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Binio Formation Characterisation Using Seismic Acoustic Impedance Inversion in the Lotus Field of the Central Sumatra Basin

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ABSTRACT - The Binio Formation, the target of this study, is located in the Lotus Field, Central Sumatra Basin. P-impedance parameters from acoustic impedance (AI) inversion analysis are used to identify rock lithology and fluid content. Petrophysical analysis was conducted on three wells using well log data to determine reservoir characteristics and identify prospect zones. The reservoir in the Binio Formation is a sandstone that is considered favourable for hydrocarbon accumulation. This study determines lithology, fluid content and reservoir structure. Sensitivity analysis showed that the porosity log parameter is sensitive to lithological separation. A potential hydrocarbon area was detected using seismic methods. Model-based inversion methods showed that the AI values of the sandstone reservoir ranged from 9,670 to 27,070 (ft/s)(gr/cc). The geological structure in the Lotus Field is generally quite complex, consisting of an anticline structure and a normal fault. Following conversion to porosity, the effective porosity value for the P1 reservoir is 0.4 (fraction). The root mean square attribute results show the presence of bright spots, and the reservoir was clearly detected within the 10 ms analysis window. The prospect zone in the P1 well lies at a depth of 2,400–2,800 ft, with interpretation indicating that the fluid content is gas.

Keywords: reservoir characterisation, acoustic impedance, seismic attributes, Central Sumatra Basin, Binio Formation.

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INTRODUCTION

The increasing demand for oil and natural gas is driving the government and the energy sector to enhance exploration and development efforts in hydrocarbon resources. According to statistical data from the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources of Indonesia, the target to meet domestic natural gas demand increased from 59% to 65% between 2016 and 2022. However, since 2016, Indonesia's natural gas production has shown a significant decline, from 1,403 BSCF to 1,168 BSCF, while reserves – both proven and potential – have also diminished as of 2021 (Ditjen Migas 2021). As a leading global oil and gas producer, Indonesia possesses considerable hydrocarbon potential, particularly in the Central Sumatra Basin, which is known for its abundant hydrocarbon resources (Heidrick & Aulia 1993; Widarsono 2013). Indonesia's total natural gas reserves have reached 62,390.13 BSCF, with the Central Sumatra Basin contributing proven reserves of 3,950.61 BSCF, possible reserves of 1,037.61 BSCF and eximated reserves of 2,138.05 BSCF. Given its vast potential, the Central Sumatra Basin remains a primary target in national energy exploration and development, significantly contributing to Indonesia's natural gas reserves (Ditjen Migas 2021).

Hydrocarbon, especially gas, in the Central Sumatra Basin represents an alternative energy source with promising economic and exploration potential, primarily in the Petani Formation, which includes several currently operating production fields (Maulana 2018). A study conducted in 2021 by the Marine Geology Research and Development Centre (P3GL) in the eastern part of the Central Sumatra Basin estimated biogenic gas reserves at 10 trillion cubic feet, underscoring the area's vast potential. Several gas fields in this basin highlight the basin's hydrocarbon significance (P3GL 2021).

One key characteristic of gas is its shallower depth, which makes it a more economical exploration target (Munadi et al. 2012). Within the Central Sumatra Basin, the Binio Formation is a major focus for gas exploration due to its dominant sandstone lithology, which is ideal for hydrocarbon accumulation (Wahyuni 2017; Pertamina 2023). This Middle to Late Miocene formation contains sandstone reservoirs classified as 'sweet gas' producers (Telford et al. 1979). Facies analysis of rock descriptions shows that the Binio Formation's lithology includes sandstones, mudstones and minor limestone inserts (Wijaya 2023). In the Mirza–Yurneli Field, Binio's sandstone reservoirs are particularly noted for their favourable hydrocarbon accumulation characteristics (Yuzariyadi 2012). Despite the Binio Formation's recognised potential, previous studies have not fully examined its fluid content or anticline structure in the Mirza Field.

A recent study in Field 'A&K' applied acoustic impedance (AI) inversion and found that the sandstone reservoirs in this region display good reservoir quality (Yilmaz 2001), though porosity levels were not examined in detail. The Binio Formation has the potential to serve as an alternative gas resource to the more extensively explored Menggala, Bekasap and Bangko Formations. Therefore, the Binio Formation in the Lotus Area represents a promising target for future gas exploration research.

Root mean square (RMS) amplitude attributes, which are sensitive to extreme amplitude values associated with porous sandstones, provide a direct hydrocarbon indicator (DHI) based on amplitude anomalies. Bright spots with enhanced amplitude contrast often indicate promising gas prospects (Aviani 2022; Hidayat et al. 2020).

Characterising gas reservoirs within the Central Sumatra Basin is essential to meet rising energy demands (Widarsono 2013). Reservoir characterisation should be conducted using seismic inversion methods that construct subsurface models by integrating seismic data and well logs as controls (Triyoso et al. 2024). This study utilises AI seismic inversion and RMS attributes to evaluate fluid content, structure and porosity of gas reservoirs, providing a clearer geological understanding and insight into hydrocarbon potential within the Lotus Field of the Binio Formation, Central Sumatra Basin. Previous studies have not fully examined the detailed fluid content, reservoir quality or anticline structures in biogenic gas reservoirs within the Binio Formation particularly in the Lotus Field. The combination of AI seismic inversion methods and RMS attributes will provide comprehensive information for hydrocarbon reservoir characterisation. The results of this study through the identification of prospective reservoir zones will offer further insight into the lithology and fluid content of the Lotus Area and guide future well-drilling efforts.

METHODOLOGY

This study uses 2D seismic post-stack time migration data supported by data from three well logs. The seismic and well log data used are presented in Table 1 and Table 2.

Table 1. Seismic data acquisition parameters: sample rate (ms) in Lotus Field

Seismic Data	Sample Rate (ms)
Line 1	2
Line 2	2
Line 3	2

Table 2. Summary of well log availability for wells P-1, P-2, and P-3 in Lotus Field

Log Data	P-1	P-2	P-3
GR	√	√	√
Caliper	√	√	-
NPHI	√	√	-
CNL	√	√	√
RHOB	√	-	√
Resistivity	√	√	√

Acoustic impedance

Pre-inversion analysis was conducted before the inversion stage to confirm whether the parameters used in earlier stages were appropriate. This analysis involves overlaying the inverted trace with well log data. It is performed through trial and error and several iterations at the well location to obtain the desired results (Wiyatno et al. 2019; Sukmono 1999). Once suitable parameters are identified, the AI seismic inversion process is conducted. This process combines previously obtained data and parameters including well log data, post-stack seismic data, wavelets, horizons and regression coefficient values. The analysis uses model-based inversion (MBI) to determine the correlation and error between the initial model and the inversion results (Tullailah et al. 2015). To achieve a high correlation, the wavelet extraction process selects the most suitable wavelet across all wells.

