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A Transformation from Acoustic and Density Properties to Reservoir Properties applied to Krishna Godavari Basin, India

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Summary

This papers deals with the transformation of acoustic and density properties into reservoir properties. The transformation is based on several rock physics models (RPMs) and has been carried out using a new inversion technique comprised of sequential inversion followed by multi-variate Newton Raphson method. Using this technique, three gas hydrate wells located in the Krishna Godavari (KG) Basin viz. NGHP-01-03, NGHP-01-05 and NGHP-01-07 have been characterized. The sonic velocity and density logs for all the three wells were provided as input and the porosity and gas hydrate saturation in all the three wells are estimated. The result obtained from each of the RPMs has been compared with the past results and the stability of the models is studied for the KG Basin.

Introduction

Here, we propose a transformation based on determination of reservoir properties from acoustic and density properties. We have tried to determine the porosity and saturation logs from sonic velocity and density of three wells drilled during the First National Gas Hydrate Programme (NGHP-01). The transformation is based on several rock physics models and the inversion process is comprised of sequential inversion algorithm followed by multi-variate Newton Raphson method. The models used are as follows: Wood (1941) model, Wyllie's (Wyllie et al, 1958) time average equation, Ramer-Hunt-Gardner model (Raymer et al, 1980) and weighted equations (Nobes et al, 1986).

Due to the presence of gas hydrates in the sediments, the bulk physical properties of the sediments are affected, thereby causing to change the P-wave velocity of the sediments. Presence of gas hydrate in the sediments significantly affects their bulk physical properties. The P and S wave velocities for pure gas hydrates are high compared to the host sediments or the fluid occupying the pores, hence the presence of gas hydrates in the sediments increases the seismic velocities. The extent of change in seismic velocities depends upon the saturation of gas hydrates present in the pores of the sediments. We have used this concept of analyzing the change in the trend of the seismic velocity to determine hydrate saturation. Also, the density log, when used with the changing velocity, can give the porosity values for different depth points of the wells.

Data

The data used here to test the transformation method corresponds to three wells located in the Krishna Godavari Basin. These wells were drilled during the NGHP Expedition 01, a downhole logging program specially designed to study the gas hydrate saturations present on the continental margins of India (Collett et al., 2008). Several Logging While Drilling (LWD) and wire-line logging devices were deployed and LWD data were acquired at five sites drilled in the Krishna Godavari (KG) Basin on the eastern continental margin of India.

Theory

Rock Physics Modeling

The rock physics models (RPMs) used here for the determination of porosity and gas hydrate saturation are empirical relations and show dependency on seismic

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velocities. Other than estimation of gas hydrate saturation in the pores, these models can be used to construct the missing sonic, porosity and density logs. These are also used to study the change in elastic properties of rocks due to the change in their mineral composition, fracturing or digenesis (compaction, cementation, and dolomitization), change in characteristics of fluid, saturation and pore pressure, and finally any variation in the reservoir effective stress and temperature. The rock physics models used in this study are as follows:

Wood (1941) model: This is one of the oldest models that have been used to determine the hydrate saturations. This method generally holds true for highly porous medium, where gas hydrate forms a part of the fluid suspension. The model is based on three phase Wood (1941) equation defined as:

$$\frac{1}{\rho V_p^2} = \frac{\phi(1-S)}{\rho_w V_w^2} + \frac{\phi S}{\rho_h V_h^2} + \frac{1-\phi}{\rho_m V_m^2} \qquad (1)$$

