Evaluating the Fluid Distribution in Mauddud Reservoir after 80 Years of Gas Injection and Production, Bahrain (Awali) Field*

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Abstract

Mauddud reservoir is one of the most prolific reservoirs in the Awali Field. The Mauddud limestone is subdivided into two connected units, Mauddud A and B. The Mauddud is a shallow-to-open marine carbonate on what is commonly referred to as the Arabian Shelf.

The Awali Anticline has undergone post-charge structural adjustments with possible associated seal failures that has permitted hydrocarbon migration to shallower horizons and subsequent aquifer water ingress. The water replaced moveable oil, leaving a significant residual oil column. When discovered in 1932 the existence of a residual paleo oil column was not identified, which subsequently led to confusion on selecting oil-water contacts. Gas injection commenced early in the field's life in 1938 in order to maintain reservoir pressure and a large gas cap soon developed. A detailed geological and petrophysical study was recently undertaken which accurately mapped the extent of the gas cap throughout both Mauddud A and B and highlighted the impact of the structure, faults and permeability heterogeneity in controlling the gas cap distribution, the displaced oil rim development as well as the water ingress pattern. Leading to a surprising discovery that oil migration had taken place both vertically and laterally, this study re-examined the application of a full suite of logs, core and pressure data in assessing the complex fluid migration history. This detailed geological and petrophysical study resulted in the development of a new conceptual geo-model based on a logical application of all available data that led to an improved geological model and an improved future drilling target plan.

Introduction

The Bahrain Field, also known as Awali Field, is a doubly plunging anticline underlying the central and southern parts of the island of Bahrain (Figure 1). Oil production began in 1933, and peaked at 76 MBOPD in 1970 before declining to about 27 MBOPD by early 2010. Reservoirs have been produced by primary depletion, natural water influx, gas injection and water flooding. Rich gas injection from the Arab Formation began in 1938 to maintain reservoir pressure. Dry gas injection from the Khuff began in 1970.

Mauddud Geology

Stratigraphy

The Mauddud Limestone is Cretaceous (Albian) in age and is part of the Wasia Group. It is underlain by the Nahr Umr and overlain by the Wara Formation (Figure 2). Initially it was treated as one interval without internal subdivisions. Early in the history of Awali Field, however, the Mauddud was subdivided into the Ba (upper Mauddud, also referred to as the Mauddud A) and the Bb (lower Mauddud, also referred to as the Mauddud B) terminology that has been entrenched at least since the BRT-1944 report, if not earlier (Figure 3). The Mauddud in Awali Field ranges in thickness between approximately 100’ in crestal areas of the anticline to approximately 122’ on the flanks of the structure, averaging about 110’ thick (BRT-1965). The upper Ba interval is generally approximately 75’ thick and is more permeable than the underlying Bb interval that generally is approximately 35’ thick. A low-resistivity, generally lower-porosity carbonate interval approximately 5’-10’ thick commonly occurs at the Ba-Bb boundary.

Lithology

The Mauddud is described in the Bapco-1944 report as soft, probably fractured, possibly slightly cavernous limestone. In the Bapco-1958 report the Mauddud is described as a soft, porous, sugary limestone with limited fractures and vugs. The Bapco-1965 report expands on the earlier works and describes the Mauddud as a medium-grained fossiliferous, fairly-well-sorted, clastic limestone, with diagenetic alteration including leaching, recrystallization and calcite cementation that have altered much of the original rock to a soft, earthy, very fine-grained, porous limestone. Fossils are locally completely leached-out, creating rather large vugs (Bapco-1965). The Bapco-1980 report similarly describes the Mauddud as light grey to white, fine to medium-grained, moderately soft to hard, fossiliferous, detrital, clean carbonate sandstone. Most of the original rock has been altered by recrystallization, leaching and cementation of secondary calcite along fractures. The Bapco-1980 report describes leaching as an important process that created vugular and channel porosity, thereby making the Mauddud an excellent reservoir with high porosity and good permeability. The CGG-2002b report states that the Mauddud consists of white to light gray, fine-to medium-grained, clean bioclastic limestone. They report that bioclastic packstones and wackestones dominate, and that lithification varies from moderately soft to hard. They also report that the average porosity is 31% and that leaching appears to be most common in the upper Mauddud. They note that core samples are commonly chalky and crumbly and that the best part of the reservoir may wash out of the core barrel.

A recent studies of the Mauddud core has identified three main lithofabrics and three sublithofabrics (Figure 4 and Figure 5). The lithofabrics as currently defined are:

- Grain-dominated packstone to grainstone (gdPS-GS).
- Suggests ‘shoal’ sediments were grain dominated.
- Reworked porous rudist debris and mdPS-gdPS with large rudist debris (higher\low-energy).
- Mud-dominated packstone to packstone (mdPS-PS) with transgressive unit, predominantly LF1 with shale concentrations (mdPS-PS).

All lithofabrics are impacted, mixed, and overprinted by extensive diagenetic alteration throughout the Ba and Bb intervals.

Mauddud Fast Features

It is essentially undisputed that something causes the Mauddud to have "fast" reservoir behaviour. Historically and currently this has generated significant interest, analyses, discussions and debates as to whether the fast zones are due to existence of high-permeability stratigraphic thief-zones (aka "fast zones" or "conductive zones"), due to dual-porosity fractured-reservoir behaviour (i.e., fractures as conductive features), due to fluid movement associated with faults, and/or due to some combination of these and/or other factors. Water movement through high permeability pathways has been recognized historically, but the concept of tying water fingers to fast zones is a new idea. Early water breakthrough in the Eastern Water Flood (EWF) was a major issue. Tatweer have generated a new and commendable working hypothesis that Mauddud low resistivity zones are thief zones. The low resistivity zones typically exhibit N-D log porosity that is lower than the adjacent rock. The concept is that these low resistivity, low ND porosity intervals have vuggy/channel porosity systems and are the highest permeability intervals/beds within the Mauddud and act as thief zones. Low resistivity is attributed to high salinity mud invasion due to high permeability into the fresher water Mauddud system thereby decreasing resistivity values. FMI images used also to examine rock fabric show that Mauddud is layered carbonate reservoir and its porous fraction is comprised of vugs, moulds, channels, patches of inter-particle or intra-particle porosity or layers due to diagenesis. The dense carbonate areas or porous areas have light shades on the images; whereas porous and mud invaded rocks, vugs, and moulds have dark shades (Figure 6).

Contacts

In the Mauddud Zone there has been changing terminology for the oil-water contact (OWC) over time. In the early years OWC was the depth of water-free oil production. Today we call this depth Top of Transition Zone (TTZ). The OWC was historically defined as the depth below which wells produce all water and no oil, or the depth of last mobile oil. However, there can still be oil saturation below the OWC that is immobile down to the Free Water Level (FWL).

Historical OWC Observations

The earliest report Bapco-1944 indicated that the original is constant at 2175' ftss. This contact is shared with the underlying Nahr Umr reservoirs. Bapco-1958 reported the same OWC at 2175' feet sub-sea. The definition of oil water contact at this time is water free oil. In the Bapco-1965 report the OWC was lowered to 2200' ftss.

Given that the field was on production and on gas injection since 1938 the inaccuracy in calculating water saturation on logs to accurately identify an original OWC are possible explanations for the difference in the values. The report Bapco-1980 uses well A-XX16 as the lowest completion in the field with water free oil as the OWC at 2201' ftss. However, this report also states that the oil saturation extends to a datum of 2450' ftss before becoming 100% wet based on log. Prior to 1980, the OWC is the water free oil depth. CGG-2002b reports two oil water contacts. The first is one traditionally accepted as 2200' ftss (now referred to as the TTZ) and the second is 2350' ftss which could be termed the FWL as this was used as the basis for the J-function calculations used in the dynamic modelling of the reservoir.

Current OWC Interpretation

Combining these early observations, with the calculated water saturation curves in the Bahrain Zone, suggest an obvious alternative. Most discussions of saturation height trends and fluid contacts implicitly assume the reservoirs are in drainage capillary pressure equilibrium, but this is not the case. In fact, many reservoirs around the world have undergone post-fill structural adjustments or even seal failures that cause the hydrocarbons to be redistributed. Assuming the hydrocarbon-water contact moves due to structural tilt, seal failure, or production, then water will imbibe into the reservoir to occupy space formerly occupied by hydrocarbons. Capillary hysteresis effects, result in imbibition not simply taking the same drainage curve taken when oil first entered the reservoir, but it may take a new path leaving residual oil in the pore space due to snap off phenomena (Figure 7).

Drive Mechanisms

Mauddud gas injection and fluid migration has impacted drive mechanisms in all zones. Gas injection has been use primarily in Ba,causing oil migration down-dip in Ba and Bb. Additionally, oil has migrated into Nahr Umr Cab and Cc. and up into Ac. Pathways of migration are likely involve flow along faults, across faults, and wellbore cross flow (Figure 8). Due to overall pressure decline, aquifer influx has resulted in edge water influx in all zones.

Gas-Cap Growth

The gas-cap has experienced several stages of development. In the early years, rich Arab gas injection was a relatively low volume to match voidage and maintain pressure in Mauddud. This period is labelled the "Saturation" period. During this time gas saturated oil that it contacted in Ba in the Central Area of Mauddud. Beginning in 1955, free gas began to form a small secondary gas-cap that was monitored with neutron tools. After this point "Gas-Cap Growth" began with an increase in size as an umbrella shape caused by down-dip gas override. It has been suggested that the free gas zone did not expand vertically due to relatively high drawdown in the oil rim which in turn caused the gas override. Tatweer now believes that the umbrella shape of gas expansion in Mauddud A is not due to drawdown in the flank area but was due to the contrast of the permeability between Ba and the underlying Bb. Compartments partially isolated by major faults in the North and Southern portion of the field have been similarly affected by structural setting resulting in a small gas cap being formed in the South and no gas cap at all in the northern area (Figure 9).

