Application of Seismic Inversion to Build a Geological Static Model of X-Field Reservoir, Malaysia

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Abstract

The common problem that encounters by oil and gas companies is a high production of water cut due to ambiguity in litho-fluid separation, resulting in high uncertainties of the static model. In this paper, litho-fluid is first classified by elastic properties parameters such as VpVs, Poisson Ratio, P-impedance, SQp and SQs through cross-plot analysis. Application of new attributes, SQp, and SQs, which derived from seismic attenuation, rock physic approximation, is examined to discriminate lithology and pore fluid. Pre-stack seismic inversion is executed to get I-p, I-s, and density and used to create 3D Model Facies through SQp and SQs function. Facies and petrophysical parameters are then upscaled into the geocellular grid associated with the inversion result for simulating the static model. Geostatistical concept through experimental variogram is applied for the simulation to interpolate the unknown part throughout the reservoir. The traditional method and inversion input of new attribute are compared based on static model results. The static models built are specified on Vsand, Vshale, porosity and water saturation to understand the behavior of reservoir study, thus the estimation of high water cut production can be estimated.

Keywords: Seismic Inversion, Static Model, Seismic Attribute, SQp, SQs

1. Introduction

Geological static model is widely used in oil and gas industry to overview the quality and potential of reservoir and the estimation of its statistical description. Seismic inversion is the main process of obtaining quantities of rock-property consist of lithology and fluid description of the reservoir from seismic data. The inversion process is carried out by extracting the wavelet from traces of seismic volume and calculate through algorithm to create the inversion. In another word, a single seismic trace is converted to earth layer properties by the process of deconvolution and gives the elastic contrast of the earth which is impedance value by removing the effect of wavelet. It may be pre-stack or post-stack, and either deterministic or geostatistical. Seismic data itself do not directly provide any direct measurements of the reservoir such as porosity, net pay, permeability and water saturation (Paparozzi et al., 2013; Grana and Rossa, 2010). Those reservoirs are important to build the static model which is usually conducted to approach an ideal condition.
to have a perfect characteristic with respecting to certain constraints as it is used for dynamic model (Saussus and Sams, 2012; Bosch et al., 2010).

One of the common problem in oil and gas companies is the high production of water cut. This excess water production is uneconomical and not desirable as costing to lift and then dispose of it. Understanding of the facies distribution and geological structure of the reservoir is important to avoid drilling in water bearing zone. This paper presents the study of geological static model of X Field, offshore Sabah by integration of new attributes, SQp and SQs (Hermana et al., 2020), from pre-stack seismic inversion associated with geostatistical approach, thus the estimation of reservoir characterization can be made to predict the possible high production of water.

2. Methodology

There are three steps in this research to generate the static model. Figure 1 illustrates the workflow including three integrated approaches of litho-fluid classification, seismic inversion, and static modeling. The details of each step are described in following sections.

![Workflow](image)

Fig. 1. Workflow has integrated three main processes (label in red color).

2.1 Litho-fluid classification:

The behavior of the fluid properties based on elastic moduli through rock-physic was analyzed. Elastic properties of Poisson Ratio, VpVs, SQp and SQs are the essential attributes employed in this study.

2.2 Seismic inversion and 3D facies model

Pre-stack seismic inversion is generated by following steps:
1. Extracting statistical wavelet from pre-stack seismic (10º, 22º, 32º).
2. Conditioning log and horizon to build low frequency model.
3. Each seismic trace is calculated by Fatti Modification of Aki-Richard equation to build inversion based on angle wavelet, derivative operation, and logarithm of Zp, Zs and density.
4. Model inverted of VpVs and density are used to create attributes of SQp and SQs.
Using the data of seismic inversion and well log, the 3D Facies Model can be generated via SQp and SQs attributes. The equations of SQp and SQs (Hermana et al., 2018), used to create the 3D Facies Model, are as follows:

\[
SQp = \frac{51}{6} \frac{(M/G-2)^2}{\rho (M/G-1)}
\]

(1)

\[
SQs = \frac{101}{3} \frac{(M/G)}{\rho (3M/G-2)}
\]

(2)

2.3 Static model

3D Facies model generated through inversion will be integrated into statistical reservoir modelling. The geostatistical is approached to create facies and petrophysical model, which includes:

- Preparing the structural model of horizons and fault
- Build a velocity model for time-depth conversion
- Create a structural model based on zones and layering
- Scale up well logs
- Create petrophysical and facies model through geostatistical approach.
- Comparing the input between seismic inversion and acoustic impedance volume.

