Improving Petrophysical Interpretation With Wide-Band Electromagnetic Measurements

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Summary

Because of their sensitivity to ionic content and surface texture, wide-band electromagnetic (WBEM) measurements of saturated rocks exhibit frequency dispersions of electrical conductivity and dielectric constant that are influenced by a variety of petrophysical properties. Factors as diverse as fluid saturation, porosity, pore morphology, thin wetting films, and electrically charged clays affect the WBEM response of rocks. Traditional dielectric mixing laws fail to quantitatively and practically integrate these factors to quantify petrophysical information from WBEM measurements. This paper advances a numerical proof of concept for useful petrophysical WBEM measurements. A comprehensive pore-scale numerical framework is introduced that incorporates explicit geometrical distributions of grains, fluids, and clays constructed from core pictures, and that reproduces the WBEM saturated-rock response on the entire kHz-GHz frequency range. WBEM measurements are verified to be primarily sensitive (a) in the kHz range to clay amounts and wettability; (b) in the MHz range to pore morphology (i.e., connectivity and eccentricity), fluid distribution, salinity, and clay presence; and (c) in the GHz range to porosity, pore morphology, and fluid saturation. Our simulations emphasize the need to measure dielectric dispersion in the entire frequency spectrum to capture the complexity of the different polarization effects.

In particular, it is crucial to accurately quantify the phenomena occurring in the MHz range where pore connectivity effects are confounded with clay polarization and pore/grain shape effects usually considered in dielectric phenomena. These different sensitivities suggest a strong complementarity between WBEM and NMR measurements for improved assessments of pore-size distribution, hydraulic permeability, wettability, and fluid saturation.

Introduction

A number of experimental and theoretical studies suggest the measurable sensitivity of WBEM to various petrophysical factors, including porosity, brine salinity, fluid saturation and wettability, clay content, surface roughness, and even pore surface-to-volume ratio. Given the complexity of the different phenomena under consideration, practical models are designed to fit measured dielectric dispersions to ad-hoc models whose parameters are marginally supported by quantitative petrophysical concepts.

Therefore, to assess whether accurate and reliable petrophysical interpretations are possible with WBEM measurements requires an analysis that (a) incorporates pore structure, pore connectivity, multiphase saturation and electrochemical effects; and (b) quantifies the contributions of each factor in the measured WBEM dispersions. However, extracting explicit petrophysical information from WBEM responses is a difficult task. Myers (1991), for instance, illustrated the non-uniqueness of WBEM measurements when a decrease of water saturation, porosity, or brine salinity yielded similar responses. Recent advances in NMR logging and interpretation (Freedman et al. 1990) can eliminate some of these ambiguities with adequate experimental conditions, and if rock wettability is known. Conversely, WBEM measurements could provide independent wettability assessment in the cases where NMR measurements alone reach their limits of sensitivity [for instance, the impact of fluid saturation history on wettability determination was studied by Toumelin et al. (2006)]. Likewise, the interpretation of NMR measurements can be biased by unaccounted rock morphology (Ramakrishnan et al. 1999) or by internal magnetic fields in shaly or iron-rich sands (Zhang et al. 2003), whereas WBEM measurements provide independent information on overall rock morphology. It is therefore timely to consider integrating both technologies for improving petrophysical analysis.

The objectives of this paper are twofold: (1) Review existing results on the extraction of petrophysical information from rock WBEM measurements, and (2) establish a proof of concept for the necessity to integrate electromagnetic measurements on the wide-frequency band from the kHz range to the GHz range, and study how WBEM techniques may yield petrophysical information unavailable from other in-situ measurements. To reach the second objective, we introduce a generalized pore-scale simulation framework that allows incorporating arbitrary rock morphology and multiphase fluid distribution.

Review of Wide-Band Electromagnetic Behavior of Saturated Rocks

Origins of Wide-Band Dispersion. As summarized by Sen and Chew (1983), two main phenomena influence the dispersion of conductivity and dielectric permittivity in saturated rocks at frequencies in the kHz-GHz range. The first effect is caused by the Maxwell-Wagner polarization in the MHz range, where various pore-geometrical effects create sigmoid-type dispersions of conductivity and dielectric constant reviewed by Toumelin and Torres-Verdín (2007). The Maxwell-Wagner effect arises in the presence of bimodal lossy and dielectric compounds (such as brine/rock systems) where no surface zeta potentials (such as those encountered at clay surfaces) are present. Ions concentrate along the edges of elongated pores and create local capacitors in the pore structure whose effective capacitance and conductivity is frequency-dependent. Such a behavior solely depends on structural aspect ratios regardless of size.

