Geophysical Prospecting, 1995, 43, 623–633

Surface NMR applied to an electroconductive medium[1]

D.V. Trushkin,[2] O.A. Shushakov[2, 3] and A.V. Legchenko[3]

Abstract

An integrated electromagnetic and nuclear magnetic resonance (NMR) method is proposed for investigating highly conductive soil areas. Using a simple model of a homogeneous half-space and the same antenna for both methods, a significant improvement in the NMR data interpretation is obtained. A case study has shown fair agreement between the results from computer modelling, field tests, and data from a nearby observation well. The electromagnetic method and the half-space model were selected for easy integration into an existing instrument used for the NMR method. A more accurate knowledge of the conductivity distribution with depth will further improve the final result.

Introduction

Surface nuclear magnetic resonance (NMR) in the earth's magnetic field, as developed by Semenov *et al.* (1989), is the subject of several studies (Semenov 1987; Semenov *et al.* 1989). The method can be used for non-invasive recording of the NMR signal of subterranean proton-containing liquids at depths down to 100 m or more.

A circular wire loop laid on the ground is employed to excite and receive the NMR signal. In our experiments, a circular antenna of diameter 100 m is used. Rectangular pulses of alternating current are passed through the wire with a frequency equal to that of the proton resonance in the geomagnetic field. The excitation pulse is followed by an induced EMF signal due to the free Larmor precession of the groundwater nuclear magnetization in the earth's magnetic field. Both the upper and lower boundaries of the subsurface water-saturated layers can be determined from the amplitude of the NMR signal and the setting of the loop current pulse intensity which is the product of the pulse amplitude and its duration (Semenov *et al.* 1989).

Various natural factors affect the NMR signal. The effects of the frequency of the excitation current pulse and the variation in magnitude of the earth's magnetic

---

[1] Received October 1993, revision accepted November 1994.

[2] Novosibirsk State University, 2 Pirogova St., Novosibirsk, 630090, Russia.

[3] Russian Academy of Sciences Institute of Chemical Kinetics and Combustion, 3 Institutskaya St., Novosibirsk, 630090, Russia.

field on the NMR signal have been studied by Tushkin, Shushakov and Legchenko (1993). The surface NMR method is sensitive to any external electromagnetic field source, such as a power-line. In order to solve this problem, the use of a different antenna, less sensitive to external noise than the circular antenna, has been investigated (Tushkin, Shushakov and Legchenko 1994). The influence of the medium conductivity on the amplitude and phase of the NMR signal has also been investigated (Shushakov and Legchenko 1994a, b, c).

Integrated NMR and electromagnetic method

The NMR signal $e_0(q)$ can be calculated using the following equation (Shushakov and Legchenko 1994a, b):

$$e_0(q) = (\omega/I) \int_V M_0(\mathbf{r})[H^2_{1\perp}(\mathbf{r})/|H_{1\perp}(\mathbf{r})|] \sin\theta(\mathbf{r})\, \mathrm{d}V(\mathbf{r}), \tag{1}$$

where $\theta(\mathbf{r}) = 0.5\gamma_H |H_{1\perp}(\mathbf{r})| \tau_p$, $\omega = \gamma_H H_0$, $q = I\tau_p$, γ_H is the gyromagnetic ratio for a proton, $\mathbf{H}_0$ is the geomagnetic field, $\mathbf{M}_0(\mathbf{r})$ is the equilibrium macroscopic nuclear magnetization, $\mathbf{H}_{1\perp}(\mathbf{r})$ is perpendicular to the $\mathbf{H}_0$ component of the loop oscillating field, τ_p is the current pulse duration and I is the loop current amplitude.

The circular loop employed in the surface NMR method to excite and receive the NMR signal can also be used to determine the effect of the medium conductivity on the signal measurement. The technique proposed is similar to the inductive method of electrical geophysical exploration (Wait 1981).

The low-frequency alternating current passing through the loop in a conductive medium under the action of an electromagnetic field (the primary field) induces electric currents. These give rise to a secondary electric field which, with the primary field, forms the total field. In this case, the measured loop impedance changes.

