TEST OF THE MRS TECHNIQUE IN SOUTHERN AFRICA

Jean Roy and Maciek Lubczynski, ITC, P.O.B. 6, 7500 AA Enschede, The Netherlands

ABSTRACT: ITC, together with ten collaborating agencies from seven countries is involved in a research project on the MRS (magnetic resonance sounding) technology since 1996, when IRIS Instruments introduced the NUMIS instrument. Thanks to regional collaboration, MRS tests were made in Botswana, Namibia and South Africa. The fieldtests were carried-out under a combination of low earth's magnetic field and high ambient noise conditions. The test sites included different aquifers from the point of view of lithology, depth and porosity • thickness product. MRS field results and operational constraints are discussed.

INTRODUCTION

The use of the NMR (Nuclear Magnetic Resonance) technology for non-invasive assessment of groundwater resources from the surface has been patented by Varian (1962). The first field tests were made by Semenov (1987) in Russia using the Hydroscope. This MRS instrument was an improvement over Varian's concept as it included a sounding capability. More recently, IRIS Instruments (1996) in France introduced a new instrument called NUMIS. Currently it is available in two versions (NUMIS^{LITE} and NUMIS^{PLUS}) respectively optimized for shallow and deeper work. A project to evaluate the MRS technology, with respect to its suitability for groundwater resource assessment tasks, was set-up at ITC (International Institute for Geo-Information Science and Earth Observation). For this purpose, a wide range of survey targets and operational conditions were defined and are gradually being tested. The series of MRS tests in Southern Africa is part of this effort and include in addition to shallow alluvium, cases of deep, low porosity aquifers in environments characterized by low ambient earth's field (B) and high natural noise level.

MRS PRACTICAL IMPLEMENTATION

Several descriptions of the MRS technique have been published (Schirov et al., 1991), (Legchenko and Valla, 2002), (Roy and Lubczynski, 2003) etc. Some MRS technique key points are: inherently selective with respect to hydrogen nuclei ($^1H^+$) and therefore to groundwater ($\leq$ 150 m), free water quantification, depth discrimination, non-invasive, within operational limits: integrating a large and operator-controllable subsurface volume. The MRS data are analyzed with respect to initial signal amplitude (E_0) providing free water content (Φ_{MRS}, i.e. without the clay-bound and micropore-bound water, signal decay rate (T_2^*) leading to granulometry (Schirov, 1991) while the frequency and the phase are used mostly for quality control. MRS is executed using the excitation moment Q (product of excitation current and pulse duration) as a sounding parameter. An MRS data set is therefore acquired by measuring the NMR response as a function of a range of Q values (e.g. 60-6000 A-ms). Data inversion takes into account the environmental conditions (i.e. loop size & shape, earth's magnetic field magnitude (B) and dip, geoelectrical layering: layers' resistivity and thickness). Following inversion, the information is available as a function of depth rather than Q: E_0 yields Φ_{MRS} (free water content, n_e estimator below the water table) while the decay information remains as a decay time constant (T_2^*) at this stage but as a function of depth (e.g. Figure 3b and 3c). In absence of magnetic distortion, the decay time parameter (e.g. Figure 3c) is directly related to the average pore size of the layer and is empirically related to the hydraulic conductivity of the media for sandstones and carbonates (Kenyon, 1997). The hydrogeological importance of the Φ_{MRS} & T_2^* information as a function of depth has been investigated by Legchenko et al., 2002, Lubczynski and Roy, 2003, Yaramanci et al., 2002 and others. Limitations and compromises in MRS data inversion (E_0 and T_2^* as a function of depth) were discussed by Legchenko and Shushakov (1998). MRS environmental constraints - A useful MRS data set can only be acquired when the NMR signal from the groundwater's precessing $^1H^+$ is large enough to be extracted in the presence of the ambient noise i.e. high enough signal to noise (S/N) ratio. The magnitude of the NMR signal is controlled by the shape and size of the MRS loop, by the location and quantity of groundwater, i.e. depth, thickness (b), water bearing layers' n_e, and by a series of environmental factors such as the electric conductivity and thickness of the subsurface formations and the earth's magnetic field homogeneity, its magnitude and its dip (Legchenko et al., 1997). Considering the ambient noise, there is presently no simple way of predicting its magnitude at a planned MRS survey location. The two main sources of noise relevant to MRS surveys are: (1) man-made electric installations (power line, electric machinery in general, powered underground cables, pumps, etc.), which generate harmonics up to the $^1H^+$ precession frequency f (over land areas this is normally in the range of .9 to 2.7 kHz) and (2) natural sources, which are dominated by lightning and may thus have a diurnal and seasonal time component associated.