The second main electromagnetic phenomenon appearing in rocks consists of substantial enhancements of the dielectric constant as frequency decreases below the MHz range. In the early 1980s, when WBEM studies for petrophysical applications were in vogue, this low-frequency enhancement was regarded as measurement noise and spurious electrode-polarization effects. Subsequent quantification of electrode polarization exhibited strong negative power laws of dielectric constant at kHz-range frequencies. This power-law effect has no apparent connection with Maxwell-Wagner polarization and is caused by the presence of static electric charges at the interface between rocks (in particularly clay minerals) and brine. The next sections of this paper review several models proposed to quantify such electrochemical effects, although none of them entirely captures the complexity of the phenomenon.

To understand the origin of low-frequency enhancement of the measured dielectric constant, let us recall fundamental postulates of electromagnetism: when an electric field \( \mathbf{E} \) of radian frequency \( \omega \) illuminates a lossy material of conductivity \( \sigma(\omega) \) and dielectric
permittivity $\varepsilon^i(\omega)$, it generates a current density $\mathbf{J} = \sigma^i \mathbf{E}$ and an electric displacement field $\mathbf{D} = \varepsilon^i \mathbf{E}$ through that material. In general, both $\sigma^r$ and $\varepsilon^i$ are complex numbers and can be written in terms of their real and imaginary parts as $\sigma^r = \sigma^r - i\sigma^i$ and $\varepsilon^i = \varepsilon^i + i\varepsilon^\prime$, where $i^2 = -1$ (the minus sign in $\sigma^i$ is consistent with the expressions that follow). As in the case of any causal physical mechanism, $\varepsilon^i$ and $\varepsilon^\prime$ are coupled through the Kramers-Kronig relationship (Landau and Lifschitz 1960):

$$\varepsilon^i(\omega) = 1 + \frac{2}{\pi} \int_0^\infty \frac{\omega_0 \varepsilon^\prime(\omega_0)}{\omega_0^2 - \omega^2} d\omega_0.$$

The latter relationship is generally used to verify the compatibility of experimental measurements with a complex expression of the dielectric constant (Milton et al. 1997). A similar relation holds between $\sigma^r$ and $\sigma^i$. With the $\varepsilon^i$ ($\varepsilon^\prime$) convention for the time-harmonic electric field of radian frequency $\omega$, the total density current $\mathbf{J}$ enforced through the material is given by

$$\mathbf{J} = \mathcal{J} + i \frac{\partial \mathbf{D}}{\partial t} = (\sigma^r - i\omega \varepsilon^i) \mathbf{E} = \sigma^0 \mathbf{E},$$

where $\sigma^0$ is the total effective complex conductivity of the material. The previously described total current density can also be expressed in terms of the real effective conductivity $\sigma_{eff}$ and permittivity $\varepsilon_{eff}$:

$$\mathbf{J} = (\sigma_{eff} - i\omega \varepsilon_{eff}) \mathbf{E},$$

so that

$$\sigma_{eff} = \Re(\sigma^r - i\omega \varepsilon^i) = \sigma^r + \omega \varepsilon^\prime$$

and

$$\varepsilon_{eff} = \Re(\varepsilon^i + i\sigma^r / \omega) = \varepsilon^i + \sigma^r / \omega,$$

and the measured dielectric constant (or relative dielectric permittivity) $\varepsilon_{eff}$, is equal to $\varepsilon_{eff}$ divided by the vacuum permittivity $\varepsilon_0 = 8.854 \times 10^{-12}$ Farad/m. When static charges are negligible at the rock/fluid interface, the current $\mathcal{J}$ and displacement $\mathbf{D}$ are in phase with $\mathbf{E}$, and both $\sigma^r$ and $\varepsilon^i$ remain real. However, if the surface of an obstacle to the propagation of $\mathbf{E}$ is electrically charged, then an ionic double layer develops at that interface. Complex values of $\sigma^r$ and $\varepsilon^i$ ensue, depending on the size of the obstacle, which explains positive out-of-phase conductivity $\sigma^r$ and from Eq. 4b implies an enhancement of $\varepsilon_{eff}$ at low frequencies.

**Power-Laws, Double-Layers, and Fractal Geometries.** If $\sigma^r$ varies smoothly at low values of frequency, a power-law of exponent (–1) follows from Eq. 4b between dielectric constant and frequency. The power law becomes a linear relationship between $\varepsilon$ and frequency on a bilogarithmic scale. This assumption is very intuitive. Lima and Sharma 1992; Lesmes and Frye 2001). Computation of the EDL potentials proceeds from the combined solution of the electrical and diffusion potentials with boundary conditions specific to the EDL (DeLacy and White 1981; Chew and Sen 1982; Cao et al. 1994).

