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Shallow Gas: From Hazard to Prospect, Prediction of Reservoir Porosity Distribution Based on Log and Seismic Data Analysis

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ABSTRACT - The accumulation of shallow gas in the Mada Field, North East Java Basin, is widespread and constitutes a significant volume, occurring in sandstone of the Early Pleistocene Lidah Formation, as confirmed by well log data and well tests. Initially, this shallow gas was considered a drilling hazard for deeper main reservoirs in the Early Pliocene Mundu–Selorejo Formations. The increasing gas demand and opportunities for new field development have shifted this shallow gas into a potential resource. Therefore, the purpose of this study is to characterize the shallow gas reservoir and identify the sweetspot area to support future development. A model-based seismic inversion technique is used to generate a P-impedance volume, which is subsequently transformed into total porosity. Seismic attributes were utilized to delineate reservoir boundaries, as shallow gas accumulations are typically indicated by amplitude anomalies, including bright spots and polarity reversals. The porosity, seismic attribute, and structure maps were integrated to identify prospective gas-bearing reservoir areas. Petrophysical data show that the target zone of Lidah Formation sandstone contains gamma ray readings of 10-80 API, porosity values of more than 0.33, and P-impedance values of 8,500-13,500 (ft/s)*(gr/cc). Study results indicate that the crossplot reveals a strong inverse correlation between P-impedance and porosity ($R = 0.871$). Low impedance corresponds with the high total porosity that indicates porous sandstone with high saturated gas. Based on the integrated analysis, a prospective gas reservoir area was identified to the south and southeast of the Mada-1 well, situated at the structural crest and characterized by the highest porosity values. This study provides a comprehensive technique for evaluating shallow gas accumulation and offers practical implications for optimizing well placement and development strategies to unlock remaining hydrocarbon potential in mature basins such as the North East Java Basin.

Keywords: shallow gas, P-impedance, seismic inversion, porosity.

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1. Introduction

North East Java Basin, as a mature basin, requires innovative strategies to unlock its remaining potential. New technologies, creative ideas, and fresh perspectives on petroleum systems and geological models are essential. This includes more reliable imaging techniques to explore deeper targets as well as modern engineering solutions designed to overcome complex subsurface drilling challenges (Wijaya et al., 2024).

Mada Field, located in the Madura Strait, North East Java Basin, produces gas from the main reservoir, the Globigerina Limestone of the Mundu-Selorejo Formations. Above this main reservoir lies shallow gas accumulation within the Lidah Formation, confirmed by well logs and well test (HCML 2011). Shallow gas is predominantly biogenic, formed through microbiological processes (Perdana et al., 2023). In many cases, the presence of shallow gas is associated with drilling hazards because penetration of a shallow gas-bearing formation can cause rapid gas influx into the wellbore, potentially resulting in well-control problems such as kicks and blowouts. Although shallow gas accumulations are commonly localized and discontinuous, when the gas is trapped within regionally continuous reservoir sands and sealed by impermeable strata, shallow gas reservoirs can also be laterally expanding, forming significant accumulations that are economically visible for development. One of the successful examples of shallow gas field development in Indonesia is in the Bentu PSC area, located in Riau Province (Perdana 2023).

This study focuses on reservoir characterization to support potential future development of this shallow gas resource. Two wells and 3D PSTM seismic data were used in this study. Reservoir characterization requires understanding key petrophysical properties, particularly porosity, which indicates the volume of pore space available for hydrocarbon storage. High porosity in gas reservoirs generally corresponds to higher gas content and defines a target zone for development.

Total porosity distribution in the study area was predicted using P-impedance volume, resulting from the seismic inversion process. The use of well data will improve prediction accuracy (Berge et al., 2002). P-impedance, defined as the product of rock density and P-wave velocity, is inversely related to porosity (Munadi 2005). P-impedance values correlated with porosity through a crossplot of well log data, allowing conversion of P-impedance volume into porosity volume. The resulting porosity distribution reflects reservoir quality. Zones exhibiting high porosity are considered sweetspots due to their enhanced gas storage potential.

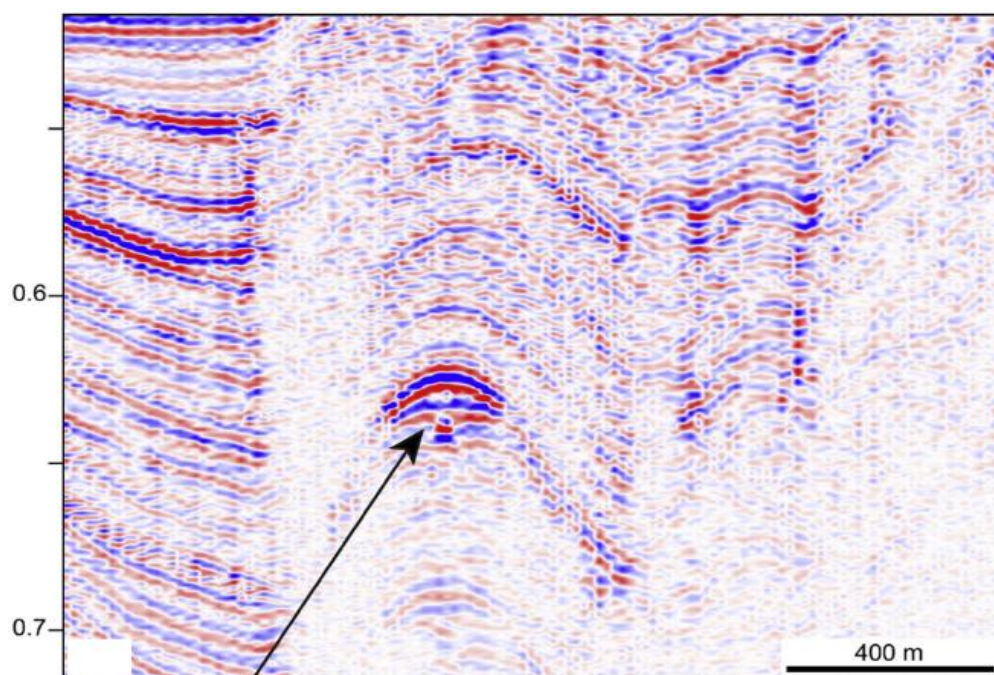


Figure 1.
Phenomena of seismic anomalies caused by shallow gas presence (Cukur et al., 2013)

Seismic attributes used to delineate reservoir boundaries (Chopra & Marfurt 2006). These results, combined with the structure map, provide critical input for development planning, particularly in determining optimal well locations.

