The impact of Cenozoic tilting on fluid contacts and hydrocarbon distribution of the Cretaceous upper Shuaiba reservoirs, Bab basin northwest Oman

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Abstract

The Late Aptian Upper Shuaiba member, deposited in the intra-shelf Bab basin, extends from Qatar to the NW of Oman (van Buchem, F. et al. 2010). It is characterized by alternations of clay-rich non-reservoir layers and relatively cleaner carbonate layers of variable reservoir thickness and qualities. The progressive infill of the intra-shelf basin was in the form of low-angle clinoforms that prograded from basin margin to basin centre. This provides the potential for both stratigraphic and structural traps with the Nahr Umr acting as a regional seal and the clay rich units as lateral and or vertical barriers. Generally higher energy shallow water facies occur up-clinoform and pass laterally down sedimentary dip to lower energy moderate water depth facies. The reservoirs are dominated by low permeability (<3mD) microporous rocks. There are more than 10 development/appraisal fields in the study area with more than 1300 upper Shuaiba penetrations. The fluid contacts data shows significant variations in OWC between the fields, up to 350m tvd difference, and more importantly variations within the fields are significant. A flat contact can't be established or derived out of the data, neither at regional, field or sector scale, using the present day depth. However the data shows that a flat OWC contact can be established when the data is plotted below top Dammam, Late Eocene. The original fluid contact, OWC, appears to have been "frozen" in its original position so that it is now tilted parallel to the post Tertiary dip. This paper presents the results of the analysis which was carried out at well, field and regional scale. Evidences are presented for a common oil-water contact that is tilted regionally and extends across several reservoir layers and across several fields to form mainly one big accumulation. The conditions under which such a tilted contact can be preserved are highlighted here. The results of the analysis had a big impact on the appraisal and development activities of the Upper Shuaiba fields. The results of this analysis provide improved methods and workflows for predicting hydrocarbon distribution and fluid contacts. These workflows and methods are important when the concept is replicated over different areas and reservoirs.

Introduction

The study area is located in the north west of Oman and it covers most of the Omani side of the Bab Basin. It includes ten development fields along with other exploration areas and traded data over fields which are being developed by other operators. A regional study was conducted by PDO over the upper Shuaiba. The overall objective of the study was to develop a set of integrated sub-surface conceptual models that better capture the upper Shuaiba carbonates reservoirs, sub-surface complexity and underpin and support further exploration, appraisal and development activities in the greater Lekhwair area. Understanding the fluid contact and hydrocarbon distribution was integrated with the other work scopes of the study and is the main focus of this paper.

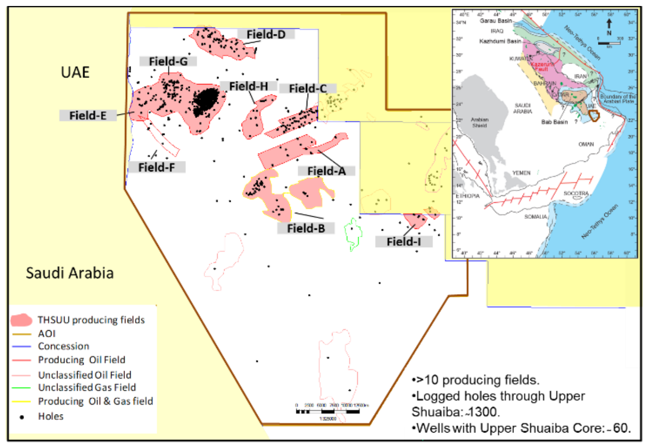

Figure 1: study area in relation to other boundaries such as countries, operators and fields.

The fluid contacts data shows significant variations in the OWC between the fields, up to 350m tvd difference, as well it shows significant variations within the fields. Previously, during the early stages of the field appraisal and development, compartmentalization was assumed to explain the considerable variation in contact depths. However, as field gets more matured with more wells and data e.g. pressure data, compartmentalization becomes invalid concept to explain the fluid contact variation. Therefore evaluation of other concepts was a key for understanding HC distribution in upper Shuaiba fields.

