Spectral induced polarization effect in unconventional reservoir rocks

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Summary

Unconventional hydrocarbon (HC) reserves, e.g., heavy oils, bituminous sands, and oil- and gas-shale substantially surpass those of conventional resources and therefore are extremely economically attractive; however, exploration and production of unconventional reserves is challenging. This paper demonstrates that one can observe significant induced polarization (IP) effects in shale reservoir rocks, which can be used in exploration for unconventional reserves. This study is based on application of the generalized effective-medium theory of induced polarization (GEMTIP) for analysis of the complex resistivity (CR) of oil- and gas-shale rocks. GEMTIP modeling provides a basis for remote petrophysical analysis of shale rocks, which we compared with an actual structural analysis of shale rocks using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and core analysis. We demonstrate that GEMTIP modeling provides an evaluation of mineral composition and volume fractions in rock samples. Spectral induced polarization (SIP) measurements were conducted for different types of shale rocks to test the feasibility of the SIP method and GEMTIP modeling for studying unconventional HC reserves. The results of this study provide a basis for future application of the SIP method for exploration and monitoring of unconventional reserves.

Introduction

Alternative energy resources such as shale gas, tar sand, and shale oil represent an increasingly important source in meeting world energy and economic needs. Unconventional gas production from both tight sand and shale formations could increase from 47 percent of the U.S. total in 2006 to 56 percent in 2030 according to U.S. Energy Information Administration and BP reports published in 2012. Shale-gas technology already plays an essential role in the market of energy resources worldwide.

Older shale-gas wells were drilled vertically, while more recent wells primarily utilize horizontal drilling techniques; both techniques require stimulation treatments to be commercially viable. Only shale formations with certain characteristics will produce gas. Shale gas is present across much of the lower 48 states in the USA. Each shale-gas basin has unique characteristics and each offers its own exploration and production problems.

Exploration and production of unconventional reserves is challenging. The development of innovative methods for discovering and monitoring them represents an important task of geophysics. This paper investigates the possibility of using the IP effect in studying the unconventional reservoir rocks, e.g., oil- and gas-shale and tight sands. We demonstrate that one can observe significant induced polarization (IP) effects in shale reservoir rocks, which can be used in exploration for unconventional reserves.

This study is based on application of the general effective medium theory of induced polarization (GEMTIP) to the analysis of the complex resistivity (CR) of oil- and gas-shale rocks. GEMTIP modeling provides a basis for remote petrophysical analysis of shale rocks, which we compare with actual structural analysis of shale rocks using a Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and core analysis. Based on this analysis we have found that, GEMTIP modeling provides a useful evaluation of the mineral composition and volume fractions in the rock samples.

We have conducted spectral induced polarization (SIP) measurements using different types of shale rocks to test the feasibility of the SIP method and GEMTIP modeling for studying unconventional HC reserves.

Modeling the SIP response in reservoir rocks

The IP phenomena in non-metallic rocks are associated with the complex electrochemical processes taking place in the porous space. Over the last 40 years several conductivity relaxation models have been developed, which provided quantitative characterization of the electric charging phenomena, including the empirical Cole-Cole model (Cole and Cole, 1941; Pelton et al., 1978), electrochemical model of Ostrander and Zonge (1978), and the GEMTIP model of Zhdanov (2008), based on generalized effective-medium theory of induced polarization, and electrochemical model of Revil et al. (2013). The widely accepted Cole-Cole model uses empirical parameters and does not address the complexity of the rock composition, while the GEMTIP model uses the effective-medium theory to describe the complex resistivity of heterogeneous rocks. The GEMTIP resistivity model incorporates the physical and electrical characteristics of rocks at the porous/grain scale and translates them into an analytic expression for the effective complex resistivity. These characteristics include grain size, porous space shape, fluid and host rock conductivities, porosity, anisotropy, polarizability, etc. (Zhdanov, 2006, 2008).

Effective-medium model for analysis of complex resistivity in hydrocarbon-saturated rocks and inversion for the GEMTIP model parameters

In the framework of the GEMTIP model, we represent a complex heterogeneous rock formation as a composite

DOI http://dx.doi.org/10.1190/segam2014-0419.1

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 a general case, the rock is composed of a set of *N* different types of grains, the l^{th} grain type having 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, 2008), we can write the following expression for the effective conductivity of the polarized inhomogeneous medium:

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

where $\hat{\sigma}_e$ is an effective-medium conductivity tensor; $\Delta\hat{\sigma}_l$ is an anomalous conductivity tensor; $\Delta\hat{\sigma}_l^p = \left[\hat{\mathrm{I}} + \hat{\mathrm{p}}_l\right]\cdot\Delta\hat{\sigma}_l$ 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 HC reservoirs.

