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Review

Methods of water saturation estimation: Historical perspective

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One of the most important tasks in reservoir engineering is characterizing different parameters of the reservoir. Water saturation is a parameter which helps evaluating the volume of hydrocarbon in reservoirs. Determination of this parameter started from 1942 by integrating some well logs in clean sandstones. After that, many scientists introduced some equations to validate this procedure in shaly sands and carbonates. To treat the problem of dependency of water saturation estimation on core analysis in previous works, other scientists proposed using rock physics and arrived at improved models of water saturation estimation. More recently, interpreters have used seismic attributes to evaluate water saturation values directly or estimating proper rock physical properties such as shale volume which are useful in water saturation estimation process.

Key words: Characterizing, well log, water saturation, rock physics, seismic attribute.

INTRODUCTION

Hydrocarbon reservoirs are the main properties of exploration and production companies. Most of the reservoirs atleast consist of two different phases of liquids. These phases are gas-water or oil-water. Some of the reservoirs have all of the three phases of gas, oil and water (Dandekar, 2006). Sandstone, as the most famous reservoir rock, has many spaces to reserve hydrocarbon. Carbonate rocks are also important kips to reserve considerable quantities of hydrocarbon.

One of the most important tasks in reservoir engineering is determining the characteristics of reservoirs to estimate their performance in future. Without a proper and accurate characterization, Many prominent errors can enter the reservoir performance prediction. These errors can finaly lead to lose the noticable values of hydrocarbone in extracting process.

Reservoir characterization is a process of describing various reservoir properties using all the available data to provide reliable reservoir models for accurate reservoir performance prediction (Jong, 2005). This process can be either qualitative or quantitative. In qualitative characterization the quality of rock is evaluated in order to see if it can be a reservoir rock. In recent years a new topic called improved reservoir characterization or quantitative reservoir characterization, has been propounded between scientists. This characterization has an important role in new reservoirs management. Quantitative reservoir characterization is the process of numeral statement of some characteristics in reservoir such as permeability, porosity, saturation, pressure and pores size. Suitable data in this characterization are cores, logs, production and seismic data.

One of the most important parameters in improved reservoir characterization is hydrocarbon saturation. Kamel and Mabrouk (2002) assumed that all void spaces in a reservoir consist of water and hydrocarbon, therefore:

$$S_h = 1 - S_w \quad (1)$$

where S_h is hydrocarbon saturation and S_W is water saturation. Since estimation of hydrocarbon saturation is

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not generally an easy task, it is recommended to determine the water saturation and predict the saturation of hydrocarbon using Equation 1.

History of water saturation estimation

First time, in 1942 Archie proposed that it is possible to determine the value of water saturation for a clean (non shaly) formation using porosity and electrical resistivity values of the formation (Archie, 1942):

$$S_W = \left[\frac{\alpha . R_W}{\varphi^m . R_t}\right]^{\frac{1}{n}} \quad (2)$$

In this equation, S_W is the water saturation of the clean formation, R_t is the corrected total electrical resistivity of formation obtained from resistivity logs, φ is porosity of the rock obtained by porosity logs such as acoustic or density, R_W is the water resistivity obtained from self potential (SP) logs or production tests, α is a constant which depends on rock type and tortuosity of the fluid path, and m and n are cementation and saturation exponents which are constant. The value of α is 0.6 for unconsolidated sand stones, 0.8 for consolidated sand stones and 1 for carbonates (Kamel and Mabrouk, 2002). Cementation exponent can get values between 1.6 to 2.4, but generally it is equal to 2 and the value of saturation exponent is diferent from 1.7 to 2.2 (Moradzadeh and Ghavami, 2001).

It should be mentioned that there are other well logs which can give the values of water saturation. As an example by combining the density log with hydrogen index obtained from NMR log, it is possible to determine the water saturation value. This procedure is only sensitive to the gas saturations and can be applied in the regions near the wells (Ellis and Singer, 2007; Holstein, 2007). Therefore the most important well logs in water saturation measurements are resistivity logs.

The main problem in application of Archie's method is determination of R_W when there is no enough production tests or SP log data (as is common in many oil fields). The other problem is the precision of the estimated φ when the rock matrix type is unknown. In addition, there is an inherent uncertainty in estimations of m and n values. To solve these problems, Hingle (1959) and Pickett (1963) presented a graphical method using two different plots that were essentially obtained from the Archie formula (Hingle, 1959; Pickett, 1963). Although these plots better predict the water saturation, their of some simplistic assumptions in Archie's formula and consequently in Hingle and Pickett's plots. More specifically, it is not possible to use these methods in shaly (unclean) and heterogeneous formations. In shaly sands, the presence of clay adds an additional conductivity.

