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The Effect of Porosity on the Seismic Waves Velocities and Elastic Coefficients in a South-Western Iran's Carbonate Oil Field

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Abstract

Seismic characteristics of reservoir rock provide the main data in the exploration of seismology, processing, and interpretation of the characteristics of hydrocarbon reservoirs. In this study, petrophysical and geophysical laboratory measurements were performed on 35 samples made of limestone in a South-Western Iran's Carbonate Oil Field. Parameters including porosity, density, and permeability were measured along with the samples' compressional and shear wave velocities under reservoir conditions. Also, in the study of microscopic thin sections, factors affecting the velocity of waves, including porosity, Poisson's ratio, density, pressure, and pore type, were investigated. The scattering of points in the velocity diagrams of elastic waves based on the petrophysical parameters of the rock indicates that the most important factor of velocity changes is the pore type in the samples with the same porosity value. Also, it is impossible to detect reflectors due to low wave amplitude by acoustic impedance changes. For this purpose, in the studied reservoir, LMR parameters ($\lambda(L)$, $\mu(M)$, which are Lame's coefficients and $\rho(R)$ which is density) were calculated using laboratory results of velocity measurement. The values of LMR parameters of seismic data were determined by the velocities of compressional and shear waves in the pre-stack stage seismic. Then, using seismic inversion, compressional and shear wave resistances were estimated, and seismic sections with $\lambda.\mu$ and $\mu.\rho$ parameters were created. The results show a good correlation between laboratory measurement of rock physics and pre-stack seismic data. Also, the factor affecting the velocity of waves, i.e., the pore types, should be considered. Uncertainty in velocity values due to the diversity of pores can show differences in the velocity of elastic waves in the same porosity value to about 1500 m/s. Also, porosity changes of up to 20 percent are visible at a constant velocity.

Keywords: Compressional and Shear Waves Velocities, Acoustic Impedance, Lame's Coefficients, Pre-Stack, Pore Types.

Introduction

The main purpose of quantitative seismic interpretation during exploration is to identify anomalies from background trends and quantify these anomalies vs. reservoir properties.

In an early screening phase, with limited well control, it can be difficult to obtain reliable information about reservoir properties, including porosity, shale volume, and saturation [1].

A good fit was obtained for the meantime relationship by studying the effect of porosity on seismic velocity as well as measuring velocity in alternating layers of Leucite and Aluminum (Wyllie et al., 1956)-(Equation 1) [2]:

$$\frac{1}{V_P}=\frac{\varphi}{V_F}+\frac{1-\varphi}{V_M} \quad (1)$$

where V_P, V_F and V_M are compressional wave velocities in saturated rocks of fluid, fluid, and solid part of rock, and φ is rock porosity, respectively. Equation (1) expresses the relationship between velocity and porosity, which is true in high-pressure rocks.

Other researchers did a lot of research and provided a variety of relationships. For example, a relationships was presented for velocity-porosity communication (Pickett, 1963 and Raiga-Clemenceau et al., 1986) [3, 4].

Walsh (1965) has also provided relationships between the elastic modulus of rock matrix and porosity, indicating how petrophysical and lithological parameters affect the velocity-porosity relationship [5].

Anselmetti and Eberli (1993) measured the velocities of compressional and shear waves on 295 carbonate plugs of the Bhama and Mayla regions and presented power equations for the porosity-velocity relationship. They showed that the velocity changes in the same porosity value, especially in high porosity, reached more than 2.5 km/s [6].

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As mentioned above, porosity is the most important factor in rock velocity control. But in carbonate rocks, pores are also almost as important as porosity in elastic behavior and, therefore, the velocity of waves.

Most of the existing theoretical equations ignore or consider the pore types appropriately, so seismic inversion analyses, amplitude vs. offset AVO, and pore volume calculations based on these equations have many uncertainties.

The effect of geometric positioning and shape of pores on elastic properties was studied theoretically by Eshelby in (1957), Hill (1965), Kuster and Toksöz (1974), and laboratory by Watt et al. (1976), Marion and Zinszner (1991), Anselmetti and Eberli (1999) and Marion and Jizba (1996) [7 - 13].