For this study, we have developed the three-phase ellipsoidal GEMTIP model for a medium with randomly oriented ellipsoidal inclusions. The expression for GEMTIP model in this case takes the following form:

$$\rho_{e\alpha} = \rho_0 \left\{ \begin{array}{l} 1 + f_1 \sum\limits_{\alpha = x,y,z} \dfrac{1}{3\gamma_{1\alpha}}\left[1 - \dfrac{1}{1 + (-i\omega\tau_1)^{C_1}\dfrac{r_{1\alpha}}{\bar{a}_1}}\right] \\ + f_2 \sum\limits_{\alpha = x,y,z} \dfrac{1}{3\gamma_{2\alpha}}\left[1 - \dfrac{1}{1 + (-i\omega\tau_2)^{C_2}\dfrac{r_{2\alpha}}{\bar{a}_2}}\right] \end{array} \right\}^{-1}$$

where

$$r_a = \frac{2\gamma_{l\alpha}}{\lambda_{l\alpha}}, \bar{a}_1 = \frac{a_x + a_y + a_z}{3}.$$

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 of the *l*-th grain, ω [Hz] is an angular frequency, τ_l [second] is a time constant, c_l is a decay coefficient, $\bar{a}_1$ [m] is an average value of the equatorial and polar radii of the ellipsoidal grains. The coefficients $\gamma_{l\alpha}$ and $\lambda_{l\alpha}$ are the structural parameters defined by geometrical characteristics of the ellipsoidal inclusions (Zhdanov, 2008; Burtman et al., 2010), and they are functions of ellipticity e_l. If all the grains are oriented in one specific direction, the effective conductivity of this medium will become anisotropic. Thus, the effective conductivity may be a tensor in spite of the fact that the background medium and all the grains are electrically isotropic.

The geoelectrical parameters of the GEMTIP model are determined by the intrinsic petrophysical and geometric characteristics of the composite medium. Therefore, effective resistivity can serve as a basis for determining the intrinsic characteristics of the reservoir rock (the porosity, hydrocarbon saturation, etc.).

We introduce a vector, **m**, of the unknown model parameters: **m**=[ρ_0, f_1, C_1, τ_1, e_1, f_2, C_2, τ_2, e_2], and a vector, **d**, of the observed data: **d** = [$\rho_\varepsilon(\omega_1)$, $\rho_\varepsilon(\omega_2)$…. $\rho_\varepsilon(\omega_v)$]. Thus, we have the following GEMTIP inverse problem:

$$\mathbf{d} = \mathbf{A_{IP}(m)}.$$

We use the regularized conjugated gradient method and extensive search method to solve this inverse problem (Zhdanov, 2002).

Experimental study of the IP effect in shale reservoir rocks

The viability of the GEMTIP conductivity model was tested with multifrequency EM measurements acquired for shale-oil, laminated shale gas and shale gas samples.

Shale rocks with a percentage of total organic carbon (TOC) above 3% are usually considered as organic-rich shales. These shales may be deposited over a wide range of depositional environments ranging from terrestrial to marine. They may have a wide geographic distribution, and they occur in sediments of all ages, from modern to Precambrian. The geochemical variations within black shales may reflect depositional conditions, including water-column conditions and those within the sediment, sediment provenance, variations in the source of organic matter, diagenetic alteration including hydrothermal alteration, and even weathering processes (Altun et al., 2006). For these reasons, shales can be classified by their composition (carbonate minerals such as calcite or detrital minerals such as quartz and clays) or by their depositional environment (large lakes, shallow marine, lagoon/small lake, and terrestrial settings).

Shale-oil, laminated shale gas and shale gas samples were provided by TerraTeck.

DOI http://dx.doi.org/10.1190/segam2014-0419.1

Shale samples and their thin sections are shown in Figure 1. All of the samples are rich in clay minerals, and they also contain some disseminated pyrite. The X-ray diffraction data for whole rock and clay mineralogy by weight (%) were provided by Terrateck as well.

