Induced Polarization of Unsaturated Sands Determined through Time Domain Measurements

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ABSTRACT

We studied the electrical induced polarization (IP) response of simple multiphase porous systems by conducting time-domain (TD) IP measurements on two different groups of sieved quartz samples: sands containing air in unsaturated pores and sands where the unsaturated pores were filled with kerosene. The analyzed chargeability vs. water content relationship showed an extreme behavior. The resistivity vs. water content relationship exhibited two distinct power law regions characterized by different values of the power-law exponents. Quartz–water–air and quartz–water–kerosene samples showed similar behavior. A conceptual model of polarizing cells is proposed to explain the observed IP phenomena. We consider a sequence of large and narrow passageways for electric current as the elementary polarizing cell. The polarization of the cell is related to the difference in effective radii of the passageways. In the saturated cell, the water-filling intergranular space is considered the large current passageway. Areas of grain contact are considered narrow passageways. In unsaturated cells, the thin water film on the grain surfaces is considered the narrow passageway. Areas of grain contact are viewed as large passageways. The polarization of unsaturated cells in this condition should be larger than that of saturated cells. With further drying, unsaturated cells start releasing water from the grain contact area, which leads to a convergence of the effective radii of large and narrow passageways and, consequently, to a decrease in cell polarization. The conceptual model is capable of explaining the observed dependence of polarization on water content. The chargeability maximum corresponds to the limit between the two distinct regions, each having a different resistivity vs. water content relationship, which we consider as the critical water content. Our model suggests that at the critical water content, pore water becomes predominantly adsorbed on the solid surface.

In the last decade, the IP method has proved to be of significant value for various environmental and hydrogeological investigations of the subsurface. It has been demonstrated in field applications that IP has the potential to distinguish between sediments of different lithological composition (e.g., Slater and Lesmes, 2002a; Kemna et al., 2004) and of different groundwater salinity (e.g., Seara and Granda, 1987), to detect inorganic and organic contaminants (e.g., Oldenburg, 1996; Kemna et al., 2004), and to predict hydraulic characteristics (e.g., Börner et al., 1996; Kemna et al., 2004). However, most of the underlying core-scale investigations (e.g., Börner and Schön, 1991; Vanhala, 1997; Lesmes and Frye, 2001; Lesmes and Morgan, 2001; Slater and Lesmes, 2002b; Titov et al., 2002; Scott and Barker, 2003) were performed on saturated media, which restricts the applicability of the results to vadose zone studies. Moreover, the influence of vadose zone parameters and state variables on IP measurements is not clear because of the lack of corresponding petrophysical data.

Studies on the variation of real (not complex) resistivity with water content were conducted by a number of authors in the context of hydrology and oil prospection (e.g., Keller, 1953; Knight, 1991; Taylor and Barker, 2002). The complex resistivity was investigated under different saturation degrees on sandstone cores in the frequency range of 100 to 106 Hz (Su et al., 2000); on sandstone, carbonate rocks, and synthetic porous media in the frequency range of 100 to 109 Hz (Capaccioli et al., 2001); and on unconsolidated sediments in the frequency range of 0.1 to 1000 Hz (Ulrich and Slater, 2004). Time domain measurements on sands with different water content are reported in Komarov (1980) and Ilceto et al. (1982).

In the low-frequency range typically used in electrical surveys, IP is related to ion diffusion produced by an electric current flowing through the porous medium. The electric current produces ion concentration gradients in areas where interfaces between solid and liquid phases are curved (Dukhin and Shilov, 1974; Fixman, 1980), for instance with pore constrictions. The ion concentration gradients in turn give rise to ion flows, which represent secondary electric currents within the pores (Marshall and Madden, 1959; Fridrikhsberg and Sidorova, 1961). These electric currents give rise to the secondary voltage, which is the manifestation of IP.

Induced polarization can be measured by two different means. In the TD method the voltage decay after excitation by a current pulse is measured, while in the frequency domain method the phase shift between injection current and voltage response is measured. The latter gives rise to a complex resistance (i.e., impedance), or complex resistivity, which generally depends on the measurement frequency used.

