Characterization of a Reservoir Fluid Based on an Analysis of Intrinsic Properties Using the Adaptive Batzle-Wang Method in Field "M"

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Abstract

The physical properties and phases of a fluid under reservoir conditions are different from those under surface conditions. The value of a fluid property may change as a result of changes in pressure and temperature. An analysis of the intrinsic properties of fluids is carried out to obtain a fluid model that corresponds to fluid conditions in a reservoir. This study uses the Adaptive Batzle-Wang model, which combines thermodynamic relationships, empirical data trends, and experimental fluid data from the laboratory to estimate the effects of pressure and temperature on fluid properties. The Adaptive Batzle-Wang method is used because the usual Batzle-Wang method is less suitable for describing the physical properties of a fluid under the conditions in the field studied here. The Batzle-Wang fluid model therefore needs to be modified to obtain a fluid model that adjusts to the fluid conditions in each study area. In this paper, the Adaptive Batzle-Wang model is used to model three types of fluid i.e. oil, gas, and water. By making use of data on the intrinsic fluid properties such as the specific gravity of the gases (G), the Gas-Oil Ratio (GOR), the Oil FVF (B_o), the API values, the Salinity, and the Fluid Density obtained from laboratory experiments, the Batzle-Wang fluid model is converted into the Adaptive Batzle-Wang model by adding equations for the intrinsic fluid properties under the pressure and temperature conditions in the field reservoir. The results obtained are the values of the bulk modulus (K), the density (ρ), and the P-wave velocity (V_p) of the fluid under reservoir conditions. The correlation coefficient of the Adaptive Batzle-Wang model with the fluid data from the laboratory experiments is 0.95. The model is well able to calculate the fluid properties corresponding to the conditions in this field reservoir. The model also generates a unique value for the fluid properties in each study area. So, it can adjust to the pressure and temperature conditions of the field reservoir under study. The Adaptive Batzle-Wang method can therefore be applied to fields for which laboratory fluid data is available, especially fields with a high reservoir pressure and temperature. The results of the fluid modeling can then be used for rock physics and Fluid Replacement Model analysis.

Index Terms: fluid analysis, Adaptive Batzle-Wang, reservoir condition, fluid physical properties, fluid replacement model

1. Introduction

One main purpose of geophysical exploration is to describe the subsurface structure. One of the most commonly used methods is seismic prospecting, but this method has a poor resolution when estimating fluid properties in a reservoir, so that more accurate and reliable data is needed to describe the subsurface conditions. Downhole or well log data is often used to validate the seismic data. But in connecting the two methods it is necessary to use information from rock physics. Rock physics modeling can characterize the three main components of a reservoir: the rock, the pores, and the fluid that fills those pores. The fluids beneath the surface have different physical properties from those on

the surface due to the influence of the varying pressures and temperatures. However, the characterization of the fluid in a reservoir is often oversimplified in geophysical exploration, given that the fluid in the rock pores greatly affects the elastic properties inferred from the seismic data, so that more analysis is needed. One of the models that characterizes the fluid properties is the Batzle-Wang fluid model,[1] which combines thermodynamic theory, empirical data trends, and laboratory fluid data to estimate the effects of the fluid pressure and temperature. The Batzle-Wang method can be used to perform calculations with three types of fluids, namely hydrocarbon gas, oil and brine. The properties of each fluid are calculated using prior information. The approach used is based on equations obtained from an empirical formulation of the data extracted from the field. The results from the Batzle-Wang method are very useful for improving the accuracy of the Rock Physics model of the reservoir. The principal seismic properties characterizing a reservoir are the primary wave velocity (V_p) and density (ρ), which can be associated with the elastic modulus parameters. The elastic modulus of the fluid will also influence the characteristics of the reservoir, so the elastic properties of the fluid are calculated using the Batzle-Wang method. The Batzle-Wang model can be used to predict the fluid properties under the influence of varying pressure and temperature, but it is still less suitable for matching the properties to the reservoir conditions in the field under study. So we need to modify it to obtain a more accurate model. In this study we want to generate an empirical equation characterizing the fluid that can match the conditions in the subsurface reservoir in the "M" field. The method used in this study to identify the fluid properties by combining the empirical Batzle-Wang equations with the fluid analysis data from the laboratory is called the Adaptive Batzle-Wang fluid model. In general, the measured fluid properties such as the density (ρ), API, GOR (R_g), specific gravity (G), and Salinity (S) can be used to produce models of the density, the primary wave velocities and the fluid bulk modulus corresponding to the subsurface conditions. The data used as input for the Adaptive Batzle-Wang model comes from fluid sampling analysis in the laboratory, and is shown in ***Table 1***.

Table 1. Fluid analysis data from laboratory.

Data	Field	
	M-1	M-2
Specific Gas Gravity	√	√
API Degree	√	√
Gas-Oil Ratio	√	√
Oil volume Factor	√	√
Density of fluid	√	√

This study was conducted using data from fields M-1 and M-2, where the parameters studied include the Specific gravity of the Gas (G), the API value of the crude oil, the Gas-Oil Ratio (R_g), the Oil FVF (B_o), and the Density (ρ) of the fluid. By using the above data, we want to construct a fluid model that can match the fluid properties in each of the two fields, which have different pressure and temperature conditions. The study was conducted in two different fields, M-1 and M-2, so as to demonstrate the applicability of the Adaptive Batzle-Wang model. This in turn can be used to improve the accuracy of fluid replacement analysis, or equivalently the Fluid Replacement Model (FRM) method, which aims to identify and quantify reservoir fluids.[2] Rock physics modeling results are also used as validators to improve the accuracy of the Adaptive Batzle-Wang model.

