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Amplitude Versus Frequency (AVF) as an Alternative Method for Detecting Gas Presence in Carbonate Reservoirs: A Case Study of the Baturaja Formation, South Sumatra Basin

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ABSTRACT - Accurate characterization of heterogeneous carbonate reservoirs remains challenging because conventional amplitude-based seismic methods may be affected by complex lithology, pore systems, and fractures. This study evaluates the application of Amplitude Versus Frequency (AVF) integrated with Continuous Wavelet Transform (CWT) to identify hydrocarbon-bearing zones in the Baturaja Formation, South Sumatra Basin. The analysis uses 3D Post Stack Time Migration (PSTM) seismic data integrated with well-log, checkshot, and marker data from three wells (B1, N1, and N2). Well-to-seismic tie analysis yielded correlation coefficients of 0.702, 0.638, and 0.805, respectively, confirming reliable seismic–well integration. CWT spectral decomposition was performed over a frequency range of 10–70 Hz, followed by AVF analysis to evaluate frequency-dependent amplitude attenuation. The results show dominant low-frequency anomalies and predominantly negative AVF gradients within the target interval, indicating attenuation of high-frequency seismic energy. These responses are consistent with low water saturation and low gamma-ray values observed in the wells, supporting their interpretation as gas-bearing carbonate reservoir zones. AVF horizon slicing further reveals laterally continuous anomalies concentrated in the eastern to northeastern part of the study area. The results demonstrate that CWT-based AVF provides complementary frequency-dependent information for hydrocarbon identification and reservoir delineation, offering a useful approach for reducing interpretation uncertainty in heterogeneous carbonate reservoirs. To the best of the authors' knowledge, its application to the Baturaja Formation remains limited, highlighting the contribution of this study to frequency-based carbonate reservoir characterization.

Keywords: Amplitude Versus Frequency (AVF), Continuous Wavelet Transform (CWT), reservoir characterization, hydrocarbon identification, Baturaja Formation, South Sumatra Basin.

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1. Introduction

Oil and gas exploration relies on accurate reservoir characterization to identify hydrocarbon accumulations and evaluate reservoir potential. Reservoir characterization involves understanding petrophysical properties, lithological distribution, and structural conditions, all of which are critical for reducing uncertainties in reserve estimation and exploration decision-making (Mineral 2022).

Seismic reflection methods are widely used for subsurface imaging and reservoir interpretation. However, conventional seismic analysis often faces challenges in distinguishing hydrocarbon-bearing reservoirs from non-productive zones, particularly in thin-layered or highly heterogeneous formations. Although Amplitude Versus Offset (AVO) analysis has been extensively applied to identify hydrocarbon indicators, its interpretation may be affected by lithological variations, data quality, and its dependence on high-quality pre-stack seismic data (Wu et al., 2014). Recent studies have demonstrated that AVO remains effective for hydrocarbon prediction in carbonate reservoirs when integrated with additional seismic analyses. (Hong Li et al., 2024) demonstrated that incorporating seismic dispersion into AVO inversion significantly improved hydrocarbon prediction in deep carbonate reservoirs. Likewise, (Hong Li et al., 2024) reported that rock-physics calibration is essential for reliable AVO interpretation because carbonate elastic responses are strongly influenced by pore types and diagenetic processes. Furthermore, (Setyawan 2021) showed that AVO inversion successfully delineated hydrocarbon-bearing carbonate intervals using Lambda-Rho and Mu-Rho attributes when supported by well-log calibration. These studies indicate that AVO can provide valuable fluid and lithology information in carbonate reservoirs; however, its reliability depends strongly on appropriate rock-physics calibration and the availability of high-quality pre-stack data. Despite these advances, AVO interpretation in carbonate reservoirs remains uncertain because carbonate rocks exhibit highly heterogeneous lithology, complex pore systems, fractures, and vugs, causing seismic responses that may deviate from conventional AVO classifications (Rutherford & Williams 1989). Consequently, hydrocarbon-bearing and water-bearing carbonate intervals may exhibit overlapping AVO responses, highlighting the need for complementary seismic attributes that provide information beyond angle-dependent amplitude variations.

To overcome the limitations of conventional amplitude-based interpretation, frequency-dependent seismic analysis has increasingly been used to investigate attenuation effects and subtle reservoir responses. Spectral decomposition provides a means of separating seismic data into individual frequency components, enabling frequency-dependent variations that may be obscured in broadband seismic data to be identified (Partyka et al., 1999). Among the available approaches, Continuous Wavelet Transform (CWT) is particularly useful because its variable time–frequency resolution allows localized spectral anomalies to be analyzed while preserving their temporal position (Sinha et al., 2005). Previous applications have demonstrated that CWT-based spectral decomposition can improve the delineation of stratigraphic features and hydrocarbon-related anomalies. For example, Mandong et al. (2021) applied CWT-derived frequency gathers and Amplitude Variation with Frequency (AVF) to delineate hydrocarbon-bearing zones, with the resulting AVF anomalies showing consistency with AVO responses and water-saturation logs. More recent applications have also demonstrated the ability of spectral decomposition to resolve subtle reservoir features, including hydrocarbon-bearing intervals and stratigraphic baffles that are difficult to identify using conventional seismic attributes alone (Durogbitan et al., 2023). However, these studies primarily demonstrate the value of spectral decomposition for identifying frequency-dependent seismic responses and improving qualitative reservoir delineation. The quantitative relationship between seismic amplitude and frequency, particularly its use for evaluating frequency-dependent attenuation, remains less extensively investigated in heterogeneous carbonate reservoirs.

This distinction is important because frequency variations in carbonate reservoirs may arise from multiple geological and seismic factors, including complex pore systems, fractures, vugs, lithological variations, diagenetic alteration, tuning effects, and intrinsic attenuation. Therefore, frequency anomalies observed in carbonate reservoirs should not be interpreted solely from spectral amplitude patterns, but should be evaluated through their amplitude–frequency relationship and supported by independent geological and petrophysical evidence. Although AVF has been demonstrated as a complementary hydrocarbon indicator (Mandong et al., 2021), the application of AVF to heterogeneous carbonate reservoirs remains relatively limited compared with its broader use for

frequency-based seismic interpretation. In addition, CWT-based spectral decomposition in carbonate settings has commonly been applied to delineate reservoir geometry and frequency anomalies, whereas the quantitative integration of CWT-derived frequency components with AVF parameters and well-derived petrophysical information remains insufficiently documented. This represents the principal research gap addressed in this study whether the integration of CWT-based spectral decomposition and AVF can provide a consistent frequency-dependent indicator for hydrocarbon identification in a heterogeneous carbonate reservoir and how the resulting seismic response can be constrained using petrophysical properties.

The South Sumatra Basin is one of Indonesia's major hydrocarbon-producing basins and contains a complex petroleum system. One of its primary reservoir units is the Baturaja Formation, an Oligocene–Miocene carbonate reservoir characterized by significant heterogeneity resulting from depositional and diagenetic processes (Satyana 2008). Previous studies have reported that the Baturaja Formation exhibits variable reservoir characteristics, reflecting the complex nature of carbonate reservoirs in the region (Widarsono, 2022). Such heterogeneity makes the Baturaja Formation an appropriate geological setting for evaluating complementary frequency-domain approaches, particularly where conventional seismic responses may be ambiguous. The complex reservoir characteristics of the Baturaja Formation create challenges in reservoir delineation and hydrocarbon identification using conventional seismic interpretation methods (Waples 2000).

Therefore, this study applies the Amplitude Versus Frequency (AVF) method using Continuous Wavelet Transform (CWT) to characterize reservoirs and identify prospective hydrocarbon zones within the Baturaja Formation of the South Sumatra Basin. The scientific novelty of this study lies in the application and integration of CWT-based spectral decomposition and quantitative AVF analysis to evaluate frequency-dependent amplitude attenuation within the Baturaja carbonate reservoir of the South Sumatra Basin. Unlike previous studies that primarily employ spectral decomposition for qualitative frequency mapping or apply AVF in other geological settings, this study combines CWT-derived frequency volumes, AVF intercept and gradient analysis, and well-derived petrophysical information to constrain the interpretation of potential hydrocarbon-related attenuation. To the best of the authors' knowledge, this represents a previously undocumented application of a CWT-based AVF workflow for hydrocarbon-oriented characterization of the Baturaja Formation in the South Sumatra Basin. The results are expected to improve reservoir characterization, delineate potential hydrocarbon-bearing intervals, and provide further insight into the applicability of frequency-dependent seismic attributes for reducing interpretation uncertainty in heterogeneous carbonate reservoirs.

2. Methodology

This study applies the Amplitude Versus Frequency (AVF) method for reservoir characterization in the Baturaja Formation, South Sumatra Basin. The dataset consists of 3D Post Stack Time Migration (PSTM) seismic data covering inline numbers 2326–2610 and crossline numbers 10201–10420. In addition to seismic data, well data including wireline logs, checkshot surveys, and horizon markers from three wells (B1, N1, and N2) were utilized. The study area is located within the South Sumatra Basin, one of Indonesia's most productive hydrocarbon basins with a complex petroleum system. The regional geological map and the base map showing the locations of seismic lines and wells are presented in Figures 1 and Figures 2, respectively.

The data processing workflow began with a well tie procedure, which integrated well logs, horizon markers, and checkshot data with the seismic dataset. This process converted geological information from the depth domain into the time domain through synthetic seismogram generation, allowing accurate correlation between well markers and seismic reflectors (Yilmaz 2001). Well tie analysis is an essential step in seismic interpretation because it minimizes uncertainty in horizon picking and improves the reliability of reservoir mapping by ensuring consistency between borehole measurements and seismic responses (Sheriff & Geldart 1995).