We present results of laboratory TD measurements conducted on sieved sands under different degrees of saturation. We discuss how the water content affects resistivity and polarization and propose a conceptual model to explain the experimental data. With regard to the application of the IP method in hydrocarbon contamination studies, we made additional measurements to investigate how the replacement of air by kerosene in unsatu-

Abbreviations: EDL, electrical double layer; IP, induced polarization; QWA, quartz–water–air; QWK, quartz–water–kerosene; TD, time domain.
CONCEPTUAL MODELS

In porous media, solid particles with an electrical surface charge, usually negative, are each surrounded by an oppositely charged ion atmosphere. The effective charge of the ion atmosphere compensates the present surface charge, and in equilibrium between diffusive and electrostatic forces the electrical double layer (EDL) is formed at the interface between solid and liquid phases (Fig. 1a). In the EDL, the average concentration of cations (in case of a negatively charged surface) is larger than that of anions (Fig. 1b).

Induced polarization in ion-conductive media has been theoretically described on the basis of two representations of the media: the granular model (e.g., Lesmes and Morgan, 2001) and the capillary model (e.g., Fridrikhsberg and Sidorova, 1961; Kormiltsev, 1963; Titov et al., 2002). In the granular model, a solid grain surrounded by its own ion atmosphere produces local ion concentration gradients under the influence of electric current (Fig. 1c). The concentration gradients give rise to ion flows, mostly represented by cations in the EDL. These secondary electric currents of diffusive nature are associated with a secondary out-of-phase voltage. A grain surrounded by its own ion atmosphere can be considered as a polarizing cell. The relaxation time ($\tau$) characterizing polarization of this cell is related to the ion diffusion coefficient ($D$) and the grain radius ($R$), $\tau = R^2/2D$ (Schwarz, 1962).

In the capillary model, electric current also produces local ion concentration gradients in areas of variation of the pore radii (Fig. 1d). The concentration gradients give rise to ion flows, mostly represented by cations in throats, which produce a secondary out-of-phase voltage. The sequence of large and narrow pores can be considered as the polarizing cell. The relaxation time ($\tau$) characterizing the polarization of such a cell is related to the ion diffusion coefficient ($D$) and the characteristic length of diffusion ($l$), $\tau = l^2/4D$ (Kormiltsev, 1963). If the large pore is much longer than the narrow pore, $l$ is equal to the length of the narrow pore. The schematic distribution of ion concentration produced by electric current crossing such polarizing cells is shown in Fig. 1e.

The above two general concepts of the pore-scale mechanism of IP seem to be equivalent because both consider the same cause of IP and both account for similar characteristic lengths of diffusion. According to these concepts, IP in fully saturated media is either sensitive to grain-size distribution or to pore-size distribution. For the investigation of unsaturated media we have to choose between the two concepts. For the granular model, however, the introduction of a nonwetting phase seems to be more difficult because a reasonable description would require numerical modeling. In contrast, the capillary model offers an easy way to introduce a nonwetting phase that can be described analytically, at least in a first approximation. Accordingly, in a study of water flow in partially saturated porous media, Tuller et al. (1999) proposed a capillary representation of the liquid phase configuration comprising large and narrow geometrical elements, which are similar to the capillary models used to describe IP. They found this geometrical representation useful to model water flow in pore corners and thin pores.

For the capillary model of unsaturated sand we consider current passageways instead of pores, and we understand narrow passageways as narrow pores and large passageways as large pores. Figure 2 illustrates the concept of the equivalence of the granular and the capillary representations for sands. We propose distinguishing three types of cells on the basis of the degree of saturation: saturated cells (Fig. 2a and 2b), unsaturated cells with large water “rings” in the grain contact area (Fig. 2c and 2d), and unsaturated cells with small water “rings” where water mostly represents a bound film adsorbed on the solid surface (Fig. 2e and 2f).

In the capillary model, IP is related to the variations of ion transparencies along the current passageways. The ion transparency is the contribution of an individual ion type to the electric current along a pore. Fridrikhsberg and Sidorova (1961) derived an expression for the
magnitude of IP ($m$) produced by a sequence of large and narrow pores:

$$m = \frac{4(\Delta t)^2}{l_1 \left[ l_1 + \frac{l_2}{\alpha_t S_2} \right] \left( \frac{S_1}{l_1} + \frac{S_2}{l_2} \right)}$$  \[1\]

where $\Delta t$ is the difference of cation transparencies in the large and narrow pores; $l_1$, $S_1$, $l_2$, and $S_2$ are the lengths and cross-sectional areas of large and narrow pores, respectively; and $\alpha_t$ is the coefficient of efficiency of the narrow pore, which depends on the surface conductivity and represents a ratio of the average capillary conductivity to the bulk solution conductivity.