2. Methodology

2.1 The Batzle-Wang method

The following summary of this model is taken from the original paper by Batzle and Wang.[1] The model combines thermodynamic theory and the empirical trends in the available data to predict the effects of pressure, temperature, and composition on the seismic properties of the fluid. Batzle and Wang examined the properties of gases, oils, and brine, the three main types of fluids found in almost all reservoirs. The fluid properties predicted include the bulk density and modulus (so speed is included) as functions of the fluid temperature and pressure, when the fluid composition is known or can be estimated. The

development of the complete fluid model is discussed in the original paper.[1] A brief summary of the fluid model, including the assumptions made and the equations used, will be discussed here. The model described here incorporates Gas, Live Oil, and Brine. When applying the Batzle-Wang model, it is assumed that at each point below the bubble point, the gas has the same properties/composition as the gas as a whole in the surface conditions. This means that there is no variation in the composition of the gas encountered during production. When applying the model, it is also assumed both that the oil left as a fluid after the gas is released (under the bubble point) has the same composition as the original Live Oil, and that the fluid is saturated with as much gas as possible in the conditions.

2.1.1 Elastic parameters of the hydrocarbon gas

The empirical equations used by Batzle and Wang to characterize the gas are derived from Thomas *et al.*[3] The relevant gas parameters are the Specific Gravity of the Gas (G), the Elastic Bulk Modulus of Gas (K_g) and the Gas Density (ρ_g). The elastic parameters can be calculated from the equation:

$$K_g = \frac{P}{\left(1 - \frac{P_{pr}}{Z}\frac{\partial Z}{\partial P_{pr}}\right)_T}\gamma_0 (1000)^{-1} \quad (1)$$

The value of the gas bulk modulus (K_g) is also influenced by the ratio of the heat capacity at constant pressure to the heat capacity at constant volume (γ_0),

$$\gamma_0 = 0.85 + \frac{5.6}{(P_{pr}+2)} + \frac{27.1}{(P_{pr}+3.5)^2} - 8.7\exp\left[-0.65(P_{pr}+1)\right] \quad (2)$$

where P is the pressure in GPa. If the data is quoted in Psi then a hydrostatic correction of 14.37 Psi must be added, and the pressure then converted into GPa. The pressure is calculated from the value of P_{pr} (the pseudoreduced Pressure), which is obtained from the value of Ppc (the pseudocritical Pressure), according to the following formulas from Katz *et al.*[4] and Thomas *et al.*:[3]

$$P_{pr} = \frac{P}{P_{pc}} \quad (3)$$

$$P_{pc} = 4.892 - 0.4048G \quad (4)$$

$$\rho_g = \frac{28.8GP}{ZRT_a} \quad (5)$$

where R is the universal gas constant (8.3145 m^3 Pa/(mol-K)) and T_a is the temperature in Kelvins. Most temperature measurements in the field are quoted in Fahrenheit and must be converted to Celsius and then to Kelvin for Hydrocarbon Gas modeling.[3,4] The relevant formulas are:

$$T_{pr} = \frac{T_a}{T_{pc}} \quad (6)$$

$$T_a = T(^oC) + 273.15 \quad (7)$$

$$T_{pc} = 94.72 + 170.75G \quad (8)$$

where T_{pr} is the pseudoreduced Temperature and T_{pc} is the pseudocritical Temperature. Calculation of the gas bulk modulus (K_g) and Gas Density (ρ_g) is also influenced by the compressibility factor (z), which is given by the following equations from Thomas *et al.*:[3]

$$z = \left[0.03 + 0.0052\left(3.5 - T_{pr}\right)^3\right]P_{pr} + \left(0.642T_{pr} - 0.007T_{pr}^4 - 0.52\right) + E \quad (9)$$

$$E = 0.109\left(3.85 - T_{pr}\right)^2 \exp\left\{-\left[0.45 + 8\left(0.56 - \frac{1}{T_{pr}}\right)^2\right]\frac{P_{pr}^{1.2}}{T_{pr}}\right\} \quad (10)$$

$$\frac{\partial z}{\partial P_{pr}} = A + 0.1308\left(3.85 - T_{pr}\right)^2 \exp\left(BP_{pr}^{1.2}\right)BP_{pr}^{0.2} \quad (11)$$

$$A = 0.03 + 0.00527\left(3.5T_{pr}\right)^3 \tag{12}$$

$$B = \left(\frac{-1}{T_{pr}}\right)\left(0.45 + 8\left(0.56 - \frac{1}{T_{pr}}\right)^2\right) \tag{13}$$

2.1.2 Elastic parameters of the live oil

The Live Oil is a gas-saturated oil hydrocarbon and therefore the parameters affecting the elastic properties of the Live Oil include the Specific Gas gravity (G), the API value of the crude oil, the Gas-Oil Ratio (R_g), the Oil FVF (B_o), and the Density (ρ) of the Live Oil. The Live Oil Density (ρ) can be calculated from a formula due to Dodson and Standing:[5]

$$\rho_\ell = \left[\frac{\rho_{pl}}{0.972 + \left(3.81\times10^{-4}\right)\left(T + 17.78\right)^{1.175}}\right] \tag{14}$$

