



Hydrocarbon Reservoir Characterization Based on the Integration of AVO and Fluid Replacement Modelling (FRM): A Case Study of the FR Field, Balikpapan Formation

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Received: September 16, 2025

Revised: October 23, 2025

Accepted: November 25, 2025

Published: November 30, 2025

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DOI: [10.29303/jppipa.v11i11.12960](https://doi.org/10.29303/jppipa.v11i11.12960)

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Abstract: This study aims to characterize potential gas-bearing reservoir zones in the FR Field within the Balikpapan Formation, Kutai Basin, through the integration of Amplitude Versus Offset (AVO) analysis and Fluid Replacement Modelling (FRM) using a single-well dataset. The Balikpapan Formation in the Kutai Basin is known for its complex stratigraphic and lithological heterogeneity, which poses challenges for seismic interpretation. The three-dimensional (3D) pre-stack seismic gathers were processed to preserve true amplitude for reliable AVO analysis. Intercept and gradient attributes were extracted to identify Class III AVO anomalies linked to gas-saturated sandstone. Validation was carried out using FRM based on well log data (V_p , V_s , and density) by simulating elastic property changes under different fluid conditions using Gassmann's equation. The FRM results indicate a decrease in P-wave velocity and Poisson's ratio under gas-saturated conditions, consistent with AVO responses. AVO attribute maps further depict the lateral distribution of zones prone to gas, offering valuable insights for well placement and field development strategies. The integration of AVO and FRM effectively reduces interpretation uncertainty and improves the understanding of reservoir characteristics within the Balikpapan Formation.

Keywords: AVO; Balikpapan formation; Fluid replacement modelling; Gas reservoir; Pre-stack seismic

Introduction

The continuous growth of global energy demand positions oil and gas as strategic resources that remain difficult to replace in the near future. Indonesia is among the countries with significant hydrocarbon reserves, particularly in the Kutai Basin, which has long been recognized as one of the most important basins for national energy development (Moss & Chambers, 1999; Jamaluddin et al., 2023). Within the onshore region, the Balikpapan Formation is the dominant Middle Miocene

unit deposited in a fluvial-deltaic system controlled by Mahakam Delta dynamics. Its complex depositional setting has produced heterogeneous lithologies, including porous sandstones, interbedded shales, and thin coal layers (Cloke et al., 1999; Jamaluddin et al., 2024), which pose challenges in subsurface characterization and complicate the detection of hydrocarbon-bearing intervals. Seismic interpretation advancements have shifted reservoir analysis from qualitative to quantitative approaches, with Amplitude Versus Offset (AVO) analysis widely applied to evaluate

How to Cite:

Yudanur, A. D., Haris, A., & Sabbeq, S. (2025). Hydrocarbon Reservoir Characterization Based on the Integration of AVO and Fluid Replacement Modelling (FRM): A Case Study of the FR Field, Balikpapan Formation. *Jurnal Penelitian Pendidikan IPA*, 11(11), 936-943. <https://doi.org/10.29303/jppipa.v11i11.12960>

amplitude variations associated with lithology and fluid content (Rutherford & Williams, 1989; Yilmaz, 2001). AVO has demonstrated effectiveness in differentiating water-filled from gas-saturated sandstones (Castagna & Smith, 1994; Haris et al., 2018; Sumantri et al., 2020), yet in stratigraphically complex settings such as the Balikpapan Formation, its responses are often affected by heterogeneity, pore pressure variations, tuning effects, and seismic data limitations resulting in ambiguous anomaly interpretation. To overcome these limitations, Fluid Replacement Modelling (FRM) provides a complementary quantitative approach by simulating elastic property changes under fluid substitution scenarios using Gassmann's theory. FRM helps validate AVO anomalies, distinguish true fluid effects from lithological influences, and strengthen confidence in seismic-based gas identification (Magoba & Opuwari, 2020; Ridwan et al., 2020; Safira et al., 2021).

The novelty of this research lies in integrating AVO analysis with FRM specifically in the Balikpapan Formation, where such combined quantitative workflows remain limited despite its geological complexity. This study not only validates AVO class interpretations using FRM-derived synthetic gathers but also quantifies the fluid sensitivity of Middle Miocene channel-deltaic sandstones, offering a more reliable interpretation framework in heterogeneity-prone setting.

