PAPERS PRESENTED AT GEOPHYSICAL MEETINGS

ON THE MAGNETIC RESONANCE SOUNDING METHOD:

principles, equipment and case histories

- **Groundwater exploration with the Magnetic Resonance Sounding method**
J. Bernard, A. Legchenko,
ASEG, Adelaide, Australia, February 2003
EAGE, Stavanger, Norway, June 2003, invited paper

- **Comparison of various loop geometries in Magnetic Resonance Soundings on the Pyla sand dune (France)**
F. Vermeersch, J. Bernard, O. Leite
2nd Magnetic Resonance Sounding Workshop,Orléans, France, November 2003

- **Combination of electrical resistivity and magnetic resonance sounding data for mapping an aquifer layer in Mauritania**
J. Bernard, M. Lemine, B. Diagana, M. Ricolvi,
SEG, Denver, Colorado, October 2004

- **Instruments and field work to measure a magnetic Resonance Sounding with NUMIS equipment**
J. Bernard
3rd Magnetic Resonance Sounding Workshop, Madrid, Spain, October 2006

- **Application use of the Proton Magnetic Resonance Sounding method (MRS) for groundwater investigations in various geological environments**
J. Bernard
AGU, San Francisco, California, December 2006

IRIS instruments

iris-instruments.com

MAGNETIC RESONANCE SOUNDING SYSTEMS

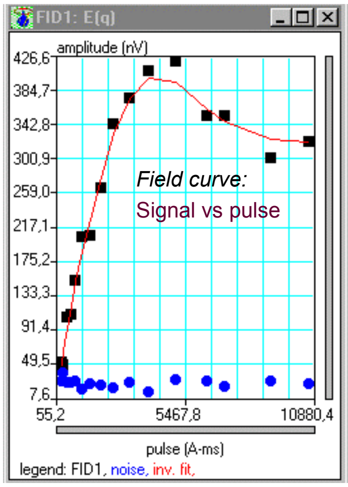
DIRECT DETECTION OF GROUNDWATER

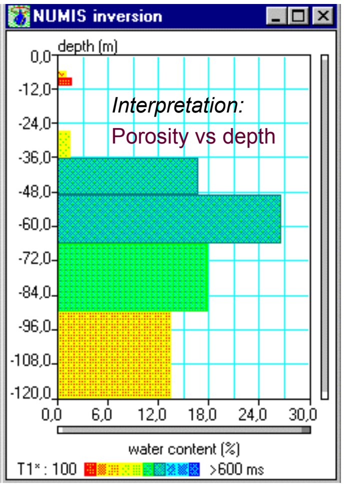
water content
permeability estimate
depth of water layers

Determination of water level and quantity
Lateral extension of an aquifer layer
Selection of the best place to drill
Prediction of yield, after calibration

Our offer:

Sale of products
Interpretation software
Rental
On-site training
Maintenance



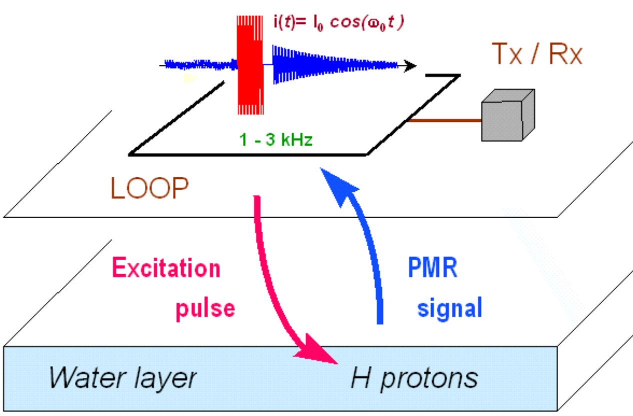


PRINCIPLE OF THE MAGNETIC RESONANCE METHOD

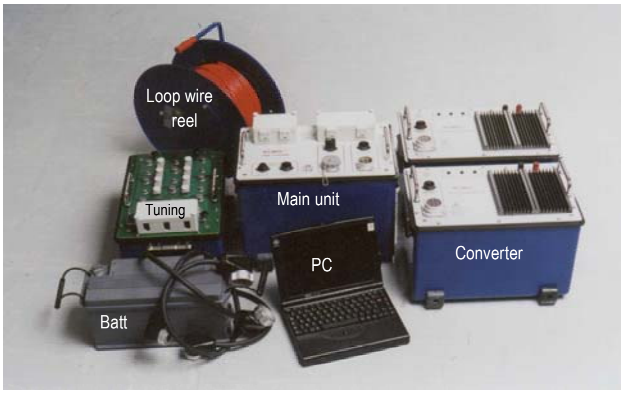
Principle: A pulse of current at a given frequency is transmitted into a loop.
The signal produced in return by the H protons (water molecules) is measured within the same loop.

How to carry out a Magnetic Resonance Sounding ?

1- ***Measure the Earth magnetic field*** to know the frequency to apply
2- ***Transmit a pulse of current*** into a loop, at this frequency
3- ***Measure the amplitude*** of the water MR signal (≈ porosity)
4- ***Measure the time constant*** of the signal (≈ mean pore size)
5- ***Change the pulse intensity*** to modify the depth of investigation
6- ***Use the inversion program*** to get the porosity versus the depth



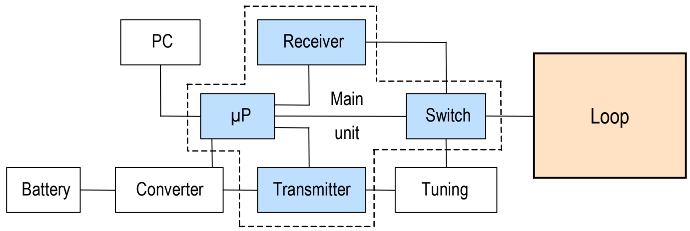
NUMIS Plus, FOR GROUNDWATER RESOURCES EVALUATION



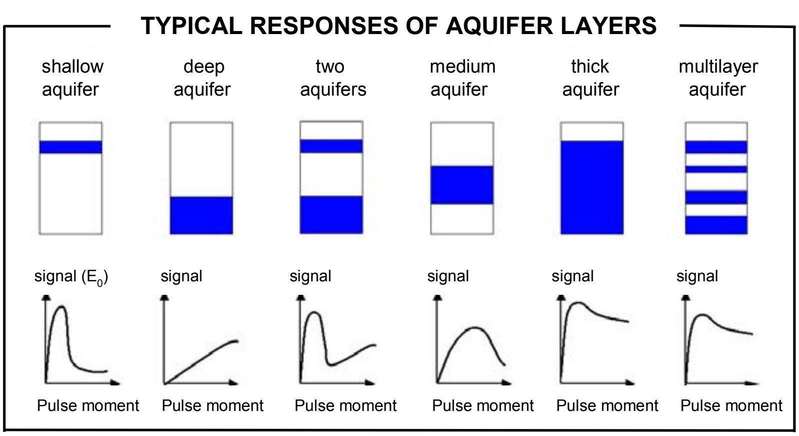
NUMIS Plus SPECIFICATIONS

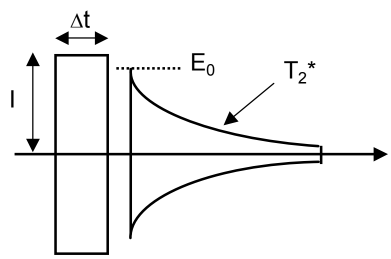
NUMIS Plus, designed to investigate water down to 100 -150m
Modular, PC driven, automatic data acquisition system
Input: two 12V batteries per DC/DC converter (0.05F, 400V max)
Tuning: Capacitor unit (60µF), 1 unit for high latitudes, 2 for low
Output: pulses up to 4000V - 450A
Pulse moments: 100 -18 000 A.ms, loop & frequency dependant
Frequency: 800 Hz (low latitudes) to 3 000 Hz (high latitudes)
Sensitivity: of the order of 1 nV after stacking and filtering

NUMIS Plus SCHEMATIC DIAGRAM



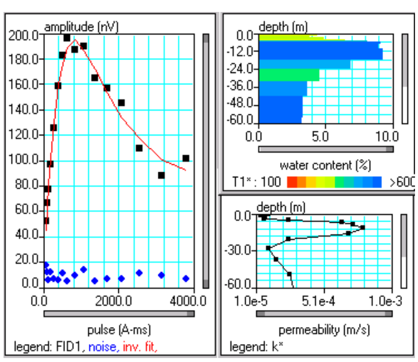
NUMIS Plus CONFIGURATIONS		
investigation depth	number of DC/DC converters	loop dimensions
100m	one	100x100m
150m	two	150x150m





E_0: Initial amplitude of signal (nV)
Proportional to the **water content** (%)
T_2*: Decay time constant of signal (ms)
Related to the **mean pore size** (permeability)
I. Δt: Excitation pulse moment (A.ms)
Related to the **investigation depth** (m)

NUMIS Lite, FOR ENVIRONMENTAL APPLICATIONS



Non-invasive groundwater level determination
Pollution study: mapping of shallow groundwater

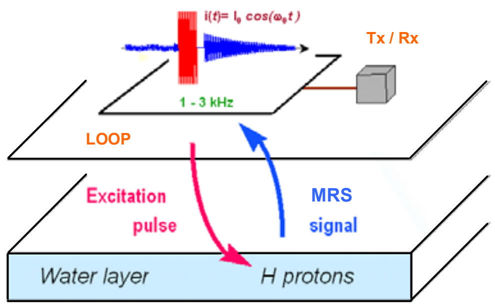
NUMIS Lite SPECIFICATIONS

NUMIS Lite is a reduced power version of NUMIS Plus, designed for shallow water investigations (about 50m)
Input: two 12 batteries, 1 DC/DC converter (110V max)
Output: pulses up to 1 000V, 150A
Pulse moments: 100 - 6 000 A.ms, loop and frequency dependant
Frequency: 1 500 Hz (medium latitudes) to 3 000 Hz (high latitudes)
Sensitivity: of the order of 1 nV after stacking and filtering
Loop dimensions: 60x60m, 1 turn or 30x30m, 2 turns

THE MAGNETIC RESONANCE SOUNDING METHOD FOR GROUNDWATER

The Magnetic Resonance Sounding method (MRS):

The MRS is the only non-invasive method which directly studies groundwater reservoirs from surface measurements:
A pulse of current, at a given frequency, is transmitted into a loop.
The signal produced in return by the H protons (water molecules) is measured within the same loop.

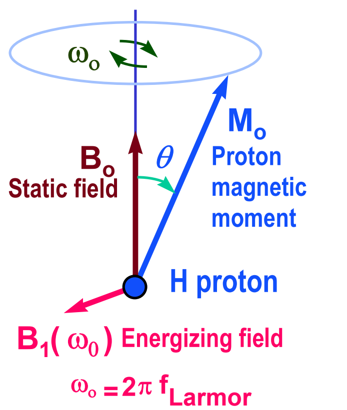


PRINCIPLE OF THE MRS METHOD

Hydrogen atoms of water molecules are energized by pulses of alternative current at the proper frequency (Larmor frequency), transmitted into a loop laid on the ground. The magnetic field they produce in return is measured and analyzed for various energizing pulse moments (intensity x duration).

INFORMATION OBTAINED

The interpretation of measurements permits to estimate the water content and the mean pore size (permeability) of each layer at depth. These parameters are useful to determine the prospects of a groundwater reservoir before drilling.



The static field B_0 (Earth's magnetic field) determines the Larmor frequency of the H protons : $f_0(Hz) = 0.04258 \times B_0(nT)$

The dynamic energizing field B_1 (loop magnetic field) produces the nutation of the H protons magnetic moment M_0 : it tilts away from the static field with an angle θ, while still precessing at the Larmor frequency.

Once the energizing field has been switched off, the protons come back to equilibrium (M_0 aligned with B_0) after a relaxation decay characterized by an initial amplitude E_0 and a time constant T_2*.

The water content (porosity) is proportional to the amplitude of the proton response.

The pore size of the medium (which is linked to the permeability) determines the time constant of this decay response.

The depth of investigation is determined by the moment of the energizing pulse (intensity x duration)

ORDERS OF MAGNITUDE IN MRS

The Larmor frequency: it is determined by the amplitude of the local Earth magnetic field and varies between 0.8 and 3.0 kHz.

The loop size: the side of the loop is of the order of the maximum investigation depth: typically, 50, 100 or 150 m.

The energizing pulse: its moment controls the depth of investigation. To reach 150 m, currents up to 400 A and voltages up to 4000 V are required during a few tens milliseconds (typically 40 ms).

The voltage measured in the loop is in the order of a few tens to a few thousands nanovolts. Stacking is used to enhance these small amplitude signals.

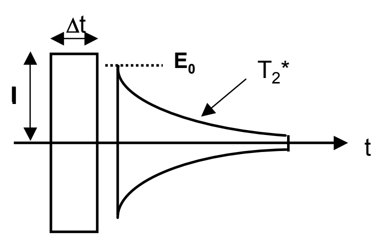
The duration of a sounding: depending on the signal to noise ratio, a complete sounding (16 pulse moment values) can take one to two hours.

