INVERSION OF DECAY TIME SPECTRA FROM SURFACE NMR DATA

O. Mohnke, M. Braun and U. Yaramanci

Technical University Berlin, Dept. of Applied Geophysics, Ackerstr. 71-76, 13355 Berlin, Germany
contact: mohnke@geophysik.tu-berlin.de

Introduction

Surface Nuclear Magnetic Resonance (SNMR) or Magnetic Resonance Sounding (MRS) is a geophysical method that allows direct determination of the water content distribution in the subsurface. The relaxation process of SNMR signals yields information about the distribution of pore radii. So far the interpretation of SNMR data is one-dimensional and focuses on the distribution of the mobile pore water. Analysis of the relaxation behaviour is done by assigning a single decay time constant (corresponding to a mean pore size) for each inversion layer. However, this approximation does not always match the hydrogeological properties of the subsurface. In analogy to laboratory- and borehole-NMR this work introduces an alternative approach to the interpretation of SNMR data in terms of decay time spectra.

Method of Surface NMR (SNMR)

In SNMR the hydrogen protons of the pore fluid are excited with an artificial magnetic field that is usually generated by a circular or figure-eight loop energized by an alternating pulse that oscillates with the local Larmor frequency of the protons. The depth of penetration is dependent on the applied excitation intensity (pulse moment q). Increasing q focuses the NMR excitation on greater depths. After termination of the exciting pulse, the responding magnetic field due to the exponential relaxation of the precessing hydrogen protons in the free pore water is measured using the transmitter loop as receiver (Schirov et al. 1991, Weichmann et al. 2000).

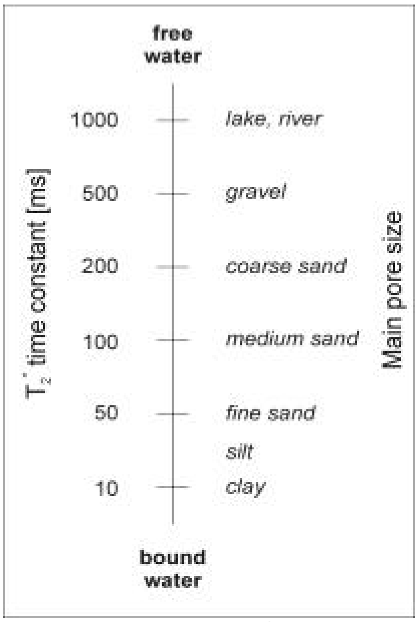

Fig. 1: Correlation of pore sizes and SNMR decay times

The amplitude at the beginning of the relaxation process (initial amplitude E_0) is directly proportional to the amount of mobile water in the subsurface. The decay time constant T_2^* (spin-spin relaxation time) is associated with the mean pore size and consequently linked to the grain size of the material (Fig. 1). The values for T_2^* range from less than 60 ms for clay and sandy clay, 60-300 ms for sands, 300-600 ms for gravel and up to 600-1000 ms for pure water (Schirov et al. 1991, Yaramanci et al. 1999). The maximum depth of investigation of SNMR is about 100 m. It is limited by the diameter of the antenna loop and the maximum pulse moment applied.

So far SNMR is used in sounding mode only, thus the inversion of SNMR data is one-dimensional. The analysis of SNMR sounding data is mainly focused on the interpretation of the water content distribution in the subsurface. Analysis of the SNMR relaxation is carried out by fitting just one decay time constant, i.e. assuming a mean pore size for each layer in the subsurface. The envelope E(t,q) of the SNMR relaxation signal is then given by:

$$E(t,q) = E_0(q)\exp\left(\frac{-t}{T^*_{2_i}(q)}\right) = w_L M_0 \int_V B_\perp(\mathbf{r})\, f(\mathbf{r}) \exp\left(\frac{-t}{T(\mathbf{r})}\right) \sin\left({}^{g}\!/_{2}\, B_\perp(\mathbf{r}) q\right) d^3 r\,, \qquad (1)$$

where M_0 is the macroscopic magnetic dipole moment of the water molecules in the subsurface and f(r) is the content of mobile water for a unit volume at the point **r**. $B_\perp(\mathbf{r})$ is the normalized component of the exciting field perpendicular to the geomagnetic field. The local Larmor frequency is given by $f_L = \omega_L / 2\pi$.

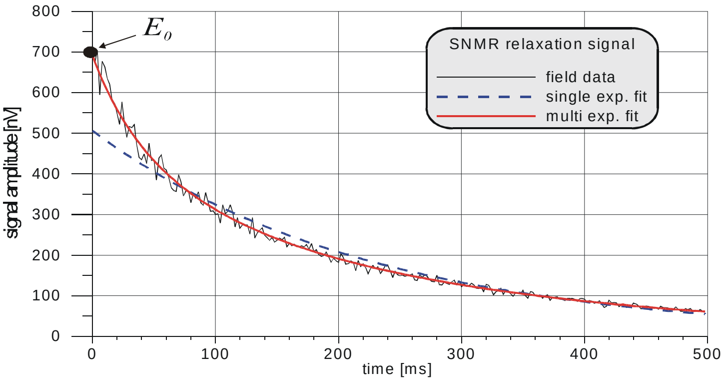

Fig. 2: Mono- and multi-exponential fits of a SNMR relaxation signal.

