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The underground application of Magnetic Resonance Soundings

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ABSTRACT

The potential application of MRS technology in locating waterbearing fractures in underground mines is studied. The determination of the presence of water ahead of mining is important to prevent accidents and to ensure higher efficiency in mining operations. In the usual surface based measurements, with horizontal loop and water layer, the geometry of the problem can be summarized by the value of the inclination of the Earth magnetic field. For MRS measurements under the geometric conditions associated with underground mining, where the loop is non-horizontal, the geometry can be described in an effective inclination that can be expressed in terms of the Earth magnetic inclination and declination, together with two further parameters that characterize the orientation of the mine wall. We examine the consequences of the different geometries on the MRS signal. Since the loop size is severely restricted in underground conditions, the feasible target depth is also severely limited. The consequences of the fractured hard rock aquifer conditions, typical of deep mining or tunneling environments, are also examined. The overall conclusion is that in underground MRS applications the signal strength is too small to enable the practical identification of fractures containing large volumes of water ahead of the mining face.

1. Introduction

Nuclear Magnetic Resonance (NMR) has become increasingly popular as a tool in hydro-geophysics and when used as a non-invasive geophysical technique to detect and quantify underground water (referred to as Magnetic Resonance Sounding or MRS), has become a new geophysical research area (Legchenko et al., 2002; Legchenko and Valla, 2002; Lubczynski and Roy, 2004). In this study the feasibility of using this method in the detection of water to facilitate safe underground mining and tunneling operations is investigated. The early detection of large quantities of groundwater ahead of underground mining or tunneling operations can be of substantial benefit. Not only may this prevent accidental flooding with its associated safety risks, but it can also substantially improve operational efficiency.

In view of the importance of the mining industry in southern Africa, it is of great significance to prevent accidental flooding in mining operations. The extent of this industry is due to the presence of vast mineral resources in the region. In the case of gold mines mining is conducted at depths in excess of 4 km. Parts of the Witwatersrand Goldfields are overlain by up to 2 km of fissured and karstified dolomitic rocks that, because it is host to excessive volumes of groundwater, exerts huge hydraulic pressures in the underlying mining area. This is a serious risk to the mining environment (Schweitzer and Stephenson, 1999; Wolmarans, 1986). As a result of structural deformation, a dense network of faults and fractures has created a hydraulic connection between the mining area and the overlying aquifer. Despite precautionary measures, uncontrollable water inflows into mining areas have occurred in the past, often resulting in devastating consequences and loss of life (Wolmarans, 1986). Detecting the presence of water ahead of a vertical mining or tunneling face, and thereby negating the need for expensive cover drilling (a term used in the mining industry to describe exploratory drilling to test for the presence of water), could impact positively on the safety and cost efficiency of these operations. In mines, where hazardous water and/or gas conditions are known to occur, cover drilling is used to investigate the virgin block up to 100 m ahead of mining (Schweitzer and Stephenson, 1999). This current practice of cover drilling is normally effective in locating such fractures, but at great cost and interruption of mining progress. This motivated investigating the possibility of detecting water ahead of mining via the non-invasive MRS technique.

Performing MRS in southern Africa presents considerable challenges for three main reasons: low Earth magnetic field; low water content in fractured rock aquifers and high electromagnetic noise. In underground conditions a further complication is the fact that the size of the T_x/R_x loop is limited by the tunnel dimensions – typically 3 m by 3 m – thus reducing the depth penetration of the technique (the experience that penetration depth is roughly equal to the diameter of the loop is discussed in Lange and Yaramanci, 2005). However, given the value of the magnetic inclination, preliminary analyses indicated that there

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could be a substantial increase in the size of the signal due the different orientation of the loop in underground circumstances.

In the usual surface application, the horizontal nature of the T_x/R_x loop and water layer results in a signal amplitude whose geometric dependence can be reduced to a dependence on the Earth geomagnetic inclination only. Underground mining is advancing along horizontal tunnels, implying vertical mine walls. Thus in order to detect water ahead of the mine face the loop will be placed vertically against the face. If we then assume that the water layers are still parallel to the loop (in other words contained in vertical fractures parallel to the mine face), then the geometry of the underground situation is basically a simple rotation of the surface application. In this case we can replace the inclination of the surface application by an effective inclination, which now depends both on the Earth geomagnetic inclination and declination, as well as on two further parameters, characterizing the orientation of the mine wall. Expressions for this effective parameter are given in the paper. Most current modeling or interpretation software does not cater for these non-surface situations. Hence, it is of considerable importance to provide the expression for the effective inclination, and to study the effects of geometry on the signal strength.

The case where the surface is sloping at low angles with respect to the Earth surface has been investigated in two recent papers (Girard et al., 2008; Rommel et al., 2006). However, these studies deviate from the assumptions made above, so that their case does not represent a straight rotation of the surface case. Hence, different approximations are made to calculate the signal amplitudes under these generalized conditions. The nature of these approximations forces them to limit the applications to small sloping angles. Our geometry constitutes a much more radical departure from the surface application. However, by assuming that the water layers, associated with vertical fracture zones, are parallel to the loop we can simplify the geometry.

2. Calculation of MRS signals in underground applications

MRS is the only known scientifically based non-invasive geophysical method capable of assessing groundwater resources. Following on the original patent by Varian (1962), and the work by Semenov and co-workers (Semenov, 1987), the method has been developed extensively in subsequent years. The method has been applied mainly, but not exclusively, to primary aquifers to assess their water content and aquifer parameters. Articles by Legchenko et al. (2002), Roy and Lubczynski (2003) and Yaramanci et al. (2002) provide good descriptions and extensive references to the application of the method to surface based groundwater exploration, while papers by Weichman et al. (2000, 2002) deal with theoretical aspects in detail.