AI is derived by multiplying rock density with the velocity of primary (P) waves. These P-waves are longitudinal compression waves influenced by porosity, matrix and fluid compressibility, rock density and composition (Veeken 2007), making them valuable indicators of hydrocarbon presence. AI is comparable to the concept of acoustic hardness. Hard, incompressible rocks such as limestone generally show high AI values, whereas soft, compressible rocks like clay tend to have lower values (Sukmono 2000). In this study, seismic inversion was conducted using the MBI technique – a post-stack inversion method used to estimate AI from seismic datasets. It is based on the convolutional model, which defines a seismic trace as the convolution of a source wavelet with the earth's reflectivity function. However, seismic traces may be affected by various types of noise – both instrumental and anthropogenic – which can degrade data quality (Wiyatno et al. 2019).

Seismic attributes

Seismic attributes derived from seismic data can be extracted in two different domains – the amplitude and frequency domains. This attribute extraction process is applied to 2D seismic data and then mapped onto the target reservoir horizon using a time window appropriate to the software capabilities, allowing geological information to be imaged from the seismic data. One useful seismic attribute is the RMS amplitude. RMS amplitude represents the square root of the average of the squared amplitudes from the original seismic trace. This characteristic makes RMS amplitude particularly effective in distinguishing between lithologies. High RMS amplitude values are generally associated with lithologies exhibiting high porosity, making this attribute a useful preliminary indicator for identifying potential reservoir zones (Tullailah et al. 2015).

Petrophysical analysis

Petrophysical analysis using interactive petrophysics is a that utilises well log data to maximise software approximation and interpretation in calculating rock property values. Well logging provides data for both qualitative and quantitative evaluation of hydrocarbon zones.

RESULT AND DISCUSSION

Petrophysical analysis

Well log data are subsurface data sensitive to changes in rock layers, making them useful for identifying reservoir target zones. Target zone identification is performed by analysing quick-look interpretations of log responses in the form of single curves. Based on the analysis of well log data from three wells – P-1, P-2 and P-3 – in the Binio Formation, the log data from well P-1 show indications of gas presence, as shown in Figure 1 (marked with a black box).

The Binio Formation in the Lotus Area is a target reservoir zone. The analysis was conducted on the interval between the top horizon of SB-4 Binio and the top horizon of SB-3 Telisa. This interval was analysed to identify reservoir lithology and fluid content.

The analysis in Figure 1 shows a potentially productive zone at a depth of around 2,600 ft. This zone has strong indications of being a gas reservoir, characterised by high effective porosity values. High porosity suggests the presence of large pore spaces, allowing for optimal hydrocarbon fluid accumulation (Serra 1984; Maulana 2018). This makes the zone a prime target for further natural gas exploration in the Central Sumatra Basin. In this zone, the dominant lithology is sandstone, known as a reliable reservoir rock (Sukmono & Abdullah 2001).

Sandstone offers porosity and permeability that favour hydrocarbon movement and storage, making it an ideal medium for fluid accumulation. The reservoir quality indicated by this sandstone lithology supports the zone's productive potential and warrants further investigation to confirm its development prospects.

The area of interest lies at a depth of 2,400–2,800 ft, where the lithology has been identified as sand. The target zone contains gas reservoirs, which can be identified through the characteristics of log curves. Lithology is interpreted using the gamma ray (GR) log, which differentiates between shale and non-shale formations. This method measures gamma radiation from radioactive elements in the rock, typically more abundant in shale.

In the P-1 well log, a GR value of <75 API indicates sandstone lithology. Analysis of the RILD resistivity log shows a curve deflection, suggesting permeability. Additionally, high resistivity values (>10 ohm-m) are thought to result from hydrocarbons trapped in rock pores. This supports the possibility of hydrocarbon accumulation in the formation. Generally, if a reservoir contains hydrocarbons, its resistivity log value tends to be high – sometimes reaching 100 ohm-m – due to the resistive nature of hydrocarbons (Mulyatno et al. 2018). Neutron and density log data were jointly analysed to observe crossover patterns, which are key indicators of hydrocarbon presence. Typically, in the presence of hydrocarbons – particularly gas – a clear crossover appears between the neutron and density logs, with the two curves showing opposing trends. Hydrocarbons cause a decrease in both neutron and density log readings. The crossover between neutron and density logs is a key indicator of hydrocarbon presence (Schlumberger 2016). In well P-1, a significant crossover is observed in the target zone, suggesting that the reservoir likely contains gas. In contrast, wells P-2 and P-3 although they exhibit the same lithology as P-1 (sandstone and shale) based on the GR log show no indication of fluid due to the absence of crossover. These findings emphasize that the Binio Formation reservoir potential is concentrated around the interval penetrated by well P-1, making it the primary target zone for further exploration.

Sensitivity analysis

Cross-plot analysis is performed to assess the sensitivity of AI and porosity logs to variations in lithology and fluid content. The multi-well cross-plot incorporates zoning based on GR cut-off values, as referenced by Munadi (2000) and Prastika et al. (2018). The sensitivity analysis across several wells revealed two distinct lithological zones, as illustrated in Figure 2: a sandstone zone (highlighted in yellow) and a shale zone (highlighted in green).

The sandstone zone is characterised by low GR readings, low AI and low density, with AI values ranging from 10,000 to 16,000 (ft/s)(g/cc). In contrast, the shale zone exhibits high GR values, high AI and high density, with AI values between 16,000 and 23,000 (ft/s)(g/cc). The boundary between these lithologies is defined by a GR cut-off of 75 API, with values below this threshold interpreted as indicative of sandstone. However, lithological separation within the cross-plot is not sharply defined, as overlapping AI values correspond to a range of density values. Density readings between approximately 1.5 and 2.2 g/cc are generally associated with sandstone, while shale typically shows densities between 2.2 and 2.6 g/cc. This overlap is attributed to the fact that AI is influenced by both lithology and the type of fluid present within the rock's pore spaces (Rosid et al. 2019a).

