Fracture characterization in basement reservoirs through seismic attributes

Riaz Alai1*, Ahmed Adnan Aqrawi2, Abu Bakar Mohamed1 and Mohamed Taher A Taha1 present the results of extensive preconditioning and attribute analyses for the purpose of fracture detection in three field data case studies offshore Malaysia.

Recent efforts to understand fracture characterization, their density and numbers have increased significantly. With the introduction of novel technologies and methodologies of data preconditioning, decomposition, and attribute analyses, new workflows have been introduced to optimally determine and visualize effective fractured networks.

In detailed seismic data analysis it is critical to determine the accurate location of effective fracture zones and their characterization as these may lead to high potential hydrocarbon exploration zones. Therefore we suggest a workflow to delineate and quantify effective fracture networks from seismic data. Our proposed methodology has been calibrated using all available surface and subsurface data that included testing results. The three core elements to this workflow are: fault network delineation, fracture density zones estimation, and effective fracture zones identification. These are then used to visualize the most potential regions in the area. Then through 3D volumetric representation of the blending results, one can quantify the amount of effective fractures per region and identify areas of interest. For a detailed description of the methodologies and workflows used to achieve the results, the reader is referred to (Aqrawi and Aqrawi, 2013) and (Alai et al., 2014). Here we showcase a sequential and systematic approach to delineate dense effective fracture zones from seismic data. Only the seismic data is used to perform this analysis, and the well data is solely used for correlation and validation. The paper discusses the integration of the sequential steps of the proposed methodology that incorporate ‘consistent’ unsteered fault networks, detailed estimation of the fracture density and effective fractures zones and the geologic and structural setting of the studied area. Three datasets were obtained from the Malay basin, which has been formed as a pull-apart related to the development of the three pagoda right lateral fault. Open fractures within the Malay basin that originated by strike-slip tectonics strike NE-SW and ESE-WNW and oblique to major bounding faults of the studied areas. Wells drilled with trajectories parallel to the bounding faults intersected higher numbers of effective synthetic fracture networks with higher testing rates. From the first dataset, numerous well data have been integrated to validate the workflows and our results are supported by well testing data. Regarding the second and third case studies, the trajectories of the planned exploration wells have been validated. In addition, our results identify potential nearby areas where appraisal wells are recommended to test additional well-developed fracture networks.

In search for effective fractures

For a better understanding of the seismic data volume, 3D volume edge identification (Hoekstra, 1996) was performed for various wavelet scales. Figure 1 illustrates the results for respectively an inline, crossline and time slice (images on the left represent the input data). Note that for each scale, different characters of the same data are highlighted, exploring series of characterizations and classifications for the purpose of optimal preconditioning of seismic data in the search for effective fractures. As fracture corridors are small in size, discontinuities are critical in detailed seismic signal analysis and extensive effort has to be made towards identifying effective fractures networks.

1 PETRONAS Carigali Sdn. Bhd.
2 Schlumberger.
* Corresponding author, E-mail: Riaz.Alai@PETRONAS.com.my
Upon considering the best areas to drill for maximum production, identifying the zones where there is a high density of effective fractures present is crucial, as it will yield the best conditions for the extraction of hydrocarbons. Determining the well trajectory can often be difficult to define and plan, as several issues can arise and one may not able to map out the entire fault system solely using the seismic data with traditional edge detection and enhancement techniques.

The representation of effective fracture zones has traditionally been performed through stochastic means from data received from previously drilled wells in the region. This may result in a large uncertainty. We suggest a method to delineate faults, fracture density and effective fracture zones accurately from migrated seismic data volumes. Firstly, geological analysis is done on the seismic data using directional dip estimations to understand the structural geology and help identify possible fault and fracture networks. After this, an enhanced directional edge detection workflow (Aqrawi et al., 2012) is implemented to delineate and later model the major and minor fault networks. Then, fracture density zones are estimated using a three dimensional curvature attribute (Boe and Daber, 2010). Lastly, upon identifying the mechanical setting of the effective fractures, one can use a directionally steered curvature attribute for the isolation of the effective fracture zones.

After identifying the effective fracture zones in addition to having an accurate fault model that emphasizes both minor and major features, one is able to plan the well trajectory much more accurately and minimize the risk involved as well. The accurate fault model will make planning the well path easier and safer. Moreover, the effective fracture zones will yield the best conditions for hydrocarbon extraction.

In the following sections, our suggested workflow is explained in further detail. Initially, geological analysis of the seismic data is performed using estimated dip and directional dip calculations (Aqrawi and Boe, 2012). This method is based on trace-to-trace cross correlation, and uses illumination and lighting to image the structural geology. This gives an indication of the overall structural geology, and helps to anticipate faults and fractures networks. Understanding the regional geology helps to validate the findings in the seismic data.

