The Use of Borehole Imaging Logs to Optimize Horizontal Well Completions in Fractured Water-flooded Carbonate Reservoirs

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ABSTRACT

Early water breakthrough has occurred in the Lower Cretaceous carbonate reservoirs (Aptian Shu’aiba Formation) in Yibal and Lekhwair fields, north Oman. Borehole Image logs were run in more than 10 horizontal wells in each field to investigate the role of faults and fracture systems, as well as facies variations and sedimentary features. These logs indicated the presence of highly-fractured zones with both open and cemented fractures. The fractures have orientations consistent with fault patterns interpreted from 3-D seismic data. High density fractured zones, in most cases, correspond to faults, some of which are below seismic resolution. The presence of fractures and/or fracture zones is the primary cause of early water breakthrough. Improved production performance was achieved by perforating non-fractured intervals to avoid early high water cuts.

INTRODUCTION

The Yibal and Lekhwair fields are located in north Oman and were discovered in 1962 and 1968, respectively (Figure 1). These two fields produce from the Lower Cretaceous (Aptian) Shu’aiba Formation and account for nearly 25% of PDO’s oil production.

The upper part of the Shu’aiba Formation, in the Yibal field, comprises shallow water shelf deposits (Figure 2). Four lithostratigraphic units have been defined in the Shu’aiba Formation. These are, from top to bottom, the pelletoidal unit, the Orbitolina unit, the bioclastic unit and basal blanket deposits. In the Lekhwair field, the lower part of the Shu’aiba Formation consists of shallow water deposits, at the base, overlain by progressively deeper-water sediments.

Renewed development drilling of the two fields by horizontal wells began in 1991. Although these wells were selected on the basis of a 3-D survey (Skaloud et al., 1992), open hole logs in many of the new wells indicated water-swept zones. Also the production performance was disappointing with high initial water cuts. In addition, a number of wells, where no swept zones were identified, also experienced high initial water cuts. This was thought to be caused by small faults and fractures.

Borehole Image logs were run in more than twenty horizontal wells in the Yibal and Lekhwair fields in order to identify the fracture systems, their orientations and their relationship to seismically identified fractures and faults. The top Shu’aiba fault maps for the Yibal and Lekhwair fields are shown in Figures 3 and 4, respectively.

Production logs were also used to identify zones of excessive water production. These logs confirmed that zones with high oil saturations, which were identified from Borehole Image logs as fractured, produced a high initial water cut. As a result cemented liners are now run in all wells to isolate potential conductive features. The interpretation results of the Borehole Image logs in the Lekhwair field has led to the ongoing conversion from an inverted 9-spot pattern to a vertical well line-drive, oriented parallel to the dominant trend of the faults and fractures (Stuart and Arnott, 1996).

Borehole Image logs have been used to characterize fractured reservoirs in many fields in the Arabian Gulf. Studies include Paleozoic clastic reservoirs in Oman and Saudi Arabia (e.g. Al-Kharusi and Binbrek, 1994; Ishak, 1994; Connally and Wiltse, 1995); as well as Jurassic and Cretaceous carbonate reservoirs in Oman (e.g. Mercadier, 1991; Akbar and Sapru, 1994). This paper discusses the application of Borehole Image logs towards understanding the important role of fractures on the drainage of hydrocarbons in Lekhwair and Yibal fields.
Figure 1: Oil and gas fields of Oman. Producing fields are shown in capital letters throughout (e.g. NATIH). Names of fields which are not connected to pipelines are capitalized conventionally (e.g. Jazal). Petroleum Development Oman’s Concession is shown in darker yellow. Other concessions and their operators are also indicated.
Figure 2: Cretaceous lithostratigraphy of Lekhwair and Yibal fields, North Oman. Production is from the Lower Cretaceous (Aptian) Shu’aiba Formation which is capped by the Nahr Umr shale.

FRACTURE ORIENTATION

Open Fractures

Borehole Image logs of horizontal wells reveal an unexpected degree of open fractures. The distribution of fractures varies significantly along the horizontal borehole. They occur in distinct zones rather than being evenly spaced. Fracture densities or frequencies vary between different reservoir units and appear to be a function of lithodensity. This results in differences in vertical permeabilities for different reservoir units.
Figure 3: Structure map of Top Shu’aiba Formation showing faults, Yibal field.
The major trend of fractures in the Yibal field is northwest-southeast with a minor number of fractures trending northeast-southwest (Figures 3 and 5). In the Lekhwair field most of the fractures have one main orientation, northwest-southeast (Figures 4 and 6). These fracture orientations probably result from the Late Cretaceous emplacement of ophiolite thrust sheets in the Oman Mountains which have a maximum stress oriented northeast-southwest (Akbar and Sapru, 1994; Loosveld et al., 1996).