Thevanayagam (1997) proposed an approach that posits the fractal nature of the observed power-laws between $\varepsilon_{eff}$ and $\omega$. Such a model is intended to capture the effective electrical properties at each rock scale. Brine chemistry and electrical properties are assumed to vary at each scale (bound fluid, clay-bound double layer, free fluid). Starting from the smallest scale, effective electrical properties are computed at each scale from (a) the brine properties at that scale and (b) the effective properties of the next smaller scale through nested mixing-laws. Thevanayagam recognized the necessity of incorporating EDL effects at the smallest scale; however, he used arbitrary values of brine conductivity and dielectric constant at each scale. In essence, Thevanayagam’s (1987) approach complements Sen et al.’s (1981) self-similar models using stepwise iterations of compounds whose electrical properties vary from scale to scale, instead of infinitesimal dilution of compounds that remain self-similar at all scales.

Rather than using arbitrary values of brine conductivities at each fractal level, Lima and Sharma (1992) incorporated fundamental electrochemical double-layer calculations around spherical clay grains based on Fixman’s (1980) model to quantify the effective conductivity and dielectric constant for clay zones. These values were then upscaled with Sen et al.’s (1981) self-similar, infinite-dilution mixing law by regarding brine as the host of the mixture, rock as spherical grain inclusions, and clay as either spherical pellets or as shells coating the rock grains. In Thevanayagam’s model, the latter approach constitutes a two-step fractal process with a different mixing law. Lima and Sharma (1992), however, made no mention of power-law effects in their work. The EDL low-frequency dielectric enhancement takes the form of a sigmoid which converges at frequencies lower than 1 kHz to high values of dielectric constant, depending on clay geometry and surface charge. It can be argued that, if the sigmoid extends along several decades of frequency and if it is truncated before reaching its low-frequency asymptote, then that dielectric constant trend behaves in similar fashion to a power law. This assumption is very plausible, considering the measurements of Lesmes and Frye (2001) of saturated Berea samples: as $\omega$ decreased from 1 kHz and 0.1 Hz, they measured an increase of $\varepsilon_{eff}$ that exactly followed a power law with exponent (–1), while below 0.01 Hz, $\varepsilon_{eff}$ converged to static values in a sigmoid fashion. Such a behavior suggests that observed power laws may be formed by truncated high-amplitude sigmoids which converge outside the measurement range. This result supports the assumption of an EDL origin for the so-called dielectric low-frequency power law.
**WBEM for Quantifying Petrophysical Properties.** Previous studies examined the influence of specific petrophysical properties of interest on WBEM measurements, including clay presence, multiphase saturation, rock wettability, and pore size; however, such studies failed to quantify the influence of the same petrophysical properties on WBEM measurements. This section summarizes results from several previous studies and emphasizes their practical limitations.

Because electrochemical and geometrical phenomena affect the dielectric response of saturated rocks, Myers (1991, 1996) considered the dispersion of dielectric constant measured in the 20–200 MHz range as the sum of (1) a clay term, where clay cation exchange capacity appears, (2) a geometric term, and (3) a vuggy porosity term. For that frequency range, Myers showed that terms (1) and (2) are sufficient to fit the dielectric dispersion of sandstones saturated with two fluid phases, while terms (2) and (3) are appropriate to fit the dielectric measurements of single-phase heterogeneous carbonates. The fitting parameters, however, have no explicit petrophysical significance and are yet to be quantitatively related to rock morphology and macroscopic petrophysical properties, such as hydraulic permeability (M. Myers 1996).

Bona et al. (1998) used a similar superposition concept to fit dielectric rock measurements performed under partial-saturation conditions with (1) a power-law term added to (2) a Maxwell-Wagner sigmoid term, but on a broader 100 Hz–100 MHz frequency range. As shown in Fig. 1, Bona et al.’s (1998) measurements of water-wet (WW) Berea samples clearly exhibit power-law behavior below 1 MHz. By contrast, measurements performed on samples treated to be oil-wet (OW) at similar values of water saturation reach sigmoid-like asymptotic behavior at values of dielectric constant much smaller than for the case of water-wet samples. Although Bona et al. (1998) did not advance quantitative methods to calculate fluid saturation under different wettability conditions, they did emphasize the potential of WBEM measurements in the kHz-MHz range to characterize rock wettability with no need for prohibitively long Amott wettability tests.

The complex refractive index method (CRIM) is known to quantify partial saturations reasonably well in the GHz range; uncertainties associated with this method are lower than those of low-frequency Archie-based conductivity calculations. However, CRIM and similar models do not account for heterogeneous carbonate pore structure and are inaccurate to quantify fluid saturation in these conditions (M. Myers 1996). CRIM also serves as a starting point for Seleznev et al. (2006) to derive a mixing law that corrects for the same geometrical parameters and that fits dielectric measurements of geometrally challenging carbonate rocks, even though their range of application was limited to 100 MHz–1 GHz. Such ongoing efforts suggest that more quantitative morphologic details can be incorporated in the interpretation of WBEM measurements to improve the estimation of petrophysical properties. Beyond their observation of power-law behaviors in the sub-MHz range, Knight and Nur (1987) also observed a correlation between measured dielectric constant and rock surface-to-volume ratio for partially saturated rocks in the range of 60 kHz–4 MHz. However, their results lend themselves to ambiguous interpretation. The largest dispersions of dielectric constant (correlated with the highest surface-to-volume ratios) also happened to be measured in tight samples with less than 1% porosity, and substantial clay content. Furthermore, these measurements were made in deionized water, which displaces the frequency range of pore geometrical effects below 1 MHz. Eventually, the exact origin of the correlation between dielectric constant and surface-to-volume ratio is difficult to determine.