To delineate the fault networks, an enhanced directional edge detection workflow (Aqrawi and Aqrawi, 2013) is used for minor and major fault estimations. Directionally steered attributes are often used to delineate features that extend in a certain direction to minimize the capturing of noise in the process. Applying the directional, three-dimensional Sobel-based edge detection filter (Aqrawi and Boe, 2011) in several angles with a small increment, and later stacking...
Case study I

In the following case study a field data example from offshore Malaysia is used to illustrate a series of attributes (Aqrawi and Boe, 2012; Boe and Daber, 2010; Chopra and Marfurt, 2007; Aqrawi and Boe, 2011 and Aqrawi and Aqrawi, 2013) towards detailed data analysis in search of effective fractures.

The above described workflow to identify effective fractures from migrated seismic data is applied and results are presented. Figure 2 (left) shows a few slices from the final migrated seismic volume. Note that the red-coloured well was tested negatively (being dry) and the blue coloured well was tested positively. Figure 2 (right) illustrates the workflow to delineate and quantify effective fracture networks from seismic data. Figure 3 shows the results of dip illumination for respectively 40, 90 and 150 degrees revealing some analysis on the geology (top) and the corresponding faults (bottom) for the various azimuths have been determined. When scanning and illuminating the entire volume along 360 degrees, a ‘consistent’ unsteered network of faults is obtained, in which we showcase the network of edges and their intensities. Figure 4 (left) illustrates the identification of the ‘consistent’ unsteered network of faults, emphasizing the fault networks and suppressing random noise. Figure 4 (right) shows the application of Sobel filters to an image.

Having the fault networks identified with a high level of confidence after multi-azimuth stacking, the fracture density these individual results, enhances our ability to define features that are present in more than one angular deviation (such as faults) while features such as noise will be suppressed. Moreover, an edge enhancement filter based on a colony theory is applied to the result (Pedersen et al., 2002).

After accurately identifying the fault networks, the fracture density zones need to be acknowledged. By using a three-dimensional curvature attribute (Daber and Boe, 2010), and emphasizing the most positive curvature, one is isolating the regions where the likelihood of dense fracture zones were developed (Chopra and Marfurt, 2007). Likewise, one must determine where and whether or not there are effective fractures. This is acquired through the use of a directionally steered three-dimensional curvature attribute, identifying the directionally most positive curvature. Knowing the type of fractures in the area and the maximum horizontal stress direction, one can define the direction of the effective fracture networks. In the study area, effective fracture networks are parallel or slightly oblique to the maximum horizontal stress as suggested by the drilling results. By determining the geological style and the fracture type, one can estimate the regions of interest where there are most likely to be effective fractures by filtering along or perpendicular to the stress direction. In this case, given the nature of the faults, fracture types and stresses, a filtering along the maximum stress direction reveals the estimated effective fracture zones.

Figure 4 (left) Towards identifying the ‘consistent’ unsteered network of faults, emphasizing the fault networks and suppressing random noise and (right) the application of Sobel filters to an image (Aqrawi et al., 2012).

Figure 5 Validating and correlating the results of respectively faults network, fracture density and effective fractures with well data [blue is positively tested well and red is negatively tested (dry well)].

Figure 6 (left) Time slice through the seismic migrated data volume and (right) its corresponding volume rendered ‘consistent’ unsteered fault network.
and zones of effective fractures have been determined. Figure 5 shows the results of their integration with both well trajectories: (from left to right), the fault networks (red arrow indicates the total depth of the well), the fracture density (red colour indicates higher density), the zone of effective fractures at the positively tested well (green colour), the fault networks at the unsuccessful well and last image shows the integration of the well trajectories with the blending results of all the three attributes’ results. In the last image of Figure 5, a cylinder shape around each well trajectory has been selected and blending of three attributes shows the integration and difference in success rate between both wells.

Note the good correlation of the obtained results for the producing well. The well intersects high density of faults, with high fracture density containing effective fractures. Note that with the calculations of the attributes, if the red well was drilled deeper, the chances of success would have been increased. Figure 6 (left) shows a time slice through the seismic migrated data volume and (right) indicates its corresponding volume rendered in ‘consistent’ unsteered fault networks.

Figure 7 (top left) shows the result of fracture density identification, (top right) blending of fracture density information with the volume rendered fault network and (bottom) blending result of all the three attributes. Note the red colour indicates fractures zones and green colour indicates the effective fracture zones.

Figure 8 (left) Data analysis result for the unsuccessful well. Note that this well does not intersect with a series of faults along the trajectory. Our results shows that if the well was drilled deeper, its success rate would have been increased. This corresponds with the regional geology prediction. (center) Volumetric representation of the blending results, (right) after being filtered on the larger volume potentials.

