FORWARD MODELLING SURFACE NMR FOR HYDOGEOLOGICAL APPLICATIONS IN AUSTRALIA

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INTRODUCTION

Groundwater plays an important part in many regolith processes (chemical weathering, solute dispersion, etc.), but collecting groundwater data usually requires drilling that can be:

a) expensive - analyses for porosity, permeability, etc in addition to drilling costs;
b) problematic - rig availability and access to remote sites;
c) under-sampled - entire groundwater regimes characterised from relatively few drill-holes;
d) non-representative - the small volume of the drill hole may not be representative of bulk hydraulic properties (e.g., groundwater in fractured geology).

For some groundwater applications, ground geophysical techniques can mitigate these problems and provide qualitative subsurface information. However, most geophysical techniques require a sufficient physical property contrast (usually conductivity) between the groundwater and its host. The Surface Nuclear Magnetic Resonance (SNMR) method is a relatively new geophysical technique that responds directly to the presence of water in the top 100 metres of the Earth. The technique shows potential as an alternative (or complement) to drilling and other geophysical methods in providing quantitative hydrogeological information.

Since its development in the 1980s (Semenov *et al.* 1982), SNMR has been evaluated in various countries including sites in Russia (Shushakov & Legchenko 1994), Australia (Schirov *et al*. 1991), Israel (Goldman *et al.* 1994) and Germany (Yaramanci *et al.* 1999). Although the number of hydrogeological and geophysical settings in which the technique has been tested is far from comprehensive, two general observations are common. Firstly, it is difficult to obtain a SNMR signal even in relatively quiet environments due to the inherently low signal-to-noise ratio of the SNMR technique. Secondly, where conditions *are* favourable (low electromagnetic noise levels, high concentrations of water at shallow depths and appropriate interpretation models), the technique has been found to return reliable hydrogeological parameters such as depth to saturated horizons, effective porosity and transmissivity. Given these observations, SNMR is ideally suited to hydrogeological investigations and aquifer characterisation in areas largely free of cultural noise such as those found in large parts of Australia.

Unfortunately, the SNMR technique is affected by other factors that are particularly relevant to its use in Australia. These include conductive ground, conductive groundwater and geomagnetic field gradients caused by magnetic geology. In order to determine the capabilities and limitations of the SNMR technique and assess its application in Australian terrains, software for forward modelling NMR physics within the Earth has been developed.

NMR PHYSICS

Hydrogen nuclei have a magnetic moment and when placed in a static magnetic field (B_0), will align such that their magnetic moment is parallel or anti-parallel to the direction of the external field. Once aligned with the field, the nuclei precess about the direction of the field at a characteristic frequency that is proportional to the field strength and known as the *resonance* or *Larmor* frequency. At this equilibrium, there is a slight excess of nuclei aligned parallel to the external field compared to the number aligned anti-parallel. This slight excess results in a net magnetization in the direction of the static field B_0. An NMR measurement is made by displacing the net magnetization vector and observing its return to equilibrium.

The net magnetization vector is tipped away from the equilibrium position by supplying a pulse of energy from a second magnetic field ($B\perp$) orientated perpendicular to B_0 and oscillating at the resonance frequency. The pulse amplitude and duration dictate how far the net magnetization vector is tipped. Following the pulse, the net magnetization vector returns to its equilibrium position and in doing so induces a signal in a receiver orientated in the same plane as $B\perp$ (Abragam 1961).

The return to equilibrium can be described by two relaxation mechanisms (T_1 and T_2). The first, T_1, is known as the *spin-lattice relaxation time* and is a measure of the time taken for a sample to reach equilibrium with its environment (the so called 'lattice') (Becker 1969). T_2 is known as the *spin-spin relaxation time* and is a

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measure of the degree of inter-nuclei interaction within a sample. In practice, T_1 can only be inferred from multiple transmit/receive cycles and T_2 is not due solely to inter-nuclei interactions but also static field heterogeneity. The influence of the latter is made explicit by renaming the spin-spin relaxation constant T_2*. Within the Earth, T_2* has been shown to be related to pore size and fluid viscosity (Kenyon 1992) and T_1 empirically related to permeability in some terrains (Legchenko *et al.* 2002).

SNMR

Most NMR applications (e.g., spectroscopy, medicine, bore-hole) employ an artificial static magnetic field to polarise the nuclei of interest. In contrast, SNMR uses the Earth's geomagnetic field as B_0. The oscillating field is generated with a wire loop (typically 100 x 100m) on the Earth's surface. With current SNMR instrumentation, this wire also acts as the receiving antenna. A current pulse is transmitted at the Larmor frequency creating the oscillating magnetic field in the Earth. During the transmitter pulse, the component of the generated field that is perpendicular to the Earth's magnetic field disturbs the equilibrium of water in pore spaces. The transmitter current pulse is halted after some duration (typically 40 ms) and the return of the hydrogen protons to equilibrium induces a current in the receiver antenna.