To simplify the model, we consider the large and narrow passageways as slits with different apertures. Although this represents a two-dimensional approximation of a three-dimensional situation, it provides insight into the general IP characteristics of a corresponding pore sequence. Figure 3a shows the main parameters for a saturated cell: slit half-apertures ($a_1$, $a_2$), the Debye length ($\delta$), and the effective charges of cations and anions ($\alpha^+$, $\alpha^-$) in the EDL. The Debye length represents a characteristic thickness of the diffuse layer, which depends on the water salinity. The higher the water salinity, the narrower is the diffuse layer (see Eq. [3]). For a partially saturated cell (Fig. 3b), $a_2$ denotes the average thickness of the water film in a large pore.

For a binary symmetric electrolyte (neglecting electroosmosis), the surface conductivity is expressed as (Dukhin and Derjaguin, 1974)

$$S_i = 4\delta FC_0 (\cosh \Gamma_1 - 1)$$  \[2\]

where

$$\delta = \frac{1}{zF} \sqrt{\frac{\varepsilon \varepsilon_0 RT}{2C_0}}$$  \[3\]

in which $\delta$ (m) is the Debye length, $z$ is the ion valence, $F = 9.65 \times 10^4$ C mol$^{-1}$ is the Faraday constant, $\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$ is the dielectric constant, $\varepsilon = 80$ is the relative permittivity of the solution, $R = 8.31$ J mol$^{-1}$ K$^{-1}$ is the universal gas constant, $T$ (K) is the absolute
temperature, \( u \) (m\(^2\) V\(^{-1}\) s\(^{-1}\)) is the ion mobility and is assumed to be equal for cations and anions, \( C_0 \) (mol m\(^{-3}\)) is the equilibrium water salinity, \( \Gamma_i = zF\phi_i/(RT) \) is the dimensionless interface potential, and \( \phi_i \) (V) is the potential at the outer side of the Helmholtz layer. Separating Eq. [2] into terms related to anions and cations and adding to each term the contribution of the volume conductivity, we obtain two partial conduc-
tances related to cations \( (S^+) \) and anions \( (S^-) \):

\[
S^+ = zFuC_0(a + 2\delta\alpha^+) \\
S^- = zFuC_0(a + 2\delta\alpha^-)
\]

with

\[
\alpha^+ = [\exp(\Gamma_1) - 1] \\
\alpha^- = [\exp(-\Gamma_1) - 1]
\]

where \( a \) (m) is the slit half-aperture, and \( \alpha^+ \) and \( \alpha^- \) are the effective charges of cations and anions, respectively, in the EDL (Fig. 3). Now we can formulate the ion transparencies \( (t^+, t^-) \) as the partial cation and anion conductances:

\[
t^+ = \frac{S^+}{S^+ + S^-} \\
t^- = \frac{S^-}{S^+ + S^-}
\]

with

\[
t^+ + t^- = 1
\]

Substituting Eq. [4] and [5] into Eq. [8], we obtain for the cation transparency:

\[
t^+(a) = \frac{1}{2} \frac{a + 2\delta\alpha^+}{a + (\alpha^+ + \alpha^-)}
\]

Considering now a sequence of slits with half-apertures \( a_1 \) and \( a_2 \) (Fig. 3a), or a sequence of current passageways with thicknesses \( a_1 \) and \( a_2 \), from Eq. [11] we obtain after some algebra:

\[
\Delta t = t^+(a_2) - t^+(a_1) = \frac{\delta/(a_1)}{1 - a_2/a_1} (a^+ - a^-) = \frac{2\delta(a^+ + a^-)}{a_1^2 + \delta(a^+ + a^-)}
\]

According to Eq. [12], the difference in cation transparency is related to the ratios \( a_2/a_1 \) and \( \delta/a_1 \). The second ratio characterizes the bond of water in the narrow slit to the solid surface. The larger the ratio, the more water is bound since a greater part of the slit volume is occupied by EDL. Calculated graphs of \( \Delta t \) vs. \( a_2/a_1 \) are dis-played in Fig. 4 for different values of \( \delta/a_1 \). The two lower graphs, showing small values of \( \Delta t \), correspond to narrow slits with an aperture 10\(^3\) and 10\(^4\) times larger than the Debye length, respectively. We consider these to be characteristic of saturated cells (Fig. 2a and 2b). In contrast, when the narrow slit has an aperture 10 and 100 times larger than the Debye length (two upper graphs), \( \Delta t \) becomes considerably larger. The two upper graphs may characterize unsaturated cells with a narrow film of bound water on the grain surface (Fig. 2c–2f). All graphs exhibit an asymptotic behavior; that is, while the ratio of slit apertures \( a_2/a_1 \) strongly affects \( \Delta t \) values in the region 3 to 30, \( \Delta t \) becomes nearly constant when this ratio further increases.

