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Sait Ismail Ozkaya¹, Wilhelm Kolkman², Joachim Amthor² (1) Baker Atlas, Manama, Bahrain (2) Petroleum Development Oman, Muscat, Oman

Mechanical Layer-dependent Fracture Characteristics from Fracture Density vs. Tvd Cross Plots. Examples from Horizontal Wells in Carbonate Reservoirs, North Oman

OVERVIEW

One of the objectives in fractured reservoir characterization is to separate dispersed layer-controlled fractures and correlate their height, and spacing to mechanical layer characteristics such as thickness, porosity, grain size clay and dolomite volumes from borehole image logs. In order to achieve this objective, it is first necessary to identify shear and opening mode fractures and separate fracture corridors from dispersed background fractures. We start with a brief introduction to fracture corridors and dispersed fractures and proceed to discuss methods of separating these two main fracture groups. This is followed by a discussion of the methods to determine mechanical layer dependent fracture characteristics using examples from two different carbonate reservoirs in three different fields in North Oman Basin.

SHEAR AND OPENING MODE FRACTURES

Fractures in borehole image logs can be divided into shear and opening mode fractures with respect to origin. Shear fractures have visible displacement and usually have small or no aperture. These fractures also have relatively lower dip angles. Opening mode fractures are generated under extension and have visible apertures on image logs but no displacement. These fractures are normally steeper than shear fractures.

FRACTURE CORRIDORS

Three major types of fractures are distinguishable in borehole image logs with respect to mode of occurrence within the Late Cretaceous Natih and Shuaiba carbonate reservoirs of Oman. These are (i) fracture corridors (ii) dispersed fractures (iii) isolated large opening mode fractures (Figure 1). Fracture corridors are fault related fracture clusters. These are tabular elongate fracture swarms, which cut through multiple layers and extend several tens or hundreds of meters. Fracture corridors often, but not always, occur at faults and may or may not have displacement.

DISPERSED FRACTURES

Dispersed fractures are often distributed randomly along a borehole and consist of two conjugate sets. Height, length and spacing of dispersed fractures are normally controlled by mechanical layer characteristics. Dispersed fractures are usually layer-bound. Fractures stopping at bedding planes may be clearly visible in borehole image logs in many cases.

LARGE OPENING MODE FRACTURES

Isolated large opening mode fractures are very common in the Shuaiba and Natih carbonate reservoirs. These isolated large fractures are different from large opening mode fractures within fracture corridors, and may not be associated with faults directly. The spacing of the large opening mode fractures correlates with layer thickness as in the Fahud field. Only widely spaced opening mode fractures are observed in the thick and porous Natih A and C units, whereas, closely spaced small fractures populate the lower thin-bedded units. It appears that the large opening mode fractures



Figure 1: Borehole image log examples of common fracture types within Late Cretaceous Shuaiba and Natih carbonate reservoirs of North Oman basin.

must belong to the group of dispersed layer-controlled fractures in the Fahud Field.

Within the Shuaiba reservoir of Saih Rawl field, however, spacing of the large opening mode fractures decreases approaching major fault zones. These fractures make 30 degrees angle with the two NW/SE faults bounding the field. These observations suggest the large opening mode fractures are extension fractures (riddles) associated with the strike slip faults.

SEPARATION OF DIFFERENT FRACTURE TYPES

In order to analyze dispersed background fractures, it is first necessary to identify fracture corridors and separate them. It is also necessary to understand the origin of the large opening mode fractures, because these fractures may be affiliated to faults or may belong to the layer-controlled fractures.

Fracture Corridors

Identification of fracture corridors and the separation of dispersed fractures and corridors is not always straightforward. A fracture cluster may be a corridor, but it may also be a highly fractured layer. A cluster is regarded as a corridor if (i) it includes large opening mode fractures and small fractures are clustered near big fractures, ii) Fractures within the clusters have only one preferred orientation, iii) the cluster is associated with a fault which is identified from seismic data and/or indications from image logs such as caliper enlargement, displacement, and breakout rotation.

Dispersed Fractures

Fracture clusters, which do not include large opening mode fractures and have conjugate sets, are probably fractured layers. Further analysis is necessary for a definitive identification of clusters. Some of the additional analysis will be explained below.

