Advances in experimental research of induced polarization effect in reservoir rocks

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Summary

We have studied the IP response of the multiphase porous systems by conducting complex resistivity (CR) frequency domain IP measurements for two different groups of samples: sands and sandstones containing salt water in pores and those whose unsaturated pores are filled with synthetic oil. We have observed the IP behavior in the imaginary parts of the analyzed complex resistivity curves. We have studied statistical aspects of CR measurements in HC-saturated samples using sand-cartridge-oil (SCO) and sandstone-oil (SSO) samples. A comparison of the complex resistivity of SCO and SSO samples with different saltwater pH values demonstrates a known shift of the IP peak to lower frequency with a decrease in pH. We used a GEMTIP model to analyze the IP parameters of the measured responses.

Introduction

The polarization phenomenon was previously studied in detail by Wait (1959), and its modern development stems largely from the work done by Bleil (1953). The theoretical foundations of the IP effect in complex multiphase heterogeneous rocks based on effective-medium theory (EMT) were developed by Zhdanov (2006, 2008a, 2008b, 2009).

In this paper we study the IP response of multiphase porous rocks by conducting complex resistivity (CR) frequency domain IP measurements. This study is based on laboratory analysis and the modeling of IP and resistivity measurements on a set of sandstone samples from southern Utah. These results are compared with those obtained for synthetic rock samples, prepared using chemically pure sand, de-ionized (DI) water, and synthetic oil.

A systematic and thorough laboratory experiment, which is the purpose of this study, is needed to understand how oil within the sandstone samples affects induced electrical polarization laboratory measurements. The fact that clay minerals have the ability to conduct electricity through ion exchange reactions with pore fluids indicates that the IP technique has a potential for HC resource evaluation. The results of the lab measurements may provide a basis for future development of low-cost noninvasive methods for direct search for hydrocarbons.

We studied the IP effect in multiphase porous rocks in view of possible application in HC exploration. The results of our study show that a resistivity of this sample is complex and frequency dependent and that the oil-saturated sands and sandstone samples can be characterized by a significant IP response. Thus, the ultimate goal of this paper is to determine the potential practical significance of the IP effect in HC exploration.

Methodology of the lab experiments

Despite decades of research, the exact origin of the IP effects is not fully understood. In addition, the IP effect should be isolated from other effects, which accompany EM measurements. The electrode polarization effect is one of the main distortion factors, especially at low frequencies, which should be isolated from the observed data. The electrode effect is related to the processes taking place at interfaces between an electrolyte and metal or metallic mineral grains. When a metal is brought in contact with water, positive metal ions will dissolve, leaving the electrons in the bulk metal. The dissolution will occur until the chemical potential in the solution and the metal reach an equilibrium. The positively charged ions in the solution are attracted to the negatively charged metal surface, and a so-called electrical double layer is formed. The ions must cross this potential barrier in order to pass into the solution, and thus the double layer tends to prevent further dissolution. Hence, the ions in the solution are separated from the metal surface by a layer of solvent molecules, which is generally on the order of a few Angstrom. The EM induction coupling should also be removed from the IP effect. The EM induction coupling is an especially important and essential issue for field measurements.

These problems are typical for interpretation of the complex resistivity (CR) spectra of mineral samples. There are limited spectral IP data available for oil-saturated rocks and for the controls of the accuracy of EM measurements on reservoir rock samples, in particular of electrical impedance spectra. In this context, the reliability of the measurements itself represents a key step for future studies of the IP effect in reservoir rocks.

In this paper, we present the new results of an experimental study of the IP effect in oil-saturated rock samples. In particular, we provide experimental data on (i) evaluating the errors in the CR measurements, (ii) dependence of the CR measurements on pH, and (iii) the shift of IP signal at low frequency range, while decreasing pH. The measurements were conducted in the facilities of the Zonge Engineering and Research Organization.

<ins>The measurement setup</ins>

We used a Zonge GDP16 CR measurement setup to test the HC-saturated rock samples. The GDP16 system contained a transmitter specially designed for laboratory measurements, a sample holder, and a decade resistance box. The sample holder consisted of two separate containers filled with a saturated $CuSO_4$-solution. Two copper screens were inserted into the solution in each of the holders to allow for current application and for measurements of potential difference across the sample. The facing sides of the containers consisted of a porous ceramic material that allows for current flow.

