Characterization of sandstone reservoir field “Q” sub-basin Jambi using the extended elastic impedance seismic inversion method

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Abstract. The extended elastic impedance (EEI) inversion method is a seismic inversion technique that can optimally predict the character of a hydrocarbon reservoir using expansion of the incident angle from -90° to +90°. In the study of Field “Q” Sub–Basin Jambi, EEI was used to characterize a sandstone reservoir and predict the existence of gas or oil using the parameters Vp/Vs ratio, lambda–rho, and mu–rho. EEI was performed to determine the maximum correlation value at the optimum chi (χ) angle for each parameter specified by the correlation between the target logs and the EEI logs. The optimum chi (χ) angle was used to create a scaled volume reflectivity that was then used to make an initial model, which was required in the inversion process. Inversion was performed using a post–stack inversion–based model. The inversion results were then used to determine the spread of the reservoir, with the results indicating the possibility of a reservoir containing gas and oil. In this study, the Vp/Vs ratio ranged between 16 and 18, the mu–rho values ranged between 25 and 35 GPa*(g/cc), and the lambda–rho values ranged between 20 and 22 GPa*(g/cc) for gas and between 25 and 27 GPa*(g/cc) for oil.

Keywords: Extended elastic impedance, Vp/Vs ratio, sub–basin Jambi

1. Introduction
The seismic method is the most common geophysical method used in hydrocarbon exploration. Seismic data analysis can effectively help in reducing the uncertainty relating to the characteristics of sub-surface features. One seismic analysis method is the inversion technique. Seismic inversion is a technique for modeling the sub-surface using seismic data as input data and well data as control data [1].

Whitcombe et al. introduced the latest inversion technique, known as the extended elastic impedance (EEI) inversion [2]. The inversion applies an assumption that the incident wave angle is not equal to zero or non–normal incidence. The incident wave angle is expanded to the range -90° to +90°. Just like the previous acoustic impedance (AI) and elastic impedance (EI) inversion techniques, EEI inversion results are also used to identify reservoir characteristics. Using EEI inversion, interpretations of porosity and fluid and lithology contents are even more accurate. The EEI inversion technique is expected to
provide more accurate, optimal predictions of (i) reservoir characteristics and (ii) oil and gas presence in sandstone reservoirs.

2. Theory

The elastic properties of rocks affect the physical parameters important in controlling reservoir characteristics. For assessing rocks, the most commonly used elastic parameters are incompressibility, bulk modulus, shear modulus, density, porosity, and Poisson's ratio.

Incompressibility relates to the ability of a fluid present in the rock to be pushed in the normal direction of the surface. Rocks filled with oil and water will be less “compressed” compared to rocks gas filled. Mathematically, the incompressibility ($\lambda$) parameter can be expressed in the bulk modulus equation as

$$k = \lambda + \frac{2}{3} \mu. \quad (1)$$

The prediction of fluid type, especially gas, in rocks is sensitive to the bulk modulus ($k$). The shear modulus ($\mu$) is the ability of rocks to withstand stresses or strains that cause a shift in one plane of the surface by maintaining the volume of the rock.

The other parameters commonly used to analyze the elastic character of rocks are the speeds of the P wave and S wave, respectively,

$$V_p = \sqrt{\frac{k + 4/3 \mu}{\rho}} \quad \text{and} \quad V_s = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

Lambda-rho and mu-rho are parameters that are closely related to incompressibility ($k$) and rigidity ($\mu$). The equations for lambda–rho and mu–rho are, respectively,

$$\lambda \rho = (V_p \rho)^2 + 2(V_s \rho)^2 \quad \text{and} \quad \mu \rho = (V_s \rho)^2 \quad (3)$$

The lambda-rho parameter is a very sensitive parameter in relation to the presence of fluids that fill rock pores as such fluids affect the incompressibility. The mu-rho parameter is very sensitive to changes in rock lithology.

The EEI method is an extension of the EI method and overcomes the limitations of the EI method in the range of angles from 0° to 90°, i.e., by yielding a $\sin^2 \theta$ value that ranges only from 0 to 1. For an angle greater than 30°, the EI method cannot be applied to prestack data [3]. However, Whitcombe et al. observed that, for an angle greater than 30°, EI may still be used and can be related to the physical properties of rocks [2]. Whitcombe overcame the inherent limitations in two ways:

