Improving the petrophysical assessment of rock-fluid systems with wide-band electromagnetic measurements

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Abstract

Due to their sensitivity to ionic content and surface texture, wide-band electromagnetic (WBEM) measurements performed on porous rocks are influenced by petrophysical factors as diverse as fluid saturation, pore morphology, thin wetting films, and electrically charged clays. In general, all of these factors simultaneously coexist in fluid-saturated rocks, and therefore a comprehensive and accurate physical model is needed to correctly interpret WBEM measurements in terms of petrophysical properties. Traditional mixing laws fail to quantify the collective influence of various petrophysical parameters on WBEM measurements. As a result, no general method is currently available for the accurate petrophysical interpretation of dielectric measurements. The objective of this paper is to quantify the sensitivity of WBEM measurements to a large array of petrophysical properties, and to show that they naturally complement with NMR measurements. To this end, we develop a comprehensive numerical model that successfully reproduces the kHz-to-GHz dielectric dispersion measured on a variety of rock and fluid conditions, wettability, and clay content. Our model is based on the solution of Maxwell’s equations at the pore scale and incorporates explicit geometrical distributions of grains, fluids, and wet clays, constructed from core pictures and measurements. Comparison of WBEM and NMR measurements emphasizes the complementary nature of the two techniques, especially in the assessment of wettability, fluid saturation, pore connectivity and morphology, hydraulic pore coupling, and pore size distributions. Because our approach integrates all of these petrophysical features, we can assess their relative influence on borehole kHz-GHz WBEM measurements acquired in hydrocarbon-bearing rocks.

Introduction

The discipline of formation evaluation principally aims at quantifying hydrocarbon reserves (in terms of rock porosity, fluid saturations and fluid types) and their producibility (through the macroscopic notions of relative and absolute permeability). For this, suites of borehole and larger-scale measurements are available which are sensitive to different petrophysical and geometrical parameters, and exhibit different spatial resolutions and radial lengths of investigation. After so many years of development, the challenge still remains to determine correct values of permeability and fluid saturation when the petrophysical conditions depart from those of clean, thick, and homogeneous flow units. Substantial progress has been made in tool design to reach unparallel measurement reliability. However, petrophysical interpretation models conventionally used to analyze these measurements are based on relatively old interpretation principles: ad-hoc empirical correlations with little predictive power, which have become incompatible with the need to characterize increasingly more complex reservoirs.

Two of the most conspicuous examples of borehole measurements whose interpretation has been oversimplified are electrical resistivity and nuclear magnetic resonance (NMR). These two measurements are used as common means to estimate hydrocarbon saturation or permeability – in combination with other measurements that can help to assess presence of clays (gamma-ray), vugs, natural fractures (borehole images), etc. Resistivity interpretation is based on the application of Archie’s laws despite the fact that the associated exponents m and n are highly dependent on rock morphology, wettability, imbibition cycle, and even saturation. Likewise, NMR measurements are strongly dependent on the rock fabric and on the pore-level distribution of fluids. The application of a priori relaxation time cut-offs to discriminate between fluids assumes clear contrasts of fluid relaxation times. Even with the accuracy of recently developed 2-dimensional (2-D) NMR techniques, proven valuable for the assessment of fluid saturation, oil grade, and wettability state under certain conditions, are constrained to cases of relatively large contrasts between hydrocarbon and pore water relaxation times and/or diffusivity. In addition, NMR measurements provide the unique possibility to assess bound or irreducible fluid volumes because proton relaxation times vary with pore size. Cutoffs are usually enforced on NMR relaxation spectra to discriminate between saturating fluids regardless of the...
geometrical configuration of pores or on the spatial distribution of surface relaxation. Diffusion coupling occurring in micritized carbonates is one example where the ‘standard’ 90-ms cutoff for carbonates is often inaccurate. Finally, permeability estimation from NMR measurements has been a major bone of contention. Besides the requirement of a clear delineation between bound and free fluid, the concept of NMR-derived permeability assumes a universal relationship between pore size and hydraulic permeability. The usual diffusion length of 5 to 10 pores actually sensed by NMR measurements is often insufficient to characterize flow capacity and to establish a universal relationship between pore-size distribution and permeability.

