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STATUS REPORT ON THE MAGNETIC RESONANCE SOUNDING (MRS) TECHNIQUE FOR GROUND WATER EXPLORATION WITH EXAMPLES FROM SOUTH AFRICAN FRACTURED ROCK AQUIFERS

by

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Report to the Water Research Commission on the project: "Evaluation of Nuclear Magnetic Resonance (NMR) as a new geophysical technique for ground water exploration in fractured rocks."

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EXECUTIVE SUMMARY

Introduction

One of the key questions in ground water exploration is where to position a borehole to ensure that an acceptable and sustainable yield which will be found. In this regard geophysical techniques are widely applied in ground water exploration to assist in this selection process. The geophysical techniques traditionally used for this purpose, however, all identify geological structures that are suitable to host ground water, but they cannot identify whether ground water is present or not.

This report discussed the theory and application of a relatively new geophysical technique developed specifically for ground water exploration. The main advantage of the technique is that it directly responds to the presence of underground water. This differs from other geophysical techniques that only provide physical characteristics of the rock formations. These physical characteristics may change due to the presence of water, but the water itself cannot be identified.

This new geophysical technique that is the topic of this research report, is referred to as the Nuclear Magnetic Resonance technique, or in short NMR. The theoretical development of the technique already started in the 1960s, but was developed for the ground water exploration in the 1980s by a group of Russian researchers. They developed the first instrumentation and interpretation procedures for the practical identification of underground water. The technique is unique in the sense that it can under favourable conditions not only determine whether ground water is present or not, but also the amount that is present in the pores and fractures of the rock formations. The method reacts to the resonance frequency of protons (H*) present in the ground water (H₂O) in the presence of a static magnetic field (the Earth's field).

In an NMR sounding a large square loop (typically 75 m x 75 m) is placed on the earth's surface and energized with an alternating current tuned to the local precession frequency of the in-situ ground water's hydrogen nuclei (1H*). When the current is switched off, the same loop is used as receiver coil to measure the decay in the precession of the hydrogen nuclei. The recorded NMR signal is analysed in terms of its amplitude, decay rate, its precession frequency and its phased reference to the excitation pulse. The initial amplitude after inversion provides the subsurface free water content, which below the water table is related to the effective porosity as a function of depth. The only water detected by the NMR technique is free water, i.e. it does not take into account clay-bound and micro-pore bound water.

Motivation to conduct this research project

The majority of South African aquifers are of a secondary nature. This means that the water is contained in fractures, joints, weathered zones, and often associated with linear geological structures. Total water saturated porosity of these secondary aquifers is typically less than 5%. With the continuously increasing demand on the potable water resources of the country, more emphasis than ever before is placed on the exploitation and development of the ground water resources in these secondary aquifers. The Department of Water Affairs and Forestry, given the task to coordinate and initiate the search for suitable ground water resources in rural areas, is often confronted with the question of which geophysical technique is the most suitable under particular geological conditions to identify exploration drilling sites. In order to achieve this goal, suitable techniques resulting in a cost effective exploration and borehole selection process, are required.

The NMR technique has proven itself in overseas studies of primary aquifers with relatively high saturated porosities (typically between 10% and 35%). The new challenge for the NMR technique is therefore to provide meaningful results under the difficult South African fractured rock aquifers conditions with low saturated porosities. The focus for the SA research programme was therefore to determine whether the NMR technique could in fact perform satisfactorily under these conditions.

Research objectives

This study had as its main objectives the following tasks:

- To study and evaluate existing literature on the applications of the NMR technique to ground water exploration and to review the theory of the NMR technique as applicable to ground water exploration.
- To identify on the basis of the results from the literature study, suitable sites in South Africa for the testing of the NMR technique and conduct field surveys using modern NMR equipment and to interpret the results.
- 3) To focus the research on the practical application of the technique with the aim to eventually assist in the selection and evaluation of potential drilling sites, and to improve our understanding of the geohydrological conditions in fractured rock aquifer systems. In particular the research was to focus on, but not restricted to, evaluating the applicability of the MRS technique under the challenging South African geological and geohydrological conditions of fractured rock aquifers.
- To undertake an overall evaluation of the technique, make recommendations as to its applicability under SA conditions and report on the findings of the complete project.

These objectives were all met and the main conclusions and recommendations that emerged from this research project are described below.

Structure of the report

The report is divided into seven chapters. Chapter 1 contains a brief introduction on the need for research in ground water exploration techniques, the motivation as to why the research project was conducted and states the objectives of the project as contained in the contract between the Water Research Commission and the CSIR. background on the application of Nuclear Magnetic Resonance techniques and specifically how these have been applied to the earth sciences, is described in Chapter 2. In Chapter 3 the theory behind the technique is described, and includes an extensive section on the application to ground water exploration, field procedures, illustrated with several examples to demonstrate the limitations and resolution of the method. In Chapter 4 a literature review is presented describing the application of NMR techniques in geophysical borehole logging in the oil exploration industry, as well as examples where the technique has already been applied to fractured rock aguifer systems. In Chapter 5 the results of interpretation procedures and simulation of MRS response for selected South African aquifer conditions are described. The first NMR experiments in ground water exploration done in southern Africa are described in Chapter 6, giving the results obtained at the different sites investigated together with the interpretations. Problems encountered during the field programme are also discussed. Chapter 7 contains the conclusions arrived at after the first experiments in southern Africa. In addition it lists a number of recommendations for future research on the method in South Africa. Some thoughts on the way forward and what should be addressed in future research programmes is also presented in this final chapter. The final section of the report contains an extensive list of references which include references to the theory of the method and interpretation techniques, as well as a wide selection of descriptions of the application of the technique.

Instrumentation, field tests and some results

To date only two commercially available NMR instruments have been developed. These are the HYDROSCOPE (the original instrument developed by the Russian research group), and the more modern French NUMIS system, developed in the late 1990s and based on the original Russian design. We were fortunate to be able to collaborate with the ITC (International Institute for Aerospace Survey and Earth Sciences) of Delft in the Netherlands to bring the French equipment to South Africa for a short field trail during the summer of 1998. The main purpose of the South African tests were to establish the applicability of the technique under our geohydrological conditions. Six sites, representing some of the South African primary and secondary aquifer conditions were selected for these tests. These six sites were an alluvial coarse sand aquifer overlying a fractured and weathered granite aquifer in the Pietersburg area, the secondary aquifers in the Nebo Granite granite of the Bushveld Complex, the Ecca sandstone aquifer underlying Karoo basalt in the Springbok Flats near Warmbaths, horizontally fractured secondary aquifer in the sedimentary

formations of the Beaufort Group of the Karoo, aquifers associated with dolerite intrusions in the Karoo near Philippolis, and the fractured granite aquifer north of Vryburg in Northwest Province.

A serious problem encountered during the filed experiments was the unexpected high electrical noise levels due to adverse atmospheric conditions during the summer rainfall season. This, coupled to the already 4 times lower amplitude signal than what is measured in Europe under similar aquifer conditions, as a result of the lower Earth magnetic field strength in South Africa, resulted in much longer recording times, low signal to noise ratios, and in some instances experiments had to be abandoned totally. These problems can, however, be overcome through improved instrumentation, noise rejection software, a better understanding of the noise spectrum and frequency of occurrence, and careful selection of test sites. Research in this regard has already started and further financial assistance to continue with the development and improvement of the technique is being sought at the moment.

To illustrate the results achieved during the short field trials in South Africa, two examples are presented below. These are from the Settlers area (Ecca Sandstone aquifer underlying a thick basalt cover, and from the Bloemfontein area (low porosity, horizontally fractured aquifer in a sedimentary succession).

Ecca sandstone, Settlers

The Ecca sandstone aquifer is extensively used for irrigation in the Settlers area. It is overlain by basalt which can reach a thickness of 100m in places. At the test site the basalt was about 22m thick. It is important to note that although the fractured contact between the basalt and the sandstone is the main water producing zone, the low primary porosity of the Ecca sandstone forms the storage for the ground water which is released into the main fracture zones. The MNR results failed to identify the fracture zone as a main water containing zone, but gave excellent results to establish the saturated porosity of the Ecca sandstone to a depth of approximately 100 m. From the clear indication of the 2-3% porosity for the sandstone, reserve determinations can now be made with greater confidence, which will in turn improve the overall management of the resource (Figure 1).

Karoo aguifer, Bloemfontein

Ground water exploitation in the Karoo is often governed by the presence and intersection of individual water bearing fractures. These fractures act as the conduit for water to flow towards the abstraction point, whereas the adjacent formations with a generally low porosity and storage, supply water to the fracture. The NMR tests done near Bloemfontein at boreholes where water was struck at a depth of around 20 m, provided a profile of saturated porosity to a depth of about 70m. The relatively high porosity zone associated with the fracturing around 20m is clearly indicated by the NMR results. The porosity then gradually decreases with depth to less than 0.5 % at a depth of 55m (Figure 2).

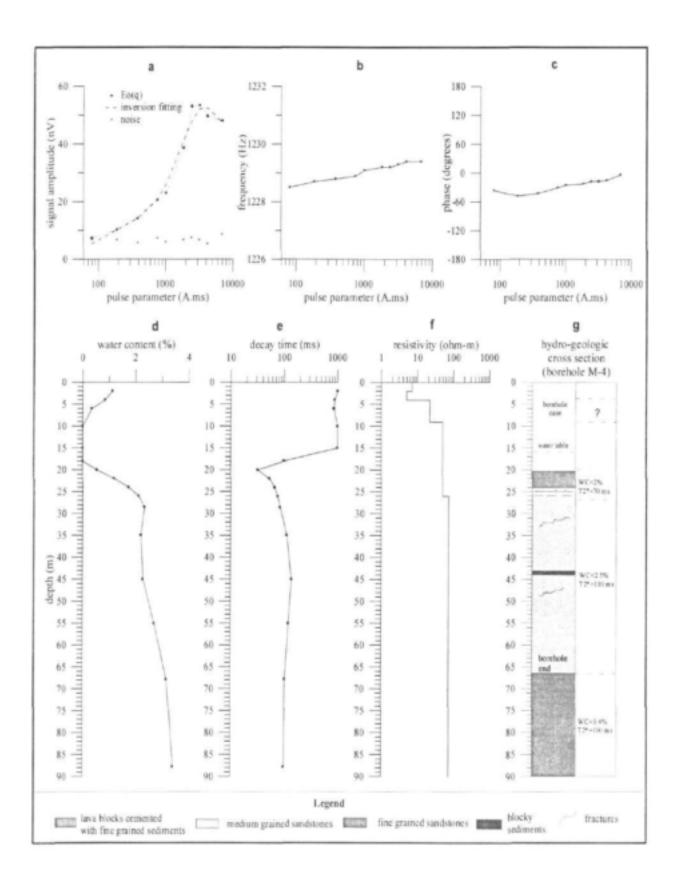


Figure 1: NMR sounding curve and inversion results at Settlers.

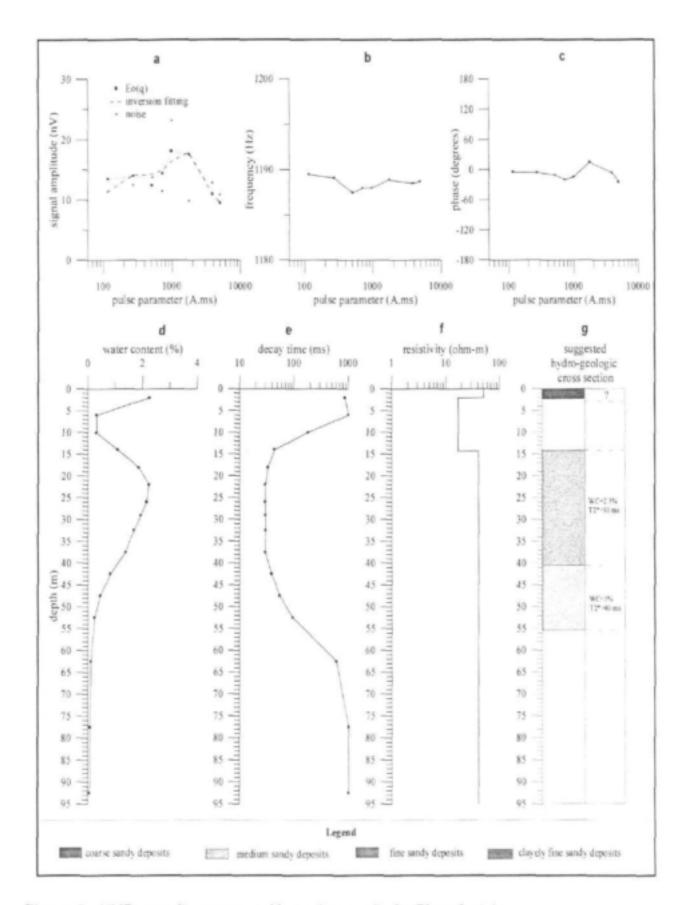


Figure 2: NMR sounding curve and inversion results for Bloemfontein

Conclusions and recommendations

The following main conclusions regarding the technique, field work, instrumentation, interpretation techniques and the results obtained in southern Africa with the NMR method can be made:

- Nuclear Magnetic Resonance is a proven technique for ground water exploration under varying conditions. Not only is the theory on which the methodology, instrumentation and interpretation techniques are based, sound, but it has been proven to provide excellent results in numerous studies world wide, including southern Africa.
- To achieve the best results with the technique, a number of conditions or a combination of these have to be met in order to perform meaningful measurements in the field. Of these the more important ones are
 - Aguifers comprising of loosely packed sand or gravel.
 - A saturated effective porosity of >5% is ideal, although it has been proven that good results can also be obtained in hard rock aquifers with lower effective saturated porosities.
 - A shallow water level with the aquifer depth not exceeding 100 m (the depth of investigation is a function of resolution and signal strength).
 - A primary aquifer or a horizontally layered secondary aquifer system (compared to aquifers associated with vertical or near vertical fracture and fault zones).
 - A homogeneous geomagnetic field, and one which will not cause the Larmor frequency to be a or close to a harmonic of 50hz.
 - No man-made sources of electrical noise close to the sounding position.
 - Measurements are to be made outside periods of high electrical noise caused by weather patterns, such as lightning and thunderstorms.
 - A large transmitter loop (signal amplitude is usually increased with increase in transmitter loop size).
 - Sensitive measuring instrumentation and appropriate interpretation software.
- Despite the fact that these "ideal aquifer" conditions are not always present in the
 areas where the ground water exploration programme is conducted, many
 excellent reports on the application of NMR in less than ideal conditions have
 been recorded. Highly fractured but shallow hard rock aquifers, and thick
 (~100m) high porosity water saturated sedimentary formations, are examples.
- The results gathered from the limited number of NMR soundings done so far in southern Africa, are very encouraging and provide proof that, when operating in low noise environments, excellent results are achieved. This has been the case in for example low porosity sandstones (~3%) underlying a water filled fracture

zone with a higher porosity, alluvium underlain by fractured granite, and zones of horizontal, water filled bedding plane fracturing in a Karoo environment.

- Under favourable conditions, the interpretation software has proven itself to the
 extent that the outcome of predictive modelling can be accepted. Theoretical
 modelling done with the existing 1-D modelling routines, indicate that even a
 fractured granite aquifer, simulated by a 20 m thick aquifer with 1% water
 saturated porosity at a depth of between 50 m and 70 m, would still produces a
 signal amplitude of about 6 nV. A theoretical multiple fractured aquifer consisting
 of 10 water filled fractures each 0.05 m wide and spaced at 10 m intervals, would
 produce a signal amplitude of about 2 nV under southern African conditions
 (lower geomagnetic field compared to for example Europe).
- However, to be able to record these low amplitude signals, the currently available instrumentation needs to be improved and made more sensitive. Technically this is achievable.
- The NMR tests done in southern Africa were conducted under different and technically difficult geohydrological conditions compared to other areas in the world, but nevertheless, it has been proven that meaningful results can be achieved.
- The measurement periods were in general much longer that in Europe, and large numbers of stacking had to be done.
- Severe thunderstorm activity places a serious restriction on the time of the year when measurements can and should be made.
- Excellent results have been achieved in the Pietersburg (water saturated alluvium overlying fractured granite), Settlers (low primary porosity sandstone aquifer) and Karoo (low porosity, essentially thin bedding plane fracture aquifer) geohydrological environments.
- The good results obtained in the Ecca sandstone underlying basalt of the Springbok Flats east of Warmbaths, Northern Province, came as a surprise because basalts are often magnetically very noisy regions.
- The current instrumentation needs further development for South African conditions, especially with regard to the internal noise levels generated by the NUMIS instrument.
- · The data collection and data formatting needs further improvement.
- Several more tests are required under different geohydrological conditions to further verify the applicability of the technique in fractured aquifer systems.

The review of the international experience indicated that the technique has until now been essentially used under primary aquifer conditions to establish the geohydrologically most promising areas (and specifically high saturated porosity areas) within the boundaries of the aquifer, and which would also be areas where high yielding production boreholes could be developed. Whereas this approach could also be used in South Africa, the surface area of

similar type of aquifers in very limited in South Africa (coastal alluvial deposits, sand filled river beds, etc.) Apart from using the technique under these rather limited primary aquifer conditions in the country, it is concluded that the technique could also be utilised in a "ground water resource quantification" mode. It is believed that this technique can be employed under the South African fractured aquifer conditions as a tool to determine our ground water resources and in that way assist in the quantification of the "ground water reserve" for individual catchment areas as required under the new National Water Act of 1998. This deviates from the approach concentrated on thus far in international MRS research programmes.

The following recommendations are made:

- Due to the promising results obtained with the initial short survey in southern Africa, it is strongly recommended that research on the technique in the local geohydrological conditions be continued. It must be remembered that the first series of measurements were done under tremendous time pressure, and under very adverse atmospheric conditions that influenced the results negatively. However, in a sense this has benefitted the research also because a number of potential problems have been identified that have not been experienced or identified in surveys done elsewhere. These identified problems will undoubtedly direct the research programme in future. Subjects for further research include the improvement of the instrumentation to reliably be able to measure low signal amplitudes, reduce the internal noise of the instrumentation, improve interpretation procedures, and the improvement of data recording, storing and formatting.
- Additional financial resources should be made available to study the seasonal and diurnal noise patterns to determine the optimum time and season for conducting NMR measurements. From the short experiments done by the German Geological Survey in Namibia (also conducted during the summer season), and the fact that they did not encounter noise problems of the same degree as was experienced during the CSIR/ITC experiments in southern Africa, illustrates that these high noise conditions may not only be attributed to seasonal conditions, but that other factors may also play a meaningful role. This highlights the need for more collaborative research in this regard. This will also lead to the development of criteria to eventually improve the S/N ratio through the development of efficient and intelligent data (noise) rejection routines.
- From a logistical point of view, it is recommended that all sites be surveyed beforehand to establish the local conditions. These surveys should include some ground magnetic measurements, noise measurements with small transportable loop systems designed specifically for noise measurements, presence of fences and powerlines, and the identification of large enough open areas preferably with

- some nearby control boreholes. This will save a considerable amount of time during the planning of a research programme.
- All boreholes where NMR surveys are conducted are to be geophysically logged
 to provide additional information in digital format which can be compared with the
 results obtained during normal geohydrological surveys. It is also recommended
 that down the hole video recordings be made at all boreholes where MRS
 research work is undertaken or of boreholes drilled to test the results of NMR
 interpretations.
- It is recommended that a few long term ELF and VLF monitoring stations be installed in the major cities of South Africa to determine which would be the best time of the day and year to perform NMR soundings.
- The use of the MRS technique for the quantification of our ground water reserves contained in the fractured rock aquifers, should be further investigated. This is believed to be a different approach to the hitherto practical applications of the MRS technique and an area where South Africa could make a major contribution to identify new applications of the technique. In this regard the technique could for example be used to determine the exploitable ground water contained in the Ecca sandstones underlying the Springbok Flats in the Northern Province and thereby assist in the sustainable management of the aquifer.

Finally, a strong case is made that future research into the application of NMR techniques for ground water exploration in South Africa should not be discontinued. It needs to be appreciated that the research is still in an early stage and that expectations should not be pitched at a too high level at this stage. Nevertheless, South Africa should take advantage of the enormous amount of research that has already been conducted on this technique internationally, while at the same time realising that the local geological, geohydrological and atmospheric conditions, result in the southern African targets being some of the most difficult targets in the world. Therefore it must be realised that it may still take a number of years before the developments have progressed to a situation where NMR soundings may become a routine geophysical technique in the geohydrologist's toolbox.

With the challenging geohydrological conditions, South Africa is in a unique position that the country, its researchers and geohydrologists can play a leading role in the further development of the MRS technique. To achieve this it is recommended that the cooperation with international research teams active in the further research and development of the technique, notably the European research group, should not only be continued, but expanded. The experience gained from the short period the author of this report could work together and meet these groups in Europe, was invaluable. Continued cooperation and contact with these groups will reduce duplication of research and field experiments, and eventually be to the benefit of not only South Africa, but also the research programmes in other countries. In this regard it is recommended that South Africa actively pursues

cooperation and involvement of international research programmes, by becoming a member of the cooperative research groups established in Europe and who are seeking financial assistance from European Union research funds. In discussions with leaders of these research team, the author realised that South Africa would be more than welcome to join these research teams provided the country contributes financially to the research.

For the future development of South Africa, the country will need to rely more and more on the hitherto under utilised ground water resources. Ground water is in many circles in this country perceived to be a minor and unreliable water resource when compared to the surface water resources of the country. By utilising improved exploration techniques, like for example the MRS technique, the success rate of drilling for ground water could be increased, and this coupled with our current much higher level of understanding of the hydrogeological conditions, the ground water resources can be managed more optimally. At the moment the MRS technique is the only technique that can provide quantitative information on the underground water resources, and for that reason financial and manpower resources should be made available to do further research on this subject. This view has also been strongly supported by the members of the Steering Committee during the evaluation of the final report.

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cooperation with the international community interested in developing the method to a level which can be applied to the challenging ground water exploration scene in southern Africa.

In particular I would like to acknowledge the major role played by Dr Jean Roy of the ITC in Delft (now in Enschede), The Netherlands, in the successful implementation of the technique to southern Africa. The dedication, enthusiasm and perseverance with which he approaches every aspect in the further development of the technique, is a special motivation to the author to participate in the future development of this technique. Through close cooperation with the international team currently working on the many challenging aspects of the implementation of the technique, the author is also convinced that this method will with time be developed to such a degree that it will be able to make a worthy contribution to ground water exploration under hard rock aquifers conditions. Dr Roy is also thanked for his critical review of an earlier draft of this report and the valuable suggestions made to improve the quality of the report.

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Note: The term Nuclear Magnetic Resonance (or NMR) is not well received in certain circles of the ground water exploration community because of the reference to 'nuclear'. Therefore a number of alternatives have been proposed lately. These include: Proton Magnetic Resonance (or PMR), Surface version of the GroundWater Nuclear Magnetic Resonance technique (or SGW-NMR), Surface Nuclear Magnetic Resonance (or SNMR) and Magnetic Resonance Sounding (or MRS). At a meeting in 2000 of interested parties in Europe, the term MRS received wide support and it was decided that MRS should be the recommended term to be used in future. For that reason MRS is widely used in this report and only where appropriate and for historical reasons, reference to the abbreviation NMR is used.

CHAPTER 1

INTRODUCTION, MOTIVATION AND OBJECTIVES

Introduction

Geophysical techniques are widely applied in ground water exploration to assist in providing answers to some of the fundamental questions in ground water exploration as formulated by Fitterman and Stewart (1986):

- · Where can ground water be found?
- · How much of it is there?
- · What is its quality?
- At what rate can the ground water resource be used without adverse effect?

To provide answers to the first two questions, is a most challenging task for geophysical techniques and where geophysical techniques often fail to provide suitable answers. In this report a relatively new geophysical technique developed specifically for ground water exploration, will be described and the results of the first field experiments employing this technique will be discussed.

A promising and relatively new geophysical technique to assist in achieving some of the goals referred to above, is currently receiving renewed interest by geophysicists involved in the ground water exploration field. This technique is referred to as the Nuclear Magnetic Resonance method, or referred to in short as NMR. The first instrument to test this technique, called the "HYDROSCOPE", was developed by a group of Russian scientists during the 1980s and had its first field trials in the same years. This instrumentation has had several disadvantages, the most important being its physical size and weight, and its low signal to noise ratio. Interpretation procedures had also not been developed properly at that stage. Further development and subsequent testing of the instrumentation in Australia and in a coastal aquifer in Israel in conjunction with electromagnetic sounding techniques followed. The results were an improvement on the earlier work by the Russian team, but still there was a lack of proper understanding of the technique. A concerted effort was begun some five years ago by the French company IRIS Instruments, a subsidiary of BRGM (the French National Geological Survey) in France. Scientists at IRIS Instruments, together with seconded members of the original Russian team have redesigned the NMR instrumentation and renewed studies of the theoretical aspect of the technique, coupled to the upgrading of existing as well as the development of new interpretation routines, are underway in Europe and in the United States.

2. Motivation to conduct this research project

By far the majority of South African aquifers are of a secondary nature. With the continuously increasing demand on the potable water resources of the country, more emphasis than ever before is placed on the exploitation and development of the ground water resources in these aquifers. Many of the rural communities in South Africa are resident in areas where the lack of surface water resources results in these communities being often totally dependent on ground water for their water requirements. The Department of Water Affairs and Forestry, given the task to coordinate and initiate the search for suitable ground water resources in these areas, is often confronted with the question of which geophysical technique should be used in identifying the most suitable exploration drilling sites. In order to achieve this goal, suitable techniques resulting in a cost effective exploration and borehole selection process, are required.

With the increasing cost of drilling, it is important that exploration borehole positions are selected in an optimal and cost effective way to minimize the number of unsuccessful boreholes. To achieve this goal, geological reasoning and different geophysical techniques can be applied in the selection of potential drilling targets. The nature of the occurrence of ground water in fractured rock aquifers provides an extra challenge to the identification of fractures and fracture zones capable of yielding substantial amounts of ground water. The application of existing or traditional geophysical techniques, such as gravity, electromagnetic, resistivity, seismic and magnetic techniques (or combinations thereof), has over the years been applied with varying degrees of success in the selection of borehole drilling targets in South Africa.

To improve the efficiency of ground water exploration drastically, will require a technique that must be sensitive to that physical parameter which distinguishes water from any other material in the subsurface. The method which in principle is able to do this, is called **Nuclear Magnetic Resonance** or **NMR** and the appropriate parameter is the resonance frequency of protons (H⁺) contained in the water (H₂O) in the presence of a static magnetic field (the Earth's field). The NMR method is at present the only method which, in principle, facilitates a direct search not only for ground water, but also hydrocarbons and some other mineral deposits.

To date the NMR technique is widely used in many applications ranging from chemical analysis to medical tomography. In the ground water exploration field the technique is still relatively unknown and has only been seriously looked at since the early 1980s. In geophysical borehole logging, commonly used in the oil exploration industry, NMR techniques have been developed since 1960. NMR techniques in the geophysical borehole logging industry (mainly used as part of oil exploration programmes) have seen some significant technological advances in recent years with the development of new high performance logging tools, laboratory equipment and sophisticated software. In addition regular short courses and seminars all dedicated to the application of NMR techniques to hydrocarbon exploration, are organised.

The NMR technique is based on selective properties of NMR combined with innovative techniques of signal excitation, detection and processing. In the NMR technique an electrical pulse at the proton resonance frequency is fed into a wire loop at the earths' surface. A detection system records the response of the water molecules to the excitation pulses. By recording this information the presence or absence of ground water can be detected, as well as a quantitative distribution of free water content with depth. It has been successfully applied in numerous, mainly water saturated unconsolidated aquifers, areas in the world to locate the presence of water and quantify occurrences under different geohydrological conditions.

Prior to this project, the NMR technique had not been applied in geohydrological investigations of South African aquifers, and only a very limited number of experiments were conducted in fractured hard rock aquifers world wide. From the published literature, however, the indications are that, there is growing interest in the application of this technique to fractured aquifers. According to readily available literature, the NMR technique has been applied successfully in Israel, Russia, France, The Netherlands, Germany, Spain, Australia, India, China, Saudi Arabia and Portugal. Some of the results of the southern African experiments (South Africa, Botswana and Namibia) conducted during this project are published in the proceedings of the 30th Congress of the International Association of Hydrogeologists held in Cape Town during November 2000 (Roy and Lubczynski, 2000a).

The selection of ground water exploration drilling targets in fractured rock aquifers, using existing geophysical and other techniques, remains problematic. NMR may provide South Africa with a new technique to improve the success rate of high yielding ground water boreholes in fractured terrain, and hence reducing the high cost of ground water exploration under these circumstances.

In the light of the overseas experience, a proposal was submitted to the Water Research Commission to test and evaluate the applicability of this technique under South African fractured aquifer conditions. This proposal was accepted and a research project was started in 1998. This report describes the results obtained during this project.

