# SURFACE NUCLEAR MAGNETIC RESONANCE IMAGING OF SUBSURFACE WATER


## PRINCIPAL INVESTIGATOR

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## OBJECTIVES

To test, evaluate & further develop the surface NMR technique for imaging of subsurface water. The technique was first implemented by scientists at the Institute of Chemical Kinetics and Combustion Technology, Novosibirsk, Russia. Applications include :

- Locating aquifers
- Identifying preferred pathways for contaminant migration


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## THE NMR TECHNIQUE

Other Methods for water content measurements:

1) **Point source measurements (intrusive)**
   a) Changes in electrical resistivity of installed water absorbing sensors.
   b) Time domain reflectometry (probe inserted).
   c) Neutron Logging (requires borehole)

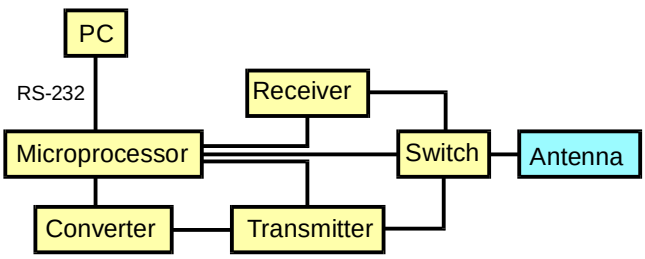
2) **Indirect measurements (non-intrusive);**
   water content inferred from measurement of, e.g.,

   a) Electrical Resistivity
   b) Dielectric Constant
   c) Seismic Velocity

Surface NMR potentially offers unique non-intrusive, direct measurement through its sensitivity to protons (hydrogen nuclei) in free water.

Our measurements employed the NUMIS instrument, manufactured by IRIS in France, which is based on the original Russian hydrometer.

**NUMIS Schematic Diagram**



## WHAT NMR TECHNIQUE MEASURES

Nuclear magnetization $\underline{M}_N$ in an applied static magnetic field $\underline{B}_0$.
Ratio $X_N = |\underline{M}_N|/|\underline{B}_0|$ yields nuclear magnetic susceptibility.

## WHY THIS IS GEOPHYSICALLY USEFUL

Only water and hydrocarbons, with magnetically free protons (hydrogen nuclei) are nuclear paramagnets, and hence have a measurable $X_N$.

An accurate measurement of $X_N$ is hence uniquely capable of sensing these economically important substances.

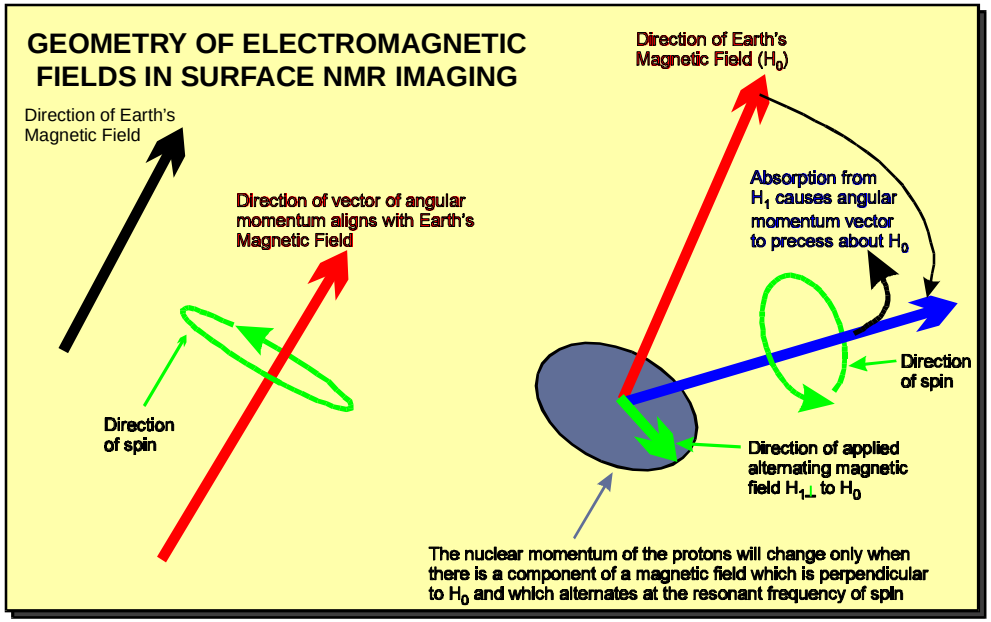
## HOW IT WORKS

- Nuclear spins are partially aligned in the earth's field $\underline{B}_0$, generating a net bulk magnetization density, $\underline{M}_N$.