Well Log P-1

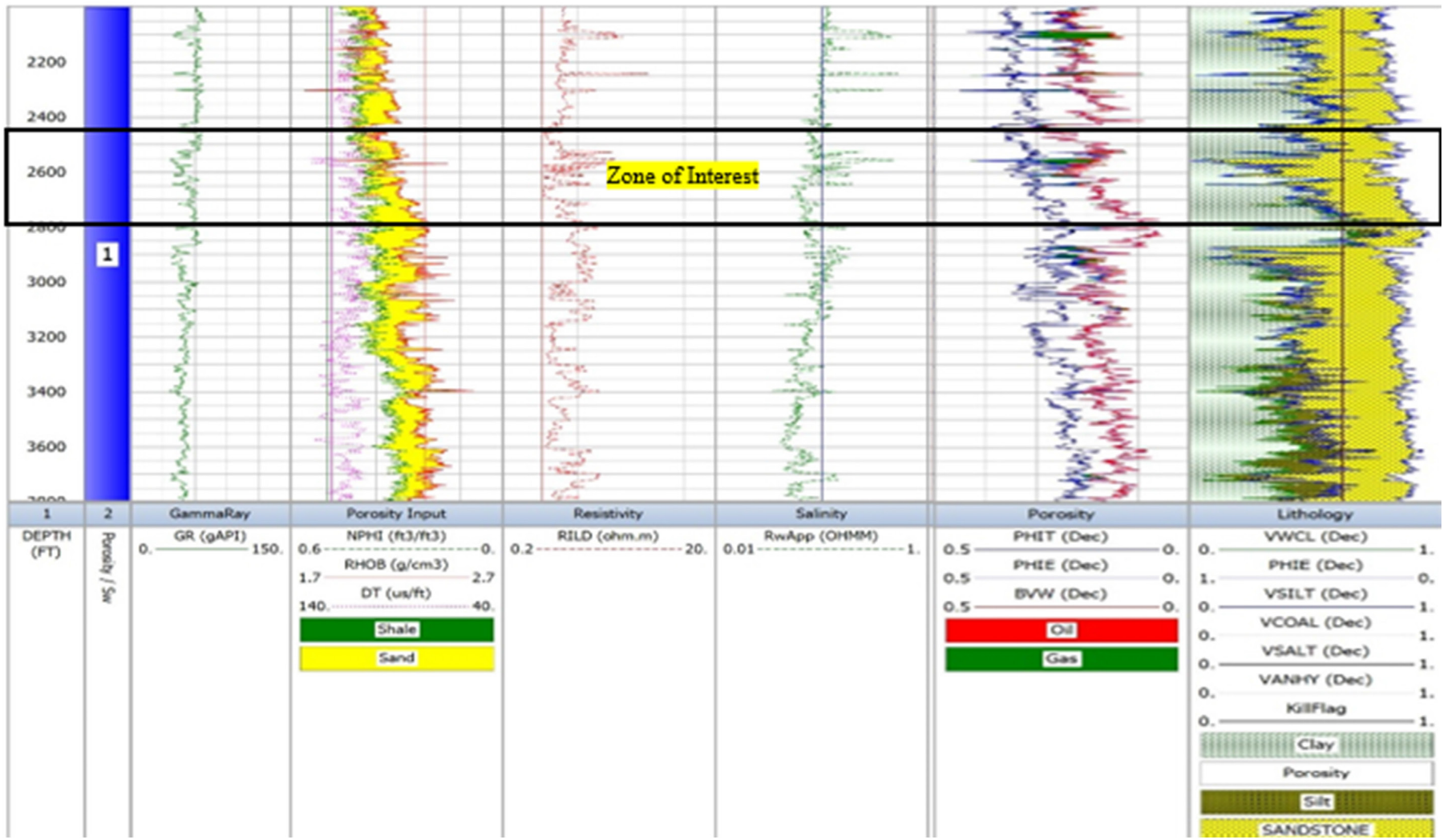

Figure 1. Log data of the P-1 well in the Binio Formation of the Lotus area.

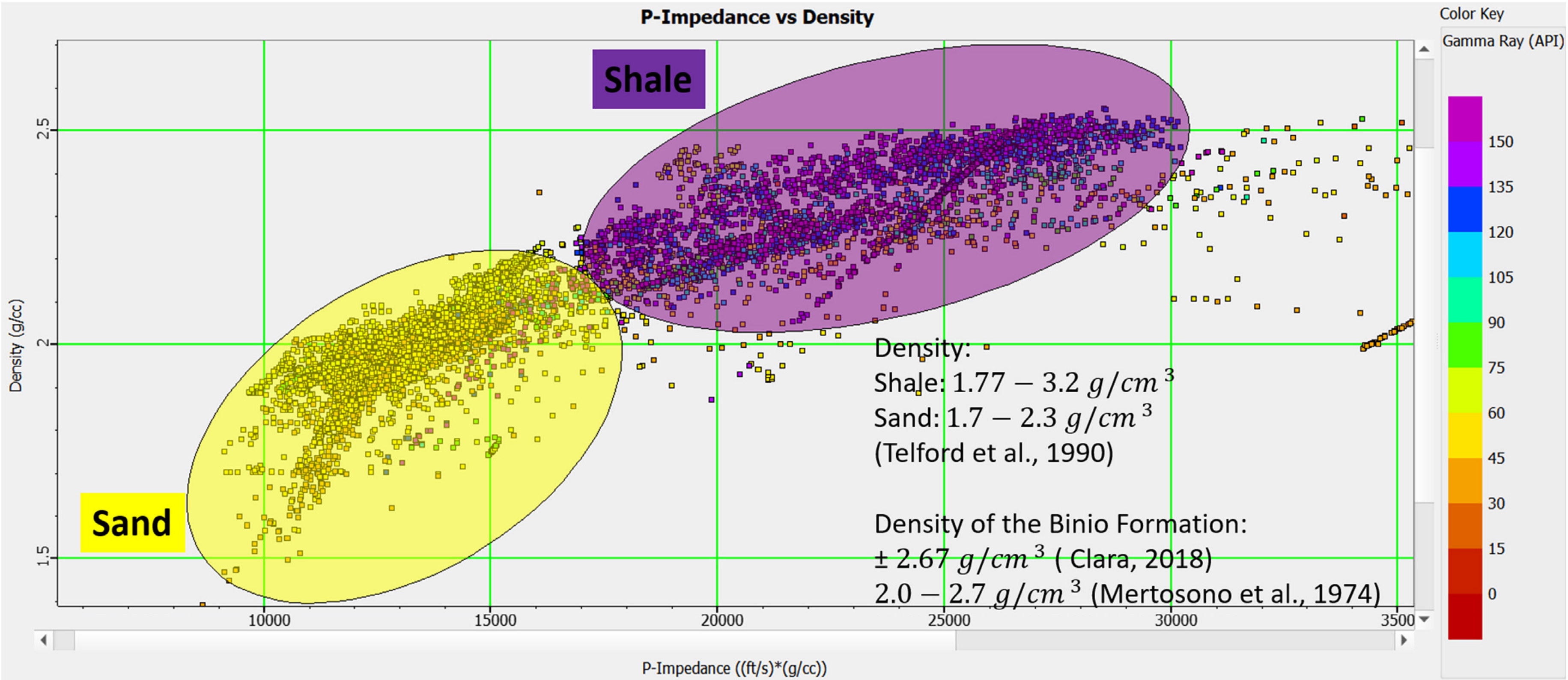

Figure 2. Cross-plot of density and P-impedance with a colour bar of gamma ray values.