Sirikarn Narongsirikul (2019) has provided the rapid rate of velocity reduction vs. porosity along with the data which is provided by (Yin1992 and Zimmer 2003) (Fawad, 2011) (Zadeh et al., 2016) for porosity-velocity communication by measuring the petrophysical properties (porosity and density) and the velocity of compressional and shear waves of seven unconsolidated natural sand with mineralogical compositions and textures [14-18].

Figure 1 shows the velocity of compressional and shear waves vs. porosity in loading mode (diagram above, circle) and unloading (low graph, square) by some researchers, such as Sirikarn Narongsirikul, in 2019. The overall porosity limit is between 24 to 44%, the compressional wave velocity is between 1.8 to 2.8 km/s, and the shear wave velocity is 0.4 to 1.2 km/s. High wave velocity changes vs. porosity are evident in all studies.

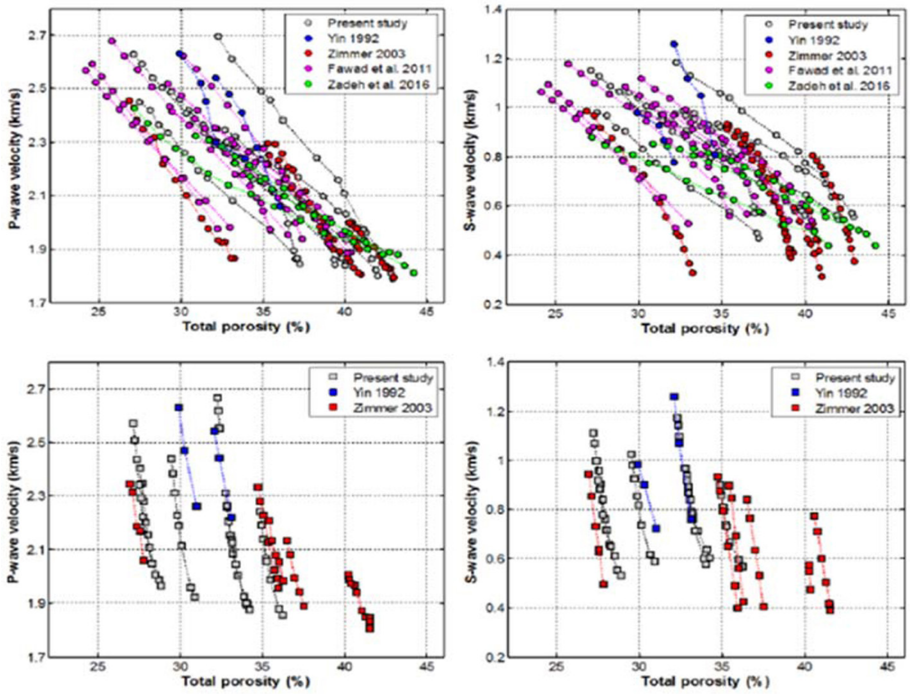

Fig. 1 Comparing P and S waves Velocities vs. Total Porosity (Sirikarn Narongsirikul, 2019). Normal loading (chart above, circle) and unloading (bottom graph, square).

The reflectors of compressional and shear waves were determined and the Poisson's ratio was analyzed by processing the common middle point *CMP* and correcting the common depth point *CDP* (Smith and Gidlow, 1987). They were able to achieve the characteristic of differentiation of the type of reservoir rock with porosity in seismic sections [19].

Using the velocity of compressional and shear waves and determining the Poisson's ratio for each reservoir rock sample [Equation (2 -4)], the Lame's coefficients are determined.

For the λ coefficient, it is not possible to define a specific definition like other elastic coefficients. In rock physics, the amount of λ is sensitive to the pore fluid, and μ is also sensitive to the type of rock matrix (Wang and Nur, 2000). Poisson's ratio has compressive dependence and increases with pressure reduction (Savic et al., 2000) [20, 21].

$$\sigma=\left[\left(\frac{V_P}{V_S}\right)^2-2\right]\bigg/\left[2\left(\frac{V_P}{V_S}\right)^2-2\right] \tag{2}$$

$$\mu=\frac{F/A}{\varphi}=\frac{P_{12}}{\varphi},\ \mu=\rho V_S^2 \tag{3}$$

$$\lambda=\rho\left(V_P^2-2V_S^2\right),\ \lambda=K-\frac{2}{3}\mu \tag{4}$$

where V_P and V_S are compressional and shear wave velocities, σ is Poisson's ratio, F/A is shear stress, φ is porosity, ρ is density and λ and μ are Lame's coefficient, and K is the bulk modulus.