The value of the Density (ρ) of the Live Oil in g/cm^3 is obtained by calculating ρ_{pl} (the density at the given pressure) and ρ_{gl} (the density due to the influence of saturated gas) through the following equations, due to McCain:[6]

$$\rho_{pl} = \rho_{gl} + \left(0.00277P - \left(1.71\times10^{-7}\right)P^3\right)\left(\rho_{gl} - 1.15\right)^2 + \left(3.49\times10^{-4}\right)P \tag{15}$$

$$\rho_{gl} = \frac{\left(\rho_0 + 0.0012GR_g\right)}{B_{ol}} \tag{16}$$

The Density (ρ) of the Live Oil is also influenced by both the Gas-Oil Ratio (R_g) and the Oil Formation Volume Factor (B_o), which in turn are affected by the API values of the Live Oil:[7]

$$R_G = 0.02122G\left[P\exp\left(\frac{4.072}{\rho_0}\right) - 0.00377T\right]^{1.205} \tag{17}$$

$$B_{ol} = 0.972 + 0.0003812\left[2.4955R_g\sqrt{\frac{G}{\rho_0}} + T + 17.778\right]^{1.175} \tag{18}$$

$$\rho_0 = \frac{141.5}{API + 131.5} \tag{19}$$

Wang[8] and Wang *et al.*[9] have shown that the ultrasonic velocity of a variety of oils decreases rapidly with density (increasing API). The P-wave velocity of the Live Oil (V_l) calculated in m/s is also influenced by the GOR (R_g) and the Oil FVF (B_o), through the pseudodensity ρ_{dl} generated by the presence of dissolved gas in the Live Oil. The equations used are as follows:

$$V_l = 2096\sqrt{\frac{\rho_{dl}}{2.6 - \rho_{dl}}} - 3.7T + 4.64P + 0.0115\left[4.12\sqrt{\frac{1.08}{\rho_{dl}} - 1} - 1\right]TP \tag{20}$$

$$\rho_{dl} = \frac{\rho_0}{B_{ol}}\left(1 + 0.001R_g\right)^{-1} \tag{21}$$

The Live Oil Bulk Modulus (K_l) in units of GPa is calculated from the density (ρ_l) and velocity of the Live Oil (V_l) through the equation:

$$K_l = \left(V_l^2 \rho_l\right) 1000^{-1} \tag{22}$$

2.1.3 Elastic parameters of the brine

The main parameter affecting the brine is its salinity (S). In the Batzle-Wang brine model, the salinity used is the weight of the NaCl fraction (in ppm/1,000,000). So the salinity will have an effect on the values of the brine density (ρ_b) and the brine velocity (V_b). The relevant equations are due to Zarembo and Fedorov[10] and Potter and Brown,[11] and are as follows:

$$\rho_w = 1 + \left(10^{-6}\left(-80T - 3.3T^2 + 0.00175T^3 + 489P - 2TP + 0.016T^2P - \left(1.3\times10^{-5}\right)T^3P - 0.333P^2 - 0.002TP^2\right)\right) \tag{23}$$

$$\rho_b = \rho_w + S\left\{0.668 + 0.44S + \left(1\times10^{-6}\right)\left[300P - 2400PS + T\left(80 + 3T - 3300S - 13P + 47PS\right)\right]\right\} \tag{24}$$

where ρ_w is the fresh water density in g/cm^3, whose value is influenced by the pressure and temperature in the reservoir. The density of the brine (ρ_b) is calculated on the basis of the fresh water density (ρ_w) with corrections made for the effects of salinity (S). Following Wilson,[12] the primary wave velocity in the fresh water (V_w) in m/s is calculated from field measurement data and the coefficients W_{ij} obtained from ***Table 2***. The relevant equation is:

$$V_w = \sum_{i=0}^{4}\sum_{j=0}^{3} W_{ij} T^i P^j \tag{25}$$

The primary wave velocity of the brine (V_b) is taken from Chen *et al.*,[12] and is calculated by combining the fresh water wave velocity (V_w) with the Salinity (S).

$$\begin{aligned} V_b = V_w + S\left(1170 - 9.6T + 0.055T^2 - \left(8.5\times10^{-5}\right)T^3 + 2.6P - 0.0029TP - 0.0476P^2\right) + \\ S^{1.5}\left(780 - 10P + 0.16P^2\right) - 820S^2 \end{aligned} \tag{26}$$

So, on using the equations for the brine density (ρ_b) and brine velocity (V_b), the value of the brine bulk modulus (K_b) without gas saturation in GPa is

$$K_b = \left(V_b^2 \rho_b\right) 1000^{-1} \tag{27}$$

2.2 The Adaptive Batzle-Wang Method

The Adaptive Batzle-Wang model uses the Batzle-Wang empirical equations and fluid parameters from the laboratory, namely the bulk modulus (K), density (ρ), and P-wave velocity (V_p), to characterize the fluid. The Adaptive Batzle-Wang method generates models for the Gas, Live Oil, and Brine fluid fractions. Of these, the Brine model in the Adaptive Batzle-Wang method is the same as in the Batzle-Wang fluid model because the effects of Salinity in each field are almost the same because the salt composition tends not to differ between fields, unlike the hydrocarbon gas and oil compositions, which are highly variable. The three elastic parameters for the fluid mentioned above are influenced by the API, the Specific Gravity of the Gas (G), the Gas-Oil Ratio (R_g), the Oil FVF (B_o), the Salinity (S), and the Density of the fluid (ρ), and the parameters will change as the pressure and temperature vary at each level below the surface. The output of the method is the values of the bulk modulus (K), density (ρ), and primary wave velocity (V_p) in the fluid, calculated using the pressure and temperature in the reservoir as input together with some rock physics analysis. The model uses the Batzle-Wang fluid mixing results found by applying the Woods Relation to the rock matrix. The model utilizes the laboratory data and the empirical Batzle-Wang equations to obtain a model that is more appropriate for the fluid conditions in the reservoir under study. Due

to the effects of changes in the pressure and temperature the values of the Specific Gravity of the Gas (G), the Gas-Oil Ratio (R_g), the oil FVF (B_o), and the fluid density (ρ_{fl}) can vary between depth levels in each field, so the fluid parameters generated by the basic Batzle-Wang model might not be appropriate for the field conditions.

