On the applicability of Gassmann model in carbonates

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Summary

Petrophysical properties (porosity, permeability), and with them seismic properties, of carbonate rocks can change significantly due to dissolution, precipitation, and cementation processes. There is continuining debate on the use of an appropriate rock model to predict the attributes of the carbonate rock reservoirs. Gassmann's model in particular has been discussed at length, both for and against its applicability for the carbonates. Most laboratory research has shown that the Gassmann's theory can predict the fluid related changes on seismic velocities in sandstones and a few on carbonates also. But as few studies have reported a change of shear modulus upon saturation in a few carbonates, the applicability of this model needs to be tested on more rigorous grounds. In this study, we have used Gassmann's equation to calculate saturated velocities for for predicting fluid effects on a wide range of carbonate rocks with different textures and porosities ranging from at an effective pressure of 50 MPa.

A majority of the data shows a reduction of shear modulus by as much as 2.5 GPa for low porosity (5% to 15%) carbonate rocks. This shear modulus reduction becomes negligible for higher porosity (45%) carbonate rocks. The difference in the dry and saturated bulk modulus varies from 15GPa to 5GPa, and is in inverse proportion to porosity. The deviations in saturated shear velocity (V_s) when plotted against porosity, clearly shows that there are effects other than density that result in the lowering of V_s. Gassmann's theory slightly overestimates V_p (300 m/s for lower velocities and reducing with higher values), but it overestimates V_s for most of the data. However, the Gassmann's predicted V_p/V_s matches measured V_p/V_s. The pronounced difference in V_p/V_s against V_P plots between dry and fluid saturated samples indicates promising result for AVO analyses. The saturated V_p-V_s trend line for all the data sets when plotted with the carbonate mudrock line of Li and Downton (2000) shows a close match.

Introduction

Petrophysical (porosity, permeability) properties, and with them seismic properties, of carbonate rocks can change significantly due to dissolution, precipitation, and cementation processes. As shown by Eberli et. al. (2003), the matrix structure undergoes drastic change, with pores taking the matrix place and vice versa. Under such conditions, a relationship between the seismic, petrophysical and rock physics attributes of a reservoir system can assist in better understanding of such complicated limestone reservoirs.

Assuming linear elasticity and the rocks to be isotropic and homogeneous, we calculated shear wave velocities from measured dry Vs and saturated density. Figure 2(b) shows that the variation in shear modulus is not consistent with Gassmann's assumptions of a saturation-independent shear modulus.

The chief mineralogy of all the five data sets is calcite. The grain size varies from fine chalk (mudstone or wackestone) of the Chalk reservoir of Danish North Sea to olitic skeletal grain stones lacking carbonate mud (grainstone, packstone, wackestone) from the Great Olitic Limestone formation. The porosity ranges from as low as 0.6% to as high as 45%. All the data have ultrasonic measurements of compressional and shear wave velocities made at 50 MPa. Water was used as the main saturating fluid except in Wang's experiments that used brine. The constant used for calculating various reservoir values are listed at table 1.

Mineral/ Fluid	**Bulk Modulus (GPa)**	**Shear Modulus (GPa)**	**Density Kg/m^3**
Calcite	74.8	30.6	2710
Dolomite	76.4	49.7	
Quartz	37	44	
Water	2.25	0	1000
Brine	2.94	0	1030
Oil	1.05	0	715

Table 1. Elastic constants and density applied in the present study (Rogen,2002 & Aseefa,2003).

Theory

The Gassmann's (1951) relation (eq.1) is used to calculate the saturated velocities and other related reservoir attributes. To calculate the difference of saturated from dry (Measured Saturated Deviations –MSD) and that of Gassmann's from saturated (Gassmann's Deviation – GD), we have used the following equations.

