



## ***Integrating Ultrasonic Velocity Measurements and Attenuation Behavior with Pore Aspect Ratio Distribution for Heterogeneity Characterizing in Grain Dominated Carbonate Facies***

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### **Keywords**

Ultrasonic measurements, Texture Heterogeneity, Aspect Ratio, Fast Fourier Transform, Attenuation Coefficient.

### **Abstract**

This study emphasizes the significance of accurately estimating dry rock elastic properties, which is crucial for reservoir fluid flow and storage feasibility assessments in carbonate rocks. However, accurately estimating these properties, especially in carbonates prone to dissolution and reprecipitation during reservoir production cycles, is challenging. Core samples and well logs are typically used to estimate dry rock properties, but uncertainties in log quality and inversion processes make laboratory measurements on core samples more reliable. The research highlights the importance of textural variation for categorizing carbonate formations into homogeneous, intermediate, and heterogeneous facie classes. Utilizing ultrasonic measurements for compressive and shear wave velocity, this study reveals how morphological changes due to texture alterations significantly impact measured and calculated values of velocity, dominant frequencies, and seismic rock property attenuation. The observed ultrasonic P- and S-wave velocities range from 2.62 to 5 km/s and 1.9 to 2.91 km/s, respectively. Dominant frequencies vary between 0.25 MHz to 0.75 MHz, while attenuations ( $1/QP$ ) exhibit values ranging from 0.6 to 0.05, illustrating pronounced differences as formations move from a heterogeneous to a homogeneous facie class. These findings provide valuable insights into understanding the influence of dry rock strength on modeling saturated seismic rock properties for feasibility investigations.

### **Introduction**

The acoustic properties of rocks are vital for geological and engineering purposes, aiding in subsurface reservoir characterization and rock strength assessment (Kleipool et al., 2015). Ultrasonic travel time measurements enable the determination of crucial parameters such as compressional wave velocity, density, and elastic moduli (Prasad, 2002). However, porosity impacts both compressional and shear wave velocities and ultrasonic wave attenuation, adding complexity to the relationship between ultrasonic velocity and porosity (Xu & Payne, 2009). Petrophysical and geomechanical properties of dry rock strength typically decline with increasing porosity. However, this trend is more complex for carbonate rocks due to inherent heterogeneity at all depths and scales (Sharma et al., 2013). Abdelhedi et al. (2017) emphasized that porosity distribution significantly influences ultrasonic velocity response in rocks. Ultrasonic techniques, proven non-destructive and user-friendly in field and laboratory settings, are instrumental in rock engineering studies (Ro et al., 2004). Ultrasonic laboratory measurements have been crucial in characterizing rocks' anisotropy and fracture characteristics (Vernik et al.; M., 2010). Integrating ultrasonic velocity measurements into rock physics models facilitates the estimation of reservoir properties and enhances the understanding of subsurface formations. Besides porosity distribution heterogeneity, this study explores the impact of aspect ratio distribution on carbonate rocks'

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ultrasonic wave velocity. This combined effect underscores the need to determine dry rock petrophysical properties and strength carefully (Xu & Payne, 2009).

A set of nine carbonate core samples from nine different boreholes in the Indian western offshore basin were picked for this work. The age of the carbonate samples varied from the Middle Eocene to the Early Oligocene and were taken from carbonate platforms offshore of western India (Sharma et al., 2006). The samples were carefully picked to represent the textural variation of the pre-defined homogeneous, intermediate, and heterogeneous facie class categories. We then selected three samples of 8%, 12%, and 19% porosity in the abovementioned facie classes. An example of each category is shown in Fig 1. The samples were subjected to dry ultrasonic measurements, and the acoustic waveform signatures were captured.



Figure 1: Homogeneous, intermediate, and heterogeneous samples.

The waveform data was subjected to a Fast Fourier Transform (FFT) analysis to produce frequency spectra, enabling the quantification of the compressive-wave velocity attenuation. The estimated attenuation coefficients were correlated against the samples' porosity and aspect ratio distribution. The strength of the dry rock without the influence of the pore fluid has many direct applications in identifying and quantifying seismic engineering properties, the structural integrity of the structure, and the interpretation of geophysical data. Future research into different rock types and porosity distributions may benefit from the methods utilized in this work.

