GEOPHYSICS, VOL. 61, NO. 4 (JULY–AUGUST 1996); P. 998–1006, 7 FIGS.

Groundwater NMR in conductive water

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ABSTRACT

A surface method of groundwater prospecting using nuclear magnetic resonance (NMR) in the Earth's magnetic field is under study. The technique is employed for hydrogeological surveys down to a depth of about 100 m. The advantage of this method is that an NMR signal can be observed only in the presence of groundwater. A circular wire loop with a diameter of 100 m is laid out on the ground to excite and receive the NMR signal. An oscillating current with a rectangular pulse-shape is passed through the loop, with the carrier-frequency being equal to the proton-resonance frequency in the Earth's field. The excitation pulse is followed by a nuclear induction emf caused by the free Larmor precession in the Earth's field.

Of practical importance is the effect of the electrical conductivity of the ground on a groundwater NMR survey. Finite-ground conductivity can result in induced currents that can screen the NMR signal. The calculations of NMR signals are based on the transformation of Maxwell's equations in terms of magnetic Hertz potentials through use of the reciprocity principle. Groundwater NMR is measured with an instrument designed at the Institute of Chemical Kinetics and Combustion, Russian Academy of Science, Novosibirsk. Experiments were conducted in the Altay region of Russia. Both NMR-signal amplitude and phase, were measured and compared with the calculated results for horizontally stratified media. Borehole logs and vertical-resistivity profiles were also used for evaluation of results.

The conductivity is shown to affect both phase and amplitude of the NMR signal at resistivities of a few to a few tens of ohm-m depending on the depth of the water-saturated layers. There is good agreement between calculated and experimental data. It is also established that the measurements of only NMR amplitude and phase are not sufficient for determining groundwater salinity.

INTRODUCTION

The original idea of surface groundwater prospecting using nuclear magnetic resonance (NMR) was introduced by Anderson (Varian, 1962). The first device, mathematical description, and an inversion method were developed by Semenov et al. (1982). The technology of groundwater surveys involving NMR was developed further by Semenov et al. (1982, 1988, 1989). The method is used to explore for groundwater up to a depth of about 100 m (Semenov, 1987a). This novel geophysical technique has been referred to as the "Hydroscope" (Semenov et al., 1982; Semenov, 1987b).

The technique can be used to register the magnetic-resonance signal of water protons in the Earth's magnetic field, $\mathbf{H}_0$, which is of the order of $5 \cdot 10^{-5}$ T. The resonance signal has a frequency of about 2 kHz in field $\mathbf{H}_0$, and is excited by a transmission field $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$ at the resonance frequency. Unlike conventional geophysical prospecting tools, the NMR method's selective characteristics permit new equipment to respond only to the water target. The effect of other minerals and structures on the NMR signal is only indirect, such as screening and relaxation of the NMR signal (Semenov, 1987a; Semenov et al., 1989).

It is important to consider the influence of the geoelectric structure of the earth on the surface NMR signal. High conductivity (low resistivity) is inherent in both saline water-saturated layers and, for example, clay-rich rocks. The resistivity of clay-rich soil and rock can be as low as 1–10 ohm-m, which is similar to saline-water–saturated rocks. In this case the model of the earth as a conductive half-space is a good description.

The aim of the present contribution is to compare the experimental and calculated surface NMR of groundwater response in conductive media. It is not always possible to describe earth formations as a simple, homogeneous half-space. Therefore, the more general model of a horizontally-

Manuscript received by the Editor June 1, 1993; revised manuscript received August 6, 1995.

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stratified medium is also considered to compare calculations with experimental data.

BASIC PRINCIPLES OF SURFACE NMR IN THE EARTH'S FIELD

The method is based on the principle of observation of the proton magnetic resonance in the Earth's field of hydrogen ^1H atoms contained in groundwater molecules H_2O.

The geomagnetic field $\mathbf{H}_0$ sets up a net nuclear spin population in thermal equilibrium, which provides a macroscopic magnetic moment $\mathbf{M}_0$ ($\mathbf{r}$) oriented parallel to $\mathbf{H}_0$ (Abragam, 1961)

$$\mathbf{M}_0(\mathbf{r}) = n(\mathbf{r})\,\frac{\gamma^2\hbar^2}{3kT}\,S(S+1)\cdot\mathbf{H}_0, \tag{1}$$

where $n(\mathbf{r})$ is the number of magnetic nuclei per unit volume, $S = 1/2$ is the nuclear spin, $\hbar$ and k are Planck and Boltzman's constants, and T is the temperature.

A circular wire loop with a diameter of 100 m is laid out on the ground. This serves as both source antenna and NMR signal receiver. A sinusoidal current pulse with a rectangular envelope is passed through the loop to excite the NMR signal. The carrier frequency of the oscillating current in this pulse is equal to the Larmor frequency ω_L of protons in the Earth's magnetic field $\mathbf{H}_0$ (Semenov et al., 1982, 1988, 1989)

$$\omega_L = \gamma_H \cdot H_0, \tag{2}$$

where γ_H is the gyromagnetic ratio of protons.

