Remote magnetic resonance sounding for exploration of pore space microstructure and aquifer macrostructure

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Abstract: Proton nuclear magnetic resonance is a type of nuclear magnetic resonance (NMR), which is widely used to detect hydrogen containing liquids, like water or hydrocarbons. The use of the Earth's magnetic field allows remote detection of fluids sub surface without generating an independent magnetic field that is expensive and complex enough to apply. An important feature of NMR in the Earth's field is that the signals produced by snow and ice are generally unobservable under experimental conditions created for liquid water prospecting. The characteristics of the RF response are associated with the molecular environment of the nuclei. This allows detecting NMR signals of water in pores of various size.

1. Introduction

Magnetic resonance sounding (MRS) is a direct method to detect aquifers, in contrast to conventional indirect geophysical methods, such as electrical exploration, seismic prospecting, etc. It has been proved that MRS in geomagnetic field can be applied to detect aquifers at depths up to 100 m and even deeper depending on the electromagnetic shielding provided by formations and the intensity of natural and anthropogenic electromagnetic noises [1-3]. The physical principle of this method implies detecting a resonance signal emitted as a result of the water proton spin magnetization. Macroscopic zones of aquifers are investigated through measurement of water proton nuclear magnetic relaxation (NMR) in geomagnetic field within rock pores and fractures. To excite the spins and receive the magnetic resonance signal, the antenna loop is laid out on the ground, in a circle of 100 m in diameter or in a figure-of-eight shape to minimize the effects of extraneous noises. A radiofrequency (RF) current $I(t) = I_0 \cos \omega_0 t$ is applied to the antenna thus producing alternating RF magnetic field in the space nearby. The frequency of oscillation is equal to the Larmor frequency of protons in the geomagnetic field. Due to resonance effect, nuclear magnetization vector is tilted away from its equilibrium direction alond the geomagnetic field and rotates around both the direction of the RF magnetic field and the geomagnetic field. After switching off of the excitation RF pulse, the magnetization precesses freely around the geomagnetic field direction. This precession induces alternating voltage in the same antenna thus producing the so called free nuclear induction signal. Magnetic resonance frequency in the geomagnetic field is several kilohertz, deadtime of measurement system is several milliseconds (Figure1.). The signal detected is produced by hydrodynamically mobile water molecules only. The water in very small pores of water-resisting rocks, e.g. clays, as well as crystallized, chemically bound, or frozen water, is characterized by shorter relaxation time, therefore, the signal is not detected after the system deadtime. The NMR amplitude is proportional to free-fluid index (i.e. movable fluid).

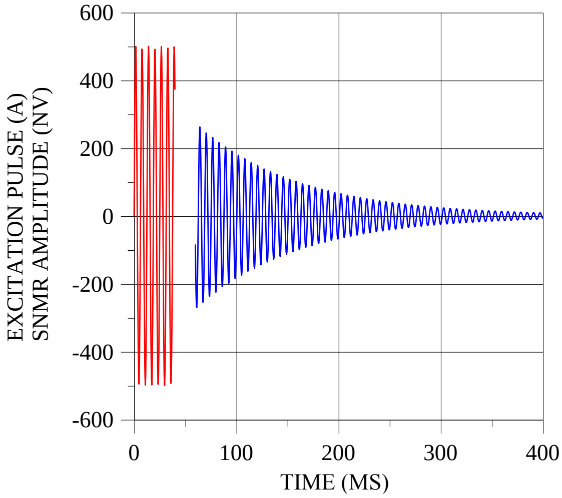

Figure 1. The principles of MRS signal detection in geomagnetic field. After the pulse of the field oscillating with the frequency equal to Larmor frequency the MRS signal (free-induction decay or FID) is induced in the antenna by nuclear magnetization freely precessing in geomagnetic field. The FID oscillates with the Larmor frequency and decays with the time constant of inhomogeneous spin-spin relaxation time. The MRS signal is detected with delay (“dead” time).

