Reducing Uncertainties in Hydrocarbon Prediction through Application of Elastic Domain

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Abstract. The application of lithology and fluid indicators has helped the geophysicists to discriminate reservoirs to non-reservoirs from a field. This analysis is conducted to select the most suitable lithology and fluid indicator for the Malaysian basins that could lead to better eliminate pitfalls of amplitude. This paper uses different rock physics analysis such as elastic impedance, Lambda-Mu-Rho, and SQp-SQs attribute. Litho-elastic impedance log is generated by correlating the gamma ray log with extended elastic impedance log. The same application is used for fluid-elastic impedance by correlation of EEI log with water saturation or resistivity. The work is done on several well logging data collected from different fields in Malay basin and its neighbouring basin. There’s an excellent separation between hydrocarbon sand and background shale for Well-1 from different cross-plot analysis. Meanwhile, the Well-2 shows good separation in LMR plot. The similar method is done on the Well-3 shows fair separation of silty sand and gas sand using SQp-SQs attribute which can be correlated with well log. Based on the point distribution histogram plot, different lithology and fluid can be separated clearly. Simultaneous seismic inversion results in acoustic impedance, Vp/Vs, SQp, and SQs volumes. There are many attributes available in the industry used to separate the lithology and fluid, however some of the methods are not suitable for the application to the basins in Malaysia.

1. Introduction
Malaysia has been producing hydrocarbons from various fields since the early 1900s, with the first field was found in onshore Miri, Sarawak. The following major discoveries were made offshore in Sarawak, Sabah and Malay Basins. The location of Malay basin is at the eastern side of Peninsular Malaysia. Malay basin is known to be an extensional pull-apart basin with anticlines trending from east to west direction including series of half-grabens. Primarily, the basin formed during the late Eocene to early Oligocene, followed by thermal subsidence leading to sedimentation in the early Miocene. Later in the middle Miocene, regional stress fields changed and the basin inverted forming east-west anticlines trend [3].

Pitfall of amplitudes is one of the many geophysical issues faced by the interpreters that lead to the misinterpretation of hydrocarbon reservoirs for examples are coal, soft shale, and high-porosity brine sand. Coal has been the excellent source rock for Malay basin reservoirs and good horizon markers, however the presence of coal masks interfere the reservoirs underneath by forming strong soft negative impedance. This is due to the acoustic properties of coal that has low density and low velocity [9], which shows similar acoustic impedance response to the gas sand. Another issue is that high quality
brine sand shows similar amplitude versus offset (AVO) response to hydrocarbon sand. In the case of poor quality gas sand, the reflectivity shows positive impedance which might be misguided as non-reservoir. In addition, unconsolidated shale or known as soft shale that occur mostly in younger sediments, produces lower acoustic impedance than the surrounding rocks; similar response as hydrocarbon sand. These issues add to the difficulties to differentiate the amplitude anomalies based on acoustic impedance alone, whether they are caused by the lithology or fluid content. Therefore, this analysis is conducted to select the most suitable lithology and fluid indicator for the Malaysian basins that could lead to better eliminate pitfalls of amplitude.

2. Methodology

This paper addresses different application of rock physics analysis such as extended elastic impedance (EEI), Poisson ratio, SQp-SQs attribute and Lambda-Mu-Rho (LMR). The elastic impedance logs can be correlated with any desirable log, in this project are gamma ray and resistivity or water saturation logs to produce EEI_litho and EEI_fluid respectively [8]. Meanwhile, the SQp-SQs attribute is adopted from Hermana et. al which SQp resembles the gamma ray log and SQs imitates resistivity log, thus both attributes are used for lithology and fluid indicator respectively [5].

2.1. Poisson ratio

Poisson’s ratio (σ) characterizes the relationship between Vp and Vs of material, which can affect the P-wave reflection coefficients [7]. The magnitudes are used to distinguish between different lithology, which generally brine-saturated sand has higher Poisson’s ratio compared to gas-saturated sand.

\[
σ = \frac{1}{2} \left( \frac{V_p}{V_p^0} \right)^2 - 2 \left( \frac{V_p}{V_p^0} \right) \left( \frac{V_s}{V_s^0} \right)
\]  

(1)

2.2. Extended Elastic Impedance

Whitcombe [8] extended the elastic impedance (EI) theory to maximize the separation of fluid or lithology by introducing the angle chi, \( \chi \) [1]. The normalization of elastic impedance equation, where the angle \( \Theta \) is replaced by \( \chi \) is shown in Equation 2.

\[
EEI(\chi) = V_{p0}\rho_0 \left( \frac{V_p}{V_{p0}} \right)^p \left( \frac{V_s}{V_s^0} \right)^q
\]

(2)

Where \( p = \cos \chi + \sin \chi \), \( q = -8K \sin \chi \), \( r = \cos \chi - 4K \sin \chi \). The EEI logs are correlated with gamma ray log to produce EEI_litho log and resistivity or water saturation log to obtain EEI_fluid log.