This additional conductivity will cause an error in water saturation estimation (Dandekar, 2006). In carbonate formations, wide range and irregular distribution of pore sizes change the rock conductivity and adversely affects the precision of Archie's formula (Van Golf-Rocht, 1982).

To alleviate this problem in shaly sands, works have been ongoing towards better determination of the effects of shale in formations (Patnode and Wyllie, 1950; Winsauer and McCardell, 1953; Wyllie and Southwick, 1954; Waxman and Smits, 1968; Poupon and Leveaux, 1971; Clavier et al., 1984; Worthington, 1985; Herron, 1986; Sen et al., 1988; Schwartz and Sen, 1988). Worthington introduced four general kinds of equation which consider the effect of shale in sands to determine the values of water saturation as bellow:

$$C_t = \frac{C_W}{F} S_w^n + X \quad (3)$$

$$C_t = \frac{C_W}{F} S_w^n + X S_w^s \quad (4)$$

$$\sqrt{C_t} = \sqrt{\frac{C_W}{F}} S_w^{n/2} + \sqrt{X} \quad (5)$$

$$\sqrt{C_t} = \sqrt{\frac{C_W}{F}} S_w^{n/2} + \sqrt{X} S_w^{S/2} \quad (6)$$

In these equations, C_t is total conductivity of fully saturated sand, C_W is water conductivity, S_w^n is water saturation of non-shaly sand, S_w^s is water saturation of shaly sand, *n* and *s* are saturation exponents for non-shaly and shaly sands, *X* is the additional conductivity added by clay and *F* is the formation factor and equals to:

$$F = \frac{R_0}{R_W} = \frac{\alpha}{\varphi^m} \quad (7)$$

application is limited in clean formations. This is because in the first kind of the Worthigton equations it is assumed that shale and sand are independent from each other in conducting the electrical current and shale has not been affected by hydrocarbon. In situation of

Table 1. The values of X according to different values of Δt_{ma} (Kamel and Mabrouk, 2002)

Matrix	$\Delta t_{ma}(\mu s/ft)$	X
Silica	55.5	1.60
Calcite	47.6	1.76
Dolomite	43.5	2.00

scattered shale, hydrocarbon will influence the shale. According to interaction between shale and sand (or shale and saturation), a third parameter will appear in the model (Models 4, 5 and 6). A classic example of the fourth kind of Worthington model is Indonesian equation introduced by Poupon and Leveaux (Equation 8). This equation is empirical and is valid for most shaly reservoirs in Indonesia (Poupon and Leveaux, 1971).

$$C_t = \frac{C_W S_W^2}{F} + 2\sqrt{\frac{C_W V_{sh}^{(2-V_{sh})} C_{sh}}{F}} S_W^2 + V_{sh}^{(2-V_{sh})} C_{sh} S_W^2 \tag{8}$$

Although all these methods could potentially detect the effect of shale and yield more realistic values of the formation conductivity and water saturation, a major obstacle remains in these methods due to their strong dependency on cores and logs analyses which are costly and time consuming. Opposite to shaly sands, there are not any highlighted works on the estimation of water saturation in carbonate formations. A few have worked on the effect of pore size and distribution in the evaluation of water saturation in these kind of rocks (Alger et al., 1989; Obeida et al., 2005; Lucia, 2007) perhaps the most significant contribution is the equation by Lucia.

$$S_W = a \times H^b \times \varphi^c \tag{9}$$

In this equation, H is the reservoir height (vertical thickness of the reservoir zone), *a, b,* and *c* are constant coefficients which are the functions of rock type and grain size. Unfortunately, Lucia formula does also depend on the analyses of cores and logs. To treat the problem of dependency of water saturation estimation on core analysis, Kamel and Mabrouk (2002, 2003) proposed using rock physics and arrived at an improved model of water saturation estimation. Their method is based on two equations as follows:

i) A first equation to determine the water saturation using a combination of Archie and Raiga formulas with two logs of acoustic and electrical resistivity (Kamel and Mabrouk, 2002) as follows:

$$S_W = \sqrt{\frac{\alpha R_W}{\left[1-\left(\frac{V_P \Delta t_{ma}}{10^6}\right)^{\frac{1}{X}}\right]^m R_t}} \tag{10}$$