WHY SOUTHERN AFRICA?

Not all sites in the world are equally easy to survey with MRS. In this regard, Southern Africa constitutes an interesting and difficult area for MRS field tests because of the following reasons: (1) many aquifers of interest in Southern Africa (like Karoo aquifers) have a low n_e and are located at deep levels; (2) Southern Africa is characterized by low values of the earth's magnetic field (B < 30,000 nT) in most of Botswana, Namibia and South Africa (see Figure 1). Since the MRS signal is proportional to B^2, this means that a given aquifer (n_e , thickness b & depth) will produce an MRS signal at least 5 times smaller in Cape Town, SA (~ 26,300 nT) than in Melbourne, Australia (~ 60,500 nT) despite the fact that these two cities are roughly at the same latitude; (3) the ambient noise from natural sources is likely to be consi-

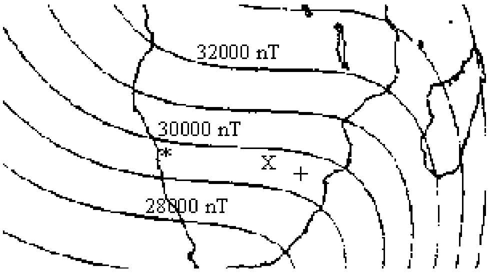

Figure 1. Earth's magnetic field in Southern Africa; US Naval Oceanographic Office (1990).+: Site 1;x: Site 2;*: Site 3 and 4.

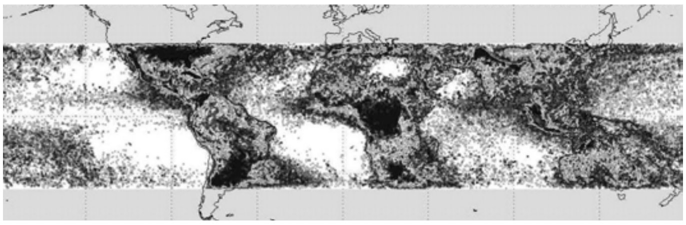

Figure 2. Worldwide 35ºN to 35ºS latitude strip, two-years average lightning frequency as observed by LIS space-borne sensor from 97/12 to 99/12, darker, high lightning frequency areas are observed in particular in SE U.S., SE South America and Central and Southern Africa, NASA (2000)

derably higher than in Europe thus making MRS surveying in Southern Africa, at least during some periods of the year, a challenge with regard to MRS S/N ratio. Natural noise needs to be investigated using empirical measurements before adequate strategies are designed. The main source of natural noise in the MRS signal frequency band is lightning. Figure 2 illustrates the worldwide distribution of lightning where Central and Southern Africa are among the areas with high natural noise levels. Additional studies on the space and time distribution of noise have been published by Chrissan & Fraser-Smith (e.g. 1996) as monthly and hourly averages. It suggests substantial seasonal and diurnal changes of noise especially in high noise areas. This has implications when MRS surveys are executed during the period of the year with the highest noise level (i.e. highest lighting occurrence frequency), in environment like Southern Africa, as MRS surveys must then be done at a particular time of the day (e.g. in our case late night to early morning). MRS surveys are best executed during the lowest noise period of the year; long term monitoring must be used to determine these periods. The specific MRS test sites in Southern Africa were identified following recommendations from the local collaborators and actual field tests of the MRS technique were first carried-out in November-December 1998.