The complex impedance of a loop of radius r_0 and wire cross-sectional radius a, situated in free space on the surface of a non-magnetic ($\mu = 1$), conductive half-space, is expressed by the following equation:

$$Z(\omega) = Z_0(\omega) + \omega L_1(\omega), \tag{2}$$

where

$$L_1(\omega) = \mathrm{i}\pi r_0^2 \mu_0 \int_0^\infty \mathrm{J}_1^2(\lambda r_0) \mathrm{e}^{-\lambda a} \alpha(\lambda)\, \mathrm{d}\lambda, \tag{3}$$

$Z_0(\omega)$ is the loop impedance in free space for the loop current frequency ω, $L_1(\omega)$ is the mutual inductance of the loop and the electroconductive half-space, $\mathfrak{J}_1$ is the Bessel function, $\alpha(\lambda)$ is the reflection coefficient characterizing the electromagnetic properties and the geometry of the conducting half-space (Wait 1958). For a homogeneous half-space,

$$\alpha(\lambda) = [\lambda - m(\lambda)]/[\lambda + m(\lambda)], \tag{4}$$

where $m(\lambda) = (\lambda^2 - k^2)^{1/2}$, $k^2 = i\sigma\mu_0\omega$, and σ is the electrical conductivity of the half-space.

Figures 1 and 2 depict the calculated imaginary and real parts of the complex impedance of a loop of radius 50 m located on the surface of a homogeneous half-space, for various frequencies of the current passing through the loop. The calculations were performed for copper wire of cross-sectional radius 2.3 mm. As can be seen in Figs 1 and 2, both parameters depend on the half-space resistivity.

In order to determine the boundaries of the water-saturated layers, (1) must be solved. In the case of horizontal, infinite, water-saturated, conductive layers, the following equation can be used instead of (1):

$$\int_0^\infty K(q, z) f(z)\, dz = e_0(q), \tag{5}$$

where

$$K(q, z) = (\omega M_0/I) \int_{x,y} [H_{1\perp}^2(x, y)/|H_{1\perp}(x, y)|] \sin\theta(x, y)\, dx\, dy, \tag{6}$$

$f(z)$ is the water concentration and z is the depth.

Equation (5) was solved by discretization of the initial integral equation, followed by the solution of a set of linear equations. Because the problem is ill-posed, the Tikhonov regularization method was used (Tikhonov and Arsenin 1977). The inverse problem (5) with the kernel (6) is linear in conductive areas (Legchenko 1992).

The modelling results of the influence of the conductivity on the NMR signal

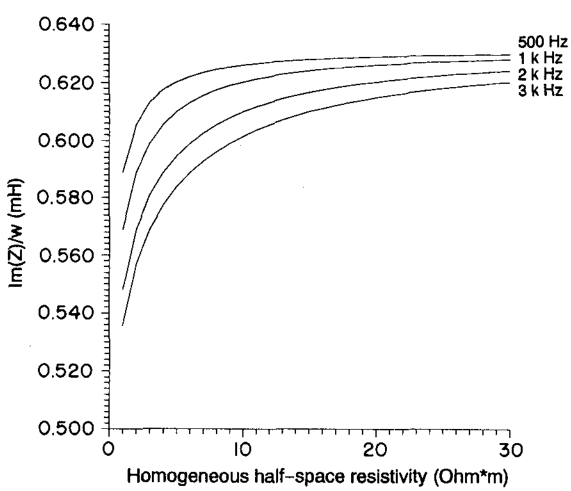

Figure 1. Graph showing the inductance of the copper wire loop of radius 50 m and cross-sectional radius 2.3 mm situated on the surface of a homogeneous conductive half-space versus the half-space resistivity, calculated for various frequencies of the loop current.