2. Bloch-Siegert effect in magnetic resonance sounding

If the water temperature is T = 293 K, and geomagnetic field strength is $B_0 = 6\cdot 10^{-5}$ T, then integral equilibrium magnetization, $M_0 = 1.93\cdot 10^{-7}$ J/(T*m³), is induced. If this magnetization is deviated from its equilibrium direction, it precesses around direction of geomagnetic field $\vec{B}_0$ with Larmor frequency of $\omega_0 = \gamma_H \cdot B_0$, where γ_H = 2.6753·10^8 radian/(s*T) is proton gyromagnetic ratio. In magnetic resonance experiments, RF magnetic field, $\vec{B}_1(t) = 2\vec{B}_1 \cos\omega_0 t$, perpendicular to $\vec{B}_0$, is applied. Interaction of nuclei (protons of water molecules) with external magnetic field, which is a sum of static geomagnetic field and RF field, $\vec{B} = \vec{B}_0 + 2\vec{B}_1 \cos\omega_0 t$, may be expressed in terms of spin Hamiltonian

$$\widehat{H} = \widehat{H}_0 + \widehat{H}_1(t) = -\omega_0 \widehat{I}_z - 2\omega_1 \widehat{I}_x \cos\omega_0 t\,, \tag{1}$$

where $\vec{B}_0 \parallel$ z, $\vec{B}_1 \parallel$ x, and $\widehat{I}_x$, $\widehat{I}_z$ are components of spin operator of nucleus, $\omega_1 = \gamma B_1$ is frequency of spin precession in magnetic field with the strength of B_1 (Rabi's frequency).

For more accurate description of spin (and magnetization) motion within the frame rotating around $\vec{B}_0$ with frequency ω_0, let us calculate two first terms of the average Hamiltonian,

$$\overline{\widetilde{\widehat{H}}}{}_1^{(0)}(t) = -\omega_1 \widehat{I}_x\,, \tag{2}$$

$$\overline{\widetilde{\widehat{H}}}{}_1^{(1)}(t) = -(i\omega_0/4\pi)\int_0^{2\pi/\omega_0} dt_2 \int_0^{t_2} dt_1 \left[\widetilde{\widehat{H}}_1(t_2), \widetilde{\widehat{H}}_1(t_1)\right] = (\omega_1^2/4\omega_0)\widehat{I}_z\,, \tag{3}$$

where [A,B]=AB-BA is a commutator of operators A and B.

Eq. (3) shows that there is resonance frequency shift (so called Bloch-Siegert shift) [4]:

$$\Delta\omega = -\omega_1^2 / 4\omega_0 . \tag{4}$$

The Bloch-Siegert shift (Eq. 4) provides an additional rotation of nuclear magnetization around z axis within the rotating ($\tilde{x}, \tilde{y}, z$) frame during pulse duration t_p:

$$\begin{aligned} \tilde{M}_x &= \frac{\omega_1 \sin\Theta \cdot \Delta\omega}{\omega_{eff}^2} \cdot (1 - \cos\omega_{eff} t_p) \cdot M_0 \\ \tilde{M}_y &= \frac{\omega_1 \sin\Theta}{\omega_{eff}} \cdot \sin\omega_{eff} t_p \cdot M_0 \qquad , \\ \omega_{eff} &= \sqrt{\omega_1^2 \sin^2\Theta + \Delta\omega^2} \end{aligned} \tag{5}$$

where Θ is the angle between static Earth's $\vec{B}_0$ and linearly polarized $\vec{B}_1$ RF magnetic fields in the lab frame.

