Induced polarization in hydrocarbon-saturated sands and sandstones: experimental study and general effective medium modeling

Summary

We have studied the induced polarization (IP) response of multiphase porous systems by conducting complex resistivity (CR) frequency-domain IP measurements for sands and sandstones samples containing salt water in pores and those whose unsaturated pores were filled with synthetic oil. The results of our study show that the oil - saturated sands and sandstone samples are characterized by a significant IP response. We used a generalized effective-medium theory of induced polarization (GEMTIP) model to analyze the IP parameters of the measured responses. A conceptual GEMTIP model of polarizing clusters is proposed to explain the observed IP phenomena. Our studies confirm earlier geophysical experiments with the application of the IP method for hydrocarbon (HC) exploration.

Introduction

The measurement of the electrical induced polarization (IP) effect has proven to be one of a few geophysical methods providing in situ information about rock mineralogy, especially in the search for disseminated minerals with electronic conductivity. At the same time, the method has been applied to study the earth materials that do not contain conductive minerals, like sedimentary rocks. The previous IP studies of nonmetallic earth materials were focused on clay mineral soils, sandy and shaly sediments containing clay minerals (Klein and Sill, 1982). Laboratory studies of the electrical characteristics of such rocks show diagnostic signatures of what they consist of and thus, can lead to a proper classification of rocks in terms of the presence of clay and other materials. At the same time, the study of reservoir rocks was limited and did not include a quantitative analysis of the relationships between the petrophysical parameters of the rock samples and the IP responses.

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 were developed by Zhdanov (2006; 2008a, b).

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 modeling of induced polarization and resistivity measurements on 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.

Preparation of the samples

We prepared two types of samples for a measurement. The first type is represented by the sandstone samples collected in southern Utah. They were cut to 30×30 mm cross section and 40 mm length size and polished to produce a rectangular shape. The second type of samples was formed by artificially prepared water and oil saturated sands and oiled sands. Figure 1 shows the photograph of these samples. The following steps describe the sample preparation.

1. Sieved commercial EMD Co. chemically purified quartz sand (0.1- to 0.25-mm grain size) was cleaned from clay and dust particles by repeated washing. The quartz mineral density was about 2.62 g cm^{-3}. After saturation in saltwater at the first stage and in synthetic oil at the second stage, as described below, the samples of the second type were placed in a sample holder, a polyvinyl chloride (PVC) tube (a cartridge). The PVC tube had 30 mm in external diameter, 27 mm in internal diameter, and was 70 mm long. It was covered at both ends by 4 mm-thick brass stoppers and sealed with epoxy glue.
2. We conducted the measurements of the IP responses of the samples at two states. At the first state, the sandstone samples and the sand cartridges had been saturated in 0.1 mM of KCl water solutions for 48 hours. We conducted the measurements on half of the samples at this state. A sand sample saturated with the saltwater was transferred to a cartridge. We kept the sandstones saturated with the saltwater and the sand cartridges isolated from the atmosphere in Ziploc bags to reach and maintain equilibrium between the liquid and solid phases.
3. The other half of the samples was saturated with synthetic light oil containing less than 0.5% of vitamin E, which was added to prevent oil oxidation. This process is described below. The sand sample saturated in saltwater was dried over a Pyrex Buchner funnel on a 90 mm perforated plate using 42.5 mm filter-paper support discs and Whatman qualitative filter paper, grade 3, at a vacuum pressure differential in excess of 0.5 atm. Immediately after removing the saltwater excess by soaking the sand with the residual saltwater on quartz grains, it was exposed to synthetic oil and soaked using the same Buchner setups three times. The product was loaded into a cartridge and stored in air isolated bags as described above.
4. For oil saturation of sandstone samples we prepared a 30/70 volume ratio solution of heptane and synthetic oil.