3. Result and discussion

3.1 Litho-fluid Classification

The cross-plot study of elastic properties is conducted to determine the litho-fluid of X-Reservoir well.

\(Vp/Vs\) vs poisson ratio

Poisson Ratio is the elastic parameter that has a relationship between P-wave velocity and S-wave velocity. While, \(Vp/Vs\) ratio is the ratio between P-wave and S-wave velocity. Thus, when these two elastic properties cross-plotted, it shows bounded exponential and has strongly function on lithology separation. The lowest part of Poisson Ratio and \(Vp/Vs\) will be gas sand, followed by oil sand, brine sand and shale. Consolidated brine sand is identified at the shallow part of the Well 1 as the Poisson Ratio is exceed 0.41 (Figure 2).

Fig. 2. Cross plot \(Vp/Vs\) vs PR.
P-impedance vs Vp/Vs ratio

From the results of both wells, P-impedance and Vp/Vs values show the lowest at gas sand. Somehow, the trends of brine sand and oil sand are overlap to each other make it hard to delineate the fluid properties. The variables that control the cross-plot is the curve created based on zoning of Poisson ratio versus Vp/Vs. Shale distribution is clearly different from the other as accumulation is concentrated at the top of cross-plot (Figure 3).

![P-impedance vs Vp/Vs](image)

Fig. 3. Cross plot P-impedance vs Vp/Vs.

SQs vs SQp

The used of SQp and SQs cross-plot is clearly the best to delineate litho-fluid properties. As shown in both wells, the shale is clearly concentrated at the highest part of the SQp and the lowest part of SQs (Figure 4 and 5). Because of the most cross-plot is hard in differentiating between brine sand and oil sand, SQp and SQs cross-plot is better to be used to separate between oil and brine sand distribution. The brine sand will be always concentrated at the top of oil sand and separated with the shale and gas zone.

![SQs vs SQp](image)

Fig. 4. Cross plot SQp vs SQs.
Fig. 5. Major of the results from cross-plot will tally with the top selection and show the right fluid properties (Gas, Brine, Oil). In this case, cross-plot SQp and SQs.

**Cross-plot result of elastic parameters (Table 1)**

<table>
<thead>
<tr>
<th></th>
<th>Depth (MD from KB)</th>
<th>Poisson Ratio</th>
<th>P-impedance (m/s)</th>
<th>Vp/Vs Ratio</th>
<th>SQp</th>
<th>SQs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Sand</td>
<td>1330</td>
<td>0.20-0.22</td>
<td>4503-6540</td>
<td>1.43-1.67</td>
<td>0.82</td>
<td>0.52-0.86</td>
</tr>
<tr>
<td>Oil Sand</td>
<td>1500</td>
<td>0.22-0.27</td>
<td>6000-7500</td>
<td>1.67-1.78</td>
<td>0.56</td>
<td>0.55-0.65</td>
</tr>
<tr>
<td>Brine Sand</td>
<td>1531</td>
<td>0.27-0.35</td>
<td>5847-7485</td>
<td>1.78-2.03</td>
<td>0.70</td>
<td>0.53-0.66</td>
</tr>
</tbody>
</table>

### 3.2 Seismic inversion

Quantitative of rock-property consist of lithology and fluid descriptions of the X-Reservoir, known as the seismic inversion process, which has been conducted in purpose to create a 3D model of facies distribution. Well analyzing and facies classification evaluation through rock-physic approach has been
Seismic inversion technically performed to increase the resolution of seismic data reflection due to its band-limited frequency and best in estimating the geological properties of the subsurface, including water saturation and porosity. Pre-stack seismic inversion is to invert a pre-stack CDP gather of PP and PS of mode conversion as there is a linear relationship of P-impedance, S-impedance, and density, and is expected to determine the litho-fluid description. The complex algorithm is analyzed through Hampson Russel Software in creating inversion results of P-impedance, S-impedance, and density. Pre-stack seismic inversion is used in this study because post-stack inversion is not sufficient to determine the lithology and fluid description of the reservoir. The fundamentals of P-impedance, S-impedance, VpVs, and density can create another elastic property regarding their relationship.