Research objectives

The research objectives as specified in the contract between the WRC and the CSIR are as follows:

- To study and evaluate existing literature on the applications of the NMR technique to ground water exploration;
- to review the theory of the NMR technique as applicable to ground water exploration;
- to identify on the basis of the results from the literature study, suitable sites in South Africa for the testing of the NMR technique and in collaboration with the DWA&F;

- to conduct field surveys using the modern NMR equipment and do the interpretation
 of results, focusing on the practical application of the technique in assisting in the
 selection and evaluation of potential drilling sites;
- to determine whether the technique will be beneficial to both the selection of suitable drilling targets and to improve our understanding of the geohydrological conditions in fractured rock aquifer systems and to evaluate whether the NMR technique can be used cost effectively under SA geological and geohydrological conditions; and
- to undertake an overall evaluation of the technique, make recommendations as to its applicability under SA conditions and report on the findings of the complete project.

4. Structure of the report

The report is divided into six chapters. Chapter 1 contains a brief introduction on the need for research in ground water exploration techniques, the motivation as to why the research project was conducted and states the objectives of the project as contained in the contract between the Water Research Commission and the CSIR.

Some historical background on the application of Nuclear Magnetic Resonance techniques and specifically how these have been applied to the earth sciences, is described in **Chapter 2**. In **Chapter 3** the theory behind the technique is described, and includes an extensive section on the application to ground water exploration, field procedures, illustrated with several examples to demonstrate the limitations and resolution of the method.

In Chapter 4 a literature review is presented describing the application of NMR techniques in geophysical borehole logging in the oil exploration industry, as well as examples where the technique has already been applied to fractured rock aquifer systems. In Chapter 5 the results of interpretation procedures and simulation of MRS response for selected South African aquifer conditions are described. The first NMR experiments in ground water exploration done in southern Africa are described in Chapter 6, giving the results obtained at the different sites investigated together with the interpretations. Problems encountered during the field programme are also discussed. Chapter 6 contains the conclusions arrived at after the first experiments in southern Africa. In addition it lists a number of recommendations for future research on the method in South Africa. Some thoughts on the way forward and what should be addressed in future research programmes is also presented in this final chapter.

The final section of the report contains an extensive list of references which include references to the theory of the method and interpretation techniques, as well as a wide selection of descriptions of the application of the technique. It is interesting to note from this list that the majority of the articles included in the list, originated after the late 1990s, which illustrates the renewed worldwide interest in the technique since it was patented in 1962 and originally developed for ground exploration in Russia during the mid-1970s.

CHAPTER 2

DEVELOPMENT AND HISTORICAL INFORMATION ON THE APPLICATION OF THE NMR TECHNIQUE IN THE EARTH SCIENCES

Nuclear magnetic resonance (NMR) has played an important role in a number of applied scientific fields including physics, chemistry, biology, and medicine since it was first discovered in the 1940s by Felix Bloch (Bloch et al., 1946) and Edward Purcell (Purcell et al., 1946). The concept of NMR has made a significant contribution to geophysics since the demonstration of NMR in the earth's magnetic field by Packard and Varian (1958). This led to the development and construction of proton precession magnetometers which are now widely used around the world for ground magnetic surveys (Telford et al., 1976). The discovery by Packard and Varian (1958) soon led to the development of the Nuclear Magnetism Log (NML) used in geophysical borehole logging. The NMR technique has long been recognized as a means of conveying information related to permeability and has been widely applied in the oil exploration industry. In the early 1960s publications by Hull and Coolidge (1960), Brown and Gamson (1960), Coolidge and Gamson (1960) and Wyman (1962) started to appear in the geophysical borehole logging literature. All these papers indicated that a qualitative relation between permeability and Free Fluid Index (FFI) exists. This was followed by Seever (1966) who developed an equation for sandstones, relating permeability to FFI. His method incorporated the physical model developed by Korringa et al. (1962). Several workers (Seever, 1966; Korringa et al., 1962; Artus, 1967; Timur et al., 1971) all based their research on finding a relationship between NMR parameters and permeability on some form of the Kozeny equation. Loren (1972) developed a quantitative technique to estimate permeability from NMR response and from an independent determination of porosity. The Nuclear Magnetism Log (NMR) was introduced commercially by the borehole logging company Schlumberger around 1980. Elleman and Manatt (1968) developed a Nuclear Magnetic Resonance spectrometer for the quantitative determination of moisture content in lunar rock samples.

The initial idea to transform the well-known proton magnetometer into a tool for ground water prospecting is ascribed to RH Varian (Varian, 1962). The first reference to the potential of NMR in the ground water field is found in the United States of America Patent application by Varian with the title "Ground liquid prospecting method and apparatus" (Khmelevskii and Chekanov, 1989; Lieblich et al., 1994). Since the granting of the US patent to Varian in 1962, no further developments to apply this geophysical technique to ground water exploration took place until the late 1970s. This was the development of an instrument by a team of Russian scientists under the leadership of A G Semenov (Semenov et al, 1988). The first prototype of this instrument (called the HYDROSCOPE) for the measurement of magnetic resonance signals from underground water was constructed at the Institute for Chemical Kinetics and Combustion of the Russian Academy of Sciences (ICKC) in Novosibirsk (Shirov et al, 1991; Semenov, 1982 in Goldman et al. 1994). In 1989 Khmelevskii and Chekanov published a paper describing some theoretical work on the

application of NMR to ground water prospecting. From their research they made the observation that bound and adsorbed water in a rock formation does not create a long lasting Free Precession Signal (FPS), while water free to move in a formation, does.

After successful feasibility studies, the HYDROSCOPE was applied in numerous hydrogeological surveys throughout the former Soviet Union. Unfortunately, all publications about these surveys are only available in Russian. Only very few applications of the HYDROSCOPE outside Russia (Australia, India and Israel) are reported in the open literature (Schirov et al., 1991; Semenov, 1987; Goldman et al., 1994).

More recently, NMR has been used for laboratory petrophysical studies (Straley et al., 1995) and in borehole logging tools (Kleinberg et al., 1992; Miller et al., 1990). In 1996 an entire issue of the journal "The Log Analyst" was devoted to NMR logging (The Log Analyst, vol. 37 (6), November-December, 1996). Semenov (1987) described the surface NMR method applied to ground water exploration, and in IRIS Instruments, (1998) the instrument used in the southern African study is described, while Schirov et al. (1990, 1991) have presented the results of the application of this method in Australia, using the HYDROSCOPE instrument.

Since the release of the first commercially available NMR instrument for ground water exploration, called NUMIS and developed by the French firm, IRIS Instruments, numerous studies have been conducted in different geological environments. Although only a few of these instruments have been built since 1995, the technique has made rapid progress. The majority of the applications are still research orientated and no real "production" surveys have yet been undertaken. Most of the recent publications describing the research results originate from four sources: Iris Instruments in France, the ITC (International Institute for Aerospace Survey and Earth Sciences) in the Netherlands, the Technical University of Berlin in Germany, and from the original designers of the HYDROSCOPE in Novosibirsk, Russia. Some of the more recent publications describing theoretical aspects of the technique and the results of field experiments are those by Lieblich et al. (1994); Trushkin et al. (1994); Goldman et al (1994); Trushkin et al (1995); Legchenko et al (1995); Gev et al. (1996); Shushakov (1996); Legchenko (1996a, 1996b); Legchenko et al (1996); Legchenko et al (1997a, 1997b, and 1997c); Guillen and Legchenko (1997, 1998); Hinedi et al. (1997); Legchenko and Shushakov (1998); Legchenko et al (1998a, 1998b, 1998c, 1998d); Yaramanci et al (1998a, 1998b, 1998c); Roy et al, (1998a, 1998b); Lavely and Blohm (1998); Legchenko and Valla (1998); Yaramanci et al (1999a, 1999b, 1999c); Möhnke and Yaramanci (1999a, 1999b), Wan and Pan (1999); Roy (1999); Supper et al (1999); and Legchenko and Beauce (1999).

CHAPTER 3

THEORY OF NUCLEAR MAGNETIC RESONANCE

3.1 Introduction

Goldman et al. (1994) make the point that a technique that is sensitive to that physical parameter which distinguishes water from any other material in the subsurface, will make a significant difference to the exploration for ground water. They refer to the NMR technique as being one which in principle, should be capable of doing just this. The appropriate parameter is the resonance frequency of protons (H*) contained in the water (H₂O) in the presence of a static magnetic field (e.g. the Earth's magnetic field). The strength of the method comes from the fact that nuclei of the same species in different chemical environments (for example the hydrogen nuclei in water, benzene or cyclohexane) possess different resonance frequencies (Emsley et al., 1967). Therefore, the NMR method is the only physical method which, in principle, facilitates a direct search not only for ground water, but also for hydrocarbons and some other mineral deposits. There is currently a renewed interest from the geophysical borehole logging industry, which operates almost exclusively in the oil exploration field, to use this method in their search for oil reserves and in optimising the positioning of production boreholes (Vinegar, 1996).

Legchenko et al. (1997a) provide a detailed description of the theory of operation of the NMR technique. The basic principal of the surface proton magnetic resonance method is similar to that of a proton magnetometer. Both techniques record the magnetic resonance signal from a proton-containing liquid (for example, water hydrocarbon). While in the case of the proton magnetometer, the receiving coil is placed in a special sample of the liquid (which guarantees the signal) and only the signal frequency is of interest, in the case of the NMR a wire loop of approximately 100m in diameter, is used as a transmitting/receiving antenna and the ground water acts as a sample. Therefore in the case of the NMR method, the existence or absence of the signal is directly linked to the presence or absence of water in the subsurface. The reliability of the technique, however, depends largely on the signal amplitude. The signal amplitude depends on a number of factors, for example: the magnitude and inclination of the geomagnetic field (which varies according to the geographical location), the electrical conductivity of the subsurface, size and shape of the antenna, and the decay time of the signal. The decay time is directly related to the pore size and magnetic susceptibility contrast of all the constituents, which makes the MRS method independent of the rock type containing the water. The NMR signal depends directly on the amount of hydrogen nuclei (*H1 or hydrogen protons) present in the subsurface, i.e. the amount of water present in the formation. Question 2 of Fitterman and Stewart (1986) "How much water is contained in the formation"? can thus theoretically be answered by the NMR technique. However, in order to estimate the quality, the NMR results have to be integrated with conventional geoelectrical measurements, such as resistivity soundings or Time Domain Electromagnetic (TDEM) soundings (Goldman et al, 1994).

3.2 Publications dealing with NMR theory

Some of the earliest papers that deal with the theory of NMR soundings are those by Semenov et al, (1978) and Khmelevskii and Chekanov (1989). Semenov et al, (1978) used free precession signals and spin echo from ground water protons to confirm the viability of Varian's theory. They illustrated the dependence of the initial amplitude of a free precession signal, precessing as a result of an impulse of alternating magnetic field, is a function of depth and thickness of the aguifer and its water content, and the magnetic inclination (Schirov, 1999). Although Khmelevskii and Chekanov refer in their paper to some 400 soundings done by Chekanov in Central Asia and the Moscow region, no field results are presented or described, apart from giving the equations derived correlating Free Water Index (FWI - also referred to as Free Fluid Index (FFI)) to porosity and for permeability. The papers by Goldman et al (1994), Thrushkin et al (1993, 1994, 1995), Lieblich et al. (1994) and Legchenko et al (1997) all give both some theoretical derivations and describe the results of field experiments. In their 1995 paper Trushkin et al describe the theory for an integrated electromagnetic and NMR method for use in very conductive environments. They further describe the results of theoretical modelling and also provide data from some field tests where this combined technique has been tested. The theory of the influence of conductive water on NMR soundings is described by Shushakov (1996), and illustrates the effect with some practical examples. In an extensive document Weichman et al (1999) described the theory of NMR in great detail, and specifically referring to applications in geophysical imaging problems. Weichman and Lavely (1999) presented a paper at the 1999 Berlin workshop describing the general forward theory of Surface NMR. In a paper describing the first NMR experiments in Australia, Schirov et al (1991), some theoretical background of the technique is given, followed by a description of the results of selected experiments in southern Australia.

IRIS Instruments have also prepared a number of short information articles in which some theoretical aspects of the technique, the instrumentation used for field measurements and how it is used, and case studies are described (Legchenko et al, 1997; IRIS, 1998; Bernard, 1999).

3.3 The method

Nuclear Magnetic Resonance is a phenomenon which occurs when nuclei of certain atoms are immersed in a static magnetic field and then subjected to a second oscillating magnetic field. Only nuclei which possess a spin will react to this secondary field. The physical principal of NMR techniques is based on the fact that nuclei of many atoms possess magnetic and angular moments. The classical model describing the presence of the moment is that of a spinning charged particle.

The NMR technique is widely used in many applications, such as chemical analysis and medical tomography. Perhaps the most well-known application is in the medical field where it is used in a scanning mode. Goldman et al. (1994) stress the point that there is, however, a significant difference between geophysical, and medical tomography. In both cases some form of non-uniform excitation of the sample is required to recover its spatial structure. However, whilst in laboratory NMR tomography (medical), the static magnetic field is non-uniform, in geophysical applications the static magnetic field (Earth's magnetic field) is nearly uniform in the scale of

regular exploration targets. Therefore, the non-uniform excitation in geophysical NMR tomography is achieved by applying an alternating magnetic field which operates at a resonance frequency, f₀.

Hydrogen nuclei are known to possess a non-zero dipole magnetic moment μ . The classical model describing the presence of a moment is a spinning charged particle such as a proton. If a spinning charged particle with a magnetic moment, μ , is placed in a magnetic field of strength H_0 , the magnetic moment will experience a torque tending to align it parallel to the field as a simple magnet would do. The magnetic field and the NMR absorption frequency must satisfy the Larmor precession condition

$$\omega = \gamma B_0 \text{ (rad/sec)}$$
 (3.1)

where

 ω is the angular frequency (rad/sec) of the excitation field (where radio frequencies are appropriate to NMR laboratory work, MRS applications are in the audio frequency range); \mathbf{B}_0 is the intensity of the magnetic field (nT); and

 γ is the magnetogyric ratio which has a characteristic ratio for each nuclear isotope and is defined by $\gamma = g\beta / \hbar$ where g is the spectroscopic splitting factor (or Landi factor), which is a measure of the spin and orbital motion of a particle in relation to its total angular momentum (g = 5.5849 for a hydrogen nucleus); β is the Bohr (or nuclear) magneton (β has a numerical value of 5.0493×10^{-24} erg/gauss for protons in water), and \hbar is Planck's constant ($\hbar = 6.625 \times 10^{-27}$ erg.sec).

The magnetic moment precesses around the applied field with a certain precession frequency defined by the Larmor frequency (Figure 3.1) (Emsley, 1967)

$$v_0 = \gamma B_0 / 2\pi \tag{3.2}$$

Substituting the appropriate values into Equation 2 and using SI units, we obtain the Larmor precession frequency of protons in water of

$$f_0 (Hz) = 0.04258 B_0 (nT)$$
 (3.3)

An important feature of this equation is that the precession frequency is independent of the initial angle of the inclination of the particle magnetic moment to the field direction.

Weichman et al (1999) explain the general theory of Nuclear Magnetic Resonance imaging of large electromagnetically active systems, with particular emphasis on noninvasive geophysical applications such as the imaging of subsurface water content, in great detail. They derived a general formula for the NMR response voltage valid for arbitrary transmitter and receiver loop geometry and arbitrary conductivity structure of the medium in which the nuclear spins reside. They also show that there are situations where the standard NMR formula cited in the literature does not always apply. The more general theory as applied to ground water exploration, is described by Goldman et al (1994) and Legchenko et al (1997c). Much of the following text is based on these papers.

For measurements of the magnetic resonance signal from subsurface water saturated layers, the free induction decay (FID) method is used (Schlichter, 1996). Passing a pulse of an oscillating current at the Larmor frequency through a transmitting coil, results in the magnetic moments of the protons in the ground water to shift away from the equilibrium position along the static magnetic field. When precessing around the static magnetic field with the Larmor frequency, the magnetic moments induce an alternating magnetic field into the receiving coil which can be measured when the oscillating current pulse is terminated.

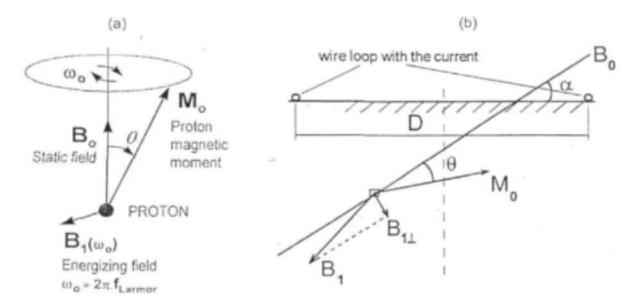


Figure 3.1: (a) Vectorial representation of the classical Larmor precession

(b) Magnetisation of protons in a secondary magnetic field caused by a current loop on the surface (after Legchenko et al, 1997c)

When conducting Surface NMR measurements, a wire loop with dimensions varying from 50 m to 150 m in diameter is laid out on the surface. This loop is used both as the transmitting and the receiving antenna. The loop is energised by a pulse of alternating current

$$i(t) = I_0 \cos(\omega_0 t)$$
 $0 \le t \le \tau$ (3.4)

The duration of the pulse, τ may be varied but in both the instruments (HYDROSCOPE and NUMIS) currently used for NMR experiments, τ is set at a constant of 40ms. The pulse is supposed to be much shorter than the signal decay time. The carrier frequency of the current is equal to the Larmor frequency of protons in the local geomagnetic field H₀, which in the case of Pretoria would be around 1 277 Hz (H₀ ~ 30 000 nT) and for Cape Town around 1 107 Hz (H₀ ~ 26 000 nT)

While it is assumed that the wire loop is placed on a horizontal surface, the geomagnetic field \mathbf{B}_0 is inclined at an angle α . The pulse of alternating current passing through the wire loop creates an oscillating magnetic field \mathbf{B}_1 . The component of the transmitted field, $\mathbf{B}_{1,1}$, which is perpendicular to the geomagnetic field, causes the nuclear magnetization of protons to shift away at an angle θ from the equilibrium position along the geomagnetic field. After the pulse is

terminated, the nuclear magnetization returns to its equilibrium position and creates a decaying alternating magnetic field. This alternating magnetic field can be measured by switching the antenna from transmitter to receiver. As \mathbf{B}_{1} depends on both the transmitting field and the inclination α , the signal also should depend on the antenna configuration and the geomagnetic field.

To determine the Larmor frequency in the field, a standard proton magnetometer is normally used. The Larmor frequency can be calculated by using Equation 3 above and it can be taken as the first approximation to set up the pulse frequency. For reliable detection of the NMR signal, the pulse frequency should not differ by more than ± 10 Hz from the Larmor frequency of protons in the water saturated subsurface. Under conditions of a fairly constant magnetic field, it is not difficult to obtain the required accuracy. If no NMR signal is recorded, it is concluded that no ground water is present in the subsurface below the loop (provided the signal strength is within the sensitivity of the instrument). If the signal is large enough, the instrument measures the frequency of this signal. This frequency is equal to the Larmor frequency of protons inside the investigated water saturated layer. Once this frequency has been established, the pulse frequency should be adjusted according to this new Larmor frequency value and measurements can be started. Small variations in the geomagnetic field over the area of the loop explain a possible difference between the Larmor frequency of protons on the surface (as measured by the proton magnetometer) and those within the aquifer (derived from the first test records). For this reason the procedure of the adjustment of the pulse frequency using the initial NMR signal is recommended.

The magnetic resonance signal oscillates at the Larmor frequency and has an exponential envelope:

$$e(t,q) = E_0(q) \sin(\omega t + \varphi_0) \exp(-t/T_2)$$
 (3.5)

where E_0 is the initial amplitude, T_2 is the decay time, ϕ_0 is the phase, and $q = I_0 \tau$ is the pulse parameter.

As γ is the physical constant characterising nuclei precessing with a magnetic moment, these nuclei have specific values for the Larmor frequency, which is given by **Equation 2**. Thus, by varying the frequency of the pulse in accordance with the Larmor frequency in the geomagnetic field, the chemical element for investigating may be selected. With current technology, only the hydrogen (H) element produces a detectable signal in the natural environment and thus the current application of NMR is focussed on the ground water and oil exploration industries.

E₀, T₂ and n₀ are to be measured by varying the pulse parameter q. In earlier research reported by Legchenko *et al* (1990); Schirov *et al* (1991); Legchenko and Shushakov (1997); Kleinberg and Vinegar (1996); Kenyon (1997); Prammer *et al* (1996), relationships between the measured parameters of the NMR signal and hydrogeological parameters of aquifers have been established. For example it was established that

 a non-zero signal can be directly correlated to the presence of water in the subsurface;

- (b) from E₀(q) measurements the water content, location and thickness of aquifer layers may be derived;
- (c) the decay time T₂ correlates with the mean size of pores of water saturated rocks;
 and
- (d) the phase no is sensitive to the electrical conductivity of the subsurface.

Assuming homogeneity of the geomagnetic field and horizontal stratification, the NMR signal can be calculated using

$$E_{\circ}(q) = \int_{0}^{\infty} K(q, z)n(z)dz \qquad (3.6)$$

where

$$K(q,z) = \omega_0 \mathbf{M}_0 \int_0^{\infty} \mathbf{B}_{1\perp} \sin(\theta) dxdy$$

$$\theta = 1/2\lambda \mathbf{B}_{1\perp}q$$

$$\mathbf{B}_{1\perp} = \mathbf{B}_{1\perp}[\mathbf{r}, \rho(\mathbf{r}), \alpha] = \mathbf{B}_{1\perp} / I_0$$

p(r) is the rock resistivity

 $0 \le n(z) \le 1$ is the water content; and

r = r(x,y,z) (Shushakov and Legchenko, 1994a, 1994b; Shushakov, 1996; Legchenko et al, 1996).

Protons removed from the antenna at a distance of more than 2D (D is the antenna (loop) diameter) produce a negligible small part of the total signal, and for calculations the range of integration in **Equation 4** can be restricted by $x,y,z \le 2D$.

Taking onto account the fact that the nuclear spin for protons is 2, the following equation can be written for nuclear magnetization:

$$M_0 = (\gamma^2 \hbar^2 / 4KT)NB_{\perp} \qquad (3.7)$$

where \hbar and k are Planck's and Boltzman's constants, respectively, N is the number of protons per unit volume and T is the temperature. In aquifers studied thus far, and at depths down to about 100-200m in unconsolidated formations, the number of protons varies according to the water content but the temperature does not vary significantly. However, the geomagnetic field does vary significantly worldwide which changes the value of M_0 . From **Equations 2, 6 and 7** it can be shown that

$$E_0 \approx B_0^2$$
(3.8)

The magnetic resonance signal is therefore a quadratic function of the magnitude of the geomagnetic field and it is proportional to a whole number of protons within the volume $x,y,z \le 2D$. The time diagram of the pulse transmission and the signal recording is depicted in Figure 3.2 (Legchenko *et al*, 1997, IRIS, 1999). With the HYDROSCOPE instrument the pulse duration is

40 ms and the period between transmitting and receiving ("dead time") is also 40 ms. With the French NUMIS instrument the pulse duration is programmable and may be varied between 5 and 100 ms, and the "dead time" is 30 ms. The recording time is fixed at 200 ms with HYDROSCOPE and may be programmed between 100 and 1000 ms with the NUMIS instrument. Although with NUMIS the pulse duration is programmable, it appears that a 40 ms pulse is rather optimal for an antenna 100 m in diameter.

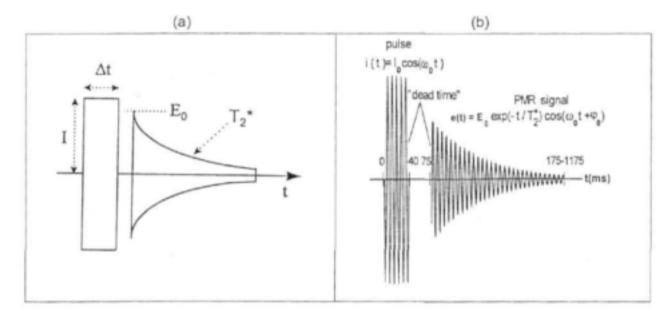


Figure 3.2: Schematic representation of the NMR excitation pulse (after IRIS, 1999 and with Δt = τ and E₀ is the signal extrapolated back to zero time) and the subsequent decay when current in the transmitter coil is switched off (after Legchenko et al, 1997).

In aquifers composed of non-magnetic rocks (an important assumption for the NMR application) the decay time of the magnetic response signal depends on the mean size of pores. It may vary between less than 30 ms in a very fine material aquifer (clays and fine sand), and about 1000 ms in a lake (100% water). Loren (1972); Prammer et al (1996) and Kenyon, (1997) studied the effect of mean pore size on the measured NMR signal by correlating the pore size with the decay time. They found that for a decay time of less than 200-300 ms, the condition set earlier that the pulse duration should be much shorter than the decay is not valid.

As the signal can be recorded with the "dead time" delay, it can be written as

$$E = E_0 \exp(-t_d / T_2^*)$$
 (3.9)

where E is the recorder amplitude, and t_d is the "dead time". This indicates that even with the simplified model the decay time T_2 may affect the water detection capability of the NMR technique. Water bound to the surfaces of pores has a short relaxation time (Kleinberg and Vinegar (1996), and thus only "free" water which has longer relaxation times, will normally be detected. Numerous field tests have led to approximate correlations between observed relaxation time and type of strata containing water (Table 3.1).

The most important factors that have an influence on the measured amplitude of the magnetic resonance signal are

- the amount of water present and the mean size of the pores in the formation saturated with water;
- (b) the magnitude and inclination of the magnetic field;
- (c) the size (dimension) of the antenna (transmitter and receiving wire loop); and
- (d) the electrical conductivity of the subsurface.

The influence of these factors can be evaluated using Equation 6.

TABLE 3.1 Approximate correlations between observed relaxation time and type of strata containing water.

Relaxation time (ms)	Strata containing water	Relative permeability	
<30	Sandy clays		
30-60	Clayey sands	Low	
60-120	Fine sands		
120-180	Medium sands		
180-300	Coarse and gravelly sands	Medium	
300-600	Gravel deposits		
600-1500	Surface water bodies	High	

Other extensive discussions on the mathematical background of the NMR method as applied to ground water exploration is provided in Semenov (1987); Khmelevskii and Chekanov (1989); Lieblich et al., (1994); Goldman et al. (1994); Trushkin et al. (1994); Shushakov (1996); and Legchenko and Shushakov (1998).

3.4 Currently available NMR instrumentation

3.4.1 The Russian "HYDROSCOPE" instrument

As mentioned earlier, the NMR method was first successfully applied as a geophysical technique in the late 1970s by group of Russian physicists (Schirov et al, 1991). They called the instrument the "HYDROSCOPE" which consists of transmitter and receiver units. The same Russian group at Novosibirsk, which forms part of the Russian Academy of Sciences, who pioneered the development of the first system called the "HYDROSCOPE", are still active in further developing their system, and have made it available for commercial application by private companies. One such company is V/O "ZARUBEZHGEOLGIA" operating from Moscow. The Israeli Government organization, the Institute for Petroleum Research and Geophysics cooperates closely with the Russian based firm Hydroscope Ltd and also markets their services internationally using the Russian HYDROSCOPE equipment.

The equipment consists of a signal generator feeding into a large wire loop, a control unit and a receiver. The signal generator generates alternating current pulses from a set of four 12V batteries coupled in series. The NMR signal received from the water protons, is then amplified by

the receiver. The control unit consists of a computer responsible for the various switching and other control functions.

As the NMR signal from the HYDROSCOPE is very weak, all possible measures need to be taken to avoid unnecessary electrical "noise" interference. For that reason batteries are used as energy source. Interference can also be expected. Field work should therefore ideally not be done in close proximity to power lines, railway lines and other sources of electrical noise.

The transmitter, with a diameter of 100m, consists of a single conductor (minimum surface area of 25 mm²) loop. According to the literature, this loop size will investigate an area of approximately 200m² (Shirov et al., 1991). As the pulse length is of the order of 200 ms, a capacitor network, with a total value of 0.1 Farad at 300V is used and, provided the capacitors are fully charged, can deliver a peak pulse current of 22,5kA. Results published in Russian publications indicate that their equipment achieves q values of the order of 10² to 10⁴ A.ms. Van der Merwe (1992) calculated that for a single conductor loop of 100m diameter, and a pulse current of 22.5kA, a field strength of 4mT can be generated in the loop. Total mass of the HYDROSCOPE power source unit is 600kg and takes up an area of about 5m² (including other measuring instrumentation and control units). These figures are based on 1991 information, and it is not certain whether improvements to the system since then have reduced the mass and size of the system.

3.4.2 The French "NUMIS" and "NUMIS" instruments

A French company called IRIS Instruments, a joint venture of the French Geological Survey (BRGM) and OYO of Japan, have entered into an agreement with their Russian colleagues from ICKC, to further develop the theory, instrumentation, interpretation techniques and software of NMR. Some of the Russian team members have been seconded to IRIS to work on the improvement of the technique in general. Two versions of an improved HYDROSCOPE have been developed by IRIS Instruments. These are called NUMIS and NUMIS PLUS.