This research is important because accurate identification of gas-bearing intervals in the Balikpapan Formation is critical for reducing exploration risk in Kutai Basin, a mature and structurally stratigraphically complex hydrocarbon province. The integrated AVO & FRM workflow minimizes uncertainty in fluid prediction, prevents misinterpretation of seismic anomalies, and enhances reservoir characterization to support exploration and development strategies in the FR field. Accordingly, this study aims to apply the integration of AVO and FRM on well RF-1 and pre-stack seismic data to improve confidence in identifying gas-bearing zones and provide a more robust evaluation of reservoir potential in complex stratigraphic settings.

Method

Regional Geology

The Kutai Basin, located in East Kalimantan, is one of the most prolific hydrocarbon provinces in Indonesia. The basin evolved through a combination of extensional and compressional tectonic regimes associated with the development of the Sunda Shelf. Its structural framework, including the Mahakam Delta and major fault systems, is shown in Figure 1 (McClay et al., 2000).

The Balikpapan Formation, deposited in a Middle Miocene fluvial-deltaic system, represents a key

hydrocarbon-bearing interval within the Kutai basin (Nugrahanto et al., 2021; Permana et al., 2022). The sandstones are generally fine- to medium-grained and moderately sorted, acting as potential reservoir rocks, while the interbedded shales serve as seals. This formation exhibits significant lithological and stratigraphic variability, which influences the reservoir's heterogeneity and hydrocarbon distribution in the basin (Ismail et al., 2020; Ali & Alvarez, 2022; El-Naby et al., 2025).

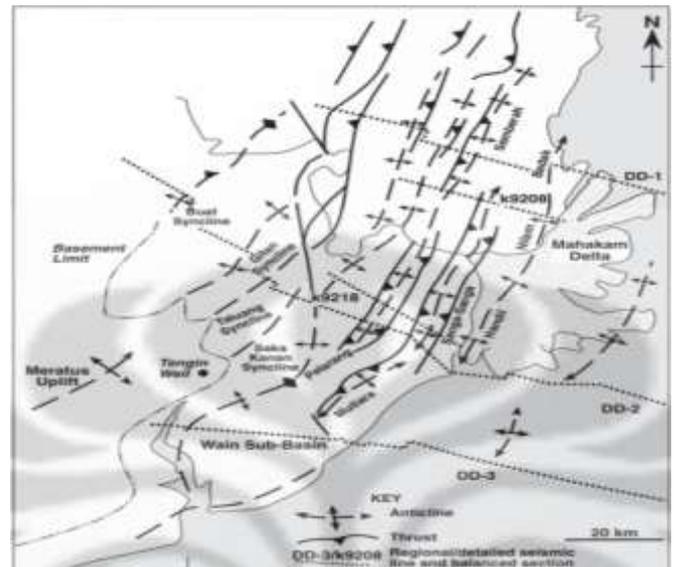


Figure 1. Structural map of the Kutai Basin (McClay et al., 2000)

Data and Study Area

This study focuses on the FR Field, located in the offshore part of the Kutai Basin, East Kalimantan. The research utilizes two primary datasets provided by Pertamina Hulu Energi: (1) Pre-stack 3D seismic data, processed using amplitude-preserving workflows to ensure the reliability of Amplitude Versus Offset (AVO) analysis. (2) Well log dataset including gamma ray (GR), density (RHOB), neutron porosity (NPHI), resistivity, and sonic logs (Vp and Vs).

Log analysis was first performed to identify lithology, estimate porosity, and detect hydrocarbon indicators. The target interval was defined at DST-6 (1550–1560 m), where low GR, high resistivity, neutron-density crossover, and low Vp/Vs ratio suggest a potential gas-bearing sandstone.

Fluids Replacement Modelling (FRM)

Fluid Replacement Modelling (FRM) was conducted using Hampson-Russell software to simulate the effect of varying fluid saturations on reservoir elastic properties, while keeping the rock frame constant via Gassmann's equation. Four fluid scenarios were modeled: 100% gas, 100% water, and in-

situ conditions. Each scenario represents a possible reservoir state, allowing the evaluation of how fluid substitution affects P-wave velocity (V_p), S-wave velocity (V_s), density (ρ), and Poisson’s ratio (ν). Modelling these scenarios provides: (1) Validation: comparison of synthetic responses with observed

seismic data. (2) Interpretation support: identify contrasts indicative of gas-bearing zones. (3) Planning guidance: assist with subsequent AVO attribute mapping to reduce uncertainty in reservoir characterization.

