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Joint inversion of Surface Nuclear Magnetic Resonance and Vertical Electrical Sounding

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Abstract

The method of Surface Nuclear Magnetic Resonance (SNMR) provides a very new technology to directly determine subsurface water distribution. The microscopic magnetization of water molecules is used to derive water content and pore size information from SNMR soundings. The observed similarity and agreement between interpreted aquifer structure from SNMR and resistivity distribution from Vertical Electrical Sounding (VES) has led to our objective to jointly invert both data sets using a generalized petrophysical model based on Archie's Law. To perform inversion of both methods, the Simulated Annealing (SA) technique was applied. Since a very fast numerical solution is available for both geophysical methods, this kind of guided random search algorithm promises better performance than least square methods. The developed inversion algorithm has been applied on a number of different synthetic data to study its properties and prove its reliability. Investigations on well-known test sites where both methods were conducted finally proved the effectiveness of the joint inversion on real data. The interpretation of the subsurface model could be optimized beyond an enhanced spatial resolution to a quantitative interpretation of the ratio of mobile and adhesive water contents, leading to prediction of hydrological parameters from geophysical investigations. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Surface Nuclear Magnetic Resonance (SNMR); Vertical Electrical Sounding (VES); Joint inversion; Simulated Annealing

1. Introduction

The application of geophysical techniques in the investigation of groundwater resources is becoming increasingly important. Due to the properties of water as an electrical conductor, electrical and electromagnetic methods used to be the main methods for its prospection. The obtained models give an image of the spatial resistivity distribution and therefore some indication on the location of the reservoir, but a quantification cannot be derived from these measurements alone. Rock models for electrical properties and their dependency on the water content tried to improve the interpretation. Detailed laboratory investigations improve the rock physics, but results are still insufficient for large-scale geophysical applications. The method of Surface Nuclear Magnetic Resonance (SNMR) now promises to close this gap since it allows the direct determination of the quantity of water in the subsurface. The magnetic moment of water molecules is used to derive water contents from SNMR soundings. This uniquely new information in geophysical measurements complements the rock model by providing the crucial parameter, namely the porosity.

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Ever since the method of SNMR was developed by Russian scientists (Shirov et al., 1991; Legchenko and Shushakov, 1998), several surveys have proved the applicability of this method for groundwater prospection (Goldman et al., 1994).

The working group on groundwater geophysics at the Technical University Berlin and the Federal Institute of Geosciences and Mineral Resources (BGR) Berlin have focused their research on SNMR and its application with other methods. The availability of a commercial instrument at the BGR, a wide range of electrical and electromagnetic methods and a well-equipped rock laboratory, including Lab-NMR, allow integrated groundwater investigations. Since 1996, several methodological studies on SNMR have been done in this workgroup. These include modeling algorithms for 1D and 1D inversion with Simulated Annealing (SA) (Mohnke, 1999) as well as a modeling routine for 3D water distribution (Eikam, 1999). Test sites in Haldensleben (Yaramanci et al., 1999a), Nauen (Yaramanci et al., 1999b) and Namibia (Lange et al., 2000) have been investigated in great detail.

The good agreement between the subsurface models by SNMR measurements and resistivity methods led to the idea to jointly invert SNMR with Vertical Electrical Sounding (VES) to one common subsurface model in expectation of an improvement of aquifer determination and characterization. The inversion scheme of Simulated Annealing adopted was already applied on SNMR soundings by Mohnke (1999) and this provided the basis of the present work.

2. Principles

The principles of the methods of SNMR and VES and their numerical implementation, the petrophysical model and inversion scheme are given in this section; note that vector values are in bold characters.

2.1. Surface Nuclear Magnetic Resonance (SNMR)

The method of Surface Nuclear Magnetic Resonance is based on the behavior of water molecules as nuclei with magnetic dipole moments, interacting with the apparent magnetic field (Shirov et al., 1991). In equilibrium, the axis of the dipole is aligned with the static magnetic field, spinning around their axis with a specific frequency. This frequency is the local Larmor frequency ω_L, determined by the gyromagnetic ratio for a proton γ_p and the intensity of the static field $|\mathbf{B}_0|$ by:

$$\omega_L = \gamma_p |\mathbf{B}_0|, \tag{1}$$

where

$$\gamma_p = \frac{e}{2m_p}, \tag{2}$$

with e being the electric charge and m_p the mass of the proton. The alignment of the dipole moments in the static field results in an induced magnetization. This magnetization is too small to be directly determined in geophysical applications. To gain measurable signals, the dipole moments $\mathbf{m}$ can be forced out of equilibrium by an additional magnetic field $\mathbf{B}_S$ by the torque

$$\mathbf{D} = \frac{\partial \mathbf{m}}{\partial t} = \gamma_p(\mathbf{m} \times \mathbf{B}_S). \tag{3}$$

The external magnetic field is applied by an antenna loop at the earth's surface and thus shows an elliptic polarization for the general case of conductive media. The resulting effect of different excitation of positive and negative oriented dipole moments can be neglected for further considerations of moderate resistivities of earth materials (Goldmann et al., 1994). The proton dipoles are forced out of equilibrium by the externally applied field. After switching off this field, the forced excitation of the protons decays to the initial orientation aligned with the static field. This gives the typically recorded NMR signal. The relaxation is influenced by interactions of water molecules and the internal surface of the rock, i.e. the pores. The initial amplitude of the signal is determined by the amount of mobile water in the subsurface. Relaxation time gives additional information about the pore structure. Deriving the SNMR signal from subsurface water distribution is depending on magnetic field conditions (Shushakov, 1996; Mohnke and Yaramanci, 2000; Weichmann et al., 1999, 2000). The formulation of the signal amplitude E is given by

