Environmental Geology (1996) 27: 329–334

A. Weller · F. D. Börner

Measurements of spectral induced polarization for environmental purposes

Received: 1 November 1994 / Accepted: 27 June 1995

Abstract Hydraulic permeability is one of the most important parameters for the evaluation of sediments relevant to environmental and hydrogeological problems. Up to now, permeability could be determined only by time-consuming and expensive methods like pumping tests or sampling and laboratory investigations. The results are confined to few locations, and they depend on the scale of the investigation method. Measurements on rock samples in a laboratory can differ significantly from well test results. Geophysical measurements are performed on different scales from high resolution measurements in boreholes up to large-scale soundings. Variations in permeability are mainly caused by varying grain size and by changes in porosity. A decrease of average grain diameter results in an increasing internal surface area. Petrophysical investigations have shown a reliable correlation between the imaginary part of electrical conductivity and the pore-space-related internal surface. The formation resistivity factor, which is related to porosity, can be determined by geoelectrical measurements if the electrical conductivity of the pore fluid is known. The internal surface area and the formation factor are the only two parameters used by a Kozeny-Carman-like equation to evaluate the permeability or hydraulic conductivity for the investigated representative volume. Complex electrical conductivity is determined by measurements of induced polarization in the frequency domain. Frequencies below 10 Hz are used to avoid electromagnetic coupling. The permeability values determined by electrical measurements in boreholes can well be compared with those derived from the grain size distribution of samples. The same algorithm can be applied to evaluate the hydraulic conductivity of subsurface layers by complex resistivity soundings. The high sensitivity of the imaginary conductivity component to changes at the internal surface may be used as an indicator for contaminations.

Introduction

Geophysical methods are increasingly applied to investigate the geological environment of waste disposal sites. With regard to the danger of groundwater pollution, hydraulic permeability governs groundwater flow and therefore can be considered one of the most important rock parameters. Geophysicists are asked if it is possible to derive the permeability from geophysical measurements on different scales. Detection and monitoring of soil and groundwater contamination are another important challenge for geophysical activity.

The relationship between electrical and hydraulic conductivity is far from simple (Mazáč and others 1985). According to the capillary model of Kozeny-Carman, permeability is related to porosity and the specific surface, which depends on the grain-size distribution. Electrical conductivity is correlated to porosity and conductivity of the pore fluid. In a given lithology with a fixed grain size, a positive correlation between hydraulic and electrical conductivity is observed, which is governed by changes in porosity. Regarding different sediments from clay to gravel, the strong influence of varying grain size causes a negative correlation between hydraulic and electrical conductivity. Thus, it is not possible to derive both porosity and grain size of sediments from conventional geoelectric resistivity measurements.

The method of induced polarization is based on a complex and frequency-dependent electrical rock conductivity. The real and imaginary part of the electrical conductivity are influenced in different ways by parameters de-

A. Weller (✉)
Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany

F. D. Börner
Dresdner Grundwasserforschungszentrum e.V., Meraner Str. 10, 01217 Dresden, Germany

scribing pore space structure and fluid properties. Vinegar and Waxman (1984), Lockner and Byerlee (1985), and Olhoeft (1985) published results of laboratory measurements. Special investigations on contaminated rock samples have shown the relationship between different pore fluids and complex electrical parameters (Vanhala and others 1992; Börner and others 1993). Measurements of multifrequency or spectral induced polarization in the field yield both amplitude and phase spectra of the electrical conductivity. This method was developed in ore prospection (van Voorhis and others 1973; Pelton and others 1978). The aim of our present work is to show how the high information content of spectral induced polarization measurements can be used for problems relevant to environmental protection and hydrogeology.

