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A Review of the Intrinsic Parameters Affecting the Elastic Characteristics of Heterogeneous Carbonate Reservoirs: Insights from Laboratory Assessments

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ABSTRACT

This research provides an in-depth analysis of how various parameters such as mineralogy, density, porosity, temperature, pressure, and structural features impact the velocities of sonic waves in carbonate rocks. Our findings reveal that the mineral composition significantly influences the elastic behavior of these rocks. The density and elastic properties of minerals, especially clay minerals, play a crucial role in affecting porosity and predominant pore types. The porosity of carbonate reservoirs impacts their elastic properties, leading to variations in sonic wave velocities depending on the different pore types present. For a given porosity, the velocities can vary considerably due to the presence of diverse pore types within the pore space. Non-interconnected porosities with spherical or near-spherical shapes, along with microporosity, alter the effective elastic properties of the rock. Additionally, temperature affects the velocity-porosity relationship in rocks, with experimental results showing a decrease in P-wave velocity as temperature increases. Under reservoir conditions, wave velocity in carbonate rocks is influenced by factors such as confining pressure, temperature, gas saturation, and effective stress. Specifically, P-wave velocity increases with confining pressure as soft pores and cracks gradually close, enhancing the dry rock bulk shear modulus. Conversely, rising temperatures cause a slight decrease in velocities and an increase in attenuation. In conclusion, this study enhances our understanding of the physical properties and behavior of carbonate rocks under reservoir conditions, thereby contributing to the exploration and production of hydrocarbon resources.

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1. Introduction

Carbonate rocks are the predominant hydrocarbon reservoirs in Iran and around the globe. This study focuses on these reservoirs, considering their inherent and heterogeneous properties. The structural composition of carbonate rocks is intricate, characterized by the method of connection, elasticity, and the density of their constituent materials. To evaluate the elastic properties and seismic characteristics of carbonate reservoirs, it is essential to obtain their seismic attributes. The velocity of wave propagation in an elastic medium depends on various factors, including mineralogy, texture, porosity, density, and reservoir conditions [1-3]. These factors can be broadly categorized as intrinsic and non-intrinsic.

In real geological conditions, various factors combine to affect the velocity of wave propagation. Consequently, general rules can be established for all types of rocks based on these characteristics [4]. For instance, dolomite exhibits a high bulk modulus value and strong interconnectivity between rock grains, resulting in relatively high compressional wave velocity and impedance. However, due to the intricate complexity and heterogeneity of reservoir rocks on a microscopic scale, the extent of changes in seismic properties in response to variations in petrophysical parameters varies from one rock to another [5]. Therefore, these rules are presented in a qualitative manner only.

1.1. Theoretical Concepts

The velocity of waves in a rock mass is influenced by several factors, including the strength characteristics of intact rock [6, 7], the degree of cementation in clastic rocks [8, 9], the density of cracks and fractures [10-12], stratification and sedimentary structures [13], as well as environmental conditions such as stress regime [14], temperature [15], and moisture content [16]. In general, low stress, high saturation, and low porosity increase wave velocity. When waves propagate perpendicular to fractures, the minimum wave velocity is observed, while parallel propagation results in the maximum wave velocity [17]. Unlike sandstones, carbonate rocks mainly exhibit porosity caused by fractures, cavities, and pores within grains, rather than intergranular porosity [18, 19]. Due to the low shape factor of most carbonate rocks, they exhibit significant anisotropy in their properties [20-24].

1.2. Research Objectives

This research aims to comprehensively investigate the environmental and intrinsic factors that impact the elastic properties of carbonate sedimentary rocks. In the industry, having a precise understanding of the behavior of such rocks in response to environmental changes is crucial for safe and principled drilling in carbonate reservoirs. By acquiring knowledge of these characteristics through this study, one can accurately predict the response of reservoir rocks to environmental factors such as pressure, tension, and shear. The visual representation of the sequential steps and interconnections involved in the execution of this study can be observed in Fig. (**1**).

2. Methods and Materials

The aim of this study is to examine the effects of various parameters on sonic velocities using laboratory measurements of carbonate core-plugs. The dataset was derived from a heterogeneous carbonate reservoir with 450 meters of available cores and an 80% recovery factor, located in the oil reservoir of the southwestern Zagros Basin.

Initially, a macroscopic analysis of the drilled cores was conducted, followed by classification based on geological characteristics, appearance, and lithology. Forty-five core-plug samples, ranging from 1.5 to 3 inches in size, were selected. These samples were meticulously cleaned with common solvents to remove contaminants such as hydrocarbons, salts, and other impurities.

For routine core tests (Rcal), the plugs were dried in a conventional oven for 24 hours. Their porosity, permeability, and grain density were subsequently measured using a helium porosimeter, a gas permeability instrument, and a Pycnometer, respectively. The velocities and sample strains of the selected plugs were measured under dry (vacuum) conditions at a reservoir temperature of 90 °C and confining pressures ranging from 5 to 65 MPa. The core-plug samples were placed in a vacuum chamber with zero pore pressure, and the confining pressure was gradually increased in 5 MPa increments from zero to 65 MPa. This method allowed for a controlled examination of the effects of various parameters on wave velocity (Fig. **2**).

