MRS

2[ND] INTERNATIONAL WORKSHOP
on the Magnetic Resonance Sounding method applied to non-invasive groundwater investigations

19 - 21 November 2003 - Orléans - France

PROCEEDINGS

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2ND INTERNATIONAL WORKSHOP

ON THE MAGNETIC RESONANCE SOUNDING METHOD APPLIED TO NON-INVASIVE GROUNDWATER INVESTIGATIONS

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INTRODUCTION

Dear Colleague,

The 2nd International Workshop on the Magnetic Resonance Sounding method applied to non-invasive groundwater investigations took place from 19 – 21 November 2003 at the BRGM Scientific and Technical Center in Orléans, France.

Considering the significant progress made in MRS development since the 1st International MRS workshop was successfully held in Berlin in 1999, the Bureau de Recherches Géologiques et Minières (BRGM) and the Technical University of Berlin (TUB) decided to continue the exchange of experience gained worldwide by different teams in MRS development and application. Aimed at increasing the contribution of geophysics to groundwater prospecting and management, the workshop constitutes an important forum for geoscientists and engineers to exchange views and practical experience, and further their knowledge and understanding of the method.

The 2nd MRS workshop is a meeting not only to those involved in MRS development and application, but also to geophysicists and hydrogeologists seeking new tools for groundwater investigations. The registration list contains more than 70 participants from 15 countries (Algeria, Australia, Burkina Faso, Chine, Denmark, France, Germany, Great Brittany, India, Jordan, The Netherlands, Nigeria, Russia, Spain and USA). The conference features 33 oral and 7 poster presentations, as well as specially prepared field demonstrations. The technical presentations cover a wide range of theoretical, methodological and application topics related to groundwater investigation using the MRS technique. There clearly should be something for everyone interested in aquifer localization and characterization.

It is our strong belief that, despite the enormous progress made in the field of communication and information techniques via the Internet, face-to-face meetings are still an essential means of informal interaction between scientists who, although representing different disciplines, are working on common problems.

In the Proceedings book you can find coverage of the technical papers that were presented during the MRS 2003 workshop in Orléans.

Organizing Committee

The four-page abstracts submitted by authors were no subject of the editing. They are integrated into Proceedings following closely their original form.

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ORAL PRESENTATIONS

TDEM AND NUMIS^{PLUS} SOUNDINGS AT THE ASH MEADOWS NATIONAL WILDLIFE REFUGE: A CASE STUDY

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INTRODUCTION

During the summer of 2002, a cooperative project between the U.S. Geological Survey, the U.S. Environmental Protection Agency, and the Bureau de Recherches Géologiques et Miniéres was undertaken to evaluate and gain knowledge of the Iris NUMIS^{Plus} magnetic resonance sounding instrument. The system was deployed at several sites throughout the United States of America (USA). One of these sites was the Ash Meadows National Wildlife Refuge. The following describes the geology, hydrology, and geophysical results in this unique desert oasis environment. Ash Meadows is located in southern Nye County, Nevada approximately 145 km northwest of Las Vegas, Nevada. Ash Meadows lies within the southern part of the Great Basin, an internally drained subdivision of the Basin and Range physiographic province. Time domain electromagnetic TDEM soundings were collected at each of the NUMIS^{Plus} sounding locations. The (TDEM) results clearly show the resistive carbonate fault blocks as well as a horizontal resistive layer that is broken by faults. These TDEM soundings provided a resistivity section for input into the NUMIS^{Plus} inversions. The NUMIS^{Plus} inversions indicate several water rich zones throughout the Ash Meadows area. Resource managers will use the results from this study to improve the hydrologic model of the Ash Meadows.

SITE DESCRIPTION

Ash Meadows encompasses approximately 202 km^2 of desert uplands and spring-fed oases. The Ash Meadows National Wildlife Refuge covers approximately 93 km^2. Paleozoic carbonate and siliceous clastic rocks make up the primary rock types of the hills, ridges, and mountain ranges. The basins are filled with sedimentary and volcanic rocks, including sandstone, siltstone, lacustrine clay and limestone, and volcanic ash and lava flows.

Ash Meadows is located in the north-central part of the Mojave Desert and is typical of most other desert regions, characterized by short mild winters, long hot summers, and low annual rainfall. Unlike most desert communities, Ash Meadows has a high concentration of springs. More than 30 springs and seeps are aligned in a linear pattern spanning 16 km and generally oriented NE-SW. The spring flow is relatively constant (Laczinack and others 1999). The exception was in the late 1960's and early 1970's when local agricultural interests pumped large quantities of ground water to irrigate local crop fields (Dudley and Larson, 1976). A consequence of ground-water pumping was a drop in the pool level in Devils Hole, which is a shaft-like opening into the ground water system through carbonate bedrock created by a collapse. This feature provides the sole remaining habitat for the endangered Devils Hole pupfish (Cyprinodon diabolis). In 1975 the U.S. Supreme Court established a minimum pool level for Devils Hole, essentially prohibiting any significant pumping from the local area. Shortly after the mandate, all agricultural and development interests in the area faded, water levels began recovering, and spring flows returned to nearly the previously measured rates (Westenburg, 1993).

The Ash Meadows area is supplied by ground water from the north and northeast, through thick rock units composed of fractured limestone and dolomite. The ground water moves primarily through interconnected fractures within the carbonates, where it is confined between two impermeable layers as it moves towards the Ash Meadows area (Winograd and Pearson, 1976). As the ground water moves into Ash Meadows under a driving head, flow is impeded by the Ash Meadows fault system. Some of the water is pushed upward forming springs directly along faults in the bedrock at the margins of the carbonate ridges. Other springs discharge from within the alluvium, which are likely fed by faults in the underlying carbonates. Within the Ash Meadows area there are two aquifers; the deeper carbonate aquifer, and the shallower alluvial basin-fill aquifer. The carbonate aquifer is composed of 4,600 m of limestone and dolomite interbedded with minor layers of siltstone, agillite, and shale of Cambrian, Ordovician, and Devonian age. The basin-fill aquifer is exposed at the surface at Ash Meadows and is composed of a complex interbedded limestones, sandstones, gravels, siltstones, and clays. Although the study area is checkered by many wells these wells were installed for agricultural water supplies and have limited or no information on lithology and geophysical parameters.

Cultural impacts are very minor in the Ash Meadows area with only small power lines supplying the Refuge Headquarters and the few private residences within the area. During the 2002 NUMIS survey at Ash Meadows, local thunderstorm activity caused problems with data collection. NMR data were only collected early in the morning, prior to afternoon thunderstorms; therefore, spatial coverage of NMR soundings was severely limited. 60 Hz EM noise in the Ash Meadows area was relatively low as determined by measurements collected at selected NMR sites using a 60 Hz EM total field system, which was developed by the USGS. The average 60 Hz total field noise was 1005 nT with a standard deviation of 228 nT. Magnetic susceptibility measurements were made using a handheld magnetic susceptibility meter. The magnetic properties of the surface sediments at the Ash Meadows area are moderate with an average susceptibility of 73×10^{-5} S.I. units.

RESULTS

Fourteen TDEM soundings were collected at Ash Meadows. A TDEM sounding was completed at each NUMIS^{Plus} sounding location. The TDEM soundings provide a resistivity section that can be used as the input model for the NUMIS^{Plus} inversions, as well as stand alone resistivity map. A Geonics Protem 47 was used with a single turn 40 m transmitter loop in a central loop configuration (Rx centered within the Tx loop). The TDEM soundings provide a generalized view of the site containing a large resistive limestone block and very possible a fault to the east. In the E-W TDEM profile (Figure 1a) a high resistivity zone can be noted centered at Site 21.5 extending to the west and east to Site 22 and Site 20. This is interpreted as the buried portion of the carbonate outcrop at “Point of Rocks Spring.” A semi-discontinuous layer can be observed from Site 24 to Site 22 with an elevation change at Site 23.5. This may be a layer of limestone or resistive water within a more porous rock. On the east side of the profile there is a noticeable break between Site 20 and Site 18, which indicates a fault or a discontinuous layer of resistive rock within the valley fill sediments.

The Iris NUMIS^{PLUS} was deployed at eight sites within the Ash Meadows study area. The data collected were of appropriate quality to allow inversion. Resistivity vs. depth profiles calculated from the TDEM soundings were used by the NUMIS^{Plus} inversion. Detailed description of the Inversion of surface NMR data can be found in Legchenko and Shushakov (1998). Profiles of estimates of percent water and permeability for E-W profile were prepared (Figure1b and 1c). The NUMIS^{Plus} percent water profile displays water contents from 0 to 11 percent, between Site 24 and Site 23 a zone containing 4 to 10 percent water from near the surface to 10 m of depth (680 m in elevation) this zone pinches out toward Site 22. Another zone of 4 to 8 percent water occurs at 675 to 660 meters in elevation. At Site 18 zone of 4 to 8 percent water is imaged between 685 and 695 m in elevation and continues east under Site 19 where another deeper zone of 2 to 4 percent water is imaged between 660 and 674 m in elevation. These layers are probably related to the faults or just the complicated sedimentary structure in the valley fill at Ash Meadows. The plots of water content show a break in the structure between Site 23 and Site 22 and between Site 22 and Site 18. Carbonate rocks buried beneath the section between Site 22 and Site 18, or the faults associated with the carbonates, may cause the breaks in the imaged layers. The NUMIS^{Plus} profile of permeability (Figure 1c) indicates a permeable zone between Site 24 and 23. As expected, the distribution of permeability is similar to the distribution of percent water in Figure (1b).

SUMMARY

Maps of increased water content and increased permeabilities can be produced, however the fact that the NUMIS has an averaging effect over the investigated volume, may preclude an exact correlation with water contents and permabilities. Due to the highly 3-D nature of the subsurface at Ash Meadows, a qualitative view of the water contents and the permabiltites may be the only outcome that can be achieved. The NUMIS^{Plus} results combined with the TDEM soundings can give a generalized model of the subsurface at Ash Meadows. This alone is a powerful tool for resource managers. However, without good well data, including detailed lithological, neutron and induction logs, a quantitative assessment of the NUMIS^{Plus} and TDEM data collected at Ash Meadows cannot be achieved.

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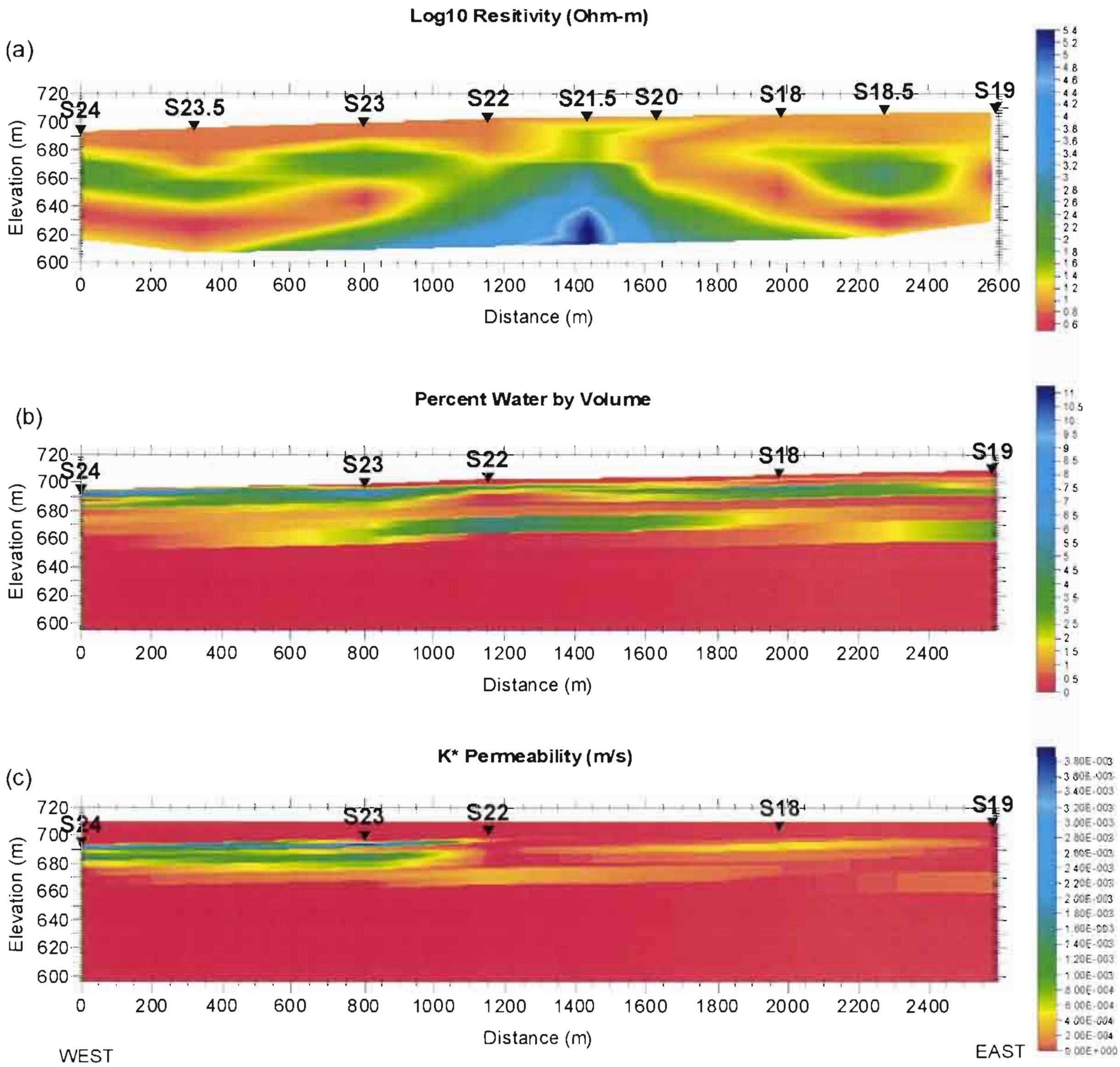

Figure 1. Results of TDEM and NUMIS soundings along the E-W profile at Ash Meadows, Nevada (a) Inverted TDEM data in $\log_{10}$ (resistivity) (b) NUMIS percent Water content, and (c) NUMIS permeability (m/s).

CALIBRATION OF MRS RESULTS USING HYDRODYNAMIC CHARACTERISTICS FROM PUMPING TESTS

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INTRODUCTION

A methodological study using NUMIS^{plus} magnetic resonance sounding (MRS) equipment was performed in France from 2000 to 2002. The main aims were to:

- compare MRS results with hydrodynamic parameters resulting from pumping tests;
- establish an empirical relationship between MRS and pumping test results;
- establish a methodology for MRS characterisation over potential groundwater exploration drilling sites for drinking water supply.

Eleven water well sites with aquifers essentially composed of chalk and sandstone were investigated in the Eure-et-Loir Department. An additional site in alluvium of the Durance River (Vaucluse) and two sites in Bajocian limestone (Vienne) completed the data set. At the beginning of 2002, the Eure-et-Loir County Council requested that ANTEA and BRGM perform MRS characterisation over eight new potential drilling sites for drinking water supply. On the basis of these MRS results, two sites were selected at the beginning of 2003. A borehole was drilled and tested at the first site, the results of which show a good correlation with the MRS results. Drilling is currently underway at the second site.

In this paper, we present the methodology, the details of its practical application and experimental verification.

INVERSION OF MRS DATA

Inversion of MRS data provides the following parameters: aquifer depth and thickness, water content and relaxation time constant. Like many other surface geophysical methods, the MRS inverse problem is ill-posed. Because of the equivalence problem, inversion may lead to several models, which in turn means that different models may fit equally well a given MRS experimental data set. In MRS, two layers of thickness e_1, e_2, with a respective water content W_1, W_2, and located at the same depth, are said to be equivalent when $W_1 e_1 = W_2 e_2$ (Legchenko et al., 2003).

Models obtained from different interpretation procedures that fit equally well experimental data constitute a space of equivalent solutions. Analysis of the solution space is a means for evaluating the uncertainty of MRS results. In an attempt to evaluate this uncertainty and so as to compare MRS results with hydrodynamic data, three different interpretation procedures were applied to the data from 14 MRS stations located near water supply wells. Three sets of models were thus obtained (figure 1):

One is the result of the automatic inversion process provided by the Samovar software using the Tikhonov regularisation method (Legchenko & Shushakov, 1998). Using appropriate regularisation parameters, models composed of a large number of layers, show quasi-continuous variation of MRS characteristics along the depth axis (figure 1d).

Two others are obtained by calibrating aquifer depth and thickness with the lithological description from boreholes drilled by two different operators (figure 1b, 1c). The models are composed of a finite number of layers that show constant MRS characteristics within themselves and marked contrasts from one layer to the next.

The equivalence of the different models is assessed by keeping the residual mean square (RMS) between the data and theoretical signals within a range of 3% for each sounding.

COMPARISON OF MRS RESULTS AND HYDRODYNAMIC PARAMETERS

Following examples of empirical relationships developed through nuclear magnetic resonance logging for estimating formation permeability (Kenyon et al., 1997), the water content and relaxation time constant T_1 were used for MRS estimation of hydraulic conductivity (Legchenko et al., 2003), which was then compared to that derived from pumping tests.

For this exercise, the most convenient expression for MRS transmissivity (T_{MRS}) was found to be $T_{MRS} = C\sum_i e_i W_i T_1^2$; with W_i, e_i, T_1 being respectively the water content, thickness, longitudinal time constant of a layer *i*, and *C* an empirical constant.

The MRS estimator $\sum_i e_i W_i T_1^2$ was computed considering different equivalent models. The results are plotted against borehole transmissivity (figure 2a), which reveals that all the equivalent models, including that given by the automatic inversion, fit similarly well the transmissivities measured in the boreholes. Obviously, as T_{MRS} is computed using the product $e_i W_i$, the results are less affected by the equivalence problem when the model is changed.

Based on an evaluation of the dispersion of these various T_{MRS} data, an attempt was made to estimate the uncertainty on MRS transmissivity, as evaluated by the Samovar software with the empirical constant C being equal to 7×10^{-11} (default value). It was found that with NUMIS data with a signal-to-noise ratio greater than five, uncertainty on MRS transmissivity estimation extends from half to twice the calculated value (figure 2b). For example, an MRS estimated transmissivity T_{MRS} of 2×10^{-3} m²/s may vary from 1×10^{-3} up to 4×10^{-3} m²/s.

EXAMPLE OF APPLICATION

Soundings with a 75-m-long square antenna were carried out over eight new potential drilling sites for drinking water supply. The site locations had been selected on the basis of classical hydrogeological analysis, and MRS was applied for aquifer caracterisation before drilling.

In the Châtillon-en-Dunois area (figure 3), four soundings were performed. CHATIL2, CHATIL3, and CHATIL4 reveal better MRS transmissivity ($T_{MRS}=2.2$ *to* $2.7x10^{-3} m^2/s$) than CHATIL1 ($T_{MRS}= 8.x10^{-4}$). From existing wells, it is known that CHATIL2 and CHATIL4 have highly contrasting yields: 40 m^3/h and almost dry, respectively. The aquifers in this area are typically composed of fractured and/or karstified chalk, which easily explains this difference: CHATIL4 does not intersect the producing fracture zone, whereas CHATIL2 does. As a conclusion of the study, the CHATIL3 site was recommended for drilling.

In January of 2003, a new exploration borehole, F1, was drilled 100 m north of the CHATIL3 MRS station. It encountered a fractured chalk aquifer at a depth of 20 m and pumping tests revealed a transmissivity of 1.0 to 2.1 10^{-3} m²/s, which is in full agreement with MRS predictions (figure 2b).

CONCLUSIONS

Based on 14 groundwater wells mainly located in Eure-et-Loir , an empirical relationship was established between MRS results and pumping test transmissivity. An attempt was made to estimate the uncertainty on MRS evaluation of transmissivity (T_{MRS}). It was found that in favourable conditions, MRS estimation of the transmissivity using the Samovar software falls within an uncertainty margin extending from half to twice its value. For example, an MRS estimated transmissivity T_{MRS} of $2x10^{-3}$ m²/s may vary from $1x10^{-3}$ up to $4x10^{-3}$.

The methodology derived from this study was successfully applied to eight new potential drilling sites for drinking water supply in Eure-et-Loir.

This work was carried out in the framework of a BRGM research programme in collaboration with ANTEA ("Agence Centre") and the Eure-et-Loir County Council.

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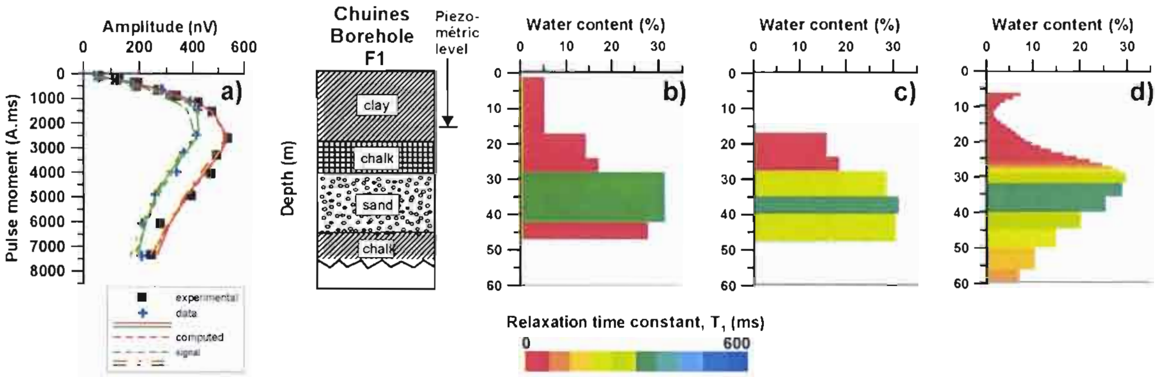

Figure 1: Example of three different models resulting from different MRS interpretations at the Chuisnes borehole site; a) experimental and computed sounding curves; b), c), d) models.

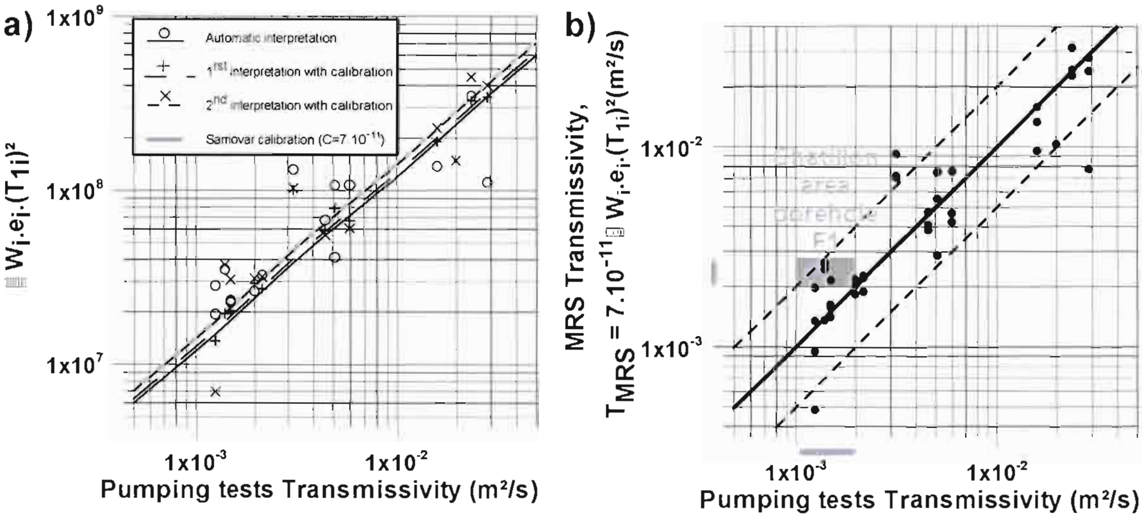

Figure 2: a) Comparison between MRS results of different interpretations and borehole transmissivity; b) Uncertainty margin (dashed lines) on MRS evaluation with Samovar software (bold line) and results obtained from F1 borehole in the Châtillon-en-Dunois area.

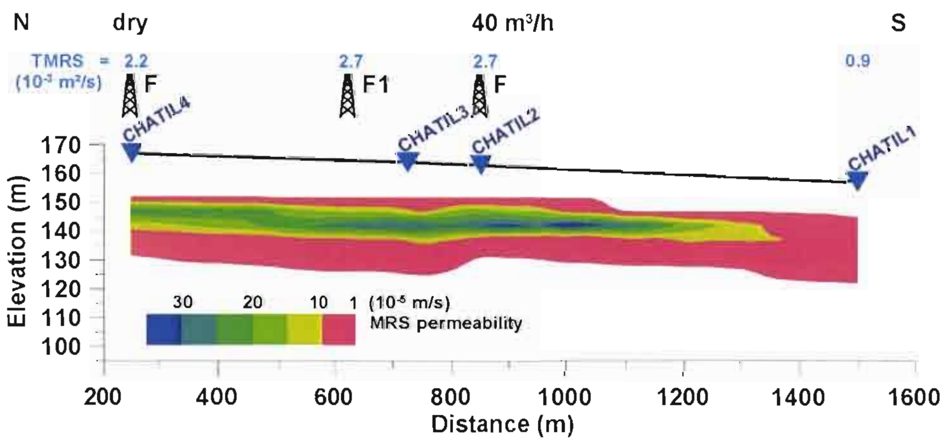

Figure 3: Vertical cross section showing MRS permeability through the Châtillon-en-Dunois area.

MRS AND RESISTIVITY CHARACTERISATION OF THE RINGELBACH CATCHMENT AQUIFER, VOSGES MASSIF, FRANCE

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INTRODUCTION

In the crystalline Vosges massif, where the bedrock is mainly composed of intensely weathered and deformed granitic and metamorphic hard rocks, water supply is mainly derived from small aquifers in the heterogeneous surficial formations and in the weathered and fissured bedrock. The geometry and hydrodynamic properties of these aquifers are still poorly known. The small Ringelbach research catchment (36 ha; 750-1000 m a.s.l.; 75% pasture and 25% forest), which has been studied since 1975, is highly representative of this type of environment (Ambroise, 1995; Ambroise et al., 1995). Several geophysical techniques have been applied to investigate the 3-D structure of the subsurface, which is composed of two types of granite partly covered by Triassic sandstone. The main goal of this study is a better understanding and numerical modelling of the hydrologic behaviour. A preliminary resistivity map of the surficial formations obtained using many short AB/2 vertical electrical soundings (VES) has made it possible to identify several contrasted formations (Schott et al., 1996). Since 1999, 25 magnetic resonance soundings (MRS) along transects and 7 long resistivity imaging profiles across the main geological formations have been performed.

SIGNAL-TO-NOISE RATIO CONDITIONS

The MRS, recorded using a 37.5-m-side figure-of-eight-shaped antenna, show a low signal amplitude (<30 nV) and a high environmental noise level (between 200 and 9000 nV, figure 1a). The signal-to-noise ratio (S/N) was improved by applying to each sounding a 100- to 300-stack program using the weighting technique described in Legchenko and Valla (2002), and a notch filter centered on 50-Hz-harmonics (Legchenko and Valla, 2003). As a result (figure 1b), the maximum amplitude of the measured signals is close to the instrumental noise value (stacked environmental noise to instrumental noise ratio EN/IN < 3), but the signal-to-noise (filtered) ratio (S/N) is generally low, i.e. less than three. Careful analysis of the data shows that 13 MRS can be modeled (figure 1b). A maximum possible value of water volume and water content per unit surface (V_W) will nevertheless be estimated for the remaining 12 MRS.

MRS ANALYSIS IN RELATION TO THE GEOLOGICAL SETTING

A preliminary analysis of the MRS data in relation to the geological setting of the site (figure 2) shows that sandstone clearly provides better MRS characteristics (amplitude and relaxation constant) than granite. Examination of the resistivity map obtained from interpretation of the electrical soundings (figure 3) shows that sandstone and fresh granite, both characterized by high resistivities, cannot be differentiated electrically, but only by MRS data. Conversely, low and high resistivity areas in the granite are not distinguished by contrasted MRS characteristics. The low resistivity area, corresponding to MRS characteristics that are as poor as the high resistivity fresh granite, is attributed to unsaturated weathered granite.

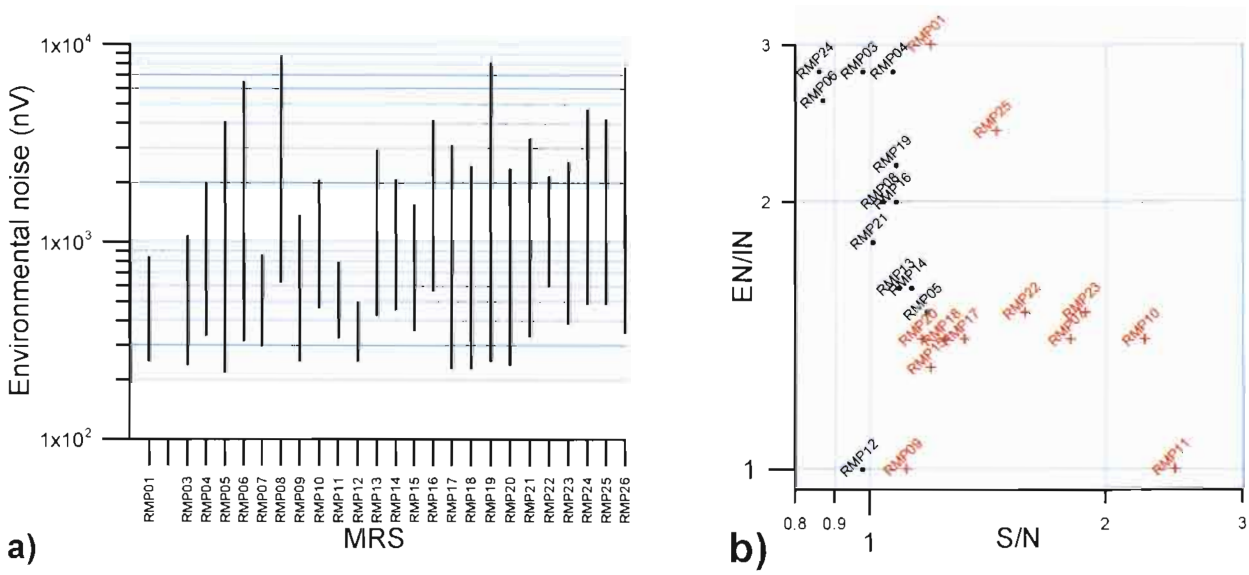

Figure 1: a) Range of environmental noise level. b) Quality evaluation based on the signal-to-noise ratio (S/N) against the stacked environmental noise to instrumental noise ratio (EN/IN). The MRS that can be modeled are represented by crosses.

WATER STORAGE MAPPING

As for any geophysical investigation method operating from the surface, the inversion of MRS in terms of the water content (W) and thickness (e) of a given layer may lead to differing modeling results because of equivalence problems. For example, two layers with respective MRS characteristics (W_1, e_1) and (W_2, e_2), situated at the same depth, that satisfy the relationship $W_1 . e_1 = W_2 . e_2$, fit equally well a given MRS experimental data set. These two layers are said to be equivalent. The water volume per unit surface (V_W), defined as $V_W = \Sigma W_i . e_i$, is thus better determined by MRS than W_i or e_i , which cannot be determined separately without external information. V_W is expressed in m^3/m^2 and has the dimension of a height.

Within the granite area, where no thickness or water content data are available, the best result that MRS can provide is V_W. For the soundings that cannot be modelled, a maximum possible value of V_W is estimated from a linear relationship established between V_W and the maximum signal amplitude of the modeled soundings of the granite. The map of V_W (figure 3), which shows a good agreement with the sandstone/granite geological boundary, is proposed as a basis for evaluating the water storage within the catchment.

A FAULTED STRUCTURE REVEALED BY MRS AND RESISTIVITY

Assuming that sandstone can be considered as a homogeneous reservoir, we attempted to model RMP7, RMP10 and RMP11 with a one-layer model of constant water content, with layer thickness being defined by resistivity imaging profiles. A very constant water content, ranging from 2.7 to 2.9%, is obtained and is thus considered as being characteristic of this formation. The NNW part of the cross section presented on figure 4, combining MRS and electrical measurements, suggests a block structure cut by a fault that downthrows the southeastern block with respect to the northwestern block.

CONCLUSION

It was possible to define the general structure of the catchment by electrical methods in conjunction with MRS, which also enabled mapping of the water volume per unit surface within the different geological formations and blocks. The corresponding map is proposed as a basis for evaluating water storage within the catchment. These results were obtained despite difficult signal-to-noise conditions (S/N < 2.5) and only half of the soundings being suitable for modeling.

The mean water contents of less than 1.5% for the granite are particularly low in comparison to similar granitic environments elsewhere, for example, in French Brittany (Wyns et al., 2003). Although a water content of 1% is not surprising for fissured granites, values of 3 to 5% are more common for weathered granite. The areas where low resistivity indicates weathered granite are thus interpreted as being unsaturated.

It is foreseen, in the framework of this project, to drill boreholes intersecting the different geological formations and sited by geophysics in order to check and calibrate the geophysical results. It is expected that these data will improve the accuracy of hydrogeological modeling.

ACKNOWLEDGEMENTS

This work was financed by the Programme National de Recherche en Hydrologie (PNRH) and a BRGM R&D project.

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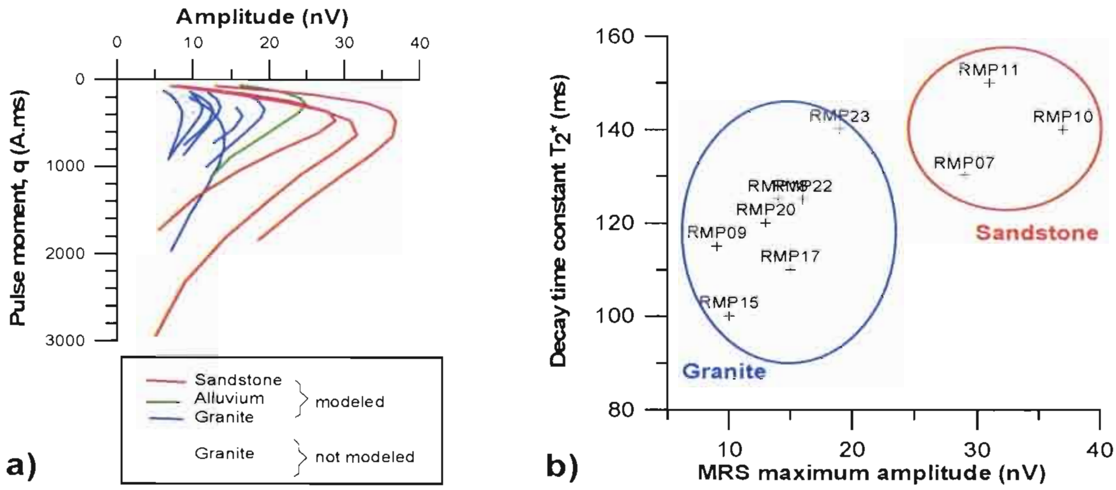

Figure 2: a) Comparison of MRS amplitudes from various presumed geological environments. b) MRS characteristics compared to the presumed geological environment of sounding.

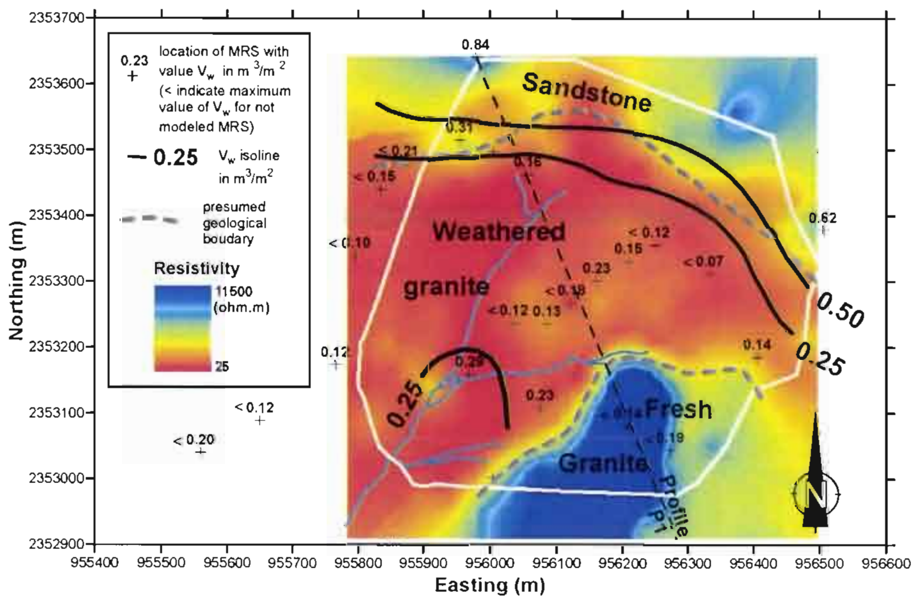

Figure 3: Map of water volume per unit surface (V_W) overlying the resistivity map at 13 m depth, results of VES interpretation and indication of geology.

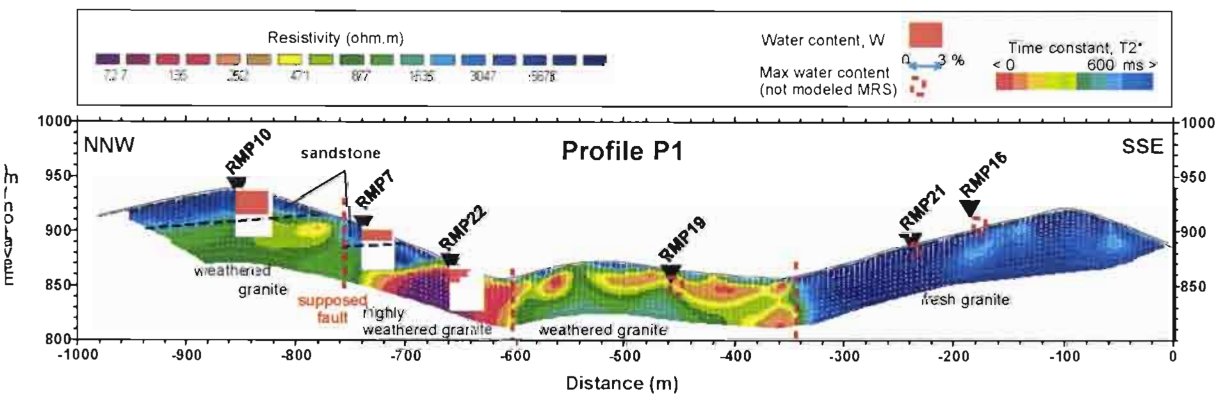

Figure 4: MRS and resistivity cross section through the catchment.

ON THE POSSIBILITY OF MRS MONITORING OF CHALK AND LIMESTONE AQUIFERS

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INTRODUCTION

Magnetic Resonance Sounding method (MRS) was initially developed for the detection of free water in aquifers. MRS capability of separation of groundwater into free and bound water is based on the measurement of signal relaxation time constant T_2^*. In some rock, bound water is characterized by shorter relaxation time constant (<30 ms) and longer time constant (>30 ms) corresponds to free water. As actually available MRS instruments cannot measure short signals, it can be said that MRS is measuring the response from mostly free water. However, relaxation time T_2^* depends not only on pores size but also on magnetic susceptibility of rocks. If the susceptibility is very low ($<10^{-5}$ SIU), then even bound water may produce relatively long signals (60-80 ms) that can be measured by MRS (Legchenko et al., 2002). For example, bound water can be measured in chalk and limestone. Thus, MRS technique could be used for monitoring of the water distribution in the unsaturated zone. In this paper, a theoretical estimation of this possibility and very first experimental results are presented.

NUMERICAL MODELING OF MRS RESPONSE FROM WATER IN CHALK

Experimental laboratory study of the water content distribution in a chalk formation in France (Weng et al., 2002), reveals a quasi-constant profile of the water content (Figure 1). The total porosity of chalk is composed of the matrix porosity and fractures porosity. While the matrix is equally saturated in both aquifer and unsaturated zone, fractures are filled with water in the aquifer and with air in the unsaturated zone. In a chalk formation, it makes the difference in the total water content of about 2 to 3% between the aquifer and unsaturated zone.

Measurements of MRS signal from water in chalk reveal a quite different profile of the water content from that measured in laboratory (Figure 2). We explain this difference by increasing size of the pores from the top towards the aquifer due to alteration of the chalk and decreasing of clay content. As the relaxation times of the magnetic resonance signal is extremely sensitive to the distance between pore walls and water molecules (a few molecular layers), slightly thinner layer of water around chalk grains close to the surface produce very short signal and thus it is barely seen by MRS instrument. This hypothesis still needs to be confirmed, but for a monitoring at the same site we could use an MRS model of water in chalk derived from experimental observations (Figure 2).

Basing on the hydrogeological model of water flow through the unsaturated zone (De Marsily, 1981) a simplified model for estimation of expected variations in the MRS signal caused by variations of the water content in the subsurface has been build. Two mechanisms that may cause variations of the water content in the unsaturated zone are considered: infiltration after rainfalls and variations of the water level (Figure 3). Modeling consists of computing the MRS response considering a water distribution given by the hydrological model and inversion of MRS theoretical signals.

As a parameter for MRS monitoring of water amount in the unsaturated zone, the MRS water volume was used. It is defined as $V_{MRS} = \int_{\Delta z} w(z)dz$, where $w(z)$ is the MRS water content, and Δz is an investigated thickness. Physically MRS water volume corresponds to a volume of water per surface unit within the interval Δz. For the models given by Figure 3, modeling results are presented in Figure 4. The error bars represent experimentally estimated accuracy of commercially available NUMIS system (Girard et al., 2003). One can see that taking into account experimental errors, only large changes in the subsurface can be reliably detected. For example, if the water level changes less than a few meters, then this variation cannot be detected.

EXPERIMENTAL STUDY

Modeling results were compared with a one-year-long monitoring of a chalk aquifer in the Somme region of France. At this site, the static water level is at about 30 m. For all measurements NUMIS^{plus} system and the 37-m-side eight-shape loop were used.

MRS results and water level variations measured in borehole are presented in Figure 5. During the observation period the water level change was four meters. Corresponding MRS water volume was measured from 0.9 to 1.5 m^3/m^2 what makes 0.6 m^3/m^2 variation around a year. If we compare these observations with the modeling results (Figure 4a), then we find that the expected variation is from 1.9 to 2.4 m^3/m^2 (0.5 m^3/m^2). Taking into account that for computing MRS signal the relaxation during the pulse was neglected, and the observed variations in the signal are close to the threshold of the instrument we consider this experience as encouraging. However, an important difference in shape of MRS water volume and water level graphics was observed. While after 21 January both graphics are in an agreement, a disagreement is observed before. It can be explained by accumulation of rain water in the unsaturated zone before causing changes in the water level. However, this hypothesis requires of serious instrumental verification.

CONCLUSIONS

Modeling results show that in the unsaturated zone composed of chalk and limestone, MRS can be a useful tool for monitoring of variation in the water content.

However, commercially available NUMIS^{plus} system is able to detect only large changes of the water content. For really efficient application of MRS to measurement of the water content in the unsaturated zone, accuracy of MRS equipment should be improved by a factor of 5 to 10 (<1% errors).

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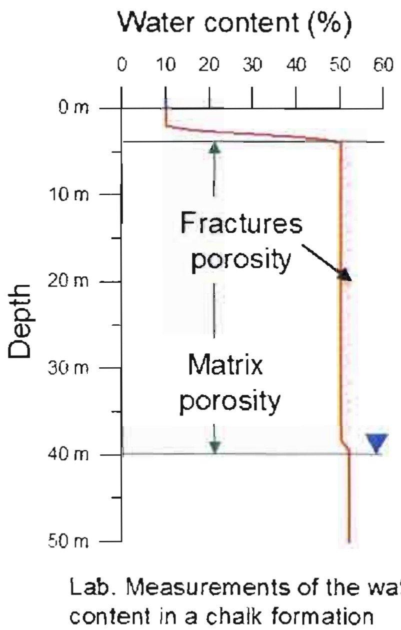

Figure 1. Water content in a chalk formation.

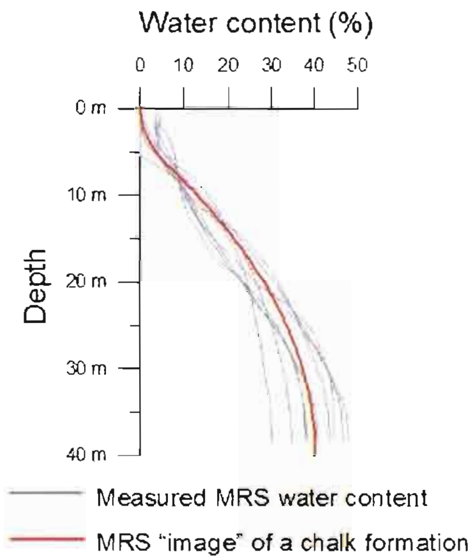

Figure 2. MRS image of a chalk formation.

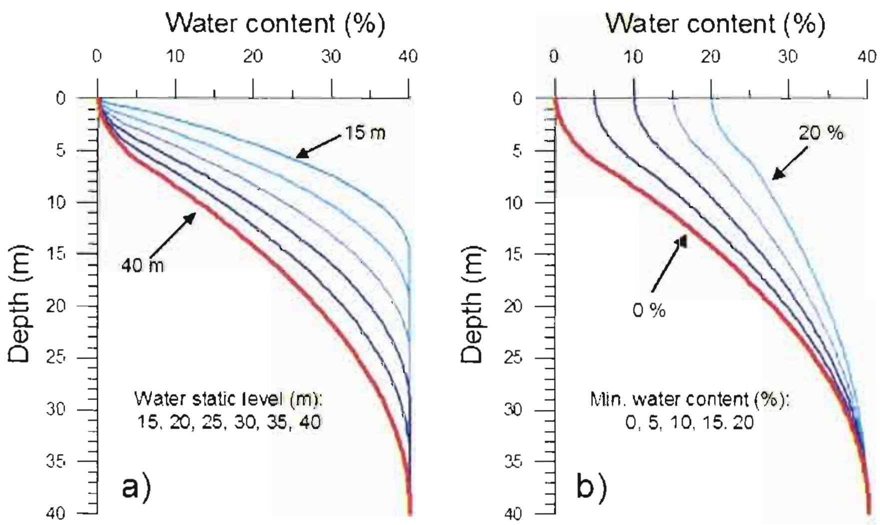

Figure 3. Modeling of MRS water content in a chalk formation.

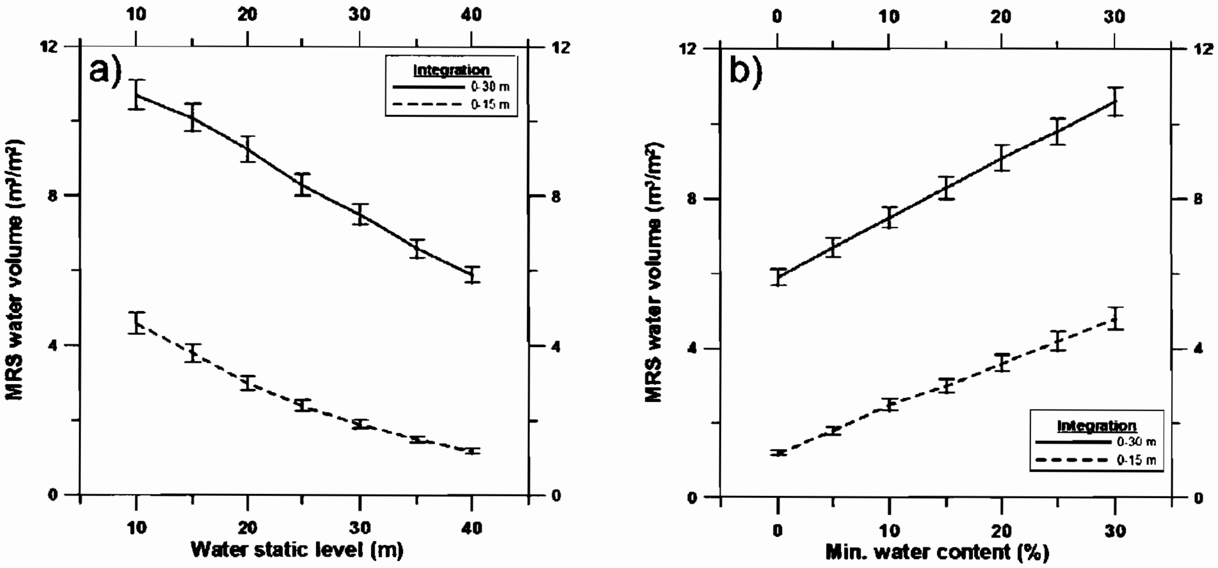

Figure 4. Modeled MRS water volume in a chalk formation.

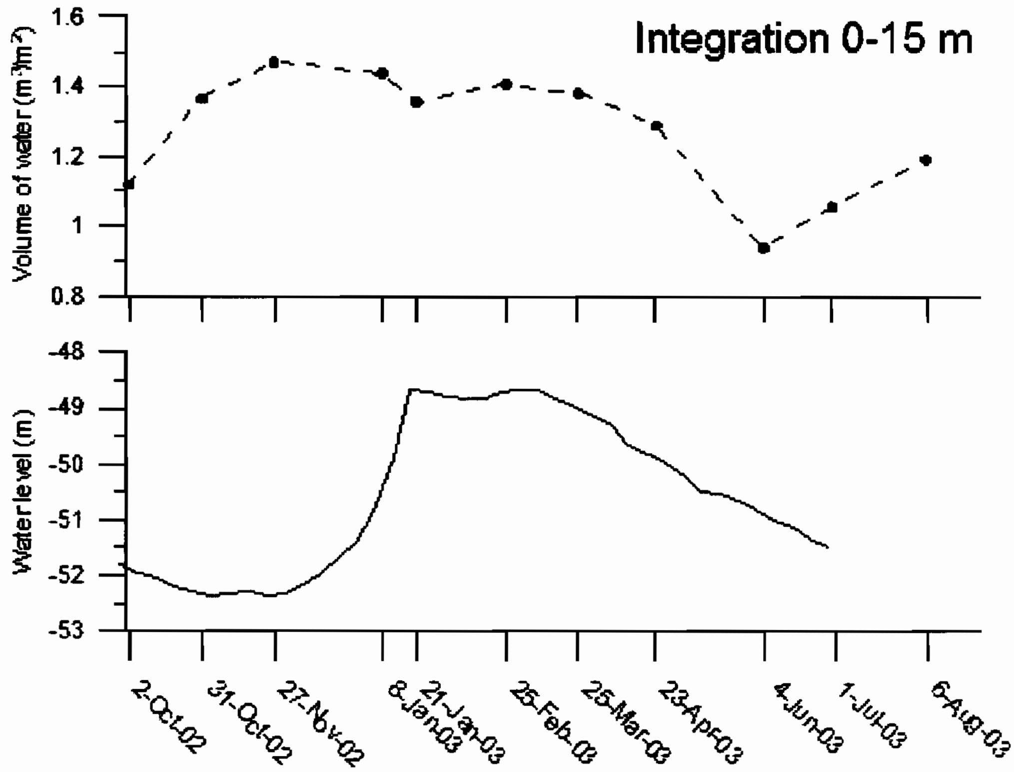

Figure 5. Experimentally observed MRS water volume in a chalk formation (France).

ASSESSMENT OF THE CONDUCTIVITY INFLUENCE ON THE COMPLEX SURFACE-NMR SIGNAL

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INTRODUCTION AND METHOD

Surface Nuclear Magnetic Resonance (SNMR) is used for groundwater exploration and aquifer characterization (e.g. [1]). The NMR-Experiment is conducted by a coincident transmitter and receiver loop at the surface exciting the protons of water molecules underground with the Larmor frequency of the earth's magnetic field. Performing a SNMR measurement with increasing excitation intensity (pulse moment) yields a complex sounding curve, where the amplitude of the relaxation signal is determined by the numbers of protons i.e. the water content. The subsurface electrical conductivity affects both the amplitude and especially the phase [2, 3].

The initial amplitude of the voltage response in the receiver loop is the integral over the water content f and the kernel function K, which comprises parameters depending on the location (e.g. conductivity) and depending on the loop geometry:

$$E_0 = \int K(q,\mathbf{r})\, f(\mathbf{r})\, dV \qquad (1)$$

In an electrically conductive subsurface, the magnetic field, effective on the proton spin, is elliptically polarized, and it can be decomposed into its components in and contrary to spin rotating direction, named co- and counter-rotating parts $\mathbf{B}^+$ and $\mathbf{B}^-$. For coincident receiver and transmitter loops, K is determined as follows:

$$K(q,\mathbf{r}) = 2\omega_0 M_0 I_0^{-1} \left|\mathbf{B}^-\right| \sin\left(\gamma q \left|\mathbf{B}^+\right| I_0^{-1}\right) e^{2i\xi(r)},$$

(2) where ω_0 is the local Larmor frequency, M_0 is the magnetisation for protons in water at thermal equilibrium, I_0 is the current amplitude in the transmitter loop, q the pulse moment, and ζ the phase. The Kernel function is generally complex, but it becomes real for electrically insulating subsurfaces. For one-dimensional conditions, Eq. (1) and (2) simplify to:

$$E_0 = \int K_{1D}(q,z)\, f(z)\, dz \qquad (3)$$

$$K_{1D}(q,z) = \int_{x,y} K(q,(x,y,z))\, dx dy\,. \qquad (4)$$

The SNMR amplitudes were inverted with a block inversion program using an optimised random search algorithm [4].

ASSESSMENT OF THE CONDUCTIVITY INFLUENCE

Figure 1a and 1b depict the complex kernel for homogeneous electrically conductive half spaces for resistivities between 10000 Ωm (quasi-insulating) and 1 Ωm. The real part of the kernel decreases for increasing conductivity whereas the imaginary part of the kernel increases with increasing conductivity. For a half space of 10 Ωm, it can be seen that the real part and the imaginary part have different sensitive areas. Figure 1c shows the amplitude for the respective conductivity model for an aquifer between 20 and 45m with 30% water content and 5% background water content. In the 1 Ωm case the aquifer is situated below the penetration depth, so the amplitudes are very small. The amplitudes are plotted in relation to the amplitude of an insulating subsurface. The phase values increase with increasing conductivity (Fig. 1d).

Synthetic data show the importance of the electrical conductivity in the subsurface for determining the water content distribution (Figure 2-4). The SNMR signals were modelled for a quasi-insulating (10000 Ωm) and for electrically conductive half spaces with resistivities of 100 Ωm, 50 Ωm, 10 Ωm, and 1 Ωm. But they were inverted using the insulating kernel in order to estimate the error in determining the water content caused by the non-consideration of the conductivity in the underground. The model grid is 0.5 m with a maximum depth of 200 m. The maximum inversion depth is 100 m, the water content between 100 m and 200 m is set to 5 %. The data were modelled with a water content of 30 % between 20 and 45 m and 5 % elsewhere. The first row (a) in each figure displays the absolute value of the respective kernel function. The second row (b) presents the modelled and fitted SNMR amplitudes with the data misfit as relative rms error in percent, and the third row (c) shows the modelled and the inverted water content with the model misfit as standard rms error.

In Figure 2 the subsurface is an electrically homogeneous half space. The SNMR amplitudes decrease with increasing conductivity. Since the values of the Kernel function decrease with increasing depth, the inversion algorithm shifts the aquifer down and calculates lower water contents. In Figure 3 only the aquifer is electrically conductive in an insulating underground. Except for the 1 Ωm case, the boundaries of the aquifer are well detected, but again the water content is underestimated. For a high saline aquifer (1 Ωm), the data fit is very poor and a realistic water content cannot be found.

Figure 4 shows the effect of an electrically conductive (100 Ωm, 50 Ωm, 10 Ωm, 1 Ωm) half space underlying an insulating layer of 100 m thickness. An effect can be seen even for the lower half space with a resistivity of 100 Ωm. The SNMR amplitudes are increased due to the bottom conductor, leading to an overestimation of the water content. The data misfit is very small, and therefore the incorrect conductivity model would not be noticed.

CONCLUSIONS

Electrical resistivities below 100 Ωm in the subsurface significantly alter the SNMR signal, and consequently, they affect the determination of the water content. Conductive structures above or in the aquifer result into an underestimation of the water content. However, conductive layers below the aquifer lead to an overestimation of the water content. The error in the water content determination increases with increasing conductivity.

Studies on test sites with good control of the underground will prove the reliability of the presented results. In the next step, the SNMR phase itself could be inverted to receive the necessary conductivity information for a more reliable water content determination.

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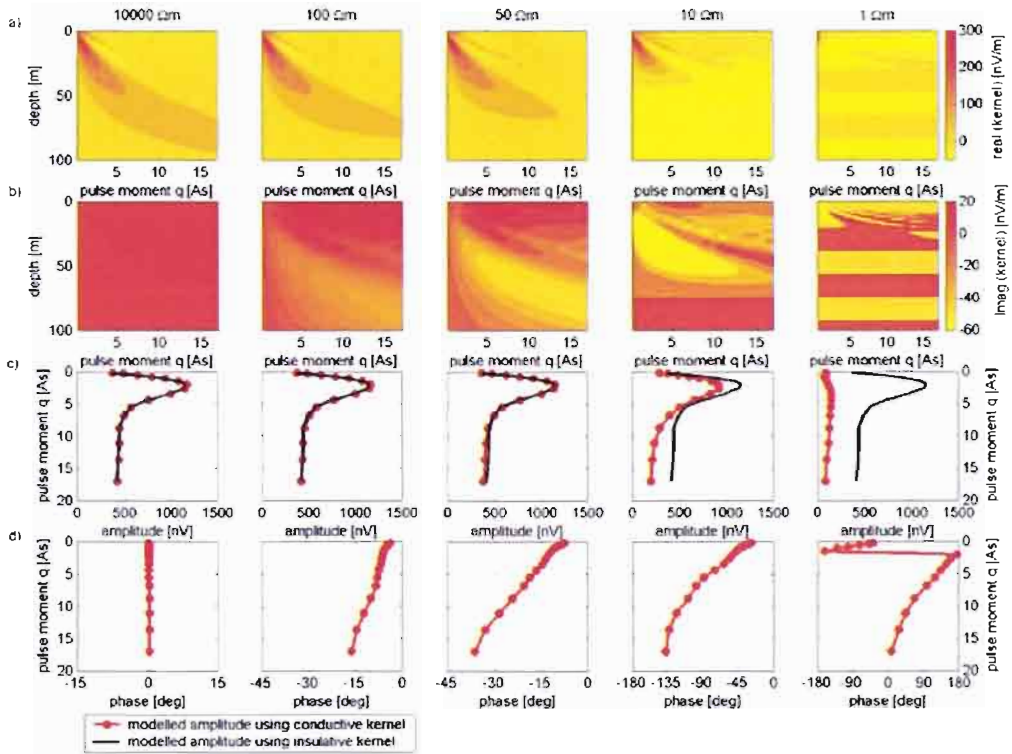

Fig. 1: Homogeneous half space, circular loop (100 m diameter), earth's magnetic field 48000 nT, inclination 60°. Complex Kernel and modelled amplitude and phase (water content: 20-45m:30%, elsewhere: 5%).