Finally, Olhoeft’s (1985) comprehensive review on mHz–MHz wide-band electrical phenomena in rocks cites oxidation-reduction reactions as a common brine-rock interface phenomenon. When surface reactions take place in a diffusion-limited (by opposition to kinetics-limited) fashion, the electrical response of a compound generally depends on the size of metallic bodies in the mixture. In rocks, these bodies can consist of pores coated with metallic deposits, or of metallic inclusions embedded in the rock matrix. To illustrate this argument, Olhoeft noted that suspensions of 1-mm metallic particles exhibit a 10-Hz relaxation mode in their dielectric spectrum, while suspensions of 10-µm particles exhibit a 100-kHz mode. An adaptation of double-layer models would provide similar results to a macroscopic model that incorporates both kinetics- and diffusion-limited reactions in saturated rocks, but it would still need to be proposed. The possibility of inferring pore-size information from WBEM measurements becomes very attractive to validate NMR pore-size estimates.

All these approaches therefore attempt to extract petrophysical information from WBEM measurements, but remain qualitative at best for not individualizing the contributions of the processes simultaneously occurring in rocks. In order to study the interactions between the different phenomena, we develop a pore-scale model generalized from that of Toumelin and Torres-Verdin (2007) for quantifying Maxwell-Wagner geometrical polarization effects.

**Development of a Generalized 2D WBEM Numerical Framework.**

**Geometrical Pore-Scale Framework.** Toumelin and Torres-Verdin (2007) developed a numerical procedure to study the limits of dielectric mixing laws to characterize pore structures in the absence of clays and saturated exclusively with brine, in agreement with both Maxwell’s equations and Kramers-Kronig relations. That model incorporates interfacial WBEM effects arising from the accumulation of charges at the boundaries between brine and grains and is based on the following procedure:

1. Build disc-shape binary pore maps where pixels represent either grain or brine in a binary fashion.
2. Assign each such pixel with DC conductivity and dielectric constant of the modeled medium (grain or brine).
3. For each given frequency between 10 kHz and 1 GHz, numerically solve Maxwell’s equations with the method of moments to compute the internal electric field and electric current within each pixel of the pore map when subject to transverse-magnetic excitation. Fig. 2 illustrates the distribution of internal currents obtained for different angles of incidence of the exciting wave.
4. Use the close-form analytical solution of electromagnetic scattering within a disc to determine the homogeneous DC conductivity and dielectric constant of a disc that minimize the discrepancy between the electric fields and the induced currents calculated within the pore map and within the disc.

Instead of assigning arbitrary pore shapes to the model, we extract the pore maps from rock digital pictures at different rates of magnification. Fig. 3 shows an example of a digitized picture of a 24%-porosity sample, which is binarized and truncated into an appropriate disc-shape pore map (white and blue pixels). This new rock model exhibits explicit distributions of pores and throats larger than the pixel resolution of the rock image. Extending the model in three dimensions on the binary skeleton of high-resolution rock tomography (Arns et al. 2005) should shed additional insight to geometrical polarization effects in complex rock structures.

**Inclusion of Clays.** Next, we incorporate clays in the rock skeleton by arbitrarily distributing clay pixels throughout the pore map, as illustrated in Fig. 3 (magenta pixels) where clay amounts to 3% of the rock volume. At each considered frequency, instead of grain or brine properties, clay pixels are assigned effective electrical properties following Lima and Sharma’s (1992) treatment of an ionic double-layer around a spheroid clay grain (see Appendix A). If the grains are larger than the pixel resolution, then several pixels form one clay-coated grain and each pixel is assigned the same electrical properties. On the other hand, if grains are smaller than pixel resolution, then one pixel represents a group of clay-coated grains that span a surface equal to that pixel. This numerical framework therefore up scales the response of the clay-bearing rock at the pixel level regardless of mixing laws.