2.1 Continuous wavelet transform (CWT)

Following the well tie process, spectral decomposition was performed using the Continuous Wavelet Transform (CWT) with a complex Ricker wavelet to obtain a high-resolution time–frequency representation of

the seismic signal. Unlike the Short-Time Fourier Transform (STFT), which applies a fixed window length and therefore provides constant time-frequency resolution, CWT employs scalable wavelets that allow adaptive resolution across different frequencies (Sinha et al., 2005). Consequently, CWT is particularly suitable for detecting thin beds, stratigraphic discontinuities, and hydrocarbon-related attenuation because it preserves both temporal and spectral information (Partyka et al., 1999). The Continuous Wavelet Transform of a seismic trace $x(t)$ is mathematically expressed as in Equation 1

$$W(a, b) = \int_{-\infty}^{\infty} s(t) \psi^*(at - b) dt \quad (1)$$

where $W(a, b)$, a , b , $\psi(t)$, and ψ^* , are wavelet coefficient, scale parameter related to frequency, translation parameter in time, mother wavelet and complex conjugate of the mother wavelet, respectively. The scale parameter is inversely proportional to frequency, allowing low-frequency components to be represented with higher frequency resolution while preserving high temporal resolution for high-frequency events (Stéphane Mallat 2009).

In this study, frequency extraction was carried out over a range of 10 to 70 Hz at 5-Hz intervals, resulting in 13 iso-frequency volumes. The 10–70 Hz frequency range was selected to encompass the effective and reliable bandwidth of the seismic data, while avoiding frequencies outside the dominant energy range that may contain limited signal energy or be more strongly affected by noise and attenuation. This frequency range therefore provides a suitable basis for capturing the frequency-dependent variation of seismic amplitude within the target reservoir interval. The extracted frequency volumes were subsequently combined through a gathering process, in which the frequency values were sequentially assigned to an analogous incident-angle parameter. This procedure enabled the implementation of AVF analysis by treating frequency as an equivalent variable to reflection angle, allowing the variation of seismic amplitude with frequency to be quantified through the AVF intercept and gradient.

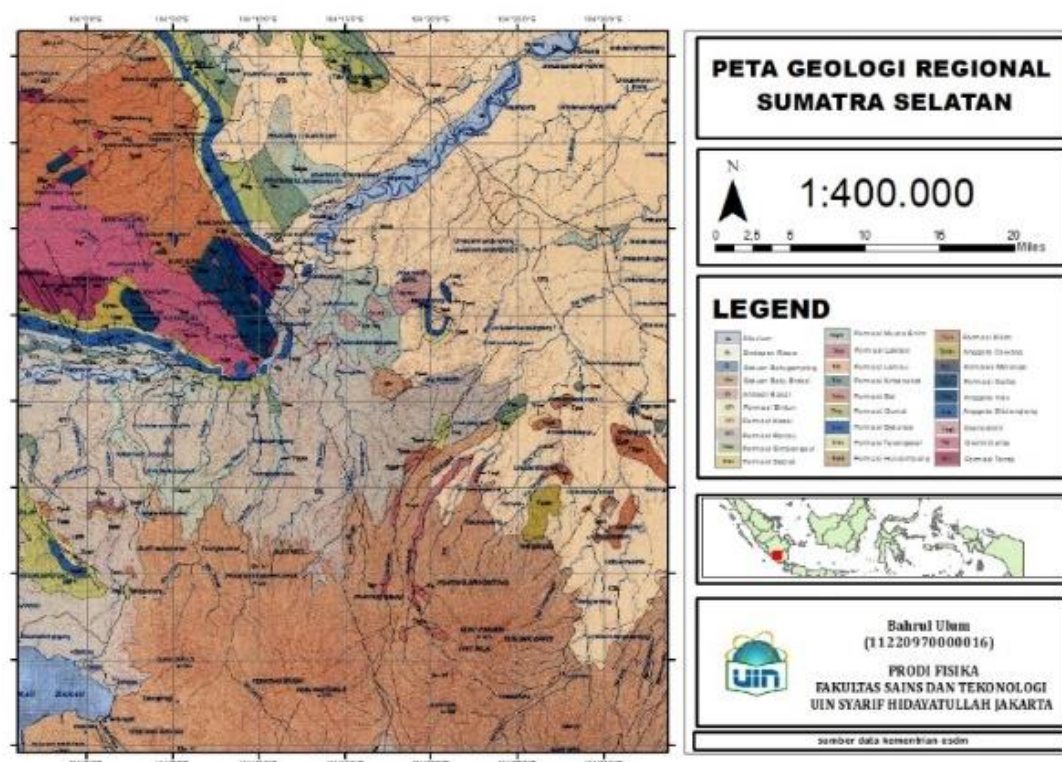


Figure 1.
Regional geological map.

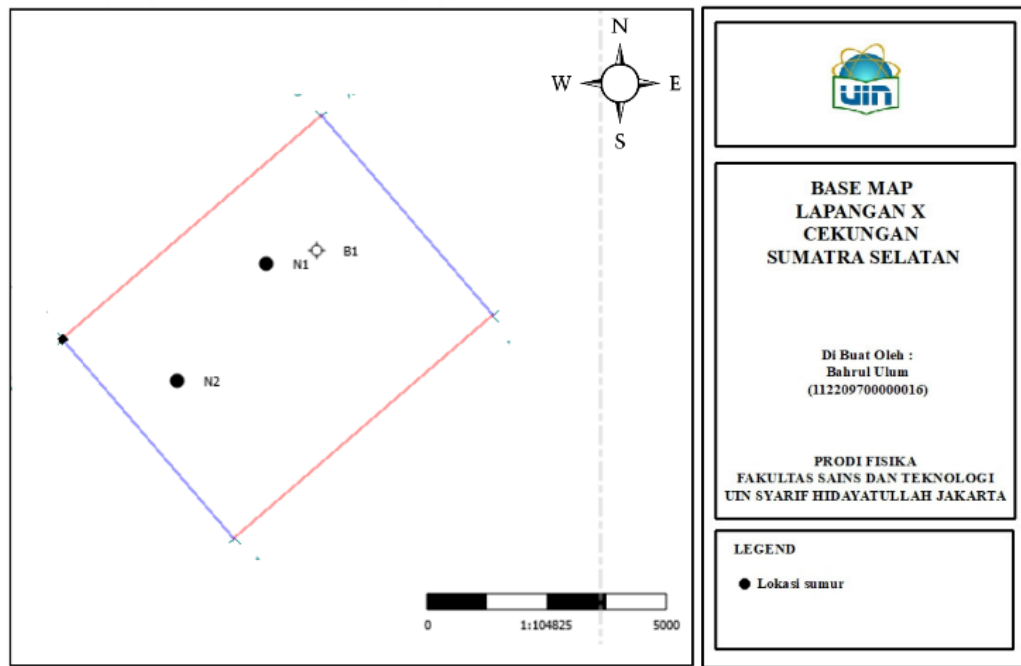


Figure 2.

Base map of the research area in the South Sumatra Basin showing the 3D seismic survey boundary, seismic inline–crossline grid, and the locations of wells B1, N1 and N2 used in the AVF reservoir characterization study.

2.2 Amplitude versus frequency (AVF)

The AVF method employed in this study consists of two main stages. The first stage involves the generation of frequency-dependent seismic amplitude information through spectral decomposition using the Continuous Wavelet Transform (CWT). The CWT decomposes the seismic signal into its constituent frequency components while preserving their temporal information, thereby enabling the amplitude response to be examined at different frequencies and time samples. The resulting frequency gather is presented in Figure 3, where each subfigure represents the time-frequency distribution of an individual seismic trace, with frequency displayed along the x-axis and time along the y-axis. This decomposition provides detailed information on the variation of seismic amplitude across the frequency spectrum and forms the basis for the subsequent AVF analysis.

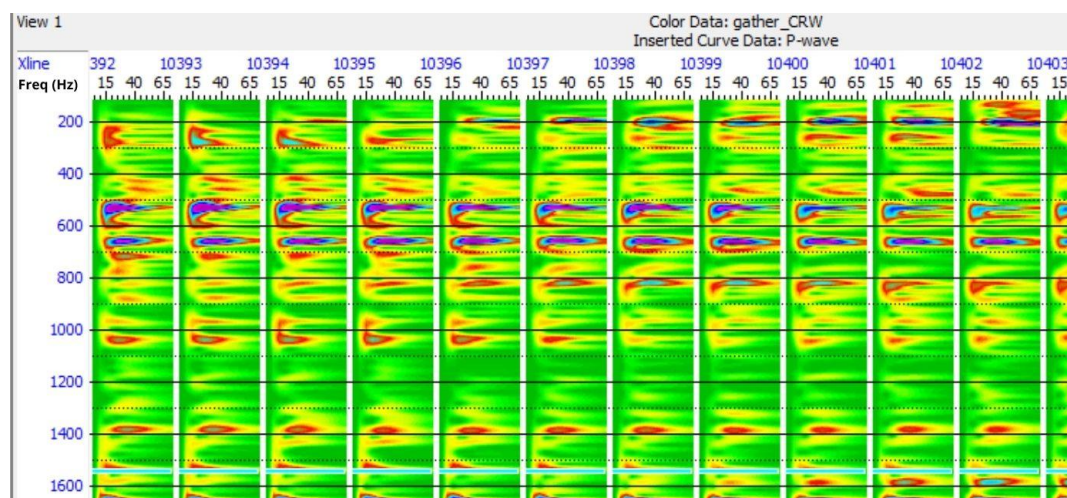


Figure 3.

Frequency gathering form the continues wavelet transform.