$$E(q,t) = E_0(q)e^{-\frac{t}{T}} \tag{4}$$

$$E(q,t) = \omega_L M_0 \int_V f(\mathbf{r}) e^{-\frac{t}{T(\mathbf{r})}} B_{S\perp}(\mathbf{r}) \times \sin(0.5\gamma_p B_{S\perp}(\mathbf{r}) q) \mathrm{d}V, \qquad (5)$$

with q the applied excitation intensity (i.e. $q = I\tau$, with τ the excitation time and I the inserted current), t the time variable, T the approximated average relaxation time, $f(\mathbf{r})$ the amount of mobile water and $B_{S\perp}$ the perpendicular component of the artificially applied magnetic field. Note that the individual specific relaxation time $T(\mathbf{r})$ for each volume element dV contributes to the entire relaxation time T of the recorded signal. Due to the principle of recording, this time constant is closely related to the T_2^*-constant in petrophysics. The argument in the sine expression determines the excitation angle Θ of the protons from their initial orientation. In the scope of a joint inversion with subsurface resistivities, only the initial amplitudes E_0 are considered. Eq. (5) thereby simplifies to

$$E_0(q) = \omega_L M_0 \int_V f(\mathbf{r}) B_{S\perp}(\mathbf{r}) \sin[\Theta(\mathbf{r})] \mathrm{d}V. \qquad (6)$$

Assuming a one-dimensional water distribution with depth, i.e. $f(z)$, the order of integration in Cartesian coordinates of the volume integral can be changed to:

$$E_0(q) = \omega_L M_0 \int_0^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B_{S\perp}(x,y,z) \times \sin[\Theta(x,y,z)] \mathrm{d}x \mathrm{d}y f(z) \mathrm{d}z. \qquad (7)$$

Since the inner part of the integral over the x–y plane is independent of the water content and only determined by known values, it can be represented by the kernel function $K(q,z)$

$$K(q,z) = \omega_L M_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B_{S\perp}(x,y,z) \times \sin[\Theta(x,y,z)] \mathrm{d}x \mathrm{d}y. \qquad (8)$$

This can be pre-calculated for each specific sounding. The values for the initial amplitudes can thus be determined by the integration over the product of the kernel function and the water distribution with depth, i.e.

$$E_0(q) = \int_0^{\infty} K(q,z) f(z) \mathrm{d}z. \qquad (9)$$

For numerical realization, Eq. (9) can be written as:

$$E_0(q_i) = \sum_{j=1}^{Z} K(q_i,z_j) f(z_j) \Delta z; \qquad i = 1,\ldots,J. \quad (10)$$

The calculation of the initial amplitude E_0 for each executed pulse moment q_i requires a two-dimensional matrix with the pulse moments in one dimension and the magnetic field conditions and excitation angles in the other one. To provide a sufficient spatial resolution while keeping a fast enough calculation, a division of the subsurface into basic layers of $\Delta z = 0.5$ m thickness has been proved in giving the best results (Mohnke, 1999). In order to compare water distribution and electrical resistivities in a common subsurface model with a finite number of homogeneous layers, basic layers are summarized over the thickness of each model layer, respectively, leading to the double summation:

$$E_0(q_i) = \sum_{n=1}^{N} \sum_{i=z_n}^{z_n+1} K(q_i,z_j) f(z_j) \Delta z. \qquad (11)$$

This method provides a very fast tool of forward calculation of SNMR amplitudes and is used for all further SNMR signal determination in this paper.

2.2. Vertical Electrical Sounding (VES)

The use of Schlumberger soundings for determination of subsurface resistivities is widespread in geophysical applications. Its simplicity and speed of survey make it the most commonly used DC measurement array. Based on the homogeneous Laplace equation for the potential of the electric field in cylindrical coordinates with radial symmetry

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2}{\partial z^2} = 0, \qquad (12)$$

and the potential difference between the measuring electrodes over a homogeneous earth given by

$$V = \frac{I\rho_1}{2\pi\sqrt{r^2 + z^2}}, \qquad (13)$$

with ρ_1 the resistivity of the first layer, a differential equation for this system is found. This differential equation can be solved for the potential V by a separation of the variables r and z. The entire solution can be determined by superposition of both solutions, and with respect to the boundary conditions for a homogeneous stratified earth, it leads to the equation known as the *Stefanescu Integral* (Koefoed, 1979):

$$V = \frac{I\rho_1}{2\pi}\int_0^\infty [1 + 2\Theta_1(\lambda)]J_0(\lambda r)\mathrm{d}\lambda. \tag{14}$$

On the basis of this expression, the method of digital linear filtering of Ghosh (1971) can be applied. The expression $\Theta_1(\lambda)$, the resistivity transfer function (often referred to as the Slitchers Kernel function), is determined by the resistivities and depths of the model layers. The Bessel function of zero order $J_0(\lambda r)$ can be expressed by a digital filter. By forward modeling, the apparent resistivities can be determined by the application of the digital filter to the resistivity transfer function:

$$\rho_{\mathrm{appi}} = \sum_{j=0}^{N_{\mathrm{filter}}} f(j)t(j - i + N_{\mathrm{filter}}),$$
$$i = 1,2\ldots,k \tag{15}$$

$$\text{with } k = N_{\mathrm{data}} - N_{\mathrm{filter}} + 1, \tag{16}$$

where $f(j)$ is the digital filter with N_{filter} coefficients and $t(j - i + N_{\mathrm{filter}})$ is the resistivity transform function. Once a digital filter is designed for a specific layout, Eq. (15) provides a fast numerical tool for the forward calculation of resistivity sounding. For the purpose of this work, the algorithm used was developed by Mundry (published in Bender, 1985). The applied digital filter contains 20 coefficients; the resistivity transform function is determined by the Perkeris recurrence relation (Koefoed, 1979). The apparent resistivities are calculated for a fixed layout with six points per decade and then determined for any layout by cubic spline interpolation.

