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Improving the Reliability of Synthetic S-Wave Extraction Using Biot-Gassman Fluid Substitution

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ABSTRACT
Usage of Castagna's relation by mean the P-wave log directly in estimation of the S-wave log gives a large error to the original S-wave log so that the result is not reliable for further analysis. This paper offers new method for S-wave log estimation based Castagna's relation which is combined with fluid replacement modeling method based on Biot-Gassman substitution and the use of petro physical data as input. The S-wave log result of the offered estimation method has a small error to the original S-wave log so that more reliable and accurate for further analysis. The offered method could be used for S-wave log estimation in various litology such as sand, limestone, dolomite and shale. The S-wave log result of the offered estimation method has successfully used for cross plot analysis of Vp/Vs ratio as function of acoustic impedance and Gamma Ray for delineation of sandstone bearing hydrocarbon from two different field.
***Keywords* -** Biot-Gassman substitution, S-wave log, P-wave log, Vp/Vs ratio

I. INTRODUCTION

Shear wave (S-wave) log data is always used in the determination of the elastic parameters of reservoir, analysis of rock physics, inversion and lambda-mu-rho [1]. However, most of the well data is not completed by the shear wave log data. Various of S-wave log estimation has been proposed [1, 2]. The famous one is Castagna's relation [3]. The use of Castagna's relation by mean the P-wave log directly in estimation of the S-wave log gives a large error if compared to the original S-wave log because castagna's relation is a good empirical tool for the wet sands and shale only, so the result is not reliable for further analysis. This paper offers new method for S-wave log estimation based on Castagna's relation which is combined with Fluid replacement modeling method based on Biot-Gassman substitution and the use of petro physical data as input. The weakness of direct S-wave estimation by Castagna's relation is compensated by applying Castagna's relation in the wet condition of reservoir only. The S-wave log resulted from the offered estimation method has a small error to the original S-wave log so that more reliable for further analysis.

II. TEORY

Castagna's relationship between P-wave and S-wave velocity

Simple empirical relationship between P-wave and S-wave velocity for unconsolidated and partially consolidated sand has been derived by Castagno [3] in the form of second order polynomial fit as follows

$$V_s = aV_p^2 + bV_p + c \quad (1)$$

where a, b and c are polynomial coefficient. The relationship is lithology dependent and different coefficient are proposed to increase the accuracy in km/s as [1].

Sand:
$$V_s = +0.804V_p + 0.856 \quad (2)$$
Limestone:
$$V_s = -0.055V_p^2 + 1.017V_p - 1.030 \quad (3)$$
Dolomite:
$$V_s = +0.583V_p - 0.078 \quad (4)$$
Shale:
$$V_s = +0.770V_p - 0.867 \quad (5)$$

Unfortunately these equations are a good empirical tool for wet sand and shale only.

The Biot-Gassmann equation

In porous and saturated rocks, basic equations for P and S-wave velocity of saturated rocks are.

$$V_{p\_sat} = \sqrt{\frac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}} \quad (6)$$

$$V_{s\_sat} = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad (7)$$

where ρ_{sat} is saturated density, μ_{sat} is saturated shear modulus and K_{sat} is the bulk modulus of saturated rocks. The problem was first addressed by Biot and then Gassmann using apparently different approaches but, as shown by Krief [4,5], these two approaches lead to the same results.

In equations (6) and (7), the saturated density can either be measured in-situ or computed from the equation h

$$\rho_{sat} = \rho_m(1-\phi) + \rho_w S_w \phi + \rho_{hc}(1-S_w)\phi \quad (8)$$

where ρ with the subscripts m, w, and hc indicate matrix, water, and hydrocarbon, S is the fraction of saturation of each fluid component and ϕ is porosity [6].

Once we have the measured or computed saturated density value, the value of the shear modulus in equations (6) and (7) can be computed from the S-wave velocity using equation (8) to give:

$$\mu_{sat} = \rho_{sat} V_{s\_sat}^2 \quad (9)$$

The value of the saturated bulk modulus can then be found from equation (3), giving:

$$K_{sat} = \rho_{sat} V_{psat}^2 - \frac{4}{3}\mu_{sat} \quad (10)$$

In order to perform fluid replacement modeling using Biot-Gassmann equation, it is assumed that the shear modulus is independent of fluid content (but not porosity) or

$$\mu_{sat} = \mu_{dry} \quad (11)$$

where μ_{dry} is the shear modulus of the dry rock, which is the rock for which the pore fluids have been fully evacuated.