However, increasing energy demand and the maturity of hydrocarbon basin have shifted the perspective toward re-evaluating shallow gas as a potential resource. The main research gap lies in the limited integration of seismic inversion and log analysis to quantitatively predict reservoir properties such as porosity in a shallow gas system. This study offers a quantitatively driven workflow for shallow gas reservoir characterization, contributing to improved resource evaluation in a mature basin.

2. Methodology

2.1 Shallow gas

Shallow gas has been an important topic for geoscientists for decades. Generally, it's more often considered as a geohazard than a hydrocarbon resource. Shallow gas significantly alters the physical properties of sediments, particularly by reducing P-wave velocity. It also affects rock geomechanical properties, making it an important consideration in offshore construction projects such as bridges and subsea structures (Kim et al., 2020). In hydrocarbon drilling operations, shallow gas can pose serious risks, as overpressured gas accumulations may trigger kicks or blowouts.

In the current condition of increasing energy demand, interest in exploring and utilizing shallow gas accumulations has grown. When present in significant volumes, shallow gas can be a valuable energy resource. Shallow gas offers advantages such as easy accessibility, wide distribution, and relatively limited exploitation to date, making it a promising future energy source (Cukur et al., 2013).

The origin of shallow gas remains debated. Some studies suggest a thermogenic origin from deeper sources requiring long-distance vertical migration, while others propose a biogenic origin formed in situ at shallow depths with minimal migration (de Bruin et al., 2022).

Seismic reflection methods are highly effective in identifying shallow gas, which commonly appears as anomalies such as bright spots, pockmarks, seismic chimneys, acoustic blanking, and mound-like structures associated with fluid escape. Figure 1 shows phenomena of seismic anomalies caused by shallow gas presence (Cukur et al., 2013).

2.2 Seismic inversion

Seismic inversion is a method that is utilized to predict rock properties such as porosity, thickness, lithology, and hydrocarbon saturation from seismic data (Berge et al., 2002). Seismic inversion is widely employed to derive quantitative rock property models from seismic survey data (Vashisth et al., 2026). Seismic inversion integrates seismic data, which have high horizontal resolution, with well data, which provide high vertical resolution, allowing for a more accurate representation of subsurface reservoirs (Sukmono 2007).

One commonly used method is model-based seismic inversion. This method starts with an initial model derived from interpreted seismic horizons and well data, which is then refined step by step iteratively (Munadi 2005). The advantage of this method lies in the strong user control over input parameters, ensuring that the inversion result is consistent with data quality and geological constraints.

Model-based inversion uses forward modeling to generate synthetic seismic traces by convoluting the initial impedance model with a source wavelet. These synthetic traces are compared with actual seismic traces to calculate an error trace. The inversion process continues iteratively until the root mean square (RMS) error is minimized or no further convergence is achieved (Cooke & Cant 2010).

If the error remains significant, a sensitivity matrix is computed, linking impedance model parameters to the synthetic response. Mathematically, this step computes the partial derivatives of the current synthetic trace with

respect to the impedance model parameters (layer thickness and impedance values). Each derivative represents a seismic trace, and collectively they form a sensitivity matrix with m rows (number of seismic samples) and n columns (number of model parameters).

The next step is to calculate corrections or updates to the current impedance model using the above error trace and the sensitivity matrix. For the mathematically inclined, these updates come from the truncated (linearized) Taylor-series approximation of the forward model, which is rewritten in Equation 1,

$$F(I) - F(IG) = \text{error trace} = \frac{\partial F(IG)}{\partial (IG)} = (I - IG) \quad (1)$$

where I , IG , F , $\frac{\partial F(IG)}{\partial (IG)}$, and $(I - IG)$ are the unknown vector of parameters that describes the real earth's impedance profile, the user supplied 'initial guess' for I that will be iteratively refined in the inversion, the forward model algorithm, the sensitivity matrix and the vector of impedance model updates to be solved for, respectively. Once $(I - IG)$ is obtained, the desired result is $I = IG + (I - IG)$.

Usually, an exact solution to this equation does not exist, so a least squared error technique is used to solve for the impedance model updates term. Furthermore, since Equation 1 is a truncated Taylor series expansion (i.e., an approximation), the above equation needs to be applied iteratively. Once a seismic trace has been processed, the inversion algorithm proceeds to the next input trace and continues iteratively until all traces within the 2D line or 3D seismic volume have been inverted.