Table 2. Coefficients used for calculating the primary wave velocity in water provided by Milero *et al.*[13] and Chen *et al.*[12]

W_{00} =	1402.85	W_{02} =	3.437×10^{-3}
W_{10} =	4.871	W_{12} =	1.738×10^{-4}
W_{20} =	-0.04783	W_{22} =	-2.135×10^{-6}
W_{30} =	1.487×10^{-4}	W_{32} =	-1.455×10^{-8}
W_{40} =	-2.197×10^{-7}	W_{42} =	5.230×10^{-11}
W_{01} =	1.524	W_{03} =	-1.197×10^{-5}
W_{11} =	-0.0111	W_{13} =	-1.628×10^{-6}
W_{21} =	2.747×10^{-4}	W_{23} =	1.237×10^{-8}
W_{31} =	-6.503×10^{-7}	W_{33} =	1.327×10^{-10}
W_{41} =	7.987×10^{-10}	W_{43} =	-4.614×10^{-13}

2.3 The Woods equation

The output from the Adaptive Batzle-Wang method, namely the values of the Bulk modulus (K) and Density (ρ) for each fluid, is then used to model the fluid mixture. A relation often used in fluid mixing analysis is the Woods equation, here taken from Mavko *et. al.*:[14]

$$\frac{1}{K_{FL}} = \frac{S_{Water}}{K_{Water}} + \frac{S_{Oil}}{K_{Oil}} + \frac{S_{Gas}}{K_{Gas}} \qquad (28)$$

where S_{water} is the water saturation, S_{oil} is the oil saturation, S_{gas} is the gas saturation, K_{water} is the bulk modulus of the water, K_{oil} is the bulk modulus of the oil, K_{gas} is the bulk modulus of the gas, and K_{fl} is the bulk modulus of the fluid mixture.

$$\rho_{fl} = \rho_w S_w + \rho_{Hyc}(1 - S_w) \qquad (29)$$

To apply the Fluid Replacement Model (FRM) the density of the mixed fluid (ρ_{fl}), obtained by incorporating the fluid saturation, is also required at each depth.

2.4 The Voight-Reuss-Hill Method

To demonstrate that the Adaptive Batzle-Wang method calculates the elastic parameters of the fluid with improved accuracy, rock physics modeling must be performed to test the accuracy of the elastic parameters. It is therefore necessary to model the minerals in the rock matrix in conjunction with the model for the fluid saturations provided by the Woods relation. The equation for the elastic modulus of the rock matrix generated by the VRH method is as follows:[14]

Voight Method: $$M_V = \sum_{i-n}^{N} f_i . M_i \qquad (30)$$

Reuss Method: $$\frac{1}{M_R} = \sum_{i-1}^{N} \frac{f_i}{M_i} \qquad (31)$$

Voight-Reuss-Hill Method:

$$M_{VRH} = \frac{M_V + M_R}{2} \qquad (32)$$

where the M_V is the Voight elastic modulus, M_R is the Reuss elastic modulus, M_{VRH} is the Voight-Reuss-Hill elastic modulus, f_i is the fraction of mineral i and M_i is the elastic modulus of mineral i.

2.5 Rock physics analysis

To test the accuracy of the fluid model, we apply rock physics analysis using the Differential Effective Medium (DEM) method to validate the elastic parameters. The DEM method models a two-phase composite by incrementally adding a small number of pores to the matrix. In the DEM method, the values of the effective moduli depend on the construction path taken to reach the final composite. The DEM method works by adding inclusions to the background model. The model is continuously changing as the inclusions are added.[14] The results of the fluid mixing from the Woods equation and the rock matrix modeling from the VRH method are used to calculate the primary wave velocity (V_p) in the saturated rock. It is therefore possible to check if the V_p value generated by the model is close to the measured V_p value. By this means, it can be determined if the saturated V_p value from the

Adaptive Batzle-Wang model is more accurate than the value from other models. The most accurate model is that which has the smallest root-mean-square-error (RMSE) after regression of the predicted and measured V_p values. In this paper, we compare the RMSE values generated by the rock physics DEM method for the Batzle-Wang fluid model and the modified model, which is the Adaptive Batzle-Wang fluid model.

2.6 Fluid Replacement Model

This study combines the Batzle-Wang fluid model and experimental fluid data from the laboratory to produce the Adaptive Batzle-Wang fluid model. In the process, the Adaptive Batzle-Wang model generates values of the Bulk Modulus (K), and Density (ρ) for each type of fluid, which are then mixed using the Woods equation and used as inputs for the rock physics analysis to obtain the primary wave velocity in the saturated rock (Vp), which is calculated from the following equation due to Han and Batzle:[2]

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \tag{33}$$

The Adaptive Batzle-Wang method can then be applied to generate a Fluid Replacement Model (FRM) using the Gassmann equation,[15] shown below:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_m}\right)^2}{\frac{\phi}{K_f} + \frac{(1-\phi)}{K_m} - \frac{K_{dry}}{K_m^2}} \tag{34}$$

where K_{sat} is the bulk modulus of the fluid-saturated rock, K_{m} is the bulk modulus of the minerals, K_{f} is the bulk modulus of the pore fluid, K_{dry} is the bulk modulus of the rock frame, and ϕ is the porosity.