Thus, the most important petrophysical estimation procedures are based on measurements that are strongly affected by a number of micro-morphological features. Our current understanding of pore-scale physics is not sufficient to correctly interpret these measurements independently. The question remains of whether joint interpretation methodologies are more suitable. As we emphasize in this paper, multi-frequency electromagnetic phenomena embodies the potential to investigate pore structure and surface effects, with sensitivities that complement those of NMR measurements. Specifically, in this paper we consider wide-band electromagnetic measurements (WBEM) in the kHz-to-GHz range. A large array of electromagnetic tools already exist that provide some of these measurements — such as array induction or laterolog in the 10-kHz range, LWD induction in the 2-MHz range, or electromagnetic propagation in the GHz range.

Petrophysical interpretation of wide-band electromagnetic measurements was the subject of intense research in the 1980s. Even though it enjoyed some success in the characterization of specific petrophysical attributes, it never became a standard petrophysical tool due to the sensitivity of the measurements to a multitude of pore-scale parameters. Modeling abilities were mostly limited to analytical solutions, which provided physical insight but were impractical to interpret real measurements performed on saturated rocks. Subsequently, NMR measurements brought to bear new and more accessible methods to probe the pore space. Therefore, the time seems ripe to take a fresh look at WBEM measurements, especially in light of their complementary with NMR measurements.

It is then appropriate to inquire: in addition to standard resistivity measurements of real conductivity in the kHz range, what are the areas where WBEM could help to improve the petrophysical assessment of porous rocks? Sen and Chew’s seminal work investigated both the effect of pore and grain eccentricity (in the MHz range) and clay double-layers (in the kHz range) on the frequency-dependent dispersion of the conductivity and its out-of-phase counterpart, the dielectric permittivity (or dielectric constant). Their work summarizes the individual effect of these phenomena on wide-band dielectric measurements but stops short of discussing possible interplay mechanisms. More recently, Bona et al. showed obvious effects of wettability on the low-frequency enhancement of measured dielectric constants, and indicated how electromagnetic measurements in the kHz-MHz range can be used to characterize rock wettability in the laboratory. There is no doubt that additional petrophysical information can be garnered from in-phase and out-of-phase electromagnetic measurements performed on saturated rocks in the kHz-GHz spectrum, including the case of partial hydrocarbon saturation. For instance, the complex refractive index method (CRIM) is known to quantify fluid saturations reasonably well in the GHz range and with less uncertainty than low-frequency Archie-derived saturations. Knight and Nur measured the sensitivity of the dielectric constant to the rock’s surface-to-volume ratio of 36%-oil saturated rocks in the MHz range. However, to quantify whether accurate and reliable petrophysical assessments are possible with WBEM measurements requires an analysis of WBEM that integrates pore structure, pore connectivity, multiphase saturation, and double-layer effects. Such a desirable approach was not practical twenty years ago. In this paper, we introduce an interpretation framework that explicitly incorporates all the abovementioned petrophysical features in the numerical simulation of WBEM measurements from pore-scale considerations.

**Different origins of wide-band polarization**

According to the fundamental postulates of electromagnetism, an electric field $E$ applied to a material of conductivity $\sigma^*$ and dielectric permittivity $\varepsilon^*$ generates a current equal to $J = \sigma^* E$ and a polarization $D = \varepsilon^* E$. In general, both $\sigma^*$ and $\varepsilon^*$ are complex numbers and can be written in terms of their real and imaginary parts as $\sigma^* = \sigma^+ i \sigma^-$ and $\varepsilon^* = \varepsilon^+ i \varepsilon^-$. Using the $e^{i\omega t}$ convention for the time-harmonic electric field of radian frequency $\omega$, the total current generated through the material is given by

$$ J_T = \sigma^* E = J + \frac{\varepsilon D}{\varepsilon \varepsilon_0} = (\sigma^* - i \omega \varepsilon^*) E \quad \text{(1)} $$