2.3. Electrical properties of rocks

To connect the subsurface resistivities with water contents, a generalized model for porous rocks has been used. The applied principle is based on Archie's Law, where surface conductivities can be neglected. The conductivity of a porous rock is then determined by

$$\sigma_0 = \frac{1}{F}\sigma_{\mathrm{w}}, \tag{17}$$

where σ_0 is the conductivity of a fully saturated rock, F the formation factor and σ_{w} the conductivity of the pore fluid. Introducing the dependency of the formation factor on the porosity and the Archie exponent m

$$F = \phi^{-m}. \tag{18}$$

Eq. (17) changes into

$$\sigma_0 = \phi^m\sigma_{\mathrm{w}}. \tag{19}$$

Extending this formulation for partially saturated rocks, the saturation factor S and the saturation exponent n have to be included. The rock conductivity is then determined by the expression

$$\sigma = \phi^m S^n\sigma_{\mathrm{w}}. \tag{20}$$

In the context of a comparison between geoelectric and SNMR data, the water content turns out to be the significant parameter to determine. From the given parameters in Eq. (20), this water content G can be derived by

$$G = \phi S, \tag{21}$$

$$\phi = \frac{G}{S}. \tag{22}$$

Extracting the expression according to water content and saturation, it leads to

$$\sigma = G^m\frac{S^n}{S^m}\sigma_{\mathrm{w}}, \tag{23}$$

$$\sigma = G^m S^{n-m}\sigma_{\mathrm{w}}. \tag{24}$$

This formula constitutes the basic dependency of rock conductivity and water content (i.e. saturation) according to Archie's Law under the assumption of vanishing influence of surface conductivity. Regarding the usual range of $m\in[1.3,2.5]$ and $n\in[1.4,2.2]$ (Schopper, 1982), it turns out that their difference vanishes, and accordingly, the term S^{n-m} approaches unity. The applicability of this assumption for sedimentary host rocks under natural aquifer conditions has been shown by Hertrich (2000). Introducing this simplification, Eq. (24) can be written in terms of the water content G, the Archie exponent m and the conductivity of the pore fluid σ_w as:

$$\sigma = G^m \sigma_w, \tag{25}$$

or as usual in geophysical resistivity applications as the reciprocal

$$\rho = G^{-m} \rho_w. \tag{26}$$

For all further conversions of water contents to layer resistivities in this work, this formulation was used, being aware of its limited validity to porous rocks.

2.4. Simulated Annealing and joint inversion algorithm

The task of a joint inversion of SNMR and VES that principally determine different subsurface parameters and are connected by the empirical relation of Archie's Law poses a demanding exercise to the inversion algorithm. A powerful tool for global optimization even for such complex systems is given by the technique of Simulated Annealing. Its principle of guided random search assures convergence to the global optimum of the system by only solving the forward problem. The method of Simulated Annealing, borrowed from thermodynamic considerations, avoids too large and expensive calculations by an effective guidance of model parameter variance. Starting from any arbitrary model, the model parameters for any further model evaluation are sought within a certain step length. This step length is dynamically adjusted during the procedure such that the evaluated model does fit the requirements better than the preceding one with a probability of 0.5. Any model that fits the given data better than the former one is accepted as optimum so far. To avoid capture in a

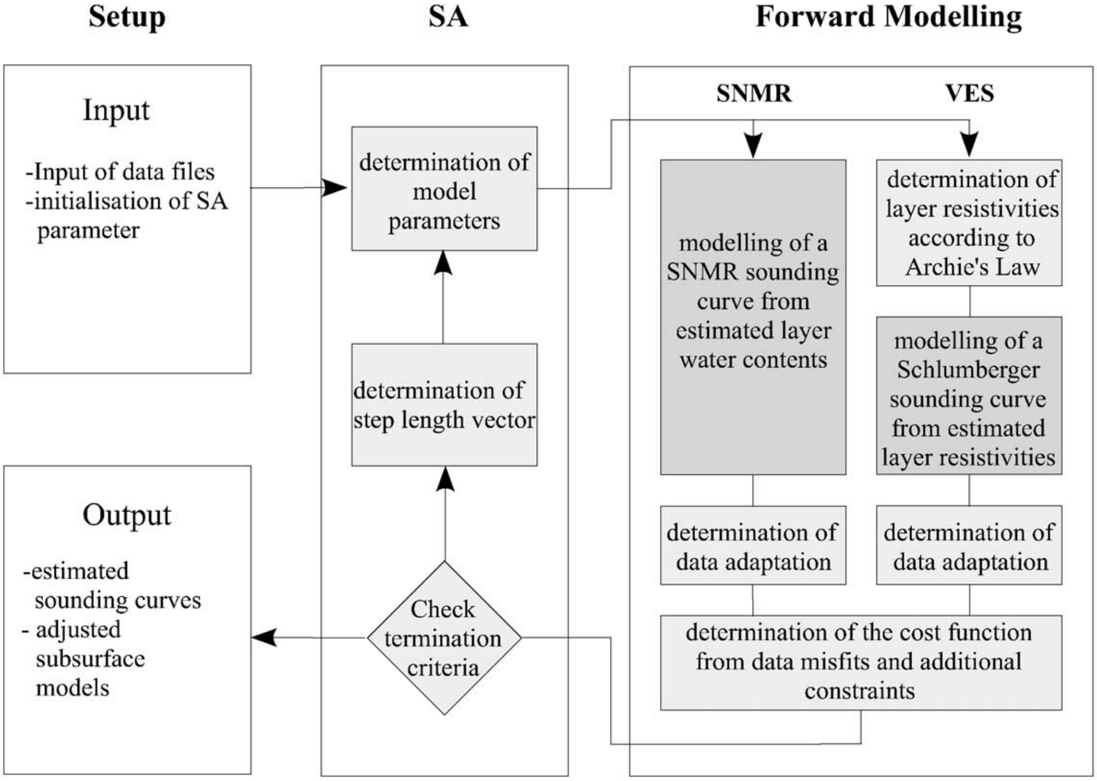

Fig. 1. Flowchart for the joint inversion scheme with Simulated Annealing.

local minimum, uphill moves are accepted with a certain probability, determined by the Metropolis Criterion. In analogy to an annealing crystal in the state of lowest entropy, model parameters are changed such that the lowest value for the cost function is reached, with decreasing uphill move probability at decreasing system 'temperature', i.e. data deviation. The employed algorithm is a modified version of the algorithm developed by Goffe et al. (1994). The crucial parameters of the inversion scheme are the number of model evaluations to determine a new step length vector, the number of trials with the current step length and the cooling rate of the system temperature. Parameter values recommended by Corona et al. (1987) have been adapted to the requirements of this work.