The palaeo contact concept was evaluated to tackle the issue of fluid contact variation. The analysis was carried out at field and regional scale and aimed to open new areas for development and to help in optimizing the ongoing development fields. Validation of the concept and establishing a workflow for palaeo contact and structure reconstruction is a key objective of this study.

The prevailing concept used to describe the upper Shuaiba stratigraphy and Bab basin infill has been that of clinoform progradation (Hamdi, A. et al. 2015). In contrast to the underlying lower Shuaiba carbonates that are clay-free, the upper Shuaiba is an argillaceous carbonate sequence. Clay content has a detrimental effect on reservoir quality of the upper Shuaiba units. Higher energy shallow water facies occur up-clinoform and pass laterally down sedimentary dip to lower energy moderate water depth facies. The shallow water facies composition changes through time from rudist dominated facies in the older clinoforms, to miliolid foraminifera dominated packstone/grainstone facies in the youngest ones.

During the Pliocene to Pleistocene the preceding formations were tilted to the NNE by about 0.5-1º due to the crustal loading (Filbrandt, B. et al. 2006). The structural and stratigraphical traps were filled before this event. This is evident by the results of the analysis presented here which showed that the contact is frozen" in its original position so that it is now tilted parallel to the post Tertiary dip.

The fields of the Greater Lekhwair area (lower and upper Shuaiba) are sourced mainly by Huqf oil (pre-Cambrian) (Terken, J. et al, 2001). Unlike the lower Shuaiba, the upper Shuaiba does not depend on anticlinal/dip closures for trap configuration. The thin carbonate reservoir beds of the upper Shuaiba are interbedded with clay-rich beds which could act as seals. In addition the clinoform reservoir geometry results in a lateral "pinch-out" of each reservoir bed where it subcrops against the base Nahr Umr. Also, down clinoform reservoir rock properties tend to become poorer with the potential for lateral changes in capillary properties, a form of lateral capillary seal. Hence the upper Shuaiba reservoirs have the potential for a wide range of structural and stratigraphic trapping mechanisms, Figure 2.

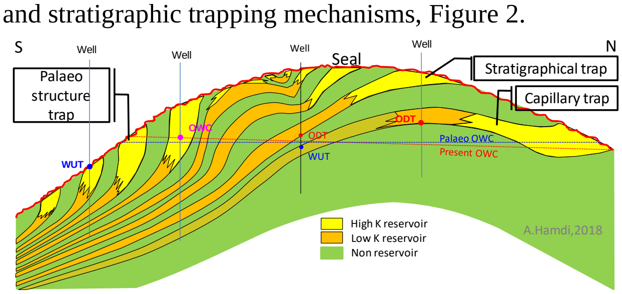

Figure 2: Schematic figure, not to scale, N-S cross section showing the reservoir geometries and the trapping mechanisms in the upper Shuaiba reservoirs in the greater Lekhwair area.

Due to the geometry of the reservoirs, the low permeability and therefore the long entry height and long transition zone, the fluid data is mostly oil down to (ODT) and water up to (WUT) data with few solid oil water contacts. There are very few OWC data points as the reservoirs are very thin to accommodate a long transition zone. A total of 184 wells were evaluated for the fluid contact analysis where inventory of ODT, WUT and OWC data were interpreted from the quality controlled logs. Four different overburden horizons were picked using the Gamma ray logs in the 184 wells.

Tilted Contact Concept

In a conventional oil reservoir, where the fluid phase pressures are in equilibrium with the capillary forces, the Free Water Level (FWL) defined by the intersection of oil and water pressure gradients is typically flat (horizontal). However, there are numerous situations where the equilibrium between fluid pressures and capillary forces has been disturbed and the assumption of a flat FWL no longer holds true.

