

Reservoir Characterization Using Acoustic Impedance Inversion and Multi-Attribute Analysis in Nias Waters, North Sumatra

Karakterisasi Reservoir Menggunakan Inversi Impedansi Akustik dan Analisis Multiatribut di Perairan Nias, Sumatera Utara

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ABSTRACT: Seismic method is one of the most frequently applied geophysical methods in the process of oil and gas exploration. This research is conducted in Nias Waters, North Sumatra using one line 2D post-stack time migration seismic section and two wells data. Reservoir characterization is carried out to obtain physical parameters of rocks affected by fluid and rock lithology. Seismic inversion is used as a technique to create acoustic impedance distribution using seismic data as input and well data as control. As final product, multi-attribute analysis is applied to integrate of inversion results with seismic data to determine the lateral distribution of other parameters contained in well data. In this research, multi-attribute analysis is used to determine the distribution of NPHI as a validation of hydrocarbon source rocks. In that area, there is a gas hydrocarbon prospect in limestone lithology in depth around 1450 ms. Based on the results of sensitivity analysis, cross-plot between acoustic impedance and NPHI are sensitive in separating rock lithology, the target rock in the form of limestone has physical characteristics in the form of acoustic impedance values in the range of 20,000-49,000 ((ft/s)*(g/cc)) and NPHI values in the range of 5-35 %. While the results of the cross-plot between the acoustic impedance and resistivity are able to separate fluid-containing rocks with resistivity values in the range about 18-30 ohmm. The result of acoustic impedance inversion using the model based method shows the potential for hydrocarbons in the well FYR-1 with acoustic impedance in the range 21,469-22,881 ((ft/s)*(gr/cc)).

Keywords : multi-attribute, limestone, acoustic impedance inversion, resistivity, Nias Waters

ABSTRAK: Metode seismik adalah salah satu metode geofisika terapan yang paling sering digunakan dalam proses eksplorasi minyak dan gas bumi. Penelitian ini dilakukan di Perairan Nias, Sumatera Utara menggunakan satu buah lintasan data seismik 2D dan dua buah data sumur. Karakterisasi reservoir dilakukan untuk mendapatkan parameter fisis batuan yang dipengaruhi oleh fluida dan litologi batuan. Seismik inversi digunakan sebagai suatu teknik untuk membuat sebaran nilai impedansi akustik menggunakan data seismik sebagai input dan data sumur sebagai kontrol. Analisis multiatribut merupakan integrasi hasil inversi dengan data seismik untuk menentukan sebaran lateral dari parameter lain yang terdapat pada data sumur. Pada penelitian ini analisis multiatribut digunakan untuk menentukan sebaran NPHI sebagai validasi batuan sumber hidrokarbon. Pada daerah tersebut terdapat prospek hidrokarbon berupa gas pada litologi batugamping dengan kedalaman pada kisaran 1450 ms. Berdasarkan hasil analisis sensitivitas, cross-plot antara impedansi akustik dan NPHI sensitif dalam memisahkan litologi batuan, batuan target berupa batugamping memiliki karakteristik fisis berupa nilai impedansi akustik pada rentang 20.000-49.000 ((ft/s)*(g/cc)) dan nilai NPHI pada rentang 5-35 %. Sedangkan hasil cross-plot antara impedansi akustik dan resistivitas mampu memisahkan batuan yang mengandung fluida dengan nilai resistivitas pada rentang 18-30 ohmm. Hasil inversi impedansi berbasis model menunjukkan adanya potensi hidrokarbon pada sumur FYR-1 dengan impedansi akustik pada kisaran 21.469-28.881 ((ft/s)*(gr/cc)).

Kata kunci : multiatribut, batugamping, inversi impedansi akustik, resistivitas, Perairan Nias

INTRODUCTION

Hydrocarbons are a strategic energy commodity for Indonesia. In addition to providing energy supplies, hydrocarbons containing oil and natural gas are also one of the largest sectors. No wonder oil and gas stakeholder is demanded to continue to increase national oil and gas production. However, many have not yet been discovered, hydrocarbon reserves are not easy to be fulfilled. Hydrocarbon exploration activities are still being carried out until now, while the activities have been carried out for escalating the discovery of hydrocarbon reserves. Seismic reflection is a geophysical method that records the propagation of seismic waves reflected from the boundary between the two mediums. Seismic method is used because seismic waves are able to penetrate subsurface so that it can produce images of the appearance of rock structures at the subsurface and display stratigraphic and depositional features to detect hydrocarbon reservoirs, this method focuses on low frequency data (Manik, 2012). The magnitude of the seismic reflection is directly related to the change in acoustic impedance between the two mediums (Sanjaya *et al.*, 2014). The greater contrast between two mediums, the reflection waves will become stronger. Acoustic impedance is the physical ability of rocks to pass seismic waves through it. So that the harder and denser the rock, the greater the acoustic impedance value (Alifudin *et al.*, 2016).

There are some weaknesses in seismic data in describing rock layers that are larger than the thickness of the tuning. Tuning thickness is the minimum thickness of a rock layer that is able to be separated by seismic data, so seismic data is less able to separate rock layers that have a thickness greater than the thickness of the tuning. This requires seismic inversion to be able to get a better figure of the rock layers and the physical properties of the layer. Well data is used to provide lost impedance information on seismic data (Ogagarue, 2016). According to Sukmono (2000), there are three types of inversion methods, that are model based, band limited, and sparse spike methods. However, this research focuses on using a model based method that has a good correlation with seismic data because this method is based on the deviation of the low frequency of the acoustic impedance model (Shankar *et al.*, 2016).

A multi-attribute method is basically a process of extracting several attributes from seismic data that has a good correlation with well data (Malik *et al.*, 2019). The ability to analyze using multi-attribute methods can be used to predict the log parameters to then see the distribution in a seismic section. In this research, multi-attribute analysis is able to predict the resistivity parameters that can indicate the hydrocarbons.