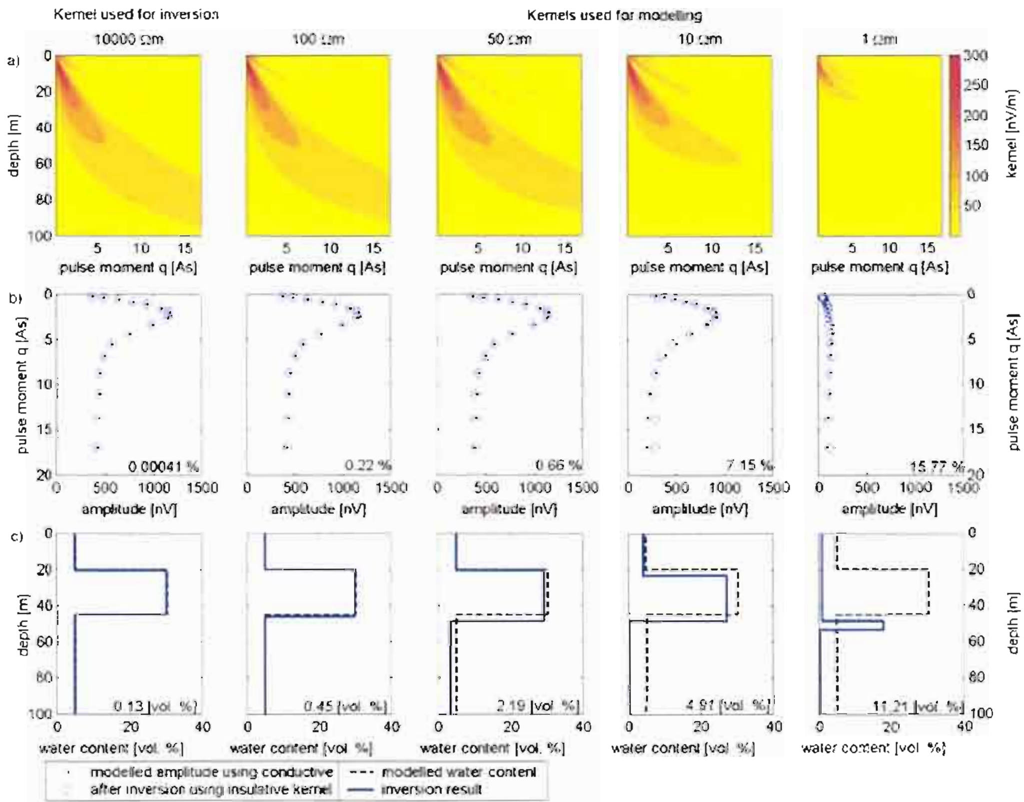

Fig. 2: Homogeneous half space, circular loop (100 m diameter), earth's magnetic field 48000 nT, inclination 60°. Amplitudes were modelled for conductive half space, but they were inverted using an insulating half space.

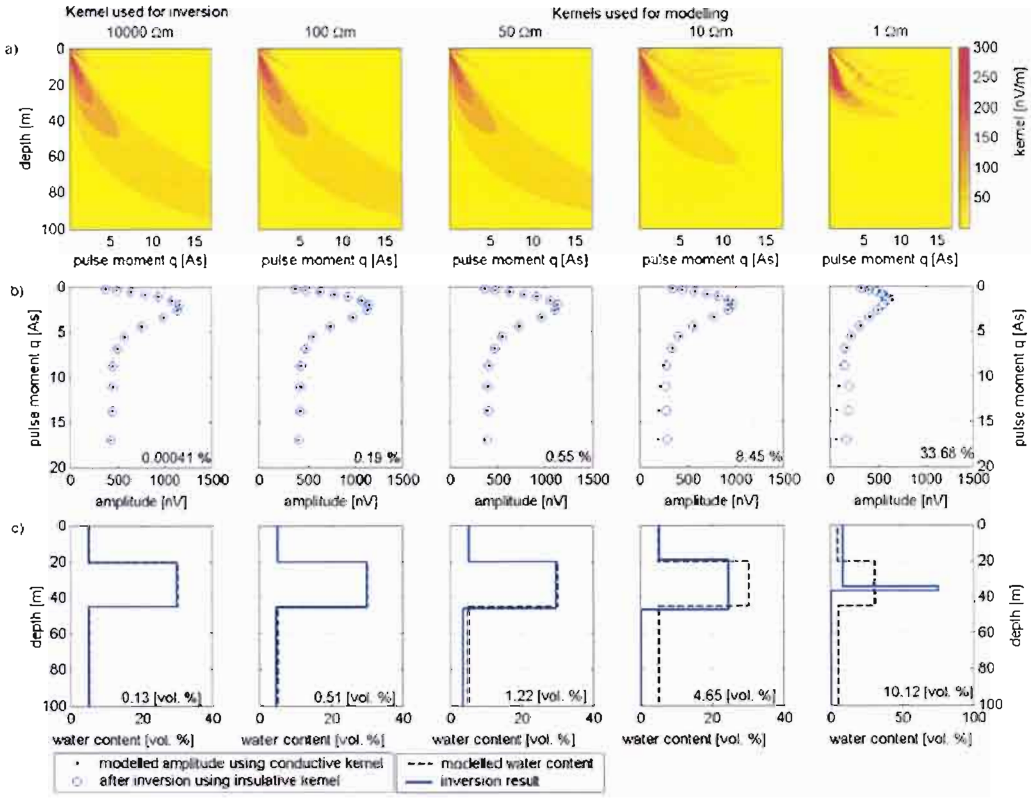

Fig. 3: Conductive aquifer, circular loop (100 m diameter), earth's magnetic field 48000 nT, inclination 60°. Amplitudes were modelled for conductive aquifer, but they were inverted using an insulating half space.

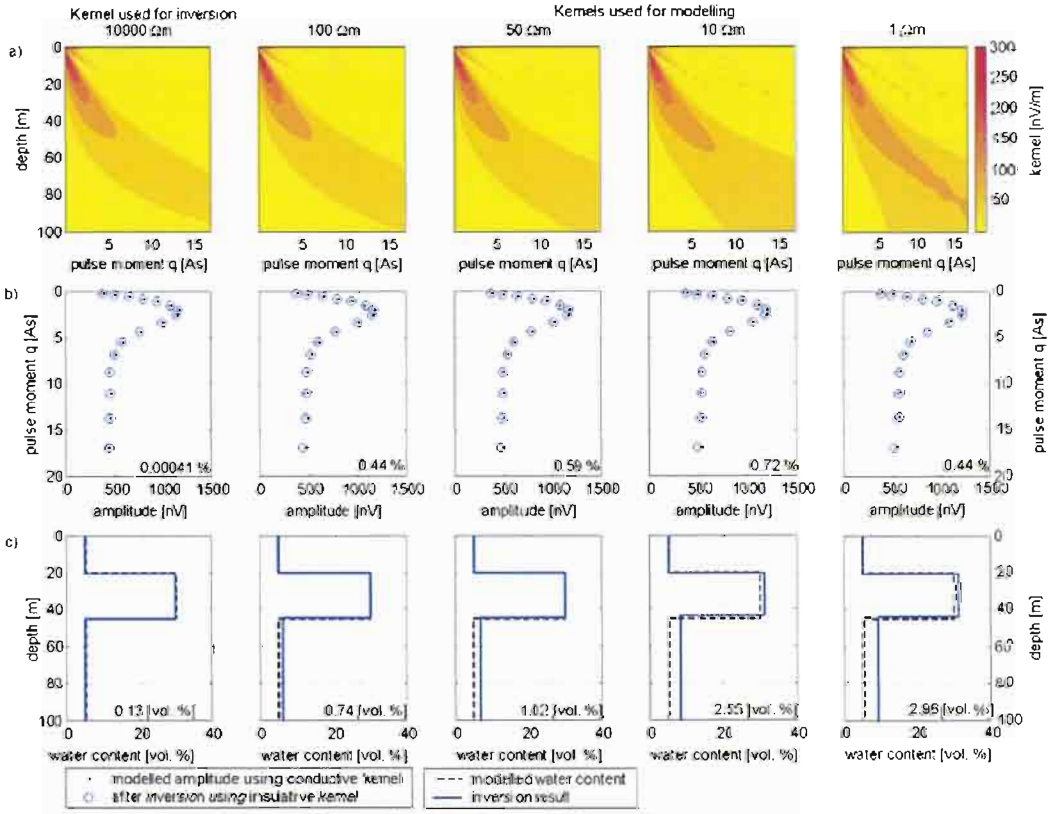

Fig. 4: Conductive layer below 100 m, circular loop (100 m diameter), earth's magnetic field 48000 nT, inclination 60°. Amplitudes were inverted using an insulating half space.

A GROUNDWATER PROSPECTING STRATEGY IN DISCONTINUOUS GROUNDS AND ARID CLIMATE : METHODOLOGY AND CASE STUDIES IN MOROCCO

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INTRODUCTION

The major constraint facing hydrogeologists for water borehole implantation in discontinous aquifers in arid areas consists in the their complexity, and particularly to the difficulty to select and determine the accurate position corresponding to a lineament of hydrological interest.

We propose in this work to define a multiexpert prospecting strategy to overcome this constraint based on: (1) the use of remote sensing images to determine lineament network and its analysis related to available geological data, (2) surface electrical prospecting using resistivity profiling in order to confirm and accurately locate fractures, and (3) the magnetic resonance sounding (MRS) to estimate the water content of aquifers.

The results of some applications in different contexts (geology and climatology) from Morocco are presented.

MULTIEXPERT METHODOLOGY

Remote sensed image processing

It consists of two stages:

Low level processing module: its goal is to determine and extract lineaments by mean of wavelet approach and classical contour detectors (Sobel, Kirch, Compas...). The obtained results from mathematical processing are confronted each to other and a map of major lineaments is established.

High level processing module: this stage consists of an analysis by a structural geologist of the above low level results: topography, geology, soil occupation maps, aerial photos, and ground checking. This analysis allows to georeferenciation and best determination of the orientation and accurate coordinates of the most important lineaments. After that we can select and optimise the number, position and direction of resistivity profiles.

Geophysical surveys

In fractured reservoirs, the use of simple electrical resistivity profiling allows to determine with accuracy the fracture location and other anomalous contacts and boundaries. A repeated resistivity profiles with different lengths permit to estimate the dip of these anomalies. The execution of spaced profiles provides the anomaly direction and thus the preferential water flow path. The profile length is beforehand determined from a vertical electrical sounding which leads also to calculate the magnetic resonance sounding matrix. On the fracture position, checked and precised by the resistivity profile, a MRS is undertaken to verify the existence of water and to estimate the water content.

RESULTS

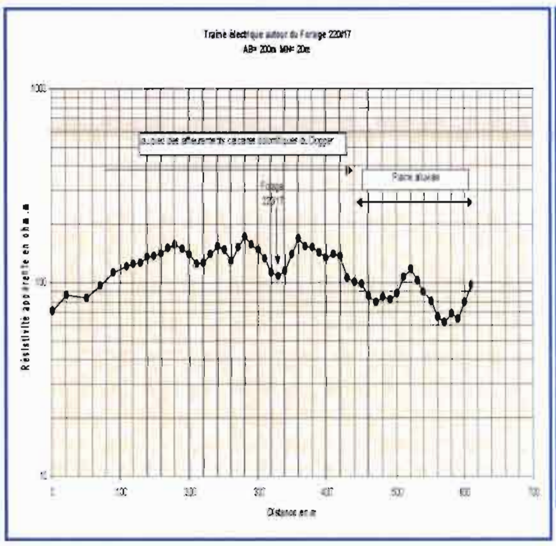
The results we present and discuss concern three different regions of Morocco, each one is characterized by geographical, geological and climatic conditions.

The Guercif target (Fig. 1&2):

This target is located in the Mahrouf plain. Geologically, it consists of Quaternary alluviums and sands, overlying Dogger limestones and dolomites. From climatic point of view, the average rainfall in the region is about 180mm/y.

The detection of faults within limestones from remote sensed images allows to conduct and orientate the geophysical surveys. At this target identified from satellite images, an electrical resistivity profiling was carried out with AB=200m beforehand chosen from a vertical electrical sounding. This profile shows a well conductive anomaly at station S28. At this location, a MRS has been performed with a square loop of 150m side.

From data acquisition and the mathematical inversion, a good signal has been observed leading to estimate the groundwater level at 43 m deep. A mechanical borehole realized on this anomalous zone has confirmed and corroborated the results already obtained by the other surveys. The yielded flow is 40l/s ; the water table is located at 42 m depth, corresponding on the well geological log to the top of Dogger limestones.



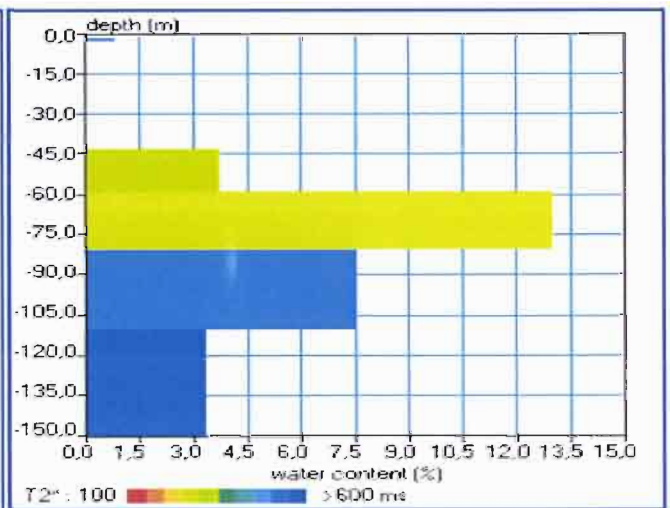


Fig. 1: Electrical profile in Guercif target.

Fig. 2: Water content versus depth in Guercif target.

The Smara targets (Fig. 3&4):

The above prospecting methodology conducted in the same order was applied to this site which has a quite different geological and climatic conditions. Indeed, in this case, we are dealing with a fractured Ordovician schists and sandstones in a zone of low rainfall, the average does not exceed 10mm/y.

The well implantation choice has been guided by the light of geophysical investigation results, showing on the one hand an anomalous zone corresponding to a fracture at station 10 of the resistivity profile; and on the other hand, a MRS signal amplitude of 90nV using a square loop of 150m side length.

The realization of a mechanical borehole yielded a low water input at 82 m depth corresponding to results beforehand predicted from the MRS mathematical inversion (Fig.3).

In the same zone, a borehole carried out in the fractured Devonian schists, where the MRS amplitude signal is about 53nV (Fig.4), gave a flow rate of 2 l/s. This result, very important for this desertic area, can be explained by lateral water arrival from the outcropping folded Palaeozoic which represents the hydrogeological limit between the Tindouf and the Laâyoun basins.

The Anezi target (Fig. 5):

This prospecting methodology was applied to Neoproterozoic sandstones and conglomerates of the Anti-Atlasic chain where the average rainfall is below 200mm/y. The same geophysical surveys in the same succession has been performed, except for the MRS that we used a rectangular loop of 100x50m rather than a square one as previously because the target is situated in a sharp valley. The results of three soundings are as follow:

- Two soundings (S1 and S2) located on the same lineament show a good signal with a maximum amplitude of 100nV observed at the 14^{th} pulse for S1 and 140nV at the 15^{th} pulse for S2.
- The sounding S3, located 50 m far from the lineament, shows a low MRS signal with a maximum amplitude of only 15nV recorded at the 12^{th} pulse. These results indicate that the main water are drained by the fractured zone.

DISCUSSION AND CONCLUSION

The three zones investigated by satellite image analysis followed by resistivity profiling and MRS are characterized by different lithologic and climatic conditions and belongs to discontinuous aquifers. The results after realization of boreholes are quite different. Thus, the interesting water flow in the Guercif region is in straight relation with the high rainfall which plays a great role in the limestone aquifer recharge. In the saharian Smara region, where the rainfall is very low, borehole execution shows a very disappointing results; here the water recharge is nearly null. The three magnetic resonance soundings in the Anezi region, where two are positioned on the lineament and the third one at 50 m far from it, show that the main water is drained by fractures. This strategy will be more efficient in areas where the climatic conditions permit a recharge of aquifers by means of fractures.

The proposed prospecting methodology allows to rationalize the groundwater exploration in such discontinuous aquifers in dry climate. Our results show that this strategy appears to be successful for optimizing borehole location, the overdrilling or negative boreholes will be greatly reduced.

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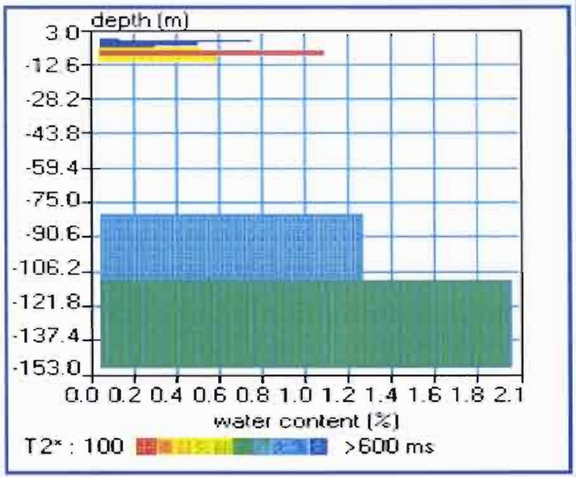

Fig. 3: Water content versus depth in Ordovician schists.

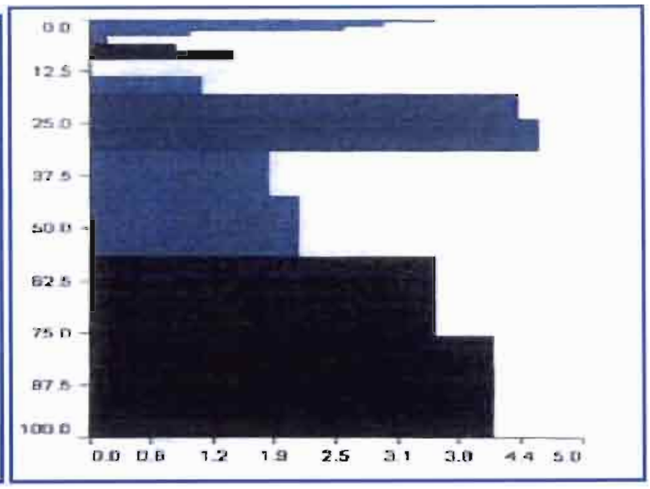

Fig. 4: Water content versus depth in Devonian schists.

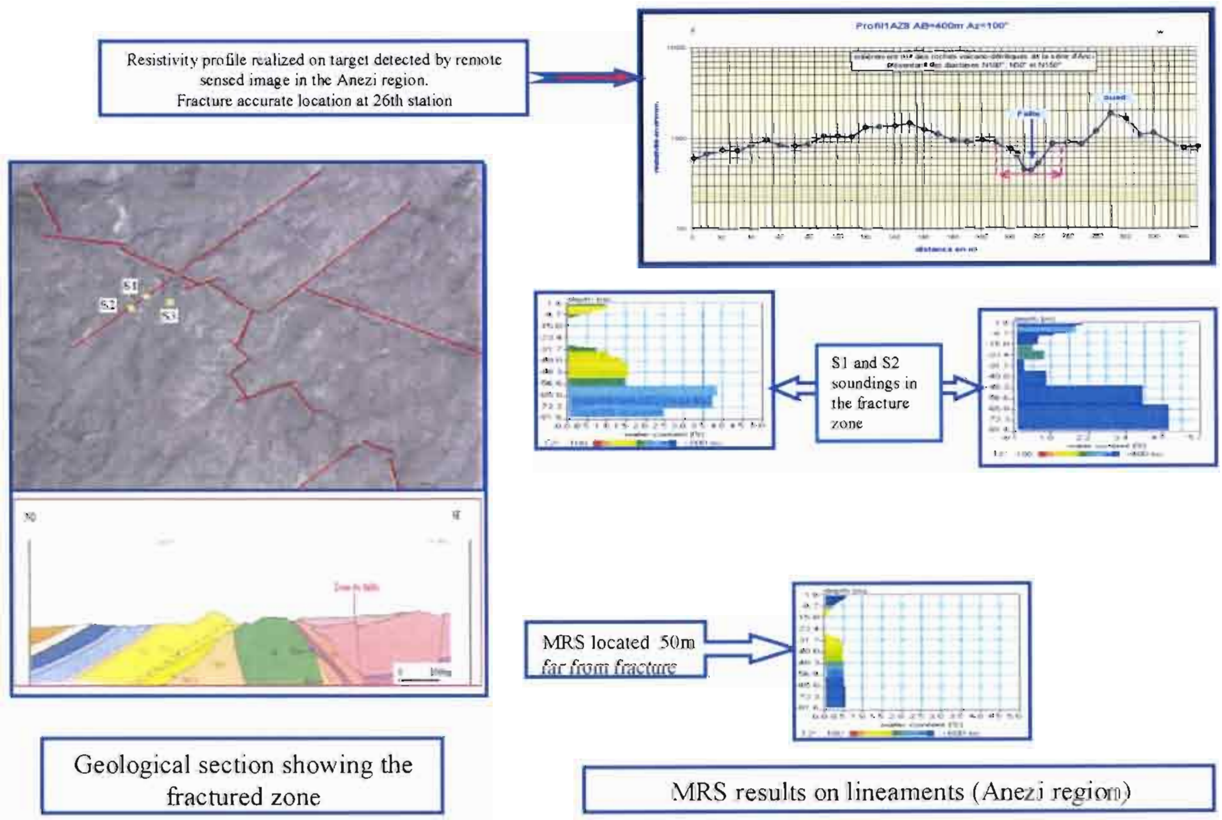

Fig 5: Example of Multiexpert methodology applied to the Anezi region.

MRS AND TEM FOR SHALLOW AQUIFER DEFINITION AT PHOSPHATE HILL, NW QUEENSLAND, AUSTRALIA

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INTRODUCTION

The WMC Fertilizers (WMCF) site at Phosphate Hill, NW Queensland, Australia, began production of diammonium-phosphate fertilizer in 1999. This site consists of a phosphate mine, beneficiation, phosphoric acid, ammonia and granulation plants, phosphogypsum stack and rail load-out facilities and is located in a remote area of the country, 130km SSE of Mt Isa. Both the raw phosphate rock and water used in the manufacturing process are sourced locally from the Cambrian Duchess Embayment.

Although the Duchess Embayment Aquifer (DEA) is expected to supply the operation until at least 2030, at start-up only basic information was known about its areal parameters. As a result, WMC performed a trial of magnetic resonance sounding (MRS) at the site in 2001 to determine the method's effectiveness for defining the aquifer. The trial produced very promising results. Given these positive results and successful stratigraphic analysis using time domain electromagnetics (TEM) in 1990, in 2002 a full aquifer definition program was undertaken using both MRS and TEM techniques.

GEOLOGY AND HYROGEOLOGY

The Duchess Embayment is a fault-bounded shelf area on the western boundary of the Burke River Outlier, which is part of the eastern Georgina Basin. It is a marine sedimentary basin consisting of shales (Inca Formation), siltstones and phosphorites (the Beetle Creek Formation - BCF) and mudstones, orthoquartzites and sandstones (the Mount Birnie Beds - MBB) on a lower Proterozoic granitoid basement (Russell & Trueman 1971). The stratigraphy at Phosphate Hill consists of both fresh/calcareous and weathered/siliceous phases of all of these, with the siliceous facies of the BCF forming both the ore body and the host to the target aquifer.

The extent and depth of the DEA was not completely defined at the commencement of operations. Previous investigations reported by Rockwater (1990) show that the DEA was associated with the ore body (siliceous BCF), was less than 100m in most areas, and was contained within sandy beds, closely-spaced jointing and bedding planes. Its thickness was believed to average 20m, extending to 60-80m in the south. Permeability and transmissivity were known to be high (up to 2700m^2/day) and the water quality was identified as fresh. The Inca Formation and the MBB act as aquacludes while the calcareous facies of all rocks were regarded as being either very low-yielding or impermeable.

AQUIFER DEFINITION PROGRAM

After the success of the trial MRS program in 2001 a full aquifer definition program was designed for implementation in 2002. This program consisted of 68 MRS loops and seven TEM lines combined with the drilling of 17 new monitoring bores. MRS loops were read at 11 of the new bore sites and the results used to determine the accuracy of the technique, with a success rate of over 80% (Table 1). 54.5% of bore sites had a correlation between measured SWL at drilling and top of aquifer defined by MRS of <6m, most showing a difference of <2m. The results of airlift tests compared to MRS predictions of %H_2O and porosity/permeability were also comparable in most cases. However, there were two sites (18% of the total) where correlation was poor.

Bore ID	Airlift (kL/day)	SWL	MRS aquifer top	%H_2O	Porosity/ Permeability	Facies
MB3001	380	37.8m	36m	4-5.5%	High	Siliceous BCF
MB3002	Nil	67.9m	36m	3.5%	High	Siliceous MBB
MB3003	254	35.7m	36m	4-8.5%	Mod-High	Siliceous BCF
MB3004	140	32.2m	36m	5.5%	High	Siliceous BCF
MB3005	Nil	48.4m	48m	2.8%	Low-Mod	Siliceous MBB
MB3007	186	37.6m	18m	3.3%	Low	Siliceous BCF
MB3008	>336	38.2m	36m	2.3-2.8%	Low-Mod	Siliceous BCF
MB3010	Nil	45.9m	48m	0.25%	High	Calcareous BCF
MB3015	Nil	71.6m	66m	0.3-1%	Mod-High	Calcareous BCF
MB3016	Trace	Dry	66m	1.3-1.6%	Mod-High	Siliceous MBB
MB3017	Nil	Dry	54m	0.5%	Low-Mod	Siliceous MBB

Table 1. Drilling *vs.* MRS results, 2002 monitoring bores.

Five of the 2002 MRS lines (37 loops) were designed to cover the same areas as the 1990 TEM surveys. The remaining lines and individual sites were to provide infill information, either in combination with the new TEM lines or alone. All TEM and six of the 11 MRS lines crossed the width of the DEA along evenly spaced northings with regular intervals between the MRS loop sites along their lines. The area covered by the entire operation was approximately 108km^2.

The combination of MRS, TEM and drilling was very successful. Both geophysical techniques (confirmed by drilling results) support the aquifer being associated with the ore body within the siliceous BCF (Figure 1 shows an example surveyed at 78000N, through the southern end of the current Brolga pit), lensoid in shape (tapering towards the surface to east and west), an average of 30m thick but up to 50m in the south, and becoming increasingly discontinuous and dryer to the north. The DEA appears to be truncated by an increase in elevation of the basement through the top of the aquifer at around 85800N and is bounded by either decreased weathering, facies change (siliceous to calcareous) or structural effects elsewhere.

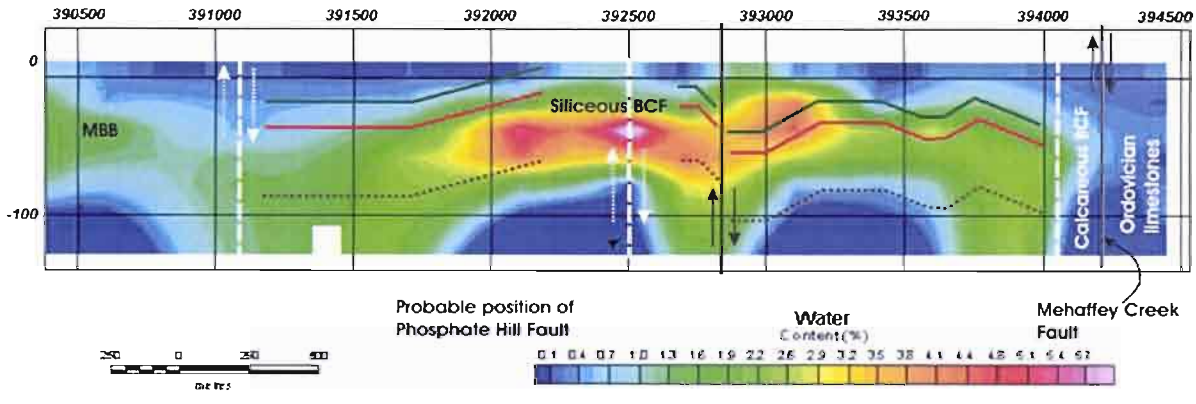

Figure 1. Aquifer at 78000N as defined by MRS readings compared to geology drawn from grade control drilling.

Both MRS and TEM were successful in identifying the calcareous and siliceous facies of the BCF. The MRS "signature" for the calcareous facies was very noticeable, consisting of a combination of high porosity/permeability and <1% H_2O content, which agrees with known conditions in calcareous areas. The aquifer is in the shape of two longitudinal lobes joined in the south-west area of the Duchess Embayment by a narrow neck, which had been subjected to little investigation. MRS and TEM surveys done across this area identified it as being predominantly calcareous, with the typical MRS signature, supported by TEM sections showing highly variable resistivities. This suggests that the neck, like the northern part of the DEA, consists of discrete siliceous, higher permeability pathways within a calcareous framework, rather than a single broad zone as was previously believed. As a result, it will be acting as a constraint on recharge into the southern zone.

The major problem encountered with the MRS technique was that of noise. A number of planned sites could not be surveyed due to noise from local 240V, 50Hz power lines and a major gas pipeline that passes through the area to the fertilizer plant. A figure-8 loop overcame this at one site but was unsuccessful elsewhere. The power lines proved to be the greatest problem, generating noise that peaked at 2235Hz, obscuring the MRS signal.

Another problem was the presence on a few readings of late-moment tails. These give the impression of a second aquifer at depth, which is known to be incorrect. The data from these sites was found to be of poor quality with response at different frequencies highly variable between pulse moments. This appears to be due to step gradients in the local magnetic field. When the data was reprocessed removing the questionable moments the results became much more realistic.

CONCLUSIONS

MRS results confirmed that the aquifer is contained within the siliceous phosphorite and siltstone horizons and has an average thickness of 30m. The results yielded an average water content of 2-5% and moderate to high porosity/permeability. Thinning of and increasing discontinuity within the aquifer were noted in the northern half of the survey area. TEM results agreed with the MRS on the extent and depth of the siliceous phase in addition to the increasing thinning and discontinuity occurring with distance north of the mine site. Aquifer definition exercises of this sort have traditionally been carried out around mine sites using a combination of TEM and drilling. TEM alone only responds well to aquifer tops, and is severely affected by conductive rocks. MRS combined with TEM and drilling allowed WMCF to cover a much larger area, much more quickly, with good geological information, aquifer thickness and quality estimates, and little influence from subsurface conductivity. The success of the program has allowed the development of a more accurate long-term water management strategy and a multi-layer aquifer model.

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STABILITY OF MRS MEASUREMENTS AND ESTIMATING DATA QUALITY

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INTRODUCTION

The objective of this study was to estimate the accuracy of the equipment currently used for magnetic resonance sounding (MRS) measurement, namely Numis$^+$, developed by IRIS instruments and BRGM. It is vital to evaluate data quality in order to constrain the inversion results. Improvements in data quality over the years have enabled the use of increasingly complex algorithms, including the effect of the electric conductivity model and a frequency offset lying between the Larmor frequency and the pulse frequency. The sensitivity of the MRS measurements renders this technique applicable to water-level monitoring.

FIELD MEASUREMENTS

For this study, we carried out MRS measurements four times a day at four different dates (May 5th, 15th, 23rd and 27th of 2003) at a test site at St-Cyr-en-Val, near Orléans, France. We used two types of Numis$^+$ equipment, a renewed prototype and a standard Numis$^+$, each twice a day. The same acquisition parameters were maintained for all the measurements, namely a figure-of-eight antenna with sides of 37.5 m (one turn of wire) to reduce industrial noise (Trushkin, et al., 1994). With this loop the ambient electromagnetic noise was varying between 300 and 500 nV in the bandwidth of +/-100 Hz around the Larmor frequency. The length of the exciting pulses was τ=40 ms. We used 16 values for the pulse (q=I. τ) and 36 signals were stacked for each pulse. The same transmitting frequency near the mean Larmor frequency for this site was adopted for all soundings: 2014 Hz. This frequency allowed us to use a narrow notch filter to remove the 50 Hz harmonics (Legchenko and Valla, 2003). These parameters are a compromise between the best possible data quality and the time needed to undertake a maximum number of soundings under the same conditions.

The values of the 16 pulses q cannot be exactly the same for every sounding with the Numis$^+$ equipment, which is why for the comparison of different soundings we first fitted a smooth curve on each sounding (in the least square sense), excluding at the same time a few anomalous points. This interpolation allows us to compare the different curves. Figure 1 shows the amplitudes of the entire smoothed MRS data set measured with two different instruments. It can be seen that, the soundings are in good agreement up to q<2000 A.ms. The instability of the last part of the signal can be explained by the variation in the geomagnetic field during the day whereas the frequency of the exciting field is maintained constant (Legchenko, 2003). The relative standard deviation calculated through all soundings ($\sigma_{rel} = \sigma$ / mean value) allows us to identify three signal parts (see Figures 1 and 2):

1: the signal is very low and the signal-to-noise ratio is low

2: the signal-to-noise ratio is high

3: the signal-to-noise ratio is lower and the signal varies after the geomagnetic field.

ESTIMATING DATA QUALITY

The RMS for each signal is estimated using the mean signal of that day as the 'true signal':

$$RMS_{k,j} = \sqrt{\frac{\sum_{i=1}^{N}\left[\left(s_{true,j,i} - s_{k,j,i}\right)^2\right]}{N}}$$, for the k^th^ sounding of the j^th^ day (N=number of pulses q).

The same mean RMS value of 5.8 nV is obtained whether calculated on the full length of the signal or without part 3 (Table 1).

	RMS for the full signal					RMS for q < 1600 A.ms				
Date	Numis+1	Numis+1	Numis+2	Numis+2	Total	Numis+1	Numis+1	Numis+2	Numis+2	Total
May-05	1.8		5.9	5.5	4.8	1.9		4.1	3.5	3.3
May-15	4.6	4.5	6.0	3.8	4.8	3.1	4.9	6.7	4.2	4.9
May-23	6.6	7.7	6.7	8.2	7.3	7.5	8.3	7.6	8.0	7.9
May-27	7.9	2.9	6.1	7.0	6.3	9.0	2.4	7.0	7.9	7.1
Mean (nV)	5.2		6.1		5.8	5.3		6.1		5.8
Mean w.o.5-may	5.7		6.3		6.1	5.9		6.9		6.6

Tab. 1. RMS on the raw data

If the results of May 5^th^ are removed because only three measurements were made that day, we obtain a mean RMS of 6.1 nV for the complete signal, and 6.6 nV for pulses q < 1600 A.ms. This latter higher RMS value is not surprising, because amplitude is higher in the first part of the signal than at the end of the curve.

As we suspected one Numis+ machine was overestimating the signal relative to the other, we calculated the difference with the 'true signal' for each day:

$$\varepsilon_{k,j} = \frac{1}{N}\sum_{i=1}^{N}\left(s_{true,j,i} - s_{k,j,i}\right)$$, for the k^th^ sounding of the j^th^ day (N=number of pulses q).

	Difference to the 'true signal'			
Date	Numis+1		Numis+2	
May-05	-0.3		4.9	-4.7
May-15	3.3	1.5	-2.0	-2.8
May-23	4.9	6.2	-3.7	-7.4
May-27	6.2	1.4	-2.9	-4.8
Mean (nV)	+3.9		-3.9	

Tab. 2. A systematic error: MRS values with Numis+1 > Numis+2.

We observe a systematic error >0 for Numis+1 compared to Numis+2. A correction of -3.9 nV was thus applied to the data measured with Numis+1, and +3.9 nV to that measured with Numis+2, which results in an RMS gain of about 1 nV compared to the raw data values (Table 3).

	RMS for the full signal					RMS for q < 1600 A.ms				
Date*	Numis+1	Numis+1	Numis+2	Numis+2	Total	Numis+1	Numis+1	Numis+2	Numis+2	Total
May-15	3.3	4.8	6.0	2.8	4.4	3.1	4.1	6.8	3.1	4.5
May-23	5.3	6.2	5.8	6.4	6.0	6.0	6.9	6.3	6.3	6.4
May-27	6.5	2.6	5.5	5.8	5.3	7.3	2.2	6.2	6.6	5.9
Mean (nV)	4.8		5.4		5.2	4.9		5.9		5.6
Bef. corr.	5.7		6.3		6.1	5.9		6.9		6.6

*The data of May 5th are removed because only three measurements are available.

Tab. 3. RMS estimation after correction of the systematic error

After correction, the RMS demonstrates more clearly the stability of the measurements, which can be estimated at less than 6 nV.

MRS MEASUREMENTS AND THE GEOMAGNETIC FIELD

During our experiments it was observed that the geomagnetic field varies throughout the day of measurement, which means that the Larmor frequency also varies. These observations were compared with the geomagnetic record at the magnetic observatory of the 'Chambon la forêt' part of the INTERMAGNET network (see for example Figure 3). It is known after modelling results that the phase shift of the MRS signal is more sensitive to the frequency offset between the oscillating source field and the Larmor frequency (of the oscillating response field) than the amplitude. The consequence of variations in the geomagnetic field on the phase values thus makes estimation of the accuracy of the phase measurement more complicated. This subject is thus currently out of scope of this paper.

CONCLUSIONS

Under experimental conditions in St-Cyr-en-Val area it was found that the instability of the measurement of MRS amplitude with Numis$^+$ system is less than +/- 6%, even though the frequency shift with the Larmor frequency is a few Hz.

It should be understood that the accuracy of measurements depends on the signal to noise ratio which in turn depends on the amount of subsurface water and stacking number. Consequently, results can be always improved by increasing the stacking number. From the other hand, time variations of the ambient electromagnetic noise and the geomagnetic field may change conditions of measurement and thus make a correct interpretation of MRS data difficult or, under some conditions, even impossible for very long soundings.

In order to use correctly advantages of the complex nature of the MRS signals, it is necessary to consider time drift of the geomagnetic field all along the measurements in the inversion scheme of the MRS signal.

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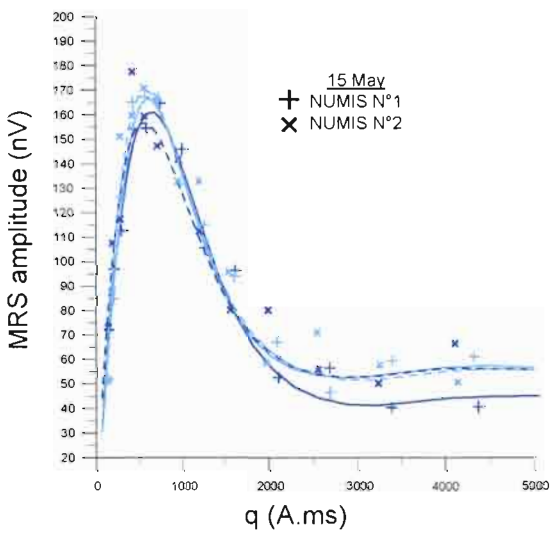

Fig. 1. Example of the MRS soundings.

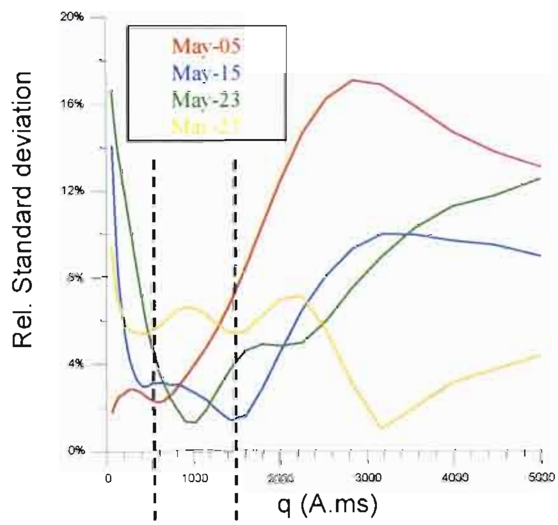

Fig. 2. Relative standard deviation.

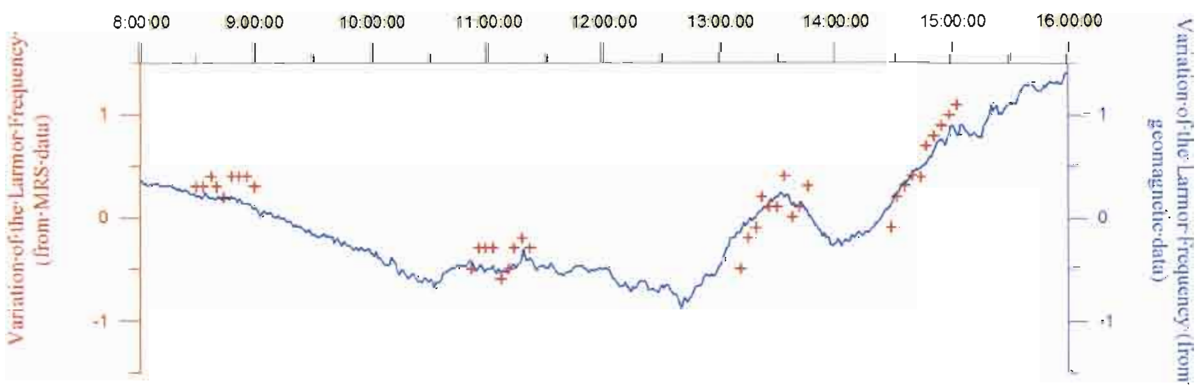

Fig. 3. Drift of the Larmor frequency calculated every minute from the geomagnetic record at the magnetic observatory of the 'Chambon la forêt' part of the INTERMAGNET network (data of May 15th), and MRS measurements of the Larmor frequency (crosses) during St-Cyr-en-Val experiments.

GROUNDWATER RESOURCES ASSESSMENT BY USING PMR SOUNDING

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INTRODUCTION

Nowadays sustainable development of water resources has already been widely accepted by China water resources administration agency. To certain extent the sustainable developing of society relies on water resources guarantee. In the northern part of China, groundwater is the main supplied water resource, so the water resources assessment needs being done before developing for the purpose of water supplying or environmental purpose. The assessment is based on some accurate hydrological parameters like permeability and hydraulic conductivity of aquifer. Hydrologist is used to getting them through drilling and pumping test. That means good spending and relatively longer time. Since 2000 we have tried getting the parameters through NUMIS (plus) sounding. After three years hard working we have found that NUMIS (plus) sounding can significantly improve the efficiency of assessment of groundwater resource, and can sharply low the expense compared with the regular means.

BACKGROUND

WULANCHABU is a county in Inner Mongolia, China. It occupies the most area of the famous WULANCHABU prairie. Local people have never gotten sufficient water resources to improve their living condition and economy. With China government launching the project of great west development, the county has met an unprecedented great chance of building a more beautiful homeland. Many infrastructures have already gotten ready to be constructed. However little of them could be done without water resources guarantee. The county government was fully aware of the situation and asked us conducting water resources assessment.

The county' s longitude is in the range of 109°16` to 114°49`, latitude is in the range of 39°27` to 43°28`. Width from East to West is 458 kilometers, length from South to North is 442 kilometers. The total area is 54,800 square kilometers. The county consists in 11 cities. The number of village is up to 280. Population is nearly 300 millions. There are a little seasonal river in the region so the quantity of surface water is very limited. Precipitation is averagely less than 240mm. Consequently the climate there is relatively dry. The area can be defined into three types of region according to the relief : mountain, hill, high plain. Geology is a little complex at some location. Generally speaking Quaternary period, Tertiary and Jurassic are the basic formation at most places. Soil, red clay, white clay, granite, tuff, basalt are easy to be nearly everywhere. Groundwater often exists in the sand formation or gravel of quaternary period, sand and clay formation of tertiary, cranny of Julio. Few aquifers exceed 200 meters depth, so the project actually focused on shallow groundwater resources assessment and processed on the basis of achieved geological information. With the help of local water resources administration agency, we got hydrological map (1 : 100000) which was finished by national geology teams in 1980s and 1990s. Unfortunately, a city was excluded from maps due to certain unknown reason. We could not finish the project when a city remained undone. On the other hand it was impossible for us doing drilling and pumping test for parameters of aquifer no matter of considering cost or time. Luckily we have learned surface magnetic resonance method and imported Numis (plus) from IRIS in 2000. It is no doubt that PMR is a newcomer in the family of geophysics, which have been widely employed in the field of groundwater investigation right now. What distinguishes it from other geophysical means is that it is able to detect subsurface water directly on the ground. We imported the method in 2000 and began field testing in the same year. A little bit by a little bit, we have made progress and begun getting the parameters through the sounding. After three years hard work, we have found that hydrological parameters can be calculated from PMR sounding data. Realizing of that, we decided to employ the method help us getting geological information on the city we needed.

MATHEMATIC BASIS OF HYDROGEOLOCAL PARAMETERS CONCLUSION IN NMR

Mathematic theory about hydrogeological parameters conclusion in NMR sounding is Seevers model . The model constructed by Mr. Seevers etc in 1966 was deduced from KST model and Kozeny formula. It is expressed as follow :

$$k = \frac{H^2}{T_s^2} * \frac{\Phi}{\tau} * \frac{(TT_B)^2}{(T_B - T)^2} . \qquad (1)$$

The equation can be simplified as : $k = C * \Phi * T^2$. (2)

Where k - permeability ratio ; C - constant ; Φ - actual pore hole ratio ; T - decay time (ms). The problem is that C is not an absolute constant. Different places and different stratifications have quiet different C values. One exponent curve cannot show geological conditions in all places. Research conducted by Miss Yuling Pan found that FID curve could be matched by three exponent attenuation curves. The curve equation is

$$M(t) = \sum_{i=1}^{3} A_i * \exp(-t / T_{2i}) , \qquad (3)$$

where T_{21} = 300ms, T_{22} = 110ms, T_{23} = 50ms respectively correspond to decay time of big pore hole, medium pore hole, small pore hole. Then the corresponding A_1, A_2, A_3 represent pore hole of three different sizes of pore hole ratio - Φ. According to this assumption, Miss Yuling Pan got such a model : $k = 2.2 * \Phi * T_2^2$, (4)

where k is permeability ratio (md) ; C is a constant, it is value is 2.2 ; Φ is effective pore hole ratio, its value is expressed with percentage ; T_2 is decay time (ms). Once we get permeability ratio "k" then it would be very easy to calculate permeability "K", hydraulic conductive ratio "T". We have tried the model in some PMR practice last year and found that in most cases it was nearly true. Realizing this, we brought the model with us in water resources assessment project. It, s proved that PMR sounding and the matched math model is a powerful tool in groundwater investigation in region where has little geological information.

PRACTICAL PMR SOUNDING IN SZW CITY GROUNDWATER INVESTIGATION

In order to control the whole region we arranged five sections perpendicular to trend of formation. We arranged 5 - 8 sounding sites on each section according to the length of the section. The total number of the sounding sites was 32. Five of them have already been conformed by drilling. The following are three sounding examples :

1. SZW-14. This is second sounding on the third section. The configuration is as following : antenna type : square ; side length : 100m (four reels with 100m of cable on

each) ; number of pulse moments : 16 ; Larmor frequency : 2385. From inversion we can see signals on FIDI E(q) is random, the value of S/N is just so- so, frequency on FIDI freq(q) changes frequently, the phase on FIDI phase (degr) keeps on raising up and falling down. Experience reminds us that the sounding is not reliable.

2. SZW-25.It is the last site on the fourth section. The configuration is just like above one. We think it is the most perfect sounding in the city' s groundwater investigation. FIDI E (q) shows that curve of the signal is a standard PMR sounding, the average ratio of signal to noise is as high as 9.0 ; FIDI freq (q) shows the frequency almost keeps in a same value. FIDI phase (degr) shows the phase is stable. The measured data we get is absolutely the true PMR signal. Looking through Numis inversion we can easily find there are two aquifers, one is located at 10m-13.4m underground, the thickness of the aquifer is 13.4m ; another at 31.9m - 42.5m, the thickness is 10.6m. The 14.8% of maximum water content, 10.4% of mean water content. The composition of the first one probably is coarse sand, the second one might be gravel. Calculating with model (4), we guarantee confidently that 60 tons/hour of groundwater can be pumped up from a well. The drilling log and the pumping test support our conclusion (fig. 1).
3. SZW-32. It is the last site on the last section. And we think it is a very good sounding . FIDI E(q) shows that curve of the signal is a standard PMR sounding, the average ratio of signal to noise is as high as 11 ; FIDI freq(q) shows the frequency slightly oscillates around a stated value in a amplitude of less than one Hz. FIDI phase (degr) shows the phase is stable. The measured data we get is absolutely the true PMR signal. Looking through Numis inversion we can easily get the thickness of aquifer is 34 meters from 8m to 42m underground, the 18% of maximum water content, 8% of mean water content. Calculating with model (4), we guarantee confidently that 60tons/hour of groundwater can be made in a well. The drilling log and the pumping test result support our conclusion (fig. 2).

PROBLEM AND SUGGESTION

We definitely believe PMR sounding is a outstanding geophysical mean in the field of groundwater investigation. We have conduct nearly four hundred soundings since we imported the equipment from IRIS in 2000. Unluckily we made little progress in the first year as there was something wrong with the receiver of Numis(plus) soon after we got it . At first we did not award that some bad thing had occurred, it resulted in some ugly interpretation. With the help of Mr. Bernard, we identified the reason why equipment could not work normally and resolved the problem quickly. The method begun showing its unique advantage. We have achieved hundreds of successful soundings especially in determining location of pumping water well in region where it is difficult to explore groundwater through regular means. To meet the water resources assessment need this year, we tried to get hydrological parameters from PMR method. It is definitely another success no matter for us or the method . Though the breakthrough in PMR (if we could consider it as a breakthrough) has already taken place, there are still some problems that need to be resolved.

1. Noise threshold

"Noise threshold" is the limited value of noise which the system can accept. As saying in MUMIS^{PLUS} user' s guide, if any part of record exceed the value, system would consider the record as "bad record", otherwise as "good record". NUMIS data acquisition program offers a range of choice in 4000nV - 200000nV. Generally if noise disturbance is smaller than 400nv, the noise threshold need to be set as 4000 in order to get reliable records ; if noise disturbance is bigger than 400nV, to make sure sounding can be done, the value of the parameter had better be a big one. We had ever met the condition that good signal and bad signal appeared by turns, and we even met the condition that the number of bad signals was more than the number of good signals. In these cases we tried to reset noise threshold in order to reduce the sounding time, but it seemed nothing had been changed. We don' t know why. Maybe the noise was too big to use the function.

2. Accurate sounding in a given range of depth

It is well known that NUMIS (plus) is able to detect one-meter-thickness aquifer. The accuracy depends on "pulse movement number", which can be set in 5 - 40. The bigger the number is, the more layer can be divided. But at the same time it also means bigger time spending. Could we find a way to do accurate sounding in a given range of depth ? For example, an aquifer is probably located at 60m - 80m underground. And we just want to know the detail information of this range of depth, whether we could build a model to operate equipment starting sounding from 60m underground and over sounding at 80m without sounding other formation. If we can do sounding this way, we would definitely get much more accurate aquifer' s information and save a little sounding time. It might be a beautiful dream. We wish our PMR colleagues are willing to come true the dream.

3. Build a model to change Larmor frequency automatically according to measured frequency of every signals.

The present PMR sounding has to be carried out with the same frequency for all pulses even if the signal frequency would vary from one pulse to another. There come a problem, in some cases the difference of signal frequency between the neighboring formation exceed 5 HZ. In order to get a reliable sounding we have to change the input frequency then start sounding from the right beginning. That results that the sounding might be done in a longer time. We do not know for sure whether the idea of building such a model is practical.

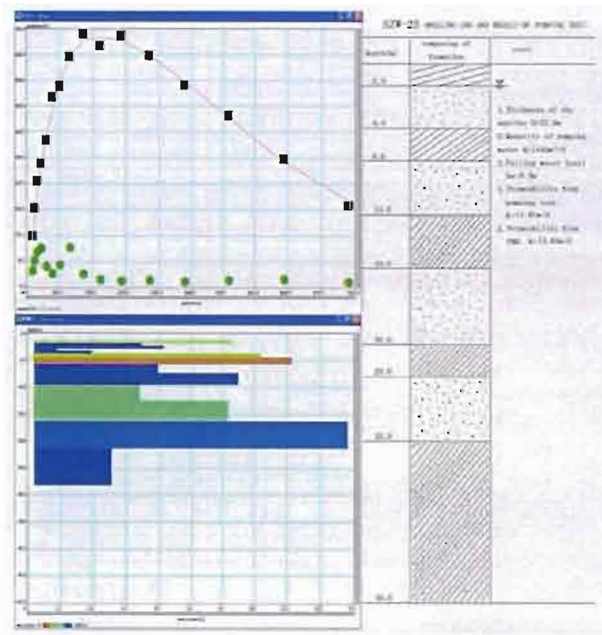

Figure 1

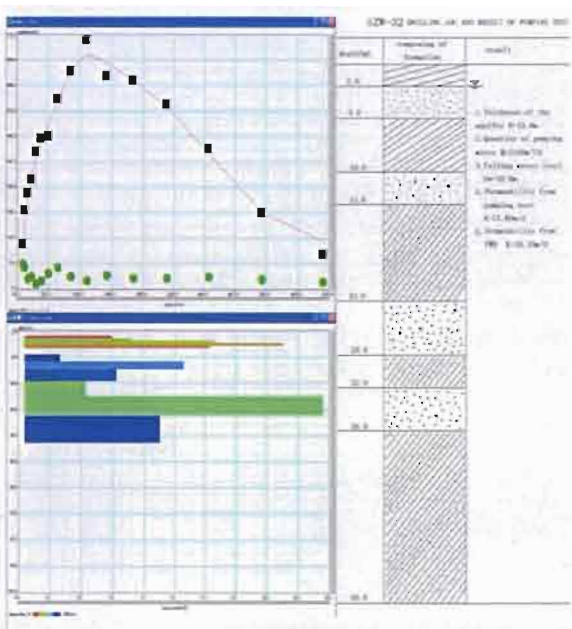

Figure 2

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SURFACE-NMR WITH SEPARATED LOOPS – INVESTIGATIONS ON SPATIAL RESOLUTION

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ABSTRACT

Groundwater investigations with soundings of Surface Nuclear Magnetic Resonance are in the present state of art performed with coincident loops and are interpreted in the sense of a one dimensional water distribution with depth [1,2]. The very large lateral range of influence questions the validity of this assumption for complex geological structures. The lateral information can generally be derived by multiple soundings on a profile and a 1.5D or 2D inversion of these data, but the high time cost per sounding restricts this technique to small structures. A new improved formulation of the NMR response for arbitrary magnetic fields [2,3] allows now investigations on the potential of separated loop measurements. The emitted signal from excited protons in the subsurface can be recorded at any arbitrary position at the surface and at multiple positions synchronously to improve survey progress. The complex connection between excited protons in the subsurface and the voltage response at remote locations explains the need to investigate the lateral sensitivity for separated transmitter and receiver loops. The results show, that the signal can, under good conditions, be recorded up to a loop separation of at least three loop radii. The spatial sensitivity varies significantly for different locations and pulse moments, offering a good lateral resolution.

MODELING

The recorded voltage response in the receiver loop is calculated by the integral over the subsurface of the response intensity, given by the kernel function K at any point, scaled by the ambient water content f:

$$V_0 = \int d^3 K_{3D}(q, \vec{x}_0; \vec{r}) f(\vec{r}) \,. \qquad (1)$$

Weichman et al. ([3,4]) have shown, that the magnetic field at any point can be decomposed into its elliptical components α, β, ξ and $\vec{b}$ being length of major and semi major axis, phase delay and ellipse orientation. The components of an ambient magnetic field, effective on the proton spin, are the parts rotating in and contrary to spin rotating direction, named co- and counter-rotating parts $\vec{B}^+$ and $\vec{B}^-$, with $\left|\vec{B}^\pm\right| = I_0(\alpha \mp \beta)$. In the general case, K is determined by the magnetic field components of both loops as follows:

$$K(q, \vec{x}_0; \vec{r}) = -2\omega_L \chi_N \left|\vec{B}_0\right| e^{i(\xi_T + \xi_R)} \left|\vec{B}_T^-\right| I_0^{-1} \sin\left(\gamma q \left|\vec{B}_T^+\right| I_0^{-1}\right) \left(\vec{b}_R \cdot \vec{b}_T + i\hat{\vec{B}}_0 \cdot \vec{b}_R \times \vec{b}_T\right), \qquad (2)$$

with subscripts R, T for receiver and transmitter, I_0 the inducing current amplitude in the transmitter loop, q the excitation intensity, called the pulse moment, and ω_L, χ_N *and* γ physical constants. The Kernel function is in general complex. For real magnetic fields, i.e. nonconductive media, and coincident loops it becomes real, since the cross product in the latter bracket then vanishes. The sensitivity of the voltage response to the water content is the partial derivative and therefore the kernel function itself. For the case of a 1D or 2D water distribution it simplifies to:

$$K_{2D}(q,\vec{x}_0;(x,z)) = \int K_{3D}(q,\vec{x}_0;(x,y,z))dy \qquad (3)$$

$$K_{1D}(q,\vec{x}_0;(z)) = \int K_{3D}(q,\vec{x}_0;(x,y,z))dxdy. \qquad (4)$$

The absolute value of these kernel functions describes the signal contribution of each volume element to the recorded signal V_0 and founds the interpretation in the next chapter.

RESULTS

Figures a) clearly show that for increasing loop separation, the recorded signal has the maximum shifted to higher pulse moments with higher contribution of the imaginary part, i.e. phase delay. Simultaneously the major contribution depth of the sounding changes to shallower regions as demonstrated in figures b). Figures c) represent the feature, that the co-rotating part of the transmitter signal excites the protons. Since this argument appears in the sine-function, the exciting amplitude distribution increasingly oscillates in space with higher excitation intensities q. The counter-rotating part reflects the emitted field intensity to the receiver loop and has a non-oscillating nature. When both coincide (Fig 1, left), the highest signals evolve from below the loop at small pulse moments where the oscillations are moderate. Increasing q increases the induced volume, but the integral signal decreases due to low signal regions. For separated loops (Fig. 1, right & Fig. 2), the integral signal is lower at small pulse moments due to the smaller excitation angles in the sensitive volume of the receiver loops, but for increasing q the signals permanently increase because the most sensitive region of the receiver loop is evolves from few or not oscillating regions, located between transmitter and receiver. This effect is stronger, the further transmitter and receiver are separated. The fact that the signal distribution is less oscillating at remote locations is finally the reason why the signals decrease only slowly with increasing separation and allows signal recording up to distances of several loop radii. Furthermore the less oscillatory character improves the model resolution in the lateral dimension.

CONCLUSIONS

Our results clearly show, that SNMR measurements with separated loops are feasible concerning signal strengths and promise improved performance in assessing 2D and correspondingly 3D structures. In particular confined signal contribution areas for different layouts and excitation intensities allow a desirable focussing. The potential to easily extend subsurface characterisation to the lateral dimension emphasises the need on modifying currently used SNMR equipment to allow measurements with separated loops. Implementation of the general formulation of the NMR response for independent transmitter and receiver offers completely new investigation schemes and allows optimisation according to spatial resolution and data quality. Schemes of inversion for this kind of measurements have to be developed which is only a matter of numerics as the full theoretical description, i.e. forward modelling, is available and possible as shown in this paper.