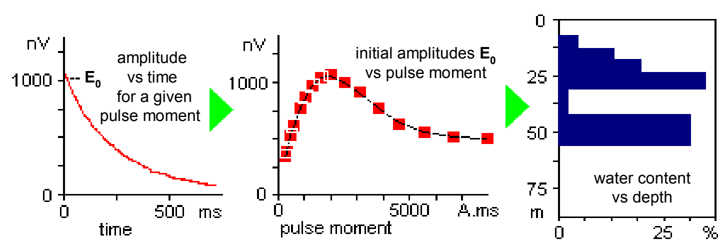
TIME CONSTANTS

T_2*: transverse time constant, related to the component of the proton magnetic moment M_0 perpendicular to the Earth magnetic field (one pulse technique measurement)

T_1: longitudinal time constant, related to the component of the proton magnetic moment M_0 parallel to the Earth magnetic field (double pulse technique measurement).

The time constants are linked to **the permeability** through the mean pore size: when the pores are large, the protons loose slowly their energy against the grains as shocks are less frequent than when the pores are small.





relaxation curves sounding curve interpretation section

E_0: Initial amplitude of signal (nV)
Proportional to the **water content** (%)
T_2*: Decay time constant of signal (ms)
Related to the **pore size** (permeability)
I. Δt: Excitation pulse moment (A.ms)
Related to the **investigation depth** (m)

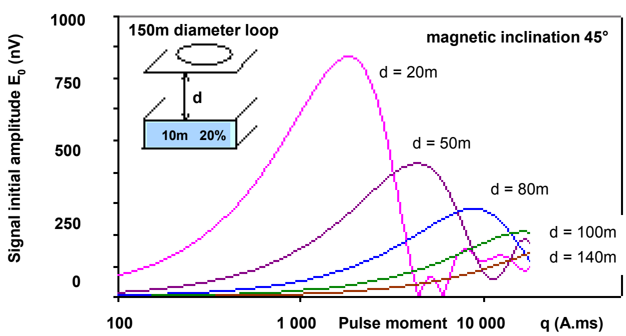
The Magnetic Resonance Sounding for Groundwater

INTERPRETATION OF MRS DATA

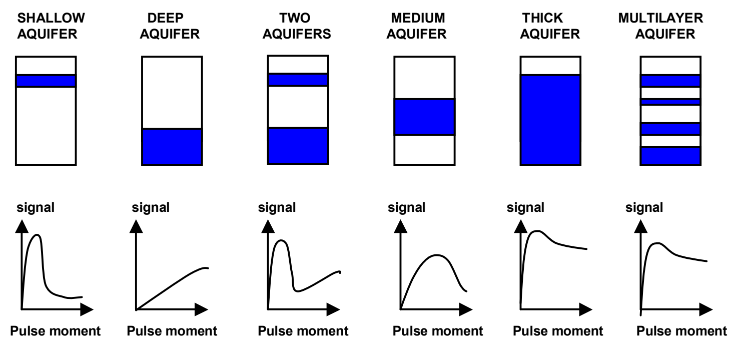
The MRS theory states that, for a given loop size, the investigation depth of a measurement varies with the moment of the excitation pulse (product of the intensity of current at the resonance frequency by the duration of the pulse). It is therefore possible to sound the ground with MRS surface measurements. Besides, it can be shown that the decay time constant of the relaxation field is related to the pore size, which potentially permits to distinguish between pore free water and clay bound water. For interpreting a MRS sounding, it is assumed that the underground is stratified at the scale of the loop dimensions. The inversion gives values of the water content, estimations of permeability, and the depth of each layer, after processing of the raw data for the whole set of pulse moments.

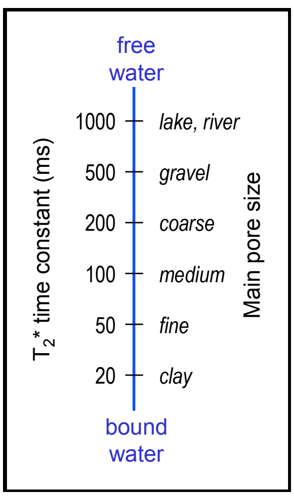
For inverting a set of field data it is first necessary to compute a matrix giving the theoretical response of thin water layers located at various depths. This matrix will take into account the general configuration of the measurements: loop dimension, Earth's field inclination, ground resistivity,… The computation of this matrix may usually takes about an hour on a PC but the results will be valid for all the soundings of a given survey. Then the inversion itself of one set of data will take only a few seconds: the results can thus be available in the field before moving the equipment to the next site. The inversion procedure is fully automatic: no initial model is required. The operator has the possibility to manually change the value of the regularization parameter for smoothing or enhancing the variations of the water content with depth according to the local context (equivalence properties).

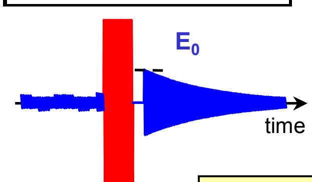
THEORETICAL SOUNDING CURVES



TYPICAL MRS RESPONSES OF AQUIFER LAYERS







MRS VERSUS OTHER GEOPHYSICAL METHODS

MRS is a direct method for groundwater detection, as it directly measures the response of the water itself (H protons). The more traditional methods (DC, TDEM, …), are indirect ones, as they measure a physical parameter which is only indirectly linked to the presence and to the quantity of water: the electrical resistivity of the layers is a function not only of the porosity (volume of water) but also of the resistivity of the water ; besides, the formation resistivity is also influenced by the conductivity of clay which makes the interpretation sometimes complex. However, the MRS cannot distinguish between fresh and salt water, as it has no relation with dissolved salts, but only to the hydrogen content.

In terms of depth determination, MRS is influenced, as other geophysical methods, by equivalence rules, due to the fact that it is an integrating method. However, for MRS , the eigen parameter is the product of the water content by the thickness of the layer, which means that the total quantity of water is always fairly well determined.

A particularity of MRS is the non linear relationship between the measured signal and the energizing pulse intensity. This means that doubling the pulse current does not mean doubling the signal: instead it increases the depth of investigation. On the other hand, the MRS signal is linearly related to the water content of the layers, which makes the interpretation quite quick.

Some specificities of the MRS method have to be pointed out: in case of magnetic rocks (volcanics,…), the Earth magnetic filed is non homogeneous, which makes the method difficult to apply. Besides, due to the very low amplitudes of the signals to measure, the MRS method is sensitive to electromagnetic noise such as power lines, and to passive conductors such as pipes, fences etc. This makes its application more difficult in industrialised areas.

A FEW MRS EQUATIONS:

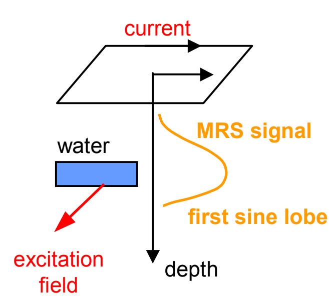
Resonance Frequency (f_0) = constant x Earth magnetic field

$e(t) = E_0 \exp(- t / T_2^*) \sin(2\pi f_0 t + \phi_0)$: relaxation with precession

$E_0 = \Sigma$ (excitation field(1A) x (water content) x Sin (excitation field x duration) volume *(simplified formula)*

Permeability = coefficient x water content x (time constant)^2

(T_1 time constant gives better estimates of the permeability than T_2^*)



Groundwater exploration with the Magnetic Resonance Sounding method

J. Bernard
IRIS Instruments, France
iris@iris-instruments.com

A. Legchenko
BRGM, France
legtchenko@exchange.brgm.fr

SUMMARY

The Magnetic Resonance Sounding method (MRS) has been used in the past years with success in various geological and geographical contexts for groundwater surveys. This method has indeed the ability of directly detecting the presence of water through the excitation of the hydrogen protons of water molecules.

The frequency to which the H protons react depends on the magnitude of the Earth magnetic field, while the intensity of the excitation determines the depth of investigation. The amplitude of the magnetic field generated in return by the water of a layer is proportional to the porosity of this layer, and the time constant of the relaxation curve is linked to the mean pore size of the material, that is to say tightly related to its permeability.

A loop laid on the surface of the ground is used for both transmitting the excitation pulse and measuring the response of the H protons. The linear relation between the measured signal and the layer porosity permits to interpret the 1D sounding as soon as the readings have been collected in the field.

The main applications of this method concern the determination of the water level and of the total quantity of water available down to 100 to 150 m depths. Magnetic Resonance Soundings can also help to select the best place for drilling, to predict a yield using a calibration, and to determine the geometry of an aquifer layer for hydrogeological modelling

A set of field examples acquired in various countries (Africa, Asia, Europe) points out both the advantages and the limitations of this method and suggests the place it should take among other geophysical methods in the methodology of groundwater investigations.

Key words: Magnetic Resonance Sounding, porosity, permeability, groundwater, NMR.

INTRODUCTION

Groundwater exploration carried out with traditional methods (TDEM, DC resistivity,…) usually leads to good qualitative success, even if an evaluation of the quantity of water present into the ground is not possible due to the indirect relation between the physical parameter measured and the water. However, for the past five years, a new procedure based on the Magnetic Resonance phenomenon has been introduced in routine applications for directly detecting the presence of water from surface measurements through the excitation of the hydrogen protons of the water molecules.

Within the limits of its application which are discussed farther, the Magnetic Resonance Sounding (MRS) method permits to estimate the total quantity of water existing at given location, its depth, and the hydraulic permeability of the formation, hence its interest for a quantitative evaluation of groundwater resources.

Initiated by the ICKC Institute in Russia (Semenov, 1987), the methodological developments have been continued at BRGM in France (Letgchenko *et al.*, 1995; Valla, 2002), Berlin Technical University in Germany (Yaramanci *et al.*, 1999) and ITC in The Netherlands (Roy, Lubczynski, 2000), among other groups.

PRINCIPLES OF THE MRS METHOD

The Magnetic Resonance phenomenon is already used by geophysicists in the Proton Magnetometry where the hydrogen protons located in the sensor casing are activated to determine their precession frequency, hence the magnitude of the Earth magnetic field. In the application of the Magnetic Resonance to groundwater studies, there are the protons of the underground water molecules which are activated to characterize the water layer.

Three magnetic field have to be considered (Figure 1):

* *The Earth magnetic field*, the amplitude B of which determines the precession frequency f of the hydrogen protons: f (Hz) = 0.04258 B(nT)
* *The excitation magnetic field* produced by a current put into a loop laid on the surface of the ground at this precession frequency
* *The relaxation magnetic field* produced in return by the protons after they have been excited by the previous field, measured within the same loop

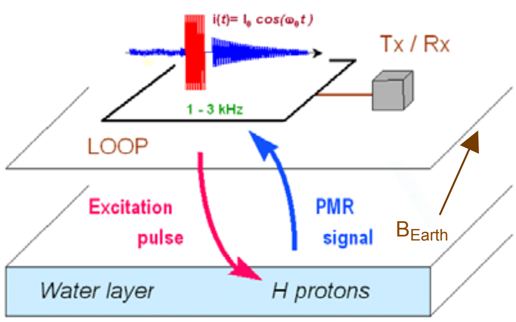


Figure 1. Principle of the Magnetic Resonance Sounding method for groundwater investigations

The initial amplitude E_0 of the relaxation (Figure 2) measured just after the excitation current has been switched off is directly proportional to the number of protons which have been reacting, namely the water content (porosity).

The time constant (T2*) of the relaxation curve is linked to the mean pore size of the material, fine grain sediments giving short decays (a few tens ms) while coarser grain sediments lead to longer decays (a few hundreds ms). The time constant is thus related to the permeability of the layer.

The intensity of the excitation pulse (its moment I.Δt, product of the intensity of the current by the pulse duration) fixes the depth of investigation, small pulses for shallow, high pulses for deeper.

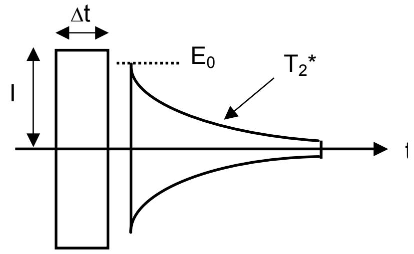


Figure 2. Envelops of the excitation pulse and of the Magnetic Resonance relaxation signal: I is the intensity of the current, Δt its duration, E_0 the initial amplitude of the signal, T2* its time constant

In practice, with the NUMIS Plus equipment developed to achieve these measurements, the loop size is of the order of the penetration depth (maximum 150m), the current ranges from a few units to a few hundreds amperes, the maximum output voltage reaches 4 000V, the duration of the pulse is about 40ms, the amplitude of the measured signal varies from a few tens to a few hundreds nV. The Larmor precession frequency in the Earth field ranges from 800 Hz (very low magnetic latitudes) to 3 000 Hz (high latitudes).

The structure of the base equation which describes the behaviour of the initial amplitude of the proton relaxation is:

$$\text{Signal} = \int k \times \text{1AField} \times \text{Porosity} \times \sin(\text{Field} \times \text{Duration}) \times dv$$

where the integral is computed over the volume elements dv where the water is located, "Field" is the component of the excitation field perpendicular to the Earth field, "1AField" is the same one normalized to a unit current (1A), "Duration" is the pulse length, "k" a parameter related to nuclear constants.

From this equation, it can be seen that there is a non-linear relation between the intensity of the current (included in the "Field" function) and the measured signal. This property explains that the pulse moment has a sounding effect: the first lobe of the sine function acts as a spatial band pass filter featuring a maximum response when the argument is 90°, which permits to separate the responses coming from various depths, by changing the intensity of the excitation current.