After the pulse, which generates the oscillating field $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$, the vector $\mathbf{M}_0(\mathbf{r})$ is tilted away from the vector $\mathbf{H}_0$ by the angle

$$\theta(\mathbf{r}) = 0.5 \cdot \gamma_H \cdot H_{1\perp}(\mathbf{r}) \cdot \tau_p, \tag{3}$$

where $\mathbf{H}_{1\perp}(\mathbf{r})$ is the alternating field component that is normal to $\mathbf{H}_0$, and τ_p is the pulse duration. The coefficient 0.5 is caused by the linear rather than circular polarization of $\mathbf{H}_{1\perp}$ ($\mathbf{r}$). The component of macroscopic nuclear magnetization that is normal to $\mathbf{H}_0$ is

$$M_{\perp}(\mathbf{r}) = M_0(\mathbf{r}) \cdot \sin\theta(\mathbf{r}). \tag{4}$$

Following the pulse, when $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$ is removed, the vector $\mathbf{M}_{\perp}(\mathbf{r})$ freely precesses about the geomagnetic field at the Larmor frequency ω_L.

The emf induced into the loop by the magnetic field of groundwater nuclear magnetization is determined by integrating over the volume (Semenov et al., 1988)

$$E_0(Q) = (\omega/I)\int_V M_{\perp}(\mathbf{r})H_{1\perp}(\mathbf{r})\,dV(\mathbf{r}), \tag{5}$$

where I is the amplitude of the excitation current $I \cdot e^{-i\omega t}$, $Q = I \cdot \tau_p$ is the excitation pulse intensity, and $E_0(Q)$ is the NMR signal that is measured.

The depth of water-saturated layers can be determined from the NMR signal amplitude dependence on the excitation-current pulse intensity Q. Figure 1 shows the dependence of the surface NMR amplitude on the current pulse intensity Q, calculated for a 10-m thick model horizontal water layer located at different depths (10–20 m, 30–40 m, and 50–60 m). A strong correlation of a maximum NMR signal with the location depth of water is clear from this example.

I have earlier discussed the effects of variations in the Earth's field $\mathbf{H}_0$ on the surface NMR signal in Trushkin et al. (1993). Some aspects of correlation between the NMR relaxation time and water-bearing soil grain size are discussed in Semenov (1987a and b) and Schirov et al. (1991). Different antenna types, such as a noise-reducing figure-of-eight-shaped antenna, are investigated in Trushkin et al. (1994).

CALCULATION OF THE SURFACE NMR SIGNAL CONSIDERING FORMATION CONDUCTIVITY

In electrically conductive media, the magnetic fields of the loop and groundwater magnetic nuclei are changed in amplitude and phase because of the screening effect of induced currents in the intervening conductive media.

The time-harmonic electric and magnetic fields $\mathbf{E} \cdot e^{-i\omega t}$ and $\mathbf{H} \cdot e^{-i\omega t}$ in source-free media of magnetic permeability μ, dielectric permittivity ε, and conductivity σ satisfy Maxwell's equations

$$\begin{cases} curl\ \mathbf{H} = (\sigma - i\omega\varepsilon)\cdot\mathbf{E} \\ curl\ \mathbf{E} = i\omega\mu\mathbf{H} \\ div\ \mathbf{H} = div\ \mathbf{E} = 0. \end{cases} \tag{6}$$

To calculate the excitation magnetic field of the loop and the surface NMR signal, a good first approximation is a model of two homogeneous half-spaces, i.e., nonconductive (air) and electrically conductive (earth). In this case, electric and magnetic fields are called normal. Sommerfeld (1926) was the first to calculate the normal field of a magnetic dipole, and the normal electromagnetic field around a loop-shaped current source was studied by Ryu et al. (1970). For a more detailed presentation see Wait (1982).

Assume that the wire loop is to be placed at the origin of a cylindrical coordinate system (r, φ, z), so that the wire is laid along the circle $r = R_0$ in the plane $z = 0$. A homogeneous and uniform formation with conductivity $\sigma_1 = \sigma$ fills the

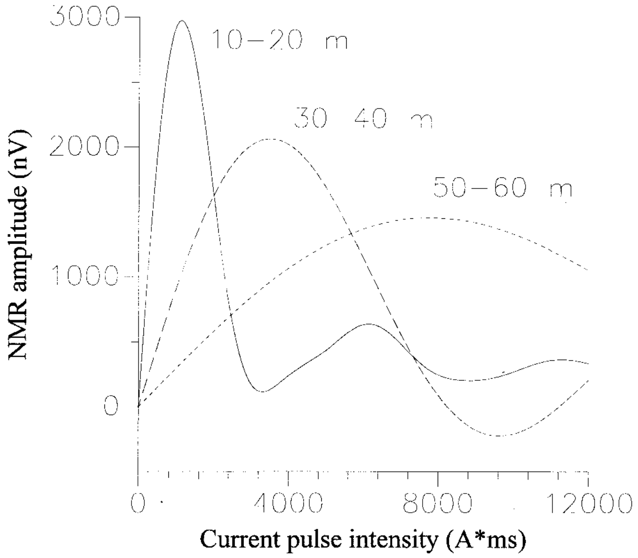

FIG. 1. An example of the dependence of surface NMR amplitude on current pulse intensity calculated for a 10-m–thick model horizontal water layer located at depths from 10–20 m, 30–40 m, and 50–60 m.

half-space $z > 0$, the air conductivity being $\sigma_0 = 0$ (Figure 2). Because of axial symmetry, the magnetic Hertz potential (Nisbet, 1955) only has a vertical component.

