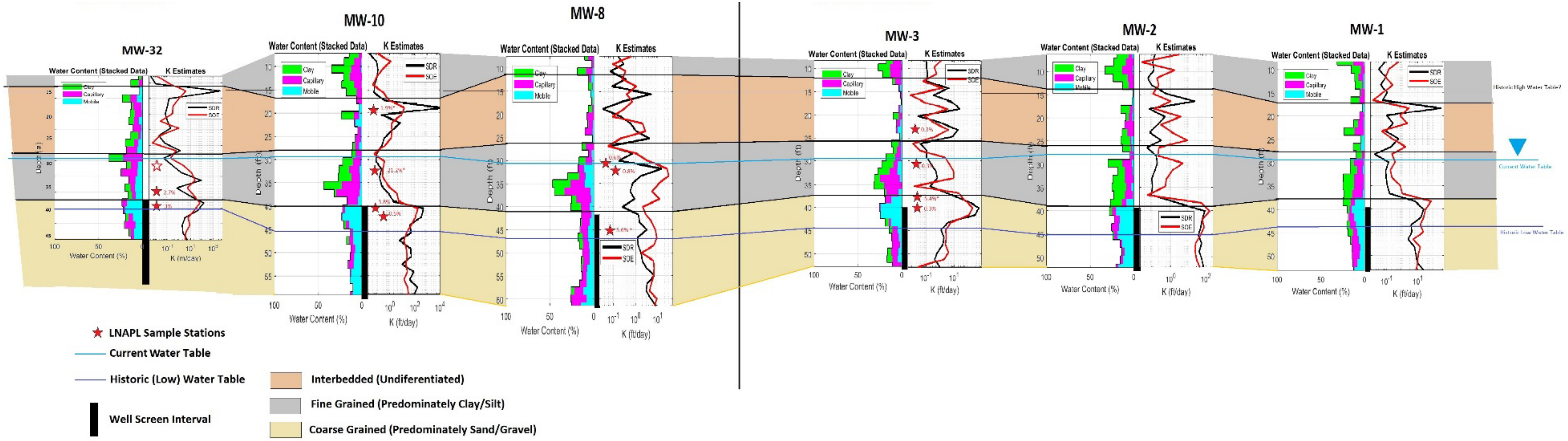
NAPL Detection Pilot Test

Product Type	Target Saturation (% pore vol.)	NMR Detected Saturation (% pore vol.)	Relative Percent Error
Fresh Diesel	10%	7.3%	27%
Fresh Diesel (duplicate)	10%	7.6%	24%
Fresh Diesel	5%	2.2%	56%
Fresh Diesel	1%	2.4%	140% (over-estimate)
Weathered Gasoline	10%	3.3%	67%

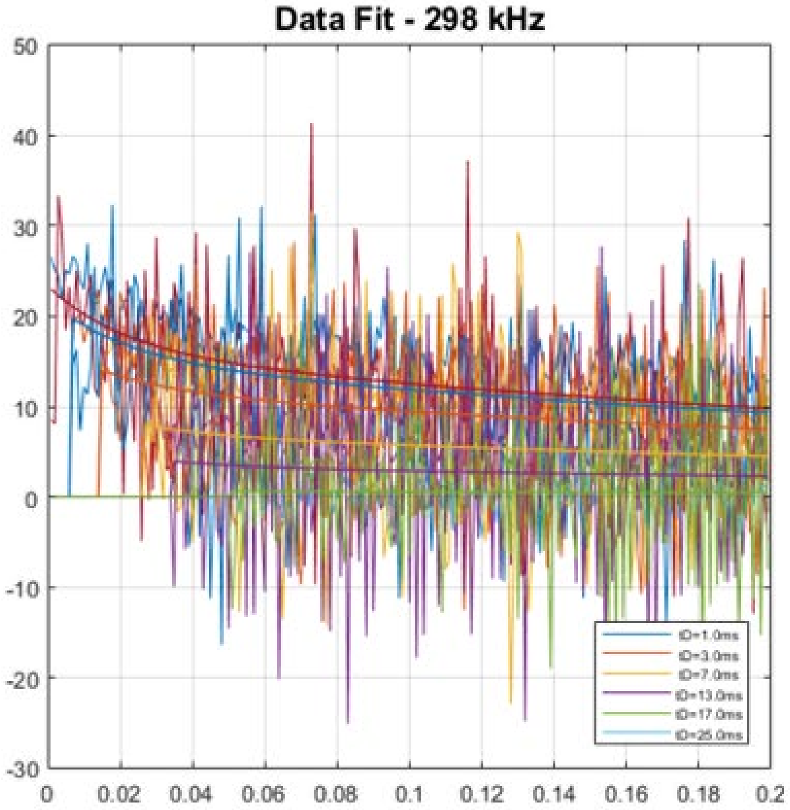
Figure modified from Spurlin, Barker, Cross, & Divine

