

# MRS-DETERMINED AQUIFER PORE-SIZE DISTRIBUTION – MULTI-EXPONENTIAL DECAY ANALYSIS

**J. Roy\***

\*ITC, P.O. Box 6, 7500 AA Enschede, The Netherlands

**Foreword** – Aquifer pore-size distribution allows lithology characterization and contributes to the quantification of the water bearing layers' flow properties. NMR (Nuclear Magnetic Resonance) petrophysics establish a direct link between pore-size and some NMR decay time constant ( $T_i$ ) so that the  $T_i$  spectrum is a scaled replica of the pore-size distribution. The MRS (Magnetic Resonance Sounding) multi-exponential decay analysis is an application to MRS of this concept widely used in NMR logging.

**Background** – Legchenko and Valla (2002) have described the MRS technique as an in-situ application of NMR to 1D subsurface characterization in terms of water bearing properties. MRS allows the estimation of both the free water content ( $\Phi_{\text{MRS}}$ ) and  $T_i$  as a function of depth down to 0.5 to 1  $L$  (MRS loop size) provided a number of constraints are met (in terms of formation resistivity, noise level, earth's field amplitude ( $B$ ), homogeneity of the earth's field at scales from  $L$  down to water/pore interface etc).  $\Phi_{\text{MRS}}$  estimation has been developed taking into account the specific MRS implementation geometry and the physical property of the host media (e.g. resistivity etc.). The use of  $T_i$  on the other hand is a result of empirical MRS observations (e.g. Schirov et al. 1991) but also of investigations in NMR petrophysics. Hore (1995) summarizes NMR as a near-ideal investigation tool: NMR responses are very sensitive to the environment where the NMR excitation is performed while the NMR responses make no significant modification to such environment.

In NMR petrophysics, pore-size is defined as  $V/S$  where  $V$  is the pore volume and  $S$  is its surface. Three NMR decay time constants are distinguished:  $T_1$  longitudinal ('spin-lattice') relaxation,  $T_2$  transverse ('spin-spin') relaxation and  $T_2^*$  free induction decay. The two relaxation time constants are affected by the bulk fluid (here groundwater) relaxation time constant ( $T_{1b}$  &  $T_{2b}$ ), and by surface relaxivity ( $\rho_1$  &  $\rho_2$ ). Moreover, according to acquisition parameters and the presence of a magnetic field gradient, the viscosity of the fluid may also affects  $T_2$ . Finally  $T_2^*$  is affected by the magnitude of the field gradient itself (if present) in addition to all the parameters affecting  $T_2$  (Dunn et al., 2002; Kenyon, 1997).

**NMR petrophysics development perspective** – Up to now, NMR petrophysics is closely tied to the oil and gas exploration and exploitation and although it started earlier (1950s), its development is linked to the developments of NMR logging. Early logging tools (1960s) used the earth's field as a static field (like MRS) and remained largely a research topic for several decades. During this period, petrophysical investigations relied mostly on  $T_1$  measurements, usually carried-out at a much higher frequency than their logging counterpart. Particularly since the mid-1990s, pulse NMR tools have been optimized for the logging environment. These operate at fields larger than the earth's field (using permanent magnets designed for variable temperature work) and their design makes use of a significant magnetic gradient to multiply the logging speed (e.g. NUMAR design) and to estimate the fluid viscosity. Currently, the main measuring sequences for logging tools lead to  $T_2$  measurements. A new generation of petrographic NMR tools, designed around the logging tools, allow laboratory measurements at the same frequency as the corresponding NMR log. Also laboratory measurements have mostly shifted from  $T_1$  to  $T_2$  measurements.

**NMR petrophysics and pore-size** - Initially the drastic reduction of NMR decay time constant in a saturated porous rock relatively to its value in bulk fluid came as a surprise. It was explained by the KST model (Korrington-Seevers-Torrey; Korrington et al., 1962), where saturated porous rock NMR decay rate is directly tied to surface relaxation and therefore to the pore-size. The NMR signal  $[E(t)]$  decay rate is modeled as an exponential decay. As part of the data set inversion, a determination is made of a best fit decay time constant  $T$  in the expression  $E(t) = E_0 e^{-t/T} \sin(\omega_1 t + \phi)$  where  $E_0$  is the initial value of the NMR signal,  $\omega_1$  is the (angular) Larmor frequency and  $\phi$  is the NMR signal phase with respect to the excitation. Many investigators followed this model and a good description of the relationship between pore-size and  $T_1$  and its use for the determination of pore-size distribution in natural rocks is illustrated e.g. in Kenyon et al. (1989): see Figure 1.

