ROLE OF COMPLIANT POROSITY IN STRESS DEPENDENCY OF ULTRASONIC VELOCITIES IN CARBONATES AND SANDSTONES

Osni Bastos de Paula, Petrobras/Curtin University of Technology
Marina Pervukhina, CSIRO
Boris Gurevich, Curtin University of Technology/CSIRO

Abstract

A study of complex dual-nature porosity of reservoir rocks is necessary for quantitative understanding of seismic wave propagation in reservoirs. We analyze here the ratios of stiff and compliant porosities in 6 samples of carbonates and 6 samples of sandstones, and effect of compliant porosity on ultrasonic shear and compressional wave velocities measured at effective stresses from 0 to 60 MPa. The compliant porosity is estimated from stress dependency of dry rock compressibility using isotropic Shapiro theory (2003). In the case of sandstones, we have direct measurements of porosity variations with pressure which validate the estimated compliant porosities. Finally, we use Gassmann equations to estimate the stress dependence of shear and compressional wave velocities in saturated rocks. Two examples discussed here show that a better estimation is obtained using the high frequency unrelaxed frame shear and bulk modulus (Mavko&Jizzba,1991) to "saturate" the samples.

Introduction

Numerous models and different approaches are described in literature aiming to explain stress dependence of velocities or elastic moduli. Here we use the isotropic model suggested by Shapiro, 2003. Basically the model takes into account stiff and compliant porosities, but in a first approximation, compliant or soft porosities are the main responsible for the non linear elastic properties changes with the variation of pressure. Variations of total, soft and stiff porosities with pressure are shown in Figure 01. We expected that it could be a good model for carbonates too, because cracks and elongated pores are very common to these rocks. Our main goal is to estimate compliant porosity from fitting coefficients of the following equation for elastic compressibility (Shapiro, 2003) without any constraints or a priori pore shape definitions:

$$C_{dr}(P) = C_{drs}\left(1 - \theta_c\, \emptyset_{c0} e^{(-\theta_c P C_{drs})}\right) \qquad (1)$$

Here C_{dr} is the bulk compressibility, P is the effective stress, $Cdrs$ is the drained compressibility of a hypothetical rock with closed compliant porosity, $\emptyset_{co}$ is the compliant porosity at zero pressure and θ_c is the piezosensitivity of the rock, defined as $\theta_c = \frac{1}{C_{drs}} \frac{\partial C_{dr}}{\partial \emptyset_c}$

Well known Gassmann (1951) equations normally provide a good estimation of the saturated rock bulk modulus from the dry rock bulk modulus, provided that the type of fluid, porosity and grain material are known. Some differences result from pressure relaxation assumption that is essential for Gassmann equations applicability. To avoid these discrepancies we use the equation (Equation 2) from Mavko and Jizba (1991) to calculate the high frequency unrelaxed shear and frame bulk modulus:

$$\frac{1}{K_{uf}} = \frac{1}{K_{dry}} + \left(\frac{1}{K_f} - \frac{1}{K_g}\right)\emptyset_c \qquad (2)$$

Where K_{uf} is the unrelaxed bulk frame modulus, K_{dry}, K_f and K_g are the dry bulk modulus of the sample, fluid and grains, respectively.

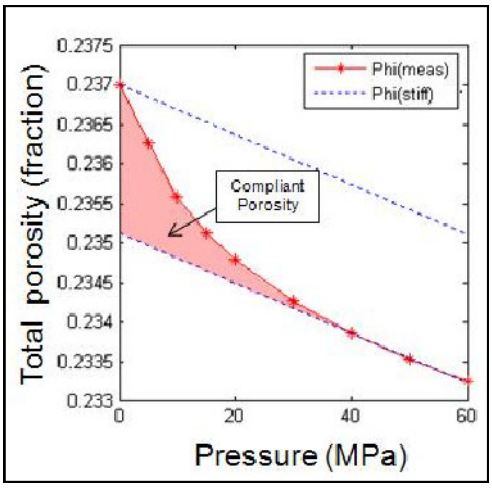

Fig. 01- Decay of total porosity with differential stress in a sandstone sample. Model showing the behavior of dual porosity (compliant and stiff).