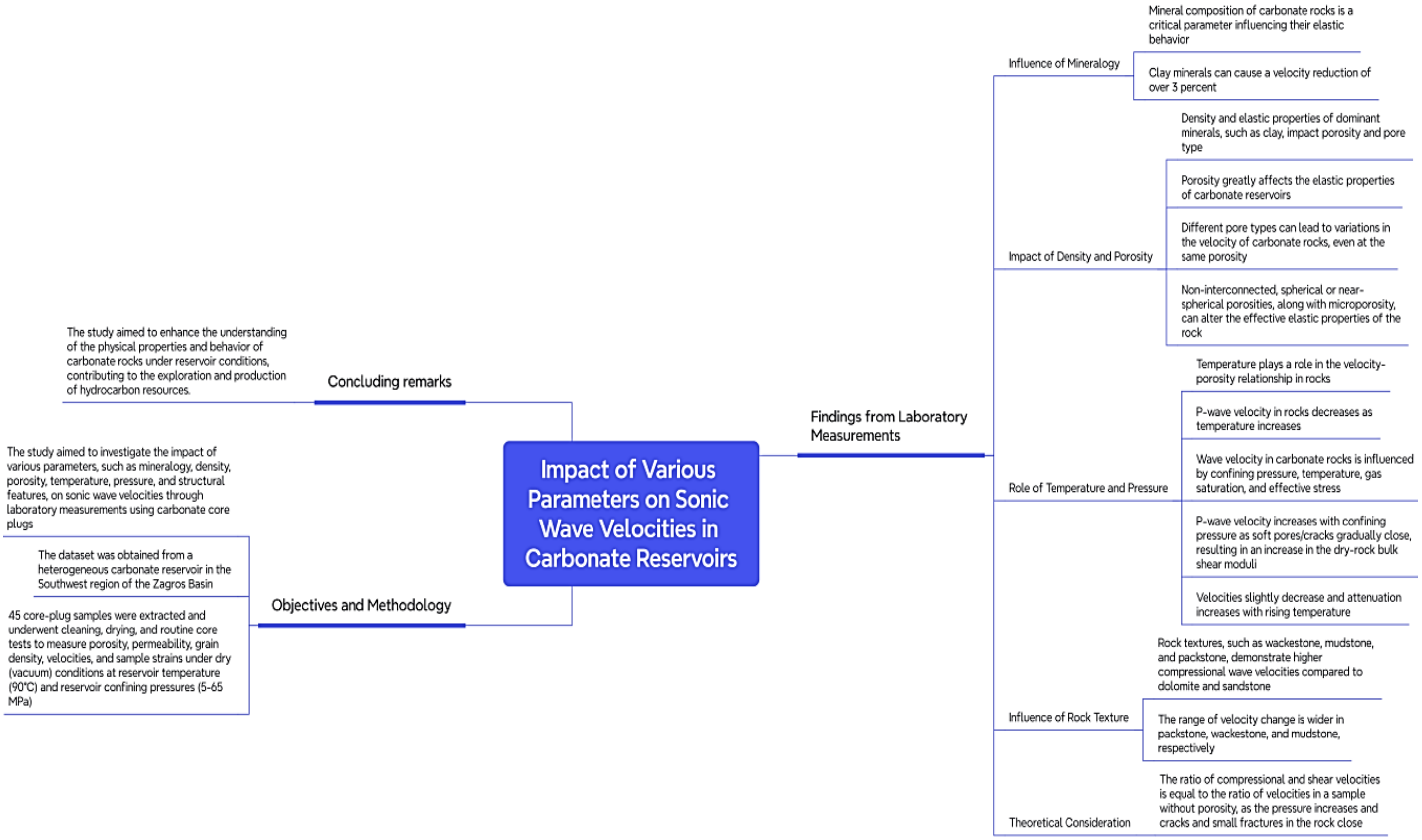

Figure 1: A mind map depicting the sequential steps of the study.

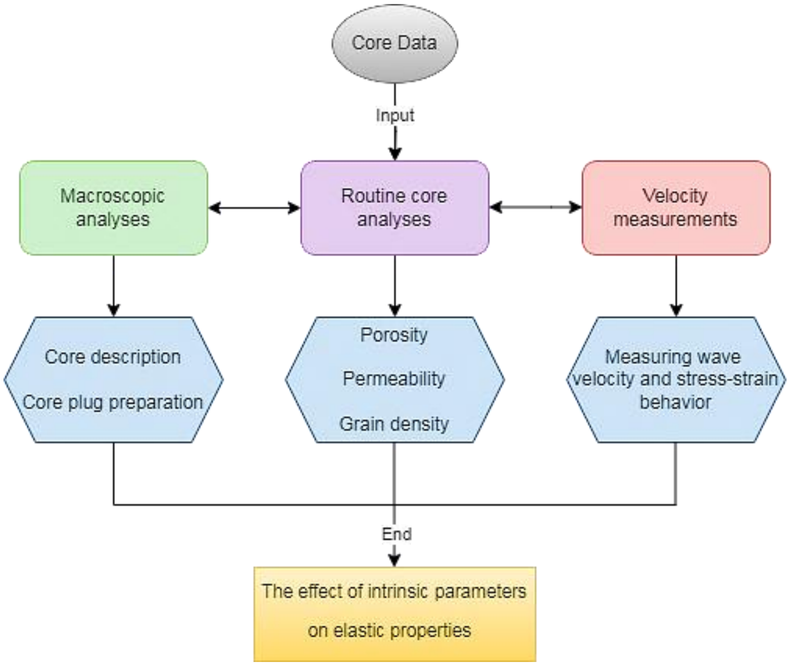

Figure 2: The flowchart of this study.

3. Results and Discussion

To achieve the research objectives, we conducted a thorough examination of the available dataset to determine the influence of sample properties on laboratory-measured wave velocities. The key findings from the study can be briefly as follows:

3.1. The effective Parameters on Velocities

3.1.1. Mineralogical Composition

The mineralogical composition of limestones plays a crucial role in determining the rock's density and velocity. External factors such as pressure and temperature are also significantly influenced by the mineral content of the rocks [25]. Carbonate rocks often contain impurities due to their sedimentary environment, which complicates accurate property predictions [26]. Among various minerals, clay minerals are particularly critical, as they can reduce velocity by over 3 percent. Generally, rock density and velocity decrease as pressure and temperature increase, with these changes being more pronounced at lower pressures and temperatures.

In a study by Sowers and Boyd [27], variations in lithostratigraphic pressure, ranging from the surface to a depth of 80 km, and temperature, from 0 to 1200 °C, resulted in less than a 1 percent change in wave velocity for quartz minerals. This minimal change highlights the stability of quartz under varying conditions. However, serpentine exhibited the slowest wave velocity compared to other minerals, indicating its distinct behavior.

Furthermore, the process of dolomitization creates intercrystalline porosity, which in turn reduces velocity [28]. The samples analyzed in this study showed a high percentage of micrite. Fig. (**3**) illustrates the relationship between micrite content and velocities under dry and laboratory conditions, emphasizing the significant role that micrite content plays in influencing seismic wave velocities in carbonate rocks.

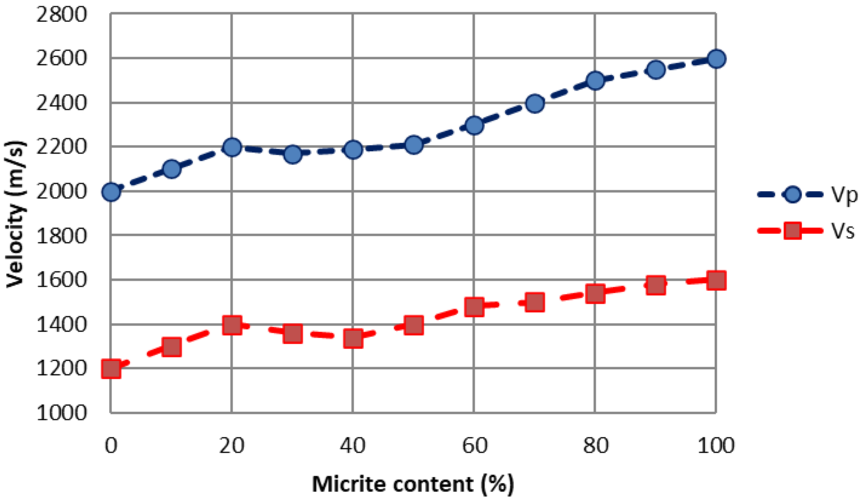

Figure 3: Micrite percentage versus wave's velocity in dry laboratory samples conditions.