REGIONAL GEOLOGY

Nias Island's forearc basin near Nias Island is underlain by a Pre-Miocene accretionary complex and probably is not underlain by any upper plate crystalline rock (Kieckhefer *et al.*, 1980). This field is located in the northwest part of Sumatra Island, on an emerging portion of the outer arc ridge of the Sunda arc system (Moore, 1979). The regional geology of the Nias and Sibolga regions refer to two geological map sheets as listed on the Sinabang Sheet Geological Map (Figure 1).

The stratigraphic sequence of the Geology Map of Nias Sheets is as follows:

- Aluvium (Qa) is a river, swamp and beach sediments consisting of chunks of limestone, sand, mud and clay.
- Gunungsitoli Formation (QTg) composed of reef limestone, silty limestone, limestone, sandstone, fine quartz sandstone, marl and sandy loam; fine layered, weakly folded. This formation having a Plio-Pleistocene in age and was deposited in a shallow marine environment.
- Gomo Formation (TmPg) is composed of claystone, marl, sandstone, limestone with tuff, tuff and peat inserts. Good layer, strong folded and sedimentary structure in the form of parallel lamination. Based on the fossil content above the age of this formation is the Early Middle-Pliocene Miocene which was deposited in the sublittoral-bathyal environment. The lower part of this formation is tinged with the Lelematua Formation while the upper part is suppressed out of harmony with the Gunungsitoli Formation.
- Lelematua Formation (Tml) consists of sandstone, claystone, siltstone, conglomerate and tufa intertwined with coal and shale. The upper part of the formation is tinged with the Gomo Formation, while the lower part overlaps unconformably the Bancuh Block.
- Bancuh Block (Tommm) is chunks of various types and sizes of rocks consisting of peridotite, gabbro serpentinitely, serpentinite, basalt, schist, shale, graywacke, conglomerate, breccia, limestone, sandstone and flint with scaly clay base mass. Based on the position of this interpreted stratigraphy is formed in the Early Oligocene-Miocene.

Basement

The bedrock in the Nias Arc Face Basin consists of several types of rocks. In Nias Island and its surrounding igneous rocks, while in the FYR-1 well, the basic rock is in the form of black rocks that are strongly deformed and exposed on the Sumatra Island.

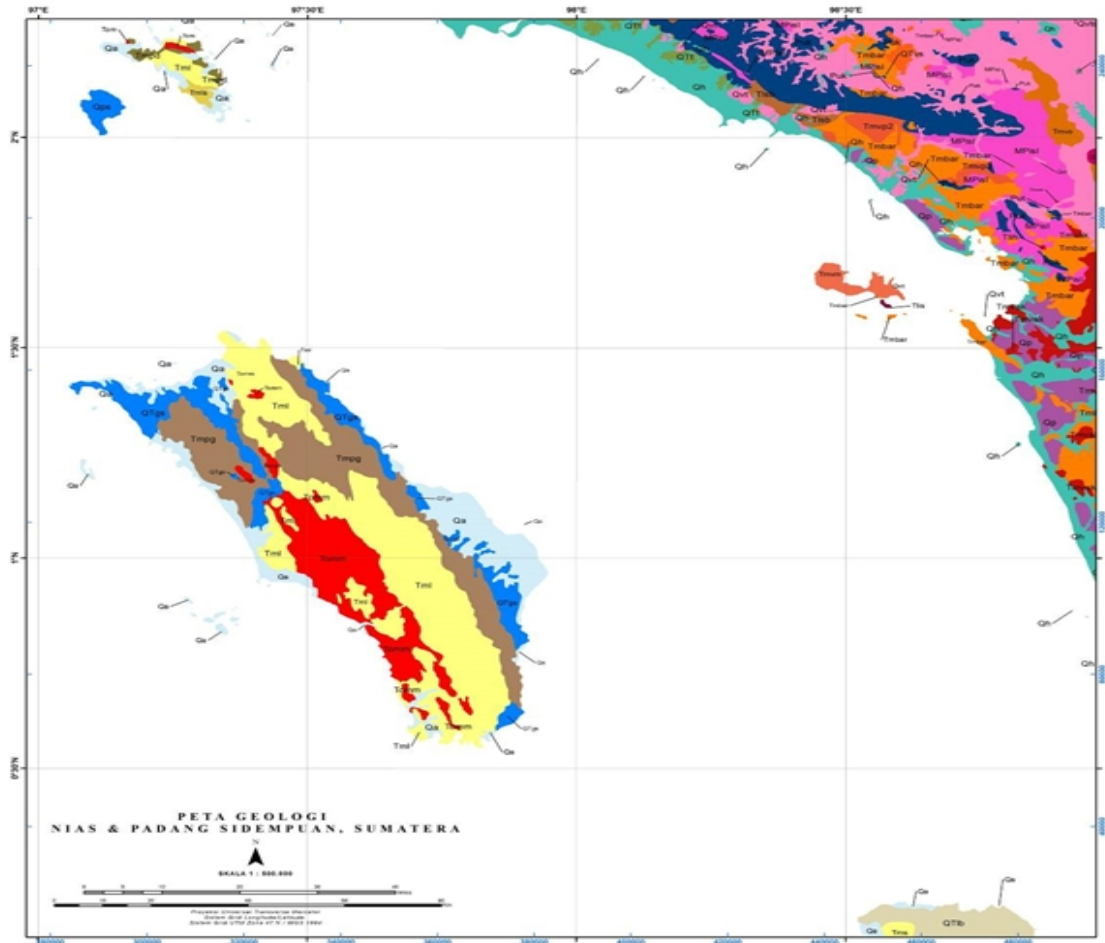


Figure 1. Stratigraphy of the western part of Sumatra and Nias Island (Djamil, 1994)