3. Results and Discussion

The values of the elastic parameters of the fluid calculated from the usual Batzle-Wang and the Adaptive Batzle-Wang models in the two different fields are shown in ***Table 3***.

Table 3 shows that the results from the Adaptive Batzle-Wang model are better than those from the Batzle-Wang model. The calculated values of the Bulk Modulus (K), Density (ρ), and Slowness for Live Oil in Field M-1 (P = 2925 P_{sig}, T = 235 F, API = 40) and Field M-2 (P = 3850 P_{sig}, T = 291 F, API = 35.1) from the Adaptive Batzle-Wang model are closer to the measured laboratory values.

The calculated values from the Batzle-Wang model have a larger percentage error than those from the Adaptive Batzle-Wang model, as can be seen in ***Table 4*** and ***Table 5***. The advantages of the Adaptive Batzle-Wang method are due to the modification of the empirical Batzle-Wang equations produced by incorporating the laboratory fluid data. In addition, the pressure (P) and temperature (T) values used as inputs in the Adaptive Batzle-Wang model are changed to match the varying P and T states at each depth, according to the P and T input logs in ***Figure 1***.

The Pressure and Temperature inputs from ***Figure 1*** are then used in the Adaptive Batzle-Wang model to obtain elastic parameters corresponding to the fluid conditions in the two fields, according to the bulk modulus logs in ***Figure 2***.

From ***Figure 2*** it can be seen in the Live Oil log that the value of the bulk modulus is 517.056 MPa for field M-1 and 625,824 MPa for field M-2. The bulk modulus calculated from Fig. 2 is then used as an input for the rock physics model. To demonstrate that the Adaptive Batzle-Wang model produces more accurate fluid parameters than the Batzle-Wang model this study uses the pore Differential Effective Medium (DEM) inversion method, as explained in Section 5.

From ***Figure 3*** and ***Figure 4*** it can be seen that the root-mean-square-error (RMSE) between the measured V_p values and the V_p values calculated by applying the rock physics DEM method to the results from the Adaptive Batzle-Wang model is smaller than the RMSE between the measured values and the values calculated from the Batzle-Wang model. So it can be concluded that the fluid parameters are more accurately calculated

using the Adaptive Batzel-Wang model. In fact, in terms of percentage differences, the Adaptive Batzel-Wang model is 17.03% better than the Batzle-Wang model in the M-1 field and 5.82% better in the M-2 field. The Adaptive Batzle-Wang model and the rock physics DEM method can also be combined with the Gassmann equation to obtain a Fluid Replacement Model (FRM). The results of the FRM can be used to model V_p, V_s, and ρ. By applying the fluid replacement model, it is possible to assess the sensitivity of the Adaptive Batzel-Wang fluid model. This also demonstrates that the output of the Adaptive Batzle-Wang model generates an appropriate Fluid Replacement Model.

Table 3. Comparison of the calculated fluid parameters with the laboratory measurements.

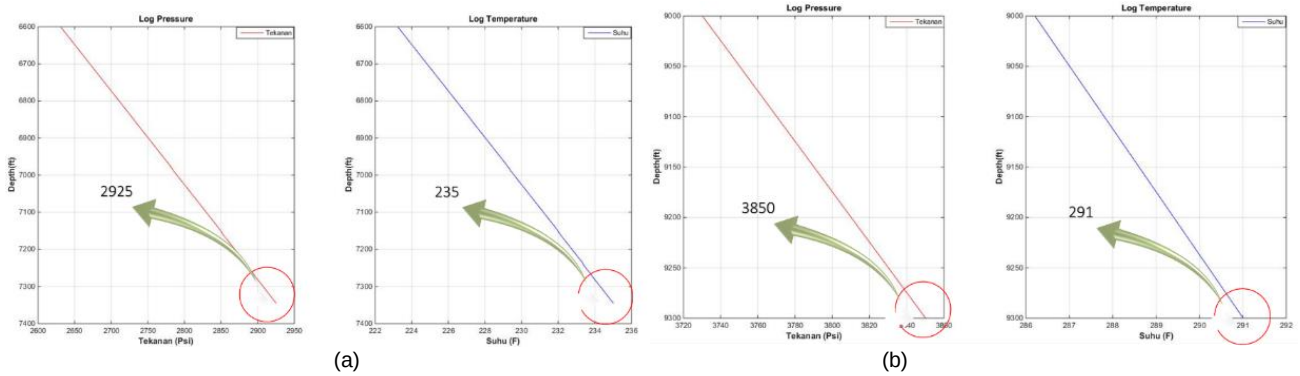
Input		Parameter of Live Oil	BW	ABW	Lab
P =	2925 P_{sig}	Bulk Modulus (Mpa)	441.6765	517.056	516.327
T =	235 F	Density (g/cc)	0.6283	0.6181	0.6182
API =	40	Slowness (us/ft)	363.5451	333.252	333.512
P =	3850 P_{sig}	Bulk Modulus (Mpa)	399.5628	625.8242	625.405
T =	291 F	Density (g/cc)	0.6632	0.6953	0.6956
API =	35.1	Slowness (us/ft)	377.9277	321.2821	321.46

Table 4. Percentage differences between the Batzle-Wang and Adaptive Batzle-Wang model values and the measured laboratory values for field M-1.