IRIS Instruments prefer to refer to the technique as *Proton Magnetic Resonance (PMR)* instead of NMR for obvious reasons. Similar to HYDROSCOPE, their system is also powered by 12V batteries, but they only use two 60 Ah ones compared to the four used in the Russian system. The transmitter is supplied from a DC/DC converter with a capacitance of 0.1F at 400V DC at a current of 0.5 A. Although neither the size nor mass is specified in the brochures, it is significantly smaller and lighter than the HYDROSCOPE. The latest version of NUMIS, called NUMISPLUS consists of

- two converter units powered by two 12V 60Ah batteries.
- two tuning units for optimizing the excitation energy,
- a transmitter-receiver unit for pulse generation and signal measurement,
- a wire loop used both as transmitting and receiving antenna, and
- a laptop PC for the control of the entire system, and for data processing and interpretation.

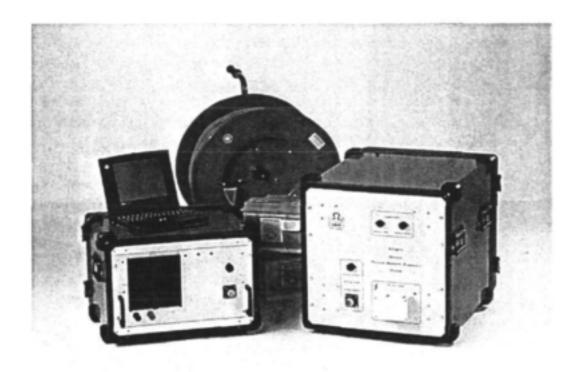


Figure 3.3: NUMIS NMR equipment (from IRIS, 1999).

The equipment is shown in **Figure 3.3** and a schematic diagram of the **NUMIS**^{PLUS} equipment is shown in **Figure 3.4**. Some of the technical specifications of the equipment are:

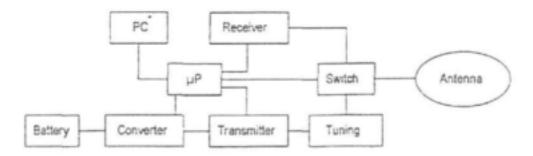


Figure 3.4: Schematic diagram showing the different components of the NUMIS and NUMIS PLUS system (from IRIS, 1999).

DC/DC converter unit

- Power supply: two 12V 60Ah batteries
- 6-8 hours recording autonomy
- Capacitance: 0.05 F
- Outputs: ∀400V DC; 0.5A
- Two converters may be used in parallel

Transmitter

- Supplied by one or two DC/DC converters
- Frequency range: 0.8 to 3 kHz

- Maximum output: 4000V, 450A
- Pulse amplitude and duration: Programmable
- Pulse moment: 100 to 18000 A.ms (loop and frequency dependant)

Receiver unit

- Band pass filter width: 100Hz
 Programmable gain: 10⁴ to 10⁶
 Noise less than 10 nV/Hz^{1/2}
- A/D converter: 14 bits
- Sampling frequency: four times the Larmor frequency
- Calibration procedure for phase reference

Tuning unit

- Tuning of the loop to the Larmor precession frequency by capacitors
- Capacitance of 9 to 30μF with one tuning unit and up to 60μF with two units

☐ Transmitting/Receiving loop

- Reels of 100m wire, 10mm² section
- Six reels for 150m investigations: impedance 1 ohm, 1.1 mH
- Four reels for 100m investigation: impedance 0.6 ohm, 0.7 mH
- Other loop configurations on request

PC computer

- Control of the entire system: converter, transmitter, receiver
- Data processing: DFT and weighted stacking
- Data interpretation: 1D inversion

IRIS Instruments also specify that the excitation frequency varies between 1.5 and 3.0 kHz and will depend on the amplitude of the local Earth's magnetic field. The excitation current in the loop has to reach intensities of 200-300 A, during a pulse that lasts a few tens of milliseconds, at the excitation frequency. As is the case with HYDROSCOPE, the relaxation time of the protons is measured in the same (transmitter) loop after the excitation current is switched off.

3.4.3 Comparison between HYDROSCOPE and NUMIS

Apart from the earlier more general descriptions by the Russian developers of the HYDROSCOPE equipment, little technical detail was known. In an article presented at the NMR workshop in Berlin in 1999, Schirov and Gatiatullin (1999), Fomenko and Shushakov (1999), Gjulumjanz et al (1999) and Schirov and Roykovski (1999) presented some comparative information on the different NMR instruments available, techniques in field measurement and new developments in the modern instruments. In a paper presented at the 58th EAGE Conference in Amsterdam in 1996 Legchenko (1996b) described some field procedures and expanded on the practical accuracy of surface NMR measurements

3.5 Field procedures

Before any NMR measurements are performed, a few other measurements at the NMR sounding site are necessary. A ground magnetic survey over the area where the loop is to be laid, and a Vertical Electrical Sounding (VES) or electromagnetic sounding are prerequisites before a MRS

is carried out. The magnitude of the Earth's magnetic field within the loop area should be measured using a proton magnetometer as this is required to calculate the Larmor frequency of hydrogen protons to be excited in the area to be investigated. A typical layout is to survey along three azimuths: perpendicular, parallel and diagonal to the main direction of the magnetic field within the area of the loop. Such a survey also provides spatial information on the presence of any magnetic structures in the survey area and indicates whether gradients in the local magnetic field are present. The inclination of the magnetic field at the survey site is required during the interpretation phase and can usually be obtained from topo-cadastral maps.

The geoelectric depth profile or vertical distribution of ground resistivity is required for the interpretation phase and can be obtained by the application of any of the known resistivity techniques, such as Electromagnetic or Vertical Electrical Soundings. In conductive terrain, a single loop TDEM sounding will provide the required information.

A low resistivity insulated copper wire is used for the MRS Transmitter/Receiver loop (Tx/Rx). Several different loop geometries are currently used. Because the magnetic field of the circular loop with a current passing through it is well known from the electromagnetic theory, a circular loop which exhibits an axial symmetry about the line passing through the centre of the loop perpendicular to its plane is the preferred configuration. However, for practical reasons a rectangular loop with similar surface area is normally used. The aim with using different loop configurations is to improve the signal quality. The magnetic responses of the square loops are similar to the response of their circular analogues.

Trushkin et al (1994) proposed the use of a "figure eight" shaped antenna where two smaller circular loops are used. A circular-eight loop configuration consists of two touching coils with currents flowing in opposite directions. The magnetic field of this two-coil loop has no axial symmetry. The noise reducing property of this loop configuration is based on the principal that when recording an MRS signal the external electromagnetic noise induces an emf in each coil. These cancel each other because the coils are connected in opposite directions, whereas the NMR signals, induced by the protons in the ground water, in each loop add up. Despite the lower signal strength, and thus shallower investigation capability, obtained with this configuration, the noise reduction achieved with this loop configuration can be of great advantage in high noise environments. An advantage of the figure-eight loop configuration is that the signal from vertical structures is maximised due to improved coupling with vertical structures. In practice, two rectangular loops touching at one corner, are usually used.

For investigating ground water occurrences associated with linear or directional geological structures, such as dykes and fault zones, Roy (1999) proposed the use of a multiple-eight square loop configuration. Improved coupling with vertical structures is achieved with a figure-eight loop configuration resulting thereby maximizing the signal. A major advantages of this loop configuration compared with the previous ones are that it concentrates the magnetic field on a small linear area beneath the loop and reduces the noise levels significantly when compared to that of the normal square loop (Owuor, 1998). The trade-off is that the depth of investigation is also reduced considerably. The different loop configurations used in NMR soundings, and the associated magnetic field distribution, is shown in Figure 3.5.

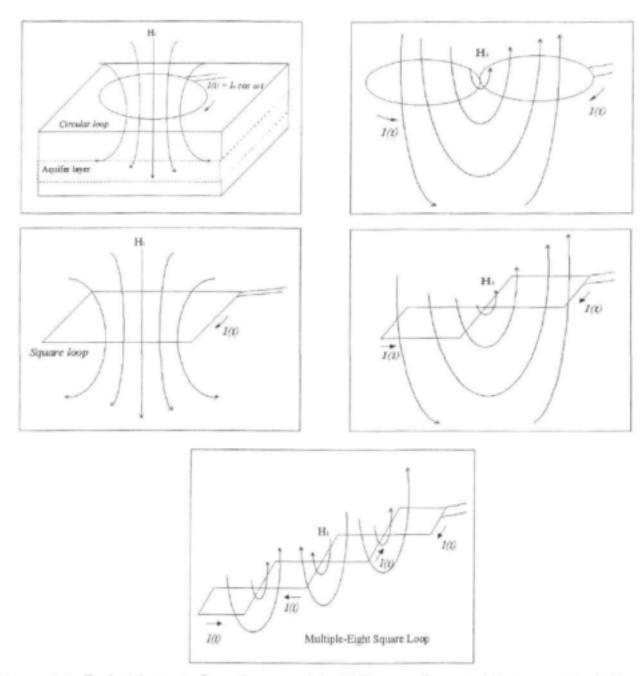


Figure 3.5: Typical loop configurations used in NMR soundings and the magnetic field distributions associated with each of the configurations.

3.6 Publications dealing with effects influencing NMR sounding curves

Not many articles have addressed this issue, probably because the initial experiments were mainly done in areas where the NMR signal was large and surveys were designed in such a way to stay away from man-made noise (e.g. powerlines, fences, engines). The article by Trushkin et al (1994) in which he describes the "figure-eight" transmitter loop is perhaps the first indication that noise effects started to influence the measurements and thus new ways to combat this were

developed. The first application of NMR in the USA described by Lieblich *et al* (1994), illustrated the problems associated with powerlines and reports on the improvement of the S/N using the "figure-eight" transmitter loop instead of the conventional square loop. Lavely and Blohm (1998) also briefly describe influence on the NMR signal from their experiences in the USA. Roy *et al* (1998a) eluded to the increasing problems experienced in Europe with man-made noise such as cultural 50/60 Hz harmonics, effects of man-made or natural conductors, geological inhomogeneities, time of day and latitude effects, after doing field surveys in France, Spain and The Netherlands. Supper *et al* (1999) reported on an experience in Pulkau, Austria where it was impossible to obtain reliable field data because the proton resonance frequency, calculated from the local magnetic field, is a multiple of the 50 Hz frequency used in the electricity network. They had a similar experience at Marz, where background noise reached levels of 6000 to 60 000 nV. They make the statement that, because of the local magnetic field values, the 50 Hz harmonic problem will be experienced in most parts of Austria.

The first NMR tests in southern Africa coordinated by Dr Jean Roy of the ITC in The Netherlands (Roy and Lubczynski, 2000a), and which this project formed part of, dramatically illustrated the effects of weather patterns, and in particular thunderstorm activity, on the quality of the field data and the associated instrument problems. In addition, the signal strength is already approximately 4 times lower in southern Africa due to the much lower geomagnetic field in the region compared to that in Europe for example. More detail on these problems is presented later in the report and has also been addressed in an MSc thesis at the ITC ((Martinez del Pino, 2000) and articles and reports by Meyer (1999), Lange et al (2000), Knödel et al, (1999) and Roy and Lubczynski (2000a). Papers and reports by Lanzerotti et al (1990), Chrissan and Fraser-Smith (1996a, 1996b, 1997) and Fraser-Smith and Bannister (1998) provide some insight into the diurnal and seasonal variations of globally measured extremely low frequency (ELF) and very low frequency (VLF) radio noise that will affect NMR measurements negatively and will assist in planning the periods over which successful surveys can be done.

3.7 Resolution and limitations of the technique and the instrumentation

3.7.1 Introduction

The Steering Committee requested that the resolution characteristics of the NMR be investigated for a variety of conditions. Specifically the fractured aquifer conditions encountered in South Africa were to be modelled to determine the applicability of the technique for the South African conditions. The WRC granted permission for the author to spend some time at the ITC in the Netherlands with Prof Roy to work on these models and prepare a document on the feasibility of applying the technique under local geohydrological conditions using the instrumentation technology available at this time in the development of the technique.

This section of the report addresses a number of simulations to test the applicability of the technique under the following three specific categories:

- simulations of geohydrological models that have been reported in the literature;
- specific questions that have arisen out of the current project; and

geohydrological conditions that are specific to fractured aquifer conditions in South Africa.

Sections 3.5.2 to 3.5.6 deal with the first two conditions, whereas Section 3.5.7 addresses some typical cases of fractured aquifers in South Africa. These simulations were done in conjunction with Dr Roy of the ITC and an MSc student, Mr Martinez del Pino, at Delft.

To illustrate the resolution of the NMR technique under different conditions, a number of theoretical models were taken from published articles as well as calculated using software supplied by IRIS Instruments. Theoretical modelling of different geohydrological conditions, such as water content, depth, aquifer thickness, loop shape, provides a way to assess the limitations and resolution of the technique. The following examples will be discussed in the next few paragraphs:

- Effect of inclination and field strength of the geomagnetic field on NMR signal.
- The NMR response for an aquifer of constant thickness, but with varying saturated porosity and depth of burial and using a square-eight loop configuration.
- Hydraulic characteristics of water-saturated rocks (quantity and location of water, and rock pore-space characteristics) and how these affect the NMR sounding results.
- Equivalence in NMR response for different aquifer conditions.
- Effect of different loop configurations and sizes.
- Effect of conductive subsurface on NMR signal.
- Effect of fractured rock aquifers with different densities of fractures, varying depths of fractures and different water content.

Some of the examples cited were taken from the published literature, whereas several specific examples for South African fractured aquifer conditions were calculated while the author spent some time at the ITC in Delft, The Netherlands and did some modelling together with Dr Jean Roy of the ITC and Mr Martinez del Pino, a MSc student at the ITC. Examples are taken from G Lange, Technical University Berlin (pers. Comm.), Pusep et al (1991); Owuor (1998); IRIS Instruments (1998); Goldman et al (1994), Schirov et al (1991); Trushkin et al (1995); Shushakov (1996), Legchenko et al (1997c); Legchenko and Shushakov (1998).

3.7.2 Effect of the geomagnetic field strength and inclination of the magnetic field

It has earlier been shown that the NMR signal strength is directly proportional to the square of the geomagnetic field (**Equation 9**). Over southern Africa the total magnetic field strength varies between approximately 26 750 nT in the south (Cape Town), to approximately 31 000 nT in the northern part of Botswana. In comparison, southern Australia which is at approximately similar latitudes, the total field strength is almost double (~60 000 nT). In Central and eastern Europe where most of the NMR field work has been done to date, the field is of the order of 45 000 nT to 55 000 nT. In **Table 3.2** a comparison is made of the relative NMR signal strength based on the local geomagnetic field alone, and assuming equal geological and aquifer conditions. These results illustrate the significant effect that the magnetic field intensity has on the signal strength.

This effect is also graphically illustrated by the different curves shown in Figure 3.6. Here the signal strength is shown for different aquifer depths with a water content of 10% at a magnetic

inclination of 40°, using an Figure-eight square loop with 100m sides.

Table 3.2: Total magnetic field values and effect on NMR signal strength

Total Magnetic field (nT)	Relative NMR signal strength	Geographical reference
26 000	1	Cape Town, Central South America
30 000	1.33	Northern Botswana
35 000	1.81	North Africa
40 000	2.37	Southern India
45 000	3	Central Europe, The Netherlands
50 000	3.7	Northern Australia
55 000	4.47	United States, Central Russia
60 000	5.33	Southern Australia

Martinez del Pino (2000) calculated the impact of the magnetic inclination angle on the NMR signal strength for a 10% water content in an aquifer situated at depths varying from being at the surface to 100 m below surface. The results are shown in **Figure 3.7**. This result is very significant as it indicates that in the case of aquifers in excess of 20m thickness, the magnetic inclination will have no influence on the NMR sounding curve.

3.7.3 Effect of aquifer thickness, depth to aquifer and saturated porosity on signal strength

Goldman et al (1994) and Legchenko et al (1997c) stated that the amplitude of the MRS signal is proportional to the total volume of water contained in the aquifer. Studies conducted in the borehole logging industry also established a relation between the decay time constant and the percentage of water saturation (Figure 3.8) (Loren, 1972; Prammer et al, 1996; Kenyon, 1997).

The effect of loop configuration and depth to the aquifer as a function of the inclination of the magnetic field on the NMR signal strength, has been studied by IRIS Instruments. They have prepared graphs of signal strength versus pulse moment for three different inclinations (0° [equator], 45°, 90° [pole]) and for two different loop configurations (square loop and Figure eight square loop). The geohydrological model is in all cases the same. These are shown in Figure 3.9. From these it can be seen that, in the case of the 75m side square loop, the signal is the largest at the pole, and only about 40% at the equator. It is also clear from these that the resolution deteriorates quickly with depth of the aquifer. At depths beyond 50m, large excitation moments (>10 000 A.ms) are required in order to resolve the aquifer layer as a separate "layer". For the Figure-eight shape loop the signal is about 60% of that of the square loop and the aquifer layer cannot be identified when buried deeper than 30 m.

Legchenko et al (1997c) report on NMR experiments done on a frozen lake in Russia. The upper 1 metre of the lake was frozen followed by 10m of water. The NMR sounding curve obtained from this experiment had a two layer response and was modelled as a upper "aquifer" with 100% saturation, underlain by a second aquifer at a depth of between 50m and 100m with a water content of 5%. The field curve and the modelled results are in good agreement (Figure 3.10).

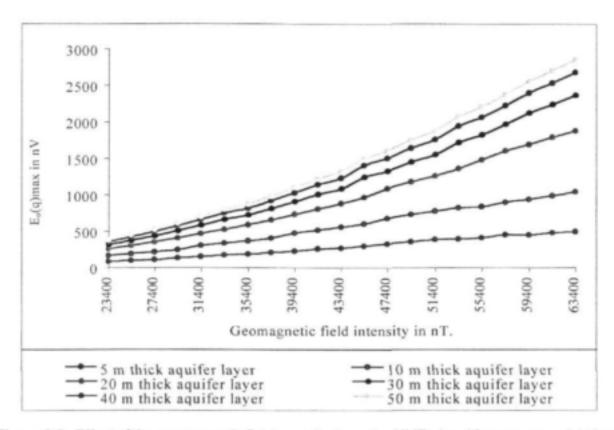


Figure 3.6: Effect of the geomagnetic field magnitude on the NMR signal for a square-eight loop with side length of 100 m. Water content is 10% and the magnetic inclination at 40 degrees (after Martinez del Pino, 2000).

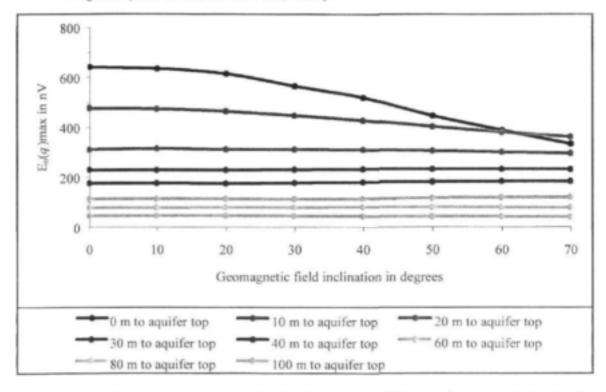


Figure 3.7: Effect of the geomagnetic field inclination on the NMR signal strength (after Martinez del Pino, 2000).

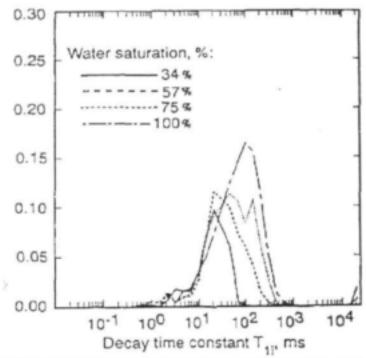


Figure 3.8: Decay time constant measured in a sandstone sample with different percentages of water saturation (after Kenyon, 1997)

Martinez del Pino (2000) investigated the effect of water content on the NRM response for a 5m thick aquifer at different depths and at a constant frequency and magnetic field inclination of 40 degrees using a square -eight loop configuration with loop sides of 100m. These conditions were modelled using a programme kindly made available by IRIS Instruments. The results are displayed in Figures 3.11 and 3.12.

Figure 3.11 indicates a linear relationship between water content of the formation and the NMR signal strength. From Figure 3.12 it is also clear that the position along the x-axis of the maximum signal is directly related to the depth of the aquifer layer, and independent of the water content. The percentage water content in the aquifer determines the amplitude of the signal.

In Figures 3.9 and 3.12 the effect of depth to the top of the aquifer (constant water content, aquifer thickness and same magnetic inclination) is clearly illustrated in that the amplitude of the signal decreases with depth and an increased pulse moment is required to recognize the

presence of the aquifer layer (position of maximum moves towards the right). Pusep et al. (1991) were the first to calculate the effect of varying depth to the aquifer and aquifer thicknesses on the signal strength. The magnitude of the signal is relative and indicates the signal strength is reduced about 5 times when the aquifer thickness is reduced by a factor of 10.

In Figure 3.13 the theoretically calculated NMR response for different depths and thicknesses of the aquifer is illustrated. These curves have been calculated by Pusep et al (1991). The depth to the aquifer is clearly associated with the position of the maximum along the q axis. These curves can in principle be used to solve an inverse problem (i.e. finding the parameters of the water layer) by means of either manual or automatic curve fitting as carried out in conventional geoelectric sounding interpretation methods.

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3.7.4 Effect of different loop configurations and size

To test the effect of five different loop configurations, a 5 metre thick aquifer (at 10% water content) was placed at different depths in a geomagnetic field strength of 45 000 nT and an inclination of 54°. The loop configurations used were circular, circular figure-eight, square, square figure-eight and multiple square figure-eight. The results are shown in **Figure 3.14**.

The results show that the circular loop results in the largest signal, and that with a circular and square configuration a resolution of approximately 100m for the aquifer can still be attained. With the square loop the signal is approximately 10-20% less than with the circular loop. The multiple square figure-eight loop may be good to investigate linear features, but is not suitable for investigating deep aquifer conditions.

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For a horizontally stratified and homogeneous aquifer, the larger the investigated area, the larger the amount of the excited hydrogen protons and hence the larger the signal amplitude. The signal amplitude is controlled by the sensitivity of the loop as a receiver, which is a function of its area. This statement is valid provided the aquifer is continuous below the loop and also extends beyond the dimensions of the loop. If the aquifer is however not continuous, as the case may be for a lens of water or a fracture controlled occurrence of water, increasing the loop size will not increase the signal size (Legchenko et al., 1997c).

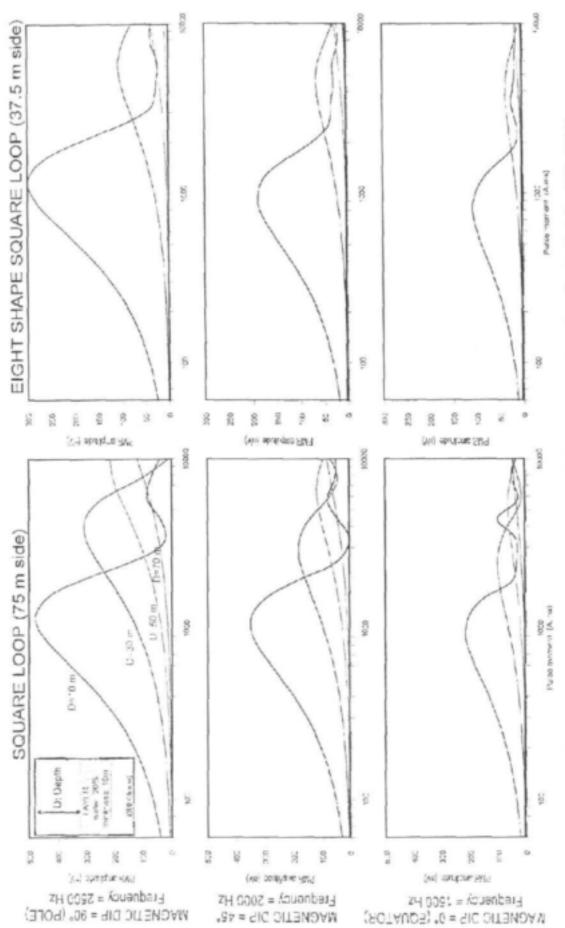
Four different loop sizes (square loop configuration with dimensions of 25x25m, 50x50m, 100x100m and 150x150m) were used for modelling the effect of loop size on the signal strength. The aquifer was taken to be 5 m thick, with a 10% water content in a magnetic field of 30 000 nT and an inclination of –64° (Northern Province, SA). The results are shown in **Figure 3.15**.

Similar calculations and observations can be made for different magnetic field strengths. The only difference will be that the signal amplitude is higher for higher magnetic field strengths and hence even the 25x25 m loop may be found suitable to be used in places.

3.7.5 Distortion of NMR signal due to electrically conductive formations

The conductivity of the medium investigated and the effect it will have on the NMR signal can be quantified by the skin depth. Electromagnetic theory states that the signal is attenuated to approximately a third (36.8%) of the initial signal at a depth $\delta = 503(\rho / f)^{\%}$ where ρ and f are the resistivity of the medium and frequency respectively (Telford *et al.*, 1990).

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MRS ground water exploration technique with applications to South African fractured rock aquifers

Figure 3.9: Effect of geomagnetic field intensity on NMR signal strength and aquifer depth (after IRIS, 1999)

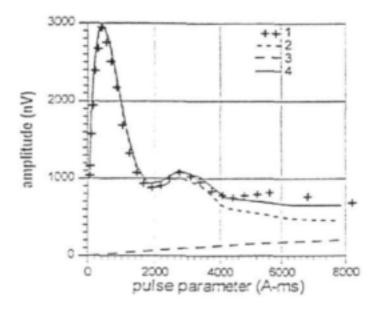


Figure 3.10: Field data measured on the Ob Lake in Russia. Curve 1 is the field curve; Curve 2 represents the modelled signal response from the water body in the lake (10m at 100%); Curve 3 represents the response from the second aquifer at a depth of between 50 and 100m; and Curve 4 is the cumulative response of the two "aquifers" (After Legchenko et al, 1997c).

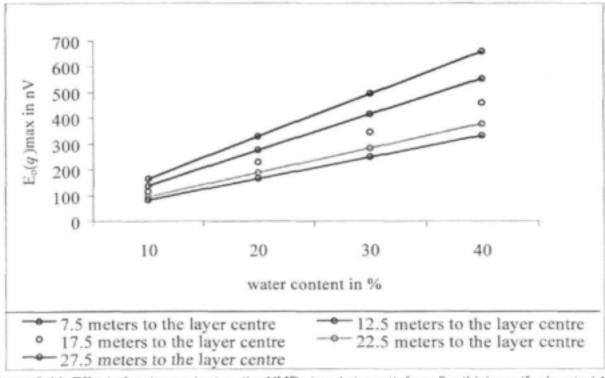


Figure 3.11: Effect of water content on the NMR signal strength for a 5m thick aquifer located 10 m, 15 m, 20 m and 25 m depth. A square eight loop configuration with L=100 m was used, frequency of 1252.4 Hz and inclination angle of 40 degrees (after Martinez del Pino, 2000).

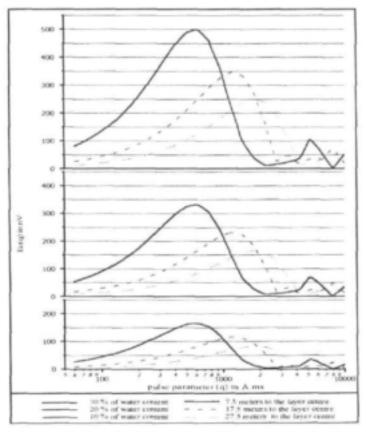


Figure 3.12: Aquifer layer of 5 metre thickness with degrees of water saturation and depth below the surface. Same loop configuration, inclination and frequency as in Figure 3.11 (after Martinez del Pino, 2000).

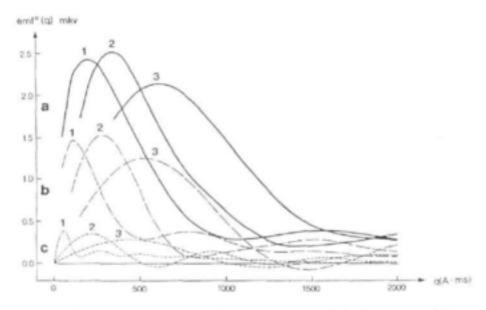


Figure 3.13: Theoretical NMR response for different depths and thicknesses of the aquifer: \triangle h= 10 m and h₁: 1=1 m; 2=5 m; 3=10 m; (b) \triangle h = 5 m and h₁: 1=1 m; 2=5 m; 3=10 m; and (c) \triangle h=1 m and h₁: 1=1 m; 2=5 m; 3=10 m. (after Pusep et al., 1991).

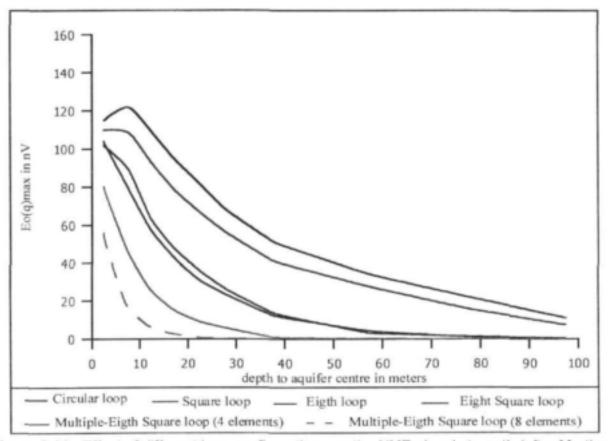


Figure 3.14: Effect of different loop configurations on the NMR signal strength (after Martinez del Pino, 2000).