The MRS signal immediately after the transmitting pulse (t=0) is

$$e_{t=0} = (\omega / I_0) \int_V \left\{ \sqrt{\tilde{M}_x^{\,2}(\mathbf{r}) + \tilde{M}_y^{\,2}(\mathbf{r})}\, B_1^2(\mathbf{r}) \sin\Theta(\mathbf{r}) / |B_1(\mathbf{r})| \right\} dV(\mathbf{r}) \quad . \tag{6}$$

MRS method calibration with regard to Bloch-Siegert effect was conducted via experiments on ice covered Novosibirsk Reservoir (Figure 2). Ice thickness and water depth were measured directly via drilling holes in the ice, and were 1±0.05m and 11±0.5m, respectively. Antenna of 50 m radius was used both for RF field generation and for the signal detection. The geomagnetic field α was 74°, proton resonance frequency was 2514 Hz ($B_0 = 5.9044 \cdot 10^{-5}$T).

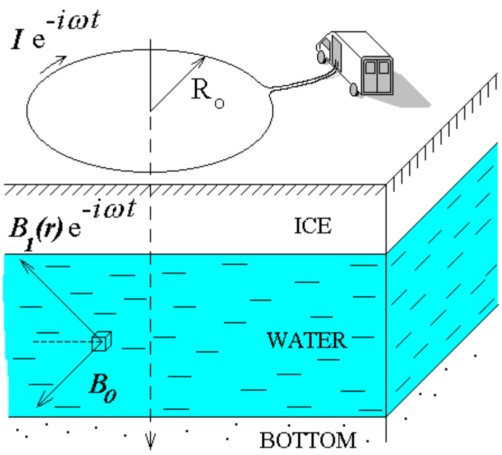

Figure 2. Experimental scheme of Bloch-Siegert effect detection on ice covered Novosibirsk Reservoir.

Figure3 and 4 demonstrate that the experimental MRS data fit particularly well with model calculations of the signal amplitude and phase with regard to the Bloch-Siegert effect.

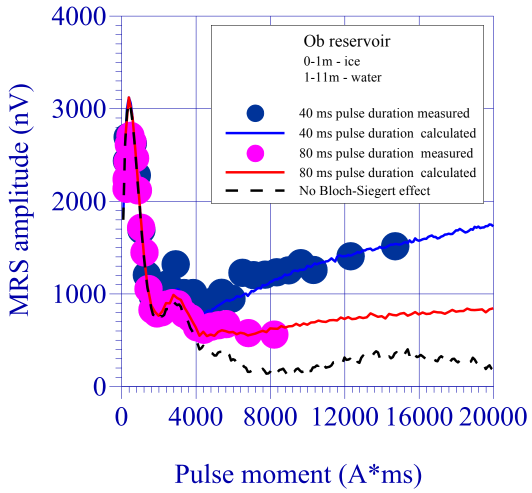

Figure 3. Amplitude of MRS signal versus the RF pulse intensity, for pulse lengths of 40 ms and 80 ms.

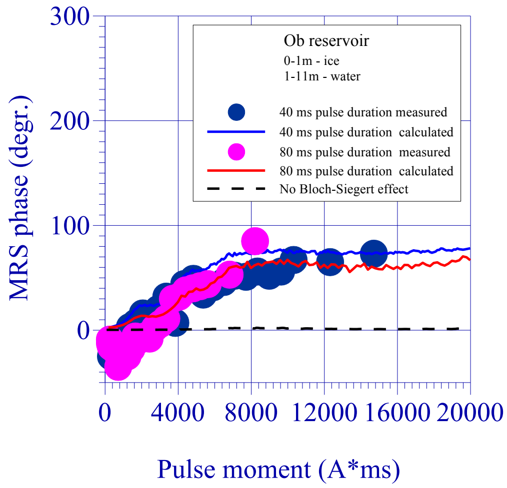

Figure 4. Phase of MRS signal versus the RF pulse intensity, for pulse lengths of 40 ms and 80 ms.

3. MRS relaxation and screening mechanisms

The investigation of double dielectric screening of the MRS signal allows estimating the total dissolved diamagnetic solids content in groundwater without drilling.