Where V_P is P-wave velocity in rock obtained from acoustic log, Δt_{ma} is the acoustic wave transition time in rock matrix, and X is a parameter obtained from Δt_{ma} using Table 1.

ii) A second equation to determine shale volume in shaly sands using a combination of three porosity logs of neutron, density, and acoustic (Kamel and Mabrouk, 2003).

$$\left(\frac{\rho_{sh}-\rho_{ma}}{\rho_f-\rho_{ma}}\right)V_{sh}^2 - \left(\varphi_N + \frac{\rho_b-\rho_{ma}}{\rho_f-\rho_{ma}} + \frac{\rho_{sh}-\rho_{ma}}{\rho_f-\rho_{ma}} - 2\frac{\Delta_{tsh}-\Delta_{tma}}{\Delta_{tf}-\Delta_{tma}}\right)V_{sh} + \left(\varphi_N + \frac{\rho_b-\rho_{ma}}{\rho_f-\rho_{ma}} - 2\frac{\Delta_t-\Delta_{tma}}{\Delta_{tf}-\Delta_{tma}} \times \frac{100}{\Delta_{tsh}}\right) = 0 \tag{11}$$

In this equation, ρ_{sh} is density of shale, ρ_{ma} is density of rock matrix, ρ_f is density of fluid, φ_N is Notron log porosity, ρ_b is total density, Δ_{tsh} is acoustic wave time in rock matrix, Δ_{tf} is acoustic wave transition time in transition time in shale, Δ_{tma} is acoustic wave transition time in rock matrix, Δ_{tf} is acoustic wave transition time in rock fluid, and Δ_t is total transition time of acoustic wave. The roots of Equation 11 are the values of shale volume.

Kamel and Mabrouk's (2002 to 2003) procedures give reasonably good results of water saturation estimation especially in shaly sands.

A review of literature, as documented here, shows that most valuable contributions to date have been focused on determination of water saturation using well logs and cores data. Graphically illustrated, the process of reservoir characterization will much benefit from more detailed studies in the first part of the process which involves seismic data, as is shown in Figure 1.

There seems to be a lack of coherent methodologies to

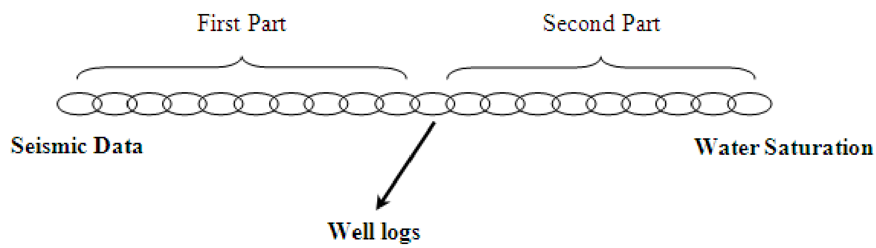

Figure 1. Reservoir characterization chain.

Table 2. Two kinds of error in seismic attributes selection (Kalkomey, 1997).

Decision	Property and attribute are uncorrelated	Property and attribute are correlated
Keep seismic attribute as a predictor	Type I Error	Correct decisio (no error)
Reject seismic attribute as a predictor	Correct decision (no error)	Type II Error

incorporate seismic data into water saturation evaluation instantly; alternatively such procedures could be used to determine only the necessary well logs that could help estimation of water saturation level to complete the first part of the chain in Figure 1.

Seismic attributes in reservoir characterization

Generally, the three most important aspects of seismic reservoir characterization are considered to be quality of seismic data, determination of proper seismic attributes, and existence of a physical relationship between attributes and the reservoir property of interest. Kalkomey (1997) introduced two kinds of errors which may occur during selection of seismic attributes. Table 2 illustrates these errors.

A Type I Error will occur if no relationship exists between the seismic attribute of choice and the reservoir property of interest, yet we opt to use the seismic attribute as a predictor. On the other hand, a Type II Error occurs when a physical relationship exists between the seismic attribute and the reservoir property of interest, but we fail to consider the seismic attribute as a predictor. The cost of a Type I Error is inaccurate prediction biased by the attribute and the cost of a Type II Error is less accurate prediction than if we would have used the seismic attribute.