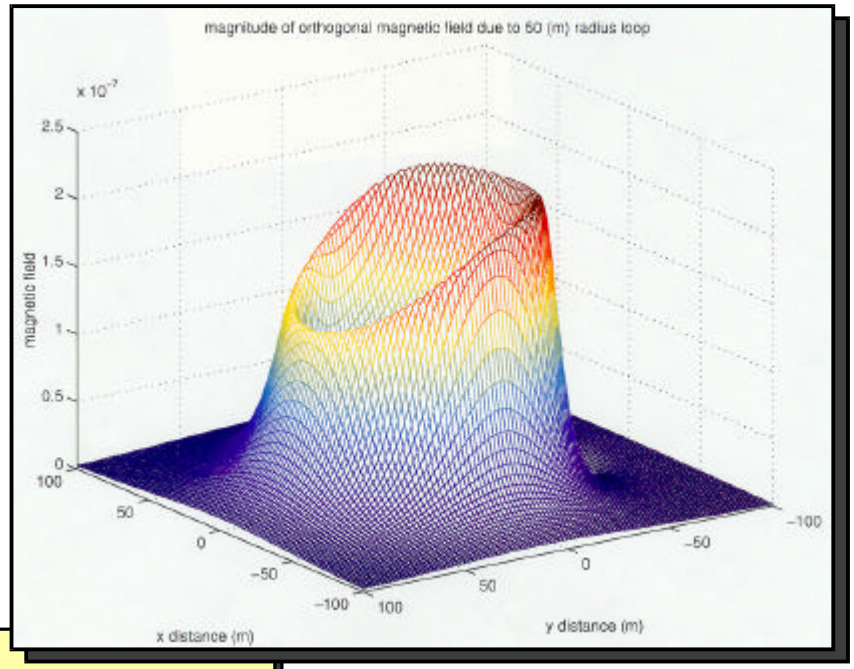
- Static measurement of $\underline{M}_N$, through associated dipolar magnetic field, is impossible.

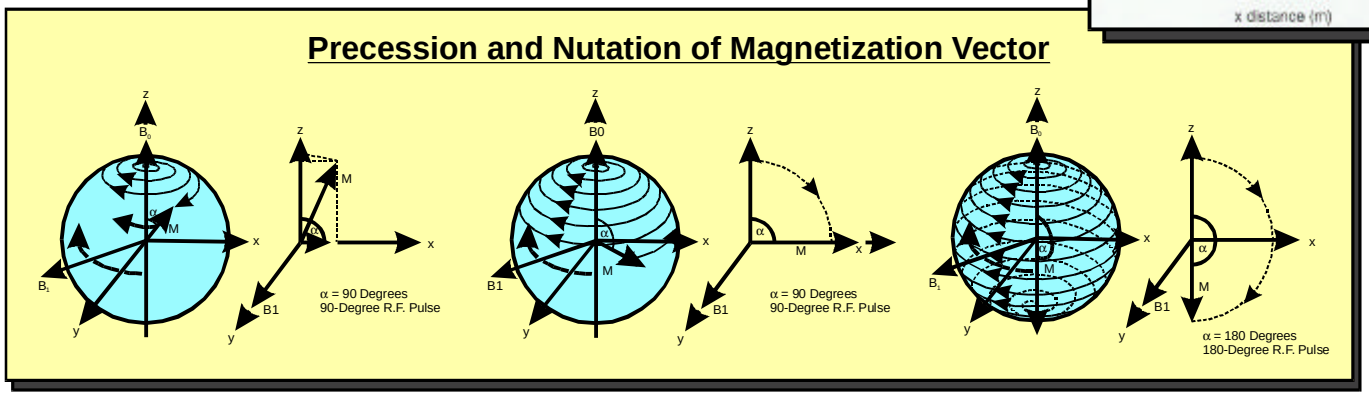
- Convert to a dynamic measurement by using an applied field $\underline{B}_1^{\perp}(t) \perp \underline{B}_0$, circularly polarized to rotate at the Larmor frequency, $\omega_L = \gamma \underline{B}_0$. This tips $\underline{M}_N$ away from $\underline{B}_0$ by an angle $\theta = \gamma\, |\underline{B}_1^{\perp}|\, \tau_P$, where $\tau_P$ is the pulse length. The precessing $\underline{M}_N$ now produces a time varying flux through the receiver coil, generating an ac voltage at frequency $\omega_L$= ~2khz, with magnitude $V_0 \sim |\underline{M}_N| \sin(\theta)$ that is within present measurement capabilities.

