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Surface Nuclear Magnetic Resonance (SNMR) – A new method for exploration of ground water and aquifer properties

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Abstract
The Surface Nuclear Magnetic Resonance (SNMR) method is a fairly new technique in geophysics to assess ground water, *i.e.* existence, amount and productibility by measurements at the surface. The NMR technique used in medicine, physics and lately in borehole geophysics was adopted for surface measurements in the early eighties, and commercial equipment for measurements has been available since the mid nineties. The SNMR method has been tested at sites in Northern Germany with Quaternary sand and clay layers, to examine the suitability of this new method for groundwater exploration and environmental investigations. More information is obtained by SNMR, particularly with respect to aquifer parameters, than with other geophysical techniques. SNMR measurements were carried out at three borehole locations, together with 2D and 1D direct current geoelectrics and well logging (induction log, gamma-ray log and pulsed neutron-gamma log). Permeabilities were calculated from the grain-size distributions of core material determined in the laboratory. It is demonstrated that the SNMR method is able to detect groundwater and the results are in good agreement with other geophysical and hydrogeological data. Using the SNMR method, the water content of the unsaturated and saturated zones (*i.e.* porosity of an aquifer) can be reliably determined. This information and resistivity data permit *in-situ* determination of other aquifer parameters. Comparison of the SNMR results with borehole data clearly shows that the water content determined by SNMR is the free or mobile water in the pores. The permeabilities estimated from the SNMR decay times are similar to those derived from sieve analysis of core material. Thus, the combination of SNMR with geoelectric methods promises to be a powerful tool for studying aquifer properties.

Key words *surface-NMR – ground water – aquifer assessment – hydrogeophysics*

1. Introduction

The first high-precision observations of Nuclear Magnetic Resonance (NMR) signals from hydrogen nuclei were made as early as 1946 (Bloch *et al.*, 1946; Purcell *et al.*, 1946). Meanwhile this technique has found wide application in chemistry, physics, tomographic imaging in medicine, as well as in geophysics. Since the amplitude of the NMR signal is related to the number of hydrogen protons, the technique can be used in surface geophysics to measure the subsurface water content of rocks and soils. At present there is no other technique in surface geophysics to assess water content directly. Apart from water content, information about other properties, such as pore size, can also be obtained from NMR.

After it was discovered that the NMR signal is sensitive to the viscosity of the fluid (high-viscosity fluids exhibit fast relaxation), the oil industry increased their research in this field. Basic work revealed a relationship between the

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NMR properties of porous media, such as sandstones, and their permeability (Seevers, 1966; Timur, 1968, 1969a,b; Loren, 1972). Current research is concentrating on the influence of pore size. In the last ten years or so NMR logging tools have been made available that use the CPGM pulse echo method (named after Carr and Purcell, 1954; Meiboom and Gill, 1958) for downhole measurement of relaxation parameters (Chandler *et al.*, 1987; Straley *et al.*, 1991). A detailed review of the use of NMR on rock cores and in boreholes is given by Kenyon (1992).

The first ideas for making use of NMR in groundwater exploration from the ground surface were developed as early as the 1960s (Varian, 1962; Barringer and White, 1968), but only in the 1980s was effective equipment designed and put to operation for surface geophysical exploration by scientists at the Institute of Chemical Kinetics and Combustion, Novosibirsk, Russia (Semenov *et al.*, 1982, 1988, 1989; Semenov, 1987; Legchenko *et al.*, 1990). Extensive surveys and testing have been conducted in sandy and clayey layers in Australia (Schirov *et al.*, 1991), on fractured limestone and chalk aquifers in France (Legchenko *et al.*, 1995) and on fractured white chalk in France (Beauce *et al.*, 1996). Tests in the U.S.A. (Lieblich *et al.*, 1994) have provided some insight into the problems of sites where there is a high noise level. Some improvement in noise reduction has been achieved using a special antenna configuration (Trushkin *et al.*, 1994).

Since both the phase and amplitude of the SNMR signal are affected by the electrical conductivity (Shushakov and Legchenko, 1992; Trushkin *et al.*, 1995, Shushakov, 1996), the conductivity distribution should be taken into account in the inversion of the data. A combination of the SNMR with the Time-Domain Electromagnetic (TDEM) method has been applied not only to detect the presence of groundwater, but also to obtain quantitative information about water content and salinity at various sites in Israel (Goldman *et al.*, 1994; Gev *et al.*, 1996).

In this paper, the basics of SNMR and the results of a study in Germany are presented. The aim of the investigation is to assess the effectiveness of the method for groundwater exploration by comparing the SNMR results with groundwater data obtained by drilling and well logging. The SNMR method is also compared with the geoelectric method and tested in combination for both groundwater exploration and determination of aquifer parameter values.

The basics of SNMR and the geology of the test site Haldensleben are described below, and the data obtained using SNMR and other geophysical methods are presented and discussed.

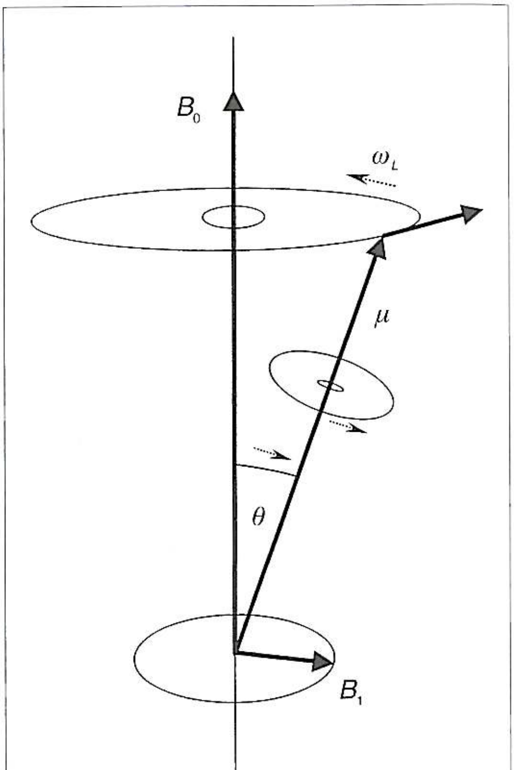

Fig. 1. Precession movement of a macroscopic magnetic moment μ around a static field B_0. The magnetic moment μ originally aligned to B_0 is deflected by a secondary field B_1 which acts perpendicular to static field B_0. The precession angle θ is proportional to the product of the excitation field B_1 by the excitation duration. The precession frequency *i.e.* the Larmor frequency is proportional to the strength of the static field B_0.

2. The SNMR method

The protons of the hydrogen atoms in water molecules have a magnetic moment μ. They can be described in terms of a spinning charged particle. Generally μ is aligned with the local magnetic field B_0 of the Earth. When another magnetic field B_1 is applied, the axis of the spinning protons are deflected, owing to the torque applied (fig. 1). Hereby only the component of the second field perpendicular to the static field acts as the torque force. When this second field is removed, the protons generate a relaxation magnetic field as they become realigned along B_0 while precessing around B_0 with the Larmor frequency

$$\omega_L = \gamma B_0 \tag{2.1}$$

where $\gamma = 0.267518$ Hz/nT, the gyromagnetic ratio for hydrogen protons.

The measurements are made using a loop usually with a circular or rectangular lay out. An alternating current

$$i(t) = i_0 \cos(\omega_L t) \tag{2.2}$$

with the Larmor frequency ω_L is passed through this loop for a limited time τ so that an excitation intensity (pulse moment) of $q = i_0 \tau$ is