However, the assumption of a mean pore size often does not comply with the petrophysical properties of the subsurface. Many NMR relaxation signals show a multi-exponential behaviour (Fig. 2). Therefore, fitting such a relaxation curve using only one decay time constant can lead to significant misinterpretation of the SNMR sounding data. For a better interpretation with regard to the pore size distribution within an aquifer, in analogy to laboratory- and borehole-NMR equation (1) is expanded to:

$$E(t,q) = \sum_{i=1}^{N} \left[E_{0_i}(q) \exp\left(\frac{-t}{T_i(q)}\right) \right] = w_L M_0 \int_V B_\perp(\mathbf{r}) \sum_{i=1}^{N} \left[f_i(\mathbf{r}) \exp\left(\frac{-t}{T_i(\mathbf{r})}\right) \right] \sin\left({}^{g}\!/_{2}\, B_\perp(\mathbf{r}) q\right) d^3 r\,. \qquad (2)$$

At this we make allowance for a fragmentation of the water content within a layer to pores of different sizes. The total water content then is the sum of these fragments over a spectrum of N decay time constants associated with the pore sizes. This spectral distribution of the mobile pore water can then be attributed to a characteristic pore size distribution in the subsurface.

Inversion of SNMR relaxation signals

Based on equation (2) the envelope E(t,q) of the relaxation signal is the superposition of N single exponential curves and generally given by:

$$E(t,q) = \sum_{i}^{N} E_{0i}(q)\, \exp(-t / T^*_{2i}(q))\,. \qquad (3)$$

For a first approximation a mean pore size distribution within a water bearing layer is assumed. SNMR relaxation curves are fitted using only one amplitude E_0 and one decay time constant T_2^* per data point (N=1; strategy A). This strategy is commonly used in the so far existing inversion schemes for SNMR data.

Considering a distribution of the mobile pore water to different pore sizes, the relaxation signal is fitted in terms of a spectral distribution of decay times (N>1) according to equation (3). Here, both the amplitudes E_{0i} and the corresponding decay time constants T_{2i}^* are free parameters in the inversion process (strategy B). A third approach for the spectral inversion of SNMR data is to use a predetermined spectrum, e.g. 20 fixed decay times, and only to optimize the corresponding amplitudes E_{0i} (strategy C).

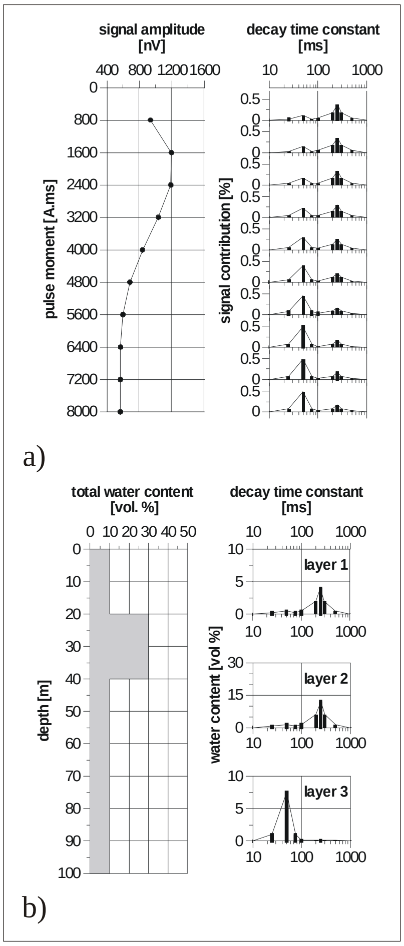

Fig. 3: 1D model; a) SNMR sounding curve & amplitude spectra, b) total water content & spectral decay time distribution.