In the second stage, the amplitude response obtained from the CWT-derived frequency components is evaluated as a function of frequency at each seismic time sample. In this study, the relationship between seismic amplitude and frequency is approximated using a linear formulation rather than the squared sine function of frequency adopted in previous AVF studies, such as (Mandong et al.2021) and (Wihardy & Khairy 2021) The linear relationship is expressed as in Equation 2

$$y = I + G \sin^2(x) \quad (2)$$

The selection of the frequency range is an important parameter in determining the reliability of the AVF response. As illustrated in Figure 4, (f_1) and (f_2) represent the lower and upper frequency limits used in the linear fitting process. In this study, the dominant frequency identified from the spectral decomposition is used as a reference for defining the lower frequency limit, while the upper frequency limit is selected based on the characteristics and usable range of the amplitude spectrum. This approach ensures that the fitting process is performed within a frequency interval that provides a representative amplitude response while minimizing the influence of poorly resolved or insignificant frequency components (Han & others 2023).

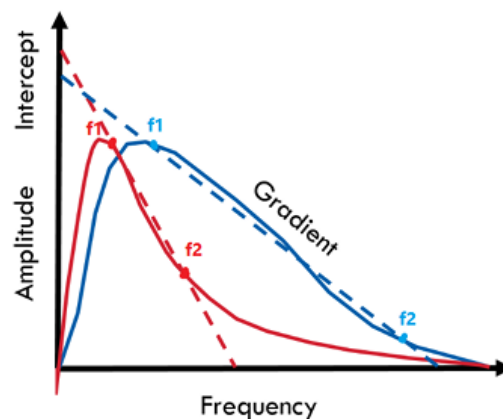


Figure 4.

Schematic illustration of AVF intercept and gradient estimation by linear fitting of spectral amplitude within the frequency range ($[f_1, f_2]$) (adapted from Wihardy and Khairy, 2021). The red and blue curves represent the spectral amplitude responses associated with hydrocarbon-bearing and non-hydrocarbon areas, respectively. The hydrocarbon-associated response exhibits a relatively larger intercept and steeper gradient, indicating stronger frequency-dependent attenuation (Han & others 2023).

The fitted intercept and gradient provide complementary information about the frequency-dependent behavior of the seismic signal. The intercept (I) represents the extrapolated amplitude at the zero-frequency reference, whereas the gradient (G) describes the rate and direction of amplitude change with increasing frequency. A negative gradient indicates that seismic amplitude decreases as frequency increases, representing a frequency-dependent attenuation response. Such attenuation may be associated with hydrocarbon saturation; however, the gradient response is not uniquely diagnostic of hydrocarbons because frequency-dependent amplitude variations may also result from lithological changes, tuning effects, pore-fluid and pore-structure variations, intrinsic attenuation, and seismic processing effects (Castagna et al., 2003; Mandong et al., 2021). Therefore, the gradient response must be interpreted in conjunction with independent geological and petrophysical information.

To enhance the spatial expression of anomalous frequency-dependent responses, the AVF attribute is calculated from the combination of the intercept and gradient parameters:

$$AVF = I \times G \quad (3)$$

where (I) and (G) are the intercept and gradient obtained from the amplitude-frequency fitting. The product of these two parameters provides an integrated measure of the amplitude level and its frequency-dependent variation, allowing anomalous zones to be more clearly delineated within the seismic volume. In particular, areas characterized by relatively strong amplitudes accompanied by negative gradients may produce distinctive AVF responses that can be evaluated as potential hydrocarbon-related anomalies when supported by geological and petrophysical evidence (Mandong et al., 2021).



Figure 5.

Workflow of AVF-based reservoir characterization, including well-to-seismic tie, spectral decomposition, frequency gathering, AVF attribute calculation, and AVF mapping using 3D PSTM seismic and well data.

The AVF attributes were calculated for each seismic sample by fitting the amplitude values extracted from the available CWT-derived frequency volumes to the frequency variable. The resulting intercept and gradient volumes were then analyzed together with the individual frequency components to assess the spatial and temporal distribution of frequency-dependent seismic responses. This integrated approach allows the AVF response to be evaluated not only from the final AVF attribute but also from its individual components, thereby providing a more robust basis for geological interpretation.

Finally, interpretation was performed through horizon slicing of the AVF attribute volume within the target interval of the Baturaja Formation. The dominant frequency distribution and reservoir characteristics were interpreted by integrating AVF results with geological and petrophysical information obtained from wells B1, N1, and N2. The integration of seismic attributes and well data provided a comprehensive understanding of reservoir geometry and facilitated the identification of potential hydrocarbon-bearing zones.

Overall, the methodological workflow begins with well-to-seismic integration to establish the relationship between the well information and the 3D PSTM seismic data. The seismic data are subsequently decomposed into frequency-dependent components using the CWT, from which amplitude information is extracted at individual seismic samples. These amplitudes are then fitted as a function of frequency to obtain the intercept and gradient parameters, which are combined to generate the AVF attribute. Finally, the AVF results are interpreted through horizon slicing and integrated with seismic geological, and petrophysical information to characterize the reservoir and identify potential hydrocarbon-bearing zones. The complete workflow adopted in this study is presented in Figure 3.

3. Result and discussion

3.1 Analysis well seismic – tie

Well-to-seismic tie analysis is a crucial step in integrating well data in the depth domain with seismic data in the time domain. The process begins with the calibration of well data using checkshot information to establish a more accurate time–depth relationship. Subsequently, a seismic wavelet is extracted from the seismic dataset. In this study, a statistical wavelet was generated with a wavelet length of 74 ms and a dominant frequency of 16 Hz. The next step involves convolving the reflection coefficient series derived from the well logs with the extracted wavelet to generate a synthetic seismogram. This synthetic seismogram is then matched with the seismic trace at the well location to establish the well-to-seismic tie. The resulting correlation ensures accurate identification of geological horizons on the seismic data and improves the reliability of subsurface interpretation.

The well-to-seismic tie results, demonstrate a satisfactory correlation between the synthetic seismograms and the observed seismic data. Correlation coefficients of 0.702, 0.638, and 0.805 were obtained for wells B1, N1, and N2, respectively. These values indicate a good to very good match between the synthetic traces generated from well-log data and the corresponding seismic responses, suggesting that the synthetic seismograms adequately represent the subsurface seismic characteristics at each well location.

Among the three wells, Well N2 exhibits the highest correlation coefficient, indicating the strongest agreement between the synthetic and seismic traces. Meanwhile, Wells B1 and N1 also show acceptable correlation values, confirming the reliability of the tie despite potential influences from factors such as seismic noise, wavelet estimation uncertainties, and variations in log quality. Overall, the correlation results indicate that the generated synthetic seismograms provide a robust representation of the seismic signal and can be confidently used for seismic interpretation.

The successful well-to-seismic tie validates the time–depth relationship established through checkshot calibration and ensures accurate positioning of geological markers within the seismic volume. This step is essential for minimizing uncertainties in horizon picking and stratigraphic correlation. Consequently, the well tie serves as a reliable foundation for subsequent analyses, including horizon interpretation, spectral decomposition, and Amplitude Versus Frequency (AVF) attribute extraction within the Baturaja Formation.

3.2 Analysis continuous wavelet transform (CWT)

The 3D Post Stack Time Migration (PSTM) seismic data were decomposed using the Continuous Wavelet Transform (CWT) method to investigate the frequency-dependent characteristics of the seismic response and to identify potential hydrocarbon reservoirs. Spectral decomposition enables the analysis of seismic signals in the time–frequency domain, allowing localized variations in frequency content to be observed with greater detail than conventional seismic interpretation. This capability is particularly useful for detecting attenuation-related anomalies associated with hydrocarbon-bearing reservoirs.

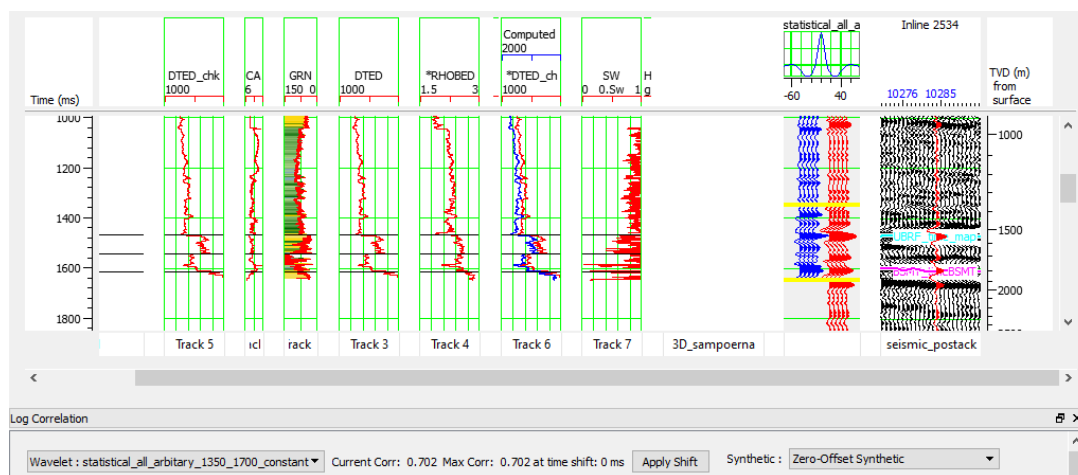


Figure 6.
Well seismic – tie, well N1.