Despite the fact that the gas did not show a major expansion vertically, it has been observed that the Bb zone was being charged with oil indicating vertical oil migration. Many newer wells in the gas cap area that exhibit gas cap development, also indicate higher oil saturations in Bb. This vertical oil migration has been observed over most of the field and is consistent with gas cap growth, starting initially in the crest and then down to the flanks. (Figure 10 and Figure 11).

Mauddud-Gas Saturation Monitoring

As the gas cap in Mauddud grew there were efforts made to monitor its expansion. As early as 1955, Neutron logs were run to ascertain the gas-oil contact. The uniformity of the porosity facilitated the process. Campaigns were regularly undertaken as the gas cap expanded. In 1957 a slim-hole Neutron was available and a campaign of some 50 wells was undertaken. The results indicated the “Umbrella” shape of the gas cap. The lateral development of the gas cap continued to be much greater than the downward movement. Whilst gas saturations were not calculated the gas cap development was well understood from the beginning of monitoring. With time a better understanding of the heterogeneity within the Mauddud reservoir has supported the early gas cap expansion that was seen.

As more sophisticated logging tools became available and coupled with advances in analysis techniques, gas and oil saturations were established. A formal log evaluation was undertaken on an ad-hoc basis until in 2010. Following this a systematic process of re-evaluating all logs since well 300 (1976) commenced. In 2012 gas was introduced into the petrophysical model as another “mineral”. All wells having a basic open-hole porosity and resistivity suite of logs now have gas, oil and water volumes and associated saturations, for all logged intervals. Fluid saturations derived from conventional logging suites have frequently been confirmed with through - casing Saturation Tools and Nuclear Magnetic Resonance tools and core analysis, and been seen to be very similar. Remaining oil saturations to gas have seen to vary considerably within the Mauddud A gas cap, in keeping with the rock texture heterogeneity and varies between 10 % and 40 % (Figure 12).

Oil and Gas below the Transition Zone

Due to variation in permeability between the upper Mauddud and lower Mauddud most of the oil moved latterly to the flank area with the development of the gas cap. The gas-water contacts currently have reached the paleo oil water contact in some portions of the field, forming an oil rim between the top transition zone and the paleo oil water contact.

Areas located away from the gas stream flows still show no impact on oil, gas and water column from the original condition. Based on recent wells, it was found that the thickness of the oil rim varies from 20-60 feet in the southeast and southwest part of the field. Most of it has been accumulated in the south east covering around 500-700 acre (Figure 13).

Gas-Cap Water Invasion

As shown on the previous maps the gas-cap reached almost full size at 600 MMbbl of HC volume (gas plus remaining oil) by 1985. Then sometime between 1990 and 1995 it is estimated that water invasion began to impact the gas-cap. Today the gas-cap hydrocarbon volume is likely between 400 and 500 MMbbl, but the invaded volume is uncertain.

The recent study discovered that XPT, N-D crossover, and resistivity all indicated water invasion in the south central gas-cap. Various Mauddud gas cap isopach maps based on Neutron-Density separation have been generated. Preliminary attempts to evaluate gas-cap thickness and evolution over time and work is continuing to refine the water impacted area. Mapping wells between 300-800 feet shows a very small area to the south where the gas cap has diminished. The second map includes wells from 801-1700 feet resulted in a gas-cap isopach map with a sinuous shape (Figure 15). It shows a larger area of diminished gas-cap and that the gas-cap is locally missing (i.e., zero gas cap thickness) in the south central part of the field. This missing gas-cap area is consistent with XPT, PLT and well production data. An estimated volume of the current gas-cap is approximately 248,000 ac-ft, whereas the estimated historical volume of the gas cap before water invasion is approximately 340,000 ac-ft. On this basis, the volume of the gas-cap has diminished approximately by 27% or more. Several new wells drilled recently on the crest, adjacent to the North South fault trends have confirmed the expansion of the water on the crest (Figure 16 and Figure 17).

Water Encroachment

Water encroachment has been historically viewed as under running the base Mauddud. Water movement through high permeability layers has been recognized historically. The fingering of water through “fast zones”, has been seen on many logs , including Resistivity, Reservoir Saturation tools, PLT’s and is undergoing further investigation. The combination of water ingress through the north-south faults either directly or through juxtaposition, coupled with permeable layers may explain the migration of water at the crest of the field (Figure 18).

Conclusion

The Bahrain Field is a very mature field that had have undergone many major changes since its initial discovery. A very early gas injection strategy together with a strong water support has resulted in Mauddud reservoir having a complex fluid history. A lack of log data in the early years of production made the evaluation of this difficult. Recent investigations into geological, petrophysical and production data has again been collated with recent well data into a single cohesive model which has resulted in the following conclusions:

- Prior to discovery Mauddud had undergone a loss of oil to shallower reservoirs.

- The OWC at discovery was probably as shallow as 2175 ft ss, with paleo residual oil as deep as 2700 ft ss.

- Early gas injection into Mauddud displaced oil towards the flanks in Mauddud A, vertically to the lower reservoir Mauddud B as well as into both the adjoining Wara and Nahr Umr reservoirs through juxtaposition.

- Permeability heterogeneity of greater than ten times matrix has resulted in rapid development in Ba with no gas cap in Bb and water fingering from edge aquifer water.

- There is evidence that the water at the crest of the field in the upper Mauddud A supports open faults as a path of water influx. Current hypothesis suggest the mechanism may be a combination of movement through faults, reservoir juxtaposition and fingering through high permeability layers.

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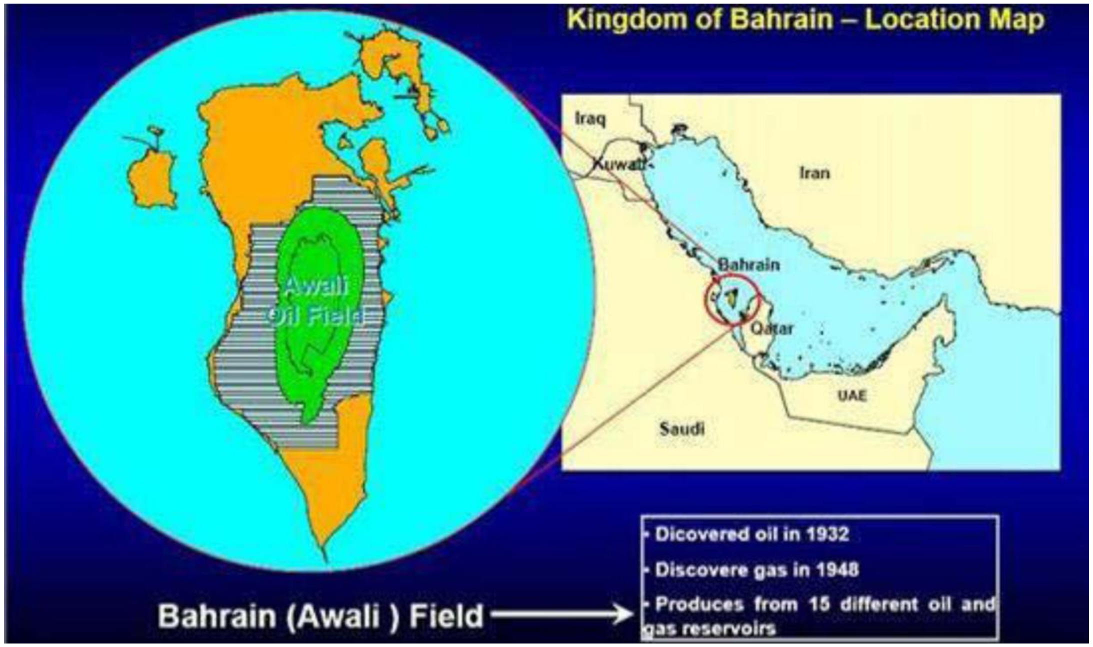

Kingdom of Bahrain – Location Map

- Dicovered oil in 1932
- Discovere gas in 1948
- Produces from 15 different oil and gas reservoirs

Figure 1. Location map of the Awali Oil and Gas Field, Bahrain.

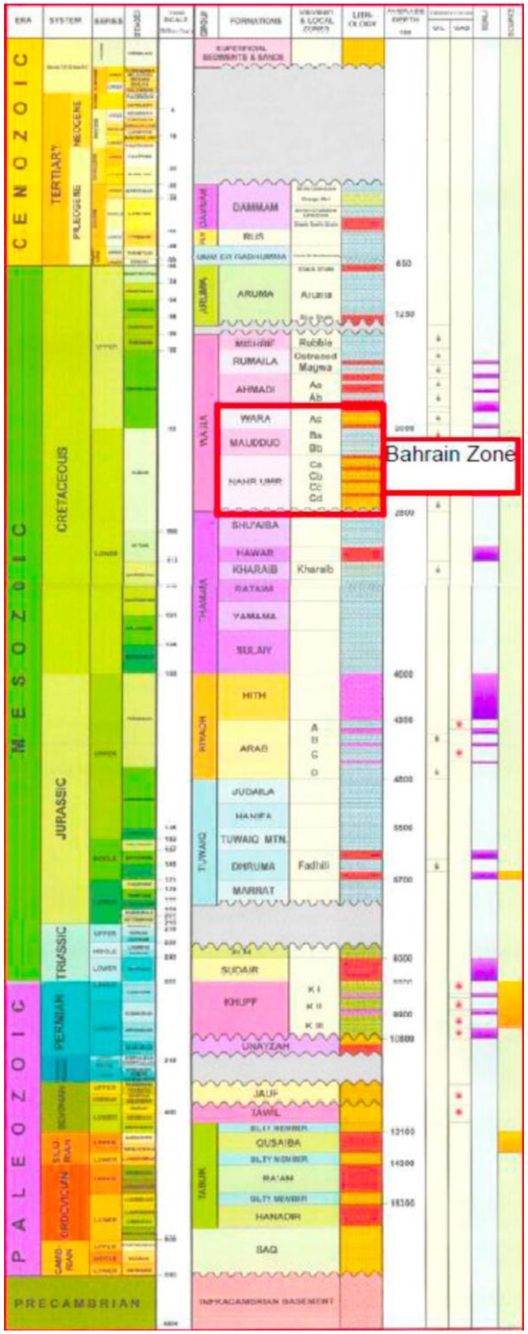


Figure 2. Stratigraphic column for Awali Field, Bahrain.

