Direct hydrocarbon indicator (DHI) pitfall assessment in prospecting pliocene globigerina biogenic gas play in “X structure”, Madura Strait, East Java Basin

V Rowi1, 2, A Haris3 and A Riyanto3

1Department of Physics, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia
2Husky-CNOOC Madura Ltd., Gedung Bursa Efek Indonesia, Tower 1, 24th floor, SCBD, Jl. Jendral Sudirman Kav. 52, Jakarta 12190, Indonesia
3Geophysisc Study Program, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia

Corresponding author’s email: aharis@sci.ui.ac.id

Abstract. Direct Hydrocarbon Indicator (DHI) has a major role in the exploration of Pliocene globigerina biogenic gas play in Madura Strait, part of East Java Basin. This study aimed to assess the DHI pitfall within the X Structure which triggered by the drilling result of Well X3 (dry hole) that contradict with Well X1 that successfully discovered gas even though both wells targeted the same reservoir body and DHI features. Low gas saturation that decreases the compressional velocity (Vp) is predicted to be the main reason behind the DHI pitfall. Considering the limitation of qualitative interpretation to investigate the DHI pitfall, this research uses seismic quantitative interpretations, such as fluid substitution modeling, amplitude variations with offset (AVO), seismic inversion, and rock physics analysis to get a full understanding behind the DHI features in X Structure. The 2D marine seismic survey consists of 49 seismic lines and wells data were used in this research. Fluid substitution and Vp-Vs-ρ modeling confirm that the DHI pitfall is related to the non-economic gas saturation (Sg < 10 %) within the reservoir. As for the AVO and inversion analysis indicated that the gas water contact (GWC) level is around 1,389 ms (± 4,023 ft SSTVD). Rock physics analysis shows that the poor reservoir quality is predicted to be the reason behind the low gas accumulation within the reservoir. Several properties cut off for gas zone were derived such as, P-impedance < 5,700 gr/cc*m/s, Vp/Vs < 2.0, porosity > 40 %, dan VCL < 22 %. This research concluded that the seismic quantitative interpretations were successfully used to assess the DHI pitfall and to delineate the economic gas accumulation zone.

Keywords: DHI pitfall, biogenic gas, globigerina, quantitative interpretation, Madura Strait

1. Introduction

Seismic Direct Hydrocarbon Indicators (DHI) amplitude anomaly has been used as a tool to discover the biogenic gas accumulation in Madura Strait until these days. The DHI anomalies such as: bright spot, flat spot, polarity reversal, and dim spot are commonly observable in almost all structural high within the Pliocene globigerinid bioclastic limestone in the Madura Strait area of East Java Basin. This bioclastic limestone (Globigerina Formation or T60) is characterized with an abundance of foraminiferal
globigerina which was deposited in two major chronostratigraphic sequences, the Mundu and Selorejo Sequence [1]. The reservoir in Globigerina Formation is grainstone-packstone dominant limestone with tremendous porosity up to 55 % and containing biogenic gas (> 97 % methane).

In 2012, Well X1 was drilled in X Structure and successfully discovered gas. This discovery was mainly driven by the evidence of DHI anomaly within the structure. This discovery then initiated the Well X3 drilling in 2013 to delineate the gas distribution in X Structure. Surprisingly, the Well X3 drilling resulted as a dry hole even though both wells were targeting the same DHI anomaly (Figure 1). This DHI pitfall phenomena indicate that there are other aspects need to be addressed when prospecting a biogenic gas play in Madura Strait. This study results suggested that DHI features are not necessarily related to economic gas accumulation.

Poor reservoir quality in Well X3 in X Structure is suspected to be the main reason behind the Well X3 drilling result. The DHI anomaly penetrated by Well X3 is expected to be triggered by the presence of a small amount of gas (Sg < 10 %) within the reservoir. Hence it increases the compressibility of the rock dramatically, the velocity will drop accordingly, and the amplitude will decrease to a negative “bright spot” in the Globigerina Formation at Well X3 which led into a DHI pitfall interpretation.

Considering the biogenic gas exploration failure in Well X3, this research is intended to investigate the DHI pitfall in X Structure through seismic QI analysis. This study shows that DHI anomaly should be analyzed quantitatively to reduce the hydrocarbon exploration risk.