Goodway et al. (1997) evaluated the LMR method (λ,μ,ρ) to determine the type of rocks and fluid anomaly of the reservoir. In this method, the amplitude of compressional and shear waves is converted to the acoustic and acoustic impedance of these waves. Then the acoustic and acoustic impedance estimation is converted to the result of multiplying the Lame's coefficients in density. In a homogeneous environment, rock density is also necessary, in addition to compressional and shear wave velocities (White, 1983) [22, 23].

Marion and Jizba (1996) have studied the relationship between bulk modules and mineral type. The results of their research show that the difference in bulk modulus of dolomite and calcite samples was insignificant.

The Wyllie Average Time Equation (1956) diagram is plotted in Figure 2 for two types of calcite and dolomite minerals. As can be seen in the figure, the difference in velocity due to the type of calcite or dolomite minerals has very low dispersion. For example, the tissue of sugar dolomite creates inter-crystal porosity. As a result, it reduces the velocity, while dolomites with preserved tissue have very high velocity. Hence, processes that alter minerals, such as sugar dolomite and dolomite cementation, along with the type of porosity, affect the velocity.

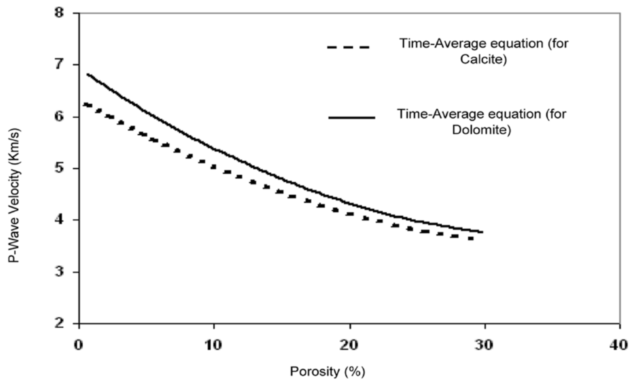

Fig. 2 Average Time Equation Diagram for Calcite and Dolomite Mineral (Wyllie, 1956).

One of the best approximate relationships for estimating velocity by density is the Gardner et al. relationship (1974), which is generally used for Siliciclastic Sandstones, Equation (5), [24].

$$V_P = 108.9\rho^4 \quad (5)$$

In which the velocity, V_P, is meters per second, and density ρ in grams per cubic centimeter. The results of laboratory research studied the velocity of compressional waves vs. bulk density in three wells in the Niger Delta basin showed that the acoustic impedance increased by decreasing porosity (increasing the bulk density), which is related to incomplete linear correlation to material incompressibility (bulk modulus), imperfectly linear correlation (Eyinla et al., 2021) [25].

Rock-physics models are essential in that they help in converting elastic parameters from inversion data to reservoir parameters. Similar templates have been made for different parameters, such as AI versus shear impedance for organic-rich shales (e.g., Vernik and Milovac (2011); Carcione and Avseth (2015)) and $\lambda.\mu$-$\mu.\rho$ cross-plots for tight reservoirs (Close and Perez, 2015) [26-28].

The template comprises models of different lithologies and fluid scenarios that are expected in an area of interest. These models can be used to understand and interpret the geology and reservoir characteristics of a given data set, either well-log data or seismic inversion data. However, the models can also be used to extrapolate away from observed data points. The rock-physics models can reveal various geologic trends, including depositional and compactional trends (e.g., Avseth et al., 2009, 2010, 2014a) [29-31].

Marion and Jizba (1996) have studied the effect of vuggy porosity at the velocity of compressional and shear waves by laboratory measurements of many core samples. By grouping the samples according to the frequency of vuggy-type pores, they observed that at a supposed velocity of 5.5 km/s, porosity could change from 5 to 15% in terms of the presence or absence of vuggy porosity.

