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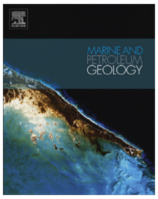

Research paper

Modelling the low-frequency electrical properties of pyrite-bearing reservoir sandstones

Tongcheng Han*, Michael Ben Clennell, Marina Pervukhina

CSIRO Energy Flagship, 26 Dick Perry Avenue, Kensington, Western Australia, 6151, Australia

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ABSTRACT

Marine controlled source electromagnetic sounding has developed rapidly in recent years to complement conventional seismic method for better discrimination of pore fluid. To obtain quantitative and reliable interpretation of the CSEM data, a robust rock physics model is vital to link the bulk rock electrical conductivity to the electrical properties and microstructure of the rock constituents, especially when some of the constituents exhibit extreme electrical behaviours (e.g., pyrite, a common mineral associated with reservoir rocks). Based on the multi-phase incremental model validated on published experimentally measured electrical conductivity of pyrite-bearing sandstones, the effects of key parameters, i.e., pyrite content, porosity, pyrite conductivity, grain aspect ratio and water saturation on the electrical conductivity of pyrite-bearing sandstones and their corresponding CSEM responses were comprehensively studied. The results are expected to assist in the CSEM data interpretation when a pyrite-bearing sandstone reservoir is encountered in the future.

1. Introduction

Pyrite (FeS_2) is the most common heavy mineral associated with sedimentary rocks and has been reported to be present in the sandstones of some important hydrocarbon producing formations throughout the world (Clavier et al., 1976). Among the physical properties of reservoir sandstones that are affected by the presence of pyrite, the electrical behaviours are the most noticeable due to the high conductivity of pyrite which exceeds the conductivity of even highly saline formation water (Klimentos, 1995; Kennedy, 2004). The presence of pyrite can therefore disturb the resistivity measurements that are used in petrophysical evaluation of oil and gas fields and this leads to overestimation of water saturation (and hence underestimation of hydrocarbon saturation). A good understanding of the electrical properties of pyrite-bearing sandstones is therefore of great importance for the interpretation of electrical resistivity logs (Kennedy, 2004). The suppression of rock resistivity by pyrite will also affect electrical survey data, including terrestrial and marine electromagnetic sounding, and pyrite effects must be corrected if those data are to be used for the estimation of hydrocarbon saturation.

So far, the study of the electrical properties of pyrite-rich sedimentary rocks has mainly focused on the frequency dependence (e.g., Clavier et al., 1976; Manning and Athavale, 1986; Clennell et al., 2010), that found the pyrite has a more significant effect in reducing electrical resistivity of the rocks at higher frequency (10 kHz–100 kHz) than at lower frequency (10 Hz–100 Hz). While the results are helpful in understanding the polarisation mechanism associated with pyrite or “IP effect” (e.g., Wong, 1979; Merriam, 2007), they fail to address directly the problem of how pyrite affects the low frequency electrical properties of reservoir sandstones that can be further employed to study the response of low frequency marine controlled source electromagnetic (CSEM) sounding, a rapidly developing exploration technique that complements the conventional seismic method for pore fluid discrimination between high conductivity formation water and low conductivity hydrocarbon (Constable and Srnka, 2007; Constable, 2010).

While careful laboratory measurements can provide accurate and reliable knowledge about the pyrite effects, it is difficult to control some specific parameters while keeping the rest constant (e.g., samples having the same porosity but with varying pyrite content) especially when studying natural rocks. Effective medium models derived on the DC (direct current) limit, on the other hand, could offer a more effective way to study comprehensively the effects of various parameters on the low-frequency electrical

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* Corresponding author.
E-mail address: tongcheng.han@csiro.au (T. Han).

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properties of pyrite-bearing sandstones that will potentially affect the signals of CSEM sounding, provided that the applicability of the models to pyritic sandstones is validated by well-controlled laboratory data.

Cosenza et al. (2009) presented a comprehensive review of the effective medium models used for modelling the relationships between low-frequency electrical conductivity and hydrological variables in soils and rocks aiming to provide a simple presentation of these theoretical approaches and to present their theoretical and practical limitations. Among these theoretical models, the differential effective medium (DEM) models are the category that has had the most success in modelling electrical properties and other physical properties (e.g., elastic parameters, dielectric permittivity, thermal conductivity and coupling properties) of reservoir rocks (e.g., Berryman, 1995; Revil, 2000; Cosenza et al., 2003; Berg, 2007; Han et al., 2011). Based on earlier works carried out within petrophysics and resistivity-logging, Gelius and Wang (2008) extended the DEM models to study production (temperature, saturation, salinity and stress) caused changes in the electrical conductivity of siliciclastic reservoir. Although these models were not developed for pyrite-bearing rocks, the similarity between clay minerals and pyrite in terms of their spatial distribution (e.g., dispersed in the pore space or forming part of the matrix) and higher conductivity than other rock-forming minerals (i.e., quartz for sandstones) makes the models adaptable to pyrite-bearing sandstones, though their validity needs to be tested.