On the contrary, the relation between the water content (porosity) and the measured signal is linear which makes the inversion process quite simple. This linearity means that the response of two layers is the sum of the responses of each one of these aquifers (Figure 3).

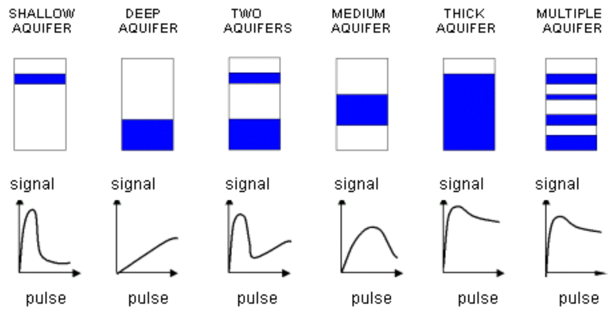


Figure 3. Typical Magnetic Resonance responses of aquifer layers, for various types of thicknesses and depths.

Being a volume integral, the signal coming from the protons is submitted to the classical **equivalence laws** between a contrast of geophysical parameter and the geometrical parameters: the effect of a thin water layer with a high water content is similar to the response of a thicker layer placed at the same average depth having a lower water content, provided that the product of the water content by the layer thickness is the same in both cases. This means that the total quantity of water is well determined, which in anyway is a useful parameter for determining the hydrogeological interest of a site before drilling.

The depth of penetration, which is a function of the surface of the loop and of the pulse moment (Figure 4), also depends on the resistivity of the formation, since the protons are excited by the total magnetic field which is lower than the free space field when the medium is conductive, due to EM induction. For example, in a 50 ohm.m formation, the penetration is reduced by 20% compared to a highly resistive area.

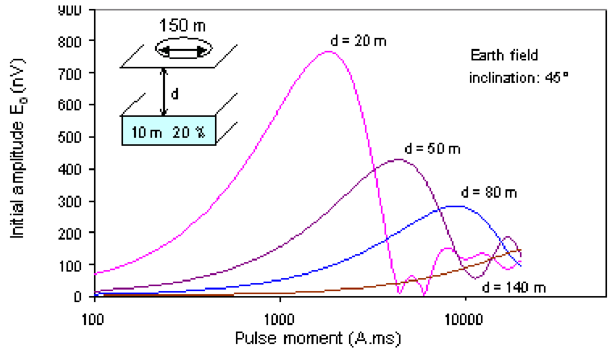


Figure 4. Theoretical Magnetic Resonance Sounding curves for a 10m thick aquifer layer having 20% water, at 20, 50, 80 and 140m depths

ESTIMATION OF THE PERMEABILITY

While the measurement of the initial amplitude of the relaxation curve gives a physical determination of the porosity after 1D inversion, transforming the value of the time constant into a permeability requires an empirical relation coming from field experiments.

At this stage, it is important to note that two time constants are defined in the Magnetic Resonance process: the first one, called **the Transverse Time Constant (referred to as T2*)** is linked to the time which is required by the component of the magnetic moment of the H protons perpendicular to the Earth field to loose their phase coherence after the excitation pulse is switched off. It is directly measured during the record of the relaxation signal after having transmitted one excitation pulse. The problem with T2* is that it depends not only on the mean pore size of the formation, but also on the inhomogeneities of the magnetic susceptibility of the grains composing the layer, which makes T2* not perfectly related to the permeability .

The second time constant, called **the Longitudinal Time Constant (referred to as T1),** is linked to the time required by the component of the magnetic moment of the H protons parallel to the Earth field to come back to equilibrium after the excitation. Usually T1 is two to four times larger than T2*. To measure T1, it is necessary to transmit two pulses of current separated by a time interval greater than T2* but lower than T1, and to measure the loss of initial amplitude after the second pulse compared to the first pulse; this loss is due to the fact that after the first pulse the magnetic moment of the protons does not have enough time to come back to its initial value, which minimizes the signal measured after the second pulse. The advantage of the T1 time constant is that it is only related to the mean pore size of the formation, which makes it a good parameter for the estimation of the permeability.

The quantitative estimate of the permeability from Magnetic Resonance readings is given by the formula:

$$\text{Permeability} = C \times \text{porosity} \times (T1)^2$$

where C is a coefficient that may vary with the geological context.

The transmissivity (m^2/s) of a formation is the product of the permeability (m/s) by the thickness (m) of the layer and represents the hydrogeological potential of this formation: as a matter of fact, the specific yield (m^2/s) of a borehole, which is defined as the yield (m^3/s) per unit of drawdown (m) is proportional to this transmissivity parameter. It is necessary to compare the results of several pumping tests with the permeability formula here above given to have a proper estimation of the potential yield which can be obtained from a site prospected with Magnetic Resonance: the yield can vary with the geological context (the C parameter), but it also depends on man-controlled parameters (screening set-up, hole washing, pump specifications, …) beyond natural parameters (transmissivity).

FIELD EXAMPLES

Magnetic Resonance Soundings in Mauritania

In a sandy area where the water is very fresh (with a conductivity of about 100µS/cm), the DC electrical soundings do not permit to distinguish wet sands from dry sands inter-bedded between clayey formations. Figure 5 shows a neat response of the Magnetic Resonance Sounding curve over a 40m depth, at least 50m thick aquifer layer having of the order of 20% of free water. The complete sounding has been carried out in 45 minutes. The method has been used to map the extension of the aquifer zone for the evaluation of the whole water resource of the area.

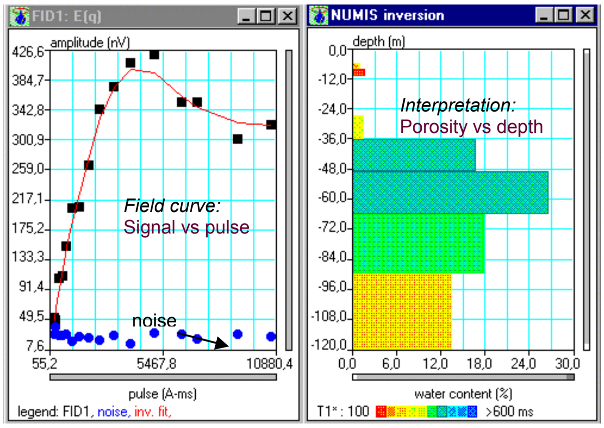


Figure 5. MRS data in Mauritania showing a thick aquifer layer, 40m deep (PHY Company data, 100x100m square loop)

Magnetic Resonance Soundings in India

In granitic areas, it is often the altered part of the granite which contains most of the water. South of Hyderabad, a survey has been carried out to locate the places where there was more water. Figure 6 displays a MRS curve which points out a 3% water layer, 10m thick, at 3m depth. The initial amplitudes measured did not exceed 35nV, which implied a stacking of two and a half hours to counter balance the EM noise due to power lines.

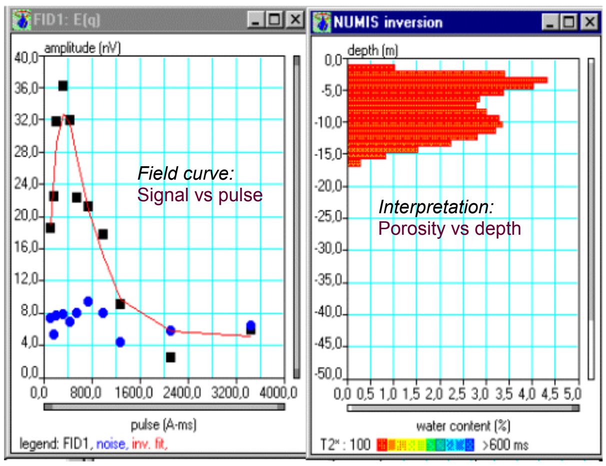


Figure 6. MRS data in India on an altered granite (BRGM data, 75x75m eight-shape loop)

Magnetic Resonance Soundings in France

A set of MRS data have been collected in various geological contexts (sand, chalk, limestone, altered granite) where the results of pumping tests were available, in order to compare the hydrogeological parameters obtained in both cases (Legchenko *et al.*, 2002). Figure 7 is a cross diagram between the "MRS" transmissivity (abscissa) and the borehole transmissivity (ordinate). The correlation, based on a C coefficient of 7e-09 (see § on the permeability) is quite good. However, due to the equivalence laws, the uncertainty on the estimation of the transmissivity is of the order of 50%.

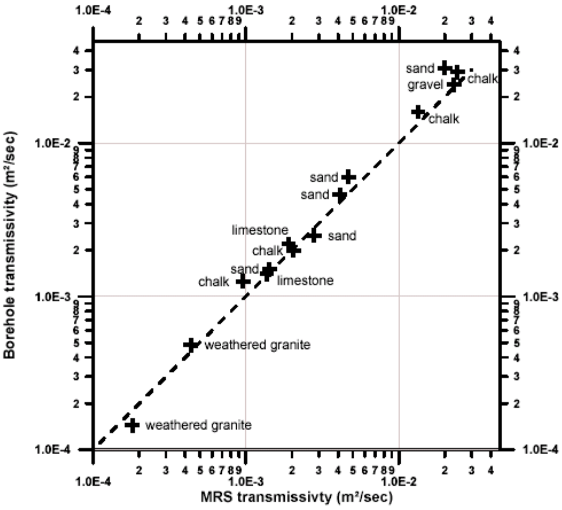


Figure 7. Correlation between the transmissivity given by MRS and that given by pumping tests (BRGM & IRD)

CONDITIONS OF APPLICABILITY

The experiments and surveys carried out up to now in various geological backgrounds permit to identify the conditions where the Magnetic Resonance Sounding method has the best chance of success:

- The water layer to investigate has to be located in the first *100 to 150m*. This depth can be decreased if the ground is conductive.

- There should be *no magnetic material* around or within the aquifer layer, since in such a case the Earth magnetic field is usually non homogeneous which prevents the hydrogen protons to have the same excitation frequency

- The *electromagnetic noise* should be as low as possible: the amplitudes of the MR signals are very low (tens to hundreds of nV in ten to twenty thousand square meters loop) and power lines, pumps, fences, pipes and magnetic storms sometimes create difficult situations not allowing to get good readings. Using figure-of-eight loops permit to improve the signal to noise ratio but decreases the depth of investigation.

- The aquifer should be close to *1D conditions* such as alluviums or porous sediments or volumic hard rock alteration. In case of fractures or faults, the difficulty may come from the dilution of the signal within the field generated by the large loop, also the localization of the fault within the loop. In such case of 2D or 3D water bearing structures, the combined use of other geophysical methods with MRS is particularly recommended

- In case of hydrogeological investigation *in saline contexts*, it is necessary to point out that the MRS technique, which involves hydrogen protons, does not have the capability to distinguish between salted and fresh water. However, TDEM or DC resistivity measurements clearly see the contact between both types of water, and the combined use of MRS, TDEM and / or DC resistivity permits to completely identify the fresh and the salted parts of the aquifer layer.

CONCLUSIONS

Both theoretical and experimental developments show interesting opportunities for the Magnetic Resonance Sounding method in groundwater investigations. The ability of directly detecting the presence of water gives the possibility to quantify the resource both in terms of porosity as well as permeability before deciding if a borehole has to be drilled or not, for optimising the survey costs.

The integration of this technique with the conventional indirect methods has to be examined on a case to case basis according to the capabilities of each one of the methods.

More developments are necessary to adapt the methodology of MRS in environments such as noisy areas or 2D aquifers.

REFERENCES

Legchenko, A., Shushakov, O., Perrin, J., Portselan, A., 1995, Noninvasive NMR study of subsurface aquifers in France, SEG Houston Conference abstract

Legchenko, A., Baltassat, J.M., Martin, C., Robain, H., Vouillamoz, J.M., 2002, Magnetic resonance sounding applied to catchment study, EEGS Meeting, Aveiro, 41-44

Roy, J., Lubczynski, M.W., 2000, The MRS technique for groundwater resources evaluation – test results from selected sites in Southern Africa, IAH-2000 Proceedings, Cape Town

Semenov, A.G., 1987, NMR Hydroscope for water prospecting, Proceedings of the seminar on Geotomography: Indian Geophysical Union, Hyderabad, 66-67

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

Valla, P., Yaramanci, U., 2002, Surface Nuclear Magnetic Resonance : What is possible ?, Special issue of the Journal of Applied Geophysics, volume 50, 230 pages

Varian, R.H., 1962, Ground liquid prospecting method and apparatus, US Patent, 3019383

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

Yulin, P., Le, W., 1999, Detecting of karst water in China with NMR method, CT theory and applicatios, vol 8 n°3

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

F.Vermeersch, B. Texier, J.Bernard

IRIS Instruments, 1 avenue Buffon, BP 6007, 45060 Orléans Cedex 2, France

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.

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.