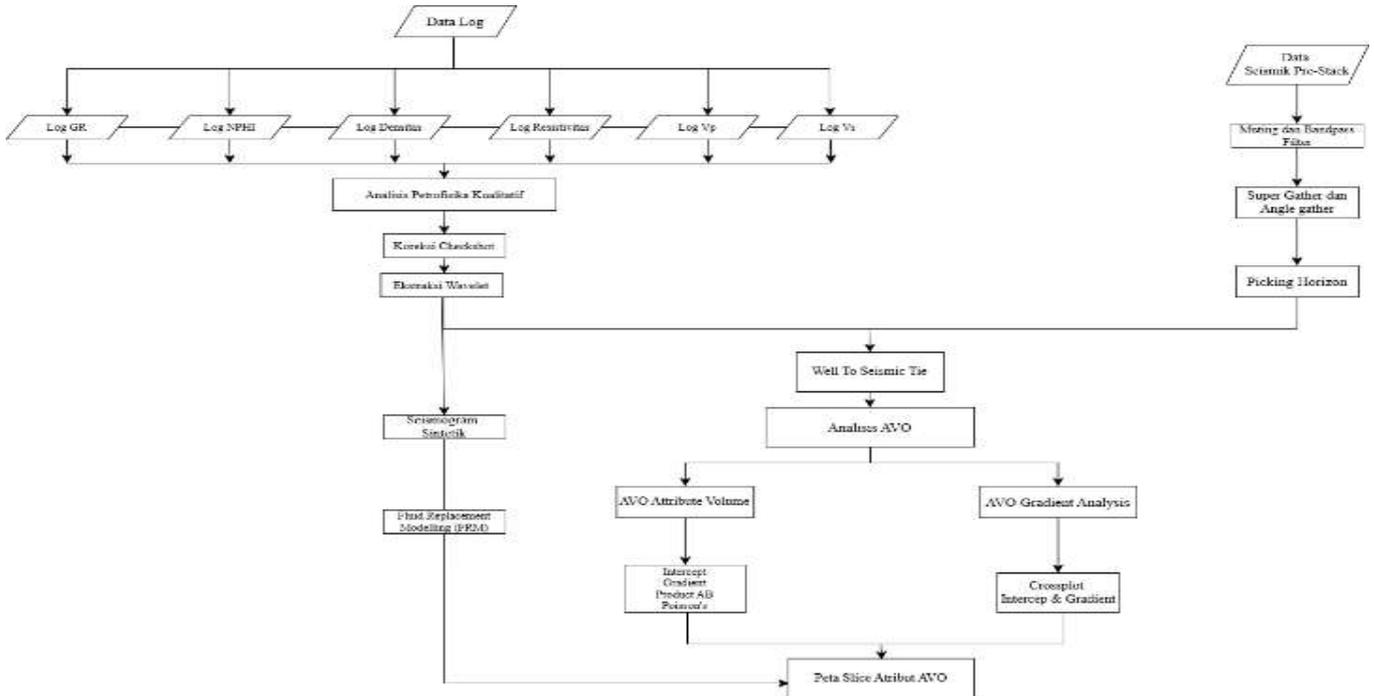


Figure 2. Research flow diagram

AVO Analysis

AVO Analysis was performed on pre-stack seismic gathers to assess amplitude variations with offset. While the Zoeppritz (1919) equations provide the theoretical relationship between reflection amplitude and incidence angle, the three-term Aki & Richards P (1980) A linearized approximation was used for practical seismic interpretation (Yilmaz, 2001; Avseth et al., 2005). The reflection coefficient is given by Equation (1).

$$R(\theta) = A + B\sin^2\theta + C\tan^2\theta\sin^2\theta \tag{1}$$

where A is the intercept, B the gradient, and C accounts for far-offset contributions. In practice, A and B are the main parameters analyzed because of their sensitivity to lithology and fluid variations. Anomaly identification in this study follows the classification of Rutherford and Williams (1989), as illustrated in Figure 3, which distinguishes AVO Classes I-IV and highlights Class III as the most diagnostic indicator of gas-saturated sandstones.

Synthetic seismograms were generated from FRM outputs to compare theoretical responses under different fluid conditions with observed seismic gathers. This integration between rock physics modeling and

seismic response analysis enables validation of amplitude anomalies before AVO interpretation (Li et al., 2016; Ding et al., 2025). Finally, AVO attributes such as intercept, gradient, and the AB product were extracted and mapped to delineate the lateral distribution of gas-prone zones (Ding et al., 2025). These attribute maps serve as an essential tool for reducing subsurface uncertainty and guiding well planning in the FR Field.