Figure 9 Top of basement depth structure map.
Furthermore, we calculated the volumetric representation of density of the connected effective fracture zones and filtered these by size only to indicate the higher potential zones from this seismic data volume. Figure 8 (left) shows the data analysis result for the unsuccessful well. Note that this well does not intersect with a series of faults along the trajectory. Our results show that if the well was drilled deeper, its success rate would have been better. This corresponds with the regional geology prediction. Figure 8 (centre) shows the volumetric representation of the blending results, and Figure 8 (right) shows the same but after being filtered on the larger volume potentials.

The red well at the left in this image indicates the red well from the previous figures, and the blue and yellow well are both positively tested wells. Figure 9 (Sherif et al., 2009) is a structural top of basement depth structure map in which the red well is indicated together with both other positively tested wells. The map illustrates the various structural elements and bounding faults of this field. It has been observed that wells that were drilled parallel to these bounding faults managed to interest a high number of fracture networks and recovered a higher hydrocarbon rate when tested.

Figure 10 (left) shows again the top of basement depth structure map and (right) result of volumetric representation of the attribute blending results from the seismic data.

Figure 11 (left) Time slice from migrated seismic data volume and (right) blending result of all three calculated attributes.

Figure 12 (left) Integration of final migrated seismic data with a time slice for a specific dip illumination characterizing the geological features for a specific illumination angle and azimuth, (right) illustration of dense fault network determined from the seismic data below the basement using the directional method from (Aqrawi and Aqrawi, 2013).
Figure 13 A series of attributes calculated from the migrated seismic data volume are depicted here at total depth of the well: a) original data, b) dip illumination for angle of 60 degrees, c) dip illumination for angle of 120 degrees, d) addition of all angles providing a 'consistent' unsteered fault network, e) volume rendering of fault network, f) merged with zones of dense effective fractures estimation, g) fracture density, h) fracture density after Laplacian transform and i) effective fracture estimations.
well trajectories. Fault network, fracture density and effective fracture zone estimations have been co-blended to better characterize the potential for each of the planned wells. The neighbouring wells have been selected based on volumetric representation of blending results zone determinations and highest concentration of corresponding fault networks, fracture densities and effective fractures estimated zones. Integration of findings for neighboring wells provides insight into higher potential zones, hence allowing us to better plan potential well trajectories for optimized productions.

A series of calculations have been performed to neighbouring planned wells for accurate analysis of effective fracture content zones. Figure 12 (left) shows an integration of final migrated seismic data with a time slice for a specific dip illumination characterizing the geological subsurface features. Note the strong amplitude of the basement and highly faulted sub-basement zone. Furthermore, the planned well is depicted in this figure up to the total planned depth.

Figure 14 Detailed analysis and integration of various neighboring planned wells for accurate analysis of effective fracture content zones: a) co-blending the ‘consistent’ unsteered fault network, fracture density and effective fracture estimations, b) overlay of larger potential zones, c) other high potential zones around the original well, d) integration of fault network, fracture density and effective fracture estimations integrated for a series of neighboring wells with similar well trajectory configurations.

Figure 15 Integration of a time section (along the NW-SE direction) with a timeslice representing the dense fault networks overlayed with effective fracture zones (green colour): a) original seismic data and b) co-rendered with fault network estimations and effective fracture zones.

Figure 11 (left) shows a time slice from the migrated seismic data and Figure 11 (right) indicates the blending result of all the three calculated attributes.

**Case study II**

In the following we present the results of a second field dataset and the workflows described earlier have been applied to optimize the characterization of effective fractures and their localization around a planned well in a fracture basement area offshore Malaysia. Some sequential workflows have been used to define zones of effective fractures for a series of planned neighbouring wells. Detailed and accurate analyses of effective fracture content zones have been performed and results have been integrated into planned neighbouring wells for optimal comparisons between highest potential well trajectories.
Figure 16 Some cross sections through the migrated seismic data volume. The trajectory of the planned well to be drilled is indicated in this picture with blue color.

Figure 17 (left) Time slice from the migrated seismic data volume at total well depth and (right) estimation of faults for a specific fault network direction.

Figure 18 (left) Calculated fracture density zones and (right) corresponding effective fractures calculation.

Figure 19 (left) Blending of the attributes of Figure 18 and (right) determined ‘consistent’ unsteered fault network.

Figure 12 (right) illustrates the dense fault network determined from the migrated seismic data volume below the basement using the directional method (Aqrawi and Aqrawi, 2013). Note the very detailed features, the continuity of the faults and the completeness of the fault network.

A series of attributes have been calculated sequentially and the results are depicted in Figure 13. Figure 13a shows the original data. Figure 13b illustrates the dip illumination for an angle of 60 degrees, respectively 120 degrees (Figure 13c). An addition of dip illumination results for all angles provides a ‘consistent’ unsteered fault network (Figure 13d). Figure 13e shows the volume rendering of the detailed fault network. Here it should be noticed that most of the faults are visible in the NW-SE direction. Figure 13f shows it is merging with the zones of dense effective fractures estimations. In Figure 13g, the fracture density is shown that was determined based on positive curvature characters in the seismic volume.