For example, in the half-space $z > 0$ with the uniform conductivity σ the magnetic field of the loop in the cylindrical frame has the form [1-3]:

$$B_{1z}(\mathbf{r}) = I_0 \cdot R_0 \int_0^\infty \frac{m^2}{m+u} e^{-uz} J_1(R_0 m) \cdot J_0(rm)\, dm \qquad (7),$$

$$B_{1r}(\mathbf{r}) = I_0 \cdot R_0 \int_0^\infty \frac{mu}{m+u} e^{-uz} J_1(R_0 m) \cdot J_1(rm)\, dm \qquad (8),$$

where R_0 is the antenna radius, $u = (m^2 - i\sigma\mu\omega)^{1/2}$, J_0 and J_1 are Bessel functions.

Distribution of water concentration with depth may be determined by inversion of the integral equation with experimentally measured and modeled NMR signal dependent on excitation intensity [3]. Figure 5 shows a comparison between MRS results in geomagnetic field and drilling and logging data of borehole 37, Novosibirsk.

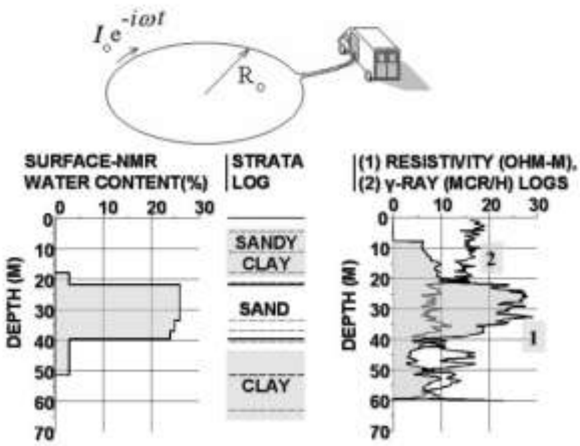

Figure 5. Comparison between geomagnetic MRS results and drilling and logging data of borehole 37, Novosibirsk.

The relaxation of the magnetization **M** that is proportional to the NMR signal is described using the Bloch-Torrey equations [5]:

$$\partial M_x/\partial t = D\,\Delta(M_x - M_{x0}) - M_x/T_{2bulk} + \gamma\,(\mathbf{M} \times \mathbf{B})_x \quad (9),$$

$$\partial M_y/\partial t = D\,\Delta(M_y - M_{y0}) - M_y/T_{2bulk} + \gamma\,(\mathbf{M} \times \mathbf{B})_y \quad (10),$$

$$\partial M_z/\partial t = D\,\Delta(M_z - M_{z0}) - M_z/T_{1bulk} + \gamma\,(\mathbf{M} \times \mathbf{B})_z \quad (11),$$

where D is the self-diffusion coefficient, T_{1bulk} and T_{2bulk} are the longitudinal and transverse relaxation times of bulk water.

The boundary conditions characterize the longitudinal (ρ_1) and the transverse (ρ_2) relaxivity on pore surface.

$$D\,(\mathbf{n}\cdot\nabla M'_x) + \rho_2\,M'_x = 0 \quad (12),$$
$$D\,(\mathbf{n}\cdot\nabla M'_y) + \rho_2\,M'_y = 0 \quad (13),$$
$$D\,(\mathbf{n}\cdot\nabla M'_z) + \rho_1\,M'_z = 0 \quad (14).$$

In resonance within rotating frame between RF-field pulses

$$\partial U/\partial t = D\,\Delta U - i\,\gamma\,G\,z\,U \quad (15),$$

where G is the magnetic field gradient, $U = M'_x + i\,M'_y$.

If we assume the uniformity of fluid in pore space and fast diffusion, the solution for the relaxation times is as follows [6]:

$$1/T_1 = 1/T_{1bulk} + \rho_1\,S/V \quad (16)$$
$$1/T_2 = 1/T_{2bulk} + \rho_2\,S/V + (\gamma\,G\,t)^2\,D/12 \quad (17)$$
$$1/T^*_2 = 1/T^*_{2bulk} + \rho_2\,S/V + (\gamma\,G\,t)^2\,D/3 + \gamma\,G\,a, \quad (18)$$

where S/V is the surface-to-volume ratio of pores, a is a core grain radius.