In the half-space $z > 0$, the solution of equation (6) for the magnetic field of the loop has the form (Shushakov and Legchenko, 1992, 1994a)

$$H_{1z}(\mathbf{r}) = IR_0 \int_0^{\infty} \frac{m^2}{m+u} e^{-uz} J_1(R_0 m) \cdot J_0(rm)\, dm \qquad (7)$$

$$H_{1r}(\mathbf{r}) = IR_0 \int_0^{\infty} \frac{mu}{m+u} e^{-uz} J_1(R_0 m) \cdot J_1(rm)\, dm, \qquad (8)$$

where $u = (m^2 - \varepsilon\mu\omega^2 - i\sigma\mu\omega)^{1/2}$ and J are Bessel functions.

The magnetic dipole fields over a horizontally stratified formation were studied by Wait (1951, 1952) and several other authors (compiled in Wait, 1982). The equations in Shushakov and Legchenko (1994b) for the magnetic field of the circular loop over the horizontally stratified earth, as well as equations (7) and (8) for the conductive half-space, are used for the calculations in the present paper.

The alternating magnetic field is doubly screened as a result of the finite electrical conductivity of the medium. First, the field $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$ of the loop is screened during the exciting pulse. Then, the field created by macroscopic transverse nuclear magnetization freely precessing in the Earth's magnetic field is screened upon the NMR signal observation. A reciprocity principle (Frank and Mises, 1935), which allows the change of source and a receiver in electromagnetic field calculations, is widely used in geophysics. To calculate the field created by the precessing nuclear magnetization with regard to conductivity, it is reasonable to use the reciprocity principle, because of the absence of cylindrical symmetry in the magnetic field of nuclei with the arbitrary geomagnetic field inclination (Shushakov and Legchenko, 1992, 1994a).

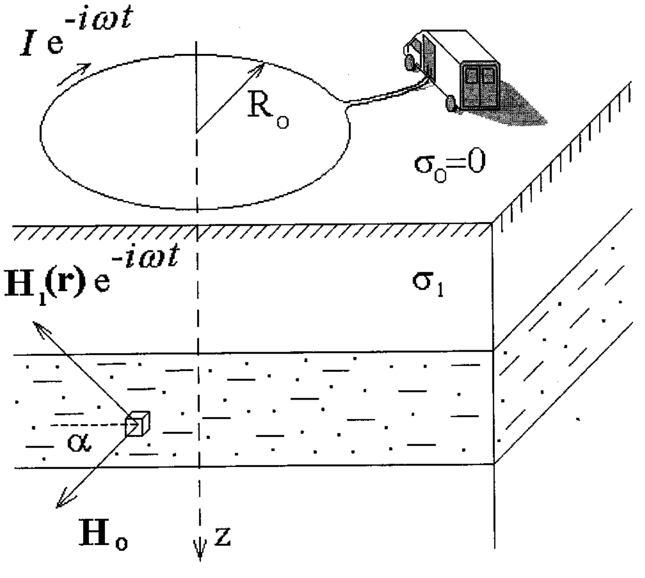

FIG. 2. Schematic representation of the R_0 radius excitation loop, model half-spaces of $\sigma_0 = 0$ conductivity (air) and $\sigma_1 = \sigma$ (earth), and the coordinate system. Also shown schematically are the magnetic fields acting on the elementary aquifer volume: the Earth's magnetic field is $\mathbf{H}_0$ and the current loop oscillating field is $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$.

The excitation field $\mathbf{H}_1(\mathbf{r}) \cdot e^{-i\omega t}$ can be regarded as a complex value in expression (5) in the presence of formation conductivity. Equations (3) and (4) can be rewritten as

$$\theta(\mathbf{r}) = 0.5 \cdot \gamma_H \cdot |H_{1\perp}(\mathbf{r})| \cdot \tau_p, \qquad (9)$$

$$\mathbf{M}_\perp(\mathbf{r}) = [\mathbf{M}_0(\mathbf{r}) \times \mathbf{H}_1(\mathbf{r})/|H_1(\mathbf{r})|] \cdot \sin\theta(\mathbf{r}). \qquad (10)$$

The NMR signal is also a complex value possessing amplitude and phase. The vector model of NMR signal formation (Abragam, 1961) gives the expression

$$E_0(Q) = (\omega/I) \int_V \{M_\perp(\mathbf{r}) H_{1\perp}^2(\mathbf{r})/|H_{1\perp}(\mathbf{r})|\}\, dV(\mathbf{r}). \qquad (11)$$

EXPERIMENT

The measurements of groundwater NMR were carried out with the equipment developed by A.G. Semenov and his co-workers at the Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk (Semenov et al., 1982). Unlike conventional techniques, (Semenov et al., 1987, 1988) the amplitude as well as the phase of the NMR signal was measured. The dependence of the NMR signal phase on conductivity was verified first by Semenov et al. (1989).

The field experiments were performed in the Altay region of Russia near Malinovoe Lake. The measured data were compared with the calculations made for a horizontally stratified medium (Shushakov and Legchenko, 1994b). The stratified-medium model was developed from borehole logs, vertical resistivity profiles, and salinity data, obtained from the Zapsibgeologiya report (1988).