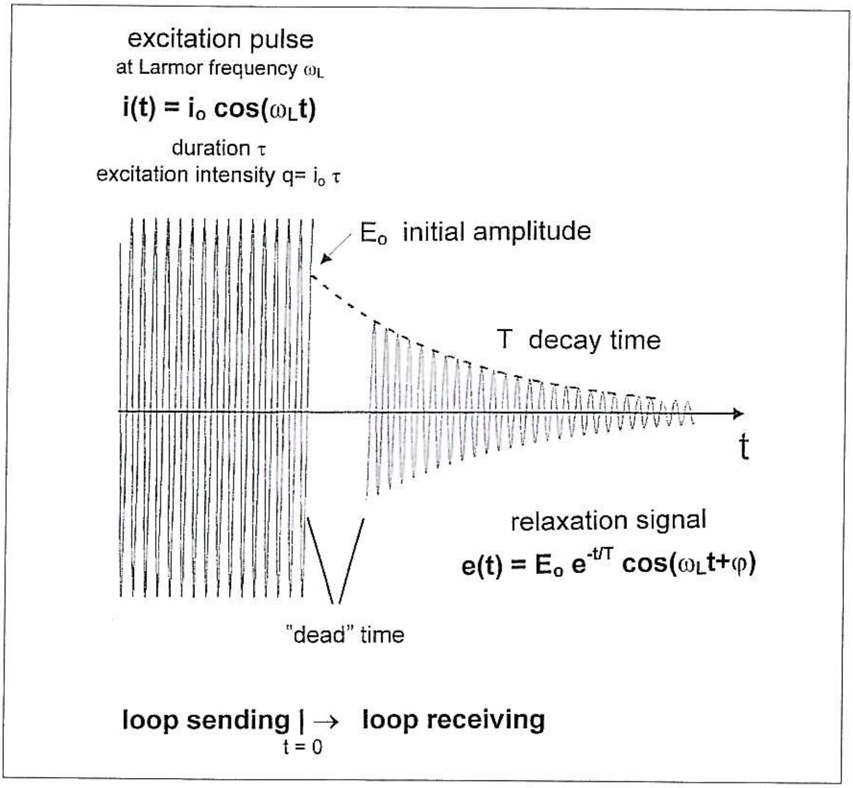

Fig. 2. Input and output signals for the SNMR measurements. The excitation pulse *i.e.* current in a loop with the Larmor frequency ω_L, amplitude i_0 and duration τ is introduced in to the Earth bringing the hydrogen protons to a deflection and precession movement. The following relaxation of protons cause a voltage in the same loop with the same frequency and decaying amplitude and a phase shift.

achieved. After the current in the loop is switched off, a voltage $e(t)$ with the frequency ω_L and decaying amplitude is induced in the loop by the relaxation of the protons (Semenov *et al.*, 1982; Legchenko *et al.*, 1990; Schirov *et al.*, 1991) (fig. 2)

$$e(t) = E_0 e^{-t/T} \cos(\omega_L t + \varphi). \qquad (2.3)$$

The envelope of this voltage (in a circular loop) is directly related to the water content and to the decay time of every volume element in the underground contributing to the signal

$$E_0 e^{-t/T} = \qquad (2.4)$$
$$= \omega_0 M_0 \int_V f(r)\, e^{-t/T(r)} B_\perp(r) \sin(0.5\, \gamma B_\perp(r)\, q)\, dV.$$

Here M_0 is the nuclear magnetisation (the magnetic moment of the unit volume dV under equilibrium conditions at $t = 0$). $M_0 = 3.29 \times 10^{-3}$ B_0 J/(T m^3) for water at a temperature of 293 K. The volume fraction of water in a unit volume dV at the location $r(x, y, z)$ is given by $f(r)$. $T(r)$ is the decay time of protons at the location $r(x, y, z)$. $B_\perp(r)$ is the component of the incident exciting field (normalised to 1 A) perpendicular to the static magnetic field B_0 of the Earth. In a conductive medium $B_\perp(r)$ is composed of the primary field of the loop and the induced field. Note that the argument of the sine function in eq. (2.4) ($\theta = 0.5\, \gamma B_\perp(r)\, q$) is the angle of deflection of the magnetic moment of the protons from the magnetic field of the Earth. E_0 can be as large as a few millivolts.

The initial amplitude E_0 at $t = 0$ is related only to the water content

$$E_0 = \omega_0 M_0 \int_V f(r)\, B_\perp(r) \sin(0.5\, \gamma B_\perp(r)\, q)\, dV. \qquad (2.5)$$

Using this equation it can easily be calculated what the initial amplitudes for various excitations intensities should be for water layers at different depths and thicknesses. Figure 3a-c shows a set of calculations after Pusep *et al.* (1991) which in fact could also be used as master curves to match the observations. It shows clearly that for deeper water layer the maximum of E_0 occours at higher q values and the strength of E_0 is directly related to the thickness of the layer *i.e.* the amount of the water.

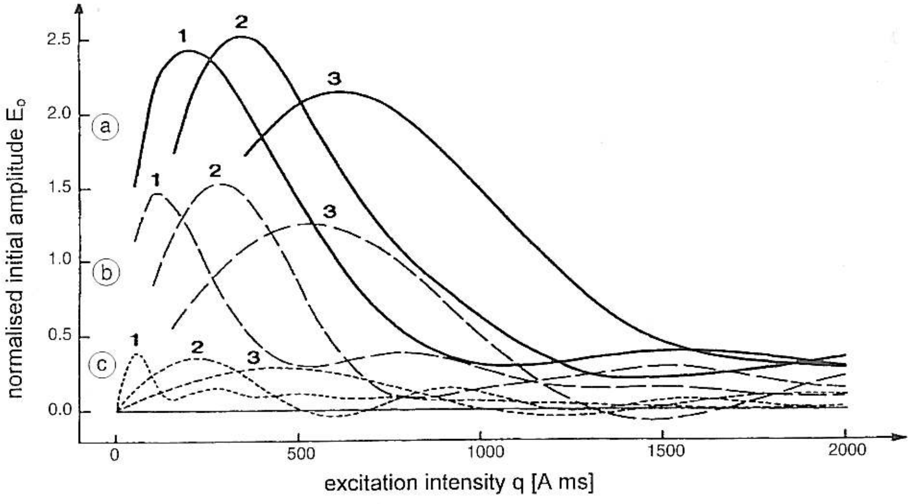

Fig. 3a-c. Synthetic responses of SNMR for water layers at different depths for: a) 10 m; b) 5 m and c) 1 m, and with different thicknesses 1 for 1 m, 2 for 5 m and 3 for 10 m (after Pusep *et al.*, 1991). The amplitudes are normalised initial amplitudes.

The recorded decay time T is supposed to be the relaxation-time constant (spin-spin or transversal relaxation time) denoted usually with T_2^* in the usual NMR terminology. This decay time can be of the order of a few milliseconds up to 1000 ms. It is related to the mean pore size and, therefore, grain size of the material as shown in fig. 4a-c. Clay, including sandy clays, usually has a decay time of less than 30 ms, whereas sand has one of 60-300 ms, gravel 300-600 ms, and pure water 600-1000 ms (Schirov *et al.*, 1991).

The phase φ is related to the phase of the excitation signal in eq. (2.2). If the conductivity of the ground is negligible, $B_\perp(r)$ will have the same phase as the excitation current; hence, $\varphi = 0$. In this terminology the usual phase shift of $\pi/2$ due to the electromagnetics is already included. If the ground has a high conductivity, a secondary magnetic field, superimposed on the primary field, is induced. This modifies the amplitude and phase of the field $B_\perp(r)$. Therefore, φ is an indicator of the conductivity of the ground and the groundwater as well. This implicit information cannot be extracted yet from the SNMR data as it requires coupled modelling of NMR and electromagnetic induction which is complicated.

The resolution and accuracy of the method depend on $B_\perp(r)$ and decrease with depth. Higher currents i_0 and/or τ are needed to excite the protons at greater depth (as long as $\tau \ll T_2^*$). By increasing q, the depth of the measurement is increased. In fact, the choice of q focuses the excitation to a certain depth range (fig. 5).

The measurements are conducted for different excitation intensities q and the main parameters recorded for every q are the initial amplitude E_0 and the decay time T. This set of data in the form of $E_0(q)$ and $T(q)$ are inverted to find the distribution of water content with depth $f(z)$ and of decay time with depth $T(z)$. Thereby eq. (2.4) is the basis of the inversion which is used in the form modified for models having horizontal layering. Two or three dimensional inversion and suitable measurement approaches for this are not available yet but are currently being investigated. The usual inversion scheme used in SNMR is based on a least square solution with a regularisation (Legchenko and Shu-