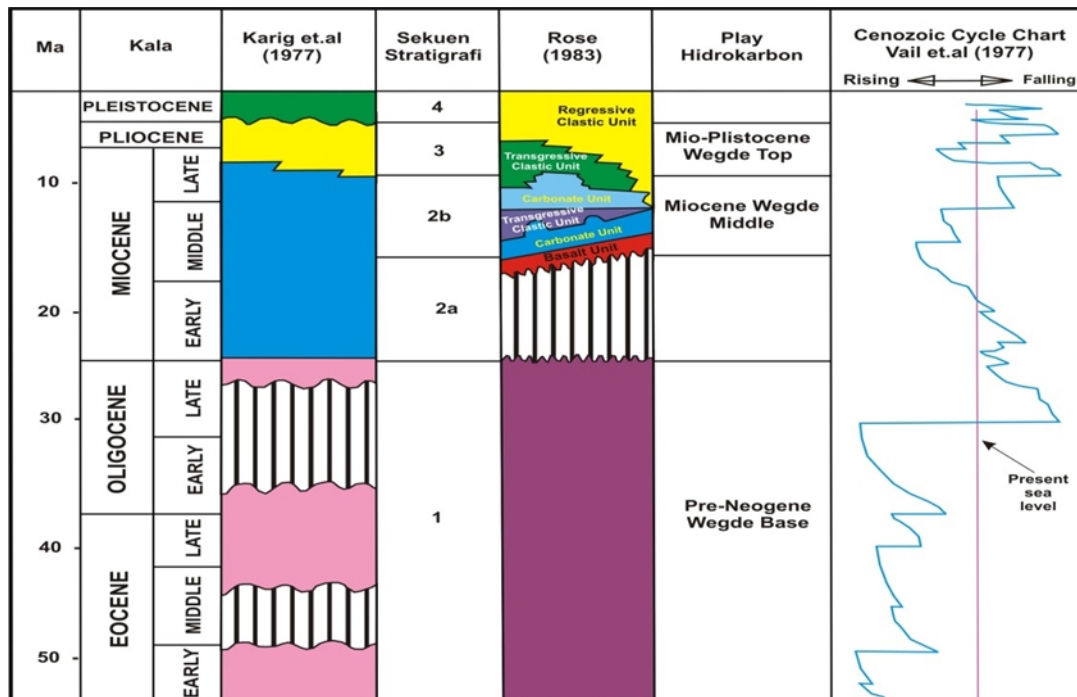


Figure 2. General Stratigraphy of the Nias Basin (modified after Karig et al., 1977, Rose, 1983, Vail, et al., 1977)

Regionally the base rock age is Mesozoic (Jura), which is characterized by Belemnite fossil.

Paleogene rocks

Paleogene sedimentary rocks may only be found in the Pini Sub-Basin in the southern part. Nias Bedrocks are similar to Simeulue Island, which is Baru Melange covered by Pinang Conglomerate Member. Gabbro (Sibau Gabbro Group) is an exotic block on the Melange, which based on K-Ar dating around 35.4 ± 3.6 Ma and 40.1 ± 2.7 Ma, which is identical to the Late Eocene. Similar outcrops were also observed in the Sibolga area, namely the development of conglomerate volcanic rock units which comprise the lower Sibolga Formation. The unit is estimated to be in the form of debris flows and riverbed deposits (braided stream). While the upper part is a sandstone unit deposited braided stream which is comparable to the upper Sibolga Formation. The formation is estimated to be comparable to well FYR-1 as Eocene-Oligocene age.

Miocene rocks

Miocene age sedimentary rocks are generally separated by angular misalignment with Paleogenous sediments. Several drilling wells have penetrated this unit, one of which is FYR-1 well. In general, Miocene sedimentary rocks are predominantly fine fractions such as claystone and shale, sandstone and limestone insertion. Some of the early Miocene age inner-outer sub-litoral sandstone inserts are thought to act as reservoirs. Early Miocene limestone growth in this region was rather slow, this was due to high sedimentation from the mainland. The growth of reef limestone is very intensive in Middle-Late Miocene. In some limestone beds, these are the main target of the reservoirs.

Pliocene-Pleistocene rocks

Pliocene and Miocene sedimentary rocks are generally separated by unconformity. This Mio-Pliocene misalignment is characterized by acceleration of growth in accretion areas due to the inclination of oceanic plates. Precipitation in this period shows a pattern of regressive deposits, such as in the Simeulue and Meulaboh sub-basins, while in FYR-1 well sub-basin occurs transgressive and regressive, possibly due to the active Batee Fault. In the FYR-1 well area, the existence of Toba tuff is very dominant. This situation continues from the west of the sub-basin (FYR-1 well) where the bottom is deposited with sandstones. There are 3 important tectonic cycles that can be recognized in the Nias Basin, namely Paleogenic Orogenics, Neogene Subsidence and Late Tertiary tectonics (Beaudry and Moore, 1985). These tectonic events were also followed

by three cycles of sediment transgression - major regressions related to sea level changes.

BASIC THEORY

Acoustic Impedance

Acoustic impedance is a physical parameter that describes the ability of rocks to pass or reflect waves (Zain *et al.*, 2017). This parameter can be used as an indicator of changes in lithology, porosity, as well as fluid content, pressure and temperature (Sanjaya *et al.*, 2014). Acoustic impedance inversion cross section has many advantages to separate and describe reservoir because it is obtained by integrating data related to rock properties (Alabi and Enikanselu, 2019). In general, rocks which have a high level of hardness then the acoustic impedance value will be high. The acoustic impedance is formulated as,

$$AI = \rho \cdot Vp \quad (1)$$

where the variable ρ is the density and Vp is the P-wave velocity.

Seismic Inversion

Seismic inversion is a modeling of the structure and physical properties of rock bases using seismic data as input and well data as a control. Basically the seismic inversion method is the opposite of forward modeling which is related to the formation of synthetic seismograms based on the earth model (Febriyono *et al.*, 2019). The high frequency information from well data is not used to obtain information contained in seismic data (Huuse and Feary, 2005). Based on the data source, seismic inversion is divided into two, namely pre-stack inversion and post-stack inversion, whereas based on the method, seismic inversion is divided into three namely model based, and band limited, sparse spike (Sukmono, 2000). This study uses 2D seismic data post-stack time migration and model based inversion method. The basic concept of the model based method is to make a geological model to be compared with seismic data, and the comparison results will later be used to update the initial model iteratively until a suitable model is obtained (Russel, 1988).