Statistical wavelet is extracted from the seismic data with a different offset (10°, 20°, 32°) and used to estimate and convolved with the reflection coefficients from sonic and density curves. Thus it creates a composite synthetic seismonogram in the seismic inversion (Figure 6). The combining of those three-statistical wavelets from the different seismic offset (near, mid and far stack) is crucial to first correlate the well tie to seismic in correct position alignment with zero phase assumption to ensure the quality data of inversion result. Seismic to well tie of X-Reservoir is retained at the top of gas sand amplitude as the indicator because it showed a good amplitude reflection on seismic data. Since the characteristic of gas sand exhibits peak amplitude (as white through indicated compression), the alignment must be adjusted to a maximum correction value, the correction value of log correlation for the well and seismic is 0.73 and is considered a good correlation. Zero-offset data is used for inversion with the taper length 25ms. Pre-stack seismic data is a band-limited where the low-frequency region from 0-10 Hz needs to be constraint from low-frequency AI model and well spectrum.

The most crucial part of extracting the wavelet from the seismic data is to compute the logarithm of the seismic inversion system. The algorithm work in the seismic inversion is quite complicated as the concept is first to come from the assumption of mode conversion where the reflection of seismic not only reflected P-wave, at the same time transmitted and reflect S-wave. Post-stack is where seismic is assumed to be reflected at the zero angles and reflect only the P-wave, while pre-stack consists of angle reflection. Through this mode conversion, there is a relationship between Vp and Vs regarding equation and Vp with density regarding Gardner’s equation. The elastic properties are well-known to hold a litho-fluid description (Zp, Zs, density) and best to estimate reservoir placement.
Equation 3 is the formula derived from the basic Aki-Richard equation and modified by the Fatti equation to create a single formula. Consisting of the seismic trace at a different angle and the system logarithm of Zp, Zs, and density, the extracted wavelet from seismic reflection and derivative operation will be the input into the matrix form and conjugate gradients to find the inverted result (Hampson et al., 2006). Means for every trace will be computed through this parameter, thus create a volume of inversion in a seismic section with the main P-impedance, S-impedance, and density. From these volumes, inversion, any equations that have a link relationship with elastic attributes inverted, can be generated to new properties, such as water saturation volume, porosity, SQP, and thus SQs.

The well log data used is to extend the band-limited of low-frequency zone, plus the initial low-frequency geological model and the trend will be input in seismic inversion regarding gaining low frequency and its high constraint to well data. The initial model of a geological model comes from the seismic parameter, such as velocity, reflectivity and impedance, and well log data. “Well 1” only is used to proceed with the model. The other method, like triangulation or kriging, could not be valid as only one well, as a result, it shows the horizontal distribution of properties distribution for the low-frequency model. The horizon picked (top of gas sand, shale, and bottom of oil sand) will terminate the interpolation of the properties assigned from the well (Figure 7).

**Fig. 7. Seismic data and low-frequency model.**

### 3.3 Inversion QC

The regression line of the plot means the quality of inversion data with the original log. The closer the line to the linear equation of y=mx +c, the better the inversion. All three elastic properties indicate a good perpendicular line to each other, show lower error that will give good seismic inversion results (Figure 8).
Fig. 8. Original log vs inverted log for P-impedance (right) and VpVs (left).

The correlation between the inverted log and the original log is good as only one well is used in the study. By the cross-plot analysis, as demonstrated in figure 9, we can see the relationship between logarithm Zp with Zs and density, particularly where there are fluid anomalies (Hampson et al., 2006). The deviation away from a straight linear fit illustrated gas sand of X-Reservoir.

Fig. 9. Gas anomaly from the cross-plot.