2.3. Lambda-Mu-Rho

Lame parameters such rigidity, \( \mu \) and incompressibility, \( \lambda \) are utilized with combination of measured density \( \rho \) in order to improve the interpretation of amplitude versus offset (AVO) [4]. These parameters use acoustic and shear impedance to discriminate fluid and lithology by using the equations;

\[
\lambda \rho = A I^2 - 2 S I^2
\]

(3)

\[
\mu \rho = S I^2
\]

(4)

2.4. SQp-SQs

These attributes are derived based on attenuation concept–rock physics approximation:

\[
SQ_p = \frac{5}{6\rho} \left( \frac{|\sigma|}{\sigma} - 1 \right)^2
\]

(5)
\[ SQ_s = \frac{10}{3\rho} \left( \frac{M}{G} \right) \left[ \frac{M}{G} - 2 \right] \] (6)

\( SQ_p \) is defined as Scaled inverse Quality factor of p-wave which is used as lithology indicator, while \( SQ_s \) is used as pore fill indicator [5]. From Equation 5 and Equation 6, the \( M, G \) and \( \rho \) represent bulk modulus, shear modulus and density respectively. The \( M/G \) is approximates as \((V_p/V_s)^2\).

Figure 1. The workflow used for this project.

Initially, the work is done on three well logs from three different fields in Malaysia basins namely Well-1, Well-2 and Well-3. Elastic logs are generated using different rock physics methods for each well. Later, cross-plot analyses are done using logs to observe which attributes can separate lithology and fluid better. The method of cross-plotting has proven to be the best method to observe separation of lithology or fluid [6]. Nevertheless, the cross-plotting analysis and EEI correlation is done at certain depth (including reservoir target) to omit the effect of depth trend.

Among the three wells used, only one field that has pre-stack seismic data which is from Field-3. The analysis is then followed by running simultaneous pre-stack seismic inversion to observe whether the elastic parameters chosen can differentiate fluid and lithology at seismic scale. The inversion is completed based on a low frequency model generated from Well-3 with application of high-cut frequency from 4 Hz to 10 Hz. Later, the inversion analysis acts as the quality control before running the inversion process.

3. Results

3.1. Feasibility Study on Well Log Data
Several elastic logs show good separation of lithology or fluid in well domain. There’s an excellent separation between hydrocarbon sand and background shale from several cross-plots generated. In Figure 2, the correlated EEI cross-plot shows good separation of gas sand from shale, which can be difficult to differentiate from logs only. The gas sand cluster is represented by the combination of low EEI_litho and EEI_fluid values. In case of Well-2, LMR cross plot manages to separate clearly the gas sand from the brine sand and shale as shown in Figure 3. The gas sand cluster is represented by the low to high values of Mu-Rho and low values of Lambda-Rho. Well-3 lithology can be distinguished the best using the SQp-SQs attributes, where the hydrocarbon sand cluster is deviated away from the wet trend from the cross-plot in Figure 4.
Figure 2. The crossplot between elastic impedance logs for Well-1 in A. The EEI_Litho log is a lithology indicator, while the EEI_fluid corresponds to the fluid indicator. B displays the Lambda-Rho and Mu-Rho crossplot, applied using Well-2. Three clusters of lithology can be separated. The colour key represents the resistivity values.

Figure 3. The combination of attenuation attributes separate shale and gas sand at the Well-3 target. The colour key represents water saturation values.