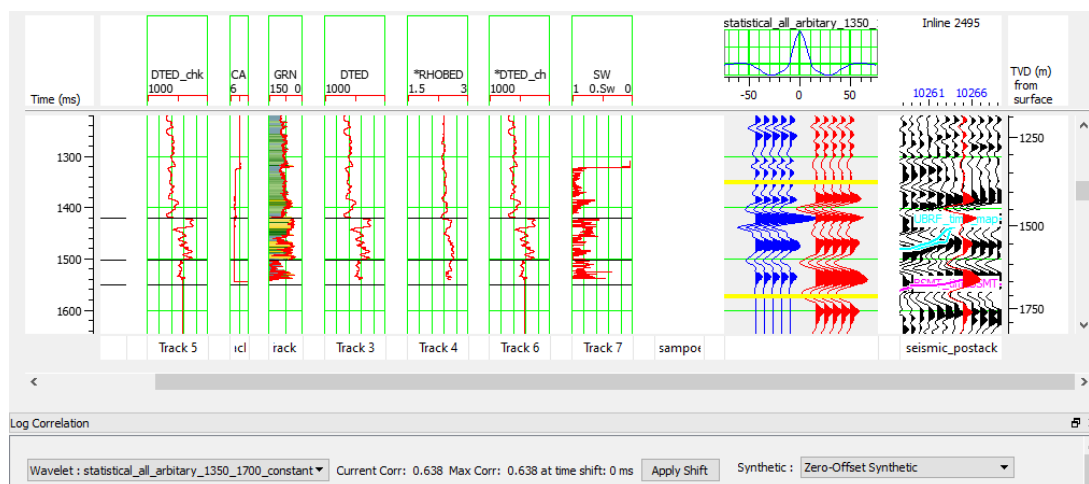


Figure 7.
Well seismic – tie, well B1.

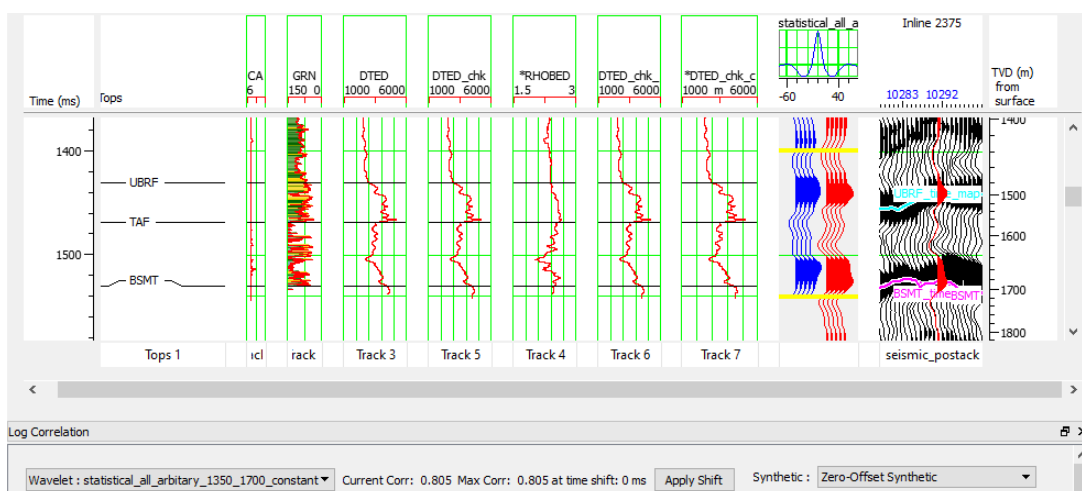


Figure 8.
Well seismic – tie, well B2

The presence of hydrocarbons within porous reservoir rocks can induce seismic attenuation, where high-frequency components experience greater energy loss than low-frequency components during wave propagation. As a result, the frequency spectrum shifts toward lower frequencies, producing a phenomenon commonly referred to as a low-frequency shadow. This anomaly is widely recognized as a potential indicator of hydrocarbon accumulation because the absorption of high-frequency energy by hydrocarbon-saturated rocks leads to the relative enhancement of low-frequency responses. Consequently, zones characterized by dominant low-frequency amplitudes are often interpreted as prospective hydrocarbon reservoirs.

The Continuous Wavelet Transform (CWT) method was selected because it provides adaptive time–frequency resolution by adjusting the wavelet window according to the analyzed frequency. Low frequencies are represented by wider windows, allowing deeper signal penetration and improved detection of large-scale geological features, whereas high frequencies utilize narrower windows, providing enhanced vertical resolution and greater stratigraphic detail. This characteristic makes CWT particularly suitable for analyzing non-stationary seismic signals and identifying subtle frequency variations associated with reservoir properties.

The spectral decomposition results obtained using the Continuous Wavelet Transform were evaluated at frequencies of 10 Hz, 20 Hz, and 40 Hz to investigate the variation of seismic responses within the target interval. At 10 Hz (Figure 8), a laterally continuous low-frequency amplitude anomaly is observed within the target zone. The anomaly appears relatively strong and persistent, suggesting the presence of attenuation effects commonly associated with hydrocarbon-bearing reservoirs. The dominance of low-frequency energy at this interval is consistent with the low-frequency shadow phenomenon reported by Partyka *et al.* (1999), who demonstrated that hydrocarbon-saturated reservoirs often exhibit enhanced low-frequency responses compared to surrounding formations.

At 20 Hz (Figure 9), the seismic image exhibits improved vertical resolution, allowing geological boundaries and subsurface geometries to be delineated more clearly. Although the low-frequency anomaly remains identifiable, the enhanced resolution facilitates a better assessment of its lateral continuity and spatial distribution. The 20 Hz frequency slice therefore serves as an important intermediate frequency for validating the extent of the anomaly detected at lower frequencies.

The 40 Hz frequency volume (Figure 10) displays sharper reflectors and more detailed stratigraphic features due to the higher vertical resolution associated with high-frequency components. However, a noticeable reduction in amplitude is observed within the target zone compared to the lower-frequency volumes. The reduction in high-frequency amplitude may indicate frequency-dependent attenuation associated with energy absorption during seismic-wave propagation through porous, fluid-saturated rocks. Since high-frequency components generally experience stronger attenuation than lower-frequency components, this response can be consistent with a hydrocarbon-related attenuation effect. However, frequency attenuation is not uniquely diagnostic of hydrocarbons and may also result from intrinsic absorption, fluid properties, lithological heterogeneity, pore structure, fractures, vugs, scattering, tuning effects, and seismic processing.

This uncertainty is particularly relevant to the Baturaja Formation, where heterogeneous carbonate pore systems and diagenetic variations can influence seismic amplitude and frequency response independently of hydrocarbon saturation. In addition, wavelet characteristics, bandwidth limitations, and spectral decomposition parameters may affect the extracted frequency amplitudes. Therefore, the high-frequency amplitude reduction observed in Figure 10 is interpreted as evidence of frequency-dependent behavior rather than definitive proof of hydrocarbon presence.

The systematic low-frequency anomalies and progressive attenuation of high-frequency amplitudes across the spectral decomposition volumes provide stronger support than an isolated amplitude anomaly. Nevertheless, the interpretation is further constrained by the subsequent AVF analysis and independent petrophysical information. Thus, the observed frequency response is considered a potential hydrocarbon-related attenuation indicator, while acknowledging uncertainty from geological heterogeneity, seismic resolution, attenuation mechanisms, and processing effects. These frequency volumes subsequently form the basis for the AVF analysis to quantify the amplitude–frequency relationship and improve reservoir characterization.

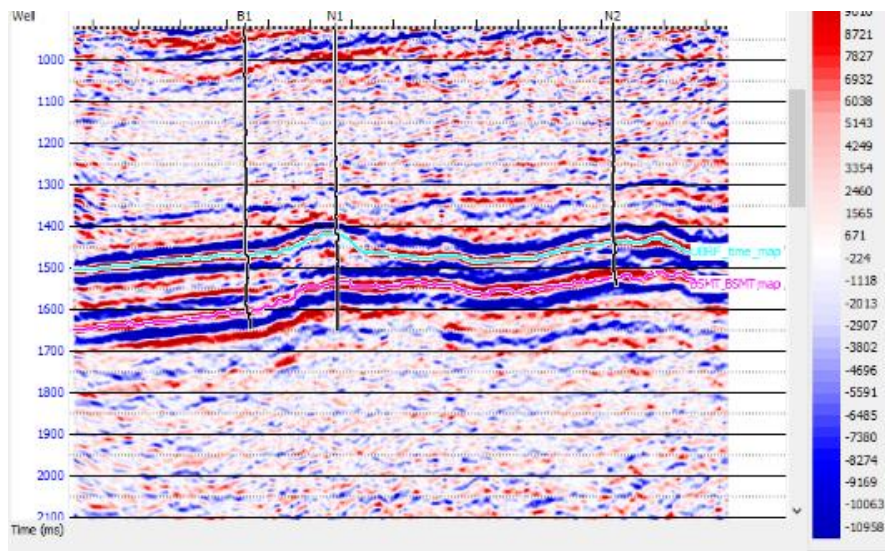


Figure 9.
Original 3D PSTM seismic section of the study area.

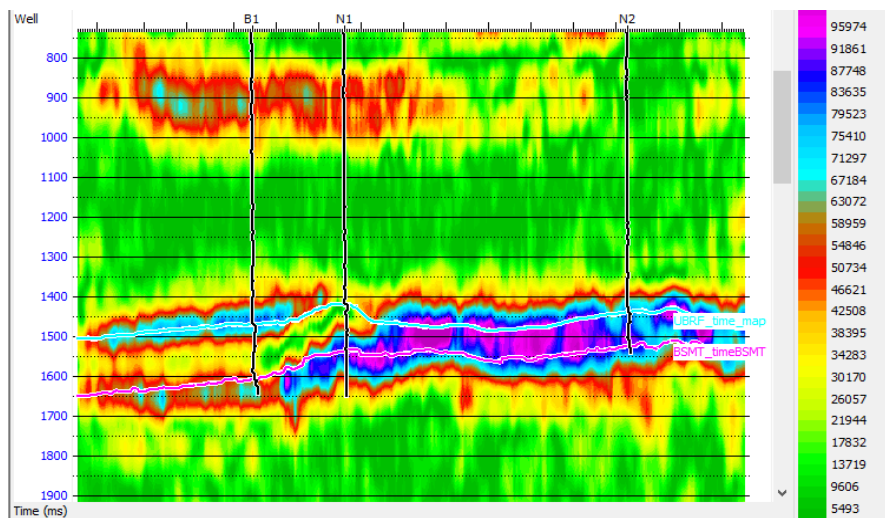


Figure 10
CWT-based seismic section at 10 Hz showing the frequency-dependent amplitude response within the target reservoir interval.