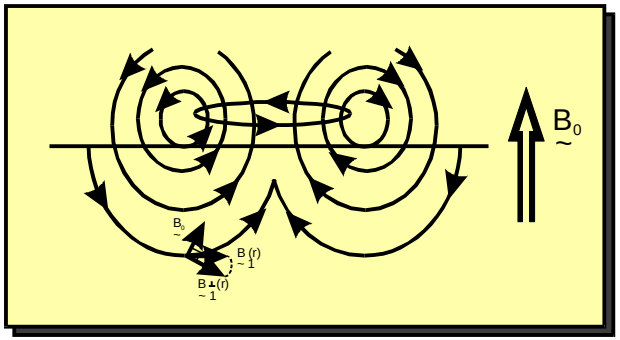
- Applied field $\underline{B}_1^{\perp}$ is spatially nonuniform, so that the tipping angle $\theta=\theta(r)$, is as well. By measuring $V(\tau_P)$ for different $\tau_P$, different r dominate the measured signal. Inversion of $V_0(\tau_P) \longrightarrow \rho_{water}(z)$ can be done for a horizontally stratified subsurface, if conductivity structure is known or inferred from other measurements.

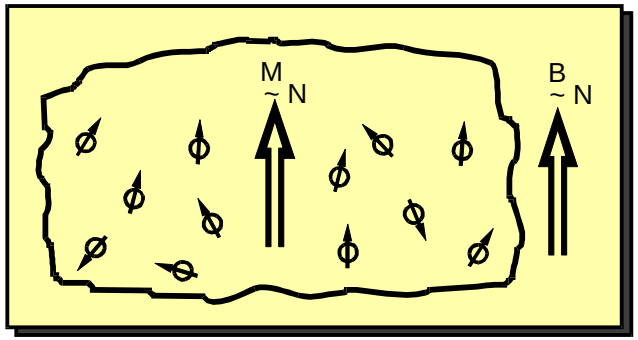



## Magnitude (⊥) Applied Field Using Inclination and Declination of Main Field in Colorado



## PERMEABILITY AND PORE SIZE DISTRIBUTION

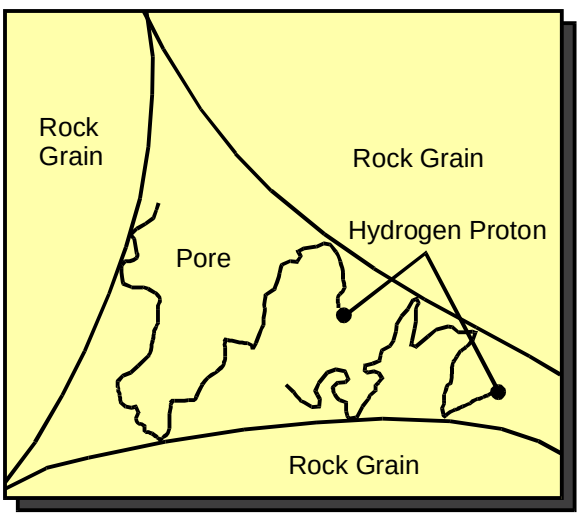
- Precession of $\underline{M}_N$ decays in time, so that
$$V(t) = V_0 e^{-i\omega_L t} e^{-t/T2},$$
where T2 is determined by interactions of spins with each other, pore surfaces, dissolved ions, molecular diffusion, etc.

- In many fine-grained porous rocks dephasing of the spins is believed to be dominated by collisions of the water molecules with magnetic impurities on the grain surfaces. This results in the estimate
$$1/T2 = \rho_2 \, (S/V)_{pore}$$
where S/V is the surface -to-volume ratio and $\rho_2$ is a constant of proportionality that contains information about the density of magnetic impurities.