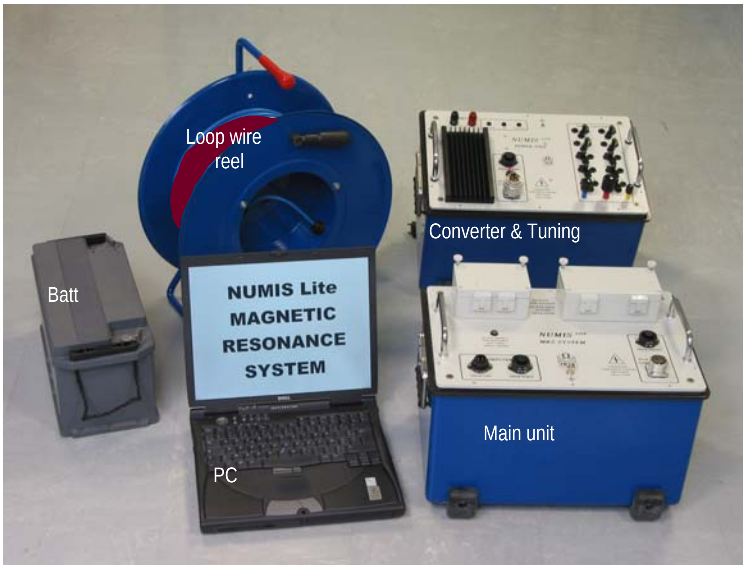


Fig 1: The NUMIS Lite Magnetic Resonance Sounding system for water investigations down to approximately 50m depth.

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.

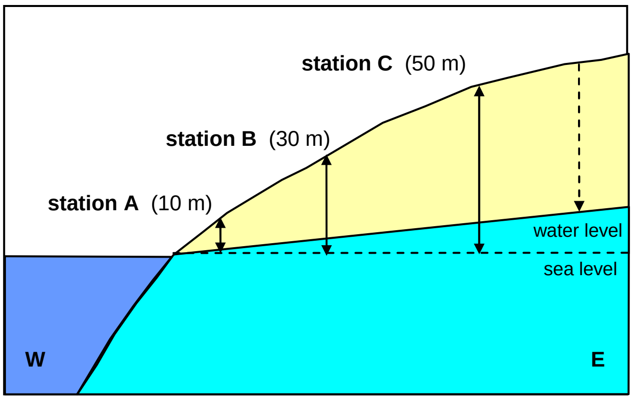


Fig 2 : Sketch (on top) showing the locations of the MRS soundings (stations A, B, C), and two pictures of the Pyla dune (top right) and of the location of station B with NUMIS Lite equipment placed on a caterpillar wheel trolley for an easier transportation on the sand (right).

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.

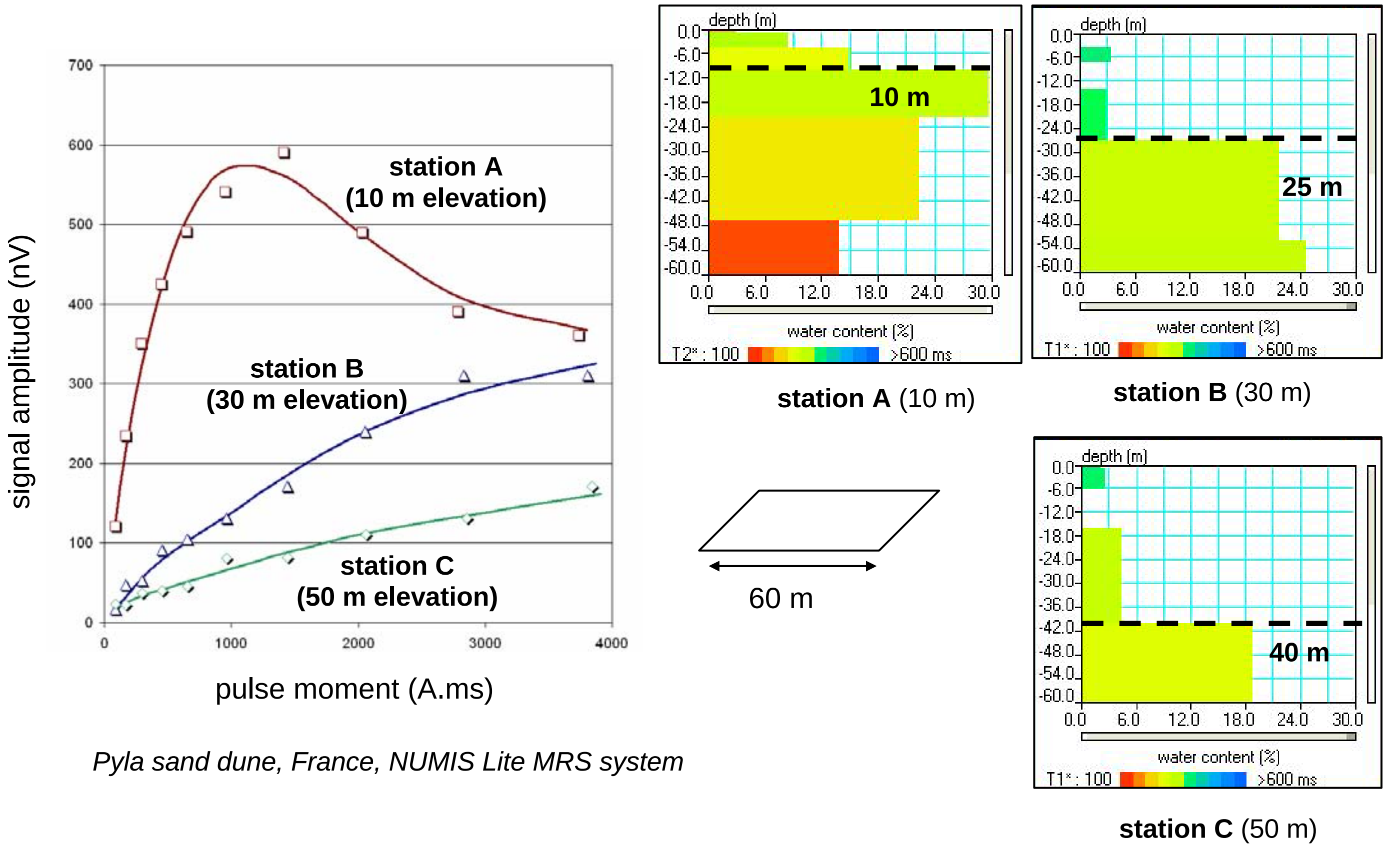
CONCLUSION

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.

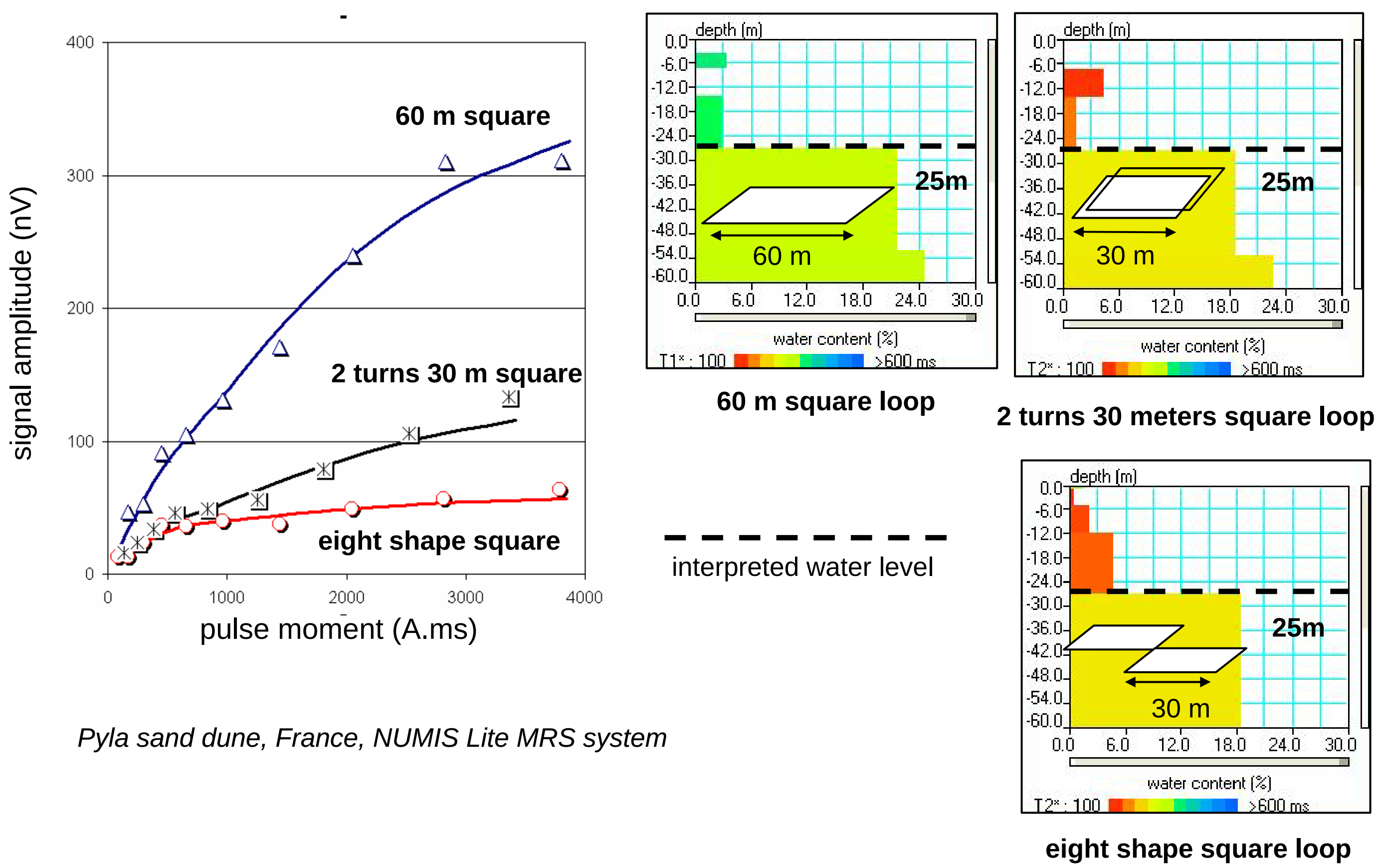
REFERENCE: Nuclear magnetic resonance as a geophysical tool for hydrogeologists, A. Legchenko, JM. Baltassat, A. Beauce, J. Bernard, Journal of Applied Geophysicists 50 (2002) 21-46

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



Pyla sand dune, France, NUMIS Lite MRS system

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



Pyla sand dune, France, NUMIS Lite MRS system

PAPER PRESENTED AT SEG MEETING, DENVER, COLORADO, October 2004

Combination of electrical resistivity and magnetic resonance sounding data for mapping an aquifer layer in Mauritania

Jean Bernard, IRIS Instruments, Mohamed Lemine, Phy, Bassirou Diagana, Centre National des Ressources en eau de Mauritanie, and Marc Ricolvi, Antea*

Summary

Within the framework of a groundwater survey for camel breeding purposes, electrical resistivity soundings have been carried out for delineating the depth and the lateral extension of an aquifer layer in the Dhar Nema area located in the South-East part of Mauritania. The geology basically consists in sand and sandstones, with clay occurrences. In the middle part of the aquifer, the DC resistivity soundings could point out the presence of water. However, in the edge parts, they could not clearly make the difference between dry rocks and fresh water aquifer layers.

On the contrary, the magnetic resonance soundings could identify the presence of water at depths of 60 to more than 100m, and gave estimations of the values of the porosity and of the permeability. The low EM noise levels and the significant quantity of water existing into the ground explain the good quality of the data. As a whole, more than 60 MRS soundings have been carried out in the area of approximately 150 x 100 km, and permitted to delineate the limits of the aquifer layer.

The first drill-hole confirms the depths determined with the magnetic resonance soundings. A campaign of new drill-holes with pumping tests is planed to ascertain the groundwater resources of this area.

Introduction

The Dhar Nema area is a 35 000 km² desert plateau located in the South East of Mauritania, slightly tilting towards the East. Its West limit close to the city of Néma consists in a 150m height cliff. The geology includes four differentiated layers, from bottom to top:

- Palaeozoic fractured shales with dolerites, which have a poor groundwater potential (Hodh series).
- Mesozoic impermeable clay formations (Néma series)
- Mesozoic continental sandstones which form the main continuous aquifer layer (Dhar series)
- Cenozoic sand dunes covering the main part of the area with some occurrences of clay

The contact between the clay and the sandstones is a paleo-topography and includes faults. Thus, the water cannot be found everywhere, but only at places where the sandstones are located under the piezometric level. In particular, the sandstones of the West part of the area are dry due to the East dipping topography (Figure 1).

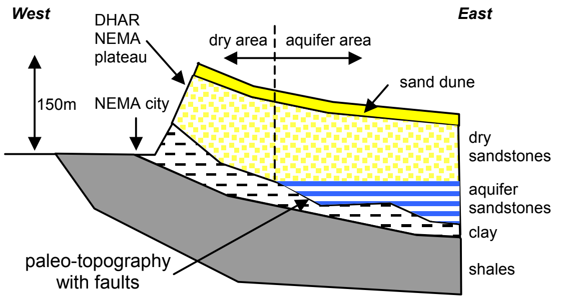


Figure 1: Simplified geological cross section the Dhar Néma area (South-East of Mauritania)

The average rain fall is of the order of 200mm per year and no surface water is available; the fractured shales can only provide a few m^3/h yields during short periods. This is the reason why the sandstones represent the main resource for developing the water supply for cattle breeding (camels, sheeps, …) and for domestic needs of small towns. The delineation of the aquifer part of these sandstones has been the goal of a geophysical survey with electrical resistivity and magnetic resonance soundings, planned to fill the gap between satellite image analysis and drill hole campaigns.

