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Effective medium modelling the effects of saturation on the joint elastic-dielectric properties of carbonates

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SUMMARY

The effects of saturation on the joint elastic-dielectric properties of porous medium is important for the understanding of elastic and electromagnetic wave propagation phenomena as well as quantifying hydrocarbon content in partially saturated reservoir rocks. We studied theoretically 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 effects of porosity and water saturation on the joint elastic-dielectric properties were also studied using validated self-consistent effective medium models for elastic velocity and dielectric permittivity. The results offered an important new possibility for estimating in situ carbonate porosity and hydrocarbon saturation using joint velocity-permittivity crossplots from co-located sonic and dielectric surveys.

Key words: elastic; dielectric; effective medium model; saturation; carbonates

INTRODUCTION

Quantifying fluid content within rocks is an important goal in reservoir characterization. Dielectric measurements are useful in determining water saturation in reservoir rocks without knowing the water salinity as water has high dielectric permittivity (Schmitt et al., 2011) but these measurements hardly can be used to distinguish between hydrocarbons with low dielectric constants (e.g., oil and gas, with dielectric permittivity of 2 and 1, respectively). On the other hand, elastic velocities of reservoir rocks are affected by fluids in the pores, and elastic methods based on the fluids effect on the elastic moduli and density of a rock is conventionally employed to determine hydrocarbon saturation (Renaud et al., 2009; Lan et al., 2011). Since elastic and dielectric methods measure complementary but independently petrophysical properties of reservoir formations 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.

This work 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. Using 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. We also study 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.

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., 2011a); however they will require to designate one phase as the connected background medium into which the other phases are imbedded and different results will be given depending on which constituent is chosen as the background. It has been shown (e.g., Han et al., 2011a) that the host background in the DEM model should be solid grains and conductive brine to give a good estimate of measured elastic velocity and electrical resistivity, respectively. The choice of different connected host background in the elastic and electrical (dielectric) simulation implies the microstructure differs from each other in the elastic and electrical (dielectric) cases, which 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 inclusion. Therefore, SC models with the same consistent microstructure are suitable for modelling of both elastic and dielectric effective properties of composite materials.

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

$$\sum_{i=1}^{3} f_i(K_i - K_{SC}^*)P^{*i} = 0,$$

$$\sum_{i=1}^{3} f_i(\mu_i - \mu_{SC}^*)Q^{*i} = 0$$

(1)

and

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

(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.

The SC modeled elastic velocity and dielectric permittivity are cross-related by using porosity and saturation as the link to arrive at the joint elastic-dielectric properties of carbonates (Carcione et al., 2007).

JOINT ELASTIC-DIELECTRIC PROPERTIES

The SC computed cross-property relationship between compressional wave velocity (V_p) and dielectric permittivity (ε) and its correlation with porosity (ϕ, 0 to 0.4) and water saturation (S_w, 0 to 0.9) is shown in Figure 1 for water-gas saturated. Both porosity and water saturation have a strong effect on the joint V_p - ε relation.

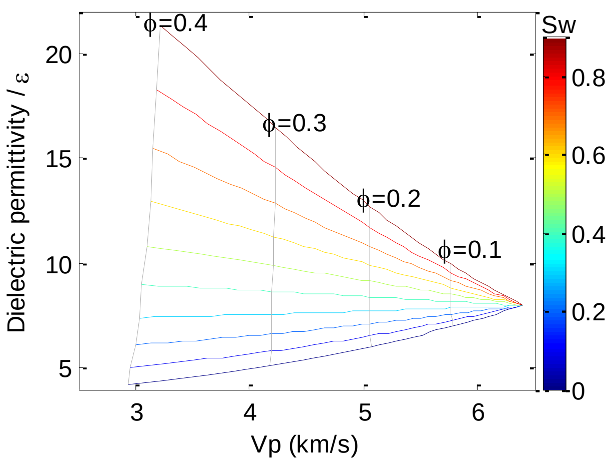

Figure 1. Computed cross-property relationship between compressional wave velocity (V_p) and dielectric permittivity (ε) and its correlation with porosity (ϕ) and water saturation (S_w) for water-gas saturated carbonates. Aspect ratios are 1, 0.5 and 0.5 for calcite, water and gas, respectively.

Dielectric permittivity shows an approximately linear correlation with compressional wave velocity at each saturation stage (colour contours in Figure 1), with slopes varying gradually from positive at low saturation conditions to negative at higher saturations. While P-wave velocity increases with decreasing porosity regardless of water saturation, the variation in the slope is an indication of the dielectric permittivity of the water-gas 'mixture' in the pores. When water saturation is low, there is only small amount of high permittivity water in the pores resulting in a lower dielectric permittivity of the water-gas mixture than that of the calcite grains, and as a result both dielectric permittivity and P-wave velocity increase when the amount of calcite with relative higher permittivity and higher velocity increases (which is equivalent to a decrease in porosity). With an increase in water saturation, the dielectric permittivity of the water-gas mixture increases and gets closer to those of the calcite grains, and therefore the effective permittivity of the carbonate increases less with decreasing porosity than at lower water saturation. At water saturation of about 0.3, the permittivity of the water-gas mixture reaches that of the calcite grains, and the permittivity of the carbonate will not change with varying porosity. With further increase in water saturation, the permittivity of the pore-filling water-gas mixture exceeds that of the grains leading to a reducing permittivity with increasing velocity (decreasing porosity). The negative linear correlation between dielectric permittivity and P-wave velocity at higher water saturation resembles the laboratory obtained positive linear relation between logarithmic electrical resistivity and P-wave velocity in water saturated sandstones by Han et al. (2011b).

The effect varying water saturation on the joint Vp - ε properties at a constant rock porosity is illustrated by the grey curves in Figure 1. Dielectric permittivity increases with increasing water saturation at all porosities as water has the highest permittivity in the constituents. By contrast the variation of P-wave velocity with water saturation is more complicated, which shows a slight decrease with increasing water saturation at lower porosities and an increasing trend with water saturation at higher porosities. The distinct behaviors of velocity with water saturation at different porosity can be explained as follows: when porosity is low, the elastic modulus of the grain matrix dominates and the addition of water has negligible effect on the bulk modulus but slightly increases the density leading to a small reduction in the velocity; as the porosity gets higher, the elastic modulus of the calcite skeleton becomes weaker and the introduction of water into the pores notably increases the bulk modulus of the carbonate, which overtakes the density increase effect and thus resulting in the increasing velocity. The modeled variations of P-wave velocity with saturation agree with the experimental observations of Knight and Nolen-Hoeksema (1990) and Gregory (1976) on low and high porosity rocks, respectively.

CONCLUDING REMARKS

Based on the validated SC models, the joint elastic-dielectric properties of carbonates and their strong relationships with porosity and water saturation are analyzed. In addition to helping understand the elastic and electromagnetic wave propagations in carbonates, the joint elastic-dielectric relations presented in this paper can serve as a template for blind saturation quantification, one of the goals in reservoir characterization, especially when porosity information is unavailable.

The theoretically derived joint elastic-dielectric relations need to be tested with controlled laboratory data before practical applications. To our knowledge, however, there seems to be a complete lack of these types of data for carbonates, and the next stage of our research is to perform such experiments and determine the more reliable joint elastic-dielectric relations.

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