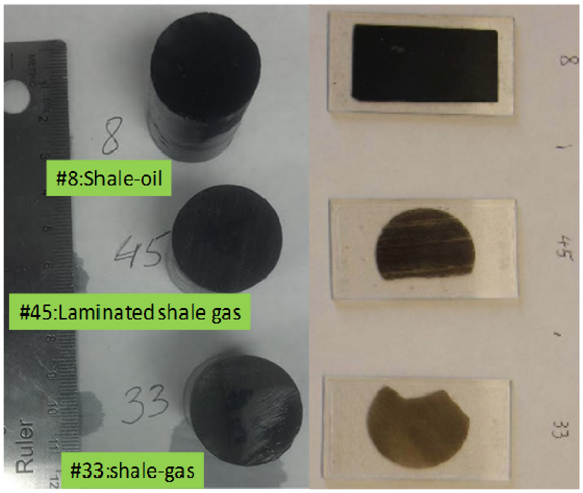

Figure 1. The left panels: photos of three shale samples. The right panels: thin sections of the same rock samples prepared for QEMSCan analysis.

The TerraTek shale samples (#8, #33, and #45) were examined using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) for structural analysis and phase evaluation. QEMSCAN® is the most powerful tool for mineralogical analysis currently employed by the minerals industry. It is a fully-automated micro-analysis system that enables quantitative chemical analysis of materials and generation of high-resolution mineral maps and images as well as porosity structure. The color-coded maps of mineral composition were created as well as a quantitative measurement of mineral abundance and inclusion size was conducted using QEMSCAN 4300, which was built on a Zeiss Evo 50 SEM platform with four light elements Bruker Xflash energy dispersive X-ray detectors. Energy-dispersive X-ray spectral analysis (EDX) involves interpretation of secondary X-ray spectra to determine elemental composition and, ultimately, mineralogy. The rock samples were prepared as standard thin polished sections, then carbon coated and submitted for the QEMSCAN measurement and analysis. The right panels in Figure 1 show samples of the thin sections prepared for the QEMSCAN measurement.

We have conducted complex resistivity measurements for each sample over a range from about 0.005 Hz to about 10000 Hz at 33 frequencies using the TechnoImaging's experimental lab. The measurement system consists of waveform generator, spectrum analyzer, PC control, and rock sample holder (Figure 2).

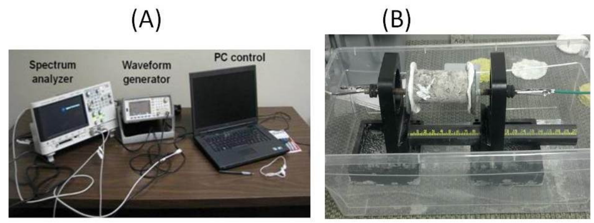

Figure 2. Complex resistivity measurement system consisting of waveform generator, spectrum analyzer, PC control (A), and rock sample holder (B).

Results of the QEMSCAN and GEMTIP analysis of the shale reservoir rocks

Figure 3 presents, as an example, the results of QEMSCAN analysis for shale-oil sample #8. Note that, 6.64% disseminated pyrite was found in this sample by the QEMSCAN measurement.

The imaginary resistivity measured for the same sample is shown in Figure 4 by red lines. We have inverted the observed complex resistivity (CR) data for the parameters of the GEMTIP models using two-phase and three-phase models. Both two- and three-phase models produce a good misfit, which is 5% for two-phase and 3.2% for three-phase models, respectively.

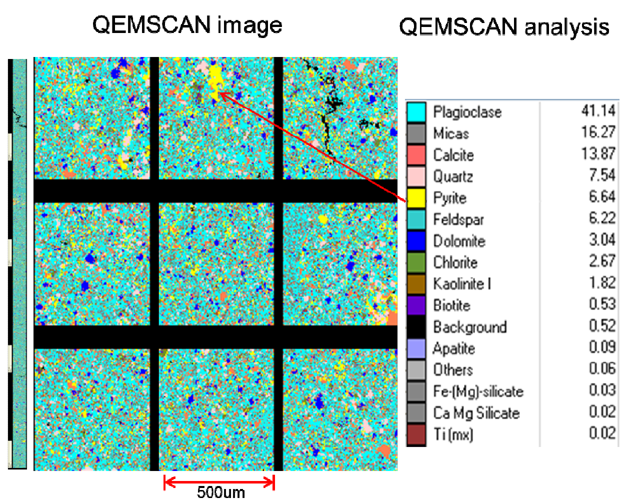

Figure 3. The QEMSCan image of shale oil on the left with a phase analysis on the right. The arrow show example of pyrite in this sample.