3. Result and discussion

3.1 Target zone identification

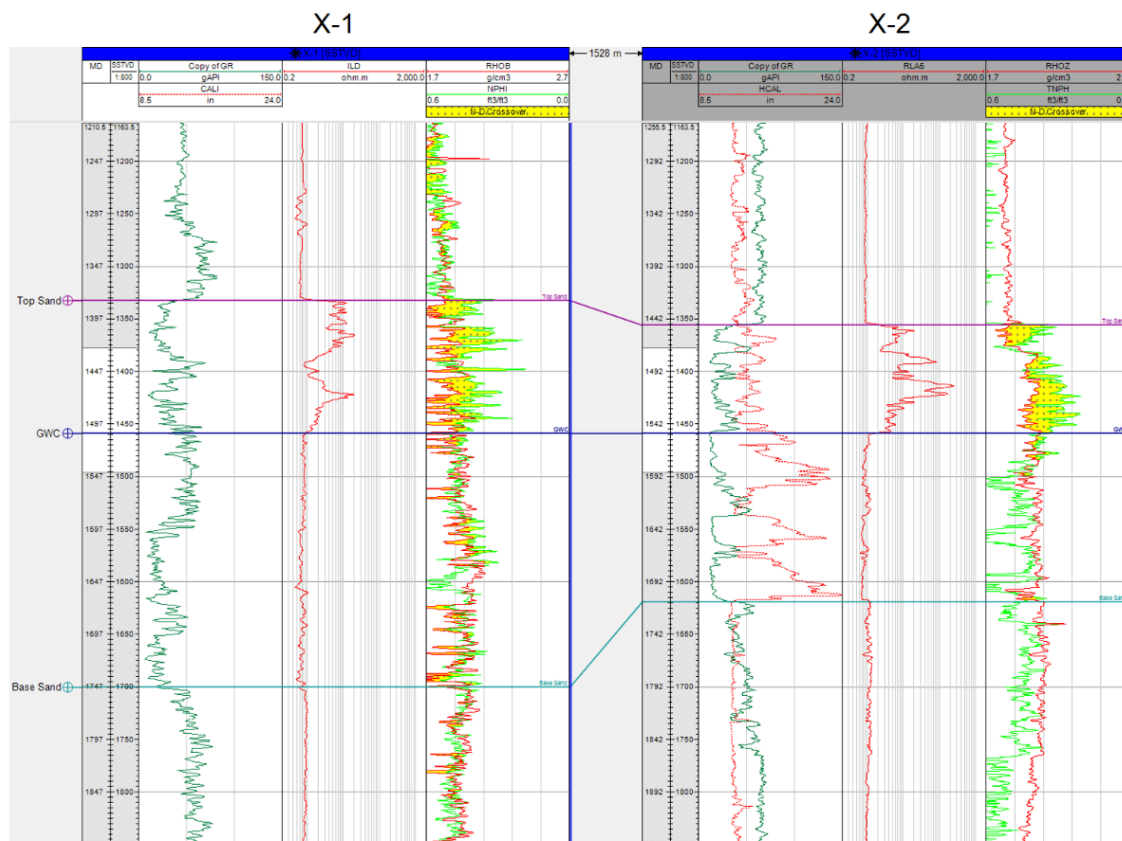


Figure 2.
Log correlation of Mada-1 and Mada-2 wells showing the gas-bearing interval from the Top Sand to the Gas-Water Contact (GWC)

Target zone identification is conducted through integrated well log analysis and correlation among two wells were used in this study (Figure 2). The gamma ray (GR) log plays a key role in distinguishing lithology, where the sandstone interval is indicated by low GR values of 10-40 API. The shale interval shows a high GR value of more than 50 API. In addition, hydrocarbon-bearing zones are generally associated with a high resistivity response of 2-250 Ohm.m, compared to water-bearing formations with less than 1 Ohm.m.

Gas presence can be further recognized through neutron-density log separation, where gas-filled intervals produce a noticeable crossover between the two curves. This characteristic response serves as a reliable indicator of gas presence within the reservoir. Gas presence confirmed by DST and MDT tests. Gas samples analysis result indicates 99% methane composition. Based on the analysis, the shallow gas interval in well Mada-1 is observed at a shallower depth and thicker compared to that in well Mada-2. This analysis suggests lateral heterogeneity in reservoir distribution and quality across the study area.

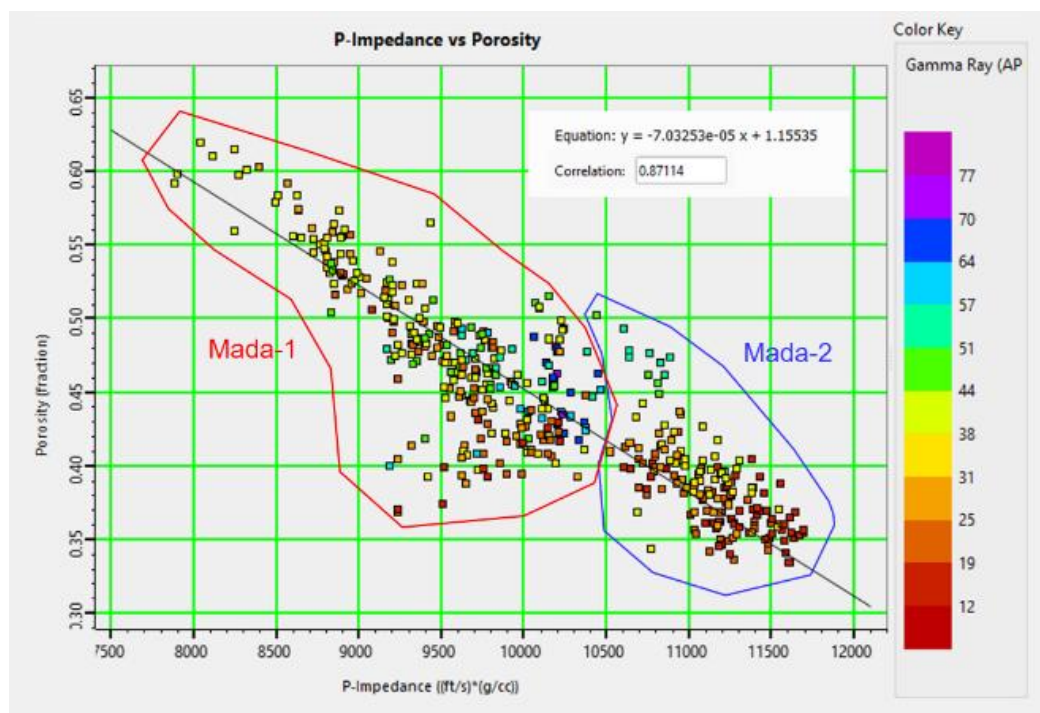


Figure 3.
Linear relationship of P-impedance versus total porosity crossplot
in the gas interval of Mada-1

3.2 Crossplot analysis

A crossplot analysis was conducted prior to the seismic inversion stage to evaluate whether the inversion results, particularly P-impedance values show a reliable correlation with porosity. This analysis was applied to the gas zone in both wells. The crossplot directly visualizes the relationship between P-impedance and porosity; it provides insight into how variations in impedance correspond to changes in porosity within the reservoir interval. Porosity log that used is total porosity, which has been validated using core porosity from the Mada-2 well; the value is 0.426. In general, total porosity in Mada-1 and Mada-2 wells is high, likely due to unconsolidated (loose) sandstone associated with relatively shallow burial depth. The inside gas interval crossplot result (Figure 3) shows a strong linear relationship, with a correlation coefficient of $R = 0.871$, suggesting an inverse correlation between P-impedance and porosity. Specifically, lower porosity values in the range of 0.35-0.40 are associated with higher P-impedance values of approximately 10,700-11,500 (ft/s)*(g/cc), whereas higher porosity values more than 0.45 correspond to lower P-impedance less than 10,000 (ft/s)*(g/cc). Increasing porosity leads to a decrease in P-impedance (Fuchs 2012). This result is consistent with the physical understanding that more porous rocks generally have lower density and velocity (Munadi 2005). Based on this logs crossplot, a regression Equation 2 was derived.

$$Por = -7.03253e^{-5} * Pimp + 1.15535 \quad (2)$$

where *Por* and *Pimp* are total porosity (fraction) and P-impedance (ft/s*gr/cc), respectively. This equation is subsequently used to transform the P-impedance volume obtained from seismic inversion into a porosity volume.