**Inclusion of Immiscible Fluids and Wettability.** The 2D pore map is assimilated to a cross section of 3D rock geometry, where multiphase saturations can also be distributed in the pore map as they would appear on a 2D cross-section of a 3D saturated rock.
Fluid distributions described in the pore maps that follow are designed to resemble a cross-section through a rock where fluid displacement takes place in three dimensions. Fig. 4 illustrates this concept and emphasizes the pixel-based structure of such a 2D model for a water-wet rock. In this model, a layer of one to two water pixels is preserved at the rock surface to enforce a strong electrical contrast at rock/water and oil/water interfaces, while oil is assumed to invade the pore structure starting from the outside of the disc.

Simulating wettability effects on WBEM measurements is a key objective to this numerical exercise. As shown in Fig. 1, large enhancements of the dielectric constant are measured at low frequencies in WW rocks with low values of water saturation. Continuity between thin brine films in the WW pores prevents energy storage within the films; therefore, the strong enhancement of dielectric constant at low values of frequency in WW rocks is primarily caused by EDL effects. In strongly OW conditions, these EDLs are inhibited because no cations are in contact with the charged clay surface. The activation of EDLs in the magenta pixels of Figs. 3 and 4 characterizes the water wettability of the rock model depicted in Fig. 3. These principles are used to construct WW and OW multiphase pore models.

Assessing Rock Morphology From Single-Phase WBEM Measurements

We now distribute the wide-band effective clay properties calculated in Appendix A into the clay pixels of Fig. 3 pore maps. Pixels labeled as “clay” in that pore map are successively assigned the electrical properties of (a) grain, (b) 0.1 S/m brine, and (c) 100-nm clay in 0.1 S/m brine background. Fig. 5 shows the corresponding dielectric dispersions for the three cases and emphasizes the influence of rock texture in the MHz range. In that figure, conductive paths created by brine in Case B decrease the ability of the rock model to store energy compared to Case A. The amplitude of the dielectric dispersion at low values of frequency is lower in Case B than in Case A. In Case C, where the inclusion of 3% dispersed clay is simulated over the entire frequency range, the dielectric dispersion is similar to that simulated for Case B at 10 MHz, but diverges exponentially below this frequency. All Cases A through C are associated with similar dielectric behavior above 10 MHz.

If we vary brine salinity in the clay-free configuration (Case A), then the simulated dielectric response (Fig. 6) exhibits the expected scaling with brine conductivity (Kenyon 1984; Toumelin and Torres-Verdín 2007). On the other hand, if brine salinity is varied in the 3%-clay rock model, then the scaling of dielectric constant with conductivity disappears and the dispersion shown in Fig. 7 ensues. We also note that high brine salinity preserves rock texture information in the MHz range while double-layer phenomena are prominent at lower values of frequency. By contrast, low brine salinities induce a dielectric response where both effects overlap in an undistinguishable manner. Such a numerical approach is therefore necessary to quantify—and ultimately invert for—rock morphological effects confounded with clay polarization.
This observation appears particularly useful when other petrophysical methods fail to properly quantify pore structure and connectivity. For example, the low surface relaxation of carbonate rocks prevents the NMR characterization of certain bimodal porosities. Appendix B describes the construction of a model for such rocks, where the simulated WBEM response depart greatly from the usual sigmoidal response of sedimentary rocks (Fig. 1) for exhibiting flat dispersions of both conductivity and dielectric constant across the entire kHz–GHz frequency range. Toumelin and Torres-Verdú (2007) also demonstrated that connectivity between pores of equal eccentricity affect both electrical dispersions, as recapitulated in Figs. 8 and 9. The different inflection behavior of the dielectric spectra simulated for pore maps D1 and D2 also suggests a possible dependence of dispersion-inflection frequencies upon the degree of pore isolation, as the internal electric currents distribute differently in the pore space when percolation is reached across the entire pore space. It is therefore important to quantify the contribution of pore geometry to the WBEM response in that frequency range.

Assessing Wettability and Fluid Saturation

Previous simulation work (Toumelin et al. 2006) emphasized the conceptual ambiguity of wettability interpretation using 2D NMR techniques for given conditions of oil viscosity and saturation history. We now conceptually confirm that WBEM techniques can circumvent these ambiguities in rocks with minimal amounts of clay. As mentioned earlier, EDL effects fully develop in water-wet cases, possibly enhanced by fractal surface roughness, while they are inhibited in OW cases. Following the method developed above, we populate the pore map of Figs. 3 and 4 with wetting and nonwetting fluid pixels to describe the progressive drainage of a WW rock by oil (Fig. 10). By contrast, Fig. 11 models the progressive drainage of an OW rock by water.