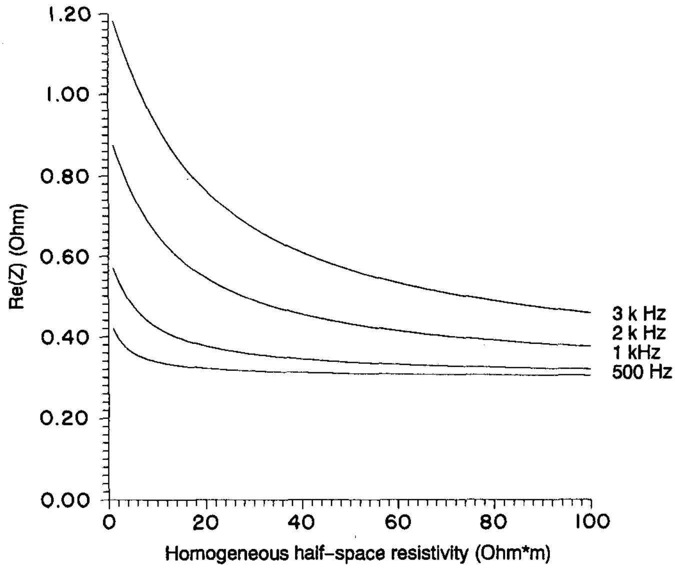

Figure 2. Graph showing the resistance of the copper wire loop of radius 50 m and cross-sectional radius 2.3 mm situated on the surface of a homogeneous conductive half-space versus the half-space resistivity, calculated for various frequencies of the loop current.

and the inverse problem solution are shown in Figs 3 and 4, respectively. For the numerical experiments, model consisting of two water-saturated layers, situated between 10 and 20 m and between 50 and 70 m, each with 10% water, was selec-

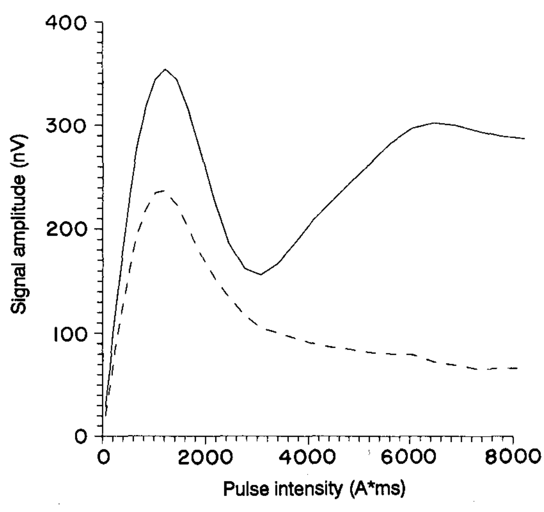

Figure 3. The NMR signal calculated for a model consisting of two water-saturated layers situated between 10 and 20 m and between 50 and 70 m with 10% water in each layer. The solid line is the signal for the case of the model in free space, the dashed line is for the model in an electrically conductive half-space of resistivity 2 Ωm.

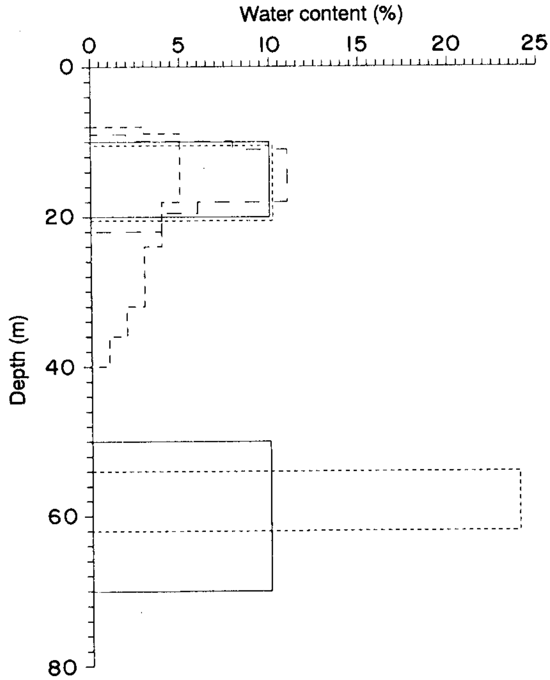

Figure 4. Inversion example for the model in Fig. 3. The solid line indicates the model, the dashed lines, in order of increasing intervals, show: (1) the model in free space; (2) the model in a conductive half-space, inversion with neglecting conductivity; (3) the model in a conductive half-space, inversion accounting for conductivity.

ted. The Larmor frequency was taken as 2500 Hz. Two cases were studied: (1) with the water layers in free space and (2) with the same layers in a conductive half-space of resistivity 2 Ωm. The effect of the conductivity on the NMR signal is not only to decrease it, but also to change the shape of the curve. The result is a distortion in the inverse problem solution. When conductivity data are available, the inversion result is considerably improved for the upper layer, but the second layer is not detected due to the screening effect and thus the absence of signal from that layer.

