Constraining C for fluid properties inversion.

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Summary

Analysis of laboratory measurements of 301 core samples found in the literature for different lithologies, clay content, porosities and pressures was employed to constrain the C constant that accounts for the frame properties of the rock in the AVO inversion method proposed by Batzle et al. (2001). The results showed that C varies for sandstones between 2 and 2.9 and for carbonates between 2.5 and 3.5. If clay content increases C decreases, and if cementation (carbonates) and porosity increases C increases. We applied this method to a small 3D seismic volume corresponding to the King Kong field in Gulf of Mexico in order to estimate the fluid properties of the reservoir (gas sandstones) and the water bearing sandstones. Specifically we used this method to estimate the fluid term, which is composed by density of the rock and the fluid bulk modulus (ρK_f). The results successfully discriminate two pay sands intervals from the background; however absolute values of fluid bulk modulus are not comparable to the results yield by well-log data available of the prospect. Probable causes are tuning effect and calibration of seismic amplitudes with well-log data.

Introduction

Several methods have been developed to extract from seismic data the fluid and rock properties; one of those is known as AVO inversion. Batzle et al., (2001) proposed a method based on Gassmann theory to extract the fluid term ($\rho\Delta K$) from P-wave and S-wave impedances.

$$\rho\Delta K = I_P^2 - CI_S^2 \qquad (1)$$

where I_P and I_S are the P-wave and S-wave impedance, respectively, ρ is density and ΔK corresponds to the saturated bulk modulus which is helpful to identify fluid properties.

The constant C depends on the dry properties of the rock and it should be calibrated according to the well-log data available in the field. They assumed $K_{dry} = \mu_{dry}$ which leads constant C equal to 2.33.

$$C = \frac{K_{dry}}{\mu} + \frac{4}{3} = \left(\frac{V_P}{V_S}\right)_{dry}^2 \qquad (2)$$

where K_{dry} is the bulk modulus and μ is the shear wave modulus of the frame.

A different way to write equation (1) is using the Gain function concept (Han et al., 2002), which simplifies Gassmann equation and offers a more clear physical meaning: fluid effects on the rock bulk modulus are proportional to Gain function, which corresponds to the dry rock properties and fluid modulus K_f.

$$\rho K_f = \frac{[I_P^2 - CI_S^2]}{G(\phi)} \qquad (3)$$

where $G(\phi)$ is the gain function and depends on the mineral and dry bulk modulus and porosity.

In order to accurately obtain from seismic data the fluid properties, we need to constrain both C and the Gain function according to the reservoir. Gain function bounds was analyzed by Han and Batzle (2002) and in this paper, we intend to use several laboratory measurements of P-wave and S-wave dry velocities from the literature in order to correlate the C constant with respect to porosity, clay content and differential pressure for different lithologies.

We will perform AVO inversion applying Equation (3) to a small 3D seismic volume from the Gulf of Mexico to analyze the effect of C on the estimation of the fluid properties.

Dataset

Laboratory measurements from previous works consist of dry compressional and shear wave velocities, porosity, density, clay content and for some samples dry bulk and shear modulus in 301 core samples. The velocities were measured at different overburden and differential pressures.

The 301 core samples include 92 carbonates (Yale and Jamieson, 1994; Wang et al., 1998), 17 volcanics (Boinott, 1999), 27 unconsolidated sands (Zimmer, 1992), 26 siltstones (Yale and Jamieson, 1994) and 139 sandstones and shales (Han, 1986; Gregory, 1976; Jizba, 1991; Domenico, 1977; Prasad and Meissner, 1992).

To test this method in real data we will use a small 3D seismic data volume from King Kong field and wireline logs. King Kong is a Plio-Pleistocene age gas reservoir in which the rock properties show a strong dependence on pore fluid (O'Brien, 2004), characteristic of deep-water unconsolidated sandstones (Figure 1). This successful well drilled two pay intervals.