The developed inversion scheme consists of the methodological parts derived above. The subsurface model to be adjusted consists of a finite number of model layers, each assumed to be homogeneous with individual values for thickness, mobile water content, adhesive water content, fluid resistivity and Archie exponent. Forward modeling of sounding curves is then conducted for both VES and SNMR. According to their dependency, SNMR amplitudes are calculated with respect to the depth of the layers and their mobile water contents. For Schlumberger soundings, first layer resistivities are determined by the depth of the layer, the sum of mobile and adhesive water contents, the resistivity of the pore fluid and the Archie exponent, and then the apparent resistivities are calculated by the method explained before. The sounding curves estimated from the two methods are then compared to the measured ones. To ensure an impartial measure for data adaptation, the percentage deviation at each point is determined and their RMS is calculated. The mean RMS of both sounding curves then provides the value of the cost function. The SA routine adjusts new model parameters and step lengths according to the scheme in section Simulated Annealing and terminates the procedure if no significant improvements of the cost function are observed. A detailed illustration of the inversion scheme is given in Fig. 1. Repeating inversion runs with different random seeds lead to different points of termination. The inversion parameters and termination criteria have to be fixed such that a convergence is assured. Illustration of termination points in dependency of the number of model evaluations for a sample data set in Fig. 2 shows the range of convergence that has to be reached.

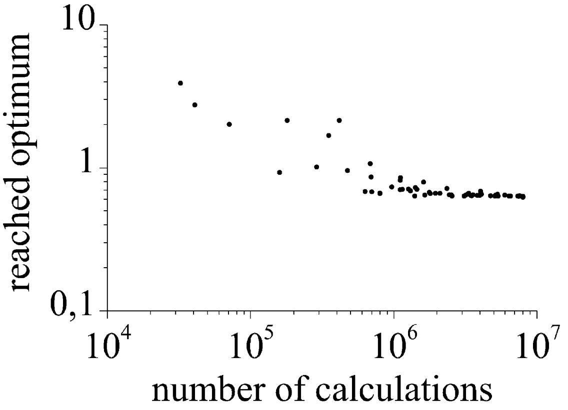

Fig. 2. Point of termination in dependency of the number of function evaluations, i.e. forward calculations.

3. Results

The application of the global optimization method to the methodological principles of SNMR and VES provides an inversion scheme to determine the specified subsurface model using their sounding curves. To investigate preferred settings and ability of the developed method, a general assessment of the algorithm was conducted. The inversion settings of cooling schedule and termination criterion were adapted to the given requirements in the application on geophysical investigation.

3.1. Synthetic data sets

Several combined surveys of SNMR and VES showed agreement in subsurface structure estimation. The synthetic model for detailed investigations of joint inversion was therefore based on geological settings found at test site Nauen (Yaramanci et al. 1999a). The subsurface was assumed to consist of three different layers. The first layer has 0% mobile and 5% adhesive water, the second 30% mobile and also 5% adhesive water and the third layer has 5% mobile and 35% adhesive water. The assumed water distribution in mobile and adhesive fraction and the corresponding sounding curves are shown in Fig. 3.

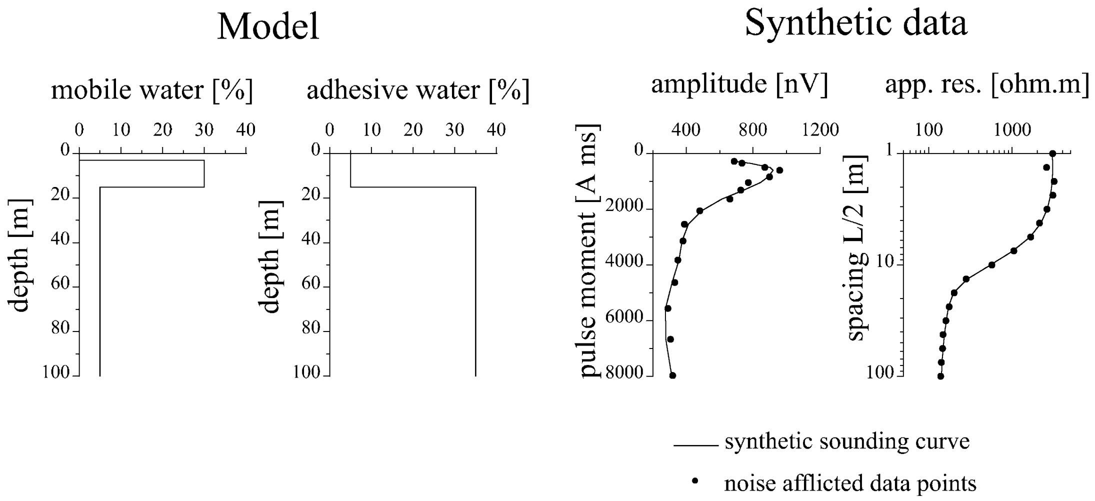

Fig. 3. Synthetic model for the algorithm assessment and the corresponding modeled-sounding curves for SNMR and VES. Data points in the sounding curves represent noise-afflicted data with 5% noise.