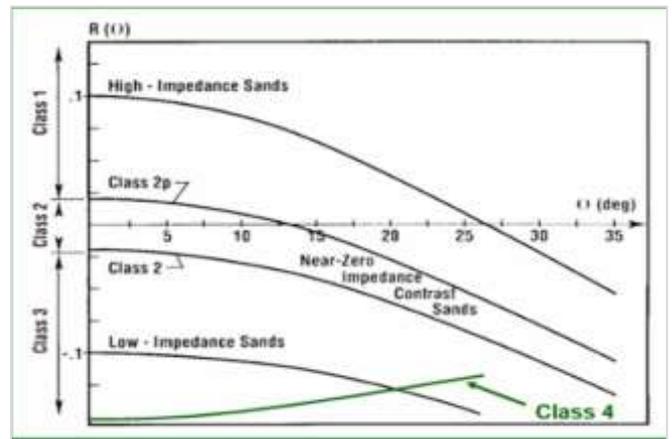


Figure 3. Classification of AVO anomalies (Rutherford & Williams, 1989)

Results and Discussion

Well Log Analysis

Figure 4 show the well log data of RF-1 within the DST-6 interval (1550–1560 m), where sandstone dominates. Gamma ray values range between 45–65 API, indicating low clay content, while density (RHOB) varies from 2.20 to 2.35 g/cc. Total porosity (PHIT) is 0.23–0.26, effective porosity (PHIE) 0.18–0.21, and shale volume (VSH) 0.15–0.25. Resistivity (RT) exceeds 80 Ω m, and water saturation (SWE) ranges from 0.25–0.35, suggesting hydrocarbon saturation of approximately 65–75%. Sonic logs show P-wave velocity (V_p) of 3600–4000 m/s and S-wave velocity (V_s) of 2100–2400 m/s, yielding V_p/V_s ratios of 1.6–1.7, consistent with gas-saturated sandstones (Castagna et al., 1998). The neutron–density crossover further confirms the presence of gas. Minor GR fluctuations indicate thin shale or coal layers, consistent with deltaic to fluvial–deltaic facies of the Balikpapan Formation (Permana et al., 2022;

Jamaluddin et al., 2024). These coal layers must be carefully interpreted, as they may mimic gas responses in density and resistivity logs.

Fluid Replacement Modelling (FRM)

Fluid Replacement Modelling was conducted to compare scenarios 100% gas, 100% water, and in-situ aiming to assess the elastic response of the reservoir to fluid variations. Figure 5 shows that each scenario yields distinct P-wave velocity (V_p), S-wave velocity (V_s), density (ρ), and Poisson’s ratio (ν), summarized in Table 1.

Table 1. Fluid Modeling Results of the RF-1 Well Reservoir

Scenario	V_p (m/s)	V_s (m/s)	Density (g/cc)	Poisson’s Ratio (ν)
Gas	2800	1500	2.05	0.18
In-situ	3600	1850	2.18	0.27
Water	4200	2000	2.25	0.31

