Identification of fractured-basement reservoir based on integration of FMI Log and seismic attributes in hydrocarbon field “I”, Barito Basin, South Kalimantan

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Abstract. As basement has very small matrix porosity, secondary porosity is needed to store hydrocarbon within the basement. Fracture is a secondary porosity, yet not all fracture can be a good secondary porosity. Open fractures have capability to store hydrocarbon, also have important roles in productivity and quality of the pre-tertiary basement reservoir. This study is aimed to identify open fractures using FMI log and seismic attributes in the Field “I”, Barito Basin. Interpreted image log (FMI) on two wells gives the azimuth and dip orientation of open fractures are ENE–WSW, NNW–SSE and WNW–ESE and also the horizontal stress orientation. The stress orientation from image log combined with leak-off test (LOT) data and density log used to identify stress fields. Azimuth and dip orientation of the open fracture from FMI log is the input of the stereonet, as an orientation filter for ant-tracking. Ant-track attribute is based on ant-colony optimization algorithm that captures only continuous features and used as edge enhancement methods for fracture-sensitive attributes. Variance is a fracture-sensitive attribute that applied as input data for ant-track algorithm. The results of ant-track map are well correlated and confirmed by image log analysis. Also, by applying ant-track attribute to the fracture-sensitive attributes succesfully able to identify faults and fractures with better resolution and visualization than only using the fracture-sensitive attribute itself, so it makes easier to interpret and get the information.

1. Introduction

Nowadays, fractured basement believed can be a potential hydrocarbon reservoirs, despite basement reservoirs are more difficult in detection and evaluation than conventional reservoirs. It has been proven by five Indonesian oil and gas fields that produced hydrocarbon from basement reservoirs [1]. Field “I” located in Barito Basin, South Kalimantan, the pre-tertiary basement is considered to be Upper Cretaceous in age and consisting of volcanics and conglomerate rocks. This study is aimed to identify open fractures using integrated Formation Micro Imager (FMI) log and seismic attributes. Conventionally, fault and fractures can be identified by discontinuity events seen in seismic profiles, but it is difficult to identify subtle fractures, especially when the data quality is poor. Seismic attributes provide better way to visualize fault and fracture which are difficult to see or hidden in the conventional...
seismic profile. Ant-track attribute is based on ant-colony optimization (ACO) to determine discontinuities such as faults and fractures in 3D seismic data [2]. The process was done in three steps: seismic conditioning, edge-detection and edge-enhancement. The effective implementation of ant-track attribute can be achieved when the output of other fault sensitive attributes are used as an input data [3]. Fracture-sensitive attribute which is variance used as an edge-detection method for ant-tracking. We applied ant-track attribute as an edge enhancement method with an orientation guide from FMI log to identify open fractures. FMI log provides information about the orientation of strike and dip of fractures as well as the orientation of horizontal stress on the well to help ant-tracking. The ant-track attribute successfully identify faults and fractures that were difficult to display in the seismic profile. Applying ant-track attribute may be able to identify faults and fractures with better resolution and visualization. The attribute makes easier to interpret and get the information of fractures.

2. Regional Geology of Barito Basin
Barito Basin is situated in southern of Kalimantan between the Meratus Range to the East and Sundaland to the West. In Early Cretaceous time, South West Borneo microcontinent drifted and attached to Sundaland. Other microcontinent, East Java West Sulawesi moving in northward direction and subducted into South West Borneo, formed island arc setting. In Eocene, extensional deformation occurred through a period of rifting and subsidence formed NW to SE horsts and grabens and NNE-SSW tertiary back arc basin with Meratus as the basement of the basins. The latest compressional tectonic regime occurs in middle Miocene then rotated SW Borneo 45° counter clock wise to its present day position [4]. Proto-Meratus Range uplifted in middle Miocene because of the previous collisions. The collision and uplifting had propagated compressional force to end also Barito Basin that rifted and subsided became inverted. Basement reservoir at Field “I” is a faulted and fractured volcanic reservoir. The Field “I” basement is considered to be upper Cretaceous in age and made by volcanics and conglomerate rocks. Well logging data shows the top of basement in well “I-1” at depth 1120 m is made up of andesite overlying with volcanic conglomerate as the lithology.