TEST RESULTS

From the first test series, four sites with S/N > 1 from three different areas are reported. Site 1 - Site 1 is located in South Africa, approximately 100 km North of Pretoria. The area was cultivated with arable soil (~ 1 m thickness) overlying a clay rich material of about 5-8 m thickness. Below that sequence up to the depth of 24m a basalt layer is found underlain by sandstone. The lowest 4 m section of basalt is fractured with some cemented joints. Together with the sandstone it creates a confined aquifer with static groundwater table at borehole depth of 16.8m. The MRS data set was acquired with a square loop of dimension L = 115 m. B was ~ 28900 nT. The data set is summarized in a graph showing (see Figure 3a) the initial amplitude, E_0 in nV on the Y-axis, and the excitation moment Q on the X-axis. In Figure 3a, the dots joined by a continuous line are the observed data points, the dotted line is the best fit inverted model as described by Figure 3b, while the stars shows the noise level (measured before or in absence of excitation pulse). A data set summary may also contain the decay rate vs Q response function. At Site 1 (Figure 3b & 3c), one observes: Φ_{MRS} < 1 % over the first 5

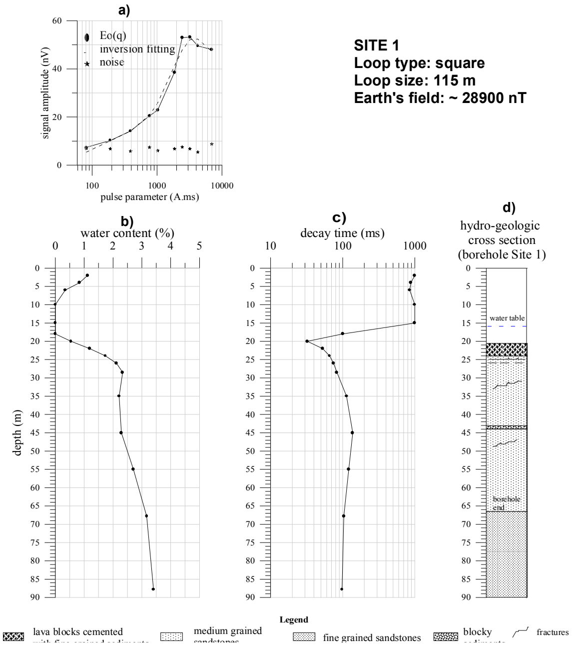

Figure 3. Site 1: a) MRS sounding, b) water content, c) decay time, d) cross-section

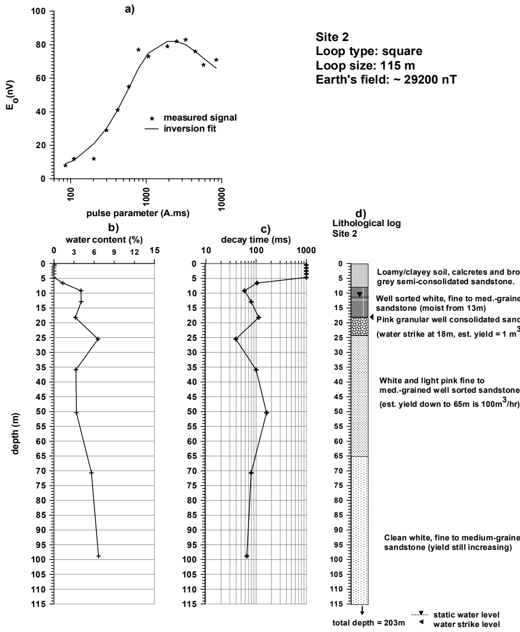

Figure 4. Site 2: a) MRS sounding, b) water content, c) decay time, d) cross-section