The velocity of seismic waves is influenced by various factors, including mineralogical composition, sedimentation history, diagenetic conditions, and environmental circumstances. Under stable environmental conditions, a clear correlation between mineralogy, sedimentation environment, and physical properties is expected [29]. These elements collectively form what is known as the Petrographic Index (The P.I. integrates these variables to offer a comprehensive understanding of the rock's physical properties).

3.1.2. Density

The relationships between compressional and shear-wave velocities and density demonstrate that both velocities increase as density rises. As density increases, the material becomes more compact, which facilitates the transmission of both compressional and shear velocities through the rock matrix. This relationship is critical for interpreting seismic data, especially in heterogeneous carbonate reservoirs, where varying mineral compositions and textures can lead to significant differences in wave velocities.

Christensen and Mooney [30] proposed an equation (Eq. 1) that establishes a link between density and compressional wave velocity. This equation has been instrumental in understanding how changes in density affect seismic wave propagation.

$$\rho\left(\mathrm{g/cm^3}\right) = 0.541 + 0.3601 V_p \tag{Eq-1}$$

Furthermore, Ludwig *et al*. [31] employed Equation 2 to estimate the compressional wave velocity based on bulk density.

$$\begin{aligned} V_p\,(\mathrm{km/sec}) &= 39.128\rho - 63.064\rho^2 \\ &\quad + 37.083\rho^3 - 9.1819\rho^4 + 0.8228\rho^5 \end{aligned} \tag{Eq-2}$$

Fig. (**4**) depict the compressional and shear impedances in relation to density. A cubic function provides the best fit for these relationships.

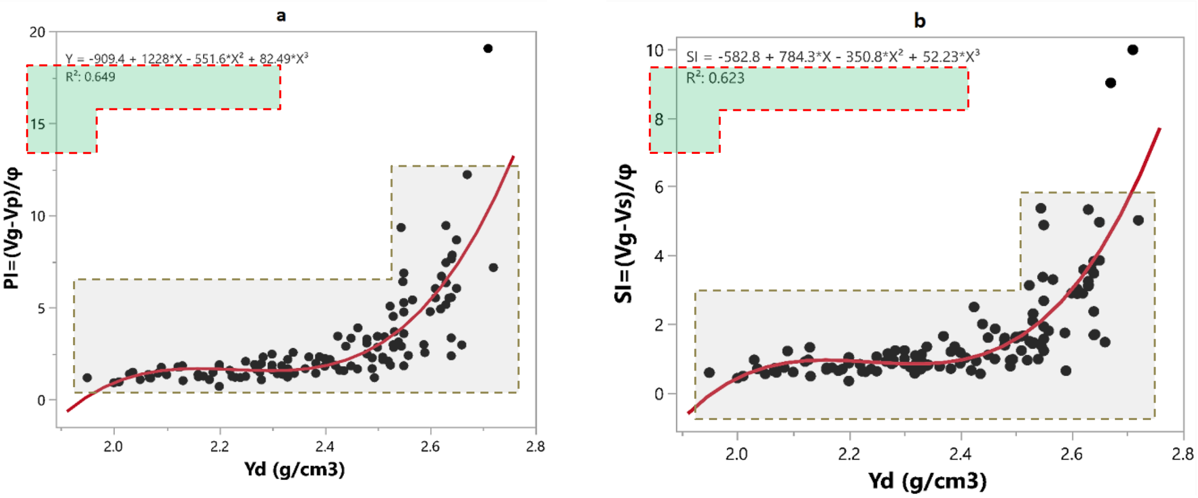

Figure 4: Diagram of grain density versus compressional (**a**) and shear (**b**) impedance.

By analyzing the investigated data, the following relationship is derived for the compressional wave velocity in dry samples (Eq. 3):

$$\left(\frac{V_{pg} - V_p}{\phi}\right) = -909.4 + 1228(\gamma_d) - 551.6\left(\gamma_d^2\right) + 82.49\left(\gamma_d^3\right), \quad R^2 = 0.65 \tag{Eq-3}$$

Where V_{pg} is the compressional wave velocity of minerals and γ_d is the dry density in gr/cm³.

Additionally, Equation 4 is formulated to describe the relationship between densities, porosity, and shear wave velocity:

$$\left(\frac{V_{sg} - V_s}{\phi}\right) = -582.8 + 784.3(\gamma_d) - 350.8\left(\gamma_d^2\right) + 52.23\left(\gamma_d^3\right), \quad R^2 = 0.63 \tag{Eq-4}$$

Where V_{sg} the shear is wave velocity of minerals and γ_d is the dry density in gr/cm³.

3.1.3. Rock Textures

Rock textures are fundamentally important in influencing the velocities of compressional and shear waves. In the analysis, wackestone, mudstone, and packstone demonstrate higher compressional wave velocities than dolomite and sandstone (Fig. **5a**). Notably, packstone, wackestone, and mudstone samples show a wider range of velocity variations. The shear wave velocity findings, illustrated in Fig. (**5b**), indicate that wackestone, packstone, and mudstone possess the highest shear wave velocities.

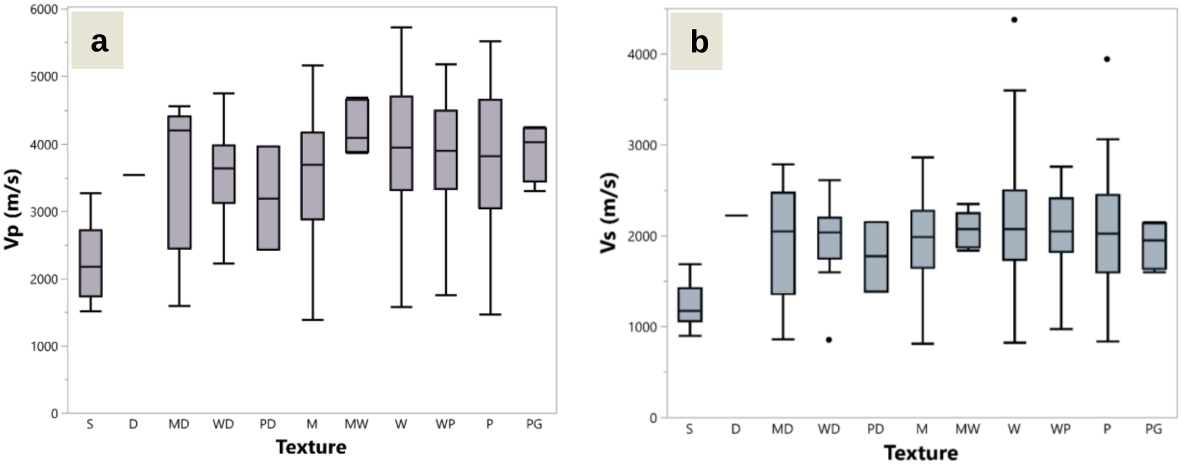

Figure 5: Compressional (**a**) and shear (**b**) wave velocities in relation to rock texture under dry and laboratory conditions.