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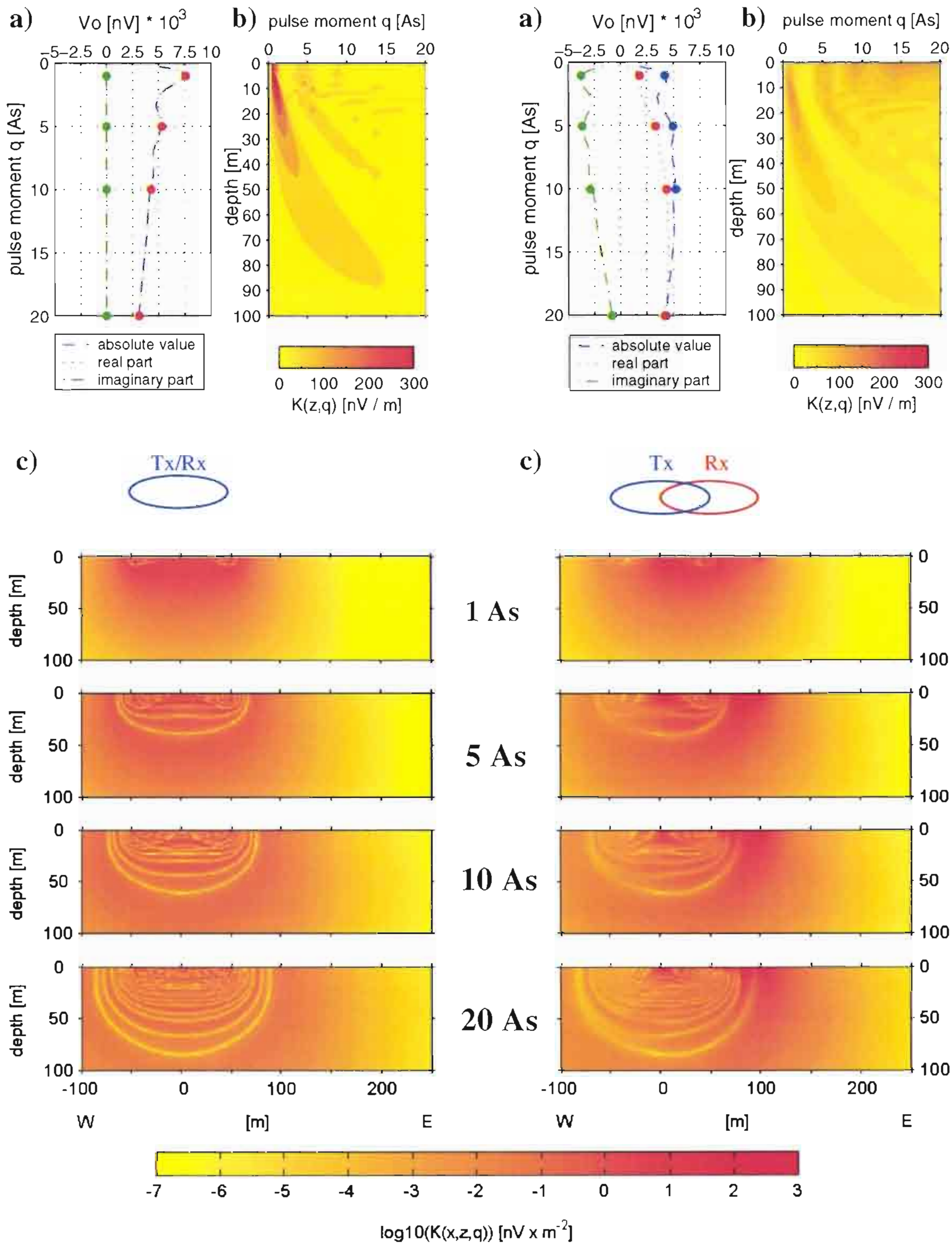
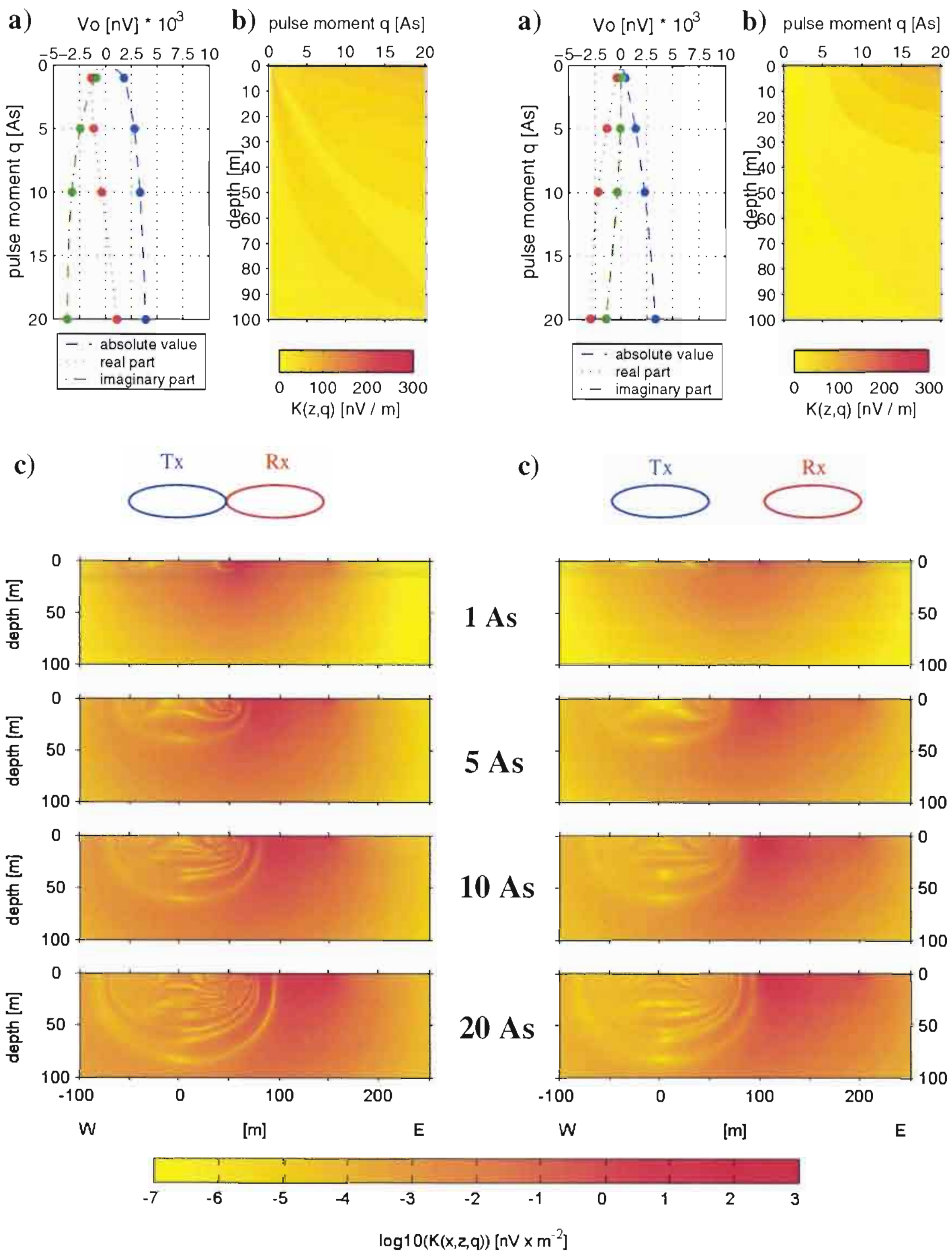


Figures 1&2. The figures show the 1D and 2D signal distribution of a SNMR sounding for up to 20 As. Models are calculated for circular loops of 100m diameter, an Earth magnetic field strength of 49000 nT, inclination of 60° and nonconductive half space. Profile direction and loop separation is in east-west direction. a) are sounding curves for a homogeneous half space with 100% water content. Signals are plotted with real and imaginary part and absolute value. The dots represent the respective pulse moments for which the 2D sensitivities are given below. b) show the absolute value

of the one dimensional kernel function obtained from Eq. 4. The vertical signal contribution is plotted on the z-axis for increasing q to the right. Figures c) describe the absolute value of the 2D sensitivity according to Eq. 3 for pulse moments of 1,5, 10 and 20 As in one single plot each. To demonstrate the dimensions of the measurement configuration, the assumed loop geometry for each set of models is displayed in the sketches above.



DEPTH OF SNMR SIGNAL CONTRIBUTION IN CONDUCTIVE TERRAINS

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ABSTRACT

To correctly invert and interpret SNMR data collected in conductive terrains, an accurate model of subsurface conductivity structure is required. Given such a model, it would be useful to determine, prior to conducting an SNMR sounding, whether the groundwater parameters of interest can be obtained. One such parameter, is the maximum depth at which water can be detected. Here we use synthetic data to estimate the depth beyond which no amount of water will contribute significantly to an SNMR sounding in a conductive half-space. This information is then used to estimate the depth range over which most of the SNMR signal is obtained.

INTRODUCTION

Australia is the driest inhabited continent and consequently, hydrogeological modelling of groundwater is important for a wide range of domestic, agricultural, industrial and environmental issues. The Surface Nuclear Magnetic Resonance (SNMR) geophysical technique (Legchenko and Valla, 2002) has the capacity to provide some of the hydrogeological parameters necessary to construct these models. For example, the technique has been used to locate groundwater (Goldman et al., 1994; Portselan and Treshchenkov, 2002; Vouillamoz et al., 2002), delineate aquifer extent (Yaramanci et al., 2002; Dippell et al., 2003) and shows potential for providing other quantitative parameters such as permeability and transmissivity (Legchenko et al., 2002)

The SNMR technique has limitations though. These include a low signal-to-noise ratio and sensitivity to geomagnetic field gradients/fluctuations. Another weakness, relevant to use in Australia, is the reduced depth of application in conductive ground. To the authors' knowledge, the only Australian SNMR field trials have been confined to magnetically quiet areas characterised by relatively fresh groundwater and low to moderate host conductivity (Schirov et al., 1991; Dippell et al., 2003). However, large parts of Australia are blanketed in variably thick, variably conductive regolith containing in places, thick conductive clay layers and hosting saline to hyper-saline groundwater.

The 'screening' effect of a conductive subsurface on SNMR signal amplitude and phase is well known (Trushkin et al., 1995; Shushakov, 1996) and an accurate model of subsurface conductivity is required for accurate inversion and interpretation of SNMR data in conductive terrains (Weichman et al., 2002). Given such a model, it would be useful to determine, prior to conducting an SNMR sounding, whether the groundwater parameters of interest can be obtained. One such parameter is the cutoff depth beyond which no water can be detected. Using synthetic data generated for water layers (of finite thickness and infinite spatial extent) in conductive half-spaces, we find the depth at which no subsequent water will contribute significantly to an SNMR sounding and use it to find the depth range over which most of the SNMR signal is obtained.

DEPTH OF SIGNAL CONTRIBUTION

The response induced in a receiver coil following an SNMR sounding with pulse moment q, is given by (Legchenko et al., 1997)

$$emf(t,q) = E_0 \sin(\omega t)\exp(-t/T_2^*) \quad (1)$$

corresponding to a sinusoid with an exponentially decaying envelope and initial amplitude E_0 given by

$$E_0(q,p) = \omega_0 M_0 \int_V b_\perp^R(p)\sin(\frac{1}{2}\gamma b_\perp^T(p)q)e^{i(\varphi^T(p)+\varphi^R(p))}w(p)dV \quad (2)$$

where the variables are the same as those given by Legchenko and Valla (2002) with the addition of the exponential term making explicit that the initial amplitude of the signal is complex and phase shifted with respect to the transmitter pulse (Weichman, et al., 2000; Valla and Legchenko, 2002). By taking numerous soundings with varying q, an E_0 amplitude profile is generated which is subsequently inverted to give an estimate of water distribution with depth. With current SNMR instrumentation, the actual received voltage following a transmitter pulse is smaller than E_0 by a factor proportional to the receiver 'dead-time' and the rate of spin-spin relaxation. Here, these considerations are ignored and only the theoretical value of E_0 is considered.

From Equation 2, it can be seen that conductive ground attenuates the initial SNMR voltage response at the receiver in three ways (Weichman et al., 2002). Firstly, the spin 'tipping' force applied with the transmitter field is attenuated with depth. Similarly, the received signal generated by spins returning to equilibrium is attenuated by the same factor. Finally, the phase of the tipping field varies at different locations resulting in phase-shifted signal contributions that, when integrated, form an interference pattern at the receiver. This attenuation limits the depth at which water can be detected in conductive ground. Legchenko et al. (1997) show maximum E_0 diminishing at depth for various half-space conductivities. Similarly, Legchenko et al. (2002) show how maximum depth of detection decreases as half-space conductivity and geomagnetic inclination increases. In both cases, the depth of detection was defined as the depth at which a 1 m thick, 100% water layer resulted in an E_0 profile where the maximum amplitude did not exceed some detection threshold (10-20 nV). Although a 1 m layer may be undetectable, thicker layers at the same depth can make a measurable contribution to the E_0 profile (Figure 1). The contribution will be additive or subtractive depending on the relative phase between these and other water bearing layers (Schirov and Rojkowski 2002).

Here we consider the depth at which no amount of subsequent water contributes significantly to the E_0 profile by redefining the depth of detection to be where a thick (50 m) rather, than a thin (1 m), fully saturated water layer fails to produce an initial amplitude greater than 20 nV. All calculations are performed for a 100x100 m coincident transmitter/receiver loop operating at a Larmor frequency of 2300 Hz and a geomagnetic field inclination of 56°S. Figure 2 shows that the new definition results in a maximum depth of detection approximately 50% greater than that of Legchenko et al. (2002).

Using this result, we can find the depth at which 95% of an E_0 profile has been accounted for. This is found by firstly finding the area under the E_0 profile of a water model consisting 100% water between the surface (1 m) and the maximum depth of detection. The 95th percentile depth is where the area under the E_0 profile of successively thinner water models differs by more than 5 percent from the initial model (Figure 2). Using the same technique, it can be shown that the depth of detection defined by Legchenko et al. (2002), corresponds to the depth at which over 98% of the total response has been accounted for.

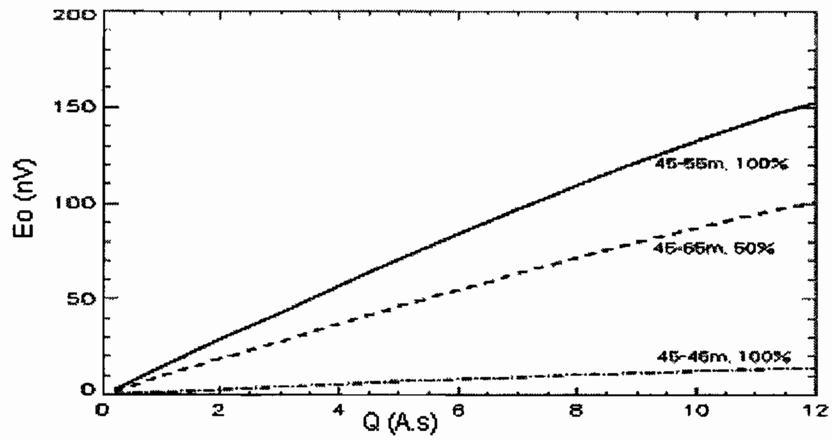

Figure 1. E_0 response for water layers of varying thickness and water content in a conductive (2 ohm-m) half-space. At large Q, thicker layers make a measurable contribution to the E_0 profile.

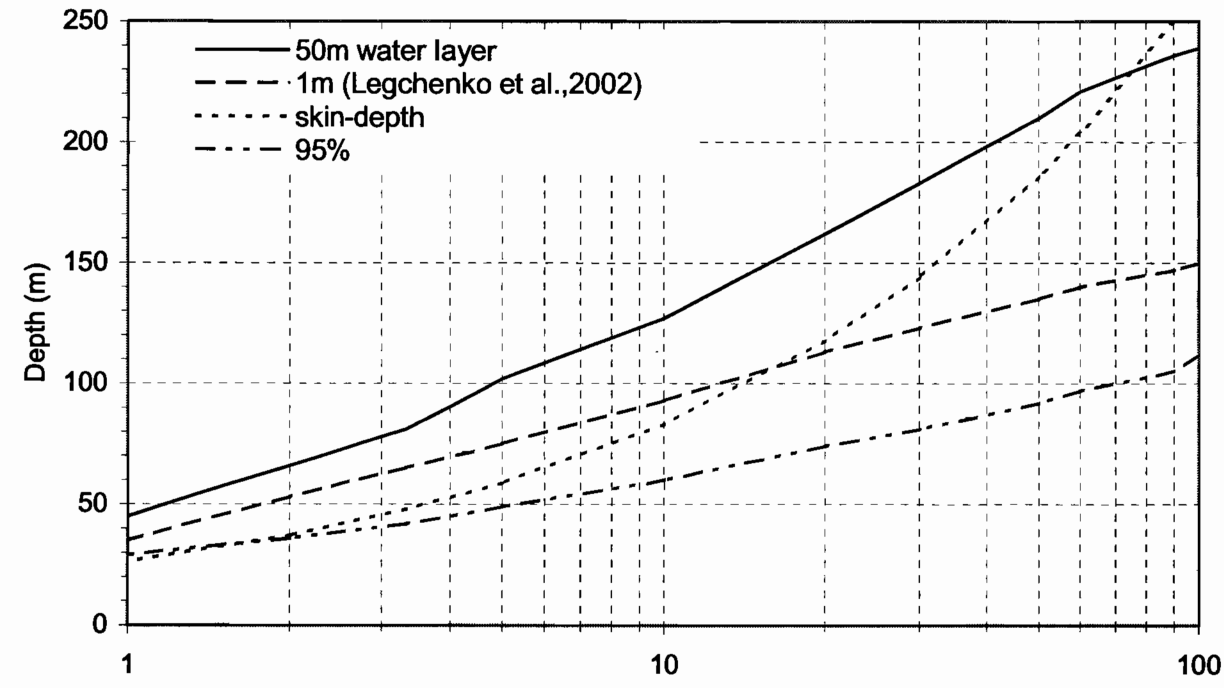

Figure 2. Maximum detection depth of thick and thin saturated layers, skin-depth and depth of 95% signal contribution, versus half-space resistivity.

CONCLUSION

Using forward modelled data, the depth of at which no amount of subsequent water will contribute significantly to an SNMR E_0 profile is estimated for various half-space conductivities. Using this maximum depth, the depth at which 95% of SNMR signal contribution is accounted for is also obtained. It is shown that for half-spaces less than 20 ohm-m, the maximum depth of detection is approximately 1.7 times skin-depth. Over the range of half-space conductivities considered (1-100 ohm-m), it was found that 95 percent of signal contribution comes from less than half the maximum depth of detection. For very conductive half-spaces (< 3 ohm-m), 95% of total signal contribution is accounted for within one skin-depth.

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HYDROLOGICAL PROPERTIES DERIVED FROM NUCLEAR MAGNETIC RESONANCE PROPERTIES OF UNCONSOLIDATED ROCKS AND SYNTHETIC SAMPLES

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INTRODUCTION

Since MRS (Magnetic Resonance Sounding)/SNMR (Surface Nuclear Magnetic Sounding) has proved to be a useful tool for the investigation of hydrological properties of the subsurface (Legchenko et al, 2002), the interest for laboratory NMR has strongly increased. In our work we therefore analyzed the NMR properties of synthetic and natural unconsolidated samples to increase the understanding and interpretation of SNMR data. To verify the NMR measurements several other measurements have been performed to obtain pore space properties (porosity Φ, specific surface S_{por}) and to obtain the saturated hydraulic conductivity (SHC) k directly.

NMR & POROUS MEDIA

Two parameter are mainly used for rock physics from NMR: First, the initial amplitude of the relaxation signal right after switching off the oscillating field and, second, the relaxation (decay) of the signal with time. The initial amplitude is proportional to the number of ^{1}H protons taking part in the relaxation process. The total water content can therefore be determined by comparision of the measured amplitude with the amplitude generated by a known volume of water from a calibration sample. The effective NMR porosity Φ_{NMR} can be calculated directly from the water volume V_{mobile} in the case of fully saturated samples:

$$V_{mobile} = (Amplitude_{sample} * V_{calibration})/Amplitude_{calibration} \quad \text{(eq. 1)}$$

which leads to the effective (mobile) porosity

$$\Phi_{NMR} = V_{mobile} / V_{sample} \quad \text{(eq. 2)}$$

^{1}H protons in adhesive water or small pores relaxes much faster than protons in free water or large pores because of a higher probability of a contact with the grain surface and the associated energy release. A pore radii distribution can therefore be derived from a spectral analysis of the relaxation times (Kenyon, 1992, 1997). An adaptation of the Kozeny-Carman equation leads to a permeability k estimation via ^{1}H relaxation times:

$$k = c * T_i^2 * \Phi^4{}_{NMR} \quad \text{(eq. 3)}$$

whereas c is a constant factor depending on the surface relaxivity of the material, Φ_{NMR} the effective NMR porosity and T_i the corresponding relaxation times (either T_1 or T_2).

SAMPLES

The samples can be devided into five different classes:

1. synthetic samples (cleaned pure glass pearls, Ø 1, 0.1, 0.01 mm, laboratory quality)
2. pure quartz sands (fine to coarse) and doped with clay (3%, 5%, 10%, 15%, 20%)
3. clayey samples (pure clay)
4. field samples taken from a bore core of a test site in Nauen, Quarternary deposits from west of Berlin, Germany
5. artificially made sand mixtures analogous to the composition of the field samples

RESULTS

Fig. 1 shows the NMR decay time as function of surface-to-pore-volume, Spor. There is a strong relation between the NMR decay time with the specific surface of $160*x^{-0.68}$ like for hard rock material. The cause for this is the influence of the pore wall relaxation, which is proportional to the specific surface.

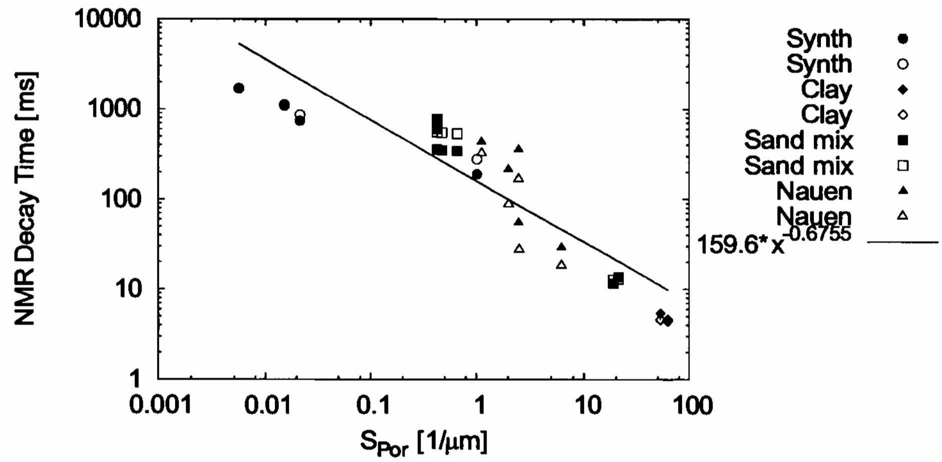

Figure 1: NMR relaxation time as function of surface-to-pore-volume, Spor.

Fig. 2 shows the SHC calculated from NMR via eq. 3 as function of the measured hydraulic conductivity obtained through permeameter measurements. The NMR_{SHC} shows a good agreement with the measured SHC for the clay samples, the glass pearls and two (clean) coarse sand samples. Intermediate grain sizes and field samples are scattered.

Figures 3a and 3b show the decay time spectra of samples composed of glass pearls and clay. For a layered sample like in Figure 3a two mean different relaxation times can be identified as two different peaks at 5 ms and 1700 ms, resulting from the clay and the glass pearls, respectively.

This is due to the difference in pore size and the fact that the sample is layered. A sample consisting of the same material but thouroghly mixed, results in just a single peak distribution (Fig. 3b). The influence of the clay apparently dominates. Thus although different pore sizes may be present in a samples, they might not be identified individually by NMR, but shielded by the clay.

The most common measurements in the field are T_2^* which than have to be compared to laboratory NMR data. It is generally assumed in SNMR that because of the low earth magnetic field strenght, the effect of magnetic field inhomogeneities is much smaller than for laboratory NMR, and therefore, T_2^* relaxation times may be compared to T_2-relaxation time in the lab ('T_2^*-effect'). Table 1 shows T_2^* relaxation times from SNMR measurements vs. T_2^*, T_2 and T_1 data from the laboratory at 2 MHz resonance frequency. A large difference of SNMR decay time for coarse sands to fine sands is observed vs. laboratory T_2^*. Lab-NMR T_2

are about two times the SNMR T_2^* for sands. For fine sands this rises to four times as much. For very fine sands and clayey sands the relaxation times are almost equal. Roughly it can be said that the NMR T_2^* relaxation times for sands are shifted up one grain size level vs. laboratory data. For T_1 the results are even more apart for sands and coarser material.

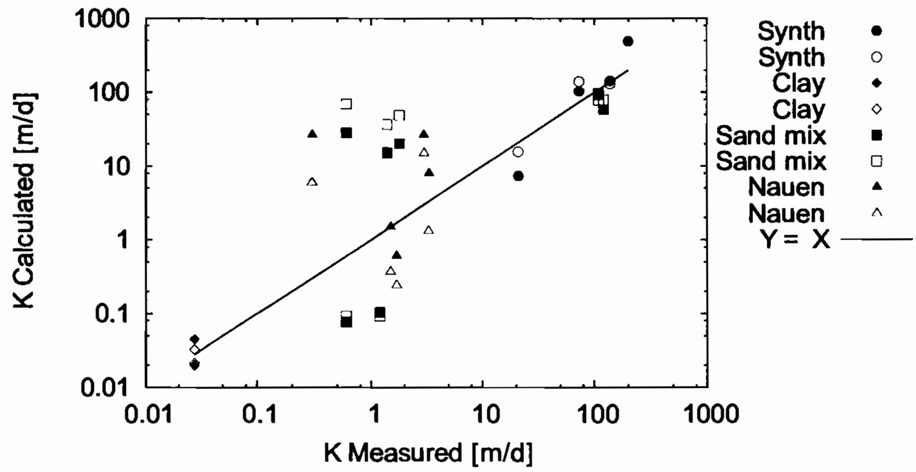

Figure 2: Saturated Hydraulic Conductivity calculated from NMR as function of measured hydraulic conductivity obtained with permeameter.

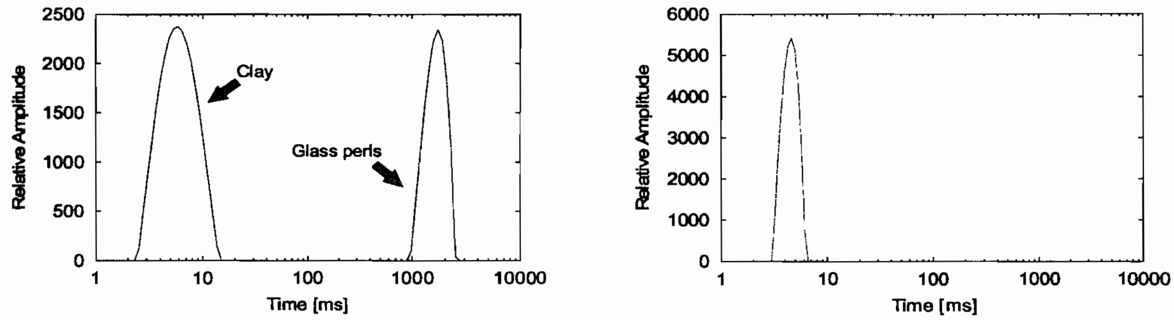

Figure 3a: (left) Pore size distribution of layered sample, (glass pearls on top of clay). Figure 3b: (right) Pore size distribution of sample with clay and glass pearls mixed.

Table 1. Observed relaxation times for NMR (Kooman, 2003) and SNMR (Schirov et al. 1991).

Sediment Type	Rel. Time, T_2^* [ms] SNMR	Rel. Time, T_2^* [ms] NMR	Rel. Time, T_2 [ms] NMR	Rel. Time, T_1 [ms] NMR
Clay	-	0.4-0.7	4-5	4-5
Silt	-	0.5	12-14	13
Sandy clays	< 30	-	-	-
clayey sands, very fine sands	30-60	0.2-0.8	30-55	20-30
fine sands	60-120	0.35-1.3	10-435	90-560
medium sands	120-180	0.7	220	535
coarse and gravelly sands	180-300	0.5-0.8	605-780	700-760
Gravel deposits	300-600	-	-	-
surface water bodies	600-1500	0.9	1800-2200	-

DISCUSSION AND CONCLUSIONS

Surface to pore volume can be well determined by laboratory NMR. T_1 and T_2 relaxation times are much better suited than T_2^* to be compared to SNMR field data. The scatter of the SHC is probably a result of paramagnetic influences. A small amount of paramagnetic material is sufficient to accelerate the relaxation processes resulting in an underestimation of the SHC. For other samples (medium coarse) the SHC is overestimated. In this case the relaxation time constant seems to be determined by the large pore radii but for the 'true' SHC the poor sorting is important. The explanation for the difference in relaxation times of NMR and SNMR (Table 1) may result from the T_2^*-effect but also from variations of the larmor frequency with time which can reduce the decay essentially (see Hertrich, this volume). Thus we recommend to use T_2 from laboratory data to explain SNMR T_2^* data by choosing at least one higher order of grain size than you would from the SNMR data. Saturated hydraulic conductivity estimates from NMR could be used for clayey and coarse material but showed a scatter for intermediate grain sizes when a pre-factor of 1.5 (eq. 3) was used. As NMR alone is not able to detect a mixture of coarse and fine material, additional data, like from induced polarisation measurements should be used, because they have shown the power to unreveal the presence of coarse material in mixed samples/layers.

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MRS AND ELECTRICAL IMAGERY FOR CHARACTERISING WEATHERED AND FRACTURED HARD-ROCK AQUIFER IN THE MAHESHWARAM WATERSHED, HYDERABAD, INDIA

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INTRODUCTION

Magnetic Resonance Sounding (MRS) and Multi Electrode Resistivity Imaging (MERI) studies were carried out for characterizing weathered and fractured aquifer in a granitic terrain in Maheshwaram watershed located 30 km south of Hyderabad (India). It is main study area of the Indo-French Centre for Groundwater Research (BRGM- NGRI collaboration project). It has a surface area of about 60 km², between Latitudes 17°06'20"N to 17°11'00"N and Longitudes 78°24'30"E to 78°29'00"E. The watershed is mainly constituted of Archean granites with isotropic texture having some dolerite dykes and quartz veins. The weathering profile is generally truncated by erosion: alterite thickness is less than 5 meters and horizontal fractures are well-developed in the fissured/fractured zone whose average thickness is about 25 m. Due to overexploitation of groundwater resources, aquifer is mainly developed in this fractures/fissured zone where vertical fracture of tectonic origin also exists. The water table depth vary from a few meters to more than 20 m from place to place and depending on the season (seasonal variations due to rainfall recharge may reach 10 m).

INVESTIGATIONS

Various geophysical investigations were carried out in the watershed since 1999 which include: Resistivity soundings with Schlumberger configuration, Resistivity and Magnetic profiling across dykes, Well-logging, Mise-a-la-masse and S.P. studies. Preliminary MRS, Electrical Imaging and Time Domain EM reconnaissance were undertaken in two locations (one at Mohabbatnagar and the other at KB Tanda) in November 1999, at a high water level, during post monsoon period. The sites investigated are shown in Fig.1. The cultural noise was found to be high during certain period of the day, whereas, the actual signal level is rather low. This tedious signal to noise conditions could be improved with an adapted measurement planning and by using the newly developped notch filter centered on 50-Hz-harmonics (Legchenko and Valla, 2003). The results of MRS and Resistivity Imaging have been compared along the two profiles and are discussed here.

RESULTS

On KB Tanda site, the cross section infrerred from MERI and MRS studies is shown in Fig.3. The resistivity cross-section define on its western side a well identified high resistivity mole and a high resistivity superficial spot in perfect accordance with surface observation of massive hard rock outcrop and boulders. As no MRS signal is observed in this area, this zone is interpreted as an unweathered, low water content massive rock, may be subjected by a fault. On the main central and eastern part of the profile, low resistivity and very low resistivity are observed at shallow depth, probably caused by clayey alterites in coherence with the mainly low value of decay time T2* defined by MRS. The high water content and longer decay time suggest that the largest amount of water is stored in the northwestern part of the profile (IPMR9,IPMR11). The maximum thickness of water-saturated weathered zone was found to be about 15m. A relatively short decay time and low water content (IPMR3) is most probably caused by a greater amount of clay or silt in the weathered zone. In depth, resistivity shows a gradual increase up 300-400 Ohm.m at 20 m depth.

On Mohabatnagar site, the resistivity profile indicates two vertical conductive zones (Fig.2) located at distances 55m and 190m. The second one extends laterally also at shallow depth. The cross section derived from the MRS results is also shown in the same figure. It shows the water content and the decay time. The upper part of PMR7 and PMR10 and the main part of IPMR13 may be due to alluvial deposits. The underlying probable weathered zone increases from almost non-existent on IPMR 13 to reach the thickness of 20m for a maximum depth of 25 m on IPMR10. A relatively long signal decay time reveals a small amount of clay in the weathered zone. The second conductive anomaly on resistivity section corresponds to a lineament detected on aerial photographs and at the same time identified as high water content from MRS.

At both the sites the 200 Ohm.m iso-resistivity curve show a good correlation with the 1-2% contour at the base of the water-bearing layer. The profiles of MRS water-content versus depth are characterised by high water content at the top and a gradual decrease with depth. MRS defined water-bearing layers of 1 to 8 % water content extending from a few meters depth down to 10-15 m except in the north of Mohabatnagar site where it is 25m. Based on open well and borehole data, it appears that this layer correspond to the water saturated weathered zone and the upper part of the fractured zone.

CONCLUSIONS

The resistivity imaging has helped in identifying certain fault zones, which exist in both sites. The MRS show a main water-bearing layer extending from the surface or a few meters depth down to 15-30m. Based on open well and borehole data it appears that this water layer mainly correspond to the water saturated weathered zone. Thus the preliminary experiment on the Maheshwaram basin show a very good agreement between resistivity imaging and MRS results and show the possibility of combined geophysical investigation for:

- evaluating water ressources in weathered as well as in the fractured zone,
- delineating water bearing structures.

ACKNOWLEDGEMENTS

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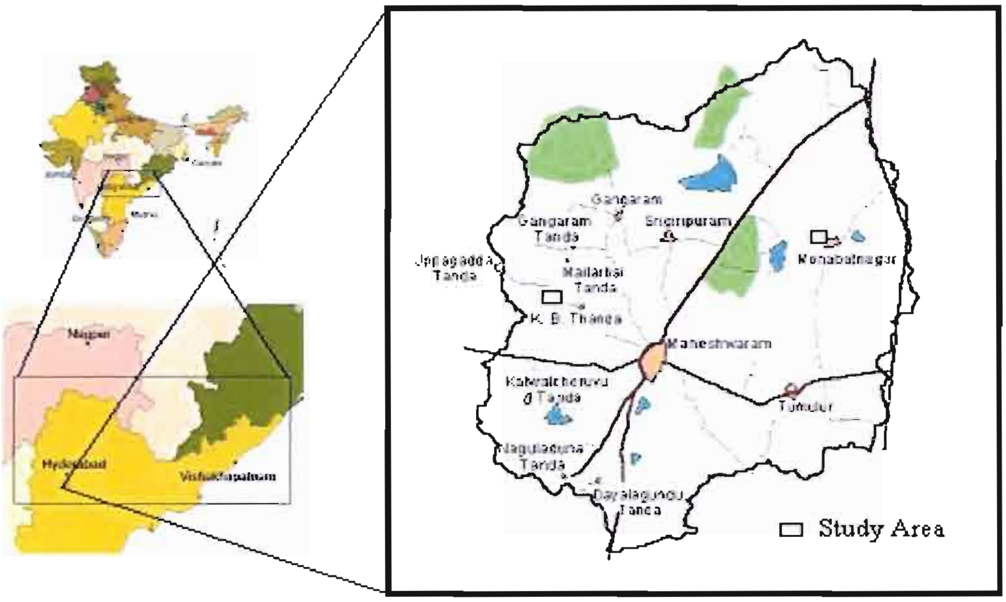

Figure 1: Location of the Maheshwaram basin.

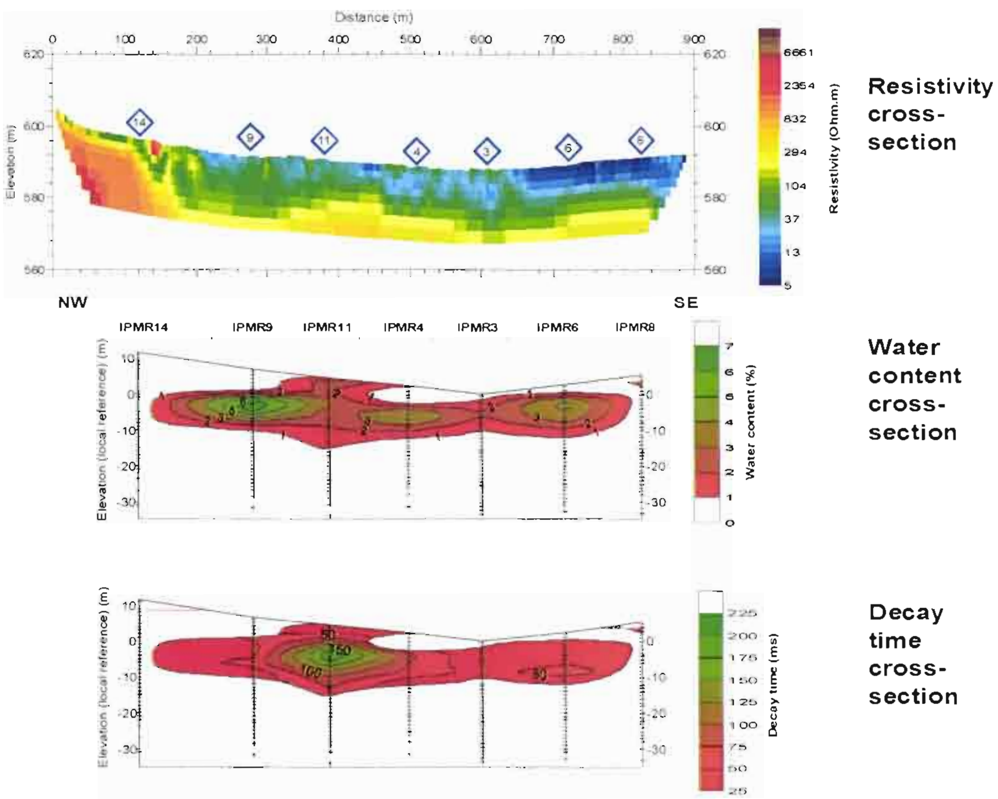

Figure 2: MRS and geoelectrical cross-section on KBTanda site.

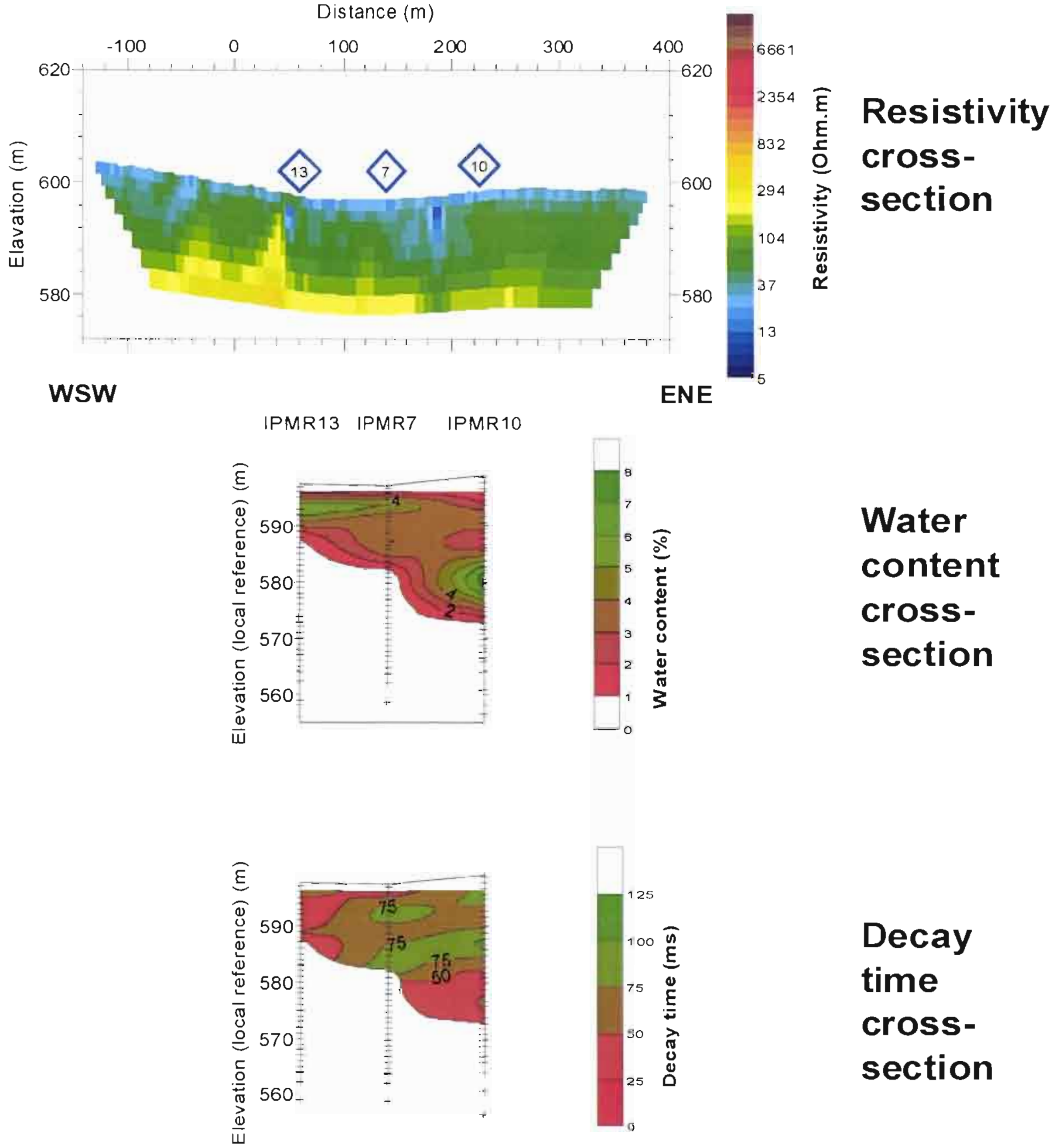

Figure 3: MRS and geoelectrical cross-section on Maohabatnagar site.

LINKS BETWEEN MRS AND THE PARAMETERS USED BY THE HYDROGEOLOGISTS: A METHODOLOGICAL APPROACH FOR THE QUANTITATIVE HYDROGEOLOGICAL CALIBRATION OF MRS MEASUREMENTS

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INTRODUCTION

A comprehensive interdisciplinary (geophysical, geological, and hydrogeological) study performed by BRGM was aimed at developing an optimal methodology for applying magnetic resonance soundings (MRS) to hydrogeological studies, and making this new geophysical method more accessible to the hydrogeological community (Lachassagne *et al.* 2003).

For hydrogeological purposes, three parameters derived from MRS data are useful: the MRS water content (*w*), the relaxation times (T_2* and T_1), and the geometry of 'detected aquifers' (depth intervals or 'layers' to which this couple of parameters is applicable: z location of top and bottom).

Being products of inversion of MRS measurements, these parameters require a certain calibration before they can be used by hydrogeologists.

POROSITY - STORATIVITY

In the saturated zone of an aquifer, *w* is related to the **effective porosity** [%] and quantifies the amount of water stored within. Effective porosity is always less than total porosity, the difference between the two being mainly linked to the pore size distribution.

In *unconfined aquifers* only (Figure 1), *w* also characterizes the **storativity** or **storage coefficient** of the aquifer, in which case, storativity is equal to effective porosity. In *confined* aquifers (Figure 1), storativity is mainly linked to the compressibility of both the aquifer and water; therefore w does not characterize the storativity of the aquifer. Depending on the rock type, MRS

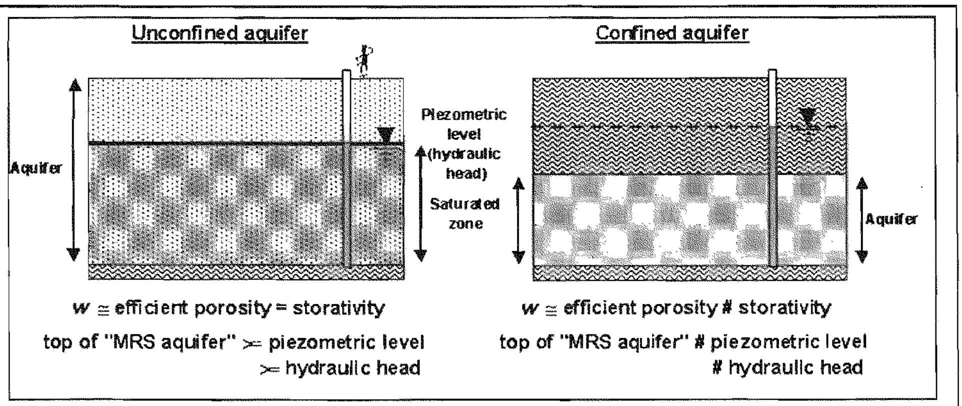

Figure 1

measurements may (i) overestimate the effective porosity by integrating both free and, partly, fixed water; or (ii) underestimate the effective porosity if loosing fixed and, partly, free water. These uncertainties can be corrected by calibrations carried out for each geological formation.

Nevertheless, even if the theoretical reasons for this are not yet clearly understood, the experience of numerous MRS measurements shows that, in most cases [porous (Legchenko et al. 2002), karstic, hard-rock (Wyns et al. 2003) aquifers], the difference between measured w and effective porosity is less than the uncertainty on this last parameter (or the lack of numerous porosity data, if not a total lack of data). The MRS tendency to overestimate effective porosity seems particularly important in chalk aquifers.

Thus, as effective porosity is a relatively expensive parameter to acquire at field scale (requiring at least a pumping test with two boreholes – a well and a piezometer - or tracer tests), MRS appears to be a very valuable method to hydrogeologists, particularly when dealing with pollutant transport problems.

HYDRAULIC HEAD

In unconfined aquifers, MRS measurements can provide data on the hydraulic head [m] within the aquifer, as the piezometric level merges with the top of the saturated zone of the aquifer (Figure 1), which is detected by MRS.

However, the MRS technique also measures signals from water in the capillary fringe within the aquifer and can thus underestimate the depth of the piezometric level. Capillary fringes can be particularly thick (over one meter) in porous fine-grained aquifers (in chalk for instance, the thickness of the capillary fringe can reach several meters within the matrix of the aquifer). In addition, some small perched aquifers, not measured with the commonly available piezometers, but that can be detected by careful observations during drilling for example, can be characterized through MRS measurements, providing their size is sufficient compared to that of the MRS antenna loop.

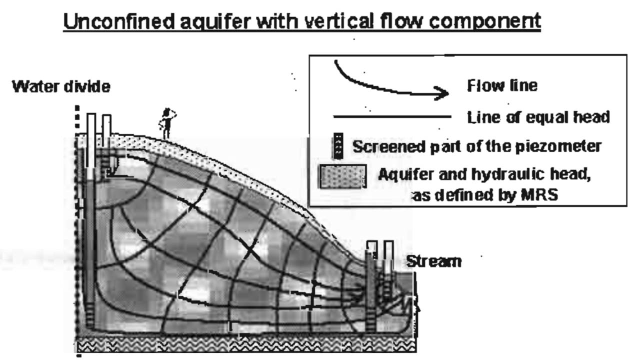

Figure 2

In the case where groundwater shows a significant vertical flow component (Figure 2), the water level measured in a well can vary considerably (from a few centimeters to decimeters, and locally a few meters) from the depthn of the top of the saturated zone of the aquifer, depending on the vertical hydraulic gradient, but also on the depth and length of the piezometer's screen. Thus, the piezometric level as deduced from MRS measurements is equal to the hydraulic head that would be measured at the top of the aquifer.

In *confined aquifers*, MRS measurements cannot provide information on the hydraulic head. The increase in water content measured by the MRS log corresponds only to water-saturated rocks. For example, in the case where a sandy aquifer overlain by clay is located at a depth of between 20 and 30 m and the piezometric level is at 5 m, then MRS will only locate the aquifer's top and bottom, between 20 and 30 m. Therefore, MRS does not measure any characteristics related to piezometric level or hydraulic head.

GEOMETRY OF THE AQUIFER

Beyond the above limitations, both in *confined and unconfined aquifers*, the **top and the bottom of the aquifer**, and thus its **thickness** (Figure 1, Figure 2), can be determined though MRS measurements.

As the vertical resolution of MRS is limited, available inversion software provides a better accuracy for the shallowest aquifer than for multi-aquifer systems, as deeper aquifers can be partly masked by shallower water-saturated layers.

HYDRAULIC CONDUCTIVITY

The **hydraulic conductivity** (or permeability) [m/s] is a vectorial parameter that not only relies on the physical properties of the medium (anisotropy, heterogeneity, etc.), but also on flow direction, the scale of the measurement (depending on the duration of a pumping test for example), etc. This parameter is highly variable and ranges over several orders of magnitude.

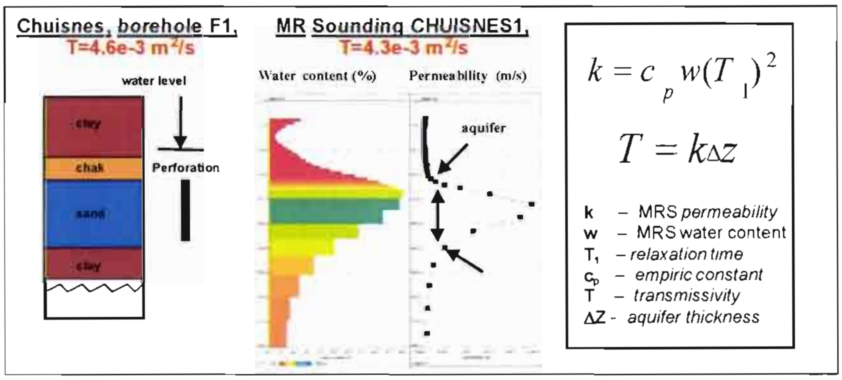

Figure 3

The volume investigated by MRS (generally a cylinder 100 m in diameter, 100 m in depth) is similar to that investigated by pumping tests, the most common method used by hydrogeologists to evaluate the hydraulic conductivity of an aquifer. Following the example of NMR logging, attempts are thus made to find a correlation between a combination of the MRS parameters (water content and relaxation time, with some constants and exponents to be adjusted in the formula), and the hydraulic conductivity (or the transmissivity: integration of the permeability on the thickness of the aquifer), as deduced from pumping tests (Figure 3). The interpretation of NMR geophysical borehole logging also relies on such a search for a correlation. This approach is consistent with the results of the considerable efforts made over previous decades (supported by the petroleum industry in particular), which have shown that only empirical links, to be assessed and calibrated for each kind of geological formation, can be established between porosity (or pore size distribution) and hydraulic conductivity.

Thus, this search for adjustments between pumping test results and MRS parameters seems to be highly promising, even if convincing results are not assured considering the conceptual difficulties involved. In addition to the attention that must be paid to the MRS data inversion (see also below), the hydrogeological data also require a great deal of care if this search is to prove successful. The direct use of permeability/transmissivity values from the literature can lead to important bias. For existing data, it practically imposes the systematic re-interpretation of the pumping tests in order to i) check the adequacy between the scale of the MRS measurement and the volume investigated by the pumping test (and thus choose the part of the pumping test curve to be considered), ii) check the validity of the required hypothesis (type of porosity, homogeneity, isotropy, location and thickness of the well screen in the aquifer, etc.), and iii) build a realistic conceptual geological and hydrogeological model of the studied site. As MRS measurements provide discretized data along the Z axis, it is also very important to acquire geological and hydrogeological data allowing assessment of the vertical distribution of the hydrodynamic parameters.

IMPORTANCE OF THE CALIBRATION PROCESS

As with most geophysical methods, MRS is submitted to the principle of equivalence. The interpretation of an MRS measurement thus requires the simultaneous analysis of all the MRS parameters (water content, relaxation time, thickness of the different layers, etc.). In the quest for hydrogeological parameters and data from MRS measurements, the calibration process is very important. The knowledge of one parameter, or even better two, makes it possible to determine with a much higher accuracy the third, or the second and third, parameters.

Thus, the MRS inversion process must comprise at least the following three steps:

1. (automatic) inversion of the data,
2. calibration of MRS parameters, on the basis of existing data when available, or on the experience of the team of geologists - hydrogeologists - geophysicists. The easiest parameter to be used for calibration is generally the thickness of the various 'layers',
3. estimation of the hydrodynamic parameters (effective porosity, permeability, transmissivity) on the basis of empirical relationships linking them with the MRS parameters, established for the studied site or similar hydrogeological contexts.

These three steps can include certain iterative procedures. For instance, step 2 would allow the precise identification of the depth of the top of a confined aquifer, or the piezometric level in an unconfined one, whereas step 1 would only provide a progressive variation along Z of the medium properties.

CONCLUSION

The MRS method is already able to provide pertinent data to the hydrogeologist, including:

- the direct detection, with a few ambiguities, of the presence of water in the subsurface; this is the basic and decisive advantage of this method, which could thus prove extremely useful, particularly in arid to semi-arid environments,
- the location of saturated formations (top and bottom), situated at depths between 0 and 100 m,
- the evaluation of hydrodynamical parameters of detected aquifers when calibration is available; otherwise, aquifers can be compared qualitatively.

Thus the MRS method provides data that cannot be obtained through other non-invasive geophysical tools. In addition, it is well adapted to the working scale of the hydrogeologist (field scale, well scale).

Through a rigorous inversion and calibration process, the MRS method also enables the quantification of the effective porosity of aquifers. In the present state-of-the–art, MRS only allows the evaluation of aquifer permeability under localized favorable configurations.

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SNMR MEASUREMENTS IN THAILAND – A NEW EXPERIENCE

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INTRODUCTION

Integrated geophysical surveys have been carried out at two locations in Thailand in the context of site investigations of abandoned landfills and planned waste disposal sites. Besides conventional methods SNMR was used for the first time in Thailand. Important for the worldwide use of SNMR is an almost square proportionality between SNMR signal amplitudes and the total intensity of the Earth's magnetic field (Legchenko et al. 1997). The total intensity shows global structures with maximum values of >70 000 nT over the polar regions and minimum values of < 20 000 nT in South America (Fig.1, left). This results in different SNMR signal amplitudes for the same hydrogeological situation. Although the survey locations are close to the equator, the geomagnetic conditions for SNMR measurements are excellent in Thailand and generally in South East Asia (Vouillamoz et al., 2002). Here, total magnetic field intensities and field inclinations are in the range of 42,000 to 45,000 nT and 10 to 15 degrees, respectively.

At all survey locations only very small signal amplitudes could be measured, which correspond to low mobile water content in the ground. Therefore, high stacking rates (>150 stacks) were necessary to acquire data with a sufficient signal to noise ratio. This led, inevitably, to long measurement periods and to a low productivity in the field. Another effect was a strong diurnal variation of the total magnetic field intensity, recorded by a proton magnetometer at a fixed point near the survey area. These observed diurnal field variations, caused by the equatorial electrojet (EEJ), are well known from magnetic exploration at low latitudes. This causes strong variations of the local Larmor frequency, shown in Fig. 2, that results in deviations of up to 3 Hz from the used pulse frequency during a sounding.

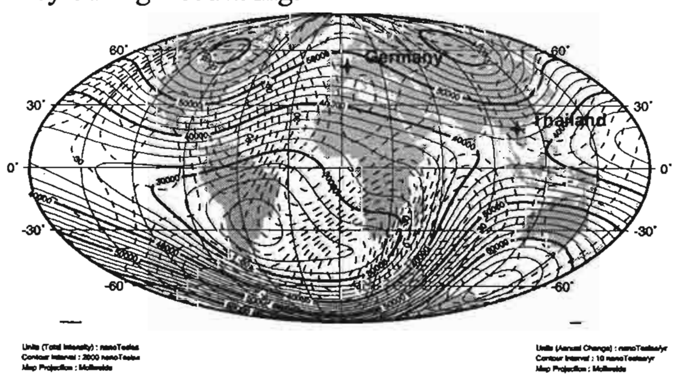

Fig.1: Global Earth's magnetic field intensity (left) and survey locations (right).

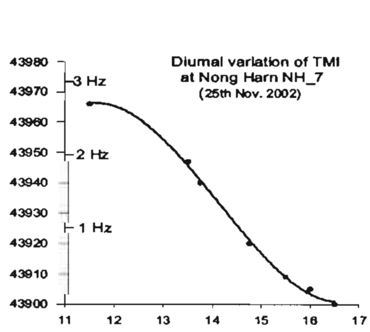

Fig. 2: Diurnal variation of the Earth's magnetic field causing a drift of the local Larmor frequency up to 3 Hz. Location: SNMR sounding NH 7.

SNMR SURVEYS NEAR CHIANG MAI

SNMR surveys have been carried out at the abandoned landfill Nong Harn, near to the provincial capital of Chiang Mai in northwestern Thailand (Fig. 1, right). At this site geological modeling, basing on results of direct current and electromagnetic methods, predicted a tectonic fault separating the investigation area into two zones of different sedimentation and water contents at the shallow depth range. The aim of this survey was to verify this model by SNMR soundings. A particular problem here is, that the waste body itself is source of a strong magnetic anomaly, probably caused by illegally disposed metal barrels. To carry out the SNMR measurements under homogeneous geomagnetic field conditions, sounding locations had to be positioned at 300 m distance from the landfill midpoint. Figure 3 shows data and inversion results of the soundings NH 6 south and NH 7 north of the predicted fault. To determine ground conductivities for enhanced inversion, dc soundings (VES) were carried out simultaneously with SNMR soundings. Ground resistivities as derived from VES are in the range of 350 - 800 Ωm at both sites. The lower water content in NH 7 compared with NH 6 verifies the geological modeling (Fig. 3, right). Interesting is the opposed phase response characteristics of the two soundings, whose causes are still unclear (Fig. 3, left).