Multi-attribute Analysis

Multi-attribute analysis is a statistical method that uses more than one attribute to predict several physical properties of the earth's surface. In this analysis, log relationships with seismic data have high correlations, with this method the log parameters in a well can be drawn for distribution at all locations in a seismic cross section. In the most common case, searching for a

function that will convert different multi-attributes into the desired property, can be written mathematically as follows,

$$P(x,y,z) = F[A_1(x,y,z), \dots, A_n(x,y,z)] \quad (2)$$

where P is a log property, variables x , y and z are coordinate functions, F is a function that states the relationship between seismic attributes and log properties and A_n is attribute m , where ($n = 1, 2, \dots, m$). In the simplest case, the relationship between log property and seismic attributes can be shown by the equation of the number of linear weights in the following equation,

$$P = w_0 + w_1 A_1 + \dots + w_n A_n \quad (3)$$

where w_n is the value of $m+1$, and A_j is m , with $n = 1, 2, \dots, m$.

METHODOLOGY

Flow chart of well analysis and post-stack seismic inversion until multi-attribute is shown on Figure 3.

RESULTS

Target Zone Analysis

Target zone qualitative analysis is done by looking at the log curves of the parameters that exist in the target well. In this study, there are one 2D seismic post-stack time migration section and two wells (FYR-1 and FYR-2), which are used in multi-attribute analysis (Figure 4). Post-stack time migration method gives better results on the continuity of seismic sections, eliminates incoherent noise, and improves seismic cross-section resolution (Farfour *et al.*, 2015). The density log curve and NPHI have a correlation in determining the target zone. This is because hydrocarbons have a low hydrogen index so neutron devices obtain high energy neutrons in the formation. In areas that are filled with