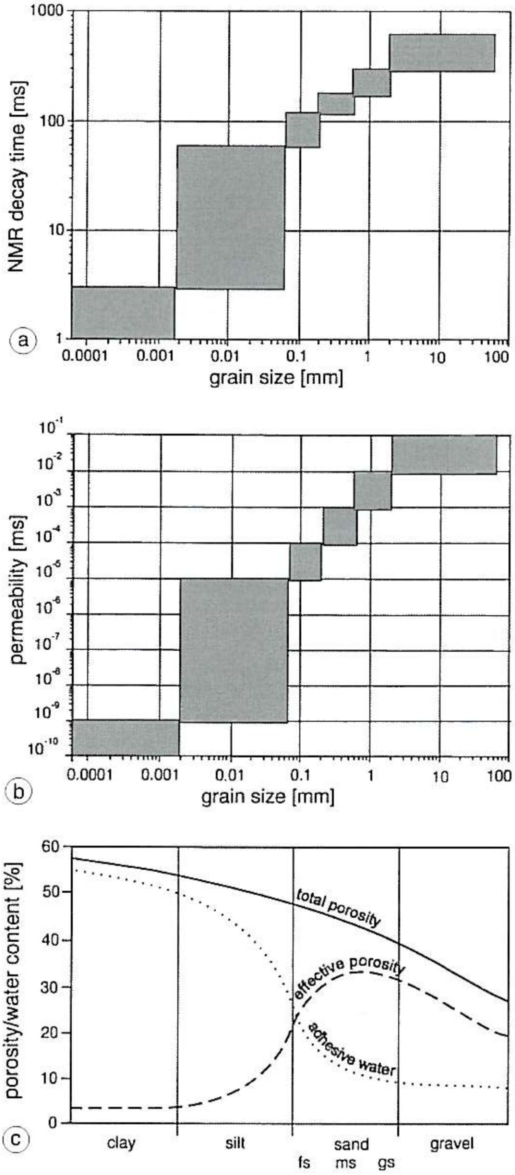

Fig. 4a-c. a) Relationship of SNMR decay time ranges to the grain size ranges of unconsolidated sediments adapted from SNMR results at different sites and from corresponding core material after Schirov *et al.* (1991); b) relationship of permeability ranges to grain size ranges after Hölting (1992); c) relationship between porosity and adhesive water for different sediments after Davis and de Wiest (1966).

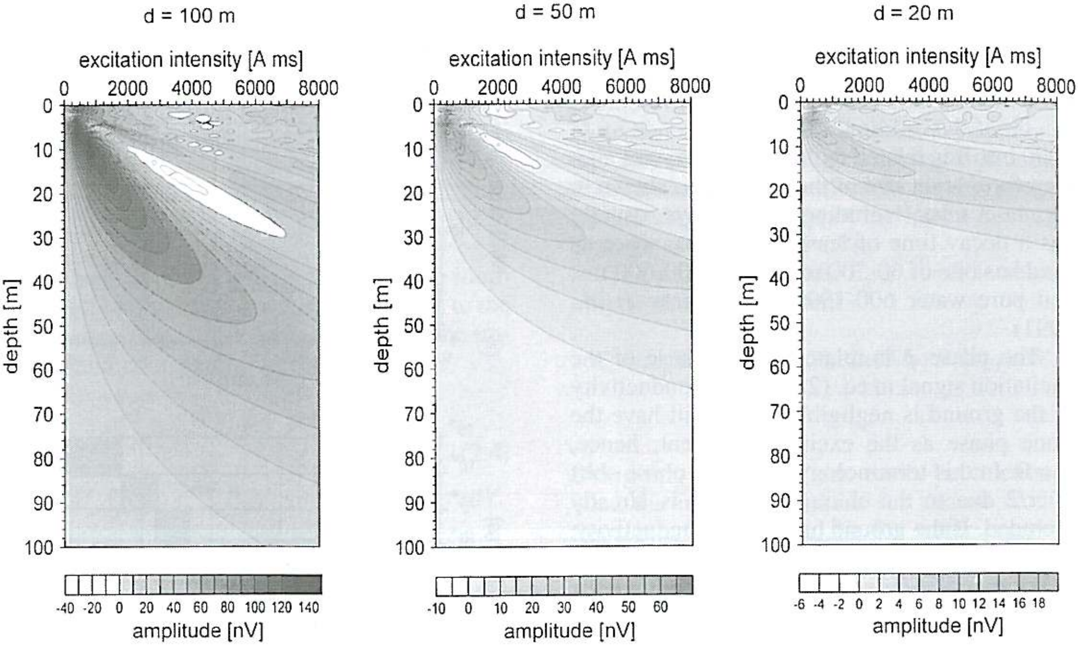

Fig. 5. Initial amplitudes of SNMR for basic layers of 1 m at various depths and for various excitation intensities. The actual initial amplitude for a fixed excitation intensity is the addition of individual contributions of basic layers (integral over depth for fixed excitation intensity). The calculations are shown for three different diameter of circular loops demonstrating the signal contribution depth getting smaller with smaller loop size. The calculations are conducted for a magnetic field strength of 48 000 nT and a declination of 60° (usual for Middle Europe).

shakov, 1998). Lately, new inversion schemes have been developed which use model optimisation with Simulated Annealing and allow more flexibility in designing the layer thicknesses imposed on inversion even with free layer thicknesses to be optimised (Mohnke and Yaramanci, 1999, 2000). The most recent development allows even a joint inversion of SNMR amplitudes with Vertical Electrical Soundings (Hertrich and Yaramanci, 2000).

3. Investigation test site

An integrated geophysical survey was carried out at a site near Haldensleben in Northern Germany for which some details were reported earlier (Yaramanci *et al.*, 1999c). At the ground surface, there are mostly Quaternary sands and gravels and there is no surface drainage network. The site has little vegetation; thus, precipitation is little influenced by the root zone and percolates through the unsaturated zone as groundwater recharge.

The geology of the area in which three boreholes B7, B8 and B2 were drilled (fig. 6) consists of Quaternary deposits: well sorted sands interbedded with cohesive glacial till and silt. The sands and gravels form good aquifers with permeability coefficients *i.e.* hydraulic conductivities of 10^{-4}-10^{-3} m/s. The glacial tills and silts, which act as aquicludes, may be as thick as 20 m. Since they are discontinuous, there are local hydraulic links between the aquifers.

The hydrogeological conditions at locations B7 and B8 are similar. The water table is at a depth of about 20 m and the depth of the base of

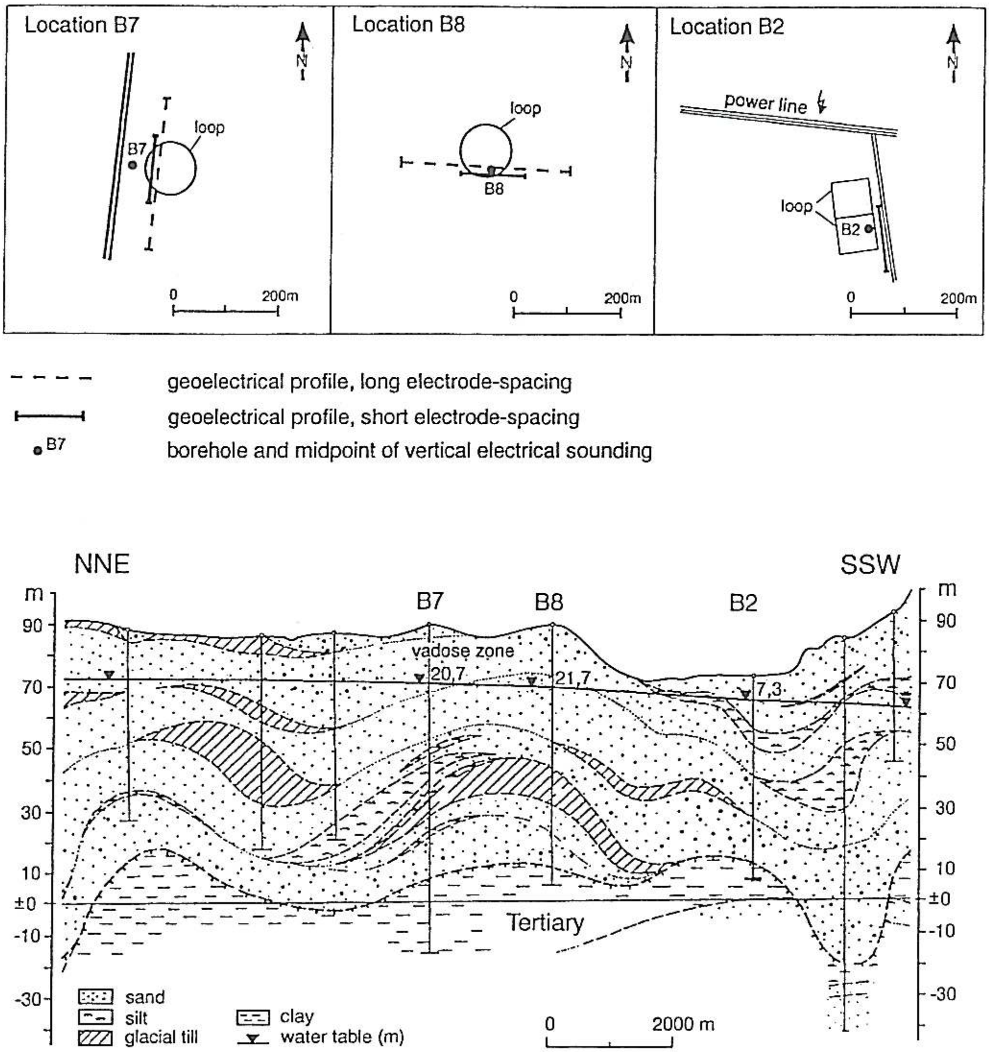

Fig. 6. Geological section at the Haldensleben/Germany test site according to borehole data, extensive geoelectrical measurements and surface geology (vertical axis highly exaggerated). At the top measurement layouts for the three locations used are shown.

the first aquifer varies between 40 and 50 m. At B7 there are interbedded impermeable tills and silts in the depth interval between 40 and 65 m. At B8 there is an impermeable till layer about 12 m thick at a depth of 47 m. At both locations there is a confined second aquifer below the till. The regional aquiclude, the Rupelian clay, occurs at a depth of 75 to 80 m, immediately below the Quaternary. The situation at B2 is somewhat different. The water table is at a depth of 7.3 m mainly due to the lower elevation of the site (fig. 6). Moreover, a ponding layer 6 m thick consisting of silt is present at a depth of 16 m.

