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Imaging of groundwater with nuclear magnetic resonance

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Contents

1. Introduction

The method of surface nuclear magnetic resonance (SNMR) is a relatively new geophysical technique that exploits the NMR-phenomenon for a quantitative determination of the sub-surface distribution of hydrogen protons, i.e. water molecules of groundwater resources, by non-intrusive means. The idea to employ NMR techniques within the Earth's magnetic field to derive sub-surface water contents was first proposed by Varian [1]. It was

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not until the late 1970s that a group of Russian scientists took up the idea and developed the first field-ready prototype of surface NMR equipment in the 1980s. It allowed for the first time the recording of NMR signals from groundwater at considerable depths in the Earth [2–4]. Numerous field applications with the Russian Hydroscope-equipment encouraged the ongoing technical developments for about a decade [5–7]. They were supported by several studies on the modeling, inversion and processing of surface NMR data [8–10]. Surface NMR became better known to western scientists when the first commercial equipment was launched by Iris Instruments (France) in 1996. A few groups worldwide actively pursued the fundamental research and applications of surface NMR. Over the past decade the continuous progress and experience has been reported at periodic international workshops (Berlin 1999, Orleans 2003, Madrid 2006), and followed-up publishing special issues of peer reviewed journals devoted to surface NMR [11,12]. Continuous technical development of surface NMR measurements has been carried out and, recently, two new suites of surface NMR hardware have been made commercially available [13,14]. The new systems extend the available technical possibilities towards improved noise mitigation schemes and multi-channel recording.

Major advances in the development of surface NMR were triggered by a revision of the fundamental equations proposed by Weichman et al. [15,16]. The improved formulation allows the correct calculation of complex-valued signals of measurements on conductive ground [17] and the calculation of surface NMR signals with separated transmitter and receiver loops. The latter feature has been studied in detail by Hertrich and co-workers [18,19] which revealed that a series of measurements at multiple offsets along a profile provides sufficient sensitivity to allow for high resolution tomographic inversion. A fast and efficient tomographic inversion scheme has been developed that provides the correct imaging of 2-D sub-surface structures from a series of surface measurements [20].

Various geophysical techniques, like geoelectrics, electromagnetics, georadar and seismics, are routinely used in a structural mapping sense in hydrogeology, to delineate bedrock and sometimes determine depth of the water table and other major geological boundaries. But surface NMR is the only technique that allows a quantitative determination of the actual water content distribution in the sub-surface. Near surface aquifers are the major source of drinking water worldwide. Additionally, these aquifers might be substantially affected by cultural pollution, mismanagement and natural retreat in the ongoing climate change. But also in many other environmental problems groundwater plays a key role. Examples are unstable permafrost and hill-slope stability in the progressive global warming or dynamics of glaciers and ice-sheets. For those issues surface NMR may provide essential information in high resolution imaging of the sub-surface water content distribution and monitoring of groundwater dynamics.

In conventional NMR applications (e.g. spectroscopy, medical imaging, non-destructive material testing) the excitation of the spin magnetization is in most cases induced and recorded by uniform secondary magnetic fields such that the recorded signal amplitude can be calibrated by samples of known spin density and the experiment can be designed such that perfectly controlled flip angles are obtained. By contrast, in surface NMR none of these requirements can be met and the amplitude of the recorded signal has to be quantitatively derived for non-uniform fields and the resulting arbitrary flip angles. Therefore, in this review article, a comprehensive derivation of the surface NMR signal is given and the formulations of the problem for 1-D and 2-D conditions are presented. State-of-the-art inversion techniques are needed to derive sub-surface models of water content distribution from measured field data state-of-the-art inversion techniques are needed and are applied with appropriate estimates of the reliability of those models given. The observed NMR relaxation times may in general provide additional information about the aquifer properties by their dependency on the pore space geometry, but their determination and interpretation are somewhat limited compared to conventional laboratory NMR techniques. A short account is given on possible schemes of relaxation time determination and future directions of surface NMR research. Since measured surface NMR signals substantially depend on the local settings of the Earth's magnetic field and the sub-surface resistivity distribution, the dependency on these parameters is described and their variability throughout the Earth is shown and accounted for in terms of likely response. As an example of state-of-the-art surface NMR measurements, the inversion and interpretation of a real data set from a well-investigated test site is presented.

2. Surface NMR measurements

2.1. Basic principle

Exploration for groundwater using NMR techniques takes advantage of the spin magnetic moment of protons, i.e. the hydrogen atoms of water molecules. In a zero external magnetic field environment, the spin magnetic moment vectors are randomly oriented. In the presence of an applied static magnetic field, the vectors precess about the magnetic field and at thermal equilibrium between the water molecules, the distribution of spin magnetic moment vectors has an alignment that results in a small net magnetic moment along the field direction (i.e. a longitudinal magnetic moment; Fig. 1a). Within the Earth, the spin magnetic moment vectors precess around the Earth's magnetic field $\mathbf{B}_0$ at the Larmor frequency $\omega_{\mathrm{L}} = -\gamma_p \mid \mathbf{B}_0 \mid$, where the gyromagnetic ratio $\gamma_p = 0.26752 \times 10^{-9}\ \mathrm{s}^{-1}\ \mathrm{T}^{-1}$. Worldwide values for $\mid \mathbf{B}_0 \mid$ vary between 25,000 nT around the equator and 65,000 nT at high latitudes, resulting in Larmor frequencies of 0.9–3.0 kHz, i.e. signals in the audio-frequency range. In surface NMR, an alternating