Petrophysical fundamentals

Electrical measurements of samples of sand, silt, clay, and sandstone have shown that the complex electrical properties are related to parameters of the pore space geometry (porosity, internal surface) and pore content (salinity) (Vinegar and Waxman 1984; Börner 1992). The fundamental relations will be summarized. In the frequency range from 10^{-3} to 10^{3} Hz, the electrical properties of porous, permeable, and water-saturated sediments can be described as follows: The electrical conductivity is a frequency-dependent complex parameter. The measured effective conductivity σ^* is the sum of volume and interface conductivity. Börner and Schön (1991) have found in investigations on samples of various sediments that the frequency dependence could be described for the real and the imaginary part of the complex conductivity σ^* by a nearly identical power law. In the frequency range of induced polarization (IP), the complex conductivity σ^* can well be expressed by the equation

$$\sigma^*(\omega) = (i\omega)^{1-p}\sigma_n \tag{1}$$

The separation in the real and imaginary part yields two real equations

$$\sigma'(\omega) = \omega^{1-p}\sigma_n' \tag{2}$$

$$\sigma''(\omega) = \omega^{1-p}\sigma_n'' \tag{3}$$

The exponent $1 - p$ characterizes the frequency dependence and is on the order of 0.0001 to 0.03. Equation 1 results immediately in a constant phase angle φ, which is proportional to the frequency exponent $1 - p$:

$$\varphi = \arctan\left(\frac{\sigma_n''}{\sigma_n'}\right) = \frac{\pi}{2}(1 - p) \tag{4}$$

Thus the complex frequency-dependent conductivity can be expressed by only two parameters σ_n and $1 - p$.

The real part of conductivity σ_n' is composed of the electrolytic conductivity of the pore space according to the well-known Archie equation and an ohmic interface conductivity, σ_i':

$$\sigma_n' = \frac{\sigma_w}{F} + \sigma_i' \tag{5}$$

σ_w is the water conductivity and F the formation resistivity factor. The imaginary part, σ_i'', originates exclusively from interface effects:

$$\sigma_n'' = \sigma_i'' \tag{6}$$

Equations 5 and 6 explain that in the case of sediments the conductivity can be described by a real electrolytic volume conductivity and a complex interface conductivity.

The relation between the complex interface conductivity and the so-called surface-to-porosity ratio S_{por} has also proved to be important. Börner and Schön (1991) have found that the imaginary conductivity component σ_n'' is closely connected to the pore-space-related internal surface S_{por}. As a simplification it can be assumed that

$$\log(\sigma_n'') \sim \log(S_{por}). \tag{7}$$

The practical application of this relation creates the possibility of determining the specific internal surface of loose sediments in the field by measurements of the complex electrical conductivity. S_{por} is an important structural parameter that is strongly related to fluid transport in porous media. Pape and others (1982) formulated a Kozeny-Carman-like empirical equation that combines the formation factor F and the surface-to-porosity ratio S_{por} (in m^2/cm^3), which is determined by the nitrogen adsorption method, with the hydraulic conductivity k (in meters per second):

$$k = \frac{0.00475}{F(S_{por})^{3.1}} \tag{8}$$

Figure 1 shows the scheme of the proposed algorithm.

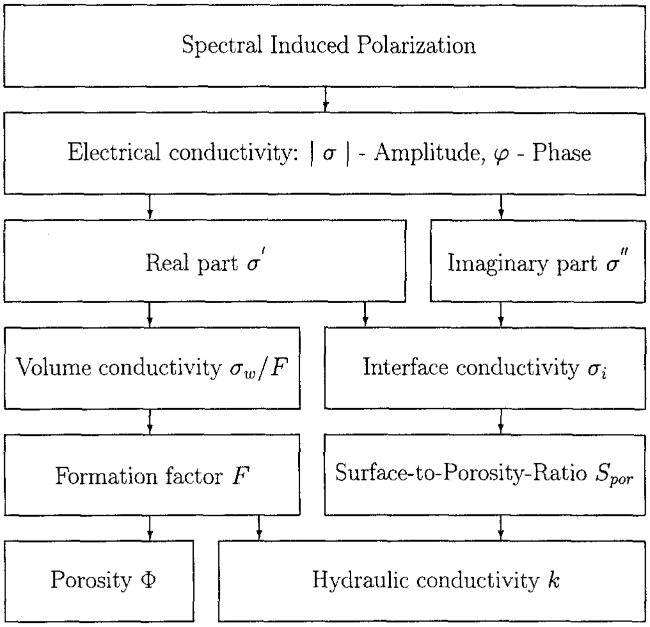

Fig. 1 Scheme of the determination of hydraulic conductivity by spectral induced polarization