2. Materials and method

2.1. Geology

X Structure is located in the Madura Strait Production Sharing Contract (PSC) area (figure 2), operated by Husky-CNOOC Madura Ltd. (HCML). The Madura Strait PSC Block is located in the South Madura Sub basin area, a back-arc basin separated from West Java Basin by the Karimunjawa Arch and bounded to the south by Java-Banda Volcanic Arc. The basin passes eastwards into the deep-water Bali-Flores basin while to the north the basin shallows onto the Madura-Kangean High which separates it from the North Madura Platform [1].

The Globigerina Formation which acts as the reservoir, consists of limestone clastic facies and characterized by the abundance of globigerina foraminifera with tremendous porosity up to 55 %. Major porosity types encountered in this sequence are inter-particle porosity and intra-particle porosity within foraminiferal shells. The source rock for the biogenic gas is derived from surrounding shale, the Lidah-Selorejo-Mundu-Wonocolo sequences. The pelagic shales of the Lidah Sequence act as the effective regional seal for Globigerina Formation. Gas generation and migration are a constant process that will

Figure 1. Seismic DHI anomalies in X Structure. Well X1 successfully discovered gas and in contrary Well X3 is a dry hole.
continue until the source material is exhausted or the aerobic methanogenesis temperature threshold (75–80 °C) exceeded or the burial depth reaches approximately 3,000 ft. The biogenic gas migrates laterally through carrier beds from adjacent areas which have sufficient TOC (> 0.5 %). The X Structure is a 4 way-dip closure with E-W trend, cut by several normal faults. The seismic feature shows X Structure is a structural trap, but tilted during Pliocene-Pleistocene due to inversion process due to the tectonic activity [1].

2.2. Seismic quantitative interpretation (QI)
Discovering, delineating, and calculating the volume of hydrocarbon accumulation are the goal for geoscientists in seismic exploration. Even nowadays, seismic data is interpreted in a qualitative manner by manually picking and tracking lateral and consistent seismic reflector showing a unique geological structure, reservoir architecture and stratigraphy [2].

In 1970, the seismic amplitude for the first time was used as a tool to directly predict the hydrocarbon accumulation. It was found that hydrocarbon traps could be associated with bright-spot amplitude anomalies. These amplitude anomalies, later known as Direct Hydrocarbon Indicators (DHI) were successfully used in hydrocarbon explorations. Nevertheless, some drilled bright spots showed dry holes in numerous cases.

These failures triggered seismic interpreters to develop more quantitative techniques to validate hydrocarbon anomalies during prospect evaluation or reservoir characterization. Some of the most prominent techniques include fluid substitution modelling, forward seismic modelling, acoustic and elastic impedance inversion, and offset-dependent amplitude analysis (AVO analysis). Fluid effects could also be discriminate from its lithology effect quantitatively by working on precise rock physics modelling and well-log analysis [2].

Therefore, the seismic quantitative interpretation (QI) techniques are important to reduce the hydrocarbon exploration risks by validating the DHI anomalies and identifying the DHI pitfall anomalies misleading as an indicator of hydrocarbon.

2.3. Fluid substitution modelling
This method will create various fluid scenarios to help seismic interpreters in explaining an observed amplitude variation with offset (AVO) anomaly [3]. Gassmann et al. sees the correlation between rock bulk modulus and pore frame and fluids bulk modulus [4]. The equation is used for rock physics modelling known as fluid substitution modelling. This method is commonly used as a tool to predict a change in seismic properties with different fluid saturations,
\[ K_{\text{sat}} = K_{\text{dry}} + \frac{1 - \left(\frac{K_{\text{dry}}}{K_{\text{m}}}\right)^2}{\frac{\phi}{K_{\text{ft}}} + \frac{(1 - \phi)}{K_{\text{m}}} - \frac{K_{\text{dry}}}{K_{\text{f}}}} \]  
(1)

\[ \mu_{\text{sat}} = \mu_{\text{dry}} \]  
(2)

where:  
- \( K \) = bulk modulus  
- \( \text{sat} \) = saturated rock  
- \( \text{fl} \) = fluid  
- \( \text{m} \) = matrix  
- \( \text{dry} \) = unsaturated rock  
- \( \phi \) = porosity  
- \( \mu \) = shear modulus

In this study, fluid substitutions were intended to identify the ideal model of seismic for each insitu, gas, and wet conditions. AVO modeling was also done by applying Shuey’s approximation to recognize the AVO response in ideal (noise free) condition, and later, it will be used as a parameter to do the AVO feasibility analysis. The fluid substitutions modeling workflow is the following:

1. Determine the parameters which remain constant during fluid substitution (Km, Kbrine, Kg, Kdry).
2. Calculate Vp, Vs, and \( \rho \) with Gassmann equation for various water saturation (Sw).
3. Generate synthetic seismic trace for various saturation.
4. Generate synthetic offset gather for each water saturation scenario by using Shuey equation.