Electrical resistivity soundings

A set of 250 Schlumberger resistivity soundings has been carried out with an AB transmitting line of 1000 to 2000m, and with one sounding every 0.5 - 1 km. On the whole studied area, these soundings permitted to clearly identify the depth of the shales (bottom of the sandstones), thanks to the low resistivity of this basement (Figure 2).

From the inversion results, the following approximate values of resistivity can be given to the various layers:

- clay and shales: 20 to 500 ohm.m
- wet sandstones: 300 to 4 000 ohm.m
- dry sands and sandstones: 3 000 to 10 000 ohm.m
- quartzites: 20 000 ohm.m

In the central part of the aquifer layer (50% of the data), the Schlumberger soundings also permitted to check if the sandstones had water or not. However, in the West part of the aquifer, it has been much more difficult to determine the presence or the lack of water, the difference between curves becoming insignificant.

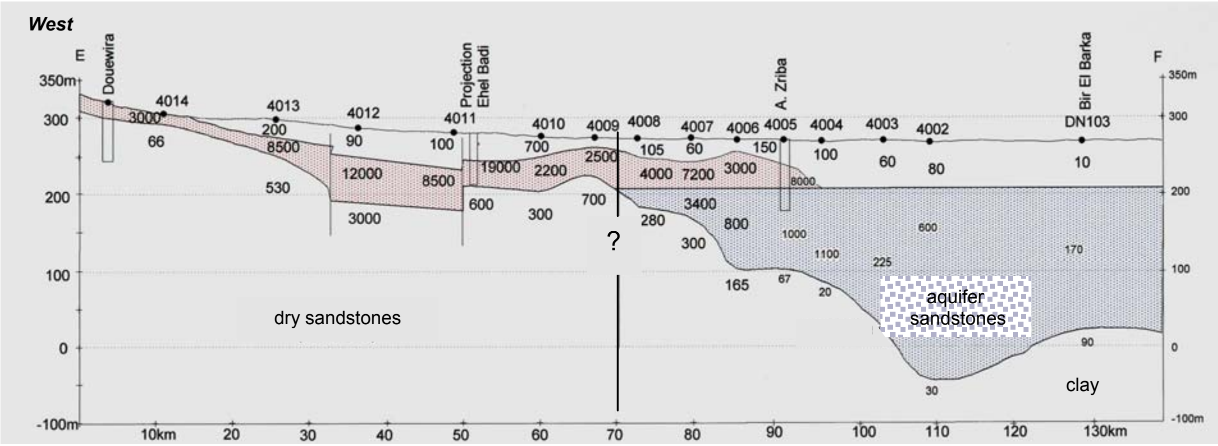


Figure 2: Interpreted resistivity section from Schlumberger soundings, in the Dhar Nema area

As a matter of fact, the water being only little salty (more than 50% of the samples taken in existing wells have a conductivity lower than 200 microS/cm, corresponding to a resistivity greater than 50 ohm.m, see Figure 3), the apparent resistivity sounding curve is not so much influenced by the presence of water when the potential aquifer layer is not very thick, as shown in Figure 4.

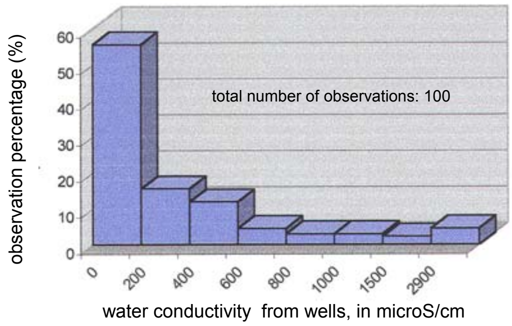


Figure 3: Statistical data of water conductivity from existing wells, Dhar Néma area

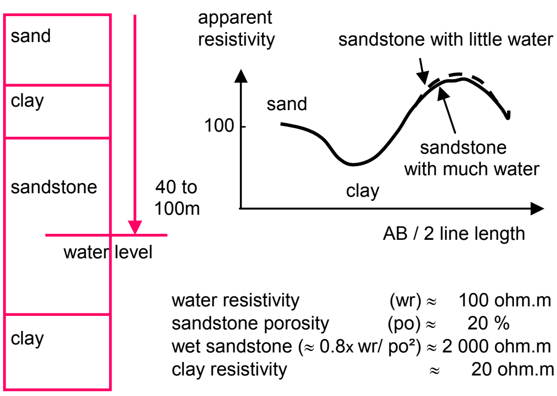


Figure 4: Schlumberger typical sounding curves close to the dry / wet wedge of the Dhar Nema plateau

To better delineate the aquifer area in its West part, the magnetic resonance sounding method (MRS) has been used, based on a direct detection principle

Magnetic resonance sounding principles

Initiated by the ICKC Institute in Russia (Semenov, 1987), the methodological developments of the magnetic resonance sounding method have been continued at BRGM in France (Letgchenko *et al.*, 1995; Valla, 2002), Berlin Technical University in Germany (Yaramanci *et al.*, 1999) and ITC in The Netherlands (Lubczynski, Roy, 2003), among other groups.

The methods consists in exciting the H protons of the water molecules with a magnetic field at a specific frequency (the Larmor frequency, depending on the amplitude of the Earth field) and in measuring the magnetic field produced in return by these protons.

The same loop is used for transmitting the excitation pulse and for analysing the relaxation signal (Figure 5).

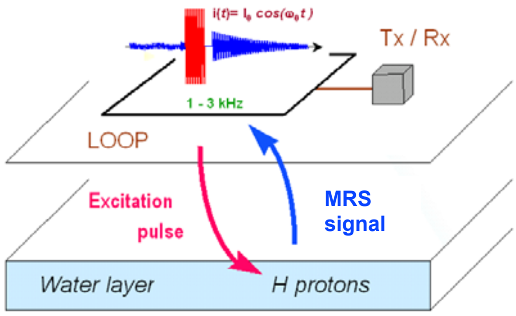


Figure 5: Principle of the magnetic resonance method

The initial amplitude E_0 of the relaxation (Figure 6) measured just after the excitation current has been switched off is directly proportional to the number of protons which have been reacting, namely the water content (porosity).

The time constant (T2*) of the relaxation curve is linked to the mean pore size of the material, fine grain sediments giving short decays (a few tens ms) while coarser grain sediments lead to longer decays (a few hundreds ms). The time constant is thus related to the permeability of the layer. By a double excitation pulse technique, it is possible to determine the T1 time constant known as the longitudinal time constant which permits to make a quantitative estimate of the permeability of the aquifer. A proportionality coefficient can be used to calibrate such a relation, after the comparison with the results of pumping tests (Bernard, 2003).

The intensity of the excitation pulse (its moment I.Δt, product of the intensity of the current by the pulse duration) controls the depth of investigation, small pulses for shallow, high pulses for deeper. The size of the loop used on the surface is controlling the maximum depth reachable.

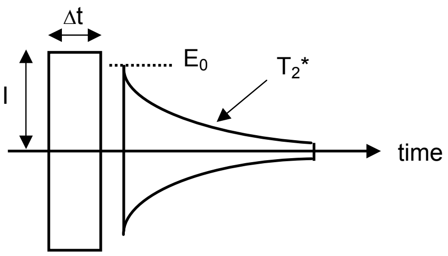


Figure 6. Envelops of the excitation pulse and of the magnetic resonance relaxation signal: I is the intensity of the current, Δt its duration, E_0 the initial amplitude of the signal, T2* its time constant

This property of the pulse moment makes it possible to sound the ground at a given position of the transmitting / receiving loop laid on the surface of the ground. A sounding curve represents the variations ot the signal initial amplitude versus the pulse moment, which gives, after inversion, the porosity versus the depth.

The determination of the porosity is submitted to equivalence laws, the invariant parameter being the product of the porosity by the thickness, that is to say the total quantity of water located in a given layer. Figure 7 gives examples of MRS sounding curves for various types of aquifer layers.

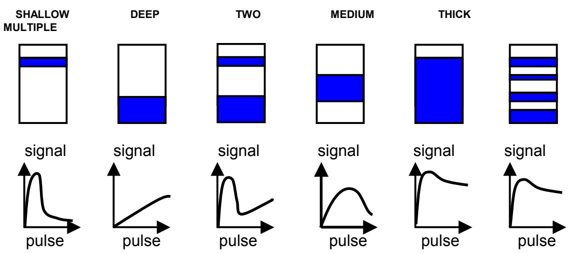


Figure 7: Typical magnetic resonance responses of aquifer layers, for various types of thicknesses and depths.

Magnetic resonance sounding data

This direct water detection MRS method has been used to delineate the sandstone aquifer in the Dhar Néma area (Figure 8).

Figure 8: Field set up of the NUMIS Plus MRS equipment in Mauritania.

A total of 67 soundings have been carried out, using a 100 x 100m loop (Figure 9). The low EM noise observed in this desert zone permitted to obtain good quality data, with signal amplitudes of up to 300 nanovolts, intensities of current of up to 300 A, and pulse duration of 40 ms. The Larmor frequency is of the order of 1 450 Hz.

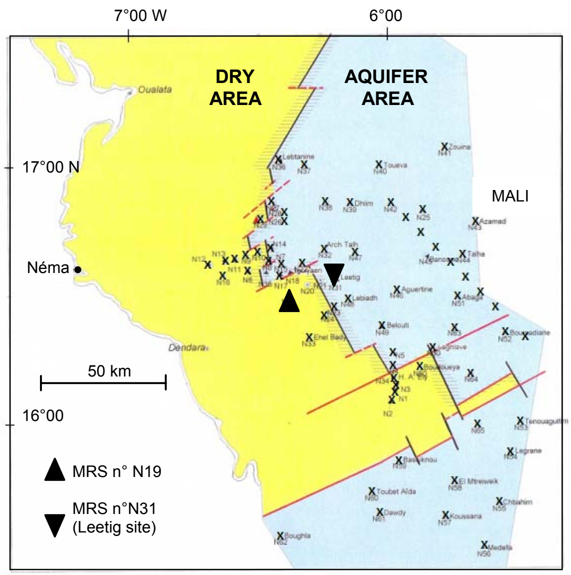
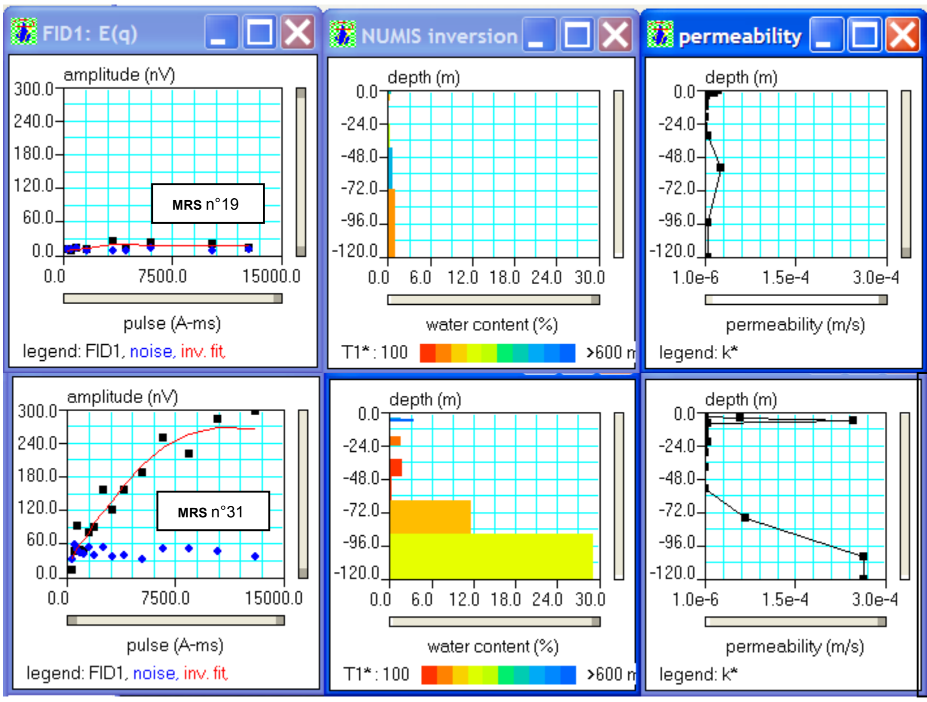


Figure 9: Location map of the 67 MRS soundings of the Dhar Néma area

The raw data and the inversion results of two representative soundings are given in Figure 10:
- MRS sounding n° N19, does not show any significant response (amplitude after stacking lower than 30 nV), which suggests that there is no water at this place.
- MRS sounding n° N31, where a 300 nV signal amplitude has been measured, which suggests that this site is located inside the aquifer area. Indeed, a borehole carried out at this location found water at 75m depth with a test airlift yield of 14 m^3/h, confirms the inversion results of the MRS sounding.



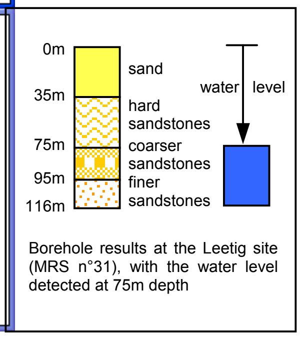


Figure 10: MRS sounding data and interpretation: on top, MRS n°19, located in the dry area; at bottom, MRS n°31, located in the aquifer area.
From left to right: sounding data, interpreted porosity (water content), interpreted permeability (before any calibration).