The electrical parameters $|\sigma|$ and φ are acquired by spectral IP measurements on the Earth's surface or in wells. The commonly measured amplitude and phase values are transformed into the real and imaginary parts of electrical conductivity. Knowing the water conductivity, the formation resistivity factor is determined by the volume conductivity. The surface-to-porosity ratio is derived from the imaginary part of the interface conductivity. Finally, Eq. 8 is applied to estimate the value of the hydraulic conductivity. The formation resistivity factor can also be used to determine the porosity Φ according the equation

$$F = \frac{a}{\Phi^m} \tag{9}$$

The coefficients a and m depend on lithology and the degree of compaction; $a = 1$ and $m = 1$ are a fairly good approximation, if no further information is available.

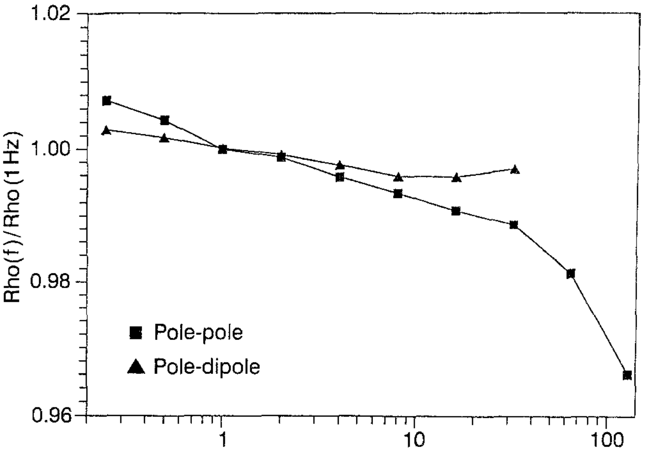

Fig. 2 Amplitude spectra of pole–pole and pole–dipole configuration

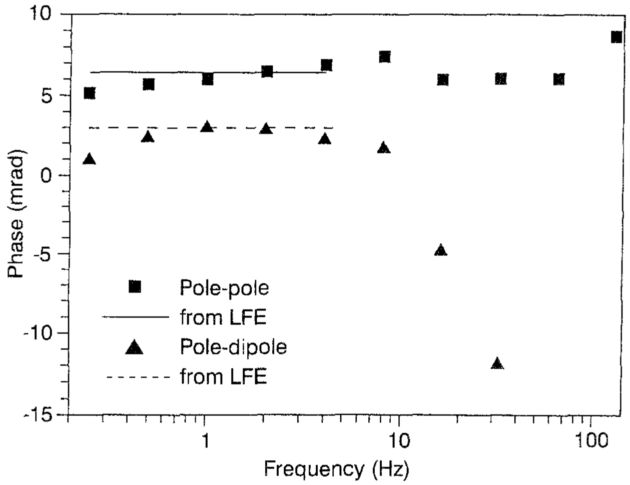

Fig. 3 Phase spectra of pole–pole and pole–dipole configuration

Measurements in boreholes

The first field tests of the algorithm for permeability determination by complex electrical measurements were performed in small boreholes. The tests required suitable equipment: a device for complex electrical measurements and a logging tool. The algorithm is based on a separation of the real and imaginary parts of electrical conductivity. The method of spectral induced polarization (SIP), which yields the amplitude and phase angles of the apparent resistivity in the frequency range from 10^{-3} to 10^4 Hz, was chosen. Our logging tool consists of four equally spaced electrodes ($a = 0.15$ m). The tool can be used in Wenner, dipole–dipole, pole–dipole, and pole–pole configurations. The small depth of penetration of several centimeters ensures a high resolution of all determined parameters.