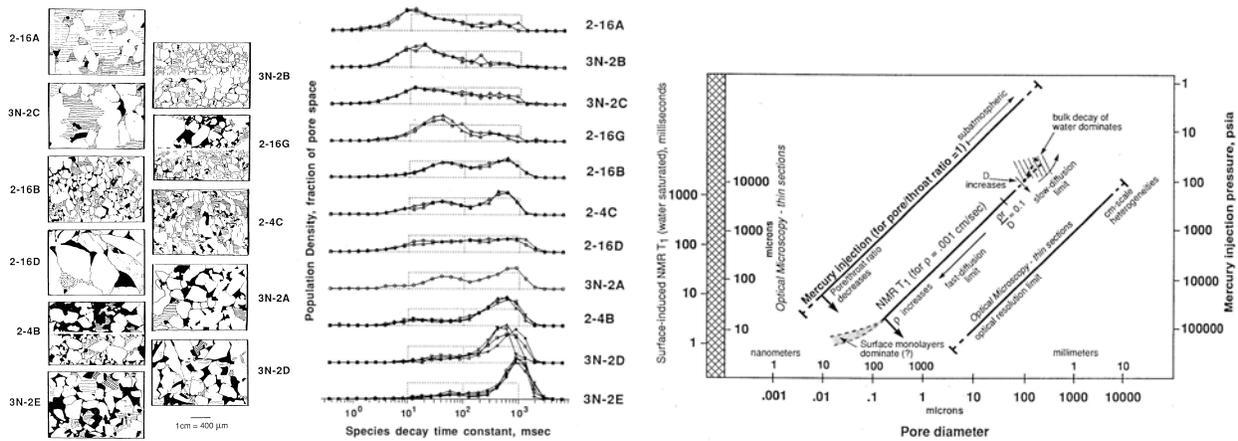


Figure 1: left- micrographs of 11 rock samples, center- corresponding NMR  $T_1$  spectra, right- correlation pore-size vs NMR  $T_1$ , optical microscopy & mercury injection (Kenyon et al., 1989).

In porous rocks, under conditions typical for near surface aquifers (< 200 m depth), the NMR decay time constant is controlled by the pore-size distribution of the water containing materials:  $T_{is} = (V/S)/\rho_i$  [ $T_i$  is  $T_{2s}$  or  $T_{1s}$  and  $\rho_i$  is the surface relaxivity ( $\rho_1$  for  $T_{1s}$ ,  $\rho_2$  for  $T_{2s}$ ) of the pore] (Kenyon, 1997, Straley & al. 1997). Such statement assumes that the surface relaxation rate ( $T_{is}$ ) is much faster than the bulk relaxation rate ( $T_{ib}$ ). Furthermore in the case of  $T_2$ , it neglects the diffusion component (a function of the fluid viscosity and NMR data acquisition parameters). The  $T_{is}$  vs  $(V/S)$  relationship is no longer linear for the cases of wide-open fractures, pebbles or larger sized fragments. MRS measurements will not measure pore-size linearly in the centimeter to meter range because it will be stuck at the bulk relaxation rate ( $T_{2B}$ ) [1 to 3 seconds (Dunn et al., 2002)]. The other end of the scale (a few microns) is currently unreachable with MRS because of its 30 ms instrumental dead-time.

Although the early petrophysical work on NMR pore-size determination was done with  $T_1$  because of its relative insensitivity to distortion effects, current work in NMR petrophysics often uses  $T_2$  for direct correspondence with NMR log results. In using results from NMR petrophysics, great care must be taken regarding terminology aspect since several terms are used differently in NMR petrophysics and in hydrogeology.

**NMR multi-exponential decay analysis** - A distinction is made here between EM skin-depth ( $\delta_{EM}$ ) and NMR skin-depth ( $\delta_{NMR}$ ). According to the investigation depth, the scale of the MRS survey can easily reach the order of magnitude of  $\delta_{EM}$ , which depends on the Larmor frequency at

the site investigated and the resistivity of the subsurface formation. However, this scale is always much smaller than  $\delta_{\text{NMR}}$ . [E.g. at 2 kHz,  $\delta_{\text{EM}}$  would range from 6 m in highly saline clays ( $\sim 0.3 \Omega\text{-m}$ ) to  $> 1$  km in unfractured limestone or crystalline rock ( $> 10000 \Omega\text{-m}$ ) while  $\delta_{\text{NMR}}$  at 2 kHz in water is  $\sim 10^{12}$  m.] In a way analogous to EM, this insures that pores decay independently of each other.