3.1.4. Temperature

The study examined the influence of temperatures at 20, 60, and 90 °C on sonic wave velocities, finding the impact to be minimal within this range. However, when temperatures exceed 100 ºC, the effect of temperature becomes significantly more pronounced, resulting in a notable decrease in sonic wave velocities. This suggests that higher temperatures may alter the elastic properties of the rocks more dramatically. The relationship between wave velocities and temperature observed in this study is depicted in Fig. (**6**), highlighting these trends.

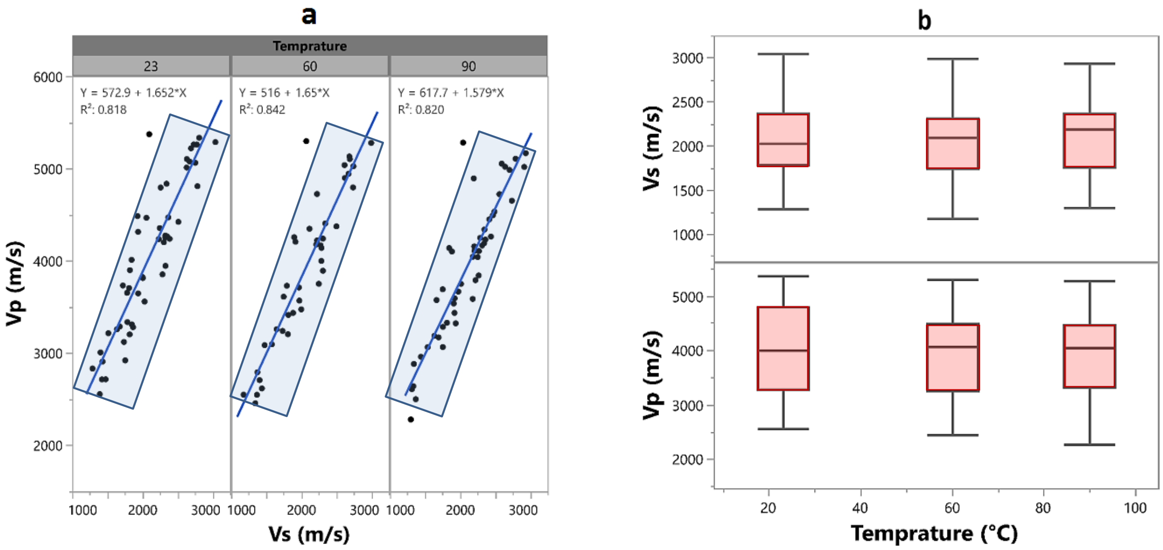

Figure 6: a) The correlation between wave velocity and temperature, with both decreasing as temperature rises. **b**) The comparison of wave velocities at the tested temperatures (20, 60, and 90 ºC).

3.2. The Effective Reservoir Condition on Velocities

Hydrostatic experiments were conducted to assess the impact of pressure on wave velocity under varying moisture and pore-pressure conditions, as noted by Mogi [32]. For dry samples, only confining pressure was applied, which induced strain due to deformation in the pore spaces and the rock matrix. In contrast, for saturated samples, the tests were carried out fewer than three distinct conditions: zero pore pressure (drained), constant non-zero pore pressure, and increasing pore pressure in line with the confining pressure (constant differential pressure). The experimental results indicated that the velocity behavior of porous rocks like sandstone and limestone remains relatively stable under these conditions [33].

3.2.1. Differential Pressure

Typically, increases in differential pressure results in higher velocities for compressional and shear waves. The rate of this increase is influenced by various factors, including moisture content, porosity, density, and rock texture.

3.2.1.1. Differential Pressure Under Dry Condition

Fig. (**7**) demonstrate the influence of differential pressure on the velocities of compressional and shear waves across various porosities. The study identified a clear, direct correlation between differential pressure and wave velocities, as well as with total porosity. As porosity increases, the constant values associated with these relationships tend to decrease. This indicates that higher porosity levels result in a reduced impact of differential pressure on wave velocities. The linear relationships, represented in Equations 6 and 7, were derived from a detailed multivariate curve fitting analysis of the collected data. This analysis method allowed for a precise evaluation of how changes in differential pressure and porosity interact to affecting wave velocities in carbonate rocks.

$$V_p = 4587 + 17.8P_d\left(\text{MPa}\right) - 62.4n_t\left(\%\right) \qquad \text{(Eq-5)}$$

$$V_s = 2677 + 8P_d\left(\text{MPa}\right) - 30n_t\left(\%\right) \qquad \text{(Eq-6)}$$

Where P_d is differential pressure and n_t is total porosity.

In addition to porosity, rock texture plays a crucial role in the correlation between differential pressure and compressional wave velocity. This relationship is illustrated in Figs. (**8** and **9**), highlighting the significant impact that different rock textures have on wave propagation. Under dry conditions, the relationship between differential pressure and compressional wave velocity remains linear across all porosities. This linearity indicates a predictable response of wave velocity to changes in differential pressure, regardless of the rock's porosity. This behavior underscores the importance of considering rock texture alongside porosity when evaluating the elastic properties of carbonate rocks.