3.3 Seismic interpretation

After defining the target zone, the next step is to perform seismic interpretation. The interpretation workflow begins with a well-seismic tie, which serves as the fundamental reference for horizon picking on seismic data. The well-seismic tie process involves integrating well log data, which is recorded in the depth domain, with seismic data in the time domain. This process started by generating a synthetic seismogram through the convolution of a seismic wavelet with a reflection coefficient series derived from the impedance log. The wavelet was determined using a statistical method, extracted around the well location. Subsequently, the synthetic seismogram matches the actual seismic trace by stretching and squeezing the signal to achieve optimal correlation. This technique ensures an accurate alignment between geological markers in the well and seismic reflections. The horizon picking process is then carried out based on the result of the well tie, by continuously tracking the reflector across the seismic volume.

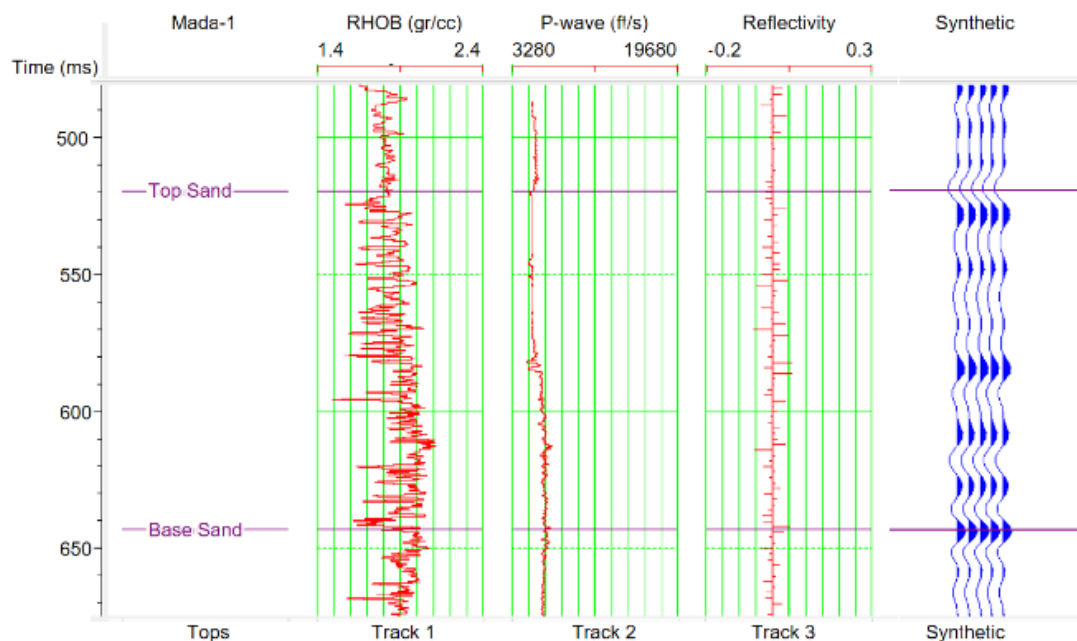


Figure 4.

Synthetic seismogram of the Mada-1 well showing the seismic response of the Top and Base Sand

In this study, seismic interpretation was performed on horizons representing key stratigraphic boundaries: Top Sand, which coincides with the Top Shallow Gas and Base Sand horizons. The Top Shallow Gas horizon is interpreted as a negative seismic event within the gas-bearing zone, while below the gas water contact (GWC), it appears as a positive seismic event. The presence of gas is commonly indicated by polarity reversal at the top of the gas-bearing area. This changes the impedance contrast from an increase to a decrease, resulting in the polarity of the seismic response being reversed (Hilterman 2001). Base Sand horizon interpreted as a positive seismic event, indicating a consistent increase in acoustic impedance across this boundary. This positive polarity typically reflects the transition to a higher impedance layer below the sandstone interval. The synthetic of Mada-1 well displayed in Figure 4. The cosine phase seismic attribute is utilized to support seismic interpretation, particularly in areas where the original seismic data have low reflector continuity. This lack of continuity is commonly observed where a reduction in acoustic impedance could weaken or distort seismic amplitudes. The application

of the cosine phase attribute enhances the continuity and clarity of seismic reflectors by emphasizing phase information rather than amplitude. Phase displays emphasize continuity or discontinuity in the seismic reflection pattern (Chopra & Marfurt 2007). It is useful for tracking horizons across zones with amplitude dimming or signal degradation. Seismic interpretation displayed on Figure 5.

The interpreted horizons were ultimately converted into a structure map, which used to define reservoir boundaries and provide lateral constrains for the inversion process. In this context, horizon interpretation plays a critical role in building the initial model and directly influences the quality and reliability of the final inversion result.