The objective of the tests was to prove that the constant phase angle model, which was observed in laboratory, is also valid under field conditions with a natural noise level. Figures 2 and 3 show the measured amplitude and phase spectra of two different configurations at two different sites. The frequency dependence of the apparent resistivity according to Eq. 1 is confirmed at low frequencies. The resistivity decreases with increasing frequency. At higher frequencies the spectra are affected by capacitive (pole–pole) or inductive (pole–dipole) effects caused by electromagnetic coupling. The measured phase angles are very small. Their values are on the order of few milliradians (1 mrad = 0.057°). Under field conditions an exact phase angle measurement is hardly possible. The deviations reach the order of the phase value. Therefore, the measured phase angles are not equal, but their values are near the phase angle φ, which results according Eq. 4 from the frequency exponent $1 - p$. In analogy to the frequency effect (FE), which is calculated in conventional IP measurements, Börner (1992) proposed to call the frequency exponent $1 - p$ the "logarithmic frequency effect" (LFE). For field application it is useful to make a multifrequency measurement and to determine the phase angle φ by the LFE. To avoid a distortion by electromagnetic coupling, a low frequency range from 0.25 to 4 Hz is used. The chosen frequencies are equal to the powers of 2. In Fig. 3 the phase angles that are determined in such a way are marked by a straight line. They do not differ very much from the average phase angle in the chosen frequency range.

The test measurements were made in a small borehole. The amplitude and phase spectra of the apparent resistivity are recorded at distances of 0.15 m. The algorithm is applied to the data acquired at each depth. The slope of the amplitude spectra yields the phase angle φ. After separating the real and imaginary parts of conductivity, the normalized pore space area S_{por} is determined. The knowledge of pore fluid conductivity is necessary to derive the formation resistivity factor F. Although the values can differ, the water conductivity measured in the well is used as an approximation of the pore fluid conductivity. The

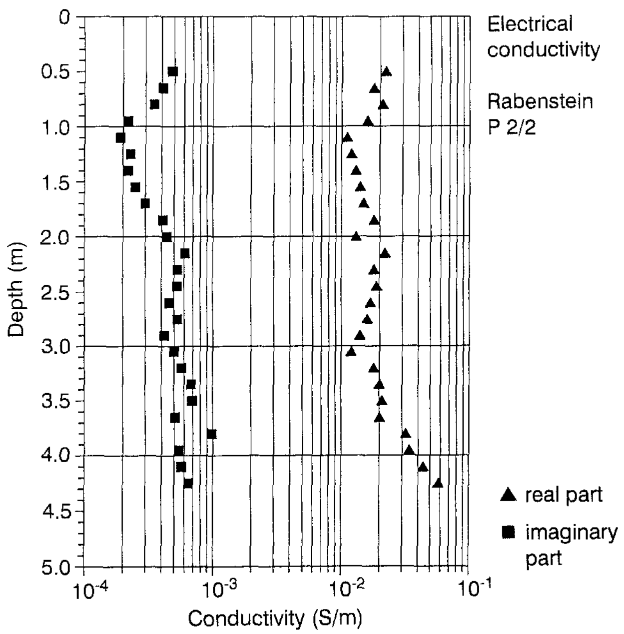

Fig. 4 Complex electrical conductivity measured in a borehole

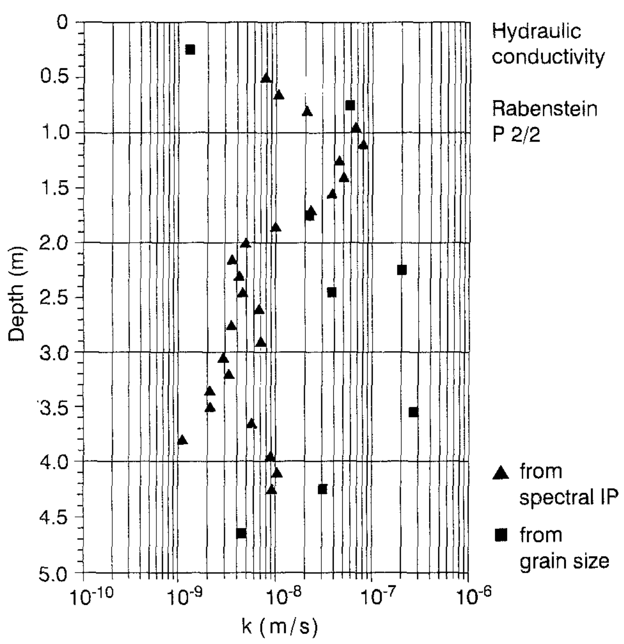

Fig. 5 Electrically determined hydraulic conductivity in a borehole

formation factor and the normalized pore space area are used in Eq. 8 to estimate an electrically determined hydraulic conductivity k_{el}. The application of the algorithm at logging data yields a vertical profile of hydraulic conductivity.