4. SNMR measurements

IRIS Instruments'NUMIS system, which is the only commercially available system for SNMR measurements, was employed. Standard NUMIS software was also used for processing and inversion. The measurements at locations B7 and B8 were carried out using a circular loop 100 m in diameter. A figure-eight loop shaped like two adjacent 37.5 m^2 was used at location B2 (fig. 6) in order to decrease the influence of noise, as was done by Lieblich *et al.* (1994). To determine the excitation frequency, the local magnetic field of the Earth was measured using a proton magnetometer. The Earth's magnetic field was B_0 = 48 757 nT; this corresponds to a Larmor frequency f_0 = 2076 Hz. The duration of the excitation current was kept constant at 40 ms, corresponding to 80 cycles. Measurements were carried out at several current strengths between 5 A and 250 A, varying the excitation intensity from 200 A ms to approximately 8000 A ms.

The signal amplitudes measured at B7 and B8 show a typical shape for sounding curves obtained for an aquifer at moderate depth (fig. 7a-c). Inversion shows that the water content gradually increases with depth from 5% in the unsaturated zone to 20-25% at 20 m, the depth of the water table. Below 30-35 m the water content decreases. At location B2 (fig. 6) signal amplitudes and water content after inversion are almost constant and very low, the maximum water content being about 10%. The noise levels were about 500 to 700 nV at B7, 100 to 300 nV at B8, and 600 to 1100 nV at B2. The inversions have an rms error less than 5%, which indicates good agreement between the observed amplitudes and the amplitudes reconstructed from the model.

Except for the two highest excitation intensities, the decay observed times at B7 are 140 to 220 ms and quite irregular. At B8, the observed decay times increase smoothly from 180 to 250 ms at 4000 A ms excitation intensity and then decrease slightly. The decay times at B2 changes from 150 to 100 and then 160 ms with increasing excitation intensity. The range of the inverted decay times being 200 to 250 ms for B7 and B8 at depths of the higher water content *i.e.* aquifer corresponds to that of medium sand (Schirov *et al.*, 1991) as shown in fig. 4a-c. The phases at B7 and B8 begin with 0° and increase to 90° and 60°, respectively, indicating the existence of more conductive layers at depth, in agreement with the results for water content.

In general, the SNMR results are in agreement with the borehole data and geoelectric data from sites B7 and B8, at least down to a depth of 40 m, clearly confirming the presence of the aquifer. Resolution with depth becomes poorer because the thickness of the horizontal layers used in inversion increases. The inferred decrease in water content with depth is not necessarily reliable. At location B2, the distribution of the water content does not correspond to the known geology, but the noise level was remarkably high despite the use of a figure-eight loop. The noise was probably due to the power line nearby (fig. 6). Usually the long dimension of a figure-eight loop is oriented parallel to power lines (Lieblich *et al.*, 1994), but in this case problems of access prevented it.

5. Geoelectric measurements

An extensive geoelectric survey was also carried out at the test location. As the geoelectric method is the technique most commonly used to explore for groundwater, it is important to compare the geoelectric data and SNMR data and to attempt a combined interpretation, particularly with respect to the aquifer parameters. Moreover, the conductivity of the ground influences the SNMR signal amplitude and phase. High conductivity can result in a reduced investigation depth, as is the case for EM methods. A conductive layer above the aquifer causes a decrease of the SNMR amplitude; the same layer below the aquifer increases the SNMR amplitude.

Investigations to rather shallow depths with multielectrode 2D resistivity measurements using a basic electrode spacing of 2.5 m and a total length of 100 m were carried out initially. The directions of the profiles at the three locations are shown in fig. 6. The data showed clearly the presence of a conductive layer *i.e.* the aquifer but not with the usual resistivities. To have an

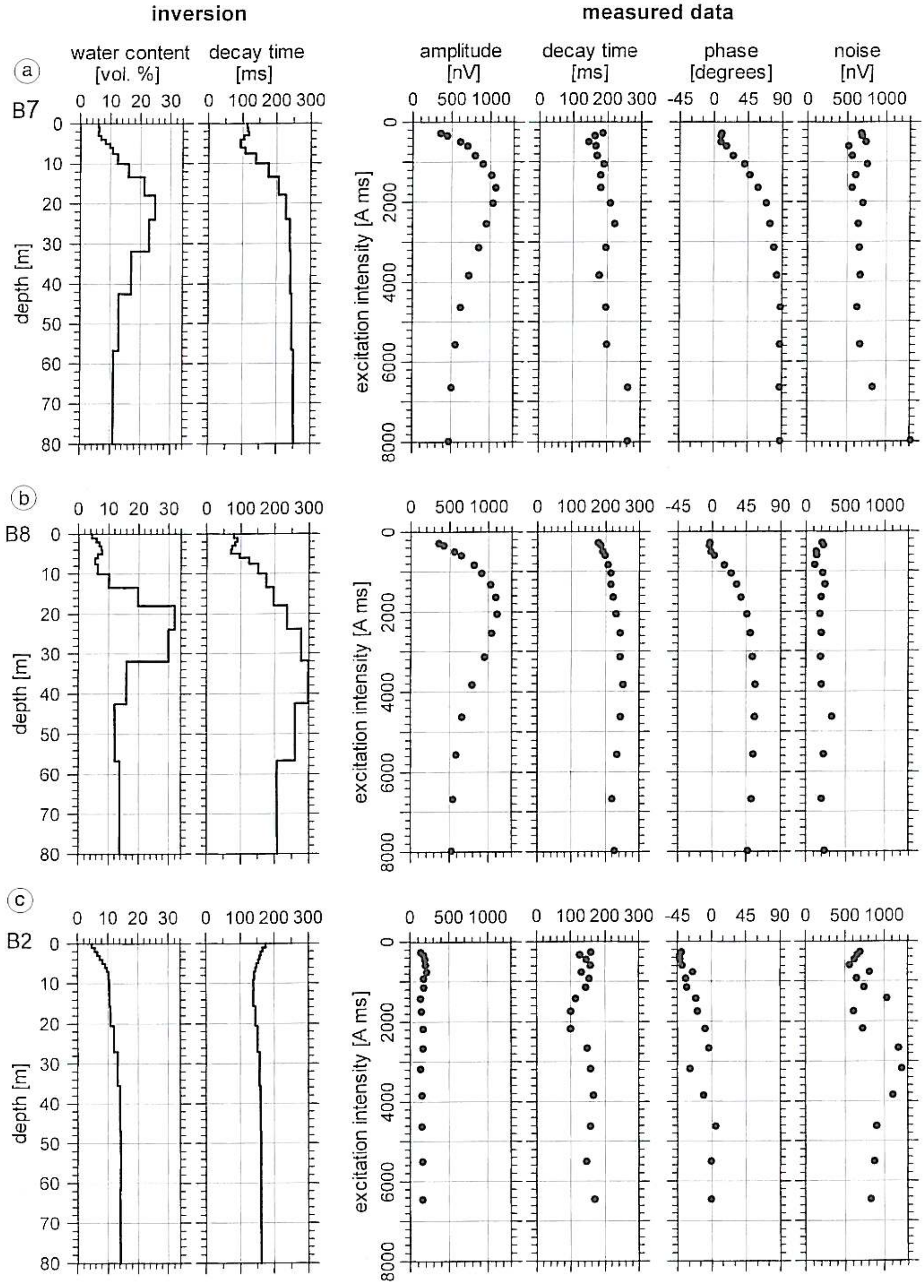

Fig. 7a-c. SNMR data and results of the inversion at the locations: a) B7; b) B8, and c) B2.