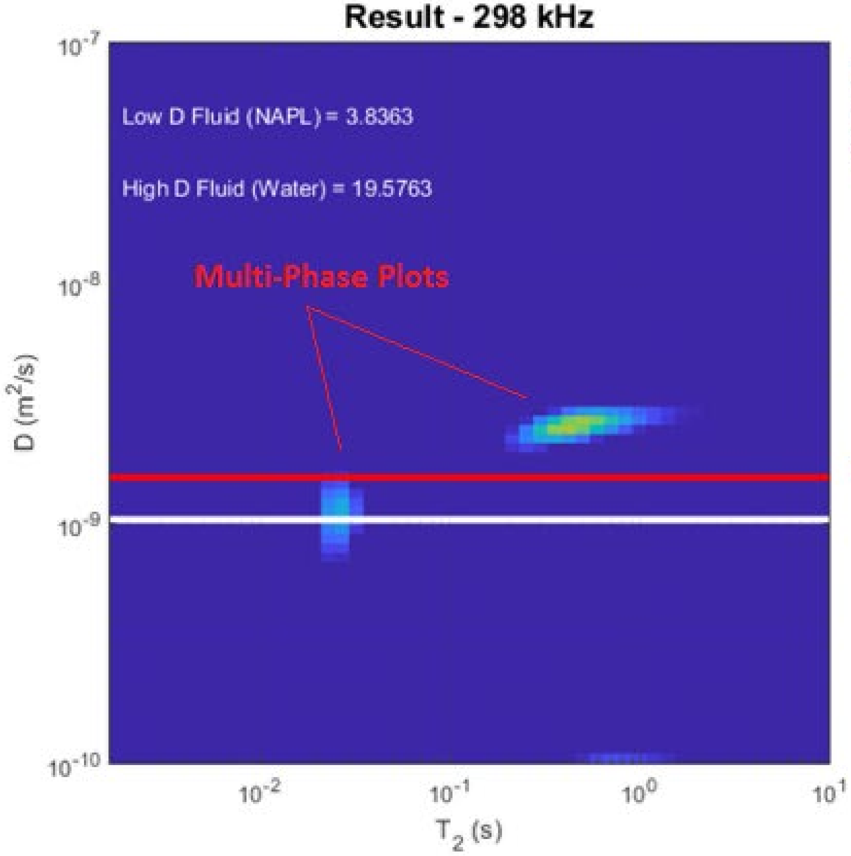
Case Study: LNAPL Site, New Mexico

- Pressure to install dozens new screened wells $$$



NAPL Detection (% Saturation) Using Diffusivity Properties of Pore Fluids: LNAPL Site, New Mexico