- $\rho_2$ tends to fall in a narrow band for a broad sampling of sedimentary rocks.

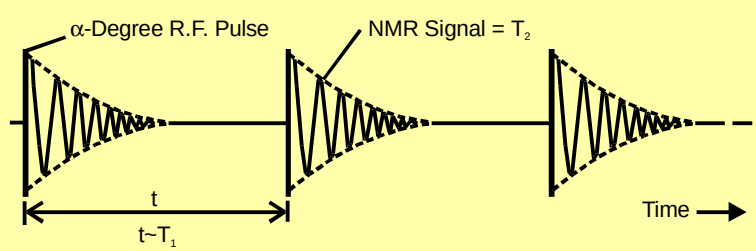
- Permeability $K \sim \varphi^3/(S/V)^2$ where $\varphi$ is the porosity. Thus $K \sim (T_2)^2$, and measured T2 yields information about the permeability if the chemical environment is well characterized from other measurements.

- If T2 < 30ms, the resulting signal decays before it can be measured. This occurs in fine pores, smaller than about 75mm, where water content is therefore not measurable with the NMR method.

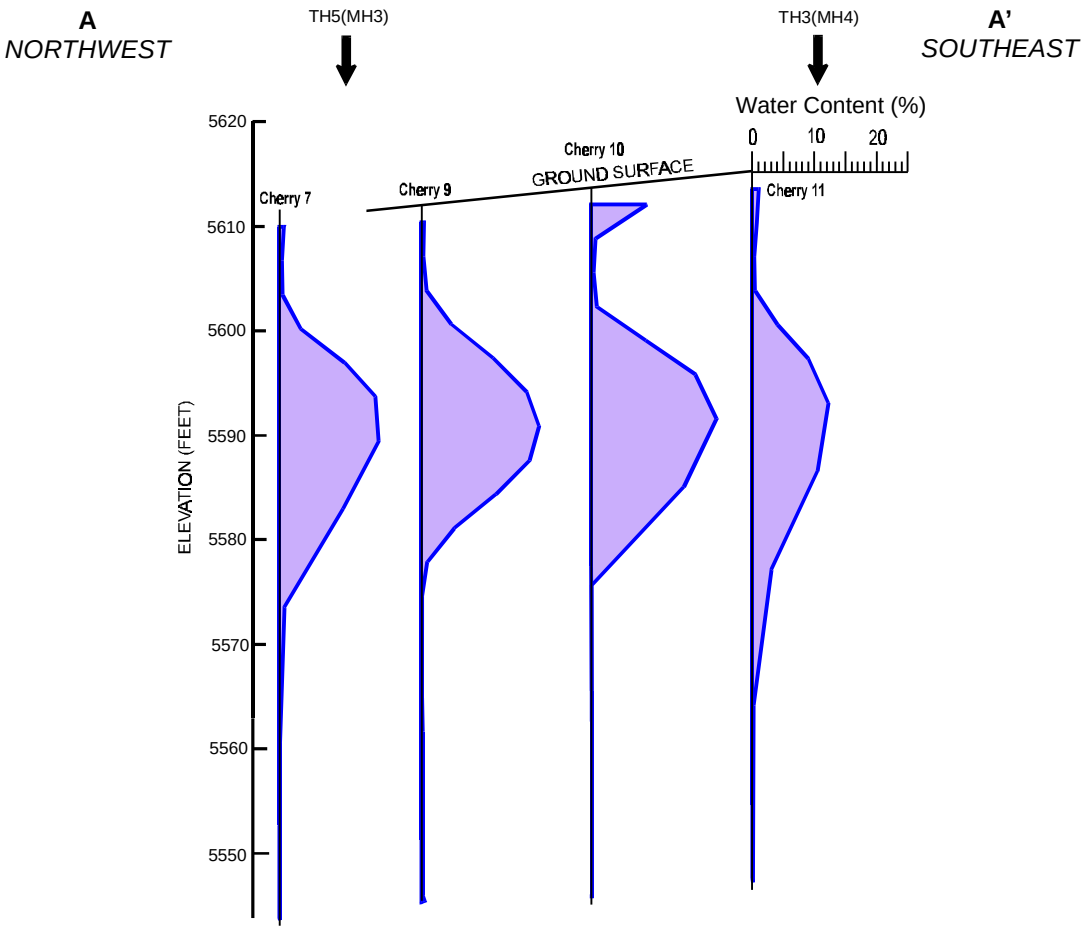


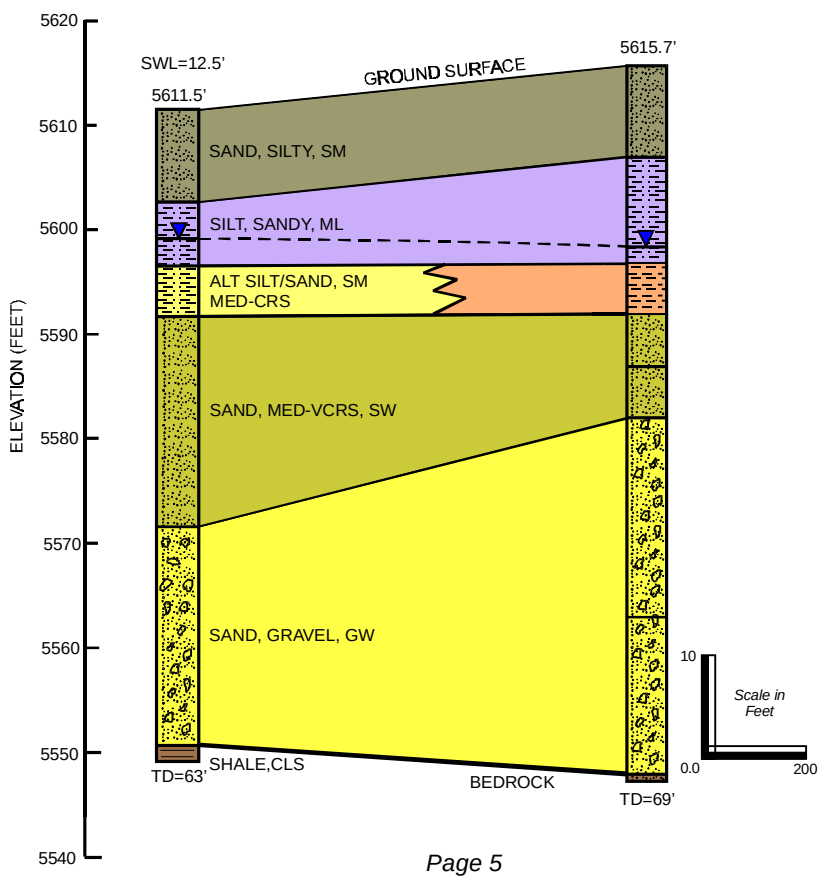

**Relaxation time $T_2$ is a function of pore sizes**

| Water Bearing Strata | Relaxation Time $T_2$ (ms) |
|---|---|
| Sandy Clays | <30 |
| Clayey, Sands, Very Fine Sands | 30-60 |
| Fine Sands | 60-120 |
| Medium Sands | 120-180 |
| Coarse and Gravelly Sands | 180-300 |
| Gravel Deposits | 300-600 |
| Surface Water Bodies | 600-1500 |