The results of velocity measurements based on porosity and the study of microscopic thin sections by Anselmetti and Eberli (1993) indicated five pore types, including inter-crystal and inter-particle porosity and micro-porosity, which reduced the velocity as well as moldic porosity, inter-particle porosity, and hard cement samples increased the velocity in the samples.

Since seismic patterns are a function of the difference in acoustic impedance and many studies, there is only one parameter, such as velocity or density, and the other parameter is estimated experimentally or formulaically. On the other hand, it is impossible to provide an empirical relationship between velocity and density to cover most carbonate rocks, so laboratory measurements and determination of the relationship between velocity and density are necessary to increase reliability.

The steps in this study include preparing samples, determining the petrophysical properties (porosity, density, and permeability), and measuring the velocity of compressional waves V_P and shear waves V_S.

The velocity of compressional and shear waves was measured on 35 plug samples under dry and saturated conditions at reservoir pressure. Also, the microscopic thin sections were interpreted to determine the type of minerals, texture, and porosity of the samples.

Finally, the most important factors affecting the velocity of seismic waves, including porosity, pore types, mineral type, density and pressure in carbonate rocks, have been investigated using the results of laboratory experiments. Since the velocity of seismic waves in rocks depends on different petrophysical factors, the determination of rock type directly and from the velocity of waves has uncertainty, so *LMR* method was used to determine the rock type by calculating the elastic coefficients.

Therefore, the same information and characteristics obtained from the experiments on the plug can be generalized to seismic sections by this method; so, in the studies of the risk reservoir modeling, the error of estimating the reservoir characteristics can be reduced.

Materials and Methods

Preparation and Determination of Petrophysical Properties of Samples

First, by examining petrophysical and geological maps for the studied formation, the plug cores were prepared as cylindrical with a diameter of 3.75 cm and a length of 6 cm. To perform the experiments, the samples are first cleaned in the Soxhlet system to remove oil, brine, drilling mud, or any other liquid from the pores. Then, the samples were dried for 48 hours in the normal oven at 60 degrees Celsius.

Porosimeter and granular density were measured using Ultra porosimeter. In this device, the volume of ruck grain is calculated by injecting helium into the sample using Boyle's law. Knowing the volume and mass of the whole sample, porosity, granular density, and bulk density of the rock are calculated. Ultra-Permeameter device was used to measure the absolute permeability of gas. The basis of this device is based on Darcy law, and the pressure difference, gas discharge, and gas permeability are measured (Core Lab website, Soxhlet, Ultra-porosimeter, Ultra-Permeameter, 2022) [32].

Measurement of V_P and V_S Velocities of Samples in Dry and Saturated Mode

The experiment was performed to measure the velocity of compressional and shear waves on core samples at triaxial overburden pressure in the dry and saturated states of the fluid. The measuring device includes a sample holder, pore pressure pump system, triaxial overburden pressure pump system, and sending and receiving compressional and shear waves (as seen in Figure 3).

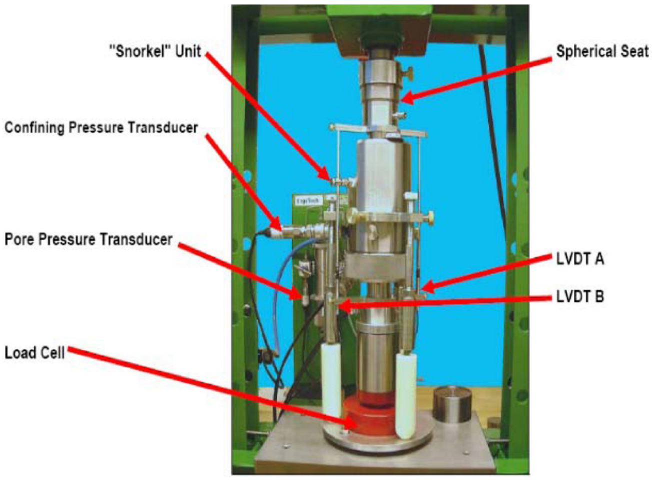

Fig. 3 The core holder part of the compressional and shear wave velocity measurement device.