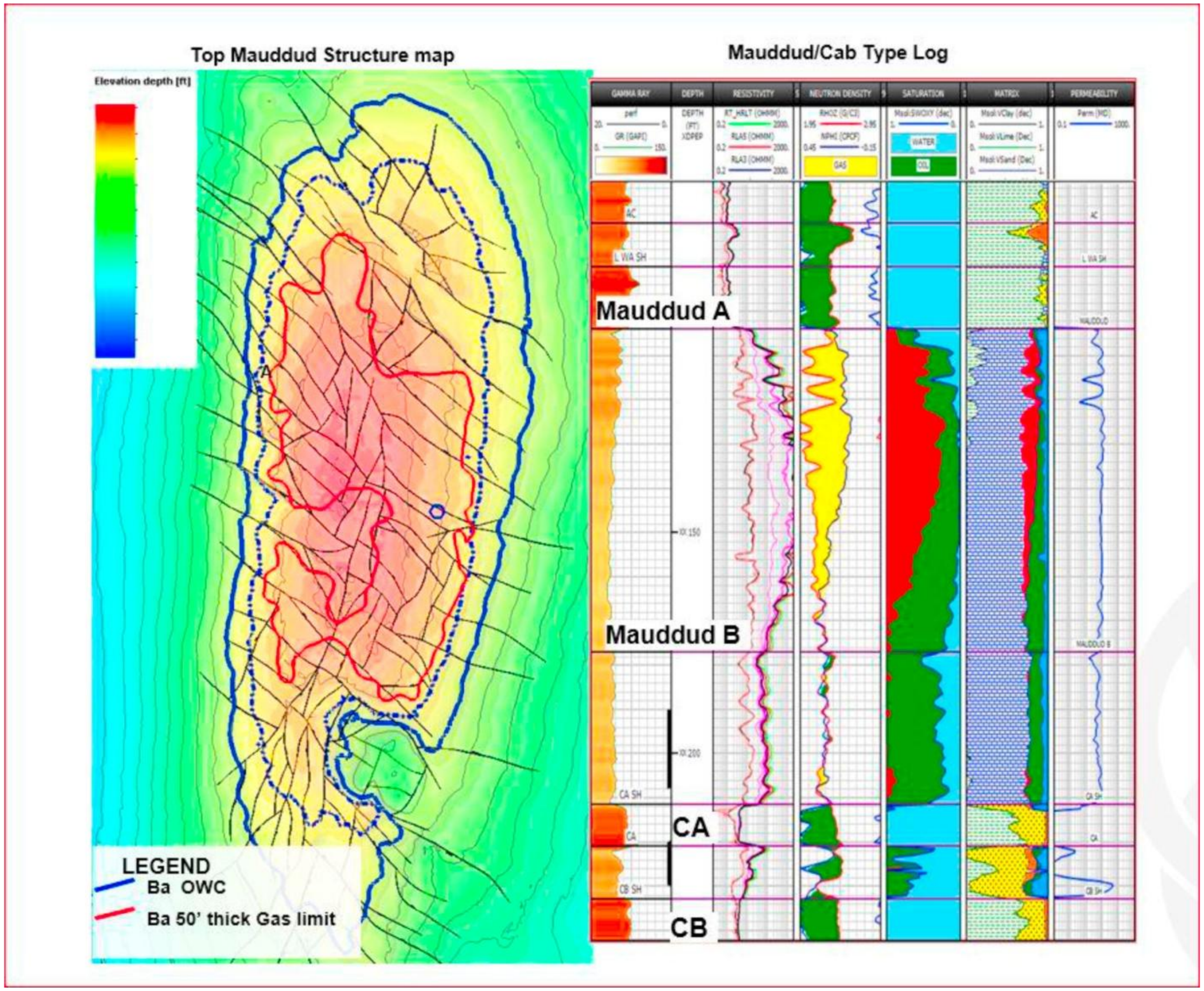


Figure 3.Mauddud depth structure map and type log.

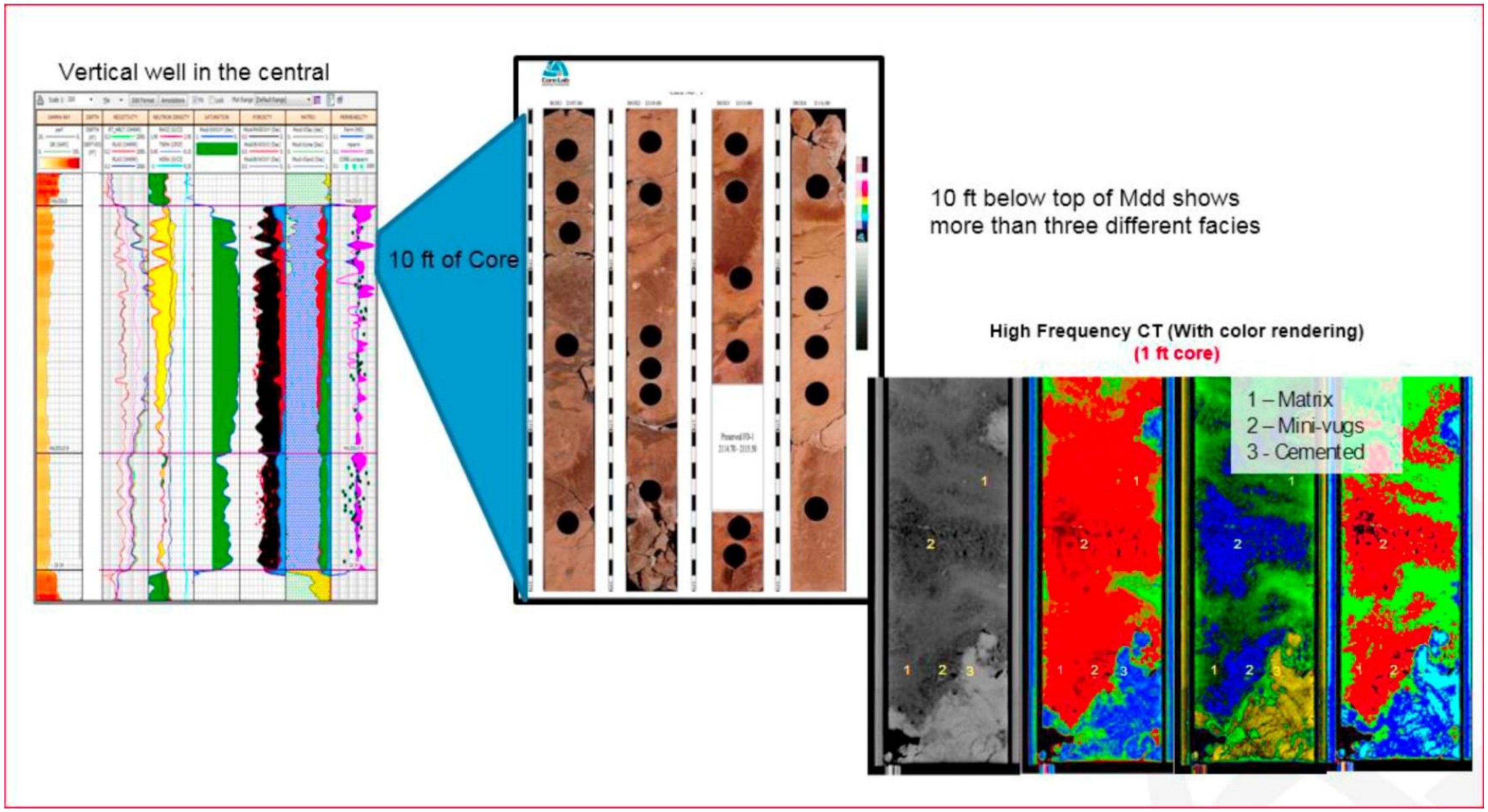
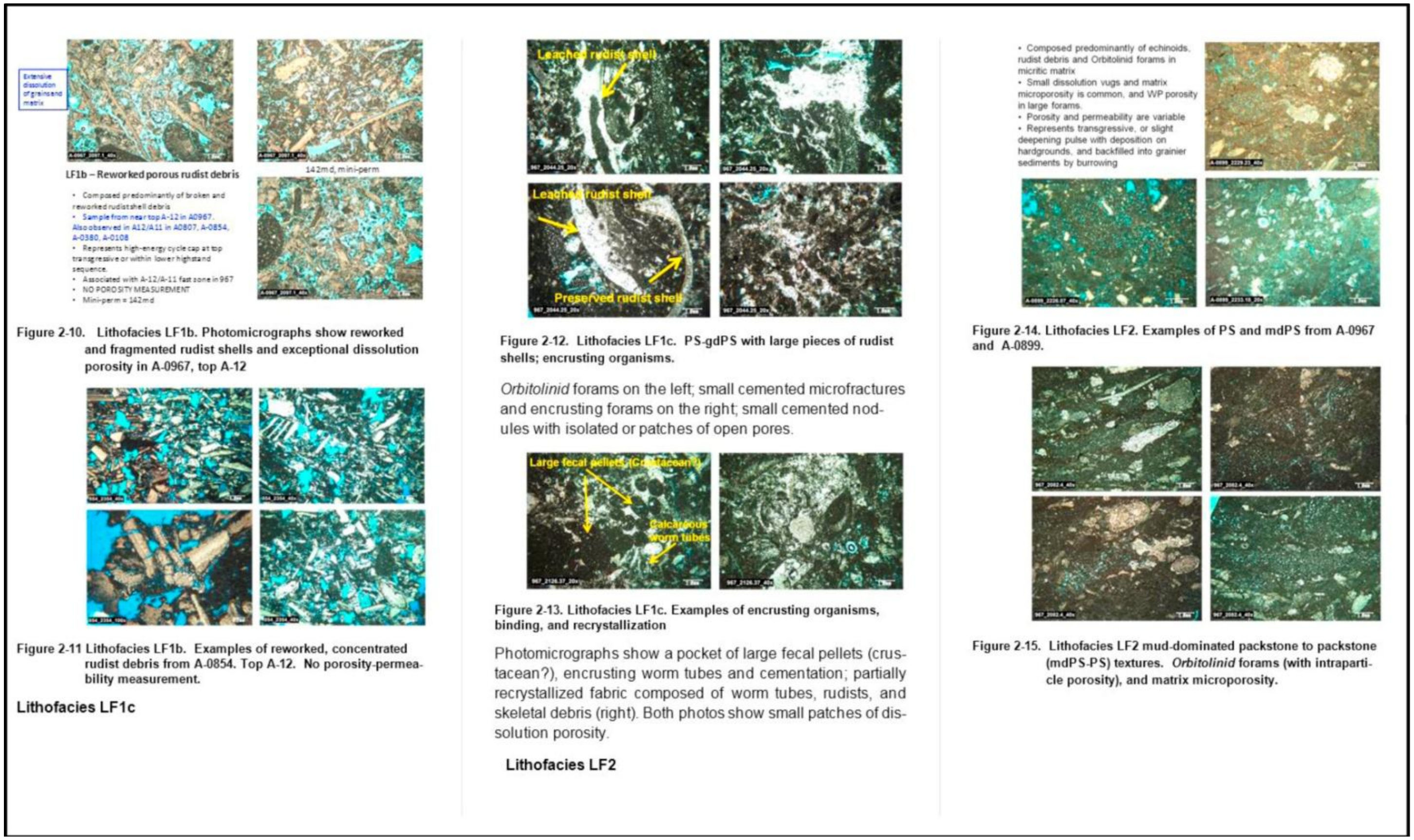