Depth structure map

The depth structure map in Figure 3 shows a contour pattern that indicates an anticline structure. This anticline is characterised by an area with a lower time elevation at the centre in purple, gradually increasing outward in green and yellow. The increasingly tight contours around the centre indicate the presence of an anticline crest, which is a classic sign of an anticline fold in seismic geological interpretation. This anticline structure is shown in the red-circled figure. Such structures often host hydrocarbon accumulations in petroleum systems (Sukmono 2007).

Depth structure maps are derived by converting time-domain data into the depth domain using linear equations obtained from checkshot data. Checkshot data provide a relationship between seismic wave travel time and true depth. The depth structure map highlights elevations that could potentially contain hydrocarbons. The depth value map of the Binio horizon uses a colour scale, with purple indicating greater depths and red representing higher elevations. The seismic cross-section shown in Figure 5 reveals the presence of an anticline structure along with several normal faults in the study area. In Figure 5, the yellow box marks the area that will be subjected to AI inversion.

Root mean square attribute

The RMS attribute, derived from amplitude data, is used to identify DHI anomalies that may suggest the presence of hydrocarbons (Zulivandama et al. 2018). Before interpretation, these anomalies must be matched with well data. The attribute results in this area show contrast compared to the surrounding region. As seen in Figure 4, the reservoir area in the Binio Formation near the P-1 well shows a noticeably different colour contrast.

This high amplitude value is due to the impedance contrast at the contact between shale rocks with lower impedance. The lower impedance is likely caused by the presence of hydrocarbons filling the pores of the sandstone. The application of this attribute also outlines the anticline structure of the Lotus Area.

Acoustic impedance inversion

Figure 6 illustrates the correlation between the initial model and the original seismic data, which is an essential step in obtaining reliable AI results. After generating the initial model, a pre-inversion analysis was conducted to assess the degree of similarity between this model and the real seismic data. In this study, the MBI method was applied, with the initial seismic model iteratively adjusted to better align with the actual seismic response, thereby ensuring higher accuracy. A strong correlation value such as the 0.99 recorded at well P-1 – indicates a good match between the synthetic model and the seismic data. The final output of the MBI, which provides estimated AI values from the seismic data, is presented in Figure 7.

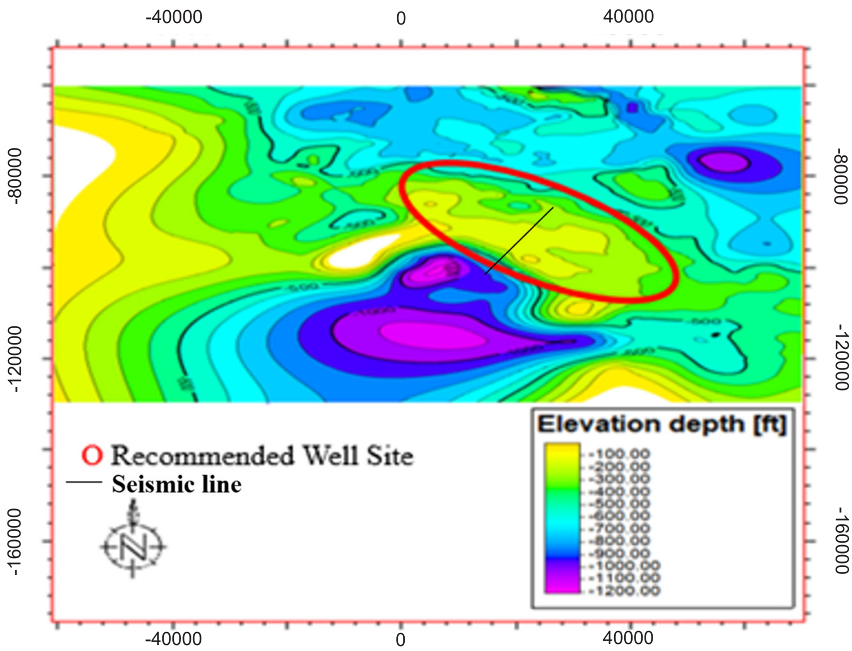

Figure 3. Depth structure map of the Binio Formation in the Lotus area.