After a drying procedure, the sandstone samples were saturated for 12 hours in this solution to evaporate heptane from the sandstones. We repeated this procedure three times to maximize the oil content in the pores of the sandstone. We used diluted synthetic oil to decrease its viscosity and, therefore, to facilitate the penetration of oil into the pores of the sandstone. The product was stored in air isolated Ziploc bags as described above.

Figure 1: Photograph of sandstone (left) and sand cartridge (right).

Data collection and acquisition

We tested the viability of the IP in HC-saturated sands with multifrequency EM measurements at Zonge Engineering and Research Organization, Inc, Tucson, Arizona. In order to measure the complex resistivity (CR) of the rock sample, we injected a current at a frequency range of 0.0156 - 9216 Hz and measured the amplitude of the voltage and its phase with respect to the current. The frequency domain data were recorded for 36 frequencies in the scanned range. The CR measurement involved normalizing the amplitude and phase data by the DC resistivity. These two parameters were transformed into the actual real and imaginary resistivity values in Ohm-m.

Control experiments

To establish an unsaturated sandstone matrix resistivity as a reference, we used the DC measurements. We found that both bare (unsaturated) sandstone and oil-saturated sandstone (without preliminary saltwater soaking) had an almost infinitely large DC resistivity. The next control experiment involved the measurement of sandstone exposed to DI water (not salted KCl water) for 12 hours. This sample had a measurable DC resistivity caused by residual salt contained in the sandstone matrix. However, the resistivity of the sample changed with time due to nonequilibrium electrochemistry in this sample. Therefore, in our experiments we found that (i) saturation with saltwater is necessary ingredient in sample preparation for EM measurement of dry and oil-containing sandstone samples, and (ii) for a systematic EM study of sandstone samples, the pH of salt water should exceed the pH of the residual salts.

In this study the samples saturated by saltwater only (as described in section 2 of the sample preparation) were considered to be the control samples for the measurement of the oil-containing samples (as described in sections 3 and 4 of the sample preparation). The samples which were not saturated by oil were prepared exactly under the same conditions as the hydrocarbon-containing samples. Therefore the difference between the measured EM responses in the controlled and hydrocarbon-containing samples corresponds to the presence of hydrocarbons and not to geometry and measurement artifacts. On the other hand, the measurement of the IP effect in the oil-saturated sand cartridge rules out the possibility of an IP effect due to metallic inclusions in the sandstone samples, which might contain traces of graphite, etc. Comparison of SCW and SCO samples rules out possible contribution of brass electrodes into IP effect. In addition, a measurement system itself was isolated from the high frequency sources and was calibrated by the internal reference to avoid possible induced charges and nonlinearity in the system response. Thus, we took all possible precautions to determine the real IP effect in the sandstones, which was entirely due to cation-radical polarization on the boundary between the oil, saltwater, and the surface of the solid rock matrix.

Data processing and interpretation

We used the measured frequency domain data to calculate real and imaginary parts of the complex resistivity curves for different rock samples. The qualitative analysis shows that the calculated resistivity curves have a characteristic shape similar to the predicted effective resistivities computed according to the GEMTIP resistivity relaxation model (Zhdanov, 2008a). We also conducted a quantitative analysis of the observed data using the GEMTIP model, which will be discussed below.

Figures 2 presents the recorded imaginary resistivity vs. frequency curves for samples SCO (sand-cartridge-oil) and SCW (sand-cartridge-water) respectively. Figure 3 present the recorded resistivity vs. frequency curves for SSO (sandstone-oil) samples. It is evident that the resistivity relaxation curves for both the SSO and SCO samples are characterized by a pronounced IP effect. Note also an essential negative IP effect in Figure 2 for the SCO sample.