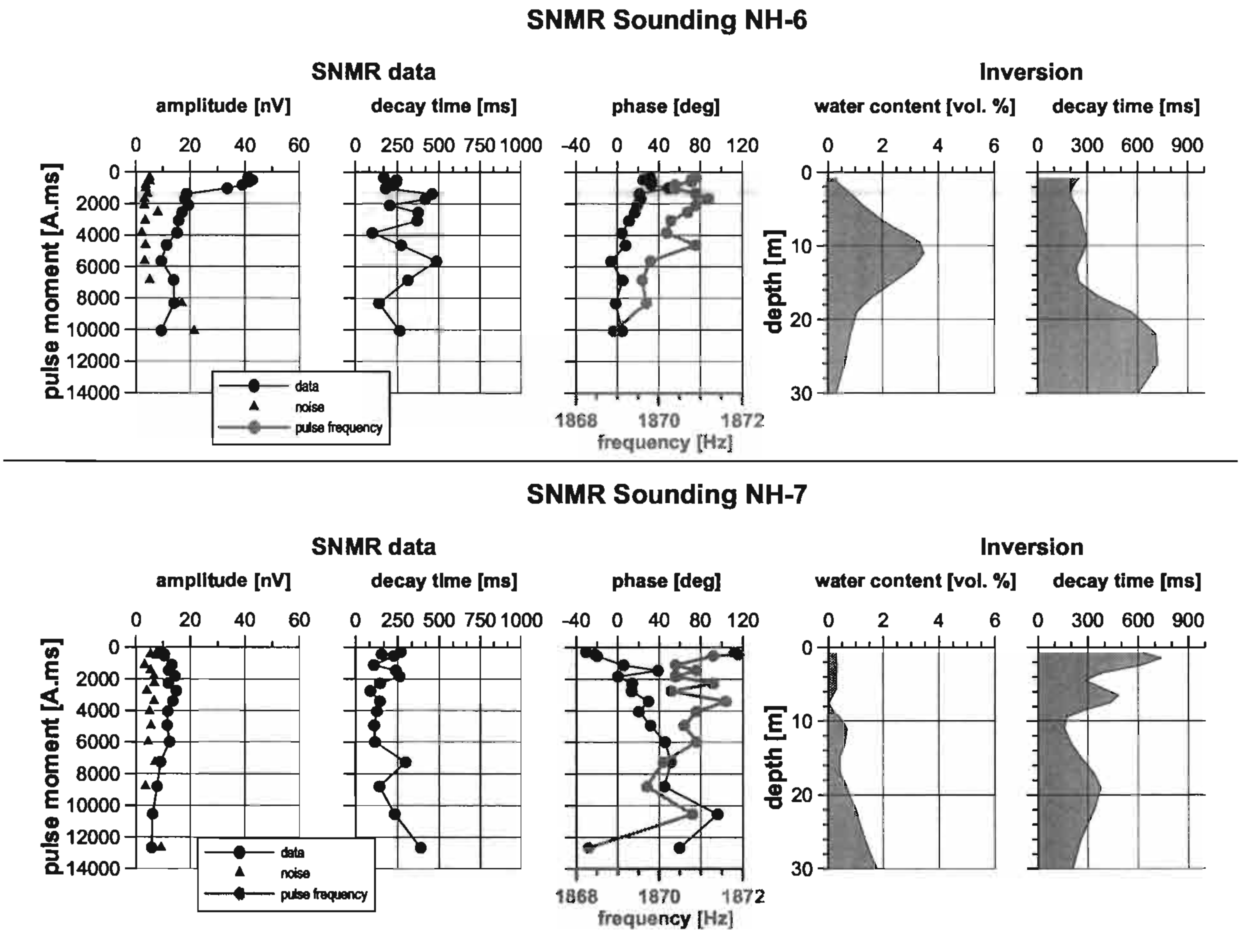

Fig. 3: Field data (left) and inversion results (right) of SNMR soundings NH 6 (top) and NH 7 (bottom) at the Nong Harn landfill. Acquisition parameters: Square-8-loop (side = 37.5 m); pulse frequency: 1871.5 Hz; stacking rate 150. Inversion with SAMOVAR (IRIS Instruments).

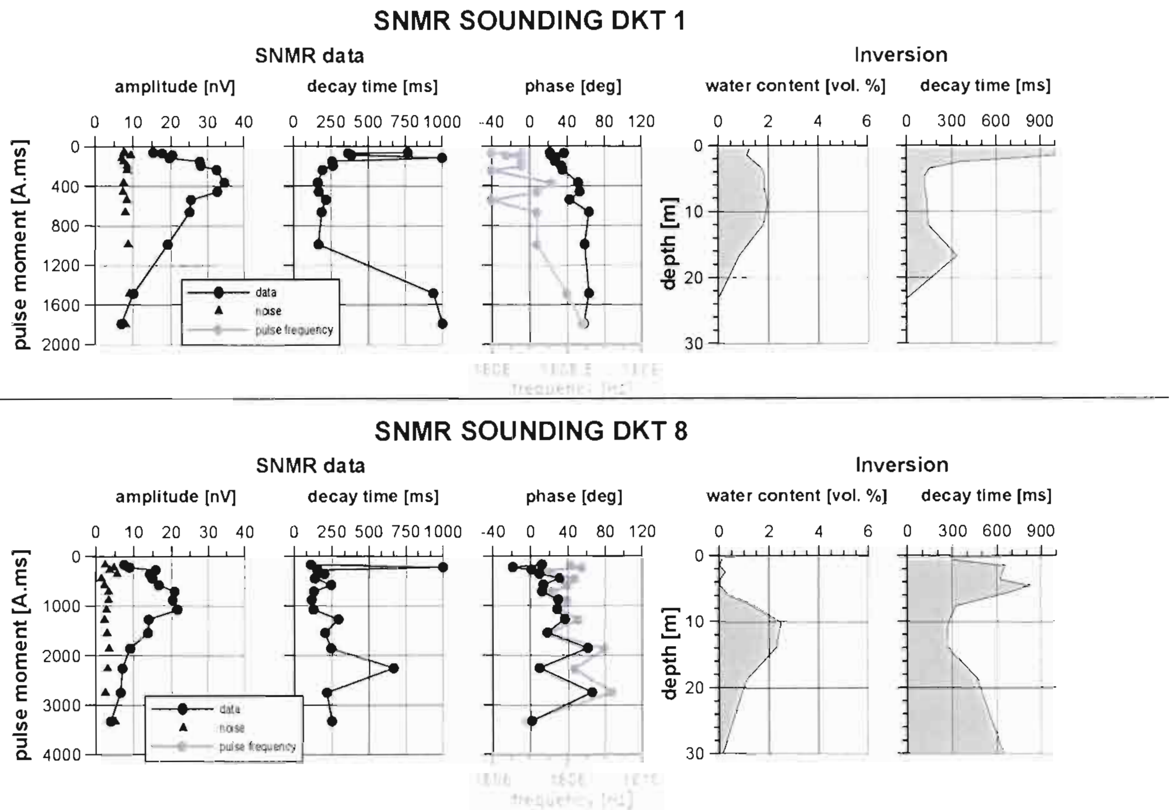

Fig. 4: Field data and inversion results of SNMR soundings DKT 1 (top) and DKT 8 (bottom) at Dan Khun Thot. Acquisition parameters: square-8-loop (side = 37.5 m); pulse frequency 1808 Hz; stacking rate 150. Inversion with SAMOVAR (IRIS Instruments).

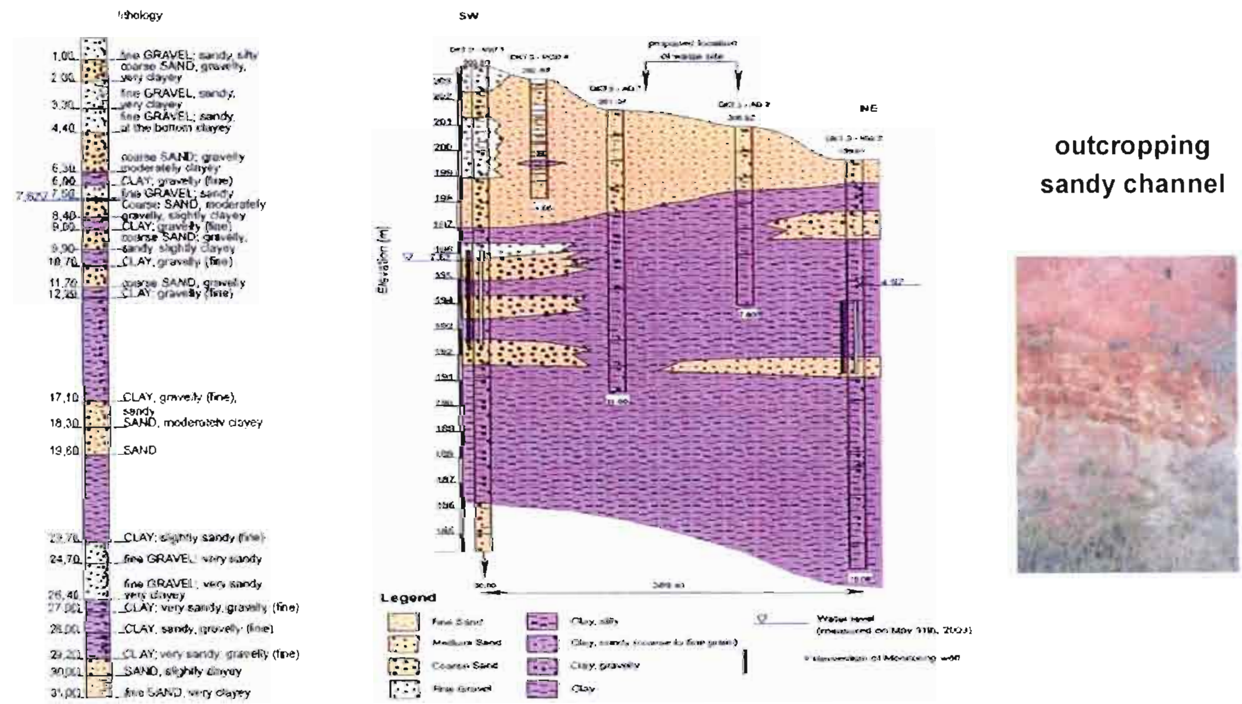

Fig. 5: Lithological profile of monitoring well MW1 (left), geological cross section (SSW-NNE) as derived from lithological profiles of drillings (middle) and a photo of a nearby outcrop showing a sandy channel in fine-grained host material (right).

SNMR SURVEYS NEAR DAN KHUN THOT

An integrated geophysical survey has been carried out nearby the town of Dan Khun Thot in the Khorat region (Fig. 1, right). This area is characterized by increased land salinization as a probable consequence of deforestation. Saline soil is the origin of various environmental problems, such as freshwater shortage during the dry season, soil degradation and decrease of crop. Geological processes which cause the soil salinization have still to be clarified. Multifrequency EM mapping indicate highly conductive material with resistivities below 5 Ωm near the surface. This was confirmed by well logging in shallow boreholes.

Two SNMR soundings (Fig. 4, left), at 80 m distance from each other, have been conducted near to the monitoring well MW-1 (Fig. 5, left). 1D Inversion results show water contents below 2.5 % in the overburden down to some 20 m (Fig. 4, right). The rapid decrease of bulk water at that depth corresponds to properties of aquicludes. However, geological cross sections derived from boreholes (litholog) show only small portions of water-bearing channels or lenses (2D or 3D structures) of coarse sands and gravel in the clayey host (Fig. 5, left and middle) that are characterized by porosities of about 20 %. As a consequence the 1D porosities determined using SNMR soundings are underestimated. Therefore, a geological setting as presupposed for the standard 1D interpretation of SNMR soundings, is not given at this location.

CONCLUSIONS AND OUTLOOK

The results of SNMR, drillings and other geophysical methods indicate, that the hydrogeological settings in Thailand are much more complicated than for Quaternary (glacial) pore aquifers. Generally, there is a small-scale change of water-bearing and anhydrous material in sediments deposited under arid conditions. When doing SNMR surveys in (equatorial) areas that have large diurnal variations in the geomagnetic field it is often necessary to retune the equipment within a single sounding. In practice this can be time consuming and, therefore, considerably reducing measurement progress. Note, that a field drift encountered while stacking a single pulse will have distorting effects that can not be compensated for. For the Chiang Mai survey area we could successfully confirm the geological model using SNMR measurements. However, the measurements at Dan Khun Thot indicate the limits of the application of the SNMR method in the presence of 2D and 3D water content distributions. In this context Warsa et al. 2002 demonstrate the limits of 1D inversion by forward modeling of simple 2D and 3D situations and Hertrich et al. 2003 suggest an approach for a 2D SNMR field setup using separated loop geometries.

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A REVISED MATHEMATICAL MODEL OF MAGNETIC RESONANCE SOUNDING

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INTRODUCTION

In standard laboratory magnetic resonance experiments, the artificial static magnetic field is perfectly homogeneous throughout the investigated volume. For magnetic resonance sounding (MRS) measurements, the Earth's magnetic field is taken as the static field. In the subsurface, however, this can be locally modified by the rocks and is generally not homogeneous over a large volume. The geomagnetic field may also vary with time. For a typical MRS setup (square loop of 75x75 m), a cube of 100x100x100 m represents the volume investigated by MRS; the duration of one sounding takes from one to several hours. Under these conditions, the geomagnetic field cannot be considered as constant. In the presence of a non-constant geomagnetic field, phase behavior is more complicated than a simple phase shift caused by electrically conductive rocks. This is not taken into account by currently available models and the associated algorithms can thus only use amplitude for interpreting field measurements. Other important characteristics of the MRS signal are longitudinal relaxation time T_1, transverse relaxation time T_2, and the observed relaxation time T_2^*. In porous media, the relaxation times are proportional to the mean pore size. Because of technical difficulties with measuring T_1 and T_2 in large volumes from the surface, only the MRS T_2^* relaxation time, which can be derived from the envelope of the MRS signal, was used initially. Whilst it is known that T_2^* is proportional to T_2, T_2^* is also sensitive to local inhomogeneities in the geomagnetic field caused by rocks, thus rendering parameter T_2^* less reliable than T_1 or T_2 for pore size estimation.

In this paper, an enhanced mathematical model that improves the accuracy of MRS data interpretation is presented.

IMAGING EQUATION

When using the classical model in the coordinate system rotating with an angular frequency $\omega = -\gamma B_0$, the signal induced in the receiver loop is proportional to the sum of the flux of the transverse components of precessing magnetic moments $M_\perp^2 = M_x^2 + M_y^2$. At time

$t=\tau$ after transmitting an alternating magnetic field $\mathbf{B}_1$, the spin magnetization will have the components:

$$M_x=-M_0\frac{\omega_1\Delta\omega}{\omega_{eff}^2}\left(1-\cos(\omega_{eff}\tau)\right),\text{ and } M_y=M_0\frac{\omega_1}{\omega_{eff}}\sin(\omega_{eff}\tau), \qquad (1)$$

with $\Delta\omega=\omega_0-\omega$ being a frequency offset between the Larmor frequency and the pulse frequency, $\omega_{eff}^2=\omega_1^2+\Delta\omega^2$, and $\omega_1=0.5\gamma B_1$. When $\Delta\omega=0$, the M_x component corresponding to the imaginary part of the MRS signal is zero and hence the signal, which is thus proportional only to M_y, is real. Otherwise it is complex. A phase shift of the transmitted magnetic field $\mathbf{B}_1$ caused by the electrical conductivity of the rocks also creates a phase shift of the MRS response. Assuming a coincident transmitting/receiving loop, we can express the phase of the signal generated by volume dV as:

$$\varphi_0=\tan^{-1}(M_x/M_y)+2\tan^{-1}(B_{1x}/B_{1y})=\varphi_{\Delta\omega}+2\varphi_\rho, \qquad (2)$$

where $\varphi_{\Delta\omega}$ and φ_ρ are the phase shifts due to, respectively, the frequency offset and the electromagnetic shift caused by the electrical conductivity of the rocks.

The spectrum of the transmitting pulse typical for MRS instruments shows that the amplitude of the second harmonic is about 20% of that of the first one, and that frequency offset is about 35 Hz. In deep water irradiated from the surface, the flip angle of spin magnetization is small even for the first harmonic. This means that water in deep aquifers mostly responds to the first harmonic and effects of higher harmonics on the MRS signal can be neglected. In water close to the surface, however, the flip angle caused by higher harmonics is significant and here must be taken into account. Consequently, in the case of exact resonance ($\Delta\omega=0$) and non-conductive rocks, the MRS signal generated by deep water may be real; for shallow aquifers, however, more than one harmonic of the pulse that has non-zero frequency offset must be considered and hence the signal is always complex.

We assume the spin system to be linear, which makes it possible to calculate the MRS response using the first few harmonics generated by the pulse. Using the reciprocity theorem and taking into account the resistivity distribution and frequency offset, the induced voltage thus becomes (Legchenko et al., 2003):

$$e_0(q)=\omega_0\int_V\sum_k\left(\frac{B_{1k}(\mathbf{r})e^{j\varphi_{0k}(\mathbf{r})}M_{\perp k}(\mathbf{r})}{I_{0k}}\right)w(\mathbf{r})dV(\mathbf{r}), \qquad (3)$$

where $B_{1k}(\mathbf{r})$ is transmitted by the k^{th} harmonic magnetic-field component perpendicular to the geomagnetic field, $0\le w(\mathbf{r})\le 1$ is the water content, $q=I_0\tau$ is the pulse parameter (I_0 and τ are the amplitude and duration of the pulse respectively) and $\mathbf{r}=r(x,y,z)$ is the coordinate vector.

Numerical modeling shows that if the existing simplified model is used, then under certain conditions the neglect of the complex nature of the MRS signal could lead to interpretation errors, such as incorrectly created or incorrectly eliminated aquifers. Complex signals can only be inverted using the enhanced model. Field measurements confirm these results and reveal a good correlation between theoretical signals obtained using the enhanced model and borehole data.

RELAXATION TIME T_1

It was experimentally shown (Legchenko et al., 2002) that in limestone (magnetization $\approx 10^{-4}$ A/m), the signals from both free and capillary-bound water were relatively long ($T_2^* > 70 \div 80$ ms), considering the threshold of the MRS instruments (30 ms). On the contrary, in basaltic gravel (magnetization $\approx 10^{-1}$ A/m), even the signal from free water was very short ($T_2^* \approx 10$ ms) and, therefore, could not be measured with a standard MRS instrument. Thus, the sensitivity to magnetization of the rocks limits the reliability of T_2^* as a parameter for estimating hydraulic conductivity and encourages the application of T_1 or T_2.

The saturation recovery method (Dunn et al., 2002) was adapted to MRS measurements. Two pulses are applied to the investigated volume and, after the first pulse, the spin magnetization **M** of the sample dV is turned off at the angle θ. During the delay τ_p, it builds up towards equilibrium along the geomagnetic field with the time constant T_1. Assuming the spin system to be linear, and neglecting relaxation during the pulse, ($\tau << T_2^*, T_2, T_1$), the perpendicular to the Earth's magnetic field component of the spin magnetization after the second pulse can be described by the equation:

$$M_\perp(\tau_p) = M_0 \exp(-\tau_p / T_1) \sin(\theta + \theta_2) + M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta_2), \qquad (4)$$

where θ_2 is the flip angle caused by the second pulse. If both pulses are set to be equal ($q_1 = q_2 = q$) and the phase shift between the current of the second pulse is equal to π relative to the current of the first pulse, then $\theta_2 = -\theta$ and Equation 4 can be simplified to:

$$M_\perp(\tau_p) = -M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta). \qquad (5)$$

For calculating the amplitude of a MRS signal measured after the second pulse, Equation 3, which describes the amplitude after the first pulse will be replaced by:

$$e_{02}(q,\tau_p) = \omega_0 \int_V \sum_k \left(\frac{B_{1k}(\mathbf{r}) e^{j(\varphi_{0k}(\mathbf{r})+\pi)} M_{\perp k}(\mathbf{r},\tau_p)}{I_{0k}} \right) w(\mathbf{r}) x(\mathbf{r}) dV(\mathbf{r}), \qquad (6)$$

where $x(\mathbf{r}) = 1 - \exp\left(-\tau_p / T_1(\mathbf{r})\right)$. Resolution of Equation 3 can provide the water content $w(\mathbf{r})$ and then, $T_1(\mathbf{r}) = -\tau_p / \log(1 - x(\mathbf{r}))$ can be derived from Equation 6.

For demonstration, normalized amplitudes measured at two sites versus the delay τ_p are shown in Figure 1. As expected, a longer T_1 was observed at the site where the aquifer has a higher yield.

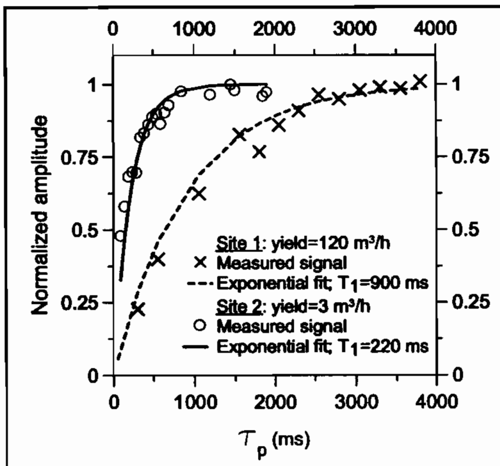

Fig. 1. Example of T_1 measurements.

CONCLUSIONS

Thus, the accuracy and reliability of MRS results can be improved by taking into account the frequency offset between the pulse frequency and the Larmor frequency and the few first harmonics of the pulse for modeling the MRS response, and by replacing measurements of T_2^* by T_1 for estimating hydraulic conductivity.

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INDUSTRIAL NOISE AND PROCESSING OF THE MAGNETIC RESONANCE SIGNAL

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INTRODUCTION

One of the major limitations of the magnetic resonance sounding (MRS) technique is its sensitivity to natural and man-made noise. Indeed, an alternating magnetic field produced by the precession of proton magnetic moments in groundwater varies between 10^{-12} and $4x10^{-9}$ T. The voltage created by this magnetic field (MRS signal) varies between 10 nV and 4000 nV when using a wire loop of 100 m diameter as a receiving antenna and, contrary to many geophysical techniques, the signal cannot be amplified by increasing the transmitter power. The frequency of the magnetic resonance signal (the Larmor frequency) is directly proportional to the magnitude of the geomagnetic field, and varies between 800 Hz and 2800 Hz around the globe.

ELECTROMAGNETIC NOISE GENERATED BY ELECTRICAL POWER LINES

A special field study was undertaken in order to learn more about industrial noise (Legchenko and Valla, 2003). The frequency range of interest for the MRS method is between 800 Hz and 2800 Hz, which corresponds to worldwide variations of the Larmor frequency set by the Earth's magnetic field. The study was carried out mainly in areas where the Larmor frequency is around 2000 Hz, but it is unlikely that this had any effect on the general nature of the results. The field data were recorded in France and abroad; the field data presented in this paper were acquired at three sites in France, one in Israel, one in the Netherlands and one in the USA.

A first appraisal of noise can be made by computing its amplitude as $\eta = \frac{1}{N} \cdot \sum_{i=1}^{N} \sqrt{X_i^2 + Y_i^2}$, where N is the number of samples in a noise record after the synchronous detector (channels X and Y). An example of noise measurements in France is shown in Figure 1. At each site, 40 consecutive 1000-ms-long records of the noise were made, at about ten-second intervals. The sampling rate was 2 ms, which makes N=500. It can be seen that even at the same test site the noise magnitude was not stable and can vary by a factor greater than two.

Industrial frequency stability is the keystone of power-line noise filtering techniques. In order to check the stability assumption, measurements were made of power-line harmonic frequencies in the investigated frequency range (37^{th} harmonic in Israel, 40^{th} in France, and 41^{st} in the Netherlands). It can be seen (Figure 2) that the frequencies vary from one record to another, but that instability is site-dependent, with the largest variations being observed in Israel. Such marked instability of industrial frequency is, in fact, very unusual and there is no clear reason why it occurs. However, even in the same country (France, Sites 1 and 2), the frequency estimates show a certain degree of instability (variations around 0.5 Hz and even higher), which can be explained partly by instability of the power-line fundamental frequency, and partly by noise influencing the accuracy of the estimation.

The proportion of 50 Hz harmonics in the noise spectra was also calculated (Figure 3). In order to diminish the spectral leakage effect caused by limited resolution of the Fourier transform on the accuracy of the estimation, the +/-1 Hz bandwidth around each harmonic was taken into account for the calculations. It was found that, depending on the site, the power-line harmonics represent only 20% to 50% of the noise energy within the +/-150 Hz bandwidth centred at about 2000 Hz. This high percentage of non-stationary noise observed in the vicinity of power lines may be explained by the fact that in the investigated frequency range, the most energetic (and probably more stable) lower harmonics are filtered out and only the higher harmonic numbers (20 to 55) are used. It is also possible that power lines, being long conductors, act as electromagnetic antennae and channel both man-made and natural electromagnetic noises from a large area, thus amplifying the grossly random background noise, especially on the vertical magnetic component that is measured with the MRS loop.

FILTERING TECHNIQUES

The efficiency of the well-known notch-filtering method was compared with the subtraction technique developed by Butler and Russell (1993) for processing seismo-electric measurements. This technique is capable of suppressing stationary power-line noise without distorting or attenuating the signal of interest. It involves subtracting an estimate of the harmonic component, with two different ways of estimating the component.

For practical implementation of the block subtraction method, it is assumed that the noise is regular and largely dominant over the signal (otherwise, filtering would not be needed) and, therefore, that non-stacked signal records are mostly noise. The strategy consists in selecting the time shift τ so that the noise sample *B(t)* from a noise record, and the sample *A(t)* that contains both signal and noise, are as similar as possible. An ideal sample rate would be an integer multiple of 50 Hz. However, the approach assumes stability and regularity, for at least a few seconds, of industrial noise generated by sources such as power lines.

The sinusoid subtraction technique is based on the representation of power-line noise as harmonics superimposed on the fundamental frequency (50 Hz or 60 Hz). The harmonic component is estimated from noise records and then subtracted from records containing both the signal and noise. The frequency of power-line harmonics, being relatively unstable, should not be determined by simply multiplying the fundamental frequency value by an integer number. During fieldwork, estimates must be made from the records, not only of the amplitude and phase of power-line harmonics, but also its frequency. When applying this technique to MRS signal filtering, it should be kept in mind that the harmonics farthest from the Larmor frequency f_0 are filtered out by the low-pass filter and do not influence MRS measurement accuracy. The few interfering harmonics (usually three, but sometimes five) are close to f_0. In the NUMIS system, synchronous detectors (3 or 5) are used for estimating power-line harmonics (amplitude, phase and frequency) using the non-linear fitting (Legchenko and Valla, 1998). For each synchronous detector, the reference frequency is set equal to one of the few fundamental harmonic frequencies close to the Larmor frequency: $f_{sd}^{k} = 50k$.

In order to complete the study, investigations were carried out on the efficiency of the notch filtering technique. This method is less sensitive to power-line harmonics instability, but introduces some distortion, the extent of which, for magnetic resonance records, depends upon the relative shift between the Larmor frequency and the harmonic frequencies, and also upon the relaxation time of the signal. When designing a low-pass filter for the MRS system, it should be kept in mind that the relaxation time of the magnetic resonance signal T_2^* varies typically from 40 ms to 400 ms and this determines the bandwidth of the filter. The Larmor frequency cannot be considered as constant, because it is affected by geomagnetic field variations within the volume investigated by MRS and also is unstable over time, and hence the bandwidth of the filter must be increased to about 4 Hz. The notch filter is centred on the power-line harmonic frequencies; as these are known only approximately, the filter cuts out +/-1Hz bandwidth around each harmonic. A combined filter, consisting of a low-pass filter centred on the Larmor frequency and a +/-1 Hz notch filter centred as close as possible to the harmonic of the fundamental frequency, is depicted in Figure 4 (dashed line). It should be noted that the notch filter removes between 3 and 5 harmonics, but they are not shown. Whilst the sinusoid subtraction method subtracts the estimates of power-line harmonics without distorting or attenuating the signal of interest, the notch filter always cuts out a narrow frequency band and, therefore, the signal may be deformed.

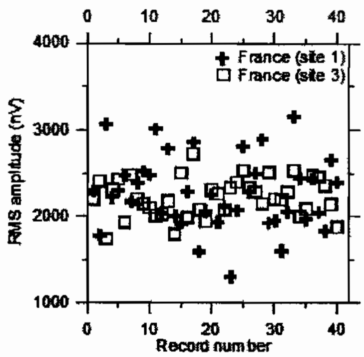

Fig. 1. Variations in the magnitude of power-line noise.

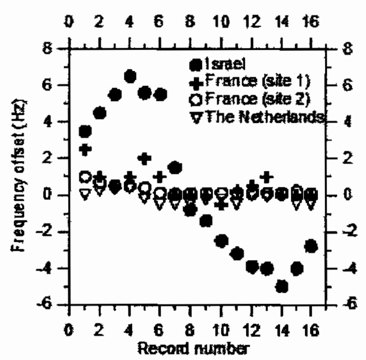

Fig. 2. Frequency of power-line harmonics.

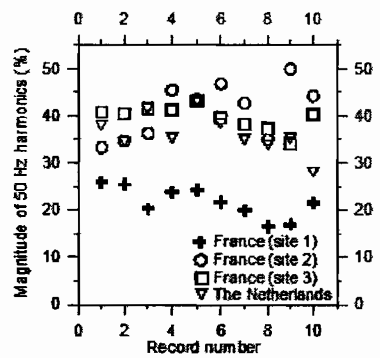

Fig. 3. Proportion of 50 Hz harmonics in the total noise.

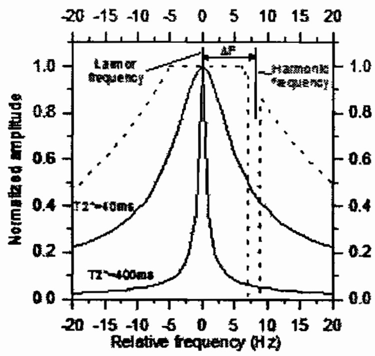

Fig. 4. Spectra of the exponential signal (solid lines) and combined low-pass and notch filter (dashed line).

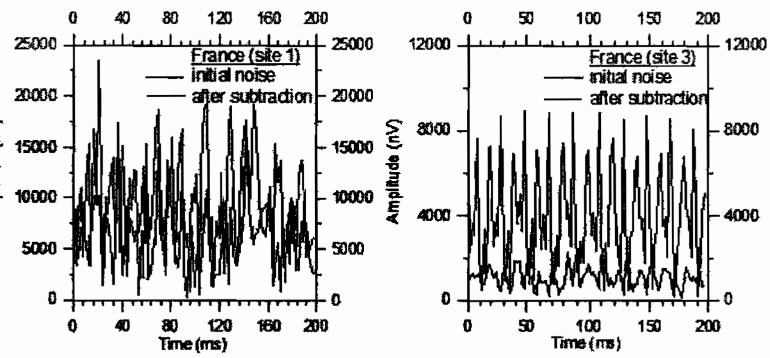

Fig. 5. Examples of the block subtraction application.

RESULTS

The efficiency of block subtraction can be demonstrated using two different noise records made in France (Figure 5). If the proportion of 50 Hz harmonics in the power-line noise recorded at Site 1 (about 20%) is compared with that of Site 3 (about 40%) (Figure 3), it can be concluded that the block subtraction method gives better results when the percentage of 50Hz harmonics (regular part) is greater. This conclusion matches exactly that of Butler and Russell (1993) concerning the efficiency of the block subtraction technique for the 0.1-1000

Hz frequency range. Independently of the filtering technique, the efficiency of the noise filtering depends on the test site. The best results are obtained at sites where the noise contains the largest percentage of 50 Hz harmonics. At the same site, notch filtering appears to be the most efficient for noise reduction as it cuts out the largest bandwidth. The sinusoid subtraction and the block subtraction are respectively less efficient. However, it should be remembered that when the Larmor frequency is close to one of the power-line harmonic frequencies ($\Delta F \rightarrow 0$), notch filtering might also distort the signal of interest. So, depending on the noise and the frequency offset, a compromise must be made between removing the noise and keeping the signal undisturbed so that signal parameters can be estimated. Based on experience gained to date, the rule for selecting the filtering method is proposed in Table 1:

Filter	T_2^*=100 ms	T_2^*=200 ms	T_2^*=400 ms
+/-1 Hz notch filter	ΔF>4 Hz	ΔF>6 Hz	ΔF>8 Hz
Sinusoid subtraction	ΔF<4 Hz	1<ΔF<6 Hz	2<ΔF<8 Hz
Block subtraction	ΔF<1 Hz	ΔF<1 Hz	ΔF<2 Hz

Table.1. Rule of selection for the filtering technique.

Figure 6 shows NUMIS records (after the synchronous detector) made with the same value of the pulse parameter containing both the signal and the noise with a different number of stacks and different filtering. It can be seen that application of notch filtering allows signal recovery using 10 stacks with about the same degree of accuracy as using 200 stacks without notch filtering.

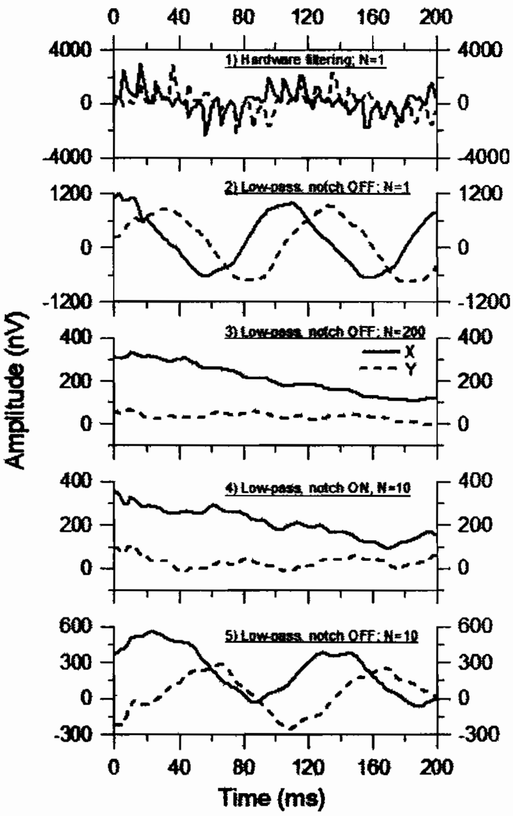

Fig. 6. Field example: filtering of signal records.

CONCLUSIONS

As the percentage of 50 Hz harmonics in the power-line noise is site dependent, the efficiency of filtering schemes based on the assumption of noise stability and regularity are also site dependent; the more regular the noise, the more efficient is the filtering. Three existing filtering methods; block subtraction, sinusoid subtraction and notch filtering were applied to magnetic resonance records. It was found that notch filtering was the most efficient, but it distorts the signal of interest when the frequency offset between the Larmor frequency and one of the power-line harmonics is smaller than 8 Hz. In this case the subtraction techniques are preferable.

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MRS CONTRIBUTION TO HYDROGEOLOGICAL PARAMETERIZATION

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INTRODUCTION

Hydrogeological system parameterization is a critical issue in modern regional, water resources management and planing but also in small-scale water resources projects. In such activities the standard hydrogeological investigations are required, which normally include drilling of investigation boreholes providing hydrostratigraphy of the system and pumping tests providing storage and flow parameters. The new hydrogeophysical method called Magnetic Resonance Sounding (MRS) provide such data as complementary (not alternative yet), valuable and cost effective tool next to the standard hydrogeological methods. The MRS as the only geophysical method is water selective and is capable to provide depth dependent information contributing to hydrogeological system parameterization. The two types of MRS output parameters, free MRS water content (Φ_{MRS}) and decay time constant (T_d) provide the two types of hydrogeological parameters, storage related parameters and flow related parameters respectively. The nature, complexity and applicability of the two MRS output parameters and their relations with hydrogeological parameters are the main scope of this paper.

HYDROGEOLOGICAL PARAMETERIZATION WITH Φ_{MRS}

Regarding a soil-rock-water relationship, there are substantial differences in terminology between disciplines of hydrology, soil science and geophysics, particularly with respect to the terminology of the least defined microscopic processes at the pore-water contact. Therefore in order to "translate" Φ_{MRS} into storage related terms the issue of the subsurface MRS water storage concept is discussed and presented in Figure 1.

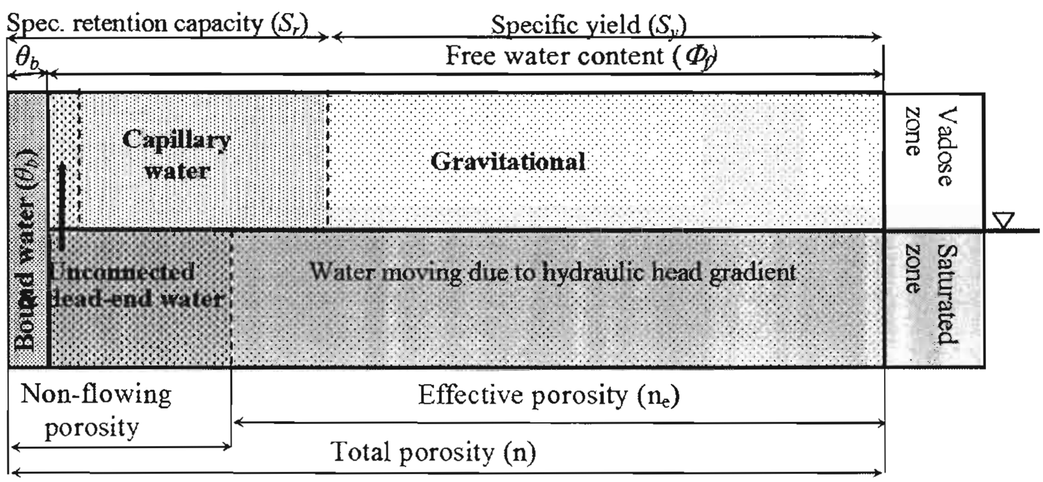

Figure 1. Aquifer storage concept – modified after Lubczynski and Roy (2003).

Free water content (Φ_f) is the percentage of water that is outside field of molecular forces of attraction of the solid particles that can be displaced by gravity or pressure gradients, with respect to the total rock volume. Bound water (θ_b) in contrast to free water is the amount of water attached to the solids by molecular forces of attraction, non-removable by gravity and/or hydraulic head gradient forces but removable by centrifugal action at acceleration 70 thousand times exceeding the acceleration of gravity. The thickness of bound water film surrounding a solid (~0.5 μm) varying with size, area and types of the mineral grains, depends on the strength of molecular forces of attraction and therefore is correlated with T_d. The exact relation is not known yet because the very short signals <30 ms are not measured yet with the current MRS instrumentation. It is however widely accepted that the measured signals after the 30 ms dead-time (current instrumental characteristic), have a decay rate corresponding to free water ($\Phi_{MRS} \cong \Phi_f$).

The hydrogeological system introduced schematically in Figure 1 consists of saturated part (aquifer) showed in the lower part of the graph and of the unsaturated part (vadose zone) showed in the upper part of the graph. In the saturated zone the free water content (Φ_f) consists of the effective porosity (n_e) part occupying fraction of the rock with water free to flow and of the part related to unconnected and dead-end porosity. The free water porosity flow in microscopic processes refers to the continual exchange of molecules from one phase to the other through molecular Brownian motion. For example, a circulating molecule may become immobilized in the course of its progress, while another one that was originally immobile may be set in motion (Marsilly, 1986). Dead-end porosity (fractures and micro-joints but also non-flowing karstic cavities etc.) often plays an important role in karstic and hard rocks while unconnected pores are abundant in volcanic and karstic rocks. In unconsolidated sediments the role of unconnected and dead-end porosity is negligible or can even be disregarded. If the MRS sounding is performed over the rocks where the dead-end and unconnected porosity can be neglected, Φ_f and therefore Φ_{MRS} as well, can be directly interpreted as n_e.

The saturated part of the aquifer can be de-saturated by natural lowering of groundwater table or by well abstraction. In such cases the gravitational water (water that can be released by gravity forces) is released from the system either by natural drainage or by well pumps. The amount of water released from the aquifer storage due to the gravity forces is characterized by specific yield (S_y). The amount of water remained immediately after de-saturation is described by specific retention capacity (S_r), in soil science also known as moisture at field capacity (θ_{FC}). The S_r consists of bound water (θ_b) and a portion of free water retained against gravity forces (θ_f). The θ_f is composed of free capillary water and unconnected and dead-end pore water. The capillary water represents the main part of the free water resistant to gravity release and sensitive to hydraulic head difference, which "wets" the solids (air stays in the middle of the voids) due to the surface tension forces. The quantity of unconnected and dead-end water in overall θ_f is usually negligible although in some secondary porosity rocks it can be important.

Under the assumption of $\Phi_{MRS} \cong \Phi_f$, S_y can be calculated from $S_y = \Phi_{MRS} - \theta_f$ (Figure 1). Practical definition of θ_f is cumbersome (unless determined by MRS on the de-saturated part of the aquifer – see below), so instead the use of S_r defined by hydrogeological methods seems to be convenient although only with regard to rocks where θ_b can be neglected. By applying S_r instead of θ_f it is expected that the Φ_{MRS} measurements provide the entire spectrum of water content including bound water. In practice this is not the case yet because current instrumental limitations do not allow for measurements of signals <30 ms covering the main spectrum of θ_b. In most of the water resources application focusing on coarse and permeable rocks, this is however not a big problem because such rocks usually have negligible θ_b permitting the assumption of $\theta_f \cong S_r$ and therefore determination of only slightly underestimated S_y (by amount of θ_b) according to the formula $S_y = \Phi_{MRS} - S_r$.

In many hydrological applications such as e.g. groundwater recharge assessment, not only S_y but also S_r is critical. As mentioned S_r can be defined by standard hydrological methods but also with MRS. This can be done in situ, by analyzing Φ_{MRS} immediately after de-watering of an aquifer at the scale comparable with the volume investigated by MRS. In such case $S_r \cong \Phi_{MRS}$

In confined aquifers, water storage consists of the elastic component called elastic storativity (S_e) and the gravitational component named by Lubczynski and Roy (2004) as specific drainage (S_d). The elastic water release is related to the water expansion and aquifer compaction attributed to aquifer pressure changes and is not directly detectable by MRS. It can however be calculated indirectly by applying MRS originated porosity (n – slightly underestimated with MRS by disregarding θ_b) to standard hydrogeological formula $S_e = S_s \cdot D = \rho_w g(\alpha + n\beta)D$, where not only n but also D (aquifer thickness) can be estimated by MRS. The other parameters such as ρ_w - density of water; g – acceleration of gravity; α - compressibility of the aquifer skeleton; β - compressibility of the water can be estimated by other data sources. The specific drainage (S_d) is the volume of water that could be potentially released from the confined aquifer by gravity forces if piezometric surface fell below the bottom of the confining layer creating unconfined conditions. That storage term is detectable by MRS and can be estimated from the formula $S_d = \Phi_{MRS} - S_r$ applying the same assumptions as used in S_y determination.

In the geophysical inversion Φ_{MRS} is determined at certain depth intervals; the larger the h/L ratio (h: investigation depth, L: loop size), the larger the influence of equivalence error in the inversion results. The most reliable quantitative interpretation of water content at the certain analyzed depth intervals can be done by integrating the product of $\Phi_{MRS} \cdot D = H_w \cong \Phi_f \cdot D$ with depth, where H_w is a free hydrostatic column of water. H_w can be estimated for single layers of interest like aquifers but also for the arbitrary depth intervals including the entire investigation depth.

HYDROGEOLOGICAL PARAMETERIZATION WITH T_D

The second important MRS output parameter decay time constant (T_d) provides the information on how mobile (extractable) is ground water and therefore it is used for parameterization of hydraulic conductivity (K) and aquifer transmissivity (T). In contrast to - storage parameterization with Φ_{MRS}, determination of hydraulic conductivity and aquifer transmissivity is only possible after establishing site (rock) specific regression functions with parameters obtained from hydraulic tests i.e. pumping tests.

In general there are three schemas of T_d measurements: T_1 (longitudinal relaxation), T_2 (transversal relaxation) and T_2^* (free induction decay time constant) schemas. In MRS so far only T_2^* and T_1 schemas are available and both can be used for K and T parameterization. According to Legchenko et al. (2002) however, T_1 schema is more accurate because it is less influenced by magnetic field inhomogenity.

The field MRS experiments indicates a good relationship between T_d and rock pore size (ratio of the pore volume to surface area) correlated with K. T_d increases proportionally with the pore size from about 30 ms in clays to 400-600 ms in coarse materials (e.g. gravels). This dependence is described by the empirical formula $K = C\, \Phi_{MRS}^a\, T_d^b$ where C, a and b are the empirical parameters to be calibrated in the field by comparison with K values obtained from pumping tests. Parameters C, a, b are site specific.

Since both MRS and pumping test experiments provide information volumetrically with depth (z), the integration of K with depth seems to be the most suitable procedure for transmissivity evaluation. In this particular way various types of rocks such as limestones with sands and clays, fractured diorites and fractured gneisses were investigated by Legchenko et al., (2002) by comparing MRS related T calculated as $T = C_1\int_{\Delta z} \Phi_{MRS} T_d^2 dz$ (a = 1; b = 2) and $T = C_2\int_{\Delta z} \Phi_{MRS}^4 T_d^2 dz$ (a = 4; b = 2) according to T_2^* and T_1 schemas with corresponding pumping test transmissivities. The best correlation was obtained with T_1 schema while using the formula with coefficients a = 1 and b = 2. However, for double porosity sandstones, a number of NMR logging and laboratory experiments showed a = 4 and b = 2 to be the most accurate coefficients (Sen et al., 1990) whereas for unconsolidated glacial rocks in Germany, Yaramanci et al., (2002) found b = 4 to be the most accurate coefficient. In this regard, recently, also Vouillamoz (2003) have made significant contribution making substantial amount of MRS and pumping test experiments with series of empirical correlations between MRS field responses and the corresponding pump test results. However, still more of such experiments in various hydrogeological conditions are needed to establish generic guidelines for appropriate use of parameters a, b and C for K and T determination in various rock types with various hydraulic porosity models.

CONCLUSIONS

Φ_{MRS} can contribute to the definition of the following hydrogeological porosity/storage related parameters: effective porosity, porosity, specific yield, elastic storage, specific storage, specific drainage, specific retention capacity and hydrostatic water column.

Only one empirical, site specific relation applying combination of T_d and Φ_{MRS} is available so far to calculate K. T is best calculated by integration of K with layer depths, which is also provided by MRS.

The advantage of MRS system parameterization over the standard hydrogeological parameterization methods relates to the MRS data integration from larger volume than in most of hydrological methods. The comparable in volume pumping test experiments are substantially more costly than MRS experiments.

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EXPERIMENTAL STUDY OF A CHALK FORMATION USING MAGNETIC RESONANCE SOUNDINGS (MRS) AT LE BOIS DE CIZE, NEAR AULT (PICARDY, FRANCE)

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INTRODUCTION

In coastal areas of France where chalk makes up the shore line (Picardy, Normandy), knowledge of its mechanical stability is important in evaluating the risk of natural hazard. The presence of water within chalk has a consequence on pore pressure, whereas the amount of water can influence the rock's mechanical characteristics. Water content thus constitutes one of the major parameters controlling collapse mechanisms.

Within the framework of the ROCC programme, nine MRS measurements (T1 to T9) were carried out along a profile perpendicular to the chalk cliff at the 'Le Bois de Cize' site near Ault (Figure 1). The aim of this survey was to test the efficiency of MRS in characterizing chalk aquifers and locating internal inhomogeneities in the chalk by mapping the water content from the surface.

Other geophysical investigations and boreholes reveal that the subsurface is composed of 5 to 10 m of clay, underlain by weathered chalk down to 30 m, and fresh chalk beneath. The chalk structure in the unsaturated zone is laterally very inhomogeneous: ranging from rather compact to karstified rocks.

RESULTS

During this survey, the NUMIS system of IRIS-Instrument was used. As the noise conditions varied along the profile, three out of nine soundings were carried out using a figure-of-eight shaped loop (Trushkin, *et al.*, 1994) with 56-m sides for each square. The depth of investigation with this loop is about 60 m. For other soundings, a 75-m-side square loop was used, giving a depth of investigation of about 100 m. The field data were inverted using the well-known Tikhonov regularization method, which provides a quasi-continuous solution (Legchenko and Shushakov, 1998).

It is known from previous experience (Legchenko *et al.*, 2002) that where the subsurface is composed of chalk or limestone, MRS can detect not only aquifers (free water), but also water in the unsaturated zone (bound water). When water in the unsaturated zone is the target, the relaxation time of the MRS signal T_2^* is usually short ($T_2^* < 80$ ms), which is comparable with the typical pulse duration for the NUMIS system ($\tau \approx 40$ ms). Under these conditions, a quantitative interpretation of the water content requires a model that takes into account the relaxation during the pulse. However, currently available models were developed with the assumption of $\tau << T_2^*$, which obviously is not respected for short signals. Consequently, MRS water content estimates provide only relative variations of water content in the subsurface. When the investigated object is a lateral heterogeneity of the water content distribution in the subsurface, MRS can be readily used. For a quantitative estimation of water content, however, the MRS results should be calibrated.

In full accordance with previous experience, the field measurements reveal very short MRS signals from bound water in the chalk. The relaxation time T_2^* varied from 25 to 130 ms along the profile. Shorter values correspond to shallow parts of the MRS log, and water in the aquifer (about 30 m deep) produces longer signals. For all soundings, the MRS response was estimated as $E_{mean} = \int_T e(t)dt$, where $e(t)$ is the amplitude and T is the recording window. Mean amplitude (E_{mean}) was used as it is considered as a more stable parameter than amplitude for comparing different soundings, especially when the relaxation time is short. Results of E_{mean} measurements against the pulse parameter are presented in Figure 2. These soundings with varying amplitude indicate that the distribution of water in the subsurface is very heterogeneous, which corresponds well to other data.

The inversion results of amplitude and relaxation time are presented in Figure 3.

The water-content cross section (Figure 3a) shows a significant amount of water above the static water level. Consequently, based only on the water content, it is not possible to distinguish between an aquifer and the unsaturated zone. Variations in the water content in the unsaturated zone, accompanied by short relaxation times, may correspond to variations in the chalk structure (compact or weathered chalk). Water in the aquifers is characterized by longer relaxation times.

The decay-time cross section (Figure 3b) shows that the water level detected by MRS (longer relaxation time) lies at a depth of 30 to 40 m in the southeastern part of the profile, and that it appears to drop suddenly to 55 to 60 m about 400 m from the cliff edge. These results are coherent with a) regional knowledge that the water level is about 40 m below the surface on the chalk plateau, and b) the borehole drilled 120 m from the cliff edge showing a water level at a depth of 73 m. The sudden drop in the water level could be related to a small valley named "Deuxième Val" on the IGN map (Figure 1), and which may reflect a preferential drainage structure that could be the cause of water-table depression.

CONCLUSIONS

This first attempt to apply the MRS method to investigating water-content distribution in weathered chalk proved promising. The results show that the method is able to locate aquifers below the static water level, and that it is sensitive to variations in the water content throughout the unsaturated zone and thus can be applied to subsurface characterization above the static water level.

Measuring the amplitude of MRS signals could enable the identification of lateral inhomogeneities in the water distribution throughout the chalk and that could be associated with variations in the rock's mechanical properties.

As the relaxation time of the MRS signal is comparable with pulse duration, quantitative estimation of the water content requires development of a mathematical model that takes into account the relaxation during the pulse. Otherwise, only relative variations of the water content can be derived from MRS measurements. It is possible, however, that some empirical relationship could be established between MRS estimation of the water content and its true values, thus providing realistic estimations of water content from MRS data.

Since the geometry of the chalk is often in 3D rather than 2D or 1D, errors when applying 1D inversion should be expected.

Additional field and laboratory study is necessary for calibrating the water content derived from MRS data.

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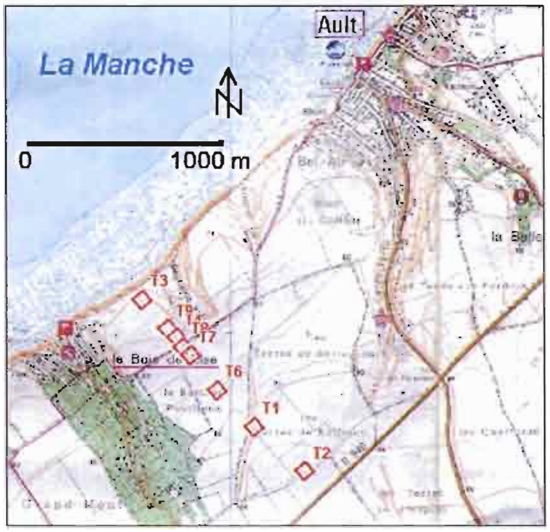

Figure 1. Location map of the MRS sites.

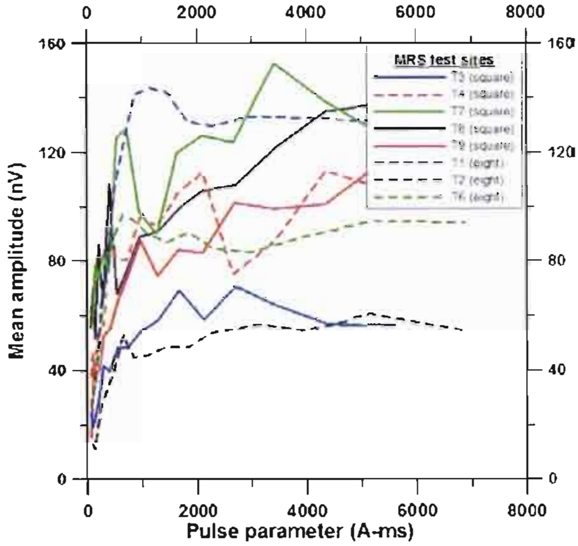

Figure 2. MRS signals.

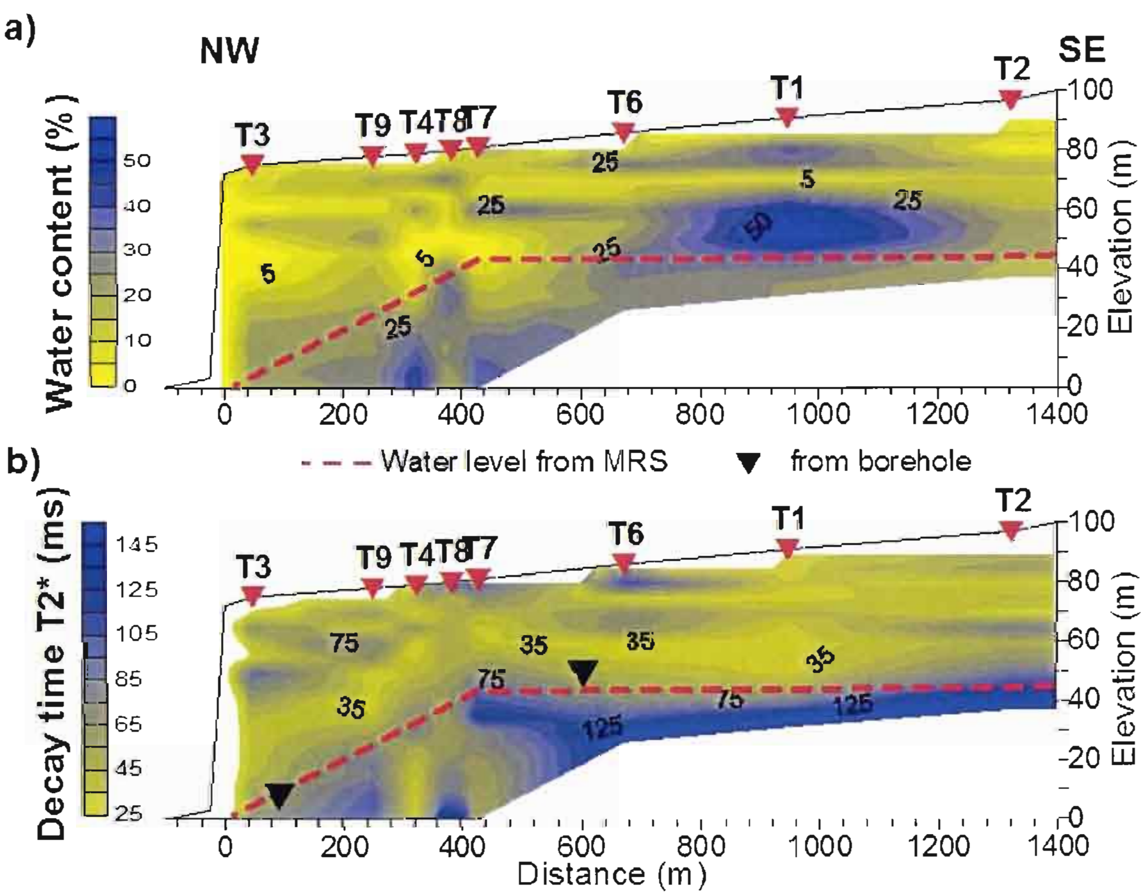

Figure 3. MRS cross sections of a) water content and b) decay time

SPECTRAL INVERSION AND INTERPRETATION OF SURFACE NUCLEAR MAGNETIC RESONANCE DATA

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INTRODUCTION

The surface nuclear magnetic resonance (SNMR or magnetic resonance sounding, MRS) method is a non-invasive geophysical method that allows direct determination of the bulk water distribution in the subsurface. In SNMR the hydrogen protons in the pore water are excited with an artificial magnetic field, generated by an antenna loop on the surface. The loop is energized by an alternating current oscillating with the local Larmor frequency ω_L of the protons. After termination of the exciting pulse, the magnetic field due to the relaxation of hydrogen protons is measured. The initial amplitude E_0 of the relaxation signal is directly proportional to the amount of water. The decay time constant T (spin-spin-relaxation time) is linked to the effective pore size. The signal phase is related to the electrical conductivity of the layers. Increasing the intensity of excitation, e.g. the pulse moment q, by raising the duration or strength of the exciting pulse increases the depth of investigation [1, 2].

INVERSION OF SNMR DATA

So far SNMR is only used in sounding mode and the inversion of SNMR data mainly concentrates on the interpretation of the water content distribution. Thereby, the standard inversion of the decay time T is done by fitting only a single relaxation constant (mono-exponential fit), i.e. assuming a mean pore size for each inversion layer [3, 4]. The envelope amplitude $E(t,q)$ of the SNMR relaxation signal for a vertical distribution of the water content is then given by

$$E(t,q) = E_0(q)\exp(\tfrac{-t}{T(q)}) = \int f(z)\exp(\tfrac{-t}{T(z)})K_{1D}(q,z)dz\,. \qquad (1)$$

The kernel function K_{1D} states the 1D subsurface NMR response sensitivity. f(z) is the water content for an unit layer at the depth z. This expression, however, often does not comply with the hydrogeophysical properties of the subsurface. In analogy to borehole and laboratory NMR we introduce a new approach to the inversion of SNMR data in terms of decay time spectra analysis, i.e. a multi-exponential fitting of the SNMR relaxation signals. This will allow an improved characterization of an aquifer with respect to its pore radii distribution. The total water content distribution is then given by the superposition of N individual water content distributions, each correlated to a characteristic decay time constant T_i, i.e. pore sizes, within a given spectrum (multi-exponential distribution). Thus, equation (1) can be written as

$$E(t,q) = \sum_{i=1}^{N}\left[E_{0_i}(q)\exp(\tfrac{-t}{T_i\,(q)})\right] = \int_V \sum_{i=1}^{N}\left[f_i(z)\exp(\tfrac{-t}{T_i\,(z)})\right]K_{1D}(q,z)\,dz\,. \qquad (2)$$

Using a predefined decay time spectrum, e.g. decay times T_i ranging from 10 to 1000 ms with 10 sampling points per decade, the corresponding amplitudes $E_0(q,T_i)$ are optimized. This yields individual SNMR sounding curves for each $T_i(q)$ reflecting a water content distribution associated to a corresponding pore size. When simultaneously fitting all measured relaxation curves of a SNMR sounding, the integral character of the method, i.e. smooth sounding curves, can be implemented in the inversion as a constraint parameter. This reduces ambiguity and yields a geologically more plausible water content distribution. However, the SNMR signal is of a complex nature, i.e. signal phase $\neq$ 0, and the SNMR phase is not fully understood, as yet. Therefore, so far only the magnitude of SNMR signal is used for inversion of SNMR field data. The incorporation of complex signal information, as it is the aim of present research, will considerably improve interpretation of SNMR data, especially for the application of a spectral/multi-exponential inversion of relaxation curves.