3.3 Analysis AVF Attribut

The results of the Amplitude Versus Frequency (AVF) attribute as shown in Figure 11, indicate a predominance of negative gradient values within the target interval. These negative gradient values suggest the occurrence of frequency attenuation, where the energy of seismic waves, particularly at higher frequencies, decreases as the waves propagate through the subsurface medium. This attenuation phenomenon is commonly associated with the presence of fluids within the pore spaces of reservoir rocks, which influence the elastic properties of the formation.

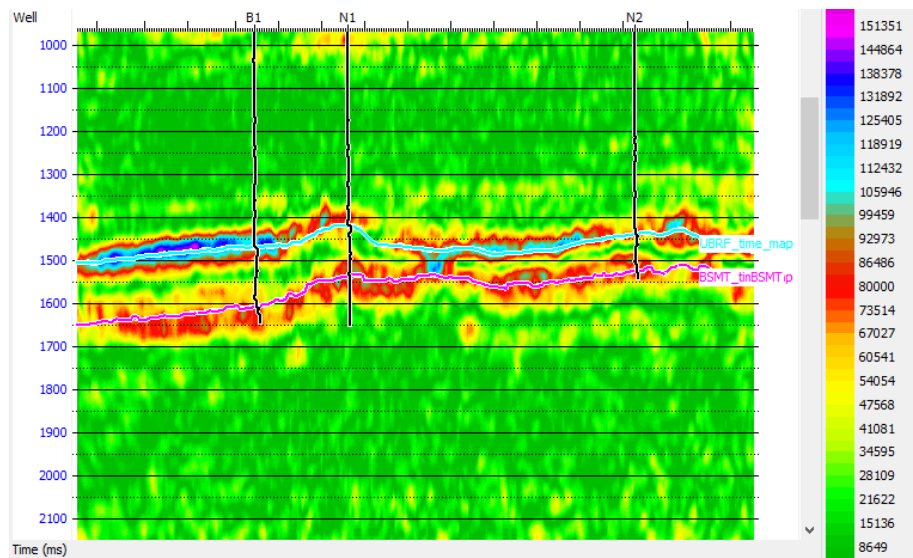


Figure 11.
CWT-based seismic section at 20 Hz showing the frequency-dependent amplitude response within the target reservoir interval.

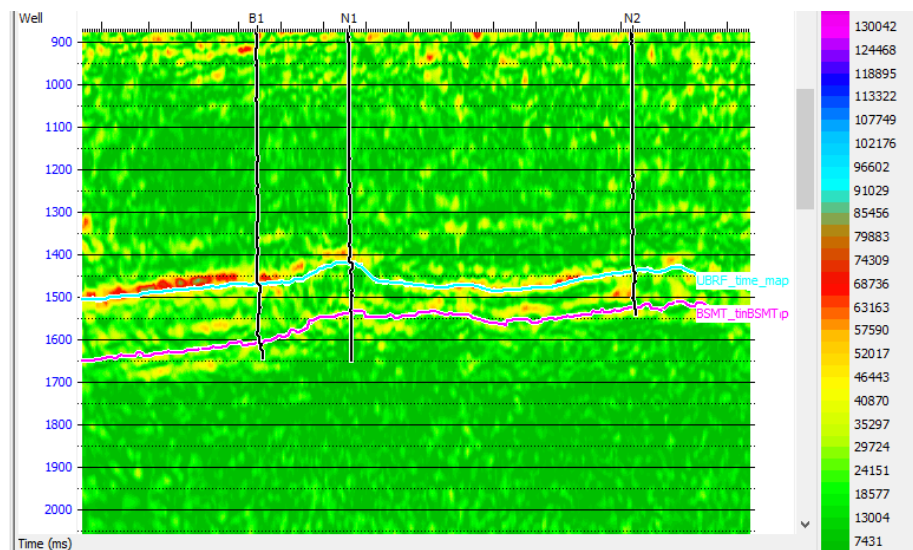


Figure 12.
CWT-based seismic section at 40 Hz showing the frequency-dependent amplitude response within the target reservoir interval.

The reduction in high-frequency amplitudes observed within the target interval indicates that the reservoir has a greater capacity to absorb seismic energy compared to the surrounding formations. This observation is consistent with the theory of seismic attenuation, which states that porous and fluid-saturated rocks tend to attenuate high-frequency seismic energy more significantly than low-frequency energy. As a result, low-frequency components become relatively dominant, producing spectral anomalies that are commonly associated with hydrocarbon-bearing reservoirs. According to Mandong et al. (2021), hydrocarbon-saturated reservoirs frequently exhibit a loss of high-frequency energy, causing the dominant frequency to shift toward lower frequencies. This phenomenon forms the basis for the application of AVF attributes as a Direct Hydrocarbon Indicator (DHI) in reservoir characterization.

The AVF interpretation was further evaluated using the well-log responses from wells B1, N1, and N2, as summarized in Table 1. At well B1, the gamma-ray (GR) value is 88.756 API, with a water saturation (S_w) of 60.43% and a bulk density (RHOB) of 2.571 g/cm³. The moderate S_w value indicates that approximately 39.57% of the pore space is occupied by non-water fluids, which may provide support for the presence of hydrocarbons when consistent with the AVF response and other petrophysical indicators. At well N1, the GR value is 89.347 API, with an S_w of 70.5% and an RHOB of 2.498 g/cm³. The higher S_w relative to B1 indicates a greater proportion of water saturation, although the remaining 29.5% non-water saturation may still be consistent with hydrocarbon-bearing pore space. At well N2, the GR value is 87.573 API and the RHOB is 2.585 g/cm³, while S_w is unavailable for the analyzed interval. Overall, the GR values range from 87.573 to 89.347 API, while RHOB ranges from 2.498 to 2.585 g/cm³ and the available S_w values range from 60.43% to 70.5%. The lower S_w at B1 compared with N1 provides stronger petrophysical support for a potential hydrocarbon contribution, particularly if it coincides spatially with the negative AVF gradient anomaly. However, the relatively high GR values observed across the three wells indicate that lithological and shale-related effects should also be considered. Therefore, the AVF anomalies are interpreted more reliably when integrated with S_w , GR, RHOB, seismic amplitude, and other available reservoir properties rather than being used as a standalone hydrocarbon indicator.

Furthermore, the AVF responses observed at wells B1, N1, and N2 are characterized by negative gradient values, indicating frequency-dependent amplitude attenuation within the target interval. This response is supported by the available well-log data, particularly the water saturation (S_w) values of 60.43% at B1 and 70.5% at N1. The lower S_w at B1 provides relatively stronger support for a potential hydrocarbon contribution compared with N1, while the absence of S_w data at N2 prevents direct evaluation of its fluid saturation. The gamma-ray values of 88.756, 89.347, and 87.573 API at B1, N1, and N2, respectively, indicate relatively similar lithological responses across the three wells, although the relatively high GR values suggest that shale-related and lithological effects should also be considered. The occurrence of negative AVF gradients across the three wells, together with the available petrophysical evidence, suggests that frequency-dependent attenuation may provide a useful indicator for identifying anomalous reservoir intervals within the heterogeneous carbonate succession of the Baturaja Formation. However, the AVF response should be interpreted as an integrated indicator rather than definitive evidence of gas accumulation, particularly because the observed S_w values and lithological responses indicate that fluid and lithological effects may both contribute to the frequency-dependent seismic response.

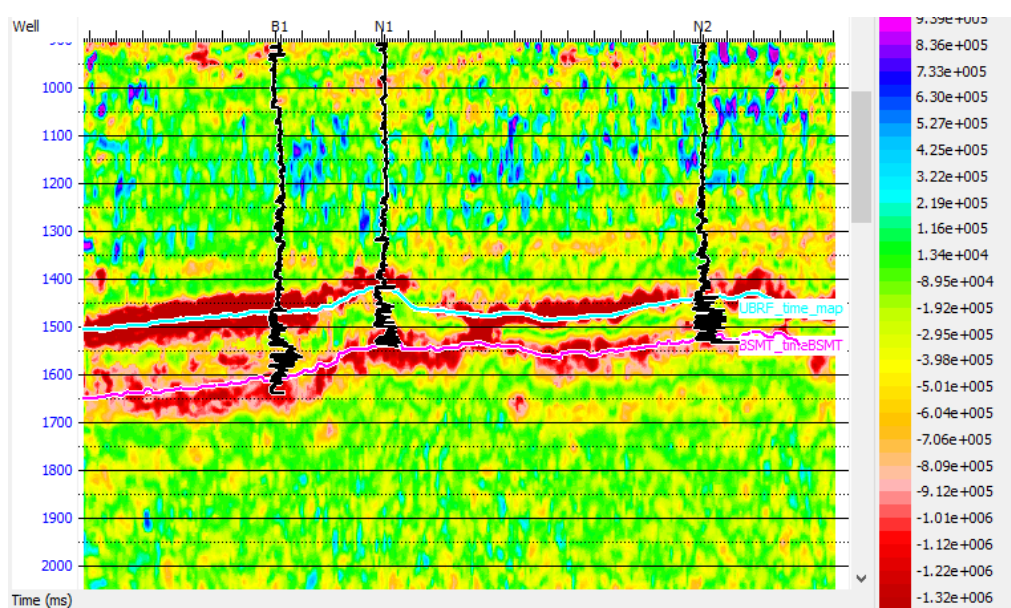


Figure 13.