In Lekhwair field, drilling-induced fractures which are always open were recognized from cores taken in a horizontal well. These fractures strike northwest-southeast which suggests that the orientation of the Late Cretaceous stress system persists to the present.

**Cemented Fractures**

Partially healed and cemented fractures were also identified in both Yibal and Lekhwair fields. Most are (sub) vertical and also associated with faults. These fractures have similar trends to those described above.

![Figure 4: Structure map of Top Shu’aiba Formation showing faults, Lekhwair field.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/2/1/19/5438104/busaidi.pdf)
Figure 5: Fracture orientation analysis from Yibal field.

Figure 6: Fracture orientation analysis from Lekhwair field indicates unilateral fracture orientation trending northwest-southeast.
ROLE OF FRACTURES IN FIELD DEVELOPMENT

Open Fractures

Open and partially healed fractures are distributed over the two fields. The open (conductive) fractures have two major consequences for field development.

1. Drilling highly conductive fractures and fracture zones can cause total mud loss, well control problems and poor cementation of the production liner.
2. Open fractures cause high initial water cuts due to direct communication with the reservoir aquifer or water injectors through the fracture system.

Figure 7 illustrates the types of water movements encountered in the Shu’aiba reservoir in the Yibal field. Figure 8 shows water movements through open faults and fractures in Yibal-341.

Although most fracture zones are swept, there are some densely fractured zones which show high hydrocarbon saturation. This occurs in the following two situations:

1. The fracture zone is located in an isolated fault block where there is no reservoir drawdown or water injection support.
2. In the layered reservoirs of the Lekhwair field most injectors are completed in the oil leg. Some of the fractured zones are isolated by sealing faults which limit the lateral movement of the injected water. In addition, the presence of shale laminations reduces the effective vertical permeability and restricts direct communication with the reservoir aquifer.

Water fingering occurs as water flows vertically from the reservoir aquifer through open faults and fractures and then laterally into highly permeable facies (Figure 8). However, not all faults are water conductive. The transmissibility of faults depends largely on the tectonic regime and on the fault throw. A large throw may lead to juxtaposition of the Nahr Umr shale against the Shu’aiba reservoir with an increased clay smear potential leading to sealing along the fault. Alternatively, water fingering may also be related to permeability contrast between different reservoir units.

Production performance shows that water movement along fractured zones in high hydrocarbon saturation areas is very rapid. This observation was confirmed by vertical wells drilled very close to horizontal producers. An open hole log for one of the horizontal producers indicated a high

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Figure 7: Types of water movements encountered in the Shu’aiba reservoir in the Yibal field.
hydrocarbon saturation across the fractured zones (Figure 9). After 10 months of production a second vertical well was drilled close to the same horizontal producer. The logs showed that part of the reservoir unit had become flushed. This is undoubtedly due to rapid water movement in the fractured zones caused by depletion.

**Cemented Fractures**

Cemented fractures have been recognized in both fields. The fractures are filled with calcite cement. In Yibal, one of the horizontal wells shows a high density of cemented fractures in the first 200 meters (m) of the well trajectory (Figure 10, right). Contrary to expectation, open hole logs demonstrated that this zone was swept. An investigation of the cemented fractures was therefore carried out from a horizontal well where two holes have been drilled in the same reservoir unit, one 15 m above the other. Cemented fractures were observed in the lower hole whereas the upper one showed open fractures. This indicates the absence of any vertical continuity of the cemented fractures between the two holes. Moreover, cemented fractures were found to be located in specific reservoir units, mostly in the less porous facies.

The presence of swept zones over parts of the hole with a high density of cemented fractures implies that cementation is only present in a limited part of the fractures. In this case the open fractures may provide a conduit for water via communication with the reservoir aquifer or nearby injector.
Figure 9: Cross-section of Lekhwair horizontal well.
Figure 10: Borehole Image log of Yibal-408 shows facies variations. The cemented fractures, seen to the right, are located in a limited zone.

Figure 11: Borehole Image log of Yibal-403 well shows contrast between facies with vuggy porosity (left) and lesser to non-vuggy facies (right).
SEDIMENTARY FEATURES AND FAULTS

Various electrofacies can be recognized from Borehole Image logs. Figure 11 shows the presence of vuggy porosity. The variation of vug frequency in different layers are clearly visible in the Borehole Image logs. Enlarged micro-fissures (into micro-channels), vugs, micro-vugs and fossil moulds, can also be recognized from the Borehole Images (Figure 12). Production log results from one of the Yibal horizontal wells indicates that most of the flow can be attributed to vuggy porosity with vugs interlinked by fractures.