The occurrence of different lithology can be determined much clearer using the histogram plot. Figure 4 shows a summary of the point distribution constructed from four different elastic properties at Well-3. Each lithology can be defined based on the distribution curves trends by assuming the points are normally distributed. In the case of Poisson Ratio, the curves can be grouped into three different lithology; gas sand, silty sand and shale [Figure 4(A)]. This case is applicable for Lambda-Rho ($\lambda\rho$) and elastic impedance (EI) distributions (B and C respectively) with three lithology types can be defined. However, both EI and $\lambda\rho$ do not show distinct separation between silty sand (yellow) and shale (green), as silty sand and shale curves might overlap with each other. Hence, it is possible for other interpreters to group the lithology into two classes only. In the meantime, SQ attribute presents four clear distribution curves. From the well display on its right, lithology can be categorized separated into shale (grey), poor silty sand (yellow), silty sand (green) and gas sand.
Figure 4. Plot A represents the frequency of Poisson Ratio distribution, B represents Lambda-Rho, C displays the plot of elastic impedance at 20° angle, and D shows distribution of SQs points. On the right side of each histogram shows the lithology type at well location with GR, resistivity and elastic parameters log (from left to right in order).

3.2. Seismic Inversion on Selected Field

The results of the inversion include various data volumes such as AI, SI and ρ from Field-3. The lithology is composed of sand, silty sand (silt-sized or poor sand) and shale. The volumes are then manipulated to form elastic volumes such as Vp/Vs, SQp and SQs and LMR. By reference to the results of feasibility from well data, SQp-SQs could define lithology and fluid based on seismic data as well. In Figure 6, acoustic impedance (AI) volume displays good separation of low and high impedance lithology. However, AI cannot distinguish between low impedance from gas sand and coal, which can be misguided as hydrocarbon reservoir. The sand package is clearly captured within the horizon window in SQp and Vp/Vs volumes as displayed in Figure 5 and 6. Both Vp/Vs and SQp volumes show low values of sand and high value for coal. Meanwhile, the sand filled with hydrocarbon can be seen well in the fluid indicator SQs, see Figure 6. Therefore, if attenuation attributes are combined for interpretation, gas sand can be determined better. LMR is known to be very useful as litho-fluid indicator through combination of high MuRho values and low Lambda-Rho values [2]. Although LMR volumes can differentiate sand similar as other lithology indicators, the fluid can be separated better using mentioned fluid indicator, SQs.
4. Conclusion
There are various methods available to delineate reservoir from non-reservoir. However, the effectiveness of each method depends on the rock properties of the reservoir, which might be different for different fields. For the sand-dominated well, it would be convenient to use conventional rock physics methods to separate the lithology and fluid. On the other hand, if the well is dominated by silty sand, it is difficult to distinguish the pay sand based on the available rock physics methods only. The analyses suggest that the most suitable method for the silty sand-dominated formation is the SQp-SQs attribute as they manage to display clear separation of hydrocarbon sand from the background trend and different lithology. The implementation of inversion of pre-stack seismic data provides better insight to the extent of the reservoir and application of elastic parameters at the seismic scale. This project can be further explored in determining reservoir properties such as porosity and water saturation for better reservoir volume estimation.

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6. References

[1] Connolly P 1999 Elastic Impedance *The Leading Edge* 438-452

[2] Ekwe A C, Onuoha K M and Osayande M 2012 Fluid and Lithology Discrimination Using Rock Physics Modelling and Lambdamurho Inversion *AAPG International Conference and Exhibition (Milan)*

[3] Ghosh D, Abdul Halim M F, Brewer M, Viratno B and Darman N 2010 Geophysical issues and challenges in Malay and adjacent basins from an E & P persepective *The Leading Edge* 436-449

[4] Goodway B, Chen T and Downton J 1997 Improved AVO fluid detection and lithology discrimination using Lamé petrophysical parameters: "\( \lambda p \)", "\( \mu p \)" and "\( \lambda/\mu \) fluid stack": from P and S inversions *CSEG Recorder* 22

[5] Hermana M, Ghosh D and Chow W S 2016 Optimizing the Lithology and Pore Fluid Separation using Attenuation Attributes *Offshore Technology Conference Asia (Kuala Lumpur)*

[6] Hicks G J and Francis A M 2006 Extended Elastic Impedance and Its Relation to AVO Crossplotting and Vp/Vs *EAGE 68th Conference & Exhibition (Vienna)*

[7] Ostrander W J 1984 Plane-wave reflection coefficients for gas sands at nonnormal angles of incidence *52nd Annual International SEG Meeting (Texas)* 1637-1647

[8] Whitcombe D N, Connolly P A, Reagan R L and Redshaw T C 2002 Extended elastic impedance for fluid and lithology prediction *Geophysics* 67 63-67

[9] Yao Q and Han D 2008 Acoustic properties of coal from lab measurement *SEG Las Vegas 2008 Annual Meeting (Nevada)* p 1815-1819