1. Changing $\sin^2 \theta$ to $\tan \chi$. Through this extension, we obtain a new equation:

$$R(\chi) = A + B \tan \chi. \quad (4)$$

2. Since the scale of reflectivity will not exceed 1, it was necessary to limit the scale of reflectivity to normal reflectivity by multiplying by $\cos \chi$:

$$R_s = R \cos \chi \quad (5)$$

$$R_s = A \cos \chi + B \sin \chi. \quad (6)$$

On the basis of this extension, Whitcombe formulated new EEI equations [2]:

$$EEI(\chi) = \alpha_0 \rho_0 \left[ \left( \frac{\alpha}{\alpha_0} \right)^p \left( \frac{\beta}{\alpha_0} \right)^q \left( \frac{\mu}{\rho_0} \right)^r \right] \quad (7)$$

$$EEI(\chi) = A \chi_0 \left[ \frac{A_0}{A} \cos \chi \frac{G}{A_0} \sin \chi \right] \quad (8)$$
As such, the range of reflectivity has an $A$ value, i.e., the intercept at $\chi = 0^\circ$, and a $B$ value, i.e., the gradient at $\chi = 90^\circ$. The EEI equivalent at $\chi = 0^\circ$ is an AI, whereas the EEI equivalent at $\chi = 90^\circ$ corresponds to the gradient impedance. Using this EEI equation, it is expected that a condition of EEI ($\chi = 90^\circ$) with EEI ($\chi = -90^\circ$) will correlate with the inverse correlation.

3. Methodology
This study was divided into several stages: data conditioning, AVO (Amplitude versus Offset) analysis, well cross-plot analysis, and EEI inversion. The various steps undertaken in the study are shown in figure 1.

4. Results and discussion
4.1. Cross-plot analysis
This analysis was carried out using the well cross-plots of certain well data parameters that are especially sensitive to the separation of lithology and fluid in the target zone. In this study, the parameters used were P-impedance (AI) vs. gamma rays, lambda-rho vs. Vp/Vs ratio, mu-rho vs. Vp/Vs ratio, and Vp/Vs ratio vs. P-impedance.

4.1.1. Cross-plot of P-impedance and gamma-ray. Cross-plots of P-impedance and gamma rays are used to analyze the lithology of the target area, wherein mu-rho is a third parameter used to distinguish sandstone reservoirs with shale. The P-impedance of sandstone, about 8,000–13,000 m/s*(g/cc) is greater than clay. The sandstone gamma-ray value (less than 80 APIs) is lower than that of shale. From the cross-plot results, it is evident that the rock lithology of the target area is crossed sandstone with shale.
4.1.2. Cross-plot of LMR and Vp/Vs ratio. The cross-plot of LMR vs. Vp/Vs ratio uses selected lambda-rho and mu-rho parameters to separate fluid in the target zone because the former is very sensitive to fluid changes within the rock lithology and the latter is very sensitive to the lithology of the reservoir.

Hydrocarbon reservoirs generally have large mu-rho values. This is because, if the reservoir rock is sandstone, the granules will be very hard and stiff. On the basis of the laboratory studies, the Vp/Vs values for sandstones range from 1.6 to 1.8. The lambda–rho value for the hydrocarbon fluid has a low value of about 22–30 GPa*(g/cc) and a high sandstone mu–rho value of 25–35 GPa*(g/cc).

4.1.3. Cross-plot of acoustic impedance and Vp/Vs ratio. The cross-plot of AI and Vp/Vs ratio is sensitive to the presence of gas anomalies. As such, an anomaly can be utilized to provide additional information on the anomalies of other cross-plots that are capable of identifying the presence of hydrocarbons.

4.2. AVO analysis

AVO analysis of the data gathered in this study was conducted with the aim of determining the AVO response from the seismic data. AVO analysis can be effectively applied to reservoirs with a gas fluid content. AVO analysis is performed by analyzing the intercept and gradient patterns in the seismic data to establish AVO classes.

In Well 1, the results of the AVO analysis showed Class I, indicating the presence of a high–cemented hard drive filled with gas fluid. The AVO analysis of Well 5 showed that Class IV can occur when unconsolidated sand is filled with gas covered by claystone.

4.3. Inversion analysis

Inversion of EEI is performed based on the initial model input of each parameter and the reflexivity volume of each parameter. In this study, the parameters used were Vp/Vs ratio, lambda–rho, and mu–rho. The EEI inversion result of the impedance volume is then used to determine the volume of the Vp/Vs ratio, lambda–rho, and mu–rho. Furthermore, all volumes were used to assess reservoir characteristics and fluid distribution based on the research data.

The inversions performed in this study used post–stack model–based inversion. Model–based inversion has a high resolution and can be applied to the thin layer reservoir present in this study area. The principle of this model–based inversion is convolution between reflexivity and the wavelets of real data. This begins with the assumption of an iterative formula, which is used to improve the initial model.