Goldman *et al.* (1994) observed some lack of correlation between TDEM and NMR data during field tests in areas of high rock conductivity, between observation wells. This could be explained by conductivity influence, which was not taken into account during the NMR data inversion.

Experimental results

Experiments were carried out near the village of Nizhnechumanka in the Altai region at borehole No. 64. The data obtained were compared with those previously obtained from boring and electrical logging (Fig. 5). Borehole No. 64 was selected

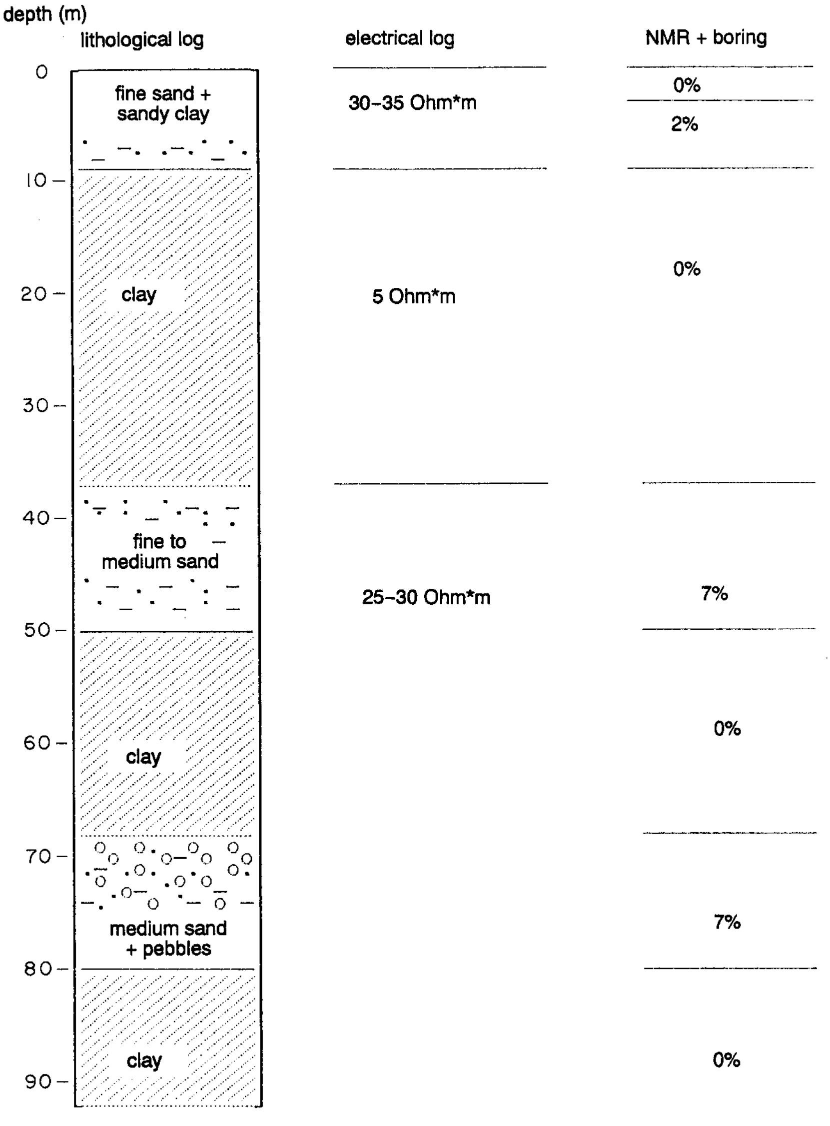

Figure 5. Borehole No. 64. The lithological log, the electrical log and the surface NMR interpretation data, obtained from borehole data.

due to the contrasting change in resistivity with depth: 30–35 Ωm from 0–9 m, 5 Ωm from 9–37 m, and 25–30 Ωm for depths of more than 37 m. According to the borehole data, there are three aquifers present, at depths of 2.5–9 m, 37–50 m and 68–80 m. The borehole and electrical logging data were obtained in the Geologo-Geophysical Expedition in the 15th region.

