Rock Physics for Sonic and Dielectric Data in Carbonates

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Abstract

Understanding storage and flow in reservoir rocks is critical for reservoir characterization. Carbonate rocks usually present a large distribution of pore sizes, with larger pores contributing more to rock permeability. Sonic and dielectric data can provide information about porosity and rock and pore texture and improve understanding of permeability and connectivity. In this paper we demonstrate that sonic and dielectric data can be combined to better understand carbonate rocks. We show as an example that it is possible to improve acoustic rock physics modelling by inputting micropores aspect ratio derived from dielectric data in an irreducible water saturation interval, raising accuracy for output parameters from acoustic modelling.

Introduction

Carbonate rocks usually present a large distribution of pore sizes, that can be classified into micro, meso and macropores. Meso and macropores have the largest contribution to rock permeability, while micropores usually hold irreducible water saturation. Limestones and dolomites might present additional large pores (vugs) due to dissolution of grains. Rock permeability is influenced not only by pore size: pore shape is another factor that can influence connectivity. Understanding storage and flow of fluids in these rocks is fundamental to reservoir characterization and production estimates. Logging tools can provide important information about reservoir properties through acoustic, dielectric or nuclear magnetic resonance (NMR) measurements, just to name a few.

Sonic logs are sensitive to both porosity and rock texture. Various rock physics models are used to parameterize the texture effects in terms of both pore shape and grain shape. For acoustics, the shape of the pores and grains will impact the compressibility of the rock formation, where spherical pores and grains are less compressible than elliptical pores and grains. The shape of the grains and pores is usually described in terms of the aspect ratio, or the ratio of minor to major axes, where a sphere would have an aspect ratio (α) of 1, while elliptical pores would have an aspect ratio less than 1.

There are three commonly used acoustic rock physics models for carbonates: Kuster-Toksoz (KT), Differential Effective Medium (DEM) and the Self-Consistent Model (SCM).

The SCM method has no background but includes grains and pores as described by their aspect ratios and bulk volume percentage. It is defined by:

$$\sum_{i=1}^{N} x_i\left(K_i - K^*_{SC}\right)P^{*i} = 0 \tag{1}$$

$$\sum_{i=1}^{N} x_i\left(\mu_i - \mu^*_{SC}\right)Q^{*i} = 0 \tag{2}$$

where K_i is the bulk modulus of the i-th inclusion, μ_i is the shear modulus of the i-th inclusion, x_i is the volume fraction of the i-th inclusion, K^*_{SC} is the bulk modulus of the effective medium, μ^*_{SC} is the shear modulus of the effective medium and P_{mi} and Q_{mi} are shape factors for the i-th inclusion. This model includes the geometrical effect of inclusions of grains and pores, but it was found that it overestimates the effect of interactions between pores.

The KT model assumes a solid background material and then inclusions of a particular shape are added according to their percentage of the bulk volume.

The KT model is defined by:

$$\left(K_{KT} - K_m\right)\frac{3K_m+4\mu_m}{3K_{KT}+4\mu_m} = \sum_{i=1}^{N} x_i\left(K_i - K^*_{KT}\right)P^{*i} \tag{3}$$

$$\left(\mu_{KT} - \mu_m\right)\frac{\mu_m+\zeta}{\mu_{KT}+\zeta} = \sum_{i=1}^{N} x_i\left(\mu_i - \mu^*_{KT}\right)Q^{*i} \tag{4}$$

where

$$\zeta = \frac{\mu(9K+8\mu)}{6(K+2\mu)} \tag{5}$$

and K_{KT} is the bulk modulus of the effective medium, μ_{KT} is the shear modulus of the effective medium. This model is limited to dilute concentrations of the inclusions.

The DEM models a two phase composite by incrementally adding the inclusion to a background (Mavko, 1998, Norris, 1985). This idea of incrementally adding inclusions to a background has been adapted to overcome the assumption of dilute concentrations of the inclusions of the KT model.

In Figure 1, cross plots of bulk and shear muduli versus porosity are shown, to illustrate the three above cited acoustic rock physics models for a calcite rock, considering different aspect ratios (AR).

In order to take into account these interactions without overestimation we have used the same methodology as in Xu White (1995) and Xu and Payne (2009). This methodology consists in estimating the elastic properties of a wet rock containing only micro cracks with bound water, what can be thought of a correction for micro cracks. This mixture is used as a background for obtaining a partially dry composition using the KT model, finally the Gassmann´s equation is used to estimate the elastic properties of the mixture. In order to respect the assumption of dilute concentration of pores and cracks for applying KT model, the inclusions are divided into N parts p_i respecting the inequality $\frac{p_i}{\alpha_i} \ll 1$. This idea has been described in Xu White (1995).

In the examples given the fluid is separated in different pore types assuming the micro cracks contain 100% brine while the intergranular porosity and vugs are associated with a composite of water and hydrocarbons. In the example, Gassmann is used for intergranular porosity these pores are 100% oil saturated.