The linear relationship described by Eq. 7 is derived from three key parameters: differential pressure, porosity, and rock texture for dry samples. This equation encapsulates the combined effects of these factors, providing a robust framework for predicting compressional wave velocities in carbonate reservoirs.

$$V_p = 5053 + 8.45P_d\left(\text{MPa}\right) - 68n_t\left(\%\right) + a\left(\text{Class}\right) \qquad \text{(Eq-7)}$$

By integrating these parameters, Eq. 7 allows for a comprehensive assessment of how differential pressure and rock texture influence wave velocities. This understanding is essential for accurate seismic interpretation, reservoir characterization, and the development of effective drilling and production strategies. The insights gained from this analysis contribute to a more detailed and nuanced understanding of the behavior of carbonate rocks under varying pressure conditions. The value of a for the different rock classes is as follows (Eq. 8):

$$\text{L}_1\text{=L}_2\text{=310, L}_3\text{=150, OM}_1\text{=OM}_2\text{=-225, OM}_3\text{=-20} \qquad \text{(Eq-8)}$$

For the shear wave velocity, Eq. 9 is obtained:

$$V_s = 2610 + 4.8P_d\left(\text{MPa}\right) - 32n_t\left(\%\right) + b\left(\text{Class}\right) \qquad \text{(Eq-9)}$$

and, the value of b for the different rock classes corresponds to Eq. 10:

$$\text{L}_1\text{=L}_2\text{=L}_3 = \text{110, OM}_1\text{=OM}_2\text{=-25, OM}_3\text{=-130} \qquad \text{(Eq-10)}$$

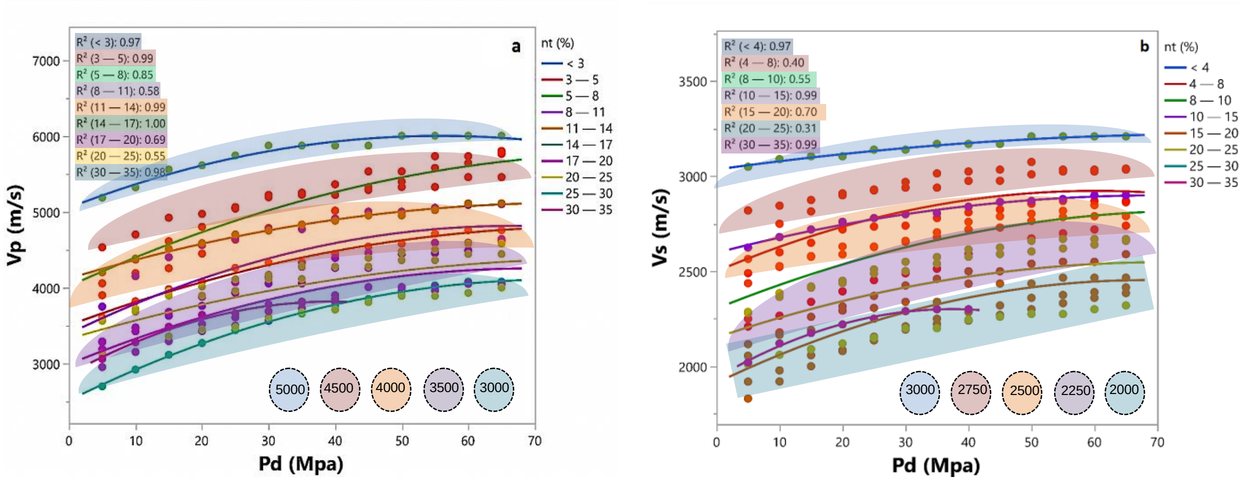

Figure 7: The compressional (**a**) and shear (**b**) wave velocities versus differential pressure for dry samples in arid conditions. The velocities range is indicated by the color-spectrum of the circular guide.

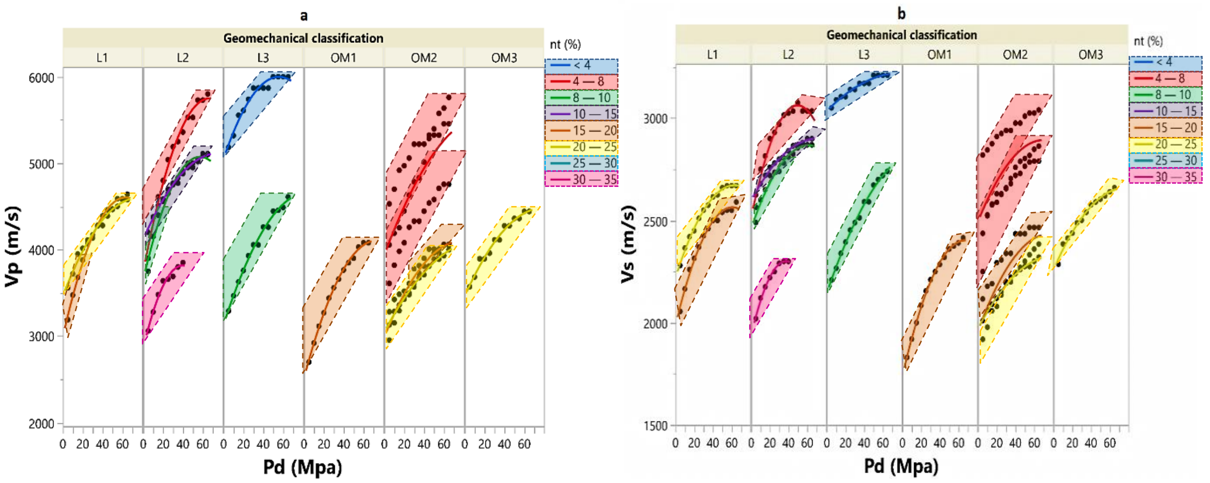

Figure 8: The correlation between compressional (**a**) and shear (**b**) wave velocities, differential pressure, and rock texture in arid conditions. The total porosity range is indicated by the color-spectrum of the rectangle guide.

3.2.1.2. Differential Pressure Under Saturated Condition

In saturated conditions, the presence of fluids within the pore spaces can significantly alter the rock's elastic properties. Differential pressure, which is the difference between confining pressure and pore pressure, directly affects the compressional wave velocity by changing the rock's effective stress state. Total porosity, which accounts for the volume of pore spaces within the rock, influences the distribution and movement of fluids, thereby impacting the wave velocity. Rock texture, encompassing the grain size, shape, and arrangement, further modifies how waves propagate through the medium. Under arid conditions, Eq. 11 is formulated to establish a correlation between compressional wave velocity and three key parameters: differential pressure, total porosity, and rock texture in saturated cores. The equation reflects how these factors interact to influence wave velocity in fully saturated rock samples, providing a comprehensive understanding of their combined effects.

$$V_p = 5140 + 6.3P_d\left(\text{MPa}\right) - 65n_t\left(\%\right) + c\left(\text{Class}\right) \qquad \text{(Eq-11)}$$

The c value for the different classes of rocks (Eq. 12):

$$L_1 = L_2 = 300,\ L_3 = 180,\ OM_1 = -225,\ OM_2 = 10,\ OM_3 = -377,\ S = -400 \qquad \text{(Eq-12)}$$