MSD (%) = $[\{\text{Sat.}\ (V_{p(\text{or } s)}) - \text{Dry}\ (V_{p(\text{or } s)})\}/\ \text{Dry}\ (V_{p(\text{or } s)})] \times 100$ …………1

GD (%) = $[\{\text{Gass.}\ (V_{p(\text{or } s)}) - \text{Sat.}\ (V_{p(\text{or } s)})\}/\ \text{Sat.}\ (V_{p(\text{or } s)})] \times 100$ …………2,

Results

For medium to high porosity rocks, shear velocity reduces appreciably with saturation (Fig. 1a, 1b, 1c, 1d, 1e). For majority of the data, the saturated shear modulus is lower than its dry values (Fig. 2b). The change in values of bulk and shear moduli after saturation appears to be inverse functions of porosity (Fig. 2c & 2d). The Gassmann's estimation of saturated V_P & V_S fails in carbonate as the shear modulus of the rocks decreases after saturation (Fig. 3 & 4). The plotting of the difference between the saturated and dry V_P & V_S shows that most of the data have experienced a bulk strengthening and shear weakening (Fig. 5)

The V_P / V_S sensitivity to fluid and porosity effects in carbonate rocks and can help in determining the prospective formations for AVO studies (Fig. 6a & 6b).

Conclusions

The Gassmann calculated velocities and modulus underestimates the saturated velocities and modulus, especially for the low porosity formation where there is no variation of shear after saturation. The effect of fluids does not seem to play an important role in these formations for calculating saturated velocities. For the high porosity formation, the Gassmann's overestimation of V_P and V_S is much more than what can be explained by density effect. The fluid in the rock seems to have played major role in the altering the shear strength of the rock. Though the determination of V_P and V_S is inaccurate in the shear altered rocks, the theory has successfully modeled the variation in the V_P/V_S ratio for the effect of both porosity and fluid as it is known to do for clastics and also to lay checks for proposed AVO study of an area.

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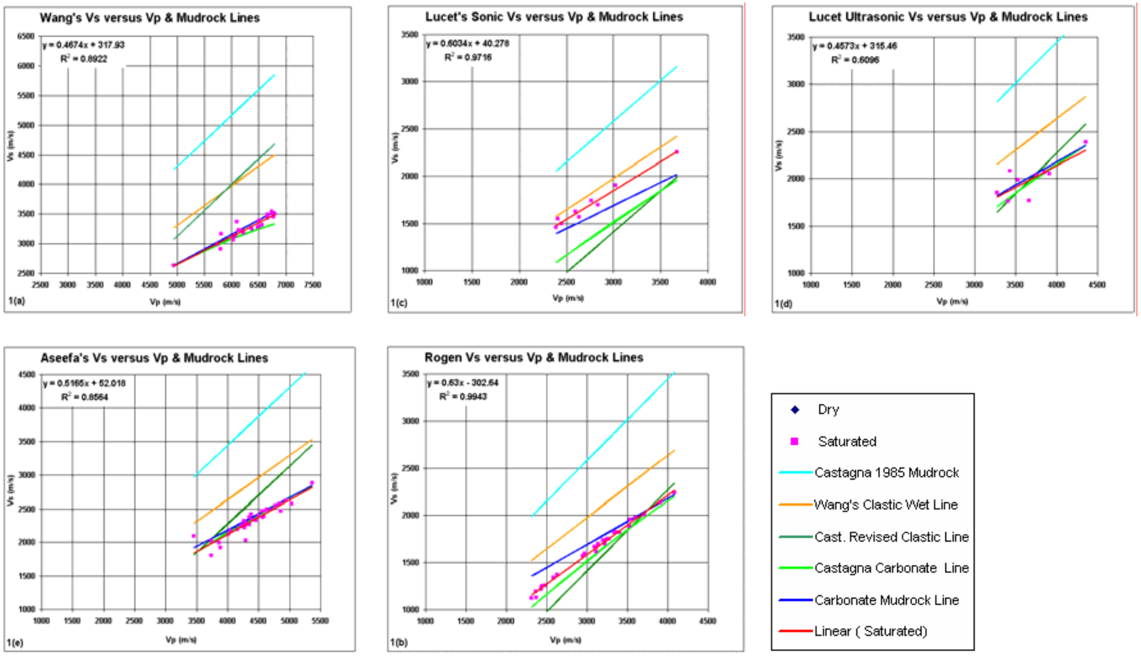

Figure 1 Trend lines for V_S versus V_P are plotted for, a) Wang, b) Rogen, c) Lucet's Sonic, d) Lucet's Ultrasonic and e) Aseefa's data set. All these trend lines are compared against the different Mudrock lines. In all the plots, the trend line for saturated velocities better matches the Carbonate Mudrock Line by Li & Downton (2000), except for the Lucet's sonic.