By the example of borehole 37 in Novosibirsk the spin-relaxation times were studied using two-pulse sequences (Figure 6, 7) [7].

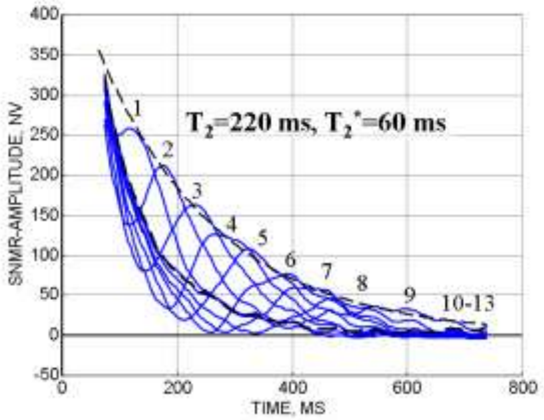

Figure 6. FID and spin-echo amplitudes measured via MRS (borehole 37, Novosibirsk), with sequence of pulses of 16 and 34 ms duration and delays between pulses from 100 to 700 ms (1-13).

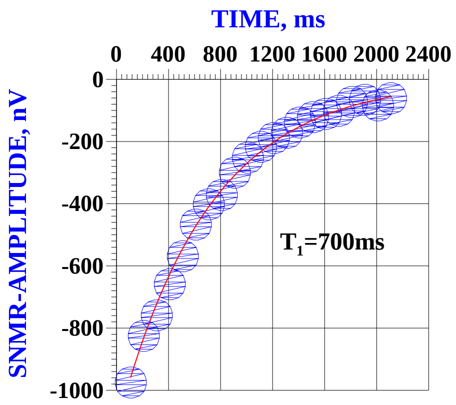

Figure 7. FID amplitude versus inversion time measured via MRS (borehole 37, Novosibirsk), with sequence of pulses of 32 and 18 ms duration and delays between pulses from 100 to 2100 ms.

Figure 6 illustrates the measurement of the homogenous spin-spin relaxation time T_2 equal to 220 ms via spin-echo method (the first pulse rotates the magnetization by 90^o, the second one – by 180^o). In this case the free-induction decay time T_2^* is 60 ms. Figure 7 exemplifies the measurement of the spin-lattice relaxation time T_1 equal to 700 ms via inversion-recovery method (the first pulse rotates the magnetization by 180^o, the second one – by90^o).

With regard to the longitudinal and transverse relaxation times for free water T_{1bulk} = 1.4 s and T_{2bulk} = 1 s measured on the ice cover of Novosibirsk reservoir, the core grain size a = 2.5 10^{-2} cm determined using drilling data, and diffusion coefficient of water D = 1.3 10^{-5} cm^2/s at 277 K, the surface relaxivities ρ_1 = 7 10^{-3} cm/s, ρ_2 = 3.5 10^{-2} cm/s and the field gradient G = 2 10^{-2} Gauss/cm have been determined.

References

[1] Shushakov O A and Legchenko A V 1994 *Geol. and geophysics* **35** 161 (in Russian)
[2] Shushakov O A 1996 *Geophysics* **61** 998
[3] Legchenko A V and Shushakov O A 1998 *Geophysics* **63** 75
[4] Bloch F and Siegert A 1940 *Phys.Rev.* **57** 522
[5] Torrey R C 1956 *Phys. Rev.* **104** 563
[6] Korringa 1956 *J.*: *Bull. Amer. Phys. Soc. (Ser. II)* **1** 216
[7] Shushakov O A and Fomenko V M 2004 *Appl. Magn. Res.* **25** 599