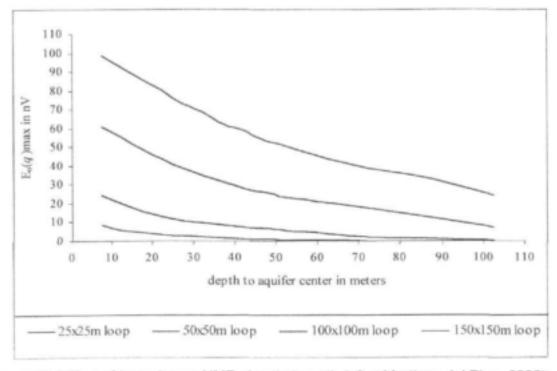


Figure 3.15: Effect of loop size on NMR signal strength (after Martinez del Pino, 2000).

Electrically conductive rocks may affect not only the alternating magnetic field H₁, but also the oscillating magnetic field generated by the precessing protons. In the case of electromagnetic soundings, attenuation and phase rotation of the EM signal occurs in both the primary and secondary fields, whereas in the case of NMR soundings, double attenuation and phase rotation occurs. The excitation signal as well as the signal from the precessing protons is attenuated and phase rotated. This will lead to a reduction in the depth of investigation when soundings in conductive environments are done. Thus the depth of investigation of the MRS technique will be reduced in the presence of conductive rocks.

In the modelling of these effects, the same aquifer parameters as used in Section 3.6.2 were used, but with a 100 m x 100 m loop size. Five earth resistivities were used in the models: 1, 10, 100, 1000 and 10 000 ohm.m. The results are shown in **Figure 3.16**.

From this graph it is clear that a highly conductive environment, say less than 1 ohm.m, has a significant effect on the signal strength. However, above a resistivity of approximately 10 ohm.m, the host rock resistivity has little influence on the signal strength. The effects of the resistivity of the medium on the MRS signal can be quantified by the skin depth. Electromagnetic theory states that the signal is attenuated to approximately a third (36.8%) of the initial signal at a (skin) depth $\delta = 503 \ (\delta/f)^{1/2}$ where δ and f are the resistivity of the medium and frequency respectively (Telford et al., 1990, Martinez del Pino, 2000).

The position of a conductive layer in the geological profile and the effect this can have on the NMR signal was also investigated through three 2 layer models. A factor 100 between the conductive and resistive layers in the mode was assumed (1 ohm. m and 100 ohm.m). Aquifer parameters were as before, and the maximum depth to the centre of the 10m thick aquifer was taken as 30m. The models used are shown in Figure 3.17 and the results of the modelling are shown in Figure 3.18. It is clear that significant attenuation occurs in the case of the conductive overburden. A conductive layer at depth enhances the signal amplitude, but as the depth of the conductive layer increases (thickness of resistive overburden increases), the signal amplitude is lower again. A possible explanation for this is that the conductive layer generates a secondary electromagnetic field as a result of induction by the primary current from the transmitter loop.

3.7.6 Equivalence in NMR response curves for different aquifers

Equivalence is defined as the situation where different geohydrological models will result in similar or nearly similar NMR sounding curves. Three conditions were investigated where the volume of water contained in the aquifer below the loop is equivalent. These three conditions were

- Aguifer 10 m thick with a porosity of 5%
- Aguifer 5 m thick with a porosity of 10%
- Aquifer 2.5 m thick with a porosity of 20%.

Signal response was calculated for these scenarios and where the depth to the centre of the aquifer is at depths of 10 m, 20 m, 40 m, 60 m, 80 m and 100 m. Loop size was 1m x 100 m, magnetic field at 30 000 nT and an inclination of -64 degrees (Northern Province conditions).

The ability of the NMR method to resolve the depth to the aquifer depends on the position of the maximum initial signal amplitude on the pulse parameter (q) axis. If this position and the amplitude do not change for a given set of aquifers, then similar equivalence conditions as in conventional electrical methods are encountered. The vertical resolution is also associated with the ability to obtain well-defined maximum initial signal amplitude. If this is not the case, then regardless of the signal detection and amplitude, vertical resolution of the aquifer position cannot be achieved. The results of the modelling are shown in two graphs, Figure 3.19 and Figure 3.20.

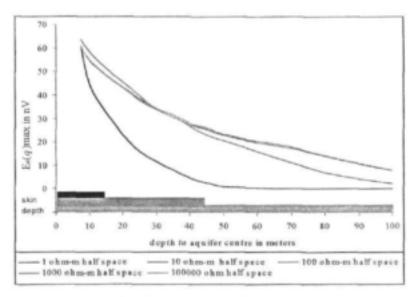


Figure 3.16: Effect of earth resistivity on the NMR signal amplitude. Aquifer 5m thick, 10% water content, loop size 100 x 100m, magnetic field = 30 000nT, and inclination at -64 degrees. Skin depth is indicated in the lower part of the figure: black = 14 m, blue = 44 m and red = 141 m (after Martinez del Pino, 2000).

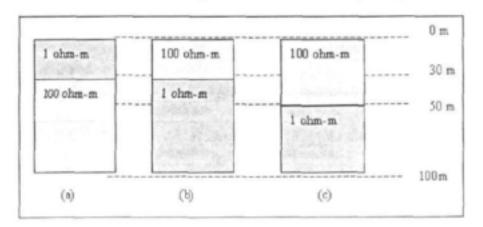


Figure 3.17: Models used to investigate the effect of a conductive layer on the NMR signal (after Martinez del Pino, 2000).

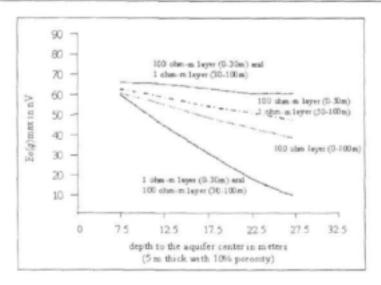


Figure 3.18: Effect of different conductive/resistive layer configurations on the NMR signal (after Martinez del Pino, 2000)

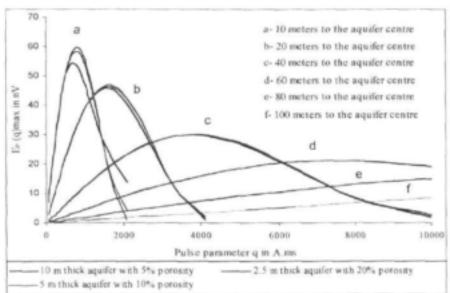


Figure 3.19: Illustration of equivalence in NMR sounding curves under different geohydrological conditions (after del Pino, 200).

The following conclusions can be made from these results:

- Under all conditions modelled, there is a well-defined maximum, which decreases gradually with an increase in depth.
- There is almost no shift in the position of the maximum signal amplitude under both the deeper and shallower aquifer conditions.
- Depth resolution is lost at a depth of about 50 m to the aguifer centre.
- The NMR signal amplitude is very similar for all three models. The aquifer response will be the same as long as the product of the aquifer thickness and porosity is constant for deeper levels.
- The position of the maximum on the q axis is very critical when studying cases of equivalence.

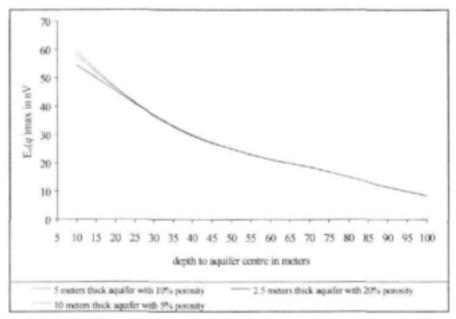


Figure 3.20: Maximum signal amplitude plotted against the corresponding depth to the aquifer centre for a 10 m, 5 m and 2.5 m thick aquifer with porosities of 5%, 10% and 20% respectively (after Martinez del Pino, 2000).

3.8 Classical examples from the literature describing the development of the technique as applied to ground water investigations

In his paper summarizing the historical development of the Surface Nuclear Magnetic Resonance technique, Schirov (1999) states that from the several hundred sites that have been investigated by conducting some 6000 SNMR soundings, the following main conclusions could be made and can be expressed as:

- SNMR can reliably detect ground water to depths of between 100 m and 200 m.
- In a homogeneous magnetic field, the effective exploration depth depends on the technical features of the instrument, geological, geophysical and geohydrological conditions:

$$H_{eff} = F(D, W, Q_{max}, T_2, S/N, \varphi, \alpha \emptyset, S)$$
 (3.10)

where D = diameter of the transmitter loop,

W= number of turns in the loop,

q_{max} = maximal excitation factor,

 T_2 = relaxation time,

S/N = signal to noise ratio,

φ = relative phase change during the experiment

α = geomagnetic inclination, and

S = sensitivity of threshold.

- Where the resistivity of the subsurface is > 20 ohm.m, quantitative interpretation can be done without having a priori data. When D>100 m, Q>15 000 A.ms, T₂ > 200 ms, S/N>0.5, and φ<20°, the interpretation can be carried out for depths between 50 m and 100 m, without having a priori information.
- Water in fractured aquifers, often produces NMR signals which are at least 10 times weaker than those from water in porous alluvial aquifers.
- The experience with the Aquatom equipment in Tatarstan indicates that the relative phase change is a reliable criterion to determine the quality of the interpretation. If the Phase change is less than 50°, the interpretation is good, if it is between 50° and 90° it is satisfactorily, and if it is more than 90° the interpretation is generally poor.
- Surveys near high voltage transmission lines should be avoided.
- Preliminary estimates have shown that phase shifts of more than 180°/10 000 A.ms to be an indicator of the presence of saline water.

In this formula Schirov has, however, neglected to mention that the quantity of water in the target, the earth's magnetic field B, and the resistivity of the earth is also required in order to obtain depth information (Roy, personal comm.; 2000).

One of the first reports published in the western world was a paper delivered at a seminar on geotomography in Hyderabad, India in 1987 by A G Semenov. In this paper he describes the general theory and applications of the NMR technique and concludes with an example from the Tabyakha River Valley where some 50 NMR soundings were done in an area largely covered by sand and clay. The results were displayed in the form of plans and cross sections indicating the cumulative water content of the formations in terms of the volume of water contained in a 1 m^2 vertical column. A contour map was constructed that showed the relaxation time T_2 which is directly related to the pore space in the alluvium.

An internal research report by Schirov et al (1990), followed by a publication by the same authors in 1991 (Schirov et al, 1991), described some of the results achieved in Australia. A common problem in Australia for electrical and electromagnetic geophysical techniques is the weathered and conductive overburden conditions which cover much of the continent. A major point of concern was the ability of the technique to perform under these electrically conductive conditions. Unfortunately they did not include any sounding curves in their published paper. Based on their results they made the following observations:

- The main limitation of the technique is the electrical noise generated by for example by the proximity of power lines.
- At all the trial sites it was possible to reliably determine the volume of underground free water, and less precisely, the depth and porosity of geological strata containing free water.
- In cases where there was no free water below 74 m, duplicate measurements showed that the repeatability of the measurement of free water volume up to a depth of 62 m, is less than 15% of the volume of free water measured. The detection of boundaries of geological strata containing free water depended generally on the noise environment and the coincidence of the physical system to the mathematical model. For this reason the aquifer boundaries could be detected less reliably.

- The conductivity of the geological layers, over the range encountered during the trials, was not a limiting factor, but led to increased measurement errors in cases.
- Measurement time per site depended on noise conditions and the volume of free water present, and varied between 40 minutes and 2.5 hours.
- The report only refers to the amplitude of the noise during the trials to be in the range of 20 to 150 nV, but does not mention the frequency. They established that the minimum distance between the measurement site and powerlines should be 300 m in the case of 220 V and 1 500 m in the case of 220 kV.

They concluded that:

- the main advantage of the NMR technology is the direct measurement of the volume of free water by a non-intrusive method. No other direct measurement technique exists with which this can be achieved;
- the major applications of the NMR technology are:
- direct mapping of the location and thickness of the underground water containing formations,
- the measurement of the volume of free water in each of the layers, and therefore the estimation of the potential yield of the aquifer;
- the estimation of the porosity of the strata containing free water, and hence estimation of the water conductivity in such strata
- the selection of the more promising areas for the development of abstraction schemes;
- the application of the NMR technology was proven under Australian conditions.

Earlier in this report (Section 3.7.3) reference was made to another classical experiment carried out in 1986 where the technique was calibrated on a frozen lake in Russia using the HYDROSCOPE equipment (Figure 3.10).

One of the few examples where the technique was evaluated in the United States of America, is by Lieblich et al, (1994). In the initial tests, a 100 m diameter circular loop was used as transmitter. The magnitude of the voltage induced in the loop by electromagnetic (EM) noise, was found to be in the microvolt range, whereas the NMR signal varied up to a few hundred nanovolts, resulting in a signal-to-noise ratio (S/N) of less than 0.1 despite applying extensive stacking. This S/N is insufficient to obtain reliable results from the inversion of the field data, and despite using stacking, a significant increase in time was required to do each NMR sounding. As a result of the high noise levels, two hours was allowed per sounding as a compromise between S/N improvement and time per sounding. The resulting improvement of about 10 to 15 times was still insufficient to obtain reliable results. A power line was believed to be the primary source of the EM noise.

In an attempt to improve the signal to noise ratio, Trushkin et al (1994) did some theoretical calculations for different loop configurations. The circular loop was re-configured to a "figure-eight" shape with its 100 m long axis orientated parallel to the power line. This resulted in a 3 to 5 times decrease in the magnitude of the noise, and about 30 to 75 times improvement using stacking. Nine MRS soundings were done using this "figure-eight" loop configuration. An

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example from these tests is shown in Figure 3.21. Trushkin et al, (1994) summarized the conclusions from these experiments follows:

- Each of the soundings correctly indicated the presence of water.
- The general trend of coarsening pore-size and increasing volume fraction of water with depth, indicated by the NMR soundings, correlates directly to the coarsening of the glacial deposits with depth as seen in the test hole data.
- The abrupt decrease in the volume fraction of water, may indicate the overburdenbedrock transition to a dense till.
- There is a lack of lateral correlation between NMR soundings, although good lateral continuity is shown by the geological descriptions of the test holes.
- The NMR data show variations in depth to the water table, which is inconsistent with the borehole data.
- There was an about 30 times improvement in S/N ratio when using the "figure-eight" loop configuration, allowing the soundings to be done within 100m of power lines.

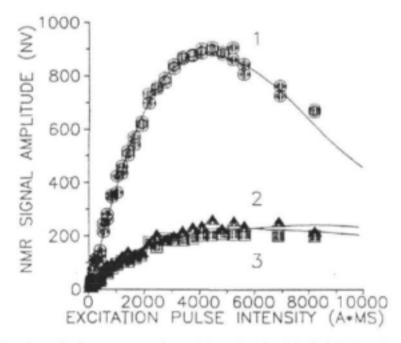


Figure 3.21: Comparison between experimental and calculated data to show the difference between (1) the normal circular loop (circles), (2) a two coil loop orientated from north to south (triangles), and (3) a two-coil loop orientated from east to west (squares). After Trushkin et al, 1994).

One of the classical papers on NMR is by Goldman et al (1994) in which an integrated NMR-TDEM survey was done on the coastal aquifers of Israel. By combining these two techniques they were able to distinguish not only the variation in water content with depth in the coastal aquifers using NMR, but also aquifers containing saline water using TDEM soundings. They described the results of 36 NMR and 12 TDEM stations occupied in the Negev Desert in Israel. Of these only 19 NMR measurements showed reasonable S/N characteristics while the rest were distorted by high ambient noise levels. Another limitation of the NMR in this part of Israel was

found to be the limited depth penetration of about 74 m. Nevertheless, a comparison with borehole data, showed that in most cases, the NMR technique, not only could detect the presence of ground water, but was also capable of delineating different subaquifers. At the same time however, the transmissivity of the aquifers are much less reliably resolved. In all instances where the NMR anomaly correlated with a drop in resistivity on the TDEM interpretation, water of a different quality was found at approximately the same depth. The TDEM anomalies reported were caused by low resistivity lithologies, while some of the false NMR signals could be explained by a low signal to noise ratio. The fresh water/sea water interface was in all instances accurately detected by the TDEM method. At the same depth, NMR measurements indicated a drastically increasing anomaly followed by the absence of water at greater depth. This has been explained by the authors as being the result of the very low resistivity of the sea water infiltrated aquifer, which could not be accommodated in the interpretation routines used for the NMR interpretation.

The authors conclude that:

- the integration of NMR and TDEM data has proved to be highly effective in detecting the presence and amount of ground water and in evaluating its quality;
- individual interpretations of TDEM data did, however, in many cases not fit the hydrogeological data;
- · false interpretations of the TDEM data were caused by low resistivity lithology;
- · the reliability of detecting water with NMR is much higher than that of TDEM;
- a comparison of the individual NMR and TDEM interpretations showed that NMR response has a higher resolving power than the TDEM method in detecting different subaquifers;
- the TDEM method proved its higher accuracy in determining mineralised ground water:
- in most cases where the NMR also showed the presence of highly mineralised water, the water concentration was drastically over estimated while the thickness of the saline water layer was significantly underestimated;
- in addition to the interpretation problems, it was concluded that the NMR method and the HYDROSCOPE in particular, suffer from severe hardware limitations. Particularly low ambient noise protection and limited penetration depth were the main limitations identified.

Unfortunately they did not publish any of their MRS curves, but only the geological and geohydrological interpretations thereof.

In the articles by Legchenko et al (1995) and Beauce et al, (1996) the results of NMR experiments on the same aquifer in France are described. However, in the case of the former article, the HYDROSCOPE was used, whereas in the second paper, the French NUMIS system was used. This allows comparison of the two sets of instrumentation. Two aquifers were studied; one in the north-eastern part of the Paris Basin at Bazancourt, and the other one was at St Cyren-Val in the southern part of the Paris Basin.

At St Cyr-en-Val three aquifers are present. The upper aquifer (20-25 m) consists of a mixture of sand, gravel and clay, and the other two aquifers consist of water saturated karst limestone separated by a sandstone layer at a depth of 50-60 m. The total thickness of the three aquifers is between 70 m and 80 m with an average porosity of 10% and a transmissivity of 2400 m²/d. At the Bazancourt site the aquifer consists of a fractured chalk with an average porosity of about 40% overlain by a few metres of other material. The chalk aquifer is between 100 m and 120m thick, has an average transmissivity of about 3000 m²/d and a permeability that varies depending on the development and density of the fractures. In the St Cyr-en-Val case the depth to the water table is not well resolved. The limestone aquifer between 28 m and 52 m (from drilling information) is clearly identified by the NMR sounding results which shows that no further water is to be expected below 55 m. The reason for the rather shallow depth of investigation is explained by the presence of the upper conductive layer (10 ohm.m) between 10 m and 28 m, which acts as a screen to deeper penetration by the NMR technique.

In the Bazancourt example, the depth to the water table is well resolved. Two aquifers are indicated by the NMR results. The presence of the second, deeper aquifer could not be confirmed from geological drilling as boreholes deeper than 25 m do not exist. A high water content (up to 35%) contained in small pores, as indicated by the short relaxation times of 30 to 50 milliseconds is indicated by the NMR results. Although variations in water content with depth could be inferred from the sounding data, these could not be correlated to geological formations due to a lack of geological depth control and too few deep boreholes. Regional geological information indicates that the second aquifer can extend to a depth of 120 m. Although the second aquifer was identified by the NMR method to extend to at least 85 m, it is not possible to resolve the total thickness of the aquifer. The short relaxation times observed, indicates fine grained material with lower water content (5 to 10%) and correlates well with the lower transmissivities and other geological observations. The NMR sounding curves, decay times, and phase are shown in Figure 3.22a, b and c respectively for the two areas with the interpretation shown in Figure 3.23.

Yaramanci and his co-workers have done several NMR studies in Germany (Yaramanci et al., 1998a; 1998b; 1998c; 1999a; 1999b; 1999c, 1999d; Möhnke and Yaramanci, 1999a; 1999b, 2000;) and have reported on a recent experiment in Namibia (Knödel et al, 1999; Lange et al, 2000). They usually combine their experiments with other geophysical techniques, especially resistivity tomography and borehole logging, and have also once successfully combined it with GPR. Extensive petrophysical tests are normally also included and then the NMR results are correlated with the petrophysical results. One such example is from the Haldensleben region in northern Germany (Yaramanci et al, 1999a). Some of their NMR sounding curves are shown in Figure 3.24. Surface NMR measurements were done at a few borehole locations and combined with resistivity, geophysical borehole logging, ground penetrating radar and laboratory determinations of permeability derived from grain size analysis. They concluded that the MRS method is able to detect ground water and the results are in good agreement with other geophysical and hydrogeological data. Using the MRS method, the water content of the unsaturated and saturated zones could be reliably determined. This information, together with the resistivity data permitted the in situ determination of other aquifer parameters. Comparison of the MRS results with borehole data clearly showed that the water content determined by the MRS method is the free or mobile water in the pores. The permeabilities estimated from the MRS

decay times are similar to those derived from sieve analyses of core material. They concluded that the empirical relationship between decay time and average grain size observed in many MRS surveys (for example Shirov $et\,al$, 1991) can be used advantageously in hydrogeological investigations (**Figure 3.25a**). Using a relationship between grain size and permeability developed by Hölting (1992) and often used in hydrogeology, they derived the following expression for the permeability coefficient k as a function of decay time T: They derived the expression

$$k = 1.1 T^{4.14}$$
 (3.11)

They stress in their paper that there is a need for the development of 2D inversion techniques as there may be distinct 2D features whose effect may not be documented fully using the current 1D inversion techniques. The inclusion of the geoelectrical information of the subsurface in the modelling is also an important aspect that is often neglected. For that reason, resistivity or EM surveys should always form part of an NMR survey programme especially where the subsurface is electrically conductive.

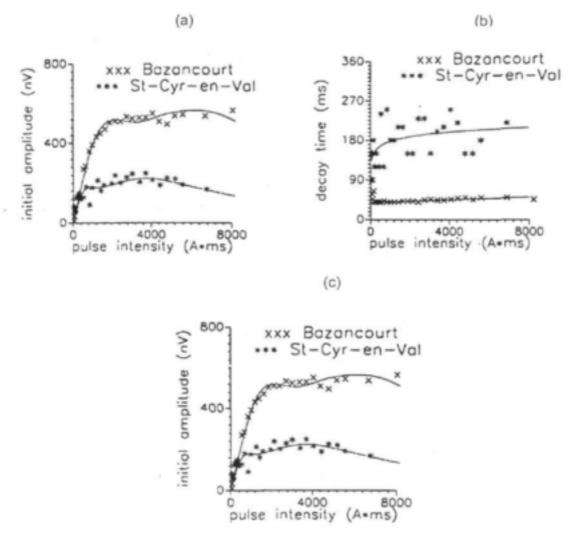


Figure 3.22: (a) NMR signal amplitude at the Bazancourt and St-Cry-en-Val sites, France (b) NMR signal decay time at the Bazancourt and St-Cry-en-Val sites, France, (c) NMR signal phase at the Bazancourt and St-Cry-en-Val sites, France (after Legchenko et al., 1995).

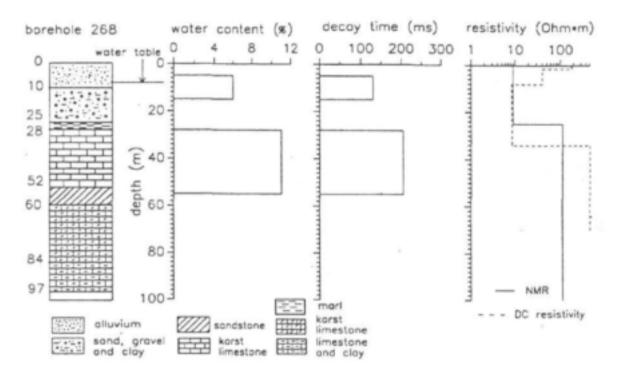


Figure 3.23(a): Interpretation results at the St-Cyr-en-Val area, France (after Legchenko et al, 1995).

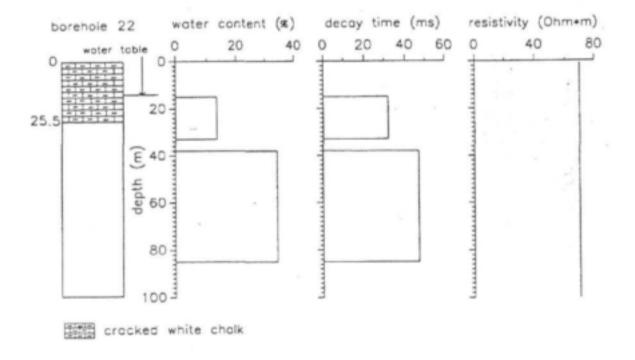


Figure 3.23(b): Interpretation results at the Bazancourt area, France (after Legchenko et al. 1995).

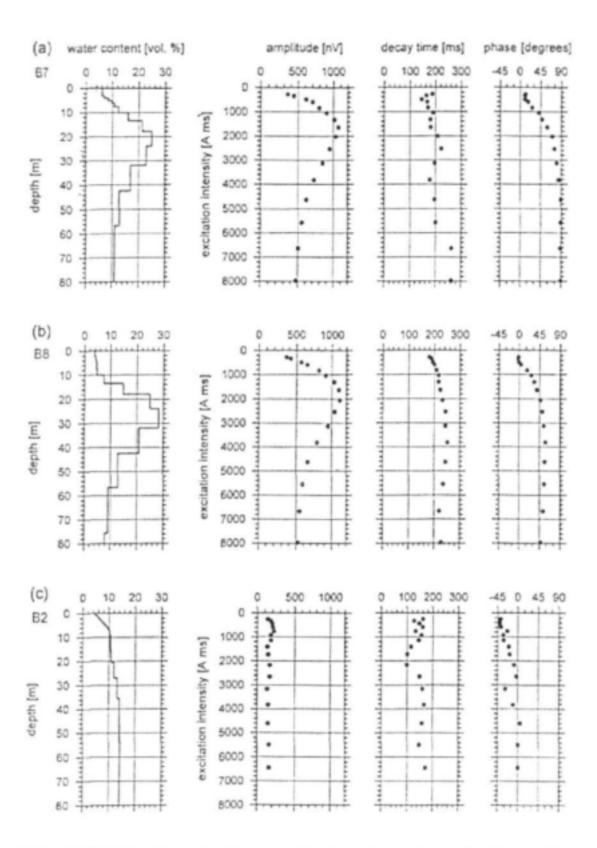


Figure 3.24: SNMR data and results of the inversion for water content in the Haldensleben survey, Germany (after Yaramanci et al, 1999).

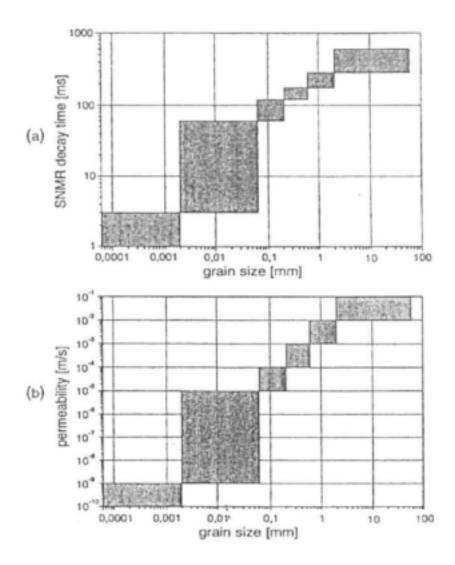


Figure 3.25 (a) Relationship of SNMR decay time ranges to the grain-size ranges of unconsolidated sediments from SNMR results at different sites and from corresponding core material after Schirov et al (1991).

(b) Relationship of permeability ranges to grain-size ranges after Hölting (1992).

One dimensional inversion of MRS data may at times be ambiguous, since different regularizations in the inversion impose a certain degree of smoothness upon the distribution of water content (Legchenko and Shushakov, 1998; Yaramanci, Lange and Knödel, 1998; 1999). The rms error, which is generally used as a measure of fit when applying inversion to geophysical data, is not necessarily sufficient for assessing the fit of a model to the observed data (Yaramanci et al, 1998). They refer to the inversion models for the MRS data, presented in their paper, yielded values for the variance that are often so large that the water content values can only be considered to be rough estimates. Despite the current shortcomings of the SNMR technique in ground water exploration, the use of the MRS technique to obtain water content and other soil properties, will increase the reliability of geophysical exploration for ground water and aquifer properties.

The Federal Institute for Geoscience and Natural Resources in Germany recently conducted a few experiments in Namibia at the coastal aquifers and also inland under fractured hard rock conditions. Except for a short abstract submitted for the European Geophysical Society Conference in April 2000, no results have so far been published. In the abstract they mention that despite the much lower signal strength generally measured in southern Africa, due to the much lower magnetic field intensity and lower aquifer porosities, good results were obtained in alluvial aquifers at depths of around 30 m. To achieve these results, they did however, have to increase the period of recording significantly and use a high number of stacking (>250). The NMR survey on basement rocks was not successful due to the inhomogeneities in the magnetic field caused by magnetic rocks which resulted in the resonance frequency drifting. This seriously affected the quality of the data.