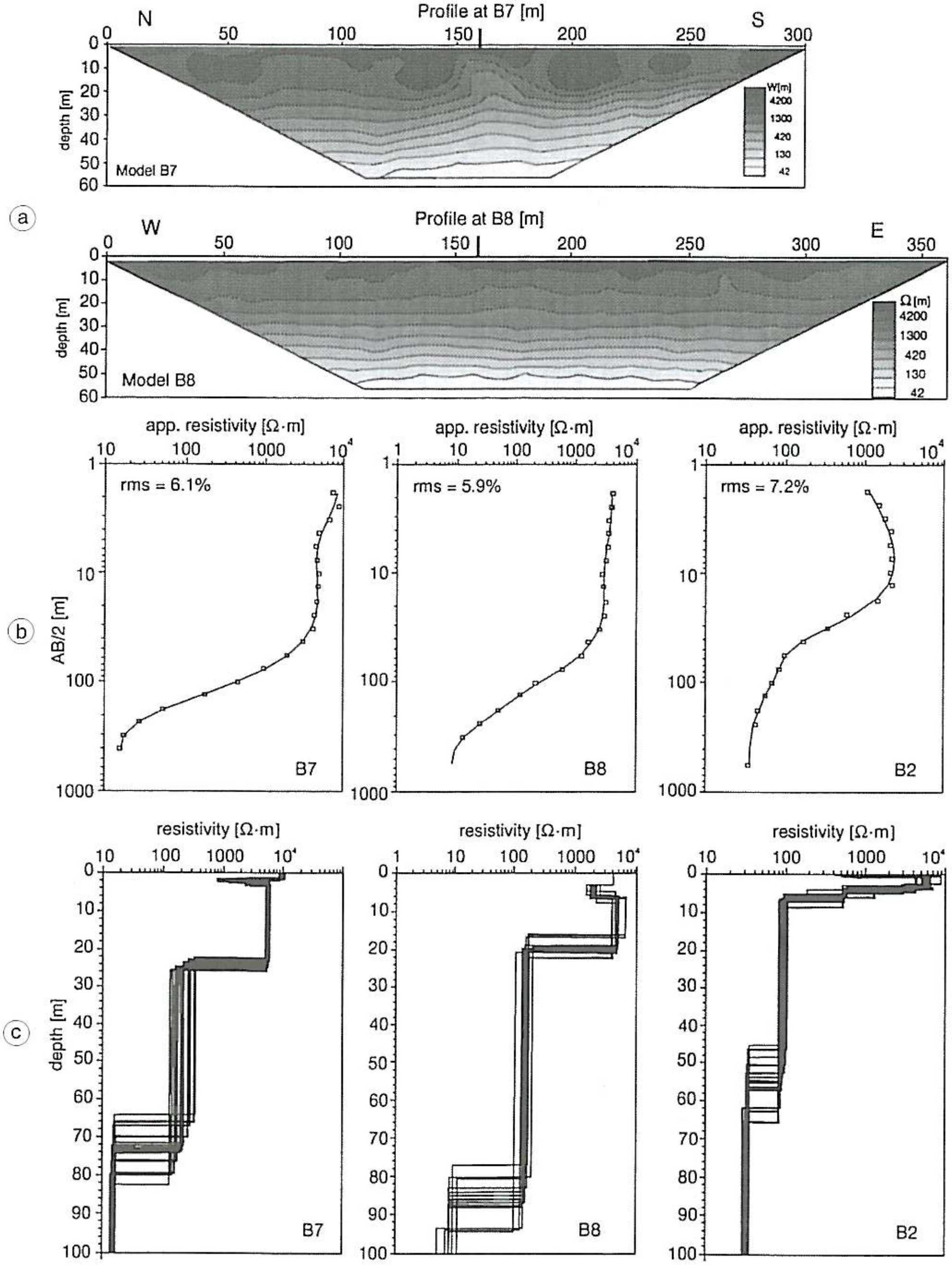

Fig. 8a-c. a) 2D resistivity sections obtained using the long electrode spacing at locations B7 and B8. The rms errors for model fitting are lower than 10%. b) In an earlier site investigation vertical electrical soundings were carried out, and c) equivalent models developed after 1D inversion by curve fitting.

appropriate depth of investigation, the 2D measurements were conducted with a larger array having total lengths of 300 m and more with an electrode spacing of 10 m. The gain in depth is obtained at the expense of a decrease in resolution, particularly in the shallow range. The 2D measurements carried out at locations B7 and B8 are shown in fig. 8a. There is a distinct and rapid decrease of the resistivity with depth, indicating the presence of groundwater. However, due to the smoothing by the 2D inversion, the abrupt change in resistivity at the water table is not visible in the inverted data.

2D inversion of geoelectric data using a nonlinear, least-squares algorithm which gives smooth models (here the RES2DINV package, Loke and Barker, 1996) is not robust enough to identify sharp resistivity boundaries, as expected for groundwater in sandy formations (Olayinka and Yaramanci, 2000). The inversion algorithms tend to «smear» the resistivity data when large differences are present. Consequently, the depth to groundwater cannot be determined precisely since 2D inversion algorithms imposing sharp boundaries are not yet widely available.

This observation is confirmed by the Schlumberger soundings (fig. 8b), which were subsequently carried out at all locations with very large electrode lay outs and using 1D inversion allowing sharp boundaries. In the three areas B7, B8 and B2, the water table is very clearly indicated at 23, 20 and 6 m, respectively (fig. 8c); these depths are in good agreement with borehole data. The resistivity of the unsaturated zone is $5\times10^3\ \Omega\cdot\mathrm{m}$, and the aquifer has a resistivity of about $100\ \Omega\cdot\mathrm{m}$. The relatively high resistivities shown by the aquifers are due to the low concentrations of total dissolved solids in the groundwater. All the Schlumberger sounding curves record the strong resistivity difference at the water table. At B2 the relatively low resistivities near the surface are visible in the sounding curves obtained using a short spacing. In 1D inversion using interactive curve matching, no *a priori* information was used. The optimal model for all three locations consists of five layers. Several thinner layers could be derived from the shape of the curve, but the results would not be reliable if there are 2D or 3D geoelectric structures.

It should be noted that the 2D geoelectric measurements included also Time-Domain Induced Polarisation (TIP) in order to detect cohesive layers (till and silt), which borehole measurements indicated as being present between the aquifers (fig. 9). However, inversion did not yield any anomalous TIP parameter values. In view of the high resistivities at shallow depths, it seemed feasible to map the groundwater with Ground Penetrating Radar (GPR). But no clear reflections were obtained from the water table, as attenuation was still high at shallow depths probably due to the considerable amount of capillary water and some thin, conductive, cohesive layers, as confirmed by well logging. Thus, problems encountered at groundwater exploration might be quite large even using relatively well developed methods like 2D geoelectrics, TIP and GPR.

6. Borehole measurements

The SNMR and geoelectric results, as well as the parameters derived from grain size analysis of cores, were checked by well logging using the following methods: Gamma-Ray log (GR), Induction Log (IL), Impulse Neutron Gamma log (ING) and Salinity log (Sal). The lithology, conductivity and water content of the various layers, as well as the conductivity of the groundwater, were derived from the measured data (fig. 9).

The ING method is sensitive to the total volume of water in the pore space. This is a fundamental difference from the SNMR method, which is only sensitive to the free or so called mobile water. Water in small pores of sediments like clay and silt and adhesive water, which is bound on the grain surface by strong molecular attraction, cannot be detected by SNMR (Schirov *et al.*, 1991; Lieblich *et al.*, 1994). Therefore, the water content given by ING logs is generally higher than that determined by SNMR. For saturated sediments the total water content equals the total porosity. The relationships between total pore space (total water content), effective porosity (free water) and adhesive water are shown in fig. 4a-c for clastic rocks.