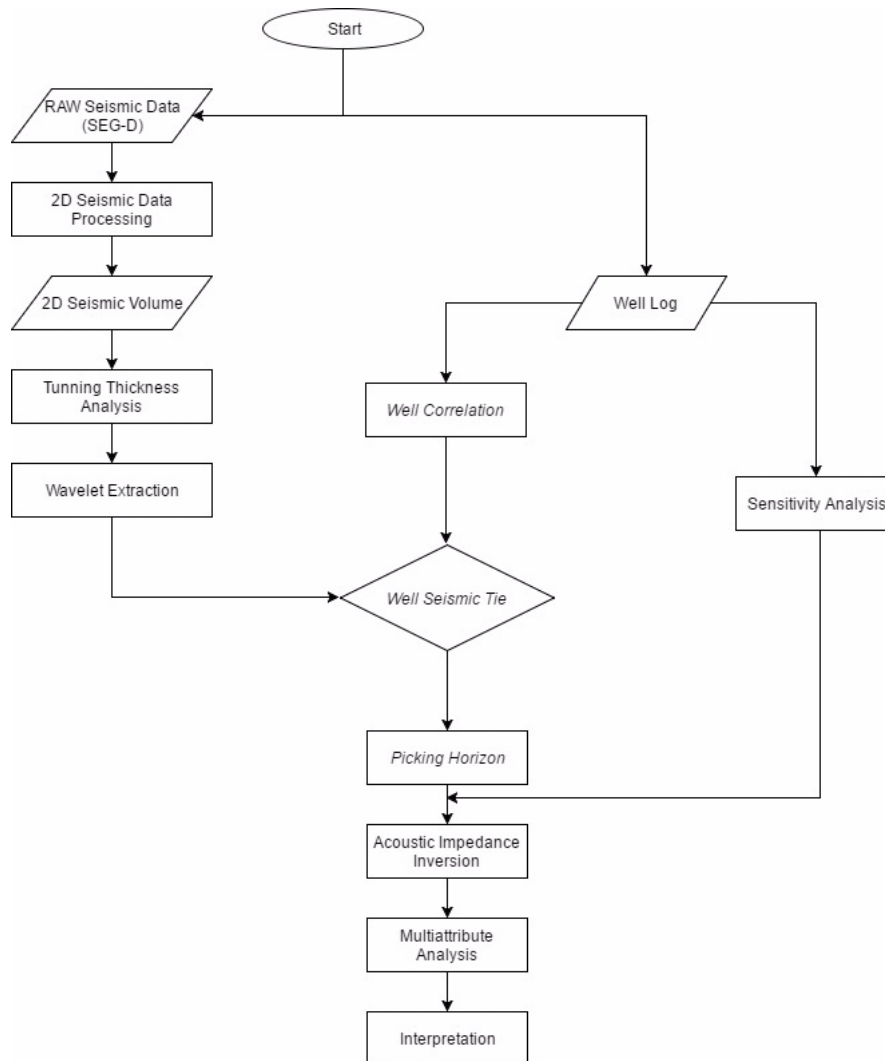


Figure 3. Flow chart of multi-attribute analysis

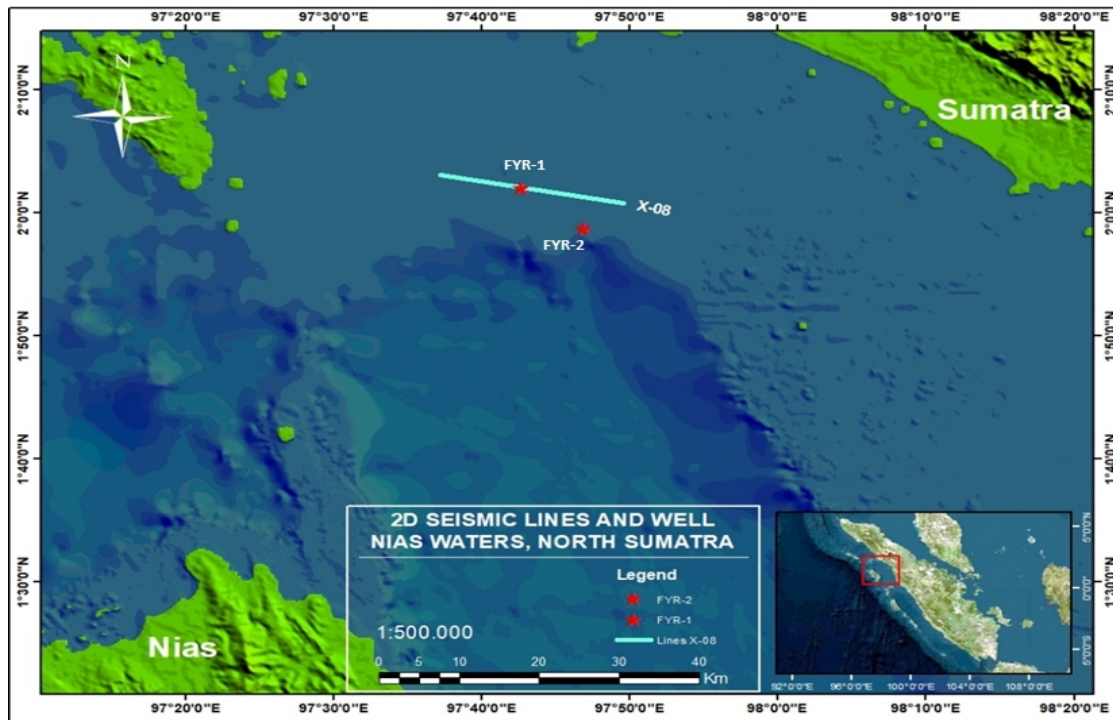


Figure 4. Wells and seismic line map location

hydrocarbons shows a lower value. More, for density logs in areas filled with hydrocarbons will show a higher in value, because of it occurs a positive separation in the area filled with hydrocarbons (Irawan and Utama, 2009). The log is able to determine the type of fluid indicated, such as gas, oil and water. In addition to the relationship between the two logs above there

needs to be validation from other logs such as the gamma ray and resistivity logs. The target zone which is generally located in limestone and sandstone lithology has a low gamma ray value so that this log curve can be used as a target zone validation, while the resistivity log plays a role in determining the fluid contained in rock formations (Figure 5).

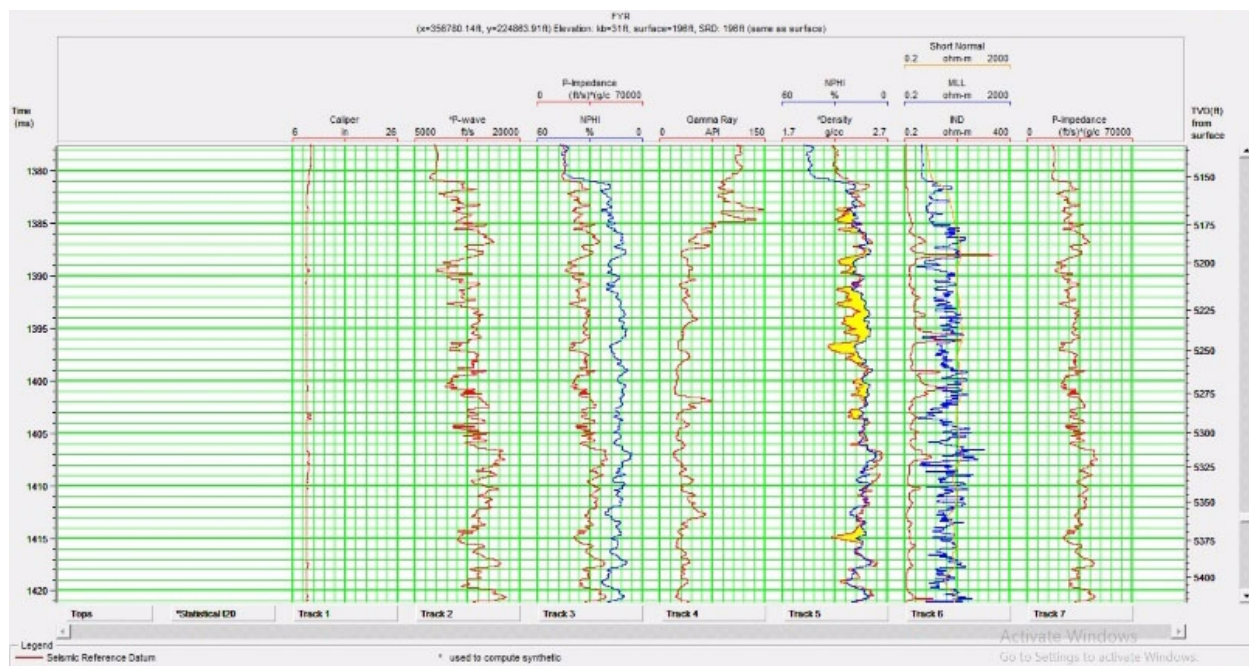


Figure 5. Analysis of target zones based on log curves

Tuning Thickness Analysis

Tuning thickness is influenced by the wavelength that passes through the rock, mathematically the value is $\lambda/4$ of the seismic wave that passes through the layer. In determining the value of tuning thickness, the average velocity (P-wave) and dominant frequency of the layer are needed (Nainggolan and Winardhi, 2012).

The thickness of the tuning causes the lack of a seismic cross section in the target layer (Table 1). This can be overcome by doing acoustic impedance inversions that include low frequency information from the log data. Whereas seismic data only has only a certain frequency ranges.

The areas that contain hydrocarbons are indicated by red zones in Figure 6. Anomaly in the form of different resistivity values that are higher than the surrounding environment is a target zone, because the physical properties of hydrocarbons are high resistivity.

Well Seismic Tie

The well seismic tie stage is carried out to bind the well data with seismic data which is useful so that each horizon in the seismic cross section is at the actual depth. High correlation will increase the level of accuracy of depth in both data.