The response induced in a receiver coil following an SNMR transmitter pulse is given by:

$$emf(t,q) = E_0 \sin(\omega t) \exp(-t/T_2^*) \qquad (1)$$

corresponding to a sinusoid with an exponentially decaying envelope and initial amplitude E_0 (Legchenko *et al.* 1997) (Figure 1). The magnitude of E_0 is directly proportional to the amount of subsurface water and is given by:

$$E_0(q,p) = \omega_0 M_0 \int_V b_\perp^R(p) \sin(\frac{1}{2}\gamma b_\perp^T(p) q) e^{i(\varphi^T(p)+\varphi^R(p))} w(p) dV \qquad (2)$$

where q is the pulse moment (current amplitude times pulse duration); M_0 is the maximum magnetization of a unit volume of water (proportional to static field strength, and inversely proportional to water temperature); γ is the gyromagnetic ratio of hydrogen; $b^T_\perp$ is the magnitude of the transmitter's magnetic field perpendicular to B_0; $b^R_\perp$ is the magnitude of the receiver field perpendicular to B_0 and w(p) is the water fraction of the sub-volume with position vector p. The exponential term contains the phase of the transmitter and receiver fields at each sub-volume. This term shows that the initial amplitude E_0 is complex and phase shifted with respect to the transmitter pulse when the ground (or groundwater) is conductive (Weichman *et al.* 2000).

The magnitude of the relaxation time constant T_2* in Equation 1 is proportional to the pore volume that groundwater occupies. Water in saturated porous material (e.g., sands and gravels) produces large time constants (>> 30 ms) while tightly-bound water molecules (such as those associated with clays or partially saturated pore space) have low time constants (< 30 ms) (Shirov *et al.* 1991). With current SNMR instrumentation (coincident transmitter and receiver), there is a 'dead-time' at the receiver immediately following a transmitter pulse (Figure 1). The presence of this dead-time means that signal contributions with small time constants are not measured and the method only responds to 'free' rather than 'bound' water. That is, water in clay layers or partially saturated pore spaces will not be detected.

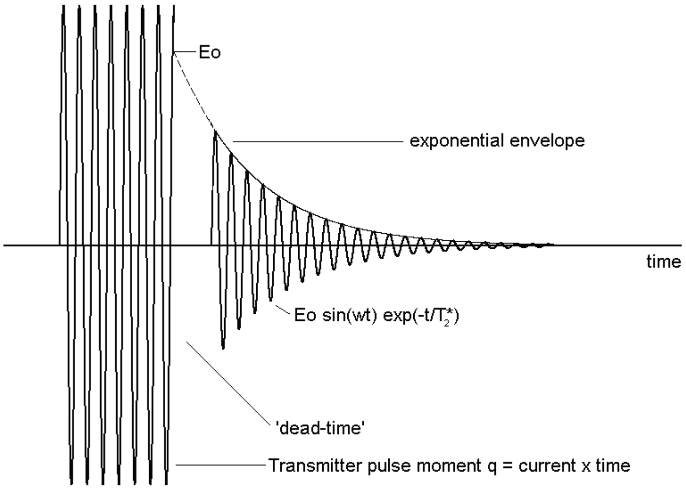

Figure 1. Idealised SNMR transmit-receive sequence (not to scale).

An SNMR sounding is made by taking numerous measurements of E_0 with varying q to produce an E_0 amplitude profile that is subsequently inverted to give an estimate of water distribution with depth (Figure 2). Groundwater properties reportedly derived from the inversion of SNMR data include: cumulative amount of free water; depth to top of saturated layer; percentage water as a function of depth and cumulative transmissivity (Goldman *et al.* 1994, Schirov *et al.* 1991, Yaramanci *et al.* 1999).