Figure 4. Mauddud core image and high frequency CT log showing the main lithofacies.



LF1b – Reworked porous rudist debris

- Composed predominantly of broken and reworked rudist shell debris
- Sample from near top A-12 in A0967. Also observed in A12/A11 in A0807, A-0854, A-0380, A-0108
- Represents high-energy cycle cap at top transgressive or within lower highstand sequence.
- Associated with A-12/A-11 fast zone in 967
- NO POROSITY MEASUREMENT
- Mini-perm = 142md

Figure 2-10. Lithofacies LF1b. Photomicrographs show reworked and fragmented rudist shells and exceptional dissolution porosity in A-0967, top A-12

Figure 2-11 Lithofacies LF1b. Examples of reworked, concentrated rudist debris from A-0854. Top A-12. No porosity-permeability measurement.

Lithofacies LF1c

Figure 2-12. Lithofacies LF1c. PS-gdPS with large pieces of rudist shells; encrusting organisms.

Orbitolinid forams on the left; small cemented microfractures and encrusting forams on the right; small cemented nodules with isolated or patches of open pores.

Figure 2-13. Lithofacies LF1c. Examples of encrusting organisms, binding, and recrystallization

Photomicrographs show a pocket of large fecal pellets (crustacean?), encrusting worm tubes and cementation; partially recrystallized fabric composed of worm tubes, rudists, and skeletal debris (right). Both photos show small patches of dissolution porosity.

Lithofacies LF2

- Composed predominantly of echinoids, rudist debris and Orbitolinid forams in micritic matrix
- Small dissolution vugs and matrix microporosity is common, and WP porosity in large forams.
- Porosity and permeability are variable
- Represents transgressive, or slight deepening pulse with deposition on hardgrounds, and backfilled into grainier sediments by burrowing

Figure 2-14. Lithofacies LF2. Examples of PS and mdPS from A-0967 and A-0899.

Figure 2-15. Lithofacies LF2 mud-dominated packstone to packstone (mdPS-PS) textures. *Orbitolinid* forams (with intraparticle porosity), and matrix microporosity.

Figure 5. Mauddud core thin sections showing the main lithofacies.

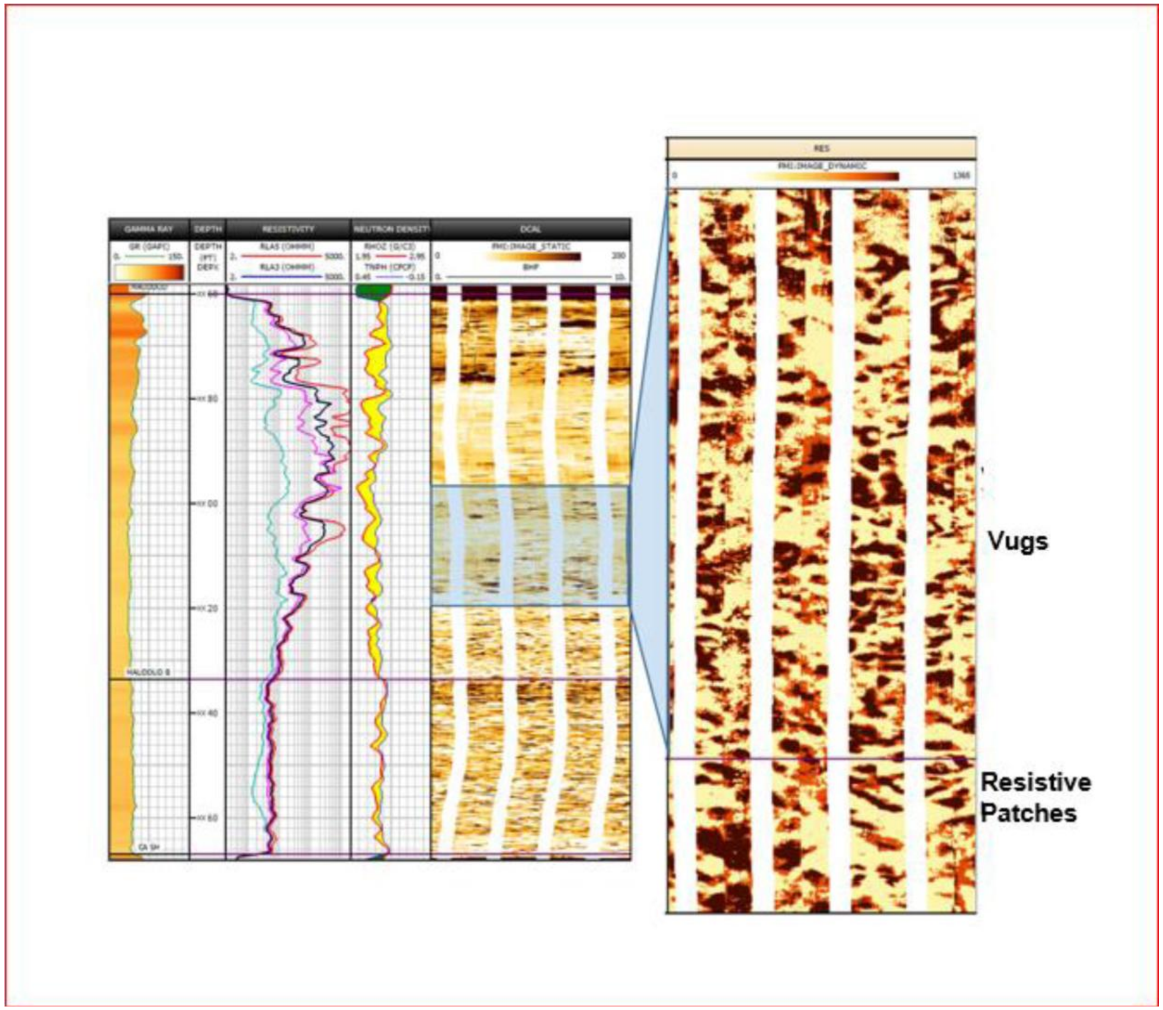


Figure 6. Mauddud FMI image data showing vugs.