Input		Parameter of Live Oil	Difference of BW (%)	Difference of ABW (%)
P =	2925 P_{sig}	Bulk Modulus (Mpa)	14.46	0.14
T =	235 F	Density (g/cc)	1.63	0.02
API =	40	Slowness (us/ft)	9.01	0.08

Table 5. Percentage differences between the Batzle-Wang and Adaptive Batzle-Wang model values and the measured laboratory values for field M-2.

Input		Parameter of Live Oil	Difference of BW (%)	Difference of ABW (%)
P =	3850 P_{sig}	Bulk Modulus (Mpa)	36.11	0.07
T =	291 F	Density (g/cc)	4.66	0.04
API =	35.1	Slowness (us/ft)	17.57	0.06



(a) (b)

Figure 1. Input Pressure and Temperature logs for field M-1 (a) and field M-2 (b) (*P*=2925 P_{sig}, *T*=235 F, API=40).

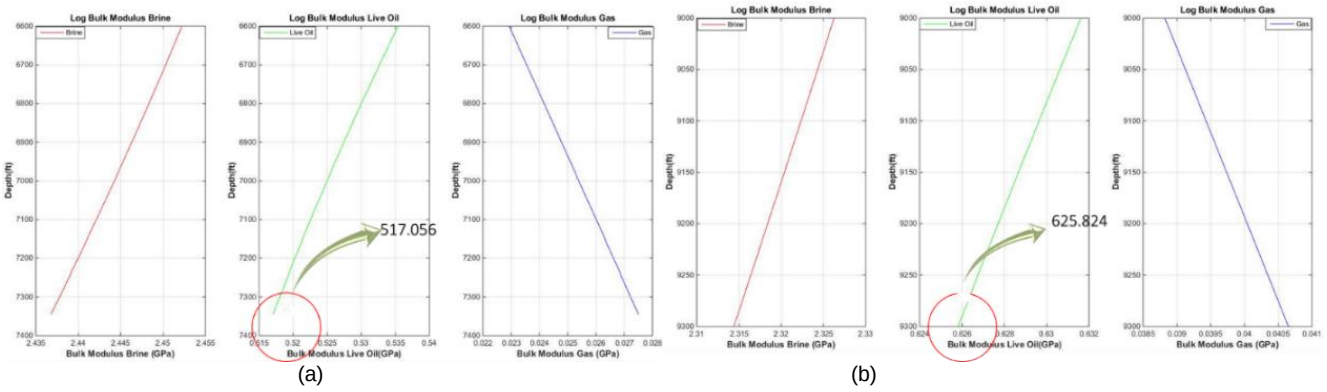


Figure 2. Bulk modulus Logs used in the Adapative Batzle-Wang model for field M-1 (a) and field M-2 (b).

From ***Figure 3*** and ***Figure 4*** it can be seen that the root-mean-square-error (RMSE) between the measured V_p values and the V_p values calculated by applying the rock physics DEM method to the results from the Adaptive Batzle-Wang model is smaller than the RMSE between the measured values and the values calculated from the Batzle-Wang model. So it can be concluded that the fluid parameters are more accurately calculated using the Adaptive Batzel-Wang model. In fact, in terms of percentage differences, the Adaptive Batzel-Wang model is 17.03% better than the Batzle-Wang model in the M-1 field and 5.82% better in the M-2 field. The Adaptive Batzle-Wang model and the rock physics DEM method can also be combined with the Gassmann equation to obtain a Fluid Replacement Model (FRM). The results of the FRM can be used to model V_p, V_s, and ρ. By applying the fluid replacement model, it is possible to assess the sensitivity of the Adaptive Batzel-Wang fluid model. This also demonstrates that the output of the Adaptive Batzle-Wang model generates an appropriate Fluid Replacement Model.

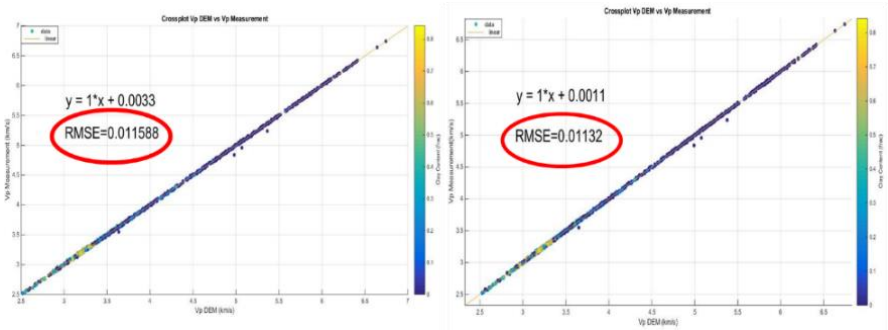


Figure 3. Results of the DEM method regression for the primary wave velocity (*V*p) values from (a) the Batzlel-Wang model (b) the Adaptive Batzle-Wang model in field M-1.

