NMR Geophysics for Groundwater Investigations

Vista Clara Inc.
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Nuclear Magnetic Resonance (NMR)

Medical MRI

NMR Geophysics
NMR Geophysics for Groundwater

• Traditional Geophysics Provides:
  – Acoustic Impedance (Seismic)
  – Electrical Resistivity (ERT/EM/MT)
  – Dielectric Constant (GPR)
  – *Hydrogeologic Properties are Inferred*

• NMR Geophysics Provides
  – Direct Quantification of *Water Content*
  – Sensitivity to *Pore Size*
  – Estimation of *Permeability*
  – *Hydrogeologic Properties are Directly Characterized*
Hydrologic Properties from NMR

Geologic Material

NMR Signal

Signal

Time (ms)
Hydrologic Properties from NMR

NMR Provides

- Water Content
- Porosity (Lithology Independent)
Hydrologic Properties from NMR

NMR Provides

- Water Content
- Porosity  (Lithology Independent)
- Pore Size V/S

$T_2 \propto$ pore size
Hydrologic Properties from NMR

Geologic Material

NMR Provides

- Water Content
- Porosity (Lithology Independent)
- Pore Size V/S
- Pore Size V/S Distribution
- Bound versus Mobile WC
Hydrologic Properties from NMR

NMR Provides

- Water Content
- Porosity  (Lithology Independent)
- Pore Size V/S
- Pore Size V/S Distribution
- Bound versus Mobile WC
- Permeability

\[ S_0 \propto \phi \]

\[ T_2 \propto \text{pore size} \]

\[ K_{KC} = \frac{\phi}{\tau(S/V)^2} \]

\[ K_{SDR} = b_{SDR}T_2^2S_0^N \]
Logging NMR vs. Surface NMR

Logging NMR:
- Requires borehole (drilling cost)
- Depth range 1000s of meters
- Vertical resolution ~ 0.5m
- Data depends on borehole conditions
- Measures water in all pore sizes

Surface NMR:
- Non-invasive (no drilling cost)
- Max depth range 100 meters
- Vertical resolution ~ 2 – 20m
- Can’t use in noisy urban areas
- Measures water in med-large pores only (not clay)
Javelin NMR Logging Tool

- Designed specifically for groundwater investigations
- Low cost, portable, wide range of probe sizes, max logging depth ~ 400m

- 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 plastic-cased holes
NMR Logging Data Interpretation

- Vertical resolution 0.5m (determined by length of coil in probe)
- Processing automated in packaged software
- Interpretation yields detailed characterization of aquifer structure and properties (bound/mobile water content, permeability)
Straightforward Interpretation

- Vertical resolution 0.5m (determined by length of coil in probe)
- Processing automated in packaged software
- Interpretation yields detailed characterization of aquifer structure and properties (bound/mobile water content, permeability)
Wireline Javelin (Introduced in 2016)

- Max logging depth ~ 1000m
- Ideal for deep groundwater wells
- 3.5 inch and 5.25 inch diameter probes
- Typical logging speed ~ 50m/hr

5.25” probe  3.5” probe
China Lake, CA 2016
Navy Well E2, NMR Logging

Navy Well E2, NMR Logging

T₂ Distribution

Water Content

K estimates

Silt/Clay

20

40

60

80

100

120

140

160

180

~ Water table

Foul smelling water at bottom of well

\[\log_{10} T₂ \ (s)\]

\[\text{Water Content}\]

\[K \ (m/day)\]

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NMR GEOPHYSICS
Denver Water ASR Pilot Study 2015

NMR Logging

40th & Colorado

Denver Formation

Upper Arapahoe

Low K

Lower Arapahoe

Low K

40th & Lima

Denver Formation

Upper Arapahoe

Low K

Lower Arapahoe

Low K
Chandler AZ, NMR Logging, 2016

High Water Production Zones
Identifying Low-K Bound Water Zones

Javelin

- Silt bound water in the vadose zone
- Water table at 20m
- Sand with interbedded silt layers
- Silt at 66m
- Silt at 71-74m
- Silt at 83m
- Bedrock at 98m

3.5” PVC well
Surface NMR

Use Earth’s field as background field and large surface coil for NMR excitation and detection.
GMR Instrument Field Procedures

• Measurement loop typically 20-150 m diameter

• Data collection takes 0.5 – 4 hours per loop location

• Multi-channel architecture used for
  • Noise Reference and Cancellation
  • Multi-coil 2D imaging

• Maximum depth of investigation 100-150m
China Lake, CA, GMR Surface NMR Inversion

Decay Time Distribution

Water Content

Estimated $K$ -- FID Integral

Silt/Clay

Water table
GMR Inversion Result  Kansas, USA

Decay Time Distribution

Water Content

Permeability Estimate

“Virtual Pump Test”

Silt/clay

Sand

Limestone

Processing and inversion can be completed in the field
Nebraska, Ogallala Aquifer

**Decay Time Distribution**

**Water Content**

**Drillers Log**

- Lithologic Units:
  - Gravel
  - Sand/Gravel
  - Sand
  - Sand/Sandstone
  - Silt/Siltstone
  - Clay

**Graphical Data**:
- Depth (m) vs. $T_2^*$ (ms) for Decay Time Distribution
- Depth (m) vs. WC (%) for Water Content
- Lithologic units represented in Drillers Log
GMR 2D Surveying Capabilities

Karst Environment
San Antonio Texas, USA

Layered Unconsolidated Aquifer
Western Washington

Low permeability formation
Cave or fracture zone

Low Permeability Silt

Upper Aquifer
Lower Aquifer
Examples: Logging NMR and Surface NMR at the Same Location
Navy Well D2, NMR Log

- **Silt/Clay**
- **Water table**

**T₂ Distribution**
- Log₁₀ T₂ (s)
- Depth (m)

**Water Content**
- Clay
- Capillary
- Mobile
- Water Content
- Depth (m)

**K estimates**
- SDR
- SOE
- K (m/day)
Navy Well D2, Surface NMR Inversion

- Decay Time Distribution
- Water Content
- Estimated K -- FID Integral

Silt/Clay

Water table

Depth (m)

$T_2^*$ (ms)

$T_2^* > 33$ ms

$T_2^* < 33$ ms

WC (%)

$K_{relative} \times 10^{-5}$
Lawrence Kansas GEMS C, NMR Log

Water table

Decay Time Distribution

Water Content

K Estimates

Silt/Clay

Sand/Gravel w/ thin clay layers at 18 – 20m

Water content table:
- Silt/Clay
- Sand/Gravel
- w/ thin clay layers at 18 – 20m
Lawrence Kansas GEMS C, Surface NMR

Water table

Silt/Clay

Sand/Gravel w/ thin clay layers at 18 – 20m

Decay Time Distribution

Water Content

K Estimates

- Water table
- Silt/Clay
- Sand/Gravel w/ thin clay layers at 18 – 20m
- Decay Time Distribution
- Water Content
- K Estimates
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