**Theory**

**Porosity and Aspect Ratio**

Porosity was assessed through a comprehensive formula, focusing on the dominant mineral calcite, given that our carbonate sample predominantly

consists of this mineral. The procedure employed to estimate porosity was based on a generalized approach, utilizing the following expression:

$$\emptyset = (2.71 - \text{Bulk density of the sample}) / 2.71$$

High-resolution FESEM (Field Emission Scanning Electron Microscopy) images were analyzed to determine the dominant pore sizes aspect ratio. Fig. 2 displays representative images. Morphological segmentation techniques were applied to these images at various resolutions, and a MATLAB code was used to determine the aspect ratio of dominant pore sizes accurately. This approach facilitated adequate characterization and quantification of the pore network's geometrical properties. Table 1 summarizes aspect ratio variations with carbonate sample porosity.

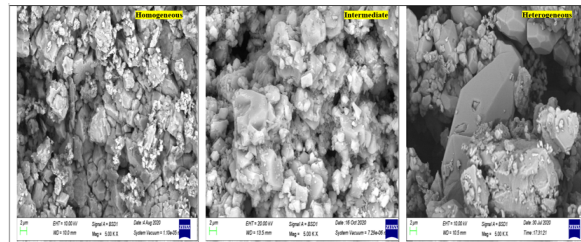


Figure 2: Representative FESEM images of each category used for determining the aspect ratio.

Sample ID	Porosity (%)	Aspect Ratio
I-14 (HOMOGENEOUS)	8	0.1341
I-28 (HOMOGENEOUS)	12	0.1529
I-45 (HOMOGENEOUS)	19	0.1314
I-23 (INTERMEDIATE)	8	0.148
I-17 (INTERMEDIATE)	12	0.0846
I-50 (INTERMEDIATE)	19	0.1362
I-40 (HETEROGENEOUS)	8	0.1021
I-42(a) (HETEROGENEOUS)	12	0.1409
I-24 (HETEROGENEOUS)	19	0.1212

Table 1: Aspect ratio vs porosity

**Ultrasonic Benchtop Measurement**

Ultrasonic transducers used in this study were composed of piezoelectric crystals embedded in an aluminum housing with appropriate backing material. Calibration was performed using aluminum plugs of matching length to the core, confirming accurate compressive and shear wave velocity measurements

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aligned well with literature values. The transducer generated a source pulse spanning 0.1MHz to 15MHz. The setup included a transmitter and receiver positioned on opposite faces of a cylindrical rock core sample, as depicted in Fig. 3.

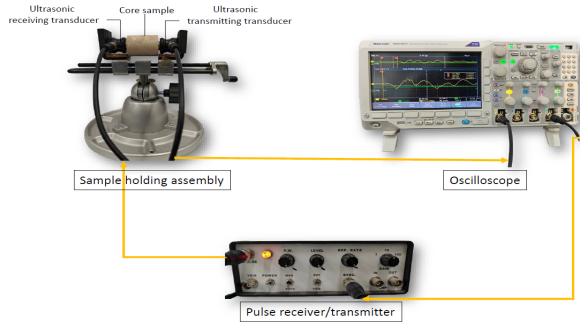


Figure 3: Ultrasonic Benchtop setup

### Attenuation Calculation

Seismic wave attenuation in rocks is influenced by physical state, lithology, porosity, pore size distribution, saturation, fluid viscosity, and permeability (Toksöz et al., 1979). Two primary processes contribute to measured attenuation: inherent absorption from energy conversion to heat and scattering or reflection from pores (O'Doherty et al., 1971). Attenuation mechanisms encompass frictional dissipation across grain boundaries, cracks, and relative motion between solids and liquids (Biot, 1956a, 1956b). To estimate attenuation, we compared recorded waveforms in the rock sample to a reference sample (aluminum) using a similar setup and acquisition parameters (sample length  $\approx$  5cm, diameter  $\approx$  3.81cm).