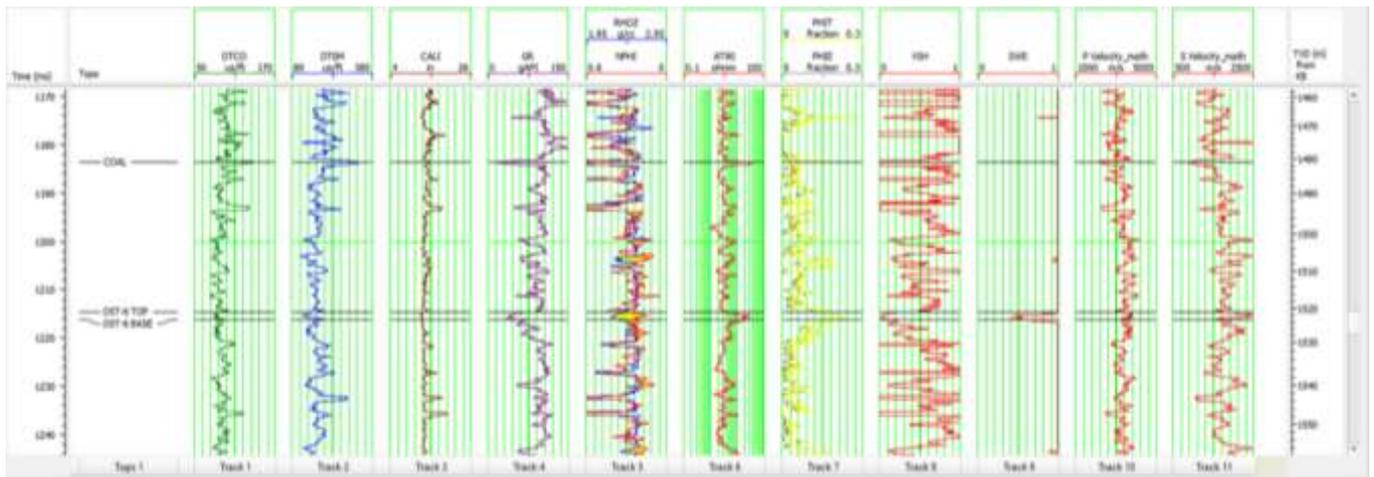


Figure 4. RF-1 well logs at the DST-6 interval (1550–1560 m)

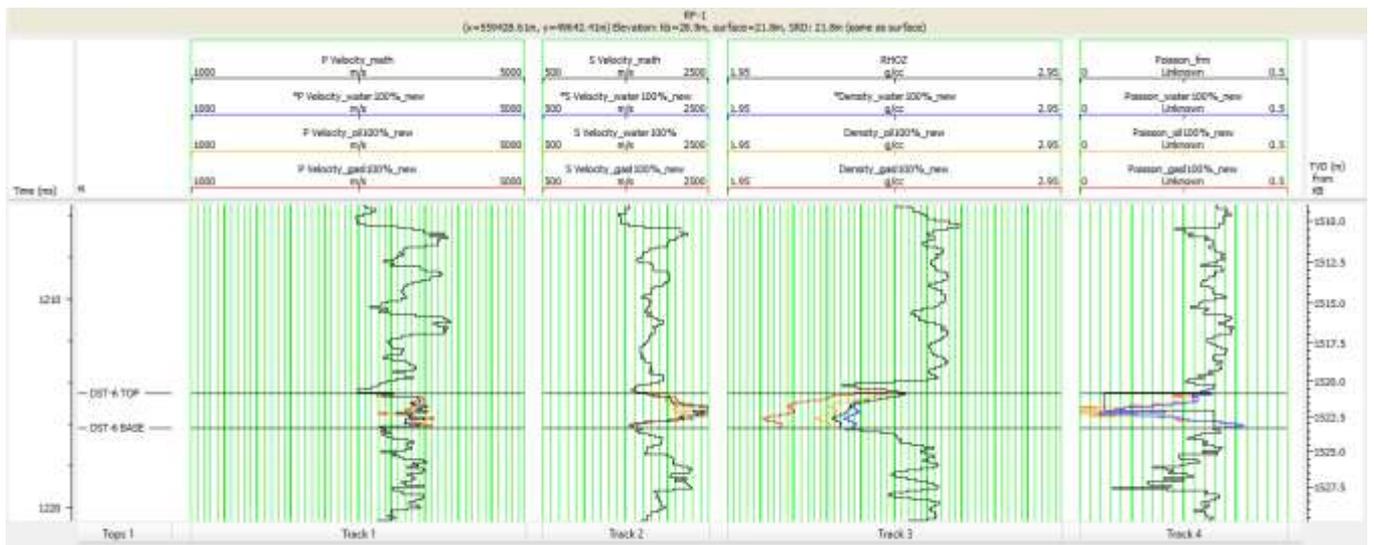


Figure 5. Fluid Replacement Modeling (FRM) results for gas, oil, water, and in-situ scenarios