The fluid substitutions modelling result (figure 3) shows that:

1. For gas case,  
   At Well X1 and X3, Top T60 (Top Reservoir) correlates with a strong negative amplitude (negative RC).
2. For wet case,  
   At Well X1 and X3, Top T60 (Top Reservoir) correlates with a strong positive amplitude (positive RC).
3. For any case, the base of the reservoir consistently correlates with a strong positive amplitude.

The in-situ case modelling for Well X3 shows an interesting result, where the Top T60 marker has the same result as a gas case result as it is opposing the drilling result. The Vp-Vs-\( \rho \)-Sw modelling (Figure 4) indicate that the compressional velocity significantly decreases at Sw = 95%. This modelling confirmed that with just a few gas saturations within the reservoir, effective fluid modulus and saturated rock bulk modulus will significantly drop.

2.4. AVO analysis

Amplitude Variations with Offset (AVO) analysis will examine seismic amplitudes as a function of reflection angle or offset to extract its rock parameters [5]. In this study, AVO analysis was done to distinguish between the gas and non-gas (brine) zone so that the gas distribution could be delineated within the X Structure. The AVO analysis was done following these steps:

1. Create AVO models for gas and brine case by using well data and Shuey’s approximation (Figure 5a).

\[ R(\theta) \approx R(0) + G \sin^2 \theta \]  
(3)

\[ R(0) = \frac{1}{2} \left( \frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right) \]  
(4)
\[ G = \frac{1}{2} \frac{\Delta V_p}{V_p^2} - 2 \frac{V_p}{V_s^2} \left( \frac{\Delta \rho}{\rho} + 2 \frac{\Delta V_s}{V_s} \right) \]  

where:  
\( R(0) \) = reflection coefficient (RC) at \( \theta = 0 \)  
\( G \) = AVO gradient  
\( V_p \) = compressional wave velocity  
\( V_s \) = shear wave velocity  
\( \rho \) = density

2. Seismic gather data preconditioning.  
3. AVO plot, intercept-gradient analysis, and AVO classification (Figure 5b).  
4. Feasibility analysis by comparing AVO models from well data with AVO models from seismic data.  
5. Delineate gas distribution.  

The AVO modelling from well data (Figure 5a) matched with the AVO plot from seismic data (Figure 5b) means that AVO analysis is feasible to be done in this study. These AVO plot analysis conclusions are:  
1. Top T60 for the gas case is class 3 AVO type.  
2. The gradient of Top T60 and Base at Well X3 is smaller compared to Well X1.  
3. Well data AVO modelling shows that Top T60 for the wet case has a positive intercept.  
4. Base reservoir for gas case indicated by increasing value of gradient.  
5. The gradient of the wet case for the base reservoir is flat.  
6. The similarity of Well X3 AVO plot features with a gas case indicate that the reservoir is not pure wet (\( Sw \neq 100 \% \)).

![Figure 3. Fluid substitution and AVO modeling at Well X1 and Well X3.](image-url)
Figure 4. Vp-Vs-Rho-Sw modeling at Well X3.

Figure 5. AVO plot, intercept-gradient, and classification.

Figure 6. (a) Gas zone delineation using AVO intercept-gradient attribute, and (b) AVO intercept-gradient plot with gas zone cluster

Since the definition of gas and wet case has been set from AVO analysis, the gas zone within the reservoir could be delineated (Figure 6). Apparently, the Gas-Water Contact (GWC) from AVO
attributes has the same depth with GWC level from pressure (Modular Formation Dynamic Tester, MDT) plot analysis (Figure 7).