The results of the well seismic tie stage of various wavelets, it is known that the statistical wavelet has the

Table 1. Tuning thickness calculation results

Seismic Line	Dominant Frequency (Hz)	P-wave Average (m/s)	λ (m)	Tuning Thickness (m)	Layer Thickness (m)
X08	23	4238,098	181,221	45,30	90

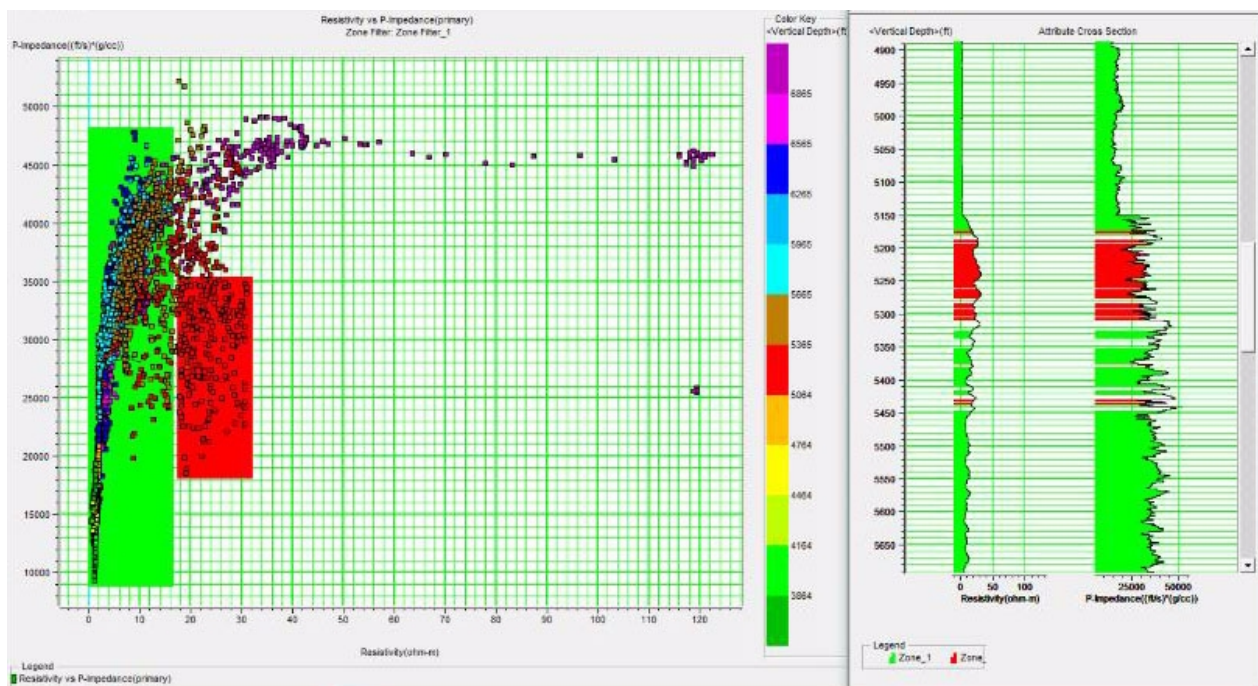


Figure 6. Crossplot AI vs NPHI

Sensitivity Analysis

The qualitative and quantitative sensitivity analysis stage can be seen from the results of cross-plots and cross sections to look for sensitive parameters that are able to separate lithology and hydrocarbons and get a cut-off value of these parameters (Kurniawan *et al.*, 2013).

highest correlation coefficient on the X08 path with a value of 0.720 (Table 2).

Table 2. Wavelet Correlation

Seismic Line	Correlation Coefficient		
	Usewell wavelet	Statistical wavelet	Ricker wavelet
X08	0,535	0,720	0,662

Initial Model Analysis

Making the initial model provides information in the form of the distribution of acoustic impedance values in seismic data with well data as a control. In this study, the initial model was made using three horizons that were obtained in the previous stage and using a 10/15 Hz high-cut filter to create an initial AI model for the inversion (Figure 7). The use of hard constraints in making the initial model is useful for combining low frequency data that matches acoustic impedance so as to minimize inversion mismatches (Li and Peng, 2017).

Multi-attribute Analysis

The stages in multi-attribute analysis begin with entering well data to be used in the multi-attribute method. Seismic impedance inversion results that have been obtained in the previous stage are used as input to the external attributes of this processing. Furthermore, determining the right attributes, this process is done several times to obtain the results of the best multi-attribute composition in all wells can see the validation error option in this process, the smaller the error value, correlation between the multi-attribute components shows better result.