After selecting the proper attributes, the next step is integration of the attributes to predict reservoir property of interest.

Pan and Ma (1997) introduced three kinds of techniques for integrating seismic attributes:

1. Techniques based on statistical relationships, such as correlation and cross plotting.
2. Techniques based on expert experience and information.
3. Techniques which use artificial neural networks, fuzzy logic, and genetic algorithms to find the relationship between seismic attributes and the reservoir property of interest.

Seismic attributes in water saturation estimation

A review of previous studies on correlation between seismic attributes and water saturation is presented next. Seismic attributes such as amplitude, instantaneous amplitude, and impedance are shown generally well-correlated with water saturation. There also seem to be a consensus amongst researchers on applicability of prestack seismic data and AVO to provide reliable information about liquids and their identification in reservoirs (Van, 2000; Varela, 2003; Li et al., 2007; Zhou et al., 2009). Some of the findings are as follows:

Investigation of oil saturation in a sand stone formation in China using 3D seismic data (Pan and Ma, 1997). Their result is presented in Figure 2. Pan and Ma use real values of oil saturation from three wells, with interpolation throughout the reservoir using 3D seismic data that makes their final results highly dependent on the output of limited number of wells.

Balch et al. (1999) predicted the water saturation in a sandstone reservoir in Mexico using artificial intelligence and seismic attributes. The reservoir in their study had two zones of hydrocarbon (L and K). Three dimensional seismic data and values of water saturation at 19 wells were used first step in a fuzzy logic algorithm to detect five attributes (reflection coefficient, frequency, instantaneous phase, amplitude and energy) that were strongly correlated with water saturation. Then, a back-propagating artificial neural network was used to find the relationship between these attributes and the value of water saturation. The results of training the network is

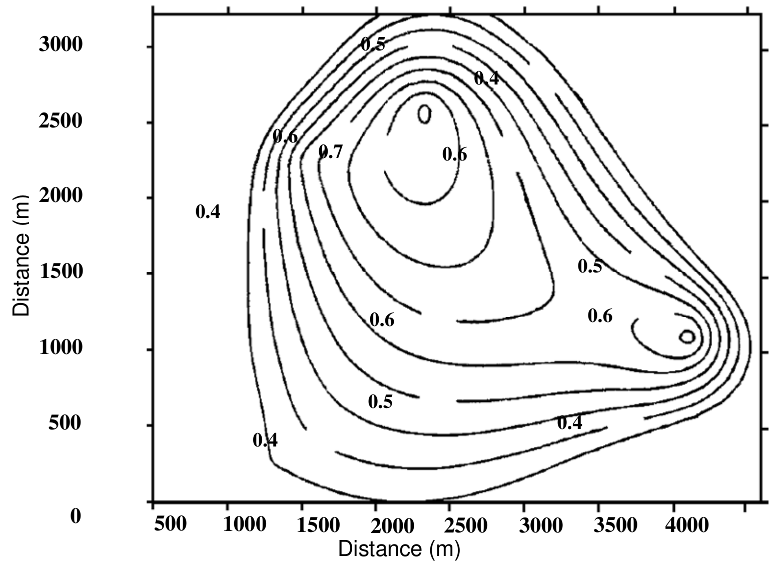

Figure 2. Oil saturation values (Pan and Ma, 1997).

