Available online at www.sciencedirect.com

ScienceDirect

Resource-Efficient Technologies 1 (2015) 34–48

www.elsevier.com/locate/reffit

Review article

Induced polarization effect in reservoir rocks and its modeling based on generalized effective-medium theory

Vladimir Burtman [a,b,*], Michael S. Zhdanov [a,b,c]

[a] *Geology and Geophysics Department, University of Utah, 115 S 1460 E, ROOM 383, Salt Lake City, UT 84112-0102, USA*
[b] *TechnoImaging LLC, 4001 South 700 East, Salt Lake City, UT 84107, USA*
[c] *Moscow Institute of Physics and Technology, Institutskiy per., 9, Moscow, Russia*

Received 7 April 2015; received in revised form 19 June 2015; accepted 20 June 2015

Abstract

One of the major tasks of the petroleum resource-efficient technologies (pREFFIT) is the development and improvement of the methods of exploration for energy resources. This review paper summarizes the results of the research on induced polarization (IP) effect in reservoir rocks conducted by the University of Utah Consortium for Electromagnetic Modeling and Inversion (CEMI) and TechnoImaging. The electrical IP effect in hydrocarbon (HC) bearing reservoir rocks having nonmetallic minerals is usually associated with membrane polarization, which is caused by a variation in the mobility of the ions throughout the rock structure. This mobility is related to the size and shape of the pores filled with electrolyte and the double electrical layers. We have studied the IP response of 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 were filled with synthetic oil. We have also studied selected carbonate reservoir formations, typical of some major HC deposits. The generalized effective-medium theory of induced polarization (GEMTIP) was used to analyze the IP parameters of the measured responses. This paper presents a conceptual model of polarizing clusters to explain the observed IP phenomena. The results of this study show that the HC bearing sands and sandstone samples and carbonate rocks 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 HC exploration.

Keywords: EM exploration; Complex resistivity; Induced polarization; Unconventional energy resources; Effective-medium theory; CEMI; REFFIT

1. Introduction

The induced polarization (IP) effect is widely used in mining applications in search of mineral resources. Until recently, the IP method did not find wide application in the petroleum industry due to the complexity and ambiguity of interpretation results. However, recent improvements in IP data acquisition and interpretation have stimulated a renewed interest in its use in hydrocarbon (HC) exploration.

The measurement of the electrical 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 method has been used, though rarely, in the fields of hydrology [1,2], hydrocarbon (HC) exploration [3,4] and in environmental studies such as mapping of polluted land areas [5]. It is worth noting that previous IP studies of nonmetallic earth materials were focused on clay mineral soils, sandy and shaly sediments containing clay minerals [6]. 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 IP effect is a geophysical phenomenon which is manifested by the slow decay of voltage in the ground after the cessation of an excitation current pulse (time domain method) or

---

* Corresponding author. 115 S 1460 E, ROOM 383, Geology and Geophysics Department, University of Utah, Salt Lake City, UT 84112-0102, USA. Tel.: +1 8012442693; fax: +1 8012646708.

E-mail address: vlad.burtman@gmail.com (V. Burtman).

http://dx.doi.org/10.1016/j.reffit.2015.06.008

low frequency variation of the resistivity of the earth (frequency domain method) [7]. In simple terms, the IP effect reflects the degree to which the subsurface is able to store electric charge, analogous to a leaky capacitor. It occurs when an electric current passes through a rock or soil. If the current is interrupted, a difference in potential, which decays with time, is observed. The rate of decay of this potential (induced polarization potential) depends on the lithology of the rock, its pore geometry, and the degree of water and HC saturation. It was noted in the pioneering paper by Conrad Schlumberger (1920) [8] that this phenomenon was taking place in the bulk volume of the rock and not on the electrodes used to measure it. In an attempt to describe the observed phenomenon, he attributed the transient voltage to an electrical polarization of the ground and thus used the same phenomenon in exploiting and locating unexposed ores. The dependency of the polarizability of rocks/soils upon their lithological composition and hydrogeological properties favors the application of the IP method for hydrogeological (groundwater) and engineering geologic investigations. The polarization phenomenon was previously studied in detail by Wait (1959) [9] and its modern development stems largely from the work done by Bleil (1953) [10].