In equation (1), V_p, V_w, V_h and V_m represent the compressional velocities of the hydrated sediment, pore-water, gas hydrate and rock matrix respectively. Similarly, ρ, ρ_w, ρ_h and ρ_m represent the bulk density of the sediment and densities of pore-water, hydrate and rock matrix respectively. ϕ is the porosity (as a fraction) of the sediments. The weighted average of the constituent components can be put in the mass balance equation to determine the bulk density of the sediment as follows:

$$\rho = (1-\phi)\rho_m + (1-S)\phi\rho_w + S\phi\rho_h \qquad (2)$$

Time Average Equation (Wyllie et al, 1958): This model states that the slowness of a rock (inverse of velocity) is dependent on all the constituents i.e. fluid, rock matrix and the hydrate residing in the pores. Pearson et al (1983) used this equation on hydrate-bearing rock and concluded that it qualitatively explains the known sonic properties of hydrate bearing sediments in consolidated medium. The three phase time average equation used by Timur (1968) and Pearson et al (1983) is defined as follows:

$$\frac{1}{V_p} = \frac{\phi(1-S)}{V_w} + \frac{\phi S}{V_h} + \frac{1-\phi}{V_m} \qquad (3)$$

The symbols used here are same as those used in equation (1). This model is based on the assumption that the hydrate present in the pores forms the part of the cementation matrix. Even when applied to marine sediments, the time-average equation with a modified matrix velocity still often overestimates velocity-porosity relationship (Nobes et al, 1986.

Three Phase Weighted Equation: Nobes et al (1986) proposed that if a weighted mean of the three-phase time average equation and the three-phase Wood equation is framed, it will hold true for all porosity values with the elimination of the drawbacks of the Wood and time average equations when used individually. The weighted mean of the Wood (1941) and time average equation is as follows:

$$\frac{1}{V_p} = \frac{W\phi(1-S)^n}{V_p^1} + \frac{1-W\phi(1-S)^n}{V_p^2} \qquad (4)$$

In equation (4), V_p , V_p^1 and V_p^2 denote the weighted velocity, Wood velocity (obtained from equation (1)) and Wyllie velocity (obtained from equation (3)). W denotes the weighting factor and n is a constant simulating the rate of lithification with hydrate concentration.

As per Nobes et al (1986), a value of $W > 1$ favours the Wood equation and $W < 1$ favours the time-average equation. As the porosity decreases equation (5) approaches the three-phase time-average equation of Pearson et al (1983). As n increases, the weighted equation also approaches the time-average equation more rapidly, because $(1 - S) < 1$. Use of both a weighting factor W and an exponential n provides flexibility in using the equation for conditions of greater consolidation and rigidity (i.e. where the time-average equation is more applicable) or greater saturation (i.e. where the Wood equation is more applicable).

Raymer-Hunt Gardner Model (Raymer et al, 1980): Over two decades, it has been found that the Wyllie model has been inefficient in producing good results for most of the cases. Raymer et al (1980) proposed a new empirical transform based on extensive field observations of transit time versus porosity. It provides superior transit time-porosity correlation over the entire porosity range and suggests more consistent matrix velocities for given rock lithology. The equation used by this model is as follows:

$$V_p = (1-\phi)^2 V_m + \phi V_f \qquad (5)$$

Inversion Technique

We have used a hybrid form of inversion technique comprised of Sequential Inversion followed by Multivariate Newton Raphson method. Before applying the algorithm, it has been tested on several mathematical functions and is found to produce good results.

Multi-variate Newton Raphson Method : Consider the case where we need to find solution to a simple linear equation of the form f (x) = 0. The basis of Newton Raphson lies in the fact that the solution of the equation is given as follows:

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)} \qquad (6)$$

This condition will be applied to the misfit function; hence instead of finding root of the equation, we need to find the minima of the function. To find this extreme condition, the solution is extended to second derivative and is given as follows:

$$x_{i+1} = x_i - \frac{f'(x_i)}{f''(x_i)} \qquad (7)$$

Similarly, for a system of n non-linear equations and n uknonwns, Newton Raphson method can be expanded to multi-variate case.

$$x_{i+1}^k = x_i^k - \frac{f'(x_i^1, x_i^2, x_i^3 ......x_i^k ....x_i^n)}{f''(x_i^1, x_i^2, x_i^3 ......x_i^k ....x_i^n)} \qquad (8)$$

This equation can be replaced by a weighted multi-variate Newton Raphson method, where each of the parameters are treated differently, with the most important one being iterated the maximum no. of times while optimization.