Figure 3 shows the vertical geological cross-section and resistivity profile of a test site. The apparent resistivity varies along the profile. At borehole site 153, the measured resistivities are 50 ohm-m with AB/2 separation equal to 25 m and more than 100 ohm-m for AB/2 equal to 60 m. At borehole site 16, however, the resistivities are 4 and 6 ohm-m, respectively. For hole 17, the resistivities are 1.5 and 2 ohm-m.

For borehole 17 the stratigraphic logs show a thick water-containing strata (aquifer) from 13 to 31.3 m depth and aquifer from 49 to 55.8 m. (The absolute elevation is shown in Figure 3 instead of the depths for each borehole). The total dissolved solids (salinity) of underground water in the aquifers is 12 g/l and 0.4 g/l, respectively. For borehole 16 there is an aquifer from 19 to 34.2 m with salinity of 3 g/l, and an aquifer from 39 to 45 m with 0.47 g/l salinity. At borehole site 153, the salinity was much less than 0.5 g/l. The salinity at borehole 153 was estimated from the data of the nearby borehole that penetrates the aquifer, denoted by a dashed line in Figure 3.

The geological profile, shown in Figure 3 was obtained using data from nearby boreholes, as well as those shown in the cross-section, and it is assumed that the profile represented is reliable. Furthermore, the calculations testify to a smaller NMR signal magnitude from deeper high-conductivity layers. Therefore, the assumption made does not allow for significant errors for the layer at the depth of 54–61 m in borehole site 16.

RESULTS AND DISCUSSION

Figure 4 shows the calculated NMR signal amplitude and phase as a function of excitation-current pulse intensity for a 10-m–thick model horizontal water layer located at different depths (10–20 m, 30–40 m, 50–60 m) and as a function of half-space conductivity. The conductivity of the water-saturated layer is the same as that of the half-space. The geomagnetic field inclination was assumed to be 90°.

According to the calculations, the electrical conductivity has a great effect on the phase and amplitude of the NMR signal. For greater depth of a water-saturated layer, the characteristic resistivity at which the changes occur is even larger. This dependence correlates with that of a skin effect depth on the resistivity. More subtle physical effects of an electromagnetic field like interference or diffraction are expected in layered media. Their consideration, however, is beyond the scope of this paper.

Figure 5 depicts the NMR-signal phase and amplitude versus excitation-pulse intensity, for a water-saturated layer at depth from 10 to 20 m, located in a uniform half-space with 1 ohm-m resistivity, and for three different inclinations of the Earth's magnetic field. The conductivity of the water-saturated layer is the same as that of the half-space. As indicated by the calculations shown in Figures 4 and 5, the influence of conductivity on the NMR signal is more significant than the dependence on the geomagnetic-field inclination. This is because the vertical component of the magnetic field of the loop shows different changes with increasing depth than the horizontal one.

Figure 6 shows the NMR-signal phase and amplitude for a water layer from 50 to 60 m located in a horizontally layered medium. The conductive layer with a thickness of 10 m and a resistivity of 1 ohm-m is situated in different positions with