The measured signal is the vectorial sum of all the individual contributions (each with its own orientation, amplitude and pore-size distribution) from the whole volume where the MRS excitation was effective in polarizing the in-situ groundwater. Similarly to the estimations done in borehole logging and petrophysical studies (Gallegos and Smith, 1988; Kenyon, 1997; Kenyon et al., 1989 etc.) the procedure and modeling is as follows. The measured signal is modeled as:  $A(t) = \sum_i A_i e^{-(t/T_i)}$ , where  $A(t)$  is the signal time series envelope,  $A_i$  is the  $i$ -th initial amplitude of the signal corresponding to the decay rate  $T_i$ . The model assumes that each pore decays as a single exponential and the pores decays independently of each other, which is reasonable considering the size of  $\delta_{\text{NMR}}$ . An observed decay curve is then analyzed as a sum of single exponential relaxation terms which when properly rescaled correspond to the poresize distribution (Howard & Kenyon, 1992). The adaptation of such strategy to MRS was suggested by Roy (2000) and by Monke et al (2001) using a somewhat different way. In the MRS approach followed here, a similar discrimination by decay rate is done: the data is first analyzed into specific decay rate components. Each component (modeled as independent contribution produced by a class of pore-size as per the starting assumption) is inverted individually to yield free water content as a function of depth for each pore-size class. In the MRS technique, the measured NMR decay rate is  $T_2^*$ . Recently Legchenko et al. (2002), Monke et al. (2002) and Vouillamoz (2003) have reported an alternate mode of MRS data acquisition where an apparent  $T_1$  is available through the use of more than one excitation pulse. In the work reported here, only  $T_2^*$  inversion are used. The technique is currently applicable only to MRS data set with very good signal to noise ratio. Furthermore the use of  $T_2^*$  means that it is tacitly assumed that magnetic gradient effects at scales from  $L$  down to individual water/pore-wall interfaces (absence of magnetic susceptibility contrast at the pore/grain boundary), are negligible i.e. that  $T_2^* = T_2$ . Although this is a reasonable assumption in many cases for MRS (site dependent), it is normally not the case for data sets produced by a laboratory NMR instrument or by a modern logging tool which use much higher

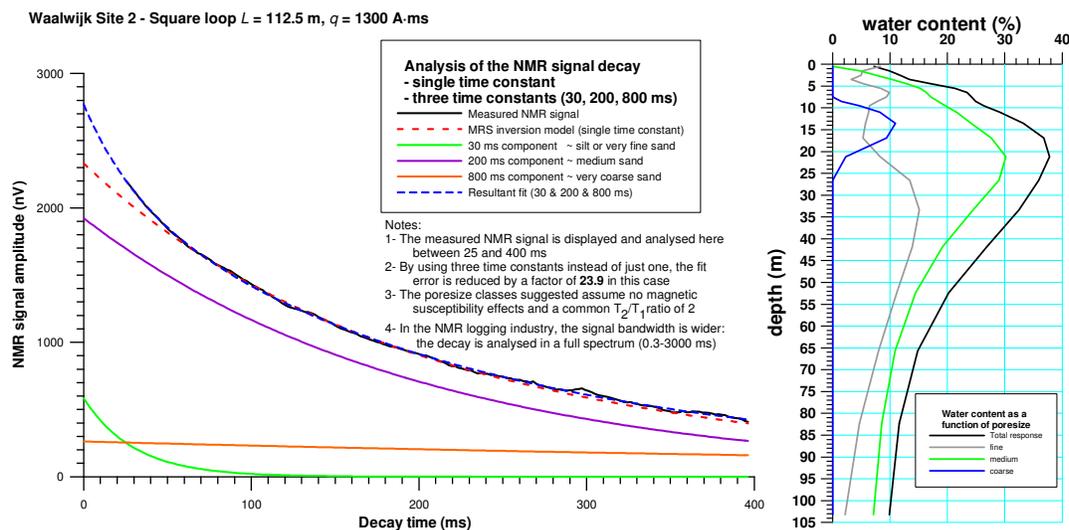


Figure 2: Waalwijk-2 multi-exponential analysis- left - decay curve, right - data inversion

fields than the earth's field and operates under significant magnetic field gradients. The previous model has been refined later by allowing different decay rates within a single pore (Coates et al., 1998); it does not contradict the overall validity of the above procedure but it refines the porosity estimation in particular by discriminating the effective (flowing) component from the bound water component (clay and micro-pores bound). The MRS implementation, with its 30 ms deadtime, cannot benefit fully from such refinement.