NMR NAPL Saturation Detection using Diffusivity Properties

Water

Diffusion Coefficient of Water

NAPL

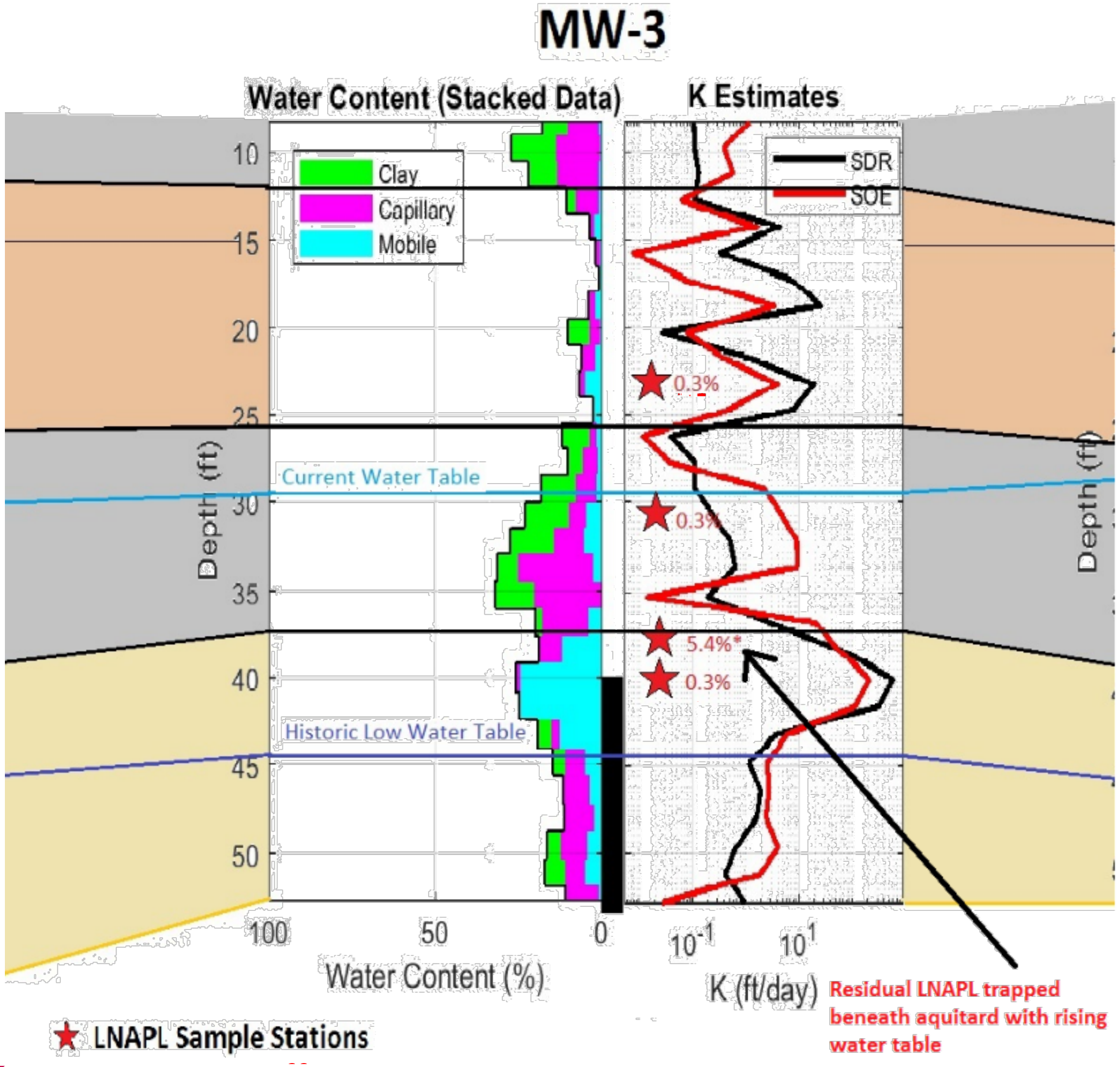
Case Study: LNAPL Site, New Mexico

Data Result:

- **Low-K laterally extensive zone mapped directly above well screens**
- **NMR NAPL Diffusion testing indicated residual NAPL trapped below low-K zone**

Outcome:

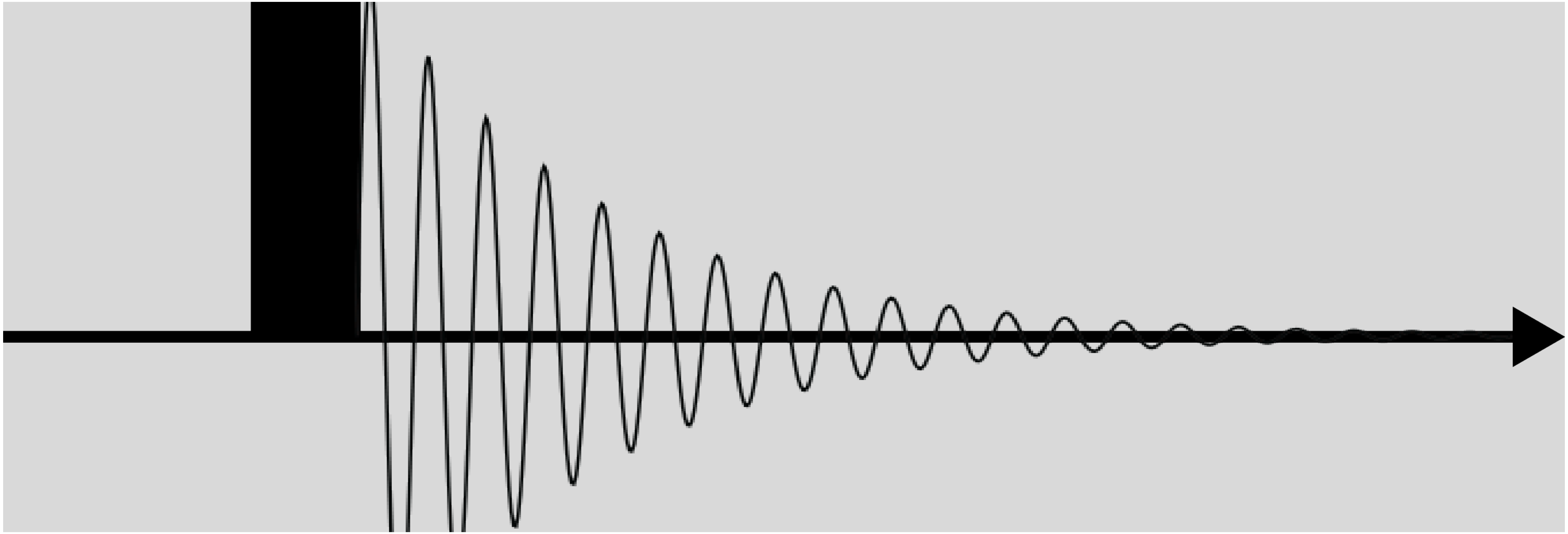
- **NMR data supported conclusion low residual NAPL and low risk of migration**
- **Data acquired using existing wells minimizing cost and risk**
- **Regulator did not require installation of new monitoring well network ($$$$)**



Summary

NMR is a viable technology for environmental and water supply practitioners

- Cost savings and reduced risk to human health and safety (non-intrusive/use of existing wells)
- Improved site characterization and CSM refinement
- Strong potential to optimize extraction well & remedial system designs
- Ability to collect HRSC hydrostratigraphic data where traditional push-tool methods can't go
- LNAPL Detection and Quantification



Thank you

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The business of sustainability

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