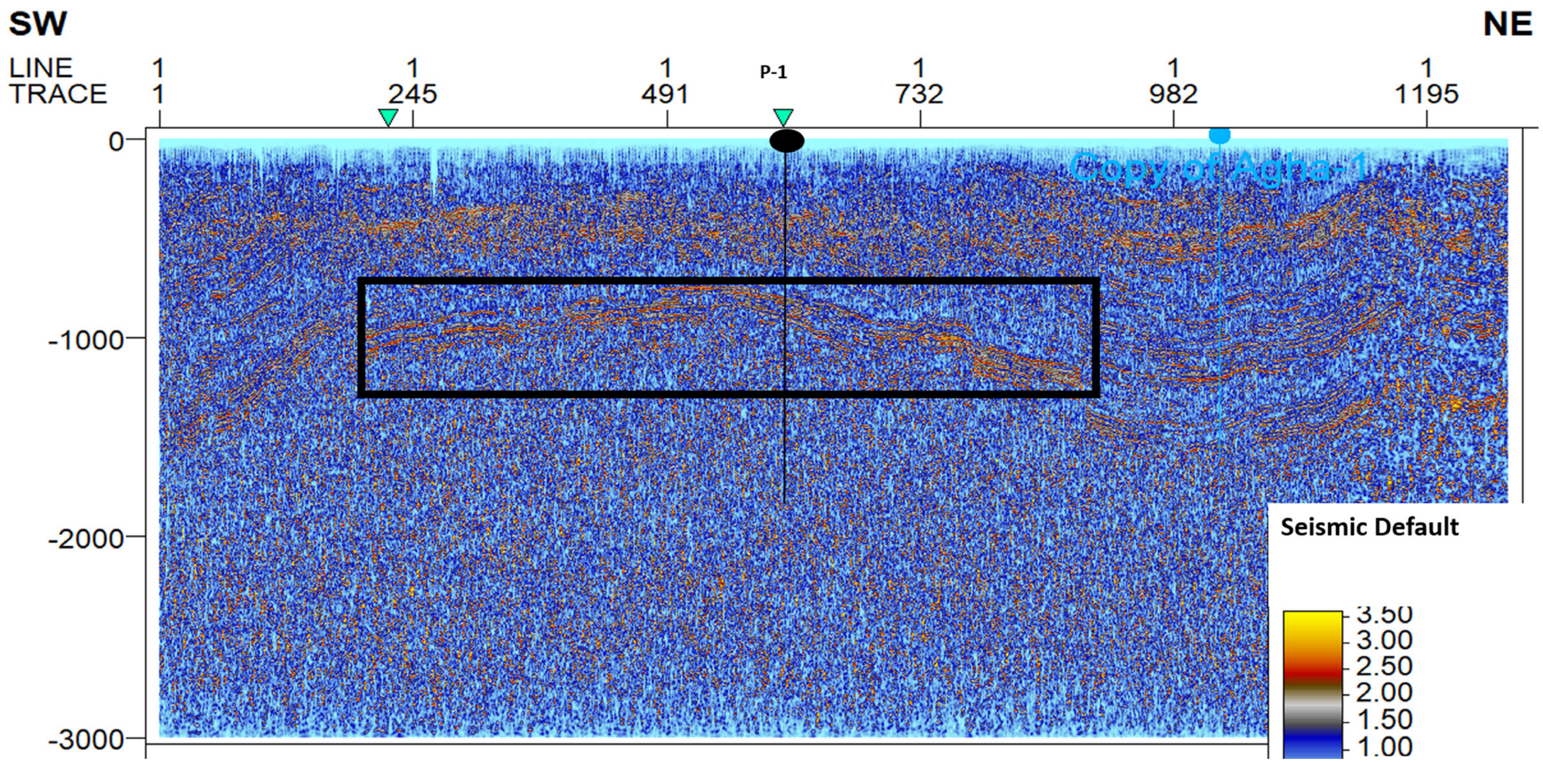

Figure 4. Root mean square attribute on the seismic cross-section of the P-1 well.

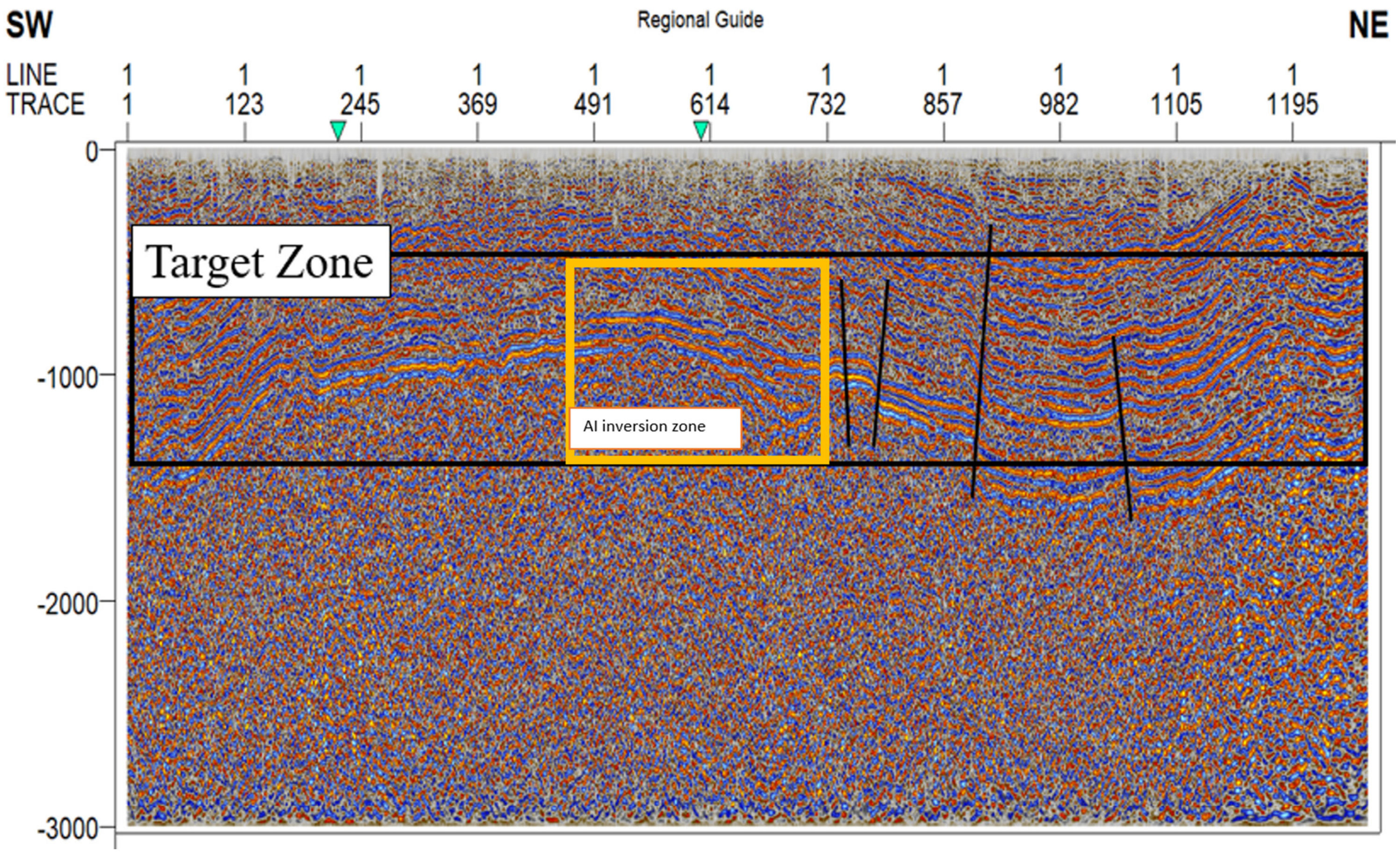

Figure 5. Seismic section of the study area.