In this system, the sample is placed in two dry or saturated conditions of formation fluid (water and oil) in the sample holder, and at the top and bottom of the transmitter and receiver of waves are embedded. Afterward, overburden pressure samples up to 70 MPa are applied. Fluid pressure can also be applied to the pores of the brain by the pore pressure system. Sending and receiving waves is done using an elastic wave generation system by transmitter and receiver. Compressional *P* and shear waves of *S2* and *S1* with frequencies of about 0.5 *MHz* are sent. To measure the pressure conditions of the reservoir, the system and sample must first be considered in stable pressure conditions. Then, by changing the effective pressure from the maximum to the minimum, different conditions can be created in the sample, and the wave passing time can be measured.
In the studied samples, the velocity measurement started from effective pressure 45 MPa and reached a pressure of about 5.5 MPa.

Application of Laboratory Data of Rock Physics in 2D Seismic Line

Preliminary information was obtained to determine the *LMR* coefficients by measuring the velocity of elastic waves on samples under pressure and reservoir temperature conditions. Petrophysical characteristics show that the range of porosity changes in limestone samples from 6 to 29.4%. The study depth for limestone is about 2665 meters, with an effective pressure limit of about 30.
In this study, a two-dimensional seismic line near one of the studied wells with appropriate signal-to-noise ratio data was selected. First, by pre-processing and amplitude preservation, the reflectors of S and P waves were determined. Then, by seismic inversion, the impedance value (the result of multiplying the velocity in density) for compressional and shear waves was determined, and by converting the impedance estimation to the result of multiplying the Lame's coefficients in density [Equation (3)], the rock type and porosity were investigated. Figure 4 shows how to determine the Lame's parameters using combined laboratory and seismic data in this study.

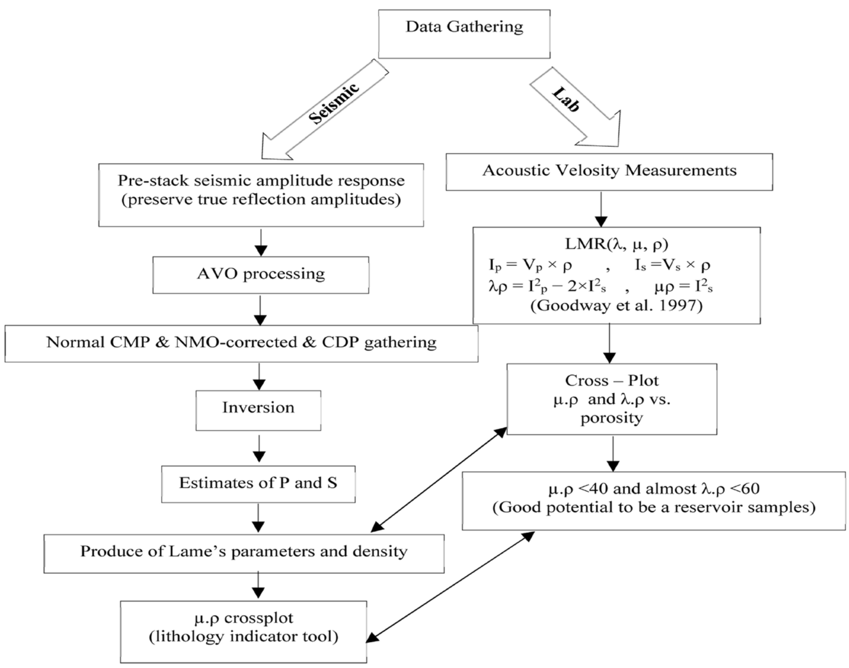

Fig. 4 How to determine the Lame's Coefficients using laboratory measurements and seismic data analysis.

Laboratory results show that the relationship between velocity and porosity for dry and water saturation samples at reservoir pressure conditions shows that the velocity-porosity diagram has a large dispersion (Figure 5).