A statistical analysis (Figure 11) shows that the median value of the interpreted porosity is 20%, which may appear rather high for a fractured sandstone; the median value of the interpreted permeability (before calibration) is of the order of 10^{-4} m/s, a priori compatible with the type of yield obtained at the MRS n°31 Leetig borehole.

Conclusions

The electrical resistivity soundings permitted to identify the presence of the aquifer in its thicker central part. However they could not determine its western limit.

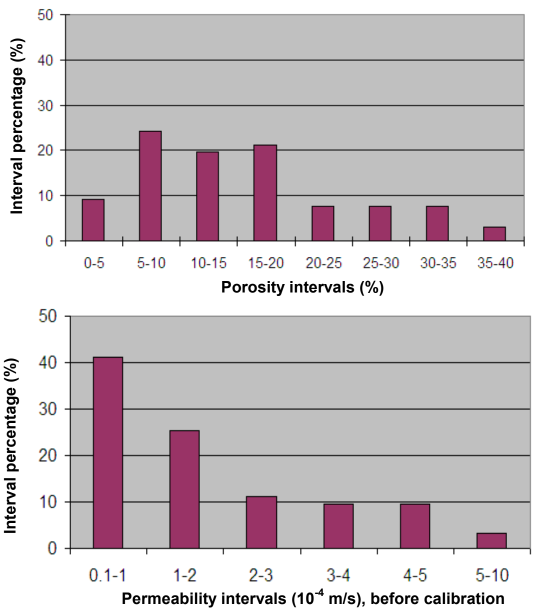


Figure 11: Statistical analysis of the interpreted MRS data

The magnetic resonance soundings shown a clear response from the water, including on the edge of the aquifer part of the sandstones. A first drill hole confirmed the depth found by the MRS sounding (75m). More drill holes will be carried out in a second phase of this project, which will permit, through pumping tests, to calibrate the permeability values interpreted from the MRS soundings

References

Bernard, J, Legchenko, A., 2003, Groundwater exploration with the magnetic resonance sounding method, ASEG Conference abstract, Adelaide

Legchenko, A., Baltassat, J.M., Martin, C., Robain, H., Vouillamoz, J.M., 2002, Magnetic resonance sounding applied to catchment study, EEGS, Aveiro

Lubczynski, M., Roy, J., 2003, Hydrogeological interpretation and potential of the new magnetic resonance sounding (MRS) method, Journal of Hydrology, 283

Semenov, A.G., 1987, NMR Hydroscope for water prospecting, Proceedings of the seminar on Geotomography: Indian Geophysical Union, Hyderabad

Valla, P., Yaramanci, U., 2002, Surface Nuclear Magnetic Resonance : What is possible ?, Special issue of the Journal of Applied Geophysics, volume 50

Yaramanci, U., Lange, G., Knodel, K., 1999, Surface NMR within a geophysical study of an aquifer at Haldensleben (Germany), Geophysical Prospecting, 47

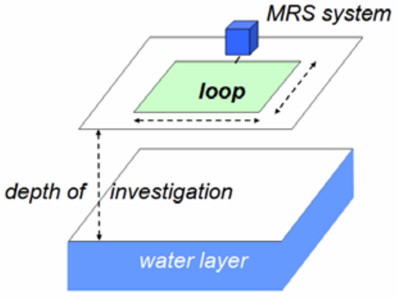
INSTRUMENT AND FIELD WORK TO MEASURE A MAGNETIC RESONANCE SOUNDING WITH NUMIS SYSTEMS

Jean Bernard

IRIS Instruments, 1, avenue Buffon, BP 6007, 45060 Orléans cedex 02, France, tel : + 33 2 38 63 81 00, email : iris@iris-instruments.com

PRESENTATION OF THE NUMIS MRS EQUIPMENT RANGE

The NUMIS equipment has been designed in the 1995's within the framework of a cooperation between the ICKC Institute in Russia, and BRGM in France. A few years after, a modular version of this initial system, the NUMIS Plus equipment, has been developed on the one hand for facilitating the transportation and on the other hand for increasing the depth of penetration from 100 to 150m. In 2003, a reduced power version has been designed, the NUMIS Lite, for groundwater investigations down to 50m depth (Fig 1).



MRS system	*version*	*loop size*	*depth*
NUMIS Lite	standard	60 x 60m	50m
NUMIS Plus	1 converter	100 x 100m	100m
NUMIS Plus	2 converters	150 x 150m	150m

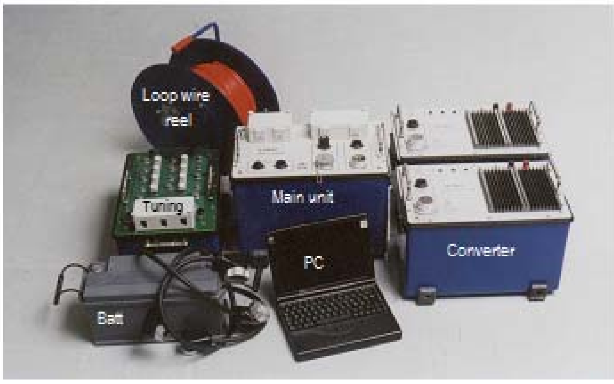


Fig 1: NUMIS Plus (left) and NUMIS Lite (right) MRS systems

NUMIS Plus (NUMIS Lite) system uses DC/DC converters to increase the voltage of the batteries up to 400V (100V), and to generate pulses up to 4000V (1000V) at the Larmor excitation frequency (1 to 3 kHz). Capacitor units are used to tune the inductance of the loop at the Larmor frequency, which optimizes the intensity of the current generated. Both systems are controlled by a PC computer from which the operator manages the acquisition process (Fig 2).

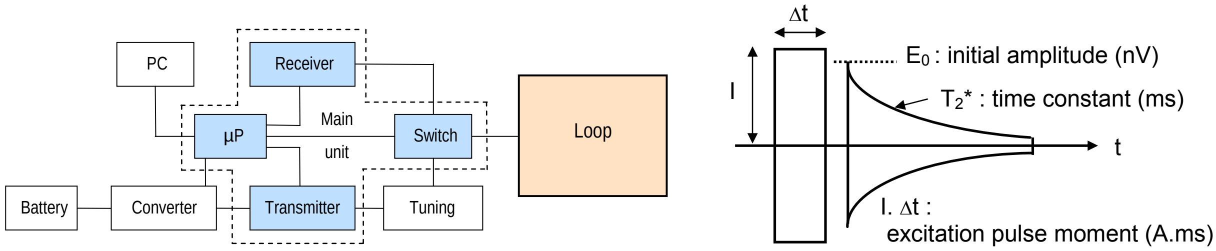


Fig 2: Schematic diagram of NUMIS Plus system and parameters measured during a Magnetic Resonance Sounding

PRESENTATION OF THE DATA ACQUISITION SOFTWARE

The ProDiviner data acquisition software ([1] and [2]) basically consists in three windows:

- a "configuration" window where the operator introduces the parameters necessary to carry out the sounding: type and dimension of the loop, value of the Larmor frequency (or that of the Earth magnetic field), number of pulse moments to measure, stacking number, recording time and number of pulses for the T1/T2* determination [3]. The set up of tuning capacitors is also proposed in this window.
- a "system" window for checking the shape of the current waveform during the injection, also the values of the battery and converter voltages, output current, output voltage, gain factor, signal phase.
- a "signal" window where the operator can follow up the sounding during the acquisition itself, with the display of the decaying stacked relaxation curves (amplitudes after first and second pulse, noise), the estimation of the initial amplitude of the relaxation curve, its time constant, its frequency. The sounding curve, the initial amplitude for the pulse moment values already measured, is also displayed during the sounding. Finally, a frequency spectrum is available for analyzing the frequency content of the relaxation curves and of the EM noise.

GENERAL CONDITIONS FOR DETECTING A MAGNETIC RESONANCE SIGNAL

The observation of a Magnetic Resonance response from underground water molecules requires a few conditions on the magnetic and the electromagnetic environment of the measurements:

- the Earth magnetic field must not vary laterally more than +/- 20 nT on the surface of the loop and in its vicinity. This corresponds to a variation of +/- 1 Hz on the Larmor frequency.
- the magnetic susceptibility of the rocks should be low enough not to perturb the relaxation of the H protons: this means that the MRS soundings are presently quite difficult in volcanic rocks for instance.

- the MRS station must be far enough from power lines, pipes, fences, pumps, … which create EM noises sometimes too large compared to the small amplitude signals to measure, of the order of a few tens nanoVolts in a 10 thousand square meters loop surface.

STACKING PROCESS AND MRS LOOP SELECTION FOR REDUCING THE NOISE

To improve the signal-to-noise ratio, a stacking process is used for reducing the relative influence of the random part of the noise. Two specific notch filtering (large, narrow) are proposed in option, recommended when the local Larmor frequency is close to the harmonics of the power line frequency (50 or 60 Hz).

When the quality of the signal is still poor after the stacking, a few techniques involving the shape of the MRS loop can be used to improve the signal-to-noise ratio:

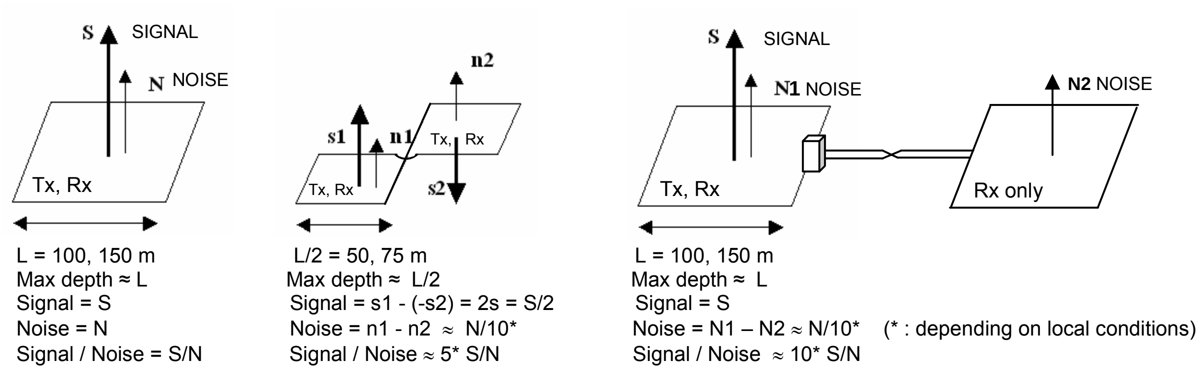


Fig 3: Square loop (left), Eight-Shape loop (middle) and Compensation-Square loop (right) configurations

The eight shape loop (Fig 3, middle part) permits to improve the signal-to-noise ratio 2 to 10 times (depending on local conditions), compared to the standard square loop (left part), but limits the depth of penetration to half of that of the same perimeter square loop enabling the same current for a given output voltage.

The recently experimented square shape using a compensation receiving loop (right part) also improves the signal-to-noise ratio but maintains the same maximum penetration depth as the standard square shape: an electronic switch unit located in series with the main square loop behaves as a short circuit during the transmission of the current, while it connects the opposite voltage coming from the compensation loop during the measurement of the MRS response. In such a way, the noise from the compensation loop cancels a large part of the noise from the main loop, while the MRS signal from the compensation loop is proved to be low enough to be negligible in front of that of the main loop.

Other loop configurations, such as multi-turn loops, can be used when the space available in the field for setting up the loop is not large enough to use the standard square loop. The comparison of the interpretation results of various soundings measured at a same location with various loop geometries usually shows a good general agreement [4].

CRITERIA FOR VALIDATING A MRS SIGNAL

The main criteria for confirming the fact that the stacked signal curve versus time displayed during the acquisition corresponds effectively to a MRS signal are:

- the stacked “signal” curve must be over the stacked “noise” curve.
- the first part of the stacked “signal” curve must be greater than its second part, because of the relaxation process which corresponds to a decaying trend.
- The main frequency computed by the processing software within the received stacked “signal” must not be farther from 1 Hz of the frequency of the transmitted excitation current.

When after stacking the operator cannot detect any significant Magnetic Resonance signal, he has to consider one of the following hypothesizes:

- the excitation frequency is not close enough to the good one, and has to be modified because of some Earth magnetic field gradient.
- the EM noise is too high in comparison to the amplitude of the MRS signal, for the number of stacks used.
- there is no water within the range of depths reached by the sounding
- the presence of magnetic rocks prevent to get a measurable Magnetic Resonance signal

The validation phase of a proper MRS signal observed at a given location is the most important one which the operator has to ensure by himself: the remaining part of the acquisition process can be automatically handled by the equipment under the control of the PC computer.

TRENDS IN THE EVOLUTION OF THE MRS INSTRUMENTATION

The improvement of the MRS instrumentation will be contemplated through the development of multi-channel acquisition receivers, on the one hand for carrying out simultaneous readings in 2D imaging techniques, and on the other hand for eliminating the environmental noise more efficiently by correlation processing techniques and decreasing the measuring time.

REFERENCES

[1] Vermeersch F., 2000, NUMIS Plus equipment operating manual, *IRIS Instruments document*.

[2] Bernard J., 2004, MRS: Step-by-step operation of NUMIS systems, *IRIS Instruments document*.