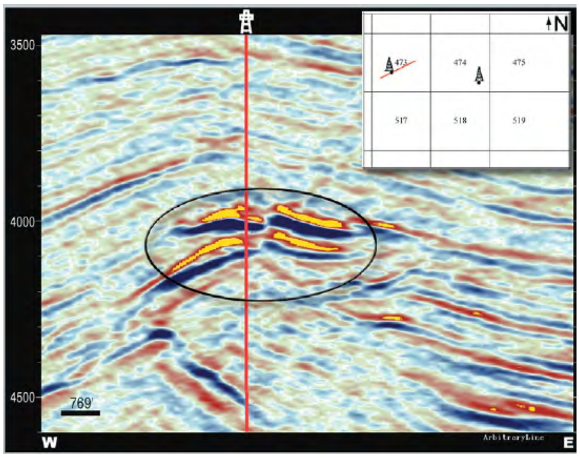

Figure 1. 3D seismic line over King Kong Field with corresponding well. Amplitude anomaly is enclosed within oval (Taken from O'Brien, 2004).

Technical approach

The following figures show the correlation for clastic sediments between C, clay content, porosity and differential pressure. Although the data is particularly scattered, rocks with similar properties tend to fall in groups. Here, we assumed clean sandstones with clay content below 0.1, shaly sandstones between 0.11 and 0.3 and sandy-shales between 0.35 and 1.

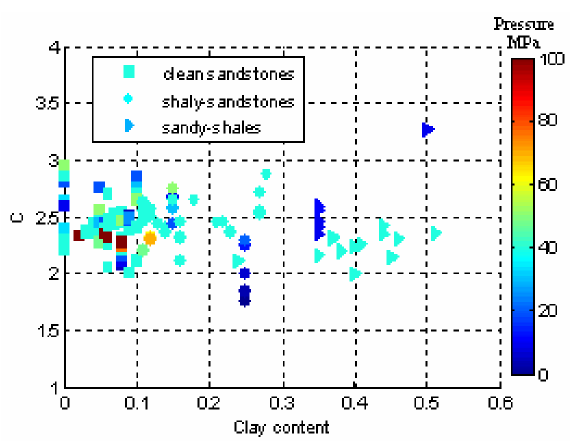

Figure 2. Correlation between C constant and clay content color-coded with differential pressure for clastic rocks.

A clear correlation between C and clay content is observed in Figure 2. C slightly decreases with clay content; however differential pressure constitutes an independent factor in this case. The general trend of C for clastic rocks varies between 2 for sandy shales and shales and 2.9, for clean sandstones.

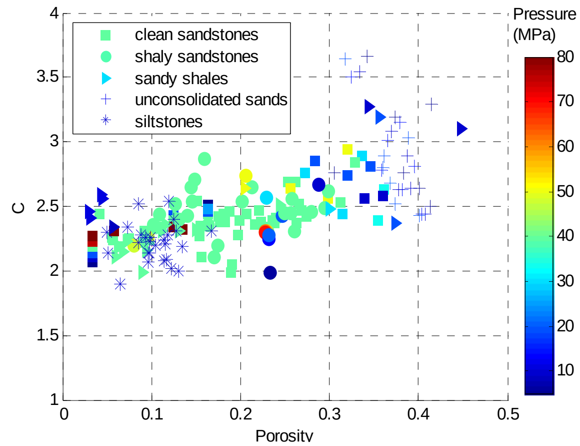

Figure 3. Correlation between C and porosity color-coded with differential pressure for clastic sediments.

Figure 3 shows C increases with porosity but decreases with differential pressure. According to these results, for high porosity rocks (low pressure), the constant C should be higher than for more consolidated low porosity rocks. As it was mentioned before, C accounts for the dry properties of the rock, therefore the difference between compressional and shear velocity becomes less significant with pressure and the porosity effect is also lower.

A set of unconsolidated sandstones and siltstones were included in Figure 3. The first are characterized by high porosity due to small grain size and well sorted grains. The latter were found to be extensively cemented by calcite. No information of clay content was found for both datasets.

Combining Figure 2 and 3, we noticed an inverse relationship between porosity and clay content. In other words, high porosity rocks mostly correspond to low clay content for this dataset.

We also investigated the effect of porosity and pressure on carbonates and volcanics rocks. The carbonates include dolostones, limestones and siltstones with dolomite. These rocks are significantly affected by diagenesis; therefore porosity and permeability vary greatly both vertically and horizontally due to secondary porosity and cementation.