The above total current can be expressed in terms of a real effective conductivity $\sigma_{eff}$ and a real permittivity $\varepsilon_{eff}$ in parallel, i.e.,

$$ J_T = (\sigma_{eff} - i \omega \varepsilon_{eff}) E \quad \text{(2)} $$

In turn, the relationships between the real and imaginary parts of the complex material conductivity and permittivity are given by

$$ \sigma_{eff} = \sigma^+ + \omega \varepsilon^- \quad \text{(3)} $$

It is remarkable that these permeability models are derived for small diffusion lengths (wherein high surface relaxivity considerably diminishes the NMR signal through diffusion across a few pores). Cases of long diffusion lengths (where low surface relaxivity allows protons to diffuse further before complete decay), which are more representative of the spatial scale of fluid flow processes, are paradoxically not taken into account by standard NMR interpretation techniques.
\[ \varepsilon_{\text{eff}} = \varepsilon' - \frac{\sigma^*}{\omega}. \]

The dielectric constant, \( \kappa \), is the ratio of the effective dielectric permittivity over that of vacuum, 
\( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \).

For pure rock minerals and for bulk fluids, conductivities and permittivities are nearly constant over our frequency range of interest, i.e., kHz to GHz. Thus, measured (real) effective conductivity and permittivity are equal to the material properties with zero imaginary (out-of-phase) contribution. For the case of rock-fluid mixtures with no surface electrical charges (zeta potentials), ions concentrate along the edges of elongated pores, thereby creating local capacitors in the pore structure whose effective capacitance depends on frequency. Out-of-phase conductivity being negligible, the low-frequency asymptote of both \( \varepsilon' \) and total polarization is toward decreasing values and takes the form of a sigmoid function. On the other hand, the high-frequency asymptote of \( \sigma^* \) is toward increasing values and takes the form of a sigmoid function (geometrical Maxwell-Wagner effect). This behavior solely depends on the eccentricities of the water zones (or, similarly, on the shape of the grains and resistive oil blobs) regardless of pore or grain size. When the surface of a resistive obstacle is electrically charged, however, an ionic double-layer develops at this surface and the ion trajectories imposed by the electric field \( E \) are constrained to follow the charged surface away from the direction of \( E \). This may result in substantial displacement currents and out-of-phase conductivity \( \sigma^* \) (electro-chemical double-layer effect). Such an effect depends on the size of the object surrounded by the ionic double-layer.

In the following sections, we consider a numerical algorithm to simulate the WBEM response of rocks for cases of negligible surface charge at the water interface. Then, we discuss the size-dependence of the double-layer effects and their compatibility with our framework. Finally, multiphase fluid geometries are considered to test previously published observations on wettability, saturation, and pore surface-to-volume effects.

**No-charge case: assessment of pore texture and connectivity**

Our numerical model follows the concepts presented in Ref. \[8\]. It is based on the solution of Maxwell’s equations in a 2-D lattice representing a rock/fluid structure, whereby each pixel stands for either rock or fluid and is associated with the corresponding bulk effective conductivity and dielectric constant. This solution involves the Green’s function for a point source and no charge, and is therefore suitable for reproducing the shape polarization that arises from purely geometrical considerations of water and rock/oil pixels arrangements (rock and oil exhibiting similar electrical properties), where the imaginary quantities \( \sigma^* \) and \( \varepsilon^* \) can be neglected.

**Inversion of macroscopic conductivity and dielectric constant**

The macroscopic conductivity and dielectric properties of the 2-D rock model considered as a single homogeneous body is calculated using Ref. \[8\]’s procedure. First, the internal currents within the 2-D rock model are computed by solving Maxwell’s equations in the frequency domain on the Cartesian lattice constructed with the 2-D rock pixels. The 2-D rock is adapted to describe a disc shape, which therefore can be assimilated to a cylinder in three dimensions. The equivalent macroscopic conductivity (and dielectric constant) of the 2-D rock is considered to be the effective conductivity (and dielectric constant) of a homogeneous cylinder were the internal currents are as close as possible (in the least-squares sense) to those calculated within the detailed 2-D rock map for the same incident electric field. **Figure 1** illustrates such a 2-D disc-shape rock model with the amplitude of the corresponding internal currents calculated at 1 GHz and 10 kHz. Many factors can affect the electromagnetic response in such complex rock geometry; therefore, it is desirable to perform sensitivity analyses based on simplistic rock models.