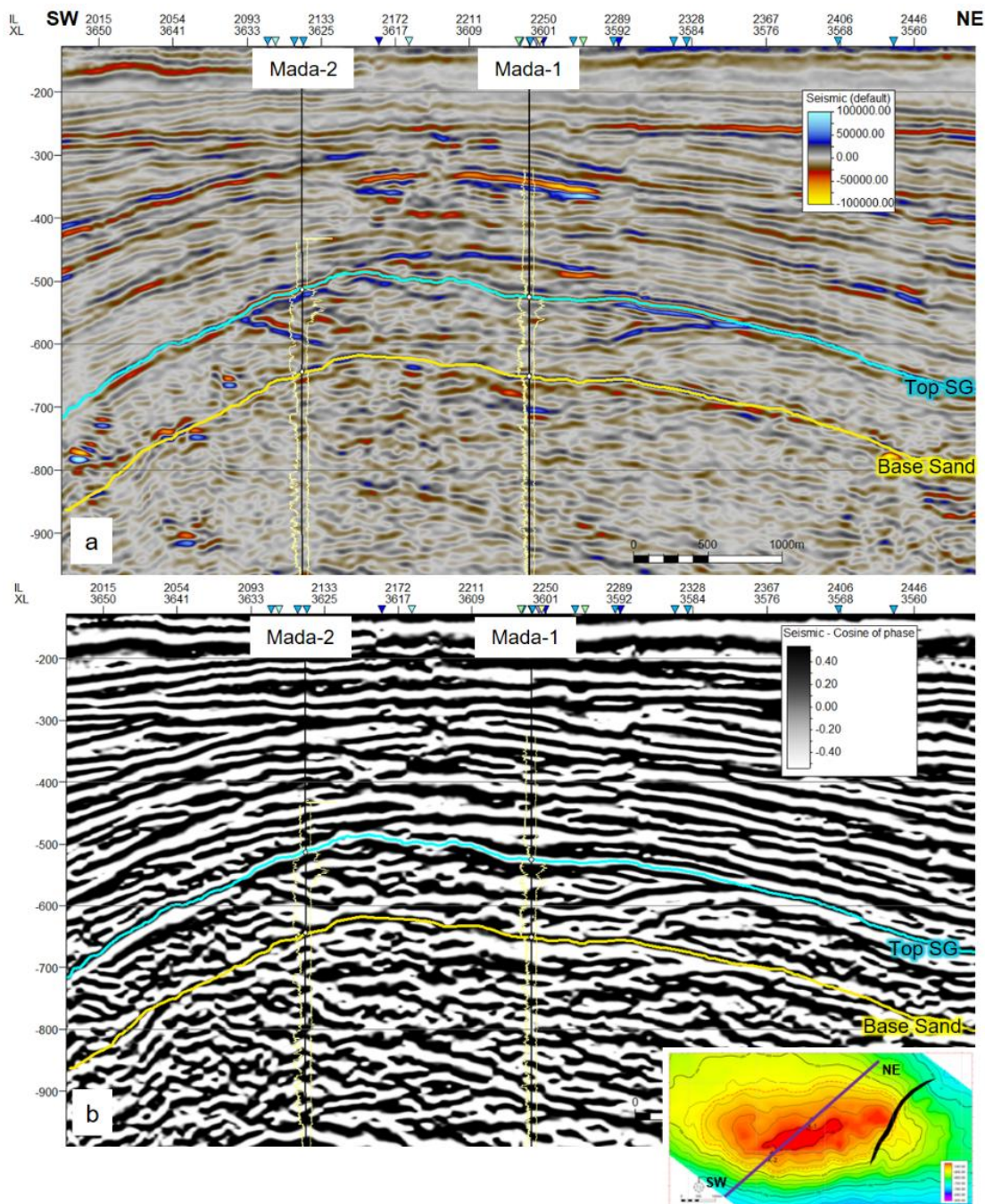


Figure 5.
Seismic interpretation of Top Shallow Gas and Base Sand on amplitude volume (a) and cosine phase volume (b)

3.4 Initial IModel

Seismic data are bandlimited and lack low-frequency information, typically below approximately 10 Hz (Fuchs 2012). As a result, seismic inversion alone cannot fully recover absolute impedance values, but only resolves relative contrasts associated with higher frequency components. Therefore, the low frequency model is required to provide the missing long-wavelength trend of impedance. The initial model is a critical component of model-based inversion, providing the low-frequency trend that ensures geologically reasonable results (Simm & Bacon 2014).

In this study, two wells containing velocity and density logs were utilized to construct the initial model, which provides the below seismic bandwidth component of the inversion spectrum, thereby enhancing the overall data bandwidth. The modelling interval is defined on the target zone between 300 and 1,000 ms. P-impedance value from each well is distributed by interpolating across areas between wells and extrapolating them into regions beyond well control. This distribution is constrained and guided by two interpreted horizons, Top Sand (Top Shallow Gas) and Base Sand. A high-cut filter with a 10-15 Hz taper was applied to the initial model building. This parameter was determined by frequency bandwidth analysis of the seismic data that used in this study.

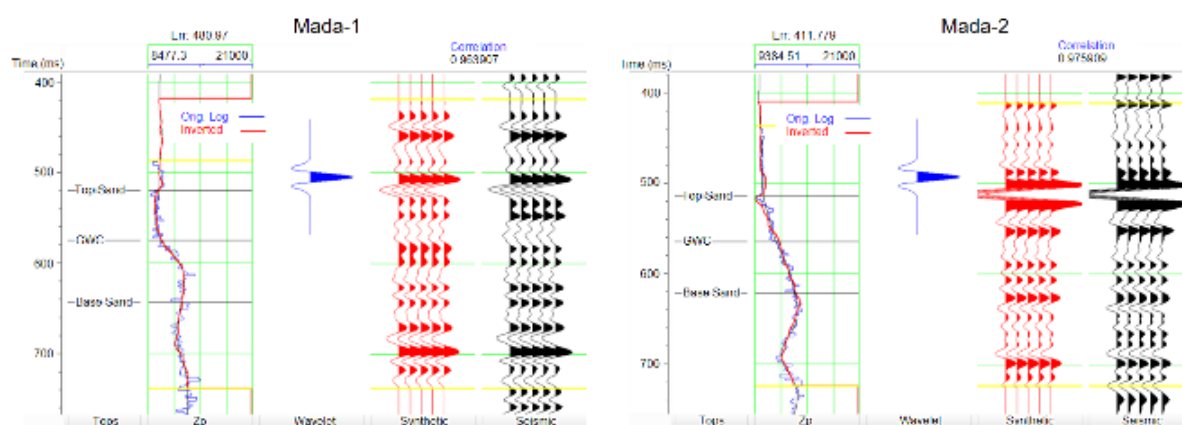


Figure 6.

Pre-inversion parameter analysis of the Mada-1 and Mada-2 wells in the log and seismic data indicates the robustness of the inversion result

3.5 Pre-inversion parameter analysis

Inversion parameter analysis was conducted to determine the most suitable set of parameters prior to performing seismic inversion. In this analysis, two key aspects were evaluated: the error between the P-impedance log and the P-impedance inverted, and the correlation between synthetic traces and seismic traces. These are essential for assessing how well the inversion results represent the subsurface properties and how closely they match the original seismic response.

The selected inversion parameters demonstrated a lower error and a higher correlation compared to other parameters were evaluated during the analysis. Those parameters include a high-cut filter in the range of 10-15 Hz, model constraint value 0.6, and 10 step iterations. These parameters produced satisfactory outcomes (Figure 6), as evidenced by inverted P-impedance curves closely matching the well log-derived P-impedance, with RMS error values of 480.97 in well Mada-1 and 441.78 in well Mada-2. Additionally, the strong correlation between the seismic and synthetic traces is reflected in the high correlation coefficients of 0.964 and 0.976 for Mada-1 and Mada-2 wells, respectively. This result indicates the robustness and reliability of the inversion result.

3.6 Inverted P-impedance volume

Model-based inversion in this study performed using a post stack 3D seismic volume. The analysis focuses on the shallow gas interval between Top Sand (Top Shallow Gas) and Base Sand (Figure 7). Low impedance values are observed, approximately 9,000-9,500 (ft/s)*(g/cc) in yellow color, indicating porous sandstone filled by gas.