DOI http://dx.doi.org/10.1190/segam2014-0419.1

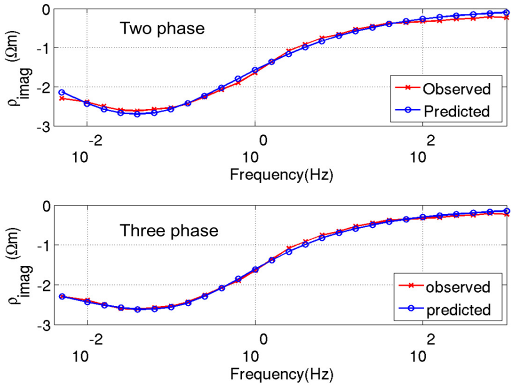

Figure 4. The complex resistivity (CR) spectra (red lines) and the data predicted based on the GEMTIP model (blue lines) for sample #8. The top panel presents the result for the two phase GEMTIP model; the bottom panel shows the result for the three-phase GEMTIP model.

Table 1 summarizes the results of GEMTIP inversion for rock sample #8. The recovered values of the volume fraction of inclusions with different electrical properties for both the two-phase and three-phase models are about 10%, which corresponds approximately to the combined volume fraction of pyrite (6.64%), determined by QEMSCAN analysis, and gas-filled porosity (p_{gas} =6.34%) determined by core analysis. It is important to note that, the three-phase inversion makes it possible to "separate" these two effects, providing volume fraction of one phase in the GEMTIP model (6.35%) representing the electrode polarization caused by disseminated pyrite, and another phase (4%) representing membraine induced polarization caused by the presense of HC in the porous space of the sample. The time constant of pyrite is larger than the time constant of HC, because the capacitance of the mineral carrying the charge is much stronger than that of the HC.

Table 1 Parameters of GEMTIP models used in Figure 4.

Variable	Units	Initial Value	Two phases	Three phases
ρ_0	Ohm-m	39	-	30
f_1	%	0.1	10	6.35
C_1	-	0.1	0.45	0.27
τ_1	seconds	0.1	1.19	2.15
f_2	%	-	-	4
C_2	-	-	-	0.59
τ_2	seconds	-	-	0.46

We should note that, the p_{gas} value in turn is directly associated with TOC in shale gas deposits. Boyer et al (2006) demonstrated that in core shale samples the ratio between TOC and p_{gas} is in 0.5-1 range. Passey et. al. (2010) reported close to 0.5 ratio between TOC and p_{gas} in shale gas deposits. This ratio was equil to 0.5 for shale samples used in our study.

The same analysis between the internal structure of the samples and their CR spectra was conducted for the shale-gas and laminated shale-gas samples. The results of the study for all three samples are summarized in Table 2.

Table 2. GEMTIP model parameters of shale samples vs. volume fraction of pyrite and porosity determined by QEMSCAN and core analysis, respectively.

Samples	**QEMSCAN results, f_1** **$f_{QEMSCAN}$, %**	**Cor analysis, f_2** **f_{gas}, %**	**GEMTIP inversion, f_1 and f_2, %**
Shale-oil	6.64	6.34	f_1= 6.35 f_2= 4
Shale-gas	1.14	7.98	f_1= 2.4 f_2= 8.11
Lam. shale-gas	3.53	1.19	f_1= 4.4 f_2= 1

One can see a clear correlation between volume fractions of different inclusions determined by inversion of CR data, and volume fraction of pyrite and porosity determined by QEMSCAN and core analysis, respectively.

Conclusions

We have conducted an experimental study of the IP effect in the shale reservoir rocks. While the exact cause of the IP effect is quite complicated, the capability of modeling this effect is very useful in improving the technique for reservoir rock discrimination.

We have examined several samples of shale rocks. The complex resistivity of these samples was measured in the lab. The shale samples were analyzed further using the QEMSCAN electron microtomography. All of these measurements provided a detailed quantitative analysis of the samples that we then used for application of the GEMTIP modeling and inversion. This study has demonstrated that the GEMTIP modeling provided an evaluation of the mineral composition and HC fractions in the rock samples. In summary, the authors believe that the results of this study provide a basis for future application of the SIP method for exploration and monitoring of unconventional reserves.

Acknowledgments

The authors acknowledge the support of the University of Utah Consortium for Electromagnetic Modeling and Inversion (CEMI) and TechnoImaging. We are thankful to TerraTek for providing the shale rock samples.

http://dx.doi.org/10.1190/segam2014-0419.1

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