Methodology

The methodology to achieve the results may be summarized in three steps. First we calculate the compressibility from the measured data. Then we find the exponential function coefficients that better fits the data using the Levenberg-Marquadt algorithm as suggested by Pervukhina et al. (2008). Then, soft porosity can be estimated as follows.

$$C_{dr}(P) - C_{drs} = ke^{(-\lambda P)} \qquad (3)$$

where $\emptyset_{c0} = \frac{K}{\lambda}$

From the regression coefficients we get compliant porosity estimation for each sample. The compliant porosities obtained are compared with the measured data and plotted (Fig. 02). The compliant porosities at zero pressure were obtained by extrapolation of a best fit linear equation in a log domain of compliant porosity as function of effective pressure (Fig. 03).

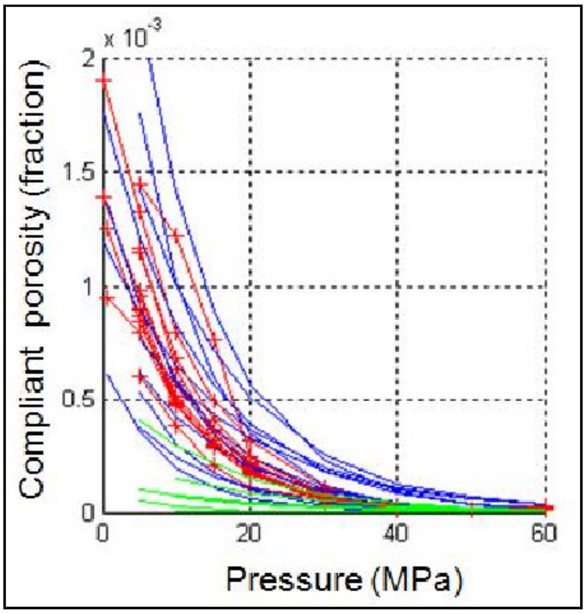

Fig. 02 – Compliant porosity as a function of effective stress. Measured values for sandstones in red and estimated values for sandstones (blue) and for carbonates (green).

The obtained values of compliance porosities are used to calculate the unframed bulk moduli (Mavko and Jizba,1991). The unframed bulk moduli are then substituted in Gassmann relations to get the estimations of P- and S-wave velocities for the brine saturated samples. These estimated velocities data are compared with the measured compressional and shear velocities of saturated samples.

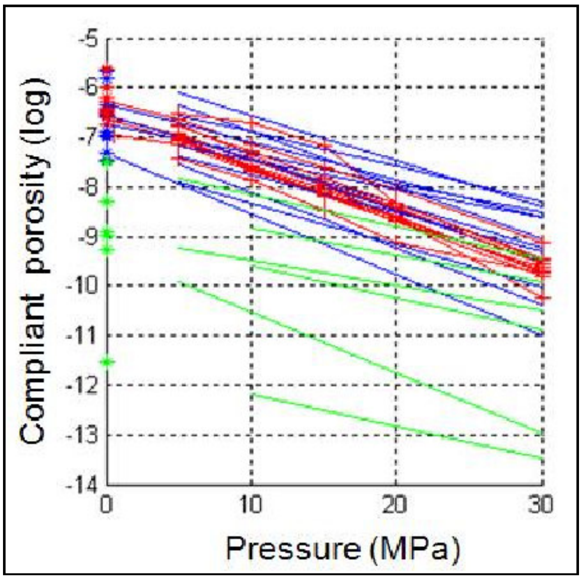

Fig. 03 – Logarithm of compliant porosity as a function of effective pressure. Measured values for sandstones in red and estimated values for sandstones in blue and carbonates in green. The correspondent asterisks are estimated values at zero pressure.