Fig. 12 shows the wide-band dispersions of dielectric constant simulated for all the pore maps described in Figs. 10 and 11, for two values of brine conductivity, $\sigma_w=0.1$ and $1 \text{ S/m}$. Each panel of Fig. 12 groups the simulation results by brine conductivity or wettability type. Several remarks stem from this comparison. First, the scaling of the dielectric constant with conductivity remains present in the EDL-free OW cases regardless of fluid saturation. This scaling disappears in the WW cases, which makes saturation estimates nontrivial. Second, each panel of Fig. 12 shows that the hierarchy of the dielectric dispersion curves with respect to water saturation or brine conductivity is enforced in the GHz range regardless of the competition between geometrical and electrochemical effects at lower values of frequency. The values of dielectric constant simulated for low values of water saturation are smaller than those simulated for high values of water saturation, which honors CRIM results. Likewise, the dielectric dispersion sigmoids of the bottom right panel of Fig. 12 exhibit a shift to the left (lower frequencies for same values of dielectric constant) when conduc-
tivity decreases. Such a behavior is consistent with the notion of conductivity scaling introduced by Kenyon (1984). However, when frequency decreases in the MHz range where EDL effects become important, this curve hierarchy disappears as dispersion curves intersect and change order.

Simulation results described in Fig. 12 exhibit a low-frequency power-law behavior for the dielectric constant of WW rock models. This power-law behavior is remarkable given the small amount of clay pixels (as low as 3% of the total number of rock pixels) and the small value of surface charge ($\sigma = 11 \mu C/cm^2$) considered in the model. Simulation results agree very well with the measured trends of dielectric constant of WW rocks (Fig. 1). Dielectric dispersions obtained from simulations and experiments exhibit (a) low-frequency convergence in OW cases, (b) low-frequency exponential behavior in WW cases, and (c) dual inflection in the MHz-range in some WW cases. Quantitatively, the absolute values of simulated and measured dielectric constants differ by a factor approximately equal to 20. It is likely that larger values of clay surface charge, clay amount, or a more accurate double-layer model, would reduce this discrepancy. However, the relative wide-band behavior of WW dielectric dispersions is identical for both simulations and measurements. In the 1-MHz range, between the two inflection points of the dielectric dispersion curves, both simulations and measurements yield values of dielectric constant equal to 10 times the value of their respective high-frequency asymptotes. In the 10-kHz range, this enhancement factor becomes approximately equal to 30 for both simulations and measurements.

It is also important to note that electrical measurements in general, and water-wet dielectric low-frequency enhancements in particular, are insensitive to oil viscosity. The only assumption formulated on the saturating oil was to assign it a dielectric constant equal to 2 over the entire kHz–GHz frequency spectrum.

Conclusions

Fractal and double-layer concepts were reconciled to explain the low-frequency dielectric behavior of saturated rocks. A generalized 2D pore-scale electromagnetic model ensued, which incorporates the simultaneous dielectric effects of pore geometry, charged clays and minerals, wettability, and fluid saturations. Despite quantitative limitations owing to the spatial resolution of the pore map and the double-layer model, we obtained very encouraging results when modeling explicit rock WBEM measurements independently from mixing rules or fitting parameters:

First, WBEM measurements are theoretically proven to be sensitive to both pore shape and pore connectivity. The flat dielectric dispersion simulated in the diffusively-coupled microporous rock model is an example where WBEM becomes a viable technique to characterize complex rocks where classic NMR interpretation fails to correctly predict petrophysical properties. One can envision a generalization of WBEM measurements to diagnose the presence of complex pore inhomogeneity, including micritized, oolithic, or vuggy carbonate rocks. However, WBEM measurements have no theoretical sensitivity to pore size except when EDL develops as pore-surface coating.

Second, simulations reproduced WBEM measurements fairly well for partially saturated rocks. They characterized wettability trends in clay-bearing sandstones, even for clay concentrations as low as 3%, and regardless of oil grade. Wide-band EM techniques
can therefore help to determine in-situ sandstone wettability and complement NMR wettability estimates which are ambiguous when oil viscosity exceeds a few cp.

A comprehensive WBEM model needs to be reliable in the presence of charged clay to perform quantitative petrophysical assessments. Clays usually form dia- or para-magnetic impurities causing internal magnetic fields which make NMR interpretation unreliable for petrophysical estimates. Consequently, WBEM techniques can improve the reliability of NMR techniques in shaly or iron-rich sands.

Table 1 summarizes the different sensitivities that are required to perform accurate petrophysical assessments of a general rock model. Pore size and connectivity are vital to assess hydraulic permeability in both clean and clayey sands. NMR measurements usually quantify pore-size distribution but not pore connectivity, unlike WBEM measurements. It is also necessary to identify a variety of fluids to perform adequate fluid typing. NMR measurements detect medium- and light-oil grades quite well, but are riddled by acquisition and inversion problems in the presence of gas and heavy oils. Oil grades whose relaxation times and diffusivities are close to those of water within confining rocks also cause NMR interpretation problems. WBEM measurements, on the other hand, are independent of hydrocarbon type; therefore, they allow wettability assessment but not fluid typing. Table 1 emphasizes the sensitivities of NMR and WBEM techniques for these and other essential criteria. Once combined, the two measurement techniques would permit a full coverage of the sensitivity domain required to perform accurate and reliable petrophysical assessments.