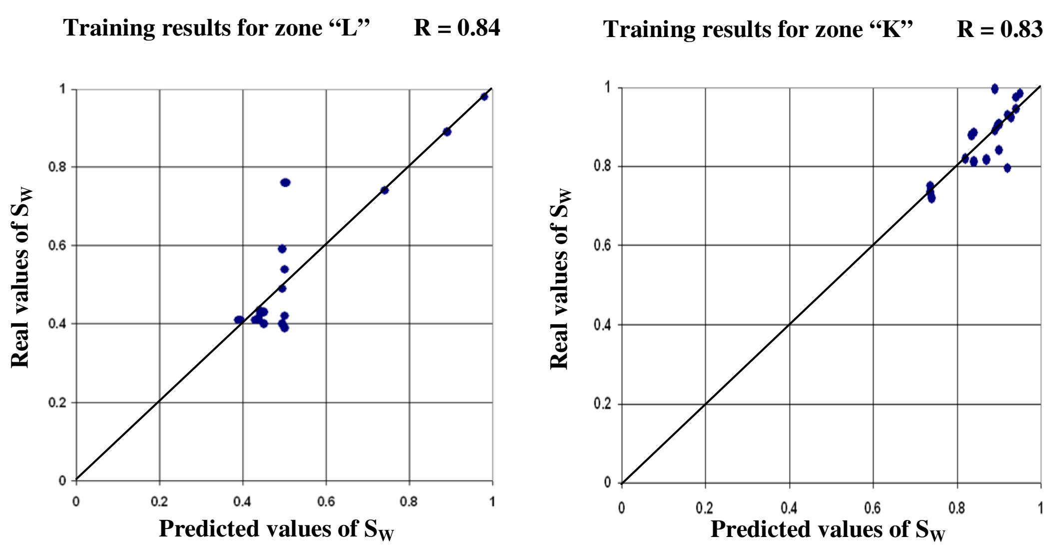

Figure 3. Correlation coefficient between real and predicted values of water saturation in zone "L" (left panel) and "K" (right panel), from Balch et al. (1999).

shown in Figures 3. The main contribution in the study by Balch et al. (1999) is using seismic attributes for water saturation estimation.

Boadu (2001) studied the effect of change in oil saturation level on seismic wave velocities and their ratio in a laboratory experiment. He applied changes to the temperature and values of oil saturation and observed a relationship between these variables and the values of P and S wave velocities and their ratio. He used an artificial neural network to express this relationship.

One of the most interesting studies in this field is the work done by Mu and Cao. They created a physical model of a sandstone reservoir in laboratory scales (Mu and Cao, 2004). They isolated the model and drilled two holes (injecting and discharging) in it. Saturating the sandstone layer with water, oil, CO_2 and CH_4 from 10 to 100 percents respectively, they succeeded in simulating seismic surveying by application of ultrasonic data acquisition; therefore, creating an environment to study the effect of change in the fluids type and saturation value on P-wave amplitude and absorption coefficient (Figures 4 and 5). The outcome of their study was an expression for determining absorption coefficient profile using Biot theory and reflection amplitude spectrum. They applied this formula for a sandstone reservoir in China (Figure 6) and reliably detected the gas zones (Figure 7) that could

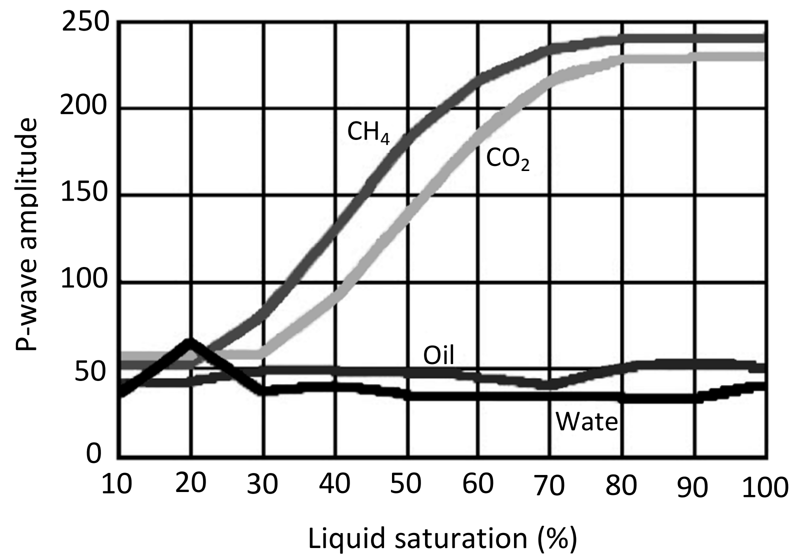

Figure 4. The relationship between amplitude of P-wave reflected from top of the sandstone layer and saturation values of different liquids (Mu and Cao, 2004).