[3] Bernard J., Legchenko A., Groundwater, exploration with the Magnetic Resonance Sounding method, *Proc. of the 16th ASEG Geophysical Conference and Exhibition,* Adelaide, February 2003, and Invited Paper at the *65th EAGE Conference & Exhibition* , Stavanger, June 2003.

[4] Vermeersch F., Texier B., Bernard J., Comparison of various geometries in Magnetic Resonance soundings on the Pyla sand dune (France), *Proc. of the 2nd International Workshop on the MRS Method*, Orleans, 19 – 21 November 2003, (118 - 120).

APPLICATION USE OF THE PROTON MAGNETIC RESONANCE METHOD (MRS) FOR GROUNDWATER INVESTIGATIONS IN VARIOUS GEOLOGICAL ENVIRONMENTS

J. BERNARD, IRIS Instruments, France

AGU San Francisco, December 2006,
Near-Surface Geophysics Session
NS 41A -1135

The Proton Nuclear Magnetic Resonance method, also called the Magnetic Resonance Sounding method (MRS), after having been a research tool during a long maturation period, is in the way of being more and more applied in the groundwater surveys for complementing the traditional geophysical methods. Its capacity to give quantitative information for characterising the water layers (depth and thickness, porosity, permeability after calibration) give it a special place in the range of geophysical tool for hydrogeologists.

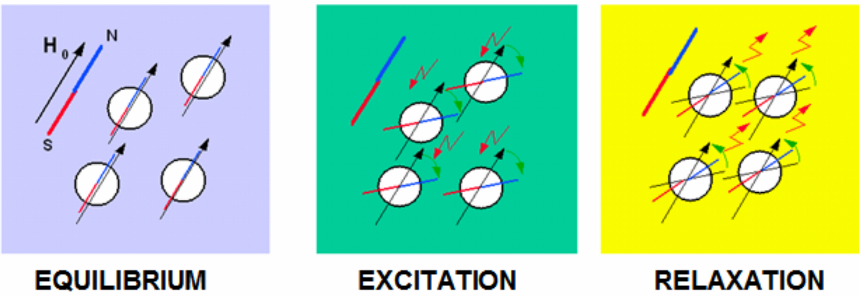
Due to the low levels of the signals which are measured in Magnetic Resonance field surveys, to make the method efficient, one must take special care of the accuracy of the Larmor frequency used in relation with the local Earth Magnetic field and of the filtering of the natural and industrial electromagnetic noises. The shape of the wire loop used to energise the ground and to receive the relaxation signals (square loop, eight-square loop, compensated square loop, …) from which the initial amplitudes and the time constants are determined is also a matter of importance as it shares the control of the depth of penetration together with the transmitter power and it directly acts on the way the local noise is primarily filtered. This study will report on the advantages and the limitations of these various shape loops with respect to these two parameters, also the basic magnetic properties of the materials which permit a measurable expression of the relaxation effects.

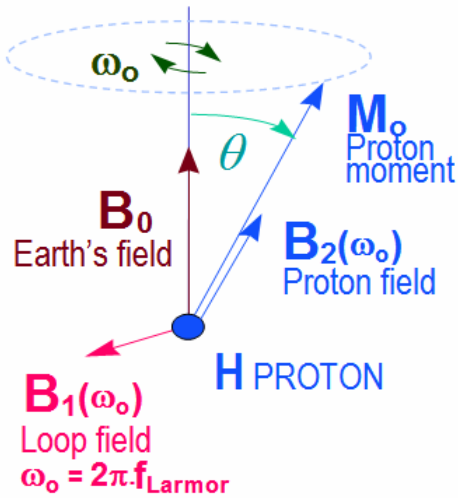
Besides, to optimise the use of a new geophysical method in groundwater surveys, it is important to have a clear view of its real output within the various backgrounds which can be met in such surveys. Field results coming from different types of aquifer, depths, geological conditions, and countries in the Western World, Asia and Africa show the data quality and the field efficiency which can be expected with the present state of the art of the technology used. Also, the correlation with hydrogeological borehole parameters, such as the yield or the transmissivity, when available, opens the way for characterizing the geological materials from surface geophysical readings.

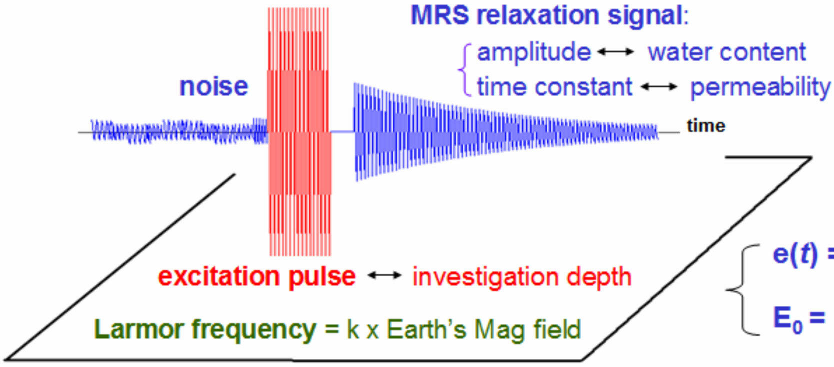
info@iris-instruments.com

MRS PRINCIPLES

MRS: direct detection of water, property of H protons of water molecules (H_2O)



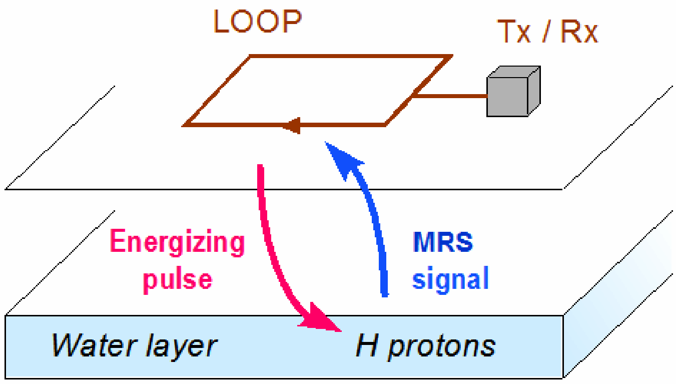


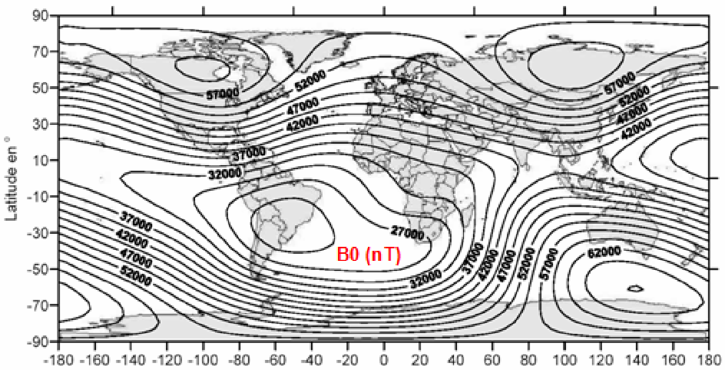


$e(t) = E_0 \exp(-t / T_2^*) \sin(\omega_0 t + \phi_0)$

E_0 = initial amplitude, T_2^* = time constant

MRS FIELD SET-UP

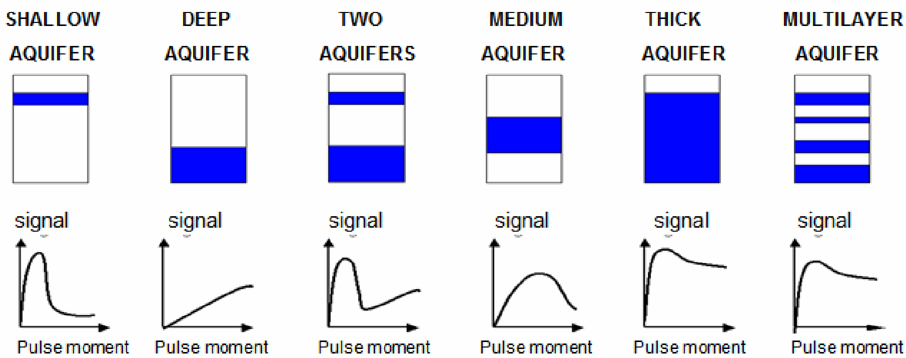




EARTH'S MAGNETIC FIELD: B_0 (nT)

EXCITATION FREQUENCY: F0 (Hz)

F_0 (Hz) = 0.04258 B_0 (nT), from 1 to 3 kHz



F_0 = Larmor frequency = $\omega_0 / 2\pi$

ω_0 = precession pulsation (resonance) = $\gamma . B_0$

γ = gyromagnetic ratio of the proton

IRIS instruments

info@iris-instruments.com

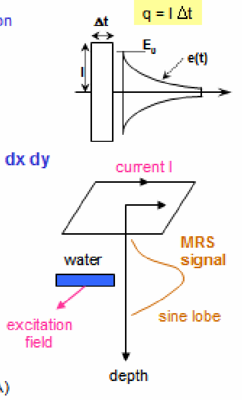
DEPTH SOUNDING

$e(t) = E_0 \exp(-t / T_2^*) \sin(\omega_0 t + \phi_0)$ relaxation equation

$E_0(q) = \int_z w(z) \times K(q,z)\, dz$ initial amplitude

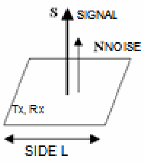
matrix (kernel)

$K(q,z) = \int_x \int_y \omega_0 M_0 h_{1\perp}(x,y,z) \sin(0.5\, \gamma\, h_{1\perp}(x,y,z)\, q)\, dx\, dy$



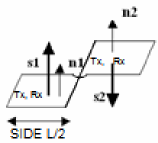
with
- $\omega_0 = 2\pi f$ (Larmor)
- $w(z)$ = water content
- $q = I\, \Delta t$ = pulse moment
- M_0 = magnetic moment of water molecules
- γ = gyromagnetic ratio of H proton
- $h_{1\perp}(x,y,z)$ = component of the excitation field perpendicular to the Earth's field, for a unit current (1A)

NOISE REDUCTION



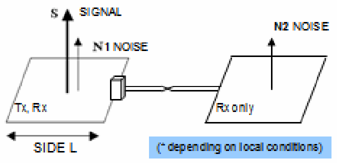
SQUARE LOOP

L = 100, 150m
Max depth ≈ L
Signal = S
Noise = N
Signal / Noise ≈ S/N



8-SQUARE LOOP

L /2 = 50, 75m
Max depth ≈ L/2
Signal = s1 - (-s2) = 2s = S/2
Noise = n1 - n2 ≈ N/10*
Signal / Noise ≈ 5 x S/N



(* depending on local conditions)

COMPENSATED 8-SQUARE LOOP

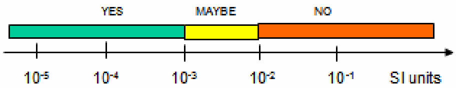
L /2 = 100, 150m
Max depth ≈ L
Signal = S
Noise = N1 - N2 ≈ N/10*
Signal / Noise ≈ 10 x S/N

CONDITIONS OF APPLICATION OF MRS

STABLE EARTH MAGNETIC FIELD (+/- 20 nT)

LOW MAGNETIC SUSCEPTIBILITY

VALUES OF THE MAGNETIC SUSCEPTIBILITY REQUIRED FOR MRS MEASUREMENTS:



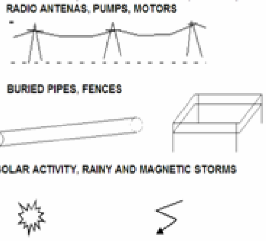
MRS MAY BE DIFFICULT TO APPLY IN VOLCANIC ROCKS

LOW ELECTROMAGNETIC (EM) NOISE

SOURCES OF EM NOISES →

MRS MAY BE DIFFICULT TO APPLY IN URBANISED AREAS

- ACTIVE CONDUCTORS: POWER LINES, INDUSTRIAL ACTIVITY, HOUSES, RADIO ANTENAS, PUMPS, MOTORS
- PASSIVE CONDUCTORS: BURIED PIPES, FENCES
- NATURAL FIELDS: CYCLIC SOLAR ACTIVITY, RAINY AND MAGNETIC STORMS



MAXIMUM AQUIFER DEPTH LOWER THAN:

- **150m** for NUMIS Plus, 4000V max voltage
- **50m** for NUMIS Lite, 1000V max voltage

MRS TIME CONSTANTS & PERMEABILITY

T_1 : Longitudinal Time Constant

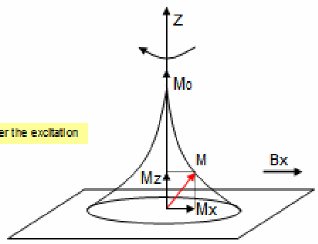
$$\frac{dM_z}{dt} = \underbrace{\gamma[M.B]_z}_{\text{PRECESSION}} + \underbrace{\frac{M_0 - M_z}{T_1}}_{\text{RELAXATION}}$$