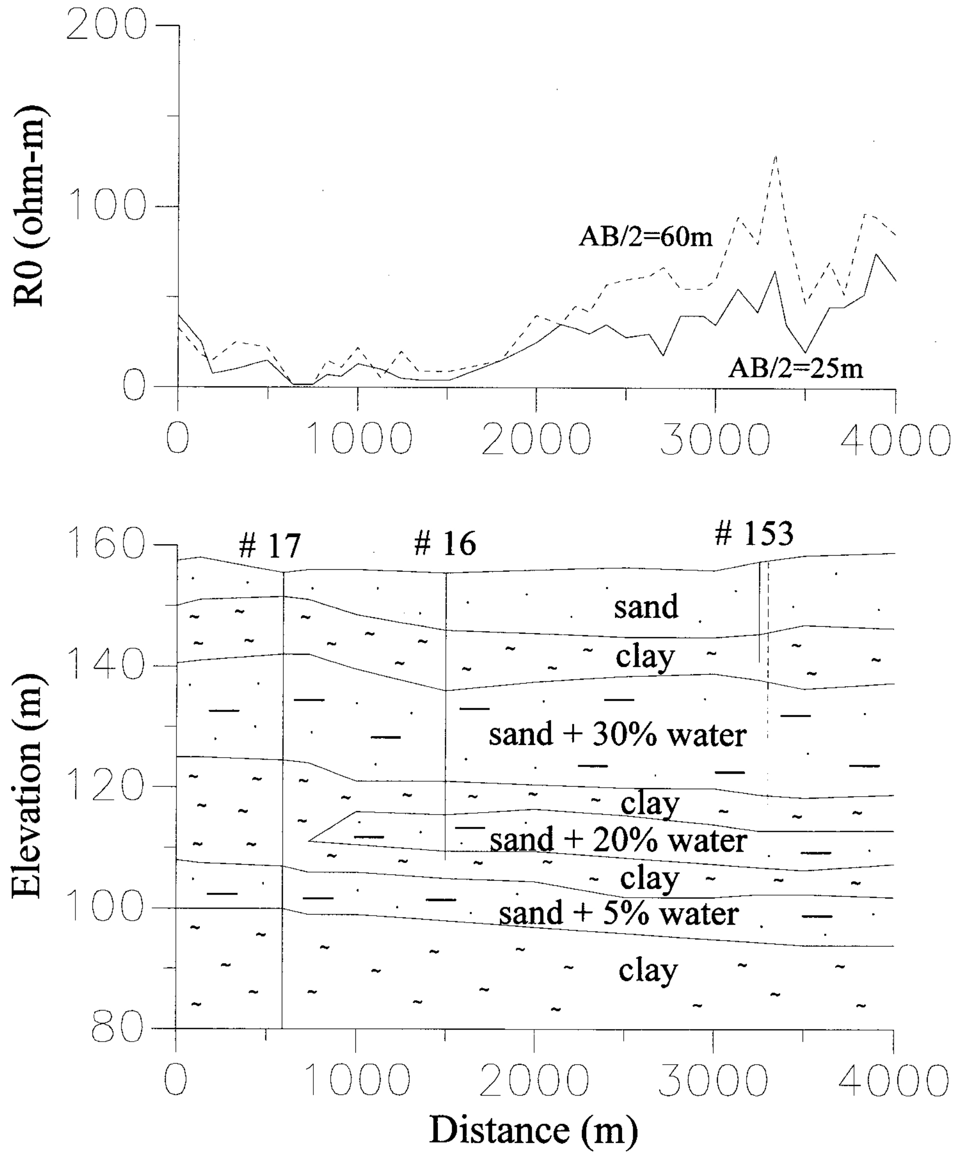

FIG. 3. Vertical geological cross-section of the test site. At the top are horizontal resistivity profiles with AB/2 separation equal to 25 m (solid line) and AB/2 equal to 60 m (dashed line).

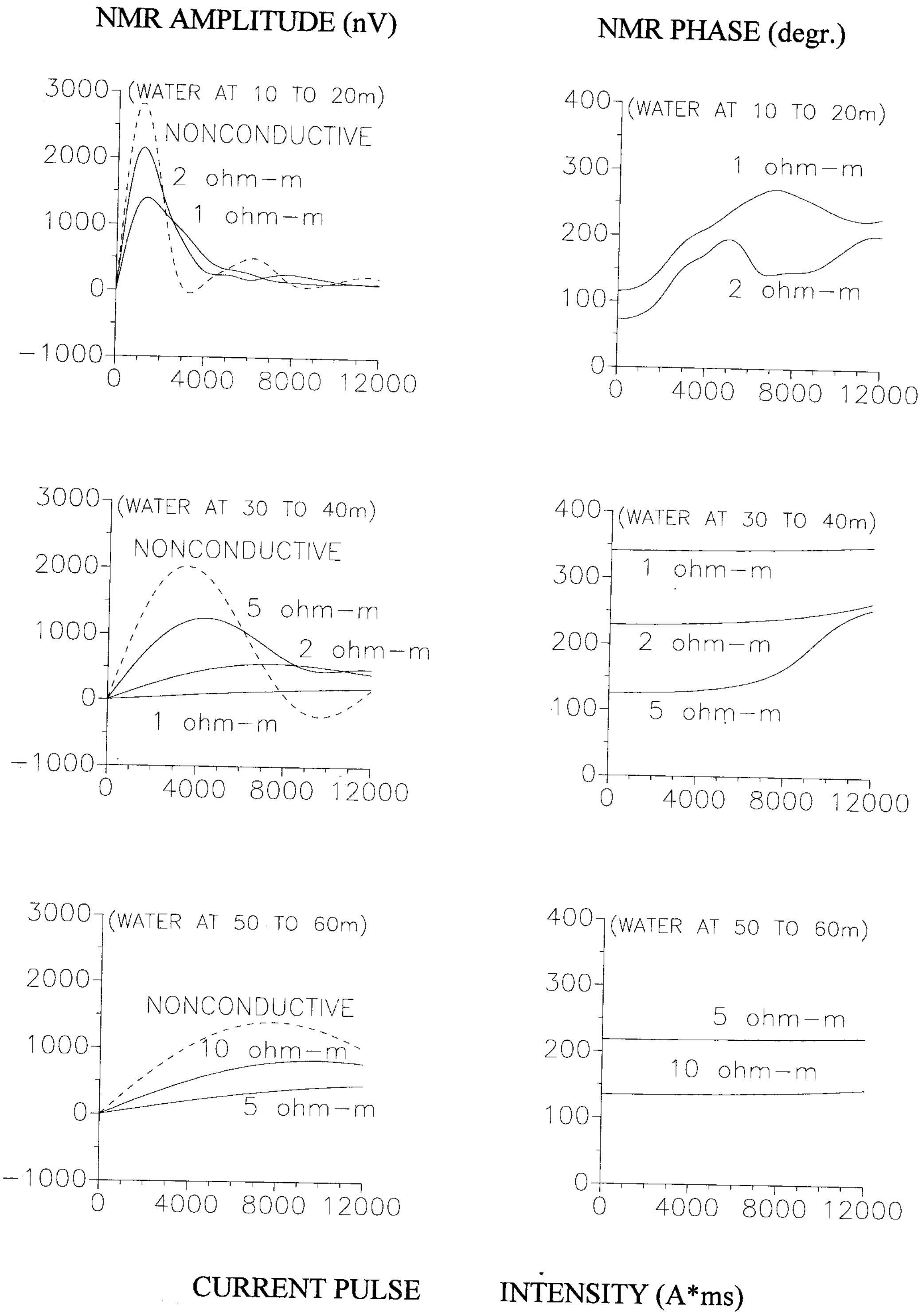

FIG. 4. NMR signal amplitude and phase versus excitation-pulse intensity, calculated for different conductive half-space resistivities as shown and at different depths for the 10-m-thick, water-saturated layer.