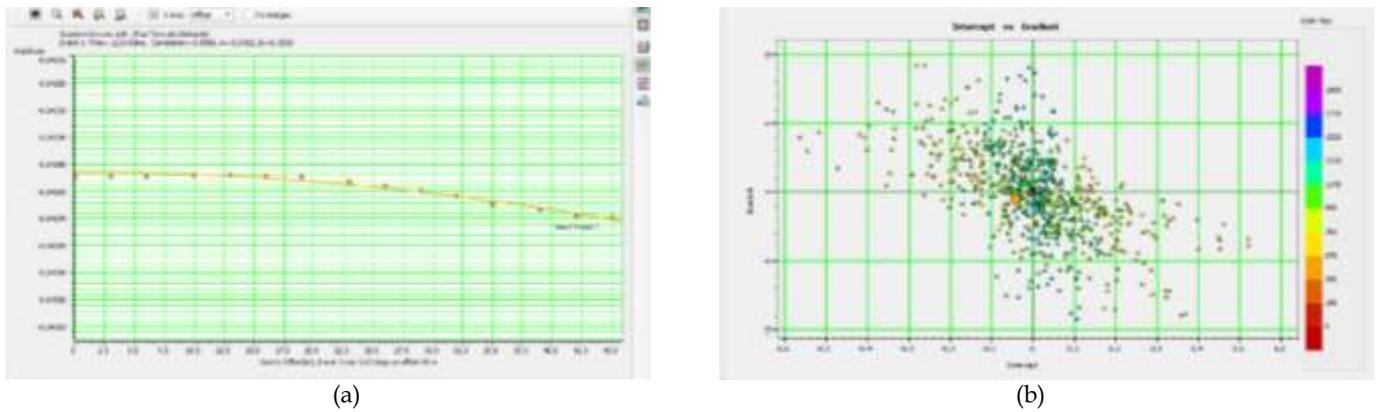


Figure 6. (a) AVO curve (amplitude vs. offset) at horizon 1214 ms for 100% gas scenario; (b) intercept-gradient (A-B) crossplot at the target horizon

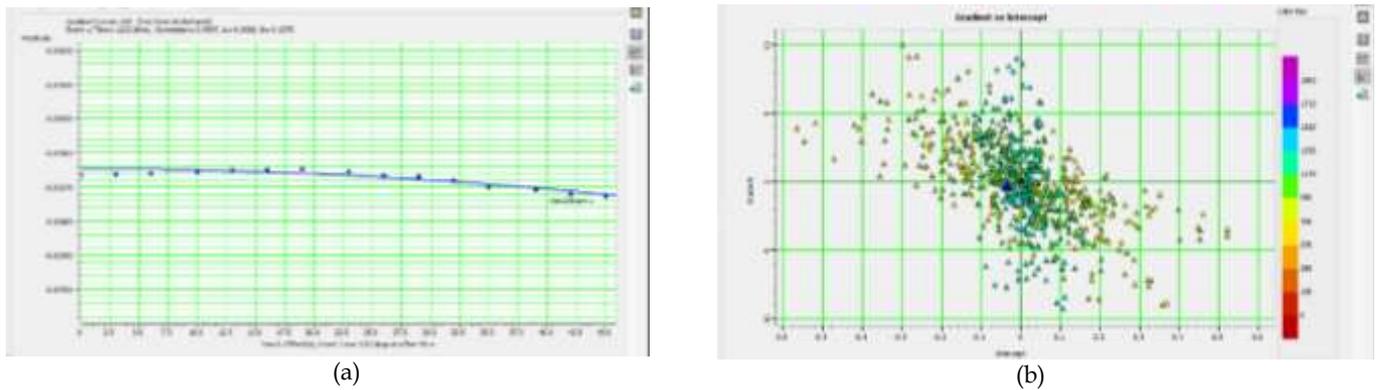


Figure 7. (a) AVO curve (amplitude vs. offset) at horizon 1214 ms for 100% water scenario; (b) intercept-gradient (A-B) crossplot at the target horizon

The gas scenario exhibits the lowest V_p (2800 m/s) and V_s (1500 m/s), with $\rho = 2.05$ g/cc and $\nu = 0.18$, reflecting the high compressibility and low density of gas. Oil and water scenarios show progressively higher elastic parameters, with the in-situ response ($V_p = 3600$ m/s, $V_s = 1850$ m/s, $\rho = 2.18$ g/cc, $\nu = 0.27$) closely matching the gas trend, indicating gas dominance in the RF-1 DST-6 interval. These results quantitatively confirm that elastic responses can distinguish gas-bearing zones, providing a basis for subsequent AVO analysis and hydrocarbon identification.

AVO Gradient Analysis

The seismic AVO analysis provides additional validation. Figure 8 presents the pre-stack gather and intercept-gradient cross plot, both of which demonstrate a Class III anomaly characterized by negative intercept and negative gradient values. This interpretation is further supported by synthetic seismograms generated from FRM. Figures 6 and 7 display the modeled AVO responses for gas and water, respectively.

