Development of and Tests with the NMR Technique to Detect Water Bearing Fractures

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ABSTRACT

The theory and application of Nuclear Magnetic Resonance Soundings also referred to as Magnetic Resonance Soundings (MRS) for the exploration of groundwater in porous aquifers has been well developed and tested. To date the method is usually applied on surface to assess the groundwater potential of thick porous water saturated geological formations. In hard rock aquifers, ground water is normally encountered in fractures or fracture zones. In this paper we describe the development of theoretical aspects of the technique for the detection of thin water bearing fractures, both from the surface as well as in underground mines. We have extended the theory to general geometries to describe the detection of discrete water saturated fractures and to investigate the application under mining conditions.

We have applied this theory to synthetic models for underground conditions under different geometries, as well as for the usual surface based groundwater exploration situation. This paper describes the results of these simulations and presents field data from both surface and underground measurements collected with a new NMR instrument developed for shallow investigations. Signal amplitudes of <100 nV are normally expected, but noise levels are often a few orders of magnitude higher. The impact of electromagnetic noise on the measurements is discussed and it is shown that this remains one of the main obstacles for the MRS method.

Key words: Magnetic Resonance, fractured rock aquifers, in-mine applications

INTRODUCTION

An extensive gold and PGE mining industry has developed around the Witwatersrand basin and the Bushveld Complex with some mines reaching depths in excess of four kilometres in the case of gold mines. The geological and geohydrological conditions in parts of the Witwatersrand gold mining district pose some serious risk components to the mining environment. The gold bearing reefs in the West and Far West Rand Basins of the Witwatersrand Goldfields are in places overlain by up to two kilometres of fissured and karstified dolomitic rocks that are host to excessive volumes of groundwater and can exert huge hydraulic pressures in the underlying mining area. The gold fields have undergone significant structural deformation during its geological history, and this has created a dense network of faults and fractures creating a hydraulic connection between the underlying gold bearing strata and the overlying aquifer in dolomitic and other rock types. Despite precautionary measures, uncontrollable water inflows into mining areas have occurred, often resulting in devastating consequences and loss of life. The most severe case occurred in 1968 at the West Driefontein mine when during underground drilling a water intersection was encountered at a depth of 874 m below surface which resulted in an inflow of 385 megalitres per day flooding the entire mine (Wolmarans, 1986). Several examples of the potentially disastrous consequences of unforeseen water and gas occurrences ahead of the mining face in deep gold and platinum mines are known.

In mines where hazardous water and/or gas are known to occur, cover drilling is used to assess the groundwater conditions of the virgin block up to 100 m ahead of mining (Schweitzer and Stephenson, 1999). A geophysical tool that can detect hazardous targets, has a quick turnaround time, and negates the need for cover drilling could have significant positive cost and safety implications for deep mining.

The development of Nuclear Magnetic Resonance (NMR) technology, a novel non-invasive geophysical technique to detect and quantify underground water created the opportunity to address the longstanding need in the South African mining industry for a tool that can detect and quantify hazardous water occurrences ahead of the mining face and thereby could impact positively on the efficiency and safety of mining operations (Legchenko and Valla, 2002; Lubczynski and Roy, 2004). A short description of the method is presented in another short paper in this volume describing surface groundwater exploration using NMR (Meyer et al, 2007).

The development of some theoretical concepts for in-mine conditions, and results of some initial surface and in-mine tests recently conducted are discussed in this short paper.

GEOHYDROLOGICAL SETTING

Groundwater occurrence in fractured hard rock environments, commonly referred to as secondary aquifers, differs appreciably from that of unconsolidated formations or rocks, also referred to as primary aquifers. In the case of primary aquifers, the water saturated porosity is regarded as being relatively homogeneous and therefore when conducting MRS experiments under such conditions, the water content per metre thickness and variations thereof can be determined. Aquifers consisting of unconsolidated or partially consolidated material can contain up to 35% water and hence would produce large signals when a MRS survey is conducted under such conditions.