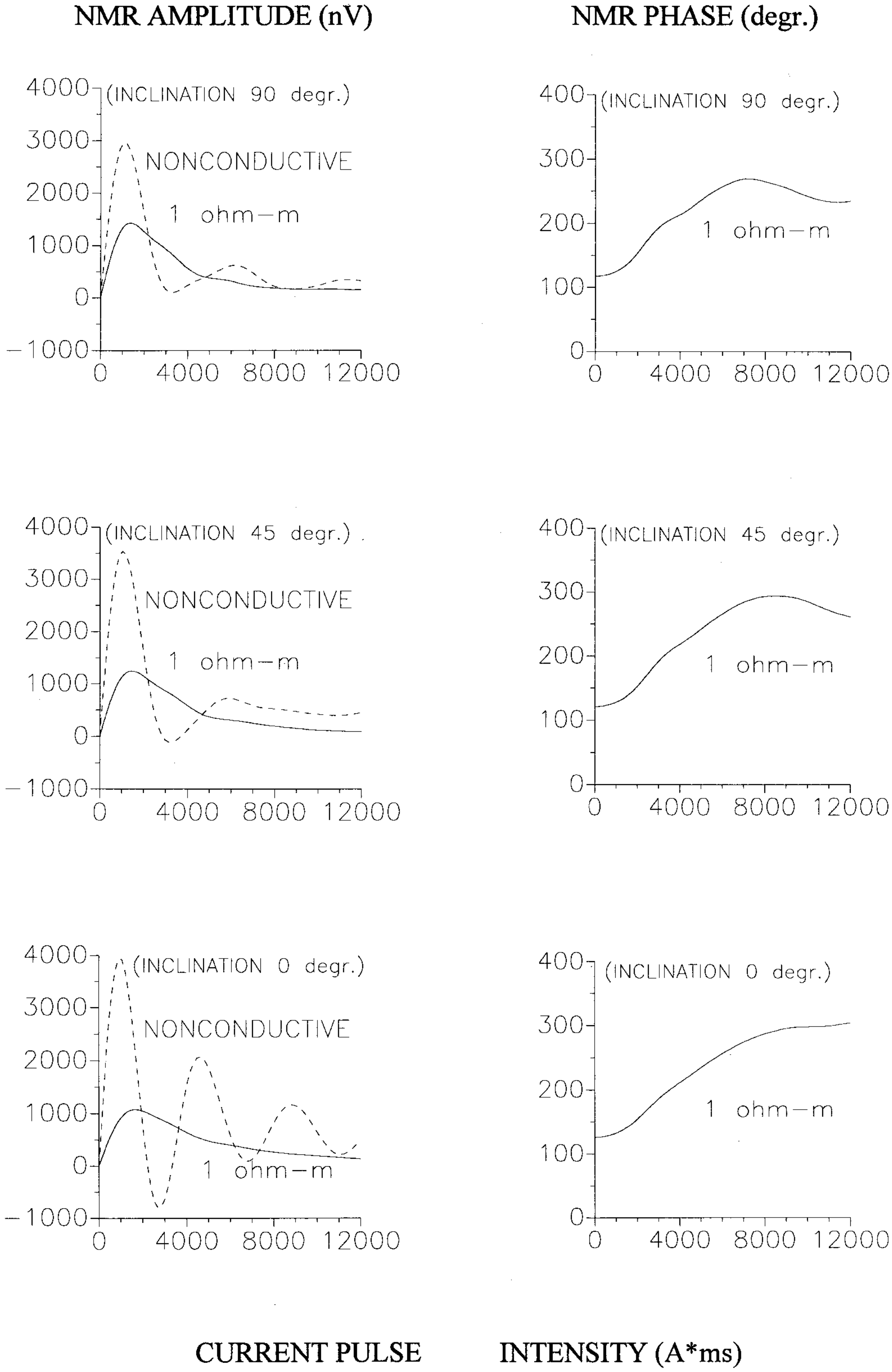

FIG. 5. NMR signal amplitude and phase against excitation pulse intensity calculated with different geomagnetic field inclinations. The half-space resistivity is 1 ohm-m. Dashed line shows the NMR signal in a nonconducting half-space.

respect to the water layer. When a conductive layer is located above the water-saturated layer, Figure 6 indicates a decrease in the NMR-signal amplitude. If the conductive layer is under the water-saturated layer, the NMR-signal amplitude increases. When the depths of the conductive and water-saturated layers coincide, the NMR-signal amplitude and phase change with the thickness of the layers. In practice, this effect corresponds to the case of a layer saturated with saline water located in a weakly conductive medium. These results contradict the measurements proposed by Semenov et al.'s (1989) for a groundwater salinity by the NMR-signal phase. Thus, it is concluded that saline and fresh water cannot be distinguished by measuring only NMR-signal amplitude and phase.