3. Methodology

3.1 Image Log Analysis
FMI log is an image log that gives information about formation response to the geophysical parameter which is the resistivity on the borehole wall. The image log provides information on the orientation of strike and dip of fractures as well as the orientation of horizontal stress on the well. The image log is displayed in the unwrapped borehole format where the cylindrical borehole surface is projected to be a flat plane, starting from North or 0° and 360°. From image log we can obtain the information about the orientation of horizontal stress as well as the azimuth and dip of open fractures. In the FMI log, fractures can be defined as planar features with no apparent displacement along their planes. The fracture may be open or tight (closed) which filled with mineral precipitates such as clays, calcite, or pyrite. For hydrocarbon exploration, we focus on open fractures (with aperture) which in the image log have a dark appearance (conductive) due to invasion by conductive drilling mud, while closed fractures have a white appearance (resistive) if the filling material of their apertures is resistive like calcite or silica. The dip orientation of fractures will be shown by the presence of a sinusoidal wave in the dynamic image. However, the trough or the lowest point can show dip and strike orientation will be perpendicular from dip orientation.

Leak-off test (LOT) data and density log were used to help estimating tectonic regime in this study area by understanding the relationship between pressure and depth [5]. The leak-off test is a test carried out to determine the strength of the open formation. LOT describes the maximum equivalent mud weight or maximum pressure that may be applied to the well during drilling. In well “I-3”, there are three interesting LOT data: 1.38 gr/cc at depth 106 m, 1.94 gr/cc at depth 607 m and 1.82 gr/cc at depth 1472 m. LOT data or mud density data then used to estimate $S_{min}$ value in the formation. The density is converted into pressure domain using equation 1. Thus, minimum horizontal stress is obtained.
Density values from the surface up to the interest zone are used to estimate the value of vertical stress ($S_v$), where $S_v$ is equivalent to overburden stress of rock. Density log data (FDC) from well “I-3” used to obtain $S_v$ using equation 2. The parameter $\rho(z)$ is the density ($\text{kg/m}^3$), $g$ is the acceleration of gravity ($\text{m/s}^2$) and $dz$ is depth (m).

$$S_v = \int_0^z \rho(z) g dz \approx \bar{\rho} g z$$

3.2 Seismic Data Processing

The seismic processing consists of three main steps, which are seismic conditioning, edge detection and edge enhancement. Seismic conditioning was done to eliminate random noise in 3D PSTM seismic data so we can improve the quality of seismic data. The automatic gain control (AGC) was carefully implemented into 3D seismic data to improve visibility of late-arriving seismic events in which attenuation or wavefront divergence has caused amplitude decay. AGC will calculate the amplitude values with normalized amplitudes in a specific window. After the trial and error, the RMS window 15 is used where the amplitude is seen more clear than the seismic data, so the amplitude that loses energy becomes stronger and clearly visible in the seismic data. Also, we use low cut frequency filter ($f \leq 15$ Hz) in order to get higher seismic resolution to delineate subtle fractures. After enhancing the quality of seismic data, variance as a fracture-sensitive attribute is applied to detect discontinuities within seismic data. Variance attribute was calculated in 3 dimensions representing trace to trace variance at specific sample intervals that measure the trace contrast between the trace of the seismic signal. The same trace gives low variance value, whereas discontinuity has a high variance value. However, the variance only counts statistical variations between one trace to another trace, so high variance value does not necessarily reflect a good structure (fracture or fault). Edge evidence applied to variance output to increase the continuity of the edges found within the data and sharpen them. Last we applied ant-track attribute as an edge-enhancement method for identifying faults and fractures. Ant-track works based on ant-colony optimization algorithm and have six parameters that determine the behavior artificial ants to identify structural objects within seismic data. These parameters can be set in order to get the final results, whether regional structural objects (fault) or local structural objects such as fractures. This study aimed to identify subtle fractures, so custom ants are distributed in the seismic data, allowing them to move along fractures and emitting pheromones. Azimuth and dip orientation from image log used as an input in the stereonet, so only open fractures mapped in the ant-track cube.