In the case of fractured hard rock or secondary aquifers the situation is completely different. Whereas in primary aquifers, the formation or rock has a primary porosity, hard rock due to its age and geological history normally has no or only a very low effective primary porosity. In this case groundwater is present in fractures, cracks, joints, and faults zones in the rock formations that only host small amounts of water relative to the volume of rock (low porosity). When conducting surface based MRS under these conditions, the bulk water saturated porosity is determined. Due to the resolution of the method, thin water filled structures such as faults, fractures and joints cannot easily be determined individually.

Disastrous flooding conditions in the case of underground mining are believed to occur when wide and highly fractured zones, often with associated conditions of large hydraulic heads, are intersected. The current practice of cover drilling ahead of the mining face, is normally effective in locating such fractures, but at a high cost. It is envisaged that by scaling down the surface MRS methodology to a 3 m diameter multi-turn coil one could be able to identify the presence of larger water filled fracture zones at distances of 5 or more metres ahead of the face.

THEORETICAL DEVELOPMENTS

The theoretical developments centre on the different Tx/Rx coil orientation underground as well as assessing the shape and amplitude of sounding curves for different geometrical conditions and orientations of the water bearing fracture zones. Simulation of the NMR response for different water filled fracture conditions is currently in progress and will be presented during the conference.

INSTRUMENTATION USED

The NMR instrumentation usually used for groundwater exploration makes use of large diameter loops (typically 50 to 100 m diameter). This is obviously impractical for underground and therefore a new smaller multi-channel system, recently developed by Radic Research of Germany, was used for the surface and in-mine experiments. The *SNMR MIDI* system designed originally for shallow groundwater assessments has been successfully tested with a Tx loop as small as 1 m diameter (www.radic-research.de). By constructing a 3 m x 3 m size coil to be able to be used underground and increasing the number of turns to 128, we were able to obtain the equivalent of a 10 m x 10 m with 12 turns coil receiver coil used for surface groundwater assessments (Fig. 1). The SNMR MIDI system utilizes a

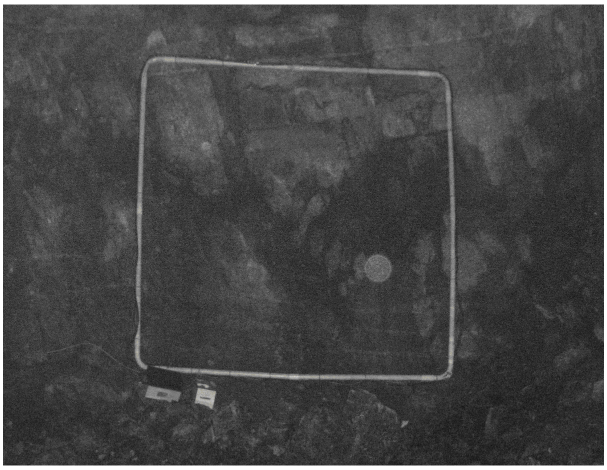

Figure 1: 3m x 3m Tx/Rx coil deployed underground against the mining face.

Remote Reference Technique (RRT) which has been demonstrated to effectively suppress cultural noise, and is thus ideal for our purpose where high noise levels were anticipated.
The RRT method consists of two smaller (1 m x 1 m) orthogonal receiver loops that measure noise before and during an NMR measurement (Fig. 2). A multivariate coherence analysis method is used to calculate the magnetic transfer function needed to predict and eliminate the noise recorded in the Free Induction (FID) record. This has the advantage of reducing the conventional stacking time and should improve measurement efficiency and S/N ratio. When noise suppression is necessary, two channels are used for the

RRT, while the third channel is for signal recording. In areas of low noise, the multi-channel instrument can also be used to do multiple soundings simultaneously with three Tx/Rx loop configurations.

Figure 2: Orthogonal 1 m x 1 m receiver coils as used underground for noise recording.