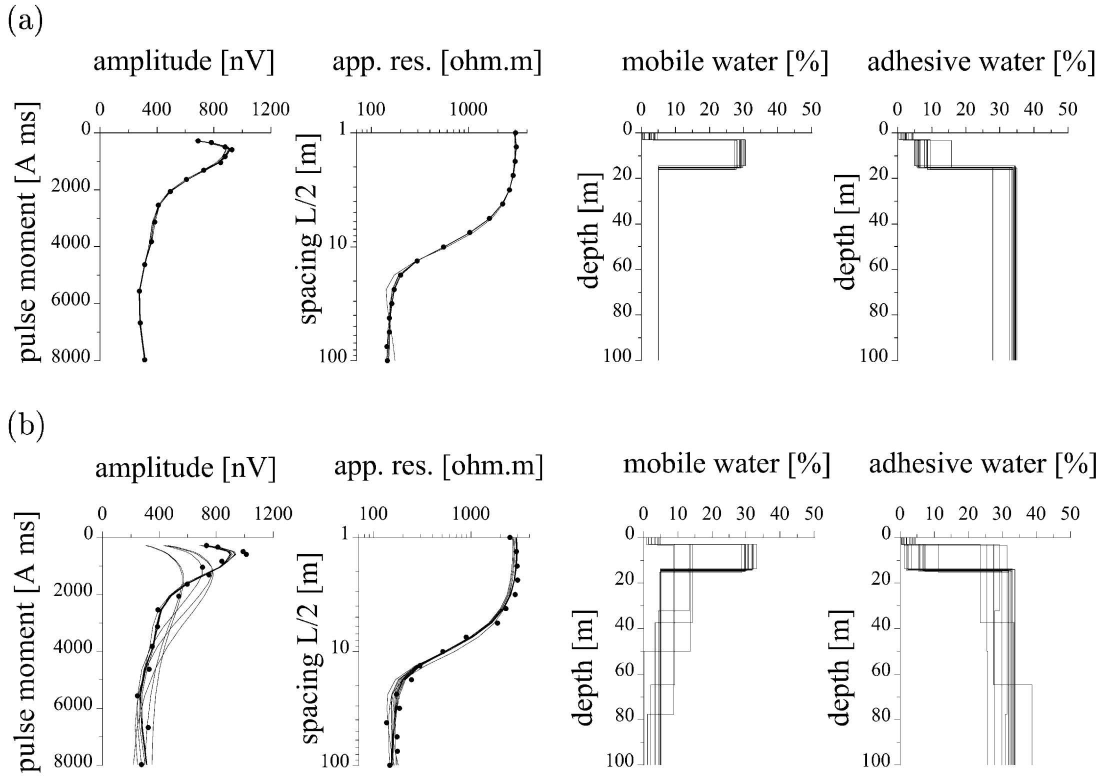

Fig. 4. Differences of inversion results for different data quality: (a) 1% noise and (b) 10% noise applied on synthetic data.

To simulate field conditions, the synthetic data points were contaminated with noise. The noise was generated such that the afflicted data point is found in a Gaussian distributed range with the original data point as mean and the amount of noise as standard deviation. Investigations on inversion settings were conducted on data sets with 5% noise. Since SA converges at different points for repetitive runs, inversion was conducted 16 times with different random seeds to get information on the reproducibility and stability of the inversion process.

3.1.1. Noise

The amount of noise on the synthetic data depreciates the reproducibility of repetitive inversion runs. The mean estimated model still represents the original one, but the variance in model estimation increases accordingly. Two examples for 1% and 10% noise are given in Fig. 4. The number of model evaluations to satisfy the termination criterion increases with increasing amount of noise.

3.1.2. Weighting

In performing model optimization in this work, the cost function represents the data adaptation of both soundings. In respect to their reliability and data quality, their contribution to the result can be weighted differently. Additionally, special focus can be given to one of the methods according to their individual sensitivities to certain depths. In case of the investigated synthetic model, it turned out that SNMR measurements are less sensitive to the first few meters, leading to a poor resolution of the vadose zone in SNMR soundings. Consequently, insignificant difference of total water content between fully saturated sand and glacial till leads to failure of VES in determination of this boundary. Main weight on VES therefore prefers a model adaptation with a single