Roy (2000a) and Martinez del Pino (2000) describe some of the best MRS curves measured yet (Fig. 3.26 and Fig. 3.27). These were measured at Waalwijk, The Netherlands and have a S/N ratio of more than 60. During this project six sites were investigated and soundings were made with square and square-eight loop configurations at each of the sites. Two of the MRS curves are discussed here, Waalwijk-1 and Waalwijk-2. Three layers containing water could be identified in this case: an upper layer between 3 m and 10 m with a water saturation of about 20%; the main water bearing layer from 10 m to 42 m with a water content of around 34%; and the upper boundary of the third layer is at 42 m with a water content of about 24%. The MRS curve is shown in Figure 3.26.

At a different site in Waalwijk (referred to as Waalwijk-2), three soundings were done at the same position but each one with a different "square-eight" loop size. The length of the sides were chosen as 37.5 m, 56.3 m and 75 m. The results are shown in **Figure 3.27**. In all cases there was almost no recognizable noise. It is clear from these results that the larger the loop, the larger the signal and the better the inversion can approximate the real aquifer conditions.

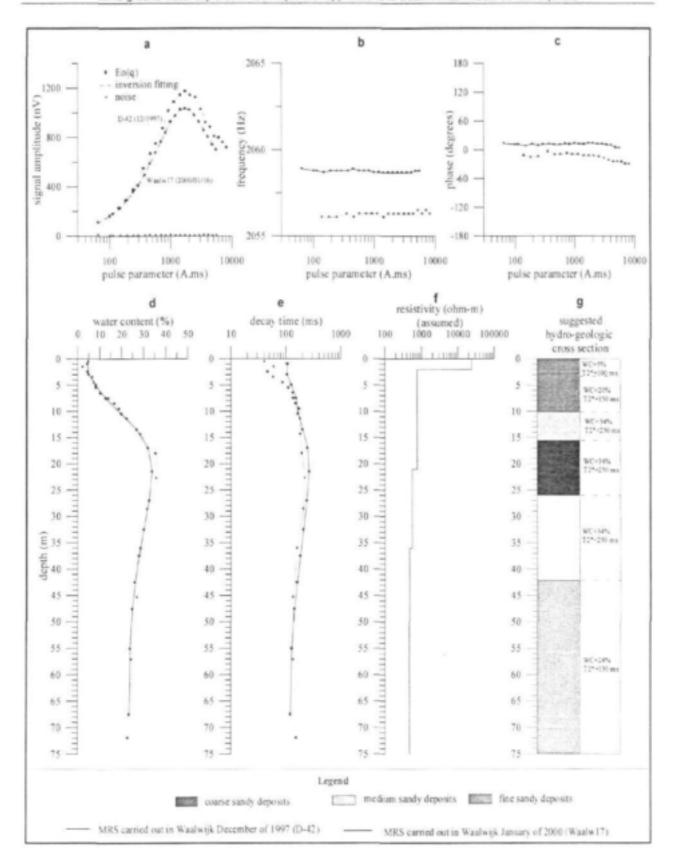


Figure 3.26: SNMR signal characteristics and inversion results of the Waalwijk-1 sounding, The Netherlands (after Martinez del Pino, 2000).

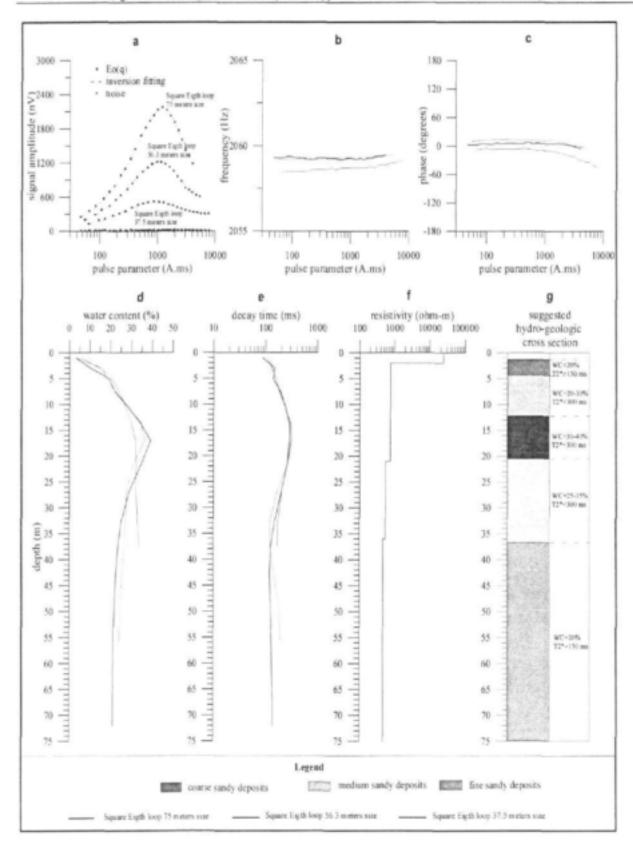


Figure 3.27: SNMR signal characteristics and inversion results of the Waalwijk-2 sounding, The Netherlands, using different square-eight transmitter loop configurations (after Martinez del Pino, 2000).

CHAPTER 4

APPLICATIONS IN GEOPHYSICAL BOREHOLE LOGGING AND FRACTURED AQUIFERS AND ADVANCES IN INTERPRETATION TECHNIQUES

4.1 Some general comments on earlier published articles

The NMR technique has been recognized as a potential technique that could be applied in different geophysical applications since the late 1950s. It was first applied to hydrogeology in Russia in the early 1970s. However, with the development of the necessary instrumentation for field work at the Institute for Chemistry Kinetics and Combustion (ICKC) in the then Soviet Union in the 1980s, the application to ground water exploration really took off. As a result of this rather short period over which the technique has been developed, and the fact that for all practical purposes, only one group did all the development, the number of published papers on the subject, and especially describing field studies, have until the mid 1990s been rather limited. Many of the reports were also written in Russian and therefore not necessarily generally available. Another consequence of this limited publication record, is that often a rather large part of each paper was devoted to repeating basic principles, theory of the method and even case histories.

There has been a significant increase in the application of the NMR techniques since the French company IRIS Instruments released their first commercial version of an NMR instrument. The results of these applications and further research has been mainly reported in conference and specialised workshop proceedings which have a rather limited circulation and in most cases only a short abstract is available. Some of the first articles published on the results achieved with the technique will be remembered for describing the pioneering research performed by the Russian team from the ICKC in Novosibirsk. Almost all the earlier reports described NMR applications under primary and alluvial aquifer conditions and only in the last 2-3 years researchers have also turned their attention to fractured aquifer systems.

In the following sections of the chapter only a few examples of NMR studies are referred to in detail. These were selected to provide a general overview of the applications reported in the literature and how the technology has improved over the years. Brief summaries of the other relevant papers are also included. At the end of the report an extensive and comprehensive bibliography and reference list is included.

Since the publication of US Patent 3019383 "Ground liquid prospecting method and apparatus", by R H Varian in 1962, a number of years passed before any further publications on the subject appeared. As the first prototype NMR equipment, called HYDROSCOPE, was developed in the Soviet Union, it is understandable that most of the initial publications and reports on the application and further development of the theoretical aspects of the technique were published by Russian researchers as first authors. They followed this up by registering their development in the Soviet Union under the title "A device for measurement of

underground mineral parameters" (in Russian) as an USSR Patent in 1989 (Semenov et al, 1989) as well as registering it with the British Patent Office under the title "Device for measuring the parameters of an underground mineral deposit" (Semenov et al, 1989).

4.2 Application of NMR to geophysical borehole logging

Before the appearance of NMR equipment for ground water exploration, most of the geophysical applications of NMR technology were in the field of borehole logging for oil prospecting, for example Coolidge and Gamson (1960); Brown and Gamson (1960); Hull and Coolidge (1960); Wymann (1962); Seever (1966); Artus (1967); Timur (1969); Timur et al (1971); Loren (1972); Brown and Neuman (1982); Jackson (1984); Crookes (1985); and Blackband et al (1986).

The articles on NMR in the geophysical borehole logging industry almost exclusively refer to applications in the oil exploration industry. In an article by Jackson (1984) the basic principles of the technique are described and how the probes are constructed, tested and calibrated. Brown and Neuman (1982) described the application of NMR geophysical logging in the oil industry in the following way:

- The identification of permeable formations. The Free Fluid Index (FFI) determined from the logging represents the portion of the total pore fluids that are free to flow. The FFI is 100% where the pore are saturated with free flowing water.
- Identify differences in permeability. Nuclear Magnetic Logging (NML)
 measurements enable the prediction of sandstone permeability. Several
 empirical relations have shown how permeability increases with increasing
 porosity, FFI, and time for alignment of the hydrogen nuclei. Each permeability
 representation depends on parameters determined from comparisons with coremeasured permeabilities.
- Recognize which zones with heavy oil contain moveable water. The signal from very viscous oil decays so rapidly that NML does not detect it and thus can be used to show movable water.
- Measure residual oil. The addition of chemicals to the drilling mud causes rapid decay of the NML signal. An NML recorded after mud invasion measures accurately the residual oil target for tertiary recovery.
- Recognize gas. An NML can be used to lessen the ambiguity due to clay minerals in the identification of gas-bearing zones using density and neutron logs.
- Measure carbonate porosity. The NML measures total porosity in clean carbonates independent of whether they are limestone or dolomite.
- Simplify log interpretation where other geophysical logs are ambiguous. The NML
 has the potential to simplify log interpretation in diatomites, chalk, and other
 special oil containing lithologies.

The Free Fluid Index (FFI) is described in more detail by Straley *et al*, (1995) where they concentrate on laboratory measurements of low-permeability clay-rich sandstone samples. They describe the correlation between the laboratory permeability measurements based on FFI and those obtained from core sample determinations and conclude that FFI values can be readily understood by comparison with laboratory measured T_1 (spin relaxation time) distribution curves and the underlying physical principles.

In a special issue of The Log Analyst (November -December 1996) a series of articles on NMR in the geophysical logging industry appeared. Kleinberg and Vinegar (1996) described the properties of reservoir fluids; Akkurt et al (1996a) described the application of NMR to the study of natural gas reservoirs; and Akkurt et al (1996b) described the selection of optimal acquisition parameters for the Magnetic Resonance Imaging Logging tool for the detection and quantification of free gas in an oil reservoir. The fact that clay bound water and fluids trapped in micro-pores generally exhibit very short (<10 ms) relaxation times and are thus not recorded by the normal NML tools which are adjusted to record the signal from capillary bound water and of free fluids was the topic for a paper by Prammer et al (1996). They demonstrated that by measuring the very short relaxation times with a tool that is sensitive to decay times of as short as 0.5 ms they could simultaneously determine total and effective porosity.

In other editions of the Log Analyst, articles on petrophysical principles of the application of NMR logging (Kenyon, 1997), the analysis of borehole cores using low magnetic field strengths (Straley et al, 1997), laboratory NMR measurements of partially saturated rocks to determine the FFI and its comparison with borehole logs (Straley et al, 1995), the determination of hydrocarbon saturation and the estimation of viscosity (Morris et al, 1996; Horkowitz et al, 1997), and a description of how the modern magnetic resonance logging tools can be used to determine the Bulk Volume of Irreducible water (BVI) which in turn provides insight into the formation's permeability (Coates et al, 1998) were published.

Owour (1998) gives a summary of NMR as applied to petrophysics. He describes the role the three relaxation time constants, Longitudinal Relaxation T_1 , Transverse Relaxation T_2 and Generalized Transverse Relaxation T_2 , have in the characterization of pore space, the relationship between these time constants, the factors that influence the NMR relaxation, techniques for the measurement of the different time constants, and finally between porosity, permeability and relaxation time constants T_1 and T_2 have been established.

4.3 Examples of applying the NMR technique to fractured aquifers

In recent years a limited number of investigations were conducted in fractured aquifer environments. One of the first papers dealing with the application of the NRM technique to fractured aquifers was that of Gev et al (1996). They found that with the NMR method the phreatic water level in the fractured aquifer could be established with reasonable accuracy and were also able to detect several deeper low transmissivity water bearing layers down to a depth of about 70m. Unfortunately no details or examples of the MRS curves were

included in the paper. Legchenko et al, (1998) described experiments in Saudi Arabia to detect aquifer horizons in fractured metasediments, granites and granodiorite. They found a good correlation between borehole and NMR results and established a linear correlation between borehole yield and signal amplitude (Figure 4.1). In this case high yields were reported from two boreholes which are associated with magnetic diorite dykes while no NMR signal could be observed at these boreholes. This can possibly be ascribed to the magnetic nature of the dykes which resulted in inhomogeneous magnetic fields. They also state that although future optimisation of the NUMIS instrumentation should make the application of the MRS technique possible in inhomogeneous geomagnetic fields, such inhomogeneous field currently present one of the main limitations of the technique.

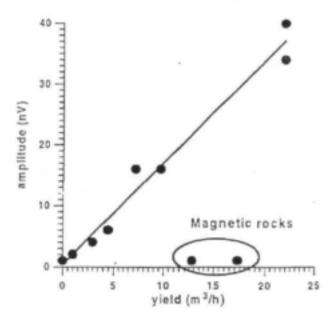


Figure 4.1: Correlation between the NMR signal amplitude and borehole yield, Saudi Arabia (after Legchenko et al, 1998).

Roy et al (1998a) also reported good results from MRS experiments in Portugal where the aquifers are found in fractured volcanic rocks. They identified water bearing zones at a depth of 14 m to 18 m in fractured Tertiary conglomerates. In addition ground water associated with fault zones at depths of 32 m to 37 m, and 48 m to 58 m could be identified. In the centre of the 48 m to 58 m zone identified from the interpreted NMR sounding data, a 0.8 m wide fracture was identified during drilling Figure 4.2. The existence of these deeper aquifers were not known at the time of the MRS survey and all ground water extraction took place from the upper Tertiary conglomerates. However, the MRS interpretation, which identified the presence of water at the depth of 48 m to 59 m, was confirmed through drilling four months later.

4.4 Recent advances in interpretation techniques

There is continuous effort to improve the interpretation techniques for NMR data. These techniques concentrate mainly on improving the inversion routines currently used. There are

three programs available for the inversion of MRS data which use different inversion schemes. The methods used are (1) smooth regularised least squares inversion, (2) smooth-inversion with simulated annealing (SA), and (3) an optimised random search algorithm which is largely independent of the starting model and can escape from local minima (Möhnke and Yaramanci, 1999a). The second method allows one to choose between two different types of regularization, being the standard "smooth" (Type I) and a

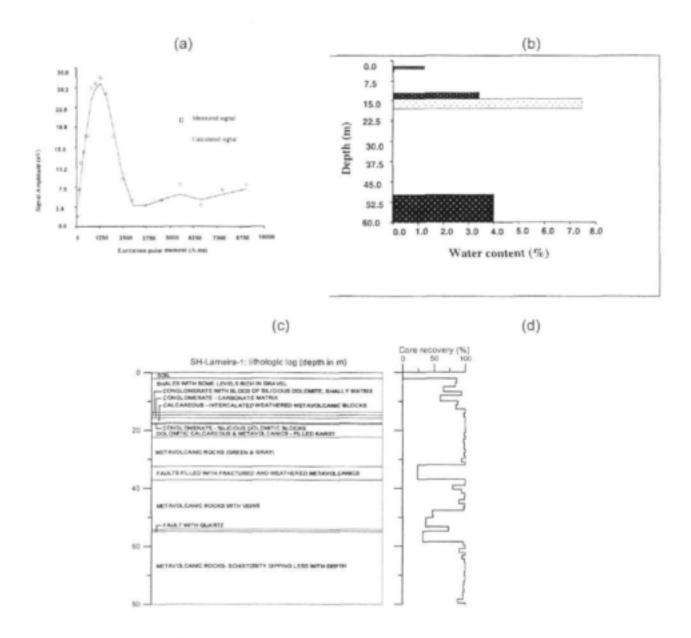


Figure 4.2: (a) MRS sounding curve and numerical inversion result at Lameira, Portugal); (b) Water content as derived from inversion (darkest pattern indicates least permeability (short decay rate), where as a light (clear) pattern indicates high permeability (longer decay rate); (c) Lithological borehole description; (d) Log depicting the % core recovery (after Roy et al, 1998a).

more "blocky" (Type II) regularization (Möhnke and Yaramanci, 1999a). Yaramanci and his team at the Technical University of Berlin are instrumental in exploring new techniques and are currently investigating the application of block inversion of surface MRS data using simulated annealing techniques (Möhnke and Yaramanci, 1999a, 1999b; Yaramanci et al, 1998b; Eikam and Yaramanci, 1999).

In the first inversion scheme, the inversion is based on a number of predefined inversion layers that have fixed positions and thicknesses. Block inversion has the advantage that there is no limitation to the use of predefined inversion layers and therefore it allows for a more realistic interpretation of the aquifer boundaries. Möhnke and Yaramanci (1999b) did a study to compare the "smooth" and "blocky " approach on a data set from Northern Germany. In analogy to the 1D inversion of VES data in geoelectrics, the inversion tries to fit the water content of each layer as well as the depth of the layer boundary for a given number of inversion layers, for example a three layer case. The results of the two approaches are shown in Figure 4.11. Drilling has confirmed a three layer case with an aquifer with a sharp upper boundary at 22 m and a lower boundary at 46 m. Using the smooth inversion Type I, only a rough estimation of the aquifer position were found, whereas with the blocky regularization approach (Type II), good agreement with the sharp upper boundary was achieved. From Figure 4.11 it is clear that the smooth inversion with Type I regularization does not identify the sharp upper boundary satisfactorily. With Type II regularization there is already a significant improvement but the block inversion approach results in the best fit to the drilling results. The advantage of block inversion is that it reduces the ambiguity in inversion of MRS data considerably and it is able to accommodate sharper aguifer interfaces compared to the other techniques. The mathematical detail of the block inversion scheme using simulated annealing is explained in more detail in a second paper by Möhnke and Yaramanci (1999b) and further examples of the application are provided in Yaramanci et al, (1998c).

Legchenko and his colleagues at IRIS Instruments have investigated the possibilities of improving the inversion results by using Monte Carlo techniques (Guillen and Legchenko, 1997, 1998). With the Monte Carlo approach they have been able to answer questions such as "What is the probability that there is a zone between two given depths where the water content is greater than x %?", or "What is the probability that there is a larger water content than say x % between two given depths, if a dry zone is assumed to be present between two other given depths?". This technique is still under development and no formal conclusions have been published yet.

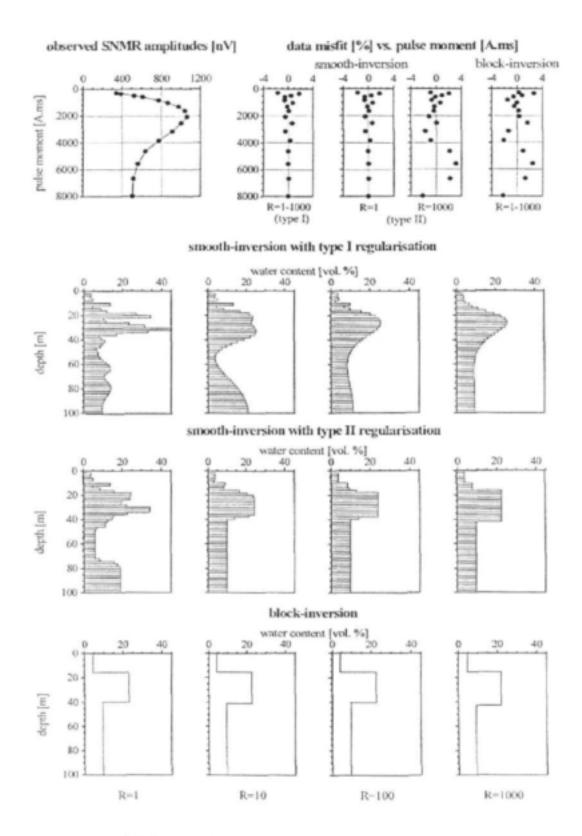


Figure 4.3: Inversion of MRS data from Haldesleben, Germany using the Block Inversion technique (after Möhnke and Yaramanci, 1999).

CHAPTER 5

INTERPRETATION PROCEDURES AND SIMULATION OF MRS RESPONSE FOR SELECTED SOUTH AFRICAN AQUIFER SITUATIONS

5.1 Data processing and interpretation procedures

5.1.1 Background

Since the development of and commercial availability of the NUMIS equipment, a number of researchers have made contributions to the interpretation of data collected with both the HYDROSCOPE and NUMIS instruments. Many of these contributions focus on data inversion techniques to obtain better models of the distribution with depth of the underground water content.

Legchenko (1996a), Guillen and Legchenko (1997, 1998) and Legchenko and Shushakov (1998) describe the original inversion techniques used in the interpretation of NMR data for ground water investigations. Yaramanci and his co-workers at the Technical University of Berlin, have developed new inversion techniques and applied these to the interpretation of a number of field measurements in Europe (Yaramanci et al, 1998a, Yaramanci et al, 1998b, Möhnke and Yaramanci, 1999a; 1999b; 1999c; 2000).

In an article by Trushkin et al (1993), the authors make a case for the use of the "Figure-eight" transmitter loop configuration to enhance the signal to noise ratio in noisy environments. Legchenko et al (1997c) describes the size of the transmitter loop and Roy (1999) gives motivations for the use of different loop configurations depending on the nature of the aquifer and illustrates their use with field examples. Goldman et al (1994) describe the output of the HYDROSCOPE instrument and how this was used to derive at water content with depth in their studies of coastal aquifers in Israel.

5.1.2 HYDROSCOPE: Interpretation of data and presentation of results

The interpretation software utilized in the NMR technology is based on a mathematical model in which some assumptions are made (as is the case in most geophysical techniques) in order to provide information on the free water content and position in the subsurface. The interpretation requires some information on the vertical geoelectrical profile which can be obtained by doing a Vertical Electrical Sounding at the measuring position.

The output produced by the HYDROSCOPE as well as the NUMIS instruments contains very similar information. A typical HYDROSCOPE output is shown in Figure 5.1 (taken from

Goldman et al., 1994). It consists of two main parts: Site identification information and instrument setup is contained in the upper 'heading' part of the figure. Below this is a histogram in the form of a hydrological cross-section of the sounding site. The depth range is divided into a number of 'layers' or 'sub-aquifers' of equal thickness (typically >20 layers; in the case of Figure 5.1 the 138m depth range is divided into 26 layers) for which NMR responses are calculated for different concentrations of water within each layer.

DEPTH		VE	T			PE	RC2	INTAGE OF WAT	72			
FROM	TO	3	2									
2	1	H	K/248	TS	TH	TL.		0 10 20	30	40	50	TDEM (Ohm-m)
								iii.	:.	:.		IDEM (Onin-m)
0.00	1.00	0.00	0	0	0	0	0	I			I	
1.00	2.00	0.00	0	0	0	0	0	I			1	
2.00	3.00	0.00	0	0	0	0	0	I			I	4.2
3.00	4.00	0.00	0	0	0	0	0	I			1	
4.00	5.00	0.00	0	0	0	0	0	I			I	
5.00	6.00	0.00	0	0	0	0	0	I			I	
6.00	7.00	0.00	0	0	0	0	0	I			I	
7.00	8.00	0.00	0	0	0	0	0	I			I	
8.00	9.00	0.00	0	0	0	0	0	I			I	
9.00	10.00	0.00	0	0	0	0	0	I			T	5.6
10.00	12.00	0.08	4	3	0	1	4	IW			T	56
12.00	14.00	0.08	4	0	0	0	0	I			T	
14.00	16.00	0.08	4	0	0	0	0	I			I	
16.00	18.00	0.08	4	0	0	0	0	I			I	
18.00	20.00	0.08	4	0	0	0	0	I			I	
20.00	22.00	0.08	4	0	0	0	σ	I			I	
22.00	24.00	0.08	4	0	0	0	0	I			I	
24.00	28.00	0.28	14	3	1	1	5	INM			I	
28.00	32.00	0.40	38	0	0	3	3	IW			1	
32.00	36.00	0.52	62	0	0	3	3	IW			I	12,5
36.00	40.00	0.54	86	0	0	3	3	IW			I	
40.00	46.00	0.82	122	0	0	3	3	IWW			I	
46.00	54.00	1.06	170	0	0	3	3	IW			I	
54.00	62.00	2.74	452	0	4	17	21	IMMONOCONO	¥.		I	
62.00	74.00	2.74	452	0	0	0	0	I			I_	
74.00	138.00	2.74	452	0	0	0	0	I			I	1.3
								111			:	
								0 10 20	30	40	50	

Figure 5.1: Example of result from a HYDROSCOPE survey using the earlier interpretation software. An improved method of displaying the results is currently used (after Goldman et al, 1994).

The inverse problem is solved by a minimization procedure in which the difference between the calculated and the measured response are minimized. The resulting histogram consists of the following columns (reading **Figure 5.1** from left to right):

- Depth to the top of each layer (m).
- Depth to the bottom of each layer (m).
- The cumulative amount of free water (m³) from the surface to the bottom of each layer in a column of 1m² base.
- The cumulative transmissivity of a column from the surface to the bottom of each layer (m²/day).
- The percentage of water within small pores for each layer.
- The percentage of water within medium pores for each layer.
- The percentage of water within large pores for each layer.
- The total percentage of water for each layer.

In the lower right hand side of the diagram the concentration of water within each layer represented by the symbol 'W' for each 2% of the total percentage of water (for example a 10% concentration of water will be represented by WWWWW). The most reliable parameter given in this diagram is the cumulative amount of free water to the bottom of the last layer within a column of 1 m². This value is derived by calculating the area under the curve $\mathrm{emf_0}(q)$. This value will obviously depend on the noise level inherent in the data. Information on the pore size or texture of the aquifer, is determined from the relaxation time T_2 of the free induction decay signal which is measured in the field. The transmissivity value is calculated from the previously calculated pore size and water quantities for each layer, and therefore is the least reliable parameter. Mathematical modelling has shown the accuracy of the detection of the free water strata boundaries to be approximately one 'layer', provided that the actual subsurface system and the mathematical model are sufficiently similar and the signal-to-noise ratio is at least 20:1.

Earlier versions of the IRIS Instruments software produced a very similar presentation of the results obtained with the NUMIS instruments. It also produced a water content (%) vs depth graph, and information about the mean pore size, but does not go into the detail of transmissivity at layer levels. By recording the signal current phase, information about the rock resistivity can be interpreted.

5.1.3 NMR data processing, interpretation and presentation of results

When doing a NMR sounding, a number of measurements of the time decaying time signal at different excitation moments (q values) are made. Typically the signal is recorded at a minimum of 16 q values. For each q value, the NMR acquisition programme generates a computer file with a name related to the site name and an extension related to the q number. The final signal value for each q value is the result of a stacking process (to improve the signal to noise ratio), which is only recorded once a set accuracy is reached. The number of values used in the stacking process is controlled by the operator. Data acquisition is terminated when this predetermined stack number has been reached or when the operator decides to prematurely terminate the data acquisition.

The first step in the interpretation is the calculation of a matrix which takes into account various parameters related to the specific conditions at the survey site. These include the shape and size of the transmitter loop, the frequency, magnetic inclination, the maximum depth of investigation required, and the geoelectrical depth profile. The computation of the matrix is a lengthy process and normally a matrix is only calculated once for a particular survey area. When interpreting different soundings from a specific area the same matrix can usually be used as conditions do not normally change that drastically.

The matrix consists of an n x m matrix where n is the number of layers (usually 100) and m is the number of pulse moments (m = 100). The values of the pulse moments depend on the depths and thicknesses of the layers and are selected in relation to the amplitude of their response with respect to the layers. The thicknesses of individual layers depends on the maximum depth of investigation and often the layers' thicknesses are selected on a pseudo logarithmic scale.

Since the NMR theory states that there is a linear relationship between the measured NMR signal measured at the surface and the water content of the layers, and having the matrix of the base model computed, the inversion to obtain the solution (water content and time constant versus depth) can be done relatively quickly. During the inversion the time constant for the decay is calculated for each layer at depth together with the water content for that layer. As explained earlier, the time constant is related to the pore size and hence the permeability of the layer. The final output usually contains various graphical representations, such as:

- signal amplitude against pulse moment;
- noise level against pulse moment water content with depth;
- decay time with depth;
- resistivity depth profile (from VES information); and
- geological sections.

Examples are shown in Chapter 6 of the report.

5.1.4 Interpretation techniques

The continuous effort to improve the interpretation techniques for NMR data has been discussed in Chapter 4. Research on interpretation techniques is currently focussing on inversion routines and is led by the German group at the Technical University of Berlin under the leadership of Prof. Yaramanci who have published widely on this topic (Yaramanci et al, 1998a, 1998b, 1998c, 1998d, 1999a, 1999b, 1999c, 1999d; Möhnke and Yaramanci, 1999a, 1999b, 2000). A future challenge for interpretation techniques would be to interpret non-horizontal water bearing structures, for example fault zones, fracture zones associated with dyke intrusions, joint planes, etc. This will be of particular importance to the South African geohydrological conditions where water occurrences are often associated with these non horizontal structural features.