**Field example from Waalwijk-2** - The concept is illustrated with its use on data set with good S/N. The acquisition of several MRS data sets with high S/N ratios was reported previously at the Bochum EEGS meeting (Roy, 2000). The analysis of the response for one  $Q$  value into 3 signal decay time constants was displayed at this meeting (Figure 2, left). The exercise was extended to the whole sounding and the 3 corresponding data sets were inverted as shown in Figure 2, right. Lubczynski and Roy (2003) reported on the correspondence of the resulting inversion with the known lithology at the Waalwijk-2 site. In general, the agreement was good but as separately reported at the Orléans meeting, the information corresponding to the 2<sup>nd</sup> aquifer was generally not recovered as a result of the standard type of MRS data inversion used here.

This constitutes an encouraging first step leading to better lithological characterization and better contribution to flow property estimation. The reliance on the  $T_2^* = T_2$  assumption is a limitation of this approach as well as the requirement for data set with high S/N.  $T_1$  or  $T_2$  approaches may eventually solve some of these limitations.

- References** - Coates, G., R., Marschall, D., Mardon, D. and Galford, J., 1998, A new characterization of bulk-volume irreducible using magnetic resonance; *The Log Analyst*, Jan-Feb. 1998, p.51-63
- Dunn, K.-J., Bergman, D.J. and Latorraca, G.A., 2002, *Nuclear Magnetic Resonance Petrophysical and Logging Applications*; Pergamon.
- Gallegos, D.P. and Smith, D.M., A NMR technique for the analysis of pore structure: determination of continuous pore-size distributions; *J. Coll. Interf. Sci.*, **122**, (Mar, 1988), 143-153.
- Hore, P.J., *Nuclear Magnetic Resonance*; Oxford Chemistry Primers, OUP, 90 p.
- Howard, J.T., and Kenyon, W.E., 1992, Determination of poresize distribution in sedimentary rocks by proton nuclear magnetic resonance; *Marine and Petroleum Geology*, **9**, 139-145.
- Kenyon W.E., J.J. Howard, A. Sezginer, C. Straley, A. Matteson, K. Horkowitz, R. Ehrlich, 1989. Pore-size distribution and NMR in microporous cherty sandstones. SPWLA 13<sup>th</sup> Annual logging Symposium, paper LL.
- Kenyon, W.E., 1997, Petrophysical principles of applications of NMR logging; *The Log Analyst*, March-April, pp. 21-43
- Korringa, J., SeEVERS, D.O., and Torrey, H.C., 1962, Theory of spin pumping and relaxation in systems with a low concentration of electron spin resonance centers; *The Physical Review*, **127**.
- Legchenko, A., Baltassat, J.M., Beauce, A., and Bernard, J., 2002, Nuclear magnetic resonance as a geophysical tool for hydrogeologists; *Journal of Applied Geophysics*, **50**, 21-46.
- Legchenko, A. and Valla, P., 2002, A review of the basic principles for proton magnetic resonance sounding measurements; *Journal of Applied Geophysics*, **50**, 3-19.
- Lubczynski, M.W. and J. Roy. 2003. Hydrogeological interpretation and potential of the new Magnetic Resonance Sounding (MRS) method; *Journal of Hydrology*, in-print.
- Mohnke, O., Braun, M. and Yaramanci, U., 2001, Inversion of decay time spectra from Surface-NMR data. Proceedings of 7th Meeting of Environmental and Engineering Geophysics, Birmingham, Great Britain.
- Mohnke, O., Yaramanci, U., and Lange, G., 2002, Realization and assessment of  $T_1$  measurements with surface nuclear magnetic resonance; 8<sup>th</sup> EEGS-ES meeting, Sept. 8-12, 2002, Aveiro, Portugal.
- Roy, J., 2000, MRS surveys under favorable conditions of S/N ratio; Proceedings 6<sup>th</sup> Meeting of EEGS-ES, Sept, 3-7, 2000, Bochum, Germany, P-EM-08.
- Schirov M., A. Legchenko & G. Creer 1991. A new direct non invasive groundwater detection technology for Australia. *Exploration Geophysics* 22: 333-338.
- Straley, C., Rossini, D., Vinegar, H., Tutunjian, P., and Morriss C., 1997, Core analysis by low field NMR; *The Log Analyst*, March-April 1997, p. 84-94.
- Vouillamoz, J.M. 2003, La caractérisation des aquifères par une méthode non-invasive: les sondages par résonance magnétique protonique; Thèse de L'Université de Paris XI, Spécialité Hydro-Géophysique.