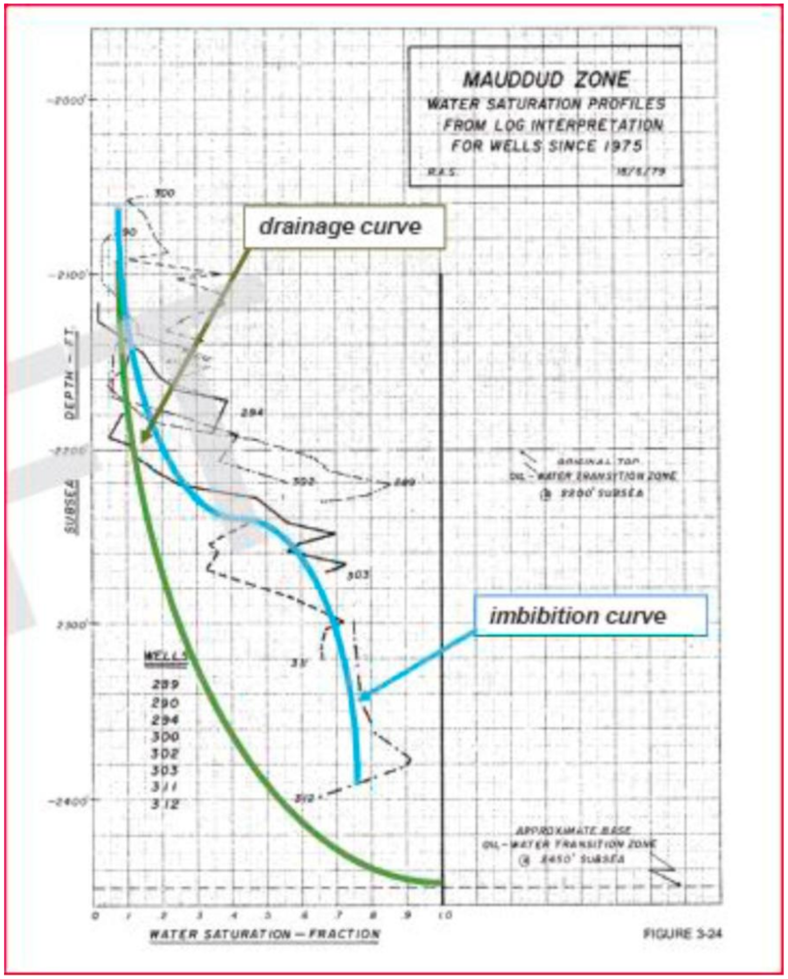


Figure 7. Saturation profiles in the Mauddud reinterpreted as a drainage capillary pressure curve above the oil-water contact, superimposed by a later imbibition curve below, extending down to FWL.

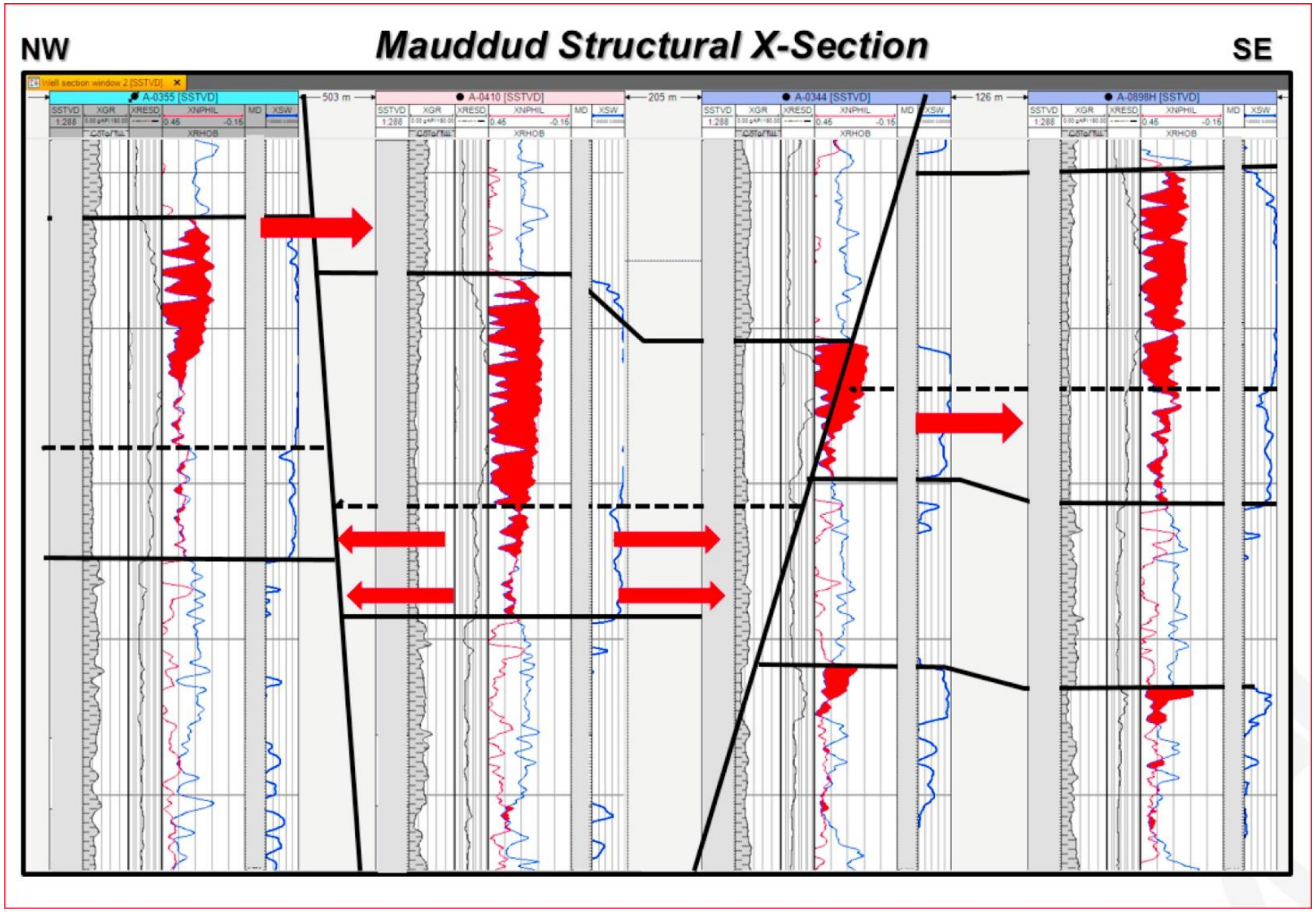


Figure 8. Mauddud gas migration along faults.

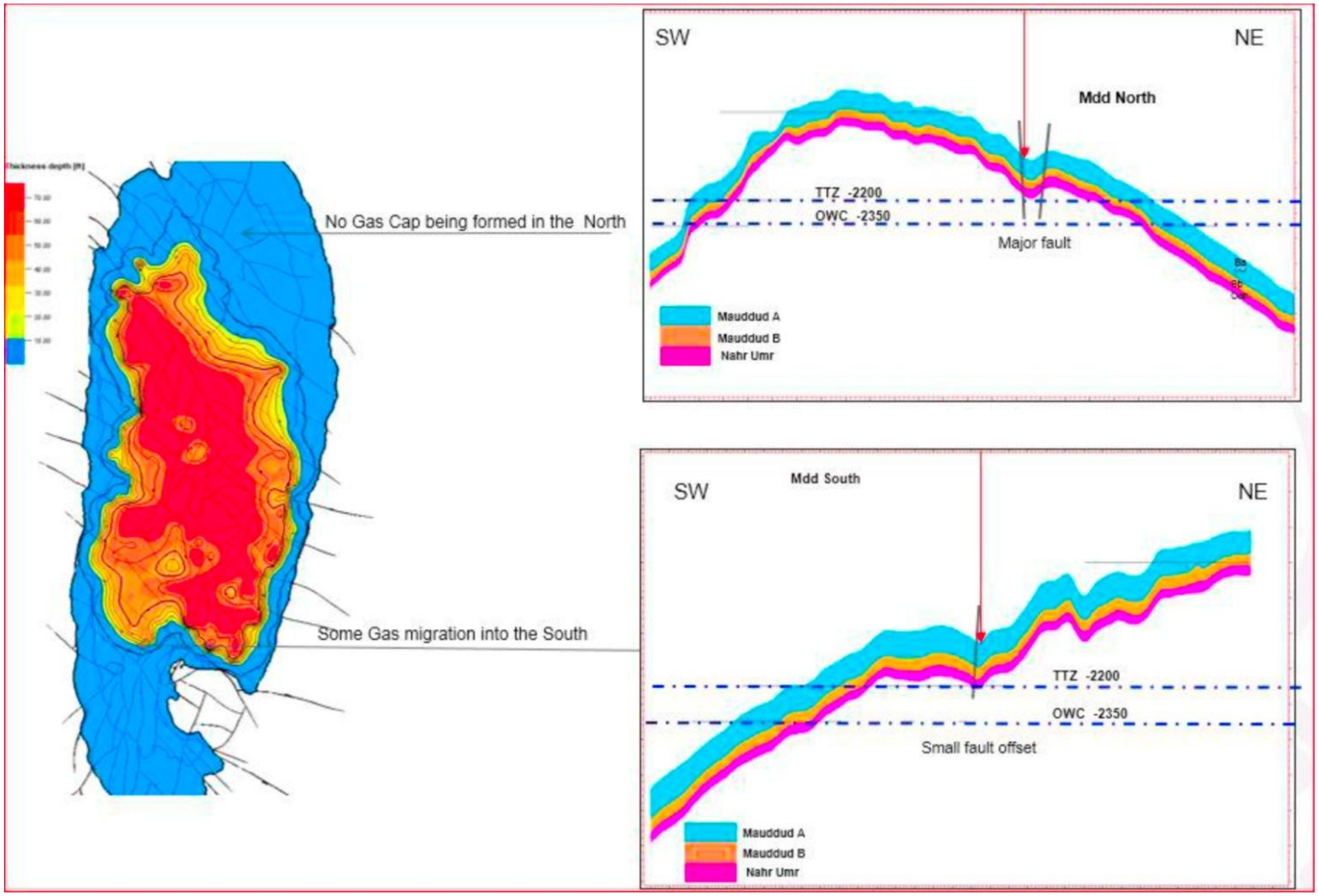


Figure 9. Mauddud gas cap thickness map and the limited gas cap in North and South areas.