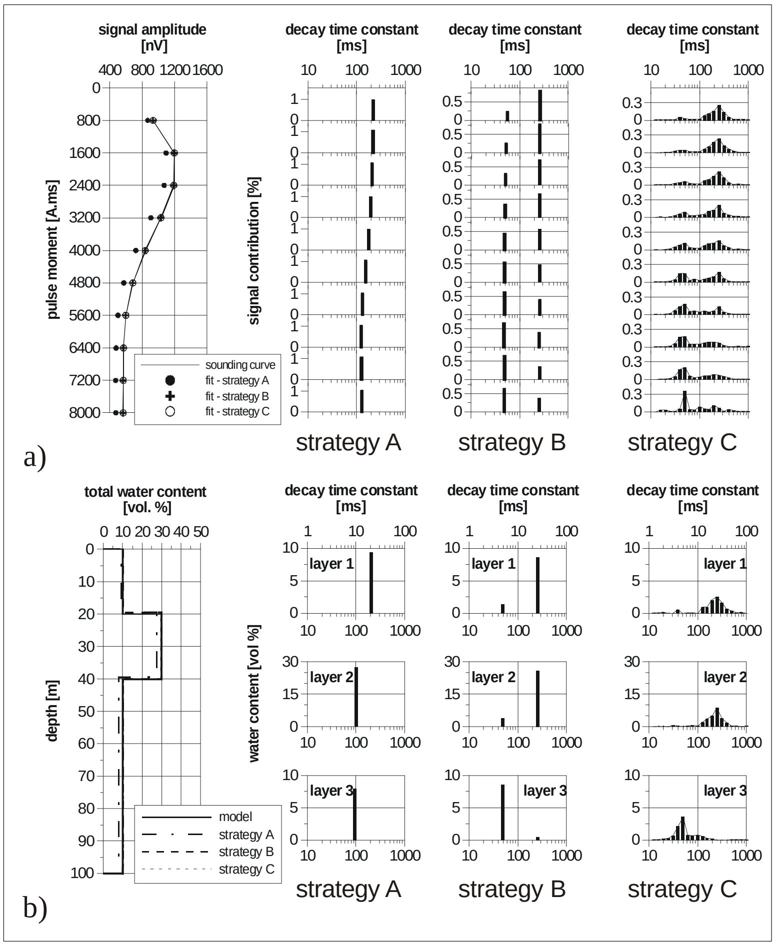

Fig. 4: a) Fit of the SNMR sounding curve using strategy A (N=1), B (N=2) and C (N=20); b) results of the block inversion for strategy A, B and C.

For every $T_2^*(q)$ a single sounding curve $E_i(t,q)$ is fitted that corresponds to the distribution of the water content within a characteristic pore size (Mohnke et al 2001). By simultaneously fitting all relaxation curves of a SNMR sounding, the integrating character of the method, i.e. smooth sounding curves, can be implemented in the inversion as a constraining parameter (regularization). To fit the relaxation curves an algorithm for global optimization problems, named simulated annealing (SA), has been used. The actual inversion is carried out using BISP, a block inversion software package for SNMR data also based on SA (Mohnke and Yaramanci 2000).

Tests with synthetic data

In order to compare and evaluate the introduced strategies for inverting SNMR sounding data inversions have been carried out for synthetic data. Fig. 3b shows a three layer model of an aquifer at 20 m depth with a thickness of 20 m and 30 vol.% of mobile water. Up to a depth of

40 m the mobile water is assigned to pore sizes with decay times distributed around 250 ms complying with fine and middle sands. The upper boundary of the aquiclude is situated at 40 m. The aquiclude is associated with decay times within the range of 50 ms, e.g. clay material. The synthetic SNMR data for this model is plotted in Fig. 3a. For smaller pulse moments, focusing the SNMR signal on shallower depths, the main signal contribution is located at 250 ms. For higher pulse moments this maximum is shifted to a main decay time of 50 ms (Fig. 3a, right).

The fitting results of the SNMR sounding curve using strategies A, B and C are presented in Fig. 4a. The inversion results showing the distribution of the water content and the decay time constants are plotted in Fig. 4b. The layer boundaries are fitted precisely for all strategies. However, for the data processed according to strategy A (N=1) the total water content is consequently underestimated (Fig. 3b, left). This is a result due to the bad fit of the relaxation curves. The spectral distribution of the water content is not detected and the decrease of decay time constants (pore sizes) with increasing depths is only slightly indicated. Both for strategy B and C the total water content complies with the given model. Using strategy B (N=2) the algorithm can find the two maxima of the T_2^* distribution. The inversion according to strategy C (N=20) also finds the two maxima and, furthermore, provides a spectral bandwidth of the decay time distribution that is in good agreement with the model.

Conclusion

Spectral analysis can significantly enhance the interpretation of SNMR data with regard to the pore size distribution (in terms of decay time distribution) within the aquifer. This is an initial approach towards improving the quantitative characterization of aquifer structures using SNMR. Next step within the scope of this work is to apply and verify this scheme on field data recorded at sites with well known petrophysical properties (Borehole measurements, laboratory NMR)

References

Mohnke, O., Yaramanci, U.; Inversion of Surface NMR amplitudes and decay times – Examination of smooth and block inversion, Proc. of the 6th EEGS Conference, Em07, 2000.

Mohnke, O., Braun, M., Yaramanci, U.; Analyse und Inversion von T_2^* - Spektren aus Oberflächen - NMR (SNMR) Daten zur quantitativen Charakterisierung von Aquiferen, Tagungsband der 61. DGG Tagung, Beitrag EMP07, 2001.

Schirov, M., Legchenko, A., Creer, G.; A new direct non-invasive groundwater detection technology for Australia, Exploration Geophysics, 22, 333-338, 1991.

Weichmann, P. B., Lavely, E. M., Ritzwoller M.; Theory of surface Nuclear Magnetic Resonance with applications to geophysical imaging problems, Physical Review E., 62, no. 1, Part B,1290-1312, 2000.

Yaramanci , U., Lange, G., Knödel, K.; Surface NMR within a geophysical study of the aquifer at Haldensleben (Germany), Geophysical Prospecting, 47, 923-943, 1999.