For carbonates and volcanics rocks, the possible values for C increase significantly with respect to the results observed for clastic rocks (Figures 4 and 5). For dolomites largely cemented by anhydrite, C roughly varies between 3 and 3.5; for limestones and dolomites, between 2.5 and 3.1 and for siltstones with dolomite, between 2.2 and 2.5.

Figure 4 also shows that for carbonates, the mechanical compaction given by depth is an essential factor controlling the frame properties of the rock than porosity in the case of clastic rocks. For carbonates the driving factors are secondary porosity and cementation but for clastic rocks is primary porosity among others.

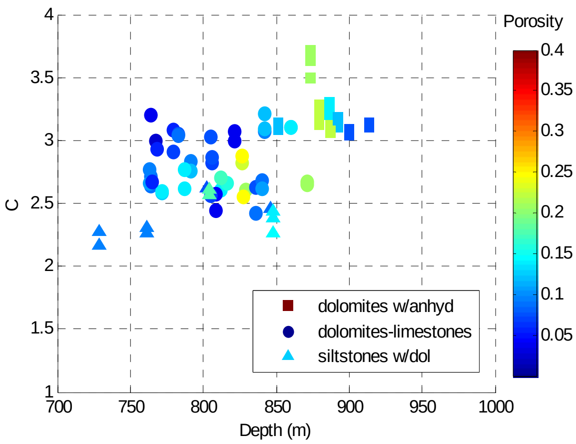

Figure 4. Correlation between C constant and depth (m) color coded according to porosity for carbonates rocks.

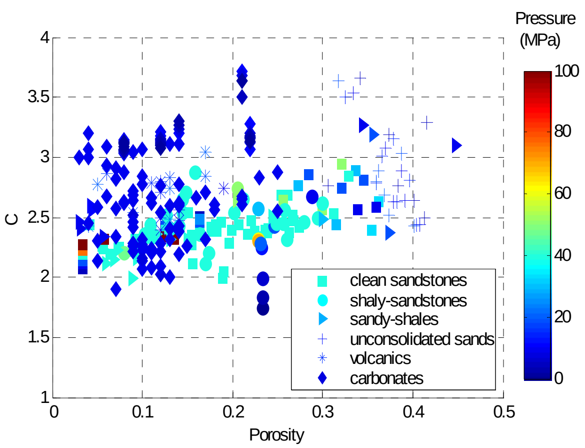

Figure 5. Correlation between C constant and porosity color-coded with differential pressure for clastic, carbonates and volcanics rocks.

The other factor we need to constrain in order to carry out AVO inversion using seismic data is the gain function. Recently, Batzle et al. (2001) and Han and Batzle (2002) published a comprehensive analysis to propose bounds for the gain function in sandstones, based on Reuss and Voigt bounds. They found that:

- For sandstones with porosity between 20-30% $G(\phi)$ is around 2 and increases with clay content .
- For clean sandstones, $G(\phi)$ increases with porosity ($G(\phi)$ tends to increase if cementation and pressure decrease).
- For reservoir sands (ϕ >15%) $G(\phi)$ is distributed in a narrow range and can be predicted but for low porosity rocks (ϕ <15%), $G(\phi)$ shows a large scatter mainly affected by clay content.

In this sense, the next step will be apply the correlations between clay content, porosity and pressure to estimate the sensitivity of C and $G(\phi)$ to obtain the fluid term (ρK_f) from a 3D seismic volume corresponding to the King Kong field. The volume consists on 41 cross-lines and 27 in-lines. Figure 5 shows two CDP gathers located in the prospect.

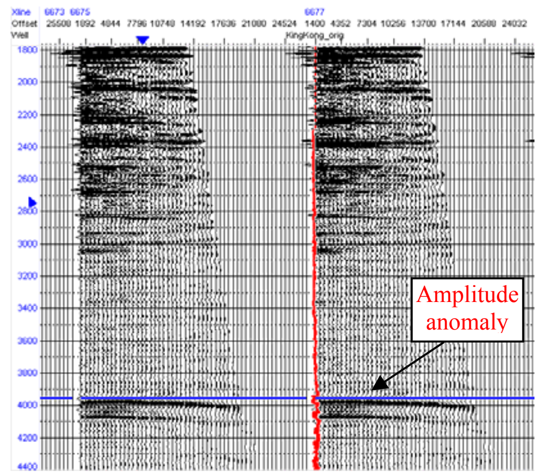

Figure 6. CDP gathers located in the prospect. Seismic processing was done to preserve the true amplitude. P-wave curve is also shown.

