High-frequency induced polarization measurements of hydrocarbon-bearing rocks

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Summary

We have investigated induced polarization (IP) effects in hydrocarbon-bearing artificial rocks at frequencies greater than 100 Hz. We have examined the instrumental and electrode phase responses of Zonge International's complex resistivity (CR) system, and optimized the performance of the Zonge system for IP measurements over the 1 mHz to 10 kHz frequency range. The reliability of the highfrequency IP measurements were confirmed by independent measurement of the same samples using the Novocontrol BDS 80 system. Our results confirm the presence of IP effects in hydrocarbon-bearing rocks, and suggest the necessity to account for IP effects in the interpretations of electromagnetic data, particularly in induction logging data.

Introduction

Induced polarization (IP) is a complex resistivity (CR) phenomenon, which manifests itself as a frequencydependent resistivity or as the slow decay in measured voltage after the cessation of an excitation current. IP responses are observed when an electric current passes through the earth, or a rock sample. When the current is excited or terminated, a potential difference is observed, which decays with time. The rate of decay depends on the lithology and pore geometry of the rock, as well as fluid content and saturation. The IP phenomenon was previously studied in detail by Wait (1959), and its modern development stems largely from Bleil (1953), Pelton et al. (1978), and Sumner (1976). IP surveys for mineral exploration are typically low frequency (i.e., DC to 100 Hz) given the predominantly low-frequency IP responses of minerals for which the polarization mechanisms are widely purported to be understood. Low-frequency IP responses have also been studied for hydrocarbon exploration (e.g., Olhoeft, 1985; Seigel et al., 2007; Davydycheva et al., 2006). However, induction well-logging for hydrocarbon exploration and production operates at higher frequencies (up to several MHz), for which the polarization mechanisms of reservoir rocks are poorly understood.

We previously reported on IP effects in hydrocarbonbearing artificial rocks (Burtman et al., 2009). A complex resistivity was measured as a function of frequency for artificial hydrocarbon- and saltwater-bearing rocks. Our analysis indicated that not only was the real spectrum of the resistivity for the hydrocarbon-saturated samples two orders of magnitude larger than for saltwater saturated samples, but the imaginary spectrum of the hydrocarbon-

saturated sample showed a distinct IP minimum, which we associated with a membrane polarization. We clarified the feasibility of measuring IP responses of hydrocarbonbearing samples by conducting a statistical analysis of IP measurements in hydrocarbon-saturated and variable-pH samples for frequencies less than 100 Hz (Burtman et al., 2010). We also compared the complex resistivity spectra of hydrocarbon-saturated samples with different saltwater pH values. The frequency of the IP peak was decreased with the decrease in the pH of the electrolyte. These results compared well to those independently reported in the literature (e.g., Slater et al., 2005). The above-mentioned analysis of the IP phenomena in hydrocarbon-bearing rocks was limited to the low frequency measurements. Despite previous attempts to measure high frequency IP responses (e.g., Vanhala, 199; Vanhala and Soininen, 1997), high frequency complex resistivity phase measurements remain a challenging problem (Kavian et al., 2009).

In this paper, we consider IP measurements at frequencies greater than 100 Hz. High-frequency IP measurements are difficult since the measured complex resistivity spectra may be contaminated with errors from electromagnetic compatibility, composite materials, and sample geometry. For the results presented in this paper, Baker Hughes provided a synthetic oil-based mud. We were able to isolate measurement artifacts from the IP of the sample itself. To avoid a possible confusion in terminology describing the IP phenomena, we will designate the measurement artifacts as *external induced polarization*, and distinguish this from *internal induced polarization*, which relates to the intrinsic property of the rock.

External polarization caused by instrument nonlinearity

We have studied the performance of Zonge International's complex resistivity (CR) system, which is used routinely for measuring the low-frequency (DC to 100 Hz) complex resistivity spectra of mineral rocks. We designate this system as a *basic CR system*, as it was tested in its original state without any modifications. Ingeman-Nielson (2005) reported on a very small phase error (less than 1 mrad) for the basic CR system for frequencies less than 100 Hz. However, the results of both R and RC tests have demonstrated that all responses of the *basic CR system* are reliable to approximately 100 Hz, and up to 2 to 4 kHz for loads below 100 k Ω . Beyond 5 kHz, the phase errors increase sharply, especially for loads larger than 100 k Ω . To optimize performance of the basic CR system for high

High-frequency IP measurements of hydrocarbon-bearing rocks

frequencies, we experimented with the phase response of different transmitters and GDP detectors, and substituted free-standing metal resistors and modified isolated amplifiers for the shunt resistor box. The *optimized CR system* was developed to minimize if not eliminate all sources of potential capacitor coupling and errors in the phase response. We designed two tests to identify the phase errors in the optimized CR system. For the resistor test (R test), a 10 k Ω free-standing metal resistor was used in the load channel. We kept the resistors in the load and reference channels the same and made CR measurements at different frequencies. We noted that the phase response should be close to zero since the reference and load channels were identical.