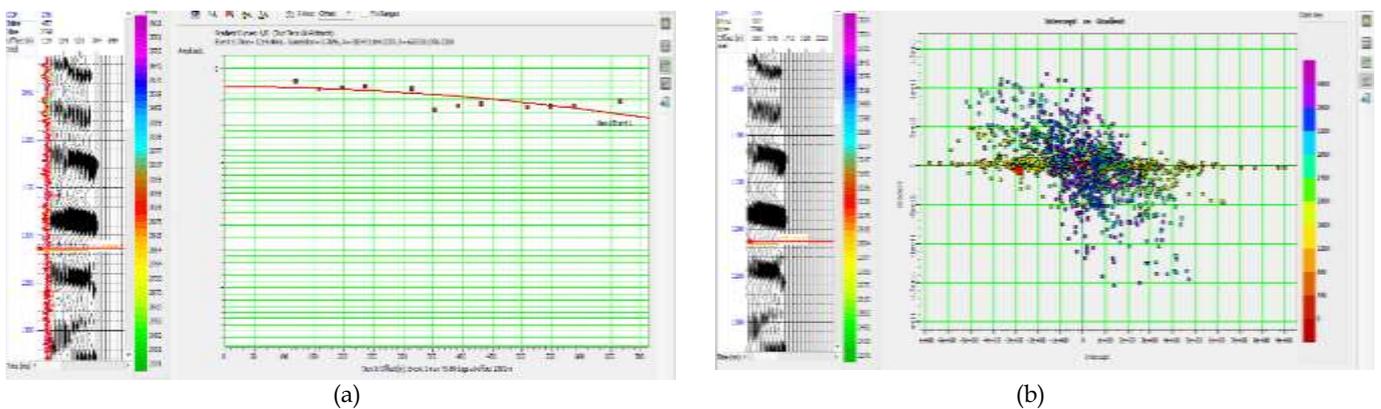


Figure 8. (a) AVO curve (amplitude vs. offset) at horizon 1214 ms; (b) intercept-gradient (A-B) cross plot

The gas scenario reproduces the strong Class III pattern observed in the field data, while the oil case shows moderate anomaly and the water case remains stable across offsets. The close agreement between the field and synthetic responses confirms that the anomaly is primarily fluid related.

AVO Attribute

AVO attribute analysis confirms the lateral distribution of the reservoir. As shown in Figure 9, the

AB product displays positive anomalies within the DST-6 interval, which are consistent with AVO Class III gas-bearing sandstone. These anomalies align with the regional anticlinal structure, indicating that gas accumulation extends laterally beyond RF-1 well. The result demonstrates the effectiveness of the AB product attribute in delineating reservoir geometry while minimizing interpretation uncertainty.

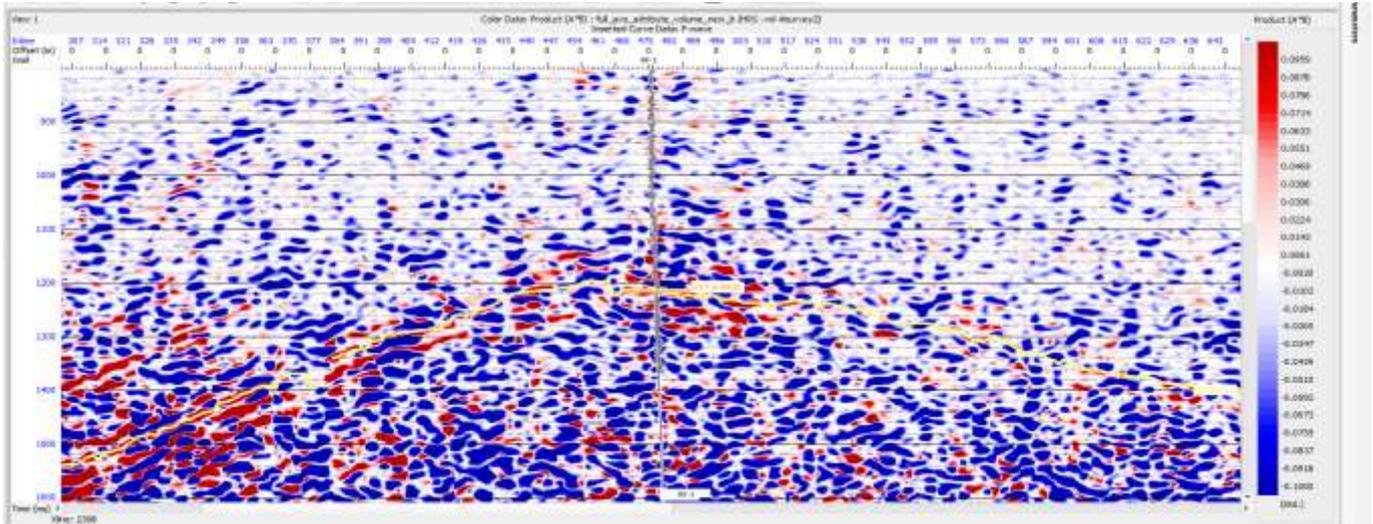


Figure 9. Seismic section of the AB product attribute

The AB product attribute map for DST-6 is shown in Figure 10, where positive anomalies (red zones) indicate Class III gas-bearing sandstone. These anomalies are concentrated around well RF-1 and extend westward along the anticline crest, suggesting laterally continuous and structurally controlled accumulations rather than being restricted to the well location. This pattern reinforces the interpretation of reservoir distribution in the Balikpapan Formation.