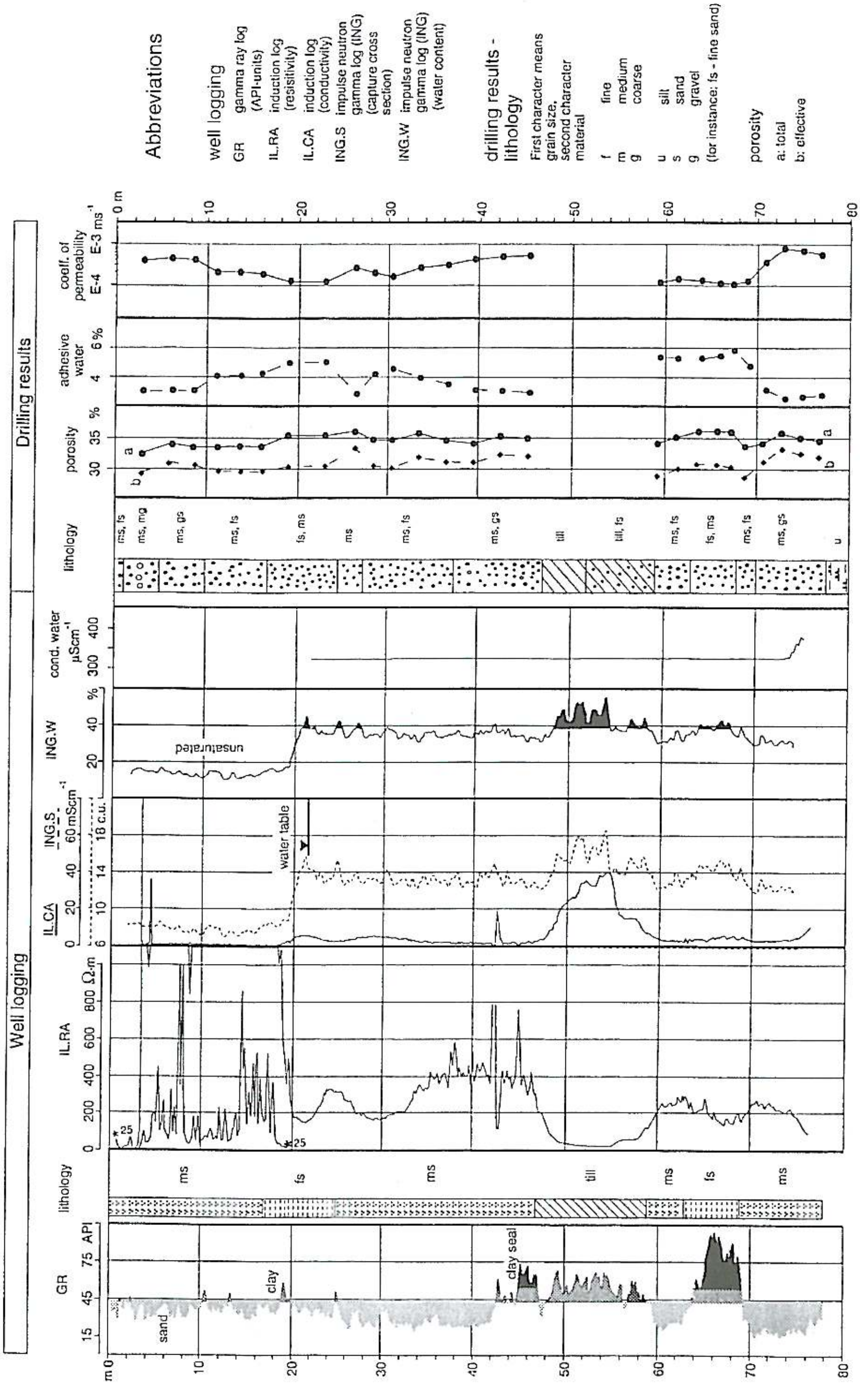

Fig. 9. Well logging and drilling results at the location B8.

The ING logs show that the water content for boreholes B7 and B8 have approximately the same range and distribution. In the unsaturated zone down to a depth of 6 m the total water content averages 15% and increases slightly to 20% at about the depth of the water table. Experience indicates that the amount of adhesive water in the saturated zone should be less than 8%. The rather high values are probably caused by the presence of percolation water.

The ING log (ING.W) gives the water content of the capillary fringe just above the water table as about 35% on average. Slightly higher or lower values are due to finer or coarser grained material (see porosity curves in fig. 4c). Clearly visible is the effect of clay seals behind the casing, where the water content is 50-65%.

In borehole B2, the thick clay seal directly below the water table causes the water content in this zone to rise to 75%. In the lower part of the borehole the water content is 3-5 % less than in B8 and B7. This is in good agreement with the porosities and permeability coefficients obtained from core analysis.

7. Discussion

The following discussion of the SNMR results will focus on test locations B7 and B8. Location B2 is not suitable for determining aquifer parameter values due to the extremely low signal-to-noise ratio, even though a square figure-eight loop was used to reduce noise.

Comparison of the SNMR results with the ING log shows that the water content determined from the SNMR data is too low by 5-10% in the unsaturated zone and by about 10-12% in the upper part of the aquifer, *i.e.*, between the water table and a depth of 40 m. In the deeper parts of the aquifer, the SNMR data indicate an unrealistically low water content, possibly due to an insufficient data density. However, the actual reason is not fully understood yet and further investigation of the inversion algorithm and the measuring procedure is necessary.

Previous work has already shown that SNMR measurements detect only free water (Schirov *et al.*, 1991; Lieblich *et al.*, 1994). Water bound on the pore surfaces has very short relaxation times and cannot be detected by SNMR yet, owing to the technically inevitable dead time of 30 ms in the measurements. Figure 4a-c shows empirical relationships between grain size and relaxation time (Schirov *et al.*, 1991), permeability (Hölting, 1992), and porosity (Davis and de Wiest, 1966) for unconsolidated sediments. Clay and silt, which normally constitute aquicludes, have higher total porosities than sandy aquifers. This means that aquicludes have a higher total water content than sands when fully saturated. But a large proportion of this water is adhesive water. This must be taken into account when interpreting SNMR results and comparing them with ING logs.

The porosity of an unconsolidated sediment depends basically on its texture, which is characterised by the particle size distribution, d_{60}/d_{10} – the degree of sorting. This value is obtained by mechanical sieve analysis of core samples. It is plausible that sediments with a lower degree of sorting are better sorted than those with a higher degree of sorting. Sieve analysis was carried out on aquifer material from boreholes B8 and B2. Porosities and amounts of adhesive water were then estimated using conventional methods (Beyer, 1964; Beyer and Schweiger, 1969). The reliability of the estimated parameters is high, especially for well sorted sands like those in the test area.

The total porosities derived from sieve analysis show good agreement with the ING logs in fig. 9 where the parameter ING.W for saturated material is a function of the total porosity. The water content derived from SNMR is lower than that obtained from the ING log by an amount approximately equal to the adhesive water (3-6%).

The water content itself gives no clear indication whether the soil is saturated or unsaturated. Therefore, it is not a direct measure of the yield of a well. In the unsaturated zone many isolated pockets of capillary water may represent a considerable volume of free water, which, however, is not exploitable groundwater. A complete evaluation of water in a soil requires a knowledge not only of the amount of water in the soil, but also its energy status. This is described by the soil water retention curve (Wilson *et al.*, 1995). The SNMR results for the test