For the RC electrical test, we inserted RC1 and RC3 circuits into the load channel. The resistivity of the reference channel was compensated by the resistivity in the load channel, which was equal to the RC impedance. The RC test should evaluate the system performance when the loads are capacitive. The different values of the capacitors should shift the phase response, and thus probe sensitivity and phase error over the different frequency ranges. The RC1-test followed a methodology described by Vanhala and Soininen (1995). We also assembled the RC3 circuit as one with a phase response at high frequencies so we could better characterize the optimized CR system. The electrical components of the RC1 and RC3 circuits are shown in Figure 1.



Figure 1. External polarization of optimized Zonge $CR(\omega)$ setup: observed (solid lines and dots) vs. predicted (dahsed lines) data of R and RC tests. Insert highlights an electrical component of RC1 and RC3. The CR response and the models for RC1 and RC3 are colored by green and red, respectively. The blue solid line shows a CR response for 10 kOhm resistor and the blue dashed line shows an ideal behavior of the resistor.

For each of the RC tests, the model response is given by the impedance function:

$$Z = \left(\frac{1}{R_1} + i\omega C\right)^{-1} + R_2,$$
 (1)

where the resistivity R_1 is taken in parallel to capacitor C, and the resistivity R_2 is taken in series to capacitor C. The phase response of the optimized CR system was evaluated using both R and RC tests (Figure 1). The responses for the RC1 and RC3 circuits are colored green and red, respectively. The complex resistivity spectra are shown in the right panel as solid lines, and the model responses for the RC1 and RC3 circuits are shown as dashed lines. The blue solid line shows the complex resistivity response for a 10 k Ω resistor, and the blue dashed line shows the ideal behavior of the resistor. The phase error for a 10 k Ω resistor does not exceed 5 mrad at 100 kHz. The phase error at the highest frequency was within 10 mrad for RC1, which had impedance larger than 150 k Ω , and 2 mrad for RC3 which had an impedance of about 10 k Ω . These errors may be due to discrepancies in the specifications of the electronic components. Any deviations between the RC circuit's theoretical and observed responses are negligible up to 5 kHz. We conclude that the optimized CR system is reliable for phase measurements across the full frequency range provided the sample impedance is reasonably small (i.e., less than 150 k Ω).

External polarization caused by electrode phase responses

Following optimization of the CR system, we studied electrode polarization. Figure 2a summarizes the polarization of CuSO₄//Cu and OYO electrodes in a faceto-face configuration. The face-to-face configuration of CuSO₄/Cu electrodes shows low polarization at low frequencies, and this increases with frequency. This is opposite to the face-to-face configuration for plastic OYO electrodes. The substantial DC polarization of the plastic OYO electrodes decreases at higher frequencies. The polarization reaches a level of instrument error around 100 Hz, and stays close to zero from 100 Hz to 10 kHz. We had to check whether this "extra" electrode polarization is an intrinsic property of the electrodes themselves, or a function of their interface in the face-to-face configuration. Indeed, there is a membrane-to-membrane interface in the case of CuSO₄/Cu electrodes and possible capacitive coupling of metal pin plates inside the plastic OYO electrodes. These factors are due to the interface structure of the electrodes rather than the electrode materials. To clarify this, we placed a separation between the electrodes, and measured the CR signal. We placed the PVC cartridge, which was filled with distilled water (DW) between the electrodes to separate them. Figure 2b shows the result of this test for the CuSO₄/Cu and OYO electrodes. It is

High-frequency IP measurements of hydrocarbon-bearing rocks

apparent that, with a separation between the electrodes, the polarization of the electrodes is within instrumental error. Indeed, Figure 2b shows a 5 mrad phase error at 100 kHz for the DW cartridge placed between the $CuSO_4/Cu$ electrodes. The results of the same tests, but with OYO electrodes, are also shown in Figure 2b. As for the $CuSO_4/Cu$ electrodes dramatically decreases both at low and high frequencies as the resistivity of the material between these electrodes decreases. For DW cartridges (i.e., very resistive media), the low-frequency polarization of the OYO electrodes does not exceed 25 mrad at low frequencies.



Figure 2. Panel (a) shows phase spectra of Cu-CuSO₄/Cu (blue line) and OYO geo-gel (red line) pairs of electrodes in the face-to-face configuration of an optimized CR configuration. Panel (b) presents the phase response of the Cu-CuSO₄ electrodes (red line) with a distilled water separation (in PVC cartridge) between the electrodes. The blue line in this figure corresponds to the same measurement for the OYO electrodes.