For the shear wave velocity, Eq. 13 is derived as follows:

$$V_s = 2640 + 2.65P_d\left(\text{MPa}\right) - 31n_t\left(\%\right) + d\left(\text{Class}\right) \quad \text{(Eq-13)}$$

The d value for the different classes of rocks (Eq. 14):

$$\text{L}_1\text{=L}_2\text{=85, L}_3 = 205\text{, OM}_1\text{=OM}_2\text{=-35, OM}_3\text{=-200, S=-200} \quad \text{(Eq-14)}$$

In the following equations, velocity data are normalized to 65 MPa pressure, and the following relationships between the normalized velocities of compressional and shear waves, the differential pressure and the porosity are derived (Eq. 15-18):

$$\frac{V_p}{V_p\left(65\text{MPa}\right)} = 0.88 + 0.065\ln\left(P_d\right) \quad \text{(Eq-15)}$$

$$\frac{V_s}{V_s\left(65\text{MPa}\right)} = 0.8 + 0.045\ln\left(P_d\right) \quad \text{(Eq-16)}$$

$$\frac{V_p}{V_p\left(65\text{MPa}\right)} = 0.74 + 0.065\ln\left(P_d\right) - 0.1n \quad \text{(Eq-17)}$$

$$\frac{V_s}{V_s\left(65\text{MPa}\right)} = 0.82 + 0.048\ln\left(P_d\right) - 0.2n \quad \text{(Eq-18)}$$

Where P_d is differential pressure and n is porosity.

3.2.2. Evaluation of Porosity Type

Eberli *et al*. [29] demonstrate that the type of porosity significantly influences the velocity of limestone. Their observations indicate that rocks exhibiting microporosity generally present lower velocity values. Importantly, the application of the sandstone porosity-velocity relationship to the analysis of limestones may yield misleading results due to geological processes such as dissolution, dolomitization, and the development of secondary porosity [34]. Consequently, even limestone samples with similar porosity levels can display considerable variations in wave velocities, attributable to differences in pore structure and subsequent wave scattering.

The principal types of porosity include vuggy, intraparticle, intergranular, and fracture porosity:

- Vuggy and Intraparticle Porosity: These types remain stable under normal laboratory pressures.
- Fracture Porosity: Exhibits greater variability; applying pressure causes fractures to close, resulting in decreased porosity.
- Intergranular Porosity: Predominantly found in limestones, does not demonstrate consistent behavior, representing an intermediate state [35].

A simplified classification delineates porosity into soft and rigid pores [36]:

- Soft Pores: Close under normal laboratory pressures.
- Rigid Pores: Remain unchanged.

Numerous methodologies exist to assess the type of porosity, including rock physics models and comparisons of simulation results with simplified models of the three typical porosity types. For this study, two straightforward methods were employed to determine the porosity of the samples:

1. Stiffness or Vuggy Porosity: Determined by the difference between the maximum velocity and the theoretical velocity.
2. Soft Porosity: Indicated by the difference between the maximum and minimum velocities.

In the majority of the analyzed samples, the differential pressure-velocity curve is linear; however, a minority of cores exhibits a horizontal curve. Fig. (**9**) illustrates the relationship between grain and maximum velocities for the three aforementioned porosity types. The fitted curve in Fig. (**9**) demonstrates:

- A steep slope in the initial segment, indicating that the difference between grain and maximum velocities is highly sensitive at low porosities, significantly affecting the porosity type of the samples.
- A moderate slope in the second segment, suggesting medium compressibility of the sample under pressure.
- A relatively flat slope at high porosities (>15%), indicating that the difference between grain and maximum velocities remains relatively constant.

The differential pressure-velocity relationship reveals a wide dispersion of data, underscoring the influence of various parameters and the aspect ratio of the pores. This comprehensive analysis provides a deeper understanding of how different types of porosity affect wave velocities, contributing valuable insights for the characterization and exploitation of carbonate reservoirs.

The relationship of the average of the data is like a form of cubic function as follows:

$$V_{\max} = V_g - 0.19n^3 + 12.14n^2 - 284n \quad \text{(Eq-19)}$$

The following equation is also given for the lower limit of the data (maximum velocity values):

$$V_{\max} = V_g - 75n \quad \text{(Eq-20)}$$

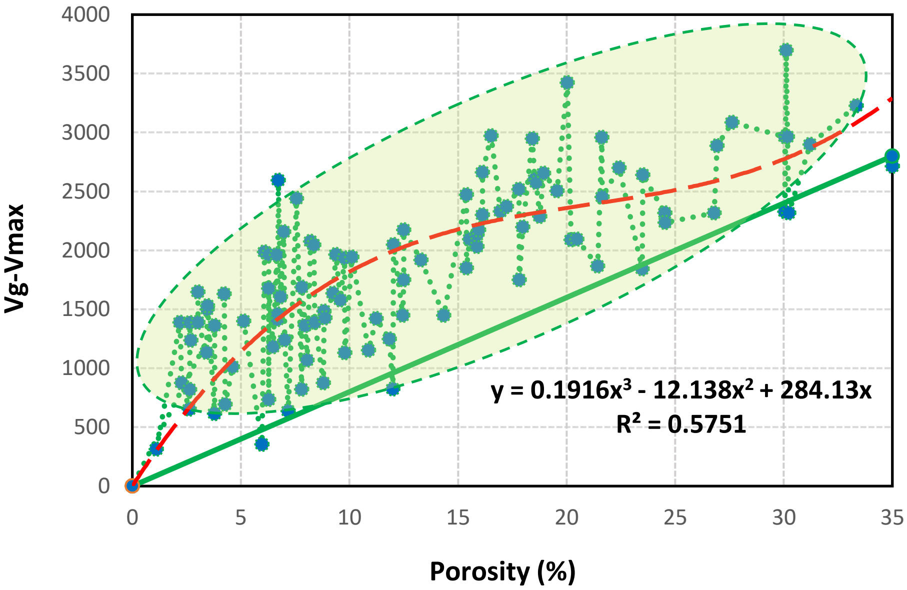

Figure 9: The relationship between grain velocity (Vg) and maximum velocity, as well as the classification of samples based on the difference between these velocities.