4. Results and Discussion

In this study area, tectonic regime identified based on FMI data and supported by LOT data and density log. Horizontal geological stress orientation can be also determined by the apperance of drilling induced fractures and borehole breakout in vertical wells from image log. They are usually orthogonal to one another in the horizontal plane or perpendicular of each other in borehole wall. The long axes of borehole breakouts are oriented approximately parallel to minimum horizontal stress ($S_{hmin}$) while induced fractures develop approximately parallel to the maximum horizontal stress ($S_{hmax}$). In the well “I-1”, drilling induced fracture shows consistently in NE-SW strike orientation in all interval, the orientation indicates the orientation of maximum horizontal stress on the well. While the breakout shows NW-SE strike orientation and indicates $S_{hmin}$. In the well “I-2”, drilling induced fractures shows E-W strike orientation and borehole breakout in NNE-SSW strike orientation. Different orientations on both wells are local, where the dominant orientation of $S_{hmax}$ or $\sigma_1$ in NE-SW of Field “I”.

If there are drilling induced fracture ($S_{hmax}$) and borehole breakout ($S_{hmin}$) in vertical well, then the tectonic regime is strike-slip [5]. $S_{hmax}$ acts as $\sigma_1$ or principle stress, and $S_{hmin}$ acts as $\sigma_3$, $S$, the state of stress in this area is $S_{hmax} > S_v > S_{hmin}$. In the vertical well, when $S_v$ is the principle stress (main stress/$\sigma_v$), the stress-induced tensile fracture can not be detected in the vertical well because stress-induced tensile
fracture defines the orientation of the principle stress. LOT data and density log are used to create pressure vs depth relationship and support the tectonic regime analysis based on FMI log. Figure 1 shows the relationship between pressure and depth in well “I-3”, the results supports FMI data analysis where $S_r > S_{hmin}$, so $S_{hmin}$ acts as $\sigma_3$ and $S_r$ acts as $\sigma_2$ instead of $\sigma_1$. From this information we can identify the tectonic regime in this area is strike-slip-regime ($S_{hmax} > S_r > S_{hmin}$).

This study focus on identifying open fractures because the fractures able for storing hydrocarbons. The presence of open fractures is increasing the permeability of the potentially basement reservoir. In well “I-1” there are six major open fractures spread over each depth interval and 68 open fractures were identified, show dominant NE-SSW, NE-SW, NW-SE, ENE-WSW, NNW-SSE, WNW-ESE strike orientation. Partially open fractures also detected in this well with the same dominant direction with open fractures. In well “I-2” partially open fractures detected in the basement with NNE-SSW and NNW-SSE strike orientation with dips varying between 30°-80°. The strike orientation of the open fracture then used as an input to ant-tracking. The strike orientation of open fractures then be inputted to the stereonet as an orientation filter where only fractures in the direction of ENE-WSW, NNW-SSE and WNW-ESE are tracked by the ant-track attribute. In the stereonet input, there are azimuth and dip parameter, where the azimuth direction is filled by the orientation informed in the FMI log. As for the stereonet input, dip orientation is not necessary to be filtered, where the azimuth orientation of open fractures have dip varying between 0°-90°. This is because regardless of strike orientation of the open fractures, the dip of open fractures varies in value, so the dip value will not be a decisive parameter for tracking. During the ant-track process, the closed fractures were filtered out and only open fractures were included from the FMI image. The riedel shear model made based on FMI log analysis shows that antithetic shear, synthetic shear and P shear will be generated in the strike-slip faulting. The result from ant-tracking shows that fractures mapped on the ant-track map of the seismic data matched with riedel shear model. This indicates that geological model and seismic data interpretations are well matched or correlated. After using the ant-track attributes, the results shows that antithetic and P are open fractures while synthetic tends to be a closed fractures. From all fractures that generated in the seismic data, which fractures able to store the hydrocarbons?

Figure 2 shows that faults and fractures zones have been detected on the ant-track map. Faults, shown by bold black color, are identified with high ant-track value due to large fault offsets in fault movement. Fractures, fracture zones and subtle fractures have small value of ant-track are shown by black to grey color. The small values of ant-track are due to a very small offset or displacement of rock due to fractures movement. Figure 3(a) shows original seismic data at time slice 840 ms. In seismic data, some faults hardly can be identified due to differences or contrast of amplitude along the discontinuity of seismic events. However, fractures are very difficult to identify on the seismic data, this is because the resolution of the fracture can not be resolved by seismic data. Another seismic attribute is required to improve the resolution of the images, in order to mapped subtle fractures. In figure 3(b), it is seen that the variance attributes emphasize the discontinuity of seismic event. With variance cube, fractures are easier to identify than just using conventional seismic data. This is because the numbers of faults interpreted in variance are bigger and more accurate than in the amplitude slice. The fault identified
more clearly, but fractures are still not visible in this attribute. So it is necessary to calculate the ant-track attributes by using variance attributes as the input to identify the fractures. Figure 3(c) is an ant-track cube, showing fractures and subtle fractures are identified more clearly and some fractures are connected to each other. Fault that already identified in variance cube appears more clear and small faults that were not seen in variance slices have been successfully identified, also the fracture zone patterns are better defined.