To verify our methodology we use ultrasonic measurements of 6 samples of carbonates (Agersborg, 2008) and 6 samples of sandstones (Siggins and Dewhurst, 2003). The total porosities were measured in laboratory, ranging from 2 to 14% for the carbonates and from 17 to 23% for the sandstones. The measurements were taken at effective stresses varying from 0 to 60 MPa. For the sandstones the axial length measurements taken during the experiment are also available. These data allow us to obtain total and compliant porosities for the samples and compare with our estimations. To obtain compliant porosities (Fig. 01) we approximate the measured porosities above 40 MPa with a linear equation and subtract it from the total porosity. It is assumed that the linear trend in the porosity-stress plot is due to the stiff porosity variation.

Results

Our estimations of compliant porosities of the sandstone samples are in agreement with the measured data (lines in blue and red respectively in Figure 02). At pressures higher than 40 MPa most of the soft porosity is almost closed, as predicted by Equation 3 and interpreted as the closure of the majority of crack-like defects.

Soft porosities obtained for the sandstones are much higher than that obtained for carbonate samples. From the Most of the compliant porosities for the sandstones are below 0.2% and all carbonate samples (in green) have compliant porosities smaller than 0.1% for minimum effective pressure (Fig. 3 and 4). The blue and brown bars of Figure 04 are the estimated and measured compliance porosities respectively. There are two results for each sandstone sample because the measurements were done also with decreasing pressure. The last six bars in Figure 04 are obtained for the carbonate samples.

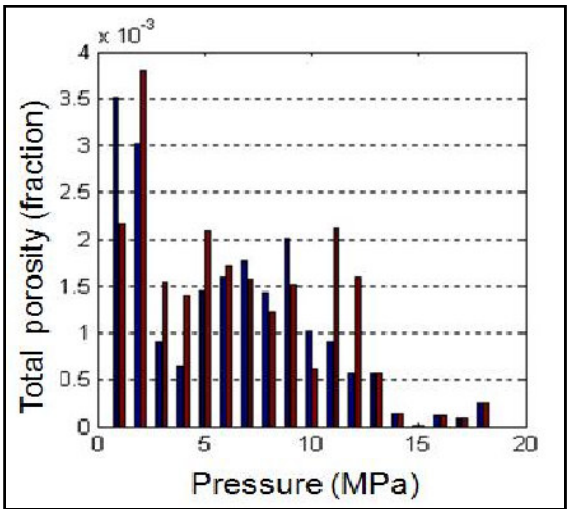

Fig. 04 – Compliant porosity of all samples. The bars in blue are estimated and in brown the measured data. The last 6 bars are the carbonates samples.

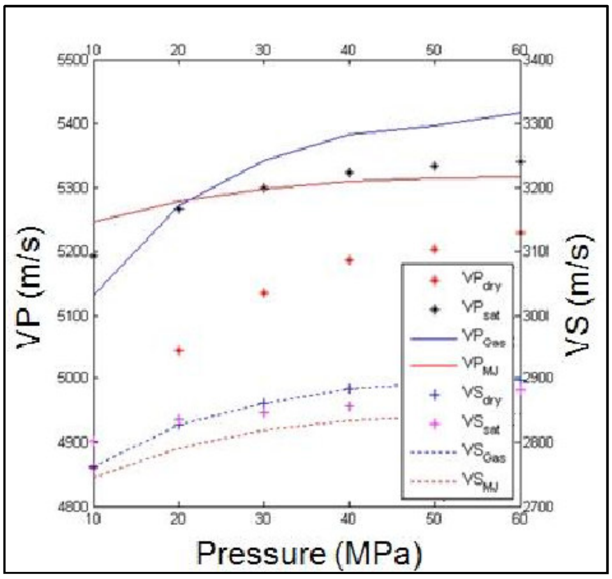

Fig. 05 – Ultrasonic measurements for a dry and saturated carbonate sample as a function of effective pressure. Estimation of saturated P and S wave velocities using Gassmann and Mavko and Jizba are marked as Gas and MJ, respectively.