Preparation of the samples

We studied several types of rock samples: sand-cartridge-oil (SCO), sand-cartridge-water (SCW), and sandstone-oil (SSO). A detailed description of these samples will be given below.

We prepared two types of samples for measurement. The first type is represented by sandstone samples collected in southern Utah. They were cut to 30×30 mm cross sections 40 mm in length and polished to produce a rectangular shape. The second type of samples was formed by artificially prepared oil-saturated sands. The sample preparation protocol followed the protocol established in our previous publication (Burtman et al., 2009) with the following differences:

1) The concentration of saltwater in the SSO and SCO samples was exactly 10 times smaller than in the original protocol. We dissolved 7.45 mg of KCl in 1L of de-ionized water (DI). The concentrations of KCl in DI water were 1 and 10 mM respectively. We compared the CR of the SCO and SSO samples with these concentrations.

2) We changed the plugs in the SCO samples from brass to copper to avoid unknown electrode polarization in the brass alloy.

3) We changed the shape of the electrodes in the SCO sample to avoid potential electrode polarization due to geometrical factors (Burtman, 2010).

Testing protocols

The testing protocol involved testing the SCO and SSO samples five times in sequence. Each frequency was taken once, but the CR at the whole frequency range was repeated five times to obtain the representative statistics. The shunt resistance (resistance equal to the resistance of a sample) was manually set every time the resistance of the sample was changed with the frequency. The measurement time for the entire frequency range measurement was about 25-35 minutes. The current during CR measurements did not exceed 0.2 mA. The time interval between adjacent measurements was more than 10 seconds, which should have allowed us to consider every measurement event to be independent and not correlated with the previous measurement. Indeed, the typical relaxation time in mineral rock samples is 1 second.

Data statistics

We have analyzed some statistical information about the observed data using the following conventional statistical parameters. The standard deviation (SD) and the standard error of the mean (SE) are calculated as follows:

$$SD = \sqrt{Var}; Var = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2; SE = \frac{SD}{\sqrt{n}}.$$

where: n is a sample size, and $\bar{X}$ is a mean value. The averaged data points were plotted with SD and SE error bars for each data set.

Data processing and interpretation

SCO measurements and data statistics

We examined the sand-cartridge-oil (SCO) samples first. The apparent real and imaginary resistivity data were used for statistical analysis and plotted in Figure 1 (A and B).

Figures 1(C and D) summarize the observed data and corresponding statistics. A comparison of SE to an average value shows that the error bars for amplitude of the apparent resistivity (0.9-1.27%) and for real resistivity (0.22-1.31%) are very similar. The same relationship between the average values and SE was observed for error bars calculated for phase (1.08-10%) and imaginary resistivity (1.01-11%). A small deviation in error bars could be explained by small changes in ρ_0, which decreased with time due to negligibly small charge-trapping in the sample.

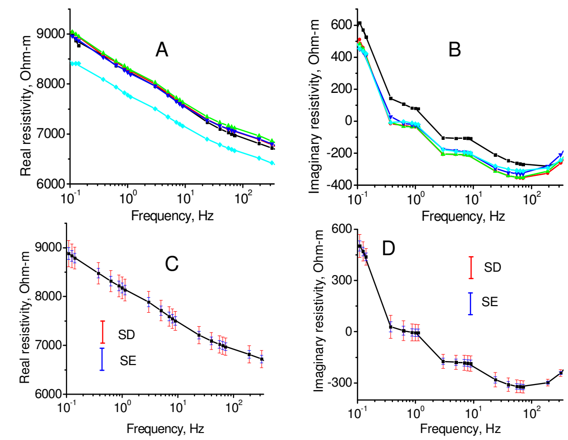

Figure 1: Spectral real and imaginary apparent resistivity plots for sand-cartridge-oil (SCO) samples measured five times in sequence. (A) Real resistivity spectra. (B) Imaginary resistivity spectra. (C) Standard deviation (SD) and standard error (SE) for the mean values of real resistivity spectra. (D) SD and SE for mean values of imaginary resistivity spectra.

SSO measurement and statistical data analysis

As in the previous section, we determined first the amplitude and phase of the apparent resistivity of the samples, and then transformed these parameters into the real and imaginary resistivities. We also calculated the statistical values of SE and SD for the observed apparent resistivity. In general, these values were lower than for the SCO CR measurements. Figures 2 (A and B) present the real and imaginary resistivites of the SSO samples. The statistical values SD and SE for the SSO samples are shown in Figure 2(C) for the real resistivity spectrum and in Figure 2(D) for the imaginary resistivity.