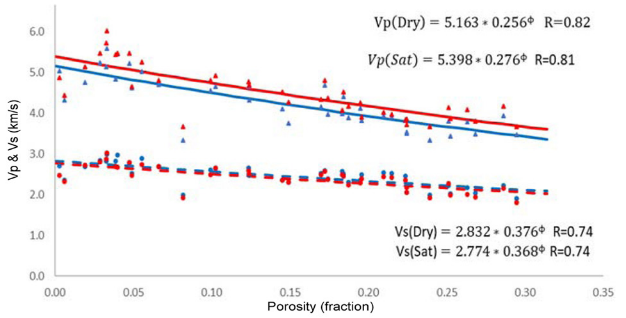

Fig. 5 Compressional and Shear waves Velocities vs. Porosity in dry and saturated. For Shear waves, when the samples are saturated, the velocities decrease, but for Compressional waves, it is completely different.

The most suitable fitting functions for the relationship between velocity and porosity for compressional and shear waves in dry and saturated conditions are modified power functions [Equation (6-9)].

$$V_P(Dry) = 5.163 * 0.256^{\varphi}\ ,\ R = 0.82 \tag{6}$$

$$V_P(Saturated) = 5.398 * 0.276^{\varphi}\ ,\ R = 0.81 \tag{7}$$

$$V_S(Dry) = 2.832 * 0.376^{\varphi}\ ,\ R = 0.74 \tag{8}$$

$$V_S(Saturated) = 2.774 * 0.368^{\varphi}\ ,\ R = 0.74 \tag{9}$$

The correlation coefficient of compressional wave velocity vs. porosity in a dry state has the highest value. The shear wave velocity in dry mode is higher than the shear wave velocity in saturation mode. Measuring the velocity of dry and wet sample waves is necessary to compare the fluid presence in rock pores. The velocity of the compaction wave increased by 5.5% in wet mode compared to the dry state, and the shear wave decreased by 2.7%.

As can be seen in Figure 5, the difference in velocity for the same porosity value reaches up to 1500 m/s. Of course, at an assumed constant velocity, porosity changes up to 15%. This difference is very high due to the changes in velocity in carbonate rocks' main minerals, i.e., dolomite and calcite. These changes can be attributed to the ability of carbonate rocks to form cement and the pore types that increase the elastic properties of the rock without filling the rock pores. Also, grain density determination experiments, representing the dominant mineral type in rocks, were carried out. The velocity diagram of compressional waves vs. granular density confirms that the effect of mineral type on controlling elastic properties is not significant (Figure 6).

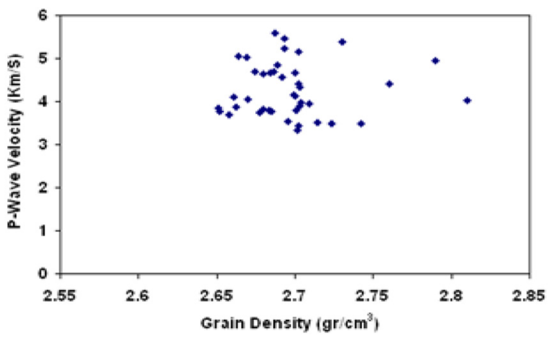

Fig. 6 Compressional Wave Velocity vs. Grain Density.

Then, for all samples, a diagram of compressional wave velocity changes vs. effective pressure in Figure 7 was presented. In all samples, the relationship between velocity and pressure with exponential functions in the form of $V_P = aS^b$ shows a good fit. By increasing pressure, the velocity increases, and as expected, the process of velocity increase decreases with an increase in pressure.

Also, the comparison of the velocity of compressional and shear waves in pore pressure mode compared to the ambient pressure for the studied samples is shown in Figure 8. Changes in V_P wave velocity in pore pressure mode increased by 6% and decreased by 2% for V_S wave.

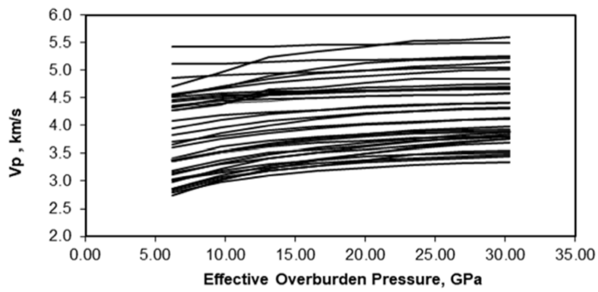

Fig. 7 Compressional wave velocity vs. effective pressure.