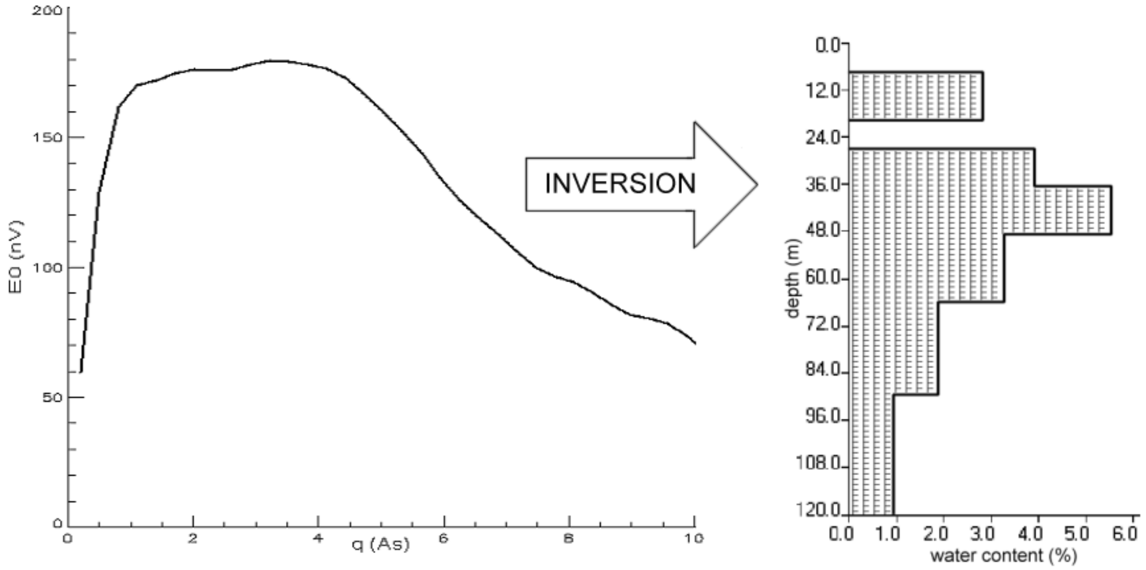

Figure 2. Example E_0 profile and resulting water distribution with depth following inversion.

SNMR LIMITATIONS AND IMPLICATIONS FOR REGOLITH-DOMINATED TERRAINS

There are a number of factors that affect the SNMR technique through signal reduction and/or distortion of inversion/interpretation results. Firstly, the SNMR effect is a small one. For example, groundwater at 25°C in a geomagnetic field with strength 50,000 nT has a net imbalance between hydrogen protons aligned parallel and anti-parallel with the Earth's field, of approximately three per 10 billion nuclei. Depending on the subsurface water distribution, signal strength is of the order of 10s to 100s of nanoVolts. The small signal makes the technique sensitive to both cultural and natural sources of electromagnetic noise (e.g., power-lines, VLF, atmospherics, etc.).

Secondly, the SNMR technique relies on the Earth's geomagnetic field to be static and uniform so that a sufficient volume of ground has the same Larmor frequency. Temporal variation in the geomagnetic field (due to solar storms interacting with the Earth's magnetosphere) and spatial gradients (caused by variations in magnetic geology) cause the Larmor frequency to change within the sample volume resulting in sub-volumes being taken off resonance and a subsequent loss of signal.

Another weakness, relevant to use in Australia, is the effect of a conductive subsurface. From Equation 2, it can be shown that conductive ground will affect the initial SNMR voltage response at the receiver in three ways (Weichman *et al.* 2002). Firstly, the spin 'tipping' force applied with the transmitter field is attenuated with depth. Secondly, the received signal generated by spins returning to equilibrium is attenuated by the same factor. Finally, the phase of the tipping field varies at different locations resulting in phase-shifted signal contributions that, when integrated, form an interference pattern at the receiver. This attenuation limits the depth at which water can be detected in conductive ground and must be accounted for in any inversion or interpretation of the data.

To date, the only Australian SNMR field trials have been confined to magnetically quiet areas characterised by relatively fresh groundwater and low to moderate host conductivity (Schirov *et al.* 1991, Dippell *et al.* 2003). The applicability of SNMR to groundwater problems in those parts of Australia blanketed in variably thick, variably conductive regolith hosting saline to hyper-saline groundwater and in the presence of geomagnetic field gradients is difficult to assess without field trials or numerical simulation. Additionally, assuming a signal can be obtained in the presence of the above conditions, accurate interpretation/inversion of the results can only be obtained with an accurate model of all the magnetic fields, both static and dynamic within the Earth. That is, accurate forward modelling is required.

FORWARD MODELLING

From Equations 1 and 2 it can be shown that the SNMR forward solution is based primarily on determining the oscillating magnetic fields of the transmitter/receiver and the static geomagnetic field within the Earth. The latter is generally assumed to be a uniform field based on geomagnetic latitude or else determined in the field via a mini-magnetic survey over the sounding site. In resistive terrain, the transmitter and receiver fields can be assumed the same as magnetic fields in a vacuum (free-space) and calculated from analytical expressions. In conductive ground however, the amplitude and phase of the fields differ from the analytical solution and must be calculated numerically.

Software has been developed to model these fields and calculate E_0 (as given in Equation 2) for conductive 1D layered Earths. In addition to modelling current SNMR configurations (coincident transmitter/receiver geometry, uniform geomagnetic fields, 1D water horizons), the software is capable of modelling separated transmitter/receiver geometries, non-uniform geomagnetic fields and 3D water distributions.

CONCLUSION

The SNMR geophysical method has potential as an alternative (or complement) to drilling for groundwater data in hydrogeological investigations. In order to explore the capabilities and limitations of the SNMR technique in Australian regolith-dominated terrains, software capable of forward modelling NMR physics in synthetic Earths has been developed. This capability will be used:

a) to determine *a priori* whether SNMR will address a particular hydrogeological problem without the need for expensive field tests;
b) as the basis for inversion of SNMR data;
c) as a tool for the development of new SNMR instruments;
d) as a research environment in which to conduct experiments. For example, testing the usefulness of multiple receivers or the benefits of sophisticated pulse sequences such as those used in medical applications.

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