The surface NMR method was performed using a "Hydroscope" instrument, manufactured at the Institute of Chemical Kinetics and Combustion (Semenov 1987). The Larmor frequency was equal to 2475 Hz. A circular loop of radius 50 m, consisting of copper wire of cross-sectional area 17 sq. mm, was used both to record the NMR signal and to measure the electrical conductivity of the medium. The loop impedance was measured using a digital inductance and resistance meter E7-8 at a frequency of 1 kHz.

In order to calibrate the complex impedance $Z(\omega)$ of the loop, special experiments were performed on the surface of the frozen Ob water reservoir near the town of Berdsk. The water resistivity measurements were carried out using a measured cell with two metal plates calibrated by measuring the resistivity of various concentrations of sodium chloride solution in water. According to the measurement data, the resistivity of the water between 1 and 14 m below the surface was 47 Ωm.

The calibration measurements gave the following values for the loop impedance: $\mathrm{Im}\,(Z)/\omega = 0.631$ mH $\pm$ 1%, $\mathrm{Re}\,(Z) = 0.330\ \Omega \pm 10\%$. The same values for the inductance and the resistance were obtained when calculated by standard methods (Kalantarov and Tseitlin 1986). The experimental values for the inductance and the resistance measured at borehole No. 64 were $\mathrm{Im}\,(Z)/\omega = 0.616$ mH $\pm$ 1%, Re $(Z) = 0.477\ \Omega + 10\%$. According to Figs 1 and 2, the resistivity of the half-space at the test site must be 7.5 Ωm.

Because of the problem of direct comparison of the NMR data with data from other geophysical methods the following method (Shushakov and Legchenko 1994c), based on both computer modelling and field experiments, was used. Borehole cross-sections and electrical logging data were used to determine all the aquifer boundaries and the distribution of electrical conductivity with depth. Measurements of the NMR signal enabled us, using (5) and (6), to determine the percentage of water in every water statum. Additional information on aquifer boundaries and the conductivity distribution from borehole lithological and electrical logs made the interpretation of the NMR data more reliable than in the routine case using NMR data only, and the results can be used as the correct water concentration distribution with depth. All the data obtained at the test site are shown in Fig. 5.

Figure 6 shows a comparison of the experimental data (dots) with the calculated data (solid line), with respect to medium conductivity, in the homogeneous half-space model of resistivity 7.5 Ωm. It can be seen that the NMR signal calculated using a conductive homogeneous half-space model is in fair agreement with the NMR signal obtained experimentally. For comparison, the NMR signal calculated neglecting the medium conductivity (dashed line) is shown. In this case the large divergence from the experimental data is obvious. Thus the model of a conductive medium in the form of a homogeneous half-space can be used with the surface NMR method to solve both direct and inverse problems.

Figures 7, 8 and 9 demonstrate inversion of the experimental NMR data from borehole No. 64. In Fig. 7, the dashed line represents the NMR inverse problem

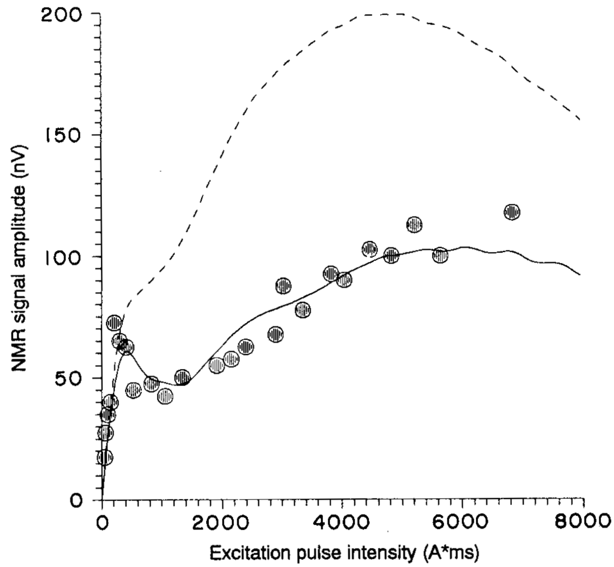

Figure 6. Comparison of the calculated NMR signal amplitude versus the current pulse intensity, with respect to the medium conductivity using the model with a homogeneous half-space of resistivity of 7.5 Ωm and the experimental data obtained at borehole No. 64. The dashed line denotes the calculated groundwater NMR signal amplitude neglecting the electrical conductivity of the soil.