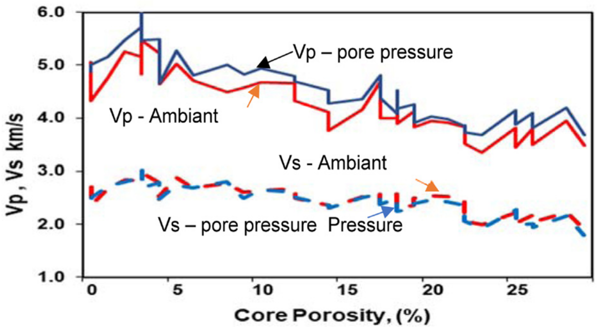

Fig. 8 Comparing the compressional and shear wave velocities, compressional wave velocity in the pore pressure vs. ambient condition increased by 6%, but shear wave velocity decreased by 2%.

To investigate the effect of pores on the relationship between velocity-porosity, the dominant porosity in the samples was determined by a petrographic study of their microscopic thin sections. In the samples, the dominant porosity included a pore, a gaping pore, very fine pores, and intergranular and unsurpassed porosity. Figure 9 shows the velocity relationship of compressional waves is based on the types of dominant porosity.

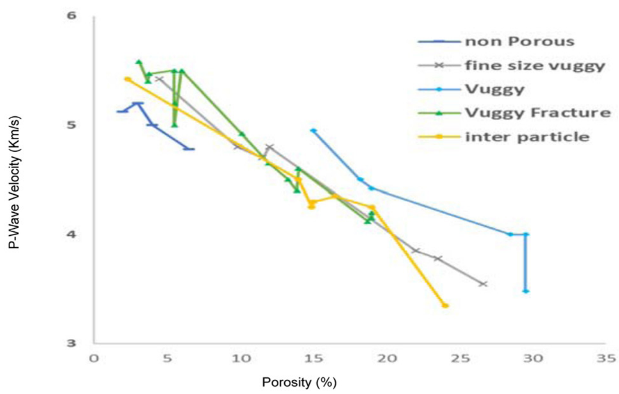

Fig. 9 Compressional Waves Velocity vs. Porosity for different types of dominant porosity in carbonate rocks

Results and Discussion

The separation of rock type in the seismic section is determined by Poisson's ratio vs. compressional and shear velocities with the Picket relationship (Picket,1963 and Dominico,1984) [3, 33]. First, Poisson's coefficient values were calculated based on the velocity of compressional and shear waves for laboratory samples.

Then, the value of Lame's coefficients was calculated based on the velocity of compressional and shear waves in water saturation conditions for laboratory samples, and $\mu.\rho$ and $\lambda.\rho$ values (the result of multiplying density in λ and μ coefficients and density in shear coefficient) were divided into fine porosity limestone with high porosity and limestone with low porosity [Equations (10 and 11)].

$$25 \prec \lambda.\rho \prec 65 \ , \mu.\rho \succ 20 \quad \text{Limestone with high porosity} \quad (10)$$

$$\lambda.\rho \succ 65 \ , \mu.\rho \succ 40 \quad \text{Limestone with low porosity} \quad (11)$$

Figure 10 displays the variation of μ within the 2D seismic line. According to this figure, the black to the dark gray area can be identified as porous. In contrast, the light gray to the white area is a non-porous and tight zone. The amount of μ in the porous and non-porous areas has a strong correlation with lab measurement results.

The value of Lame's coefficients vs. velocity of compressional and shear waves is calculated according to equations (10 and 11) in reservoir conditions for laboratory samples. Then, according to the flowchart shown in Figure 6 in the 2D seismic section, $\mu.\rho$ and $\lambda.\rho$ values were calculated, and in Figure 11, the variations of those parameters are shown in a 2D seismic line.