AVF attribute seismic section showing negative gradient anomalies within the target reservoir interval, integrated with Gamma Ray (GR) log responses from wells B1, N1, and N2 to support the interpretation of frequency-dependent attenuation and potential hydrocarbon-bearing zones.

Table 1.
AVF attributes and petrophysical parameters of wells B1, N1, and N2.

Well	AVF Attribut	GR	Sw	RHOB
B1	-1.70095×10^6	88.756 API	60.43%	2.571 g/cm ³
N1	-1.17377×10^6	89.347 API	70.5%	2.498 g/cm ³
N2	-1.32474×10^6	87.573 API	-	2.585 g/cm ³

The integration of AVF attributes with well-log information demonstrates a consistent relationship between low-frequency anomalies, negative gradient values, and the petrophysical properties of the reservoir. The observed attenuation pattern suggests the presence of hydrocarbon-bearing zones within the Baturaja Formation. These findings are consistent with the study of [Mandong et al. \(2021\)](#), which demonstrated that AVF attributes derived from spectral decomposition can effectively delineate hydrocarbon reservoirs through the analysis of frequency-dependent amplitude variations.

The present results also support the findings of [\(Hong Li et al., 2024\)](#), who reported that hydrocarbon prediction in carbonate reservoirs can be significantly improved by incorporating frequency-dependent information because conventional AVO responses are often affected by fracture systems, vuggy porosity, and strong lithological heterogeneity. Unlike conventional AVO analysis, which relies on amplitude variations with offset and commonly requires high-quality prestack seismic data and rock-physics calibration for reliable interpretation in carbonate reservoirs [\(Yongyi Li et al., 2003\)](#), the CWT-based AVF method evaluates amplitude variations with frequency, enabling the identification of seismic attenuation associated with hydrocarbon saturation. The consistent negative AVF gradients observed at wells B1, N1, and N2 indicate that the proposed method successfully characterizes gas-bearing carbonate reservoirs and provides complementary information that reduces the ambiguity commonly encountered in conventional AVO interpretation.

Therefore, the results indicate that AVF analysis based on Complex Ricker Wavelet (CRW) spectral decomposition provides an effective and reliable approach for reservoir characterization and hydrocarbon identification within the study area.

3.4 Analysis intercept vs gradient

Analysis of wells B1, N1, and N2 shows a consistent negative AVF gradient, indicating decreasing seismic amplitude with increasing frequency. Well B1 exhibits the strongest attenuation, with the highest intercept $A = 99,683.82$ and the most negative gradient $B = -117,663.81$, although its correlation coefficient is relatively lower $R = 0.7825$. N2 shows an intermediate response $A = 72,310.45$, $B = -73,391.92$; $R = 0.8920$, while N1 exhibits the weakest attenuation $A = 51,644.29$, $B = -40,940.74$ with the highest correlation $R = 0.8992$.

The larger intercept and more negative gradient at B1 indicate stronger low-frequency dominance and greater high-frequency attenuation compared with N1 and N2. However, the absence of distinct clusters in the gradient–intercept crossplots indicates that these parameters alone cannot definitively discriminate hydrocarbon presence. The observed differences are therefore interpreted as variations in frequency-dependent seismic response, potentially influenced by reservoir heterogeneity, pore structure, fluid effects, and attenuation mechanisms, and should be integrated with independent petrophysical evidence.

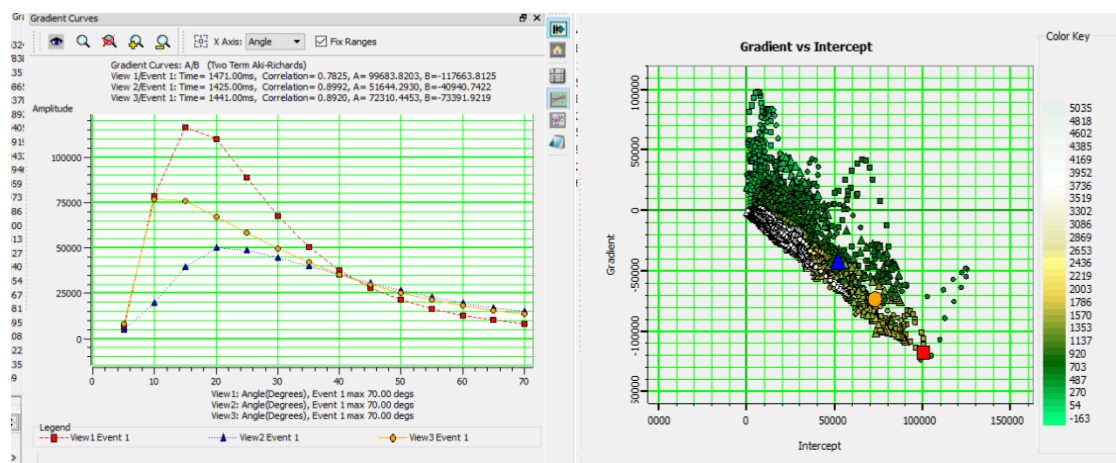


Figure 14.

Intercept–gradient kurva & crossplot of the UBRF zone showing the distribution of AVF responses and the separation of anomalous points associated with potential hydrocarbon-bearing reservoir intervals.

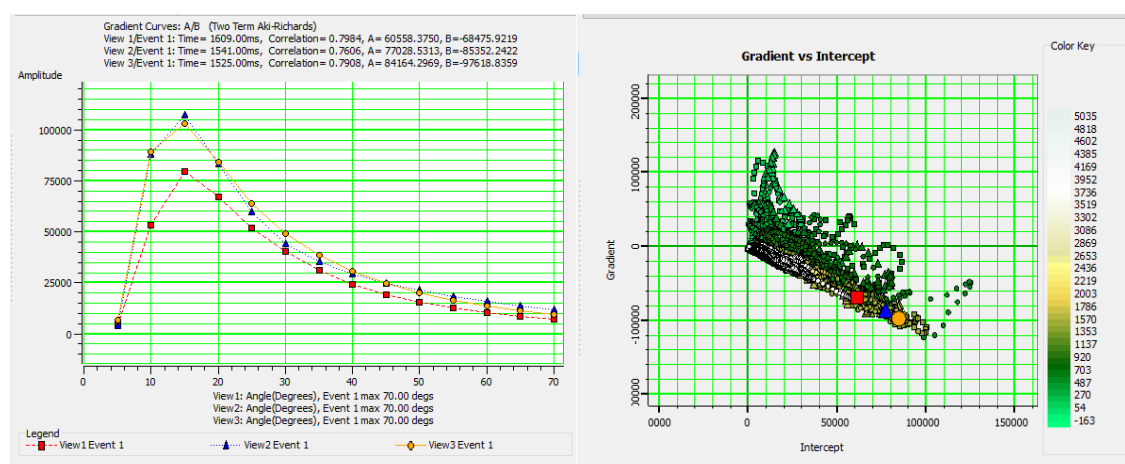


Figure 15.

Intercept–gradient kurva & crossplot of the BSMT zone showing the distribution of AVF responses and the separation of anomalous points associated with potential hydrocarbon-bearing reservoir intervals.

Analysis of wells B1, N1, and N2 in the BSMT interval shows a consistent negative AVF gradient, indicating decreasing seismic amplitude with increasing frequency. Well N2 exhibits the strongest attenuation, with the highest intercept $A = 84,164.30$ and the most negative gradient $B = -97,618.84$, with a correlation coefficient of 0.7908. N1 shows an intermediate response $A = 77,028.53$; $B = -85,352.24$, $R = 0.7606$, while B1 exhibits the weakest attenuation $A = 60,558.38$, $B = -68,475.92$, $R = 0.7984$.

The gradient magnitude follows the order $N2 > N1 > B1$, indicating that N2 has the strongest frequency-dependent attenuation within the BSMT interval. However, the relatively similar correlation coefficients and absence of clear cluster separation indicate that the AVF parameters alone are insufficient to definitively discriminate hydrocarbon presence. The observed variations are therefore interpreted as differences in frequency-dependent seismic response that may reflect variations in reservoir properties, fluid effects, and geological heterogeneity.

These results indicate that AVF analysis is capable of capturing frequency-dependent attenuation phenomena associated with reservoir properties. Therefore, when integrated with well-log data and geological interpretation, AVF attributes can provide additional insights into reservoir characterization and assist in identifying zones with potential hydrocarbon accumulation.

3.5 Analysis slicing AVF

The results of Amplitude Versus Frequency (AVF) attribute slicing on the UBRF_time_map horizon at intervals of 0 ms, +5 ms, +10 ms, and +15 ms reveal variations in amplitude distribution across several zones within the study area. The AVF attribute provides detailed information on amplitude and frequency responses, allowing changes in reservoir characteristics, subsurface geometry, and potential hydrocarbon accumulations to be identified more effectively. In general red to pink colors represent relatively high amplitude values, whereas green to blue colors indicate lower amplitudes. High-amplitude zones are interpreted as areas with significant acoustic impedance contrasts and are therefore considered potential hydrocarbon-bearing reservoirs accumulations to be identified more effectively. In general, red to pink colors represent relatively high amplitude values, whereas green to blue colors indicate lower amplitudes. High-amplitude zones are interpreted as areas with significant acoustic impedance contrasts and are therefore considered potential hydrocarbon-bearing reservoirs.