RESULTS

The initial experiments conducted to date with the SNMR MIDI system included surface and underground targets. Due to a number of constraints, all tests were done close to urban areas and this had the disadvantage of introducing high background noise levels.

Due to the limited depth penetration of the system the surface based tests were done where shallow groundwater conditions were expected such as wetland areas, and areas where water saturated ground conditions adjacent to dams occur. Unfortunately extremely high noise levels were experienced at most test sites as is shown in Figure 3a. In the 10 m x 10 m (12 turns) receiver coil the recorded noise levels were in excess of 500 mV (Channel 1) while the pair of smaller 1 m x 1 m orthogonal reference coils (Channels 2 and 3) still showed noise amplitudes around 100 mV. In Figure 3b the effect of the Reference Coil on reducing the noise is illustrated. At the top is the noise as recorded at Channel 1 in the Rx coil, while the bottom display shows the noise also at Channel 1 as predicted from the measurements performed at the two orthogonal reference coils. The centre display shows the true signal at Channel 1 when the calculated noise (lower part) is subtracted from the time series originally recorded at Channel 1. An approximate 4-5 time improvement in the S/N ratio is achieved in this way.

To date, two underground tests have been conducted. The first was at the Madikwe Platinum Mine in the Eastern Bushveld at a depth of about 150 m below surface, while the second was at Tau Tona Gold Mine, some 2.9 km below surface. The results at Modikwa were not very promising as excessive noise conditions were encountered that occasionally saturated the different receiver channels Figure 4). The excessive noise is believed to have originated from ongoing mining activity at levels above and below the mining face where our experiments were conducted. The upper graph in Figure 4 shows the signal plus noise as recorded by a vertical 3 m x 3 m Rx coil in Channel 1 to be >7 V. Noise amplitudes as measured by the two smaller and vertical orthogonal reference coils are at at levels of about 1.5 V. At the time of writing this abstract the Tau Tona data had not yet been analysed; however, the observed noise levels were still relatively high, but significantly lower than at Modikwa.

CONCLUSIONS

From the measurements performed to date, it is clear that electromagnetic noise remains the most important problem when conducting NMR measurements. To date no effective methods have been developed to reduce noise levels that are present in build-up areas or mines to such levels as to allow NMR measurements to be conducted successfully in order to identify water bearing fractures in mines ahead of the mining face.

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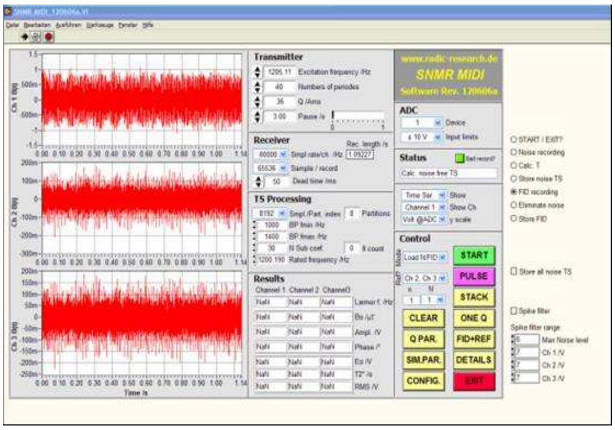

Figure 3a: Screenshot showing lower noise levels during a surface experiment. Top graph is Channel 1 (10 m x 10 m loop); the other two are Channels 2 and 3 (reference loops). Channel 1 shows levels of between 500 mV and 1 V, Channels 2 & 3 noise have amplitudes of ~100 mV!