**Sensitivity analysis of pore shape effects and connectivity**

As emphasized by Bona et al., the shape of either water inclusions in a rock background or grain inclusions in a water background induces frequency variations of conductivity and dielectric permittivity. Maxwell-Garnett or Lynne/Sillas analytical models can be used for each of these cases under the condition of macroscopic homogeneity and low concentration of the inclusions (thus avoiding electromagnetic coupling and percolation of the inclusions). In rocks, however, some of these assumptions are violated and the above models become inaccurate. Specifically: (1) water-filled pores only form a minority of the bulk volume, (2) diagenesis and other geological events alter the possibly clean homogeneous grain assembly that forms the rock skeleton, and (3) even at low volumetric concentration, the water zones remain connected in water-wet rocks and water percolation exists through thin films. It is then an ambiguous undertaking to define which feature, either the thin film eccentricity percolating at the rock surface or the grain eccentricity that makes up the rock fabric, controls the wide-band electromagnetic dispersion.

To address these issues, four pore geometries were tested as shown in **Fig. 2**, with the resulting dispersions of conductivity and dielectric constant displayed in **Fig. 3**. As expected, the disperse disk-shape water pores of configurations A exhibit low enhancement of permittivity and low apparent conductivity. In case B, the higher magnitudes of the low-frequency dielectric enhancement and the high-frequency conductivity enhancement relate to the higher aspect ratio of the water pores. However, the dielectric dispersion curve departs from the sigmoidal shape predicted by effective medium theories and includes two inflection points, as experimentally noticed in previously published partially-saturated rock measurements. This discrepancy can be explained by the existence of mutual interactions (or electromagnetic coupling) between the pores. Pore maps C and D consistently exhibit higher conductivities but low enhancement because the water phase is percolating across the medium. In case C, the shape of dielectric dispersion exactly
matches a sigmoid. By comparison, the flatness of the dielectric dispersion for pore model D is due to the non-planeness of the rock grains defined between the water throats. It is remarkable, however, that the relatively flat dielectric dispersion baseline (about 16 dielectric units-wideband) is not equal to map C’s high-frequency asymptote (7 dielectric units), while effective medium theory states it should. This suggests that the high eccentricity of the pore throats consistently included in medium D, where the throats are for this 50-nm resolution model 100-nm thick by 3 to 5-μm long, also plays an important role. The simulation results also yield the counter intuitive result that for higher densities of high eccentricities, it is possible to obtain values of apparent dielectric constant that are higher than the dielectric constant of any component\(^8\) (in this case, water at about 80).

**Enforcing throat connectivity at the core scale: simulation of a rock exhibiting strong diffusive coupling**

Let us consider an example where strong pore connectivity, together with mineralogy, is responsible for low surface relaxivity, whereby NMR measurements do not follow conventional interpretation schemes: micritized carbonates. Figure 4 shows high-resolution rock pictures of such a micritized rock at two different magnifications. Figure 5 shows the numerical model that was constructed to match the geometry: a low-resolution pore map with a dual-porosity system (left disk). The rock pixels can be either assigned the pure rock matrix properties if the intragranular micropores are considered isolated one from another, or they can be assigned the apparent conductivity and dielectric permittivity of a well-connected matrix as a two-step process if the intragranular pores are assumed to connect the pore space (right disk). The corresponding results are shown in Fig. 6: the fact that all grains are coated with a water layer eliminates all dispersions – and of course increases the apparent conductivity for connectivity purposes. Again, the existence of dead ends where electrical storage occurs in disconnected water zones is the key to dielectric enhancement. It is therefore likely that a rock exhibiting strong diffusion coupling will also exhibit high electrical conductivity and abnormally constant electromagnetic dispersion.