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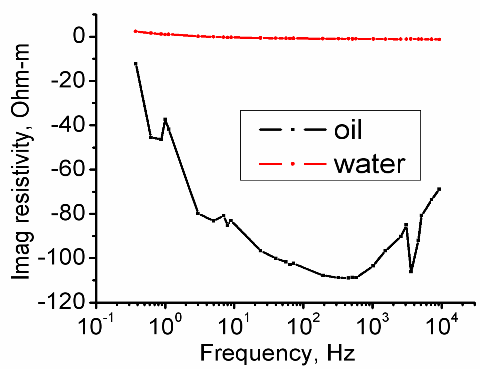

Figure 2: The imaginary parts of the resistivity vs. frequency curves for the water (SCW) and oil-saturated sand (SCO) cartridges.

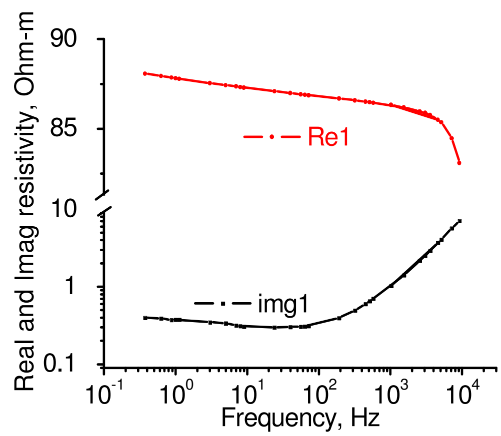

Figure 3: The real and imaginary resistivities of the oil-saturated sandstone (SSO) sample.

Both Olhoeft (1985) and Titov (2004) observed a similar phase/imaginary part increase at higher frequencies (near 10^3 Hz) that is seen in the data for samples SSO and SCO. Olhoeft (1985) attributed this increase to the cation exchange capacity (CEC) effect at higher frequencies. He also reported sizable negative IP effects in several samples. However, the nature of the negative IP effect still has to be clarified (Walker, 2008). Although the sand-cartridge-oil (SCO) sample exhibited a broad IP peak, it still could be compared to the IP peak in the saltwater-saturated sandstone sample (SSO). The difference is possibly due to the principally different configuration of pores in the sandstone samples and, therefore, to the different geometry of the 'distributed capacitor' in HC-saturated sands. We applied the principles of the generalized effective-medium theory (Zhdanov, 2008a) to analyze and interpret the observed data.

Basic formulas of the effective-medium theory of induced polarization

In the framework of the GEMTIP model, we represent a complex heterogeneous rock formation as a composite model formed by a homogeneous host medium of a volume V with a complex conductivity tensor $\hat{\sigma}_0(r)$ (where **r** is an observation point) filled with grains of arbitrary shape and conductivity.

In the general case, the rock is composed of a set of N different types of grains, the l^{th} grain type having a complex tensor conductivity $\hat{\sigma}_l$. The grains of the l^{th} type have a volume fraction f_l in the medium and a particular shape and orientation.

Following Zhdanov (2006, 2008a), we can write the following expression for the effective conductivity of the polarized inhomogeneous medium:

$$\hat{\sigma}_e = \hat{\sigma}_0 + \sum_{l=1}^{N}\left[\hat{I} + \hat{p}_l\right]^{-1}\left[\hat{I} - \Delta\hat{\sigma}_l^p(r)\hat{\Gamma}_l\right]^{-1}\cdot\left[\hat{I} + \hat{p}_l\right]\cdot\Delta\hat{\sigma}_l f_l, \tag{1}$$

where $\hat{\sigma}_e$ is an effective-medium conductivity tensor; $\Delta\hat{\sigma}_l$ is an anomalous conductivity tensor; $\Delta\hat{\sigma}_l^p = \left[\hat{I} + \hat{p}_l\right]\cdot\Delta\hat{\sigma}_l$ is the polarized anomalous conductivity; $\hat{p}_l$ is a surface polarizability tensor; $\hat{\Gamma}_l$ is a volume depolarization tensor; and index l corresponds to the grain of the l^{th} type.

The last formula provides a general solution of the effective conductivity problem for an arbitrary multiphase composite polarized medium. This formula allows us to find the effective conductivity for inclusions with arbitrary shape and electrical properties. That is why the new composite geoelectrical model of the IP effect may be used to construct the effective conductivity for realistic rock formations typical for mineralization zones and/or petroleum reservoirs.