In Figures 05 and 06 we describe two examples of the *P* and *S* wave velocities as a function of effective pressures for one carbonate and one sandstone samples. We plot the measured data for both dry and brine saturated sample and compare the predictions made by the Gassmann approach with the Mavko and Jizba moduli. The compliant porosities used in Equation 2 are the estimations obtained using Equation 3.

For the carbonate sample (Fig. 05), the Mavko and Jizba predictions for the compressional wave velocity fit the measured data better (error of 0.42%) than the Gassmann prediction (error of 0.91%). For the lower pressures Gassmamm predictions underestimates the real data, opposite to Mavko and Jizba, that overestimates the compressional wave velocities for the saturated sample. The same for the shear velocity, where the error of fitting diminishes from 1.64% for Gassmann to 1.25% for Mavko and Jizba prediction. In both cases, the estimations are lower that the measured shear velocity of the saturated sample.

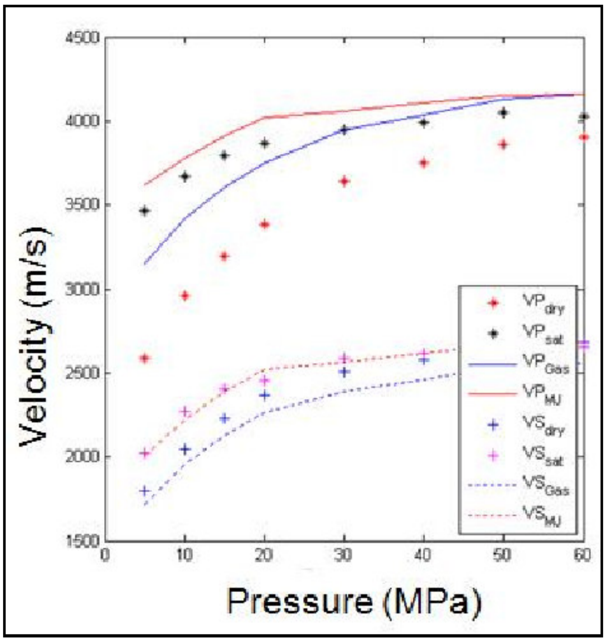

Fig. 06 – Ultrasonic measurements of a dry and saturated sandstone sample as a function of effective pressure.

For the sandstone example (Fig. 06), the *P* and *S* velocities predicted from dry to saturated are also better in this example for the Mavko and Jizba predictions than using the traditional Gassmann equation. In the case of *P* waves, the fit between measured and estimated values for Gassmann is about 4.08% dropping to 2.0% for Mavko and Jizba An analysis of the Figure 6 shows that after 20MPa all the compliant porosities seems to be closed, and the parallelism of the Mavko and Jizba predictions and the measured data are remarkable.

Gassmann underestimates the *P* velocities for pressures less than 20MPa and overestimates for higher pressures. In the case of shear waves, the difference drops from 8.1% (Gassmann,1951) to 2.2% (Mavko and Jizba,1991).

Conclusions

The sandstones compliant porosities estimations using the Shapiro theory (2001) for isotropic media is in agreement with measured porosities. The methodology presented here is shown to be useful and robust enough to provide better evaluations of important reservoir rock properties.

The compliant porosities obtained for the analyzed sandstones are more than two times higher than that obtained for the carbonates samples.

The behavior of the stress dependent ultrasonic velocities for the 2 analyzed samples can be better predicted using the additional constraint provided by compliant porosities present in the Mavko and Jizba equation.

This work shows that the dual porosity model is a good choice and that squirt effect must be considered at higher frequencies. The unrelaxed frame moduli of Mavko and Jizba fit the measured data in the best way.

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