We estimate P-wave and S-wave reflectivity volume using the following approximation proposed by Fatti et al. (1994). A V_P-V_S empirical relationship was assumed.

$$R(\theta) = R_P\left(1+\tan^2\theta\right) - 8\left(\frac{V_S}{V_P}\right)^2 R_S \sin^2\theta \qquad (4)$$

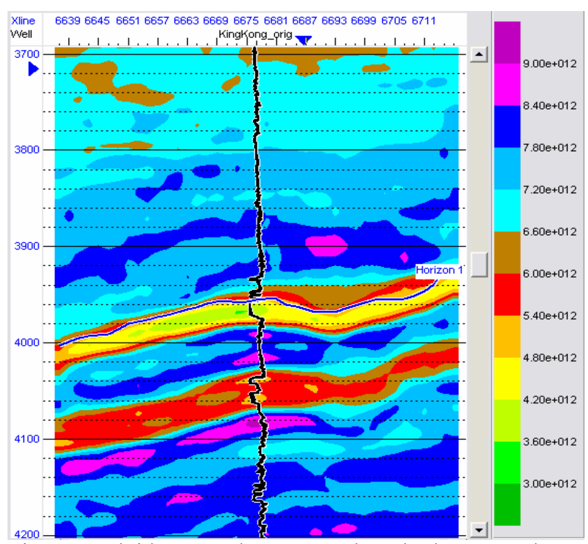

Figure 7. Fluid term volume. Note how both pay sands are easily separated from the background.

P-wave and S-wave impedance are inverted from the seismic volume; the low frequency component is estimated based on the velocities calculated from well-log data. Once impedances are estimated, we calculate the fluid term using Equation 3 (Figure 7). We chose 2.5 for both C and G(ϕ).

Both anomalies are clearly discriminated from the background. We estimated the fluid term for both pay sand intervals located at 3956 ms (11848 ft) and 4040 ms (12120ft) approximately and for comparison we estimated the fluid term for a water sand interval located at 3745 ms (10992 ft). To estimate K_f from the fluid term we assumed average densities for gas and water bearing sandstones from different well logs of Gulf of Mexico. Since we have wireline logs in the prospect we are able to compare these results with the fluid bulk modulus calculated from the seismic inversion (Table 1).

Interval	$K_{f\,(seismic)}$	$K_{f\,(well\text{-}log)}$
Gas sand (3965 ms)	1.65	0.24
Gas sand? (4040 ms)	2.27	0.60
Water sand (3745 ms)	3.05	2.61

Table1. Fluid bulk modulus (GPa) for different sand intervals computed from well-log data and using AVO inversion of seismic data.

The results obtained using this inversion method provide good relative estimations of the pore-fluid properties of the rocks. However, they are not comparable in absolute terms with the results from well-log data. Better methods to calibrate seismic data are necessary. On the other hand, since Equation 3 is based on Reuss bound (low frequency), we should expect the use of higher C values for seismic inversion. Further study needs to be done in this area.

The deeper gas sand yields higher K_f than expected, a possible reason is the tuning effect which increase significantly the seismic amplitudes. The sonic log shows that two thin layers compose this reservoir. However, the result from well-log data also shows K_f too high for gas, which makes us think that light oil can be another possibility.

Variations of C and G(ϕ) by 5%, which is approximately the error associated to those estimations cause variations of K_f by 12%.

Conclusions

The aim of this work was to present a more quantitative estimation of fluid properties by using fundamental rock physics. We applied a simple equation in order to extract the fluid properties of the rock based on seismic impedances. The Han and Batzle method and similar techniques have been widely used to estimate the "fluid term" from well-log and seismic data. In this paper we also applied this technique to King Kong field (Gulf of Mexico) to calculate the fluid properties but constraining C according to numerous laboratory measurements for different lithologies, porosity ranges, clay content and pressures. The analysis of the lab measurements shows that C varies for sandstones between 2 and 2.9 and for carbonates between 2.5 and 3.5.

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