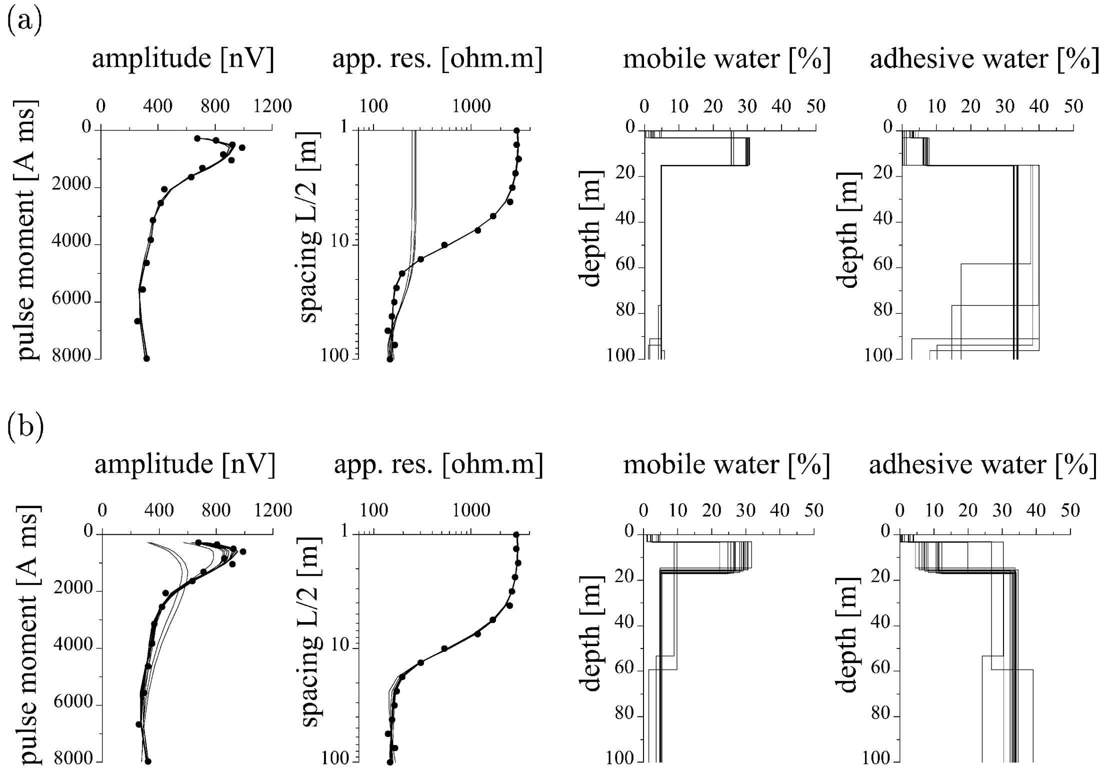

Fig. 5. Influence of different contribution of each method to the cost function with (a) 70% SNMR, 30% VES and (b) 30% SNMR, 70% VES.

layer of saturated zone and underlying till. Both effects become visible in Fig. 5, where joint inversion was conducted with a SNMR to VES ratio of 70:30 and 30:70, respectively.

3.1.3. Number of layers

The suppression of equivalent models is one of the expected results of joint inversion. Inversion has, therefore, been tested where the number of layers was different from those of the synthetic model. Performing inversion with two model layers leads to a convergence with either an adapted vadose zone without detecting the sand/till boundary or an adapted sand/till boundary, not resolving the vadose zone. Defining the number of model layers to adjust higher than the synthetic one does not affect the ability of subsurface estimation. The algorithm adjusts any additional layer in depths over 80 m where none of the methods contains significant sensitivity. In Fig. 6, the reproducibility of the right model is shown for three and five inversion layers.

3.1.4. A priori information

The performance of model adaptation with fixed subsurface parameters was investigated. Correctly tied up parameters just reduce the number of values to adjust and decrease calculation time. Interesting features are the performance with parameters fixed at wrongly values and the corresponding soundings. It turned out that inversion performance is not affected by wrong fixed values. Multiple inversion runs always show a high reproducibility with high accuracy. The water contents are adjusted by the algorithm such as to compensate the differing expansion of the aquifer which mainly determines the curve shape with both methods. The sounding curves principally show a significant shift from the initial data point but are reproduced accurately. Wrong a priori information can

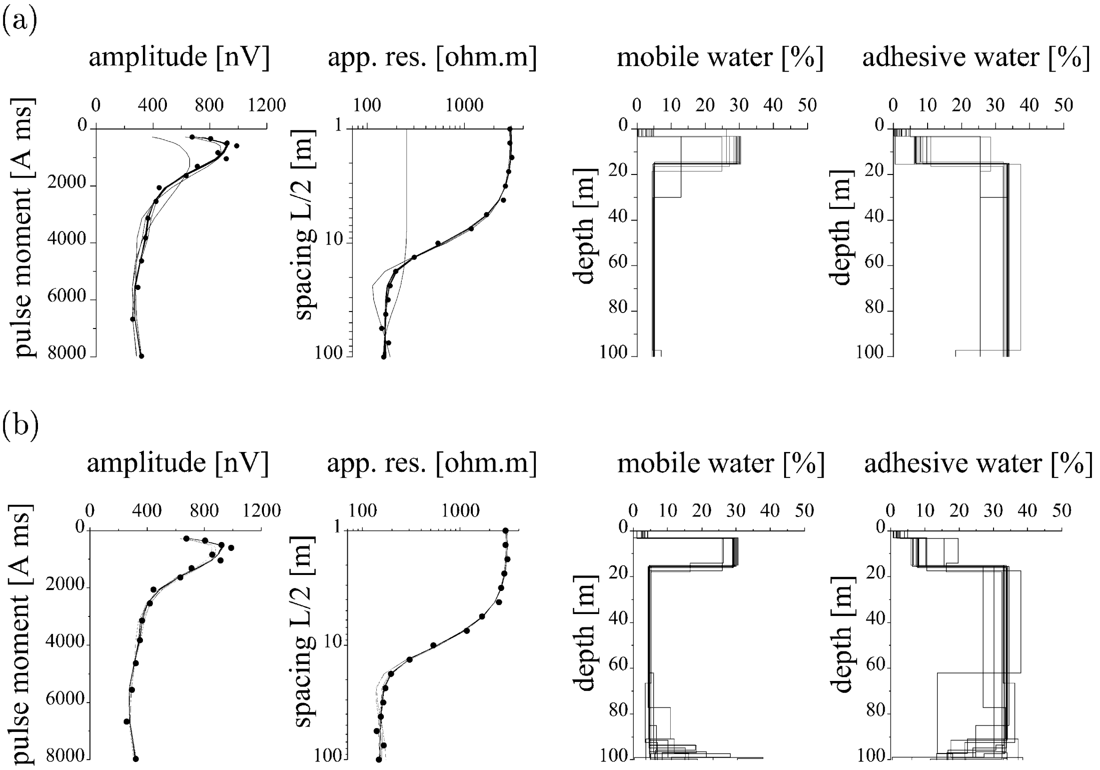

Fig. 6. Influence of different number of model layers on the accuracy of model adaptation for (a) three layers, which is the number of the synthetic model, and (b) five layers.

also be identified by a bad data fit and differing curve shape even if satisfactory inversion performance seemingly points to good model fit.