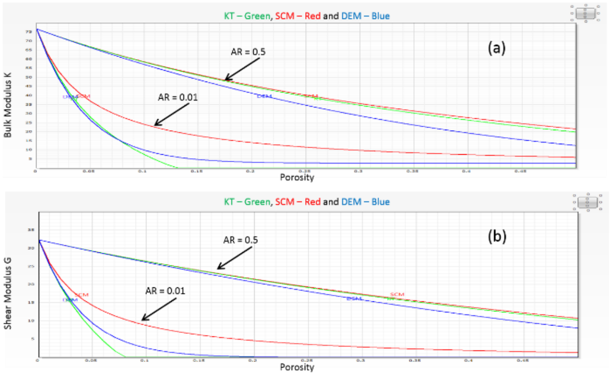

Figure 1 - Cross plots of bulk (a) and shear (b) moduli versus porosity, showing the effect of different pore aspect ratio (0.5 and 0.01) for the Kuster-Toksoz (KT, green), Differential Effective Medium (DEM, blue) and the Self-Consistent Model (SCM, red).

Dielectric logging measurements were first introduced in the late 1970s, with measurements at a single frequency mainly focusing on calculating resistivity-independent oil saturations. However, data quality was low and highly sensitive to borehole rugosity. Current dielectric logging tools are more reliable and allow multifrequency measurements. Rock physics models can be used to evaluate rock texture information based on the dielectric dispersion curve.

One simple mixing formula that can be used to model dielectric data is based on:

$$\varepsilon_{eff}^{1/m} = \sum_{n=1}^{N} \phi_n \varepsilon_n^{1/m} , \qquad (6)$$

where ε_{eff} is the effective permittivity, m is the cementation exponent, ϕ_n is the fractional volume of the n-th phase and ε_n is the permittivity of the n-th phase. When m is assumed to be 2, it becomes the complex refractive index mixing formula (CRIM) (Birchak, 1904). This is a simpler model, mainly used to estimate water filled porosity.

Another model was developed by Maxwell-Garnett (1904), based on a random distribution of spherical particles in a host matrix:

$$\varepsilon_{eff} = \left[1 + \frac{3\phi(\varepsilon_s - \varepsilon_b)/(\varepsilon_s - 2\varepsilon_b)}{1 - \phi(\varepsilon_s - \varepsilon_b)/(\varepsilon_s - 2\varepsilon_b)}\right], \qquad (7)$$

where ε_{eff} is the effective permittivity, ϕ is the porosity, ε_s is the permittivity of the spherical inclusions and ε_s is the permittivity of the host. It is also possible to rewrite the above equation for multiple (n) spherical inclusions:

$$\frac{\varepsilon_{eff} - \varepsilon_b}{3\varepsilon_a + (\varepsilon_{eff} - 2\varepsilon_b)} = \sum_{n=1}^{N} \phi_n \frac{\varepsilon_n - \varepsilon_b}{3\varepsilon_a + (\varepsilon_n - \varepsilon_b)} , \qquad (8)$$

where $\varepsilon_a = \varepsilon_b + \eta(\varepsilon_{eff} - \varepsilon_b)$, with 0<η<1.

Furthermore, Seleznev et al. (2006) developed the textural model combining both CRIM and Maxwell-Garnett models, where the host to the inclusions is a CRIM background and η is the depolarization factor of the inclusions.

Method

Since both logging measurements are sensitive to rock texture, it is possible to compare outputs from both tools or to use outputs from one model as inputs to complement the other modelling.

The acoustic measurements can be combined with density to estimate dynamic bulk (K) and shear (μ) modulus. Both of these elastic properties are sensitive to mineralogy, porosity and porosity type. In addition to that, K is sensitive to fluid composition while μ is not affected by fluid composition.

The many parameters involved in the modeling cause an ambiguity when using only sonic data for characterizing porosity type in the formation. Using dielectric for characterizing the aspect ratio of micro cracks and NMR to separate the porosity will reduce the uncertainties in the modeling.

In this paper, we discuss one possible application for combination of dielectric and sonic data, providing an example for a modeled dolomite.

Because aspect ratios are usually different for macro and micropores, it is important to consider such effect on the calculations. In Figure 2, the cross plot shows the effect of considering microporosity on the effective medium model for acoustic data. The black curve represents the SCM for calcite and brine with only one type of porosity, with an aspect ratio of 0.2. The red curve, on the other hand, represents the Self Consistent model taking into account 25% of microporosity on the rock. For a same value of total porosity, including the microporosity effect in the model significantly reduces the modeled bulk modulus.

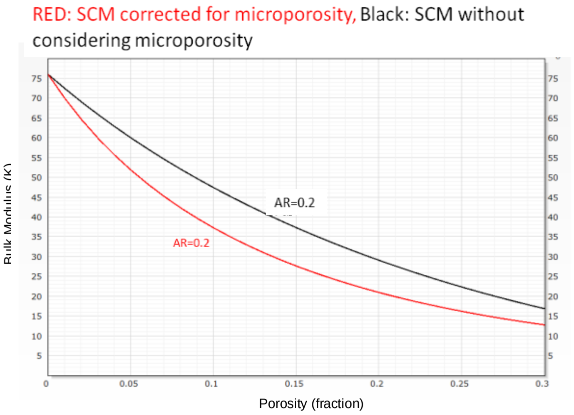

Figure 2 - Cross plot of bulk moduli versus porosity for a brine saturated calcite rock, considering microporosity in the matrix (red curve) and without considering microporosity (black curve).