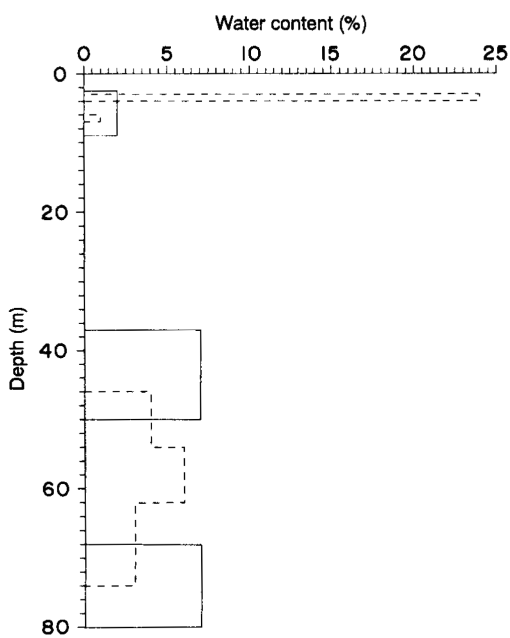

Figure 7. Comparison of the data from borehole No. 64 (solid line) with the solution of the inverse problem using the free-space model (dashed line).

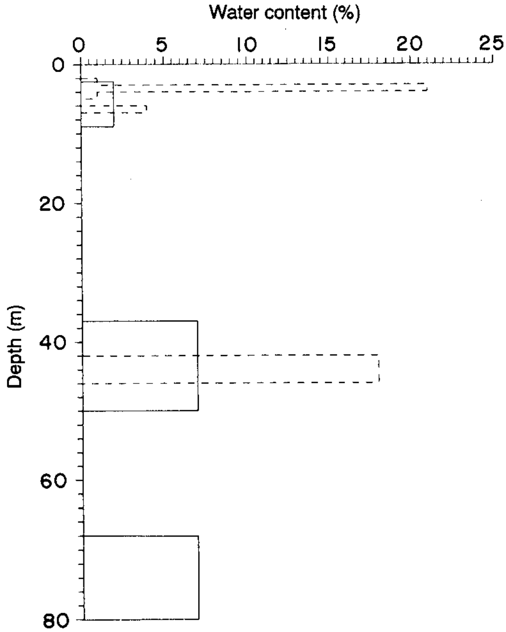

Figure 8. Comparison of the data from borehole No. 64 (solid line) with the solution of the inverse problem using the model of a homogeneous half-space with resistivity 7.5 Ωm determined by measuring the loop impedance (dashed line).

solution using the free-space model. This solution differs from the data obtained from the borehole (solid line). In Fig. 8 the borehole data are compared with the solution of the inverse problem using the homogeneous half-space model of resistivity of 7.5 Ωm, obtained by measuring the loop impedance. It can be seen that the main aquifer (from 37 to 50 m) is fairly well approximated. Figure 9 shows the solution using the horizontally stratified model, corresponding to the electrical log at borehole No. 64. The inversion result is further improved, but the bottom layer has not been detected.

According to the field experiments, the most significant improvement occurred for the aquifer situated at a depth between 37 and 50 m. The deep aquifer (68–80 m) was not detected. This could be explained by the screening effect, and it correlates with the modelling results (Figs 3 and 4). Two main factors affect the detection of the upper aquifer. Firstly, the shallow strata of sand and clay are less homogeneous than at greater depths; secondly, the available borehole data (shallow part of the log) are inaccurate.