**From wettability to pore and grain size: electrical double-layers in non-clayey rock**

Several theories exist to explain the origin of dielectric enhancements observed at low frequencies in a variety of conditions. We now discuss how these enhancements can be summarized as double-layer effects and be efficiently parameterized and quantitatively integrated into the framework discussed above.

**Exponential enhancement or incomplete convergent sigmoid?**

In the early days of WBEM petrophysical applications, substantial dielectric-constant enhancements below the MHz range in non-clayey rocks were regarded as measurement noise and/or spurious electrode polarization effects. Subsequent quantification of electrode polarization showed that, on the contrary, a strong negative power law could be correlated with such measurements under some conditions, such as the example of Berea samples at low values of water saturation (Fig. 7). This power-law behavior can be justified by fractal arguments\(^8\), whereby rock, bound water, microporosity, or macroporosity can all be accounted for at different scales using different volumes and different water complex conductivities at each scale.

That model is not easily amenable to our numerical framework. However, let us remark that the very concept of changing the effective water complex conductivity depending on whether the water is clay-bound, capillary-bound, or moveable, mirrors electro-chemical models where the effective water complex conductivity is frequency- and size-dependent. The analogy between the two methods can also be pursued by considering that power-law enhancements resulting from the fractal process could be the truncation of a high-amplitude sigmoid that would converge at low frequencies outside the measurement range. But what could lead to such high values of dielectric constant without referring to this much convenient, but not always insightful, power-law? Let us consider the geometric argument of the very high aspect ratio of thin films included in the water-wet cases reported by Bona et al.\(^4\). This strong water wettability implies high connectivity of the water films (cf. the low values of \(n\) observed in water-wet rocks, see Ref. \([1]\)) and little electrical storage zones. Therefore, following the remarks made earlier in this paper on pore model D, dielectric enhancement due to water films might not be necessarily high. If we now take into account that any rock/water and oil/water surface exhibits some surface charge, heretofore neglected surface effects come into play. Ionic double-layers form at the rock/water and oil/water interfaces, the imaginary conductivity becomes substantial, and the 1/\(\omega\) factor in Eq. (4) at least partially justifies that an apparent power-law behavior can be fitted perfectly.

**Double-layer model: size and charge dependence**

Specific models exist to assess the influence of double-layers on the dispersion of effective conductivity and dielectric permittivity. Most of these models are based on physical-chemical models that describe a double-layer formed around a single grain with no regard to the general geometrical rock structure. The Lima-Sharma’s\(^9\) model is one of the few approaches that upscales single-grain double-layer effects to the rock scale, possibly partially saturated, by way of effective medium theory. Its application, however, is restricted to clay double-layers and is subject to the usual restrictions of effective medium theories, whereby no notion of anisotropy, wettability, or accurate pore and fluid spatial arrangement is taken into account. In this paper, we adapt Lima-Sharma’s\(^9\) approach into a more general framework based on the numerical simulation of pore/fluid arrangements to include all double-layers, both due to clays and wettability effects.

In this method, resistive obstacles are approximated as spheres or radius \(a\) with a given counter-ion surface charge density \(\beta\). Ions in the double-layer of diffusivity \(D\) will move around the insulating sphere and build up a stationary charge. The corresponding diffusion time, \(\tau\), is given by
\[ \tau = \frac{a^2}{2D} \] ........................................(5)

By defining \( CR \) as the charge ratio of \( \beta \) (in units of 1/m³) over the density of ions in the bulk water (in 1/m³), and \( \delta \) as the dimensionless ratio of \( CR \) divided by the obstacle size, i.e.,
\[ \delta = \frac{CR}{a} \] ........................................(6)

the complex conductivity associated with the double-layer can be written as a function of the pore water conductivity, \( \sigma_w^* \), as follows:
\[ \sigma_{\mu l}^* = \frac{\delta \sigma_w^*}{1-\delta Y} \] ........................................(7)

where \( Y \) stands for the frequency-dependent build-up due to the oscillation of charges around the insulating grain, given by
\[ Y = \frac{1+(1-i)\sqrt{\omega \tau}}{2+2(1-i)\sqrt{\omega \tau} - 2i\omega \tau} \] ........................................(8)