T_1 = time necessary for M_z to come back to M_0 after the excitation

T_2 : Transverse Time Constant

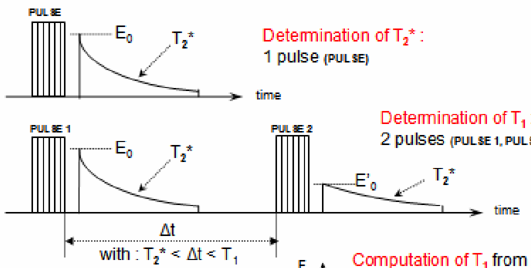
$$\frac{dM_x}{dt} = \underbrace{\gamma[M.B]_x}_{\text{PRECESSION}} - \underbrace{\frac{M_x}{T_2}}_{\text{RELAXATION}}$$

(same equation for My)



(BLOCH's equations, 1947)

T_2 = time necessary for M_x and to M_y to come back to zero after the excitation



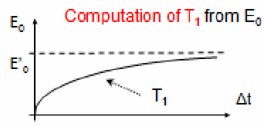
Determination of T_2^* :
1 pulse (PULSE)

Determination of T_1 :
2 pulses (PULSE 1, PULSE 2)

Computation of T_1 from E_0 and E'_0 :

$E'_0 \approx E_0 (1 - e^{-\Delta t / T1})$

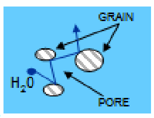
$T_1 \approx -\Delta t / \mathrm{Log}(1 - E'_0 / E_0)$



At the time Δt after the first pulse, the magnetic moment of the H protons must have vanished in the plane perpendicular to the Earth's field (after T_2^*), but it must still be in its way back to M_0 along the Earth's magnetic field direction (before T_1)

small pores (low permeability) → many shocks of H_2O against grains → quick decrease of energy → short time constant

high permeability → few shocks/time → slow decrease → long time const



TIME CONSTANT	FACTORS	CORRELATION WITH PERMEABILITY	NUMBER OF PULSES	
T_2^* (transverse)	mean pore size Δ Susceptibility	approximative	one	1
T_1 (longitudinal)	mean pore size	good K = c*porosity* $(T_1)^2$	two	1.3

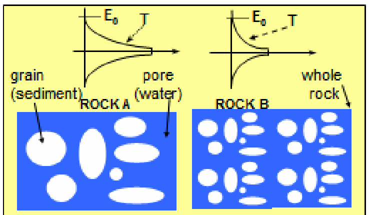
CONCLUSION: T1 better than T2* for determining the permeability, but more acquisition time is required

T_2^* (ms) TIME CONSTANT	MEAN PORE SIZE	PERMEABILITY
1000	(free water) lake, river	HIGH
500	gravel	
200	coarse	MEDIUM
100	medium	
50	fine	LOW
20	clay (Bound water)	

info@iris-instruments.com

MRS & HYDROGEOLOGICAL PARAMETERS

POROSITY:
water volume / rock volume, in %



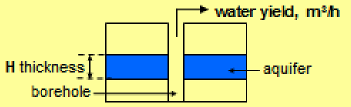
POROSITY A = POROSITY B
PORE SIZE A > PORE SIZE B
PERMEABILITY A > PERMEABILITY B

POROSITY scale
0%: hard rock
1%: fractured rock
10%: sand, alteration
30%: gravel, alluvium

PERMEABILITY:
ability of the water to move into the rock, in m/s
Small grains (small pores) → low permeability
Large grains (large pores) → high permeability

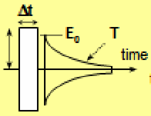
PERMEABILITY scale
10^{-9} m/s: clay
10^{-6} m/s: low
10^{-3} m/s: high
10^{0} m/s: extreme

TRANSMISSIVITY:
permeability x thickness in m²/s

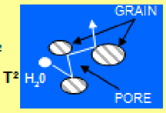


WATER YIELD:
proportional to the transmissivity of the aquifer layer, in m³/h
ex: 10 m³/h (or about 2.8 l/s)

ESTIMATION OF HYDROGEOLOGICAL PARAMETERS FROM MRS DATA



porosity ≈ E_0
permeability ≈ $E_0 \cdot T^2$
transmissivity ≈ $H \cdot E_0 \cdot T^2$

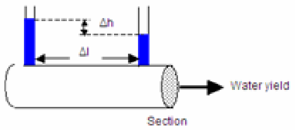


low permeability
→ small pores
→ quick decrease of energy
→ short time constant

PERMEABILITY:

Permeability = water yield / sample section / hydraulic gradient

with hydraulic gradient = Δh / Δl



IN HYDROGEOLOGY:

Yield = factor x Transmissivity x Drawdown
(m³ / s) (1) (m² / s) (m)

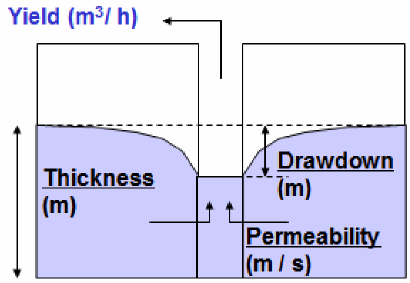
Transmissivity = Permeability x Thickness
(m² / s) (m / s) (m)

IN MAGNETIC RESONANCE:

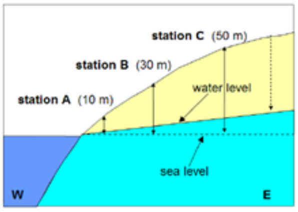
Permeability = coeff. x Porosity x (T1)²

Transmissivity = coeff. x Porosity x Thickness x (T1)²
= coeff. x (Equivalent Water Thickness) x (T1)²

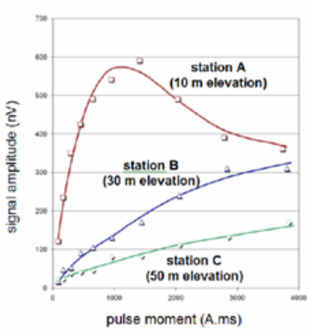
THE PERMEABILITY OF AQUIFERS CAN BE ESTIMATED FROM MRS DATA, AFTER CALIBRATION ON KNOWN BOREHOLES



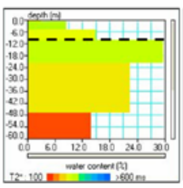
MRS SURVEY IN FRANCE



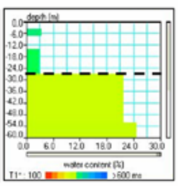
SAND DUNE



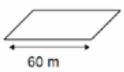
Pyla sand dune, France, NUMIS Lite

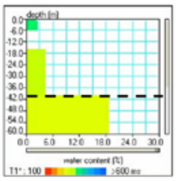


station A (10 m)



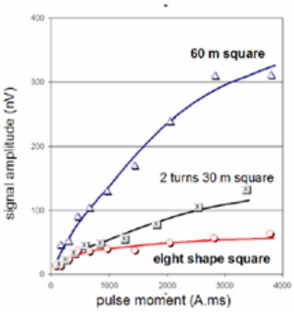
station B (30 m)



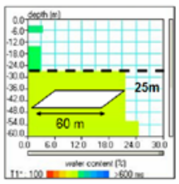


station C (50 m)

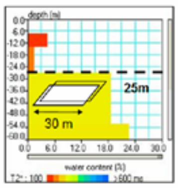
MRS soundings for a 60m side square loop, at various elevations: station A (10m), station B (30m), station C (50m)



Pyla sand dune, France, NUMIS Lite

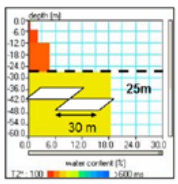


60 m square loop



2 turns 30 meters square loop

interpreted water level



eight shape square loop

MRS soundings with various loop shapes, at the same elevation (station B, 30m)

IRIS instruments
info@iris-instruments.com

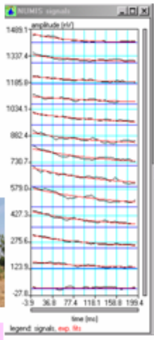
MRS IN BURKINA

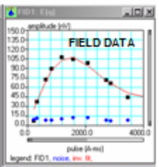
Loop: 125*125m square

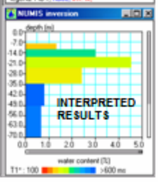
Frequency: 1412 Hz

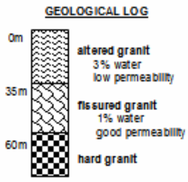
Geology: granit and gneiss

Targeted yield: 5 m³ / h





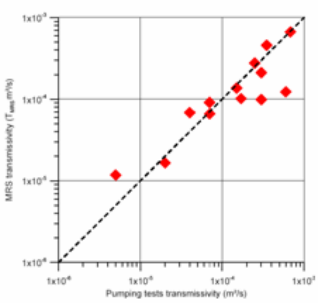




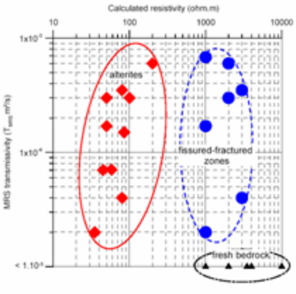
GRANITE

Sanon site, 30 km North West of Ougadougou

IRD and ACF data, with the cooperation of BRGM and IRIS Instruments

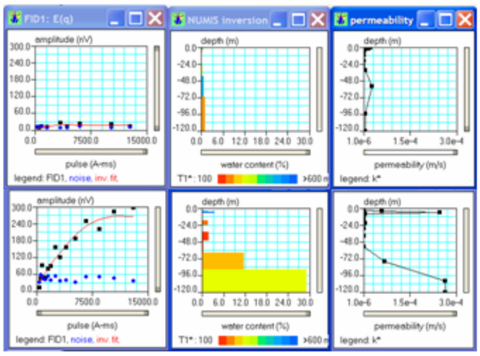


Transmissivity from MRS data compared to transmissivity from pumping tests



Identification of altered, fissured and hard bedrock areas, with MRS and resistivity data

MRS IN MAURITANIA

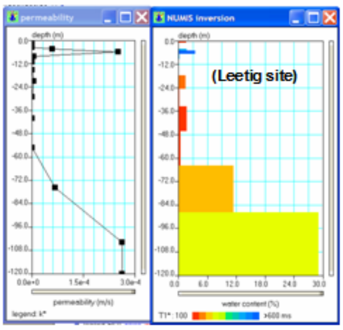


MRS ref N19, located in the dry area

MRS ref N31, located in the aquifer area

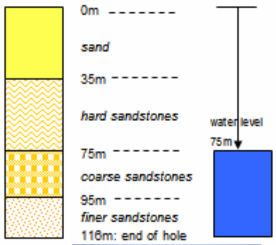
(Leetig site)

SANDSTONES



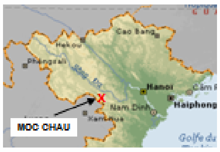
Borehole airlift yield: 14 m³/h

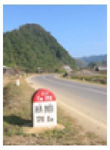
MRS transmissivity: about 0.01 m²/s *(estimated before any calibration)*



MRS SURVEY IN VIETNAM

KARSTIFIED LIMESTONE AREA, km 178, Son La road, MOC CHAU





BOREHOLE: water yield: 4 m3/h

(100m away from MRS site)

0-15m: sand and silts

15-25m: fractured limestone

25-100m: limestone

ALLUVIUMS OF THE RED RIVER, HUNG YEN PROVINCE, VAN LAM DISTRICT, LACLAO VILLAGE

geology: sequences of sand and clay layers

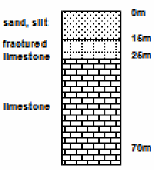
agricultural area, 20 km NE of HANOI

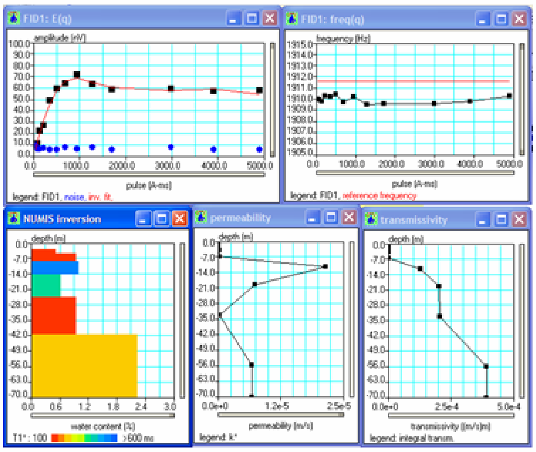
LIMESTONE

EIGHT SQUARE LOOP, 75m side

estimated resistivity 100 ohm.m

128 stacks





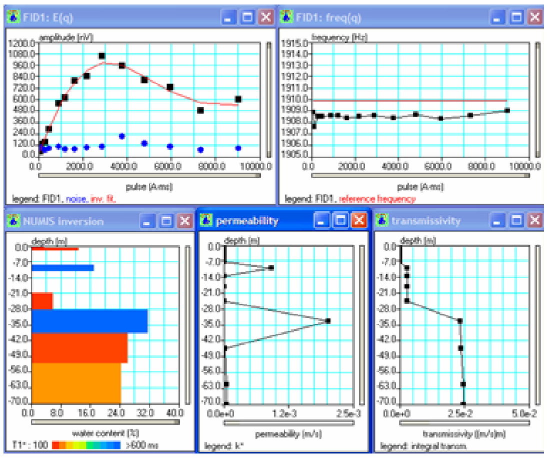
ALLUVIUMS

SQUARE LOOP, 100m side

estimated resistivity 30 ohm.m

128 stacks

water layers positions, according to boreholes a few km around the MRS site



info@iris-instruments.com