The amplitudes of plane seismic waves in both the reference and the rock sample can be represented by the following expressions: -

$$\begin{aligned} A_1(f) &= G_1(x)e^{-\alpha_1(f)x}e^{i(2\pi ft - k_1 x)} && \text{Aluminum Sample} \\ A_2(f) &= G_2(x)e^{-\alpha_2(f)x}e^{i(2\pi ft - k_2 x)} && \text{Rock Sample} \end{aligned}$$

where,  $A$ =amplitude,  $f$ =frequency,  $x$ =distance,  $k=2\pi f/v$ =wavenumber,  $v$ =velocity,  $G(x)$ =geometrical factor which includes the spreading reflection coefficient. The attenuation coefficient,  $\alpha(f)$ , is frequency dependent and is related to frequency by the expression,  $\alpha(f)=\gamma f$ , where  $\gamma$  is constant. The value of  $\gamma$  is obtained from the slope of the graph  $\ln(A_1/A_2)$  vs frequency. Furthermore,  $\gamma$  is related to

the quality factor ( $Q$ ) through the equation  $Q=\pi/(\gamma v)$ . The attenuation is then calculated by taking the inverse of the quality factor ( $Q$ ).

### Methodology

The methodology adopted in this study is shown with the help of a flowchart in the Fig.4

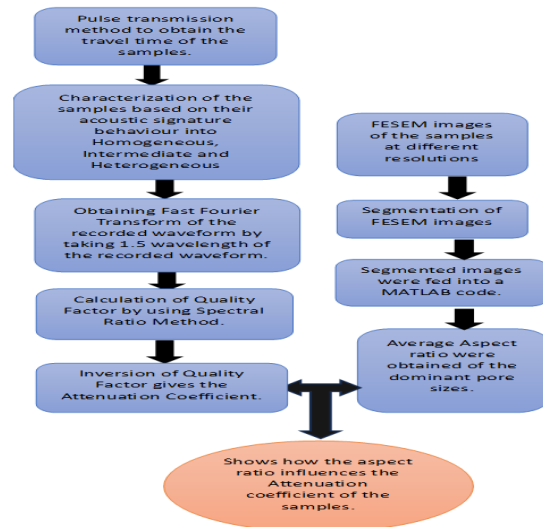


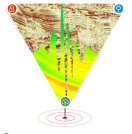
Figure 4: Flowchart of the methodology adopted.

### Results and Discussions

This study subjected nine carbonate rock samples with 8%, 12%, and 19% porosities to dry ultrasonic measurements to identify their acoustic signatures. These carbonate samples range in age from the Middle Eocene to the Early Oligocene and were taken from carbonate platforms offshore of western India (Sharma et al., 2006).

### Acoustic Classification of Samples

The ultrasonic waveform acquired in the three facie classes are presented in Figure 5a. The first break arrival times correlate with low porosity and high dry frame strength, while waveform sharpness diminishes with increasing textural heterogeneity (heterogeneous > intermediate > homogeneous). This trend is similarly observed in the shear-waveform analysis (Figure 5b and 5c). Unlike the heterogeneous and intermediate samples, shear wave travel time remains



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consistent for both 0° and 90° polarizations, confirming substance homogeneity.

for comprehending its impact on seismic rock properties.

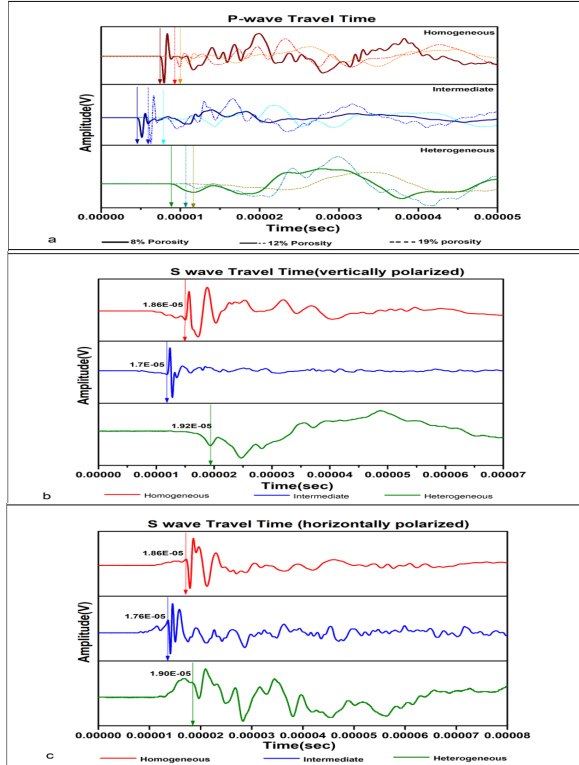


Figure 5: The acoustic signature characterizing the carbonate samples textural heterogeneities. a,b, and c depicting the compressional and shear waves (both horizontally and vertically polarized)

