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Saturation effects on the joint elastic–dielectric properties of carbonates

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ABSTRACT

We used a common microstructural model to investigate the cross-property relations between elastic wave velocities and dielectric permittivity in carbonate rocks. A unified model based on validated self-consistent effective medium theory was used to quantify the effects of porosity and water saturation on both elastic properties (compressional and shear wave velocities) and electromagnetic properties (dielectric permittivity). The results of the forward models are presented as a series of cross-plots covering a wide range of porosities and water saturations and for microstructures that correspond to different predominant aspect ratios. It was found that dielectric permittivity correlated approximately linearly with elastic wave velocity at each saturation stage, with slopes varying gradually from positive at low saturation conditions to negative at higher saturations. The differing sensitivities of the elastic and dielectric rock properties to changes in porosity, pore morphology and water saturation can be used to reduce uncertainty in subsurface fluid saturation estimation when co-located sonic and dielectric surveys are available. The joint approach is useful for cross-validation of rock physics models for analysing pore structure and saturation effects on elastic and dielectric responses.

1. Introduction

Quantifying fluid content within rocks is an important goal in reservoir characterization. While dielectric measurement is useful in determining water saturation without knowing its salinity (Chew, 1988; Schmitt et al., 2011), it can be difficult to distinguish between low dielectric constant hydrocarbons (e.g., oil and gas, with dielectric permittivity of 2 and 1, respectively). Similarly, the elastic velocity of reservoir rocks is also affected by fluids in the pores, and elastic methods based on the fluid effect on the elastic moduli and density of a rock are conventionally employed to determine hydrocarbon saturation (Domenico, 1976; Khazanehdari and Sothcott, 2003; Renaud et al., 2009; Lan et al., 2011). Since elastic and dielectric methods measure complementary but independent petrophysical properties of reservoir formations that are related through porosity and fluid properties within the pores, the joint interpretation of co-located elastic and dielectric data could offer a better way to quantify fluid saturation provided the saturation effects on the joint elastic–dielectric properties are well understood.

Whereas there are numerous experimental and theoretical investigations of the saturation effects on elastic and dielectric properties of carbonates (e.g., Gregory, 1976; Knight et al., 1998; Baechle et al., 2005; Seleznev et al., 2004, 2006; Vanorio et al., 2008; Markov et al., 2012), few studies of the joint elastic–dielectric properties exist in the open literature.

Carrara et al. (1994) proposed an electro-seismic model to evaluate porosity and degree of fluid saturation in carbonates, and the model was tested by Carrara et al. (1999) by measuring compressional wave velocity and electrical resistivity on carbonates with varying porosity and brine saturation. Because the problem of low frequency electrical conductivity (or reciprocally electrical resistivity) is mathematically equivalent to that of high frequency dielectric permittivity (Carcione et al., 2007), the electro-seismic model given by Carrara et al. (1994) can be adapted to a joint elastic–dielectric model. However, this electro-seismic model is essentially a harmonic average equation that is known to perform poorly at high porosities (e.g., Berryman, 1995).

Kazatchenko et al. (2004) proposed a method for joint modelling of acoustic velocities and electrical conductivity from unified microstructure (defined as the geometry of the rock-forming materials and how they are arranged in the rock) of rocks based on effective medium approximation of two component media, composed of grains, which constitute a solid frame and pores saturated by a fluid. They used this method to calculate the acoustic velocities and electrical conductivity for carbonate formations with a primary pore system. Although dielectric permittivity can be modelled in place of electrical conductivity, Kazatchenko et al. (2004) did not give explicit joint elastic–electrical (dielectric) correlations. Furthermore, because the model was developed for a 2-phase medium, the effect of fluid saturation on joint elastic–electrical (dielectric) properties could not be modelled and investigated.

Pervukhina and Kuwahara (2008) modelled both elastic and electrical properties of equilibrium interfacial energy controlled microstructures

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that might be typical for rock in the high temperature environment of the lower crust and upper mantle. The rock was assumed to be fully saturated with melt or brine. They applied the model to the data of collocated magnetotelluric and seismic tomography experiments.

Based on a comprehensive study of the pressure and petrophysical control on the joint elastic–electrical properties of reservoir sandstones (Han et al., 2011a, 2011b), Han et al. (2011c) developed a joint elastic–electrical effective medium model for sandstones with pore-filling clay minerals, which can be mathematically adjusted to model the saturation effects on the joint elastic–dielectric properties of carbonates. Carbonate rocks without clay are expected to have simpler electrical responses than shaly sandstones. However, assumptions in the model for sandstones might be different from those for carbonates (e.g., critical porosity of 0.5 used for sandstones in the combined self-consistent approximation and differential effective medium model may not be valid for the carbonate case), and therefore the proposed model needs to be tested before it is applied to carbonates.

This paper studies theoretically the saturation effects on the joint elastic–dielectric properties of carbonates for the understanding of elastic and electromagnetic wave propagation phenomena as well as quantifying hydrocarbon content in partially saturated carbonates. Based on validated self-consistent effective medium models for elastic velocity and dielectric permittivity, we show for the first time the cross-property relations between elastic velocity and dielectric permittivity (the joint elastic–dielectric properties) of carbonates with a unified microstructure (the microstructure described by the elastic and dielectric models are consistent) and the effects of porosity and water saturation on the joint elastic–dielectric properties. The results show the potential for estimating in situ carbonate porosity and hydrocarbon saturation using joint velocity–permittivity crossplots from co-located sonic and dielectric surveys.