We apply the 4-phase incremental model developed by Han et al. (2015) based on the Asami equation (Asami, 2002) to study comprehensively the effects on various parameters (pyrite content, porosity, pyrite conductivity, grain aspect ratio and water saturation) on the electrical conductivity of pyrite-bearing reservoir sandstones. The results are then used to forward model the CSEM responses associated with the conductivity caused by varying the pyrite content parameters. Before application of the incremental model, its validity to the conductivity of pyrite-bearing sandstones is tested on published experimental data. The aim of the study is to provide a sensitivity analysis of the effect of pyrite content and distribution on CSEM responses, which can potentially aid in the interpretation of CSEM survey data for better reservoir characterisation.

2. Multi-phase incremental model based on Asami equation for electrical properties of pyrite-bearing sandstones

2.1. Asami equation

Based on Maxwell–Wagner theory (Maxwell, 1891; Wagner, 1914) Asami (2002) derived an equation for the electrical conductivity (σ) of a 2-phase mixture where dilute ellipsoid inclusions (with conductivity of σ_g) are oriented randomly as a suspension within a background medium with conductivity of σ_a, given as

$$\sigma = \sigma_a\left[1+\frac{1}{3}\Phi\sum_{k=x,y,z}\frac{\sigma_g-\sigma_a}{\sigma_a+(\sigma_g-\sigma_a)L_k}\right], \tag{1}$$

where Φ is the volume fraction of the inclusions, and L_k is the depolarisation factor of the inclusions along the k-axis satisfying $L_x+L_y+L_z=1$.

Equation (1) is derived for the case of a low volume fraction of inclusions or dilute suspension ($\Phi << 1$), implying that there are no interactions between the inclusions. This is obviously not the case for reservoir rocks where the inclusions (i.e., quartz for sandstones) not only interact with the suspending medium (i.e., formation water) they also contact each other.

To account for this problem, Asami (2002) increased the initial low volume fraction gradually by infinitesimal addition of the grains so that Equation (1) derived for dilute suspensions is valid in each addition of the grains. Therefore the increment in effective conductivity of the new mixture $d\sigma$ due to an infinitesimal addition of the grains is related to the increment in volume fraction $d\Phi'$ by submitting $\sigma + d\sigma$, σ and $d\Phi'/(1-\Phi')$ for σ, σ_a and Φ in Equation (1), respectively,

$$-\frac{d\Phi'}{1-\Phi'} = \frac{3}{\sigma(\sigma-\sigma_g)}\left[\sum_{k=x,y,z}\frac{1}{\sigma+(\sigma_g-\sigma)L_k}\right]^{-1}d\sigma. \tag{2}$$

By successive infinitesimal additions of grains, the mixture reaches the final grain volume fraction Φ and conductivity σ, an integral equation is obtained as

$$\int_0^{\Phi}-\frac{d\Phi'}{1-\Phi'} = \int_{\sigma_a}^{\sigma}\frac{3}{\sigma(\sigma-\sigma_g)}\left[\sum_{k=x,y,z}\frac{1}{\sigma+(\sigma_g-\sigma)L_k}\right]^{-1}d\sigma. \tag{3}$$

Solving this equation and approximating the quartz in sandstones to be spheroids ($L_x = L_y \neq L_z$), the final form of the Asami equation is obtained:

$$\phi = \left(\frac{\sigma_a(1+3L)+\sigma_g(2-3L)}{\sigma(1+3L)+\sigma_g(2-3L)}\right)^{C}\left(\frac{\sigma-\sigma_g}{\sigma_a-\sigma_g}\right)\left(\frac{\sigma_a}{\sigma}\right)^{3T}, \tag{4}$$

where $\phi = 1-\Phi$ is the volume fraction of suspension (i.e., porosity for reservoir sandstones), $L = L_x = L_y = (1-L_z)/2$, and $T = \frac{L(1-2L)}{2-3L}$, $C = \frac{2(1-3L)^2}{(2-3L)(1+3L)}$.

The z-axis depolarisation factor L_z for oblate spheroids with aspect ratio $\alpha < 1$ is given by

$$L_z = \frac{1}{1-\alpha^2}-\frac{\alpha}{(1-\alpha^2)^{3/2}}\cos^{-1}\alpha. \tag{5}$$

2.2. Multi-phase incremental model

The Asami model (Equation (4)) reduces to the well-known Hanai-Bruggeman (HB) equation for electrical conductivity (Bruggeman, 1935; Hanai, 1960a, b; Bussian, 1983) in the case of spherical grains ($\alpha = 1$ and $L_z = 1/3$) and further simplifies to Archie's equation (Archie, 1942) when the conductivity of the grains (σ_g) is negligible. However the model was developed for a 2-phase medium and cannot be applied to the multi-phase case. I.e., pyrite-rich hydrocarbon-bearing reservoir sandstones that contain four phases formation water (brine, of variable conductivity), hydrocarbon (oil or gas, insulating), quartz (plus all other nonconductive mineral grains) and pyrite (a strongly conductive mineral). Motivated by the incremental method employed by Asami (2002) and Berg (2007), Han et al. (2015) presented a multi-phase incremental model to extent the Asami equation to be able to model the conductivity of real reservoir rocks that contain more than 2 phases.

As shown schematically in Fig. 1, the inclusions in the incremental model are introduced in an infinitesimal manner (C/n, where C is the initial concentration of each phase and n is the incremental number that is set to be 1000) into the background medium forming a new effective medium for the next step where the next phase is included. After all the 3 inclusion phases (i.e., hydrocarbon, pyrite and quartz) are added in the first increment where water is the staring background medium, the next