Method

The transformation from acoustic and density properties to reservoir properties can be divided into several steps. These have been clearly demonstrated by the flow chart shown in figure 1. This transformation accepts acoustic and density data as its input. As the value of reservoir properties such as porosity, water saturation etc. varies from zero to one, the transformation has been kept independent of range of the parameters. The models required at each step of inversion are obtained from the rock physics modeling equations.

To check the accuracy of the output, we have used square misfit function. Lower the value of the misfit function, higher is its probability to get selected. The misfit function used here is as follows:

$$\text{Misfit} = \left(\frac{V_i - V_c}{V_i}\right)^2 + \left(\frac{\rho_i - \rho_c}{\rho_i}\right)^2 \qquad (9)$$

In equation (9), V_i and ρ_i represent the sonic velocity and density obtained from the field data. On the other hand, V_c and ρ_c denote the velocity and bulk density obtained using the transformation.

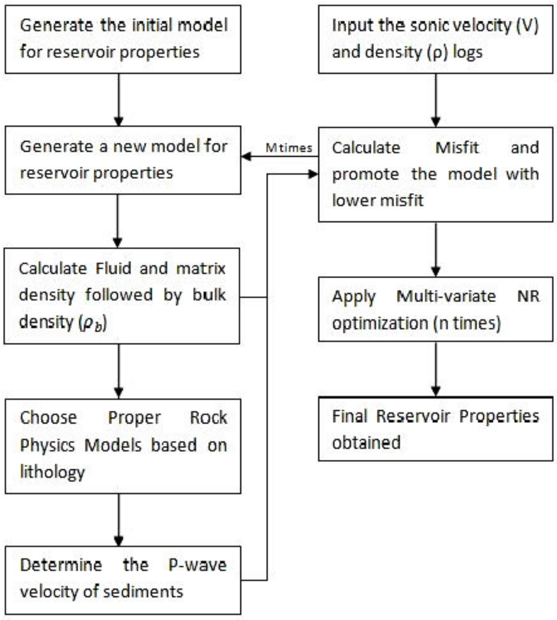

Figure 1: Flowchart demonstrating the workflow for the transformation from acoustic and density properties to reservoir properties based on rock physics modeling and multi-variate Newton Raphson inversion

Numerical Results and Discussions

Several rock physics models together with a hybrid inversion technique have been applied here to determine the reservoir properties of three wells located in the Krishna-Godavari basin, India. We have tried to determine the porosity and gas hydrate saturation in each of the wells. Shankar and Reidel (2010) have already mentioned the location of bottom seismic re lectors (BSRs) for each of the wells, and we have limited our inversion only upto the BSRs.

The rock physics models used here are empirical in nature and are not applicable for all values of porosities. Dewangan et al (2009) have stated that the critical porosity value for the Krishna Godav ri Basin varies from 62-65%. Hence, the porosity of the region is very high and the gas hydrates are probably to be the part of the fluid suspension.
Figure 2 shows the variation of compressional velocity with porosity for three different rock physics models viz. Wood's model, Wyllie time average equation and three phase weighted mean. At porosity values near to 65%, the Wood's curve is found to approach the weighted curve. The Wyllie curve is found to move away from the weighted mean. This indicates that for the KG Basin region, the Wood's curve will produce better results. Table 1 shows the misfit values for the three wells for the four models used in this paper. It is found that the misfit values for the Wood and weighted curve are very small and close to each other. On the other hand, misfit values obtained by the Wyllie model and Raymer-Hunt-Gardner model are very high which denotes that the results generated by these models are arbitrary in nature. Raymer et al (1980) stated that their model is applicable for all values of porosities, but it is found to fail in this case.