The process uses an initial model determined from well log data and refines it iteratively to match the measured seismic data. In practice, this inversion enables geophysicists to obtain a clearer and more detailed picture of the rock and fluid properties within the reservoir. The MBI results for the vertical cross-section of AI values in the sandstone reservoir show a range between 9,670 and 27,070 (ft/s)(g/cc). This range aligns with the results of the previous cross-plot analysis, which indicated that sandstone reservoirs have AI values between 9,000 and 17,000 (ft/s)(g/cc), while shaly sand ranges from 12,000 to 26,000 (ft/s)(g/cc).

This comparison demonstrates that the MBI results accurately describe the lithological distribution, as the derived AI values are consistent with the expected characteristics of sandstone and shaly sand. These results reinforce the interpretation that MBI can be effectively used to distinguish between sandstone and shaly sand reservoir layers based on AI distribution.Porosity is one of the key parameters in reservoir characterisation, particularly in determining the fluid storage capacity of rock. Figure 8 illustrates the porosity distribution within the Binio Formation, with values ranging from 0 to 0.5 v/v.

The target zone, located within the Binio Formation, is predominantly characterised by medium porosity, intersected by zones of higher porosity. The most prominent porous zone, identified as the zone of interest, is located at a depth of approximately 850 ms and exhibits porosity values between 0.33 and 0.4 v/v. This interval is, according to Koesoemadinata (1980), classified as well-porous, and is visually represented by the blue-to-purple colour range.

The high porosity observed in the Binio Formation is attributed not only to its dominant sandstone lithology but also to the presence of interbedded shale layers. These intercalations contribute to the overall porosity by influencing the physical and petrophysical characteristics of the reservoir.

Based on the known relationship between acoustic P-Impedance and porosity, there is an inverse correlation, as shown in Figure 9: low impedance values indicate higher porosity and vice versa (Sukmono 1999). Reservoir rocks with high P-Impedance values tend to be denser or ‘tight’, indicating lower fluid storage capacity (Butar 2023; Hartagung & Rosid 2022; Rosid et al. 2019b). Conversely, in porous sandstone reservoirs such as those in the Lotus Field, P-Impedance tends to be lower, indicating significant pore space for hydrocarbon accumulation. Thus, the seismic inversion results provide a distribution of P-Impedance values that can then be translated into porosity maps. Areas of high porosity are identified as prospective zones for hydrocarbon build-up.

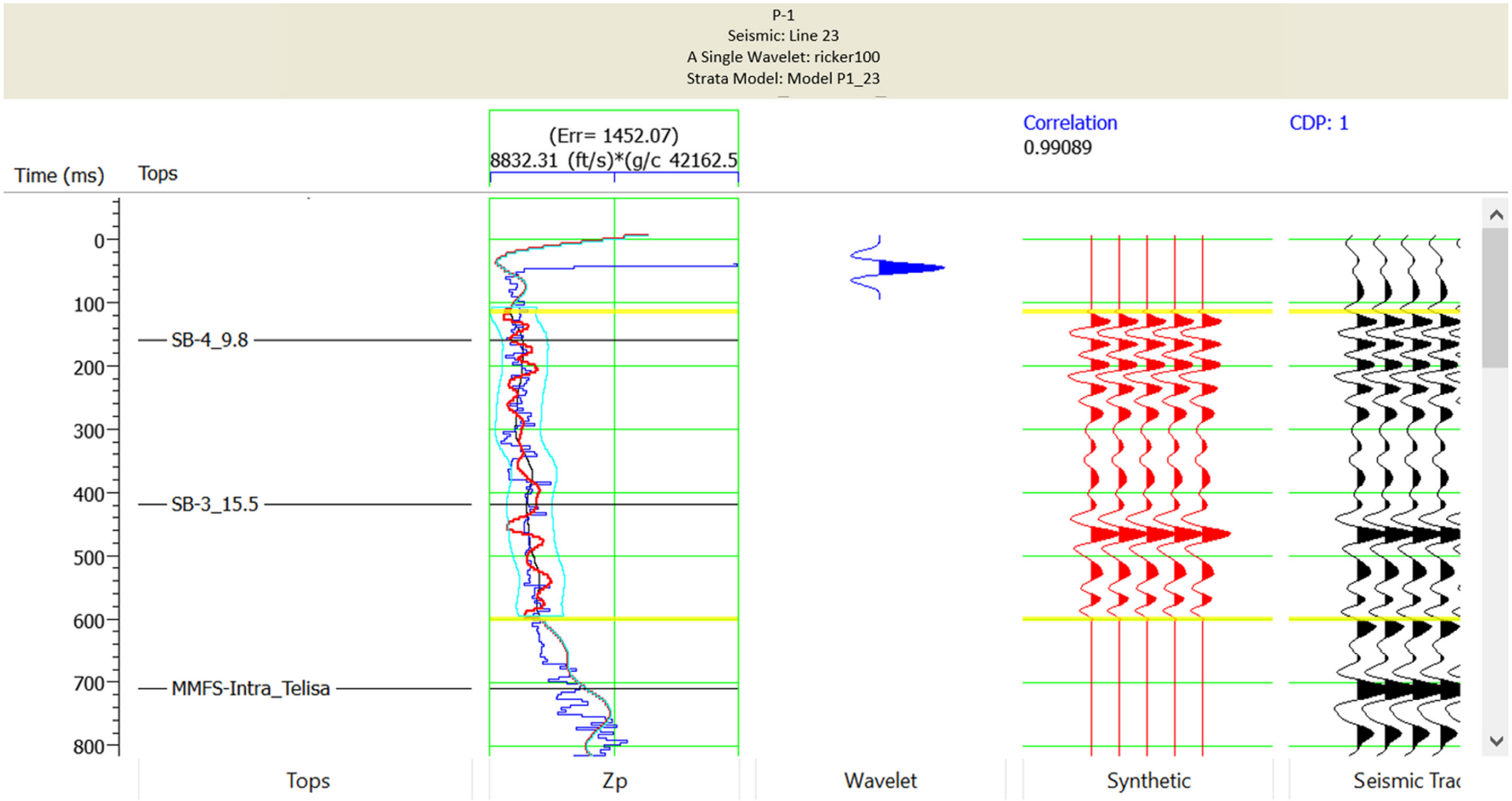

Figure 6. Correlation between initial model and actual seismic data.