In order to demonstrate how dielectric and sonic data could be combined, one can consider a dolomitic carbonate reservoir, drilled with oil-based mud. NMR logs provide information about micro, meso and macroporosity content and can also indicate fluid distribution in an interval.

For an interval, with macropores filled with oil/mud filtrate and micropores filled with brine, we would have dielectric response corresponding only to the microporosity region (brine filled). This is because dielectric measurements are highly sensitive to water (water permittivity close to 1 GHz is around 70) but show low or no sensitivity to oil (permittivities might range between 2 and 2.4) or matrix (permittivities vary according to lithology, going between 4 and 10).

In Figure 3 are represented dielectric dispersion curves for a dolomitic carbonate sample with 20 p.u. porosity, 30% of the pores is filled with brine and the remaining is filled with oil or mud filtrate. The dispersion curves were obtained according to the textural model, developed by Seleznev. The black curve represented the dispersion for the dolomitic sample with very thin water filled micropores (α=0.05). The green curve is the other extreme, with micropores almost spherical (α=0.9). Between these two cases, the red line represents elliptical micropores with α=0.2. It is very clear that the dispersion curves are very sensitive to the micropores aspect ratio. Therefore, for this sample, it is possible to have micropore aspect ratio as an output of the dielectric measurement.

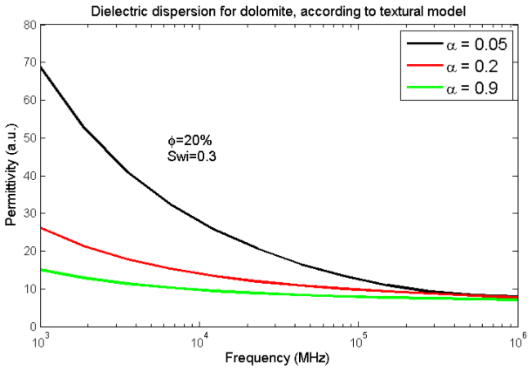

Figure 3 – Dielectric dispersion curves for a dolomite sample, with 20 p.u. porosity, 30% of the pores filled with water and the remaining filled with oil/mud filtrate. Aspect ratio of the water filled micropores ranges from 0.05 to 0.9. Higher permittivity is seen for the thinner micropores (black line, α=0.05) and lower permitivity is seen for more spherical micropores (green line, α=0.9).

Both K and μ are highly sensitive to the aspect ratio of micro cracks α. Figure 4 is illustrating this fact for bulk modulus, these values are obtained for fixed micro porosity of 6 p.u. and the bulk modulus is estimated using the methodology from Xu and Payne described above for different α. As can be seen in this plot, for 20 p.u. porosity and same mineralogy and fluid composition, the bulk modulus can vary 20 GP only by changing α. If dielectric can be used to characterize the micro porosity, the uncertainty on the sonic modeling will be reduced and the aspect ratio of intergranular porosity and the amount of vugs can be included on an inversion model reducing the difference between the elastic properties from acoustic measurements and the modeled acoustic properties.

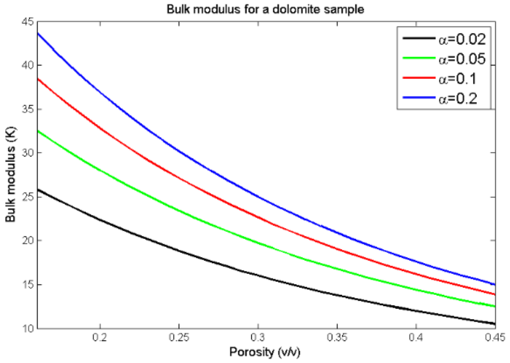

Figure 4 – Static bulk modulus estimated for a sample with 100% dolomite, fixed microporosity of 6 p.u. brine in

the micropores, oil in the interparticle porosity with fixed aspect ratio 0.2, and porosity varying between 10 and 45 p.u.. The black curve corresponds to microcracks with aspect ratio α= 0.02, the green curve corresponds to α= 0.05, the red curve corresponds to α= 0.1 and the blue curve corresponds to α= 0.2.

Conclusions

In this paper we have demonstrated one example of how sonic and dielectric data can be combined to better understand carbonate rocks. We have showed it is possible to improve acoustic rock physics modelling by inputting micropores aspect ratio derived from dielectric data in an irreducible water saturation interval. A better acoustic model provides, for example, a better understanding of the macropores and vugs texture and content, which is helpful for understanding permeability and connectivity in rocks.

As future work, we plan to apply this methodology in log data, making use of laboratory dielectric measurements, that allow more accuracy and different samples saturations. We also plan to test additional ways of complementing and comparing information obtained from sonic and dielectric logs.

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