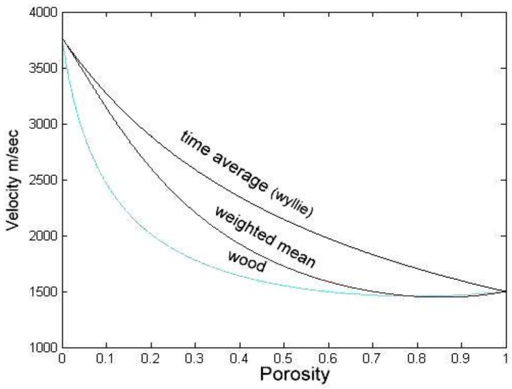

Figure 2: Graph showing the P-wave velocity trends at different porosity values obtained for the Wood's model, Wyllie's time average equation and the three phase weighted equations (W=1.2)

Table1: Final misfit values obtained for NGHP-01-03, NGHP-01-05 and NGHP-01-07 sites of the KG Basin using four different rock physics models

Site in KG Basin(Well)	NHGP-01-03	NGHP-01-05	NGHP-01-07
Wood (1941)	0.0096	0.0133	0.0083
Wyllie (1958)	0.8235	0.6797	0.6225
RHG (1980)	0.5849	0.3596	0.2607
Weighted(1986)	0.0037	0.0014	0.0085

High misfit values for Wyllie model and Raymer-Hunt-Gardner model state that these models are inapplicable over the Krishna Godavari Basin and cannot be used for the estimation of gas hydrate saturation in this region. An empirical correction in the Wyllie model, which helps eliminate the velocity shift, can make this model applicable over all values of porosities for the determination of gas hydrates. The misfit values obtained for the case of Wood's model are very low which states that the results obtained by this model are good. Wood's model, as stated before, is based on the assumption that hydrates form part of the fluid suspension. The Krishna Godavari Basin's lithology is mainly comprised of shaly loam. Hence, Wood's model can be one of the best models that can be used for the estimation of hydrate in the pores of the sediments in this region.

But, the porosity of the region is lower than the porosity value at which Wood's empirical relation was given. Also, from figure 2, it can be seen that the Wood's model will over-predict the hydrate saturation at the given sites. The porosity log obtained from field when plotted at zero hydrate saturation is found to overlap the weighted curve. Hence, we have tried to predict the hydrate saturation using the weighted mean of the Wood model and Wyllie's time average equation. The optimum value of W and n for KG Basin are found to be 1.27 and 1.0 respectively. Using this model, the output generated holds lower value of misfit than the Wood's method which makes it more superior. Figure 3, figure 4 and figure 5 show the porosity and hydrate saturations for the three wells mapped using Wood's model and weighted mean method respectively. From the results of these models, it is found that the wells of the study area show the presence of about 10-20% of gas hydrate in the pores of the sediments.

For zero saturation of gas hydrate, the weighted equation is independent of the exponent n. Thus from here, the value of W is determined. It can be seen that the weighted mean (W = 1.27) of Wood and Wyllie equations is suitable to some extent for this region. For W = 1, the weight of Wood as well as Wyllie equations in the three phase weighted equations are equal. For W > 1, the equation favours Wood equation. The computed value of W and n may not be absolutely correct and may exhibit a variation of around +10%. Larger values of n simulate the behavior of consolidated and cemented matrix, but the accuracy of saturation estimates for hydrate is reduced.

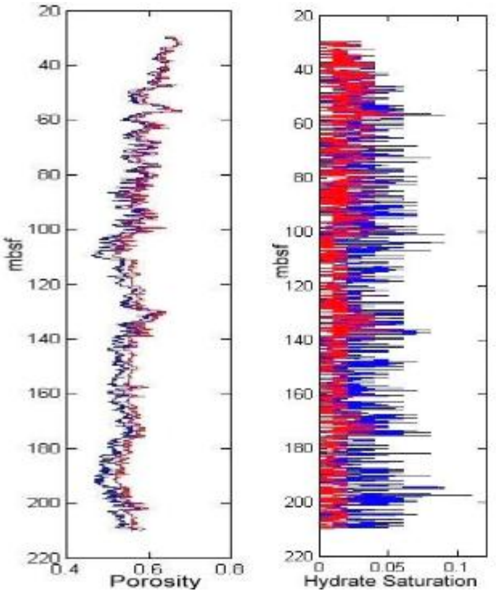

Figure 3: Porosity (left) and hydrate saturation (right) measured at the NGHP-01-03 site of KG Basin measured using Wood's model (blue) and weighted mean method (red)