m, next a dry interval down to about 20 m, and then a porous interval containing ~ 2 to 3 % water. The absence of MRS water response between 16.8 and 20 m in a non-porous basalt interval serves as example how the MRS detects water. For the 'blocky' zone, the Φ_{MRS} increases from 0-0.5% at 20m depth to 1.5-2% at 24 m depth, so the MRS results suggests that the zone has a lower n_e and pore-size than the sandstone layer below. From 24 m downward, the MRS-derived Φ_{MRS} is 2 to 3.5 % and agrees with the typical porosity of fresh sandstone in the investigated area. Site 2 - Site 2 is located in Botswana ~ 150 km NE of Gaborone. The site is located within the Karoo formation where the main Ntane sandstone aquifer is highly fractured and has highly productive hydrogeological condition - well abstraction > 100 m^3/h. Figure 4a summarises the MRS data set. As compared to Figure 3, the MRS response has a higher peak (>80 nV for Site 2 vs <60 nV for Site 1) and the peak is located at a lower value of the excitation moment ($Q \approx 2500$ vs $Q \approx 5000$ for Site 1). An examination of Figures 4b-4d shows that the groundwater distribution pattern as a function of depth is also different from Figures 3b-3d. There is less water in the first 5 m but the water table is shallower (observed 11.5 m at Site 2 vs 16.8 m at Site 1). Considering the first 70 m, the $\Phi_{MRS} \bullet b$ product where b is the porous media thickness [i.e. the integral of Φ_{MRS} along the depth dimension] for this site is 2.5 m. The hydrogeological borehole data indicates that the aquifer is unconfined with 8 m of Kalahari sand (black organic soil, clay, loamy sand) and underlain by well-sorted and highly fractured Ntane Sandstone. The groundwater table stabilizes at depth of 11.5 m. The hydraulic conductivity and transmissivity are 10.5 m/day and 1000 m^2/day respectively and were obtained through pumping test. Site 3 & Site 4 - Site 3 and Site 4 are both located in the Omaruru Delta in Namibia. The two sites are located at a distance of a few kilometers from each other, within the same alluvium aquifer, but at different earth field value (B difference ~ 1000 nT) however at the scale of the MRS loop, each site has an homogeneous B. A comparison between Site 3 and Site 4 MRS data sets (Figures 5a & 5d) shows that the data from Site 3 is barely above noise level while the data from Site 4 has an MRS signal peak approximately ten times higher than Site 3 peak. Site 3 has only one significant water bearing layer centered around 10 m depth (see Figure 5b), with a $\Phi_{MRS} \bullet b$ product of about 0.2 m, spread over the 5-20 m depth interval, and a very short decay time of 30 ms, which represents a material with very small pores (e.g. clayey fine sand). Site 4, contrary to Site 3, indicates two water-bearing layers (Figure 5e,f). The shallow one, similar to the shallow layer at Site 3, is centered at around 12 m with a 0.1 m $\Phi_{MRS} \bullet b$ product spread over the 8-14 m depth interval. The deeper layer is centered at depth of 37 m and has a $\Phi_{MRS} \bullet b$ product of about 2.2 m spread over the 19 to 75 m interval (i.e. an average Φ_{MRS} of nearly 4% over that interval). The deeper water-bearing layer has a $\Phi_{MRS} \bullet b$ product,

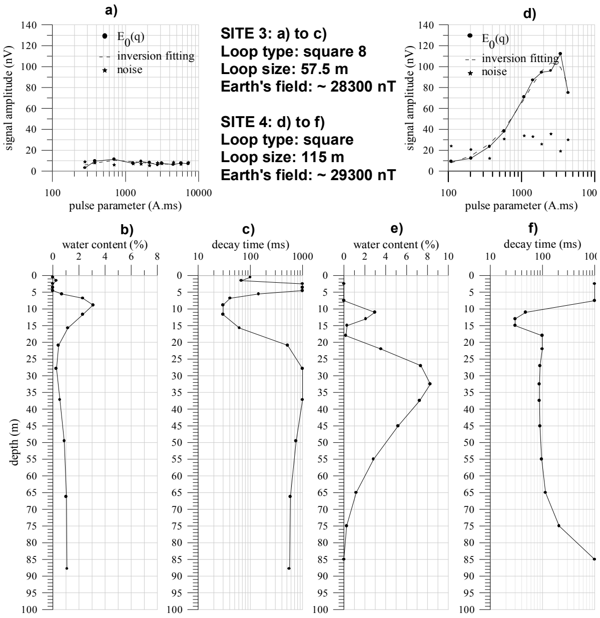

Figure 5: Site 3: a) MRS sounding, b) water content, c) decay time; Site 4: d) MRS sounding, e) water content, f) decay time