5.2 Calculation of NMR response for selected South African examples

5.2.1 Introduction

As part of the interpretation process and to assist in the selection of realistic initial models, different geohydrological scenarios for some of the South African experimental MRS sites were modelled to simulate the MRS response. One of the main aims of the project was to assess the MRS technique under fractured rock aquifer conditions. Experimental sites were therefore selected in areas where water strikes were known to occur at specific depths. These conditions were modelled to establish what the MRS response would be and to see how it compared with the field curves. This approach assisted the project team to evaluate the result obtained from the inversion routines, and to adjust the conceptual model of the aquifer conditions. Theoretical MRS response curves were calculated for the Settlers area (basalt overlying sandstone), granite aquifers (weathered and fractured), and the Karoo fractured rock aquifer conditions.

5.2.2 Settlers, Northern Province, South Africa

The geohydrological conditions around Settlers on the Springbok Flats north of Pretoria are as follows: The Ecca Group sandstones are in many places overlain by basalt of the Letaba Formation of the Lebombo Group. The contact is often weathered and in places acts as an excellent water bearing zone which occasionally has been reported to yield 10 l/s and more. At the MRS site the contact between the overlying basalt and the sandstone is weathered and fractured over a distance of about one metre and occurs at a depth of approximately 25 m. The sandstone from 26m down to at least 70m is homogeneous and unfractured. From drilling records it is apparent that very few water strikes occur in the sandstone and that almost all of the water strikes reported in this area are related to the contact zone. This scenario was the subject of a few model calculations determining the NMR signal strength under various geohydrological models. The different models are listed in Table 5.1, whereas the simulated NMR sounding curves for these models are displayed in Figures 5.3 to 5.6.

Table 5.1: Detail of the different Settlers models investigated

Model # & Figure #	Depth interval (m)	Porosity over depth interval (%)	Total Magnetic Field (nT)	Frequenc y (Hz)	Loop size (m)	
1 & 3.20	23.3 - 24	100	29695	1265	115	
2 & 3; Fig 3.21	21 - 23	10 and 30	29695	1265	115	
4 & 3.22	24 - 100	4	29695	1265	115	
5 & 3.21	24 - 100	2.14	29695	1265	115	

Model 1 represents a 700 mm wide open fracture filled with water (100% porosity) (Figure 5.3). Although this model is highly unlikely in nature, it indicates the magnitude of the NMR signal that can be expected from such a situation. It is important to note that the model curve indicates that the MRS signal would drop to near zero at a q value of 4000 to 5000 A.ms. This is however not reflected in the field curve. The field measurement done at this borehole, gave a similar signal amplitude but there is no sudden drop in the signal strength at g values above about 2000 A.ms as suggested by the model (Figure 5.4). The Eo value alone does not provide sufficient information to determine the porosity - thickness relationship; this relationship can only be determined from the E_0 vs. q curve. If the fractured zone is made 2m wide, and by allocating a 30% porosity to it, a similar amplitude response is obtained. These two models have similar porosity-thickness product (0.6 m and 0.7 m respectively). Judging from the video recording made of the borehole, 30% porosity over a 2 m section may not be that unrealistic. A 10% porosity for this zone only results in a 20 nV signal amplitude (Figure 5.4) compared to the 65 nV measured in the field. Although the 30% porosity gives a reasonable match between the field and theoretically calculated curves, the pump testing yield of only 4 l/s does not support such a high porosity. Two other scenarios were modelled: no contribution to the signal from the fracture zone, but a 4% and 2.14 % homogeneous porosity from 24m to 100m depth (Figures 5.5 and 5.6). The calculated curves for these two models compare favourably to that of the field curve. There is therefore strong support that a significant contribution to the measured MRS signal is derived from a thick low porosity aguifer section.

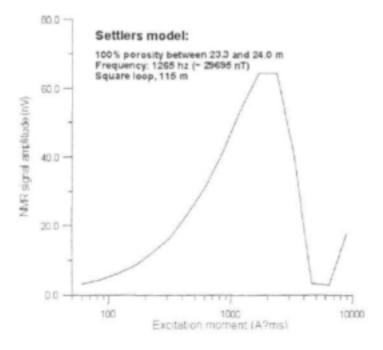


Figure 5.2: Theoretical NMR sounding curve to simulate the response of a 100% porosity fracture (open fracture) at a depth of 23.3 m to 24 m at borehole M4, Settlers.

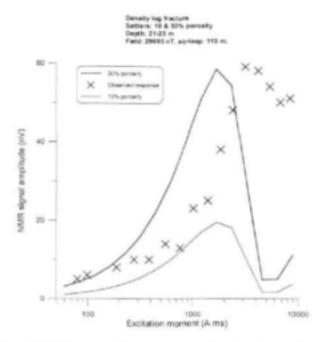


Figure 5.3: Theoretical NMR sounding curves to simulate the response of different porosities over the fractured zone as indicated by the Density log (21 m to 23 m), borehole M4, Settlers.

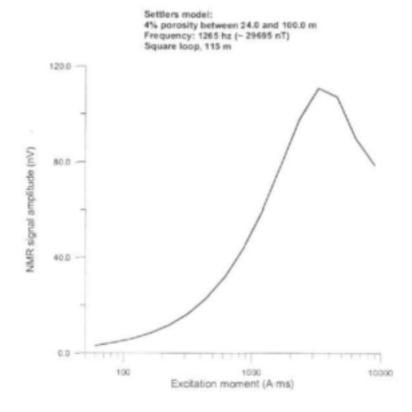


Figure 5.4: NMR sounding curve for a constant porosity (4%) of the sandstone aquifer at Settlers.

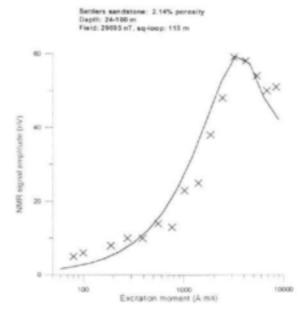


Figure 5.5: NMR sounding curve for a constant porosity (2.1%) of the sandstone aquifer at Settlers.

5.2.3 Weathered and fractured granites (Pietersburg, Nebo, and Coetzersdam and other Archaean granites)

One extreme condition to simulate the fractured granite aquifer in the Northern Province or Coetzersdam area was modelled during the stay in Delft. A 1% porosity over a 10m thick section at a depth of 95-105m was modelled. Magnetic field was set at 29695nT and the loop size was taken as a square loop with 115m sides. The result is shown in **Figure 5.7**. It can be seen that at an excitation moment of 10 000 A.ms, a signal of only 1.8nV is reached. This excitation moment is close to the limits of the existing instrumentation, such as the NUMIS systems.

Another model used for simulating the response is one where the porosity is kept at 1%, but this occurs over the interval 50m to 70m. The maximum signal reaches only about 6 nV, but the maximum excitation moment is shifted far to the right and may be out of reach of the commercial NMR equipment (Figure 5.8). A similar type condition as above was also modelled (1% porosity) but with the fractured zone being even shallower (34-48 m instead of 95 -105 m and 50 m - 70 m; example from the Nebo granite) with the same geomagnetic field conditions but with two different loop configurations. This model gives a signal of about 9 nV, and in theory should be possible to be observed in field measurements, provided the ambient noise levels are very low. The results are shown in Figure 5.9. This geohydrological model was also simulated with a 3-segment figure-eight loop (side length of 25.8 m) configuration. The maximum signal at an excitation moment of 10000 A.ms is only about 1 nV. This result is shown in Figure 5.10.

Another model calculated for a granitic type terrain, was one where 10 thin (0.05 m) horizontal fractures containing 10% of water, are simulated at 10 m intervals in the vertical profile. This configuration reduces the signal strength by a factor of about 5. The results are shown in Figure 5.11.

5.2.4 Karoo aquifers, Free State Province

Only one model simulating Karoo aquifer type conditions was calculated. The upper layer resistivity was taken to be 30 ohm.m with a 1% porosity at a depth interval between 90-110 m. Similar comments as were given in the previous example can be given in this case. The signal is small and the maximum will only be reached at a large excitation moment. Bedding plane fractures often act in Karoo aquifers as the conduits for water to reach the boreholes and should be the position in the succession where the highest porosity can be expected. The results of this simulation is shown in **Figure 5.12**.

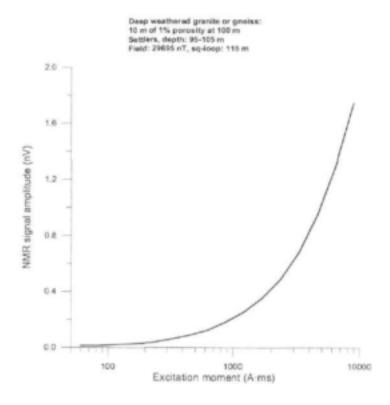


Figure 5.6: NMR sounding curve for a 1% porosity at 100 m depth in granite

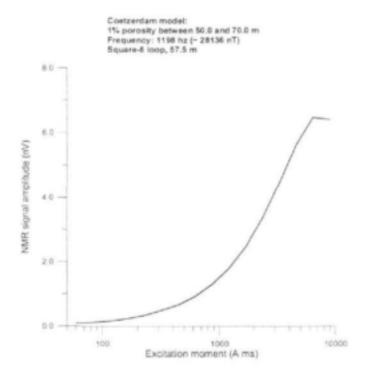


Figure 5.7: NMR sounding curve for a 1% porosity between 50 m and 70 m in granite.

Neutron zone

Nebo model: 1% porosity Depth: 34-48 m

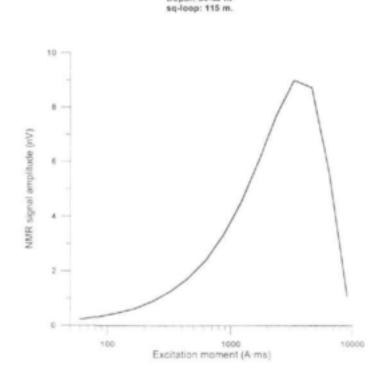


Figure 5.8: NMR sounding curve for a 1% porosity between 34 m and 48 m depth in granite.

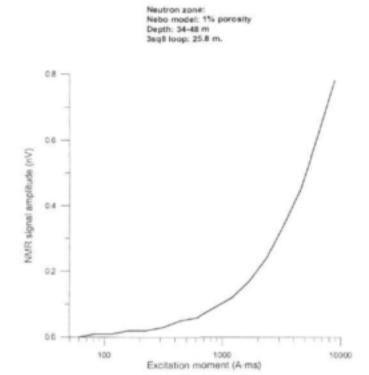


Figure 5.9: Same as Figure 5.9, but with a different loop configuration.

North-East fractured horizons: 5 cm thick 10 % porosity 10 horizons: one at 10 m depth and at each 10 m increment Field: 29695 nT, sq-loop: 115 m

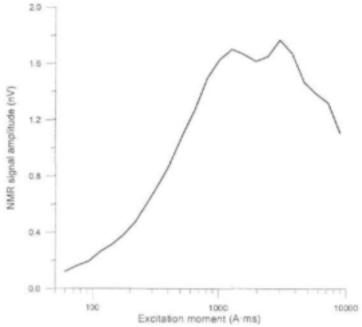


Figure 5.10: NMR sounding curve with 10 thin layers with 10% porosity each.

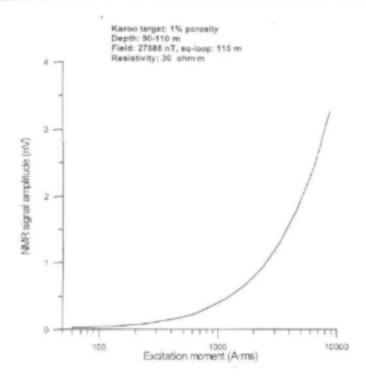


Figure 5.11: NMR sounding curve in a conductive Karoo environment (1% porosity at 100m)

CHAPTER 6

EXPERIENCES AND RESULTS OF THE SOUTH AFRICAN EXPERIMENTS

6.1 Rationale for the selection of South African test sites

From the onset of the project it was the intention to test the technique and a commercially available instrument system on specifically fractured rock aquifers. From the available literature, internal reports and field experience with the system (mainly from Europe), it has already been proven that the technique provides excellent results under alluvial aquifer conditions. Therefore the emphasis was on selecting test sites where aquifer conditions are well known in order to be able to calibrate and evaluate the test results against known conditions.

In the course of the selection process a wide spectrum of hydrogeologists were consulted. These included staff from the Directorate Geohydrology, Department of Water Affairs and Forestry (Head Office as well as Regional Offices), Consultants and Universities. For logistical reasons and time constraints, some restrictions were placed on the area to be covered. For example, the Table Mountain Group, in light of the current focused interest on the exploitation potential of these rocks, would be an interesting type locality to study, but because of the distances involved, additional time and cost considerations, tests on these formations were not considered. The different geohydrological conditions that were originally considered at the start of the selection process were:

- Beaufort and Ecca Groups of the Karoo Super Group
- Malmani dolomite formations (Zeerust, Delmas, Kuruman)
- Granitic terrains, i.e. Nebo granite of the Bushveld Complex (Western, Eastern and Northern Lobes), Archaean granite in the Northwest Province (Derdepoort, Coetzersdam, Louwna, Stella) and Limpopo Mobile Belt
- Karoo basalt in the Springbok Flats
- Ventersdorp lava
- Zululand Coastal Plain (target being the deeper karstified Uloa Formation)

After the initial selection process, the areas listed in **Table 6.1** were selected. The motivation for selecting these sites is also given. In order to qualify as a test site, a number of important criteria had to be met. These included:

- · Not close to electrical transmission lines and electrified railway lines;
- Preferably more than 500 m from boundary fences;
- In a magnetically homogeneous area;
- No dolerite intrusions or other linear features within or close to the transmitter loop area.

Table 6.1: Sites originally identified as experimental sites for NMR experiments.

Geology	Locality	Motivation	Target depth (m)	
Alluvial aquifer	Greefswaldt,	To test and calibrate	30 m	
	Limpopo River,	instrumentation	maximum	
Alluvial and	Sand River,	To test and calibrate	30 m	
Granite, Limpopo Belt	Pietersburg	instrumentation	maximum	
Basalt, Karoo	Springbok Flats	High yielding fractures at	100 m	
		contact between basalt and Ecca sandstone	maximum	
Vryheid Formation, Ecca	Philippolis	Fractures associated with dolerite intrusions	35 m	
Beaufort Group, Karoo	Bloemfontein	Ground water associated with bedding plane fractures	40 m	
Nebo Granite	Nebo, Eastern Bushveld Complex	Weathered and fractured granite associated with major lineations	50 m	
	Potgietersrus	Deeply weathered granite basins	40 m	
Limpopo Mobile Belt granite	Dendron	Weathered and fractured granite	50 m	
Archaean Granite	Coetzersdam, NW Province	Weathered and fractured granite	70 m	
	Stella	ditto	60 m	
Malmani Dolomite	Zeerust	High yielding boreholes with large variation in water strike depth and water level.	75 m	
	Delmas	High yielding karstic	80 m	
		formation	maximum	
Ghaap Plateau Dolomite	Kuruman	High yielding fractured dolomite under cover of Kalahari sand	60 m	
Uloa Formation	Richards Bay/Lake	High yielding aquifer under	100 m	
	Sibayi area	cover of water saturated, but low yielding alluvium	maximum	
Sandstone, Soutpansberg group	Thohoyandou, Northern Province	High yielding aquifer associated with fracturing and linear intrusions	50 m?	

Other considerations that were taken into account were that the selected area or target had to be representative of typical water bearing hard rock environments in South Africa.

Although it was realised that this was a too ambitious list of sites to be covered, we had to have sites in reserve in case some of the conditions set above could not be met. Some of the sites were also inspected before field work started.

6.2 Field work and description of aquifer conditions at the different test sites

6.2.1 Preparatory work

A cooperation agreement was reached between the ITC in Delft, The Netherlands according to which the experiments in South Africa would form part of a larger ITC research project in which they were testing and evaluating the NMR method under southern African geohydrological conditions. They would be responsible for leasing the equipment from the French company IRIS Instruments, whereas the field work, interpretation and other logistical support would be a joint responsibility between CSIR and ITC. Despite the large weight of all the equipment, it was air freighted to South Africa, because the lease agreement stipulated a daily rental charge and arrived on 13 November 1998. The first two days were spent on equipment unpacking, checking and adjusting for South African conditions, and preparing a VW Combi in order to accommodate all equipment. Field work started on Saturday 15th November 1998 in the Sand River at Pietersburg. This site was chosen for the following reasons:

- A number of instrument adjustments still had to be made, and it was important to
 do these at a site where we were confident that a strong signal could be
 measured. As this was a 'dual' aquifer (saturated alluvium above fractured
 gneiss) with saturated porosity in the alluvium of between 10% and 20%, a
 relatively large signal could be expected.
- · It is a site where aquifer conditions are well known.
- The results at this site were crucial to the planning of the work in Botswana, Namibia and South Africa, as it provided information about the time period over which measurements had to be made, rough estimates of maximum signal to be expected in southern Africa, size and configuration of transmitter loops, and the performance of the instruments under relatively high temperature conditions.

The first results were extremely disappointing and despite several instrument adjustments and modifications, no signal that made any sense could be recorded. Overheating of the instrument due to inadequate ventilation of the electronic components was identified as part of the problem (this was later partly solved with the installation of an additional fan). Numerous modifications were suggested by the manufacturers, IRIS Instruments in France, and implemented in the field, and additional dedicated software was sent regularly from France to test specific parts of the instrument.

Although several of the modifications were worthwhile, it eventually turned out that adverse climatic conditions in the form of severe thunderstorms during the summer months were the main reason for the extremely high noise levels encountered. This was only realised when the first of these storms reached Pietersburg after a few days of testing. Before that the storms were restricted to areas south of Pietersburg and mainly around Pretoria and Johannesburg. With hindsight, these conditions should have been realised earlier and the tests planned for another period of the year.

As it was in the middle of the rainy season in the northern part of Southern Africa with its associated thunderstorm activity, there was not much which could be done to eliminate this effect on the measurements. After some more tests, and to make the best out of the situation after having gone to all the trouble and cost to bring all the equipment to southern Africa, it was established that the only time of the day during which it was possible to make reasonable measurements, was between about 03h00 and 11h00. This restriction then forced a total change in the planning of each days' activities, but led to the collection of valuable data for different aquifers in southern Africa. All these tests took the best part of the first week, which resulted in re-scheduling of the entire test programme for southern Africa. The date for shipping the instruments back to France was fixed and therefore the field work could not be extended.

Table 6.2: Programme for the first NMR test in southern Africa

Date (1998)	Activity/Locality					
11-12 November	Arrival of Dr J Roy from ITC; instrument shipment cleared through customs and unpacked					
12-13 November	Preparation and adjustment of instruments; leave for Pietersburg					
14-18 November	Field tests at Sand River, Pietersburg					
18 Nov – 5 December	Depart for Botswana and Namibia (Dr Roy), and field work in Botswan and Namibia					
6-7 December	Letaba Basalt/Ecca sandstone aquifer near Settlers					
8-9 December	Nebo granite, Bushveld Complex					
10 December	Ecca sandstone, Bloemfontein					
11December	Beaufort siltstone, Philippolis					
13 December	Coetzersdam, Kuruman district					
14 December	Packing of instruments and shipping back to France					

During the period 19 November to 4 December 1998 field work was done in Botswana and Namibia. The survey in South Africa started on 5 December 1998 and the instruments were shipped back to France on 14 December 1998. During this time field tests were done at 5 additional sites in South Africa: Settlers, Nebo, Bloemfontein, Philippolis and Coetzersdam.

6.2.2 Tests at the Sand River aguifer, Pietersburg

The tests at the Sand River alluvial and fractured gneiss aquifer had a dual purpose. Firstly, it was necessary to test and adjust the instrumentation to the southern African conditions, and secondly to establish what magnitude of the signal can be expected in southern Africa under relatively high porosity (~20%) and controlled conditions. Mr Carl Haupt of Water Management Systems in Pietersburg, kindly provided the geohydrological information on the

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site and the Municipality of Pietersburg gave permission to do the tests in their well field area. The tests were done near the confluence of the Sand and Bloed Rivers to the north west of Pietersburg.

The alluvial aquifer attains a maximum thickness of 24 m in the area and the alluvium ranges from a fine, sometimes clayey sand, to a coarse sand. Near the contact with the weathered gneiss, sub-rounded pebbles are often encountered. The water level is seldom more than 5m below surface. Although the alluvial aquifer consists in places of fairly coarse material, and hence should be a good aquifer, experience has been that the deeper weathered and fractured gneiss rocks, contribute most of the water to the borehole. Borehole yields vary from about 1 l/s (no alluvium and weathering) to more than 20 l/s (20 m alluvium, weathering to 27 m and several fracture zones at depth).

6.2.3 Tests at Settlers on the Springbok Flats

Extensive geohydrological investigations were done in the southern part of the Springbok Flats by Weaver (1987) as part of an investigation for the water supply to a planned coal driven power station in the then Bophuthatswana. The original data from field work, drilling and pump testing records etc. were kindly provided by Mr Graham Hubert of E Martinelli and Associates of Randburg.

Basalt of the Letaba Formation overlies the Clarens Sandstone Formation and Elliot Siltstone formation. The ground water resources are represented by four aquifers. The aquifer associated with the fracturing and weathering of the basalt of the Letaba Formation at its contact with the underlying Clarens Formation is high yielding and confined. The aquifers associated with the Clarens and Elliot Formations, are low-yielding, unconfined primary aquifers. The deeper Ecca Group aquifer is confined and saline. The target for the NMR tests was the fracturing and weathering at the contact between the basalt and the sandstone.

Two boreholes were selected as test areas. These were boreholes M4 and M11(Martinelli and Ass., 1987). The main water strike in borehole M4 was at 24 m (3.3 l/s), and in borehole M11 water strikes were at 43 m, 63 m and 74 m with a total yield of ~10 l/s. Water strikes are predominantly associated with the contact between the basalt and the sandstone, but water yields of between 1 l/s and 7 l/s have also been reported from either the basalt or the sandstone (for example boreholes M1, M5, M6, M8 and M11).

The first sounding was done at borehole M4, and based on the relatively strong "water" signal recorded at this position where the target was relatively shallow, it was decided to test another deeper target in the same geological and geohydrological environment. Borehole M11 was selected for this purpose. Only a very small signal could be recorded at borehole M11, before noise due to the buildup of large thunderstorms forced us to abandoned further measurements.

6.2.4 Tests near Nebo on the Nebo granite, Bushveld Complex

The Nebo granites of the Bushveld Complex are generally known as areas where it is difficult to site high yielding boreholes. During the University of Pretoria WRC funded project to develop an integrated multi-disciplinary approach to ground water exploration and development in granitic aquifers, the Nebo granite has been targeted (Combrinck, 1999). A high success rate with new exploration boreholes, sited on the basis of an integrated approach to the interpretation of geophysical and geological information, has been achieved. Boreholes with yields of up to 25 l/s and more have been drilled recently based on the results achieved by this integrated approach to exploration. These borehole positions were selected by integrating data from aeromagnetic and aerial electromagnetic geophysical data sets, together with field mapping of the structural geology and aerial photography interpretation. For more information on the exploration and drilling information, the reader is referred to Combrinck (1999).

6.2.5 Tests at Bloemfontein on the Ecca Group

This site was recommended by Prof van Tonder of the IGS as a typical test site for fractured Ecca with high yield boreholes. Tests were done on the farm Hartebeeshoek some 20 km to the west of Bloemfontein where several boreholes had been drilled into fractured Ecca sandstones for irrigation purposes. The water bearing fractures are usually associated with horizontal bedding planes although minor cross cutting fractures also do occur (Botha et al. 1998). The boreholes in this area are all high yielding (>5 l/s) and the water is normally struck at depths of less than 30 m. Because of the relative high yields from depths of less than 30 m, no deeper boreholes have previously been drilled in the area. It was also believed that an extensive dolerite sheet underlies the area and that by drilling deeper than 30 m one would intersect solid non-water bearing dolerite (van Tonder, pers. comm.). Subsequent to the MRS survey, two deeper boreholes were drilled in this area, but no dolerite sheet was observed at depth. Water was struck at between 21 and 22 m below surface. This area represents a typical example of the current interpretation of Karoo aquifers: horizontal fractures act as conduits to transport water to the boreholes, but the main water storage is in the low porosity surrounding sedimentary formations (Botha et al. 1998).

The two newly drilled boreholes were also used to do different tracer tests to establish the porosity variation with depth. These tests consisted of "Point dilution" (Source and Radial Convergent) and "Injection-withdrawal" testes (Riemann, 2001)

6.2.6 Tests at Philippolis, Southern Free State on the Lower Beaufort Group

The test site at Philippolis was selected after discussions with Prof J Botha and staff at the Institute for Groundwater Studies at the University of the Free State in Bloemfontein. It was recommended as a site that resembles a typical Beaufort Group ground water occurrence. In both the Ecca and Beaufort cases the ground water occurrences are often associated with horizontal bedding plane fracturing or along fracture zones associated with vertical or near vertical dolerite dyke intrusions.

The test area selected is known as "Well field D" and is situated to the south west of the town. All boreholes in the Philippolis area are situated on a ring dyke system (Prof J. Botha, pers. comm.). Six boreholes have been drilled here at this specific well field, some of which are associated with a dolerite dyke intrusion. One of these boreholes (Bh D15), located at the intersection of a fault and an approximately northeast trending weathered dolerite dyke intrusion, is a current production borehole of the Municipality and has been drilled to a depth of 50 m. Metamorphosed shale occurs to a depth of 21m, with green to grey shale to 50 m. Pumping from this borehole depends on the water level of the reservoirs of the Municipality and the submersible pump is automatically activated. However, the borehole is currently pumped daily for about 8 hours at a rate of about 1 l/s. The power supply for the pump is from a dedicated 3-phase overhead power line, with an approximately 25 m underground cable to the borehole. Weathering is present to a depth of approximately 10 m and only a short section of steel casing (<5 m) was installed in the borehole. Water strikes occurred at depths of 9, 10,12, 13, 18, 22, 24,32 and 37m; the main water strikes being at 10m (0.6 l/s), 24 m (3.6 l/s) and 32 m (2.5 l/s). Water is pumped from the borehole to the reservoir through a 100 mm PVC pipe and according to Mr van der Westhuizen of the Philippolis Municipality, who is responsible for the operation of the well field, no earthing wire is installed alongside the pipe. A gravel road lined with a fence and a local telephone line runs approximately 50m to the east of the dyke and parallel to it.

6.2.7 Tests at Coetzersdam near Vryburg on Archaean Granite

The aquifer at Coetzersdam can be considered as consisting of two parts that are hydraulically connected: an upper weathered granite part and a deeper fractured granite part. This aquifer is exploited extensively for irrigation and in several areas it is hugely over utilised. Typical yield from boreholes in this area is between 15 l/s and 50 l/s. Some years ago the CSIR was involved in an extensive geophysical study and geohydrological study of this aquifer on behalf of the Department of Water Affairs and Forestry and based on the results several high yielding boreholes (>40 l/s) on the farm Hartebeeslaagte were drilled by the owner. These boreholes were identified as target sites for further tests of the NMR technique.

6.3 Experiences gained during the South African field experiments

6.3.1 Earth's magnetic field in southern Africa

The 1995 National maps of the geomagnetic field over southern Africa were kindly supplied by the Magnetic Observatory in Hermanus (S A Magnetic Observatory, 1995). These maps are updated every 5 years. Information on the Earth's total magnetic field and the magnetic inclination was required to make certain adjustments to the instruments. Accurate information on the geomagnetic field is important as it forms a critical part in the interpretation of the sounding data. The total magnetic field intensity and the variation in inclination over southern Africa is shown in Figures 6.1 and 6.2.



Figure 6.1: Total magnetic field intensity (nT) over southern Africa for 1995 (SA Magnetic Observatory, Hermanus).

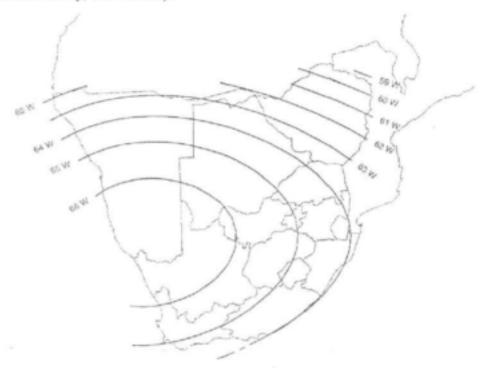


Figure 6.2: Magnetic inclination in degrees over southern Africa for 1995 (SA Magnetic Observatory, Hermanus).

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At each position where NMR soundings were done, a short ground magnetic survey was done to determine the local magnetic field strength and the magnetic gradient across the area where the loop was to be laid out. This was done with an EDA total field proton magnetometer. The average magnetic field in the survey area was calculated and this value is used when selecting certain instrument settings and to determine the Larmor frequency for that area. This also serves to determine whether the area underlain by the loop is not traversed by a dolerite dyke or similar linear feature which may negatively affect the measurements and also creates a non-homogeneous magnetic field.