Figure 10 indicates the relationship between the inverted log (red) with the original log (blue) for Zp, Zs, density, and VpVs. As the inverted line almost resembles the original log, the result is quite satisfactory. The analysis of synthetic and seismic trace shows a low error anomaly. This is called Sparse Spike pre-stack inversion where it measures the difference between synthetically produced and seismic data by linear programming method.
The results of pre-stack seismic inversion delineate the lithology, and facies from the seismic section. P-impedance, VpVs, and density are the fundamentals of elastic properties and will be derived to execute another elastic property through relationship equation. From the results (Figure 11), we can see for the Gas Sand reservoir, and all three elastic properties show a clear change in response. P-impedance value depends on P-wave velocity; thus, it has a relationship with the porosity under Wyllie’s Equations. An increase in porosity of sand reduces the value of P-impedance as it reduces the P-wave velocity. Other than that, low VpVs and density value validate and agree that the lithology is sand and the main fluid is gas. SQp and SQs are then generated through trace math and equation based on the parameter VpVs and density.

As the SQp is close to gamma-ray log response and SQs is close to resistivity log response, it can clearly delineate the litho-fluid. The green color in SQp indicates sand lithology while blue is shale. The red color in SQs represents high resistivity usually hydrocarbon, and blue represents low resistivity indicating brine response. The 3D model facies is generated through facies attributes of SQp with clear delineating sand
and shale distribution. This 3D volume will be then inputted into a reference in building reservoir geological static model. It can be useful to determine the trend of facies along the reservoir.

Cross-plot between low SQp and high SQs marks the gas sand distribution (Figure 12). Low SQp give sand response, high SQs give hydrocarbon response. SQp and SQs attributes are much better in separating brine and oil sand as the cross-plot is not intercept compared to P-impedance and VpVs. Lateral distribution of Gas Sand (red color), Oil Sand (green color) and Brine Sand (blue color) clearly describe the quality of new SQp and SQs attributes in determining lithology and fluid properties.

3.4 Reservoir characterization static model

The results of seismic inversion proved SQp attribute is better in a delineation of facies distribution as the function is derived from rock physics approximation and seismic attenuation (Figure 13). The structural model is first built based on the understanding of the deposition environment of the reservoir. Unconformity of the gas sand is set as an erosional surface and every layer below are defined as an unconformable surface (Figure 14).
The result of 3D facies model through inversion is finally integrated into the static reservoir modeling of facies and petrophysical parameters. The input data used is usually log-facies profile at well location that has been upscaled into the geocellular grid and 3D facies volume as soft data for experimental variogram and generate facies realization by sequential indicator simulation algorithm (Figure 15). Sequential indicator simulation produces high-resolution of facies by sequentially visiting every grid cell along its random path and calculate any number of stochastic realizations of the property based on the upscaled well observation and the variogram (Paparozzi et al., 2013).

**Fig. 15.** Upscaled facies, well log and water saturation.
As there is only one well data used in the study, where the vertical direction of variogram is concerned, the best option in performing distribution of facies and petrophysical properties is by applying 3D model facies attributes. The result SQp and SQs input will be compared with the common acoustic impedance volume input (Figure 16).

SQp and SQs property is the first resampling analog with the structural model. To account for non-stationarity, the reservoir was subsided into 3 sub-layers named gas sand to sand 1, sand 1 to oil sand (GWC), oil sand to base (OWC) (Figure 17). The layering was built according to stratigraphy sequence of the reservoir where gas sand to sand 1 is the unconformity of erosional and the layers below are set as unconformable. The experimental variogram is computed for every layer for SQp with estimating the direction for major and minor distribution. Variogram type of spherical is estimated to find the best geostatistical value of anisotropy range for the reservoir. For instance, the zone of gas sand to oil sand range used for both sand and shale facies (Major-413.571, Minor-198.825, Vertical- 37.5) and estimated based on the range value of histogram where no more correlation. The same variogram setting must be used for both sand and shale if only two facies used. The vertical range for variogram needs to be constant as one well used. To have more valid result, the trends of SQp attributes become the trend for building the facies distribution.