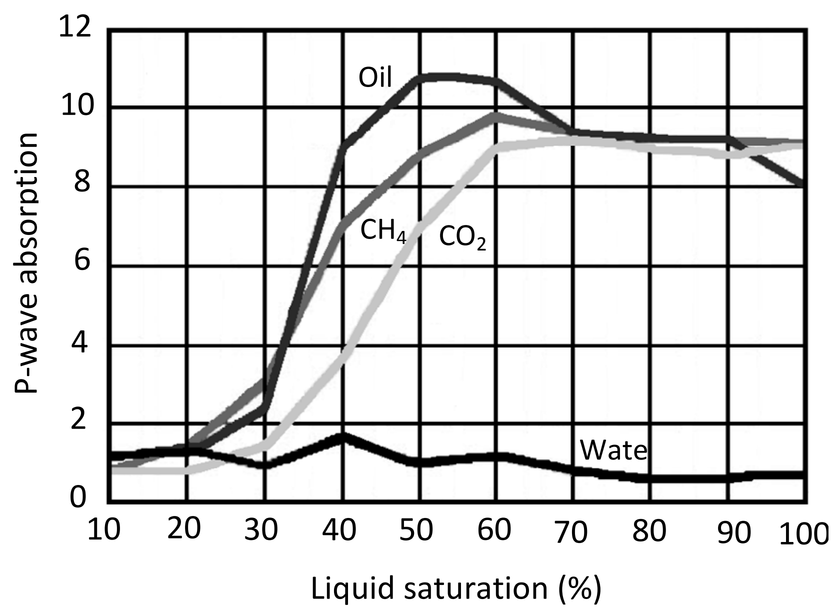

Figure 5. The relationship between P-wave absorption coefficient in sandstone layer and saturation values of different liquids (Mu and Cao, 2004).

not be seen on the initial seismic section in Figure 6. It is clear from Figure 7 that Mu and Cao's formula had detected other zones as gas; further drillings indicated that these zones in fact belonged to the coal seems that lied underneath the gas layer. This potentially presents a problem in the discrete gas and coal detection methodology of Mu and Cao.

Kitamura et al. (2006) studied the effect of water and gas saturation on P and S wave velocity values in sandstone samples. They changed the temperature at restricted pressure value to 130 MPa for each saturation degree and determined the P and S wave velocities for each temperature. Their results are shown in Figure 8.

CONCLUSIONS

Water saturation is one of the most important parameters in reservoir characterization procedure. This parameter can be either predicted from core data, well logs, or seismic attributes directly or can be estimated from an intermediate parameter such as shale volume in sand

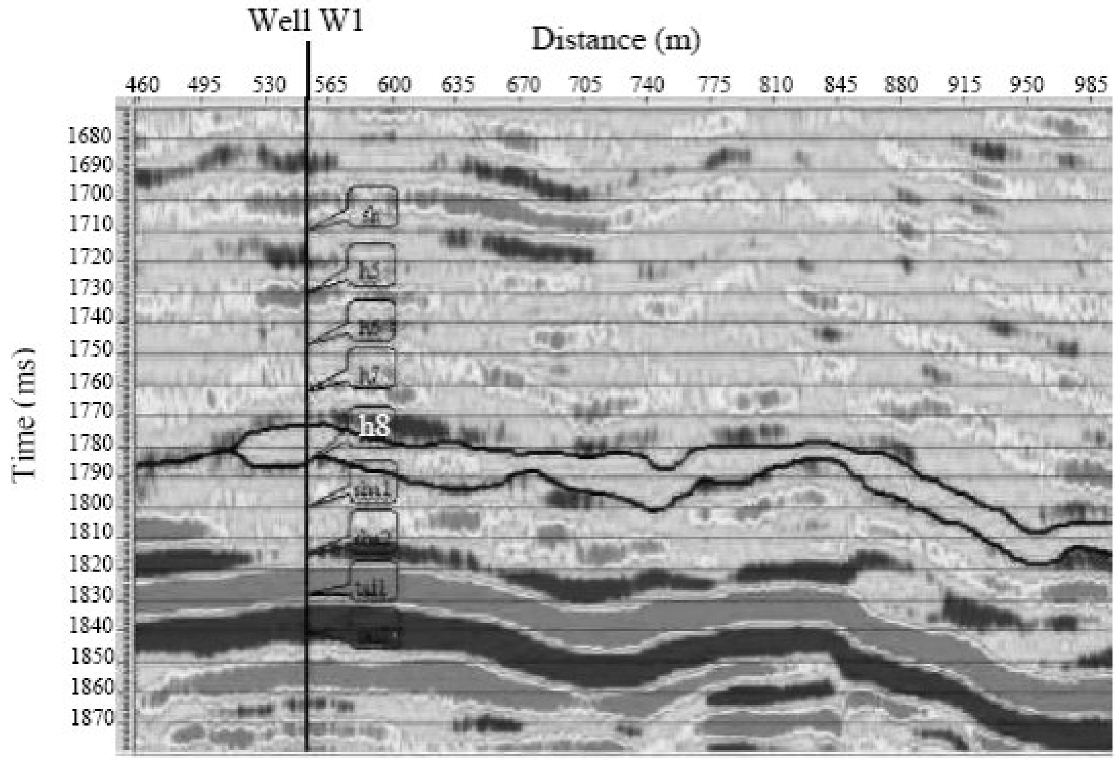

Figure 6. Seismic profile of the reservoir – h8 is a zone of gas (Mu and Cao, 2004).