It follows from the above expressions that effective real conductivity and dielectric constant for the double-layer can be calculated as
\[ \sigma_{\text{eff}} = \sigma_w \text{Re}\left(\frac{\delta}{1-\delta Y}\right) + \omega \varepsilon_0 \kappa_w \text{Im}\left(\frac{\delta}{1-\delta Y}\right) \] ........................................(9a)

\[ \kappa_{\text{eff}} = \kappa_w \text{Re}\left(\frac{\delta}{1-\delta Y}\right) - \frac{\sigma_w}{\omega \varepsilon_0} \text{Im}\left(\frac{\delta}{1-\delta Y}\right) \] ........................................(9b)

**Application to wetting phenomena**

Double-layer effects are particularly important in clayey rocks where the clay surface charge \( \beta \) is high and the charge ratio \( CR \) takes on values larger than 10 \( \mu \)m\(^10\). If we now consider weak double layers with surface charge 100 times, and even 10,000 times smaller than this nominal value (as expected for very clean rock grains immersed in water), significant double-layer effect exists down to the Hz range as shown in Fig. 8. Focusing on our range of interest of 10 kHz to 1 GHz, Fig. 9 indicates that these effects remain substantial for values of \( CR \) larger than 1/1000 of that of charged clay and for grains as large as 100 \( \mu \)m for \( CR = 0.1 \) \( \mu \)m. We remark that, since the asymptotic values of \( \kappa_{\text{eff}} \) in Eq. (9b) tend to zero when \( \delta \) also tends to zero at high frequencies, an additive correction is required to the rock’s dielectric constant.

**Wetting double-layer for well-connected microstructures**

Because the influence of the double-layer is maximal when the resistive obstacles (in our case, the grains) are small, we reworked the \( \mu \)m-grain microporous-rock model of Fig. 5 to account for possible weak double-layers. In the same fashion as Fig. 6 compares the conductive and dielectric dispersions of the rock model with and without enforcing water throats between all the micron-size grains, Figs. 10 and 11 compare the apparent electrical properties of (1) a grain coated with double-layer water (“1-grain double layer”), (2) the dispersion obtained for map D by parameterizing each grain pixel with double-layer properties (“throat micro-model”), (3) the dispersion obtained for the bimodal model for Fig. 5 (left) by parameterizing each grain pixel with map D’s properties (“2-step macromodel”), and (4) the bimodal model parameterized directly with the double-layer properties without going through map D (“1-step macromodel”). In both cases of weak surface charge density, double-layers around the micrograins typical of this micritized carbonate are responsible for conductivity shortcuts that cause the 1-step and 2-step models to yield similar results. Specifically, because the micritic grains of this sample are so small, substantial enhancement of the dielectric constant could be obtained for the microporous model. The grain-scale dependence of the wetting double-layers therefore favors recognition of micro-grains, and could be a way to emphasize coupled micro-porosity. Further insight into this technical issue will be provided with the simulation of oil distributions and double-layers in the macro-pore space.

**Comprehensive models with multiphase saturation, wettability and grain morphology**

Returning to the models that gave inception to the present discussion, let us now consider in Fig. 12 the geometry of the next steps of our work to assess the effect of multiphase saturations of WBEM measurements. If wetting double-layers can play a role in single fluid saturation, they will most definitely play a role in multiphase saturations. In the latter situation not only does the high-frequency dielectric constant decrease because the water volume decreases, but also variations of water pore geometry and constriction as well as new double-layers at the water/hydrocarbon play a dominant role for the case of very tight pores and emulsions.

**Assessment of water saturation**

If the determination of fluid saturation is not an issue for core analysis, it is one of the most important and difficult quantities to assess in-situ. With the advent of 2 MHz-range LWD measurements, operators now acquire real-time and invasion-free resistivity measurements. However, if the conductivity of the saturated rock is dispersive, the question arises as to whether Archie’s laws remain accurate at 2 MHz with the same exponents estimated in the kHz-range. It appears as though in weak double-layer cases and in most geometrical-induced dielectric dispersivity, little or no difference is observed between kHz and MHz-resistivity. This is not true for frequencies above the MHz range. Another issue is to target volumetric mixing laws, such as CRIM, for the estimation of fluid saturations almost independently of salinity at 1 GHz. Previous work by Myers\(^1\) showed interesting trends of saturation-dependent dielectric dispersion in clayey sands, wherein surface double-layers are not negligible.