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References
Fig. 12—Frequency dispersions of dielectric constant simulated for the pore maps of Figs. 10 (water-wet cases, WW) and 11 (oil-wet cases, OW), for two values of brine conductivity. Top left panel: all simulation results for $\sigma_w=1$ S/m; top right panel: for $\sigma_w=0.1$ S/m; bottom left panel: all water-wet geometries; bottom right panel: all oil-wet geometries.

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Appendix A—Quantitative Incorporation of Electrical Double Layers

Following de Lima and Sharma (1992), we embed the effective values of conductivity and dielectric constant for the ionic double layers of wet clay from Fixman’s (1980) model. Clay particles are represented as spheres of radius a and consist of resistive core and counterion surface charge density \( \beta \) (in units of \( 1/m^2 \)). Ions in the double-layer of diffusivity \( D \) displace around the insulating sphere and build up a stationary charge. The corresponding diffusion time \( \tau \) is given by the ratio

\[
\tau = \frac{a^2}{2D} \quad \text{(A-1)}
\]

while the double-layer efficiency \( \delta \) is defined by the dimensionless ratio

\[
\delta = \frac{\beta}{ac} \quad \text{(A-2)}
\]

where \( C \) is the density of cations in the bulk water (in units of \( 1/m^3 \)). The complex conductivity associated with this double-layer \( \sigma_{DL} \) can be written as a function of the pore water conductivity, \( \sigma_w \), as follows:

\[
\sigma_{DL} = \frac{\sigma_w}{1 - \delta \sigma_w} \quad \text{(A-3)}
\]

In this equation, \( Y \) stands for the frequency-dependent conductivity buildup caused by the time oscillation of charges around the insulating grain, and is defined by the equation

\[
Y = \frac{1 + (1 - i)\sqrt{\omega \tau}}{2 + 2(1 - i)\sqrt{\omega \tau}} \quad \text{(A-4)}
\]

From these expressions, it follows that the values of real effective conductivity and dielectric constant for the clay particle and its EDL can be approximated by the equations

\[
\sigma_{eff} = \sigma_w \left( \frac{\delta}{1 - \delta Y} \right) + \omega \varepsilon_i \kappa_w \frac{\delta}{1 - \delta Y}, \quad \text{(A-5a)}
\]

and

\[
\kappa_{eff} = \kappa_w \left( \frac{\delta}{1 - \delta Y} \right) - \frac{\sigma_w}{\omega \varepsilon_i \kappa_w \frac{\delta}{1 - \delta Y}} + \kappa_{gran}, \quad \text{(A-5b)}
\]

The practical use of Eqs. A-5 requires quantification of the constants \( \beta \) and \( C \) included in Eq. A-2. As noted by Glover et al. (1994), \( \beta \) depends on ion surface adsorption and brine pH, as well as electrolyte concentration. However, it is reasonable to assume a constant clay surface charge density in the order of 10–20 \( \mu C/cm^2 \), or \( 6-12 \times 10^{-17} \) ions/m², as measured by Sonon and Thompson (2005) in smectites. In this paper, we assume a conservative value of \( \beta = 11 \mu C/cm^2 \) or \( 6.9 \times 10^{17} \) ions/m².

The brine cationic density \( C \) is linked to the electrical properties of the brine. Stroud et al. (1986) recapitulate existing correlations between \( \kappa_w \) (in S/m), \( \kappa_w \), temperature \( T \) (in °C), and salinity \( X \) (in ppm) through the equations

\[
\sigma_w = T + 21.67 \times 45.56 \left( \frac{0.0123 + 3647.5}{10000(0.0095)} \right)^{-1}, \quad \text{(A-6a)}
\]

and

\[
\kappa_w = \left[ \frac{1}{87.69 - 0.3921T + 0.000217T^2 + 58.443(1000 - X)} \right]^{-1} \quad \text{(A-6b)}
\]

By dividing \( X \) by the molecular atomic mass of the dissolved salt and multiplying the result by the elementary charge, one obtains the expression for \( C \).

Using Eqs. A-1 through A-6 for different clay sizes \( a = 100 \) and 1000 nm, and for brines with different conductivities of 0.1, 1, and 10 S/m, we generated the wide-band dielectric dispersions shown in Fig. A-1. These results exhibit expected sigmoidal shapes.
whose amplitudes vary primarily with salinity. For 100-nm clay particles, if the frequency range is limited to frequencies above 10 kHz, only brine conductivities lower than 10 S/m will affect the rock dielectric response ($\varepsilon_{\text{eff}} \approx \varepsilon_{\text{grain}}$); when clay size increases, this effect becomes more important. As salinity decreases, $\varepsilon_{\text{eff}} \approx \varepsilon_w$ for 100-nm clay particles, but $\varepsilon_{\text{eff}} > \varepsilon_w$ for larger clay size at low frequency. If the frequency range is truncated in the kHz range, the ascending part of the sigmoids locally fits a power-law expression between frequency and dielectric constant. Such a behavior is in agreement with discussions included in previous sections of this paper.