**MATERIALS AND METHODS**

**Studied Parameters**

Wait (1982) defined the TD IP characteristic as the increase with time of the overvoltage caused by an infinite unit current step. Komarov (1980) proposed use of the derivative of the corresponding voltage transient with respect to the logarithm of time, the so-called differential polarizability \( (\eta_d) \), for theoretical and experimental evaluation of the IP effect. We find the differential polarizability convenient for analysis of IP because the behavior of \( \eta_d \) vs. time is similar to that of the phase of complex electrical conductivity vs. reciprocal of frequency. For more details concerning \( \eta_d \) the reader is referred to Titov et al. (2002). In our study we used the differential polarizability obtained at different times to evaluate the IP transient behavior.

We also determined the chargeability \( (M) \), which is the typically used measure of the IP effect in TD field surveys (e.g., Telford et al., 1990):

\[
M = \frac{1000}{t_{\text{max}} - t_{\text{min}}} \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{U(t)dt}{U_0} \text{ (mV/V)}
\]

where \( U(t) \) is the voltage between times \( t_{\text{min}} \) and \( t_{\text{max}} \) after the end of the current pulse (here we used a time window defined by \( t_{\text{min}} = 1.5 \) ms and \( t_{\text{max}} = 0.92 \) s), and \( U_0 \) is the voltage averaged over the pulse duration.
We calculated the bulk resistivity ($\rho$) of the sample from the measured voltage $U_0$, the current crossing the sample, and the geometrical factor calculated for the employed holder configuration.

Because the chargeability represents a measure of polarization magnitude relative to conduction magnitude (Keller, 1959; Sharapanov et al., 1974; Lesmes and Frye, 2001; Slater and Lesmes, 2002a) and thus is approximately linearly related to the bulk resistivity, we also calculated the normalized chargeability ($MN$), given as $MN = M\rho$, to separate the effects of conduction and polarization.

**Measurement Setup**

As the sample holder, a PVC tube (15 mm in external diameter, 12 mm in internal diameter, and 100 mm long), covered at both ends by cellophane porous membranes, was used. The tube ends were squeezed between two copper electrodes used for current injection. Two Cu/CuSO$_4$ nonpolarizing electrodes were symmetrically placed on the tube, in direct contact with the sample surface, to measure the voltage across the sample. To prevent leakage of electrolyte from the electrodes into the sample, the copper sulfate was actually prepared with gelatin. All measurements were made in a Faraday cage to reduce electromagnetic noise.

Rectangular current pulses of opposite polarity were injected into the sample using a laboratory transmitter, where pulses and pauses of the same duration were used (50% duty cycle). The employed transmitter is capable of switching off the current within several microseconds. For the voltage measurements, the STROB-M instrument (Shereshevsky et al., 1999), a multifunctional measuring device developed at the Russian Institute of Exploration Geophysics (VIRG–Rudgeofizika), was used in conjunction with a preamplifier with 90 M$\Omega$ input resistance. The dynamic range of the instrument is 160 dB. Measurements are controlled by a built-in microprocessor. Receiver and transmitter were synchronized using a quartz timer.

As usual in the TD technique, the voltage decay, $U(t)$, was sampled in a sequence of time windows during current off-time. We here used 50 to 200 different time windows. The value recorded for time window $j$ is given by

$$\eta_j = \frac{100}{(t_{k+1} - t_k)U_i} \int_{t_k}^{t_{k+1}} U(t)dt \ (\%)$$

where $t_k$ and $t_{k+1}$ are the integration limits, and $U_i$ is the average of the measured voltage during current on-time.

More details on the measurement setup and procedure were previously described in Titov et al. (2002).

**Sample Preparation**

Sieved commercial quartz sand of 0.1- to 0.25-mm grain size was cleaned from clay and dust particles by repeated washing. Sand particles were of isometric form. The quartz mineral became nonpolarizing due to evaporation of water. The electrical contact with the sample surface, to measure the voltage across the sample. To prevent leakage of electrolyte from the electrodes into the sample, the copper sulfate was actually prepared with gelatin. All measurements were made in a Faraday cage to reduce electromagnetic noise.