Conclusions

The surface NMR method for groundwater prospecting has obvious advantages due to direct measurement of the subsurface water NMR signal. One of the limi-

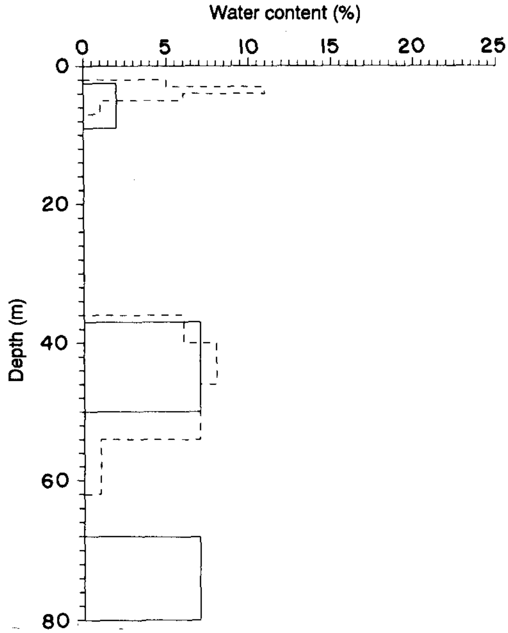

Figure 9. Comparison of the data from borehole No. 64 (solid line) with the solution of the inverse problem using the model of a horizontally stratified half-space, corresponding to the distribution of electrical conductivity with depth according to the electrical log at borehole No. 64 (dashed line).

tations of the method is the effect of rock conductivity on the NMR signal and, as a result, the distortion of the inverse problem solution.

The integration of an electromagnetic and an NMR method into one device using the same antenna and a homogeneous half-space model was investigated. This led to a significant improvement in the inversion result with only minor complications in the NMR method.

Using a horizontally layered model and the distribution of electrical conductivity with depth, it is possible to improve NMR data inversion results in highly conductive rock areas to the accuracy of the method in non-conductive rock areas.

The screening effect causes the depth of investigation to be decreased and to depend on the rock conductivity value. This decrease in the depth of investigation cannot be compensated for mathematically, but needs an increase in both the sensitivity of the NMR signal receiver and the power of the excitation pulse generator to overcome it.

References

Goldman, M., Rabniovich B., Rabinovich M., Gilad D., Gev I. and Schirov M. 1994. Application of integrated NMR-TDEM method in groundwater exploration in Israel. *Journal of Applied Geophysics* 31, 27–52.

Kalantarov P.L. and Tseitlin L.A. 1986. *Inductances Calculation* (in Russian). Leningrad, Energoatomizdat, 415.

Legchenko A.V. 1992. *Solution of the NMR geotomography inverse problem* (in Russian). Ph.D. thesis. Computing Centre, the Siberian Branch of the Russian Academy of Sciences, Novosibirsk.

Semenov A.G. 1987. NMR hydroscope for water prospecting. Proceedings of Seminar on Geotomography, Indian Geophysical Union, Hyderabad, 66–67.

Semenev A.G., Schirov M.D., Legchenko A.V., Burshtein A.I. and Pusep A. Ju. 1989. Device for measuring the parameters of underground mineral deposit. GB Patent 2198540B.

Shushakov O.A. and Legchenko A.V. 1994a. Calculation of proton magnetic resonance signal of underground water considering medium electric conductivity. *Geology and Geophysics* 35, 130–136 (in Russian).

Shushakov O.A. and Legchenko A.V. 1994b. Groundwater proton magnetic resonance in the horizontally stratified media of different electrical conductivity. *Geology and Geophysics* 35(10), 161–166 (in Russian).

Shushakov O.A. and Legchenko A.V. 1994c. Groundwater NMR in conductive media. *Geophysics*, in press.

Tikhonov A. and Arsenin V. 1977. *Solution of Ill-Posed Problems*. John Wiley & Sons, Inc.

Trushkin D.V., Shushakov O.A. and Legchenko A.V. 1994. The potential of a noise-reducing antenna for surface NMR groundwater surveys in the earth's magnetic field. *Geophysical Prospecting* 42, 855–862.

Wait J.R. 1958. Transmission and reflection of electromagnetic waves in the presence of stratified media. *Journal of Research of the National Bureau of Standards* (*US*) **61**, 205–232.

Wait J.R. 1981. *Geo-Electromagnetism*. Academic Press, Inc. p. 235.