Complex resistivity measurements of internal induced polarization of oil-based mud

We previously measured the low-frequency IP responses from artificial rocks saturated with synthetic mineral oil (Burtman et al., 2009, 2010). For this study, Baker Hughes provided an oil-based mud, which we then used in our high-frequency IP experiments. Oil-based mud is a drilling fluid, whose base is a petroleum product similar to diesel fuel. The exact composition of the oil-based mud was not disclosed. The sample holder was assembled as an empty PVC cartridge with ribbon O-rings on the side attached to the OYO electrodes using mounting ribbons. Different liquids could be placed in the sample holder through a hole drilled in the PVC wall. The PVC tube was first mounted between the OYO electrodes, and then filled with liquid using a syringe. The cotton pads were not used for contacts. The same syringe was also used to evacuate the liquids from the PVC tube. First, tap water (TW) and distilled water (DW) were tested as control experiments. Following these tests, the oil-based mud sample was measured. Results are shown in Figure 3.



Figure 3. $CR(\omega)$ measurments of mud oil based mud (Oil mud) vs. tap water (TW) and distelled water (DW), and OYO electrodes in face-to-face configuration. Left panel (a) shows the real resistivity, and the right panel (b) shows the imaginary resistivity.

The following DC resistivities were used for calculating the complex resistivity: $R_{DC}^{oil-mud} = 106.8 \text{ k}\Omega / \text{m}$, $R_{DC}^{DW} = 91.4 \text{ k}\Omega / \text{m}$, $R_{DC}^{TW} = 15.6 \text{ k}\Omega / \text{m}$, and $R_{DC}^{OYO-OYO} = 51.5 \text{ k}\Omega / \text{m}$. We observed the internal IP of the sample to be much larger than the external IP, implying that polarization due to the optimized CR system and OYO electrodes was negligible. We also noted that the tap and distilled water polarization from 1 kHz was also negligibly small. The oilbased mud showed a well pronounced peak rising from 1kHz and extending to higher frequencies. It is obvious from Figure 3 that the electrode-related artifacts are practically negligible compared to the oil-based mud sample's complex resistivity response. This is similar to a conclusion that we previously reached for hydrocarbon-saturated rocks (Burtman et al., 2009).

Dielectric spectroscopy of oil-based mud

For organic solvents and suspensions. the dielectric spectrum exhibits relaxation. It is well known that the real part of the complex resistivity is related to the resistivity and loss terms, and the imaginary part is related to the polarization. In the case of the complex dielectric constant, the real part is related to the polarization and the imaginary part is related to the resistivity and loss terms. The dielectric spectrum of the oil-based mud sample was measured using a Novocontrol BDS 80 system. The frequency dependence of ε ', as shown in Figure 4a, supports our initial interpretation that IP responses should

High-frequency IP measurements of hydrocarbon-bearing rocks

be expected in oil-based mud samples at high frequencies. The dielectric constant ε ' is related to the polarization strength and can be converted to imaginary resistivity. These results can then be compared to our complex resistivity results from the Zonge CR system in Figure 4b. Despite instrumental and methodological differences between these two measurements, it is apparent that the imaginary resistivity calculated from the ε ' measurements follows the trend observed in CR measurements, i.e., the nonlinearity of the imaginary resistivity spectrum observed in the 100 Hz to 10 kHz range is reproduced in independent measurement. This nonlinearity continues to grow at elevated frequencies for the dielectric measurements.



Figure 4. Left panel (a): Dielectric function (ε) of the oilbased mud (OBM) sample measured using dielectric spectroscopy. Right panel (b): Comparison of the imaginary resistivity obtained by the CR(ω) and dielectric spectroscopy measurements.

Conclusions

The methodologies for high-frequency (up to 10 kHz) IP measurements using the Zonge complex resistivity (CR) system have been developed, and these are based on electrical R and RC circuits, studies of electrode polarization, and optimization of the measurement system. We have demonstrated that it is possible to deconvolve an intrinsic IP response from external polarization factors as nonlinearity in response to measurement setup and electrode polarization. Our new results have validated the reliability of the high-frequency IP measurements that were independently confirmed by measuring the CR spectrum of the same samples using the Novocontrol BDS 80 system. In this paper, we measured the IP responses for oil-based

In this paper, we measured the IP responses for oil-based mud, which showed an IP response from 100 Hz to MHz frequencies. As such, we have experimentally shown the need to account for IP effects in reservoir rocks. This will be particularly important for interpretation of induction well logs. That said, further research is required to fully understand the frequency-dependence of different polarization mechanisms that occur in reservoir rocks.

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EDITED REFERENCES

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