FIELD CASE

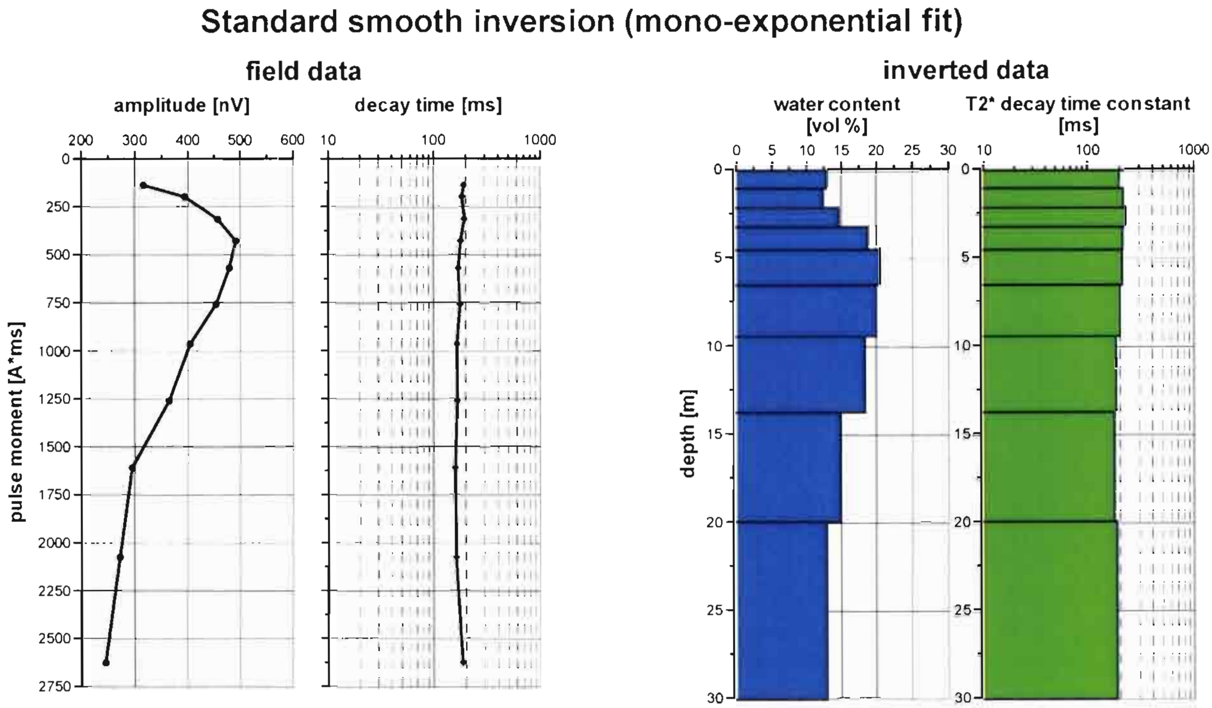
For an initial comparison of the standard interpretation (mono exponential fitting) of SNMR data and the spectral approach (multi-exponential fitting) a data set (circular-8-loop, 1 turn, diameter of loop segments: 50 m) from the Nauen site has been inverted using both schemes. The geology of the Nauen site mainly consists of an interbedding of Quaternary sands. The water table is at a depth of about 3 m. Geoelectrics and GPR indicate the lower boundary of the aquifer (medium sands) at 12 - 13 m depth. Results from core analysis show total porosities of about 30 - 35 % with about 23 – 28 vol.% of mobile water within the aquifer [5].

Fig. 1a shows the fitted SNMR sounding curve using conventional smooth inversion (mono-exponential fit). The data fit shows a signal maximum at an excitation intensity of 470 A.ms of 488 nV and decay times in the range of 195 ms for the aquifer and about 170 ms for the aquiclude. The inversion results presented in Fig. 1b confirm an aquifer between 2-3 and 12-14 m. However, the interpreted water content of about 20 vol. % within the aquifer slightly less then the results from core analysis. Inversion of decay times show no significant variation between aquifer and aquiclude.

The results of the spectral data fit and inversion results are plotted in Fig. 2. The inversion was carried out using a modified block inversion scheme [4]. In this case we used a decay time spectrum having a range of 10-1000 ms and 10 sampling points per decade. Besides the standard representation of SNMR sounding curves (Fig. 2a, left) the fitted data is plotted as it is used in laboratory- and borehole-NMR (Fig. 2a, right). Block inversion yields a three layer case (Fig. 2b, left) with an aquifer between 3 and 13 m depth. The inverted total water content of 25 vol. % corresponds well with the results from core analysis. Fig. 2b, right shows the spectral distribution of the water content. Here, the upper two layers show a dominant decay time at about 250 ms, whereas for the third layer (aquiclude) the water content is mainly associated with decay times of about 150 ms, indicating smaller pore sizes of the host material.

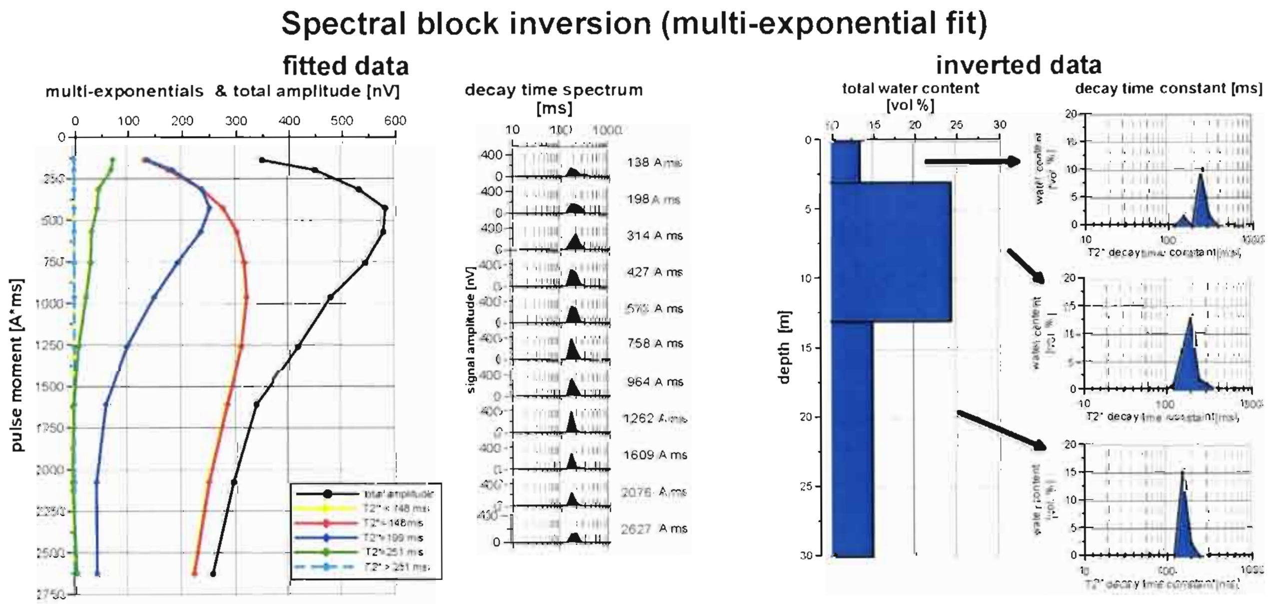
The inverted layer boundaries for both inversion schemes are generally in good agreement with results from other geophysical surveys carried out at this site [5]. However, the block inversion allows a better interpretation of the known sharp boundaries of the aquifer.

The standard inversion yields only small decay time differences between aquifer and aquiclude (difference between mean decay times $\Delta T \sim 30$ ms). Spectral inversion shows a more distinct discrimination between those two geological units with respect to decay times (difference between dominant decay times $\Delta T \sim 100$ ms). However, the decay times expected for aquiclude properties ($T < 100$ ms) as given by [1] were not fully attained. This is due to a data quality of the sounding being to low for a reliable interpretation of SNMR data in terms of decay time spectra.



a) b)

Fig. 1: a) Mono-exponential data fit of SNMR sounding curve from Nauen. (Acquisition parameters: circular-8-loop D = 50 m, 1 turn, frequency 2084 Hz). b) Standard smooth inversion results: total water content (left) and decay times (~ pore sizes).



a) b)

Fig. 2: a) Multi-exponential data fit (10 decay time constants per decade) of SNMR sounding curve from Nauen. (Acquisition parameters: circular-8-loop D = 50 m, 1 turn, frequency 2084 Hz). b) Spectral block inversion results: total water content (left) and distribution of water to characteristic decay times (~ pore sizes).

CONCLUSION

SNMR relaxation signals often show a multi-exponential behavior. Therefore, the application of a spectral inversion of SNMR data yields an optimized data fit of the SNMR relaxation curves and consequently

- a more accurate interpretation of the water content of aquifers and
- an improved description of pore sizes (and therefore of derived parameters like hydraulic conductivity)

but needs

- high quality data with a high S/N ratio in order to achieve a reliable discrimination of water content associated to different decay times (~pore sizes) and
- additional complex signal information to improve the inversion of SNMR data.

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FREQUENCY DISPERSION OF NUCLEAR MAGNETIC RESONANCE (NMR) RELAXATION: IS IT POSSIBLE TO SCALE FROM LABORATORY TO THE FIELD ?

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MOTIVATION

The need for well founded interpretation of MRS/SNMR field data has steeply increased the interest in NMR properties of unconsolidated rocks. Structural parameter as porosity, pore size distribution or permeability of unconsolidated rocks can be well determined by laboratory NMR. T_1 (INVREC) and T_2 (CPMG) relaxation times at 2 MHz are much better suited than T_2^* (FID) for the analysis. This is partly due to inhomogeneities of the instrument magnetic field and partly due to paramagnetic nuclei in the samples. CPMG and INVREC pulse-sequences can correct this effect for. In SNMR/MRS usually the FID is measured by energising a quasi-90 degree pulse or T_1 (Saturation Recovery) is measured by applying two succeding quasi-90 degree pulses (Legchenko et al., 2002).

At higher precession frequencies (higher magnetic field strengths) T_1 can be as much as two times T_2. At low frequencies T_1 equals T_2 (Bené, 1980). The questions that have to be answered are:

- Is it already true at typical values of the earth's magnetic field (equivalent to 2 kHz precession frequency) that T_1 equals T_2?
- Is the ratio T_1/T_2 or the ratio T_2/T_2^* frequency independent?
- Is it possible to quantify those ratios?
- Can decay times derived from SNMR be compared directly to laboratory NMR decay times?
- If not, are there any relations or estimates that can help with the hydrogeological interpretation of SNMR data/models?

THEORETICAL BACKGROUND

NMR is observed with nuclei of certain atoms which are immersed in a static magnetic field and exposed to a secondary oscillating magnetic field. At equilibrium, the net magnetization vector is along the direction of the static magnetic field B_0 and is called the equilibrium magnetization M_z^0. The time constant which describes how $M_z(t)$ returns to its equilibrium M_z^0 value is the spin lattice relaxation time T_1, with $M_z(t) = M_z^0 * (1 - e^{-t/T1})$. The time constant which describes the return to equilibrium of the transverse magnetization, M_{xy}, is called the spin-spin relaxation time, T_2, with $M_{xy}(t) = M_{xy}^0 * e^{-t/T2}$. The net magnetization in the xy plane goes to zero while the longitudinal magnetization grows up to M_0 along z. In addition to T_2 the magnetization in the xy plane starts to dephase because each of the spins is experiencing a slightly different magnetic field and rotates at its own Larmor frequency. The longer the elapsed time, the greater the phase difference. This leads to the faster decay time T_2^* that strongly depends of magnetic field gradients in the sample. To measure T_1 or T_2 particular types of pulse echoes (sequences of the secondary magnetic field) can be applied. The most common are: a single 90 degree pulse or free induction decay (FID) for T_2^*, echo trains of 180 degree pulses or CPMG (after Carr, Purcell, Meiboom and Gill) for T_2 or a particular mixture of 90 and 180 degree pulses (inversion recovery, INVREC) for T_1.

T_1 is also called spin-lattice relaxation, because energy is exchanged with the surrounding media. T_1 is the time the macroscopic magnetization needs to return to the equilibrium (Curie) magnetization:

$$M_0 = \frac{N\gamma^2 h^2 I(I+1)}{3k_B T} H$$

whereas N denotes the number of nuclei, H the magnetic field, I the spin quantum number, h Planck's constant, k_B the Boltzmann constant, T the temperature and γ the gyromagnetic ratio. The return to equilibrium is reached via the dissipation of energy to repositories for thermal energy, namely translation, rotation or vibration (the lattice). In the general case (after Bene, 1980 or Fukushima and Roeder, 1981) T_1 equals to:

$$\frac{1}{T_1(\omega_0)} = A\left[\frac{\tau_c}{1+\omega_0^2\tau_c^2} + \frac{4\tau_c}{1+4\omega_0^2\tau_c^2}\right] \qquad \text{(eq. 1)}$$

with $A = \left(\frac{\mu_0}{4\pi}\right)^2 \frac{3}{10}\frac{\gamma^4 \hbar^2}{r^6}$ and the nuclear correlation time $\tau_c = \frac{1}{6}\frac{a^2}{D_S}$, where D_S is the surface diffusion coefficient of a sphere and a the corresponding sphere radius. T_1 at room temperature is ≈ 3 s for water and τ_c is about 10^{-12} s (Bené, 1980).

In contrast to T_1 stands T_2, which is also called spin-spin relaxation. T_2 relaxation exchanges no energy with the surrounding media and T_2 is due to the interaction of the spins among themselfves only.

$$\frac{1}{T_2(\omega_0)} = \frac{A}{2}\left[3\tau_c + \frac{5\tau_c}{1+\omega_0^2\tau_c^2} + \frac{2\tau_c}{1+4\omega_0^2\tau_c^2}\right] \qquad \text{(eq. 2)}$$

In fluids T_1 equals almost T_2 because of the small correlation time (Fukushima and Roeder, 1981) even for higher field strengths. For small $\omega_0\tau_c$,, e.g. in the earths magnetic field, $\omega_0\tau_c \approx 10^{-8}$, and therefore

$$\frac{1}{T_2} \cong \frac{1}{T_1}. \qquad \text{(eq. 3)}$$

A spread in Larmor frequency because of magnetic field gradients (e.g. from paramagnetic ions in the rock matrix or inhomogeneities of the primary magnetic field) causes the relaxation signal to decrease to the relaxation time T_2^*:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma\Delta H_0, \qquad \text{(eq. 4)}$$

where $\gamma\Delta H_0$ is the distortion of the static magnetic field. When T_2^* is dominated by magnetic field inhomogeneities resulting from the primary field, T_2^* delivers little information about the sample, but on fundamental molecular processes, e.g. intrinsic to the fluid. In liquids experimental data show that T_2 and T_1 mostly equal T_2^* (after Fukushima and Roeder, p. 27). This is valid for the bulk magnetization, but for the hydrogeophysical case with fluids in porous media this is no longer valid as of the interaction of the spin with local magnetic inhomogenieties/matrix paramagnetic elements.

DATA AND DISCUSSION

Table 1 shows T_1, T_2 and T_2^* relaxation data acquired at different larmor frequencies. The data from Shirov et al. (1991)[1] and Legchenko et al. (2002)[2] have been derived from SNMR measurements, the data from Müller et al. (2002)[3] and Kooman (2003)[4] at 2 MHz and from Willamowski (1997)[5] at 400 MHz from laboratory measurements.

	Relaxation [ms]							
	2 kHz (SNMR)		2 MHz			400 MHz		
Sediment Type	T_2^*	T_1	T_2^*	T_2	T_1	T_2^*	T_2	T_1
Clay	-	-	0.4-0.7[4]	4-6[4]	4-5[3,4]	0.01[5]	4[5]	11[5]
Silt	-	-	0.5[4]	12-14[4]	13[4]	-	-	-
Sandy Clay	<30[1]	-	-	-	-	-	-	-
clayey/very fine sand	30-60[1]	-	0.2-0.8[4]	30-55[4]	20-30[4]	-	-	-
fine sand	60-120[1]	310[2]	0.4-1.3[4]	10-435[4]	90-560[4]	-	-	-
medium sand	120-180[1]	420[2]	0.7[4]	220[4]	540[4]	0.05[5]	2[5]	53 0[5]
coarse/gravelly sand	180-300[1]	600[2]	0.5-0.8[4]	600-800[4]	700-760[4]	-	-	-
gravel	300-600[1]	-	-	-	-	-	-	-
surface water	600-1500[1]	-	0.9[3,4]	-2500[3]	3000[3]	-	-	-

Table 1: Relaxation data at different precession frequencies. Data at 2 MHz and 400 MHz are laboratory measurements, data at 2 kHz are from SNMR field measurements. The superscript numbers denote the above references.

The coarser the material the slower the relaxation for T_1, T_2 and T_2^* for all frequencies, but for T_2^* at frequencies higher than 2kHz. Only for small field strengths (2kHz) the T_2^* relaxation shows a clear dependance of the grain size like T_1 and T_2. The higher the Larmor frequency, the shorter the T_2^* relaxation time, e.g. for medium sand is ≈150 ms for 2 kHz, ≈1 ms for 2 MHz and 0.05 ms for 400 MHz. This shows clearly the effect of increasing magnetic field gradients and therefore increasing spread in Lamor frequency with higher field strengths. Comparing T_2 for medium sands at 2 MHz and 400 MHz shows that there is apparently a strong influence from magnetic field gradients, as T_2 at 2 MHz is 200 times bigger than at 400 MHz. Comparing T_1 at different field strenghts shows that not only the 2 MHz and the 400 Mhz values coincide well, but also for 2 kHz. Comparing T_2^* at 2 kHz and T_2 at 2 MHz shows that there is a 1:1 correlation for material finer than medium sand. For material coarser than medium sand a "relaxation shift" for SNMR T_2^* towards 2 MHz T_2 of a factor of 1.5-2 must be taken into account, but this may depend on the presence of paramagnetic nuclei.

These results fit also well to results of SNMR-T_1 and SNMR-T_2^* from measurements in Haldensleben (Yaramanci et. al, 1999) and Nauen (Mohnke, pers. comm.), where values of 155 ms for T_2^* for grain sizes between 0.1-1 mm correspond to values of 300-400 ms for T_1 respectively.

CONCLUSIONS

Summarizing, it becomes clear that SNMR T_1 values can be well compared to T_1 values acquired in the lab not only at 2 MHz, but also for higher field strengths. Secondly the T_2^* SNMR values cannot be compared to T_2^* data from the laboratory for any frequency. Thirdly it is not absolutely nessecary to perform T_1 SNMR surveys to obtain "good" relaxation data to derive pore properties, instead T_2^* SNMR values can be compared to T_2 values with a certain correction (rule of thumb) factor.

Nevertheless this work did only scratch the topic of frequency disperison of NMR relaxation. Beside deeper theoretical understanding of the dispersion of relaxation mechanism further work should focus on gathering additional experimental data, as:

- to perform 2 kHz laboratory experiments
- to perform experiments at intermediate field strengths (e.g. 200 kHz)
- to study T1/T2(f) for water and other fluids (DNAPL, LNAPL)

Finally I propose to establish an as broad as possible database of NMR/SNMR relaxation times including samples/rocks to gather the SNMR-user knowledge. This database should include not only the NMR parameter, but also additional hydrogeophysical parameter, as porosity, hydraulic conductivity or salinity. Furthermore geophysical parameter like electrical conductivity or induced polarisation could be included to build up the base for future enhancement of geophysical NMR data interpretation.

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APPLICATION EXAMPLES OF SNMR DETECTION GROUNDWATER METHOD IN HYDROGEOLOGICAL INVESTIGATIONS IN CHINA

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ABSTRACT

In this paper, it is shown that surface NMR method is the only new geophysical method for detection groundwater with real examples. Combining with Chinese practice, using NUMIS and NUMIS$^+$ in 12 provinces and regions of China groundwater resources prospecting has been made, pore water, fissure water and karst water have been detected, underground hot water resources discovered and estimated and perspective areas of fresh underground water resources in some oilfield in North-East of China confined using integrated geophysical methods. Facts show that in detection depth range SNMR method plays a role of direct detection groundwater, identification of apparent resistivity and guiding drilling technology of water well. Besides, some experiences of detection groundwater using SNMR are obtained, a monograph <Theory and practice of detection groundwater with SNMR> in Chinese published and a series of scientific publications about detection groundwater with SNMR method is issued. Keywords: SNMR method; Hydrogeology; Application Examples.

OVERVIEW

Detecting groundwater by high and new-technologies

In China, geologists and geophysicists have found much groundwater by using remote sensing, geophysics, isotopes, geographic information system (GIS), new drilling and well completion technologies.

Rich groundwater has been found in north-west of China

Chinese geologists and geophysicists have found rich groundwater in dry areas in north-west of China by using high and new technology.

More than 350 wells have been drilled for various survey and exploitation in recent years, which is equivalent to find 13 big water source regions. More than 50 water source regions and areas rich in water have been found. About one billion m^3 of water can be produced each year, which is equivalent to build 10 big reservoirs.

Great achievements have been obtained in finding water in deserts. In the Taklamagan desert, which is named "dead sea", a big "underground reservoir" has been found, which provides up to one billion m^3 of water each year. It has a storage of 36 billion m^3 of water which equal to the storage of the Three Gorges reservoir (39.3 billion m^3) and so on.

China has the foundation and strength to carry out the detection of groundwater by NMR technology

During the summer of 1965, Zhang Changda and Cui Xiufeng did some experiments of NMR technology to find groundwater. From 1992 to 1993, the research group of NMR detection groundwater in China University of Geosciences (Wuhan) investigated the NMR technology at home and abroad. In 1994, cooperation with Moscow State University was established. At the end of 1995, our group visited Novosibirsk Institute of Chemical Kinematics and Combustion (ICKC) and the Moscow hydrogeological tomography company and confirmed the application results of NMR detection groundwater.

APPLICATION EXAMPLES

Since the first set of NUMIS was introduced to China University of Geosciences at the end of 1997, geophysicists in the university have made detection groundwater practice in 12 provinces and autonomic regions.

(a) Defining the perspective areas of fresh groundwater resources in an oilfield by new technology and new methods

The development of the oilfield is restricted by water deficiency, and more than ten millions yuan RMB is expended on transmit the water.

From July to August in 2001 according to the geological and geophysical conditions in the working area, transient electromagnetic sounding (with TEM-67), surface NMR sounding (with NUMIS system), frequency sounding with hybrid source field (with EH-4 conductivity imaging system) and traditional vertical electric sounding (VES) were carried out to accomplish 800km^2 of general survey area and more than 230 km of lines and 230 physical points.

In the general survey of fresh groundwater, NUMIS system is used to realize quantitative interpretation rapidly, provide hydrogeological parameters, distinguish the abnormity of the resistivity and guide the well completion technology.

Following achievements have been obtained during the survey of groundwater resources in the oilfield:

1. By contrasting the materials of sounding data near well, the relation between the resistivity of the aquifer in the working area and the groundwater's mineralization (M) can be concluded: The aquifer with high$M$ (M>3g/l) has the resistivity ρ<10Ω·m; with middle M (M=2～3g/l), ρ=10～15Ω·m; with low M (M<2g/l), $\rho\geq$15Ω·m. The statistic results above establish the basement of defining the perspective areas of fresh underground water resources in the oilfield.
2. The relation between electrical property of the aqueous stratum and the abnormity of the NMR sounding method has been established and the perspective areas of fresh underground water resources have been defined. It is shown in the quantitative interpretation (fig.1) made through several methods that the buried depth of the aqueous stratum's top plate is about 10 to 100m, and the stratums with the resistivity of 10 to 30 Ω·m correspond with the abnormity of NMR sounding. Thus the stratum is confirmed to be stratum with fresh water by combining direct with indirect geophysical methods, and the foundation of defining perspective areas of fresh underground water resources for the oilfield has been made. After the survey was finished, 3 wells were drilled in the perspective areas and the water is of good quality (M<1g/L). These results prove that our interpretation is correct.

(b) Finding the water source for meeting an urgent

1. Good karst water is found in Xiangji town in Yong'an, Hubei province. Xiangji town in Yong'an, Hubei province is the farming and animal husbandry development area for Wuhan Dingli Company. When the road and electricity are extended to the area, it was found that there wasn't enough water. The area was counted as water deficient area, and the residents lived on turbid water from the surface ground. Most of the working area is cultivated farmland and covered by the sandy clay, clay and subclay of quaternary system (Fig.2,c). The sandshale of silurian system and limestone of triassic system expose in cleuch and topographic low. In May 1998, we used NUMIS system to detect groundwater within 2 km^2 in the development area. We used NMR sounding (add up to 12 NMR sounding stations) chiefly and resistivity method secondarily. According to the

result, excellent karst water was found in the area, and the daily capacity of tree wells added up to 5000 tons (Fig.2a, b), which provided the water for farming, animal husbandry and the residents.

2. Groundwater is found in weathered granite and the well completion technology is guided: the NMR detection groundwater research group in China University of Geosciences carried out the prospecting of groundwater in north of China from July to August in 1999. They used NMR sounding chiefly and resistivity method secondarily to accomplish 36 NMR sounding points, confined the prospective area for groundwater, and determined the position for the water well. The NMR sounding interpretation guides the well completion technology: 48.5 m pipe is put down by one-time hoisting method ($84m^3$ daily capacity). The water of the well has good quality and is suited for drinking.
3. Groundwater is provided for transformer stations of the Three Gorges electric network The fissure water in bedrock (348 tons daily capacity) has been found by using NMR method in a metamorphic rock area in Xiaogan county, Hubei province. In addition, the fissure water in red beds (more than 80 ton daily capacity) has been found in Changsha, Yiyang city, Hunan province. The above interpretations are consistent with the drilling, and the groundwater detected is used in production, living and fire control for some transformer stations in the Three Gorges electric network.
4. Estimating the groundwater resource and providing a basement for developing and using the hot groundwater: in 2000, hot groundwater with the temperature of 79 °C was found by using NMR method in Anxi county, Fujian province. The daily capacity was larger than 1000 tons. The groundwater provides a basement for developing and using the hot groundwater.

CONCLUSIONS

SNMR method provides new technologies for detecting groundwater resources with the depth of 100~150 m and quantifying in the hydrogeological work. The SNMR method has acquired good effect in China.

The interpretation level of SNMR method and the resisting electromagnetic interference capability of NUMIS should be improved to extend the application area of the method.

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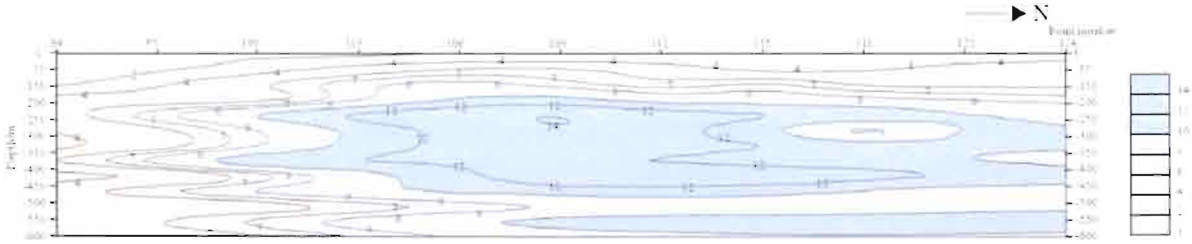
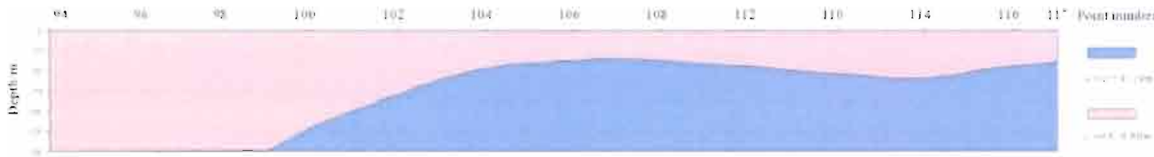
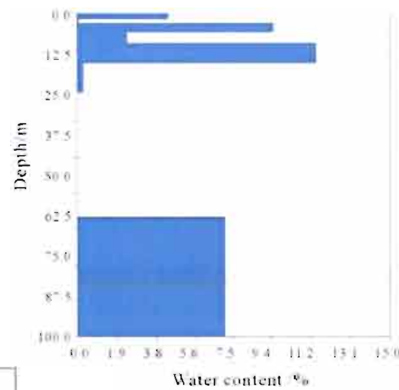


(a) the EH-4 resistivity of line 30—I in general survey of an oilfield —— depth sectional view

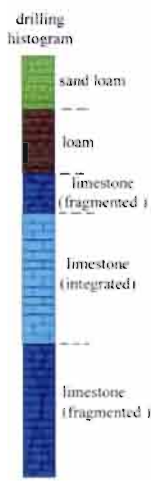


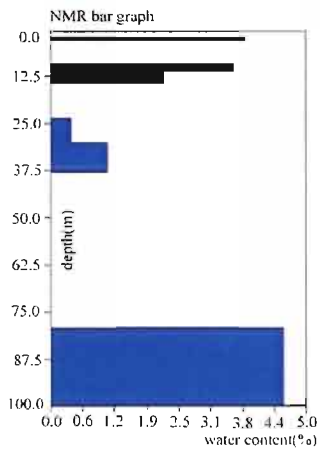
(b) the geoelectric sectional view of line 30—I in general survey of an oilfield



(c) NMR sounding histogram of point 106/30- I

Fig.1 the integrated interpretation figure of line 30- I in general survey of an oilfield





(a) (b) (c)

Fig.2 the comparison diagram between the NMR sounding interpretation and the drilling material in I work area in Hubei province lithological column; (b) water content bar graph of NMR sounding; (c) job site in the field.

IS MRS METHODOLOGY READY TO FULFILL HYDROLOGISTS DEMANDS?

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INTRODUCTION

The Instituto Geológico y Minero de España (IGME) is especially interested in finding the role of MRS in groundwater investigation in developed countries, and specifically in Spain, where the shallow penetration and the noise effect are important limits for MRS implementation. Three years ago, we participated in the proposal of an international co-operation Project for the development of MRS. The trials made to get some help from the European V FP failed, and in the meanwhile we have continued to experiment with MRS. With this purpose, during the last years we have made a special effort to spread among the hydrologists this new geophysical method. We have carried out several surveys in collaboration with Local Authorities as well as with Public Water Management Institutions, using NUMIS equipment. We have also had the opportunity to verify the performance of HYDROSCOPE instrumentation. During the fieldwork we have had contact with some tens of hydrologists. All of them are convinced of the innovative capabilities that MRS offers to the water direct detection problem. But, at the end of their visit, they always put the same question: ¿can you give me the effective porosity and transmissivity?. This question is reflecting the technical situation in most of the Spanish main aquifers, which existence is already rather well known. It seams that there is no demand for a geophysical tool to detect the presence of water in the first one hundred meters. What they need is to be offered an alternative methodology for the determination of the hydrodynamic parameters of aquifers, in order to improve the models. Searching for shallow water is attractive only for the private sector of wells users, who manifest their interest in MRS as an alternative to water witching or dowsers.

With this panorama, the question for us can be expressed in this way: is MRS methodology ready to fulfil the hydrogeologists demands?. Trying to find for an answer, we are here to summarise some of the results of our experience, from the scope of users of the methodology, and not from a theoretical or research point of view. Three points will be shown: the noise, the qualitative and the quantitative use of MRS data, and the determination of hydrodynamic parameters.

THE PROBLEM OF NOISE

At the 1st Workshop on MRS held at Berlin in 1999 we presented our promising experiences in getting data in environments with high electromagnetic noise. One of our conclusions at that time was that the effect of noise, though it affects to all the quantitative use of the data, is especially disturbing for the determination of the time constant. We are learning how to deal with some aspects of noise in order to improve the signal/noise ratio, but we do not know yet what to do with its time dependence. In Fig. 1 several cases are presented. When there is a strong signal from the groundwater, and no noise is disturbing it, you get good records (fig.1-a), but this situation is rather unusual. Even in the presence of noise, but with enough amplitude of the water-signal, you can handle the measuring parameters to get acceptable records (Fig.1-b and 1-c). When no water is present, the results of the MRS are normally clear to interpret (fig. 1-d). The existence of a high level of noise with a small water-signal, makes it nearly impossible to measure a good record (fig. 1-e). But the worst, and the most normal situation, is that noise is time dependent in developed regions. In fig. 1-f we show the same MRS as the one in fig. 1-c, but measured at a different time. It is obvious that the results attained from both soundings are not only different, but with a very different degree of trusting. To solve this problem it is not enough to make a small survey of noise previous to the MRS measurements. One would need a time dependent map of noise of the area, which is nearly impossible to do and means a significant time consuming field methodology for getting fair records. This problem has not a clear solution, and creates a feeling of uncertainty and distrust among the users.

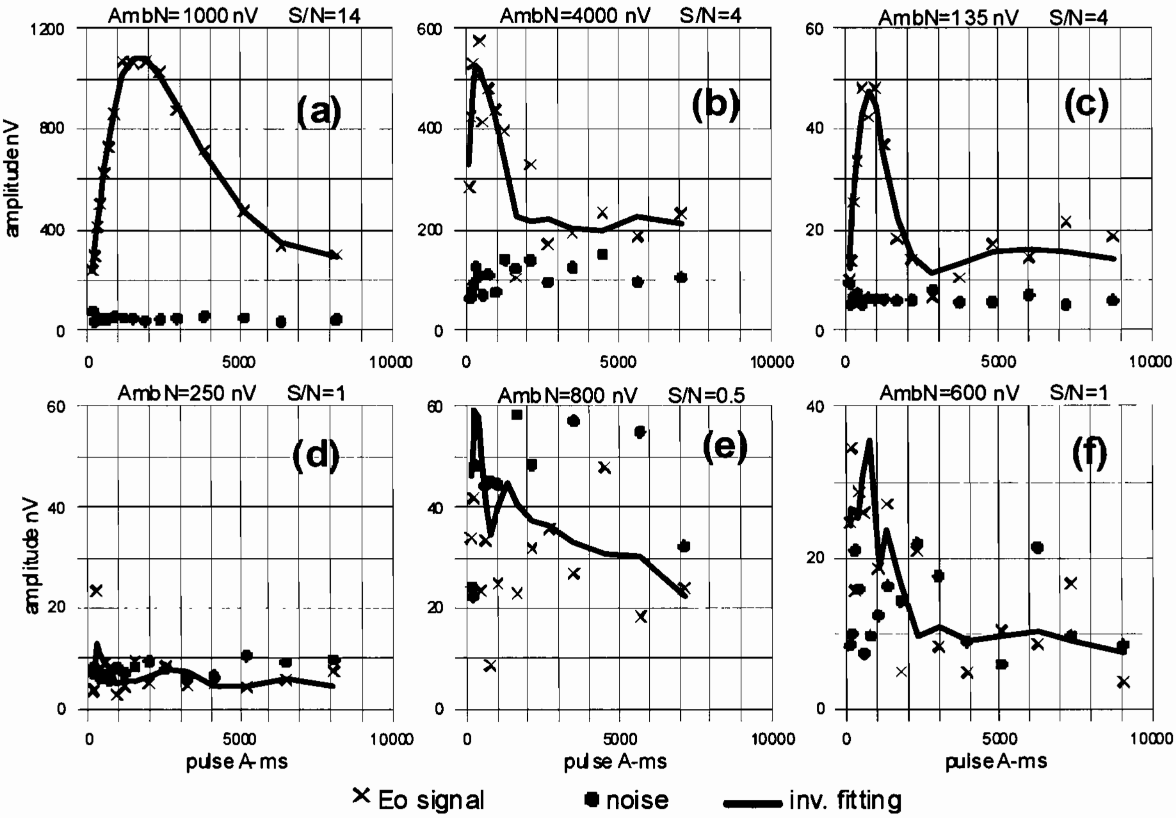

Figure 1. Results of several MRS with different ambient noise (AmbN) and Signal to Noise ratio.

THE QUALITATIVE AND THE QUANTITATIVE USE OF MRS

From the point of view of the qualitative use of the results, in our experience MRS can be used as a good tool to locate an aquifer and to differentiate its water layers. It is also possible to map the limits and heterogeneity of the aquifers, and it also allows getting a good approximation to the piezometric level. An example of the first type of application is given in Fig.2, where the evolution of an aquifer in a Quaternary layer of sand and gravel of 15 m of thickness is well design. In this case, a deeper aquifer, which existence was unknown, was also detected within the sandy clay of the Tertiary basement. In Fig. 4, an example is given of the correlation between the piezometric level determined by MRS and the actually measured values in a set of wells. The deviation in most of the cases is smaller than 0.5 m. In brief, we find that the qualitative use of MRS is rather satisfactory, and can be a good help to hydrologists.

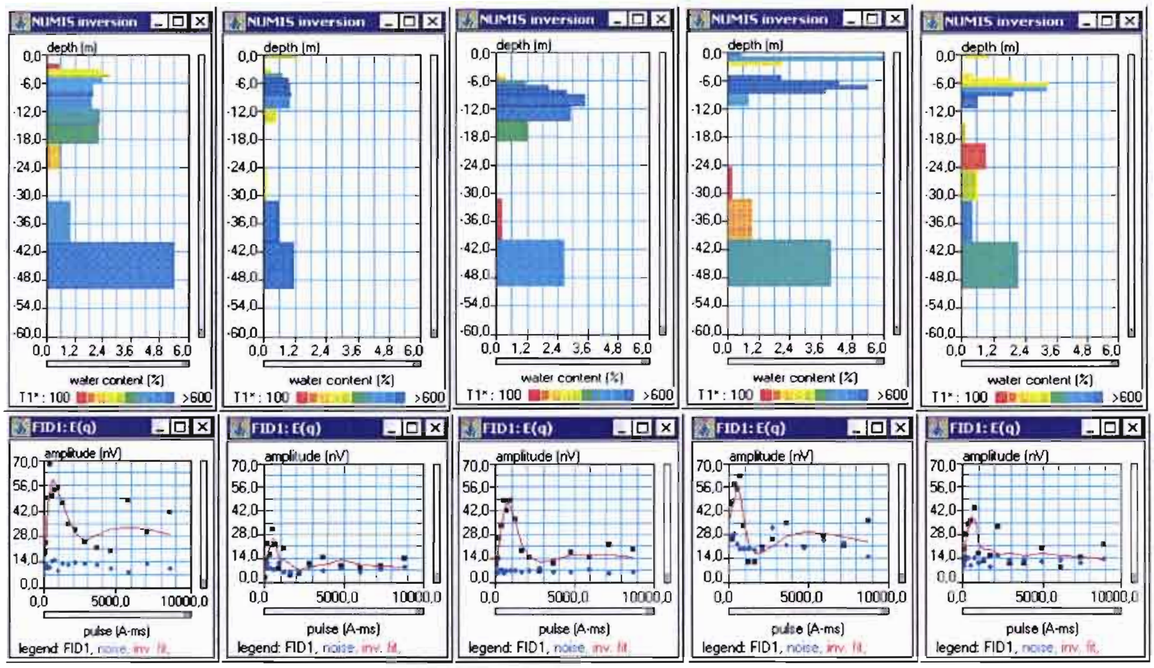

Figure 2. Example of the qualitative use of MRS results to map an aquifer in a sedimentary layer. A second and yet unknown aquifer within the sandy clays of the basement has been found.

The problems arrive when trying to use the quantitative results, because of the effect of noise and of the many parameters that affect the solutions that can be found in the inversion problem. The uncertainty in the election of the filters to reduce the noise influence, the choice of regularisation and other processing parameters, and the differences achieved using different instrumentation and different inversion schemes do not contribute to clarify the capabilities of the method. In Fig. 3 the water distribution with depth obtained at the same place using NUMIS and HYDROSCOPE instrumentation, with equivalent antenna and noise conditions are shown. Though the solution given for the two aquifers could be seen qualitatively equivalent for both soundings, the water distribution is a little far to be so equivalent.

HYDRODINAMIC PARAMETERS

Finally, in the use of the quantitative results, several empirical values for the factor to be used in the calculation of the permeability from T_1 and T_2^* at several test sites have already been published. They show a wide range of variation for the same lithology. The need of calibration of MRS data with pumping tests gives good results, but it also gives rise to important limitations: due to the heterogeneity on alluvial aquifers, the values determined for one area may be not valid for other places of the same aquifer, as shown in Fig. 4. In areas with no pumping tests available, the MRS values will always remain as a qualitative approximation.

CONCLUSION

In conclusion, the possibilities of MRS to solve the most important hydrogeological problem at a global scale, as it is the search for water in the first hundred of meters of the underground, are good and clearly established. But, our feeling, as users of MRS in a developed country, is that the possibilities to give the hydrologist an answer to their needs in the aquifer control are more limited, though not at all negligible, and still remain in the academic stage.

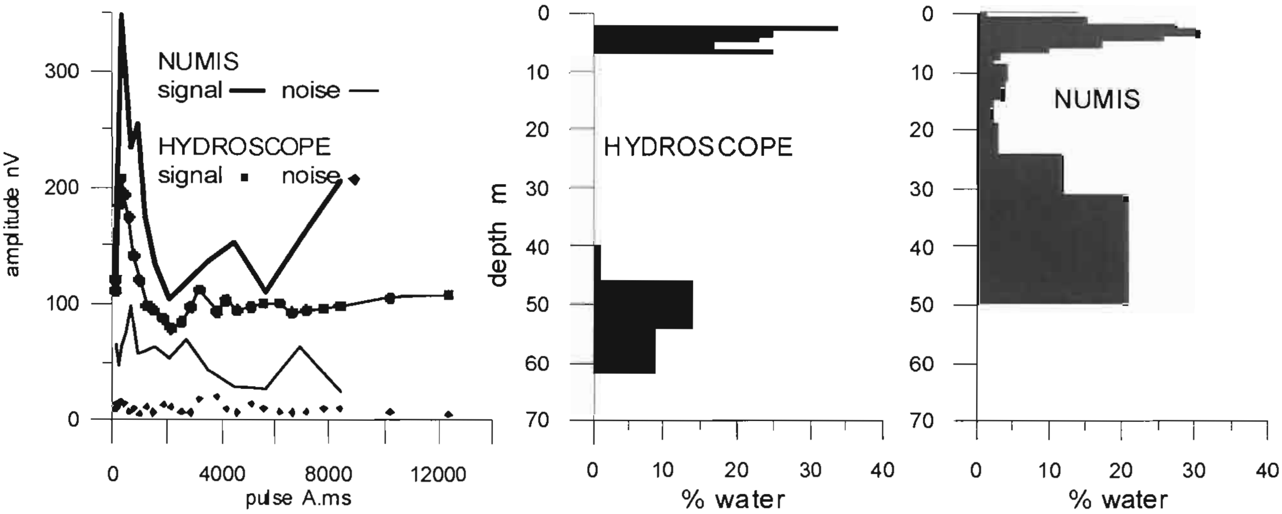

Figure 3. Example of different results attained using different instrumentation.

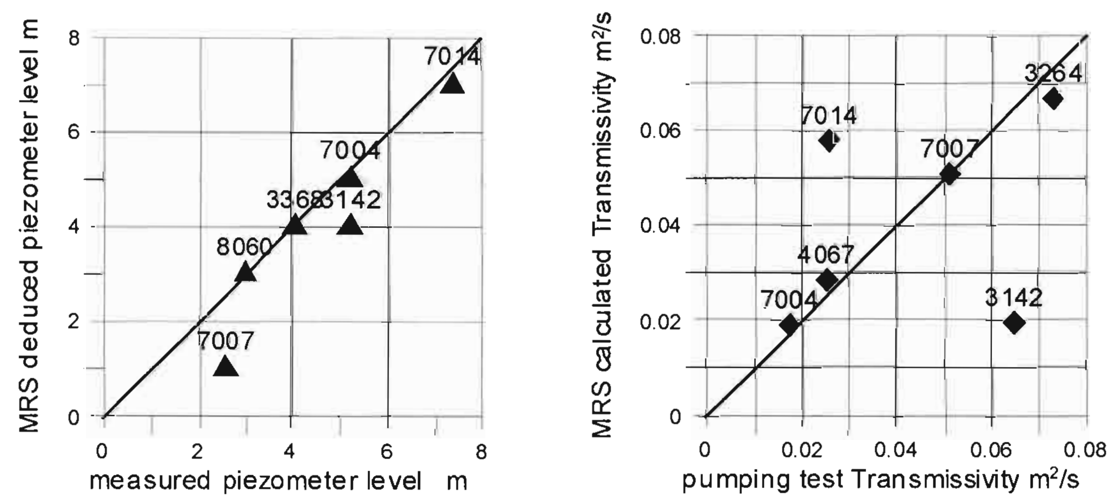

Figure 4. Examples of quantitative use of MRS results for a set of wells of the same aquifer.

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INTEGRATED STUDY (MRS, GPR AND 2D ELECTRICAL IMAGING) OF GROUNDWATER IN A 2D GEOLOGICAL CONTEXT

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INTRODUCTION

This paper presents an integrated geophysical study undertaken in French Brittany on a small catchment 15km south of Quimper (Figure1). In such catchment, high levels of manure corresponding to intensive agricultural land use, lead to an environmental hazard with worrying nitrate concentrations in surface and ground waters. In this region, there is hence a major interest to shallow groundwater characterization. The crystalline basement may be considered as impervious relatively to the weathered materials. As a matter of fact, the hydrological and geochemical processes involved in streamwater fluxes at outlet of the catchment are mainly related both to fast run off phenomenon during rainy events and to backward fluctuations in shallow groundwater quantity and quality.

GEOPHYSICAL METHODS INVOLVED

Near surface geophysics applied to hydrogeology more and more associates MRS and electric imaging. GPR because of its strong sensitivity to conductivity, acts like a complement to characterize structural organization down to a few meters depth. .In Kerbernez area, many boreholes were drilled in addition to MRS survey and 2D electric imaging profiles to follow the hydrogeological processes.

The hereafter described survey associates MRS, GPR and 2D electrical imaging along a 500 m profile (Figure 1). 6 MRS were done using NUMIS^{plus} equipment (Iris Instruments) and a so called "height square loop" with 37.5m side length. The 2D electrical imaging was made along the same profile using SYSCAL R2 MULTINODE system, with 64 electrodes and using a "roll along procedure. The chosen inter-electrode spacing was 2m and measurements were made using 4 different electrode configurations (Wenner alpha, Wenner beta, forward and reverse pole dipole). The GPR survey was made on the first half of this profile using a Pulse Echo 100 equipment (Sensor and Software) with 50, 100 and 200 MHz antennas.

RESULTS – INTERPRETATION

MRS survey shows that the noise level is rather important in the area (800-8000 nV). On the contrary, the MRS signal is generally weak (<90 nV). Nevertheless, using a "height square loop" that allows to reduce noise influence; it was possible to characterize ground waters between 0 and 40 m. The top of the aquifer varies between 2 and 6 m, in good agreement with piezometric observations, and its thickness lies between 10 and 40 m. The most important water bearing structure is located close to the outlet of the catchment. The estimation of hydrological parameters shows a large spatial variability for such an aquifer. Particularly hydraulic transmissivity varies between $2{,}6.10^{-5}$ à $2{,}6.10^{-3}$ m²/s.

Electrical imaging allows to precise the lateral extension of water bearing structures revealed by MRS. It also allows to identify vertical structures that may be interpreted as faults in the granitic basement and that may explain the important variations of weathered materials thickness along the surveyed profile (Figure 2).

GPR profiles were done along 210 meters, down the northern slope of the watershed, between borehole 1 to 6 throug 4. The radargrams are shifted using the topography. Three frequencies were used 50MHz, 100MHz, 200MHz that respectively allow depth investigation of approximatively one, three and 10 meters depending of the attenuation distribution. Nevertheless, in the radargrams time scale is still used because of the difficulties to give a proper velocity distribution. Furtermore, the higher the antenna frequency, the better the accuracy for underground details description.

Attenuation is generally due to clay and water content, while granite even in their altered form lead to good penetration. Along the profile we distinguish two propagation conditions:

- fractured and weathered granite does not imply strong attenuation, but many diffraction pictures due to fracturation ;
- high electrical conductivities lead to strong attenuation of the GPR signal.

Those zones are underlined in respectively in blue line and red arrows (Figure 3). When compared to the 2D electric imaging, GPR sections show good qualitative correlation (takein into account that the discrepancy between investigation depths for electric and GPR survey. Conductive and resistant anomalies in electric imaging correspond to the zone were GPR signal is strong and weak; and this is true for all frequencies.

Between 150 and 210 meters along the profile the presence of water near the surface (top of the groundwater) induced increasing apparent frequency in the signal, which is in accordance with MRS survey interprtation. On the other hand, the lack of accuracy of the MRS survey (comparing to GPR) does not allow a good correlation between the level of fracturation in the granite well evaluated in GPR, and the hydraulic conductivity determined from too few surveys in MRS.

CONCLUSIONS

In conclusion, it appears that 1D MRS application in contexts that present strong spatial variations is feasible. Nevertheless complementary measurements using 2D electrical imaging and/or GPR seem necessary in order to estimate more accurately the geological settings or the lateral extension of water bearing structures revealed by MRS.

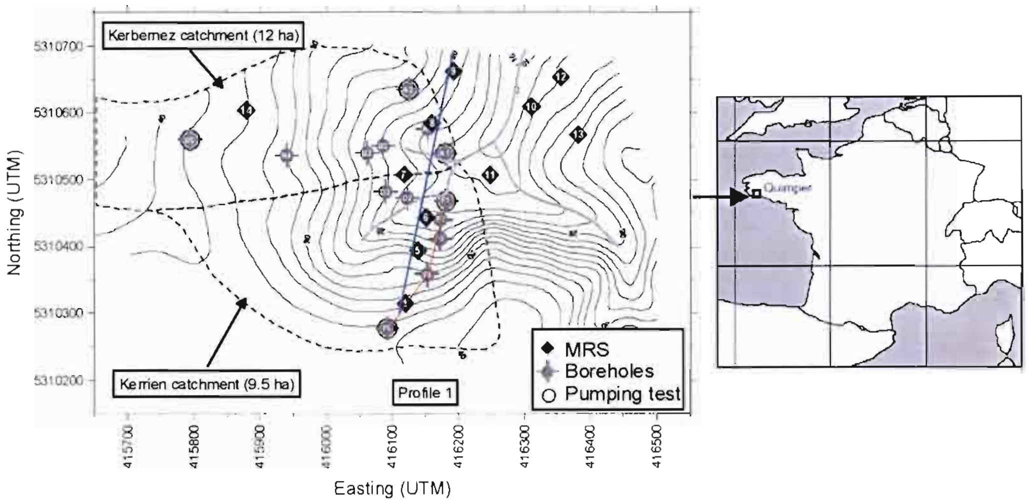

Figure 1 : Kerbernez watersheds (French Brittany): situation map of survey - MRS, boreholes, pumping test + roll-along electric acquisition (bleue lines) + GPR profiles (red lines).

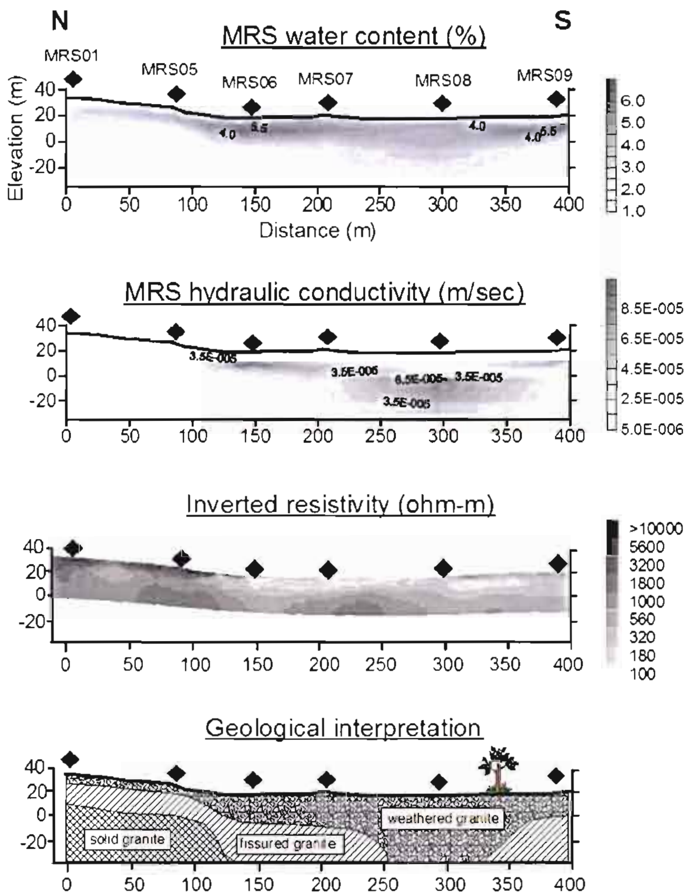

Figure 2 : MRS interpretation in hydraulic conductivity and water content versus electric resistivity imaging. Geological interpretation is shown below.

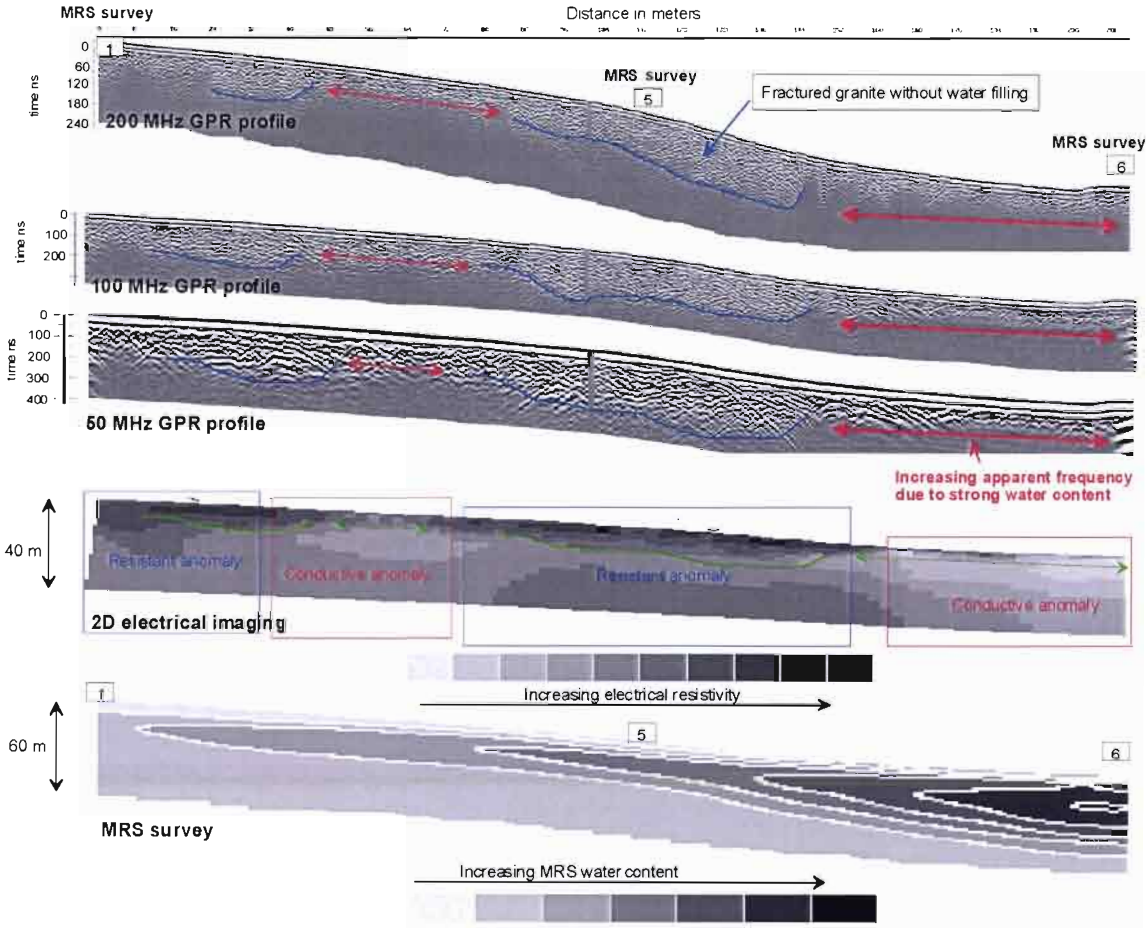

Figure 3 : GPR 50, 100 200 MHz profiles, 2D electrical imaging, and MRS water content distribution.

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

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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 (Φ_{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). Φ_{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 (ρ_1 & ρ_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 (Korringa-Seevers-Torrey; Korringa 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 $E(t) = E_0\, e^{-t/T} \sin(\omega_l t+\varphi)$ where E_0 is the initial value of the NMR signal, ω_l is the (angular) Larmor frequency and φ 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.

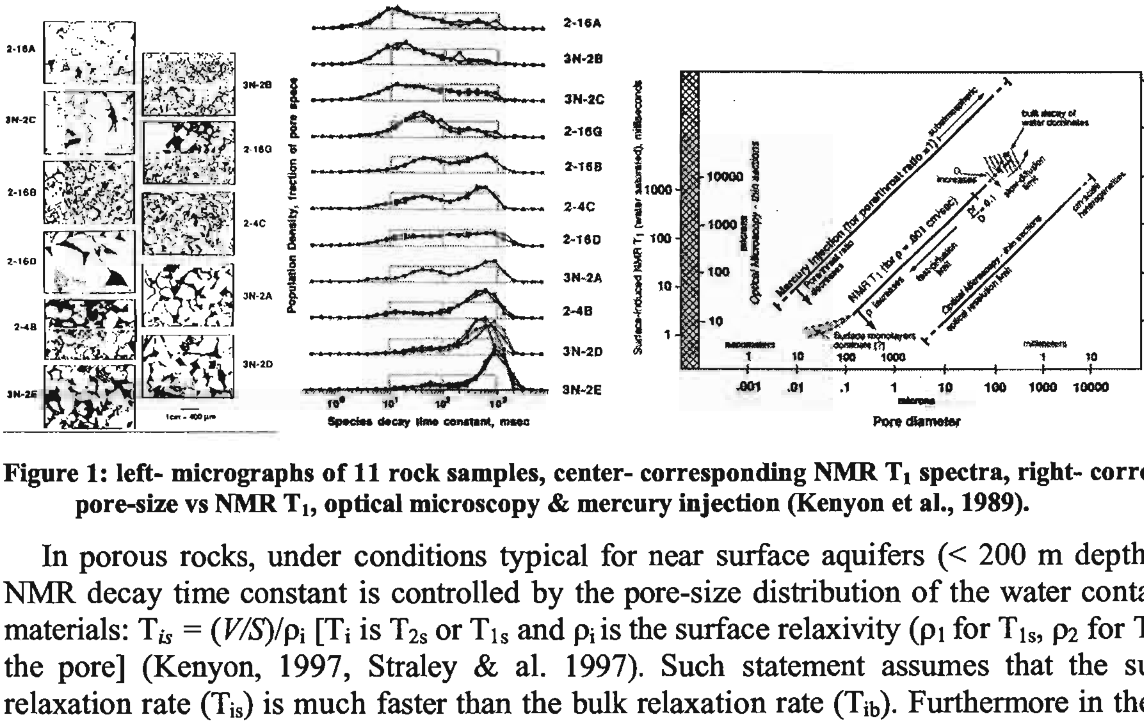

Figure 1: left- micrographs of 11 rock samples, center- corresponding NMR T_1 spectra, right- correlation pore-size vs NMR T_1, optical microscopy & mercury injection (Kenyon et al., 1989).

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 ρ_i is the surface relaxivity (ρ_1 for T_{1s}, ρ_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 (δ_{EM}) and NMR skin-depth (δ_{NMR}). According to the investigation depth, the scale of the MRS survey can easily reach the order of magnitude of δ_{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 δ_{NMR}. [E.g. at 2 kHz, δ_{EM} would range from 6 m in highly saline clays (~ 0.3 Ω-m) to > 1 km in unfractured limestone or cristalline rock (> 10000 Ω-m) while δ_{NMR} at 2 kHz in water is ~ 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: $A(t) = \sum_i A_i e^{(t/Ti)}$, 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 δ_{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.