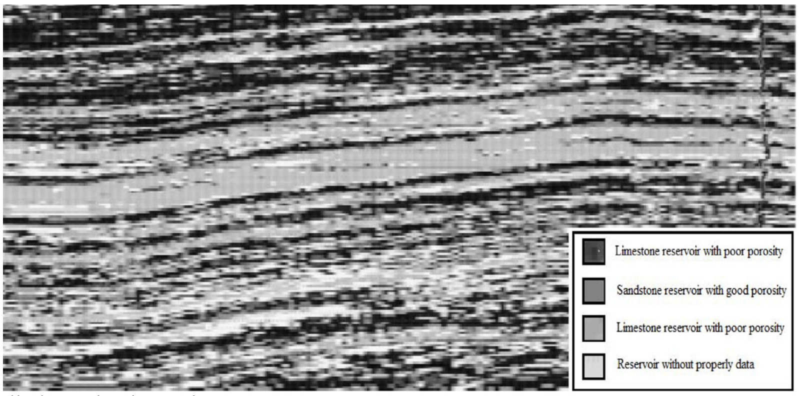

Fig. 10 $\lambda.\rho$ and $\mu.\rho$ values applied to seismic section.

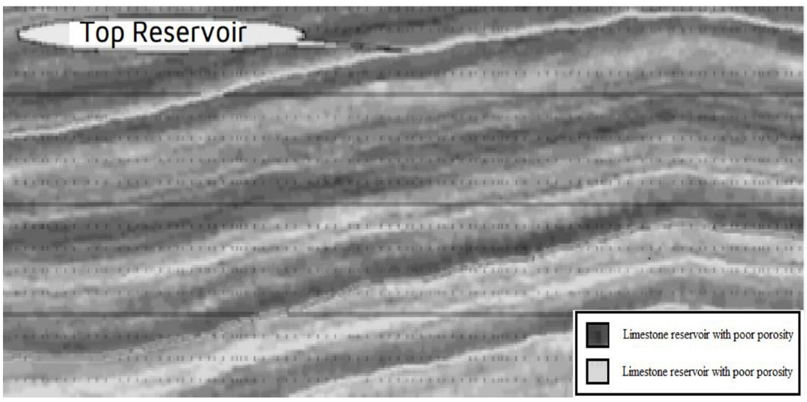

Fig. 11 $\mu.\rho$ variation values in seismic section.

According to the figure, the black-to-dark-gray region can be identified as a porous area. In contrast, the light gray to the white area is non-porous and narrow. $\mu.\rho$ and $\lambda.\rho$ values in the porous and non-porous areas are strongly correlated with the results of laboratory measurements.

Also, μ.ρ changes were calculated based on porosity for all samples in the laboratory condition. Samples with suitable reservoir conditions have porosity above 15% and $\mu.\rho<40$ In Figure 11, using seismic data processing, limestone separation Lame's coefficients with good and weak porosity were performed.

The ability of *LMR* as a lithology indicator for carbonate reservoir was examined in this study. Initial knowledge about the value of $\lambda.\rho$ and μ.ρ and criteria for porous and non-porous zones extracted from lab measurements. The weighted stack method was applied to the 2D seismic data to produce reflectivity of P and *S*. $\mu.\rho$ section shows it can use as a robust lithology indicator tool in the carbonate reservoir.

Conclusions

- *LMR* method, based on Poisson's ratio values and Lame's coefficients, can be used by combining core laboratory data and seismic data in determining rock type, porosity, and fluids in a porous environment.
- The seismic section of $\mu.\rho$ is a suitable tool for detecting reservoir rock type in the studied formation.
- Generalization of rock physics data of laboratory samples to seismic lines showed acceptable results about the determination of reservoir properties of the studied formation.
- The velocity of elastic waves in carbonate rocks depends

on parameters such as diagenesis, mineralogy, pore structure, fluid type, pressure, and temperature, as well as in incurable carbonates in a ratio of grain to matrix, shape, size, and sorting of grains.

- In the velocity diagrams of V_P and V_S elastic waves vs. porosity in the studied samples, the difference in velocity in the same porosity value reaches about 1500 m/s. On the contrary, at a constant velocity, the porosity changes to 20%.
- μ.ρ and λ.ρ values in porous and non-porous regions were strongly correlated with the results of laboratory measurements. However, due to the changes in the velocity of the same porosity value and the changes in porosity at a constant velocity, the seismic section data may be uncertain.
- The velocity diagram of elastic waves vs. density is confirmed by the fact that the effect of the mineral type on controlling elastic properties is not significant.
- The main dispersion factor in wave velocity diagrams vs. porosity can be the pore types forming porosity in carbonate rocks.

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