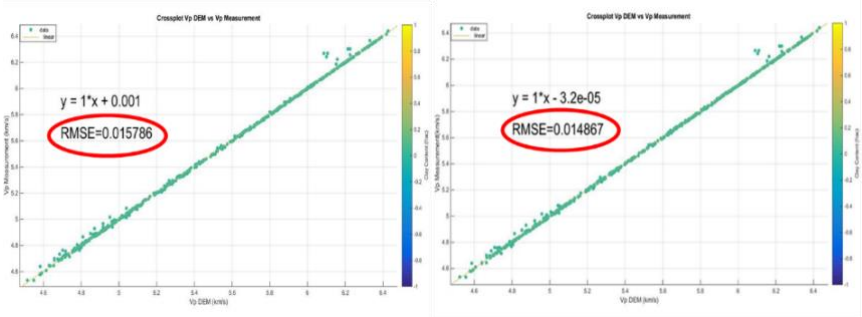


Figure 4. Results of the DEM method regression for the primary wave velocity (*V*p) values from (a) the Batzlel-Wang model (b) the Adaptive Batzle-Wang model in field M-2.

The results in ***Figure 5*** can be interpreted as showing that there are carbonate zones at depths of about 7000-7100 and 7200-7400 ft. This conclusion is reinforced by the very small clay volume log at these depths, and the logs also display a high density and low porosity there. The small values in the log of V_p (slowness in μs/ft) indicates that there is denser lithology here than elsewhere. This is due to the effect of the carbonates at these depths.

From ***Figure 6*** it can be seen that different water saturations correspond to shifted V_p curves in the two models. This shows that differences in the fluid content will affect the values of V_p.

Figure 7 shows that the log is of a clean carbonate formation. This can be seen from the log of clay volumes, which are zero. From ***Figure 7*** it can be conjectured that there is a stiff carbonate zone filled with fluid or cementation. In the zones with red and yellow markers fluid is suspected because the porosity in the zones is large and the density is small, and the small values in the V_p log confirm the presence of fluid. The zones with blue and black markers are suspected to be dolomitized stiff carbonate zones because of their decreased porosity and increased density, as well as the large values in the V_p log. The layers are suspected to be compact zones formed by diagenetic processes. Comparison of the DEM model with the measurements shows considerable differences in the carbonate zone because the secondary porosity in the DEM model adjusts more to the conditions of the pore type, while the V_p measurements from the FRM only take account of the total porosity in the formation.

The varying water saturations of 10%, 40%, and 100% indicate differences in the fluid content. In zones with red and yellow markers the fluid saturation is between 40% and 60%. The presence of hydrocarbons is supported by the porosity and density logs in ***Figure 7***, as there is a zone suspected of containing 60% hydrocarbons. Also, the zones with blue and black markers indicate that 100% water saturation best matches the in-situ saturation. It is suspected that water fills the formation and causes dolomitization, thus increasing the rock density. The results obtained will indicate whether the output of the Adaptive Batzle-Wang model is sensitive to the secondary porosity values from the DEM modeling.

4. Conclusions

The reservoir fluid can be characterized by the values of the bulk modulus, density, and primary wave velocity. These three parameters are heavily influenced by the pressure and temperature, and the intrinsic properties of each fluid also affect the results of the reservoir fluid modeling. The presence of fluid affects the rock physics, so the accuracy and suitability of the fluid model should be investigated more deeply. Modeling the fluid in the M-1 and M-2 fields by using the Batzle-Wang model modified by the inclusion of fluid data from the laboratory yields an improvement in the accuracy of the rock physics parameters compared with the values predicted in surface conditions. The Adaptive Batzle-Wang model therefore provides a more accurate description of the fluid. The model is applicable to reservoir fluids under a variety of field conditions, especially at high pressures and temperatures. This model can also be adapted easily to the conditions in the field by using fluid data from the field. Accurate fluid models are also very useful for the construction of fluid replacement models.

5. Additional Considerations

The results from the Adaptive Batzle-Wang model will be more convincing if more fluid data from laboratory measurements is available. The trends used in the empirical equations will then be more accurate, especially if data is available for each sample of gas, oil, and water. The method also requires data on the pressure and temperature in the area under study. A lack of such detailed data is the main challenge to extending the applicability of the method.

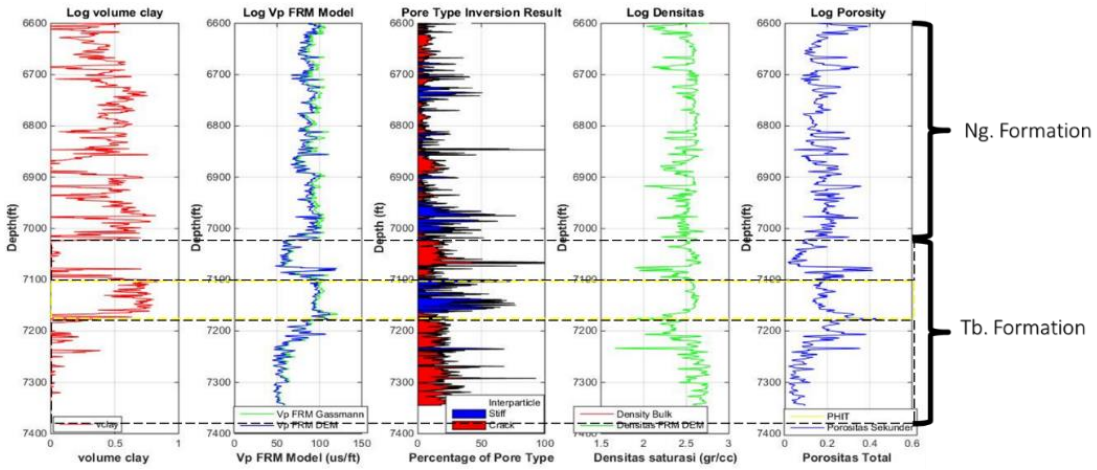


Figure 5. Values of V_p calculated using the Adaptive Batzle-Wang model and the FRM in field M-1.