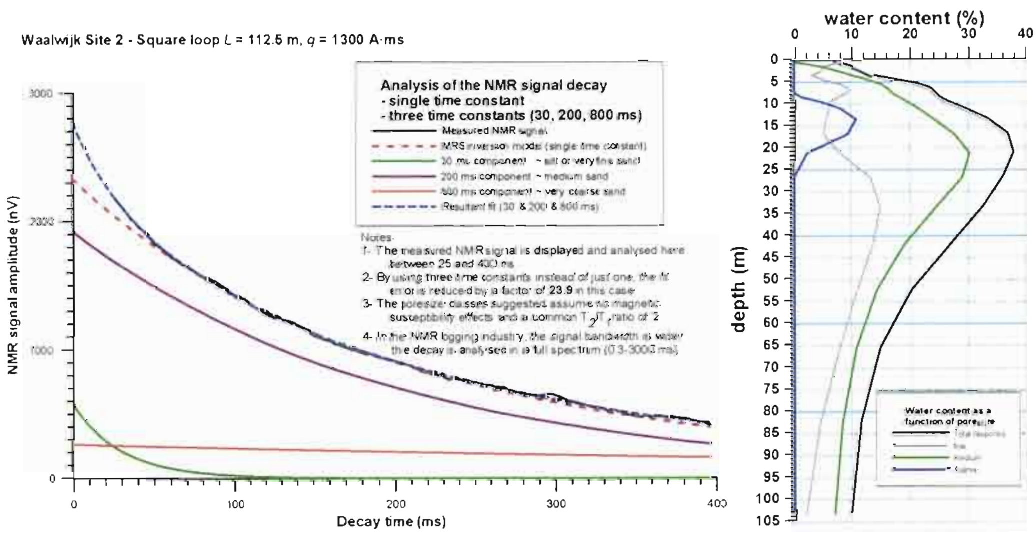

Figure 2: Waalwijk-2 multi-exponential analysis- left - decay curve, right - data inversion.

The technique is currently applicable only to MRS data set with very good signal to noise ratio. Furthermore the use of T2* 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 T2* = T2. 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 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 2nd 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.

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THE CASE OF AN MRS-ELUSIVE SECOND AQUIFER

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INTRODUCTION

At ITC, interest on the MRS (Magnetic Resonance Sounding) technique is on-going since its commercial introduction in Europe in 1996. Soundings have been done at selected sites in the Netherlands from 1997 onward with both the NUMIS and the NUMIS^{PLUS} instruments. The country is densely populated and industrialized so that at numerous locations, cultural noise does not allow the acquisition of reliable MRS data sets. As part of the countrywide space utilization planning, however, a number of parks have been set aside. These are less or not electrified so that, from an MRS perspective, even if the level of urbanization and industrialization is high, it was possible to find sites with low level of cultural noise (e.g. 50 Hz harmonics due to electrical power grid). Under such conditions, in South-West of the country, because of low artificial noise, shallow groundwater table and high porosity of the near-surface aquifer, MRS data sets were acquired with high signal to noise ratio (S/N) (e.g. S/N = 96 for the second data set presented here). These data sets show a monotonous single peak anomaly corresponding to single aquifer data inversion. However, in the first 200 m below surface, two or even three extensively documented aquifers (Dutch state agency NITG-TNO) are present.

NEAR SURFACE AQUIFERS

Figure 1: Sites location : 1: Delft, 2: Waalwijk

According to the specific locations, the first (top) aquifer is either unconfined or confined by a clay-rich aquitard. In both cases it is characterized by a specific yield and/or specific drainage reaching ~ 20 %. Because of a reduced exposure to contaminants, the characterization of the second aquifer is of interest even if its storage and flow properties may be less than the top aquifer. For this presentation, we will examine the MRS responses from two sites (see Figure 1): one with upper confined aquifer near Delft [1] and the other one with upper unconfined aquifer near Waalwijk [2]. The aquifers in the South West of the country are composed of unconsolidated sands and gravels interchanged with clay layers – aquitards. Even if aquifers are often characterized down to ~ 250 m, in this study, only the first 100 m below surface is of concern because of the range of the MRS investigation.

In Western Netherlands, the depth of the fresh/brackish water interface increases inward from the sea. This interface is reaching a depth of 100 m at a distance of 30 to 60 km from the sea with local irregularities (NHV, 1998). At the Waalwijk location (~ 75 km from the sea), the MRS response is due to fresh water while at Delft (~ 15 km from the sea), the salinity pattern is locally more complex: the town is located over a fresh water aquifer but to the east where MRS data sets were acquired the top aquifer has brackish water.

At the Delft site (Lubczynski and Roy, 2004), the top layer is a clay aquitard [0-15 m, vertical hydraulic conductivity (K_v) = 0.0036 m/d]. Below, there is a confined aquifer [15-39 m, horizontal hydraulic conductivity (K_h) = 32 m/d], followed by a clay aquitard (39-45 m, K_v = 0.0072 m/d) and then a second aquifer (45-128 m, K_h = 12 m/d), which contains clay horizons. Due to the salinity of the water, the formations have lower resistivity (between 4 and 11 Ω-m according to results of VES done at the MRS site) than at the Waalwijk-2 site, described below, and the attenuation of the MRS signal with larger values of Q (excitation moment) is noticeable (see Figure 2).

At the site Waalwijk-2 (Lubczynski and Roy, 2003), two aquifer layers are observed in the depth range of interest, the layers being separated with a clay aquitard. Downward leakage occurs in the aquitard as evidenced by the reported head decline with depth. The 0-6 m depth interval is unsaturated. The upper aquifer layer (6-52 m) is unconfined and is highly permeable, K_h is estimated at 24 m/d. The underlying clay aquitard (52-85 m) is intercalated by sandy horizons and its K_v is 0.004 m/d. The next aquifer layer (>85 m), with a K_h of 5 m/d, has at least 3 thin less permeable horizons unlikely to be resolved with MRS so the whole sequence from 85 to 180 m is considered here as a single aquifer layer. Except in the aquitard, with a ~ 20 Ω-m resistivity, the water bearing layers have an estimated resistivity of ~ 60 Ω-m. The unsaturated zone has ~ 120 Ω-m resistivity.

An examination of the observed MRS responses (MRS & geoelectric sections) and of subsequent modeling exercises allows distinguishing two different cases represented respectively by the Delft and the Waalwijk sites.

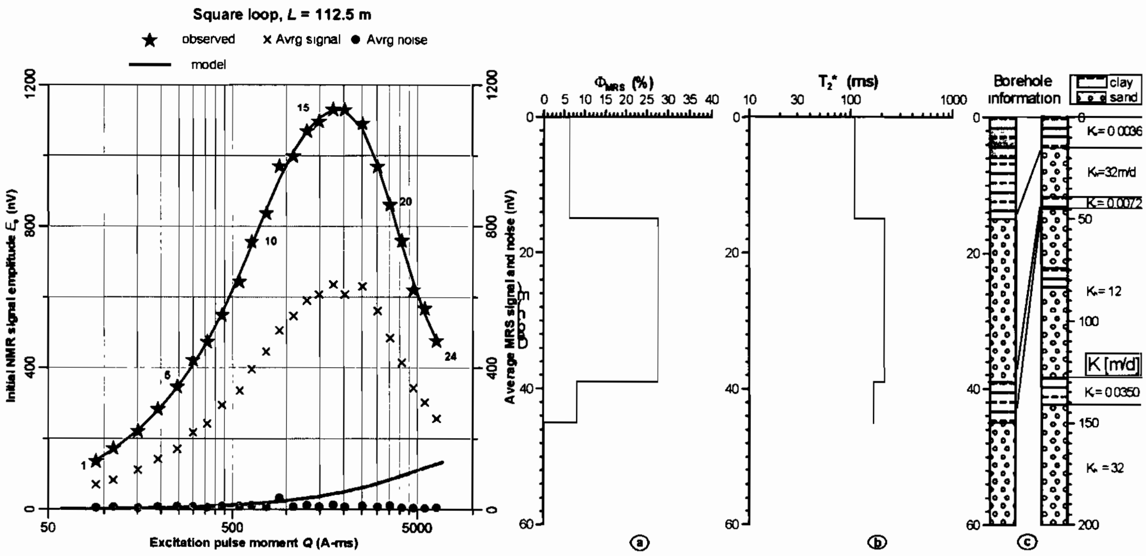


Figure 2: MRS response at the Delft site; left: data set, center: inversion results, right: well data

DELFT CASE

In the first case, at the Delft site see Figure 2, we observe on the E_0 vs Q response (initial value of the NMR signal versus excitation moment), a properly developed peak followed by a rapid decrease of the signal amplitude as the Q is increased past the peak response. Modeling results suggest that this rapid decrease is due to the skin depth attenuation caused by the low resistivity of the formations; this corresponds to a brackish/saline environment. Because of the reduced K_h for the second aquifer (12 vs 32 m/d) and the presence of clay horizons, the 2nd aquifer is modeled with 10% water and 75 ms decay time. The expected response is shown in gray in figure 2. Even at the maximum Q value of 7000 A-ms, the MRS signal expected from the 2nd aquifer is still less than one third of the observed signal: we expect that current inversion tools will not reliably extract the characteristics of the 2nd aquifer under such conditions. Therefore under such conductive environment, we currently detect only the top aquifer; such conclusion may change in the future according to the development of the inversion scheme described in the next section.

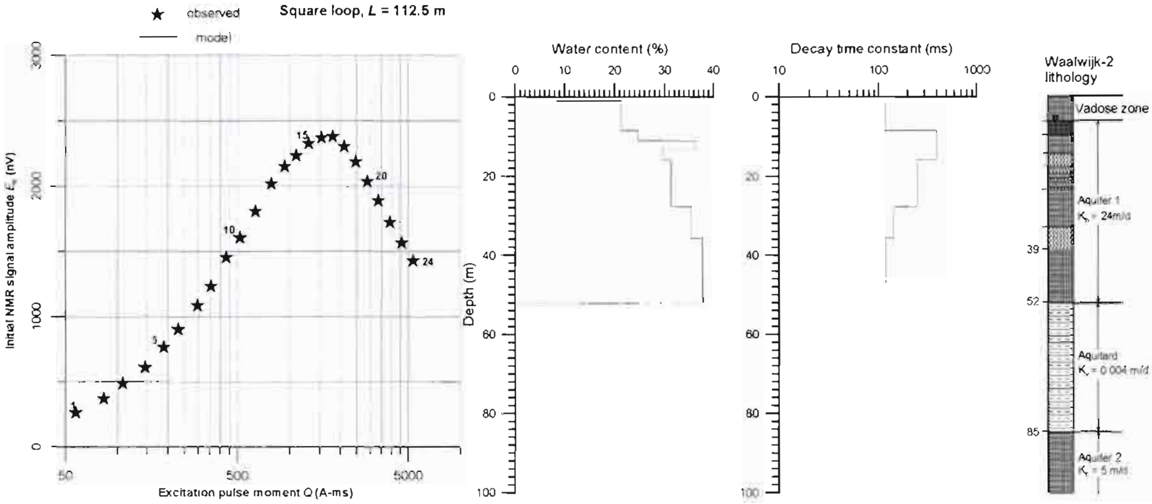
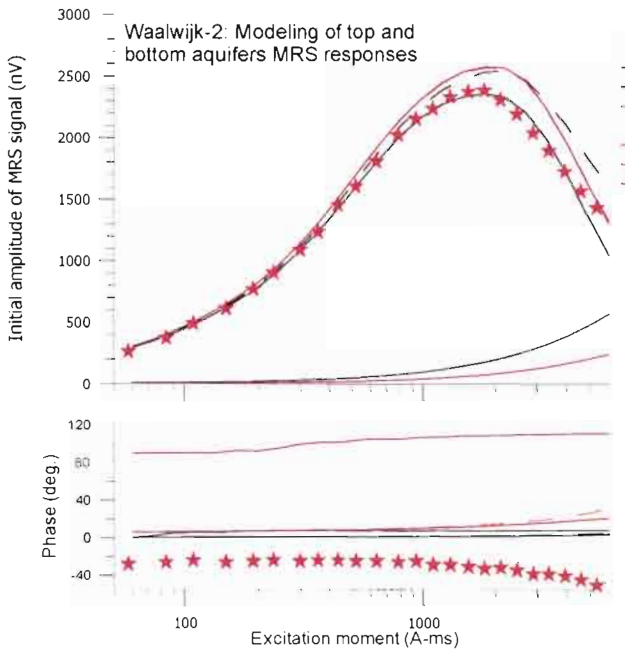
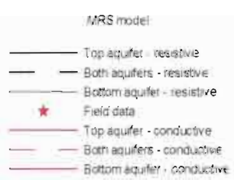


Figure 3: Waalwijk-2 site; left: MRS data set, center: inversion results, right: well data

WAALWIJK-2 CASE

In the second case, at Waalwijk-2, we observe on the E_0 vs Q response, that following the peak response, a normal 'tail' is observed resulting in the above-mentioned inversion of a single aquifer. In order to investigate the case of such un-detected 2nd aquifer, the following modeling was done: (1) the resistivity of the subsurface was estimated from nearby borehole resistivity logs (an in-situ VES or TDEM sounding is not yet available for this site) (2) the MRS response, shown in Figure 3, was modeled with both resistive and conductive [as estimated in (1)] media, the modeling was done in 3 steps: top aquifer only, 2nd aquifer only and both aquifers. A display of such modeling exercise is shown in Figure 4.





For the purpose of Figure 4, the water content in the 2nd aquifer was set the same as the top one, which is most probably an over-estimation. In the display both the initial amplitude (E_0) and the phase (φ) are shown as a function of the excitation moment (Q). The black curves correspond to the resistive case, the colored curves to the conductive case while the actual field measured data are shown with a star.

Figure 4: MRS numerical modeling for Waalwijk-2 top and 2nd aquifers.

OBSERVATIONS RELATED TO FIGURE 4

The following observations are made with respect to this modeling exercise: (1) clearly the water content is under-estimated when the media are considered as resistive; this is generally expected when the aquifer is within or under a conductive medium, (2) in the resistive case, the response from both aquifers is larger than the response from the top aquifer alone while in the conductive case, the response from both aquifers cannot be distinguished amplitude-wise from the response of the top aquifer alone, (3) the phase of the 2nd aquifer is very different from the phase of the top aquifer in the conductive case but not in the resistive case, (4) the actual field data shows a small but significant phase excursion toward the high excitation moment (Q) values, (5) the phase difference between the top and 2nd aquifer response is sufficient (over 110°) to explain that the resultant from the top and the 2nd aquifer responses is the same as the response from the top aquifer alone amplitude wise.

About item (5), let's recall that, contrary to EM induction at high induction numbers, NMR responses are summed directly with due regards to phase and orientation of the magnetic vectors. For example, two collinear vectors of amplitude A will have a resultant amplitude of 2A when their phase difference ($\Delta\varphi$) is 0°, A with a $\Delta\varphi$ of 120°, and 0 with a $\Delta\varphi$ of 180°.

CONCLUSIONS WITH RESPECT TO STANDARD DATA INVERSION AND MODELING EXERCISE

Thus, while we know that we have a second aquifer with high porosity within the depth range of the MRS implementation (NUMIS) at both the Delft and the Waalwijk-2 sites, we cannot detect them with the standard inversion scheme. With knowledge of the geoelectric section, normally available from a VES or TDEM sounding, it is possible, at least for the Waalwijk-2 case, to understand how the 2nd aquifer is masked and how it can be detected and its upper section characterized. Due to the loop size and Q instrumental limitations at the time of the field data acquisition, the bottom of the 2nd aquifer will remain undetermined. In fact, the signal from the second aquifer is skin-depth attenuated due to the electrical conductivity of the aquitard but it is still well within the dynamic range of the MRS instrument. However it is phase shifted so that the phase vector sum of the signals due to the upper and the second aquifer result in an amplitude very nearly the same as if the top aquifer was alone.

The current conclusion from such exercise on the Waalwijk-2 site, is that, by proper discrimination of the phase, in this case around 111° for the 2nd aquifer and around 6° for the top aquifer, two separate inversions can be carried-out: one for the top and one for the bottom aquifer. The results would then be merged for the site interpretation. All the above assumes that no other factors than formation conductivity is responsible for the observed phase shifts. As previously observed by Legchenko et al. (2003) and by Weichman et al. (2000) other sources of phase shift are observed such as the difference in frequency between the MRS instrument excitation frequency and the in-situ Larmor precession frequency which will have to be taken into account. Braun and Yaramanci (2003) have also stressed the information content of the phase in MRS data sets. The contributions from ITC, NITG-TNO and IRIS Instruments at various stages of these investigations are gratefully acknowledged.

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MRS (MAGNETIC RESONANCE SOUNDING) SURVEY IN A DETRITAL COASTAL AQUIFER IN CASTELLON, SPAIN

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INTRODUCTION

The Geophysics Department of IGME (Instituto Gelógico y Minero de España) has carried out during November 2001 a survey with Magnetic Resonance Soundings (MRS) in a detrital coastal aquifer in Castellon province (east Spain). The hydrogeological target of the survey was to verify the usefulness of this method for mapping the different saturated levels of this aquifer, and to obtain information about the productivity and lateral continuity of each level. Seven MRS were measured in a north south profile about five km long (Fig 1).

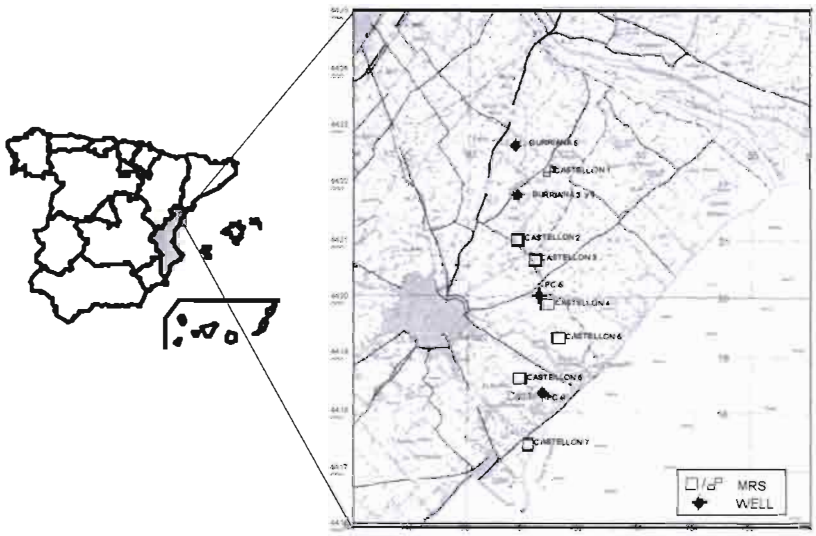

Figure 1. Situation map.

GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT

The Castellon plain is a densely populated area, with a big agricultural and industrial expansion. The survey was made nearby the town of Burriana (Fig.1), in an area of orange trees, with many pumping wells, pipelines and other industrial installations. From the geological point of view it is a tectonic low formed during the Tertiary Age, filled with Plioquaternary deposits of gravel, sands and conglomerates in a silty-clay matrix. These deposits lay either on Mesozoic materials or on low permeability Miocene materials.

Included in the Plioquaternary deposits, two aquifers can be distinguished, an upper one constitutes by conglomerates and a lower one by sands and gravel. The distribution of materials within these deposits is very heterogeneous, with abrupt changes of facies and lense deposits, being difficult to establish their lithological continuity.

The geological model becomes more simple toward the coastline, where the shallower aquifer has 60 m of thickness in average, and the deeper one of Miocene Age reaches 160 m. These aquifers are separated by impermeable marl and clay materials. The groundwater in the plain is highly contaminated by agricultural pollution and seawater intrusion.

Although several geophysical campaigns of Vertical Electrical Soundings (VES) were made in the plain, only one of them (surveyed in 1971 and reinterpreted by J.L. Astier in 1973) has one VES inside the area of the MRS survey. The interpretation of this VES shows layers with low resistivity values, probably due to the seawater intrusion effect at that time. There is also lithological information from some wells. All this information has been taken as a reference in the calculation of the different coefficients and models needed in the interpretation of the MRS. In figure 2 it can be seen the description of the wells, their correlation and the model adopted for the inversion matrix.

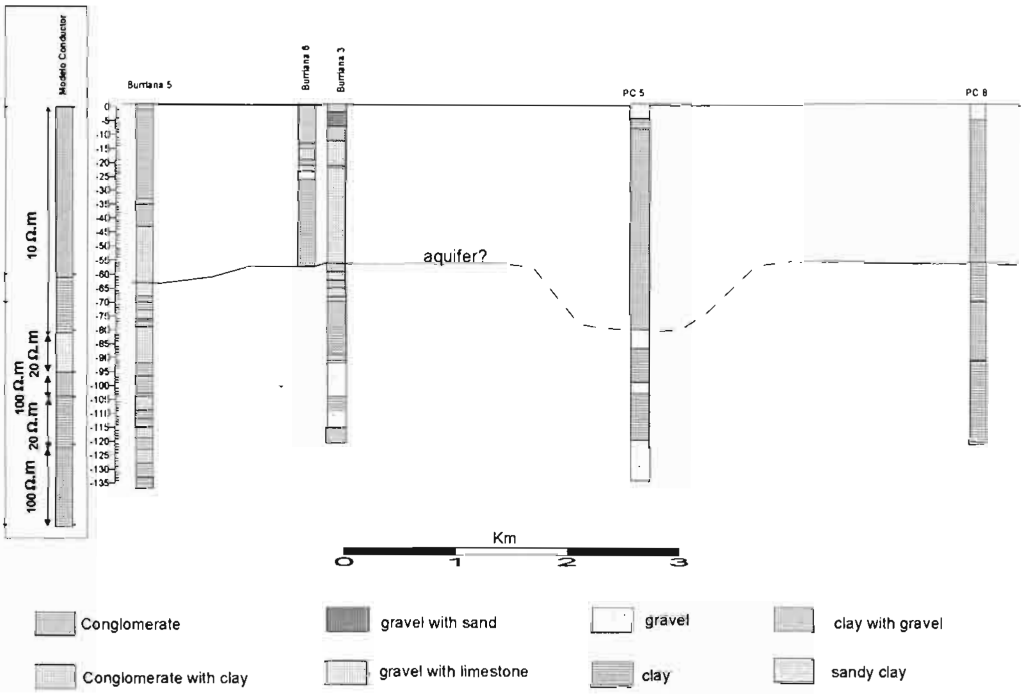

Figure 2. Lithological profile from wells. At the left is the model adopted for the inversion matrix

MEASUREMENTS ANALISYS

All MRS were measured using a square loop of 150 m side, except MRS Castellon1, the northern one, that was measured with a two square 37,5 m side eight shape, because the high noise level produced by a close pipeline.

The survey was made with a Numis Plus equipment from IRIS Instruments, and the whole calculation was made using the software for interpretation provided with the equipment. In figure 3a the maximum signal amplitude vs pulse curves are shown for all the MRS; the measured amplitude is high, between 400 and 1100 nV, and the shape of these curves indicates the presence of water roughly at the same depth for all the points. In figure 3b the environmental noise curves for every MRS are shown, except castellon7 because of its high noise value; the noise level vary from 1000 nV to 4000 nV, but the curves depicted a regular shape without remarkable peaks. The high signal measured and the stability and homogeneity of the noise together with the number of stacks used (32-64), has produced very good quality MRS field curves with high signal to noise ratio (3-17).

In figure 4 we have drawn a profile with the geological information from the wells and the interpreted distribution of the water content (%) and T1 decay time (ms) with depth. We can see the existence of a shallow and porous layer, with water only on MRS Castellon 5 ,6 and 7; underneath a water level is found at a mean depth of 37,5m. This level is in good agreement with the geological information obtained from the wells, being thicker in the centre of the profile, reaching 50m depth under Castellon 4, and decreasing in thickness toward the coastline. MRS Castellon 5 is the only one that reaches a deeper water level bellow 50 m. The mean water content of the water layer is 15 %, reaching the maximum value on Castellon 3 (23%). The calculated T1 values, according to the known empirical table from Schirov, fit very well with the lithology indicated by the wells. For its use in a qualitative way, we did also calculate the permeability of each layer using the expression:

$$K_f = C\,\Phi\,(T_1)^2$$

adopting the default value for the C coefficient provided by the software. The qualitative distribution of the transmissivity is in accordance with the lithological material, and will be verified when pumping tests are available.

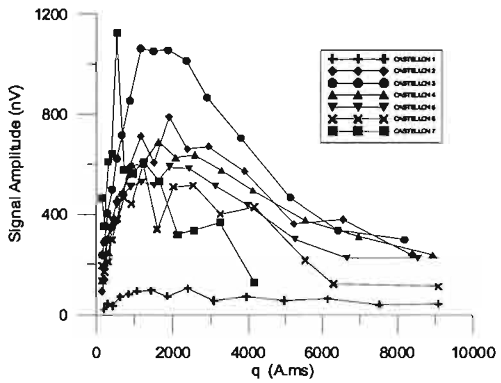

Figure3a Signal amplitude vs pulse.

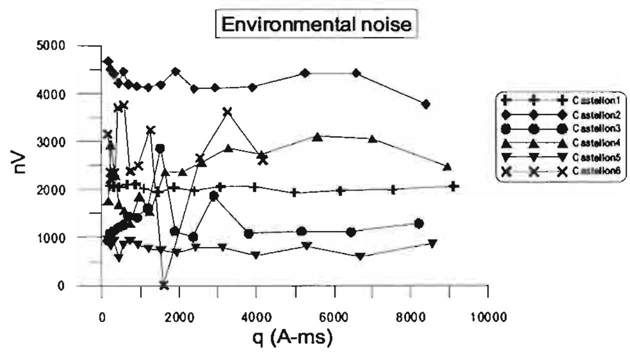

Figure 3b Environmental noise vs pulse.

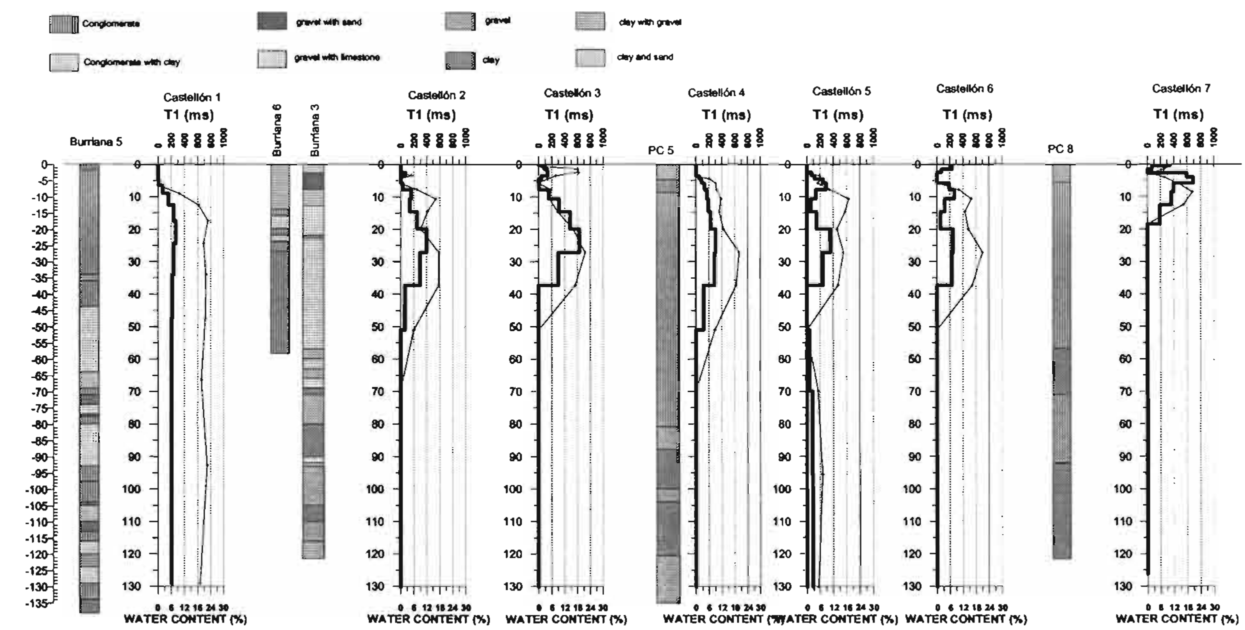

Figure 4. Profile with the information from the wells and the interpreted water content (%) (step diagram) and T1 decay time (ms) (thin line) distributions with depth.

CONCLUSIONS

The MRS data have shown the existence of an aquifer with a first shallow level and a second deeper one that reaches a mean depth of 37,5 m. This second level is thicker in the centre of the profile and decreasing in thickness toward the coastline. Mean values of hydrogeological parameters, effective porosity, permeability and transmissivity have been calculated. Default values for coefficients in the formulas of calculation have been used. In the future, when values from pumping tests are available a correlation between these calculated MRS hydrogeological parameters and the measured ones from pumping tests will be established.

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HYDROCARBON CONTAMINATION OF AQUIFERS BY SNMR DETECTION

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ABSTRACT.

Surface NMR can be used to unambiguously detect subsurface water in suitable geological formations to a depth of 100 meters and more depending on the presence of natural and cultural electromagnetic noise. Mathematical routines yield depth distributions of the liquid, provided that the liquids are present in horizontal layers and not in pores that are too small to be detectable at present. Furthermore, determination of pore size distributions is now possible with relaxation time measurements.

Experiments were performed at shallower depths to detect signals from deposits of subsurface gasoline and diesel fuel near Abakan, Siberia. Surface NMR signals were observed with multiple T_2 relaxation times at sites containing both gasoline and water. The identification of gasoline and water signals were made on the basis of making measurements much farther from the apparent source of contamination and obtaining only one T_2 component, presumed to be water. We are not aware of any other surface NMR experiments that have detected subsurface organic contaminants, especially in the presence of water.

INTRODUCTION

Aquitards and aquifers often have different ranges of electrical resistivity and density. Nevertheless, surface electrical and density technique is often (but not always) able to indirectly delineate the coarse-grained alluvial deposits, which have potential of being aquifers. The SNMR method, on the other hand, allows direct and noninvasive (remote) sounding of groundwater distribution versus depth. Moreover other proton-containing liquids such as hydrocarbons can also be studied.

An earlier study [1] discusses some aspects of the surface nuclear magnetic resonance (SNMR) sounding signal of bulk water detected below the ice surface of Ob reservoir near Novosibirsk. Such SNMR experiments of bulk water are useful for calibration and testing the method. As it was partly reported earlier in [2], investigation of spin relaxation times T_2^*, T_2, T_1 is important for information about the microstructure of pores as well as diamagnetic, paramagnetic, and hydrocarbon contamination. The present study identifies hydrocarbon contamination based on SNMR relaxation.

EXPERIMENTAL AND TEST SITES

The SNMR experiments were performed using the Hydroscope-3 equipment made in the Institute of Chemical Kinetics and Combustion of Siberian branch of the Russian Academy of sciences, Novosibirsk. The technique uses maximal pulse moment up to 20000 A*ms (at 40 ms pulse duration), the battery capacitance 0.2 F, and possibility of two-pulse sequence. The 2 17m diameter three-turn loops were connected in a figure-eight configuration [3] to detect hydrocarbon pollution.

A team from Siberian Branch of Russian Academy of Sciences (SBRAS), Yuzhno-Minusinsk Hydrogeological Enterprise (YMHE), and New Mexico Resonance studied leaky underground storage (LUST) near Abakan. Anatoly Krivosheev and Vladimir Yashchuk of YMHE had monitored numerous LUST sites near Abakan and south of Krasnoyarsk region from borehole measurements. Figure 1 exemplifies a borehole measurement of a 27-cm thick gasoline layer over water at a site in Abakan. At another location, Borehole #52 near a leaking tank of gas station (Abakan), the depth of the gasoline layer was 1.15 m. The dissolved hydrocarbon content in groundwater was 7.15 mg/l. The lithological log of Borehole #52 is clay sand 1-4 m, medium-grained sand 4-5 m, clay and pebbles 5-9 m, and gravel 9-11 m.

Figure 1. An example of hydrocarbon pollution of groundwater (Abakan).

RESULTS AND DISCUSSION

Borehole #52 was located at a gas station on the embankment of Enisei River. Figures 2 and 3 exemplify the hydrocarbon (gasoline) pollution of aquifer detected near the gas station but on the flood plain of the river. Surface NMR signals were observed with two T_2^* relaxation rates at a site, known to contain both gasoline and water and close to the gas station.

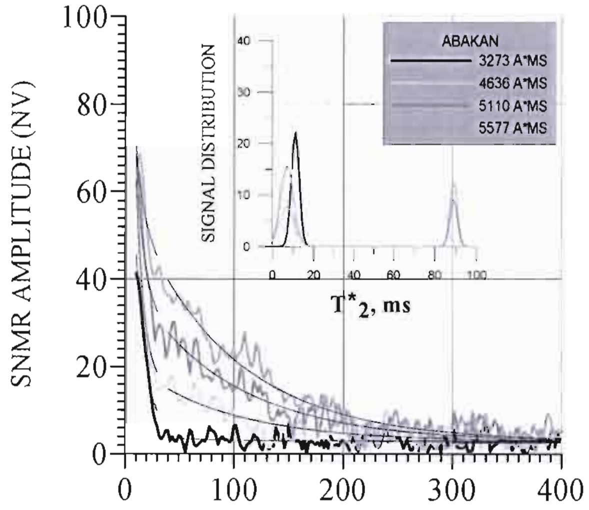

Figure 2. An example of SNMR amplitude versus time at different pulse moments. Near Borehole #52 at leaking tank of gas station in Abakan.

The identification of gasoline and water signals were made on the basis of making measurements 150 meters farther from the source of contamination, and closer to the Enisei River, and obtaining signals with only one T_2^* component (Fig. 3), presumed to be water [4].

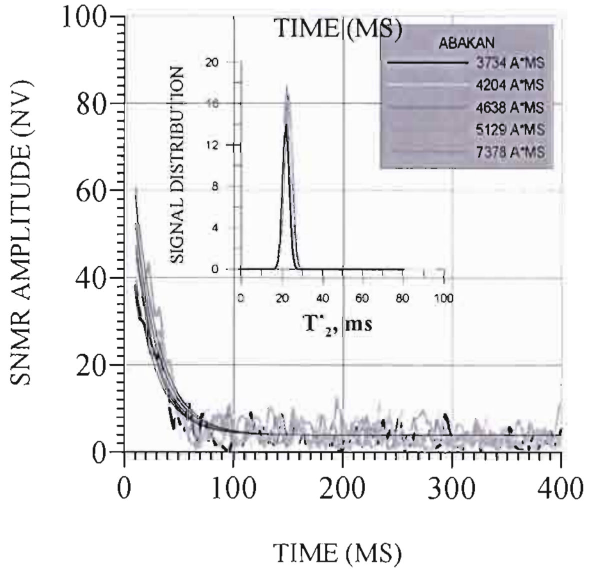

Figure 3. An example of SNMR amplitude versus time at different pulse moments. 150 m away from site of Fig. 2, Abakan.

Since the rock surface is usually water-wetted and the non-wetting phase remains in the bulk, the NMR signal of wetting phase (water) has much shorter relaxation times (~10 ms), while the non-wetting phase (hydrocarbon) exhibits close-to-bulk relaxation behavior (~90 ms). The surface-NMR results obtained are in good agreement with earlier laboratory and NML measurements [5-7]. The pore-surface water-proton relaxation times of ~10 ms (inset, Fig.2) are shorter than the bulk relaxation times of ~20 ms (inset, Fig 3), also in good agreement with past work [5-7].

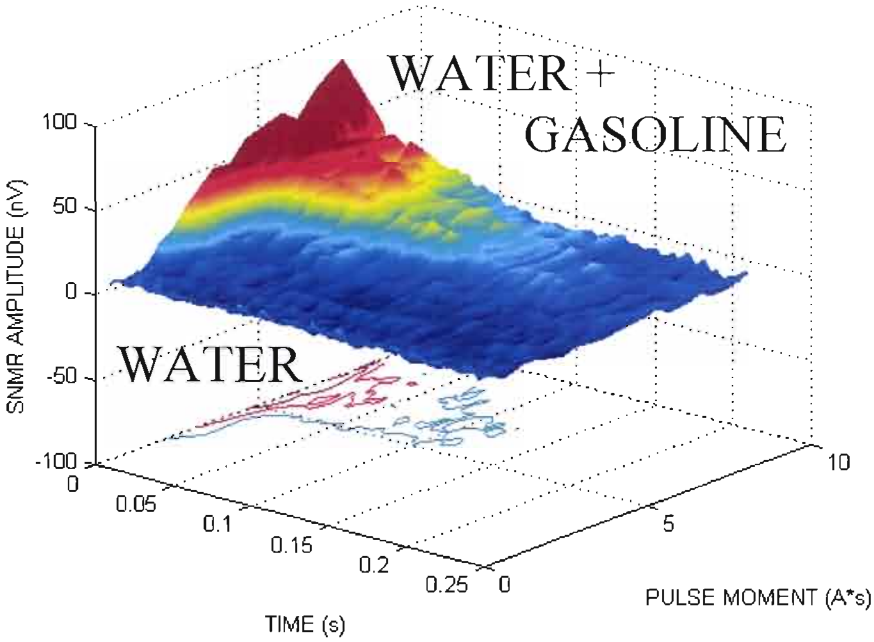

Figure 4. An example of SNMR amplitude versus time and pulse moment. Near Borehole #52, Abakan.

Figure 4 shows a 3-D stacked plot of the SNMR amplitude versus time and pulse moment, the data of Fig. 2, taken near Borehole #52, Abakan. There are only short lifetimes at low moments while there are both short and longer relaxation times at high moments, as can be seen also in Fig. 2. If the shorter relaxation times are due to water, these results indicate that it is at shallow depths while the gasoline with possibly the longer relaxation times occur only for the larger pulse-moments which imply that they are at greater depths. These results are contrary to the situation shown in Fig. 1 or even at borehole #52 where gasoline was over water.

CONCLUSIONS

Surface NMR signals were observed with multiple T_2 relaxation rates at sites with known deposits of subsurface gasoline and water near Abakan. The identification of gasoline and water was made using measurements much farther from the source of contamination and obtaining only one T_2 component.

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COMPARISON OF VARIOUS LOOP GEOMETRIES IN MAGNETIC RESONANCE SOUNDINGS ON THE PYLA SAND DUNE (FRANCE)

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MRS EQUIPMENT PRESENTATION

The first Magnetic Resonance Sounding systems designed by IRIS Instruments for groundwater detection (NUMIS and NUMIS Plus) were dedicated to the maximum depth of investigation reachable, namely 100 to 150m, in relation with the maximum output voltage of the excitation pulse (3000 to 4000V) they could provide. These systems proved to be efficient down to such depths in various types of geological environment.

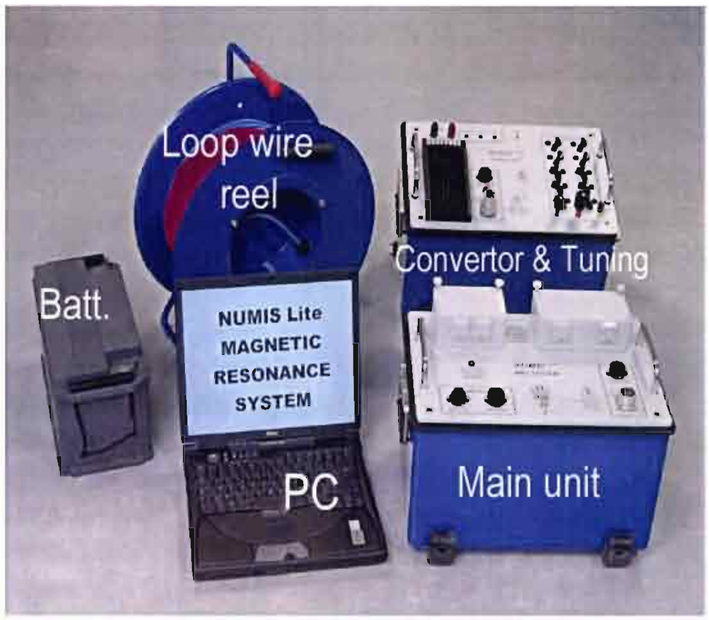

Fig 1 : The NUMIS Lite Magnetic Resonance Sounding system for water investigations down to approximately 50m depth.

Apart from these relatively large water depth investigations, a certain number of hydrogeological issues deal with more shallow depths: non invasive monitoring of the water table in temperate climates, hydrogeological studies related to surface pollution, water investigation in fractured aquifers of outcropping basement areas, etc. These applications lead us to design a reduced power system characterized by a lower weight, which gives more flexibility in the field in terms of logistics.

NUMIS Lite system (fig 1) features only two units: the first one includes the DC/DC converter (24V to 110V) and the capacitor components for the loop tuning; the second one includes the transmitter and the receiver functions for the pulse generation and the signal measurement. A PC computer drives the readings (Windows version recently developed) and ensures the on-site interpretation of the sounding at the end of the data acquisition. The 1000V excitation pulse voltage transmitted by NUMIS Lite permits to reach investigation depths of about 50m.

The NUMIS Lite new system has been recently tested on the Pyla sand dune in France to check its operation and its specifications for instrumental purposes and to compare the MRS data obtained with various loop geometries for methodological purposes.

LOOP SIZE DISCUSSIONS AND GEOLOGICAL BACKGROUND

In the MRS principles, the depth of penetration increases with the surface of the loop and with the intensity of the current of the excitation pulse. However, for a given maximum output voltage of the excitation pulse, the intensity of the current decreases when the size of the loop (its impedance) increases. That is why a compromise has to be found to optimise the penetration, also taking into account the internal behaviour of the transmitter with regards to the values of the loop inductances.

With the NUMIS Plus equipment which features 3000V maximum output voltage (resp. 4000V in option), the recommended side of the square loop is 100m (resp. 150m) to reach a maximum investigation of 100m (resp. 150m). In the NUMIS Lite equipment which features 1000V, the side of the recommended square loop is 60m. In case there is too much EM noise to take readings, it is possible to use a 30m side eight shape square loop. In such a case, the penetration is reduced by approximately 50%. A third possibility is suggested with the NUMIS Lite equipment, a two turns 30m side square loop, which has a higher inductance than the two other configurations, but which offers the possibility to work on a smaller area on the ground, which is sometimes very useful in field conditions where the available space to set up the loop is limited. All three loop configurations use the same length of wire, 240m.

The Pyla sand dune, located on the South West part of France near Bordeaux, on the shore of the Altlantic Ocean, has been chosen to perform a series of tests of the NUMIS Lite new MRS equipment (fig 2). This site is particularly adapted to check both the capability of the instrument and the accuracy of the interpretation software, as the loop can be laid on the ground at various elevations above the sea level which gives a good indication of the water level under the location of the loop. A GPS receiver has been used to know as precisely as possible the elevations of the stations where the various Magnetic Resonance Soundings have been carried out. The dune is known to be basically composed of sand, although no accurate geological section is available.

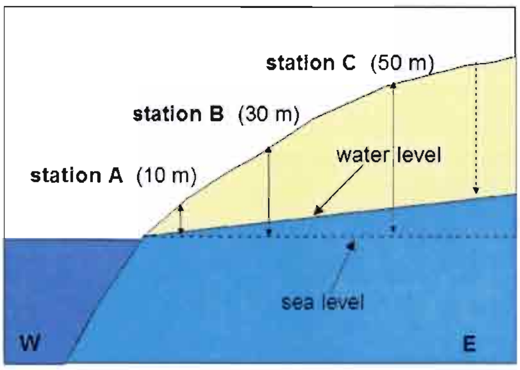

Fig 2 : Sketch (on top) showing the locations of the MRS soundings (stations A, B, C), and two pictures of the Pyla dune (top right) and of the location of station B with NUMIS Lite equipment placed on a caterpillar wheel trolley for an easier transportation on the sand (right).

FIELD DATA AND RESULT INTERPRETATION

A total of five soundings have been carried out: three of them used the 60m side square loop at elevations of 10m (station A), 30m (station B), and 50m (stations C); two other soundings have been made at station B (30m elevation) with the eight shape loop and with the two turns 30m side square loop. The frequency was 1963 Hz.

The three first MRS soundings are interpreted in fig 3: in all three of them, the EM ambient noise was of the order of 1000 nV, while the amplitude of the signal was of the order of a few hundreds nV. A stacking number of 64 has been taken for each one of the ten pulse moment values at stations A and B, 128 for station C, for a good quality of the readings. The stacked noise value decreased down to about 20 nV. The interpretation, carried out with a 100 ohm.m layer hypothesis, points out water levels at respectively 10, 25 and 40m depths for stations A, B and C at elevations of 10, 30 and 50m above the sea level. Those interpreted depths are quite compatible with the elevation figures, if one takes into account the usual gravimetric effect of the rain water. Given the quality of the data of station C, it seems obvious that in such conditions, the maximum investigation depth could be greater than 50m.

The three soundings carried out at station B (30m elevation) are plotted in Fig 4. The ambient noise levels were 1000 nV for the 60 side square loop, 400 nV for the two turn 30m side square loop (which offers a surface 50% of the previous loop), and 200 nV for the 30m side eight shape square loop (which is suppose to reduce the noise down to 20 to 10% of the noise of the 60m side square loop). Again the interpretation is quite good on all three of them, showing the water level at 25m, while the sea level is 30m depth at this station. The equivalence effects do not have to be forgotten which may usually vary the interpreted depth in a proportion of 10 to 20%.

The value of the porosity (water content) appears to be of the order of 20% in all five soundings, which seems to be quite coherent with the sand nature of the geology of the site. In the sounding of station B (30m elevation) , the two pulse technique has been used to obtain the T1 time constant parameter (about 300ms against about 200ms for T2*), which suggests a permeability of 2. 10^{-4} m/s corresponding to a good potential aquifer layer.

CONCLUSIONS

The data measured and interpreted in this survey show that both the interpretation software and the equipment (NUMIS Lite) permit to reach good quantitative results in case of favourable conditions (reasonable EM noise, no magnetic material, presence of enough water). The coherence of the interpretation of the various loop configurations must incite the operator to use the one which best fits its local constraints.

The NUMIS Lite system, by its compactness and handiness will permit in the future to test the MRS method in more geological, geographical and application contexts when the required penetration does not exceed 50m.

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Fig 3: MRS SOUNDINGS FOR A 60m SQUARE LOOP, at various elevations: stations A. B. C

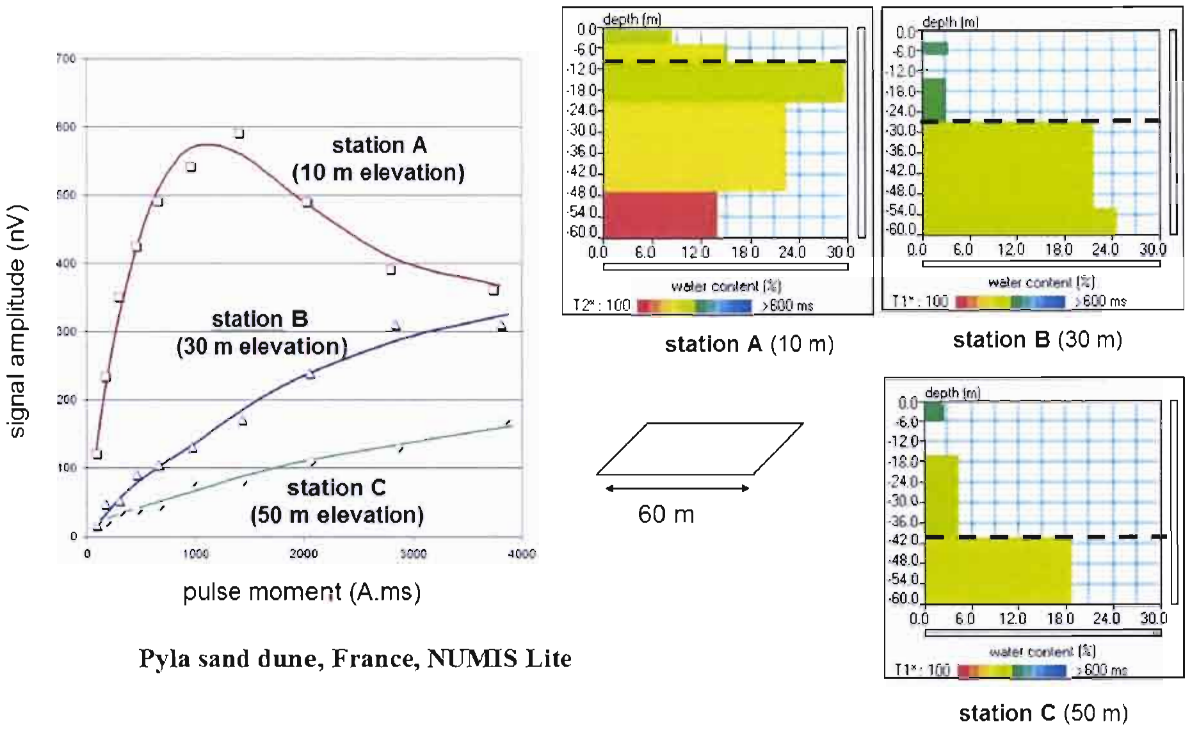
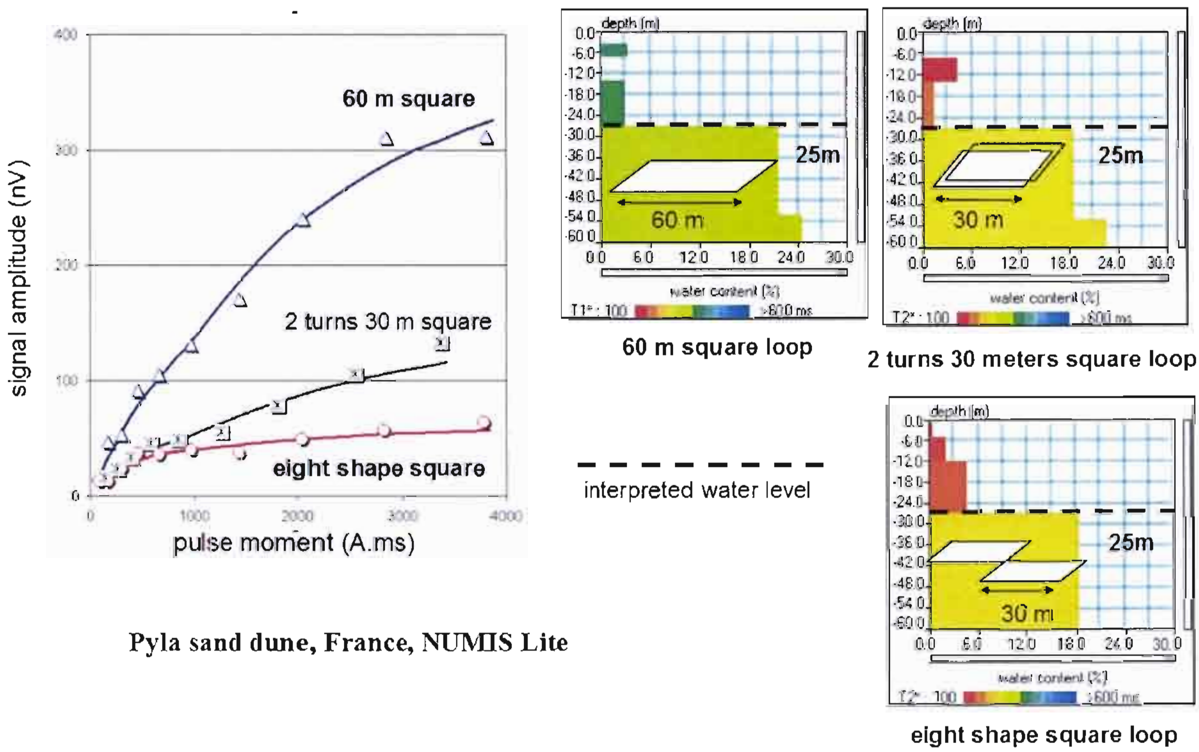


Fig 4: MRS SOUNDINGS WITH VARIOUS LOOP SHAPES, at the same elevation: station B (30 m)



MAGNETIC RESONANCE SOUNDING: APPLICATION TO THE CHARACTERIZATION OF THE CRYSTALLINE BASEMENT AQUIFERS OF BURKINA FASO

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INTRODUCTION

Basement aquifers are of particular importance in tropical regions both because of their widespread and accessibility and because there is often no readily available alternative source of water supply. Even in more humid regions, water quality considerations can favour their use (Wright, 1992).

Basement aquifers are developed within the weathered overburden and fractured bedrock of crystalline rocks which are mainly of Precambrian age. The usual conceptual model of the basement aquifer describes several zones in the lithological sequence. The alterites (regholith) consist in weathered and decayed rock; their permeabilities vary in accordance with lithology but is usually low; they play the major part of storativity in aquifer functioning. The underlying weathered-fissured zone (saprock) and the fractured bedrock present typically low storativity, but permeability commonly increases at lower levels due to a lesser development of secondary clay minerals and a high permeability of open fractures (Lachassagne, 2001).

There are a number of important constraints to development of basement aquifers. The failure rate of low yield boreholes for rural water supply is high in the drier regions (typically in the range of 40 to 50 %), and the implementation of high yield boreholes for urban or irrigation purposes is always a challenge for hydrogeologists. Furthermore, the low storativity of basement aquifers often leads to unsustainable yield of boreholes.

Therefore, there is an important need both to improve the current methodology for high yield borehole implementation and to evaluate more precisely the overall resources and aquifer occurrence to assist development efficiency and long-term sustained control.

In this paper, the contribution of Magnetic Resonance Sounding (MRS) to the characterisation of basement aquifers in Burkina Faso is presented.

BACKGROUND

Basement aquifers are of significant extent in Burkina Faso territory (around 80% of the total country surface area). To measure the contribution of MRS method to characterise these aquifers, a survey was conducted from November 2002 to January 2003 in granite and associated rocks of Precambrian age.

MRS were implemented around recent boreholes drilled both in the alterites, in the weathered-fissured zone and in fractured bedrock. All of the 13 boreholes were tested with step-test pumping tests (total pumping duration of 4 hours), and 6 of them were used to conduct aquifer tests (pumping duration of 72 hours). The aquifers local transmissivities were calculated from the recovery period of step-tests, and the storativities were calculated from piezometers records with Theis and Jacob methods (Kruseman, 2000). The geometry of the aquifers was deducted from boreholes reports and the water static level (WSL) was measured while implementing the MRS. The Numis^{Plus} ® equipment was used to set up the MRS with a square loop of a typical 150 meters side. The adapted saturation recovery method was used to measure the longitudinal relaxation time (Legchenko et al., in press) and the storativity and transmissivity of the aquifers were estimated from MRS as (Vouillamoz, 2003) :

$$S_{MRS} = 4{,}3 \cdot 10^{-3} \cdot (w \cdot \Delta z)$$
$$T_{MRS} = 3 \cdot 10^{-7} \cdot \left(S_{MRS} \cdot \left(T_1^*\right)^2\right) \qquad (1)$$

where S_{MRS} is the MRS storage coefficient, T_{MRS} is the MRS transmissivity (m²/s), w and Δz are respectively the MRS water content (%) and saturated thickness (m), and T_1^* is the observed longitudinal relaxation time.

MAIN RESULTS

Field results obtained in Burkina Faso show that the reservoir type could be estimated from MRS data. The Table 1 indicates that the average value of water content is higher and the average value of longitudinal relaxation time shorter for water in alterite reservoirs than for water in fissured-fractured reservoirs. According to equations (1), it means that the storativity is higher and the transmissivity is less for the alterites than for the fissured-fractured zones, which is in accordance with the typical hydrogeological conceptual model. However, the values margins are large and ambiguity still remains when interpreting the MRS data alone.

Table 1 : MRS parameter and reservoirs type.

Reservoir	Water content (%)			T^*_1 (ms)		
	Max.	Average	Min.	Max.	Average	Min.
Alterites	6	3	1	600	400	180
Fissured-fractured bedrock	2,5	1	0,2	1500	650	350

The reservoir geometry is described by MRS in 1D with an average difference with boreholes data of +/ 12% for the depth to the top of the saturated reservoir, and +/- 17% for the depth to the fresh bedrock (Figure 1).

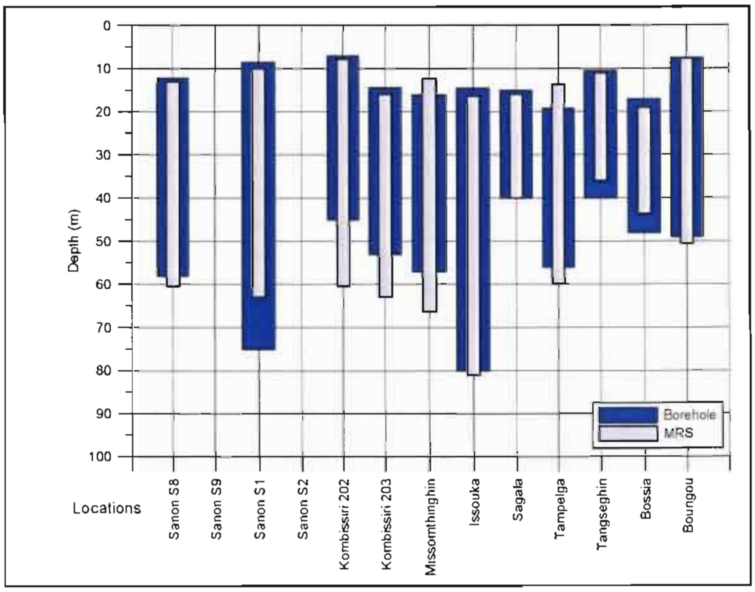
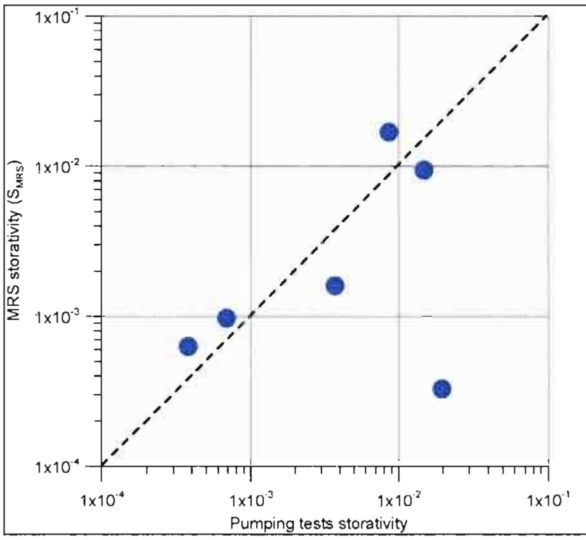


Figure 1 : geometry 1D of the aquifers.

The aquifer hydraulic properties were estimated after a calibration process, according to equation (1). The average difference with properties calculated from pumping tests data are respectively +/- 80% for the storativity (Figure 2) and +/- 41% for the local transmissivity (Figure 3).