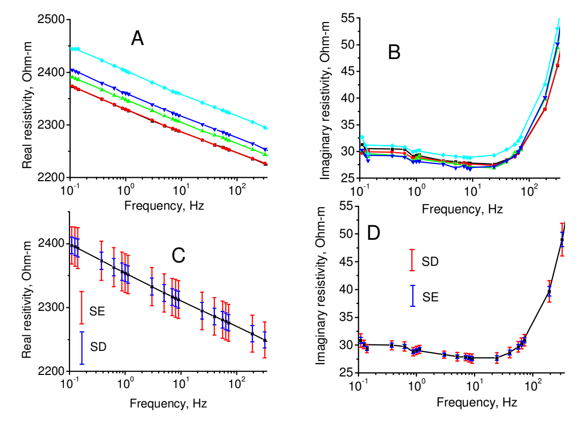

Figure 2: Spectral real and imaginary apparent resistivity plots for the sandstone-oil (SSO) samples measured five times in sequence. (A) Real resistivity spectra. (B) Imaginary resistivity spectra. (C) Standard deviation (SD) and standard error (SE) for the mean values of the real resistivity spectra. (D) SD and SE for the mean values of the imaginary resistivity spectra.

Comparison of CR of SCO and SSO samples with different pH values of contained saltwater

We conducted a study of SCO samples with variable saltwater pH. This is an important problem in the case of the IP effect in nonmetallic media, e.g., in reservoir rocks. Beside an obvious fundamental academic interest, the solution of this problem is also critical in order to verify the feasibility of the IP method in HC exploration. It was observed by Slater (2005) and Jougnot (2010) that the IP peak was shifted toward a lower frequency as the pH of the electrolyte became smaller. To reproduce this observation in our experimental measurements of the reservoir rock samples, we tested two SCO samples and two SSO samples. In each case we changed the pH of the saltwater used for the sample preparation only. Figures 3(A) and Figure 3(B) present the real and imaginary spectra of SCO samples with different saltwater pH absorbed on the sand cluster. Similar behavior was observed in the SSO samples. Figures 3(C) and Figure 3(D) compare the real and imaginary spectra of the SSO samples with different saltwater pH values, which were the same as for the SCO samples. The observed experimental results correspond well to those reported in the literature (e.g., Slater, 2005): the frequency of the IP peak decreases with the decrease in the pH of the electrolyte.

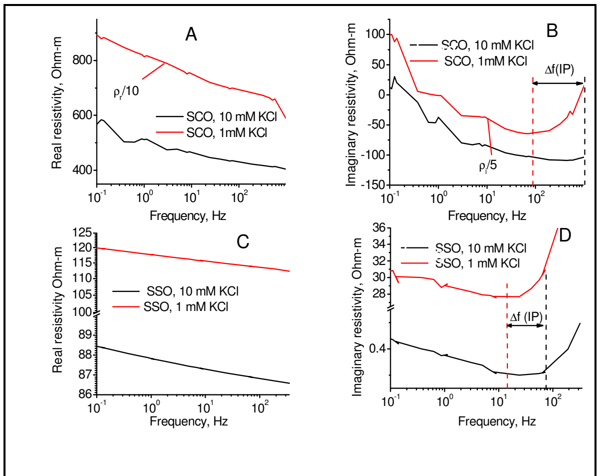

Figure 3: CR spectra of SCO and SSO samples, which were prepared using different saltwater pH values (1 and 10 mM). (A) The real parts of the resistivity-vs.-frequency curves for the sand-cartridge-oil (SCO) samples. (B) The imaginary parts of the resistivity-vs-frequency curves for the sand-cartridge-oil (SCO) samples. (C) The real parts of the resistivity-vs.-frequency curves for the sandstone-oil (SSO) samples. (D) The imaginary parts of the resistivity-vs-frequency curves for the sandstone-oil (SSO) samples.