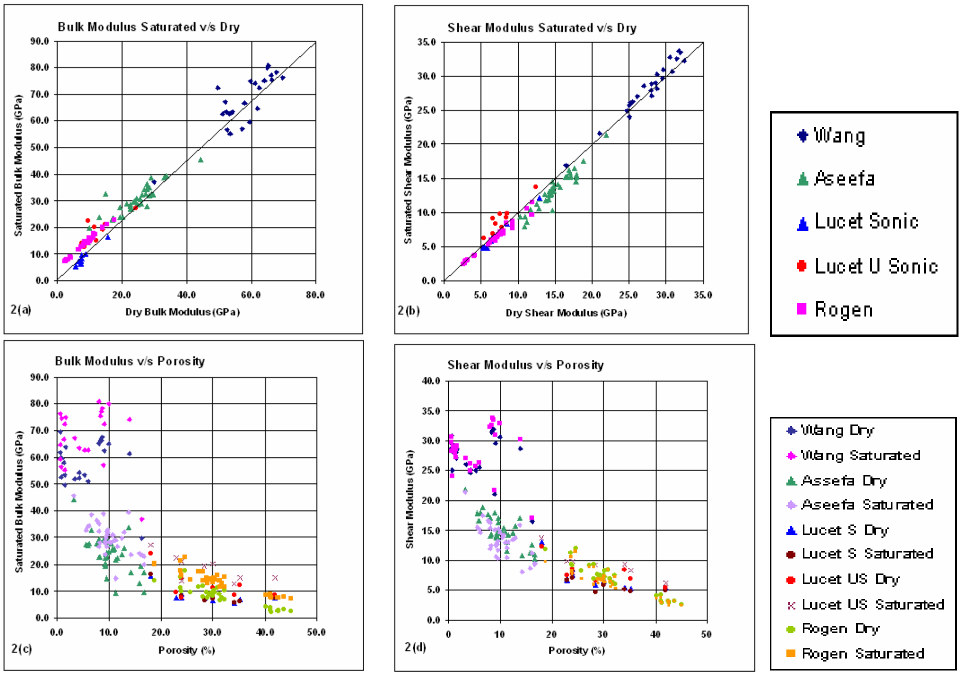

Figure 2 Saturated and Dry modulus, bulk in a) and shear in b) , shows an increase in bulk modulus for all the data sets except for Lucet's sonic and a few points of Wang's data but a decrease of shear modulus for majority of the data. The difference between Dry and Saturated, bulk modulus in c), varies from 15 to 5Gpa with increasing porosity and over the same porosity range, shear modulus in d) varies from 2.5GPa to negligible with increasing porosity. The order of the legend from top to bottom indicates increasing porosity.