Figure 2 shows an inversion that gives the P–impedance with the mu–rho parameter around the zone of interest. The P–impedance value for the mu–rho parameter has a value equivalent to the mu–rho value. The inversion result shows that further down, approaching the zone of interest, the P–impedance value for the mu–rho parameter is higher (indicated by the purple color), i.e., about 8,400–8,700 (m/s)* (g/cc)). From the inversion result, it can be assumed that the P–impedance value for the high mu–rho parameter indicates the presence of a sandstone reservoir. At the top of the interest zone, it shows a low value, indicating the presence of shale.

The mu–rho parameter can be used to provide both lithology and fluid information. From the anomalous volumes, it can be observed that a high mu–rho value indicates the distribution of a sandstone reservoir, whereas a low value indicates shale. The value of mu–rho is about 25–35 GPa*(g/cc).

Figure 3 shows an inversion result that gives the P–impedance with the lambda-rho parameter around the zone of interest. The P–impedance for the lambda-rho parameter has a value equivalent to that of lambda-rho. This result shows that there are areas in the zone of interest with a P–impedance value for the low lambda-rho parameter. Lambda-rho correlates rock incompressibility with fluid content in reservoir rocks. Sandstones filled with gas have a high compressibility value compared with sandstones filled with oil; therefore, the lambda value of gas-filled sandstones is lower than that of oil-filled sandstones.
In field “Q” of the study area, the gas-filled sandstones are represented by areas with a P-impedance value for the small lambda-rho parameter (indicated in yellow), i.e., about 6,300–6,500 (m/s)*(g/cc). Meanwhile, oil-filled sandstones have a P-impedance value for higher lambda–rho parameters (indicated in light blue), i.e., about 7,500–7,800 (m/s)*(g/cc). The result for lambda-rho volume shows
that there is an anomaly for the low lambda-rho value of about 20–22 GPa*(g/cc) (indicating the presence of gas fluid) and for the lambda-rho of about 25–27 GPa*(g/cc) (indicating the presence of oil fluid).

Figure 4 shows an inversion result giving the P-impedance value for the Vp/Vs ratio around the zone of interest. The P-impedance of the Vp/Vs ratio has a value equivalent to the Vp/Vs ratio. The Vp/Vs ratio contains information on incompressibility and rock rigidity. Therefore, it can be used to indicate the presence of a reservoir and its fluid content. However, because the bulk modulus value of the reservoir rock has a greater influence than the shear modulus, the Vp/Vs ratio is better at indicating the presence of rock fluid. In Field “Q” of the study area, the fluid–containing sandstones showed a P–impedance value for the low Vp/Vs ratio parameter (indicated in green), i.e., about 5,700–6,000 (m/s)*(g/cc).

The Vp/Vs ratio can describe sub-surface fluids or rock compaction beneath the surface. The Vp/Vs ratio of reservoir rock filled with hydrocarbon fluids is low. This is because the P-wave value decreases as it passes through the fluid-filled reservoir, whereas the S-wave value passing through the fluid is relatively small. The Vp/Vs ratio for each well shows uniformity, with values of about 1.6 to 1.8.

4.4. Characteristics and distribution of reservoir and fluid
It can be seen in figure 5 that high values of mu-rho are widely distributed on Horizon M and Horizon N. On Horizon M, sandstone is scattered from the northeast to the southwest, whereas on Horizon N, the sandstone reservoir is distributed across almost the entire study area. In relation to gas distribution in the study area, the slicing result for Horizon M shows anomalous low Vp/Vs ratios and low lambda-rho values scattered across the reservoir from northeast to southwest. The result of slicing for Horizon N shows the spread of gas and oil. It can be seen that, on Horizon N, the anomalous low Vp/Vs ratios and low lambda–rho values are spread to the southeast of the study area; the slicing result of the lithologic distribution shows a reservoir zone in the southeast section.

Figure 4. EEI inversion result for the Vp/Vs ratio parameter.
5. Conclusion

EEI inversion using the Vp/Vs ratio, lambda–rho, and mu-rho parameter approaches were effectively applied in this study. These three parameters used in the EEI inversion were effective in characterizing the sandstone reservoir as well as identifying the fluid. The Vp/Vs ratio for hydrocarbons in this field was shown to have a low value of about 1.6 to 1.8. The value of lambda-rho was also low, i.e., for gases, it was about 20–22 GPa*(g/cc), and for oils, it was about 25–27 GPa*(g/cc). The mu-rho value in this field was shown to be high, i.e., in the range 25–35 GPa*(g/cc). In Horizon M, the fluid spread from northeast to west. In Horizon N, the fluid spread in the southeast area.

Acknowledgments

We thank the DRPM Universitas Indonesia for supporting the financial in publishing the results through grant of PITTA 2017.

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