3.2. Real data sets

3.2.1. Test site Haldensleben

Detailed geophysical investigations have been conducted at the test site in Haldensleben (Yaramanci et al., 1999b), where a large aquifer system occurs in tertiary sediments. The water table is met at 20 m depth and the aquifer is bounded to the bottom by a till layer at some 40 m. Extensive geophysical data are available from 1D- and 2D-geoelectrics, Radar and SNMR, supplemented by borehole logs on groundwater drills.

Similar to the investigations at the test site Nauen, geoelectric single inversion is not able to detect the sand/till boundary due to the small resistivity contrast (Fig. 7a). Least square SNMR inversion points to an area of high mobile water content but distinct boundaries cannot be determined (Fig. 7b).

Joint inversion of both methods was conducted assuming an Archie exponent of 1.5. Although fluid resistivities from well logs point to values of some 29.7 Ω m, inversion settings were fixed at resistivities of 14.8 Ω m. Extensive evaluation of model settings justifies this assumption. Conducting joint inversion with six model layers yields a stable convergence to a model that fits both sounding curves in an excellent manner. Results for the data fit and the corresponding estimated subsurface model are shown in Fig. 7c and are interpreted as follows.

- The determined layer boundaries of the found model do reliably represent the subsurface conditions derived from borehole data. The upper boundary of

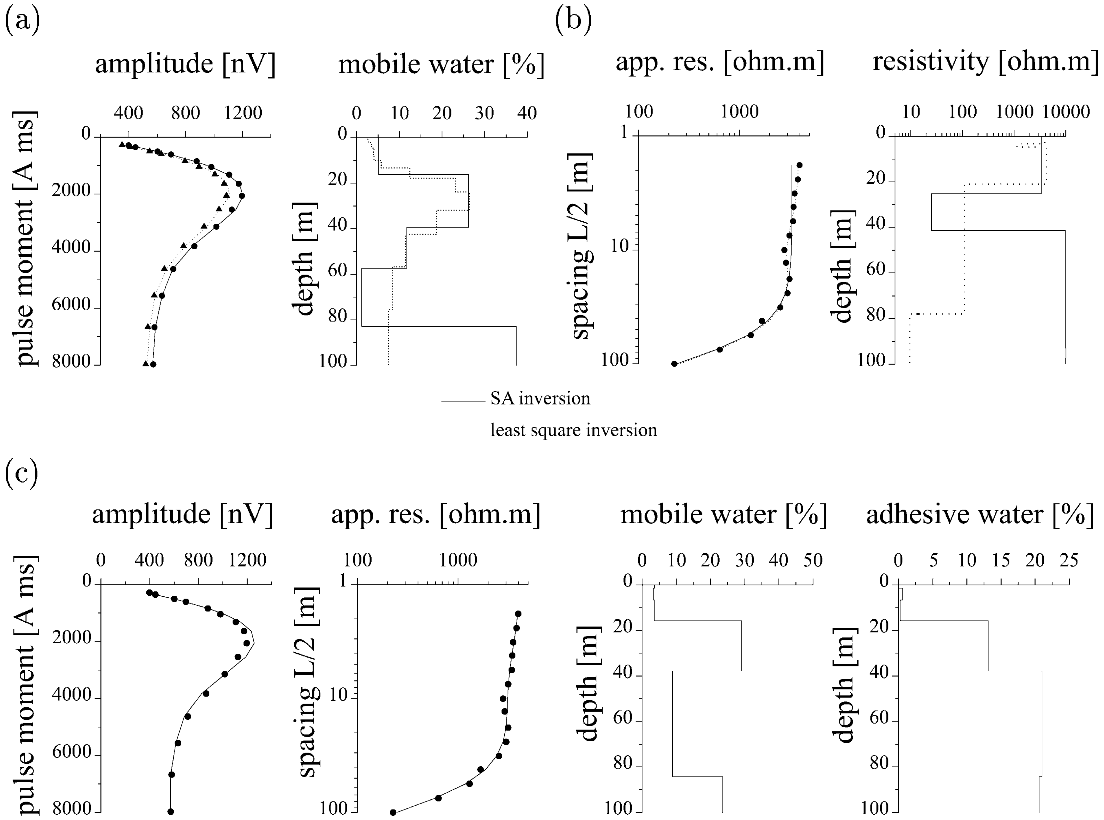

Fig. 7. Results of test site Haldensleben. (a) Single inversion of SNMR data, (b) single inversion of VES data, both with SA and least square inversion, and (c) joint inversion of both methods with mobile and adhesive water contents as separate model parameters.

the aquifer is adjusted such to fit both measurements equally and fits the expected groundwater table. The lower boundary is determined appropriately in the range of the assumed till layer.

- The determination of the adhesive water contents provides uniquely new information. Under presumption of a reasonable fluid resistivity and a moderate Archie exponent, the content of adhesive water is determined to have expected values for sand and till layers.
- The joint inversion leads to more reliable determination of mobile water distribution than single SNMR inversion.
- Some model equivalence in VES inversion is suppressed by the application of joint inversion.