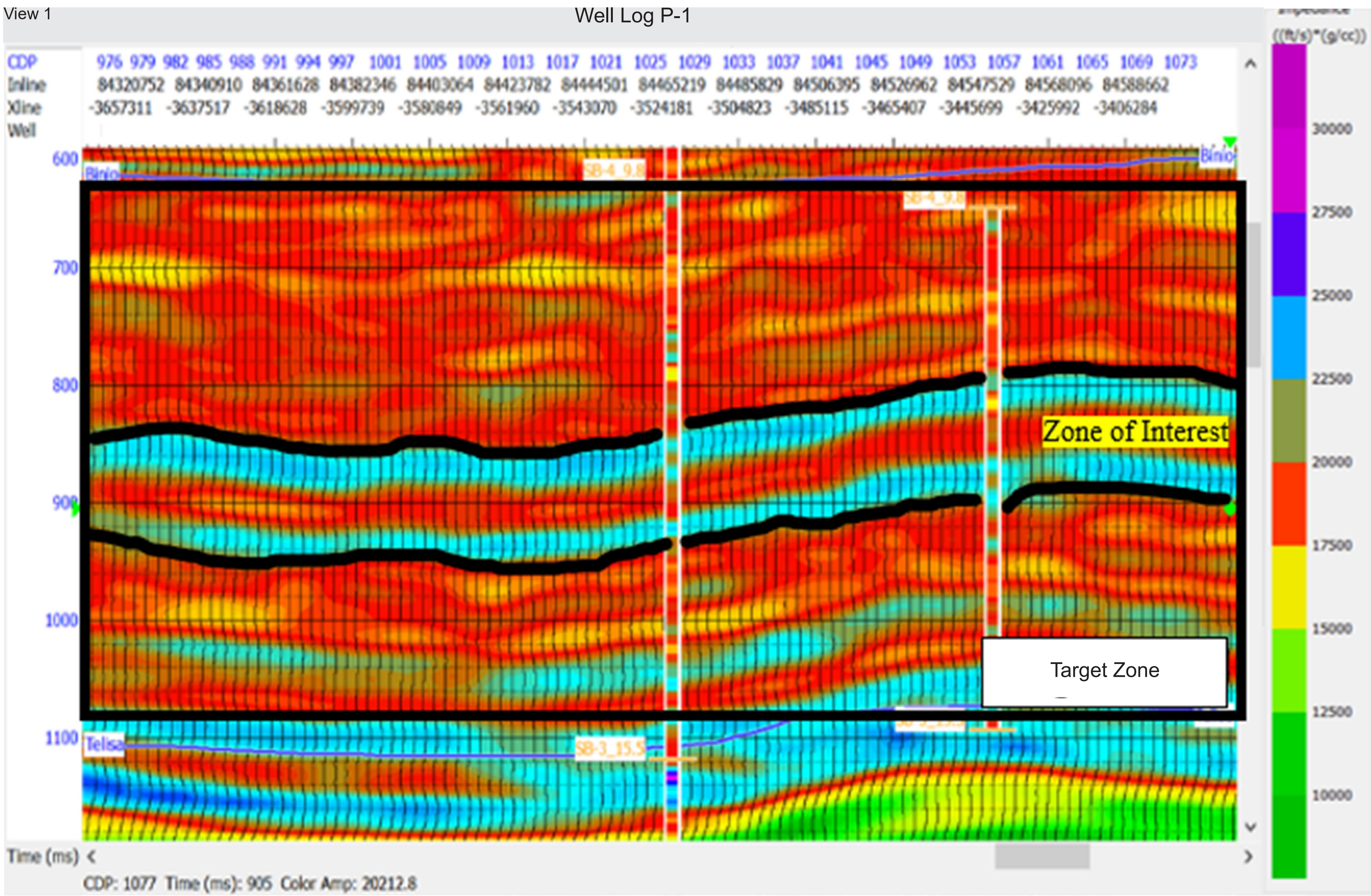

Figure 7. Acoustic impedance section of the Binio Formation (in black box).