The Biot-Gassmann equation can be written:

$$K_{sat} = K_{dry} + \frac{\left(1-\frac{K_{dry}}{K_m}\right)^2}{\frac{\phi}{K_{fl}} + \frac{1-\phi}{K_m} + \frac{K_{dry}}{K_m^2}} = K_{dry} + \frac{\beta^2}{\left(\frac{\phi}{K_{fl}} + \frac{\beta-\phi}{K_m}\right)} \quad \text{and} \quad (12)$$

$$\beta = 1 - \frac{K_{dry}}{K_m} \quad (13)$$

where K_m is bulk modulus of matrik, K_{fl} is bulk modulus of fluid, K_{dry} is bulk modulus of dry, K_{sat} is modulus bulk of saturated rock, ϕ is porosity and β is called the Biot Coefficient, the ratio of the volume change in the fluid to the volume change in the formation, when hydraulic pressure is constant. If $\beta = 0$ then $K_{dry} = K_m$ and $K_{dry} = K_{sat}$ or purely elastic condition. Mavko rearranged the Biot-Gassmann equation to the form [7]:

$$\frac{K_{sat}}{K_m - K_{sat}} = \frac{K_{dry}}{K_m - K_{dry}} + \frac{K_{fl}}{\phi(K_m - K_{fl})} \quad (14)$$

The bulk modulus of fluid K_{fl} is normally calculated using the Reuss average given by

$$\frac{1}{K_{fl}} = \frac{S_w}{K_w} + \frac{S_{hc}}{K_{hc}} \quad (15)$$

The Reuss average is used for uniform distribution of the fluids, for patchy saturation, the linear Voigt average could be used.

There are many alternate forms of the Biot-Gassmann equations besides equation (14), but this form to be the easiest to work with when performing fluid replacement modeling.

It assumed that the saturated, matrix (mineral) and fluid bulk modulus are known, as well as the porosity, from laboratory or petro physics analysis then the only unknown in equation (14) is the dry rock bulk modulus. This can then be computed by re-arranging equation (14) to give

$$K_{dry} = K_m \frac{x}{1+x} \quad (16)$$

Once K_{dry} is able to be computed, then the fluid value can be changed by using new saturations in equation (15) and then re-compute K_{sat} and thus ρ_{sat} and V_{p_sat}. For the case of a fluid change only, the shear modulus and dry rock bulk modulus will not change. However, if the porosity in equation (14) changes, both the dry rock and shear modulus will change. To change these parameters, there is no clear consensus as to which method to use [6]. .

The P wave modulus

It is needed the elastic parameter of P-wave modulus for fluid replacement modeling. The P-wave modulus is defined as

$$M = V_{p\_sat}^2 \rho_{sat} \quad (17)$$

where M is P-wave modulus, V_{p_sat} is P-wave velocity of saturated, and ρ_{sat} is saturated density.

If modulus bulk of matrix and modulus shear of matrix has been known from laboratory or petro physics analysis then P-wave matrix modulus defined as:

$$M_m = K_m + \frac{4}{3}\mu_m \quad (18)$$

where K_m is bulk modulus of matrix, and μ_m is shear modulus of matrix.

III. METHOD

The workflow of S-wave velocity estimation using fluid replacement modeling could be seen in Figure 1. The input for this process is density log, P-wave velocity log, porosity log, water saturation log and bulk modulus of matrix, density of matrix, bulk modulus and density of fluid. The porosity log, water saturation log and bulk modulus of matrix, density of matrix, bulk modulus and density of fluid could resulted from petro physics analysis. The S-wave estimation process is done after the rocks are really fully saturated by water (S-wave in wet condition) so the weakness of Castagna's relation can be compensated. Then the estimated S-wave is calculated from S-wave in wet condition. By using this S-wave, modulus bulk dry of the rock could be calculated and could be used to calculate the true modulus bulk of saturated reservoir rock. Finally the true saturated density, P-wave and S-wave could be calculated as well.