Other variations in acoustic behavior can be mapped through elastic property variation attributed to the inherent differences in the carbonate samples' porosity pore aspect ratio distribution. Fig. 6 shows a plot of bulk modulus against porosity for the three facie classes. Heterogeneous samples consistently exhibit lower modulus values than homogeneous ones, affirming texture's impact on bulk modulus reduction due to wave energy scattering and property attenuation. The bulk modulus for intermediate-class samples often falls between homogeneous and heterogeneous values, challenging the defined boundaries. On a bulk scale, bulk modulus dependence on porosity is nearly linear for homogeneous samples, somewhat nonlinear for heterogeneous samples, and almost logarithmic for intermediate samples. Understanding and characterizing this intermediate facie class is crucial

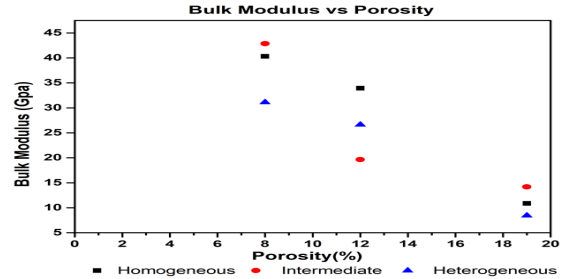


Figure 6: Bulk Modulus vs Porosity plot of the nine carbonate samples.

**Seismic Amplitude Attenuation Analysis**

We utilized the Fourier Transform to analyze data in the frequency domain and plotted amplitude spectra for compressional waveforms of reference aluminum and sample waveforms (Fig. 7). The same vertical scale was employed for amplitude representation across all porosities in the three classes. Dominant frequencies for reference aluminum and the three pre-determined carbonate facie classes were recorded. Notably, the dominant frequency envelope in the three pre-identified classes shifted to lower frequencies with increasing heterogeneity, indicating heightened frequency attenuation with increased heterogeneity. Additionally, the figure illustrates that increasing porosity leads to reduced waveform amplitudes within well-defined facies.

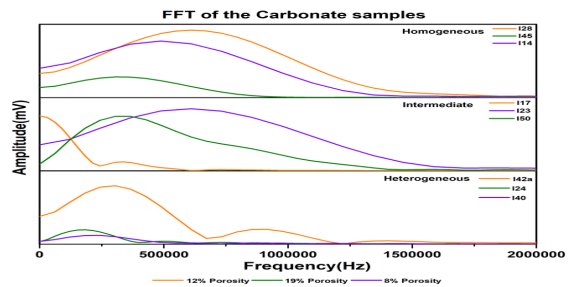
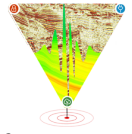


Figure 7: Fast Fourier Transform of the samples. The same color represents the same porosity.

Attenuation coefficients provide crucial insights into the samples' energy loss and damping properties, shedding light on changing rock properties, fluid behavior, and wave interaction with internal morphology. In Fig. 8, attenuation coefficients were



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calculated for the three facie classes across varying porosities. A MATLAB code was employed for amplitude-dependent attenuation computation. Like ultrasonic waveform amplitudes in Fig. 7, homogeneous and heterogeneous samples exhibited the expected behavior, with attenuation coefficients increasing with heterogeneity for each porosity value. However, the intermediate sample showed varying attenuation coefficient values across the scale, emphasizing that misinterpretation of seismic rock properties can occur without understanding the nature of heterogeneity.

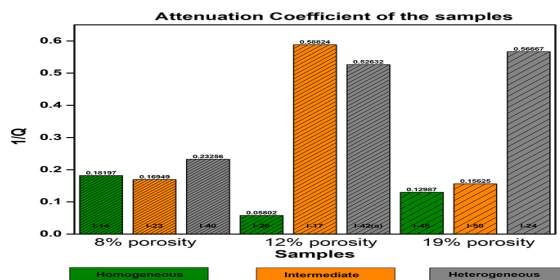


Figure 8: Attenuation coefficient of the samples. The same color indicates the same porosity.