# Results and Interpretation



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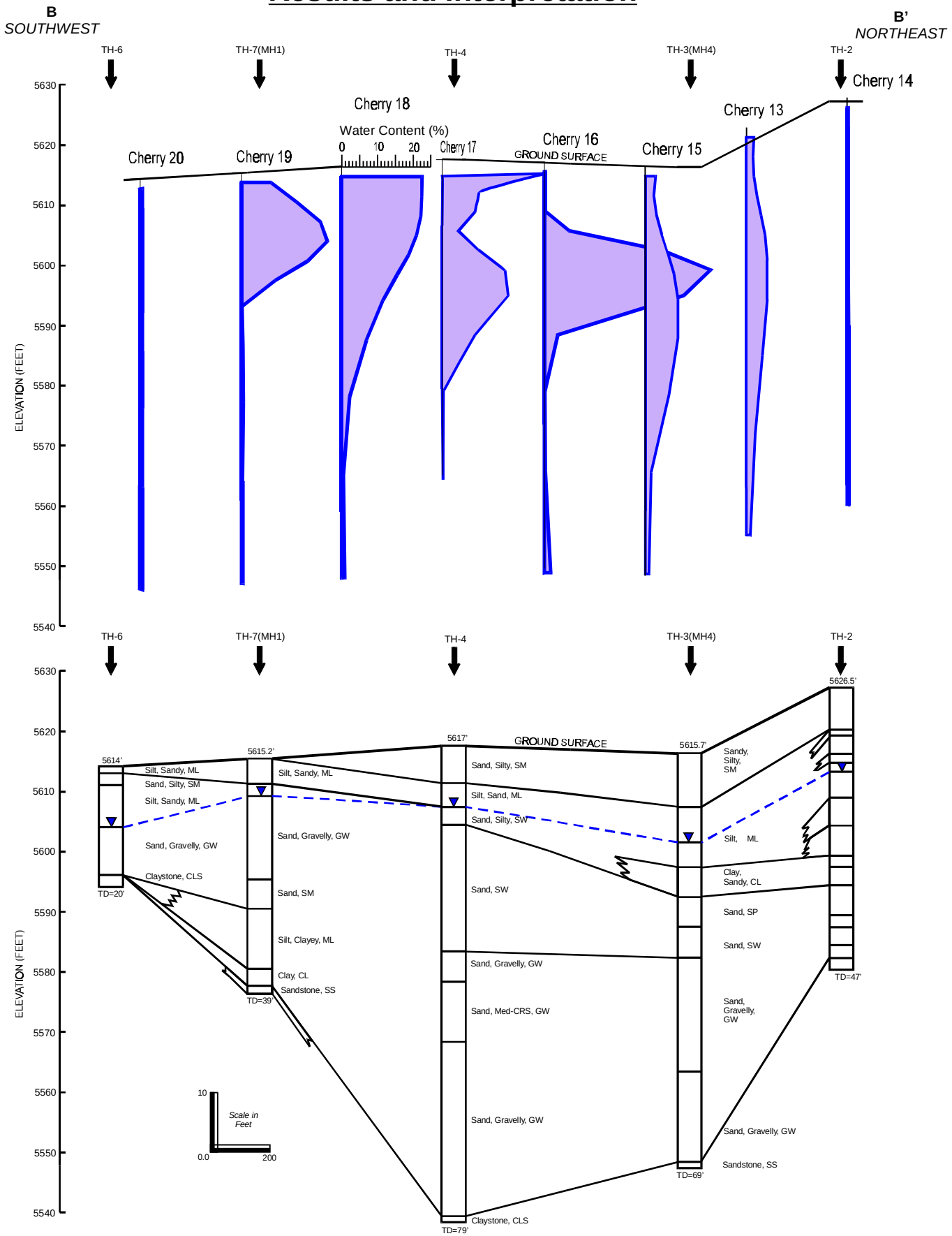

## CONCLUSION

- Present NMR technology can detect subsurface water confined in high porosity media in diverse geologic & environmental settings.

- Absorbed water (Vadose Zone) and water in fine-grained (e.g. clay) sediments are not detectable with present instrument.

- Accurate inversion, $V(\tau_P) \rightarrow \rho_{water}(z)$, requires independent knowledge of geoelectric section (dielectric and conductivity structure).

- Low signal/noise is an issue in many urban settings (e.g. 60Hz noise from power lines).

- Field deployment can be time consuming due to stacking time and time required to locate the exact Larmor frequency. In the present measurements, two days at cost of $3-5K were required at each site. Borehole methods are then competitive with this.

- Advances in modeling, signal processing and instrumentation must still be made for the method to find practical use.

## FUTURE DIRECTION

- Improve modeling of the NMR response through more sophisticated treatment pf the inverse problem.

- Devise more efficient experimental protocol to reduce field deployment time.

- Devise new experimental design strategies for source and receiver geometries for improved depth focusing. Different geometries may give enhanced resolution at different depths and could be chosen to best suit any a priori knowledge one has about the measurment environment.

- Devise more sophisticated pulse sequences for greater resolution and sensitivity to T2 and $\rho_{water}$.

- Improve noise rejection with new receiver designs.

- Develop coil and electronics technology for measurement of earlier times to constrain finer-grained regions with shorter T2.