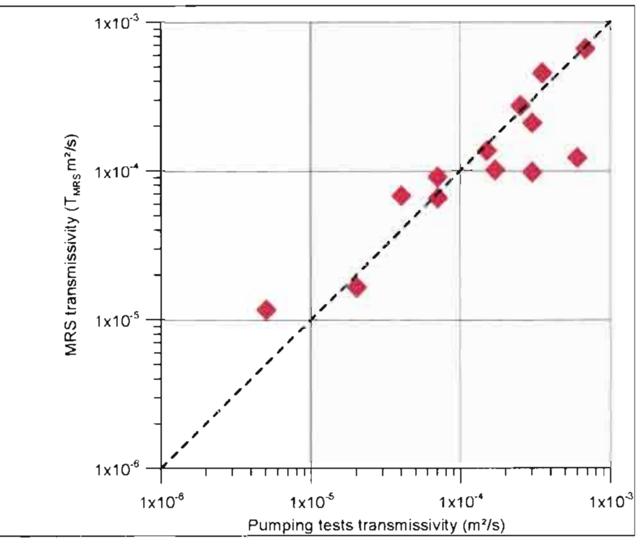


Figure 2 : aquifers storativity.

Figure 3 : aquifers local transmissivity.

The main limitations of MRS in such geological contexts are (1) the duration of data acquisition which ranges between 6 and 20 hours due to the low signal to noise ratio, (2) the 1D measurement which does not allow to describe the reservoir structure over a scale corresponding to the loop size, and (3) the loss of resolution with depth which does not allow to measure small signal coming from depth productive fractures (Figure 4).

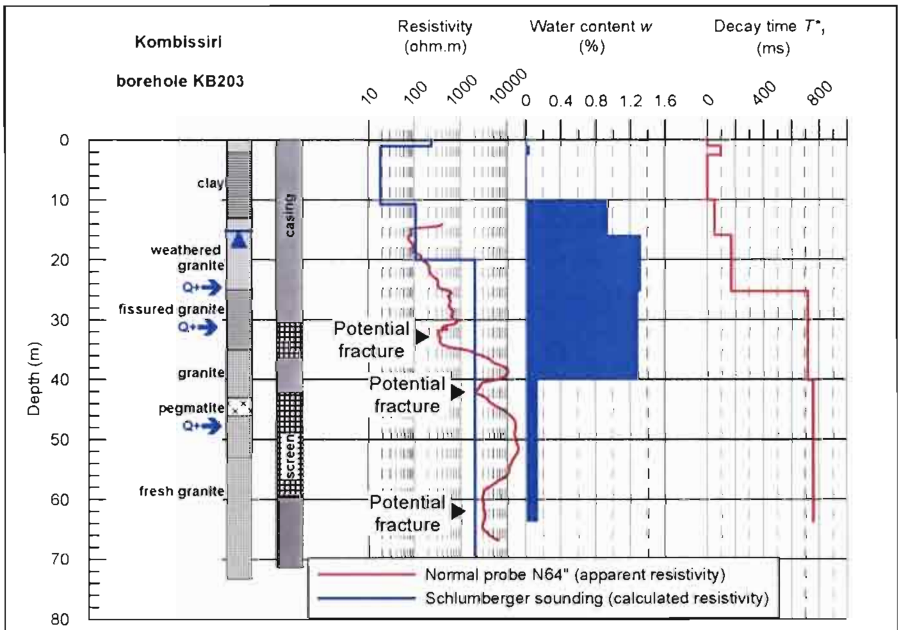


Figure 4 : MRS loss of resolution with depth : the deepest fracture zone is not identified by the MRS.

However, the characterisation of aquifer is improved if the MRS is jointly interpreted with electrical resistivity methods. When the MRS resolution is not sufficient in depth, the 1D electrical soundings is often able to precise the depth of the substratum. In heterogeneous contexts, the 2D electrical imaging can underline the structures of the aquifers.

With the available data, the type of reservoir is well estimated when it is jointly characterised with its electrical resistivity and its MRS transmissivity (Figure 5).

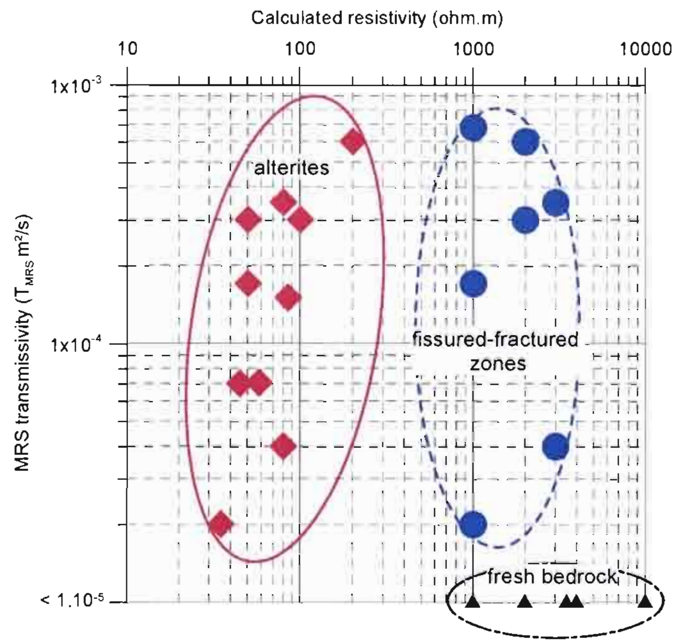


Figure 5 : type of reservoir defined with both electrical resistivity and MRS transmissivity.

CONCLUSION

The main conclusions of the comparison between the MRS results and the borehole data are : 1) the geometry of the weathered part of the aquifer is well describe by the MRS, 2) the storativity and the transmissivity can be reasonably estimated from MRS data after calibration, 3) the main MRS limitations are the 1D approximation in high heterogeneous contexts and the loss of resolution when looking for deep narrow fractures, 4) MRS is a useful tool to characterize aquifer in crystalline context. Its joint use with 1D electrical sounding and 2D resistivity imagery is promising to support hydrogeologists for both borehole implementation and reserve evaluation.

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3-D MODELLING AND ASSESSMENT OF 2-D INVERSION OF SURFACE NMR

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SUMMARY

The geophysical field method of surface nuclear magnetic resonance (SNMR) allows a direct determination of hydrogeological parameters of the subsurface. The amplitude of the SNMR signal is directly linked to the amount of mobile water. The relaxation behaviour of the signal correlates with pore sizes and hydraulic conductivities of an aquifer. The signal phase is related to the electrical conductivity of the subsoil.

Currently the SNMR technique is used only in sounding mode, thus, the inversion is one-dimensional. We introduce a 3-D forward modelling scheme for SNMR amplitudes and decay times, that can be used for two and three-dimensional interpretation of SNMR surveys. For a better understanding and insight of the capability of the method we calculate the SNMR response of 2-D and 3-D models, i. e. the SNMR relaxation signal for various locations of the antenna loop. This allows to investigate the spatial signal sensitivity of the method and shows the limits and problems of the 1-D inversion and interpretation of 2-D and 3-D structures.

METHOD

The method of SNMR is based on the principle of the magnetic resonance of protons of hydrogen atoms in the Earth's magnetic field. In SNMR an alternating current pulse through a wire antenna at the surface stimulates the NMR signal. An external static magnetic field B_0 causes the nuclei to align themselves in one of two orientations with respect to B_0. After termination of the exciting pulse the response field due to the relaxation of the precessing hydrogen protons is measured. The initial amplitude E_0 of the signal corresponds to the water content in the sub-surface [1, 2]. The decay time T_2^* (spin-spin relaxation time) of the SNMR signal corresponds to pore sizes. The fundamental integral-equation that governs the amplitudes $E_0(q)$ of NMR as a function of the pulse moment q is given by

$$E(t,q) = E_0(q)e^{-t/T_2^*(q)} = \omega_0 M_0 \int_V e^{-t/T_2^*(\mathbf{r})} f(\mathbf{r}) \cdot B_\perp(\mathbf{r}) \cdot \sin\theta(\mathbf{r})\, dV, \qquad (1)$$

in which ω_0 is the local Larmor frequency of the hydrogen protons and M_0 is the nuclear magnetization of the protons. The water content and the decay time for an unit volume at the point r in the subsurface are given by f(r) and T_2^*(r) respectively. $B_\perp$(r) states the component of the exciting magnetic field perpendicular to the Earth's geomagnetic field. The tilt angle of the protons is given by $\theta(r) = 0.5\gamma B_\perp(r) q$. Increasing the pulse moment q ($q = I_0\tau$, where I_0 and τ are the amplitude and duration time of the current pulse, respectively) increases the depth of penetration of the method.

NUMERICAL MODELLING

We introduce a 3-D forward modelling of SNMR initial amplitudes and decay times [3,4,5]. A prismatic three-dimensional body model is divided into small cubic cells of dimension $\Delta V = \Delta x \Delta y \Delta z$. The water content f(x,y,z) and the decay times T_2^*(x,y,z) are assumed to be constant in each cell. Then the integral equation is approximated by the finite summation

$$E(t,q) = \omega_0 M_0 \sum_z \sum_y \sum_x e^{-t/T_2^*(x,y,z)} f(x,y,z) \cdot B_\perp(x,y,z) \sin\theta(x,y,z) \Delta x \Delta y \Delta z. \qquad (2)$$

From this relation, the complete SNMR signal can be calculated as a function of a three dimensional distribution of the water content f(x,y,z) and decay time $T_2^*(x,y,z)$ in the subsurface.

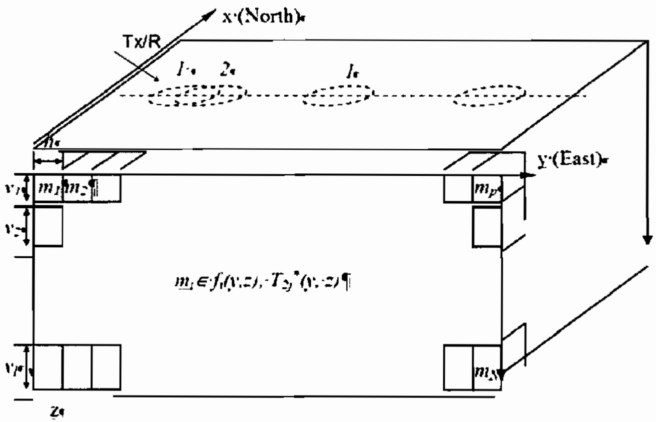

Fig. 1: 3-D modeling of surface NMR measurement for l=1,..,L sounding points.

Fig. 1 represents the 3-D model-discretization for which SNMR model have been calculated using one turn circular loop of radius 50 m in a geomagnetic field of 48000 nT at an inclination of 60^0 and declination of 0^0 in a low conductive half-space. The initial amplitude for $t = t_0$, the start of the record, is then given by

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y \sum_x f(x,y,z) \cdot B_\perp(x,y,z) \sin\theta(x,y,z) \Delta x \Delta y \Delta z\,. \qquad (3)$$

The inner part of the integral is commonly written as the product of a kernel function and the water content

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y \sum_x f(x,y,z) \cdot K_{3D}(q;x,y,z) \Delta x \Delta y \Delta z\,. \qquad (4)$$

For a study of 2-D we assume the water content to be in 2-D distributed. We obtain

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y f(y,z) \cdot K_{2D}(q;y,z) \Delta y \Delta z\,. \qquad (5)$$

2-D SENSITIVITY OF SNMR

To study spatial sensitivity for SNMR surveys we modeled 2-D sensitivities for three different field layouts. The T_x/R_x antenna (1 turn circular loop, radius R = 50 m) is shifted at the surface for intervals of 50 m, 100 m and 150 m between sounding points each for a west-east and south-north profile. The sum of the kernels (magnitudes) of a set of measurements along a profile now gives the 2-D sensitivities to the water distribution. Fig. 2 presents the distribution of sensitivities for pulse moments q = 1, 10, 20 A.s., respectively. To evaluate the lateral resolution of each survey the 2-D kernels are compiled.

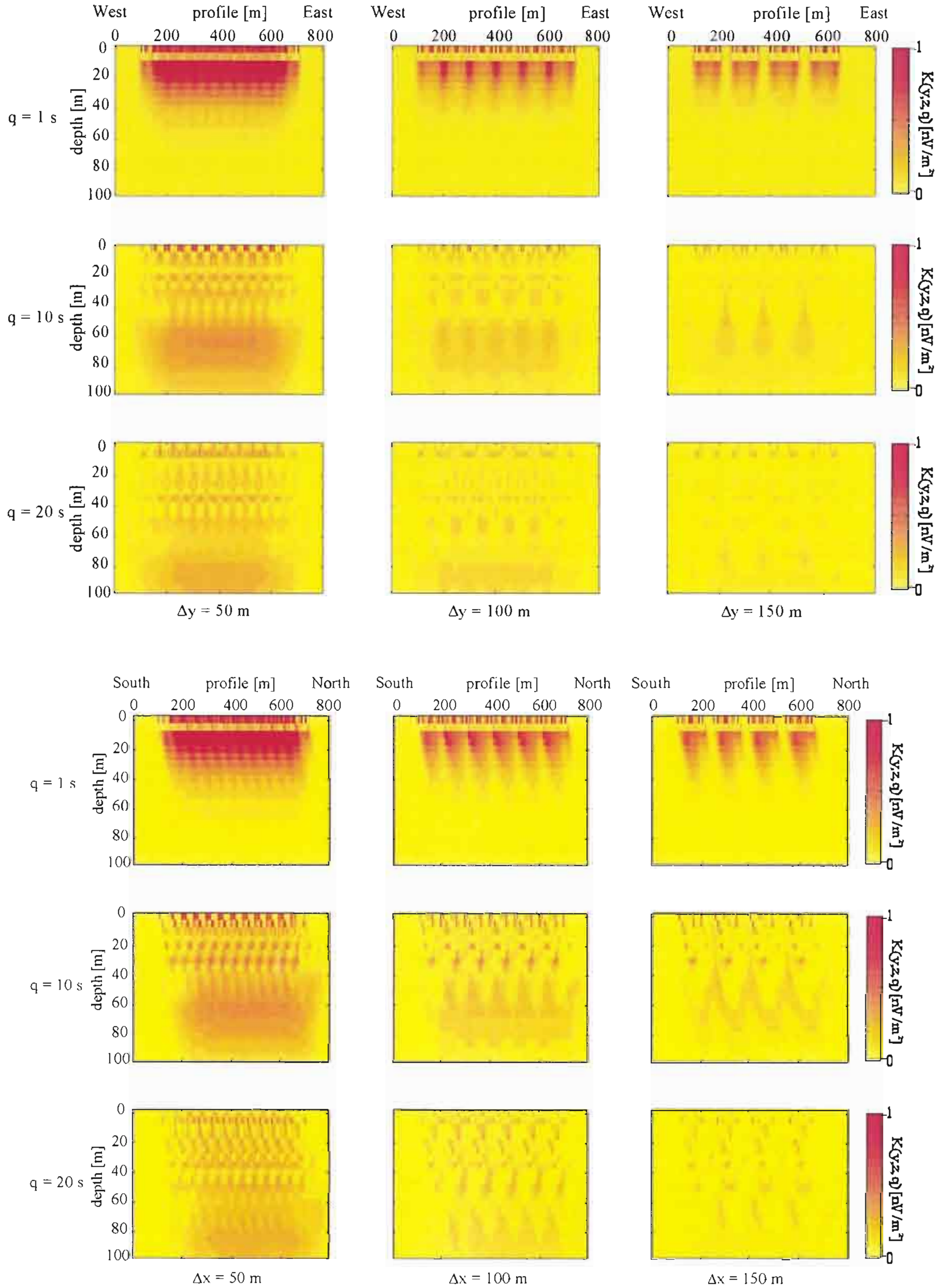

Fig. 2: 2-D sensitivities for SNMR sections in west-east (top) and south-north (bottom) for sounding point intervals: 50 m (left), 100 m (center) and 150 m (right); earth magnetic field B_0 = 48000 nT; I = 60^0;circular loop of radius 50 m, 1 turn.

Increasing pulse moment q increases the depth of penetration as well as the lateral extension of the sensitive region. A sounding interval of 50 m (1 R) with 50 m overlap yields the best lateral coverage. The consistency of lateral coverage rapidly decreases for 100 m (2 R) interval for of smaller section than the 1R interval. For 150 m (3 R) intervals, which would be the fastest survey progress, the sections display almost no consistent lateral coverage. Therefore only smaller intervals would be favourable for a 2-D inversion of field data. However, the lateral resolution can generally not exceed the sounding intervals.

For South to North profile direction a northward shift of sensitivities can be observed. Therefore, regions of low sensitivity occur in the southern part of the profile whereas regions of high sensitivity can be observed beyond the northern profile limits.

CONCLUSION & OUTLOOK

2-D SNMR sensitivities are necessary to evaluate lateral and vertical resolution of 2-D SNMR surveys. As the depth of penetration is determined by the pulse moment q, the lateral resolution depends on sounding point separation. Intervals smaller than one loop diameter are recommended for 2-D surveys for sufficient coverage. SNMR signal contributions are non-symmetrical, therefore, profile directions have to be considered for survey design and inversion. 2-D sensitivities provide fundamental information for 2-D inversion of SNMR profile measurements.

The next step within the scope of this work is to develop an inversion algorithm and design optimized field layouts based on 2-D sensitivity studies for SNMR data. In order to calculate stable solutions of inversion method it is necessary to apply regularization methods and also analyze the regularizing. Development of a constrained matrix inversion based on these studies is actually in progress. Finally, 2-D inversion will be performed for experimental data to prove the performance of the method.

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APPLICATION OF SNMR METHOD IN ENGINEERING GEOLOGY

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ABSTRACT

The nuclear magnetic resonance is nowadays one of the sophisticated techniques. We firstly applied surface nuclear magnetic resonance (SNMR) method to study of landslide and obtained obvious of result. It is a creative point for the application of SNMR method and expanding the applied realm of the new method as well. There are some disadvantages when the traditional geophysical method used for study of landslide. However, make use of the SNMR method in detecting groundwater directly, the features of groundwater in landslide can be determined accurately, especially the existing of aquifer, the position of impervious course and the depth of landslide. These are very important in prospecting, monitoring and treating landslide. In this paper, the method and technique of SNMR used to detecting landslide are discussed; The parameters of hydrology and geology which are correlated to the stability of landslide are obtained by the SNMR data; A landslide monitoring in Three Gorge, the depth of landslide plane correctly determined with SNMR and the results correspond to drilling data, and the example shown that SNMR method is a fast and valid method in probing into landslide.

INTRODUCTION

NMR technique is one of the greatest results in advanced physics study. NMR phenomenon was simultaneously discovered in 1946 by American physicians E.M Purcell (Harvard University) and F Bloch (Stafford University), both they have been awarded the Nobel Prize of physics in 1952.As present, NMR have been widely used in certain field, Such as physics, chemistry, biology, medicine and petroleum-chemistry as well as earth science.

The application of NMR in earth science began as early as in 1954, M Packard (Member of F Bloch group in Stafford) and RH Varian had successfully observed free nuclear induction caused by water proton in geomagnetic field, that is FID signals. From which high accuracy, stability in performance proton precession magnetometers have been prepared, including ground and aero-proton magnetometers which one mainly used in geological and mineral resources investigation.

The second application of NMR in earth science is nuclear magnetic logging (NML) and its related rock core testing and analysis in lab. Developed for nearly 40 years, NML technique could possibly assess the permeability and porous structures in sandy rock and complex reservoir strata, stored deposits, residual oil distribution and fluid saturation as well as its viscosity, which has become a highlight in oil well logging techniques.

The third application in earth science is water finding. The causes of landslide and its evolution are closely related with groundwater activity, rainfall and seepage of surface water. Because of the water action, there exist some obvious differences in conductivity, permeability, permittivty, activity of electric-chemistry, relaxation, radioactivity and wave velocity between physical properties caused by integrated rocks and damaged rocks, both are in landslide body. So far, the methods for investigating landslides are: resistively methods, VLF, Shallow seismic, GPR, natural acoustic radiation, electromagnetic radiation, radioactive survey and radio penetrating, etc.

The methods above respectively reflect the variation of physical property of landslide body from various aspects, it is, however, not a direct method to detect the distribution and variation of groundwater closely associated with landslide. Then, the surface nuclear magnetic resonance (SNMR for short) is the only one to directly detect groundwater, which can give the occurrence of groundwater about the studied section directly. With the help of National Natural Science Foundation of China, we began to study landslide problem with SNMR system for the first time, and did some tests, monitoring in Zhao Shuling, Ba Dong County, Hubei, and preliminary results have been obtained.

FEASIBILITY OF STUDYING LANDSLIDE AND SNMR PRINCIPLE

SNMR principle

NMR is a phenomenon of physics based on atomic nucleus property, which means the matter with nuclear paramagnetic absorbs selectively electromagnetic energy [4]. On theory, the unique condition of NMR application is the magnetic moment of atomic nucleus, which is not zero. The Hydrogen atomic nucleus has paramagnetic, and its magnetic moment is not zero. As the hydrogen nucleus is the proton with highest abundance and largest gyromagnetic ratio of paramagnetic nucleus in the strata. Under the action of stable geomagnetic field, hydrogen proton processes along the geomagnetic direction, just like a top processes along the earth's gravitation, its procession frequency (Larmor angular frequency) is dependent on geomagnetic field intensity $\boldsymbol{B}_0$ and hydrogen proton gyromagnetic ratio γ

$$\omega_0 = \gamma * B_0 \qquad (2\text{-}1)$$

Under the action of geomagnetic, hydrogen proton is at certain energy levels. If the protons in groundwater are excided by alternative magnetic field $B_1(\omega_0)$ with the Larmor frequency, making them to transit in energy levels, that NMR is generated.

In general, the alternating field pulses with Larmor frequency are introduced in surface loop (transmitting/receiving coil), the envelope curve of alternating current pulses is rectangular. Under excitation of alternating magnetic field caused by alternating current in earth, the macro-magnetic moments of hydrogen protons in underground water are formed. This macro-magnetic moment produce procession in geomagnetic field, its processing frequency is the behavior of hydrogen protons. After switching off the current pulses, the NMR signals caused by different exciting pulses are picked –up with the same loop, the envelope of the signals attenuates as exponential curve. The intensity and decay speed of the signals are directly related to the quantity of proton in water, that is, the amplitude of signal is in direct proportion to free water content which is being investigated, from which a direct water finder method, SNMR, is introduced.

SNMR survey system and parameters

The device we used is NUMIS equipment from France. It is an advanced direct waterfinder with high output power and high receiving sensitivity controlled with PC. The whole system consists of DC battery (2 vehicle batteries), DC/DC converter, and transmitter transmitting/receiving antenna, tuning units, receiver, portable PC and some accessory connector. The connecting scheme in the field is given in Fig 1.

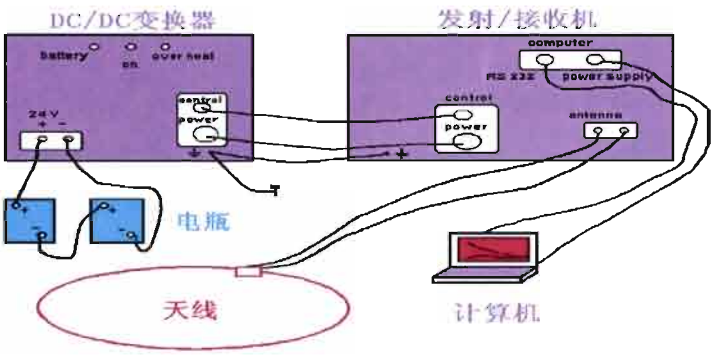

Fig. 1. Components of NUMIS station and the diagram of interconnections.

The survey parameters are following:

- The initial amplitude of NMR signal E_0;
- E_0 is in direct proportion to water content in water –bearing strata;
- The averaged relaxation time of NMR signal;
- The initial phase of NMR signal.

The useful parameters related with hydrological geology and engineering geology through interpretation to the raw data could be obtained: the depth of water-bearing strata, the thickness, the water content and water-bearing strata category (mean porosity and the conductivity of the strata).

The feasibility of detecting landslide with SNMR

It is indicated that over 80% landslides events have relationship with underground water. SNMR could obtain the information about underground water, so SNMR could play an important role in study of landslide to determine the sliding boundary layers and recognize the water-bearing strata:

Near landslide surface, the mechanics property of rocks has changed, water-bearing saturation is much higher than integrated rock, and otherwise the permeability is largely enhanced.

From SNMR, the water-bearing volume percent in aqueous strata could be obtained, or the permeable coefficients between strata could be calculated. In comparison with normal mean value of aqueous property, it is possible to deduce the existence of the landslides.

With SNMR direct inversion, the histogram of variation of water content with depth could be obtained to deduce the number of landslide boundary and the depth of each landslide surface. From certain SNMR survey, it is possible to obtain the space distribution of landslide surfaces and to decrease the drilling quantity.

From two monitoring in flood and drought periods at a landslide during the course of one year, it could provide some important parameters for qualitative analysis to landslide stability.

From different period monitoring in several year at a landslide, it could provide real data for further creating landslide geological models, assessment of stability and prediction.

As analyzed above, it is feasible to detect landslide with SNMR, and to create models of stability analysis and prediction with measured SNMR data.

THE APPLICATION IN STUDYING LANDSLIDES AT THREE GORGE WITH SNMR

Zhao Shu Ling landslide is a large typical in Three Gorges area, its stability directly relates the safety of Ba Dong county , Three Gorges power station and the smooth of transportation. For the correct assessment of Zhao Shu Ling landslide the rock and soil structures of landslide and the property of underground water should be determined, for the purpose of reality models of landslide. We applied NUMIS system made in France to monitor the landslide for three years and get some successful results. The preliminary analysis results for the surveyed data are as follows.

The comparison results of one SNMR point result and drilling data

Fig .2 is the inversion result of SNMR on landslide in Zhao Shu Ling at Ba Dong county. It is can be seen from the result, (1) there exists a aqueous strata at shallow surface with less water content, so it is not the target strata for our study; at the depth of 18m, an aqueous strata with large water content occurs; at depth of about 40m, there is a obvious water-bearing strata which water-bearing content is relative large, (2) the aqueous strata near about 18m in depth has large seepage coefficient, near about 40m has relative large seepage coefficient, (3) the water content between two strata is small, which is water-resisting layer. From which we deduced that there is a landslide boundary near about 18m; near about 40m a landslide boundary surface. Drilling data evidence that a landslide boundary at 18.2m in depth and another at 42m in depth. So it is evidenced that SNMR technique is feasible, effective, inexpensive and rapid in recognizing landslide surface with its measured data.

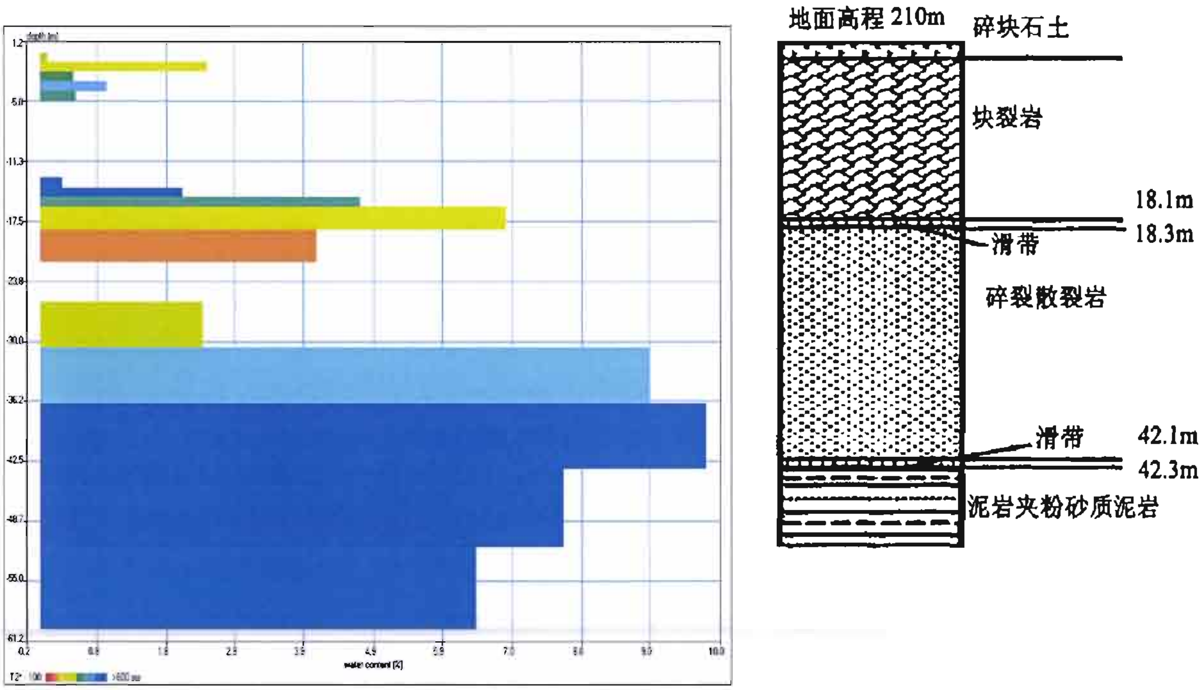

Fig. 2. The inversion result of SNMR on the landslide in Zhaoshuling, Badong ,Hubei; and the drill column of Zhaoshuling landslide.

The comparison analysis of SNMR result in flood period and the comparison analysis of SNMR result in drought periods

Six reality measurements have been carried out in Zhao Shu Ling landslide, Ba Dong. Three comparison results in drought period indicate (1) the variation of water content at shallow water-bearing strata is violent;(2) water content at 18m has certain variation without violent, basically, the depth of the strata keeps stable;(3) the water-bearing at 40m aqueous strata has certain variation, which is still stable without violent, the depth of aqueous strata is basically unchangeable. The three comparison results in flood period have the same similar rules.

The comparison analysis of flood and drought periods results

The comparison between flood and drought period has the following rules: (1) the results of SNMR indicate that the depths of two landslide boundaries, at 18m and 40m,are basically unchangeable during the course of flood and drought periods;(2) the results of SNMR indicate that water content, at 18m and 40m surface, has certain variation, water content in flood period is larger than that in drought period.

From the result analyzed above, the underground water distribution, and the information of season variation as well as useful reality measured data about Zhao Shu Ling landslide, Ba Dong county have been obtained, providing evident basis for further stability evaluation and landslide model in concordant with reality condition.

CONCLUSIONS AND DISCUSSION

The preliminary conclusions obtained with SNMR to the problems of landslides are as following:

- To study landslide with SNMR technique is the first attempt, which is available method through our investigation and practice;
- From some parameters, such as depth of water-bearing strata, thickness, water content, the variation of permeability etc, the landslide boundary existing and space distribution could be correctly determined, which is identical to the bore hole data;
- Through the monitoring result from different seasons at landslide body, the geologic model of landslide could be created with the help of SNMR result to provide basis for further assess the stability;
- Compared with other methods, SNMR method has advantages of advanced theory, rapid, accurate and inexpensive;
- For the first time to study landslide with SNMR, some faults may exist in the paper content. We authors wish to express our hearty welcome to any criticism and suggestions for the purpose of enhancing application effect with SNMR in landslide investigation.

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POSTER PRESENTATIONS

SNMR INVESTIGATIONS WITH VARIABLE PARAMETERS AND LOOP GEOMETRIES – A COMPREHENSIVE STUDY

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INTRODUCTION

In common SNMR investigations it is expected that the result is independent of preset parameters of pulse lengths and reasonable clock frequency and completely covered by appropriate compilation of the kernel functions for the respective loop geometry. A comprehensive study of a set of measurements at the same site could clearly point out that the measurements strongly depend on the choice of parameters and that even for the same parameters but different loop geometries the data interpretation yields inconsistent subsurface models. Whereas the influence of pulse duration and frequency shift can be well described by an extend formulation of spin dynamics, the influence of the loop geometry remains puzzling.

INFLUENCE OF THE MEASUREMENT PARAMETERS

At the test site Nauen (Germany) [1] we conducted SNMR measurements with a figure-of-eight loop with varying pulse duration (20-80ms, Fig. 1). All measurements were performed on one day within four hours with exactly the same loop. The chronological order of the measurement is as follows: 20ms, 40ms, 80ms, 60ms, 70ms, 50ms, 30ms. The maximum pulse moment is for all measurements about the same by varying the maximum current. The frequency shift is moderate (< 1Hz) within the duration of the measurements; the clock frequency was set to the same value each time. The amplitudes are strongly dependent on the pulse duration, namely the amplitudes increase with decreasing pulse duration. It is not a simple shift, but this behaviour is also pulse moment dependent. The phase values do not show a clear proportional behaviour to the pulse duration, but there is the tendency that the phase values are higher for smaller pulse durations. The decay times do not seem to be dependent on the pulse duration. However, the decay time characteristic is not reproducible with a variance of some 20-40ms between the soundings. The data processing should be improved in determination of the SNMR parameters.

Further more we studied the influence of the preset clock frequency at the test site Nauen (Fig. 2). The measurements were conducted directly one after the other with three clock frequencies: appropriate frequency (2088.6 Hz), too small frequency (2086.8 Hz) and too high frequency (2090.8 Hz). The pulse duration is 40ms. The recorded amplitudes are much higher if the clock frequency is preset too small. The deviation of clock frequency and Larmor frequency is smaller for the 2090.8 Hz case, so the effect of a too high frequency seems to be smaller for the amplitude, but it is still prominent in the phase values. Again the decay times are not clearly affected by the clock frequency. However, the decay time curve for the appropriate frequency is much smoother, both other curves run even in opposite direction for small pulse moments.

Parallel to the SNMR sounding, magnetic measurements have been conducted with a PPM magnetometer 250m apart (Fig. 3). The derived Larmor frequency shows a constant offset from the resonance frequency determined by the SNMR measurements. However, there are some outliers caused by imprecise frequency determination of the SNMR processing. Overall, the frequency shift during the SNMR sounding can be explained by the variation of the earth magnetic field; no magnetic field gradient seems to be present.

STUDIES WITH DIFFERENT LOOP GEOMETRIES

Figure 4 shows a comparison of measurements with different loop geometries at the test site Nauen. The geology consists of quaternary deposits [1]. The first aquifer is in a depth of 2-21m, the upper boundary of the second aquifer is at approx. 30m, the lower boundary is not determined. We used a figure-of-eight loop, a long-eight loop with a separation of 75m between the coils and a circular loop. The measurements with the figure-of-eight loop and the long-eight loop were conducted at the same day. The inversion result for the figure-of-eight loop from the standard inversion software yields reasonable water contents for the first aquifer, but unrealistic high values for the second aquifer. A large number of measurements at this site show the same characteristic, whereas the results for the long-eight loop and the circular loop are consistent with the known geology. This is consistent with several other published SNMR surveys conducted in eight-shaped loop configuration.

Figure 5 shows SNMR measurements at the test site Haldensleben (Germany) [2] with a figure-of-eight loop, a circular loop with a diameter of 100m and a circular loop with a diameter of 150m. The subsurface consists of quaternary deposits: sands interbedded with till. In contrary to the test site Nauen, the aquifer at the test site Haldensleben is quite deep, i.e. the upper boundary of the aquifer is at 20m. Thanks to an upgrade of the Numis device we achieved twice as high pulse moments in Nauen than in Haldensleben (max. 8As in Haldensleben and max. 16As in Nauen). Because of the quite deep aquifer and the smaller pulse moments, the effect of the loop geometry on the inversion result cannot be clearly seen. However, there is obviously a mirror symmetry of the frequency shift and the phase values. This effect can be considered for the calculation of the kernel function and thus the inversion results are more reliable [3].

CONCLUSIONS

The field data clearly demonstrate a strong dependency of the SNMR signals on measurement parameters like the pulse duration and the clock frequency. Even small deviations affect significantly the recorded data. It clearly indicates the necessity to incorporate the appropriate frequency shift and the pulse duration for each single sounding in the compilation of the kernel function to get consistent subsurface models.

Different loop geometries also affect the inverted model of water content distribution. Especially measurements with figure-of-eight loops lead to unrealistic high values. This effect is more prominent for shallow aquifers. Apparently, there are still systematic errors in the treatment of figure-of-eight loops, that are not solved yet.

Further investigations will be conducted to prove the connection between field set up and SNMR data. The kernel functions will be optimised to yield consistent subsurface models for all loop geometries and field conditions.

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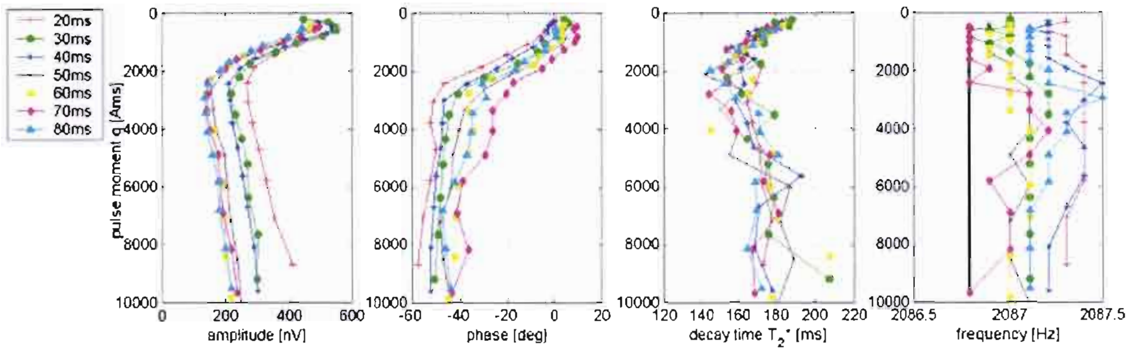

Fig. 2: Figure-of-eight (d=50m), measurements with different pulse duration using the same settings, test site Nauen.

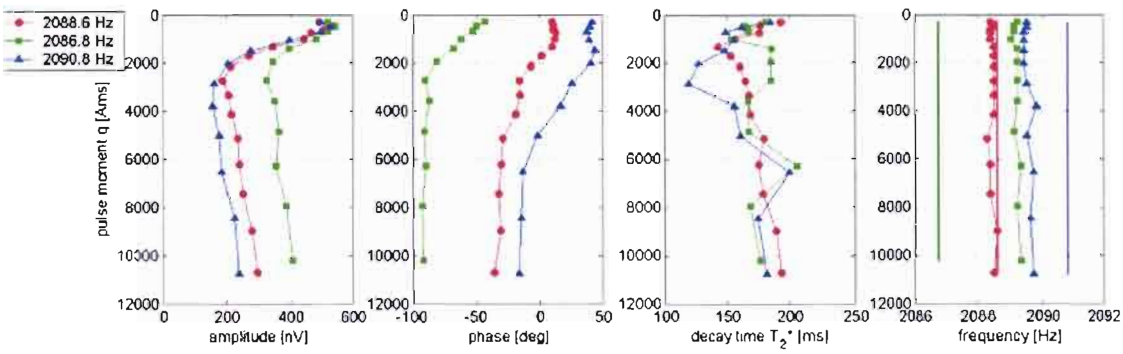

Fig. 3: Clock frequency test for figure-of-eight (d=50m) measurements, pulse duration 40ms, test site Nauen.

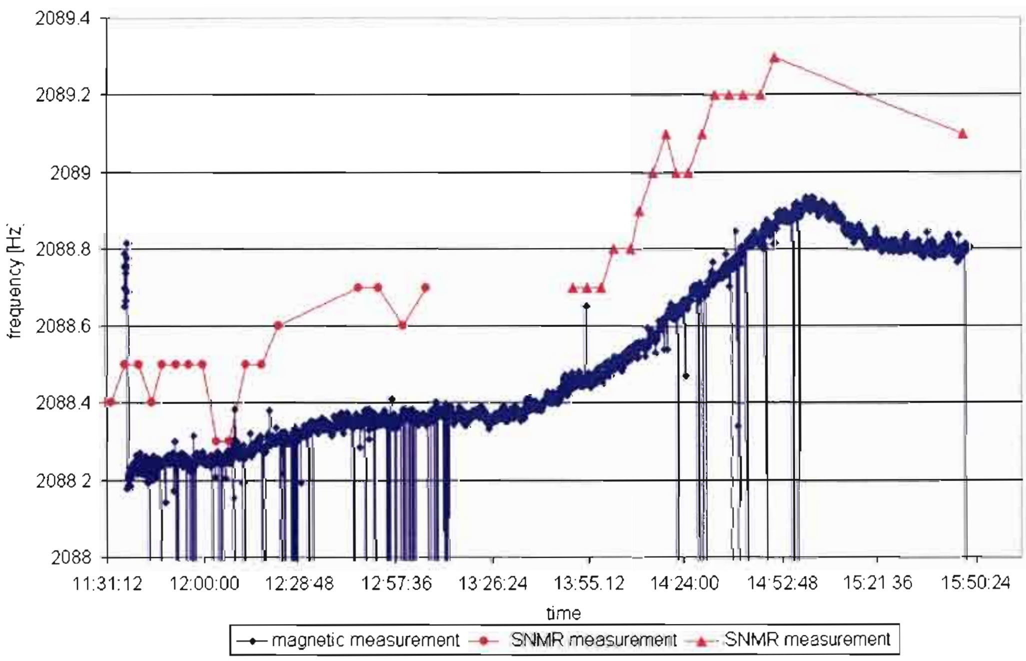

Fig. 4: Magnetic measurements and SNMR measurements, test site Nauen.

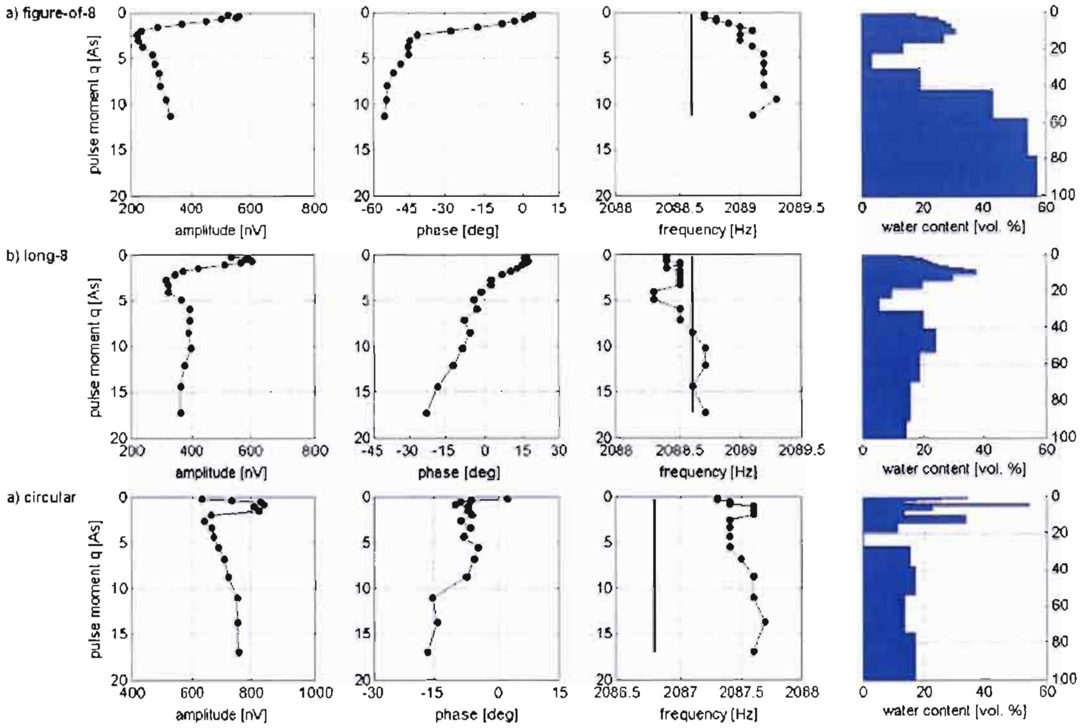

Fig. 5: Comparison of measurements with figure-of-eight (d=50m), long-eight (d=50m, separation 75m) and circular loop (d=100m), pulse duration 40ms, inclination 60°, test site Nauen.

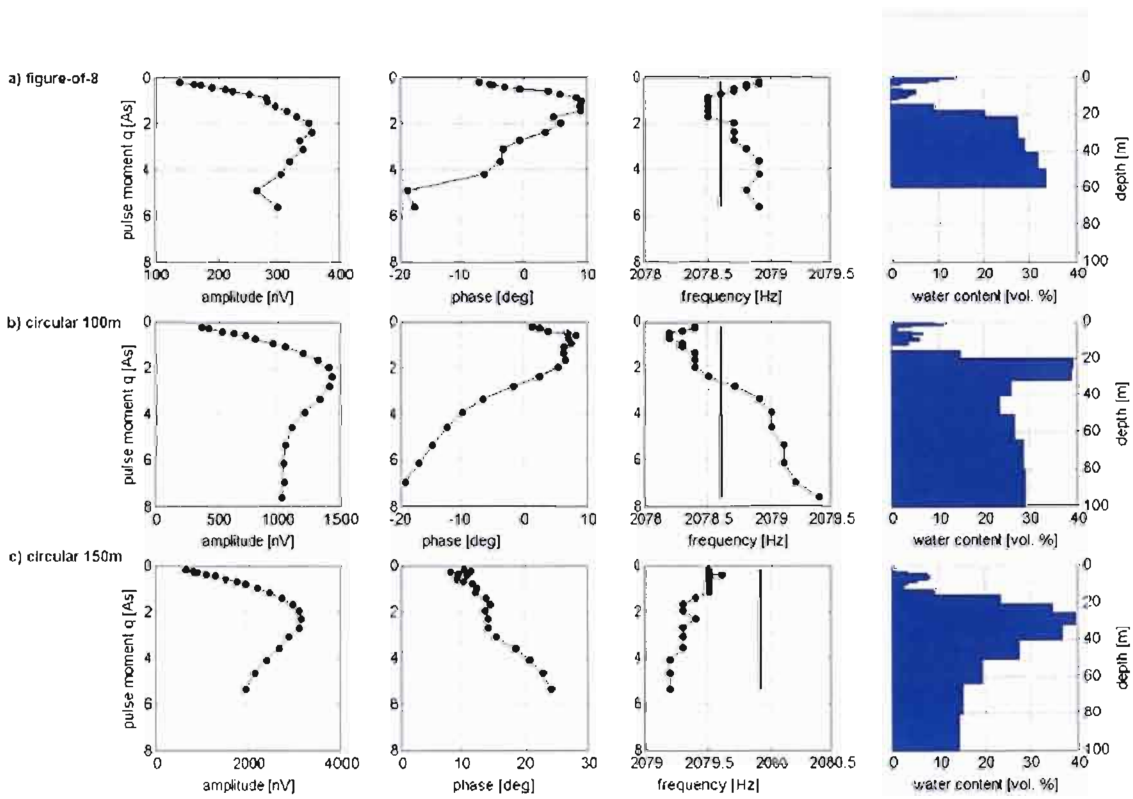

Fig. 6: Comparison of measurements with figure-of-eight (d=50m), and circular loop with d=100m and with d=150m, pulse duration 40ms, inclination 60°, test site Haldensleben.

COMPLEX TRANSIENT SPIN DYNAMIC IN MRS APPLICATIONS

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INTRODUCTION

In applications of the Magnetic Resonance Sounding (MRS) technique for geopysical investigations, the interaction between the ensemble of spins under investigation and the perturbing rf-field is assumed to fulfill the approximations for laboratory conditions. That are a balanced ratio of static and rf-field magnitudes, pulse durations that are small compared to the relaxation constant of the spin system and a perfectly met resonance frequency. In realisations of the MRS measurements none of them is met. The rf-source is inhomogeneous, that means the magnitude varies strongly over the investigated volume. The technically possible pulse durations are not small enough to be neglected for estimated relaxation constants for sedimentary rocks. In most cases the resonance frequency is not perfectly met by the rf-field since the earth magnetic field may vary during the period of a MRS sounding in a range that significantly influences the spin dynamic process. Implementation of the general solution of the Bloch equation allows a quantitative evaluation on the respective importance of these parameters. Incorporating all parameters into an extended MRS-kernel function then allows a significantly improved interpretation of complex MRS-measurements, now fitting the phasing that could not appropriately been considered and used yet.

THEORY

The evolution of the spin perturbation during the application of an energising pulse is given by the Bloch equations [1]. The general solution of this set of differential equations, assuming equal relaxation constant T1 and T2, exhibits the evolution of the in-phase and out-of-phase components of the transversal magnetization and the longitudinal magnetization, respectively [2]. These equations are commonly implemented for the "laboratory" case and lead to the known simple trigonometric functions for the spin perturbation [3]. It is well known that the spin precession is damped by relaxation processes after shutting down the external field leading to a transient decay of the signal. Exactly the same processes also act on the spin system during the pulse, leading to transient evolution of the signal during the pulse and yield a steady state between perturbing and relaxation forces for long times [3]. The importance of these effects is now dependent on the ratio of perturbing and static magnetic field strength, the accuracy by which the spin precessing frequency is met and the pulse duration in respect to the relaxation constants. We easily find that for parameter ranges of MRS field conditions the temporal evolution of the spin dynamic is in an intermediate state between the two common approximations of "short" pulses, as assumed for laboratory experiments, and the steady state solution, as used for continuous wave applications. Consequently, for MRS applications the full transient evolution of the spin dynamic during the energising pulse has to be considered to model the complex spin magnetization and therefore the MRS-signal correctly. It is obviously not valid to assume the amplitudes to be met exactly and only to have a mismatch in phase adaptation. Truly for a complex signal, a mismatch in the signal phasing implicates an error in amplitudes, too.

EVALUATION

Dominant influence on the magnetization evolution has the field magnitude of the energising pulse i.e. the perpendicular projection of the loop field on the spinning axis of the magnetization vector. In MRS applications this field is generated by an antenna loop at the earth's surface and is therefore strongly inhomogeneous through the induction volume. Its field strength approaches the range of the earth's field close to the surface and vanishes towards remote distances. The South-North cross-section of the spatial distribution of the effectively acting magnitude for a 100 m loop at 60° inclination and 48000 nT is shown in Figure 1a. The evolution of a unit magnetization vector for respective parameters is shown in figures 1-3. Figure 1b shows a significant decay already during the energising pulse for constant parameters at different rf-magnitudes. Since no frequency shift occurs here, the signal is real, and only the in-phase component is plotted. For these conditions already at smallest possible pulse lengths of 20 ms the amplitude is decreased by some 10% compared to the laboratory approximation. At pulse lengths of up to 80 ms, the technical maximum of the MRS device NUMIS, the amplitude is decreased to nearly 60%.

The signal generally becomes complex when the frequency of the energising pulse is shifted from the precessing frequency of the spin system (Figure 2). The influence of the frequency deflection increases with decreasing rf-magnitude, i.e. decreasing nutation frequency. In case of a phase deflection an out-of-phase component arises and the signal becomes complex. Additionally, the nutation frequency increases slightly. Interesting to note, that the out-of-phase component is much stronger influenced than the in-phase part. The evolution of the in-phase component is independent of the sign of the frequency shift, whereas the out-of-phase part is asymmetric and has a change of sign across the resonance frequency. This agrees with signal shape of continuous wave measurements [3]. The nutation frequency increases independent of the sign of the phase shift.

The relaxation processes, that equilibrate the spin energy, acts on the spin system during the energising pulse. The assumption of the laboratory approximation that the pulse length can be neglected compared to the relaxation constants is by far not satisfied. Figure 3 shows the evolution of a unit magnetization during the pulse for a range of decay constants of natural rocks. Already at large decay constants of 300 ms corresponding to coarse material and smallest possible pulse length by the NUMIS, the influence of the relaxation during the pulse is in the order of some 5 %. For average conditions of decay constants of some 150 ms and 40 ms pulses the deviation from the laboratory approximation amounts around 25 % and reaches even more than 70 % for the worst case of decay constants of 50 ms and longest possible pulses of 80 ms. The clear indication that the measured signal is influenced by the choice of the pulse length is given by systematical tests by M. Braun and M. Hertrich [5]. In case of high damping (T=50ms) the characteristic of the solution as an intermediate state between laboratory and steady state approximation becomes obvious as the damped oscillation is not symmetric to zero but converges to the steady state for long times.

In the general formulation the influence of frequency and damping effects depend on the nutation frequency of the spin system. Since this is strongly inhomogeneous throughout the induction volume the MRS kernels have to be appropriately compiled for each specific field condition, taking into account the measured decay constants and frequency shifts of each sounding, respectively. The total phase lag of MRS-measurements finally consists of two generally distinguished components: the electromagnetic phase lag due to a conductive ground [4] and a nuclear spin phase due to quantum mechanical properties of the NMR experiment in the conditions appearing in geophysical large scale applications.

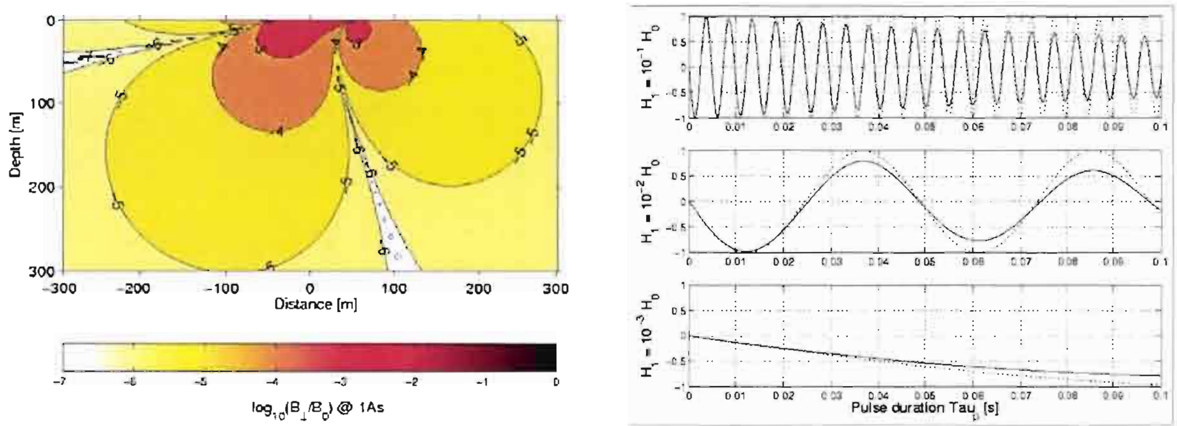

Figure 1: a) South-North cross section of the spatial distribution of the effectively acting energising field. b) Transient evolution of a unit spin magnetization vector for H_0/H_1 ratios of 10^{-2}, 10^{-3} and 10^{-4}. Larmor frequency is 2 kHz, inclination of 60° N, pulse duration 100 ms and a decay constant of 200 ms. Solid lines show the exact solution, dashed lines the laboratory approximation.

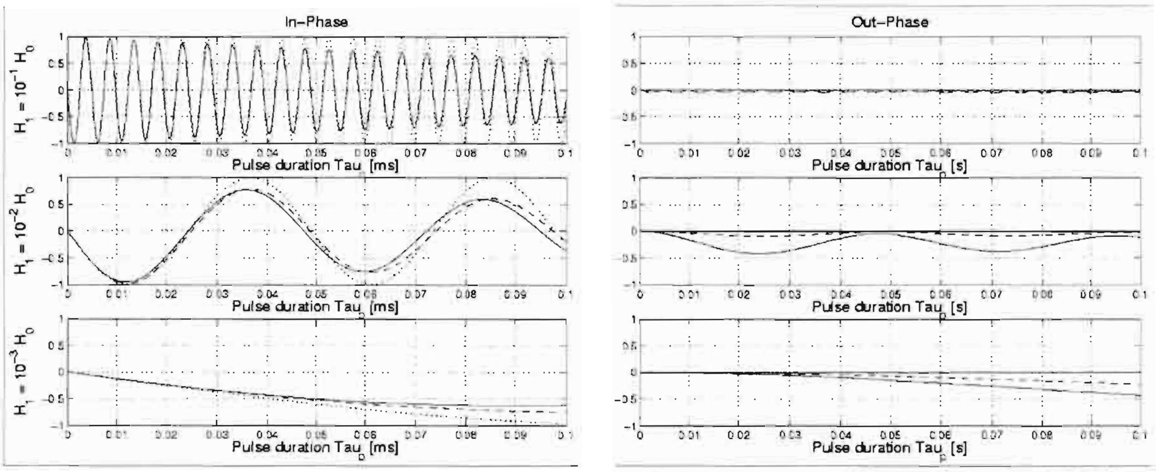

Figure 2: Transient Evolution of the spin magnetization for parameters of figure 1, but variable frequency shift df = 1 Hz (dash doted), 5 Hz (solid) and the laboratory approximation (dashed).

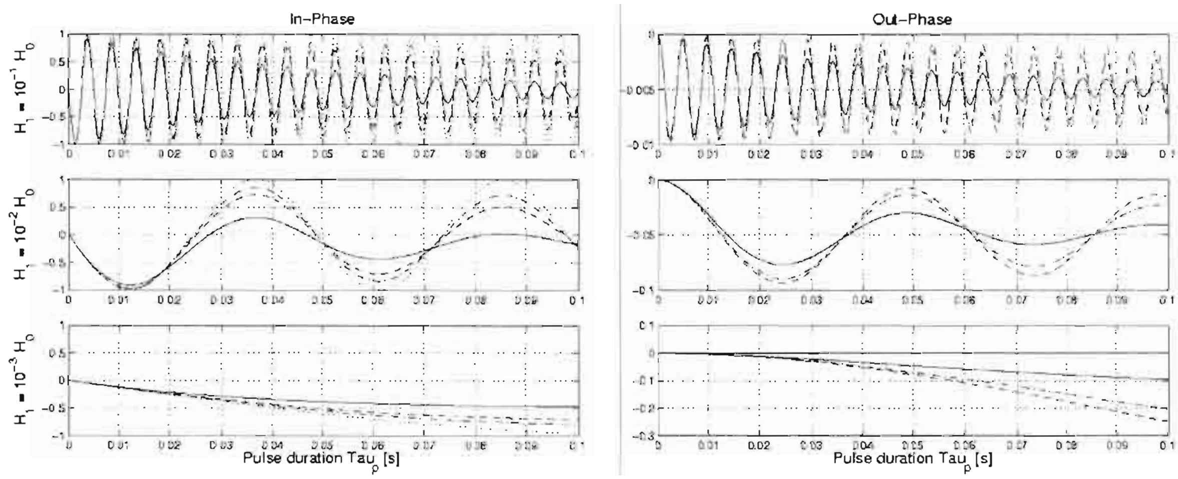

Figure 3: Transient evolution of the spin magnetization for parameters of figure 1 with variable relaxation constants T_r = 300 ms (solid), 150 ms (dashed), 50 ms (dash dotted) and the laboratory approximation (dotted). (Out-Phase components are individually scaled for a better visibility).

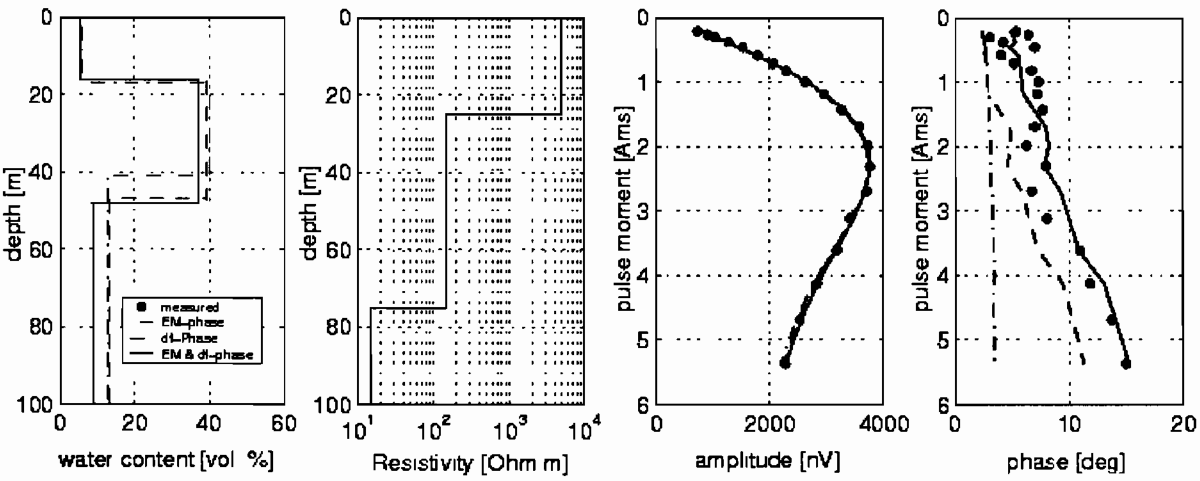

Figure 4: Inversion models of a real data set with kernels implementing only phases due to EM-effects (dash-dotted), only frequency (df) effects (dashed) and the general solution (solid).