Although the anomalies provide strong evidence of gas presence, potential limitations such as tuning effects in thin beds, lithological variations, or amplitude noise should be considered. Nevertheless, Figure 10 demonstrates the significance of AB product mapping by delineating the lateral extent of gas reservoirs and guiding well placement in structurally favorable zones.

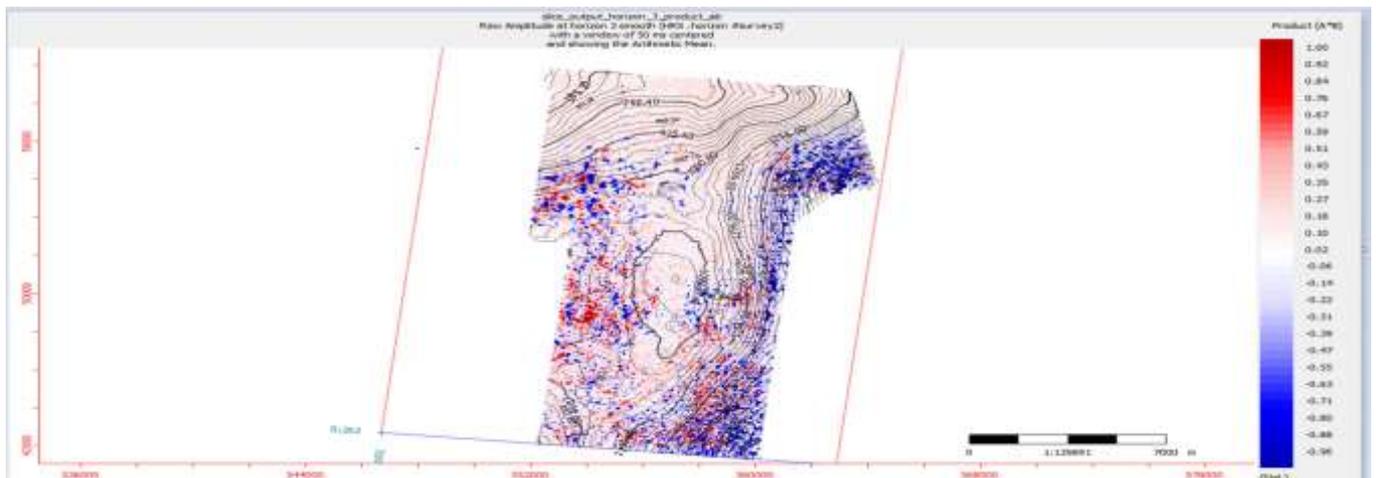


Figure 10. AB product distribution map within the DST-6 interval

Conclusion

This study demonstrates that the DST-6 interval (1550–1560 m) of the Balikpapan Formation is dominated by porous sandstone with strong indications of gas presence. Well log analysis (low gamma ray, high resistivity, neutron–density crossover, and low Vp/Vs ratio) and Fluid Replacement Modelling (FRM) consistently indicate gas saturation, while AVO analysis reveals Class III anomalies supported by intercept–gradient cross plots and synthetic seismogram validation. AVO attribute maps further confirm the lateral continuity of the gas-bearing sandstone, aligned with regional anticline structures. The integration of AVO and FRM has proven effective in reducing interpretation uncertainty in complex stratigraphy, offering a new interpretive framework for onshore Kutai Basin reservoirs. This study provides both academic and practical contributions: advancing quantitative seismic applications in Indonesia and supporting drilling and field development planning in gas-prone areas. Future work should focus on integrating AVO–FRM with simultaneous elastic inversion or machine learning approaches to improve resolution and robustness across different stratigraphic intervals.

Acknowledgments

Thank you to Pertamina Hulu Energi for providing the data and permission to use it in this study. The authors also thank the Department of Physics, Universitas Indonesia.

Author Contributions

Conceptualization, A.H.; A.D.Y.; methodology, A.H.; A.D.Y.; S.S.; formal analysis, A.D.Y.; writing—original draft preparation, A.D.Y.; writing—review and editing, A.H.; A.D.Y.; supervision, A.H. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

No conflict of interest.

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