**Appendix B—Construction of a WBEM Model to Quantify WBEM Microporosity Effects**

Presence of diffusion coupling in microporous carbonate rocks with low surface relaxivity prevents NMR measurements from correctly quantifying pore-size distributions, bound fluid volumes, and hydraulic permeability (Ramakrishnan et al. 1999; Toumelin et al. 2003). In this paper, we show that WBEM measurements have the potential to reduce ambiguities on such complex rock morphologies. A WBEM geometric model is built from rock images and two-step electromagnetic upscaling in the absence of double-layer effects. We synthesized a carbonate rock model from core data, core pictures, and NMR measurements of a micritized rock sample exhibiting diffusion coupling (Sample A from Toumelin et al. 2003). This sample includes a complex porosity made of dissolution vugs (amounting to 10 of the 24% porosity of the sample, with pores sizes in the 15–50 μm range), primary-porosity macropores (4% porosity, 5–15 μm range), and abundant micritized intra-granular porosity (10% porosity, submicron range).

Following the dual-porosity structure shown by the high-resolution images of Fig. B-1, Fig. B-2 shows an equivalent twoscale 2D rock model amenable to the simulation of WBEM measurements. This figure comprises two disks with two different spatial resolutions that constitute the two steps of the upscaling method. The left disk of Fig. B-2 forms a 501×501-pixel map of a low-resolution rock model (1 pixel = 0.5 μm) and captures the general dual porous structure of the micritized carbonate sample (10% intergranular and 15% intragranular porosities). However, its low spatial resolution neglects the submicron micro pores and microthroats existing within the microporous grains. This is why we also use a higher-resolution micromodel (right disk of Fig. B-2) that explicitly enforces the presence of 100-nm brine layers between micrite grains, as shown in the right disk of 501×501-pixel resolution (1 pixel = 50 nm). Once the dispersions of isotropic conductivity and dielectric constant are computed for the high-

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Fig. A-1—Frequency dispersions of pure clay dielectric constant simulated for different values of clay size and brine conductivity through Eq. 9b. Open markers: $a=100$ nm, closed markers: $a=1$ μm. Squares: $\sigma_w=10$ S/m; triangles: $\sigma_w=1$ S/m; circles: $\sigma_w=0.1$ S/m. Dotted lines identify the bulk dielectric constant of quartz (4) and water (80). The locally-straight lines obtained between 1 kHz and 10 kHz for $a=100$ nm and between 100 kHz and 500 kHz for $a=1$ μm appear as power-laws of dielectric constant behavior with respect to frequency.

Fig. B-1—High-resolution scanning electron microscope (SEM) images of a carbonate sample exhibiting diffusion pore coupling at 140X (left panel) and 1400X (right panel) magnifications (Toumelin et al. 2003a)
resolution micromodel, they are assigned to the grain pixels in the low-resolution rock model. The effective conductivity and dielectric constant obtained for the low-resolution model constitute the effective properties of the coupled micritized rock.

Fig. B-3 illustrates the distribution of electric-current strength calculated at frequencies below 1 MHz within the low-resolution rock model after two-step upscaling. Incorporation of the microscale model in the two-step upscaling process plays a fundamental role in the effective response of the coupled rock model. Fig. B-4 compares the wide-band dielectric dispersions calculated for the coupled model, with and without two-step upscaling, with the frequency dispersions calculated for the generic model of Fig. 3. In the absence of upscaling, the dielectric response of the coupled macromodel (left disc of Fig. B-2) is similar to that shown in Fig. 5 for the generic rock, except for the amplitudes of the dielectric constant. That amplitude is larger in the generic model than in the coupled macromodel because eccentricities and dead-ends are more prominent in the generic model. Once the micro-model (right disc of Fig. B-2) is incorporated as the first step of the upscaling, the dielectric dispersion of the coupled model becomes remarkably flat. Presence of a water layer between all micrite grains effectively connects all the pores of the macromodel and eliminates the geometric dielectric enhancement of the rock. Existence of dead ends where electrical storage occurs in disconnected water zones is therefore the key to dielectric enhancement. Given these simulation results, it is likely that a rock exhibiting strong diffusion coupling will also exhibit high electrical conductivity and abnormally constant electromagnetic dispersion. Therefore, special emphasis can be placed on WBEM measurements to characterize abnormal heterogeneous rock morphologies and refine the estimation of petrophysical properties performed with NMR measurements.

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