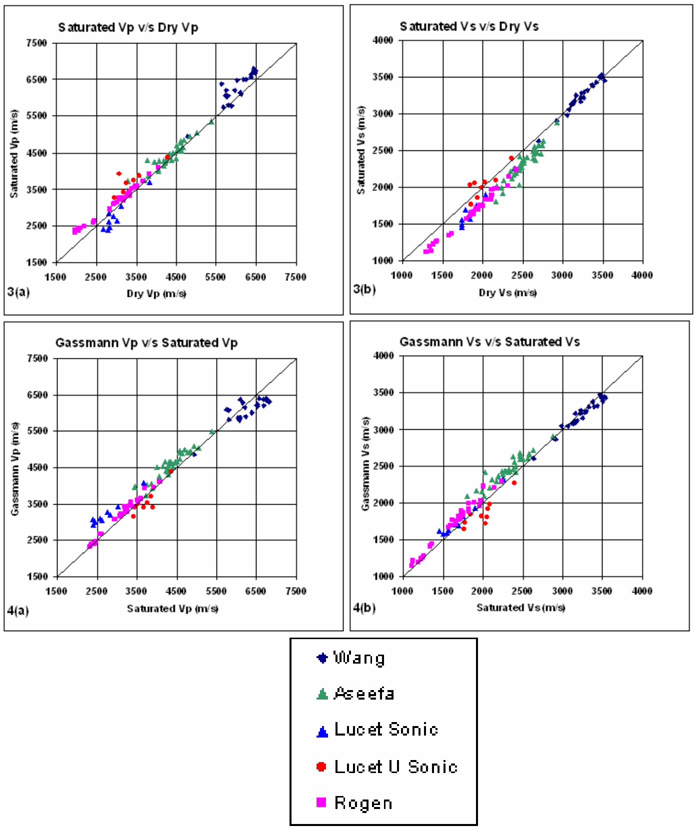

Figure 3 & 4 Saturated versus Dry 3a) compressional velocities and 3b) shear velocities. Saturated VP is overestimated for most of the data points and saturated VS is underestimated for most of the data points. The Gassmann's versus Measured 4a) compressional velocity, 4b) shear velocity, overestimates the saturated velocities except for the Lucet's ultrasonic and Wang's data points. The order of the legend from top to bottom indicates increasing porosity.

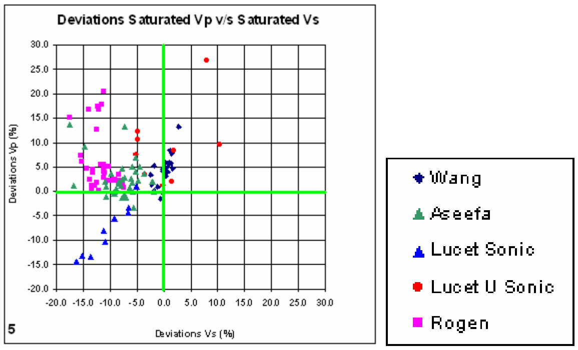

Figure 5 deviations for Vp versus deviations for Vs indicates an over all bulk strengthening and shear weakening. The order of the legend from top to bottom indicates increasing porosity.

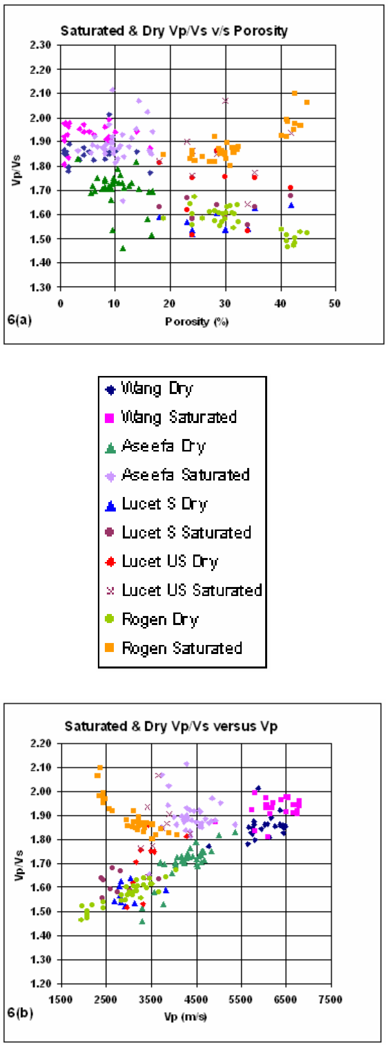

Figure 6 Plotting is done for separating the effect of fluid and air/gas in the pores and is shown as, a) Saturated and Dry Vp/Vs versus Porosity, b) Saturated and Dry Vp/Vs versus Vp. The Vp/Vs ratio is 1.90 for low porosity rocks and decreases linearly up to 1.45 with for a 45% porosity data. Plotting of Vp/Vs versus Vp is an excellent tool for differentiating formation filled with fluid from that of gas. For low porosity data this difference is not very appreciable but as the porosity increases the difference becomes more and more prominent. As in this case the difference of Vp/Vs versus Vp is 0.05 for low porosity data but is as large as 0.60 for high porosity data set. The order of the legend from top to bottom indicates increasing porosity.

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