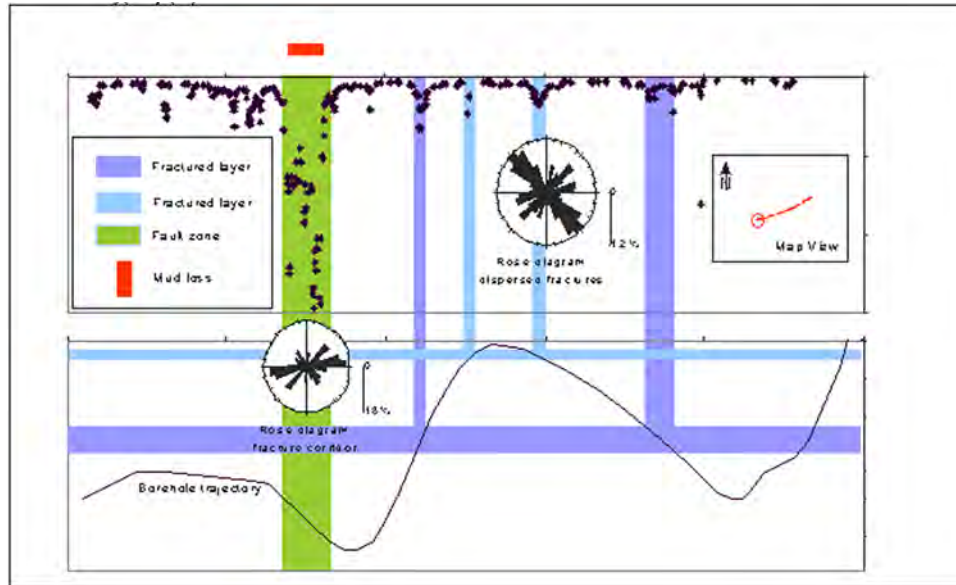


Figure 2: This well intersects a fault-related fracture corridor at 1750 m. Fractures outside the corridor are regarded as dispersed layer-controlled fractures. Mud losses and distinct differences in orientation provide further evidence that the fracture cluster at 1750 m is a corridor. Dispersed fractures occur in four clusters which correspond to two highly fractured layers. The fracture clusters at 1530 and 1680 m represent a fractured layer 5 m below reservoir top. The clusters at 1600 and 1650 m represent a thin fractured layer 1 meter below the top.

IDENTIFICATION OF LAYERS WITH DIFFERENT FRACTURE SPACING

Vertical wells would be ideal to evaluate mechanical layer-dependent fracture characteristics, but although vertical wells provide a wealth of information on reservoir layers they do not intersect sufficient number of fractures to allow a meaningful interpretation. Only image logs from horizontal wells provide the amount of fracture information that is necessary for understanding and modeling. Fortunately, horizontal well trajectories are never straight but fluctuate, traversing several mechanical layers within a reservoir. Fracture density plots with depth from reservoir top reveal mechanical layers with different fracture densities and establish a fracture density to layer thickness relationship. Other diagrams such as flattop cross sections, or open hole log porosity plots with depth from reservoir top can be used to identify additional factors which determine fracture spacing such as porosity, shale content and dolomite volume. Fracture dip angle within different mechanical layers provides information on tensile strength and fracture types and helps identify vertical fracture patterns. In combination with field scale structural controls, such stratigraphic controls are sufficient to generate 3D predictive fracture models.

Flattop Cross-sections

Composite diagrams with fracture density plots and flattop cross sections are very useful in deciding whether a fracture cluster is a fault related corridor or a highly fractured mechanical layer, especially if the borehole trajectory fluctuates and intersects the same layers more than once. Fracture swarms which occur repeatedly whenever the borehole is at the same depth from reservoir top correspond to fractured layers. Fracture clusters which occur only once at the same depth are probably corridors, but other sources of information such as stick plots, clustering of large opening mode fracture clustering, and fracture orientation must be utilized to identify corridors with some degree of confidence. The composite diagram from the Upper Shuaiba reservoir of the Yibal Field intersects a fault-related fracture corridor at 1750 m (Figure 2). Fractures outside the corridor are regarded as dispersed layer-controlled fractures. Mud losses and distinct differences in orientation provide further evidence that the fracture