Figure 7 compares the calculated and measured NMR-signal phase and amplitude at borehole sites 153, 17, and 16. The resistivity of soil was estimated from the resistivity profile (Figure 3) using a one- or two-layer earth model (Wait, 1982). The groundwater salinity data and the loop impedance measurements (Trushkin et al., 1995), as well as location of strata boundaries (Figure 3) were also taken into account to estimate the resistivity of aquifers.

The location of aquifers in borehole 153 was determined from the geologic profile (Figure 3). The volume content of water $n(z)$ in equation (1) was calculated from the NMR data, and, in addition, the experimentally determined location of stratum boundaries coincides with the data in Figure 3. A resistivity high was observed at borehole site 153 (Figure 3). Therefore, the volume content of water $n(z)$, obtained at borehole site 153 by the NMR data-inversion algorithm that regards as well as disregards the conductivity, is reliable. The surface NMR inversion procedure is described shortly in Trushkin et al. (1995).

Since the greatest distance between boreholes is only 2.7 km, it is assumed that the principal properties of water-bearing rock, such as porosity, do not significantly change along the cross-section (Figure 3) and, therefore, the water content $n(z)$ does not appreciably vary within each water-saturated layer.

There are three aquifers at borehole site 153 (15–33 m, 43–50 m and 54–61 m) with, as determined from the NMR data, a volume water content $n(z) \cdot 100$ [equation (1)] of 30%, 20%, and 5%, respectively. The resistivity is about 50 ohm-m using a one- or two-layer model. According to the modeling results considered above, this level of medium resistivity has practically no effect on the surface NMR signal.

For borehole site 17, the calculations were performed for two aquifers at 13–31 m and 50–56 m depth, which provided 30% and 5% water content, respectively. The resistivity of the near-surface layer (from 0 to 13 m), determined from the dc apparent resistivity data and from the cross-section (Figure 3), was about 1.5 ohm-m. The resistivity of the aquifer at 13 to 31 m, estimated from the salinity data and the loop impedance measurement, was approximately the same value.

At borehole site 16, the NMR signal was calculated for three layers, 19–34 m (30% water), 39 to 45 m (20% water), and 49 to 57 m (5% water). The resistivity was determined to be 4 ohm-m from 0 to 40 m, and 7 ohm-m from 40 m to downward.

Figure 7 indicates a fair agreement between calculated and measured data. It should be noted, however, that the calculated NMR-signal amplitudes at borehole sites 16 and 17 correspond, in the absence of conductivity, to the measured-signal amplitude at borehole site 153. At the same time, when conductivity is taken into account, the NMR-signal amplitude decreases about three times for borehole 17 and two times for borehole 16.

CONCLUSIONS

The NMR signal caused by groundwater was calculated as a function of conductivity. For a uniform half-space, with a

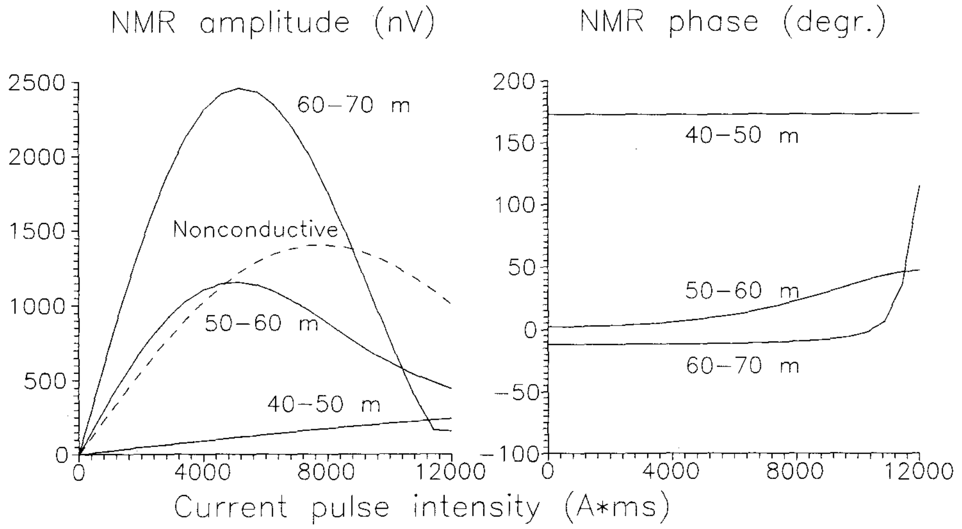

FIG. 6. NMR signal amplitude and phase as a function of excitation-pulse intensity calculated for a three-layer formation model and a different relative arrangement of the water-saturated and conductive layer. Aquifer is located at a depth of 50 to 60 m. The depth of the conductive layer is shown in the figure; this layer has a resistivity of 1 ohm-m. The dashed line shows the NMR signal amplitude in the absence of the 1 ohm-m conductive layer.