3.2.2. *Test site OmDel*

Improvement of model estimation and interpretation was successfully performed on data recorded in Namibia. At the location at the Omaruru delta (OmDel), detailed investigations were conducted. In these settings, groundwater is artificially recharged from the Omaruru River into the delta sediments. These sediments contain some 5% porosity overly granitic basement. In some layers, a high salt content occurs so that a derivation of groundwater settings from resistivities fails. Scattered salt aggregations and low vegetation at the surface lead to lateral inhomogeneities and therefore a distorted VES sounding curve. Conduction of SNMR investigations is constrained by the low signal due to the low geomagnetic field intensity and low water content. The single inversion of both methods does not provide a unique subsurface model. VES inversion result fits the curve shape quite well, but the obtained model does not reflect the assumed surface geology. SNMR single inversion shows a region of enhanced water content at about the assumed depth, but repetitive inversion

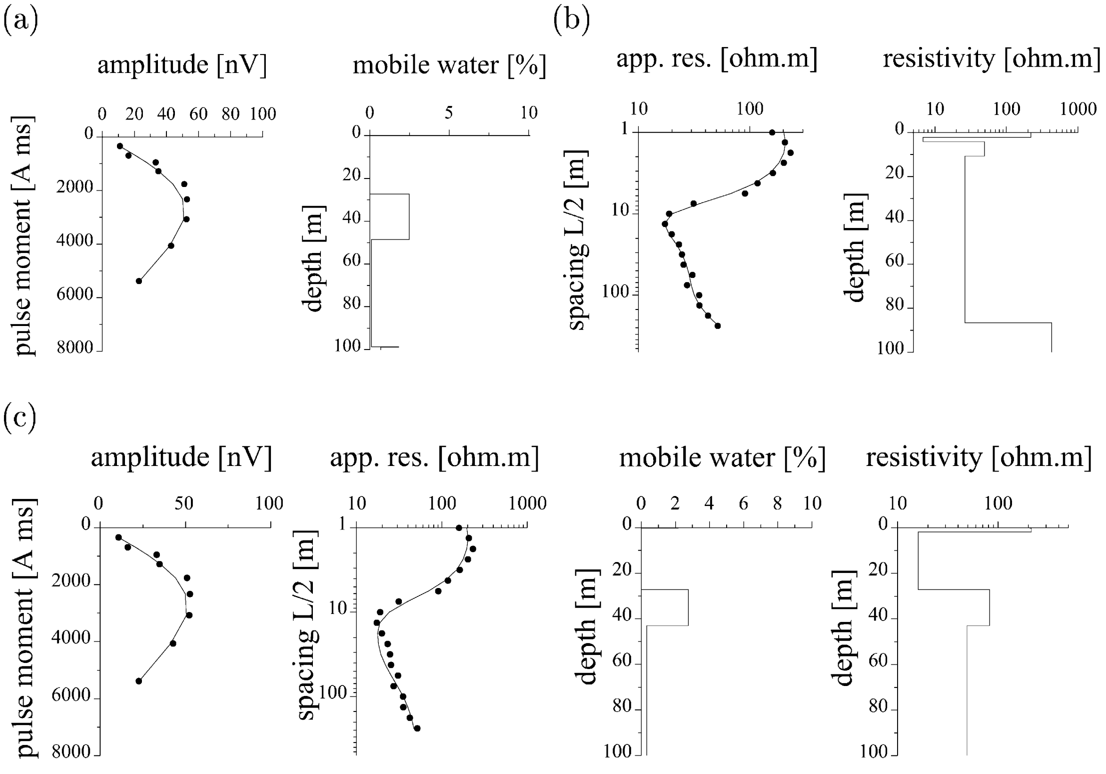

Fig. 8. Results of test site OmDel. (a) Single inversion of SNMR data, (b) single inversion of VES data and (c) joint inversion of both methods with well-adjusted aquifer and increased resistivities in this layer.

runs yield several different models with similar data fit.

Joint inversion on both data sets from this test site was conducted with four model layers. Local settings of high variety in fluid resistivities and sediment character (i.e. Archie exponent) do not allow the determination of detailed petrophysical properties. The attainment of specific layer depth is the main focus of the joint inversion exercise. None of the single inversions did yield any reasonable model estimation and the joint inversion result did not show a satisfying data fit. The implementation of a priori information derived from least square inversion of geoelectric data finally yields the adaptation of both sounding curves with a reasonable subsurface model. Inversion results and the corresponding model are shown in Fig. 8. The following facts are to be pointed out in model interpretation.

- In spite of poor data quality, a model can still be found that fits both sounding curves. Hence, none of the single inversions lead to consistent subsurface estimations, introduction of a priori information on layer depths did succeed in providing a convincing model.
- Peculiar scope on the estimated mobile water contents and their corresponding SNMR data adaptation underline the ability of reliable water content estimations by this method, even under difficult conditions.
- The presumption of fluid resistivity and Archie exponent at arbitrary values leads to unreasonable total water content. Due to the loss of additional information on these parameters, no enhanced interpretation on the quantity on water content can be done.
- The predicted VES sounding curve derived from the common subsurface model shows higher deviation from measured ones than single inversion results. Since investigations on the influence of lateral inhomogeneities did show similar effects (Basokur, 1999), the obtained model can still be accepted as a reliable subsurface approximation.
- Interpretation of the resistivity distribution with depth yields surprising results. The depth layer containing the highest amount on mobile water (i.e. the aquifer) contains a contrast of higher resistivities to overburden and substratum. Effects of attenuation of saline pore fluid by flowing fresh water gives plausible explanation of this phenomenon, but this is still being investigated.

4. Conclusions

The development of a joint inversion algorithm for SNMR and VES did succeed in a reliable method of common model estimation. The underlying assumption of layer resistivities determined by total water contents still constrains the interpretation due to the limited validity of the simplification of Archie's Law. Nevertheless, uniquely new information is obtained for certain geologic settings. The estimation of adhesive water contents provides improved aquifer characterization that cannot be derived by any single inversion technique. Beyond this additional parameter, case studies did underscore the ability of extended model characterization with regard to layer depth and model equivalence. The optimization method of Simulated Annealing did demonstrate its reliability under several conditions like noisy data, different number of layers and a priori information. The principle of SA as an optimization scheme that is only based on forward modeling of different methods now allows the implementation of new geophysical applications. The implementation of other methods of determining resistivity to adjust model layers depth better is also under conideration as pore size sensitive methods like relaxation constants in SNMR soundings and induced polarization (IP) to derive further petrophysical and hydrological parameters. The underlying rock model to connect water contents and resistivities or even IP effects is one of the major topics to improve.

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