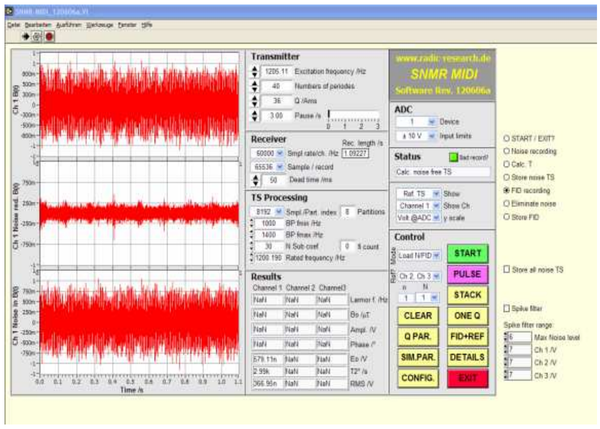

Figure 3b: Reference technique as applied at the site shown in Fig. 3a. Top is Channel 1 time series, middle shows noise reduced version of Channel 1, while bottom shows noise at Channel 1 (as predicted from reference loops)

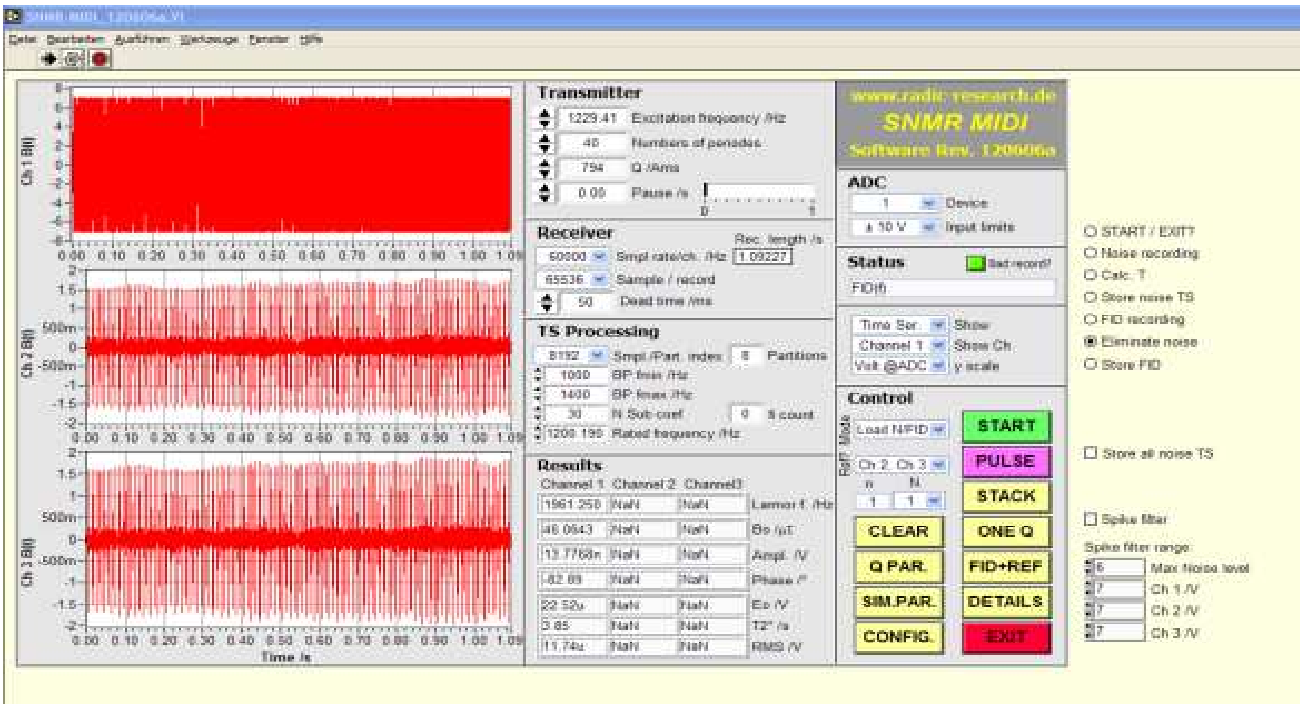

Figure 4: Screenshot showing the high level of in-mine noise at Modikwa Mine. Top graph is Channel 1 (3 m x 3 m loop); the other two are Channels 2 and 3 (reference loops). Channel 1 is clipped at ~7 V, Channels 2 & 3 noise have amplitudes of ~1.5 V!