Modeling of the CR curves using the general effective medium theory of induced polarization (GEMTIP) model

Originally, a two-phase GEMTIP model (Zhdanov, 2006, 2008a) was used to determine the IP parameters from the recorded electrical data:

$$\rho_{eff} = \rho_0 \left\{ 1 + f_l m_l \left[1 - \frac{1}{1 + (-i\omega\tau_l)^{C_l}} \right] \right\}^{-1},$$

$$m_l = 3\frac{\rho_0 - \rho_l}{\rho_0 + \rho_l}, \tau_l = \left[\frac{a_l}{\alpha_l}(2\rho_0 + \rho_l) \right]^{1/C_l},$$

where ρ_{eff} [Ω-m] is the resulting effective resistivity, ρ_0 [Ohm-m] is the matrix resistivity of the rock being modeled, f_l is a volume fraction of a grain, m_l is a grain chargeability ω [Hz] is an angular frequency, τ_l [second] is a time constant, C_l is a decay coefficient, ρ_l [Ω-m] is a grain resistivity, a_l [meter] is a grain radius, and α_l is a surface polarizability coefficient. We applied the GEMTIP model to fit the experimental data. The five fitting parameters were varied. The meaning of the GEMTIP parameters for an oiled sandstone sample was modified for an oil-reservoir model (Burtman 2009). In addition to C_l and α_l, which were optimized to fit the experimental data, the fraction volume, parameter f_l was varied as well.

Figure 4 shows the observed real and imaginary resistivity data for the SCO samples and the corresponding theoretical resistivity curves obtained using the GEMTIP model for spherical grains. The mean data shown in Figure 1 (C and D) were used as an input file, following statistical data analysis.

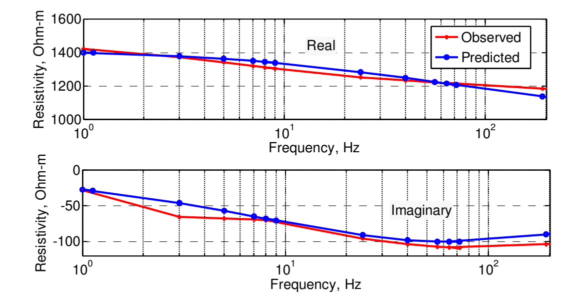

Figure 4: The imaginary resistivity spectrum of a sand-cartridg-oil (SCO) sample. The lines formed by stars represent experimental data, while the lines formed by circles corresponds to the theoretical GEMTIP model.

The initial and resulting parameters of the GEMTIP model for data obtained from the measured sandstone sample are summarized in Table 1.

Table 1: Initial and resulting parameters of the GEMTIP model for an SCO sample.

Variable	Units	Initial	Recovered
Oil resistivity, matrix, ρ_0	Ω-m	10^5	-
Fraction of cond. sand clusters, f_l	%	0.5	0.35
Decay coefficient, C_l	-	0.75	0.86
Saltwater resistivity, ρ_l	Ω-m	300	-
Conductive cluster size, a_l	mm	5	1.2
Surface polarizability coefficient, a_l	Ω-m2/secCl	0.5	0.47
Misfit	%	-	5.47

Conclusion

The results presented in this paper contribute to a better understanding of the nature of the IP effect in HC reservoirs. We have developed a model in the context of the effective-medium approach to describe a mechanism of induced polarization in oil-saturated sands and a methodology for experimental study of this effect.

We have observed a pronounced IP effect in sand-cartridge-oil (SCO) and sandstone-oil (SSO) samples, which were artificially saturated with synthetic oil. A careful comparison of the EM response from oil-saturated sandstones with control samples (sand cartridges) demonstrated that the difference in shape and amplitude of the peak of the IP response is attributed to the difference of structural features in oil-saturated sandstones.

First, we have also studied statistical aspects of CR measurements in HC-saturated samples using SCO and SSO samples. The error bars for complex resistivity amplitude and phase for both the SCO and SSO samples were smaller than those for the real and imaginary resistivities of the same samples. Overall the statistical evaluation proved the reliability of our measurements.

Second, comparison of the complex resistivity (CR) of the SCO and SSO samples with different saltwater pH values demonstrated a known shift of the IP peak to a lower frequency with the decrease in pH (Slater, 2005).

Third, we applied the effective-medium approach, GEMTIP, to analyze the complex resistivity of the oiled sandstone. The numerical comparison of the experimental data with the data predicted by the GEMTIP model, based on the rigorous solution of Maxwell's equations for a heterogeneous media, has proved the validity of the GEMTIP model for analysis of the induced polarization phenomenon in reservoir rocks.

The results of our study show that the oil-saturated sands and sandstone samples are characterized by a significant IP response. These experimental observations, compared with the theoretical modeling based on the GEMTIP approach, confirm earlier geophysical experiments with the application of the IP method for hydrocarbon (HC) exploration.

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