2.5. Seismic inversion
A simple model-based post-stack inversion was done in this study (Figure 8) and aimed to distinguish the internal properties of the reservoir. The inversion result shows that the low impedance value is distributed above the probable GWC and interpreted as a gas zone; meanwhile the high impedance value is dominating the area below the GWC and interpreted as a non-gas zone. Despite the fact that Well X3 resulted as a dry hole, inversion result shows that there are low impedance layers and suspected to be correlated with zones where the gas saturation slightly increases ($S_g < 5\%$).

Crossplots of rock properties derived from well logs and petrophysical data (Figure 9) concluded that acoustic impedance (AI) cutoff for the gas zone is below 5700 g/cc•m/s. This gas zone is bounded by porosity ($\phi$) cutoff around 40\% and clay volume about 22\%. This crossplot analysis confirms that the gas is more likely to be distributed within clean and high porosity facies.

![Figure 7. MDT pressure plot analysis from Well X1 and X3](image)

![Figure 8. (a) Well X3 log section shows that there is two zone where the gas saturation slightly increase, and (b) Model-based inversion section. Green-yellow (low AI) and blue-purple (High AI).](image)
3. Results and discussion

Fluid substitutions combined with AVO modeling were proven to be a good method to detect the gas presence and its distribution in the globigerina reservoir in X Structure. Even though such an uneconomic gas accumulation in Wells X3 has a DHI pitfall anomaly, yet the AVO shows that the low gas saturation has a smaller AVO gradient compared to the gas case at Well X1.

Seismic inversion (Figure 8) successfully characterized the internal properties of the reservoir in this study. Albeit high impedance (= poor reservoir quality) dominated the reservoir interval below the predicted GWC, low impedance layers detected in Well X3 and match with the slight increase of gas saturation intervals based on the petrophysical water saturation log and total gas reading from mudlog data. This finding supports the fluid substitution modeling (Figure 3) which concluded that Well X3 is not a pure brine case.

A simple rock physics analysis using a Porosity-Vp crossplot template (Figure 11) suggest that reservoir quality in Well X3 has a high clay content, poor porosity, and highly cemented compared to Well X1. This analysis is confirmed by thin section images (Figure 12) that shows the reservoir quality in Well X3 is poor.

![Figure 9](image)

**Figure 9.** Crossplots of rock properties derived from well logs and petrophysical analysis data. Water saturation used as color scale. (a) Al vs Porosity crossplot, (b) Al vs VCL crossplot.

![Figure 10](image)

**Figure 10.** Rock physics analysis (Porosity-Vp crossplot). (a) High porosity reservoir mainly distributed in Well X1, (b) High gas saturation concentrated in Well X1, (c) Low VCL and low cemented facies mostly clustered in Well X1, (d) Low Vp/Vs (< 2) which indicate the gas accumulation concentrated in Well X1.
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Figure 11 (continued). Rock physics analysis (Porosity-Vp crossplot). (a) High porosity reservoir mainly distributed in Well X1, (b) High gas saturation concentrated in Well X1, (c) Low VCL and low cemented facies mostly clustered in Well X1, (d) Low Vp/Vs (< 2) which indicate the gas accumulation concentrated in Well X1.

Figure 12. Thin section images from globigerina reservoir interval. (a). Typical specimen of Well X1 which dominated by grainstone-packstone facies with excellent porosity and low clay content, (b). High calcite cement detected from thin section specimen. This type of facies is highly distributed in the reservoir of Well X3.

4. Conclusion
The most notorious limitations of hydrocarbon exploration by DHI anomalies approach is the assessment of gas saturation in a reservoir from the seismic response, as a low gas saturation (5 %) tend to show similar responses as a commercial gas saturation (up to 100 %). This modelling confirmed that with just a few gas saturations within the reservoir, effective fluid modulus and saturated rock bulk modulus will significantly drop.

This study concluded that Well X3 is not pure brine (Sw = 100 %). AVO analysis and fluid replacement modeling shows that the Pliocene globigerina reservoir at Well X3 is saturated with uneconomic gas accumulation (as low as 5 %). This low gas saturation evidence is possibly geologically controlled by the reservoir quality. Biogenic gas is predicted not optimized to migrate into the reservoir in Well X3 due to the poor reservoir quality.
This study results suggested that DHI features are not necessarily related to economic gas accumulation. Further analysis such as seismic QI and rock physics analysis need to be done to reduce the uncertainty when prospecting a biogenic gas within the globigerina limestone in Madura Strait.

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