**RESULTS**

**Time Dependence of Differential Polarizability**

Examples of observed differential polarizability vs. time are shown in Fig. 5 on a double logarithmic plot. For the measured time range the differential polarizability graphs show relatively weak time dependency. The differential polarizability slightly decreases with increasing time for all values of water content and for both QWA and QWK samples. Similar behavior of the phase sensitivities of complex electrical conductivity vs. frequency for saturated soils (Vinegar and Waxman, 1984), for soils contaminated by organic and inorganic substances (Börner et al., 1993; Börner et al., 1996), and for unsaturated unsaturated sediments (Ulrich and Slater, 2004) were previously reported.

**Chargeability, Resistivity, and Normalized Chargeability**

The results of the measurements on the QWA and QWK samples are displayed as plots of chargeability, resistivity, and normalized chargeability vs. volumetric water content ($W$) on double logarithmic plots (Fig. 6, 7, 8). As for the differential polarizability, the chargeability of the QWA and QWK samples shows a similar behavior (Fig. 6). The chargeability was found to lie in the range of 2.4 to 32.3 mV V$^{-1}$, depending on the saturation level. The chargeability shows a maximum at $W = 0.08$, which divides the plot into two regions.
The maximum type behavior is in accordance with data reported in Komarov (1980) and Iliceto et al. (1982). The resistivity of the QWA and QWK samples (Fig. 7) shows a similar behavior to that observed for chargeability and differential polarizability. The resistivity varies from 290 to 3600 $\Omega$ m depending on the saturation degree. The plot can be also split into two regions, each characterized by a power-law relationship. The power-law exponent calculated according to Archie’s Law (1942) was found to be 1.3 for $W > 0.08$ and 0.21 for $W < 0.08$. Note that the limit between the two regions (hereafter referred to as Region 1 and Region 2) determined from the resistivity measurements coincides with the water content value where maximum chargeability is observed.

Figure 8 shows the normalized chargeability of the QWA and QWK samples. For both sample types the normalized chargeability shows a trend to increase with increasing water content. Accordingly, the overall behavior can be roughly approximated by a power-law relationship, with slightly different exponents for the QWA (0.53) and QWK (0.36) samples.
**DISCUSSION**

We measured IP on 0.1- to 0.25-mm sand samples. To explain the chargeability behavior, let us assume that the samples are composed of spherical particles of the same size with a packing from loose to dense (Fig. 2). If sands are fully saturated (Fig. 2a and 2b), there are two limiting cases for the form of polarizing cells. The particle packing determines these forms: for the loose packing the section of inter-grain-filling water is of curvilinear rhomb type; for the compact packing the section is of curvilinear triangle type. As shown in Fig. 2, these cells can be represented by a sequence of one large pore and three or four narrow pores, depending on the packing type. The polarization of these saturated cells is low because they are electrically shunted. Most current density lines follow the way of minimum resistance in the bulk solution, and the part of current flowing through the polarizable part of the cells near the grain contact becomes small. Moreover the effective diameter of the narrow pore seems to be much larger than the Debye length; consequently, the difference in ion transparency should be small (Fig. 4, lower graphs).

It is only a rough approximation to assume that, in the course of evaporative drainage, cells lose the water simultaneously and uniformly. Realistically, the largest cells should drain first, and they should release the inter-grain-filling water first. Because of surface tension the water also moves from cell centers into areas of grain contacts that produce unsaturated cells, as shown in Fig. 2c and 2d. Compared with the saturated cells, these unsaturated cells should polarize differently. The bound water film on the grains corresponds to the narrow pore. Areas of grain contact filled with water, and thus forming “rings,” can be considered as the large pores. The polarization of unsaturated cells should be higher than that of saturated cells because the variation in the effective pore radii becomes larger, and therefore also the variation in the ion transparency. The bound water film should roughly correspond to narrow pores 10 to 100 times larger than the Debye length (Fig. 4, upper graphs), which produces high values of $\Delta \tau$. Moreover, in contrast to saturated cells, unsaturated cells cannot be electrically shunted by current flowing through the bulk solution. In the course of the drying procedure the number of unsaturated cells increases, and correspondingly also the polarization of the whole sample (Fig. 6). This increase of polarization, however, is limited by the total number of polarizing cells.

We believe that the mechanism described above gives rise to the observed maximum of chargeability, and that the maximum will be reached when all saturated cells are transformed into unsaturated cells. It may be noted though, that in Region 1 chargeability and resistivity decrease similarly with increasing water content (Fig. 6 and 7). Therefore the variation of chargeability, considered as a capacitance/conductance ratio, may be explained in this region also by the variation of resistivity.