We used a simplest case of a spherical two-phase GEMTIP model for data modeling. It could be shown that in this case formula (1) could be simplified (Zhdanov, 2006, 2008a) and used to determine mineralization or hydrocarbon saturation from the recorded electrical data:

$$\rho_{e\alpha} = \rho_0 \left\{ 1 + f_l m_l \left[1 - \frac{1}{1+(-i\omega\tau_l)^{-C_l}} \right] \right\}^{-1}, \qquad (2)$$

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

where $\rho_{e\alpha}$ [Ohm-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 volume 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 [Ohm-m] is a grain resistivity, a_l [m] is a grain radius, and α_l is a surface polarizability coefficient.

Conceptual model of sand-cartridge-oil sample

We consider a multiphase model, which is formed by sand clusters (Prince et al, 1995), covered by a layer of conductive saltwater and oil matrix as a structural model. In this model, the saltwater-filling space is considered as a "conductive grain", which sustains the large current. The volume filled by oil is considered as a "rock matrix" having mostly dielectric properties. The areas of contact of the individual grains are considered as narrow conductive passageways through the thin water films on the grain surfaces. These areas of contact form large sand clusters, covered by a layer of water, which are treated as large conductive passageways. The polarization of the saltwater-saturated clusters in this condition should be larger than that of the saturated oil, which occupies the rest of the porous space. In this model the IP effect is caused mostly by the electrical double layers formed on the boundaries between the sand clusters and oil matrix. The conceptual model is capable of explaining the observed frequency dependence of the IP effect in structural terms. Our model suggests that at the critical water content, pore water becomes predominantly adsorbed on the solid surface. Therefore, a generic cation exchange capacity (CEC) effect and the electrical double layers on the surface of the sand clusters form a spatially distributed capacitor (see right panel 2 in Figure 4). The shape and composition of this spatially distributed capacitor define the nature of the IP effects in hydrocarbon-saturated sands. We calculate the resistivity relaxation curve for this model using the GEMTIP approach. The GEMTIP curve fits well the electrical imaginary resistivity response of the sand-cartridge-oil (SCO) sample, as shown at Figure 4.

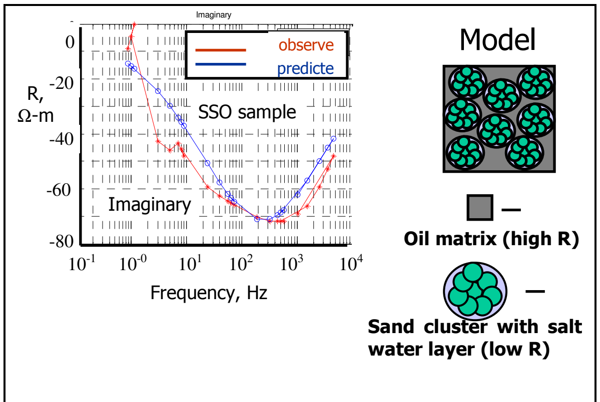

Figure 4: The electrical imaginary resistivity response of the sand-cartridge-oil (SCO) sample. The lines formed by stars represent experimental data, while the lines formed by circles corresponds to the theoretical GEMTIP model data. The conceptual model of oiled sandstone samples is shown in the right panel.

Conclusions

In this paper we have examined the possibility to detect the IP effect in HC saturated rock samples. We observed a pronounced IP effect in sandstone samples, which were artificially saturated with synthetic oil. The observed IP effect was attributed to membrane polarization phenomena. We have developed a conceptual model of sand-cartridge-oil sample. The GEMTIP method was used to analyze the IP effect in the HC-saturated sands and sandstones. In an agreement with the earlier geophysical experiments our study confirms the feasibility of employing the IP method for HC exploration.

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EDITED REFERENCES

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