For a specific amount of porosity, the compressional and shear wave velocities are as follows (Eq. 21 and 22):

$$V_p(\text{n}) = V_p(\text{grain}) - a * n_t(\%) \quad \text{(Eq-21)}$$

$$V_s(\text{n}) = V_s(\text{grain}) - b * n_t(\%) \quad \text{(Eq-22)}$$

The coefficients a and b are a function of pore shapes and can be obtained from Eq. 23 and 24:

$$a = \left(V_p\left(\mathrm{grain}\right) - V_p\left(\mathrm{n}\right)\right)/n \tag{Eq-23}$$

$$b = \left(V_s\left(\mathrm{grain}\right) - V_s\left(\mathrm{n}\right)\right)/n \tag{Eq-24}$$

3.2.2.1. Theoretical Analysis of Porosity Coefficients

In theory, low values of coefficients 'a' and 'b' indicate the presence of vuggy or stiff porosity, where velocity remains relatively independent of porosity. Conversely, higher values of these coefficients suggest the presence of fracture porosity. As pressure increases, both fracture porosity and intergranular, or "soft," porosity tend to decrease. This behavior is due to the closure of fractures and the compaction of intergranular spaces under pressure.

In practical terms, changes in the ratio of soft to stiff porosity result in an increase in velocity and corresponding variations in the coefficients 'a' and 'b'. This relationship is critical for understanding the seismic response of different porosity types under varying pressure conditions.

Fig. (**10**) illustrates the relationship between compressional wave velocity and coefficient 'a'. The blue line represents values of 'a' associated with stiff porosity, indicating a higher resistance to pressure changes and minimal impact on velocity. In contrast, the brown line indicates larger values related to soft or cracked porosity, which are more susceptible to pressure changes and demonstrate a greater impact on velocity.

The boundary between these two zones was established based on the mean and standard deviation of the observed data. This classification helps differentiate between the effects of stiff and soft porosities on wave velocities. A notable observation from this figure is that the extent of fracture porosity is limited, with stiff porosity occurring more widely. This implies that most of the analyzed samples exhibit characteristics of stiff porosity, making them less sensitive to pressure changes.

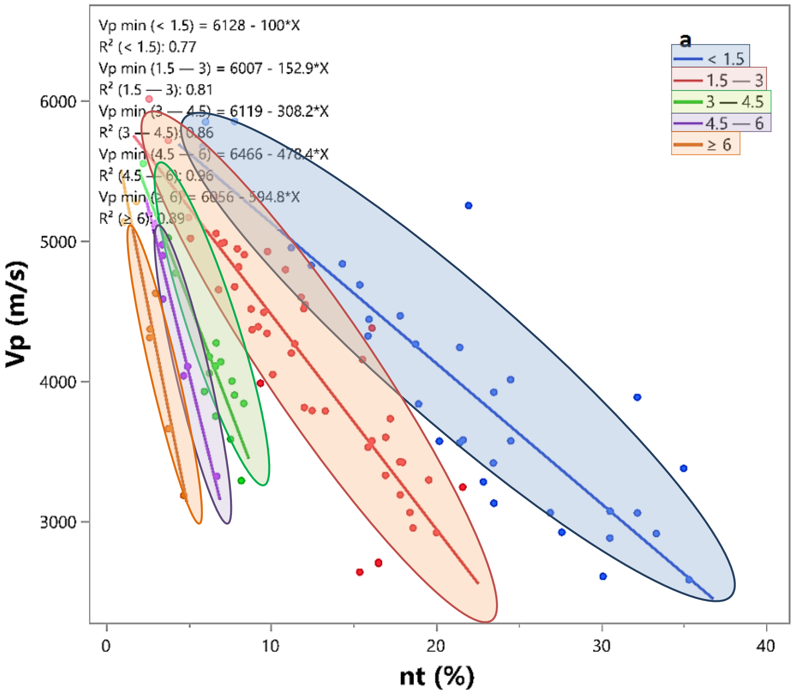

Figure 10: Classification of samples based on coefficient "*a*" while considering the variations in compressional wave velocity as a function of changes in the total porosity of the samples.

Fig. (**11**) further emphasizes this point by showing the distribution of porosity types across the studied samples. The prevalence of stiff porosity suggests that these rocks are more stable and exhibit higher velocities under differential pressure. This insight is crucial for predicting the behavior of carbonate reservoirs during drilling and production activities.

Understanding the interplay between different porosity types and their influence on seismic velocities is essential for accurate reservoir characterization. By leveraging the theoretical and practical relationships of coefficients 'a' and 'b', this study provides a comprehensive framework for assessing the elastic properties of carbonate rocks, thereby aiding in the efficient and effective management of hydrocarbon resources.

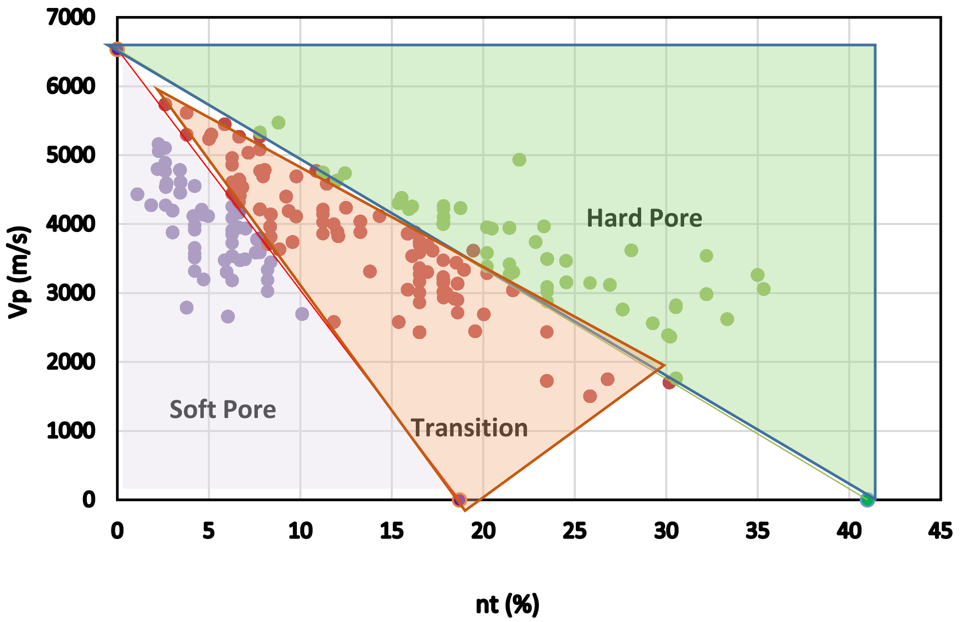

Figure 11: Samples classification based on porosity. The range of changes in the pore type is marked with different colors.