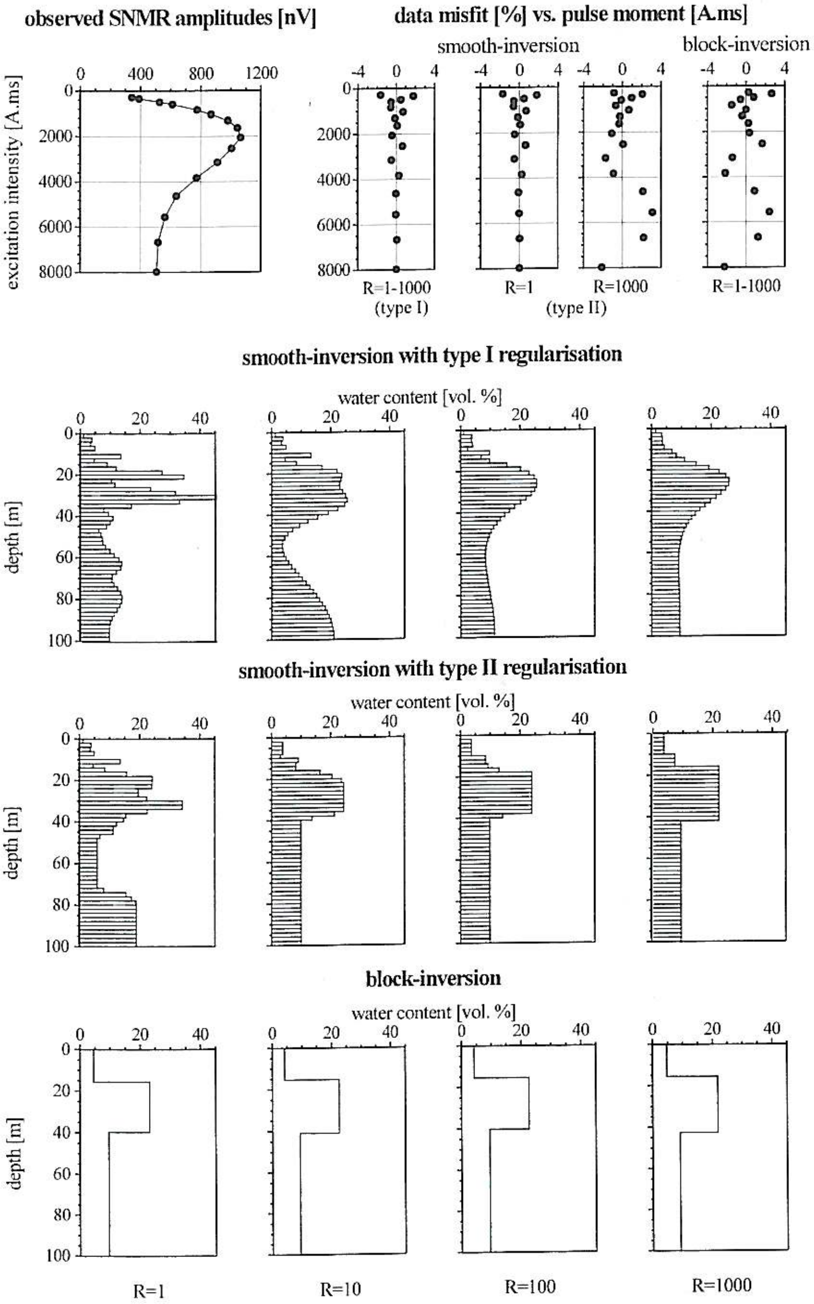

Fig. 10. Results of different kind inversion schemes for the initial amplitudes at the location B8 (after Mohnke and Yaramanci, 2000). At the top the measured data and the data misfits for different inversions. The lines below show the results for three different inversion schemes with different degrees of regularisation *i.e.* imposed smoothness in the inversion.

area show a relatively large amount of water in the unsaturated (vadose) zone. This is in good agreement with the ING log, which shows 12-15% total water on average (fig. 9).

Geoelectric methods are the geophysical techniques most widely used in groundwater exploration. The electrical resistivity measured depends to a large extent on water content. But there is not an unambiguous relationship between water content and resistivity. The resistivity also depends on the salinity of the water, pore structure, and to a large extent on clay content. The resistivity of sandy material is described by the well known Archie relation (Archie, 1942; Dannowski and Yaramanci, 1999) which did not yield reliable estimates of water content for the Haldensleben site (Yaramanci *et al.*, 1999c).

In order to obtain permeabilities *i.e.* hydraulic conductivities from SNMR measurements, the empirical relationship between decay time and average grain size observed in many SNMR surveys (Schirov *et al.*, 1991) can be used (fig. 4a-c). The relationship between grain size and permeability (fig. 4b) often used in hydrogeology (Hölting, 1992) can be used to derive an expression for the permeability coefficient k (in m/s) as a function of decay time T (in s)

$$k = 1.1\ T^{4.14}. \qquad (7.1)$$

The decay times of around 100 to 200 ms from the Haldensleben survey yield permeability coefficients of approximately 0.8×10^{-4} to 1.4×10^{-3} m/s, which are in very good agreement with those derived from the core material (fig. 9). Therefore, it is suggested that eq. (7.1) be used to estimate permeabilities from decay times in future studies. Some modification of this equation may be needed in the future with an increase in the database.

As in any geophysical measurement, the inversion plays a key role by interpreting the data. The limits of inversion and also the imposed conditions in terms of geometrical boundary conditions as well differences in the basic physical model used may lead to considerable differences. A recent investigation on this which also led to the development of a new inversion scheme demonstrates very well the variety of inversion results still within an acceptable range (Mohnke and Yaramanci, 2000). An example is given for the data of the location B8 in Haldensleben in fig. 10. In particular, the introduction of free adjustable boundary layers which are to be optimised in the inversion give good results for aquifers with sharp boundaries, *i.e.* small capillary zones

8. Conclusions

The use of SNMR for groundwater exploration is still in an experimental stage. Nevertheless, the results already obtained with this method and those described in this paper show that the SNMR method has the potential to advance to a valuable tool for groundwater exploration and aquifer characterisation.

Only a 1D inversion method is available for SNMR data, but it is suitable for the configuration used. Future developments have take 2D configurations and inversions into account, as there may be distinct 2D features whose effect may not be documented fully using a 1D interpretation. It also generally appears to be very important to include resistivity data in the interpretation of SNMR, but not at the particular site in Haldensleben since the resistivities of the unsaturated zone and aquifers are not too low.

The 1D inversion of SNMR data may also be ambiguous, since different regularisations in the inversion impose a certain degree of smoothness upon the distribution of water content (Legchenko *et al.*. 1998; Yaramanci *et al.*, 1998; Mohnke and Yaramanci, 1999, 2000; Hertrich and Yaramanci, 2000) and may lead to quite differing results, making it impossible to decide which is the most realistic model without supplementary information. The rms error, usually used for any geophysical inversion, is not necessarily sufficient for assessing the fit of a model to the observed data (Yaramanci *et al.*, 1998). The inversion of SNMR data presented here yield values for the variance that are so large that the water content values can only be considered to be rough estimates.

At sites where no *a priori* information is available, SNMR should always be carried out in conjunction with electrical methods, *i.e.* direct current geoelectric, electromagnetics and even GPR. This will help to decrease ambiguity in the results and also allow hydrogeological parameters to be estimated. But despite all the difficulties, the quality of geophysical exploration for groundwater and aquifer properties will have an increased degree of reliability by using SNMR as a direct indicator of water and soil properties.

The results obtained here and at a further test location in Nauen/Berlin (Yaramanci *et al.*, 1999a,b) show that the potential of SNMR is not restricted to determining the water content of aquifers, but also free water in the unsaturated zone, which is not available groundwater. This is important for environmental research, because this water affects contaminant transport in several ways. To evaluate the potential of the unsaturated zone to protect groundwater resources, detailed knowledge of the water content and permeability of this zone is required. The SNMR results together with the geoelectric data obtained at the test locations show that the SNMR method is a promising tool for this purpose. In fact, SNMR may turn out to be the only suitable nonintrusive tool for examining the degree of saturation in the unsaturated zone under certain soil conditions.

The importance of the SNMR method lies in its ability to measure water content directly. In this respect it is unique, since all other geophysical methods measure water content indirectly via resistivity, seismic velocity, etc. Using SNMR in combination with other geophysical methods, the problem of salinity in determining the water content from the resistivity can be resolved. Moreover, properties of the pore can be deduced if the water content is known and salinity is sought or *vice versa.*

List of symbols

ω_L	Larmor frequency
γ	gyromagnetic ratio
B_0	magnetic field of the Earth
B_1	secodary magnetic field
t	time
$i(t)$	alternating current in the loop
τ	duration of alternating current
q	excitation intensity (pulse moment)
i_0	current amplitude
$e(t)$	voltage in the loop
E_0	initial amplitude
T	observed relaxation time
T_2^*	spin-spin relaxation time
φ	phase
M_0	nuclear magnetisation
r	location of volume elements, $r(x, y, z)$
$f(r)$	water content at location r
$T(r)$	decay time at location r
$B_\perp(r)$	magnetic excitation field perpendicular to Earth's magnetic field at location r
k	hydraulic conductivity

REFERENCES

ARCHIE, G.E. (1942): The electrical resistivity as an aid in determining some reservoir characteristics, *Trans. Am. Inst. Mineral. Met. Petr. Eng.*, **146**, 54-62.

BARRINGER, A.R. and J.F. WHITE (1968): Groundwater survey method and apparatus, *U.S. Patent* #3, 398, 355.

BEAUCE, A., J. BERNARD, A. LEGCHENKO and P. VALLA (1996): Une nouvelle méthode géophysique pour les études hydrogéologiques: l'application de la résonance magnétique nucléaire, *Hydrogéologie*, **1**, 71-77.

BEYER, W. (1964): Zur Bestimmung der Wasserdurchlässigkeit von Kiesen und Sanden aus der Kornverteilung, *Wasserwirtsch.-Wassertech. (WWT)*, **14**, 165-169.

BEYER, W. and K.H. SCHWEIGER (1969): Zur Bestimmung des entwässerbaren Porenanteils der Grundwasserleiter, *Wasserwirtsch.-Wassertech. (WWT)*, **19**, 57-60.