We can see from figure 3, by using ant-track attributes the fractures are enhanced in resolution and visualization. Ant-tracking from variance provided good interpretable information about the continuity of fracture and subtle faults which leading the interpretation of intensity and quality of the basement reservoir. Improved resolution of the faults and fractures images made the interpretation of fault intensity easier to detect the location of potential developed fractures.

Ant-track maps shows good results in identify the distribution of open fractures. This quality of the ant-track map can be determined from the correlation with the FMI data. The higher the correlation between the ant-track results with the FMI data, the better the quality of the ant-track map. In the ant-track map, the orientation of the open fracture around the well “I-1” is correlated at each time slices very well, makes the distribution of open fractures in the well and seismic data correlated and confirmed to each other. So ant-track maps can be used to delineate open fractures in vertical and horizontal direction. Improved visualization and resolution of the fractures distribution can make the interpretation of the intensity of the open fracture easily, where high fractures intensity makes an area can be a potential good reservoir. Based on the ant-track map, the fracture intensity is very high and almost all fractures are connected to each other. The fracture width (aperture) is also quite high, allowed open fracture for storing hydrocarbons. Another attributes that prove the quality of basement reservoir is RMS amplitude (figure 4(a)). The RMS amplitude attribute is used to estimate fracture distribution which is likely related to the distribution of the density. This assumption is based on the velocity of the seismic waves. The blue to purple area shows low RMS amplitude value, while the yellow to green color shows the high RMS amplitude value. High amplitude shows high acoustic impedance values can be occurred due to high density. Where seismic wave velocity will be higher in the dense rock. Therefore, an area with low velocity zone or an area that has low RMS amplitude value are due to the discontinuity that makes amplitude decaying or loss energy. Discontinuity has low amplitude value or close to zero. The determination of the quality of fractured-basement reservoir also supported by geological interpretation. Previously, the tectonic regime that applies in this field is strike-slip faulting. The interpretation of fault movement is shown in figure 4(b), where the interpretation of the fault is based on variance map. It is seen that in the blue circled part, the fractures have extensional tectonics movement (sinistral motion), so the fracture in this area is most likely open fractures. While in other areas seen that the tectonic
movement is compressional, so then fractures are closed to geologically features. Figure 4(c) is an ant-track map at time slice 840ms, the green circled area have high fracture intensity and the fractures are well connected to each other, compared to other area.

Based on geological and geophysical interpretation, the potential play of fractured-basement reservoir is in yellow area of figure 5. The area has low RMS amplitude value and high fracture intensity also supported by geological analysis. Region X can be a first priority fractured-basement reservoir potential to be drilled compared to other areas. It has high intensity and connectivity than other areas, and there is major fault that makes faulted-anticline, which the hydrocarbons might be trapped in that area. So, drilling is recommended in orthogonally to the strike of the open fractures, in order to produce more hydrocarbons. A horizontal well in NE to SW direction is suggested for producing fractured-basement reservoir in X area.

5. Conclusion and Recommendation
Based on the analysis result from FMI log and well data, tectonic regime in this area is dominated by strike slip faulting. Variance could identify faults, but couldn’t map the subtle fractures. Ant-tracking from variance attribute can identify subtle fractures better than variance attribute itself. By using ant-track attribute, fracture and fault are identified in better visualization and the subtle fracture can be clearly seen. Region X can be a first priority fractured-basement reservoir potential to be drilled compared to other areas, due to high intensity and connectivity. This study suggests the optimal orientation to drill horizontal wells is in NE to SW direction, in order to produce more oil from potential fractured-basement reservoir since the open fracture have dominant NW-SE strike orientation (by penetrating the fractures orthogonally).

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