which is more than 10 times larger than the $\Phi_{MRS} \bullet b$ product of the shallow water bearing layer observed at Site 3 and at Site 4. Moreover the longer decay time of about 100 ms indicates coarser pore-size (e.g. Schirov's class: fine to medium sands) indicating better hydraulic conductivity. Further tests in Southern Africa – Later, further MRS tests were made in Botswana around Maun using the later version NUMIS^{PLUS} MRS instrument. The targets were shallow, porous paleo-channels ($\Phi_{MRS} \bullet b$ product 2 to 9 m). This resulted in data sets with considerably higher S/N (up to 24:1) than what was previously observed in Botswana. A first analysis of this data set was made. With the availability of new hydrogeological information about several of the sites tested, a more detailed empirical comparison of the MRS results with hydraulic tests and grain size analysis is being worked on.

CONCLUSIONS

1. MRS was field tested in Southern Africa, under conditions of low B, deep water table and low n_e showing limitations (Nov-Dec 1998) in noise threshold/sensitivity and noise rejection
2. Unfavorable natural noise conditions were observed in Southern Africa, which restricted the use of MRS to a certain time of the day. Sites with high enough water content at shallow depth, resulted in inverted parameters compatible with hydrogeological information.
3. Φ_{MRS} used below the water table as an estimator of n_e is compatible so far with data acquired from other sources. T_2^* is directly linked to pore-size and hydraulic conductivity in absence of magnetic distortion; the nature of this relation is still being investigated.
4. With improvements, the MRS technique will constitute a fast and low cost tool suitable for groundwater resources evaluation at sites in Southern Africa and elsewhere. Because of its characteristics, the MRS technique has a potential to play an important role in numerical groundwater resources modeling tasks.

Acknowledgments - We want to acknowledge with thanks the collaboration and support from CSIR, DWA-Botswana, DWA-Namibia, GSD-Botswana, GSN-Namibia, IRIS Instruments-France, ITC, WCS-Botswana and WRC-Botswana. E. Martinez del Pino and L. Kgotlhang have contributed to the figures and to the analysis of the data sets acquired in Southern Africa.

REFERENCES

Chrissan, D.A., & A.C. Fraser-Smith, 1996. Seasonal variations of globally measured ELF/VLF radio noise. Radio Science, 31(5): 1141-1152.

IRIS Instruments 1996, NUMIS data sheet.

Kenyon, W.E. 1997, Petrophysical principles of applications of NMR logging; The Log Analyst, March-April: 21-43.

Legchenko, A., A. Beauce, A. Guillen, P. Valla, & J. Bernard, 1997, Natural variations in the magnetic resonance signal used in PMR groundwater prospecting from the surface; EEGS-ES Journal 2: 173-190.

Legchenko, A.V. & O.A. Shushakov, 1998, Inversion of surface NMR data; Geophysics 63: 75-84.

Legchenko, A. and Valla P., 2002, A review of the basic principles for proton magnetic resonance sounding measurements; Journal of Applied Geophysics, 50, 3-19.

Legchenko A., Baltassat, J.M., Beauce, A., and Bernard, J., 2002, Nuclear magnetic resonance as a geophysical tool for hydrogeologists; Journal of Applied Geophysics, 50, 21-46

Lubczynski M.W., and Roy J., 2003, Hydrogeological interpretation and potential of the new Magnetic Resonance Sounding (MRS) method. Journal of Hydrology, in press.

NASA, 2000, LIS and OTD web site: http://www.thunder .msfc.nasa.gov.

Roy J., and Lubczynski M.W., 2003, The MRS technique and its use for groundwater investigations; Hydrogeology Journal, in press.

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

Semenov, A.G., 1987, NMR Hydroscope for water prospecting; Proc. Seminar on Geotomography: 66-67, Hyderabad, Indian Geophysical Union.

U.S. Naval Oceanographic Office, 1990, Earth's magnetic field: Total Intensity (F, nT) WMM-90.

Varian, R.H., 1962, Ground Liquid Prospecting Method and Apparatus; US Patent 3,019,383.

Yaramanci, U., Lange, G., and Hertrich, M., 2002, Aquifer characterisation using Surface NMR jointly with other geophysical techniques at the Nauen/Berlin test site; Journal of Applied Geophysics, 50, 47-65.