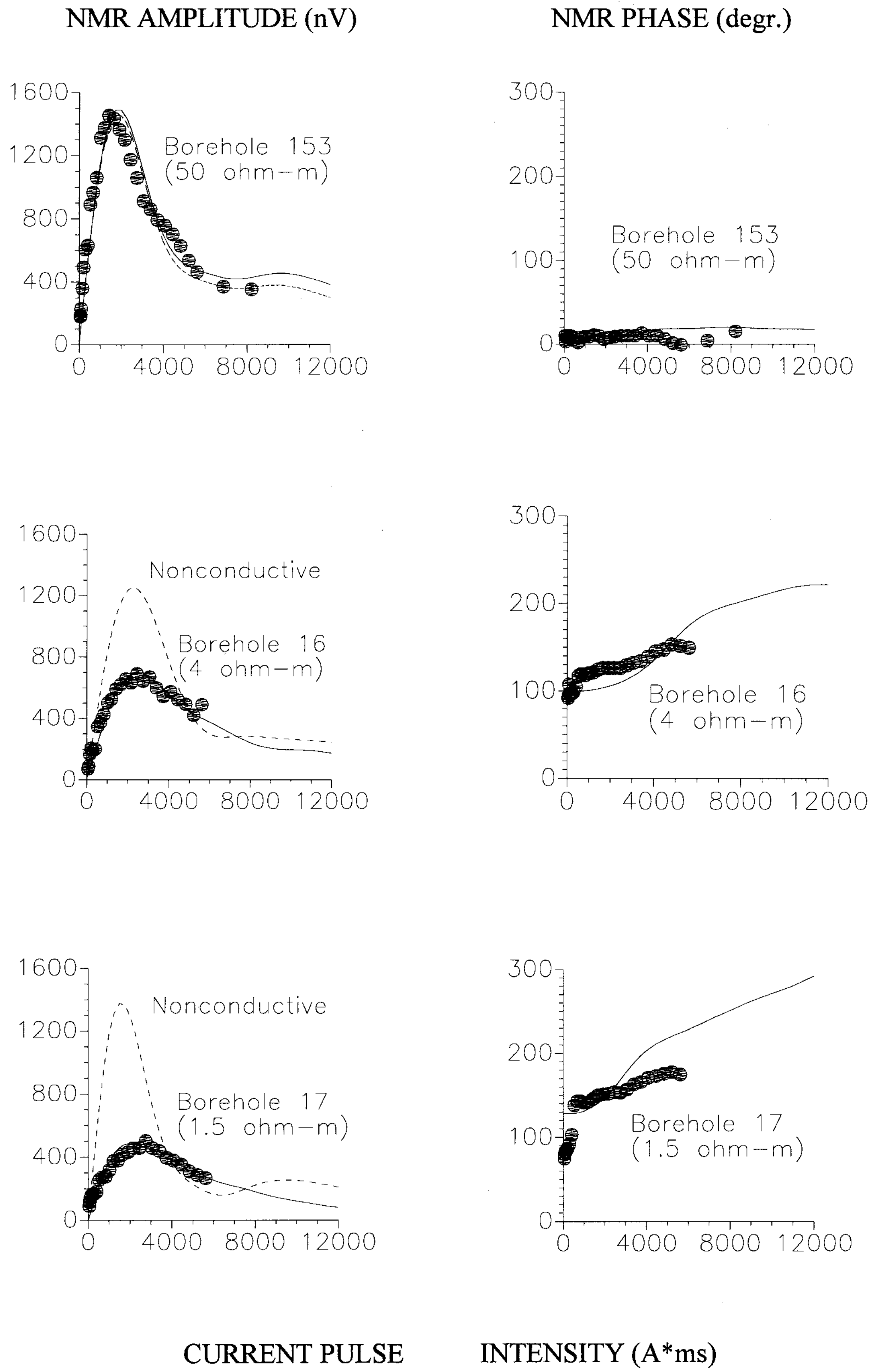

FIG. 7. Comparison of measured with calculated NMR amplitude and phase, as a function of excitation pulses at borehole sites 153, 17, and 16. Points show the experimental results, solid lines represent calculations. Dashed lines show calculated NMR signal amplitude in the absence of conductive layers.

resistivity of a few ohm-m to several tens of ohm-m (depending on the depth of water-saturated layers), the NMR-signal amplitude and phase are shown to vary substantially because of magnetic-field screening.

When the formation is conductive, the NMR-signal curve shape versus excitation-pulse intensity (e.g., maximum position) undergoes considerable modification.

The dependence of the NMR-signal phase and amplitude on geomagnetic field inclination has been studied by taking into account an oscillating magnetic-field screening that results from the conductivity of the medium. From this, the Earth's field inclination has been shown to have a minor affect on the NMR signal.

Calculated and experimental groundwater NMR signals have been compared in terms of formation conductivity. Good agreement was found between these data.

Some characteristics of groundwater NMR-signal behavior have been examined for layered formations, specifically. It is shown that the groundwater salinity cannot be determined by measuring only the NMR-signal amplitude and phase.

While working toward this publication, I also investigated the integration of an electromagnetic method and surface NMR into one device, using the same antenna (Trushkin et al., 1995). This led to a significant improvement in the NMR-signal-inversion result, with only a minor complication in the surface NMR method.

ACKNOWLEDGMENTS

The author is grateful to D. V. Fitterman, A. Sezginer, and D. K. Butler for fruitful suggestions about improvement of this paper, to M. D. Schirov for assistance in obtaining the borehole and resistivity data, and to A. V. Legchenko for valuable discussions. H. M. Kluyver edited the final version of this paper.

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