When a field is tilted after initial oil accumulation the equilibrium situation is disturbed. Oil is expected to re-migrate trying to re-establish the equilibrium. In one part of the field, uplifted part, oil will move to displace water (drainage) while on the opposite side of the field water will try to replace the oil (imbibition). In areas of imbibition residual oil saturation will always be left in the pore space i.e. the saturation will not return to zero saturation. In the area of drainage the time taken to re-establish equilibrium might be considerable (geological time scale). Therefore the result is a tilted fluid contact. *Figure 3* is a cartoon diagram illustrating the concept of tilting hydrocarbon trap with the associated processes .i.e. drainage and imbibition.

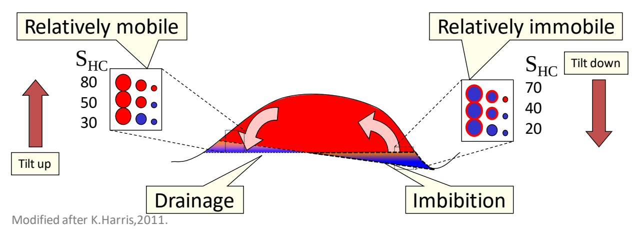

Figure 3: carton diagram illustrating the concept of tilting HC trap with the associated processes, modified after K.Harris, 2011.

An estimation of a possible OWC depth can be obtained however by inventorising Oil-Down-To (ODT) and Water-Up-To (WUT) data from a group of wells. This, together with some knowledge of capillary property variations in the rocks should allow an assessment of whether the data is consistent with a relatively flat OWC and flat FWL or whether there is evidence for tilting.

Palaeo reconstruction workflow

Reconstruction at any palaeo time applies to any data which are associated with depth. The main assumption with the reconstruction is that the reference marker or horizon was deposited flat across the entire trap to be evaluated i.e. the low of original horizontality in sediments by Steno, N., 17th century. Regional conformable markers, preferably good seismic reflectors, are more appropriate to this process. Reconstruction at any particular palaeo time is carried out by subtracting the present day true vertical depth value of the data from that of the reference marker which represents the palaeo time. For example, in the case of this study, the TVDSS depth of the fluid contact data, e.g. OWC, is subtracted from the TVDss depth of top Dammam at the same XY coordinate.

Predicting the best palaeo reference

The selection of the best palaeo reference marker, i.e. the time at which the HC contact is the flattest, was judged based on plots of fluid data in reference to different palaeo markers i.e. top Shammar, top Rus, top Damamm and present day sea level. The conclusion of Dammam being the best reference can be derived for most of the fields. Figure 4 is a comparison plot of fluid data in one of the upper Shuaiba fields, with a single rock type, at the present day tvdss depth and the three different palaeo depths. The flattest OWC can be established below Dammam as indicated by Plot-B.

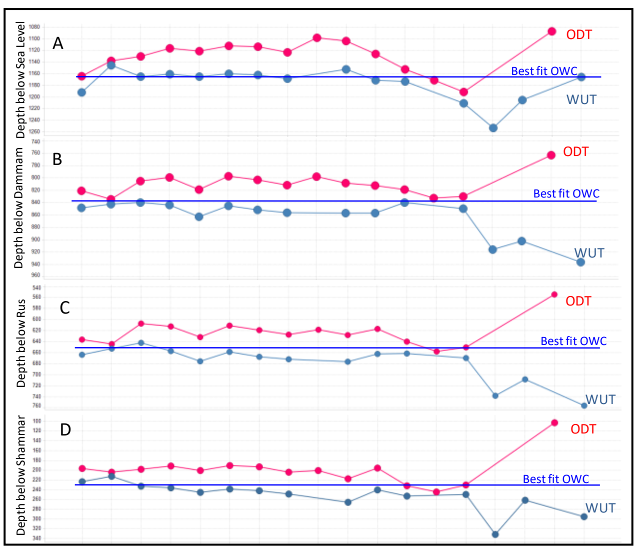

Figure 4: comparison between ODT-WUT data at A: present day tvdss, B:Dammam, C:Rus and D:Shammar.