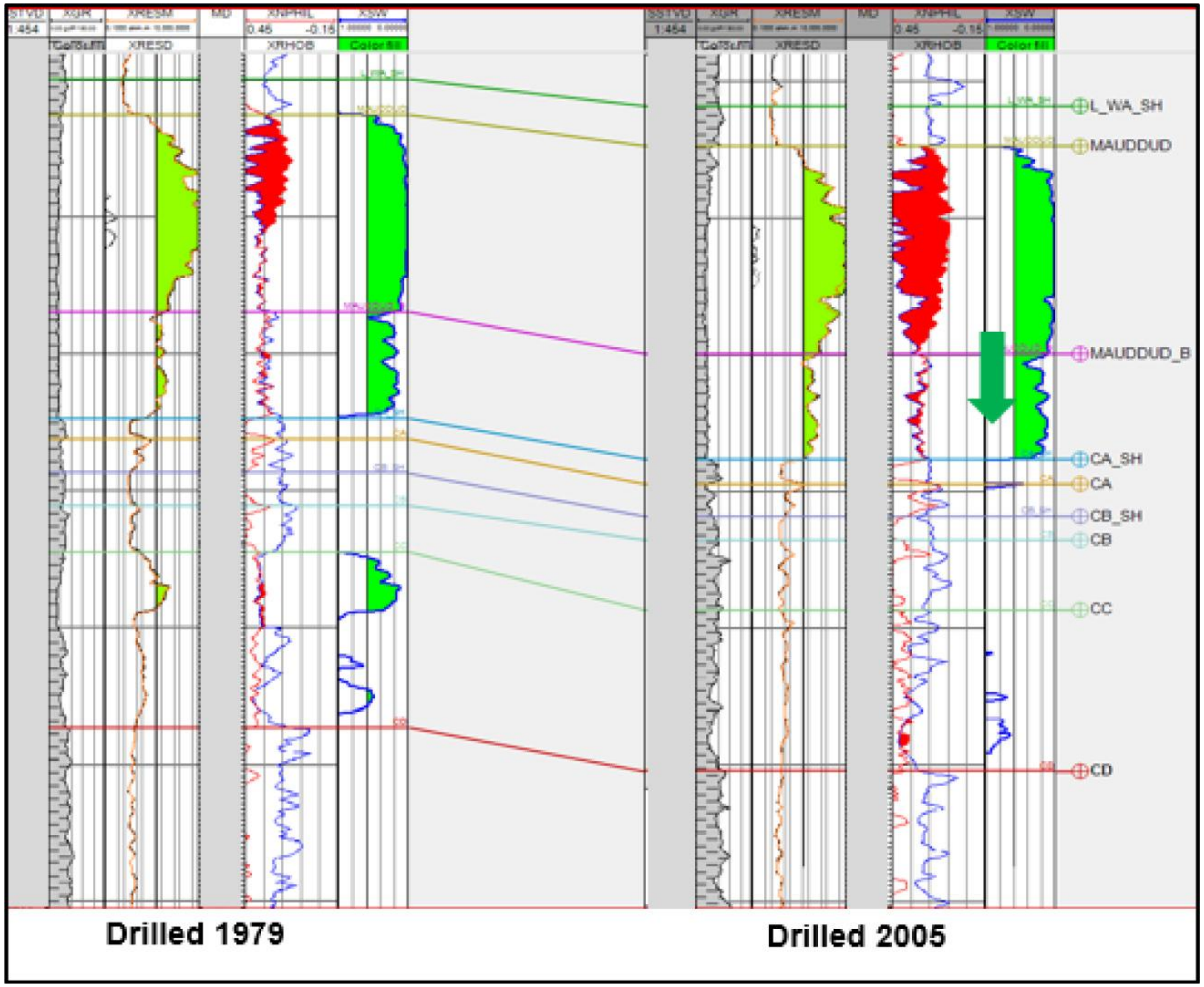


Figure 10.Vertical oil migration down to Bb zone (Crestal area).

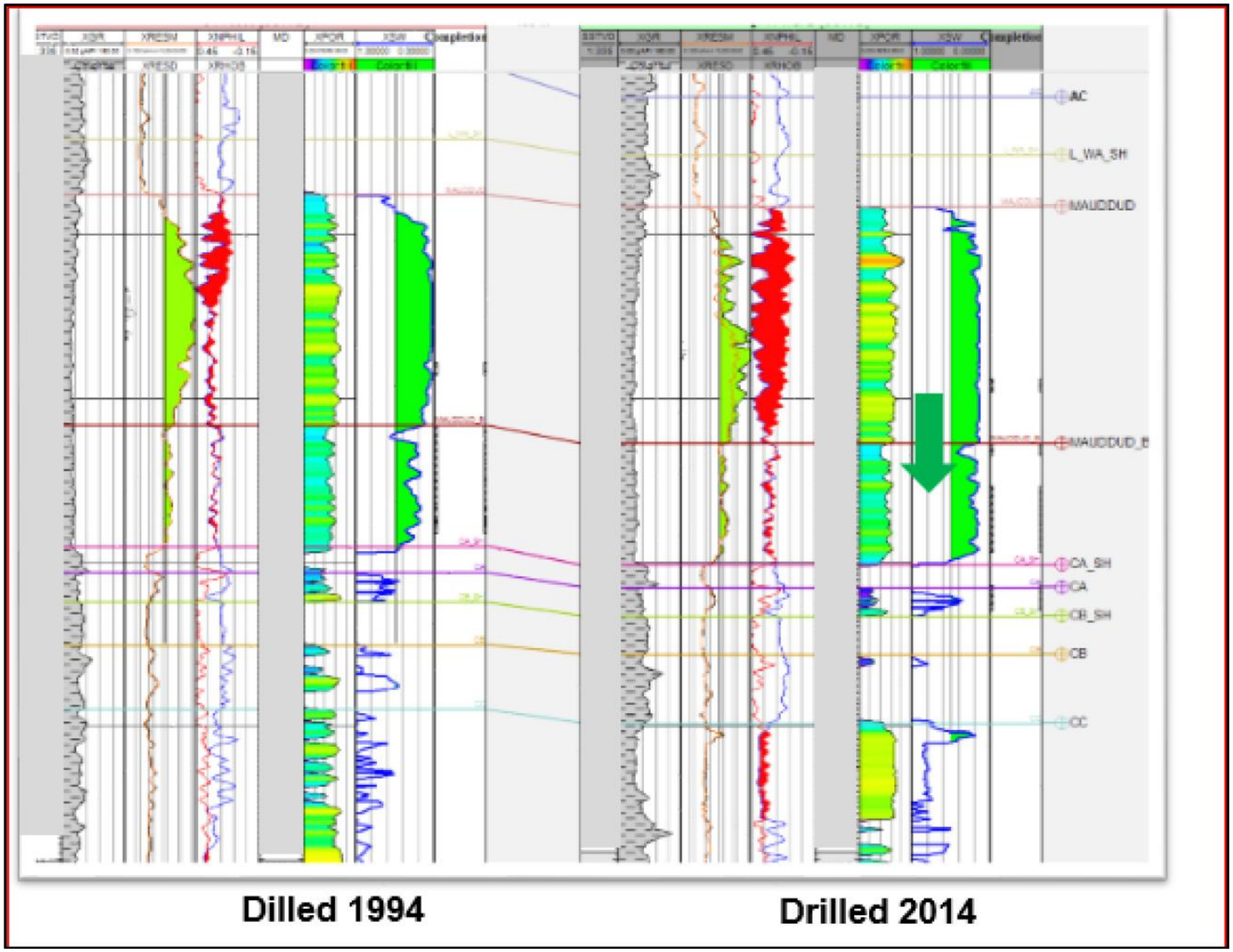
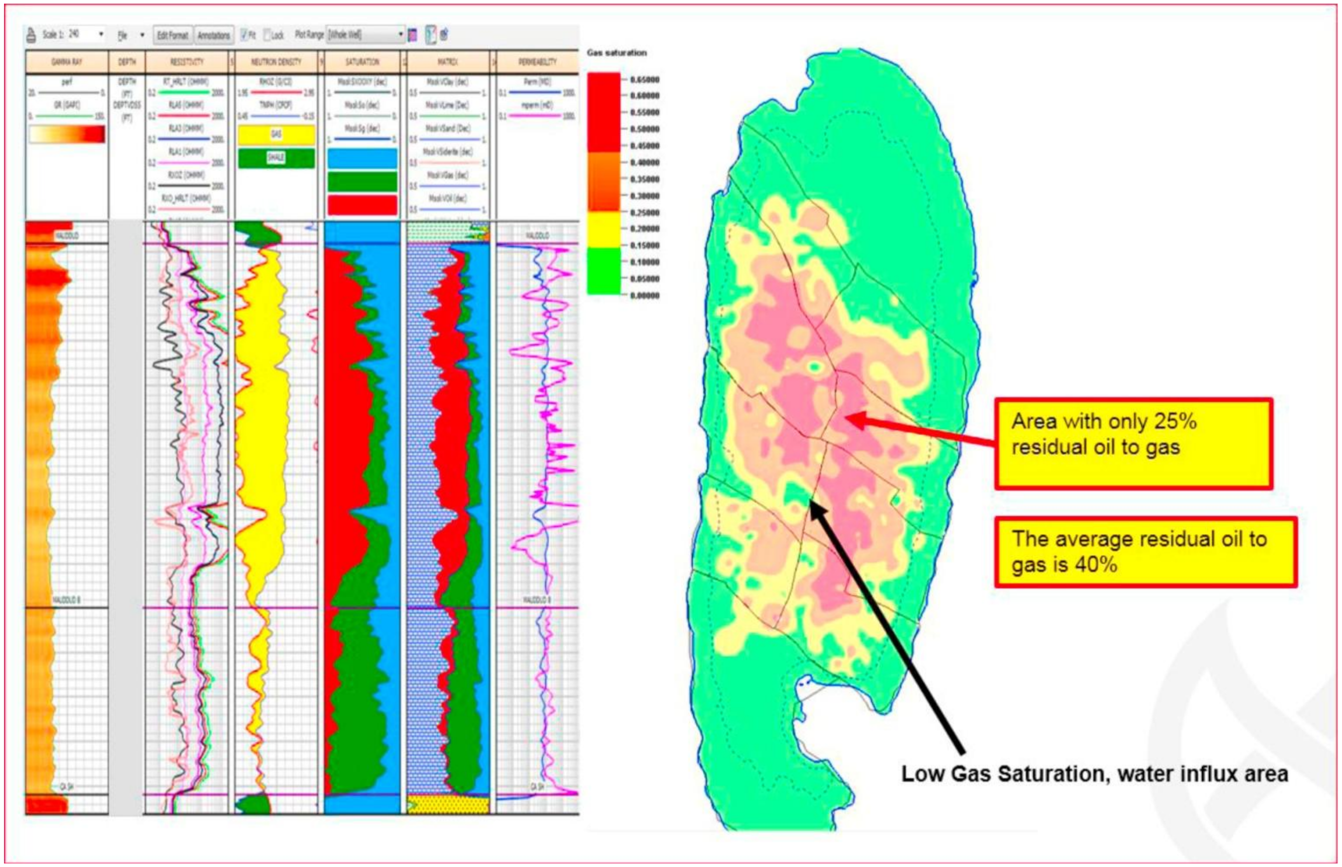


Figure 11. Vertical oil migration down to Bb zone (Flank area).