P-impedance is highly sensitive to fluid changes (Othman et al., 2022). The presence of gas in a reservoir has a significant effect on seismic response, primarily by reducing impedance. This occurs because gas has both lower bulk density and P-wave velocity of the rock. The P-wave velocity drops dramatically when gas is introduced into the reservoir (Russell & Hampson 2006). As a result, gas saturated formations typically have lower acoustic impedance compared to the same formations filled with water or oil. Moderate and high P-impedance, approximately 10,500-12,500 (ft/s)*(g/cc), observed below GWC and shale interval below Base Sand horizon.

A relatively flat GWC was observed in well Mada-1, suspecting a fluid contact within the reservoir. However, this behavior appears to be disturbed in well Mada-2, where the P-impedance shows an increasing trend from the Top Shallow Gas down to GWC. This upward decrease in impedance contrast suggests a deviation from the expected fluid distribution, which may indicate heterogeneity within the reservoir, such as variations in lithology and fluid saturation.

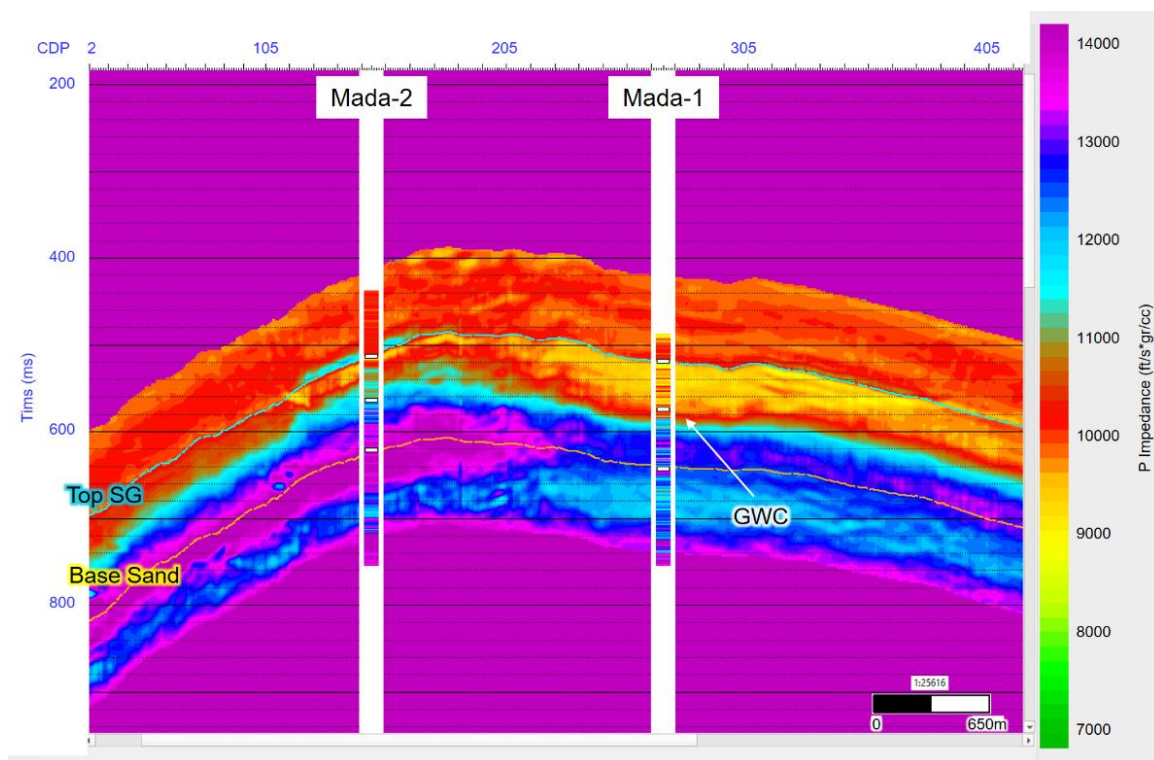


Figure 7.
Inverted P-impedance section across Mada-1 and Mada-2 wells
indicates heterogeneity within the reservoir, where low P-Impedance shown in yellow color

3.7 Attribute seismic

A seismic attribute is a quantitative measure of a seismic characteristic of interest (Chopra & Marfurt 2006). Seismic attributes play a key role in predicting and mapping reservoir characteristics, including facies distribution, lithology, pore-fluid content, and the spatial distribution of reservoir units (Rezaei et al., 2026). Seismic attributes in this study were primarily utilized to delineate the distribution of the gas reservoir. The presence of gas in this study is indicated by a polarity reversal at the top of the gas-bearing area. It serves as a key diagnostic feature in identifying hydrocarbon accumulation. Amplitude-based seismic analysis applied to map the spatial extent of gas-bearing zones. An anomaly in seismic amplitude interpreted to highlight areas affected by gas saturation, allowing for clearer delineation of the reservoir boundaries (Figure 8).

Red colors represent negative seismic amplitudes, which are an indicator of gas presence within the reservoir. These negative amplitudes are typically associated with a decrease in acoustic impedance caused by gas saturation. In contrast, blue colors correspond to positive amplitudes, indicating areas with no gas presence, where the reservoir is filled with water and maintains relatively higher acoustic impedance.

3.8 Conversion of inverted P-impedance volume to porosity volume

The ultimate goal of rock physics is to relate seismic properties such as acoustic impedance to reservoir parameters including porosity (Dvorkin et al., 1994). Impedance volumes derived from inversion are commonly used to predict porosity through empirical relationships calibrated at wells (Chopra & Marfurt 2007). Seismic inversion outputs serve as the primary input for this transformation, where P-impedance volumes calibrated with well data are then used to estimate porosity across the entire seismic volume (Vorobiev et al., 2025).

The conversion of the acoustic P-impedance volume derived from inversion into a total porosity volume was carried out based on the crossplot analysis performed in the previous step. Once the relationship between acoustic impedance and porosity is established from well logs, seismic inversion results can be transformed into porosity estimates (Russell & Hampson 2006). This relationship, expressed in Equation 2, represents the correlation between P-impedance and porosity in this study.

This approach allows for the prediction of porosity variations away from limited well locations, enhancing reservoir characterization and reducing uncertainty in subsurface interpretation (Dolberg et al., 2000). This method provides an effective way for generating 3D porosity cubes that describe the spatial distribution of reservoir properties. Precise porosity estimation is critical for effective exploration and production, as it directly influences reservoir characterization, recovery efficiency, and field development strategies (Rezaei et al., 2026).