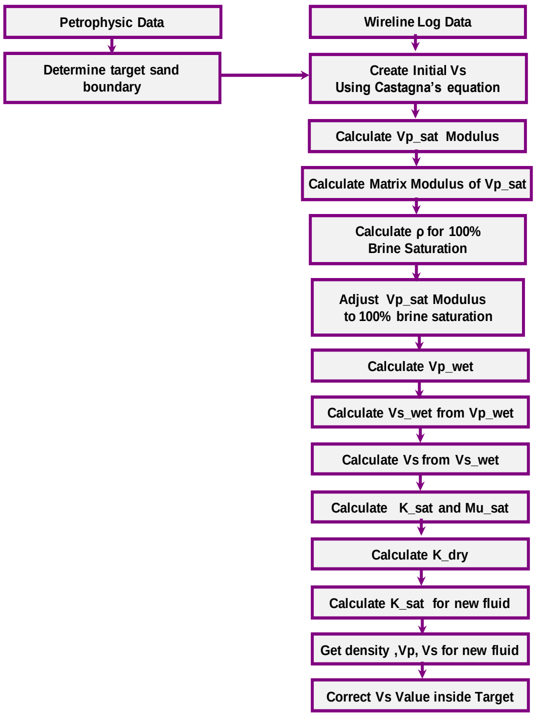


Figure 1. Workflow of S-wave velocity estimation using fluid replacement modeling

IV. EXPERIMENT AND DISCUSSION

S-wave log estimation method is tested to estimate S-wave log of sands bearing gas from #PMK-2 well, Mawar field, Kutai Basin, Indonesia which has original S-wave log. The gas sand reservoir as objective of tested zone is in the depth 626 ft to 700 ft. The estimated S-wave log is compared to the original S-wave log and the estimated S-wave log from directly Castagna's relation. The estimated S-wave log using fluid replacement modeling is more accurate than the estimated S-wave log from direct Castagna's relation (Figure.2). The fourth log in the Figure 2 are the overlay of original S-wave log (red color), estimated S-wave log using direct Castagna's relation (magenta color) and estimated S-wave log using fluid replacement modeling (blue color).

The estimated S-wave log using fluid replacement modeling more coincides with the original -wave log than the estimated S-wave log using direct Castagna's relation. Therefore, the estimated S-wave log using fluid replacement modeling more accurate and reliable for further analysis than the estimated S-wave log using direct Castagna's relation. The benefits of the offered estimated S-wave is that S-wave estimation process done after the rocks is really fully saturated by water (brine), so the weakness of Castagna's relation can be compensated.

Cross plot of Vp/Vs ratio versus acoustic Impedance as function Gamma Ray of #PMK-2 well using the S-wave velocity which is estimated using fluid replacement modeling method could be seen in Figure 3. Two characteristic sand reservoirs which are bearing gas could be clustered in the cross plot as well. The cluster of two gas sand reservoirs is separated from the cluster of dry sand, shale and coal. This cross plot is the basis for simultaneous inversion and Lambda-mu-rho analysis. The conventional acoustic impedance inversion will fail if applied to this sand reservoir because the acoustic impedance value of the gas sand is superimposed with dry sand and shale.

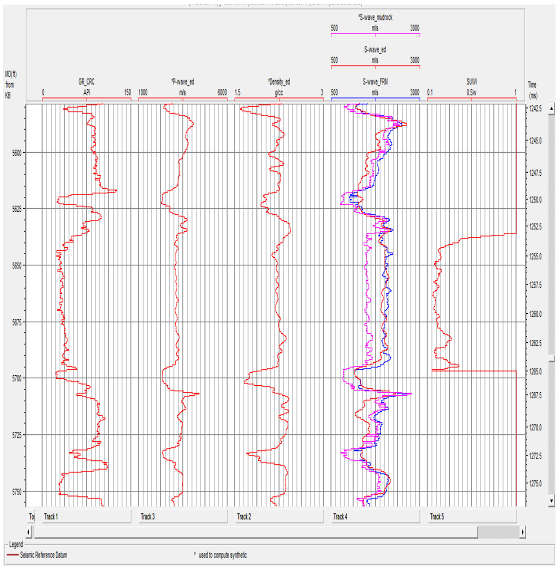


Figure 2. The comparison of original S-wave velocity, S-wave velocity estimated using fluid replacement modeling method and direct Castagna's relation from #PMK-2 well, Mawar field, Kutai Basin, Indonesia.