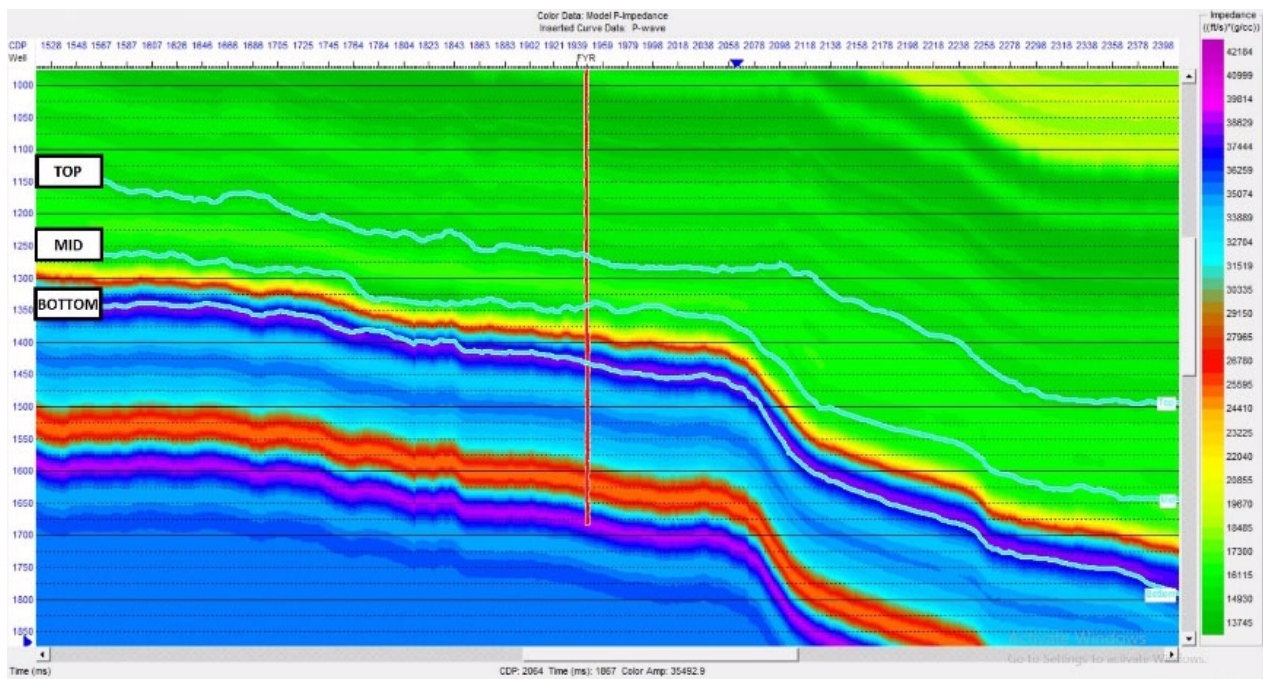


Figure 7. Initial model result

Acoustic Impedance Inversion

Inversion analysis is determination of inversion parameters before inversion is performed. This is useful to determine suitable parameters used at the inversion stage so that the correlation between the initial model with high inversion results is obtained.

The results of testing several seismic methods show a high correlation on model based inversion (Table 3). The existence of a high correlation will also help increase the suitability of inversion results with the geological form of the earth (Sukmono, 2000).

Tabel 3. Results of coefficient correlation inversion analysis

Seismic Line	Correlation of Inversion Analysis		
	Model Based	Band limited	Sparse spike
X08	0,998	0,955	0,954

Figure 8 shows the error value in the multi-attribute composition, the lowest point that touches the x-axis shows a bad correlation. Multi-attribute analysis results indicate the error level.

Acoustic Impedance Inversion

The results of seismic inversion can be seen from the distribution of acoustic impedance values in the seismic cross section shown in Figure 9. Based on the distribution of acoustic impedances in the cross section, physical characteristics of the target zone can be seen. A change in the acoustic impedance value is an indication of the different layers in the rock. Based on the analysis of the target zone in the two wells it can be seen that the FYR-1 well has a hydrocarbon potential, this is seen from the intersection of the density curve and NPHI, while the remaining wells are dry wells.



Figure 8. Validation of multi-attribute error results

Figure 9 shows the target zone which is indicated by a red circle. In this zone, the acoustic impedance value decreases from an impedance value of around 40,000 ((ft/s)*(gr/cc)) to 21,469-28,881 ((ft/s)*(gr/cc)). The target zone area which is at a depth of around 1450 ms has a low impedance value distribution spread from CDP 1946 to 1990. To ensure that the area is a target zone containing hydrocarbons then a resistivity distribution is made from the multi-attributes.

Multi-attribute Analysis

Analyzing a number of reservoir properties (porosity, resistivity and V_{shale}) able to optimize the boundary conditions of the target zone containing hydrocarbons (Alao and Oludare, 2015). In this research, multi-attribute analysis is used to create resistivity log distribution in seismic section line X08, log porosity and V_{shale} analysis cannot be done in this study due to limited data in both wells. Multi-attribute analysis using the linear regression method with step wise regression technique is to look for attributes with the smallest validation error value. Based on the results

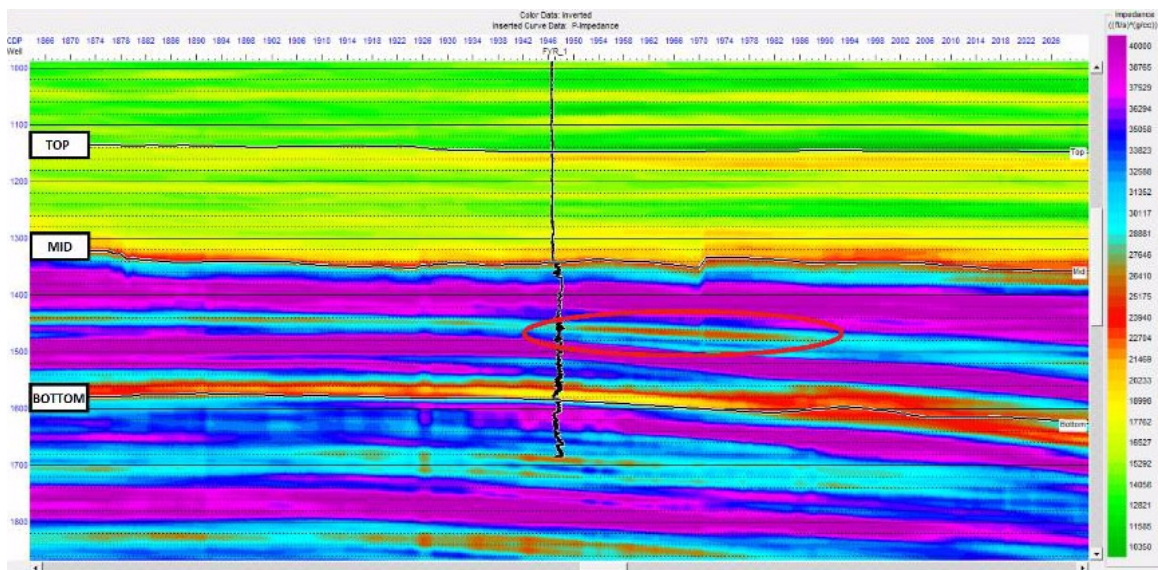


Figure 9. Acoustic Impedance Inversion Results

of the validation error graph as shown in Figure 8, the prediction of porosity distribution has the best correlation on the composition of 2 (two) attributes with 5 (five) points. The results of the multi-attribute linear validation show a very good correlation of 0.81.