The method presented was applied at the Rabenstein test site. In the vicinity of four new water gauges, small boreholes were placed to make density, humidity, and spectral IP measurements. The water gauges and the boreholes are located in an area of deeply weathered schists. Previous tests had shown that the method works quite well in sandy sediments. The weathered schists possess a considerable silt and clay fraction. Figure 4 shows, for one location, the logs of both the real and imaginary parts of electrical conductivity acquired by spectral IP measurements. These values are used to determine the log of hydraulic conductivity shown in Fig. 5. All values of hydraulic conductivity are in the interval from 10^{-9} to 10^{-7} m s^{-1}. Rock samples were collected from another borehole at a distance of 1 m. The hydraulic conductivity of the samples was derived from the grain-size distribution. These laboratory values are included in Fig. 5. The differences between the geophysical and the laboratory values reach up to two orders. There are several reasons for the differences. The schists are inhomogeneously weathered, and there exists no horizontal layering, so a distance of 1 m can cause considerable differences; however, there are also differences resulting from the two methods. In contrast to the laboratory method, the electrical method considers the natural deposition (porosity, structure).

During drilling of the neighboring water gauge, core samples were collected and then investigated in a triaxial device for flow-rate tests. The hydraulic conductivities determined by this expensive method are in the range 1×10^{-9} to 3×10^{-8} m s^{-1} (W. Jäger, unpublished data). They show the same range as the electrically determined values at depths greater than 2 m.

The tests in Rabenstein have shown that the geophysical method of determination of hydraulic conductivity can also be applied to clayey weathered schists. The electrically determined hydraulic conductivities can well be compared with those from laboratory tests. The values of hydraulic conductivity are available only several hours after the field measurement. This seems to be the main advantage of the geophysical method.

Complex resistivity sounding

The successful application of the electrical method of determination of hydraulic conductivity in boreholes suggested tests to estimate the hydraulic conductivity of subsurface layers by complex resistivity soundings. The tests were made in a Schlumberger configuration with spacings from 1.3 to 100 m. At wider spacings, the data were affected by electromagnetic coupling. At each spacing, the amplitude and phase spectra of the apparent resistivity in the frequency range below 4 Hz are recorded. The data processing includes the determination of the amplitude $|\rho_s|$ at the basic angular frequency $\omega = 1$ rad s^{-1} and the average phase angle φ, which results from the LFE. A complex resistivity sounding yields both a sounding curve of the amplitude of the apparent resistivity and a curve of the phase angle. An inversion program is used to search for a suitable layered model by minimizing the deviation between measured and calculated data. For each layer the amplitude of the electrical conductivity, the phase angle, and the thickness are determined. From the complex layer conductivity, the formation factor and the normalized internal surface are derived. Both values are used to estimate the hydraulic conductivity of the layer by Eq. 8.

Figures 6 and 7 show two complex resistivity sounding curves. The curves were interpreted by a three-layer model. The highly resistant second layer consists of gravel. In Table 1, all parameters are indicated that are derived from both soundings. The water conductivity of 200 mS m^{-1} was determined in a neighboring water gauge. The comparison of both sounding curves shows that the amplitude curves are similar, but the phase curves are quite different. In the case of sounding B, negative phase values are recorded for spacings from 32 to 56 m. Thus, the resulting phase angle for the second layer becomes very small. Its value reaches 0.9 compared with 5.6 mrad for the second layer of sounding A.