The method is based on the excitation of hydrogen nuclei ($^1H^+$) in groundwater through energizing a transmitter coil (T_x) on the Earth's surface with an alternating current tuned to the local precessing frequency (the Larmor frequency) of the hydrogen nuclei. The Larmor frequency, which is directly proportional to the local value of the Earth's magnetic field, is around 1200 Hz in Johannesburg, South Africa. If groundwater is present, energizing the coil at this frequency causes excitation (precessing) of hydrogen nuclei, and when the current is switched off the nuclei return to their stable orientation. The signal strength depends on the number of hydrogen nuclei present (directly proportional to the water content). The shape of the resulting decay curve as a function of time contains information on the underground water content. The transmitter coil is also used as receiver (R_x) to record the signal produced by the return of the nuclei to the ground state. By energizing the coil with different current strengths for a fixed time period (called the pulse moment $q = \text{current} \times \text{pulse length}$) and recording the signal decay for each pulse moment, a sounding curve is produced. This sounding curve is analyzed in terms of its amplitude, frequency and phase and provides information on the subsurface free water content with depth.

Various descriptions of the theory of MRS in its application to waterbearing geological structures exist (Legchenko and Valla, 2002; Weichman et al., 2000). We will review this theory with an emphasis on the geometrical aspects. As is the case in surface based MRS, it is assumed that the aquifer surface (or water filled fracture zone) is parallel to the plane of the T_x/R_x loop. Although fractures can have multiple orientations, large fracture and fault zones that are nearly vertical are commonly found in deep South African mines. The inclination ($\approx -60°$) and declination ($\approx -17°$) of the Earth's magnetic field in South Africa are substantially different from those encountered in the Northern hemisphere, so that it is of value to understand quantitatively how this aspect influences the applicability of MRS in the Southern hemisphere. In addition, in its application to mining, the geometries encountered are entirely different again. Since, the existing inversion MRS software often does not allow the user to take into account the particular dependence on these geometrical aspects, we will discuss the relevant geometrical relations explicitly, and comment on the major differences between different applications.

Legchenko and Valla (2002) give the following expression for the induced voltage $E(t)$:

$$E(t) = \int_V \mathrm{d}^3 x \omega_0 M_0 w(\vec{x}) b_\perp^{R_x}(\vec{x}) sin\left(\frac{1}{2}\gamma b_\perp^{T_x}\left(\vec{x}\right) q\right)\ \mathrm{e}^{-t/T_2^*(\vec{x})}, \tag{1}$$

where:

$\vec{x}$	spatial coordinate with origin at the center of the loop
ω_0	Larmor frequency $= \gamma\lvert\mathbf{B}_0\rvert$
$\mathbf{B}_0$	Earth's magnetic field
γ	proton gyromagnetic ratio
M_0	nuclear magnetization for protons in water
$w(\vec{x})$	water content distribution
$B_\perp^{T_x}(\vec{x})$	perpendicular component of the magnetic induction
$B_\perp^{R_x}(\vec{x})$	same as $B_\perp^{T_x}(\vec{x})$, but referring to the signal received
$b_\perp^\alpha(\vec{x})$	$B_\perp^\alpha(\vec{x})$ divided by the current through the loop; $\alpha = T_x$ or R_x
q	pulse moment $=$ current $\times \Delta\tau$
$\Delta\tau$	pulse length
t	time elapsed since start of pulse
T_2^*	transverse relaxation time

By perpendicular component we mean the component that is perpendicular to the Earth's magnetic field $\mathbf{B}_0$. Under the current conditions $B_\perp^{T_x}(\vec{x})$ equals $B_\perp^{R_x}(\vec{x})$, so we will often use the short-hand notation $B_\perp(\vec{x})$. In Appendix A we discuss explicit expressions for the magnetic induction fields generated by a circular loop with radius a. We have verified the correctness of our numerical algorithms by comparing with some of the results given by Legchenko and Valla (2002).

To facilitate the numerical analysis of Eq. (1) we list some of the units used in the calculation of the induced voltage. In view of the smallness of the signal it has become customary to express the induced voltage in nV. Consequently the response E_d, which is discussed in Section 3, is expressed in nV/m. By using the units $[x^3] = \mathrm{m}^3$, $\omega_0 = \mathrm{s}^{-1}$, $[B_0] = \mathrm{nT}$ (nano tesla), $[M_0/B_0] = \mathrm{J\,rad}^{-2}\,\mathrm{T}^{-2}\,\mathrm{m}^{-3}$, $[w(x)] =$ dimensionless with values between 0 and 1 (percentage water/100) and $\left[b_\perp(\vec{x})\right] = \mathrm{nT/A}$, we can express $E(t)$ in nV. The dimensionless nature of the product $\gamma b_\perp(\vec{x}) q$ follows from using the units $[\gamma] = 0.2657\ \mathrm{s}^{-1}\ \mathrm{nT}^{-1}$, $[q] = \mathrm{A.s}$, and the units for $b_\perp(\vec{x})$ mentioned above. For those familiar with nuclear physics units it is instructive to verify the relationship: $\gamma = 2g_p \frac{e\hbar}{2m_p}$, by converting to the units above. For 293 K (20 °C) one finds $M_0/B_0 = 3.403 \times 10^{-3}$ in the units given above (see Legchenko and Valla, 2002).

As indicated in the introduction, the geometry of the MRS experiment plays an important role in the mine wall application. Hence, we discuss this now in some explicit detail. The geometry in