![Fig. 16. SQp 3D Model Facies and RMS input for experimental variogram computation.](image)

For the petrophysical modeling, within each facies (sand and shale) the properties of porosity and permeability are simulated by Gaussian random function simulation. It produces a realization of property which honors the well data and a target of the histogram for the property. Plus, it randomly picks along its random distribution. The trend input for both porosity and permeability are SQp. The result of petrophysical modeling and facies modeling is QC with the histogram to validate the quality of the result. The histogram shows the distribution of values of upscaled, well logs and property value. The better the result when all values are the same.

The same workflow is applied to simulate acoustic impedance input. The RMS attribute is built to get the anisotropy range for variograms. Anisotropy used is different for every sub-layer. For instance, for the gas sand zone (Major-1500, Minor-77, Vertical- 37.5) based on the size of the distribution of RMS at the location (Figure 18).
From the result in figure 19 and figure 20, value of the facies is deterministic. The facies indicator is divided by two, which is sand (yellow) and shale (grey). X-Reservoir is mainly in gas sand. The result has shown that the soft blue indicates high porosity and red with low porosity. For the water saturation, the red means low saturated while blue is mainly water. Estimation of the distribution of water saturation has highly affected the production of water cut. If the estimation is correctly guessed, it will reduce the possibility of producing high water cut. The contact between OWC and GWC which commonly ambiguous can be estimated and delineate correctly through SQp and Sqs attributes based on seismic inversion result.

The results of static for both SQp input and RMS input indicate different distribution for facies and properties. As the distribution is honoring only one vertical data, the distribution is quite a bias to the facies and properties and the data more randomly populate at the nearby area (Figure 19). Somehow, the new SQp attributes proved that the 3D facies model that has been created from seismic inversion managed to populate the properties clearly without clear bias to well data (Figure 20). As for the exploration process with limited well data, the application of SQp attributes is the best to create a static model. This study is crucial to improve from the traditional use of seismic amplitude changing into new attributes of inversion result as input.
Fig. 19. Facies, porosity and water saturation model for SQp input (3D Facies Model).

Fig. 20. Facies, porosity and water saturation model for AI input.

The integration of geostatistical enables to manipulate and creating multiples set of stochastic realization of reservoir properties, particularly in facies (Vsand, Vshale), porosity and permeability. Up to this part, the volumetric calculation such as total net-pay and the total oil in place of the reservoir based on the stochastic result can be generated associated with the desired uncertainties used (P10, P50, P90). Thus, the dynamic model can be simulated with the desired input parameter.

4. Conclusion

The workflow of this study includes integration of multiples disciplines: seismic inversion, rock-physic, reservoir facies modelling and geostatistical simulation. It aims at applying a reliable probability volume of petrophysical properties and facies based on new elastic attributes (SQp and SQs). Both models of seismic inversion and static models can be useful in quantitative interpretation. Well log litho-fluid classification, pre-stack seismic inversion and building a geological static model based on new attributes have successfully completed throughout the study. Application of pre-stack seismic inversion to build a geological static model is one of the crucial subjects in the oil and gas industry. Seismic inversion algorithm and concept on how it works needed to be understood clearly to create a good inversion result. A quality of inversion that enables to identify of litho-facies through a rock physic approach is important to generate
a good static model, significantly in the exploration phase where limited well log data used. The input of the 3D model facies of seismic inversion is successfully managed to create a geological reservoir static model better than traditional method when involving only on well. This study has proved that new attributes of SQp and SQs are able to delineate litho-fluid description which is important in identifying the accurate zone for oil-water contact (OWC) to avoid high production of water cut. The knowledge of geostatistical is important to control the population of the facies and properties, thus will lower the uncertainty of net-pay and volume calculation.

The static model needs at least three wells to populate the data accurately. More wells should be given to create a good static model to honor the vertical distribution analysis. Quality checking must be accurately analyzed in seismic to well tie part, inversion analysis and static model (upscaled and grid) will give high quality of results. Building a geological static model should always in a team where combining petrophysicist, geologist and geophysicist work to build an ideal model of reservoir characterization.

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References