**Pore size in partially-saturated rocks**

Knight and Nur\(^2\) observed a correlation between measured dielectric constant and rock surface-to-volume ratio in partially saturated rocks in the range of 60 kHz – 4 MHz. Their results lend themselves to ambiguous interpretation: a surface-to-volume dependence is related to surface charge effects. Knight and Nur’s\(^2\) also found high dielectric constant dispersions (correlated with high surface-to-volume ratios) for
samples with ultra-low permeability (<1 mD), low porosity (<8%), and possible clays (where even the use of deionized water is usually not sufficient to cancel the double-layer effects given the high surface charge densities). Furthermore, their use of deionized water should theoretically shift any pore geometrical effects discussed in this paper from the MHz to the kHz range. These petrophysical and measurements issues could have different and possibly combined influences that only pore-scale modeling can detangle.

Wettability effects
Finally, let us mention wettability as one main object of study for this paper. We refer to Bona et al.6 for the analysis of wettability effects on the measured dielectric dispersion on real and artificial rocks. The main issue that we want to emphasize is that the quality of these measurements is independent of oil viscosity, as long as one is able to distinguish between strong enhancements due to wettability, and those due to clays – for instance, via independent gamma-ray measurements. This could be very useful in combination with 2-D NMR techniques, whose accuracy for wettability and saturation estimation is limited to certain types of oil grades. Consider, for instance, the case depicted in Fig. 13 adapted from Ref. [3]. Both oil and water peaks can be differentiated on a T2/Diffusivity cross-plot, the oil peak lying on the T2/Relaxivity correlation line that characterizes oils for these specific PVT conditions. The interpretation uncertainty here resides in the oil wettability and has quite a few unsuspected consequences, thereby causing uncertainty in the estimation of both the oil grade and the pore size distribution.

Conclusions
While NMR focuses primarily on pore-size and short-range pore connectivity, WBEM measurements are strongly affected by pore shape and connectivity. We introduced a numerical method which concomitantly enables the accurate quantification of these petrophysical effects on NMR and WBEM measurements. In the presence of small grains, tight pores, and clay content, where surface charge concentrations are relatively high, WBEM measurement exhibit sensitivity to pore and grain size, which opens new possibilities for the combined, more accurate interpretation of NMR measurements. Previous work showed that WBEM measurements can be used for the assessment of wettability and saturation which, combined with NMR measurements, could considerably reduce the uncertainty associated with the estimation of these two petrophysical parameters.

Our current work embodies a proof of concept. Extensive experimental work with both WBEM and NMR measurements and collection of large petrophysical measurements are required to confirm these trends and to parameterize models beyond the current capabilities. It is expected that this paper will generate sufficient interest to consider further laboratory and numerical studies among petrophysicists and formation evaluation specialists.

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References
Fig. 1. (a) Example of a 500x500-pixel resolution disc-shaped 2-D rock model adapted from a real-rock thin section that has been digitized and binarized (black: pore space filled with water; gray: rock matrix). (b) Magnitude of internal currents calculated from the explicit solution of Maxwell’s equations for 1-MHz and 100-MHz excitation.

Fig. 2. Pore maps used for the sensitivity analysis of pore eccentricity and connectivity. Black pixels represent the pore space filled with water, while gray pixels represent the rock matrix. All models exhibit porosities between 6 and 8%. Map A: water discs randomly distributed in rock host. Map B: randomly distributed water ellipses with an aspect ratio of 16. Map C: platey grains connected by high aspect-ratio throats. Map D: rounded grains fully connected by pores with high aspect-ratio throats.

Fig. 3. Conductivity (left panel) and dielectric constant (right panel) dispersions simulated in the 10 kHz – 1 GHz range for the four media described in Fig. 2.
Fig. 4. High-resolution Scanning Electron Microscope (SEM) pictures of a carbonate sample exhibiting diffusion pore coupling at 140X (left panel) and 1400X (right panel) magnifications (adapted from Ref. [4]).