Pyrite nodules were also identified from Borehole Images (Figure 13). These nodules, which are concentrated in the uppermost 3 m of the Shu’aiba Formation are used as a depth marker while drilling horizontal wells in the Yibal field. The presence of these pyrite nodules has been confirmed from the cuttings.

Bedding or sedimentary layering was observed in horizontal wells from both fields with dips...
Figure 14: Borehole Image log from Yibal-355 shows high angle layering with dips ranging from 8° to 25°. These differ from common sedimentary layering of approximately 3° and are probably related to fault block rotation.

Figure 15: Faults with significant displacement and changes in the gamma ray response are often observed to coincide with zones of high density fractures. This relationship is often confirmed by 3-D seismic and/or drilling data.
ranging from 8° to 25° (Figure 14). These high angle beds are different from common sedimentary layering (approximately 3°) and are probably related to fault block rotation.

While crossing faults of major displacement, a change in the gamma ray response was often observed concurrent with zones of high density fractures (Figure 15). Therefore, sudden changes in gamma ray and the presence of densely fractured zones were interpreted as fault boundaries, often confirmed by 3-D seismic and/or drilling data. The analysis of fractures indicates that the hanging wall blocks are more fractured than foot wall blocks. This may be due to the juxtaposition of different lithotypes across the fault.

**WELL COMPLETION AND PERFORMANCE**

The Lekhwair reservoirs are parallel “layer cakes” and are developed by both edge water-flooding and crestal water injection. These wells are completed with a cemented liner across the reservoir interval. Since the Shu’aiba reservoir of this field is characterized by high density fracturing, direct communication with water injectors occurs in some wells. Production rates in these wells were disappointing with initial water cuts above 90%. Figure 16 shows the production performance of Lekhwair well L-216 where the water cut is between 80% and 90%.

![Figure 16: Initial water cuts in wells like Lekhwair-216, which are in close communication with water injectors, can exceed 90%.](https://example.com/figure16.png)

![Figure 17: Lekhwair well L-183 shows a dramatic decrease of water cut from nearly 100% to less than 5% occurred in early 1995 just after the fractured zones were isolated.](https://example.com/figure17.png)
Since standard open hole logs do not indicate conductive features, the Borehole Image log became an ideal tool to run in highly fractured blocks to avoid perforation across fractures or conductive zones. This method so far has yielded good results in the Lekhwair field. In general, wells where Borehole Image interpretation was used to select the completion intervals showed better production performance. Figure 17 shows an example from Lekhwair well L-183 where a dramatic decrease of water cut occurred in early 1995 just after the fractured zones were isolated.

Some wells, for example Lekhwair well L-221 (Figure 18), although completed based on the Borehole Image results, still produced high initial water cuts. This could occur in wells which intersect densely fractured zones where fractures cannot be avoided. It could also occur in wells where highly permeable layers separate some of the perforations from nearby water fingers. Some wells may be drilled parallel to the fault trend. In these cases the fractures may be close to the well bore but not evident on the Borehole Image. In some wells high water production could be related to poorly-cemented liners.

Figure 18: Although Lekhwair-221 was completed with the benefit of the Borehole Image log, it still produces high water cuts of 3,000 to 3,500 barrels/day as it is drilled into a highly fractured block.

Figure 19: The water cut in Lekhwair-230, located in a non-fractured block, peaked at 1,500 barrels/day in early 1996, and decreased sharply afterwards.
In the Yibal field, most of the fractured zones are already flushed. The Borehole Image log still needs to be run for better well completion in parts of the Yibal field (North Flank) where fracture densities are high.

In both fields wells drilled in fault blocks with low fracture density, for example Lekhwair well L-230 (Figure 19), show very low initial water cuts. The relationship between water cuts and fracture density is clearly seen in Figure 20.

CONCLUSIONS

Based on the integration of the Borehole Image logs and Production logs in Yibal and Lekhwair fields, we conclude that fractures are the primary cause of early water breakthrough. Production logs in horizontal wells can be used to identify zones of excessive water sweep which correspond to fractures seen in Borehole Image logs. Densely fractured zones, in most cases, correspond to faults. Drilling perpendicular to the fracture orientation is recommended in order to intersect the maximum number of fractures. In this manner the fracture zones can be identified and isolated.

The Borehole Images in horizontal wells identify faults which are below seismic resolution. Wells completed with Borehole Images produce lower water cuts. Production logs in wells with high water cuts show that 90% of the water comes from fractured zones either via poorly-cemented liners or high permeability facies created by leaching of interlinked vugs and fractures. Zones which do not contribute any flow have high vuggy porosity. However the vugs are not linked. Most of the cemented fractures are associated with less vuggy facies, while the open or partially-cemented fractures are associated with interlinked vuggy facies.

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