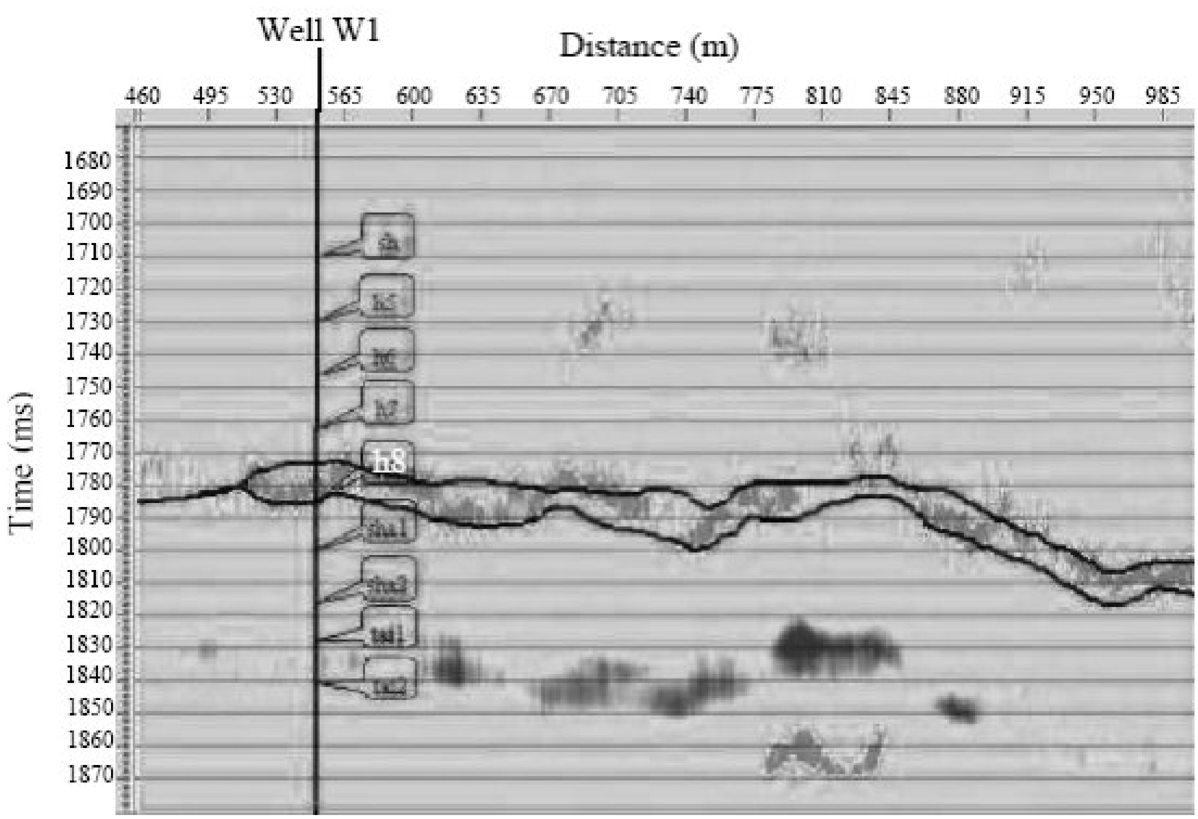

Figure 7. Black zones are zones of high absorption coefficient and indicate the existence of gas in the formation (Mu and Cao, 2004).