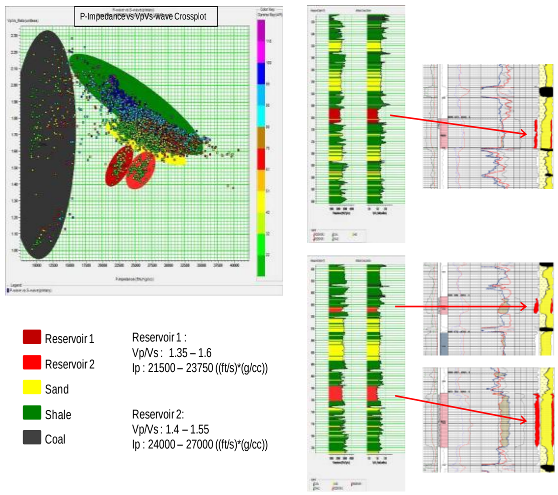
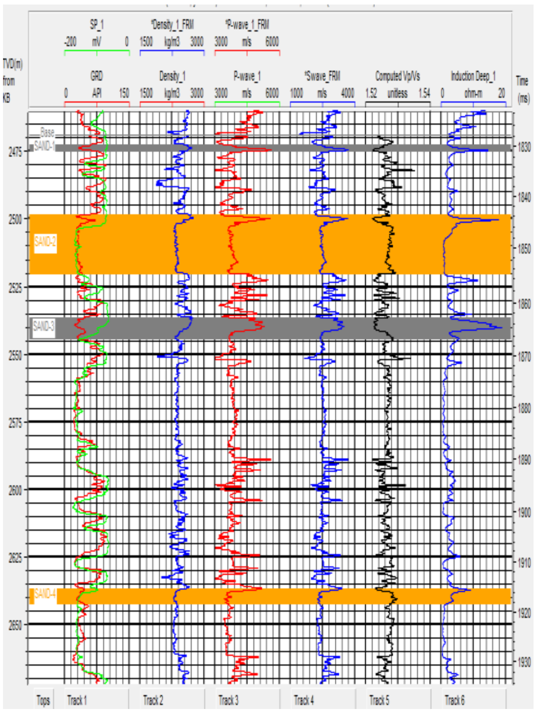


Figure 3. Cross plot of Vp/Vs ratio versus acoustic Impedance as function Gamma Ray using the estimated S-wave velocity from from #PMK-2 well, Mawar field, Kutai Basin, Indonesia.

The S-wave log estimation method using fluid replacement modeling is applied for S-wave estimation of oil saturated sandstone in Middle Missisauga formation from #L-30 well, Penobscot field, Nova Scotia Basin, Canada. Figure 4. shows Log data of #L-30 well from Middle Missisauga formation [8]. The blocky interval is the oil saturated sandstone with high acoustic impedance. Cross plot of Vp/Vs ratio versus acoustic impedance as function Gamma Ray of #L-30 well using the S-wave velocity estimated using fluid replacement modeling method is displayed in figure 5. The cluster of high acoustic impedance sandstone which saturated with oil can be seen clearly. The low value of Vp/Vs ratio and high value of acoustic impedance from sandstone bearing oil could be clustered which are separated from wet sand and shale as well, so it is potential to delineated using simultaneous inversion or lambda-mu-rho analysis.



Gambar 4. Log data of #L-30 well containing oil saturated sandstone from Middle Missisauga formation

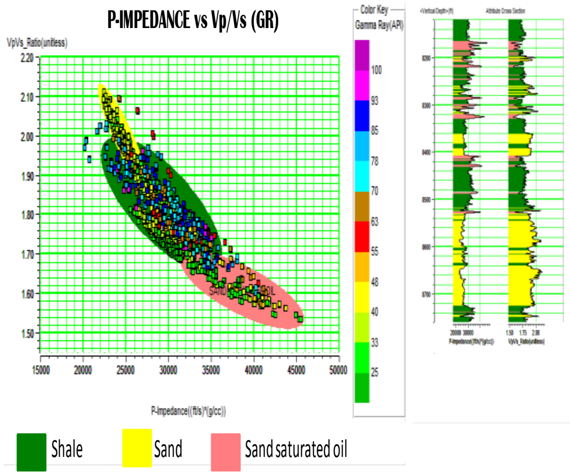


Figure 5. Cross plot of Vp/Vs ratio versus acoustic Impedance as function Gamma Ray using the estimated S-wave velocity from of #L-30, Penobscot field, Nova Scotia Basin, Canada.

V. CONCLUSION

We have proposed new method for estimation of S-wave log based Castagna's relation which is combined with Fluid replacement modeling method based on Biot-Gassman substitution and the use of petro physical data as the input. The S-wave log result of the offered estimation method has a small error to the original S-wave log so that it's more accurate and reliable for further analysis. The offered method could be used for S-wave log estimation in various litology such as sand, limestone, dolomite and shale. The S-wave log result of the offered estimation method has successfully used for cross plot analysis of Vp/Vs ratio as function of acoustic impedance and Gamma Ray for delineation of sandstone bearing hydrocarbon from two different field.

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