The enormous reduction of the phase angle is related to a subsurface hydrocarbon contamination at this site. The hydrocarbons that penetrate the pore space adhere to the

Fig. 6 Complex resistivity sounding A

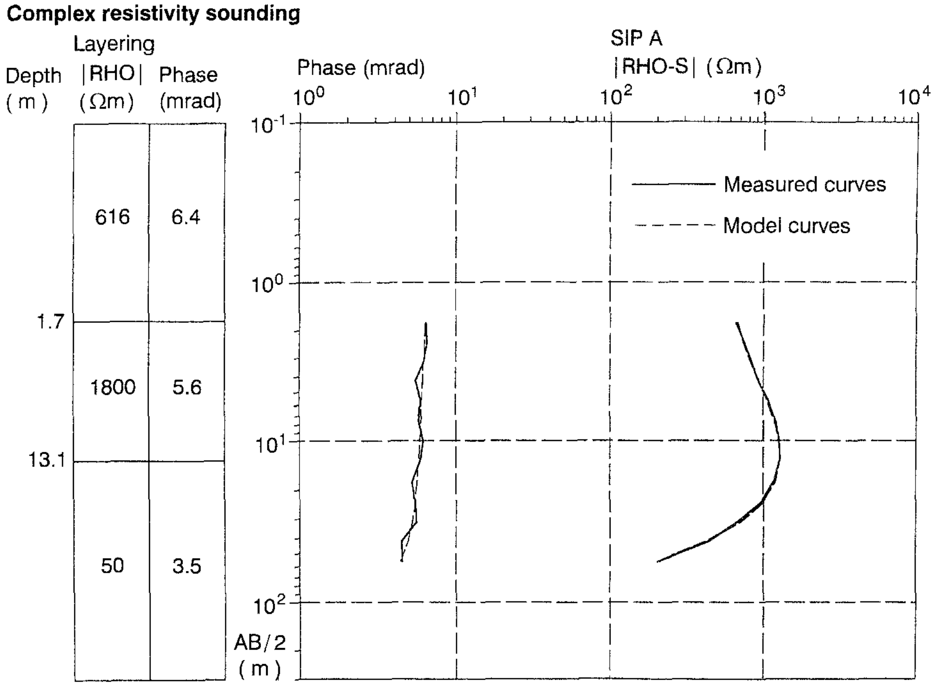

Fig. 7 Complex resistivity sounding B

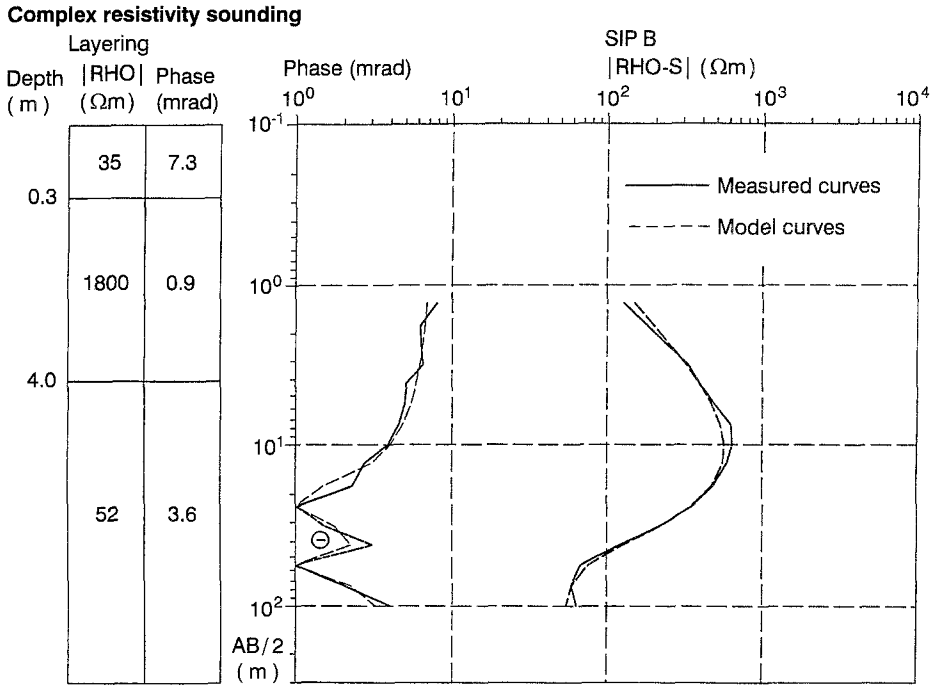

Table 1 Layer parameters derived from complex resistivity soundings

Sounding and layer	$\lvert\rho\rvert$ (Ωm)	φ (mrad)	σ'_n (mS m^{-1})	σ''_n (μS m^{-1})	F	S_{por} (μm^{-1})	k (m s^{-1})
A1	611	6.4	1.64	11	132	0.91	5.0 E-5
A2	1800	5.6	0.56	3	381	0.27	7.5 E-4
A3	50	3.5	20.0	69	10.4	5.99	1.8 E-6
B1	35	7.3	28.5	209	7.55	18.1	8.0 E-8
B2	1800	0.9	0.56	1	363	0.04	2.1 E-1
B3	52	3.6	19.2	69	10.8	5.95	1.7 E-6

internal surface. They affect the formation of the electrical double layer, which is necessary for the imaginary conductivity component. In consequence, the phase angle is reduced. This behavior of the phase angle can be an appropriate indication for hydrocarbon contamination.

Summary

An alternative method for determination of hydraulic conductivity was presented. From petrophysical investigations, relations between electrical and hydraulic properties of sediments were derived that are used by an algorithm to determine the hydraulic conductivity. This algorithm was tested in combination with measurements of the complex conductivity in boreholes. Considering the different scales and conditions of the measurements, the electrically determined hydraulic conductivities can well be compared with the values from laboratory tests. The algorithm can also be applied to complex resistivity soundings, but the precision will be limited because of the principle of equivalence. Compared to the time-consuming and expensive laboratory methods, the electrical method enables a quick and effective determination of the hydraulic conductivity in the field at different scales. The high sensitivity of the imaginary part of electrical conductivity to changes on the internal interface between the solid and fluid phase in sediments may be used under certain conditions as an indicator for contaminations.