Vacquier et al. (1957) [1] and Marshall and Madden (1959) [2] described, respectively, the time domain IP measurements on artificial clay and sand mixtures and a theoretical model for membrane (clay) polarization. Ogilvy and Kuzmina (1972) [11] described additional time domain measurements on artificial mixtures, while Roy and Elliot (1980) [12] used horizontal layers of varying clay–sand composition to model negative apparent chargeabilities due to geometric effects. Vanhala and Soininen (1995) [13] carried out laboratory measurements using spectral IP on soil samples in order to assess the effect of mineralogy, grain size distribution, moisture content, and electrolyte composition on the resistivity of soil material. Rocks, which contain clay minerals, often display electrical properties which cannot be predicted by the bulk electrical properties of the constituents [14]. Interactions between clay minerals and ground water can produce polarization phenomena and decrease the resistivity.

The electrical resistivity of the reservoir rocks depends directly on the electrical resistivity and fluid saturation of the pores, as well as the clay (sands or zeolite) content. When clay is present, the resistivity becomes frequency dependent because of a fundamental charge storage mechanism that introduces double layers of electrical charge and a capacitive-like element in the equivalent circuit representation of the rock. Vacquier et al. (1957) [1] studied the membrane polarization effect in groundwater prospecting. He found that the ratio of two chargeability values measured at different times after cut-off of the current pulse, i.e., a quantity roughly dependent on the relaxation time, could be related to the grain size of the sediment. Marshall and Madden (1959) [2] presented a membrane-polarization model which, although an ultimate simplification for sediment texture, gave qualitatively correct predictions of how grain size affects the phase spectrum of the sediment.

As we discussed above, the IP effect is caused by the concentration gradients that develop at solid and liquid phase boundaries in response to the current flow. This effect is especially strong in the presence of clay materials. Keller and Frischknecht (1966) [15] made a qualitative development of this concept based on anion blockage to demonstrate that theoretically there is a peak polarization response for different clays and their concentrations. The variation in the intensity of polarization implies that clay content also changes from place to place in the rock.

The dependency of resistivity on clay type and content has been used as a parameter for a prediction of porosity and hydrocarbon saturation from well logs. Waxman and Smits (1968) [16] and Waxman and Thomas (1974) [17] have assumed that the resistivity of rocks is frequency dependent, which is true at low frequencies. They developed a semi-empirical model for describing the dependence of resistivity on clay content, expressed as CEC per unit volume. Vacquier et al. (1957) [1] found that the chargeability of sand–clay mixtures was proportional to the constituent clay and its ionic exchange characteristics. The importance of rock texture for the IP effect is manifested by a weak IP in compact clays (low CEC), and a strong IP in sediments with disseminated clay particles (high CEC) on the surface of larger grains. Increased electrolyte salinity (ion concentration) and electrical conductivity decrease the IP effect [6].

Parkhomenko (1971) [18] found that for fixed clay content, the chargeability of a rock is greater for clays having higher ion exchange capacities. However, this does not apply in the case of massive or pure clay. She observed that the largest IP effects were obtained for clay contents in the range of 3–10%. Higher or lower clay content corresponded to a lower IP effect. Parkhomenko (1971) [18] also noted that the IP effect increased with increasing water content until an optimum saturation is reached, beyond which IP decreased. The salinity and composition of the electrolyte have a profound influence upon the mode of occurrence of this maximum. With increasing concentration, the maximum IP response is depressed and shifts slightly toward the lower water contents. In a study with shaly sands, Ogilvy and Kuzmina (1972) [11] demonstrated the occurrence of a maximum IP response for optimum water content.

Keller and Frischknecht, 1966 [15], and Ogilvy and Kuzmina, 1972 [11], studied the effect of grain size parameters on the IP response. They have reported that the IP effect is low in the extreme cases of clean gravels or pure shales but it attains a maximum value at some intermediate grain size. Dakhnov (1962) [19] found that, with the fully saturated reservoir rock, the IP response was approximately proportional to the specific surface area of the constituent grains. It must be noted that this specific surface area increases with a decrease in grain size.

De Lima and Sharma (1992) [20] demonstrated that a model of a membrane polarization phenomenon could be reduced to a Cole–Cole model. Boadu and Seabrook (2000) [21] used a double Cole–Cole model to explain a laboratory measurement on the soil samples which showed a frequency dependent electrical response (FDER). They have demonstrated that the FDER resistivity and phase spectra of the soil contain valuable information about its porosity, hydraulic conductivity, texture, and fluid properties.

The first systematic experimental attempt to demonstrate that the IP effect is actually an intrinsic property of petroleum was accomplished in mid 1980s [22]. The transport properties