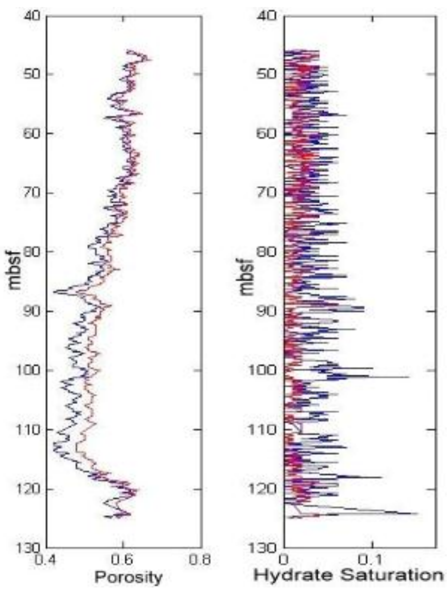

Figure 4: Porosity (left) and hydrate saturation (right) measured at the NGHP-01-05 site of KG Basin measured using Wood's model (blue) and weighted mean method (red)

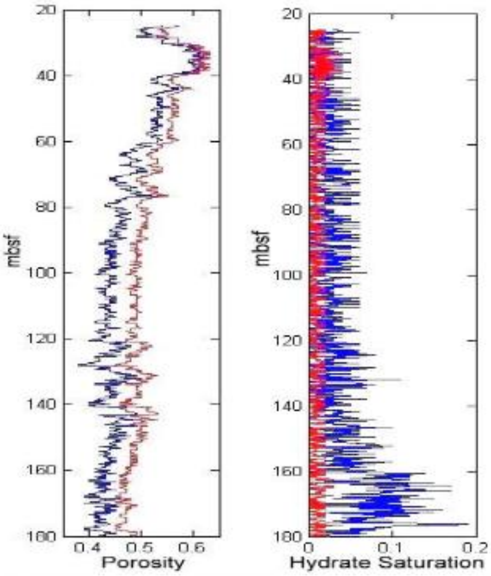

Figure 5: Porosity (left) and hydrate saturation (right) measured at the NGHP-01-07 site of KG Basin measured using Wood's model (blue) and weighted mean method (red)

Conclusions

We have presented a transformation technique for determination of reservoir properties from sonic and density properties based on rock physics modelling approach. The transformation technique has been tested on the wells drilled at NGHP-01-03, NGHP-01-05 and NGHP-01-07 sites of the Krishna Godavari basin during the NGHP Expedition 01. We have used four different rock physics models in our transformation viz. Wood model, Wyllie's time average equation, Raymer-Hunt-Gardner (RHG) model and three phase weighted equation. Due to the lithology of the study area, some of our models fail to produce adequate results. Wyllie model and RHG model show a large deviation from real value which makes them inappropriate models for the KG Basin. However, it has been noticed that the error deviation is a function of porosity. Hence, some empirical correction applied to these models can make them applicable in the KG Basin.

Wood's model and weighted mean model estimated about 10-20% hydrate present in the wells. Also, the misfit value for these models is very low, which permits them to be applicable to this region. Figure 3, figure 4 and figure 5 show the porosity and hydrate saturation estimated by the two models at the three sites of the KG basin. Thus, the transformation proposed in this paper, when used with Wood's model and weighted mean, can be used for predicting the gas hydrate saturation in the Krishna Godavari Basin.

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