Porosity Transformation

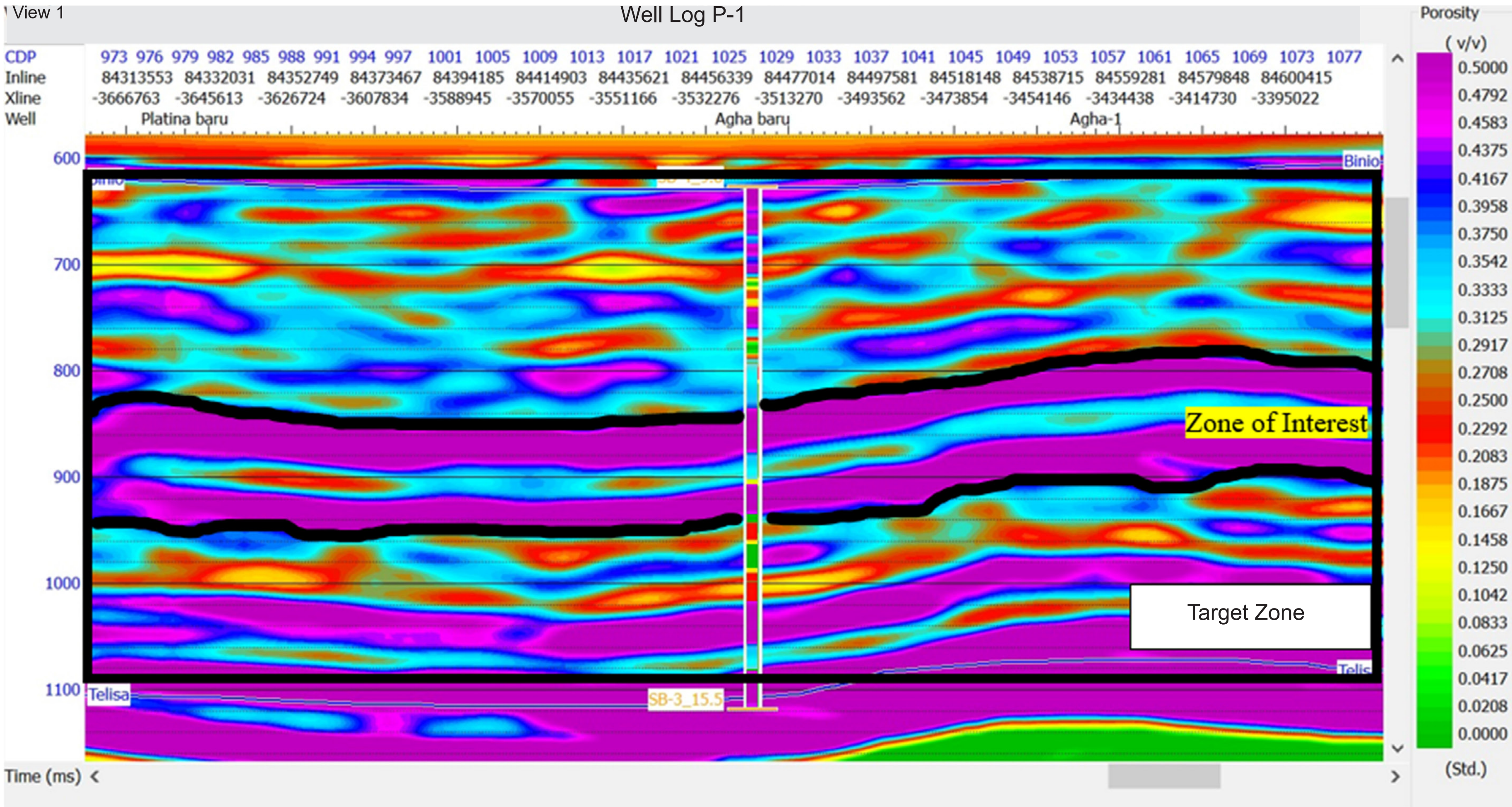

Figure 8. The porosity cross-section of the study area shows the dominance of sandstone with high porosity.

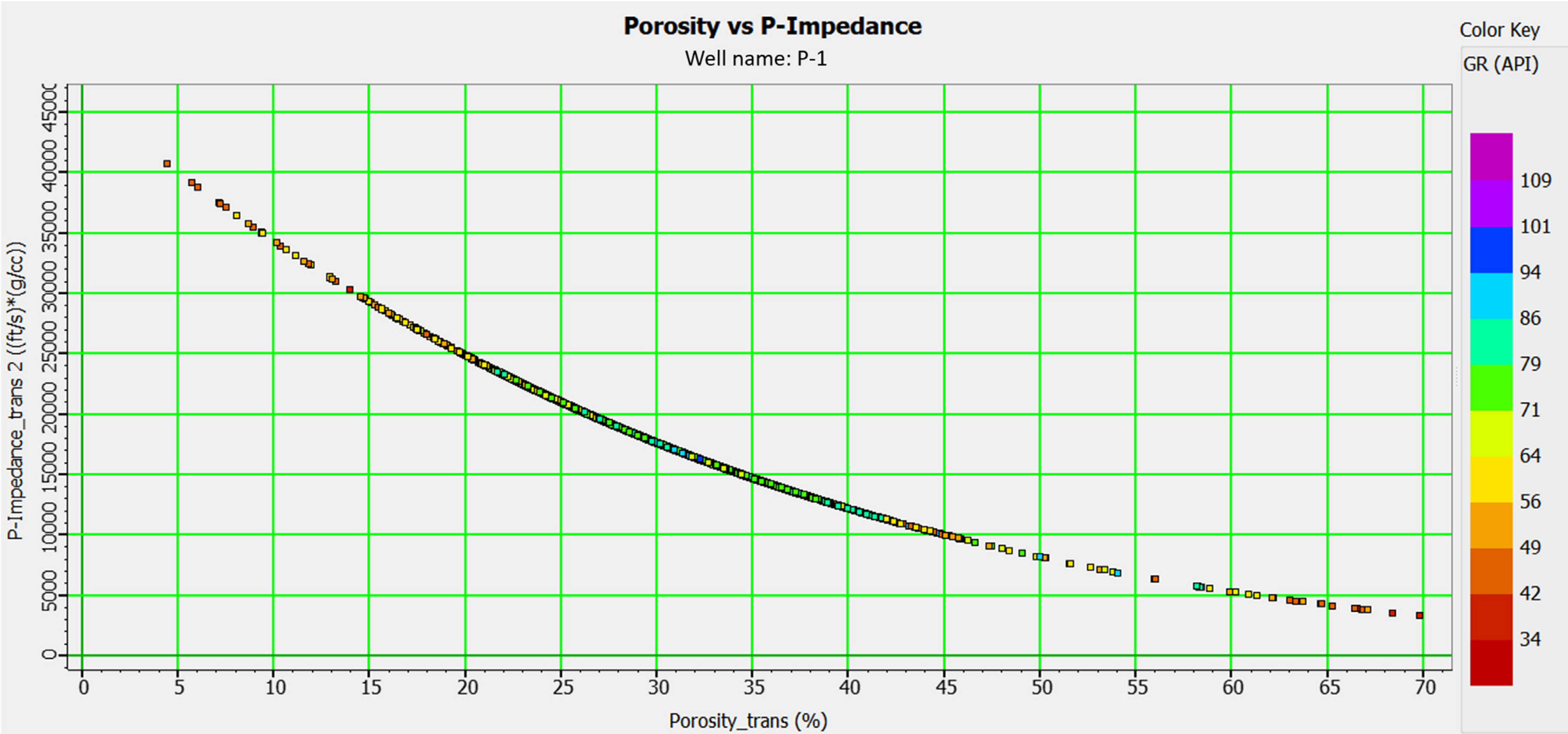

Figure 9. Relationship between P-Impedance and porosity.

CONCLUSION

This study identifies hydrocarbon prospect zones within the Binio Formation of the Lotus Field through an integrated approach combining seismic inversion and petrophysical analysis. Seismic inversion techniques – specifically AI inversion – were used to characterise subsurface lithology and structural features. The results indicate well-distributed porosity within the sandstone intervals. MBI of vertical AI cross-sections in sandstone reservoirs revealed AI values ranging from 9,670 to 27,070 (ft/s)(g/cc), which align closely with well log data indicating high porosity values of up to 0.4 (fraction). Further petrophysical evaluation confirmed the presence of gas-bearing zones in well P-1, reinforcing the hydrocarbon potential of the reservoir at a depth of 2,400–2,800 ft. The identification of structural traps, such as anticlines and normal faults, further enhances the likelihood of hydrocarbon accumulation. Based on seismic interpretation, a new drilling location is proposed near well P-1, at an approximate depth of 200 m within a structural closure. This location is recommended as a promising target for future drilling and is expected to contribute to increased hydrocarbon production in the field.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
AI	Acoustic Impedance	(ft/s)(g/cc)
MBOPD	Thousand Barrels of Oil Per Day	
BSCF	Billion Standard Cubic Feet	
MSTB	Thousands of Stock Tank Barrels	
GR	Gamma Ray	API
CNL	Compensated Neutron Log	%
API	American Petroleum Institute	
RILD	Resistivity Deep Laterolog	ohm-m
PHIE	Effective Porosity	ohm-m
PHIT	Total Porosity	ohm-m

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