2. Methodology

Effective medium models suitable for simultaneous simulation of the effect of saturation on both elastic velocity and dielectric permittivity include averages, complex refraction-index method (CRIM), self-consistent (SC) models and differential effective medium (DEM) models among others (Carcione et al., 2007). The averages and the CRIM do not specify the geometric details of how the inclusions are arranged relative to each other and therefore can only predict the upper and lower bounds of the effective properties (Mavko et al., 2009). DEM models (Berryman, 1995) can be extended to give good estimations of a 3-phase elastic and electrical medium (e.g., Han et al., 2011c); however they require to designate one phase as the connected background medium into which the other phases are embedded and different results will be given depending on which constituent is chosen as the background. It has been shown (e.g., Han et al., 2011c) that the host background in the DEM model should be solid grains to give a good estimate of measured elastic velocity but should be the conductive phase to predict electrical resistivity. The choice of different connected host background in the elastic and electrical (dielectric) simulation implies the microstructure in each case is different and therefore is inconsistent. In the SC models (Berryman, 1995), on the other hand, all the constituents are equivalent and connected without one single component playing the role of host matrix for the others distributed as isolated inclusions. Therefore, SC models with the same microstructure are suitable for modelling of both elastic and dielectric effective properties of composite materials.

2.1. Self-consistent models

The SC models for elastic velocity and real relative dielectric permittivity (referred to as SC elastic model and SC dielectric model, respectively) of a 3-phase medium are given respectively as (Berryman, 1995)

$$\begin{aligned}\sum_{i=1}^{3} f_i\left(K_i - K_{SC}^*\right)P^{*i} &= 0\\ \sum_{i=1}^{3} f_i\left(\mu_i - \mu_{SC}^*\right)Q^{*i} &= 0,\end{aligned} \tag{1}$$

and

$$\sum_{i=1}^{3} f_i\left(\varepsilon_i - \varepsilon_{SC}^*\right)R^{*i} = 0, \tag{2}$$

where f_i, K_i, μ_i and ε_i are the volume fraction, bulk and shear modulus and dielectric permittivity of each constituent, respectively; K_{SC}^*, μ_{SC}^* and ε_{SC}^* are the effective self-consistent bulk and shear modulus and dielectric permittivity of the composite material; and P^{*i}, Q^{*i} and R^{*i} are the coefficients that take into account the geometric factors of the i-th component in the elastic and dielectric self-consistent effective medium, respectively.

The volume fractions of solid grains (f_g), brine (f_b) and hydrocarbon (f_h) are given by $f_g = 1 - \phi$, $f_b = S_w\phi$ and $f_h = (1 - S_w)\phi$, respectively, where ϕ is the porosity and S_w is the water saturation in the porosity.

2.2. Test on laboratory examples

To test the applicability of the SC models to simulating the effects of saturation on the elastic and dielectric properties of carbonates, we compare the modelled bulk modulus and dielectric permittivity with published laboratory data on carbonates, as shown in Figs 1 and 2, respectively.

Whereas the SC dielectric model predicts the variation of dielectric permittivity as a function of water saturation in carbonate well, the SC elastic model reproduces the bulk modulus of carbonate for water saturation below 0.9, above which the dramatic increase in bulk modulus fails to be predicted. In fact the sharp increase in the bulk modulus approaching full water saturation is caused by the break-up of the interconnected gas phase and the filling of the central volumes of the pores with water (Knight and Nolen-Hoeksema, 1990) indicating a significant change in the geometry of the pore-filling fluids occurs at this saturation stage, which therefore could not be modelled by the same geometric

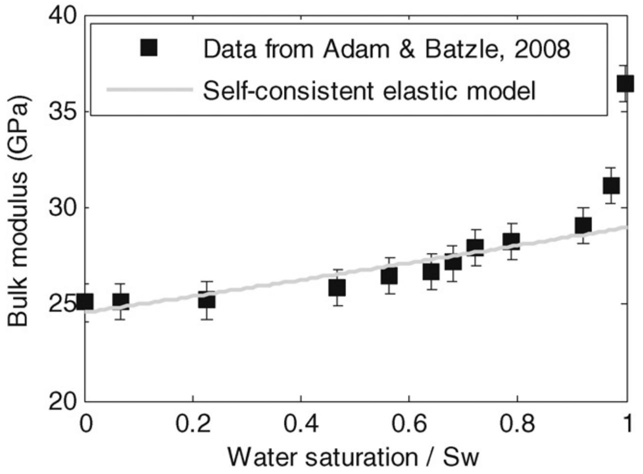

Fig. 1. Comparison of the SC elastic model with laboratory measurement of the ultrasonic bulk modulus as a function of water saturation in a carbonate. Physical properties are used for calcite, water and air as given in Table 1 with fitting parameters of aspect ratios 1, 0.55 and 0.5 for calcite, water and air, respectively. Laboratory data from Adam and Batzle (2008).