Considering the complete formulation for compilation of MRS - kernel functions into finally leads to an optimal adaptation of the complex MRS - signal (Figure 4).A good amplitude fit can be achieved for all used kernels, but the adjoint subsurface models differ somewhat. Looking closely on the phase adaptation one finds an almost constant phase lag for a pure conductive kernel; involving the full spin dynamic but an insulating ground, the phase lag mirrors the frequency shift during the measurement but differs from the measured phase values. Only the implementation of complex transient spin dynamics and conductive medium into the kernel function finally fits the measured phase lags within the data accuracy and yields a plausible model.

CONCLUSIONS

- Full complex transient spin dynamic has to be considered in MRS applications.
- MRS signal phasing is considerably affected by earth's magnetic field variations. So individual kernel functions have to be compiled for each sounding.
- Implementation of the general solution to the compilation of kernels improves the model adaptation; phasing is appropriately met.
- The general solution bears a different spatial sensitivity. Inversion results with general kernels yield improved model of the subsurface water distribution.

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APPLICATION OF NUCLEAR MAGNETIC RESONANCE SOUNDINGS TO GROUNDWATER RESERVES MAPPING IN WEATHERED HARD-ROCK AQUIFERS (BRITTANY, FRANCE)

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INTRODUCTION

The quality of groundwater and river water is increasingly threatened by the growing use of fertilisers and pesticides in agriculture. In the hard-rock context of Brittany, one of the key points in characterising the impact and durability of this diffuse pollution is a better understanding of the structure and functioning of the aquifers. For this, we must aim to quantify and locate the volumes and quality of water stored in the different hydrogeological compartments of the aquifers. An original methodology was thus developed for quantitative mapping of groundwater reserves in hard-rock regions by adopting a dual approach: (i) geometrical aquifer modelling based on both field observations and existing well data (lithology, weathering and piezometry), and (ii) measurements of water contents using Magnetic Resonance Soundings (MRS).

Following this approach, 204 MRS measurements using Numis equipment were performed from 1998 to 2003 on 13 watersheds within the Armorican massif (French Brittany), in various geological environments. These results were obtained in the framework of several projects funded by the Regional Council of Brittany, the County Council of Finistère, the Loire-Brittany Water Authority, the Ministry of Industry (BRGM Public Service grant) and the Ministry of Research (BRGM R&D project).

CONCEPTUAL MODEL OF HARD-ROCK AQUIFERS (WYNS *ET AL.*, 2003)

Most hydrogeological systems within weathered crystalline basement environments can be represented by a sub-horizontal two-layer system cut by vertical fractures of tectonic origin that act as drains:

- an upper layer composed of unconsolidated alterite (20-30 m thick) that, considering its relatively high effective porosity, plays an essential storage role with respect to infiltrated rainwater.
- a lower layer, including the fissured zone (about 50 m thick), that has a drainage role with respect to the overlying storage layer, at least at the scale of intersecting drill holes, as well as a minor storage role. It locally supplies perennial springs that contribute to the minimum flow of rivers.

WATER TABLE MODELLING

As there is generally no piezometric map available for the study area, the elevation of the top of the aquifer is modeled from DEM data and water table elevations measured in sparse boreholes. An empirical relationship is established between the difference in elevation between the topographic surface and the basal thalweg surface ('a' on Fig. 1), and the difference in elevation between the measured water table and the basal thalweg surface ('b' on Fig. 1). This relationship allows us to calculate directly the elevation of the water table from the DEM and the elevation of the envelope-surface of the thalweg base for each grid node.

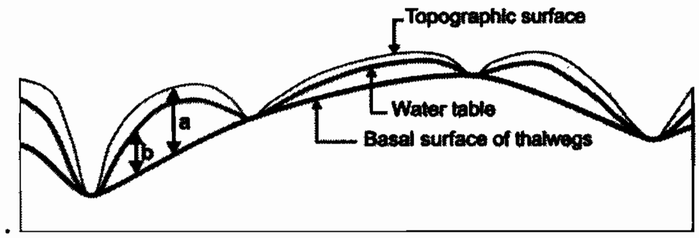

Figure 1: Principle of water-table modelling (from Wyns *et al.* 2003).

GENERAL PROCEDURE FOR MAPPING GROUNDWATER RESERVES

The quantitative mapping of groundwater reserves in weathered basement environments is based on:

- the calculation, for each grid node, of the thickness of each weathering horizon located beneath the water table;
- the evaluation, using MRS, of the mean water content for each of these horizons and for each lithological facies in the study area (Fig. 2).

HORIZON MODELLING WITHIN THE WEATHERING PROFILE

Depending on the available data, elevation values for the base of the alterite are determined through geometrical modeling of drill-hole data and/or MRS results. Because of poor signal-to-noise (S/N) conditions at the soundings end, the MRS inversion results do not generally enable the geometry of the fissured zone to be defined.

The thickness of the alterite in the saturated zone is obtained by calculating the difference between the elevation of the water table and that of the basal alterite surface. The thickness of the fissured zone in the saturated zone is calculated in the same way.

MAPPING GROUNDWATER RESERVES

Assuming that the physical properties resulting from supergene weathering vary vertically for the same lithology according to the difference in elevation with respect to the base of the alterite (Wyns *et al.*, 1999), we can try, for each geological formation, to characterise the average properties of each weathered layer fromMRS. Where possible in terms of S/N level, we attempted several magnetic resonance soundings for each geological formation in the aim of calculating average water contents for the alterite and the fissured zone (Wyns *et al.*, 2003).

Where S/N conditions are unfavourable and horizon geometry cannot be defined, the water reserves are directly obtained by computing water volume per unit surface, V_W, such as $V_W = \sum W_i e_i$ (Legchenko *et al.* 2003). V_W, which is expressed in m^3/m^2, has a dimension of a height and is better determined by MRS than W_i, which cannot be derived without fixing horizon depth and thickness.

The total water reserves computed for the La-Roche-sur-Yon region are presented as a thickness map on Figure 3a. It shows a high degree of correlation with the geology, as expected on the basis of MRS water-content profiles and water volume (Fig. 3b).

Reserves in the in alterite are only 85.10^6 m^3, with most of the reserves being located in the fissured zone (513.10^6 m^3). This is mainly due to the better preservation of the fissured zone, the alterite being more widely eroded, but also to the geometry of the water table with respect to the weathered layers. The elevation of the water table, however, is above the base of the alterite over most of the study area, which indicates that recharge is largely controlled by the properties of the alterite.

CONCLUSION

The present study demonstrates the feasibility of quantitative mapping of groundwater reserves within weathered aquifers of differing geology on the basis of geometrical modelling and MRS water-content evaluation. For the La-Roche-sur-Yon region, it has provided new data concerning aquifer structure. Due to the intense erosion of the alterite, 85% of the groundwater reserves is contained in the fissured zone, compared to only 15% in the alterite. It must be borne in mind that tectonic fractures are not taken into consideration, as their reserves are insignificant compared to those of weathering-related fissures.

According to Shirov *et al.* (1991), MRS water content corresponds to contents of free water as opposed to water bound to the grains. Values measured in the granite environment of Brittany (5 to 10%) are relatively similar to effective porosity. Higher values (15 to 20 %) obtained in certain metasediments (Brioverian schist) indicate that bound water may contribute to MRS water content. Additional field and laboratory study is necessary for calibrating the water content derived from MRS data.

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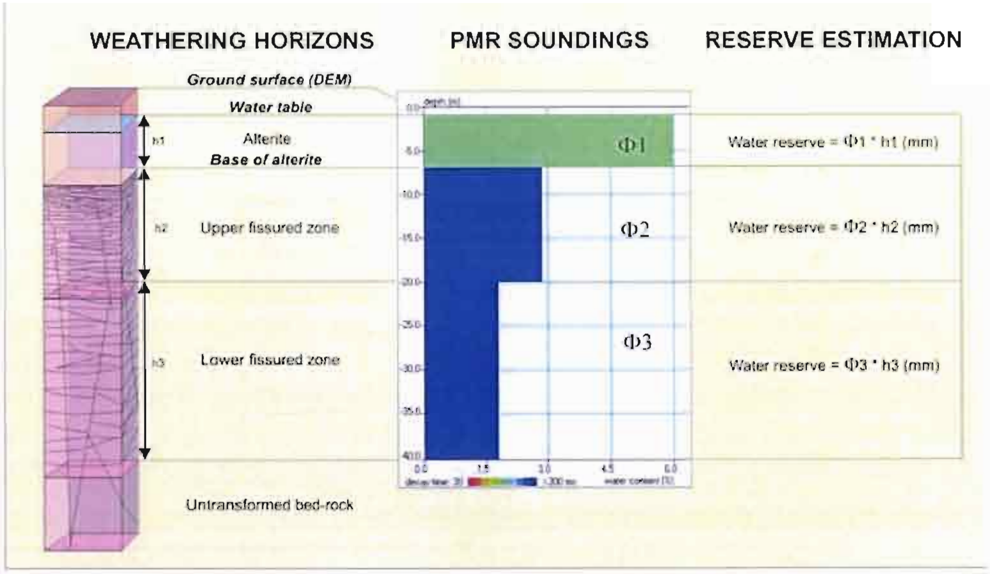

Figure 2: Stages involved in mapping groundwater reserves (from Wyns *et al.* 2003)

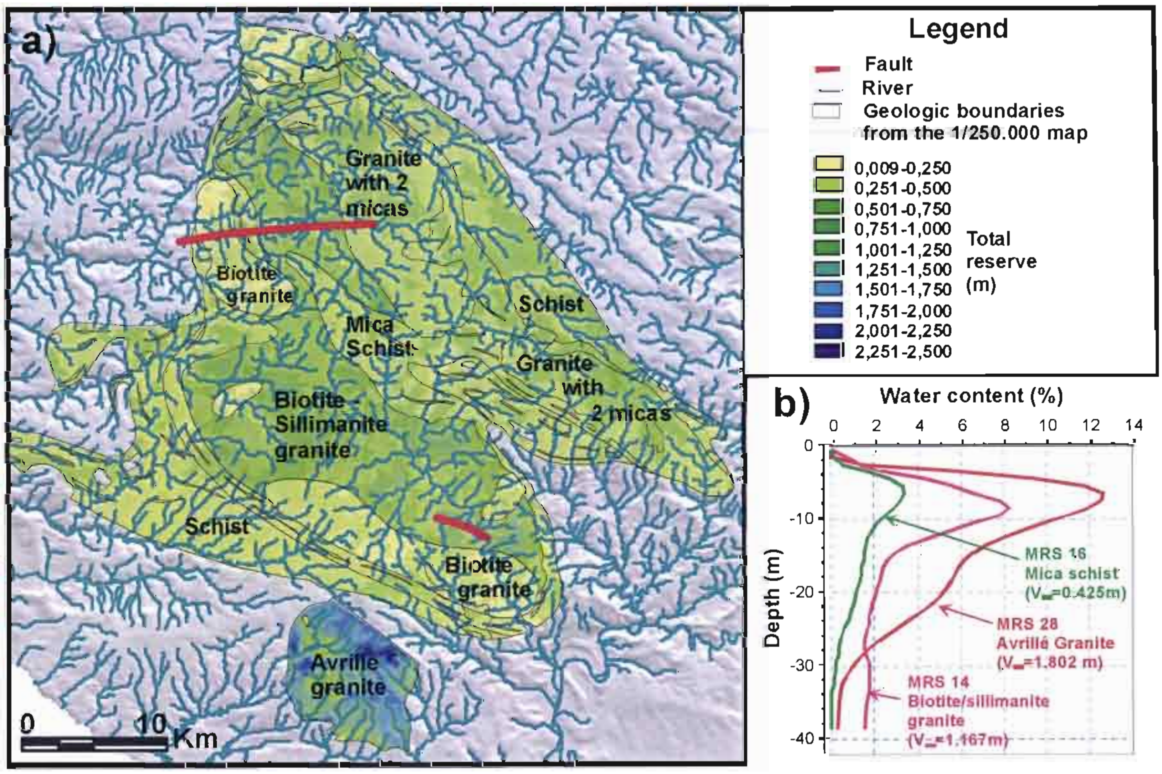

Figure 3: La Roche-sur-Yon region: a) Thickness map of total reserves in the weathered aquifers. b) Example of MRS water content profiles measured in different geological settings.

REALIZATION AND ASSESSMENT OF T1 MEASUREMENTS WITH SURFACE NUCLEAR MAGNETIC RESONANCE

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INTRODUCTION & METHOD

The method of Surface Nuclear Magnetic Resonance (SNMR or Magnetic Resonance Sounding MRS) is based on the excitation of hydrogen protons in the mobile pore water by a magnetic field that oscillates with the local Larmor frequency. In practice the excitation is realized by an alternating current flowing through a transmitter loop at the surface. The excitation intensity defines the investigation depth of the method and is characterized by the pulse moment q (the product of the current I and the pulse duration τ). Increasing the pulse moment q, the NMR excitation focuses on greater depths. After the termination of the stimulating pulse the magnetic resonance field caused by the precession of the hydrogen protons (acting as small dipoles) around the axis of the geomagnetic field, is measured using the same loop as receiver [1, 2]. The signal amplitude is directly proportional to the amount of free water in the pore space. The relaxation behavior of the NMR signal (decay time constant) is dependent on the effective pore size of the material (Fig. 1). SNMR is the only geophysical method, that allows a direct characterization of aquifers by surface measurements. In SNMR usually the free induction decay (FID) of the excited hydrogen protons is measured (Fig. 2, A). This decay is described by the relaxation time T2* and is strongly affected by diffusion processes caused by static geomagnetic field inhomogeneities (Fig. 1). In well logging NMR and laboratory NMR such field dependent diffusion processes can be eliminated by the application of suitable pulse sequences (e.g. Inversion Recovery, CPMG). Thus, the measured relaxation times are defined only by the pore sizes of the material and are not affected by diffusion processes [3].

With the upgraded NUMIS Plus system it is possible to determine the longitudinal relaxation time T1 of SNMR signals that is independent of diffusion processes. Analogous to a 90° – 90° pulse sequence in the laboratory NMR, two successive NMR pulses of the same intensity q are emitted (Fig. 2, B). However, in SNMR there is no constant excitation over the full range of the investigated volume (i.e. constant tilt angle distribution of the magnetic moments), but rather an area of maximum excitation (tilt angle) within the focused depth. Therefore, for T1 measurements with SNMR only a quasi 90° - 90° pulse sequence can be realized. From the NMR response of the ground water a corresponding time constant T1 can be derived [4]. For sake of measurement progress default T1 measurements are conducted using only a single pulse sequence, i.e. two reading points. With the recent upgrade of the NUMIS Plus system of the Federal Institute for Geosciences and Resources (BGR) this technique is now also available in Germany.

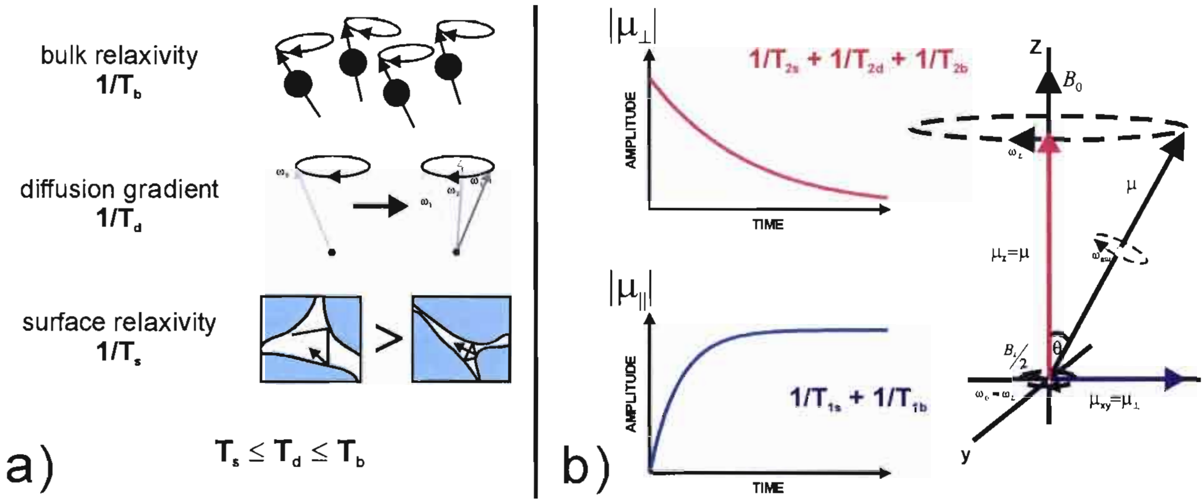

Fig. 1: Basic mechanics of Nuclear Magnetic Resonance (NMR). a): relaxation processes. b): composition of transversal (T2) and longitudinal (T1) NMR signal

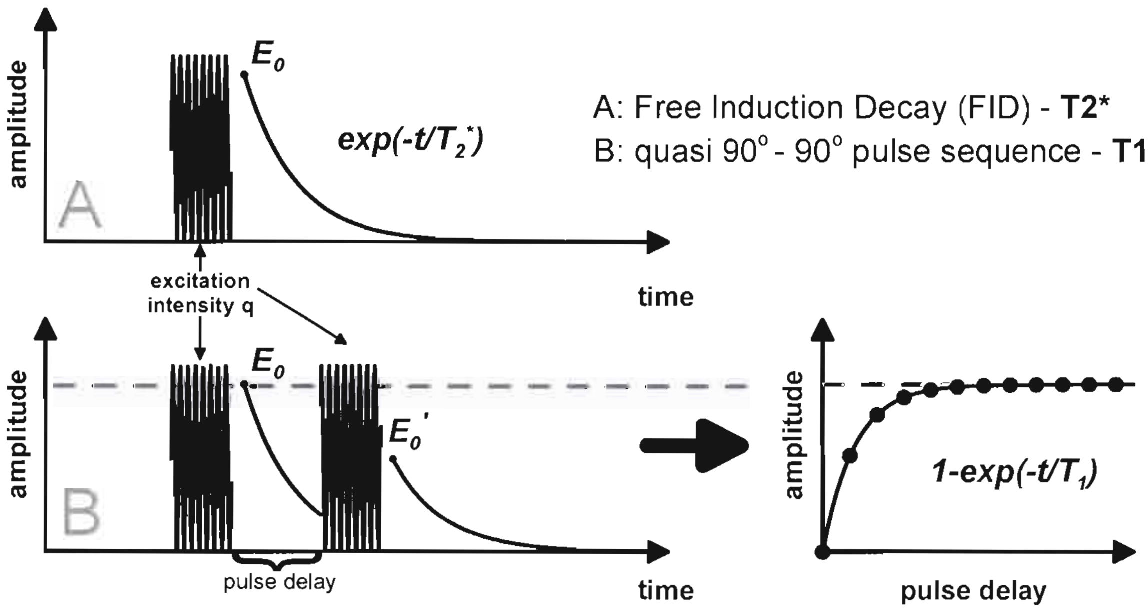

Fig. 2: Schematics of SNMR measurements of A) relaxation time T2* (diffusion effects) using FID and B) longitudinal relaxation time T1 using a quasi 90° - 90° pulse sequence (no diffusion effects).

FIELD CASE

Within the scope of the geophysical part of the INTERURBAN research group [5] T1 surveys have been conducted at a site in Berlin (Germany). The geology of the site consists of glacial deposits of fine and medium sands, typical for the Berlin region. Level measurements confirm the water table at a depth of 3 m. The measurements have been carried out using a circular loop with a small diameter (D = 24.2 m) for SNMR purposes. This antenna loop has an effective investigation depth of less the 20 m, but allows a higher resolution than conventional SNMR surveys with loop diameters > 50 m. The result of the standard smooth inversion (Fig. 3) show an increase of the water content at a depth of about 3 m. This corresponds well with the upper boundary of the aquifer. However, the water content is underestimated. The inverted decay times (T2*) between 130 and 150 ms are typical for these sediments [1, 2].

For the maximum amplitudes ($q \approx 60$-90 A.ms) of the sounding curve the NMR excitation is focused on the depth of about 3-4 m. Therefore, the measured signal decay is linked to pore-sizes within the aquifer. In order to obtain information regarding T1 within the aquifer, the pulse intensity of the T1 measurements has been chosen according to the maximum amplitudes of the SNMR sounding (in this case $q = 90$ A.ms for each of the two pulses transmitted). The curve of the recorded T1 quasi 90°– 90° pulse sequence (Fig. 4, left) consists of 52 reading points with pulse delays between 20 and 1000 ms (recording time of about 15 minutes per reading point). The increase of the variance in the data with pulse delays > 280 ms is due to the reduced stacking number used for these measurements.

The fitting of the T1 curve (Fig. 4, right) has been carried out using 3 different approaches [6]. In FIT 1 the fitting is carried out using a single relaxation constant T1 (mono-exponential fit) as it is also done for standard SNMR inversion. For FIT 2 both amplitudes and corresponding decay time constants are independent variables in the curve fitting process. A third approach (FIT 3) uses a fixed spectrum of 20 decay times with T1 ranging from 10 to 1000 ms. Here, only the corresponding amplitudes are optimized (multi-exponential fit).

Using FIT 1 yields T1 times of 96 ms being smaller than the measured T2* times. Both for FIT 2 and FIT 3 the fitting is improved significantly and the maximum of the signal contribution is found at T1 times of circa 150 ms. However, these values are in the order of magnitude of the measured T2* times. This is presumably due to the converging of T2 and T1 decay times for low frequencies (for SNMR 2 kHz). The resulting decay times correspond to laboratory NMR measurements of samples from this site ($T1_{lab} = 160$ ms).

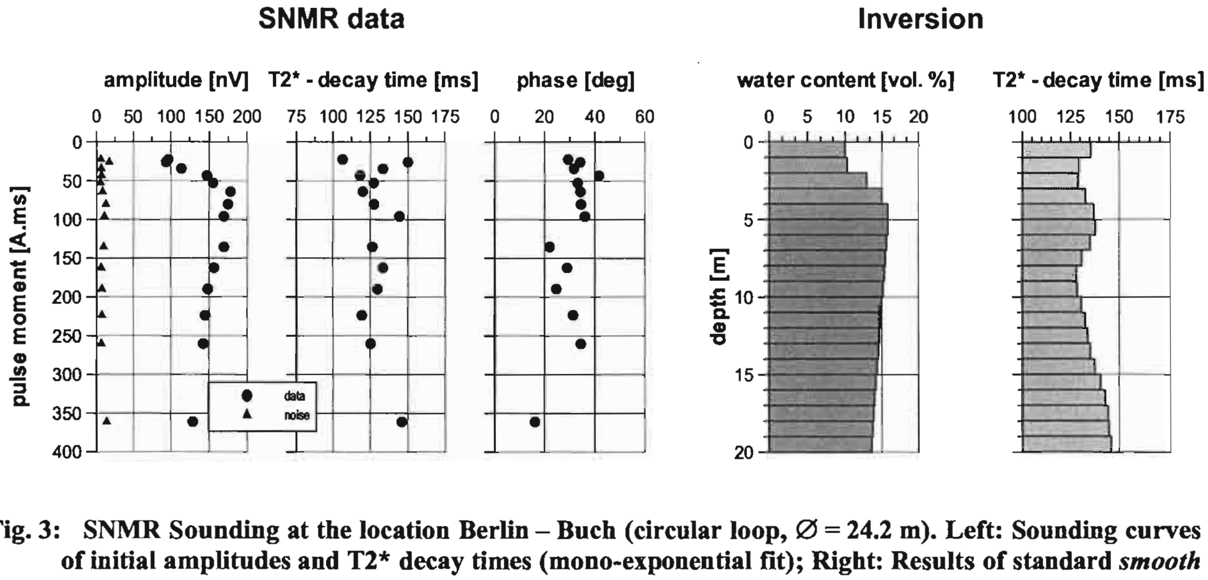

Fig. 3: SNMR Sounding at the location Berlin – Buch (circular loop, Ø = 24.2 m). Left: Sounding curves of initial amplitudes and T2* decay times (mono-exponential fit); Right: Results of standard *smooth* inversion for water content and decay times.

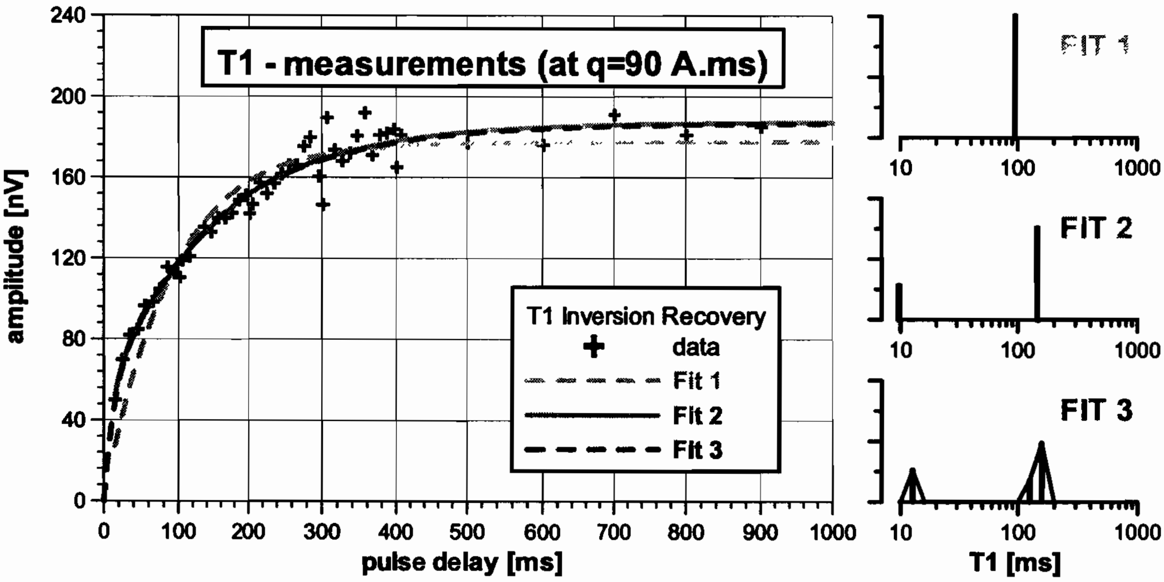

Fig. 4: T1 measurements at the location Berlin (Buch). Left: Longitudinal relaxation time T1 near the maximum of the SNMR sounding curve (pulse moment q = 90 A.ms). Right: Curve fit using mono- (FIT 1) and multi-exponential fits (FIT 2 & FIT 3).

CONCLUSION

With the newly available SNMR instrumentation it is possible to carry out T1 measurements that are not affected by diffusion processes. SNMR measurements show generally a low signal to noise ratio and, therefore, a considerable variance of single reading points. Thus, for a reliable determination of T1 relaxation times, it is necessary to scan a T1 curve using a sufficiently high number of sampling points in conjunction with an appropriate high stacking rate. In practice determination of T1 times is carried out by the interpolating only two reading points. This saves measurement time but is less reliable and has to be evaluated with caution. For a better understanding of the relation of T2* and T1 in SNMR and quantitative association of T1 decay times with pore sizes further measurements at petrophysical intensely studied sites (borehole geophysics and laboratory NMR) have to be conducted and evaluated.

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HISTORY AND FUTURE DEVELOPMENTS FOR SMALL SCALE APPLICATIONS OF NUCLEAR MAGNETIC RESONANCE

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MOTIVATION

The nuclear magnetic resonance (NMR) technique is mainly known in geophysics for well logging and laboratory applications. In recent years, Surface NMR (SNMR, or Magnetic Resonance Sounding, MRS) has become available for hydrogeological applications (e.g. Shirov et al., 1991; Yaramanci et al., 1999; Legchenko and Valla, 2002). NMR is observed with nuclei of certain atoms which are immersed in a static magnetic field and exposed to a secondary oscillating magnetic field (Purcell et al., 1946). The amplitude of the signal is proportional to the amount of spinning nuclei, e.g. ^{1}H-protons and the decay of the signal contains information on the pore space. The power of SNMR lies in the fact, that it is the only available geophysical technique which provides direct information of the water content and structural parameters, like porosity or pore size. These abilities of SNMR make it a promising tool for much broader applications in near surface geophysics than for hydrogeophysical exploration alone, like ground water quality, waste disposal site exploration, soil physics, dam wetness/stability or agriculture (agro-geophysics) research.

In general, the NMR signal is proportional to the resonance frequency ω and proportional to the (nuclear) magnetisation, which itself is also proportional to ω. In summary this means that the NMR signal is theoretically $\sim \omega^2$ (exactly: $\omega^{7/4}$ because of energy splitting effects, see Abragam, 1983). The advantages of performing NMR in the earth magnetic field are its homogeniety (approx. 10^{-10}) and the permanent availability of the field. The disadvantages are that no fine structure can be resolved due to the small signals.

HISTORY OF LOW/EARTH FIELD NMR

NMR spectrometer can be divided into four different types:

- Instruments that evaluate the frequency of the measured precession signal (as used in proton precession magnetometers, see Packard and Varian, 1954).
- Instruments that are used to evaluate the physical properties of nuclear spins (frequency domain instruments or continous wave (cw) mode).
- Instruments that are used to evaluate the physical properties of fluids in pores (e.g. the water in cells or oil in rocks) in the time domain (or pulse mode) for relaxation measurements.
- Instruments for imaging purposes (mapping of relaxation to a coordinate in the tissue/rock, like in magnetic resonace imaging, MRI, in medicine).

In 1948 Varian presented the first geopyhsical application of NMR by showing how the amplitude of the earth magnetic field can be derived from the frequency of the precession signal. Later, Varian proposed to explore groundwater resources by using NMR in the earth field, but no instrument was build (Varian, 1962). In Geneva, Bené founded one of the first groups in the mid 1950's working on earth field NMR. The spectrometer had to be operated in the forest in a wooden hut to minimize field inhomogenieties. The first spectrometer was a cw-mode instrument (see Bené, 1980) and was used for body fluids and medical applications. Besides Bené two other groups started work for medical NMR applications in the 1950's: Florkowski in Krakau and Powles and Cutler in London. Later work on medical application has been done in the 1980's by Favre in Lyon and Péto in Belgium since the 1990's. A further development path is followed by Stepisnik in Llubjana since the mid-1980's.

In the early 1980's a group in Novosibirsk developed the first NMR instrument for geophysical/hydrogeological applications after the Varian patent (Semenov et al., 1988), the instrument was called Hydroscope. The data provided by this instrument yield information about water content vs. depth and mean pore size of the layers. It uses surface coils of 80 - 200 m diameter and its penetration depth is from several meters down to 200 m. The receiver dead time is 25 ms which allows to detect only mobile and no clay bound/capillary water. Since 1996 Iris Instruments in Orleans, France, offers the only commercially available MRS instrument, NUMIS. NUMIS can be seen as a technologically improved version of the russian instrument. It allows the use of coils down to 5 m diameter, the S/N ratio is enhanced by quadrature detection and nonlinear filtering (Legchenko and Valla, 2002). The increasing application of Surface-NMR with the IRIS and the russian equipment made it necessary to develop the appropiate theoretical work for data modeling and interpretation. The most comprehensive paper up to now was published by Weichmann et al. (2000).

Also during the 1980's, Rollwitz (1985) showed the prospects of using an permanent magnet to derive soil water content for agricultural purposes. Since 1994 the group of Blümich in Aachen is developing a low field NMR using a small low field permanent magnet for quality control and archeological purposes (NMR Mouse, Blümich, 1998). The instrument is constantly developed for higher penetration depths but still reaches only some mm. In 1996 a consortium of oil and exploration companies started the Deeplook network to develop logging tools for the determination of petrophysical properties up to 50 m into the formation (see www.Deeplook.com).

Parallel to the development of purely geophysical instruments a new generation of low field NMR for broader applications has been followed. Goedecke developed an "in vitro" and "in vivo" (laboratory and field) instrument to determine T_2 after Packard and Varian in the earth field with shim coils to remove gradient fields for medical purposes. The sensitive volume is ¼ l and relaxation times from 25 ms up to some 100 ms in biological tissues have been evaluated (Goedecke and von Boetticher, 1999). In 1997 Willamowski presented an earth field spectrometer designed for measuring contamination of soil samples in the laboratory and in the field via polarisation spectroscopy. She shows examples of high quality chemical shift experiments in laboratory environment using shim coils to remove gradients. The linewidth is 0.1 Hz, which is sufficient for discriminating C- and O-bound H-protons. Unfortunately the field-version was never tested (Willamowski, pers. comm.). In 2002 McDermott et al. at Berkeley presented a low field NMR for medical and analytical purposes with a field of some mT which is equivalent to a precession frequency of ~100 Hz. They used SQUIDS as magnetometer and scalar (or J-) coupling, which is frequency independent, to deliver binding information.

The main disadvantages of the existing intruments are: 1. Continous wave instruments are too unsensitive in low fields. 2. The strong dependence of the location because of sensitivity to inhomogenieties and noise. 3. The necessary shim-coils for some instruments to minimise field gradients. 4. The dead times between pulse and recording start is 25-100 ms, therefore only mobile water can be detected. 5. The data processing could be optimised by faster ADC and making time series available. 6. Chemical shift analysis is virtually impossible.

FUTURE DEVELOPMENTS

For further development of earth field NMR three paths may be feasible: 1. The miniaturisation of the NUMIS using smaller loops. The advantages of this concept are its relative simplicity and the well defined penetration depth. The main disadvantage is the low S/N ratio with decreasing loop size. 2. To maximise the well logging NMR concept. In well logging a static field much stronger than the earth field is used and therefore the data quality is much higher. The structure of the primary field is well known, additional pulse sequences can be applied which enable the discrimination of H_2O and hydrocarbons. The main disadvantages are the low penetration depth (for current tools some cm) and the high costs for a magnet. These costs could be reduced, because a magnet for SNMR must not meet the high standards of temperature stability as a well logging tool magnet. 3. To generate a primary field with an electromagnet (e.g. two parallel cables). The realisation may be technically simple, but the corresponding theoretical work must regard the inhomogenieties of the primary field.

Our development path focuses on the first option, as the basic equipment is available and can be used for testing and comparisons. The first step was to design an improved receiver coil and to build a data acquisition unit. The objective of the receiver coil is to enhance the S/N ratio for the small loop sizes necessary for small penetration depths (fig. 1). The main differences to the NUMIS receiver coil consists of two elements: The utilisation of a first order gradient coil to enhance S/N ratio and the utilisation of many windings to enhance signal strength. Much care must be taken to correct for the capacitance between the windings to enhance S/N, e.g. by orthocyclic winding. The data acquisition unit consists of an ADC with a sampling rate of 100 kHz and an analog bandpass to remove multiples of 50 Hz and signal energy above the precession frequency.

MODEL CALCULATION

To evaluate the feasibility of the proposed concept, we performed model calculations for a single coil with 1 m diameter and 100 turns (coinciding transmitter and receiver loops). Fig. 2 shows the results for 25% water from the program COSSMO (Hertrich and Yaramanci, 2003). The amplitude has a maximum of 17 nT for smallest pulse moments (0.0001 A*ms). The average amplitude is between 5 and 15 nT even for higher pulse moments. This is barely above the resolution limit, but still only two-four times smaller than the smallest signals already recorded with the existing instrument, so additional data processing may be necessary.

RESULTS

The model calculations show that measurements with the NUMIS and a small coil should be possible with a corresponding data acquisition sys-tem. The instrument review and the model calculations show furthermore that improved signal processing (e.g. digital filtering, weighted stacking or additional local noise compensation) may be essential to improve S/N and to enable interpretation of the data. A separate receiver coil system would furthermore enable promising 2D and 3D data acquisition for separated loop, multireceiver configurations and even surface to borehole measure-ments (Hertrich and Yaramanci, 2003).

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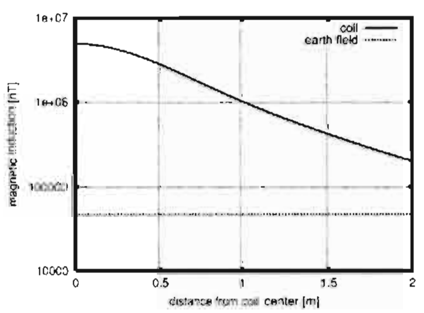

Fig. 1: Magnetic field strength of the secondary field on the symmetry axis of a first order gradient coil for 2 Amps (coil) vs. distance from coil center and earth magnetic field strength (earth). The gradient coil has 300 turns for the inner coil, the diameter of the inner coil is 75 cm, the outer coil has the same effective area.

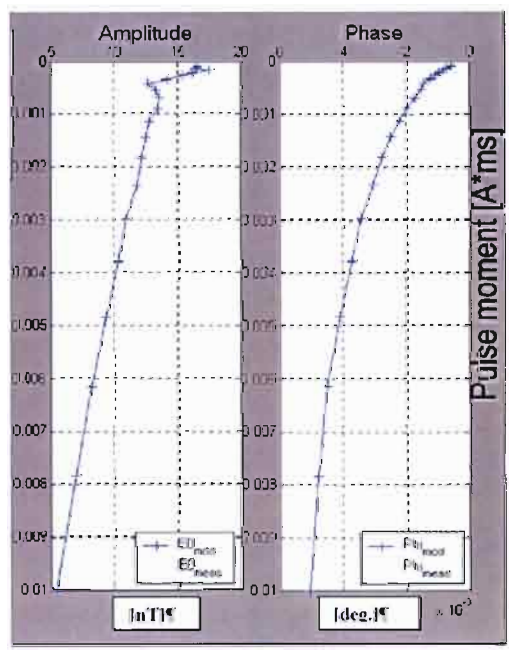

Fig. 2: Synthetic sounding curve for a 1 m coil with 100 turns. Amplitude and phase vs. pulse moment (right). The model consists of a 100 Ωm halfspace with 25% water content.

GEOPHYSICAL SURVEY SPATIAL AND TEMPORAL VARIATIONS OF THE SALTWATER INTERFACE, VADOSE ZONE FLOW PROCESSES INTO THE COASTAL ZONE AND COMPARATIVE STUDY WITH MRS METHOD

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Subsurface discharge of fresh water from coastal aquifers, called submarine groundwater discharge (SGD), has been recognized as an important component of the hydrological cycle.

One of the more important challenges facing natural resource managers today is how to identify, measure and monitoring the cumulative impacts of land use decisions across space and time. Understanding the multi-variable dimensions of groundwater management can be improved through the application of innovative information technologies (application of neural networks to data analysis, optimization, pattern recognition, image identification, et cetera) and with using new generation a non-invasive techniques for subsurface exploration (petroleum, mineral, geothermal and groundwater exploration).

This operative monitoring system has abilities and advantages are defined by its multifunctional methodological application, that could be used as an operative system for water search tasks (ground water table), definition of waste level, monitoring changes in subsurface horizons, etc. Also this system could be applied to solve long-term tasks for monitoring nature subsurface ecosystem, subsurface horizons, soil salinity level, salinity grade, ground water level. All these parameters can be used to track seasonal and climatic changes in selected area.

The distinctive difference of proposed regional monitoring system is measurement of soil's humidity along all the depth down to ground water level. It is not possible to detect these subsurface horizon humidity parameters by other monitoring means, such as: observation wells, ground digs, etc. The development of three-dimensional hydrologic models requires information on the physical characteristics of the subsurface including the location and extent of geologic units, the hydrologic properties of these units, and the quality of water contained in them. Traditionally this information has been obtained from knowledge of subsurface geology, and ground-water observation and test wells. Relying only on wells for this information can be highly uncertain because of the large inter-well spacing due to expense. Also, access considerations may constrain well placement to locations less desirable from a ground-water model development stand point. While wells provide detailed vertical information and allow sampling of geologic materials and groundwater, the distance from the well that this information is valid is often unknown. The consequences of limited aquifer-property information on the resulting groundwater model is a complex issue that must be considered in the modeling process consequently, using auxiliary means to obtain more detailed information is highly desirable. Geophysical measurements provide a relatively inexpensive way of augmenting borehole information to reduce the uncertainty of the estimated physical properties between boreholes. By correlating borehole information with interpreted geophysical data, detailed well information can be interpolated between or extrapolated from wells with confidence. Geophysical measurements can provide information on the types of geologic materials at depth, thickness and lateral extent of these units, and the quality of groundwater contained in them. While information on aquifer physical properties such as permeability, porosity, and transmissivity can not be directly determined from geophysically measurements, knowing the extent of geologic units is invaluable to model development.

A fundamental understanding of the processes involved is presently not available. Insight in the controlling processes and the development and testing of a coupled variable-density flow, multispecies transport, and reaction code will increase the possibilities for sustainable management of coastal aquifers.

Techniques and methods existing now and toolkit for measurement and definitions of structure groundwater flow into the coastal zone basically are based on local measurements physics-chemical parameters of the freshwater and saltwater in intrusion zone, which to include in themselves radioisotope and MRS instrumentations.

In the last some years on the basis of portable geophysical instrumentation are offered a new technique for operative monitoring of the transite salt/water intrusion zone (geoelectrical parameters: conductivity, salinity, porosity) which allows essentially to expand a database, in addition to already existing, about salt/water intrusion disgage zone and to obtain the operative data on speeds of change groundwater flow, sum total volume of the stock and another hydrogeophysical information.

MONITORING

MARSES TEM sounding instrument that is based on time domain electromagnetic sounding technology. MARSES TEM is a portable geoelectrical sounding instrument that was made to meet requirements in small dimensions, simple and intuitive usage, and reliability.

The depth of subsurface sounding is about 150-200 m using TEM technology. Areas of application are following: prospecting of deposits, hydrogeological research, geological survey, required before construction of buildings, ecological research, archeology and subterannean objects search, monitoring of a high risk industrial and engineering objects, research and tests of rock samples.

The structure of this monitoring system organisation is outlined at Figure 1. A number of MARSES instruments should be placed in area of ecological hazard to provide measurement in respective points. Using radio system it would be possible to transmit data to headquarters, where data is processed and stored for future use and reference. Using modeling and visual presentation software it would be possible to make information visual with graphs, charts, time variation and other easy to understand what is happening in monitored area.

The significant advantage of this system in comparison to known ecological hazard monitoring systems is cost effectiveness - it doesn't require expensive satellite monitoring of the ground area or employment of satellites in data transfer. Another advantage is compact and ready to use instrument that allows accomplishing measurements at required area rapidly. Moreover, the cost of this device is less than competitors'.

Despite many competitors' instruments with similar areas of application, MARSES TEM has reasonable advantages among small depth sounding devices. Because MARSES TEM hardware has been developed to be employed in space research missions it has unique portability and dramatically low in weight.

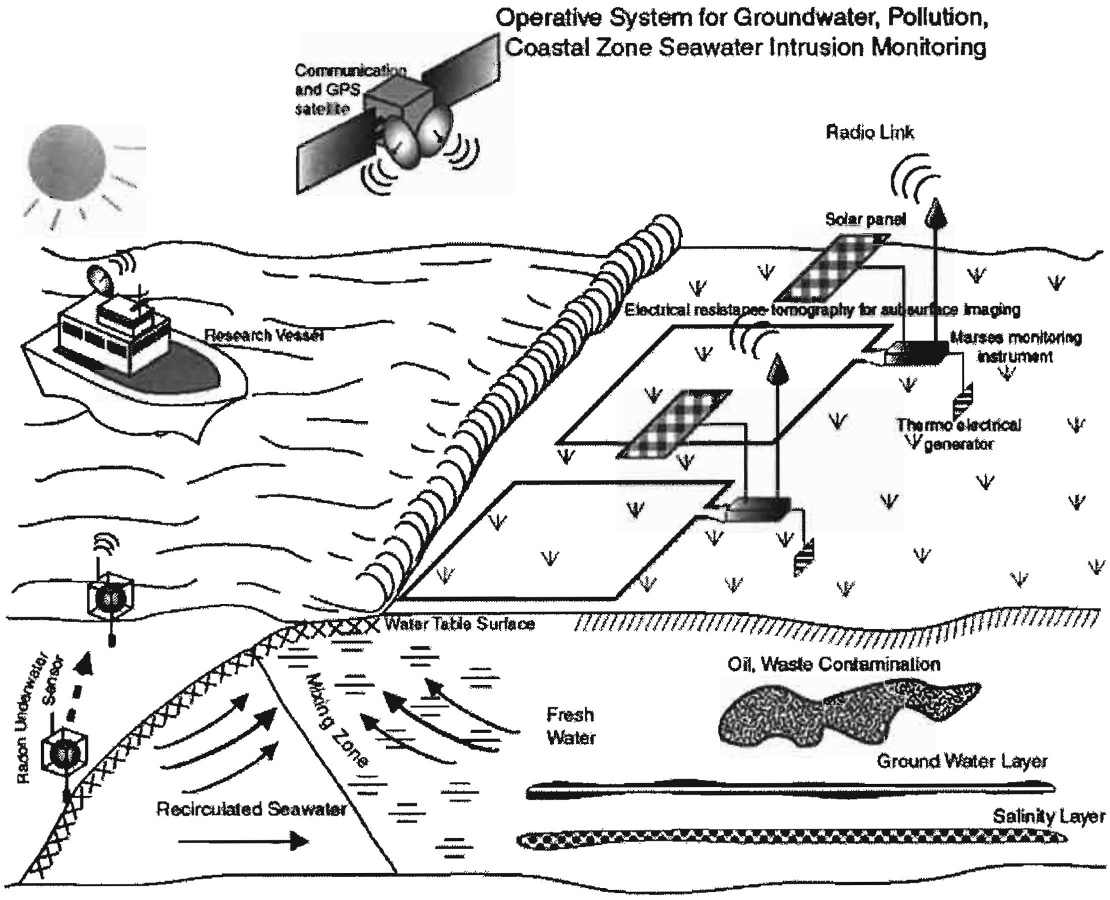

Figure 1. The subsurface monitoring system organization structure.

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MAGNETIC RESONANCE SOUNDINGS APPLIED TO LOCALIZATION OF SATURATED KARST AQUIFERS

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INTRODUCTION

The main advantage of the Magnetic Resonance Sounding method (MRS), compared with other geophysical tools for water prospecting is that the MRS is sensitive only to subsurface water. Inversion of MRS field data reveals the water content $w(\mathbf{r})$ and the relaxation time $T_1(\mathbf{r})$ with $\mathbf{r} = r(x,y,z)$ being the coordinate vector (Legchenko, and Shushakov, 1998; Legchenko, et al., 2002). In a porous medium the relaxation time T_1 is proportional to the mean pore size $1/T_1 \sim S/V$ (Kenyon, et al., 1997), where S and V are the surface and volume of pores respectively. Usually MRS is applied to characterization of continuous aquifers. However it can be also a tool for localization of saturated karst aquifers.

MRS AS A SATURATED KARST DETECTOR

Schematically a karst system can be presented as it is shown in Figure 1 (Mangin, 1975). A correspondence between MRS response and schematic karts zones is presented in Figure 2. Consequently, for aquifer karst localization two estimators can be used:

$$k_x(z) = \frac{w_x(z)T_{1x}^2(z)}{w_r(z)T_{1r}^2(z)}, \qquad T_x = \frac{\int_z w_x(z)T_{1x}^2(z)dz}{\int_z w_r(z)T_{1r}^2(z)dz},$$

where x and r are two of N MRS stations $(1,..,x,..,r,..N)$. The reference station r is often (but not necessary) selected so that $\{\ k_{x\max}(z) \le 1\ \}$ or $\{\ T_{x\max} \le 1\ \}$ for all soundings $(x = 1,..,N)$. In fact, the estimators k_x (K-estimator) and T_x (T-estimator) are normalized MRS permeability and transmissivity of aquifers. Water in saturated dissolution figures (i.e. conduit and cave) is usually characterized by a strong increase in both K and T estimators in comparison with unsaturated and epikarstic zones (Figure 3).

Using $T_1 > 400ms$ criterion for dissolution figures identification, the capability of MRS to detect water in function of its depth and volume was investigated (Figure 4). Modeling results show that water in saturated dissolution figures can be easily identified at shallow depth. For deeper investigation, larger volume of water is necessary : 100 m^3 of water is detectable at 5 m deep whereas 250 m^3 is needed at 15m.

FIELD EXAMPLE

MRS tests have been carried out over a well-known karst system near Montpellier (France) (Vouillamoz, et al., 2003). A profile of several soundings crosses a saturated karst conduit (Figure 5). To improve the signal to noise ratio the eight-shape loop was used (Trushkin, et al., 1994). The investigated volume can thus be approximated by a parallelepiped of 120x50x50 m. It is an obvious limitation of 1D technique applied to investigation of 2D/3D target.

Using the T-estimator, MRS map was build (Figure 5). It shows clearly a high-transmissivity channel that fits well the known conduit. For more detailed investigation, a cross section was drawn using the K-estimator (Figure 5). The location of the saturated conduit is underlines by an increase of the K-estimator, and the water bearing epikarst is also identified (stations 11, 12); it is probably drained in the northern part of the section (stations 9, 10).

CONCLUSIONS

The MRS is a useful tool which could take place in the hydrogeologist toolbox : it could estimate the spatial variations of permeability and transmissivity which underline karstic structures bearing water (as the epikarst, conduits and caves). The permeability and transmissivity estimators are calculated from magnetic resonance signal sent out by the hydrogen atom of water molecule : it causes the main advantage of MRS, i.e. to measure a signal induced exclusively by groundwater. But it leads also the main limit of the MRS, i.e. the groundwater quantity has to be enough to send out a signal which can be measured. Using Figure 4, it becomes possible to estimate if the targeted karst anomaly could be detected by MRS.

One should also keep in mind that the geometry of the 3D structures could only be approached with 1D soundings.

For low magnetic signals, i.e. small or deep amount of water, the measurement duration of a MRS could reach up to 20 hours : in karstic environment, an average of 1 sounding per day should be planed.

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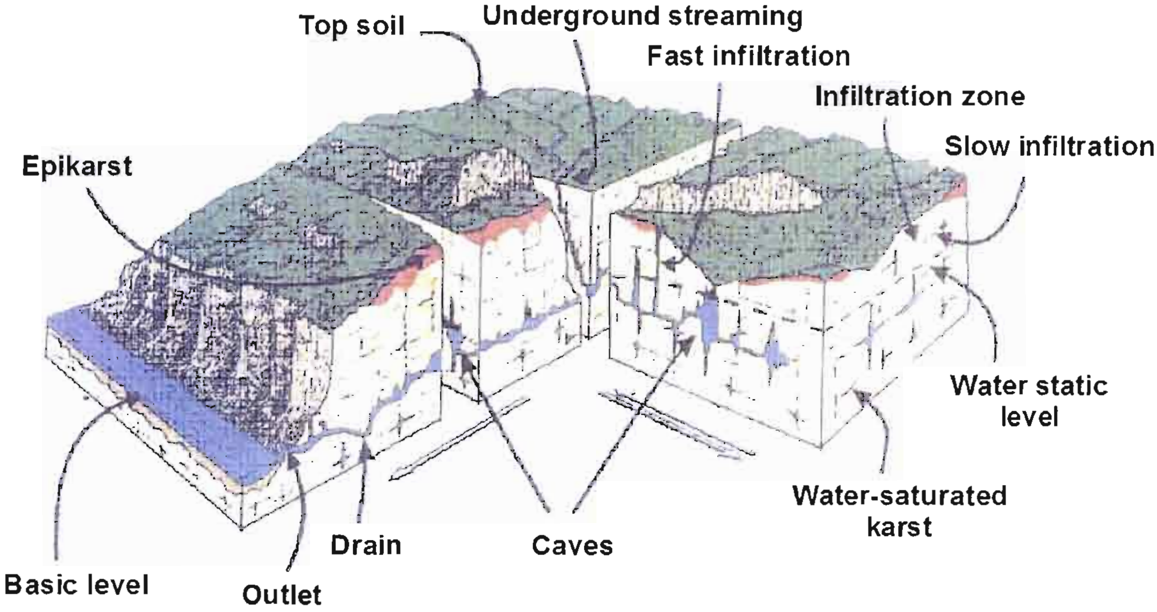

Figure 1. Schematic presentation of a karst system (Mangin, 1975).

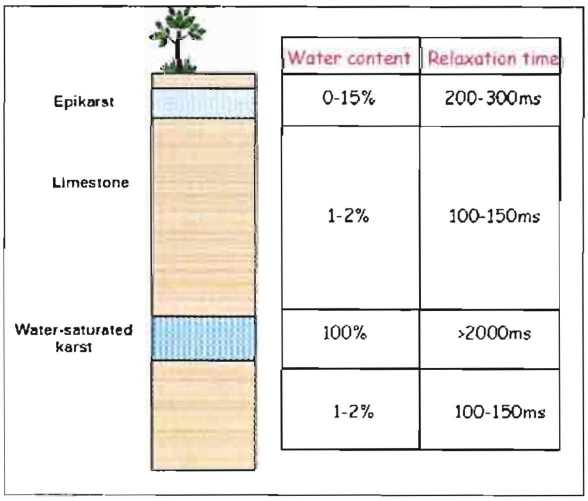

Figure 2. MRS response from a karst system.

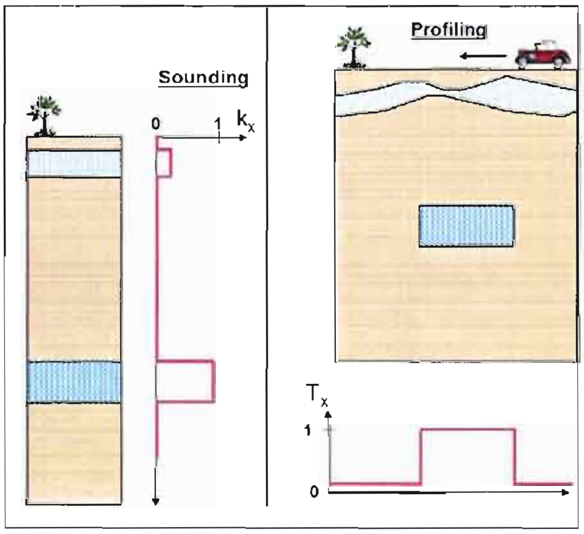

Figure 3. MRS application scheme.

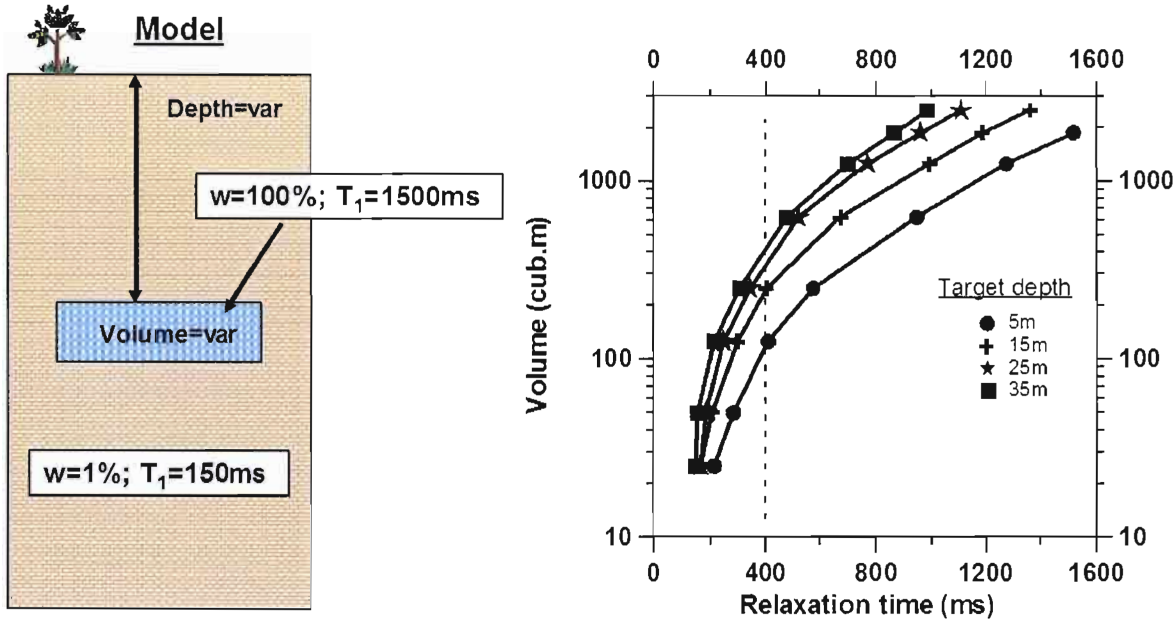

Figure 4. Modeling of MRS relaxation time from water-saturated karst.

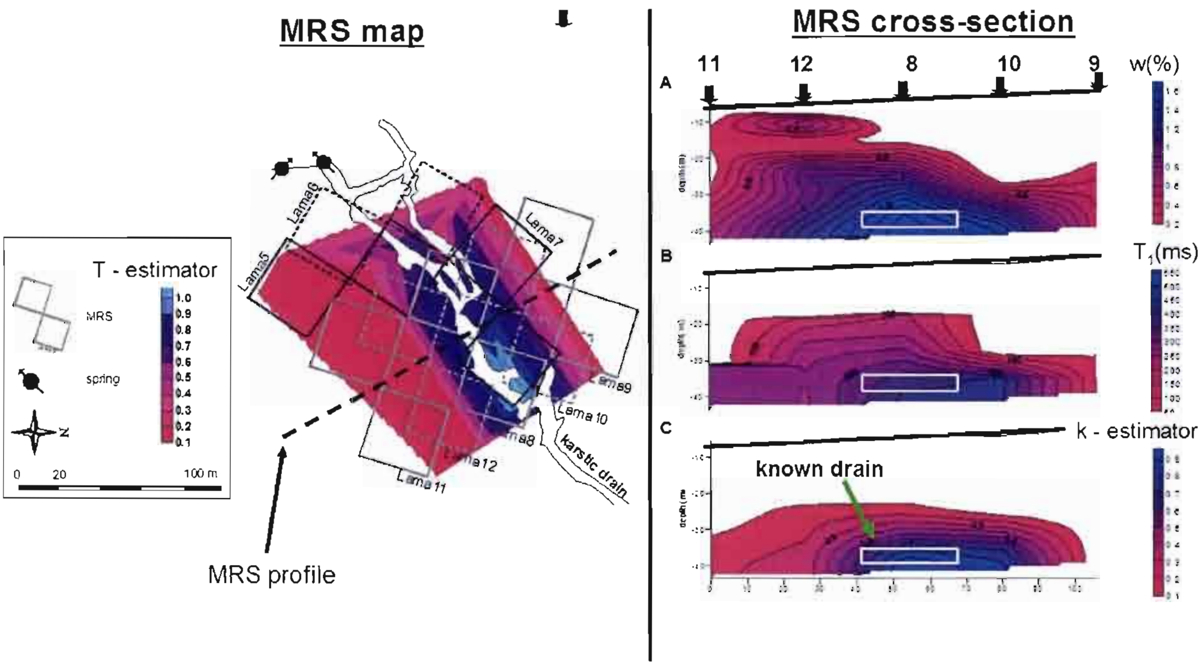

Figure 5. Example of MRS application to karst localization (Lamalou, France).

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