6.3.2 Signal strength in southern Africa

For a given aquifer (effective porosity, thickness and depth) one can expect the signal response in southern Africa to be of the order of 4 times lower than in Europe or Australia (see Chapter 3, Table 3.2). In addition, our primary target during this project, were fractured hard rock aquifers, which will have at best a porosity of only a few percent compared to that of alluvial and primary aquifers where this method has been tested predominantly until now (mainly Northern Europe - see Chapters 3 and 4 for examples). In these countries typically porosities are of the order of 20%. These two factors lead to an NMR signal that may be 40 times lower in the fractured rock environments tested in South Africa relative to other parts of the world. Added to this are the extremely high noise levels recorded in southern Africa during summer periods due to the thunderstorm activity. Conditions are thus much more demanding than in Europe, Australia and the USA.

6.3.3 Noise levels in southern Africa

The principle natural noise source for Extremely Low Frequency (ELF) and Very Low Frequency (VLF) signals is lightning. Therefore long-term variations of the noise must relate to changes in the global thunderstorm activity. The Space, Telecommunications and Radioscience Laboratory at the University of Stanford in California, USA, has conducted a global survey of ELF and VLF since 1985 (Chrissan and Fraser-Smith, 1996a, 1996b; 1997). Eight measurement stations around the world record the noise amplitudes in sixteen frequency bands in the 10 Hz to 32 kHz frequency range (the typical frequency range covered by commercial NMR instruments is about 1-3 kHz). Although these measurements do not cover southern Africa, they are of importance to NMR experiments worldwide, as it gives some insight into period(s) during the day and the year which can be expected to have the highest noise levels and should therefore, if at all possible, be excluded for NMR field experiments. Examples of diurnal and seasonal variations of VLF radio noise during November for Stanford, USA and Dunedin, New Zealand respectively is shown in Figures 6.3 to 6.6. These figures clearly show marked differences in the noise levels for the two stations over a 24 hour period. At Stanford for example, the noise level in the 2-3 kHz frequency band peaks around 04h00 whereas that for Dunedin peaks around 12h00. For

Stanford low noise levels are recorded during the period 15h00 to 24h00, and for Dunedin the period is from about 19h00 to 07h00.

The seasonal variations for the same two stations are shown in **Figures 6.5 and 6.6**. At Dunedin the low noise period (for the same frequency band) occurs around June-July, whereas for Stanford the period is January to March.

Similar data for southern Africa have not been traced. In view of the much lower NMR signal recorded in South Africa, and especially when investigating fractured aquifers, information of this nature is of vital importance in order to plan the field surveys optimally. If such information is not available for South Africa, it is strongly recommended that a start be made with the recording of similar long term radio noise spectra.

Practical experience during the first NMR experiments in South Africa indicated that the summer months are not suitable for such tests in view of the high incidence of thunderstorm activity. Despite this, relatively low levels of noise were experienced during the period 03h00 to approximately 11h00. This period of the day was identified during the first measurements at Pietersburg, and became the norm for the rest of the surveys in southern Africa. The motivation for this decision is also substantiated by the diurnal variation of global lightning activity over land (Christian et al, 1998). This distribution is shown in Figure 6.7 and shows that the maximum lightning occurs in the late afternoon. Approximately 60 percent of the land-based lightning occurs between 12h00 and 20h00 local time, whereas the oceanic lightning has no significant variation throughout the diurnal cycle.

The period during which the NMR instrumentation was available in southern Africa was fixed and could not be changed. This, together with the desire to conduct as many as possible soundings during the limited availability of the instrumentation in southern Africa, and the limited period each day during which measurement could be performed, placed an enormous strain on the field crew. A typical field day started at 03h00 in the morning, measurements continued till 11h00-12h00, followed by the collection of all cables, packing of instrumentation, moving to the next site, surveying the new site and laying out the cables for the next days' measurements. In the case of the South African soundings, the tests sites were often several hundred kilometres apart, which resulted in extremely long days in the field.

6.3.4 Instrument limitations

A number of discussions were held between representatives of IRIS Instruments of France and Dr Jean Roy of ITC, as well as during the visit by the author visit to IRIS Instruments in November 1999. These centered mainly around problems experienced with the performance of the instrumentation in South Africa, special modifications to the instrument for the conditions experienced in southern Africa, and ways to improve the signal to noise ratio of the instrument.

1 80 62

mp/Li

California, during the month of November for eight frequency channels Diurnal variations of ELF/VLF radio noise at Stanford, for the years 1986 to 1993 included (Chrissan and Fraser-Smith, 1997) Figure 6.3:

10.2 10%

BHALLI

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Figure 6.4: Diurnal variations of ELF/VLF radio noise at Dunedin, New Zealand, during the month of November for eight frequency channels for the years 1986 to 1993 included (Chrissan &Fraser-Smith, 1997)

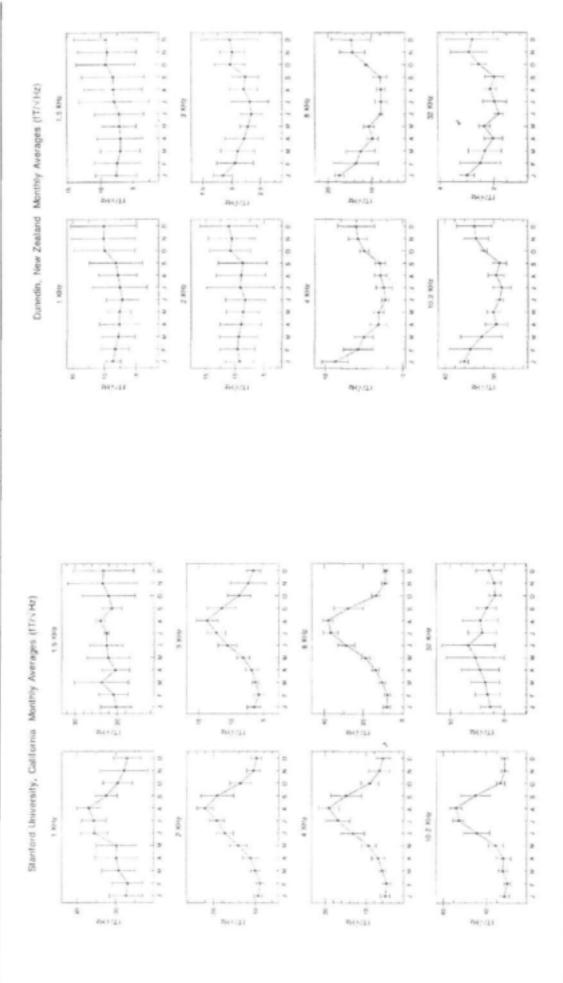


Figure 6.5: Seasonal variations of ELF/VLF radio noise at Stanford, California, for eight frequency channels for the years 1986 to 1993 included (Chrissan and Fraser-Smith, 1996a).

Figure 6.6: Seasonal variations of ELF/VLF radio noise at Dunedin, New Zeeland, for eight frequency channels for the years 1986 to 1993 included (Chrissan and Fraser-Smith, 1996a).

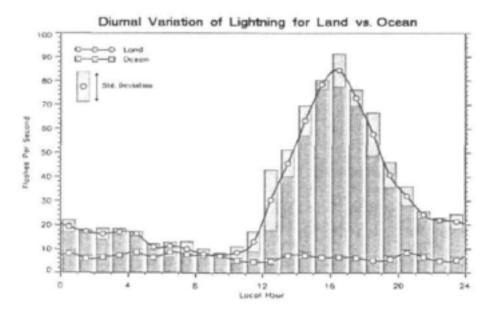


Figure 6.7: Diurnal variation of global lightning activity over land and the ocean (after Christian et al. 1999).

During an in depth analysis of some of the data sets recorded in South Africa (and specifically those from the Nebo granite and Coetzersdam) and further instrument testing by IRIS Instruments, it became apparent that there was a synchronous leakage problem in the instrument which has the effect that signals less than about 6-10 nV are highly unreliable irrespective of the amount of signal stacking performed. It also became apparent that another limitation of the instrument was related to data formatting. We were not aware of these two limitations at the time the surveys were done in South Africa. Had we been aware of these limitations during the field surveys, less time would have been spent on those test sites where extremely low signals were recorded; in particular Nebo and Coetzersdam, and more time could have been spent on the Karoo aquifers at Bloemfontein and perhaps included some work on other aquifers in South Africa, such as the Zululand coastal aquifer and dolomitic aquifers.

6.3.5 Sand River aquifer, Pietersburg

As already mentioned, the first tests were conducted on this dual alluvial/fractured rock aquifer. After instrument adjustments and realising that the only time available for measurements was in the very early hours of the day (03h00 to ~11h00), good results were obtained. Two different transmitter configurations were tested; (1) the standard square loop with dimensions of 75m x 75m, and (2) two smaller square loops forming a figure-eight with dimensions of 56m x 56m each. The second configuration was done in an attempt overcome the high levels of electromagnetic noise experienced, created by thunderstorm activity and from a nearby power line.

6.3.6 Settlers

Measurements were done at two boreholes at Settlers. The geohydrological targets in these two boreholes ranged from 25 m (at borehole M4) to 75 m (at borehole M11). In both cases only single loop configurations were used. For the shallower target at borehole M4 the loop size was 115 m x 115 m, whereas a loop size of 150 m x 150 m was selected for the deeper target at borehole M11.

A strong "water" signal could be observed in the case of borehole M4, but the results were very disappointing in the case of the deeper target at borehole M11. Measurements were discontinued at the deeper target after a few hours due to increase in the noise levels and because it was decided to rather spend the time on different types of geology than test the applicability of the technique at deeper targets.

Two direct current resistivity soundings were done subsequently at borehole M4. These two soundings were done perpendicular to each other to determine the degree of anisotropy present in the basalt formations. Previous investigations in this area indicated that severe anisotropy exists in parts of the Springbok Flats, and most of this originates from the basaltic Letaba Formation.

6.3.7 Nebo granite

Ground water occurrence is controlled by two almost perpendicular structural directions. These directions are around 030° (fracturing & faulting) and 110° to 130° (fracturing along dolerite intrusions). NMR measurements were done along both these directions. Due to the linear structural features, we opted for multiple small rectangular loop configurations strung together to form a long figure eight configuration consisting of 6 square loops. The dimensions of each of the squares was 26 m x 26 m. The first measurements were done along the ~120° direction and the loop was centered around borehole W5111, which has a reported blow yield of 25 l/s. A similar configuration was used during measurements along the second structural direction (~030°) with borehole W5111 near the northern end and borehole W49434 near the southern end of the loop configuration.

Despite the high reported yield from borehole W5111, the NMR signal strength was in both cases very low and close to the noise threshold of the instrumentation. The signal strength was probably negatively affected by the rather small loop sizes, but this was done in an attempt to test the linear loop configuration in cases were the target is a linear feature. In hindsight, this was perhaps not a good choice, as subsequent studies done by DWA&F on the Nebo granite at other locations, points to the presence of horizontal or near horizontal fractures supplying water to the linear feature which appears to act more as a transport zone than the primary water bearing structure.

Again direct current Vertical Electrical Soundings (VES) were done in directions similar to the structural features. Despite distortions caused by traversing the linear structural features with the current electrodes, the soundings indicated very shallow weathering and extremely high resistivities (10 000 ohm.m) for the solid granite.

6.3.8 Bloemfontein

At this location a single square loop with dimensions of 115 m x 115 m was used. The target was a water saturated fracture (presumably horizontal or near horizontal) at a depth of about 25 m. Boreholes drilled subsequent to the MRS tests revealed that the main water strike is at a depth of between 21 m and 22 below ground surface. Due to limited time left to complete the South African programme no further tests with different loop configurations were tested here. Vertical electrical resistivity soundings were done subsequently and the results used during the interpretation of the NMR sounding curve.

6.3.9 Philippolis

Two sites were selected in Karoo aquifers due to the renewed interest in Karoo aquifers and also to test the concept of water strikes associated with horizontal fracturing. The research done by the IGS at Philippolis provided another test case with well documented geohydrological information.

Two different loop configurations were tested here. As a start the normal 75 m x 75 m square transmitter loop was used. Three boreholes, D15 (production borehole), D16 and D17 were located within the loop. The results were disappointing and indicated some severe interference from an as yet unknown source. The power supply to the borehole originates more than a kilometre from the borehole where it branches off another power line. At this point all three phases of the supply line were disconnected. We were also assured that there is no earthing wire buried along the pipeline and that a PVC pipeline runs from the borehole to the reservoir in town. Despite all these precautions, the measurements were severely influenced by noise. It was intended to investigate this situation further as similar results have been observed in other countries where, despite taking the necessary precautions by disconnecting the power supply to a borehole, no sensible signal could be observed. Despite trying two different loop configurations, the figure eight and by moving the loop further away from the borehole and associated electrical installations, no improvement was observed. Factors that may be responsible for these poor results and questions that come to mind are:

- What is the composition of the pipe used in the pipeline from the pump to the main water distribution conduit? Does it contain any metal?
- Is there a ground wire parallel to this pipeline either in the same trench as the pipe or elsewhere?
- Assuming that the well casing is a steel casing, is the pump electrically grounded to the casing?
- Is the ground wire coming from the transformer connected to the well casing? If not where is it connected?

Although these questions seem to be very academic, answers are needed because measurements are often done close to equipped boreholes. If is known that boreholes equipped with electrical installations are causing interference with the NMR signal, then suitable precautions have to be devised to prevent this in future. For this reason some additional tests were done in November 2000 to establish the cause of the interference observed during the MRS survey.

Arrangements were made with the Town's electrical engineer, Mr van der Westhuisen, to disconnect the power supply to the borehole to establish the same conditions as was the case during the MRS measurements. A 20 m x 40 m grid was laid out across the original area where the square loop was laid out. The overhead power supply line crossed the original square loop perpendicular. At each of these stations a smaller square loop (25 turns) with 5 m side lengths was laid out and the natural induced field was observed for a few minutes and recorded to get an indication of the noise levels. Noise measurements were done under different configurations of the electrical installation; borehole submersible pump earth connected and disconnected, and the earth on the 11kV/380V transformer disconnected as well as connected. Background noise levels were found to be higher close to the power line. However, no significant difference in noise levels was observed under the different electrical installation configurations. The reason for the increased noise levels close to the power line may be two fold: Firstly, the power line is parallel and very close to the dolerite dyke. The weathering zone associated with the edges of the dyke are more conductive and may therefore allow natural telluric currents to be channeled along these zones. Secondly, the long overhead power line may act as an antenna in which current can be induced thereby producing a low induced magnetic field.

These noise levels were, however, much lower than the ones observed during the MRS survey. Another possible cause was therefore investigated. Some of the grid lines were extended to the east towards the fence and telephone line. The noise measurements along these lines indicated high noise levels when approaching the fence and telephone lines. From the noise measurements done at Philippolis, it is thus concluded that the main source of the noise influencing the MRS survey, originated from the fence and telephone lines, with a smaller contribution from the power line and possible channeling in the conductive weathered structure along the dolerite dyke.

6.3.10 Coetzersdam

By the time we reached Coetzersdam near Vryburg, only one day remained for field work and therefore only one sounding could be done. The 115 m x 115 m loop was laid out between the four high yielding boreholes, A-1, A-29, He-26 and He-27 on the Farm Hartbeeslaagte. There was no power supply to the boreholes due to problems experienced by Escom after severe thunderstorm activity.

Measurements were disappointing as the noise levels were extremely high despite starting the sounding at about 0400 in the morning. Thunderstorm activity could, however, be

observed in all directions which resulted in a poor signal to noise ratio. By 11h00 in the morning it was decided to abandon all further measurements. By that time it started raining and further heavy thunderstorms were encountered for the rest of the day.

6.4 Results of the interpretation

6.4.1 Interpretation programme

Part of the agreement between the ITC and CSIR was that the data gathered in southern Africa (including those in South Africa) will be used by MSc students studying at the ITC. Mr Martinez del Pino was identified to use the South African data as part of his thesis. Under the guidance of Dr Roy, the author and Mr Martinez del Pino worked together on the data at the ITC in Delft, and also calculated the NMR response that could be expected from typical South African fractured rock aquifers. Some of the results have already been reported in Chapter 3 of this report.

6.4.2 Interpreted results from the Pietersburg sounding data

The final interpretation of the Pietersburg data is presented in **Figure 6.8**. The upper part of the figure shows the (**Figure 6.8(a)**) field measured sounding data, the recorded noise, and the best fit inversion to the data. The signal to noise ratio for this particular sounding was about 1. **Figures 6.8(b)** and **6.8(c)** show the frequency and phase at the respective pulse parameters respectively. In **Figure 6.8(d)** and **(e)** the outcome of the inversion is shown. The interpretation shows that the high water content in the upper alluvial aquifer dominates the sounding curve and that the technique does not have the resolution to recognize the deeper water bearing fractures that are present in the granite. The section between 5 m and 16 m has a porosity of between 5% and 18%. The thickness of the alluvium as indicated by the NMR result is in good agreement with the ~15 m thickness of the alluvium in this area.

Over the main water bearing layer the average decay time (T2) is only about 50 ms, which according to Table 3.1 (Chapter 3) corresponds to a sand containing a significant amount of clay and hence should have a low permeability. Although boreholes in the area in general have high yields (5-15 l/s) the high yielding zones are often found in the fractured granite and do not necessarily relate to the overlying saturated alluvium. The low permeability indicated by the decay time, is in agreement with the conductive nature of the alluvium (~20 ohm.m) as displayed by the VES curve. The water conductivity is in general <50 mS/m. Unfortunately the loop could not be laid out directly at a borehole due to physical constraints (river, power line, sand works and dense vegetation). However, there are 14 boreholes within close proximity of the NMR sounding position which indicate an average alluvium thickness of 13 m. The alluvial thickness contour map compiled by WSM Consulting Engineers from Pietersburg indicates an alluvial thickness of ~15 m at the NMR sounding site. The weathered gneiss extends below the alluvium to a maximum depth of 37 m, whereas major water strikes have been reported in the nearby boreholes at depths from 29 m to 56 m.

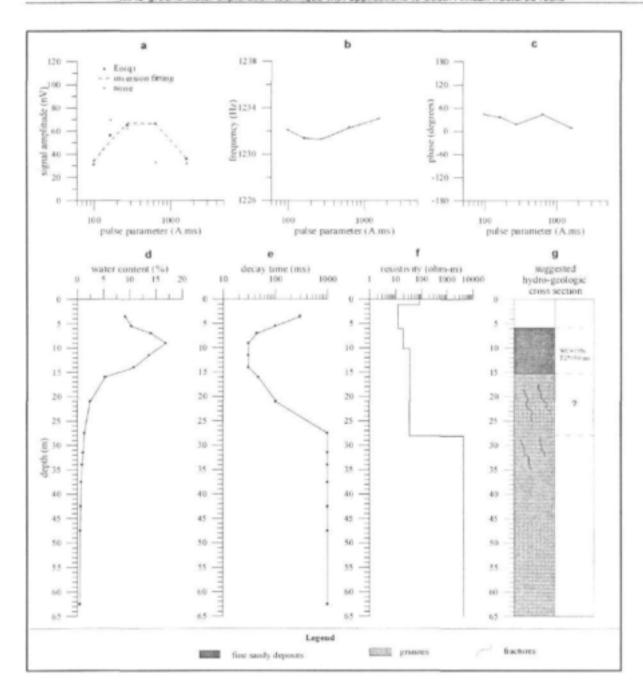


Figure 6.8: NMR sounding curve and inversion results at Pietersburg.

What is of significance from these results, is that the weathered zone is not reflected as a prominent water saturated zone. It is concluded that the gneiss has been weathered to a clay resulting in a low "free" water component. This result is in agreement with the field observations during drilling.

It is further important to note the amplitude of the measured NMR signal, as well as the signal/noise ratio of the signal and noise amplitudes. As comparison, typical NMR sounding curves from Europe measured on alluvial aquifers, the signal amplitude is typical a few hundred nV and larger. Note that the NMR signal is, in the case of Pietersburg, at least a factor 10 smaller.

6.4.3 Settlers data

As reported earlier, two NMR soundings were measured at Settlers. The results of only one of these will be discussed here as the noise levels were too high at the second site and no reliable results appear to have been recorded. At the first sounding position (borehole M4) the reported target was at about 25m at the contact between the overlying basalt and the sandstone.

The best interpretation of the Settlers data is presented in Figure 6.9. The upper part of the figure shows the (Figure 6.9(a)) field measured sounding data, the recorded noise, and the best fit inversion to the data. The signal to noise ratio for this particular sounding was about 5. Figures 6.9(b) and (6.9(c) show the frequency and phase at the respective pulse parameters respectively. In Figures 6.9(d) and 6.9(e) the outcome of the inversion is shown.

The initial signal amplitude in the case of the Settlers data is relatively high (~50nV) and the sounding curve is well defined with a high S/N ratio. This was the best S/N ratio observed at any of the South African NMR soundings.

The result of the inversion indicated the presence of two water bearing layers. Details on their water content, decay times and layer resistivity can be seen in the lower section of Figure 6.9. Three horizons containing water are identified by the inversion. The upper one is in the upper 5 m of the profile which contains less than 1% water. No water is present in the section between 10 m and 18 m. The water level at the time of the measurements was at 17 m. The second section containing water occurs from a depth of about 20 m to about 25 m with a maximum porosity of just over 2%. The main fracturing occurs at the contact zone which extends from about 22 m to 25 m with the maximum fracturing and weathering at 23.4 m to 24 m. The corresponding decay time at this depth is about 70-80 ms. The Ecca sandstone extends from 24 m to the end of the borehole (66 m) and the inversion results indicate that the sandstone has an average porosity of around 3% and that it is very constant down to about 100 m. This is in agreement with the video recording that was made inside the borehole and which showed that the sandstone is very homogeneous from 24 m down to the bottom of the hole a 66 m. The decay time for the entire length of the sandstone is on average 100 ms indicating a reasonable hydraulic conductivity for the sandstone. At 43 m to 44 m the video recording indicated some slight fracturing, but this can not be recognized by the inversion result.

It is concluded that although the drilling indicated that the main water strike was at 24 m, the sandstone is the main aquifer that supplies the water to the fracture at 24 m and that the sandstone should be regarded as the main aquifer.

A few general statements about this inversion result are worth noting:

only below the water table is the water content equivalent to effective porosity;
 above it is related to the moisture content;

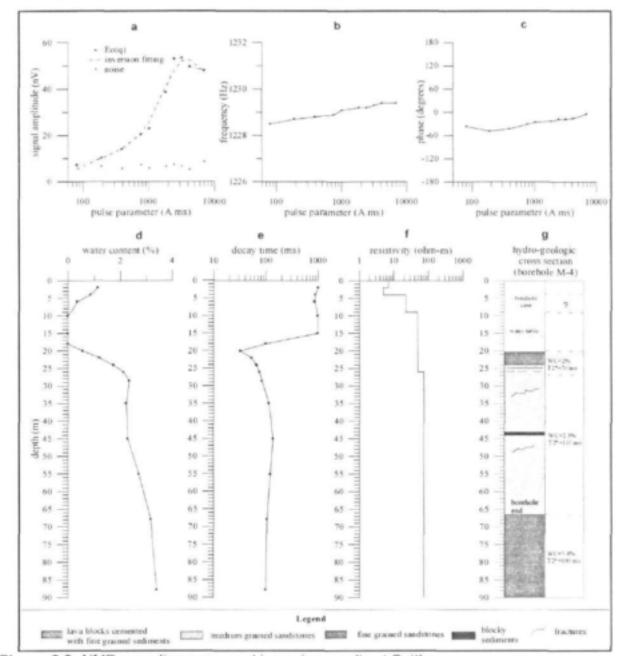


Figure 6.9: NMR sounding curve and inversion results at Settlers.

- the indicated water content below the water table is not equivalent to the total porosity because the clay-bound water is not detected by the system;
- the non-porous rock (in this case the overlying unweathered basalt), even when it is located below the water level, does not contribute to the NMR signal;
- a value of 1000 milliseconds chosen for the time constant is an undetermined value and not a value greater or equal to 1000 milliseconds; and
- any information below about 80m depth is less reliable than the shallower information.

For the excitation moments between 1000 A-ms and 8500 A-ms, the signal to noise ratio was the best have been recorded in southern Africa.

6.4.4 Bloemfontein

For this dataset the observed noise was at about the same level as the signal amplitude over the acquisition time window. Towards the end of the data recording noise levels increased leading to an average S/N ratio of about 1.

The final interpretation of the Bloemfontein data is presented in Figure 6.10. The upper part of the figure shows the (Figure 6.10(a)) field measured sounding data, the recorded noise, and the best fit inversion to the data. The signal to noise ratio for this particular sounding was about 1. Figures 6.10(b) and 6.10(c) show the frequency and phase at the respective pulse parameters respectively. In Figures 6.10(d) and 6.10(e) the outcome of the inversion is shown.

As was the case in the previous soundings (Pietersburg and Settlers) the inversion indicates some moisture in the upper sections above the water level. In the case of the sounding at Bloemfontein it starts with a moisture content of about 2% close to surface and drops to practically zero at 6 m depth. At a depth of 10 m the water content starts to increase again and reaches a peak of just over 2% at a depth of 22 m. This is in good agreement with the new information from the recently drilled boreholes. Moist soils are reported from 4 to 8 m. whereas the section from 8 to 12 m is recorded as fine sandy dry soil. From 12 m to 21 m moisture content increased again with the main water strikes occurring between 21 and 22 m. In earlier reports from the boreholes in the vicinity the first depth at which some moisture containing layers are found is around 10 m. Rest water level in these boreholes is around 16 m below ground level. The main water bearing layer according to the inversion result, occurs from about 14 m to 45 m and exhibits an average porosity of about 1.5%. Between 22 and 70 m alternating layers of siltstone, shale, mudstone and sandstone are found. The maximum porosity, according to the inversion, occurs at 22 m, which is the depth at which the main water strike occurs. The decay time remains almost constant at 25 ms over the section from 15 m to 40 m. Judging from the decay time only, the hydraulic conductivity should be low. However, the farmers pump for long periods and from closely spaced boreholes, at a rate of approximately 4 l/s. The farmers also tend not to drill deeper than 18-20 m. The new boreholes also indicated that the earlier belief that a dolerite sheet is present from about 25 m is not true. The MRS survey was done in the centre of a large dolerite ring complex with the dolerite dipping towards the centre of the structure. The MRS results predicted no dolerite to a depth of at least 50 m (still some porosity present at this depth), and this was confirmed by the new borehole information. The 70 m deep boreholes ended in shale and mudstone formations.

The MRS results are therefore in agreement with the current geohydrological interpretation of Karoo aquifers, which is that horizontal and other fractures act as the conduits for transporting water to boreholes, and that the surrounding low porosity sedimentary formations act as the storage system for ground water and which supplies water to the fractures. Additional investigations to determine the aquifer characteristics are planned for this area.

6.4.5 Coetzersdam

The final interpretation of the Coetzersdam data is presented in Figure 6.11. It must, however, be stressed that due to the excessive noise levels, and therefore a low S/N ratio, the data sets should not be considered to have a high reliability and should be repeated in future when higher performance MRS equipment. The upper part of the figure shows the (Figure 6.11(a)) field measured sounding data, the recorded noise, and the best fit inversion to the data. The signal to noise ratio for this particular sounding was about 1. Figures 6.11(b) and 6.11(c) show the frequency and phase at the respective pulse parameters respectively. In Figures 6.11(d) and 6.11(e) the outcome of the inversion is shown.

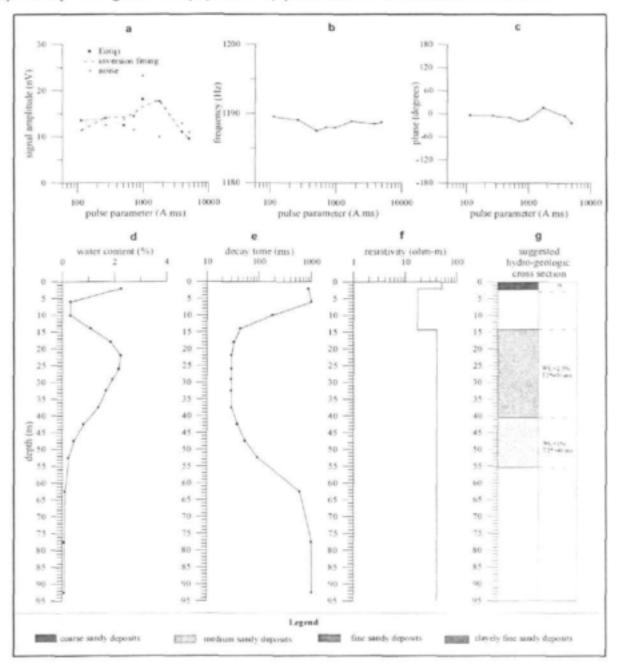


Figure 6.10: NMR sounding curve and inversion results at Bloemfontein.

A very low amplitude signal was recorded at this locality (only 5-15 nV) with exceptionally high noise levels during the recording period. The measurement was preceded by severe thunderstorms, and the lightning activity could still be observed at a distance at the time when the data was recorded. This resulted in the average S/N ratio of about 1.3. Another complicating factor was that the Larmor frequency at this locality is close to a 50 hz harmonic. At the time of the measurements, the instrumentation and data recording software, had only limited noise rejection capabilities. Despite all power lines in the vicinity being out of order due to the severe thunderstorm of the previous night, the effect of 50 hz noise could still be noticed.