The total porosity distribution across wells Mada-1 and Mada-2, as shown in Figure 9, reveals distinct variations in reservoir characteristics between the two locations. In the Mada-1 well, porosity values are relatively high, more than 0.40, which indicates a well-developed and high-quality reservoir zone. Additionally, a relatively flat GWC was observed in this area, indicating a stable fluid interface within the reservoir.

In contrast, the porosity profile in the Mada-2 well shows a different trend. Instead of maintaining consistently high values, the porosity gradually decreases with depth, from approximately 0.40 at the Top Sand (Top SG) to around 0.30 near GWC. This downward reduction in porosity suggests changes in fluid saturation within the reservoir and variations in lithology, indicating the presence of a transition zone or heterogeneity that affects reservoir quality and fluid distribution.

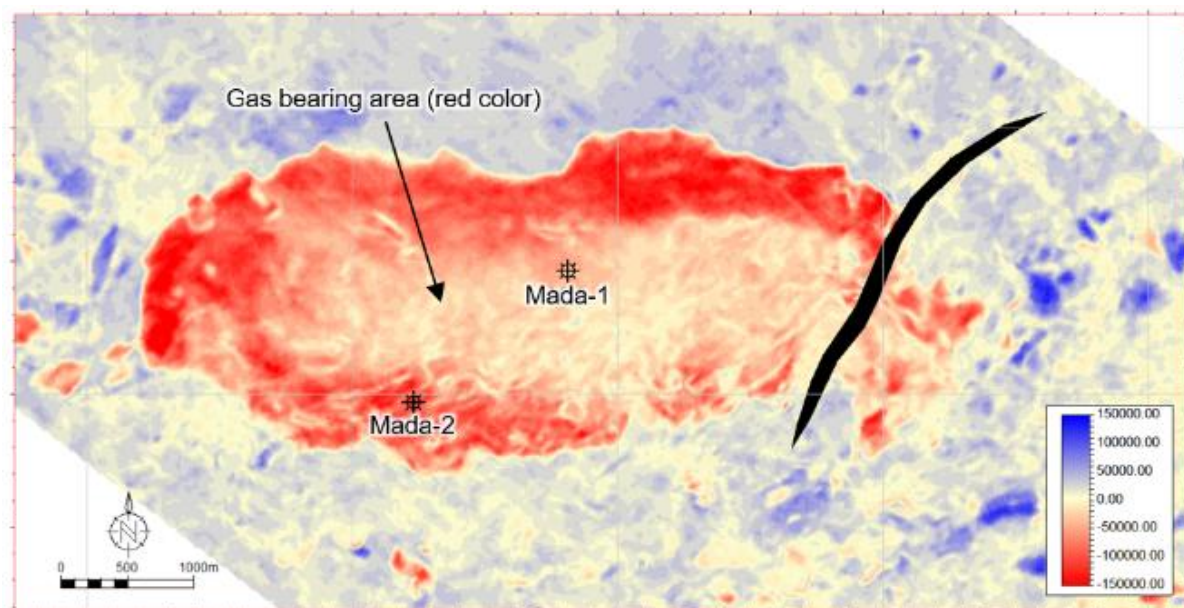


Figure 8.
Amplitude-based seismic attributes highlighting the lateral extent and boundaries of the gas reservoir

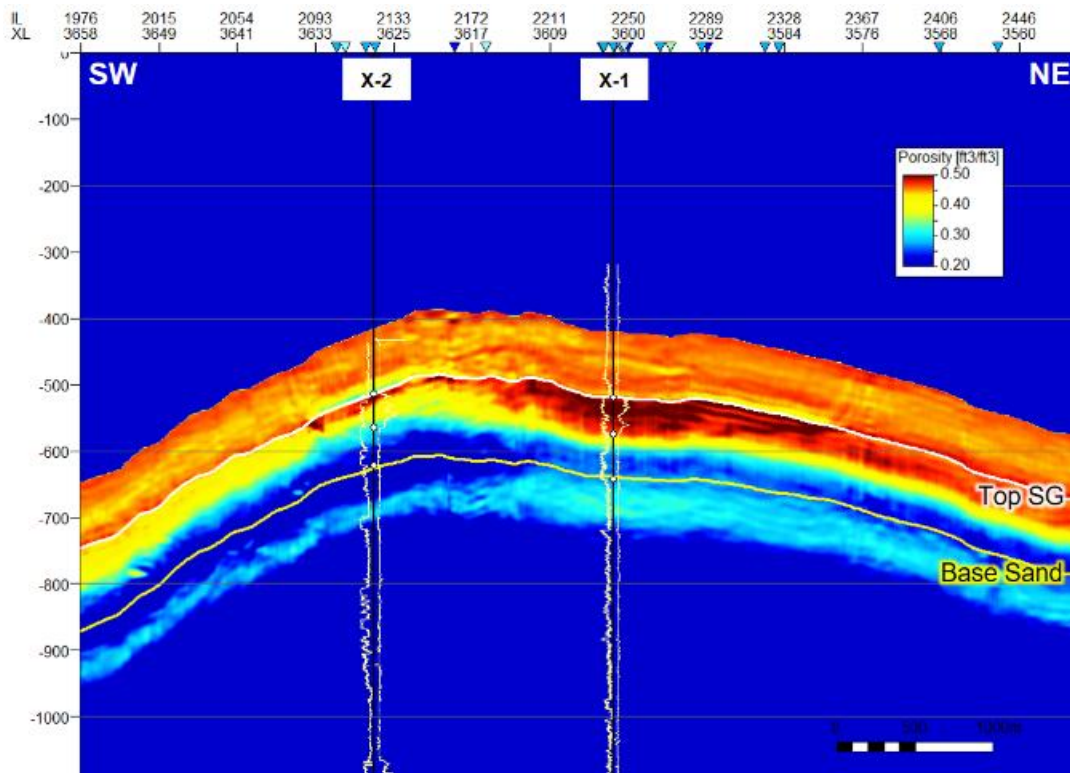


Figure 9.