At the 0 ms slice, a prominent high-amplitude anomaly is observed in the eastern to northeastern part of the study area. This zone is characterized by dominant red to pink colors with amplitude values ranging from approximately -1.35×10^6 to -2.47×10^6 , contrasting sharply with the surrounding areas, which are dominated by green, yellow, and blue colors with amplitudes ranging from approximately -4.0×10^5 to -1.0×10^6 . The presence of this anomaly suggests a reservoir zone exhibiting a strong AVF response associated with frequency-dependent attenuation effects (Figure 16).

At the +5 ms interval, the high-amplitude anomaly remains well developed and displays good lateral continuity in the eastern and northeastern portions of the study area. The anomaly exhibits a distribution pattern similar to that observed at the 0 ms slice, indicating that the reservoir extends laterally and likely belongs to the same reservoir system. The persistence of high amplitudes at this interval suggests a consistent frequency response related to the presence of fluids within the reservoir (Figure 17).

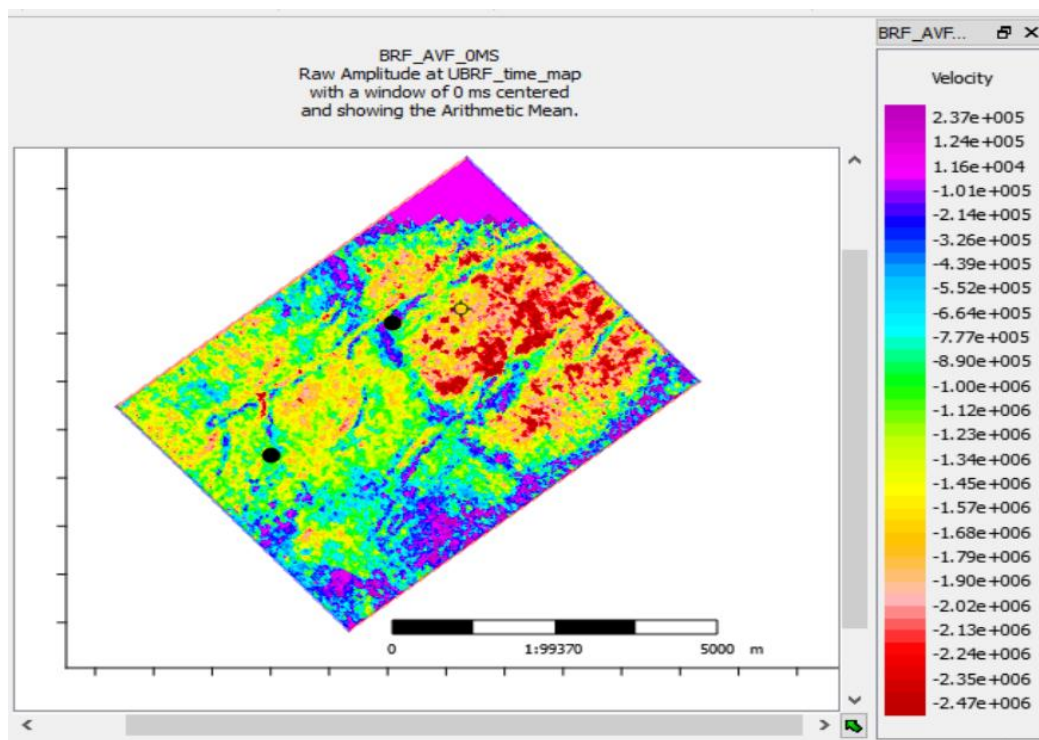


Figure 16.

AVF attribute map at a 0-ms interval slice showing the spatial distribution of negative AVF anomalies associated with frequency-dependent amplitude attenuation within the target reservoir interval of the Baturaja Formation.

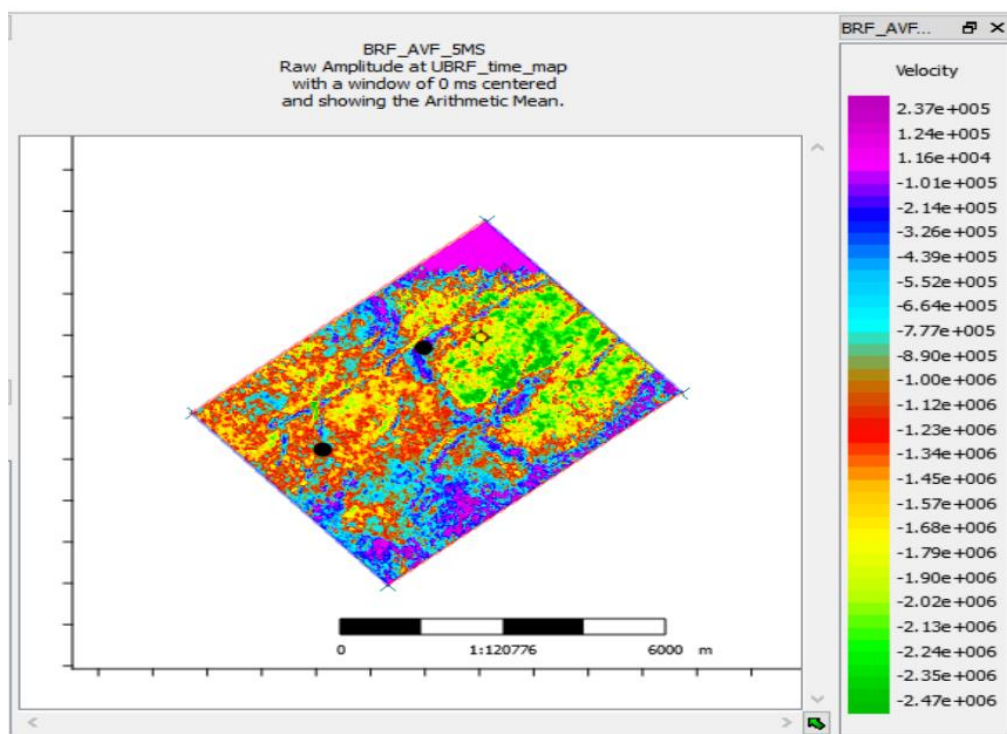


Figure 17.

AVF attribute map at a 5-ms interval slice showing the spatial distribution of negative AVF anomalies associated with frequency-dependent amplitude attenuation within the target reservoir interval of the Baturaja Formation.

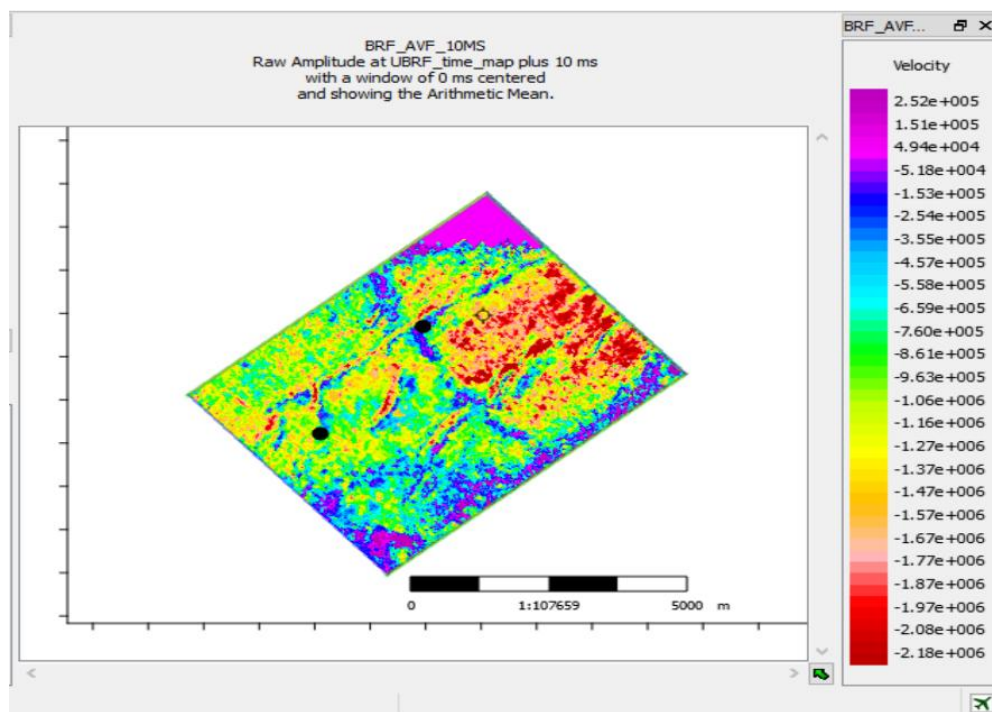


Figure 18.

AVF attribute map at a 10-ms interval slice showing the spatial distribution of negative AVF anomalies associated with frequency-dependent amplitude attenuation within the target reservoir interval of the Baturaja Formation.

At the +10 ms interval, the high-amplitude anomaly is still present in approximately the same location, although its areal extent begins to decrease compared to the shallower intervals. Nevertheless, the anomaly maintains good lateral continuity and remains clearly identifiable. This observation suggests that the reservoir continues into this interval, although the effective reservoir thickness or quality may begin to diminish (Figure 18).

At the +15 ms interval, high amplitudes are still observed in the eastern to northeastern area, but with a more limited spatial extent and amplitude values ranging from approximately -1.39×10^6 to -2.18×10^6 . The surrounding areas are dominated by lower amplitudes, ranging from approximately -7.0×10^5 to -1.2×10^6 , which may indicate a reduction in reservoir quality or proximity to the lower boundary of the reservoir interval. Despite this reduction, the consistent occurrence of high-amplitude anomalies across all slicing intervals indicates that the reservoir exhibits relatively good lateral and vertical continuity (Figure 19).