A Laplacian transform was furthermore applied on the positive curvature attributes highlighting the detailed features (Figure 13h). Finally, Figure 13i shows the effective fracture estimations, based on known FMI log measurements in the region. It shows that the effective fractures are mainly situated in the NE-SW direction.

Figure 14 illustrates the analysis and integration of various planned neighbouring wells for accurate analysis of effective fracture content zones. Figure 14a shows a co-blending of the fault network, fracture density and effective fracture estimations. Figure 14b illustrates an overlay of larger potential zones near the areas of investigation. Figure 14c highlights the other high potential zones around the original planned well. Figure 14d shows the integration of the fault network, fracture density and effective fracture estimations.
integrated for a series of neighbouring wells with same well trajectories. For this analysis, we introduced five more wells with similar well trajectory to the original blue-coloured well cutting through the effective fractures that are situated in the NE-SW direction. For all the six neighbouring wells, the integration of fault networks, fracture density and effective fracture estimates have been volume rendered so that only their ‘correlation’ is visualized. This allows us to improve the understanding of the concentration of ‘correlated’ effective fractures for each well.

From this analysis we conclude that in comparison with the blue well, there are zones of possibly more potential success (purple, yellow and black wells) and zones of possibly less potential success (red and green wells).

Figure 15 shows the integration of a time section along the NW-SE direction and a timeslice representing the dense fault networks overlayed with green-coloured effective fracture zones in Figure 15a. Note that other potential zones are also overlayed in this picture. Figure 15b shows the same time section co-rendered with fault network estimation and effective fracture zones.

Case study III
In this last example, we present the results of a third field dataset and the workflows described earlier have been applied similarly as to the previous two field datasets to verify the location of the planned well. Figure 16 shows some cross-sections through the migrated seismic data volume. The planned well to be drilled is indicated in this picture with blue colour.

Figure 17 (left) shows a time slice from the migrated seismic data volume at total well depth and Figure 17 (right) indicates the estimation of faults for a specific fault network direction. Figure 18 (left) shows calculated fracture density
zones and in Figure 18 (right) its corresponding effective fractures calculation is shown. Figure 19 (left) shows the blending results of the attributes of Figure 18 and Figure 19 (right) illustrates the determined ‘consistent’ unsteered fault network. Figure 20 (left) illustrates the integration display of effective fracture volumetric representations with time slice from the migrated seismic data volume at total well depth. The blue well is planned to be drilled. Figure 20 (right) shows the filtered results towards larger potential areas. The green well, with similar trajectory, indicates a larger potential at total well depth. Figure 21 (left) shows the ‘consistent’ unsteered fault network for planned wells, and Figure 21 (right) shows the integration with the seismic data, cylindrically cropped around the well trajectories. Figure 22 (left) shows the time slice of faults integrated with volumetric representation of ‘consistent’ unsteered fault networks along the well trajectory. Figure 22 (right) illustrates the time slice integration of seismic data with volumetric representation of fault networks along both well trajectories. Figure 23 (left) shows the time slice integration with volumetric representation of fault networks along both well trajectories and Figure 23 (right) shows the result additionally blended with volumetric representation of larger potential zones.

Concluding remarks
The study proposes a new workflow for searching and recognizing optimal and effective fracture networks from migrated seismic data volumes. Blending of all three attributes and validation with existing wells showed a good correlation in these naturally fractured reservoirs. The paper discussed the integration of the sequential steps of the applied methodology that incorporated ‘consistent’ unsteered fault networks, detailed estimation of the fracture density and effective fractures zones and the geologic and structural settings of the studied areas.

We presented our results on three different field data sets to highlight the major values. Detailed analysis of volumetric representation of the three co-blended attributes may help with planning and designing future exploration well trajectories.

Using these methods in which we correlated effective fracture estimation with positively and negatively tested wells, one can now use the workflow to better plan future well trajectories in nearby fields or unexplored fractured reservoir prospects.

The workflows and methodology outlined in this paper may provide a reasonable approach towards defining effective fracture networks and assets for the design of well trajectories when other data are missing or incomplete. From the first dataset, numerous well data were integrated to validate the workflows which were later on supported by well testing data. Regarding the second and third case studies, the trajectories of planned exploration wells have been validated. In addition, the results identified potential nearby areas where appraisal wells were recommended to test additional well-developed fracture networks.

Acknowledgements
We thank Petronas Carigali Sdn. Bhd. for the permission to present the results and data. The authors would also like to thank Thuy Lan Hoang and Abdhes Kumar Upadhyay for their help in providing and loading the data.

References