### Aspect Ratio Estimation and Analysis

Characterizing facies behavior in carbonates using ultrasonic travel times and amplitudes has limitations, particularly without considering the dominant aspect ratio in the facies. Digital rock analysis on FESEM images was conducted at multiple resolutions, and a MATLAB code was used to determine the aspect ratio of the dominant pore size, ranging from 0.10 to 0.16 (Fig. 9). Analysis of predominant pore sizes aspect ratios revealed a decrease in attenuation coefficient with increasing aspect ratio. Elongated and rounded pores offered less resistance to acoustic wave passage than angular or fractured pores. Samples with intercrystalline or interparticle porosity and larger aspect ratios (0.10 to 0.16) exhibited favorable pore geometry for effective wave transmission, Xu and Payne (2009), except for sample I17 with fractures, resulting in higher attenuation. Aspect ratio is a crucial parameter for synthesizing rock physics models, considering its role in anisotropy, seismic wave propagation, fluid flow, mechanical behavior, and providing insights into rock texture and fabric.

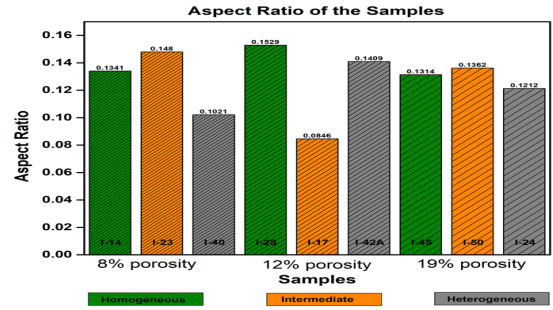


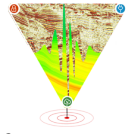
Figure 9: Aspect ratio of dominant pore size of the samples. The same color indicates the same porosity.

### Discrepancies Between Ultrasonic and Sonic Log Measurements

Established literature acknowledges the higher ultrasonic Vp and Vs values than sonic logs. This difference is due to the frequency variance of around 1MHz for the ultrasonic lab and approximately 20 kHz for the sonic log. Horsrud (2001), Fjaer et al. (2008), and Birch (1960) also highlighted downhole conditions like pressure and temperature as contributing factors. Table 1 presents the variations between ultrasonic Vp and sonic log measurements, confirming higher ultrasonic lab Vp except for two samples due to clay minerals (kaolinite). A clear trend emerges from comparing these two datasets: homogeneous samples show a 14.6% variation in Vp values between the two datasets, followed by the intermediate samples, which indicate a lesser but still significant deviation of 12.6%, further followed by a 9.6% variation in Vp between the two datasets for the heterogeneous samples. These findings provide critical insights into seismic wave behavior and fundamental inputs for rock physics models, emphasizing the profound influence of geological composition.

Samples	Vp(km/s) (Ultrasonic measurement)	Vp(km/s) (Log measurement)	Changes (%)
I-14	4.72	3.9	-3.5
I-28	5.54	4.2	17.4
I-45	3.95	4.09	24.1
I-17	4.58	4.04	11.8
I-23	5.67	4.88	13.9
I-50	3.88	3.3	14.9
I-24	3.45	3.21	6.9
I-40	5.33	4.15	17.1
I-42A	5.01	5.7	-6.9

Table 2: Showing variation of P-wave at ultrasonic and wire-line log frequencies.



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**Conclusions**

The complex morphology of carbonate rocks emphasizes the need to integrate acoustic measurements, calculated velocity, attenuation, bulk porosity, and pore-scale characterization for a well-constrained interpretation of physical properties.

Dry rock properties importance is undeniable in rock physics feasibility investigations, necessitating reliable estimation for exploration and development projects.

The shear waveform effectively reflects variations in fabric morphology, including mineral composition, distribution, grain arrangement, and aspect ratio, discernible through wave amplitudes.

Segregating carbonate formations into homogeneous, intermediate, and heterogeneous facie types through integrated interpretation highlights the importance of developing this understanding at the field scale using rock physics models. This integration aids proper facie type identification and comprehension of their response to measured properties.

Results emphasize the role of pore connection, homogeneity, and aspect ratio in wave transmission and energy loss within samples. Dominant frequencies, attenuation coefficients, and velocity fluctuations interact, confirming correlations found in the study. Angular or fractured pores hinder wave propagation, while intercrystalline or interparticle porosity with rounded and elongated pores enhances acoustic behavior.

Various factors, including frequency, pressure, temperature, subsurface characteristics, and drilling-related issues, influence P-wave velocity discrepancies between sonic logs and lab (ultrasonic) values. Integrating these measurements enhances understanding of subsurface formations, aiding reservoir characterization and associated decision-making.

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