Distribution of saturation versus present and palaeo depth analyses were carried out in integration with the core rock typing analysis. The distribution of the data looks more convergent with the depth below Dammam than that with the TVDSs depth where outliers exist. *Figure 5* shows two examples of the oil saturation versus present and Dammam Palaeo depth for two different rock types. On the other hand the back calculated FWL from such plots show a very narrower range compared to the ones calculated using the present day depth, Table 1.

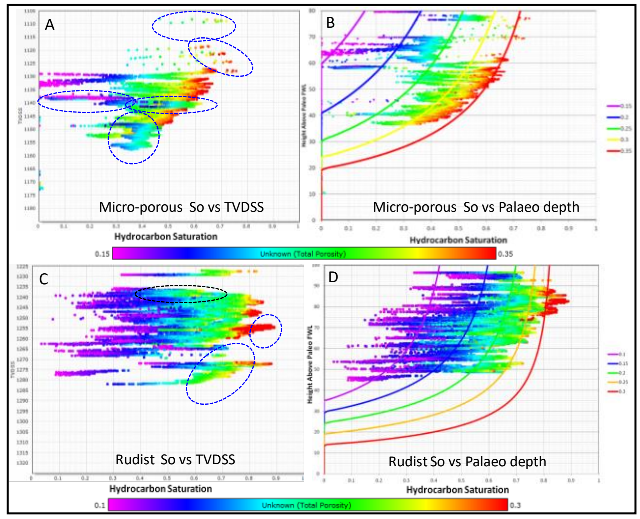

Figure 5: Cross-plot of measured log saturation (dots) versus Palaeo-depth for two different rock types(micro-porous and Rudist), colour-coded by porosity. The best-fit saturation function is represented by coloured solid lines on plot-B&D with the same colour code for porosity. The data (dots) is tightly constrained in colour bands (porosity).

Field	FWL (mTVD below to Dammam	FWL (mTVD below Sea Level)
A	880	1260
B	880	1175
C	880	1330
D	880	1373
E	840	1190
F	840	1153
Range	**40m**	**220m**

Table 1: Saturation Height function estimated FWL per field in reference to depth below Dammam and depth below sea level.

Field Examples

Field-C: the reservoirs in this field are multiple layers, 2-10m thick separated by argillaceous layers that prevent inter-reservoir communication. The fluid data plots in Figure 6 show that the contact is very flat when the data is plotted at Dammam time. The established contact can be set assertively at 842m below Dammam (TVDbd).

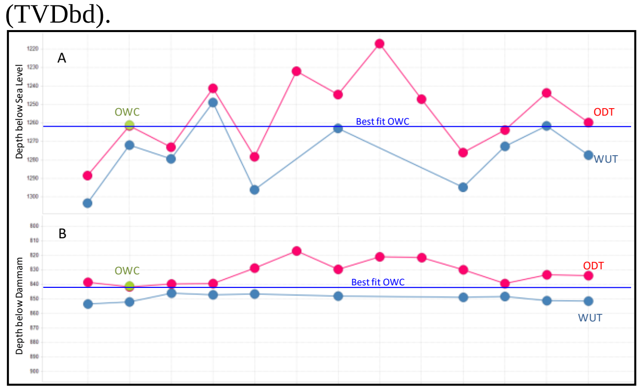

Figure 6: comparison between ODT-WUT data in Field-C at A: present day tvdss, B: depth below Dammam

Field-D: the field consists of three main reservoir layers, up to 20m thick, separated by argillaceous layers. *Figure 7* is the fluid contact data plots of Field-D By comparison the plots show that the contact is also very flat when the data plotted at Dammam time. The established contact can be set at about 842m below Dammam (TVDbd), i.e. similar to that of Field-C.