BLOCH, F., W.W. HANSEN and M.E. PACKARD (1946): The nuclear induction experiment, *Phys. Rev.*, **70**, 474-485.

CARR, H.Y. and E.M. PURCELL (1954): Effects of diffusion on free precession experiments, *Phys. Rev.*, **94**, 630.

CHANDLER, R.M., W.E. KENYON and C.E. MORRISS (1987): Reliable nuclear magnetism logging – with examples in effective porosity and residual oil saturation, *Trans. SPWLA*, Paper C.

DANNOWSKI, G. and U. YARAMANCI (1999): Estimation of water content and porosity using combined radar and geoelectrical measurements, *Eur. J. Environ. Eng. Geophys.*, **4**, 71-85.

DAVIS, N.S. and R.J.M. DE WIEST (1966): *Hydrogeology* (Wiley & Sons, NewYork).

GEV, I., M. GOLDMANN, B. RABINOVICH, M. RABINOVICH and A. ISSAR (1996): Detection of the water level in fractured phreatic aquifers using Nuclear Magnetic Resonance (NMR) geophysical measurements, *J. Appl. Geophys.*, **33,** 277-282.

GOLDMAN, M., B. RABINOVICH, M. RABINOVICH, D. GILAD, I. GEV and M. SCHIROV (1994): Application of the integrated NMR-TDEM method in groundwater exploration in Israel, *J. Appl. Geophys.*, **31**, 27-52.

HERTRICH, M. and U. YARAMANCI (2000): Improvement on aquifer characterisation by joint inversion of surface-NMR and geoelectrics, in *Proceedings of 6th Meeting of Enviromental and Engineering Geophysics, Bochum.*

HÖLTING, B. (1992): *Hydrogeologie* (Enke Verlag, Stuttgart).

KENYON, W.E. (1992): Nuclear magnetic resonance as a petrophysical measurement, *Int. J. Radiat. Appl. Instrum., Part E, Nuclear Geophysics*, **6** (2), 153-171.

LEGCHENKO, A.V. and O.A. SHUSHAKOV (1998): Inversion of surface NMR data, *Geophysics*, **63,** 75-84.

LEGCHENKO, A.V., A.G. SEMENOV and M.D. SCHIROV (1990): A device for measurement of subsurface water saturated layers parameters (in Russian), *USSR Patent 1540515*.

LEGCHENKO, A.V., O.A. SHUSHAKOV, J.A. PERRIN and A.A. PORTSELAN (1995): Noninvasive NMR study of subsurface aquifers in France, in *Proceedings of 65th Annual Meeting of Society of Exploration Geophysicists*, 365-367.

LIEBLICH, D.A., A. LEGCHENKO, F.P. HAENI and A.A. PORTSELAN (1994): Surface nuclear magnetic resonance experiments to detect subsurface water at Haddam Meadows, Connecticut, in *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Boston*, vol. 2, 717-736.

LOKE, M.H. and R.D. BARKER (1996): Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method, *Geophys. Prospect.*, **44**, 131-152.

LOREN, J.D. (1972): Permeability estimates from NML measurements, *J. Petrol. Technol.*, **25**, 923-928.

MEIBOOM, S. and D. GILL (1958): Compensation for pulse imperfections in Carr-Purcell NMR experiments, *Rev. Sci. Instrum.*, **29**, 688.

MOHNKE, O. and U. YARAMANCI (1999): A new inversion scheme for surface NMR amplitudes using simulated annealing, in *Proceedings of 60th Conference of European Association of Geoscientists and Engineers, Helsinki*, 2-27.

MOHNKE, O. and U. YARAMANCI (2000): Inversion of surface-NMR amplitudes and decay times – Examination of smooth and block inversion, in *Proceedings of 6th Meeting of Enviromental and Engineering Geophysics, Bochum* (EM07).

OLAYINKA, A.I. and U. YARAMANCI (2000): Assessment of the reliability of 2D inversion of apparent resistivity data, *Geophys. Prospect.*, **48**, 293-316.

PURCELL, E.M., H.C. TORREY and R.V. POUND (1946): Resonance absorption by nuclear magnetic moment in a solid, *Phys. Rev.*, **69**, 37-38.

PUSEP, A.Y., V.S. BASHUROVA, N.V. SHOKHIREV and A.I. BURSHTEIN (1991): *Software Development for the NMR Tomography of Subsurface Water Bearing Horizons*, USSR Acad. Sci. Novosibirsk, pp. 89 (in Russian).

SCHIROV, M., A. LEGCHENKO and G. CREER (1991): A new direct non-invasive groundwater detection technology for Australia, *Explor. Geophys,* **22**, 333-338.

SEEVERS, D.O. (1966): A nuclear magnetic method for determining the permeability of sandstones, *Trans. SPWLA*, Paper L.

SEMENOV, A.G. (1987): NMR hydroscope for water prospecting in *Proceedings of the Seminar on Geotomography*, Indian Geophysical Union, Hyderabad, 66-67.

SEMENOV, A.G., A.I. BURSHTEIN, A.Y. PUSEP and M.D. SCHIROV (1988): A device for measurement of underground mineral parameters (in Russian), *USSR Patent 1079063*.

SEMENOV, A.G., A.Y. PUSEP and M.D. SCHIROV (1982): *Hydroscope – An Installation for Prospecting Without Drilling* (in Russian), USSR Acad. Sci., Novosibirsk, 1-26.

SEMENOV, A.G., M.D. SCHIROV, A.V. LEGCHENKO, A.I. BURSHTEIN and A.Y. PUSEP (1989): Device for measuring the parameter of underground mineral deposits, *Great Britain, Patent 2198540B*.

SHUSHAKOV, O.A. (1996): Groundwater NMR in conductive water, *Geophysics*, **61**, 998-1006.

SHUSHAKOV, O.A. and A.V. LEGCHENKO (1992): *Calculation of the Proton Magnetic Resonance Signal from Groundwater Considering the Electroconductivity of the Medium* (in Russian), Russian Acad. of Sci., Inst. of Chem. Kinetics and Combustion, Novosibirsk, No. 36, 1-26.

STRALEY, C., C.E. MORRISS, W.E. KENYON and J.J. HOWARD (1991): NMR in partially saturated rocks: laboratory insights on free fluid index and comparison with borehole logs, *SPWLA, 32nd Annual Logging Symposium*, 1-25.

TIMUR, A. (1968): An investigation of permeability, porosity and residual water saturation relationships, *Trans. SPWLA*, Paper K.

TIMUR, A. (1969a): Producable porosity and permeability of sandstones investigated through nuclear magnetic resonance principles, *Log Anal.*, **10** (Jan.-Feb.), 3-11.

TIMUR, A. (1969b): Pulsed magnetic resonance studies of porosity, movable fluid and permeability of sandstones, *J. Petrol. Technol.*, **21**, 775-786.

TRUSHKIN, D.V., O.A. SHUSHAKOV and A.V. LEGCHENKO (1994): The potential of a noise-reducing antenna for surface NMR groundwater surveys in the earth's magnetic field, *Geophys. Prospect.*, **42**, 855-862.

TRUSHKIN, D.V., O.A. SHUSAKOV and A.V. LEGCHENKO (1995): Surface NMR applied to an electroconductive medium, *Geophys. Prospect.*, **43**, 623-633.

VARIAN, R.H. (1962): Ground liquid prospecting method and apparatus, *US Patent 3019383*.

WILSON, L.G., L.G. EVERETT and ST. J. CULLEN (Editors) (1995): *Handbook of Vadose Zone Characterization and Monitoring* (Lewis Publishers, New York).

YARAMANCI, U., G. LANGE and K. KNÖDEL (1998): Effects of regularisation in the inversion of surface NMR measurements, in *Proceedings of 60th Conference of European Association of Geoscientists and Engineers, Leipzig*, 10-18.

YARAMANCI, U., M. HERTRICH and G. LANGE (1999a): Examination of surface-NMR within an integrated geophysical study in Nauen, Berlin, in *Proceedings of 5th Meeting of Environmental and Engineering Geophysics* (HyP2).

YARAMANCI, U., G. LANGE and M. HERTRICH (1999b): Surface NMR combined with geoelectrics and radar for aquifer studies in Nauen/Berlin, in *Proceedings of 61st Conference of European Association of Geoscientists and Engineers, Helsinki*, 2-28.

YARAMANCI, U., G. LANGE and K. KNÖDEL (1999c): Surface NMR within a geophysical study of an aquifer at Haldensleben (Germany), *Geophys. Prospect.*, **47**, 923-943.