Acknowledgments Our investigations are part of the research project Subsoil of waste sites, which is funded by the Federal Ministry of Research and Technology (BMFT, No. 146060 5 A0). The work by A.W. was financially supported by the Deutsche Forschungsgemeinschaft through a Werner-Heisenberg-Stipendium. We thank the colleagues of the firm Geophysik GGD in Leipzig for their support during the field measurements.

References

Börner F (1992) Complex conductivity measurements of reservoir properties. In: Worthington PF (Ed), Advances in core evaluation III—reservoir management. Reading: Gordon and Breach Science Publishers. pp 359–386

Börner F and Schön J (1991) A relation between the quadrature component of electrical conductivity and the surface area of sedimentary rocks. Log Anal 32:612–613

Börner F, Gruhne M, and Schön J (1993) Contamination indications derived from electrical properties in the low frequency range. Geophys Prospect 41:83–98

Lockner DA and Byerlee JD (1985) Complex resistivity measurements of confined rock. J Geophys Res 90:7837–7847

Mazáč O, Kelly WE, and Landa I (1985) A hydrogeophysical model for relations between electrical and hydraulic properties of aquifers. J Hydrol 79:1–19

Olhoeft GR (1985) Low frequency electrical properties. Geophysics 50:2492–2530

Pape H, Riepe L, and Schopper JR (1982) A pigeon-hole model for relating permeability to specific surface. Log Anal 23:5–13

Pelton WH, Ward SH, Hallof PG, Sill WR, and Nelson PH (1978) Mineral discrimination and removal of inductive coupling with multifrequency IP. Geophysics 43:588–609

Vanhala H, Soininen H, and Kukkonen I (1992) Detecting organic chemical contaminants by spectral-induced polarization method in glacial till environment. Geophysics 57:1014–1017

van Voorhis GD, Nelson PH, and Drake TL (1973) Complex resistivity spectra of porphyry copper mineralization. Geophysics 38:49–60

Vinegar HJ and Waxman MH (1984) Induced polarization of shaly sands. Geophysics 49:1267–1287