Total porosity section across Mada-1 and Mada-2 wells reveals distinct variations between the two locations, with the highest porosity shown in dark red

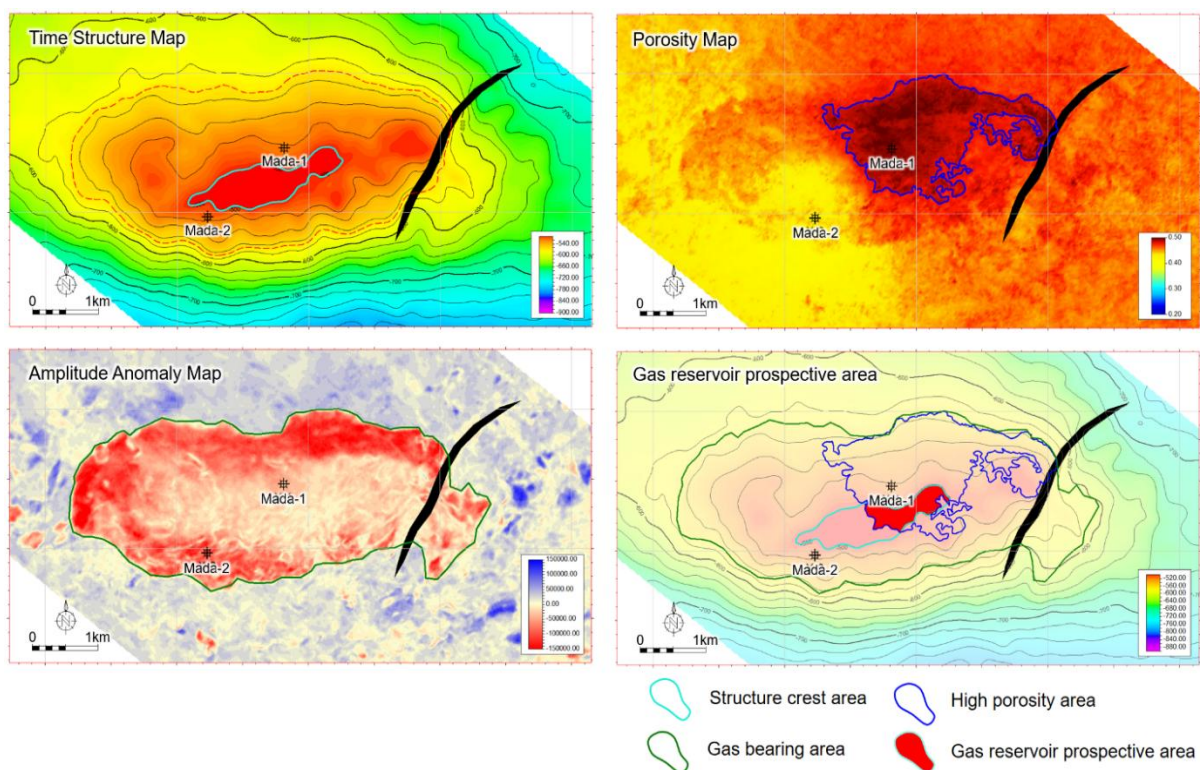


Figure 10.

Structure map (a), porosity map (b), amplitude anomaly map (c), and prospective reservoir map (d). The integrated prospective map (d) identified a sweetspot area located to the south and southeast of the Mada-1 well

3.9 Prospective area determination

Structural map, seismic attribute, and porosity distributions map were integrated to identify the sweetspot of this shallow gas reservoir (Figure 10).

Structure contour map is one of the most important tools for three-dimensional structural interpretation because it represents the full three-dimensional form of a map horizon (Groshong 2006). It plays a key role in defining the geometry of the reservoir and understanding the spatial relationship between existing wells and structural features. It helps identify structural highs that are typically associated with hydrocarbon accumulation.

Seismic attributes are employed to delineate the lateral extent and boundaries of the gas reservoir, providing additional constraints on the distribution of gas-bearing zones. Meanwhile, the porosity map is used to evaluate the lateral distribution of reservoir quality.

The porosity map was generated by extracting average porosity values within the interval between the Top Shallow Gas horizon and the GWC, which is approximately 50 ms below the Top Shallow Gas. This approach provides a representative distribution of porosity across the gas reservoir interval, allowing for a clearer evaluation of lateral variations in reservoir quality. In general, the eastern part of the structure indicates higher porosity compared to the western part, suggesting better reservoir properties in that region.

By integrating these datasets, a reliable and comprehensive method for selecting potential well locations can be achieved. Based on the integrated analysis, a potential area was identified in the south and southeast of Mada-1 well. These areas are located within the gas-bearing area, located in a structural high (crest) above -500 ms and characterized by the highest porosity values.

4. Conclusion

Reservoir characterization of the shallow gas interval in Mada Field demonstrates that inverted P-impedance effectively predict porosity distribution. The established inverse relationship between P-impedance and porosity enables reliable transformation of seismic-derived P-impedance into porosity volumes, improving subsurface understanding in areas with limited well control.

The application of model-based seismic inversion in this study demonstrates the reliability in predicting subsurface properties, particularly P-impedance. This is supported by the integration of a well-constructed initial model that incorporates low-frequency trends derived from well log data and geological constraints, ensuring that the inversion results remain geologically consistent. Integration of porosity distribution, with seismic attributes and structural interpretation enhances the delineation of shallow gas reservoir boundaries within the Lidah Formation. This integrated analysis provides a more comprehensive technique for evaluating shallow gas accumulation, including its lateral extent and potential sweetspot area.

The study result indicates that shallow gas, initially considered as a drilling hazard, represents a potential resource when properly characterized. The application of integrated seismic inversion and attribute analysis offers practical implications for optimizing well placement and development strategies to unlock remaining hydrocarbon potential in mature basins such as the North East Java Basin.

5. Acknowledgement

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6. Declarations

6.1 Author contributions

A.H. Saputra: conceptualization, methodology, data analysis, investigation, visualization, writing original draft & editing. A. Haris: supervision, validation, writing review.

6.2 Funding statement

The authors declare that no external funding was received for this research.

6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

The author(s) used Copilot to assist. After using this tool, the authors review and edit the content as needed and take full responsibility for the publication's content.

7. Glossary of terms and symbols

Terms & symbols	Definition	Unit
2D	Two-Dimensional (Seismic)	
3D	Three -Dimensional (Seismic)	
AI	Acoustic impedance	(ft/s)*(g/cc)
API	American petroleum institute	
DST	Drill Stem Test	
GR	Gamma ray	API
GWC	Gas Water Contact	
MDT	Modular Dynamics Tester	
PSC	Production Sharing Contract	
PSTM	Pre-Stack Time Migration	
RMS	Root Mean Square	
SG	Shallow Gas	

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