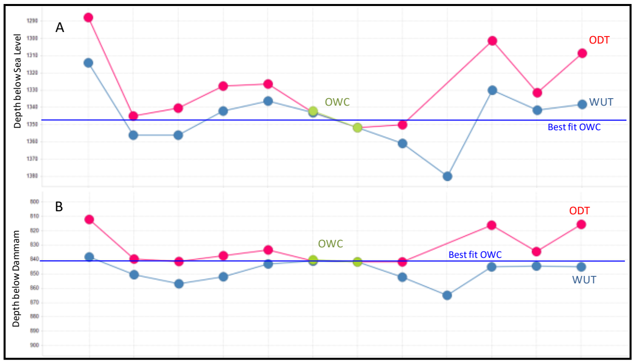

Figure 7: comparison between ODT-WUT data in Field-D at A: present day tvdss, B: depth below Dammam

Field-B: the field can be described as stacked or layer cake reservoirs of relatively constant thickness, 2-5m, separated by argillaceous layers and dominated by low permeability (<3mD) microporous reservoir. It is the most basinal part of the prograding clinoforms. Figure 4, presented earlier, are the fluid contact data plots of the Field-B data. By comparison the plots show that the contact can be set very flat when the data is plotted at Dammam time and the established contact can be set at about 840m below Dammam (TVDbd), i.e. similar to that of Field-C and Field-D.

All the upper Shuaiba fields were evaluated using the same approach. Most of the fields show a flat OWC when the data is referenced to the depth below top Dammam surface. Most of the fields show a flat OWC at about 840 m below Dammam depth. Few exceptions are recorded where the established contact are slightly shallower or deeper than the 840m.

There are two abnormalities to this conclusion. The first one is related to a field with many ODT but very little WUT data. The fluid contact plots at Dammam time are not any better than the same at present day depth, Figure 8. The field structure is mainly a result of a series of uplifts caused by the reactivation of the deep-seated Jurassic faults due to the compression during the early to late Cretaceous. Thin Shammar shale acts as the seal over the crest of the field where Nahr Umr, Natih and Fiqa are totally eroded. The thin seal is less effective and the potential for seal leak is higher especially during faults reactivation. This is evident by the discovery of the economical volumes in Shammar above the field and the HC shows in the shallow Palaeocene strata. Based on the oil typing analysis, the oil in Shammar is the same oil as that in Shuaiba and Kharaib. The same analysis indicate that the Field has received very recent top-up charge of Tuwaiq oil to the NW of the field, *K.Harris,, 2011*. The two charges, possible breach and leak, in addition to the post Dammam tilting make the predictability of the fluid contact extremely difficult in this field.

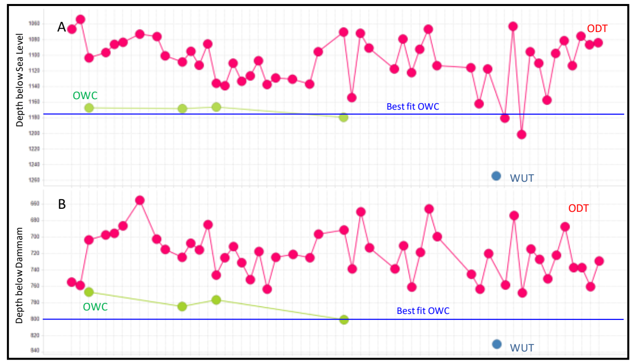

Figure 8: comparison between ODT-WUT data in Field-L at A: present day tvdss, B: depth below Dammam

The far southeast developments of the upper Shuaiba show a flat palaeo OWC contact at about 1100m below Dammam, Figure 9.