3.2.3. Velocity Ratios

As the pressure increases, the velocity of compressional and shear waves converges to a constant value due to the closure of cracks and small fractures within the rock. Theoretical studies have demonstrated that the ratio between compressional and shear velocities becomes equivalent to the ratio of velocities in a sample without porosity. This convergence is critical for understanding the elastic properties of rocks under high-pressure conditions [37]. Fig. (**12**) illustrates the changes in the velocity ratio of compressional and shear waves relative to the theoretical velocity observed in some of the analyzed samples. The equations used to describe these relationships are as follows:

$$R_{pg} = \frac{V_{pg}}{V_{sg}} 3R_g \qquad \text{(Eq-25)}$$

$$\text{Ratio} = \frac{R_p}{R_{pg}} \qquad \text{(Eq-26)}$$

For most samples at low pressures, the velocity ratio surpasses one. As the differential pressure increases, this ratio tends to approach one, indicating that the rock's behavior becomes more homogeneous and less influenced by microstructural features like cracks and pores. This trend aligns with the theoretical prediction that, at higher pressures, the velocities of compressional and shear waves stabilize as the rock matrix compacts and fractures close (Fig. **12**).

However, there are exceptions to this general trend. In some cases, the velocity ratio initially exceeds one and subsequently approaches one as the pressure continues to rise. This variability can be attributed to the unique microstructural characteristics of each rock sample, such as the distribution and orientation of fractures, the presence of anisotropy, and the degree of cementation.

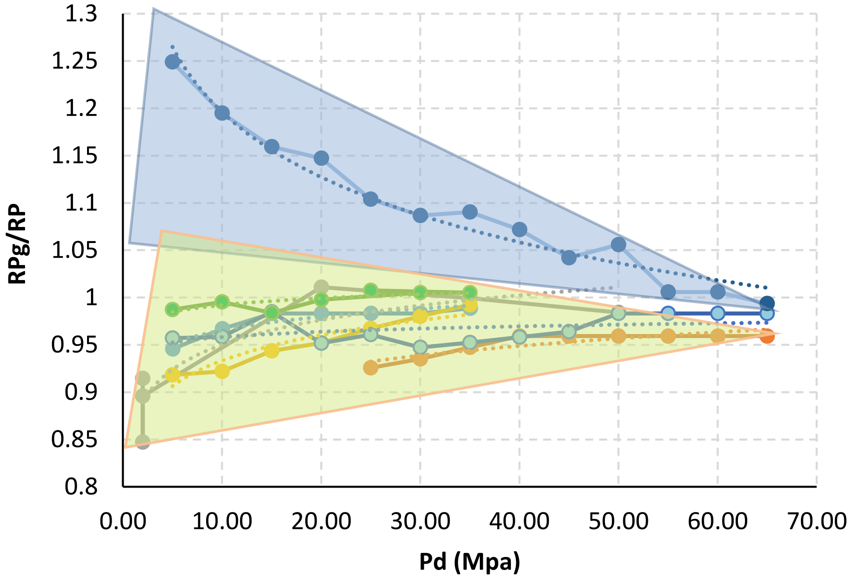

Figure 12: Modifications in the velocity ratio of compressional and shear waves compared to the theoretical velocity.

Understanding these variations is crucial for accurate seismic interpretation and reservoir characterization. By examining the relationship between compressional and shear wave velocities under different pressure conditions, geoscientists can better predict the behavior of subsurface formations [38, 39]. This knowledge aids in the development of more effective drilling and production strategies, ensuring the efficient extraction of hydrocarbons while maintaining the integrity of the reservoir [40]. The detailed analysis provided by this study highlights the importance of considering both theoretical predictions and empirical observations when evaluating the elastic properties of rocks. The insights gained from these findings contribute to a more comprehensive understanding of how pressure influences wave velocities, enhancing our ability to manage and optimize hydrocarbon reservoirs effectively.

4. Conclusion

This study comprehensively examines the effects of various parameters, including mineralogy, density, porosity, temperature, pressure, and structural features, on the elastic properties of carbonate reservoirs through laboratory measurements. The findings highlight several key insights that enhance our understanding of these reservoirs. The study indicates that different minerals exhibit distinct elastic properties. Identifying dominant minerals in carbonate rocks is crucial for understanding their overall elastic behavior. Notably, clay minerals play a significant role, as they can reduce wave velocity by over 3 percent, which is essential for accurate seismic interpretations. The density of carbonate rocks significantly influences their elastic properties. Generally, higher density correlates with increased elastic moduli, such as the bulk modulus and shear modulus. As density rises, both compressional and shear-wave velocities also increase. This relationship underscores the importance of density in predicting wave velocities and rock behavior. Rock density and velocity typically decrease with increasing pressure and temperature, with more pronounced changes occurring at lower pressures and temperatures. However, the study found that the effect of temperature was negligible at the tested levels (20, 60, and 90 °C). Nonetheless, the impact of temperature may become more significant at higher temperatures (>100 °C), suggesting a threshold beyond which thermal effects are more prominent. The rock textures of the samples, including wackestone, mudstone, and packstone, exhibit higher compressional wave velocities compared to dolomite and sandstone. The range of velocity change is broader in packstone, wackestone, and mudstone, respectively. These variations highlight the strong influence of texture on wave propagation and underscore the need for detailed petrographic analysis. As pressure increases, cracks and small fractures in the rock close, causing the velocities of compressional and shear waves to stabilize at a constant value. This behavior emphasizes the role of differential pressure in modulating wave velocities by affecting the rock's microstructure. Theoretical studies have shown that the ratio of compressional to shear velocities in a sample devoid of porosity is equivalent to the same ratio in the studied samples. This consistency provides a robust framework for understanding wave propagation in porous media.

The findings of this study are crucial for improving seismic data interpretation, reservoir characterization, and the development of more effective drilling and production strategies. By integrating the effects of mineralogy, density, porosity, temperature, pressure, and texture, this research offers a comprehensive understanding of the elastic properties of carbonate rocks. These insights aid in the efficient and sustainable exploitation of hydrocarbon resources, ensuring that reservoir management practices are both effective and environmentally responsible.

Abbreviations

a	Coefficient indicating stiff porosity	*(Unitless quantity)*
b	Coefficient indicating soft porosity	*(Unitless quantity)*
c	Constant (specific to an equation)	*(Various)*
μ	Shear modulus	*(Pa)*
ρ	Density	*(kg/m^3)*
σ	Stress	*(Pa)*
φ	Porosity	*(Unitless quantity)*
n_t	Total porosity	*(Unitless quantity)*
P_d	Differential pressure	*(Pa)*
V_g	Grain velocity	*(m/s)*
V_p	Compressional wave velocity	*(m/s)*
V_s	Shear wave velocity	*(m/s)*
Y_d	Grain density	*(kg/m^3)*

Conflict of Interest

The authors hereby declare that they have no significant financial or nonfinancial interests to disclose. Additionally, there are no competing interests that could be perceived as influencing the content of this article.

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