Area with only 25% residual oil to gas

The average residual oil to gas is 40%

Low Gas Saturation, water influx area

Figure 12. Gas cap area gas saturation and residual oil to gas.

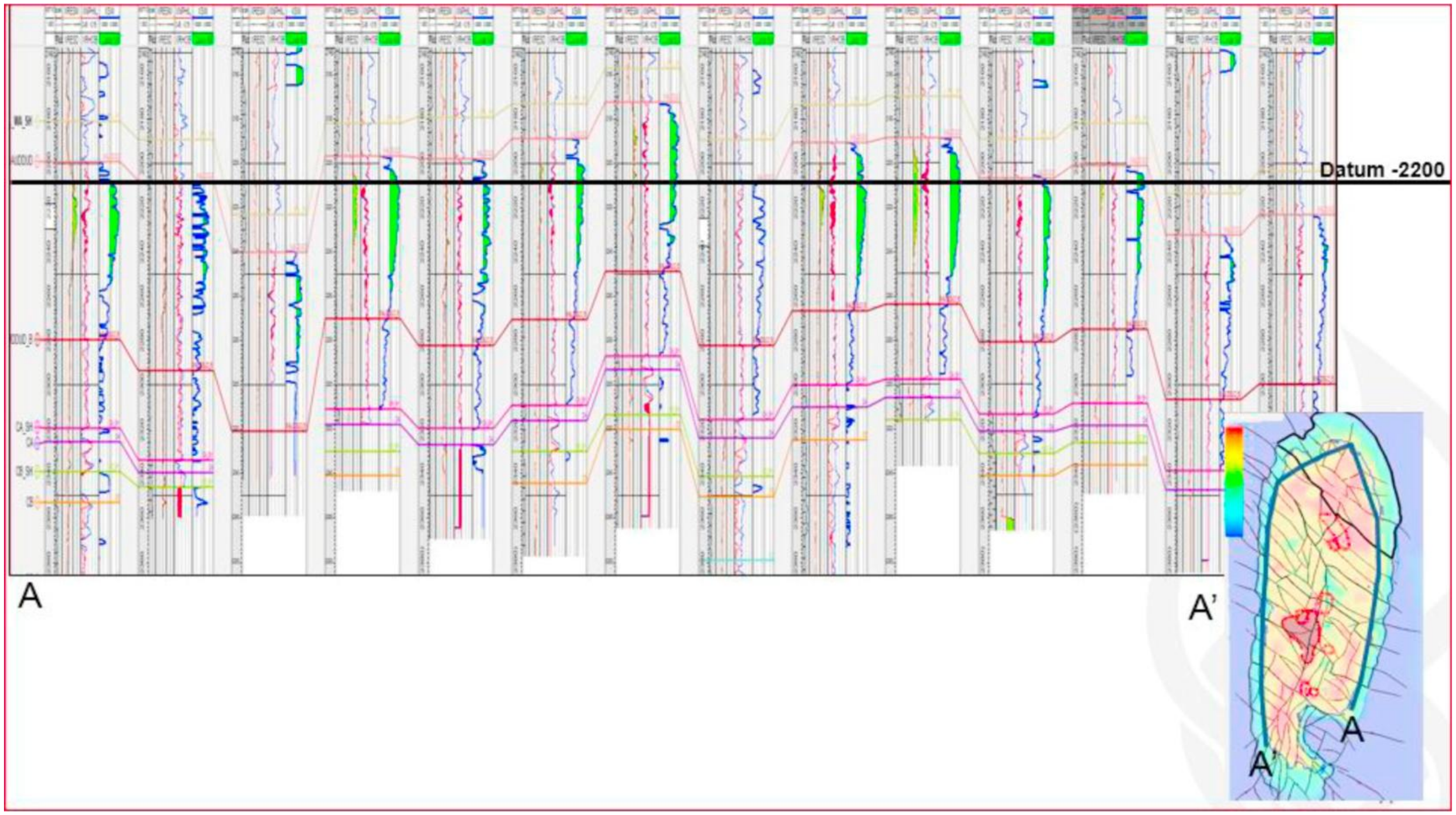


Figure 13. Gas and oil below the top transition zone.

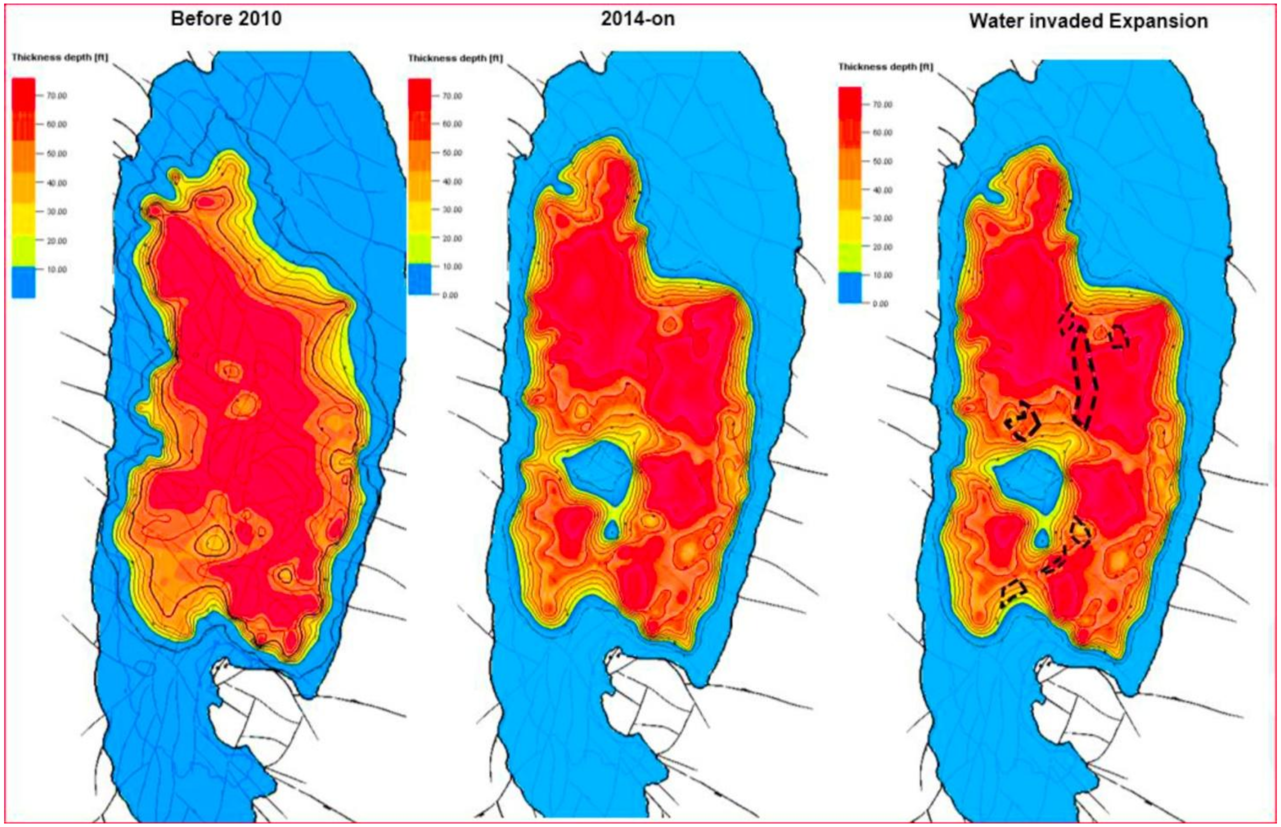


Figure 15. Gas cap development with time.