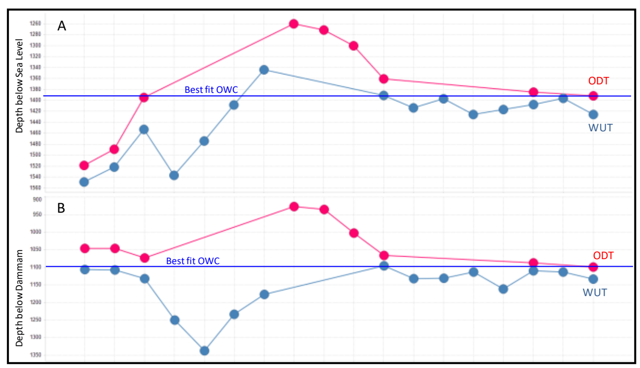

Figure 9: comparison between ODT-WUT data in the upper Shuaiba SE fields at A: present day tvdss, B: depth below Dammam

Compared to the NW fields, discussed previously, the OWC here is about 250m deeper which is indicating the possibility of a different accumulation. The reservoir geometry, rock quality and trapping mechanisms within the SE area require further definition and analysis. They were not the focus of the upper Shuaiba regional study. Therefore the big NW accumulation was carried over as the focus of this study.

The interpreted OWC was mapped over the NW accumulation. The intersection of the OWC with top upper Shuaiba at Dammam Palaeo time is shown by the thick solid pink line on the map in Figure 10.

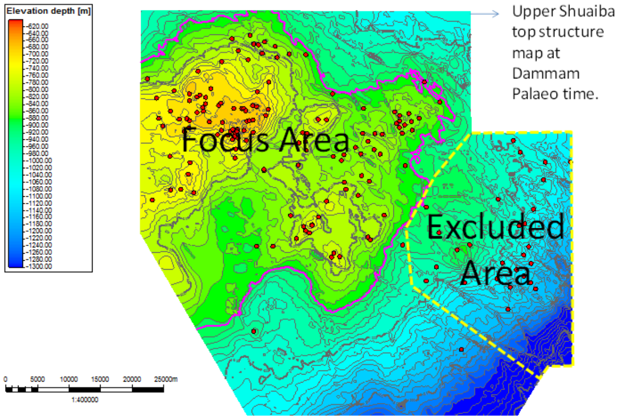

Figure 10: the areal definition of the NW accumulation (focus area) and the SE area (excluded area).

Reasons for upper Shuaiba palaeo contact

Generally tilted contacts can be caused by two different conditions i.e. current reservoir conditions which include density variation and aquifer strength and preserved conditions which include compartmentalization, seat seal, capillary effect and time (Harris, K. 2011). The upper Shuaiba carbonate units dip gently, average 0.5 degree, and their properties deteriorate toward the aquifer which is generally very weak. The aquifers in most of the fields with tilted contacts were found to be very weak and no clear evidences were found for hydrodynamic flow. The changes in the oil density in the north Oman “tilted” fields are too small to have caused the significant tilting of the contacts. The fault throws are small and displays a carbonate carbonate juxtaposition. Therefore these faults are expected to be of non sealing characteristics, supported with the pressuer data.

Upper Shuaiba has multi-conditions which have different degrees in prevention of re-equilibrium of the fluids post the tilt. The capillary effect is high and is related to low permeability of reservoir and the nature of the rocks which are mainly microporous. The microporous rock in the case for upper Shuaiba has a permeability ranges between 1-5mD. On the other hand the average tilt is about 0.5 degree to the NNE which result in relatively lower elevation change before and after the tilts compared to the entry height of the low permeability rock. The reservoir was charged pre-Tertiary and the tilt occurred during the Pliocene to Pleistocene which is considered not long enough for equilibrium to be re-established under the other conditions of the trap.