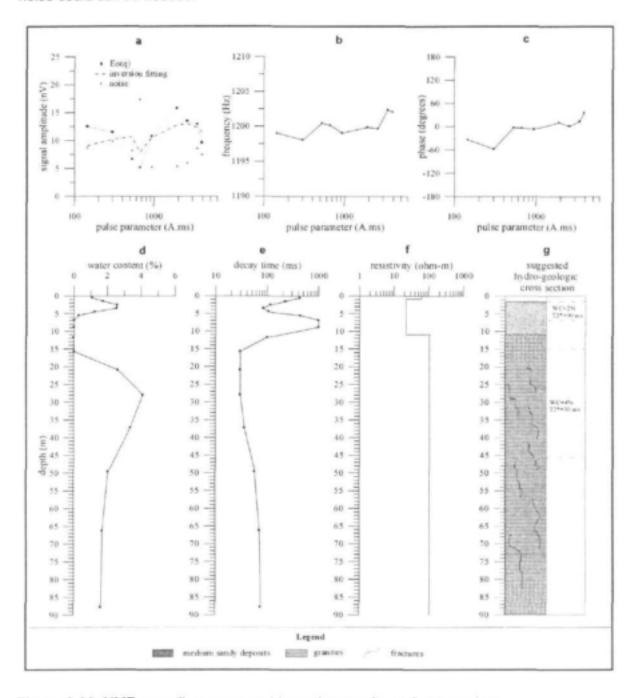


Figure 6.11: NMR sounding curve and inversion results at Coetzersdam.

Again the indications from the inversion are that some moisture is contained in the upper 5m of the succession. This is followed by a dry section of some 10 m. At 16 m depth the moisture content starts building up to a maximum of just over 4% at a depth of 28 m. Over the section 28 m to 50 m the water content decreases gradually to reach 2% at 50 m. Below 50 m it remains constant at about 2%. The corresponding decay times are 30 ms over the upper section (16 m - 45 m) and 70 ms below 45 m. It is interesting to note that the decay time, and hence the hydraulic conductivity increases towards the deeper fractured levels. The resistivity soundings in this area showed very deep fracturing with a resistivity of the fractured granite around 100 ohm.m. This is in agreement with the MRS results.

6.4.6 Nebo

Two NMR soundings were done on the Nebo granite. These were selected on the basis of two prominent structural directions; at ~020° and ~120° -130°. Because the ground water occurrences are associated with these linear near vertical structural features, a multiple figure-eight transmitter loop configuration was used. Again extremely high noise levels were experienced. Measurements in the 020° direction in particular were more affected than in the direction perpendicular to it. It would appear that some channeling of current took place along this structural direction. The average S/N ratio was 1.1, and this is clearly visible on Figures 6.12(a) and 6.13(1a). As was stated in the case of the Coetzersdam results, it must also be stressed here that due to the excessive noise levels, and therefore a low S/N ratio, the data sets should not be considered to have a high reliability and should be repeated in future when higher performance MRS equipment.

The final interpretation of the Nebo data is presented in two figures, Figure 6.12 and Figure 6.13. Again in both cases the upper part of the figure shows the (Figure 6.12(a) and 6.13(a)) field measured sounding data, the recorded noise, and the best fit inversion to the data. The signal to noise ratio for this particular sounding was about 1. Figures 6.12(b), 6.13(b), 6.12(c) and 6.13(c) show the frequency and phase at the respective pulse parameters respectively. In Figures 6.12(d), 6.12(e), 6.13(d) and 6.13(e) the outcome of the inversion is shown. It must also be noted that the inversion programs are designed for 1D horizontally layered models, and therefore not well suited for the conditions experienced at Nebo. Therefore the inversion results are probably not reliable.

Despite the software limitations, the data were nevertheless processed, but only the upper few metres of the inversion result should be regarded as reliable.

6.5 Correlation between effective porosity derived from borehole tracer tests and MRS tests, Bloemfontein

6.5.1 Determination of kinematic (effective) porosity from tracer tests

As part of the MRS experiments at Bloemfontein, two new boreholes were drilled at the site where the MRS experiments were conducted. The purpose of these boreholes was to verify

the results obtained with the MRS method, and to perform tests to determine the vertical variation in hydraulic conductivity. These could then be directly correlated with the MRS interpretation of porosity with depth. The porosity depth determinations were done using tracer techniques and were conducted by Kornelius Riemann of the Institute for Groundwater Studies at the University of the Free State in Bloemfontein (Riemann, 2001). The aim was to compare the porosity/depth predictions resulting from the two techniques.

Single well tracer tests at different depths in the boreholes were done. By using point dilution and single-well injection-withdrawal tests, these tests provide the Darcy and seepage velocities at the depth of the test. These values can in turn be used to calculate the kinematic (or effective) porosity.

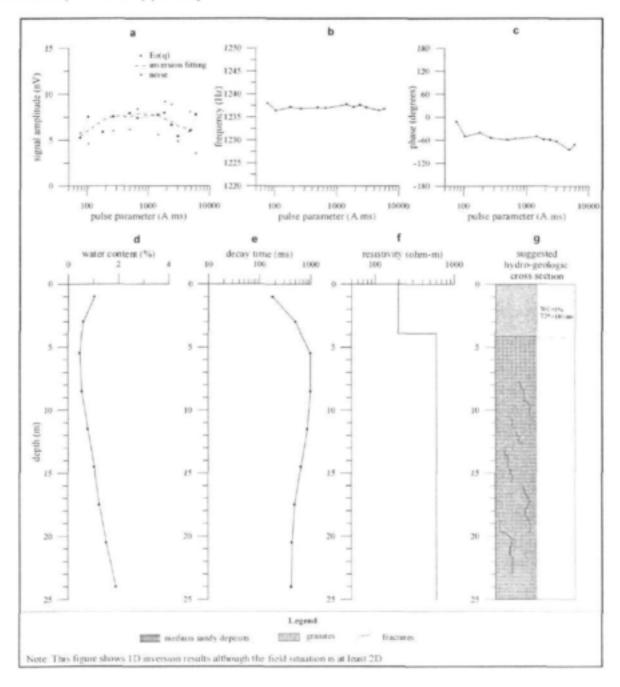


Figure 6.12: NMR sounding curve and inversion results at Nebo (direction 020 degrees).

A combination of the point dilution and radial convergent test were also applied to obtain estimates of the kinematic porosity in the section of the borehole where the main water strike occurred.

6.5.2 Brief description of the theory of the technique

The point dilution test is a single well tracer test, derived from Drost and Neumaier (1974). A tracer is introduced into a borehole and allowed to drift under natural conditions, while the concentration of the tracer is measured continuously. From the dilution of the tracer the Darcy velocity, q, is computed according to the formula

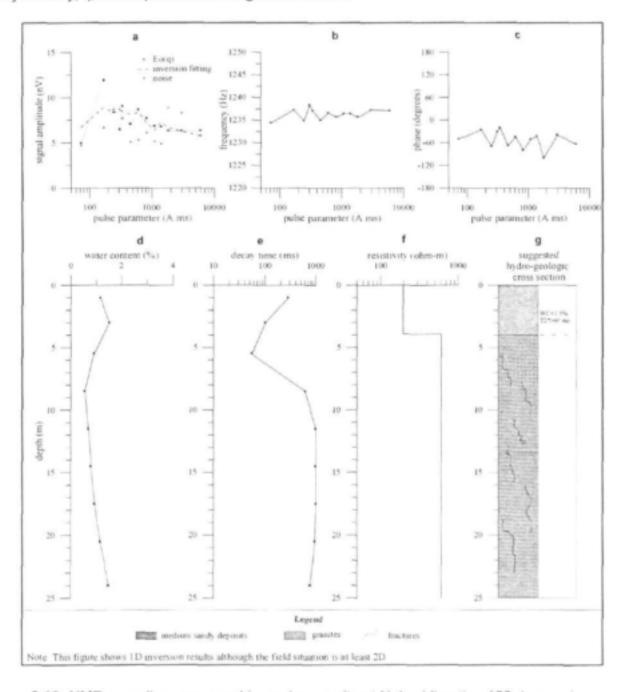


Figure 6.13: NMR sounding curve and inversion results at Nebo (direction 122 degrees).

$$q = -\frac{W}{\alpha A t} \log \left(\frac{C}{C_0} \right)$$
(6.1)

where

W is the volume of fluid in the test section.

A is the cross sectional area normal to the direction of flow,

 C_0 is the tracer concentration at time t = 0,

C is the tracer concentration at time t,

 α is the borehole distortion factor which usually has a value of between 0.5 and 4.2 for an open borehole.

Note that

$$q\alpha=v^*$$
,

where v* = apparent velocity inside the borehole.

If the kinematic porosity is known, the seepage velocity can be computed from Eq. 6.2

$$v = q/E$$
 (6.2)

The single well injection-withdrawal test (also known as the drift and pump back test) was first described by Borowczyk et al. (1966) and by Leap and Kaplan (1988). This test is performed by injecting a tracer solution into a test borehole and it is then allowed to drift under the influence of the natural hydraulic gradient for a period of time. The test borehole is then pumped to recover the tracer. The groundwater velocity is determined by the following equation (Leap and Kaplan, 1988):

$$v = \sqrt{Qt_p / \pi \varepsilon b} / t_d \qquad (6.3)$$

where

v is the seepage velocity [m/day].

Q is the pumping rate to recover the tracer [m³/day]

t_p is the elapsed time from start of pumping until the centre of mass of the tracer is recovered [day],

ε is the kinematic porosity [fraction, dimensionless],

b is the aquifer thickness [m], and

 t_d is the time elapsed from the injection of tracer until the centre of mass of the tracer is recovered [day].

By combining Eqs. 6.2 and 6.3, the kinematic porosity of the tested section can be derived

$$\varepsilon = \frac{\pi b q^2 t_d^2}{Q t_p}$$
(6.4)

A radial convergent test is conducted between two boreholes, where one borehole is used as the source for the tracer while the other borehole is used for abstracting water. The tracer concentration in the water from the abstraction borehole is continuously monitored. From the tracer concentration in the abstraction borehole the seepage velocity can be obtained. The approximate solution for converging radial flow with a pulse injection as given by Sauty (1980) can be written as:

$$c(r,t) = \frac{\Delta M}{2Q\sqrt{\pi\alpha_L vt^3}} \exp\left[\frac{(r-vt)^2}{4D_L t}\right]$$
(6.5)

where

 ΔM is the injected mass of tracer per unit section [ΔM = Mass (kg) / Thickness (m)], α_L is the longitudinal dispersivity,

 D_L is the longitudinal dispersion coefficient [$D_L = \alpha_L \times v$], [m^2/s],

v is the advective seepage velocity [m/s],

Q is the pumping rate of the borehole [m3/s], and

r is the radial distance [m] between the two boreholes.

If a point dilution test is used as the source in the injection borehole, the Darcy velocity q can be estimated using Equation 6.1. The seepage velocity v is obtained by fitting Equation 6.5 to the data from the breakthrough curve. The relation $v = q/\epsilon$ (Eq. 6.2) can then be used to estimate the kinematic porosity and this value could be compared to the kinematic porosity estimated with Eq. 6.4.

In all three types of tracer tests conducted on these boreholes, it was necessary to specify a thickness of the tested section. During the dilution part of the tests it is very important to ensure a continuous mixing in the tested section. Therefore a special setup, shown in Figure 6.14, was used and was used in the following way:

The submersible pump with a discharge rate of 0.4 l/s was used to abstract water from the borehole. The pumped water flows through a closed flow cell, where the electrical conductivity (EC) of the water was measured continuously during the test. The outflow from the flow cell flows into an open container and from there back into the borehole. The pulse injection of the tracer occurred through the open container. For the single well tests salt was used as a tracer, while for the radial convergent tests salt and fluorescein were used.

The length of the tested section was fixed to 2 m between pump inlet and outlet of the injection pipe. The depth of the section varied from test to test, with the depth reference being the pump inlet.

During January and February 2001 several single well and two radial convergent tracer tests were conducted on these boreholes (Table 6.3). The single well tests were conducted at different depths in borehole BH 2, while the radial convergent tests were both conducted between BH 1 and BH 2

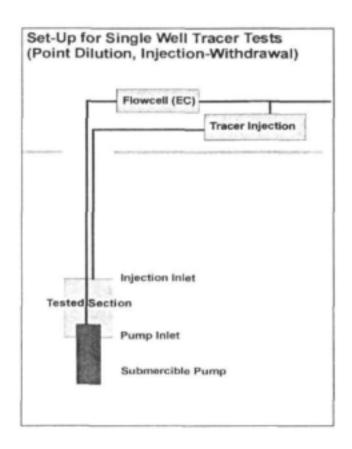


Figure 6.14: Set-Up for Single Well Tracer Test

6.5.3 Test results

The distance between the two boreholes used for the tests is about 6 m. Both boreholes were drilled to a depth of 70m with a diameter of 160 mm. Solid PVC casing was installed to a depth of 18 m and 16 m for boreholes B1 and B2 respectively to prevent collapse in the upper sections. The static water level in both boreholes is around 18.5 m below ground level. Up to the depth of the water strikes at 21 m (borehole B1, blow yield <1l/s) and 22 m (borehole B2, blow yield 1 l/s) a succession of weathered sandstone and siltstone was encountered, followed by some fracturing at the depth of the water strikes. The geological description below the water strike is provided in Table 6.3.

In Table 6.4 porosity values derived with the different techniques are listed. The single well tests show a large variation in the flow velocity over the whole depth of the borehole. The variation in the Darcy and seepage velocities observed over the whole depth of borehole BH2 is partly attributed to abstraction in nearby production boreholes while some of the

tracer tests were conducted. As the tests had to be done on different days, unfortunately no control could be exercised on the pumping schedule of the farmer. The tests yielding a Darcy velocity under 0.1 m/day were conducted when none of the nearby production boreholes were pumped, while the other tests were conducted on days when one production borehole close to the test borehole was abstracting water for irrigation purposes.

Table 6.3: Tracer tests done in the test boreholes at Bloemfontein.

Borehole #	Depth Geology interval (m)		Type of test		
B-1	20 – 22	Siltstone, fractured at 21 m	Point Dilution (Source for Radial Convergent)		
B-2	25	Carbonaceous shale and mudstone	Radial Convergent (Abstraction Borehole)		
B-2	21 – 23	Siltstone, fractured at 22 m	Point Dilution (Source for Radial Convergent)		
B-1	25	Carbonaceous shale and mudstone	Radial Convergent (Abstraction Borehole)		
B-2	19 - 21	Siltstone	Point Dilution and Injection Withdrawal		
B-2	21 - 23	Siltstone	Point Dilution and Injection Withdrawal		
B-2	24 - 26	Siltstone	Point Dilution and Injection Withdrawal		
B-2	26 - 28	Siltstone	Point Dilution and Injection Withdrawal		
B-2	29 - 31	Siltstone	Point Dilution and Injection Withdrawal		
B-2	34 - 36	Siltstone	Point Dilution and Injection Withdrawal		
B-2	39 - 41	Siltstone	Point Dilution and Injection Withdrawal		
B-2	44 - 46	Siltstone	Point Dilution and Injection Withdrawal		
B-2	49 - 51	Shale, sandstone from 50m Point Dilution and Injection Withdrawal			
B-2	54 - 56	Shale and mudstone	Point Dilution and Injection Withdrawal		

The kinematic porosity values using Eq. 6.4 yielded values between 1% and 6%. Both techniques indicate maximum porosity over the section 22 m to 25 m, and decreasing with depth. The kinematic porosity derived from the tracer tests do, however, not show the smooth variation in porosity as derived from the MRS data. What is however important is that the values derived with the two techniques are of the same order and in general show the same pattern with depth.

The increase in Darcy velocity from about 40 m and deeper, and the spuriously high kinematic porosity (tracer) around a depth of 45 m, can not be explained at this stage and needs to be investigated further. There was no indication of a water strike during drilling, nor was a change in geology obvious at this depth.

6.5.4 Conclusions

Although the tracer test derived porosity values are in general higher than those calculated from the MRS results, they show the same trends. Assuming that the theoretical base

according to which the porosity values have been calculated is correct, it is reassuring that the two methodologies provide similar results. The disadvantage of the tracer test technique to determine a porosity is that one or more boreholes are required, whereas in the case of MRS, the porosity can be obtained from surface measurements. The MRS technique therefore provides a way to estimate the amount of water stored in an aquifer without the need for drilling.

Table 6.4: Comparison of porosity determinations derived from tracer and MRS tests,
Bloemfontein

Tested section (m)	(Point dilution test, m/d)	Seepage velocity (Injection- withdrawal test, m/d)	Kinematic porosity (%) (from Eq. 6.4)	Depth and corresponding porosity derived from MRS interpretation (%)
2.5	-			2.2
6			-	0.4
10	-	-	-	0.3
14	-		-	1.0
19 - 21	0.06	5.37	1.1 % ± 0.5 %	(20 m) 2.0
21 - 23	0.07	1.95	3.8 % ± 0.5 %	(22 m) 2.2
24 - 26	0.39	8.55	4.5 % ± 0.5 %	(25 m) 2.2
26 - 28	0.16	9.30	1.7 % ± 0.5 %	(27 m) 2.1
29 - 31	0.35	10.68	3.3 % ± 0.5 %	(30 m) 1.85
34 - 36	0.30	11.02	2.7 % ± 0.5 %	(35 m) 1.5
39 - 41	0.62	nd	nd	(40 m) 1.1
44 - 46	0.50	7.92	6.3 % ± 0.5 %	(45 m) 0.6
49 - 51	0.66	nd	nd.	(50 m) 0.35
54 - 56	2.56	nd.	nd	(55 m) 0.2
62	-	-	-	0.1
77	-	-	-	0.1
92	-			0.05

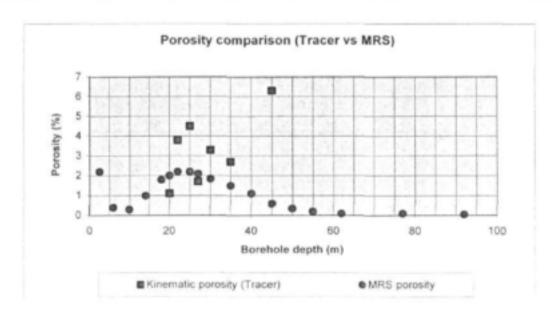


Figure 6.15: Comparison of porosity determinations derived from tracer and MRS tests.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Objectives

This study had as its main objectives the following tasks:

- To study and evaluate existing literature on the applications of the NMR technique to ground water exploration and to review the theory of the NMR technique as applicable to ground water exploration.
- 2) To identify on the basis of the results from the literature study, suitable sites in South Africa for the testing of the NMR technique and in collaboration with the role players from the South African geohydrological community and conduct field surveys using modern NMR equipment and to interpret the results.
- 3) To focus the research on the practical application of the technique with the aim to eventually assist in the selection and evaluation of potential drilling sites, and to improve our understanding of the geohydrological conditions in fractured rock aquifer systems. In particular the research was to focus on, but not restricted to, evaluating the applicability of the MRS technique under the challenging South African geological and geohydrological conditions of fractured rock aquifers.
- To undertake an overall evaluation of the technique, make recommendations as to its applicability under SA conditions and report on the findings of the complete project.

These objectives were all met and the main conclusions and recommendations that emerged from this research project are described below.

7.2 Conclusions

The following main conclusions regarding the technique, field work, instrumentation, interpretation techniques and the results obtained in southern Africa with the NMR method can be made:

 Nuclear Magnetic Resonance is a proven technique for ground water exploration under varying conditions. Not only is the theory on which the methodology, instrumentation and interpretation techniques are based, sound, but it has been proven to provide excellent results in numerous studies world wide, including southern Africa.

- To achieve the best results with the technique, a number of conditions or a combination of these have to be met in order to perform meaningful measurements in the field. Of these the more important ones are
 - Aquifers comprising of loosely packed sand or gravel.
 - A saturated effective porosity of >5% is ideal, although it has been proven that good results can also be obtained in hard rock aquifers with lower effective saturated porosities.
 - A shallow water level with the aquifer depth not exceeding 100 m (the depth of investigation is a function of resolution and signal strength).
 - A primary aquifer or a horizontally layered secondary aquifer system (compared to aquifers associated with vertical or near vertical fracture and fault zones).
 - A homogeneous geomagnetic field, and one which will not cause the Larmor frequency to be a or close to a harmonic of 50hz.
 - No man-made sources of electrical noise close to the sounding position.
 - Measurements are to be made outside periods of high electrical noise caused by weather patterns, such as lightning and thunderstorms.
 - A large transmitter loop (signal amplitude is usually increased with increase in transmitter loop size).
 - Sensitive measuring instrumentation and appropriate interpretation software.
- Despite the fact that these "ideal aquifer" conditions are not always present in the
 areas where the ground water exploration programme is conducted, many
 excellent reports on the application of NMR in less than ideal conditions have
 been recorded. Highly fractured but shallow hard rock aquifers, and thick
 (~100m) high porosity water saturated sedimentary formations, are examples.
- The results gathered from the limited number of NMR soundings done so far in southern Africa, are very encouraging and provide proof that, when operating in low noise environments, excellent results are achieved. This has been the case in for example low porosity sandstones (~3%) underlying a water filled fracture zone with a higher porosity, alluvium underlain by fractured granite, and zones of horizontal, water filled bedding plane fracturing in a Karoo environment.
- Under favourable conditions, the interpretation software has proven itself to the
 extent that the outcome of predictive modelling can be accepted. Theoretical
 modelling done with the existing 1-D modelling routines, indicate that even a
 fractured granite aquifer, simulated by a 20 m thick aquifer with 1% water
 saturated porosity at a depth of between 50 m and 70 m, would still produces a
 signal amplitude of about 6 nV. A theoretical multiple fractured aquifer consisting
 of 10 water filled fractures each 0.05 m wide and spaced at 10 m intervals, would
 produce a signal amplitude of about 2 nV under southern African conditions
 (lower geomagnetic field compared to for example Europe).
- However, to be able to record these low amplitude signals, the currently available instrumentation needs to be improved and made more sensitive. Technically this is achievable.

- The NMR tests done in southern Africa were conducted under different and technically difficult geohydrological conditions compared to other areas in the world, but nevertheless, it has been proven that meaningful results can be achieved.
- The measurement periods were in general much longer that in Europe, and large numbers of stacking had to be done.
- Severe thunderstorm activity places a serious restriction on the time of the year when measurements can and should be made.
- Excellent results have been achieved in the Pietersburg (water saturated alluvium overlying fractured granite), Settlers (low primary porosity sandstone aquifer) and Karoo (low porosity, essentially thin bedding plane fracture aquifer) geohydrological environments.
- The good results obtained in the Ecca sandstone underlying basalt of the Springbok Flats east of Warmbaths, Northern Province, came as a surprise because basalts are often magnetically very noisy regions.
- The current instrumentation needs further development for South African conditions, especially with regard to the internal noise levels generated by the NUMIS instrument.
- The data collection and data formatting needs further improvement.
- Several more tests are required under different geohydrological conditions to further verify the applicability of the technique in fractured aquifer systems.

The review of the international experience indicated that the technique has until now been essentially used under primary aquifer conditions to establish the geohydrologically most promising areas (and specifically high saturated porosity areas) within the boundaries of the aquifer, and which would also be areas where high yielding production boreholes could be developed. Whereas this approach could also be used in South Africa, the surface area of similar type of aquifers in very limited in South Africa (coastal alluvial deposits, sand filled river beds, etc.) Apart from using the technique under these rather limited primary aquifer conditions in the country, it is concluded that the technique could also be utilised in a "ground water resource quantification" mode. It is believed that this technique can be employed under the South African fractured aquifer conditions as a tool to determine our ground water resources and in that way assist in the quantification of the "ground water reserve" for individual catchment areas as required under the new National Water Act of 1998. This deviates from the approach concentrated on thus far in international MRS research programmes.

7.3 Recommendations and the way forward

The following recommendations are made:

 Due to the promising results obtained with the initial short survey in southern Africa, it is strongly recommended that research on the technique in the local geohydrological conditions be continued. It must be remembered that the first series of measurements were done under tremendous time pressure, and under very adverse atmospheric conditions that influenced the results negatively. However, in a sense this has benefitted the research also because a number of potential problems have been identified that have not been experienced or identified in surveys done elsewhere. These identified problems will undoubtedly direct the research programme in future. Subjects for further research include the improvement of the instrumentation to reliably be able to measure low signal amplitudes, reduce the internal noise of the instrumentation, improve interpretation procedures, and the improvement of data recording, storing and formatting.

- Additional financial resources should be made available to study the seasonal and diurnal noise patterns to determine the optimum time and season for conducting NMR measurements. From the short experiments done by the German Geological Survey in Namibia (also conducted during the summer season), and the fact that they did not encounter noise problems of the same degree as was experienced during the CSIR/ITC experiments in southern Africa, illustrates that these high noise conditions may not only be attributed to seasonal conditions, but that other factors may also play a meaningful role. This highlights the need for more collaborative research in this regard. This will also lead to the development of criteria to eventually improve the S/N ratio through the development of efficient and intelligent data (noise) rejection routines.
- From a logistical point of view, it is recommended that all sites be surveyed beforehand to establish the local conditions. These surveys should include some ground magnetic measurements, noise measurements with small transportable loop systems designed specifically for noise measurements, presence of fences and powerlines, and the identification of large enough open areas preferably with some nearby control boreholes. This will save a considerable amount of time during the planning of a research programme.
- All boreholes where NMR surveys are conducted are to be geophysically logged
 to provide additional information in digital format which can be compared with the
 results obtained during normal geohydrological surveys. It is also recommended
 that down the hole video recordings be made at all boreholes where MRS
 research work is undertaken or of boreholes drilled to test the results of NMR
 interpretations.
- It is recommended that a few long term ELF and VLF monitoring stations be installed in the major cities of South Africa to determine which would be the best time of the day and year to perform NMR soundings.
- The use of the MRS technique for the quantification of our ground water reserves contained in the fractured rock aquifers, should be further investigated. This is believed to be a different approach to the hitherto practical applications of the MRS technique and an area where South Africa could make a major contribution to identify new applications of the technique. In this regard the technique could for example be used to determine the exploitable ground water contained in the Ecca sandstones underlying the Springbok Flats in the Northern Province and thereby assist in the sustainable management of the aquifer.

Finally, a strong case is made that future research into the application of NMR techniques for ground water exploration in South Africa should not be discontinued. It needs to be appreciated that the research is still in an early stage and that expectations should not be pitched at a too high level at this stage. Nevertheless, South Africa should take advantage of the enormous amount of research that has already been conducted on this technique internationally, while at the same time realising that the local geological, geohydrological and atmospheric conditions, result in the southern African targets being some of the most difficult targets in the world. Therefore it must be realised that it may still take a number of years before the developments have progressed to a situation where NMR soundings may become a routine geophysical technique in the geohydrologist's toolbox.

With the challenging geohydrological conditions, South Africa is in a unique position that the country, its researchers and geohydrologists can play a leading role in the further development of the MRS technique. To achieve this it is recommended that the cooperation with international research teams active in the further research and development of the technique, notably the European research group, should not only be continued, but expanded. The experience gained from the short period the author of this report could work together and meet these groups in Europe, was invaluable. Continued cooperation and contact with these groups will reduce duplication of research and field experiments, and eventually be to the benefit of not only South Africa, but also the research programmes in other countries. In this regard it is recommended that South Africa actively pursues cooperation and involvement of international research programmes, by becoming a member of the cooperative research groups established in Europe and who are seeking financial assistance from European Union research funds. In discussions with leaders of these research team, the author realised that South Africa would be more than welcome to join these research teams provided the country contributes financially to the research.

For the future development of South Africa, the country will need to rely more and more on the hitherto under utilised ground water resources. Ground water is in many circles in this country perceived to be a minor and unreliable water resource when compared to the surface water resources of the country. By utilising improved exploration techniques, like for example the MRS technique, the success rate of drilling for ground water could be increased, and this coupled with our current much higher level of understanding of the hydrogeological conditions, the ground water resources can be managed more optimally. At the moment the MRS technique is the only technique that can provide quantitative information on the underground water resources, and for that reason financial and manpower resources should be made available to do further research on this subject. This view has also been strongly supported by the members of the Steering Committee during the evaluation of the final report.

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The geophysical approach used in this project introduced two innovations relative to the traditional approach for groundwater exploration used on the Nebo granites. In the first instance the area was investigated on a regional scale rather than the very localized scale used in the past. In the second instance, airborne geophysical data was used as an aid in identifying and mapping structures of regional extent. In the first test area airborne data included magnetic, radiometric and electromagnetic values. Interpretation of these results indicated that airborne magnetic data should be sufficient to allow for the mapping of major structures. Downward continuation of this data significantly reduced the amount of ground follow-up that was needed to locate the target in the field. The electromagnetic technique then proved to work exceptionally well in determining whether there were weathering associated with the target structure and in locating an optimum borehole position. In the second test area the airborne data were limited to magnetic and radiometric information. Since only four targets, all with the same strike orientation, were drilled in this area, it is difficult to evaluate the geophysical results for this area, except that the interpreted structures were intersected in the drilled boreholes.

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