Bayesian Theorem Application to Model Reservoir Facies Distribution on Deltaic Depositional Environment, Case Study of Browse Basin

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Abstract. Successful Hydrocarbon exploration and reservoir characterization always related with good understanding of geology and geophysics aspect. One of the fundamental issues is to get reliable parameter distribution and quantify the confidence level of the parameter model in 3D. The case study in this paper will be applied in Browse field that and the result will be a distribution model in 3D of facies and hydrocarbon fluid. The workflow that will be introduced in this paper is the combination between rock physics analysis, simultaneous seismic inversion and Bayesian estimation theorem. Rock physics analysis includes well log conditioning and correlation analysis between reservoir parameter (porosity, saturation, Vshale, etc) with seismic parameter (acoustic impedance, vp/vs, shear impedance, etc) to obtain facies classification in well log scale. The simultaneous seismic inversion method is used to obtain seismic parameter cube to be correlated with rock physics result to drive the facies distribution. Bayesian estimation theorem assembles initial knowledge about a model before observing the inversion attributes. The probability density function later will be used to drive the facies distribution combined with well log data and seismic data; and also estimate the confidence level distribution in 3D. The result can be used to identify new play in the Browse field.

1. Introduction
Browse basin is a northeast-trending depocenter, located at offshore NW of Australia. This basin has high potential of gas hydrocarbon accumulation from Paleozoic, Mesozoic and Cenozoic sediments, but as yet unproduced. One of the reservoir rocks that consist hydrocarbon is sandstone of Plover formation from the early Jurassic (Figure 1). The Plover Formation was deposited during periods of active faulting during Jurassic extensions and has, therefore, interpreted as a syn-rift succession (Struckmeyer et al., 1998 [1]; Blevin et al., 1998 [2]). The sandstone depositional environment of Plover Formation is mainly fluvial to tidally influenced deltaic system with some mouth bars (Tovaglieri & George., 2012 [3]). Consequently, thickness and lateral continuity of this unit are highly variable throughout the Browse Basin.

Due to variable lateral continuity and depositional environment behaviour, it is more difficult to distribute the facies distribution only with statistical method. In this paper the author used a combination of rock physics analysis, simultaneous inversion, and Bayesian theorem application to characterize the facies distribution in the studied area. The rock physics analysis consists of parameter extraction and sensitivity analysis to define the facies in well based. Continued with simultaneous inversion to
characterize the physics parameter distribution in field scale of the studied area. And finally, with Bayesian theorem, multiple physics parameter from simultaneous inversion can be used to extract the facies distribution and probability cube in the studied area.

![Figure 1. General Browse Basin Stratigraphic Column, seismic cross section and browse basin map](image)

2. Method

This study used angle stack 3D seismic and well log data as primary input. Other input such as velocity cube and borehole image log were used as cross validation and low frequency building supplementary data. The analysis is started with data loading and Q/C, continued with well tie, wavelet extraction, petrophysical analysis, borehole image processing, seismic interpretation, sensitivity analysis, simultaneous seismic inversion, and finished with the Bayesian theorem application. There will be facies distribution result from this analysis is a hydrocarbon bearing distribution cube.

2.1 Rock Physics

Rock physics method explains the reservoir rock in subsurface with physics properties such as porosity, rigidity, and compressibility. These properties are affecting on how the seismic wave travels trough formation. The objective of rock physics analysis in this paper is to find relationship between rock properties in subsurface with observed seismic response (Figure 2).
2.2 Simultaneous Inversion

Simultaneous seismic inversion method is an inversion technique with Aki-Richards formula to calculate the reflectivity in different offset in pre-stack seismic data or angle stack. Simultaneous inversion is used to characterize reservoir rock and fluid parameter to inversion result, such as, P-impedance, S-impedance, density, and VP/Vs. Shear wave (S wave) is being used to characterize fluid and compressional wave (P wave) that sensitive to change of fluid in the pore and S wave is related to interaction with rock matrix.

In seismology, seismic wave reflectivity and transmission in bedding boundary is formulated by many scientists, one of them is equation formula from Knott-Zoepprits. This equation is simplified by Aki-Richards, known by Aki-Richards equation (1980) [5]:

$$ R(\theta) \approx \frac{1}{2} \left( \frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right) - 2 \left( \frac{V_s}{V_p} \right)^2 \left( 2 \frac{\Delta V_s}{V_s} + \frac{\Delta \rho}{\rho} \right) \sin^2 \theta + \frac{1}{2} \frac{\Delta V_p}{V_p} \tan^2 \theta \tag{1} $$

The assumption that being used is change of property ($\Delta V_p/V_p$, $\Delta V_s/V_s$ and $\Delta \rho/\rho$) relatively small, hence second order can be ignored and $\theta$ with a value less than 90° (Ma, 2002 [6]). Equation (1) can be simplified with S wave impedance and P wave impedance parameter as below:

$$ R(\theta) \approx (1 + \tan^2 \theta) \left( \frac{\Delta \rho}{2 V_p} \right) - 8 \left( \frac{V_s}{V_p} \right)^2 \sin^2 \theta \left( \frac{\Delta V_s}{2 V_s} \right) - \tan^2 \theta - 4 \left( \frac{V_s}{V_p} \right)^2 \sin^2 \theta \left( \frac{\Delta V_p}{2 V_p} \right) \tan^2 \theta \tag{2} $$