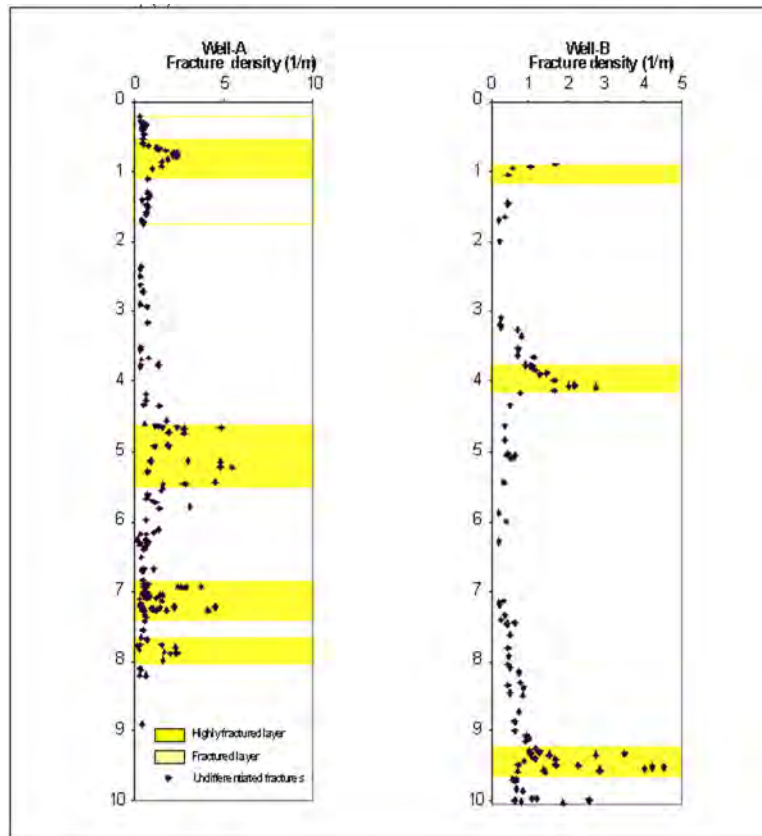


Figure 3: Two example plots of fracture density versus TVD from reservoir top clearly reveal mechanical layers with different fracture densities. Note that thin layers have high fracture density, whereas thick layers are sparsely fractured. Well A is the well shown in Figure 2.

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Fracture density plots with depth from reservoir top

Once fracture corridors are identified, they must be separated and the density of remaining fractures is plotted with depth from reservoir top. Such plots reveal different layers with different fracture densities. Histograms showing the number of fractures per borehole length within fixed depth intervals from reservoir top are useful to confirm or identify fractured layers. These diagrams have three main uses (i) identify thickness of mechanical layers with different fracture densities, find average thickness and compare it with the fracture height calculation from borehole image logs, (ii) measure the thickness of each layer with different fracture density and correlate with fracture density, (iii) identify highly fractured layers.

Two example plots of fracture density versus TVD from reservoir top clearly reveal mechanical layers with different fracture densities (Figure 3). Note that thin layers have high fracture density, whereas thick layers are sparsely fractured. Well A is the well shown in Figure 2.

Horizontal wells and sidetracks in different reservoir units

Horizontal wells and especially sidetracks which penetrate different reservoir units provide information on fracture characteristics at different levels. Sidetracks help to identify fracture corridors and allow direct comparison of

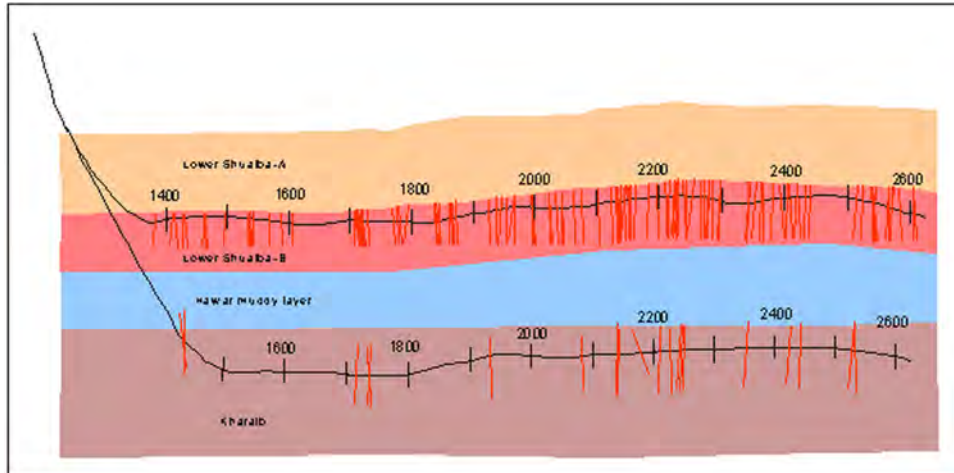


Figure 4: Upper lateral of a well in the Lekhwair field, which is drilled through Lower Shuaiba and the lower lateral through the Kharab Reservoir. The laterals are not far from each other and drilled in the same direction. The cross section view shows that the Shuaiba is more fractured than the Kharab.

dispersed fracture spacing within different units. Two side tracks of a well in the Lekhwair Field were drilled within Shuaiba and Kharab reservoirs which are separated by the Hawar muddy carbonate layer. The sidetracks reveal that Kharab is far less fractured than the Shuaiba (Figure 4). The two laterals are close to each other and drilled in nearly the same orientation.

CONCLUSION

Three fracture types are common within the Late Cretaceous carbonate reservoirs of the North Oman basin. These are (i) fracture corridors (ii) layer controlled dispersed fractures and (iii) isolated large opening mode fractures. Flattop cross sections, fracture density plots with depth from reservoir top and stick plots are useful in the identification of fracture corridors and the analysis of layer-controlled fractures. Flattop cross sections help identify fractured layers. The thickness of mechanical layers and their fracture densities are measurable on fracture density plots. Stick plots of multilateral wells reveal differences in the fracturing characteristics of different reservoir units.