The further decrease of the grain-contact water volume in the unsaturated cells in the course of drainage causes a reduction of both the diameter and thickness of the grain-contact water rings (Fig. 2e and 2f). This in turn can result in a decrease of the variation of effective pore diameters and, consequently, a decrease of the difference in ion transparency (Fig. 4). That is, the entire water in the pore space tends to transform into bond water. Therefore, the polarization of the cells decreases, and similarly, chargeability of the entire sample decreases, with further decrease of the saturation level (Fig. 6).

The resistivity shows the typical dependence on water content (e.g., Komarov, 1980). At high saturation levels (Region 1), $\rho(W)$ shows a power-law relationship with a typical value of the power-law exponent (1.3) according to Archie’s Law (1942) (Fig. 7). At moderate saturation degrees (Region 2), the power-law exponent becomes considerably smaller (0.21). This behavior is in agreement with data from Taylor and Barker (2002), except that we did not reach the third region of very low saturation where the resistivity increases at an increasing rate with decreasing saturation. The moderate saturation level corresponds to the transition between high and low saturations, which corresponds to the region of critical saturation (Knight and Nur, 1987). In contrast to our data, Ulrich and Slater (2004) approximated the dependence of real conductivity on saturation by a single power-law relationship. However, for two samples in their study (corresponding to a drainage cycle), a decrease of the power-law exponent with decreasing saturation is actually visible in the data (Fig. 6b and 6c in Ulrich and Slater, 2004).

We believe that the weak increase of resistivity with decreasing water content below the critical saturation is related to electrical conduction through water films surrounding the solid grains (i.e., the narrow passage ways). The further decrease of water content (Region 2) in the course of drying mainly affects the water rings,
which make up only a small contribution to the sample resistivity. In this region we found the chargeability to not be proportional to resistivity.

In the previous section we used power-law fits to describe the overall trend of the normalized chargeability vs. water content relationship (Fig. 8). However, the goodness-of-fit is poor (coefficient of determination is 0.58 for QWA and 0.49 for QWK samples). Although the spreading of data points is large, we believe that the normalized chargeability actually increases with increasing water content up to the critical saturation and then becomes constant (solid curve in Fig. 8). Such behavior would be in accordance with the proportionality of resistivity and chargeability in Region 1 and the disappearance of this proportionality in Region 2. We also note that this supposed behavior of normalized chargeability seems to be confirmed by part of the data presented in Ulrich and Slater (2004; see their Fig. 6a).

The presented data do not show large differences in the electrical properties for QWA and QWK samples. In our experiments water represented the wetting phase relative to the quartz grains. We therefore believe that kerosene played an inert role and did not produce additional polarizing cells and charged interfaces.

CONCLUSIONS

As a result of our experiments we detected the point of critical water saturation from both resistivity and chargeability measurements. According to our conceptual model, this critical saturation corresponds to the change of the pore-water geometry from bulk water to an adsorbed water film. In terms of electrical properties the critical saturation can be related to the disappearance of the linear relationship between chargeability and resistivity for higher saturation degrees. The resistivity power-law exponent decreases at the critical saturation. At the field scale, however, saturation levels below the critical saturation do not frequently occur. Therefore, for most investigations of the vadose zone we can virtually consider the chargeability of sands as a decreasing function of water content. Knowing this relationship, however, is a prerequisite for exploiting the potential of the IP method proved for saturated environments, for instance for improved lithological characterization or estimation of hydraulic permeability, also in vadose zone studies.

The replacement of air by kerosene did not produce significant changes in both resistivity and chargeability distributions. Therefore we believe that for such simple system as investigated here, kerosene plays an inert role and does not produce additional charged interfaces. However, the influence of nonaqueous phase liquids on the IP response of partly water-saturated porous media will generally depend on the mineralogy of the solid matrix and the chemistry of the different phases filling the pore space. Therefore, application of the IP method in hydrocarbon contamination studies will probably always require some sort of site-specific calibration.

We presented a simple, analytical capillary “slit” (i.e., two-dimensional) model to quantify the polarization of saturated and unsaturated sequences of narrow and large pores in terms of resulting differences in cation transparency (for negatively charged surfaces). Our future work will include the extension of this approach to more realistic pore space geometries on the basis of numerical modeling. Therefore, the polarization of multiphase porous systems can be theoretically predicted with higher accuracy, which is expected to contribute to an improved understanding of IP signatures in vadose zone studies.

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