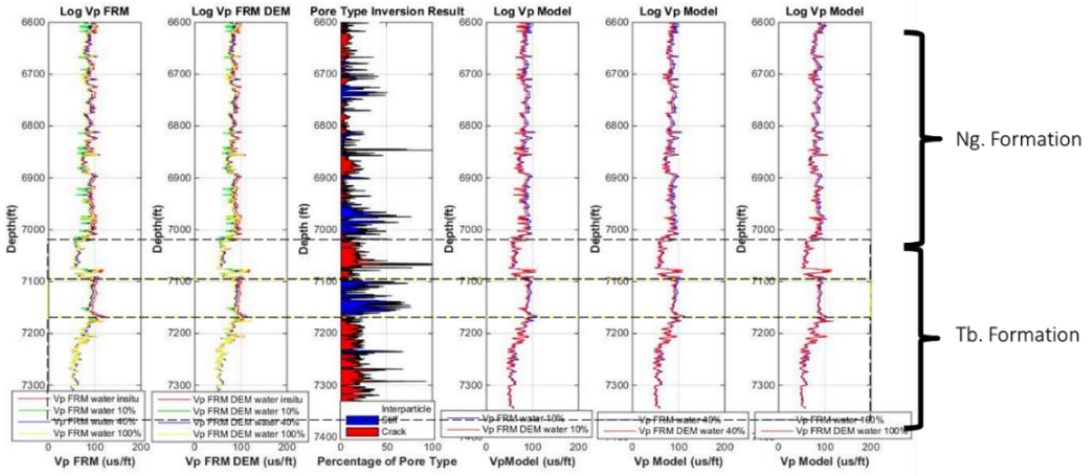


Figure 6. Comparison Logs of the values of the primary wave velocity V_p calculated using the Adaptive Batzle-Wang model, the FRM and the combined FRM/DEM model and the measured V_p values in field M-1.

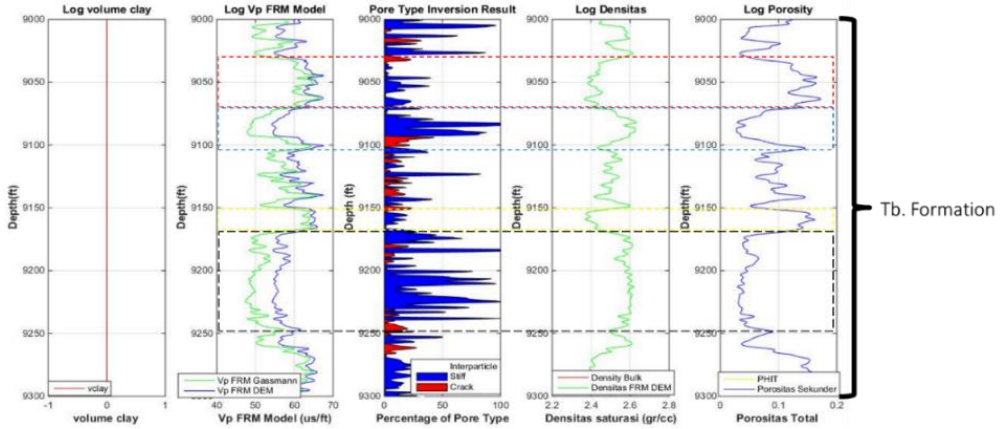


Figure 7. Values of V_p calculated using the Adaptive Batzle-Wang model and FRM in field M-2.

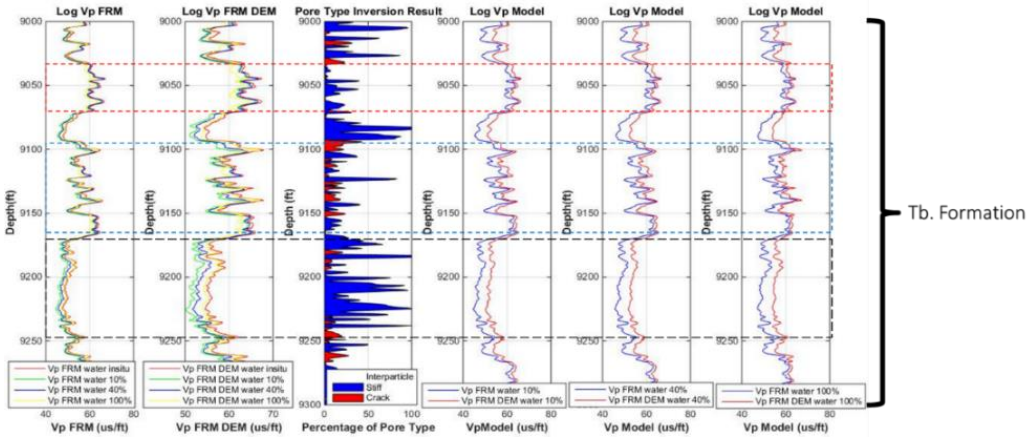


Figure 8. Comparison Logs of the values of the primary wave velocity *Vp* calculated using the Adaptive Batzle-Wang model, the FRM and the combined FRM/DEM model and the measured *Vp* values in field M-2.

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