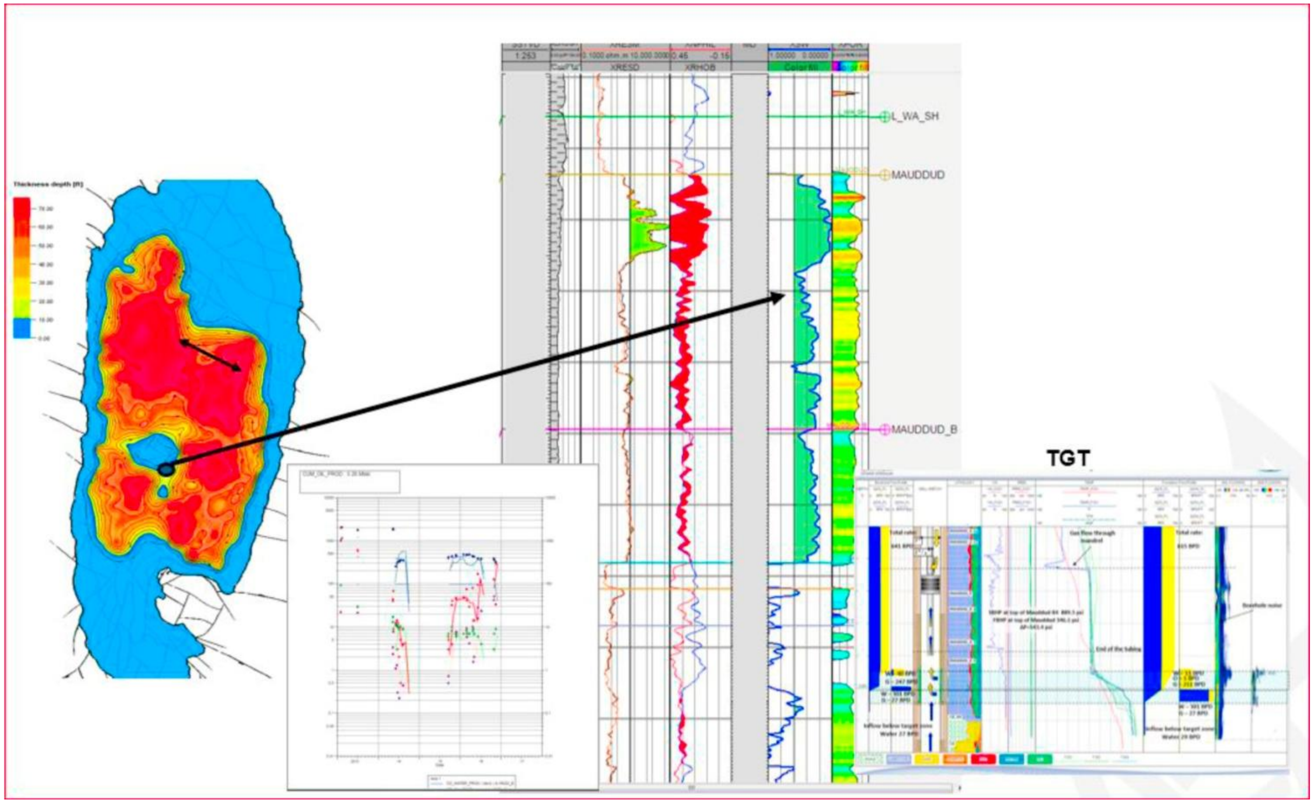
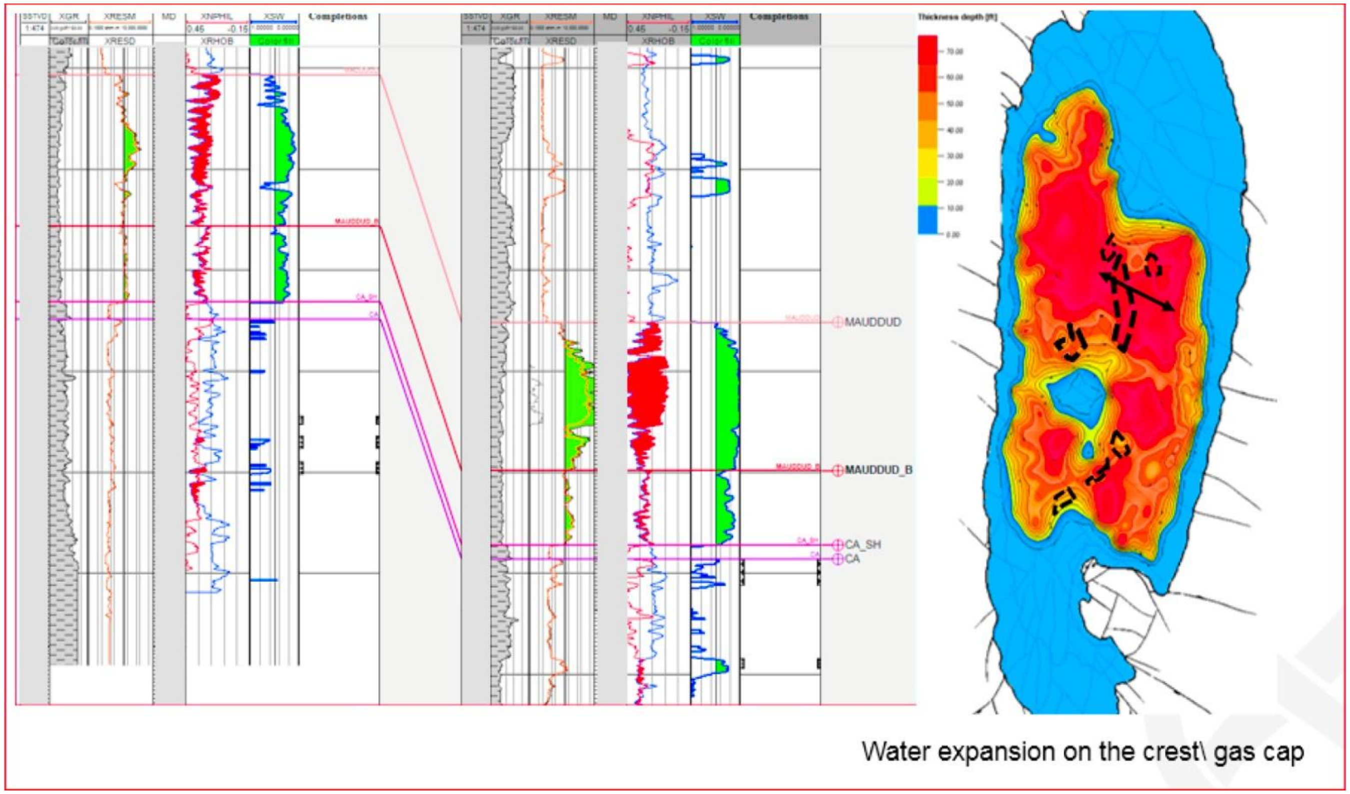


Figure 16. Water encroachment in the gas cap.



Water expansion on the crest\ gas cap

Figure 17. Water expansion on the gas cap (crestal area).

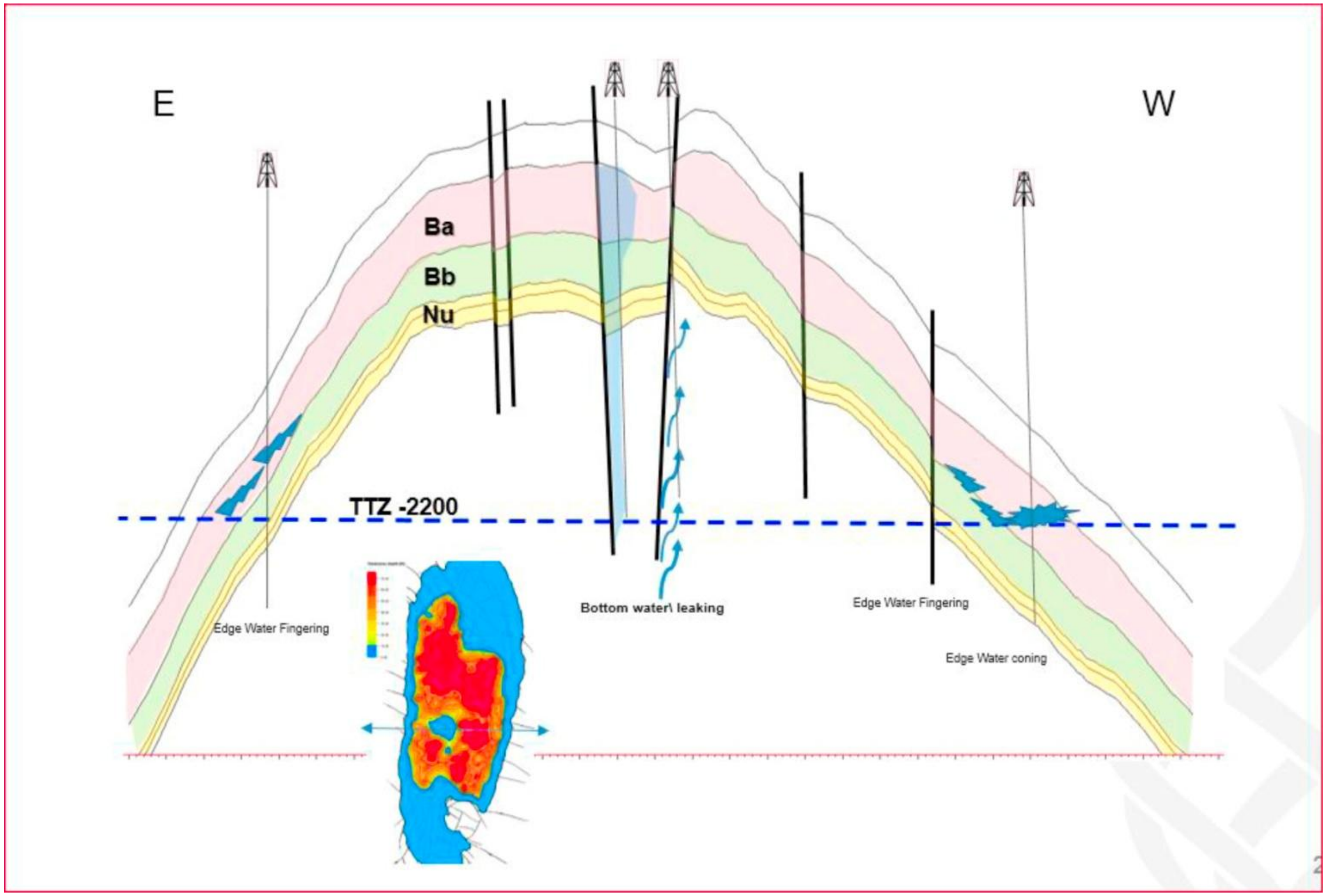


Figure 18. Maddud water encroachment model.