Overall, the AVF attribute slicing results suggest that the prospective reservoir zone is predominantly distributed in the eastern to northeastern part of the study area. The relatively continuous distribution of high-amplitude anomalies across multiple time slices indicates the presence of a laterally extensive reservoir body with favorable hydrocarbon potential. The consistency of these anomalies throughout the analyzed intervals further suggests good reservoir continuity both laterally and vertically. The highest concentration of AVF anomalies is observed in the northeastern part of the study area, corresponding to the locations of wells B1 and N1, where negative AVF gradients are consistently associated with low water saturation and low gamma-ray values, indicating gas-bearing carbonate reservoirs. In contrast, well N2 also exhibits negative AVF gradients indicative of gas saturation, although the anomalies are less extensive than those observed around wells B1 and N1. This spatial agreement between the AVF anomaly distribution and well-log interpretation demonstrates that the identified hydrocarbon-bearing zones are geologically consistent and laterally continuous within the carbonate reservoir. These results demonstrate that AVF attributes are effective for delineating reservoir distribution, evaluating reservoir continuity, and identifying prospective hydrocarbon-bearing zones within the Baturaja Formation. The successful correlation between AVF anomalies and petrophysical evidence from all three wells confirms that the CWT-based AVF method is capable of effectively characterizing heterogeneous carbonate reservoirs. By capturing frequency-dependent attenuation associated with gas saturation, AVF provides reliable complementary information for hydrocarbon detection and reduces the uncertainty commonly encountered in conventional amplitude-based interpretation of carbonate reservoirs.

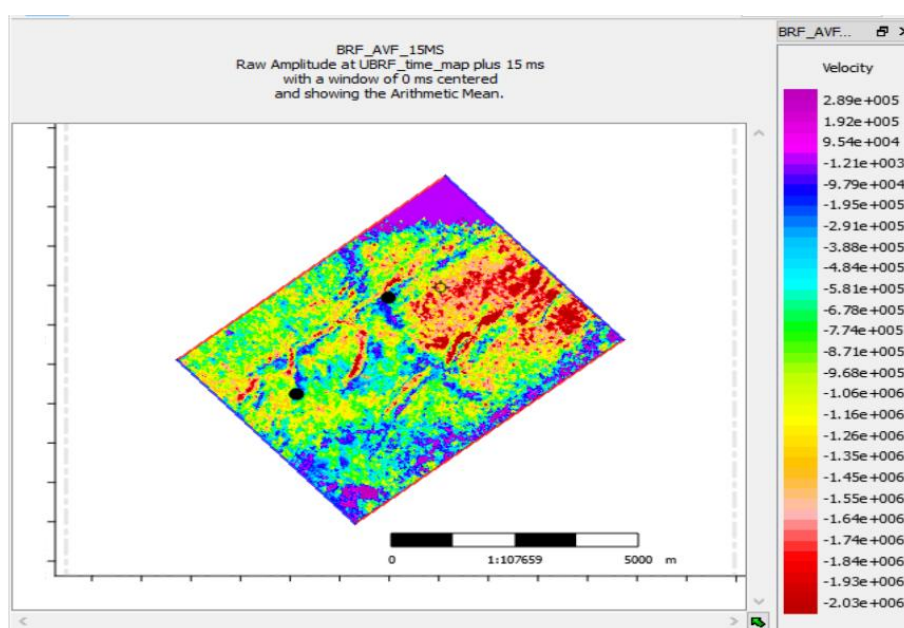


Figure 19.

AVF attribute map at a 15-ms interval slice showing the spatial distribution of negative AVF anomalies associated with frequency-dependent amplitude attenuation within the target reservoir interval of the Baturaja Formation.

4. Conclusion

The integration of Continuous Wavelet Transform (CWT) and Amplitude Versus Frequency (AVF) successfully identified frequency-dependent anomalies in the Baturaja Formation. The results show low-frequency anomalies and predominantly negative AVF gradients, indicating attenuation that may be associated with gas-bearing reservoir zones. The anomalies are mainly distributed in the east–northeast area and show good lateral continuity. Integration with well-log data, particularly water saturation and gamma-ray, provides additional support for the interpretation. Therefore, CWT-based AVF can be used as a complementary method for identifying prospective hydrocarbon zones, although it should be integrated with geological and petrophysical data for more reliable interpretation.

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6. Declarations

6.1 Author contributions

Tati Zera: Supervision, Methodology, Validation, Writing Review and Editing. Bahrul Ulum: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Software, Visualization, Writing Original Draft, Writing Review & Editing. Pradityo Riyadi: Supervision, Methodology, Validation, Visualization, Writing Review. Jarea Yurika Lubis: Data Curation, Formal Analysis, Software, and Visualization.

6.2 Funding statement

None.

6.3 Competing interest

None.

6.4 The use of AI and AI-assisted technologies

During the preparation of this work, the authors used Consensus GPT and Cloud AI to support literature exploration, language refinement, and manuscript drafting. The AI-assisted outputs were critically evaluated, verified against the original references, and substantially revised by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content presented in this publication.

7. Glossary of terms and symbols

Terms & Symbols	Definition	Unit
AVF	Amplitude variation with frequency	Unitless
AVO	Amplitude Variation with Offset	Unitless
CWT	Continuous wavelet transform	Unitless
STFT	Short-Time Fourier Transform	Unitless
SW	Saturation Water	SW
GR	Gamma Ray	GR

8. References

- Castagna, J. P., Sun, S., & Siegfried, R. W. (2003). Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons. *The Leading Edge*, 22(2), 120–127. <https://doi.org/10.1190/1.1559038>
- Durogbitan, A., Simon, E., Auduson, A., Ekene, O., & Collins, I. (2023). Use of spectral decomposition in identifying stratigraphic baffles below seismic resolution; A case study of UTB field, offshore Niger Delta. *Journal of Applied Geophysics*, 217, 105193. <https://doi.org/10.1016/j.jappgeo.2023.105193>
- Han, X., & others. (2023). Amplitude Versus Frequency (AVF). *GeoConvention 2023*. <https://geoconvention.com/wp-content/uploads/abstracts/2023/91410-amplitude-versus-frequency.pdf>
- Li, H., Yin, H., Tang, J., & Xiao, P. (2024). Application of AVO Characteristics Analysis and Seismic Dispersion AVO Inversion to the Carbonate Hydrocarbon Reservoirs in Region Y of the Tarim Basin, China. *Geofluids*, 2024(1). <https://doi.org/10.1155/2024/3034459>
- Li, Y., Downton, J., & Goodway, B. (2003). Recent applications of AVO to carbonate reservoirs in the Western Canadian Sedimentary Basin. *The Leading Edge*, 22(7), 670–674. <https://doi.org/10.1190/1.1599694>
- Mandong, A. F., Bekti, R. P. A., & Saputra, R. I. A. (2021). Amplitude Variation with Frequency as Direct Hydrocarbon Indicator for Quick Look and Different Insight of Hydrocarbon Delineation. *Jurnal Geofisika*, 19(2), 62. <https://doi.org/10.36435/jgf.v20i2.517>
- Mineral, K. E. dan S. D. (2022). Peran Sektor Eksplorasi dan Produksi Migas dalam Mendukung Kebutuhan Energi Nasional dan Pemetaan Struktur Menggunakan Data Seismik di Cekungan Sunda. *Laporan Statistik Energi Indonesia 2022*. <https://www.esdm.go.id/assets/media/content/content-laporan-statistik-energi-2022.pdf>
- Partyka, G., Gridley, J., & Lopez, J. (1999). Interpretational applications of spectral decomposition in reservoir characterization. *The Leading Edge*, 18(3), 353–360. <https://doi.org/10.1190/1.1438295>
- Rutherford, S. R., & Williams, R. H. (1989). Amplitude-versus-offset variations in gas sands. *Geophysics*, 54(6), 680–688. <https://doi.org/10.1190/1.1442696>
- Satyana, A. H. (2008). Carbonate reservoir characteristics of Baturaja Formation, South Sumatra Basin. *Indonesian Petroleum Association Proceedings*.
- Setyawan, D. (2021). Hydrocarbon Mapping on Reservoir Carbonate Using AVO Inversion Method. *JPSE (Journal of Physical Science and Engineering)*, 6(1), 19–25. <https://doi.org/10.17977/um024v6i12021p019>
- Sheriff, T., & Geldart, L. (1995). *Exploration Seismology* (2nd ed.). Cambridge University Press.
- Sinha, S., Routh, P. S., Anno, P. D., & Castagna, J. P. (2005). Spectral decomposition of seismic data with continuous-wavelet transform. *Geophysics*, 70(6), P19–P25. <https://doi.org/10.1190/1.2127113>
- Stéphane Mallat. (2009). *A Wavelet Tour of Signal Processing* (3rd Edition). Elsevier. <https://doi.org/10.1016/B978-0-12-374370-1.X0001-8>
- Waples, D. (2000). *Geochemistry in Petroleum Exploration*. Springer.
- Widarsono, B. (2022). Rock Wettability Characteristics Of Some Indonesian Limestones Case Study: Baturaja Formation. *Scientific Contributions Oil and Gas*, 34(2), 105–116. <https://doi.org/10.29017/SCOG.34.2.796>
- Wihardy, G. G., & Khairy, H. (2021). Slope of Spectral Amplitude: Simple Yet Effective Hydrocarbon Indicator. *Jurnal Geofisika*, 19(2), 57. <https://doi.org/10.36435/jgf.v20i2.523>
- Wu, X., Chapman, M., Li, X.-Y., & Boston, P. (2014). Quantitative gas saturation estimation by frequency-dependent amplitude-versus-offset analysis. *Geophysical Prospecting*, 62.
- Yilmaz, Ö. (2001). *Seismic Data Analysis*. Society of Exploration Geophysicists. <https://library.seg.org/doi/book/10.1190/1.9781560801589>