Fig. 5. Two-step 2-D model of a rock designed to replicate the rock structure shown in Fig. 4. Left disk: 501x501 pixel map of a low-resolution model (1 pixel = 0.5 \( \mu \text{m} \)) capturing the general dual porous structure of the micritized carbonate sample (10% intergranular and 15% intragranular porosities). Right disk: 501x501 pixel map of a high-resolution micro-model (1 pixel = 50 nm) enforcing explicit 100-nm throat connectivity between the micron-size grains (same as map D of Fig. 2).

Fig. 6. Conductivity (left panel) and dielectric constant (right panel) dispersions simulated in the 10 kHz – 1 GHz range for the medium described in Fig. 5, by assuming that either no connection exists between the micropores (“1-step macromodel”), or that the micropores are very well connected (“2-step macromodel”). For this latter case, the apparent pixel conductivity and dielectric constant assumed when solving the internal currents in the bimodal pore map are those resulting from the connected throat model D of Fig. 2 (“throat micro-model”).
Fig. 7. Wide-band dielectric spectra measured on Berea rock saturated with water and oil. Open squares: oil wet sample saturated with deionized water (Sw = 36%, water conductivity at 100 Hz: $1.57 \times 10^{-3}$ S/m). Solid dots: oil wet sample saturated with brine (Sw = 44.6%, NaCl salinity: 75.8 g/l, brine conductivity at 100 Hz: 9.5 S/m). Open up triangles: water wet sample saturated with deionized water (Sw = 20.1%). Solid down triangles: water wet sample saturated with brine (Sw = 21.9%). Data were corrected for electrode polarization (Solid lines).

Fig. 8. Wide-band dielectric dispersion (1 Hz – 1 GHz) for a single spherical grain coated with a diffusive double-layer of the type described by the Fixman-Lima-Sharma model, for different values of charge ratio, CR, and grain radius, a. Dispersions are computed for both a strong double-layer effect, as typically encountered in clay-coated grains ($CR = 10 \mu$m and $a = 1 \mu$m), and for weakly-charged double-layers as encountered at a clean quartz/water interface ($CR < 1 \mu$m). For each value of $CR$ (0.1, 0.01 and 0.001 $\mu$m), three grain sizes are considered: 1 $\mu$m (dotted curves), 10 $\mu$m (dashed curves) and 100 $\mu$m (plain curves).

Fig. 9. Enlargement of Fig. 8 within the range of interest (10 kHz – 1 GHz), for the weak double-layers ($CR < 1 \mu$m). As long as $CR > 0.01 \mu$m and $a < 100 \mu$m, the effective conductivity of the coated grain is characterized by substantial dielectric enhancement.
Fig. 10. Dispersions of conductivity and dielectric constant calculated for the microporous model of Fig. 5, accounting for double-layers on all the grains ($\tau = 0.5$ ms) and for $\delta = 0.03$.

Fig. 11. Dispersions of conductivity and dielectric constant calculated for the microporous model of Fig. 5, accounting for double-layers on all the grains ($\tau = 0.5$ ms) and for $\delta = 0.1$.

Fig. 12. (a) Pore map from Fig. 1 representing the original rock fabric. (b) Rock fabric now assimilated to spheroidal grains with low eccentricity where double-layer effects can take place depending on the surface charge and size of the spheroids. (c) Geometrical configuration of possible oil blobs filling the pore space for partial oil saturation (in orange), and around which double layers effects may also appear depending on the size of the oil blobs.
Fig. 14: Diagrams describing 2D-NMR wettability and fluid type uncertainties for a rock sample partially saturated with medium oil grade, after a case simulated in Ref. [3]. The red and green peaks are the T2/D measured peaks. The interpretation scenario to the left assumes oil wettability, and yields a pore size S and some oil grade. The interpretation scenario to the right assumes water wettability, and yields a pore size at least 3 times smaller and a heavier oil grade. Currently, there is no direct way to distinguish between the two scenarios.