Fatti et al [7] in 1994 simplified the (2) equation by removing $\rho$ parameter where the $V_s/V_p$ ratio is around 0.5 and small angle as below:

$$ R(\theta) \approx (1 + \tan^2 \theta) \left( \frac{\Delta V_p}{2 V_p} \right) - 8 \left( \frac{V_s}{V_p} \right)^2 \sin^2 \theta \left( \frac{\Delta V_s}{2 V_s} \right) \cdot \tan^2 \theta. \tag{3} $$

During the simultaneous inversion, one of the algorithms that's being used is simulated annealing. A simulated annealing algorithm is a vector solution that optimized with an acoustic impedance value, followed by $n$ shear impedance value, where $n$ is amount of layers. The algorithm will search for lowest cost function with Monte-Carlo method (Figure 3).
The given initial model is reflection coefficient of zero-offset P and S impedance at interface I can be calculated by the equation below:

\[
\frac{\Delta I_p}{2I_p} = \frac{I_p^i - I_p^{i-1}}{I_p^i + I_p^{i-1}} \quad \text{and} \quad \frac{\Delta I_s}{2I_s} = \frac{I_s^i - I_s^{i-1}}{I_s^i + I_s^{i-1}}
\]

Hence the ratio of average Is/Ip between layer i-1 and layer I can be calculated by the equation below:

\[
\frac{I_s}{I_p} = \frac{I_s^i + I_s^{i-1}}{I_p^i + I_p^{i-1}}
\]

By replacing the equation (5) and (4) into the equation (3), reflection coefficient R (Θ) can be calculated in every offset and every layer boundary.

2.3 Bayesian Theorem

A Bayesian theorem in short understanding can be viewed as conditional probabilistic. The theorem itself stated if we have two events x and y, we can design the probability of occurrence of each event by \( P(x) \) and \( P(y) \). If we consider of the probability of these two events, we can design this as joint probability of \( (P(x,y)) \) that is given by:

\[
P(x, y) = P(x|y)P(y) = P(y|x)P(x)
\]

In this case, \( P(x/y) \) is the probability of x to occur given that y already occurred, the same situation applied to \( P(y/x) \) and \( P(y/x) \) can be defined as conditional probability. From equation (6), if we want to know how the probability of y is, given x already happened, we can re-arrange the equation into:

\[
P(y|x) = \frac{P(x|y)P(y)}{P(x)}
\]

To complete equation (7), according to the total law of probability:

\[
P(x) = P(x|y)P(y) + P(x|y^c)P(y^c)
\]

In equation (8) above, the \( P(y^c) \) is defined as the probability of not having y to be happening. Therefore the complete Bayesian equation to define the conditional probability of y to be happened given x that already happened is:

\[
P(y|x) = \frac{P(x|y)P(y)}{P(x|y)P(y) + P(x|y^c)P(y^c)}
\]

The product of Bayesian calculation is a posterior PDF from each alternative. Below is a probability density function (PDF) for hydrocarbon bearing facies. Hydrocarbon bearing facies has low AI and low Vp/Vs ratio (Figure 4).
3. Result and Discussion

3.1 Seismic Inversion Result

The simultaneous seismic inversion was done in Plover formation only as target formation. The results are acoustic impedance cube (AI), Vp/Vs cube and density cube. The relative misfit of the inversion result is relatively low which is 27\% and the residual cube has low amplitude means the simultaneous seismic inversion result is valid to be used for further analysis.

The acoustic impedance in the Plover formation is relatively low compared to Triassic formation and there are some low acoustic impedance reflecting high permeability – gas bearing facies or shale facies. The Montara formation above Plover formation has a mostly lowest acoustic impedance related to shale facies developed in this formation. The cross section with well data in figure 5 below shows good coherency between acoustic impedance from simultaneous seismic inversion with acoustic impedance from well data.

Another simultaneous inversion result is Vp/Vs cube. NE-SW cross section of Vp/Vs cube with some wells at figure 6 below shows good coherency between the inversion result with Vp/Vs log data from well. The Vp/Vs in Triassic and Montara formation mostly have high value. The Plover formation Vp/Vs is relatively low compared to Triassic formation and Montara formation, with some very low Vp/Vs value at lower Plover formation related to gas bearing sand facies.
3.2 Hydrocarbon Bearing Facies Distribution

The probability density function of the gas bearing facies, water bearing facies and shale from acoustic impedance and Vp/Vs cross plot is being used to predict the hydrocarbon bearing facies distribution. Similar to sand facies distribution that act as a reservoir, the hydrocarbon bearing facies are mostly distributed at the lower part of the Plover formation. Based on the NE-SW cross section at figure 7 below, most of the highest hydrocarbon bearing facies probability is at the lower part of the formation. Cross validation with well log data such as water saturation shows good coherency, hence the facies prediction with Bayesian theorem is valid.

The probability cube can be extracted into horizon probe (geobody) where the facies distribution in field scale can be seen clearly. The hydrocarbon bearing facies distribution shows gas accumulation mostly on the NE part of the field, similar to mud log data and petrophysical analysis result. The geometry of the hydrocarbon bearing facies distribution shows that the sand with gas bearing only at NE part, the sand facies at SW part is mostly filled with water (Figure 8).
**Figure 8.** Probability Map of Hydrocarbon Bearing Facies Distribution shows gas mostly accumulated at NE part of the field

### 4. Conclusions

The application of combination between rock physics, simultaneous seismic inversion and Bayesian theorem application is proven to be a powerful tool to predict facies distribution in tectonically active and poor facies lateral continuity condition compared to geostatistical method. The studied area shows the sand distribution is NE-SW trend similar with browse basin axis with geometry as a channel. The gas accumulation is mainly on the NE part of the field.

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