Impact of trap tilting

The uplifted side of the trap will experience oil trying to displace water, drainage process, where on the opposite side the water is displacing oil, imbibitions process, Figure 3. The behaviors of the two processes are different. The Shuaiba in the NW Oman is considered to be Mixed Oil-water wet, K.Harries.2003. Under the two processes the invading fluid replaces the occupant one, initially in the larger pore-throat of the reservoir. In the drowning side of the reservoir, the oil saturation will still be high as the oil in the small pore throat rock is difficult to be displaced and therefore oil saturation will still be under the new OWC. Normally, under the assumption that reservoirs are under drainage conditions, cap-curve measurements on core samples are made in order to determine the shape of the oil saturation profile and the irreducible water saturation. When the trap is tilted, the shape of the function will not fit the saturation seen by the wells because the function is basically representing a drainage process where on the other hand the reservoir is experiencing drainage and imbibitions behaviors.

Value of palaeo contact prediction

The value of defining palaeo structures and fluid contacts is high and well rewarding. Mapping the palaeo structures and the areas with imbibition and drainage due to tilting has a great value in the understanding of HC distribution and the optimum development of the fields. The high saturation section in the imbibed area could not be attractive as the low saturation section in the drainage area.

Implications of using palaeo contact versus flat or stepped contact are not limited to the changes of the in-place volumes but will affect the field development, well counts and well placement. In the past, before concluding the application of the palaeo contact concept in the upper Shuaiba fields, faults are assumed as sealing ones in order to explain the contact variation between different blocks. Interpretation of many isolated blocks within a small field was a result of this approach. The segmented field required many more development wells. On the other hand several HC potentials were missed out as they are not associated with present day structures. Similarly the areas between the existing developments were not targeted as the existing developments were assumed as disconnected accumulations. With the application of the regional palaeo contact concept, palaeo structure and one big accumulation, more areas were opened as prospects for drilling. Following the application of these concepts, many exploration and appraisal wells were drilled, validated and proved the concepts. The HC reserves estimation was firmed up, matured and booked for the entire area. The contact uncertainly was significantly reduced and therefore unlocked many near-field potentials which changed volumetric, change the well counts and optimized the locations. More emphasis was put in defining the imbibitions effects on the log response during field evaluations.

Conclusion and recommendations

The prograding clinoforms of the Late Aptian, thin and low permeability upper Shuaiba carbonate reservoirs were initially charged during the Paleocene by migration through vertical faults. Subsequent to this initial charge, during the Pliocene to Pleistocene the traps were tilted to the NNE by about 0.5-1o due to the crustal loading. The original fluid contact, OWC, appears to have been "frozen" in its original position so that it is now tilted parallel to the post Tertiary dip. This "frozen" OWC position is probably a result of the relatively low permeability of most upper Shuaiba reservoir layers and because the thin layers are only in contact with aquifer over a small surface area in the down-dip positions. The small elevation change was not enough to overcome the capillary forces of the low permeability reservoirs. On the other hand the time, since the tilt to the present day, was not sufficient for the re-equilibrium to take place. The study showed that a flat OWC can be established when the fluid contact data is plotted in relation to the depth below the Eocene Dammam surface. The analysis showed that most data is consistent with a single oil accumulation that formed after initial charge and extends over a large area extending for more than 40km. It also showed that the far south east developments are related to a different accumulation as the established contact is much deeper than that of the North West accumulation. The centre or axis of the tilt is not well defined. Evidences for imbibitions were seen by some of the log data in one of the upper Shuaiba field where the reservoirs are relatively thick and more permeable. This contrasts with Lower Shuaiba reservoirs where evidence for water imbibitions is much more widespread.

The application of the palaeo contact concept has proved its value through the development of the upper Shuaiba reservoirs. New exploration/appraisal prospects were identified and targeted. A drilling campaign proved the hydrocarbon potential of new areas and the validity of the palaeo OWC and the palaeo structures concepts. Following the validation of the palaeo contact concept, all the static modeling in this area has adopted the same method for mapping the fluid contact. This resulted in better knowledge of the HC distribution and reserves estimation. More emphasis were put on the imbibitions effects on the log response during field evaluation. The development is optimized, near field exploration is encouraged, and development of fields was accelerated.

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