Based on Figure 10, there is a red colored zone at a depth of 1450 ms which has a higher resistivity value than the surrounding area. The cross-plot results show that the target zone has a resistivity value in the range of

reference in determining the distribution of hydrocarbons in the cross section of the inversion results and multi-attribute analysis. Hydrocarbon zone have a character consisting of acoustic impedance value between 18,000 and 35,000 ((ft/s)*(g/cc)) and resistivity values in the range of 18-31 ohmm. The acoustic impedance inversion distribution value by model based method on 2D seismic line X08 gives better results than the other methods. Based on the

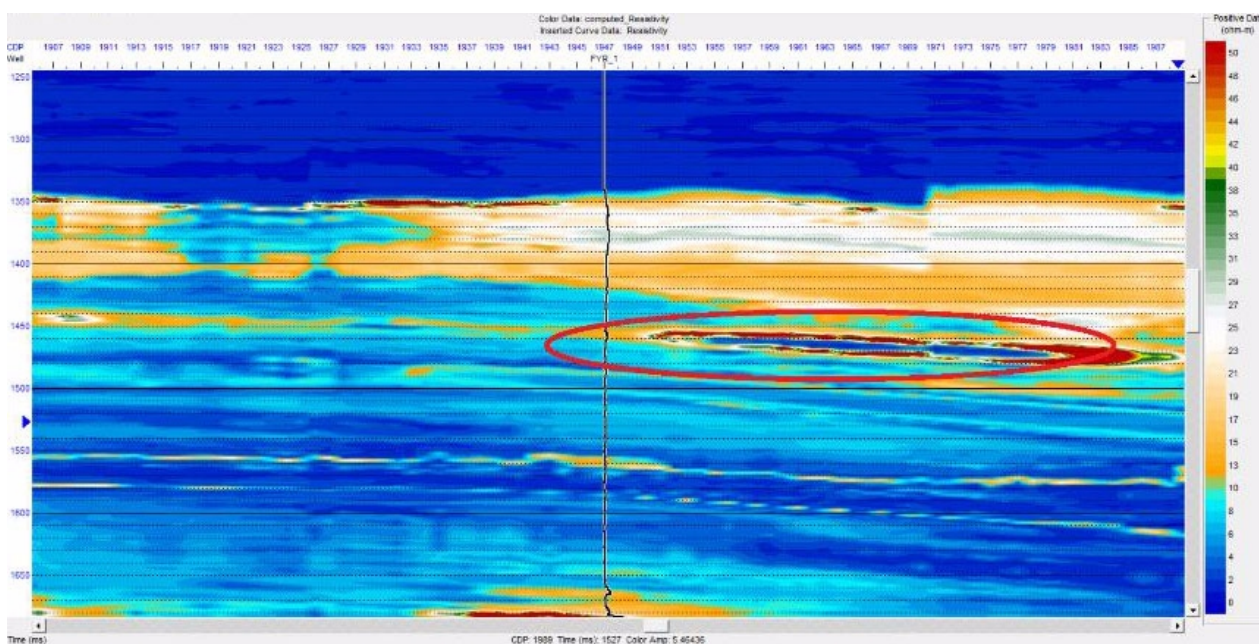


Figure 10. Distribution of multi-attribute resistivity

18-30 ohmm. The results of the resistivity distribution using multi-attribute analysis have resistivity values in the range of 19-30 ohmm, the existence of resistivity higher than the target zone allows the insertion of other rocks in the layer. By combining the results of the acoustic impedance distribution and the resistivity distribution, it can be seen that the zone is a target zone containing hydrocarbons.

DISCUSSION

Both of these two wells are crossed by seismic lines X08 with an azimuth of 100 with length 23.3 km. The azimuth on the seismic lines is the direction of the ship's direction, with an azimuth of 100 meaning the ship is moving from the west (280) to the east (100). Based on the analysis of the target zone, hydrocarbon was found in the FYR-1 well. Below is the hydrocarbon with zones N17-N16. The target zone in the FYR-1 well consists of gas trapped in limestone with depth range about 1450 ms. The parameters yielded from sensitivity analysis results is used as a lithology separator and the appearance of hydrocarbons, so it can be used as a

results of this inversion, there is a bright spot with an acoustic impedance value between 21,469 and 28,881 ((ft/s)*(g/cc)) at depth about 1450 ms that crosses from east to west towards the western FYR-1 well. The bright spot area has an acoustic impedance value which match with the cross-plot analysis results, so it can be assumed that the area is a target zone containing hydrocarbons. Then, Multi-attribute analysis is performed to map the resistivity distribution based on the best composition available in seismic data (Altoairqi *et al.*, 2017). Multi-attribute analysis produces a map of the resistivity distribution as shown in Figure 10. This resistivity distribution can be used as a validation of the hydrocarbon distribution that has been mapped on the results of the previous inversion. In Figure 10, the area indicated by a red circle has resistivity value between 18 and 32 ohmm. This value indicates compatibility with the range of values ??obtained based on sensitivity analysis. So it can be seen that the zone at depth around 1450 ms elongated from southeast to northwest is a zone containing hydrocarbons.

CONCLUSIONS

The results of cross-plot analysis between acoustic impedance (AI) and resistivity show that these parameters are sensitive in separating the target zones which containing hydrocarbons in limestone. Based on the results of cross-plot analysis show the target zone has a physical character in the form of acoustic impedance values in the range of 18,000-35,000 ((ft / s)*(g/cc)) and the value of resistivity in the range of 18-31 ohmm. Acoustic impedance inversion results are able to describe the distribution of hydrocarbons with a range of value 21,469-28,881 ((ft/s)*(g/cc)). Afterward, the resistivity distribution of multi-attribute analysis results is used as validation of acoustic impedance inversion result data in the target zone. The target zone resistivity distributions show the values which correspond to the characteristics of the cross-plot results, in the range of 13-30 ohmm. Based on the range of those parameters, the hydrocarbon zone elongated from east to west toward the FYR-1 well.

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