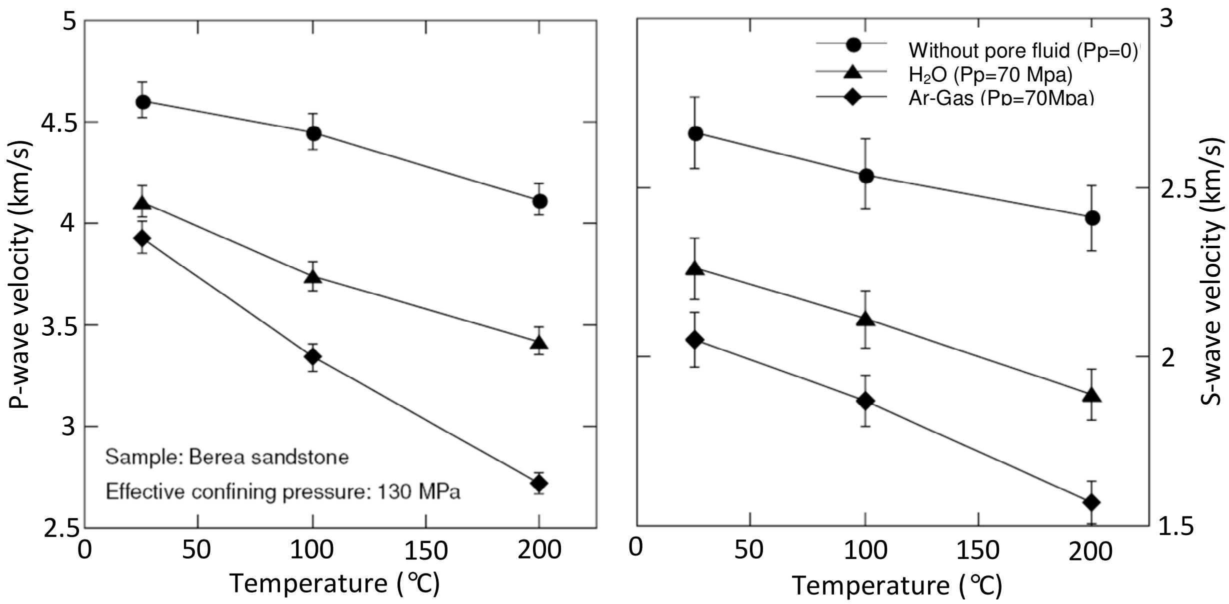

Figure 8. The P and S wave velocity values for dry, saturated with water, and saturated with gas samples (Kitamura et al., 2006).

stone reservoirs. Over the past decades, we have witnessed developments in using well log data to estimate water saturation. This process was started from Archie formula in 1942 and progressed by the works of Patnode and Wyllie (1950), Winsauer and McCardell (1953), Wyllie and Southwick (1954), Waxman and Smith (1968), Poupon and Leveaux (1971), Clavier et al. (1984), Worthington (1985).

To treat the problem of dependency of water saturation estimation on core analysis in previous works, Kamel and Mabrouk (2002, 2003), proposed using rock physics and arrived at an improved model of water saturation estimation. All of the proposed procedures till that time reveal the superior progress in second part of the reservoir characterization chain (from well logs to water saturation estimation).

More recently, interpreters have used seismic attributes to evaluate water saturation values directly or estimating proper rock physical properties such as shale volume which are useful in water saturation estimation process (Pan and Ma, 1997; Balch et al., 1999; Boadu, 2001; Mu and Cao, 2004; Kitamura et al., 2006; Lucia, 2007). These methods apply artificial intelligence computational agents such as “fuzzy logic”, “genetic algorithms” and “neural networks” or “statistical approaches” to detect unknown non-linear relationships between different seismic attributes and the reservoir property of interest which is here the water saturation value.

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Nomenclature

Sw, water saturation; **Sh,** hydrocarbon saturation; tortuosity factor; **Rw**, water resistivity; φ**,** porosity; **R_t,** corrected total electrical resistivity of formation; **m,** cementation exponent; **n,** saturation exponent; **C_t,** total conductivity of fully saturated sand; **C_w,** water conductivity; S_w^n, water saturation of non-shaly sand; S_w^s, water saturation of shaly sand; **s,** saturation exponent for shaly sand; **X,** additional conductivity added by clay; **F,** formation factor; **V_{sh},** shale volume; **C_{sh},** shale conductivity; **H,** reservoir height; **V_p,** P-wave velocity; Δ_{tma}, Acoustic wave transition time in rock matrix Δ_{tsh}, Acoustic wave transition time in shale; Δ_{tf} , Acoustic wave transition time in rock fluid; Δ_t, Total transition time of acoustic wave; ρ_{sh}, shale density; ρ_{ma}, rock matrix density; ρ_f, fluid density; ρ_b, total density; φ_N, notron log porosity.

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