The Oil Drum: Europe
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

GHAWAR: an estimate of remaining oil reserves and production decline (Part 1 - background and methodology)

Posted by Euan Mearns on April 25, 2007 - 7:50pm in The Oil Drum: Europe
Topic: Supply/Production
Tags: aramco, ghawar, matthew simmons, production decline, reserves, saudi arabia [list all tags]

A two dimensional (2D) volumetric reservoir model has been developed for the Ghawar oil field in Saudi Arabia which is the world's largest field producing over 5 million barrels of oil per day. This represents 6% of global oil supplies. Understanding the current status of this super giant is central to the peak oil debate and to understanding the security of future global energy supplies.

This article was too large for a single post and has been split in two. Part 2 - "The Results" will follow very shortly.

Stuart Staniford has been working independently on the same problem and will post his results next week.

Introduction

Stuart Staniford (SS) has led a very lively debate about Saudi Arabian oil supplies on the TOD in recent weeks. Stuart (who now has 6 posts on the subject) has adopted a position describing a current crisis in Saudi oil supplies. I have adopted a counter position of "business as usual" in the Saudi oil industry. To date I only have two posts on the subject and this article in part is intended to lay out my views in more detail. A list of all recent Saudi posts on TOD is given at the end of this article (at the end of Parts 1 and 2).

Saudi Arabia, together with most other Middle East (ME) OPEC countries are secretive about their oil resources and this tends to obscure the actual position on their reserves and their productive capacity. The main issue with ME OPEC reserves estimates is that they were substantially raised in the 1980s, and since then reserves have not been declined for annual production (Figure 1). Neither of these practices should be acceptable to analysts based in the OECD.

Publication of Twilight in the Desert, authored by merchant banker Matthew Simmons caused quite a stir in Saudi Aramco, the state owned Saudi oil company. Simmons described a Saudi oil industry teetering on the brink of decline and raised concerns about the impact of falling Saudi oil production upon the Global economy. This seems to have prompted Aramco to release more data, so much in fact that it is now possible to make this independent assessment of the oil reserves remaining in Ghawar.

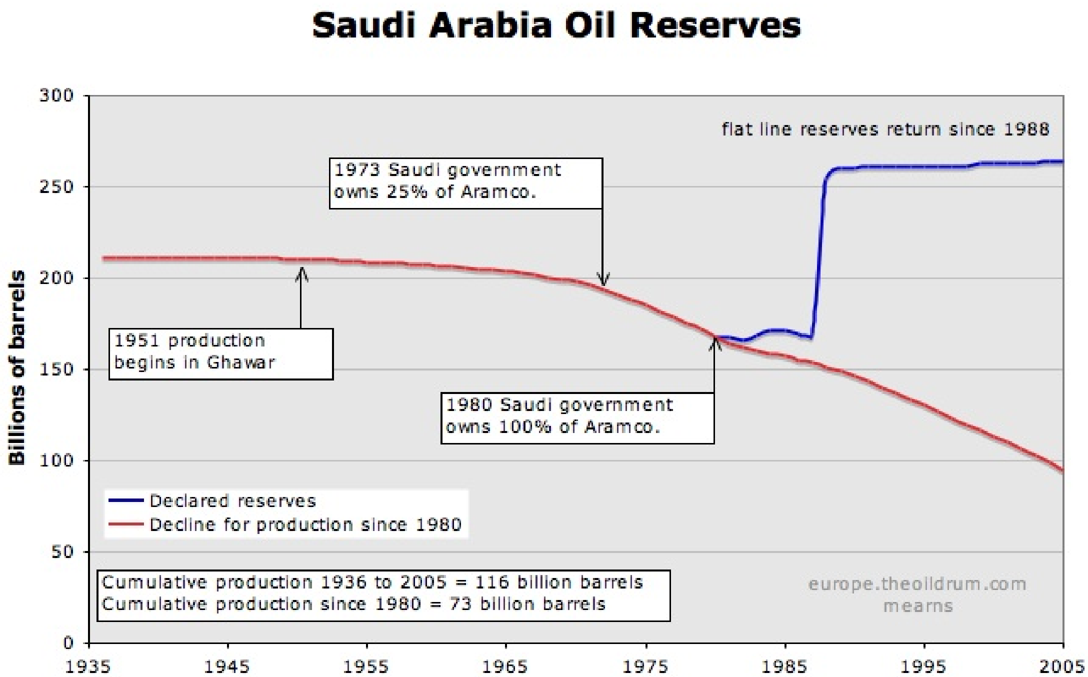

Figure 1. *Saudi Arabian oil reserves since 1980 (BP statistical review) show a sharp rise in 1988 and since then reserves have not been properly adjusted for production, discoveries or revisions (the flat blue line). Since 1980, the red line tracks reserves decline for production (**BP statistical review**) pointing to a current figure of around 95 billion barrels (2005, not adjusted for revisions and discoveries). Prior to 1980, Saudi Aramco was still part owned by American companies and the 1980 reserves figure, therefore, is probably the most objective figure available. Between 1973 and 1980, there was a rolling program of nationalisation of oil resources in Saudi Arabia.*

The red line has been extrapolated back from 1980 to 1936 using SPE centennial data (1936 to 1965) and BP data from 1965 to 1980. This points to an initial Saudi reserve figure of 211 billion barrels, not adjusted for revisions and discoveries made since 1980.

Ghawar

Ghawar, located close to the Arabian Gulf coast of Saudi Arabia is the largest oil field in the world (Figure 2). At 164 miles long and about 16 miles wide, it is difficult even for experienced geologists to comprehend the size of this colossal structure (Figure 3).

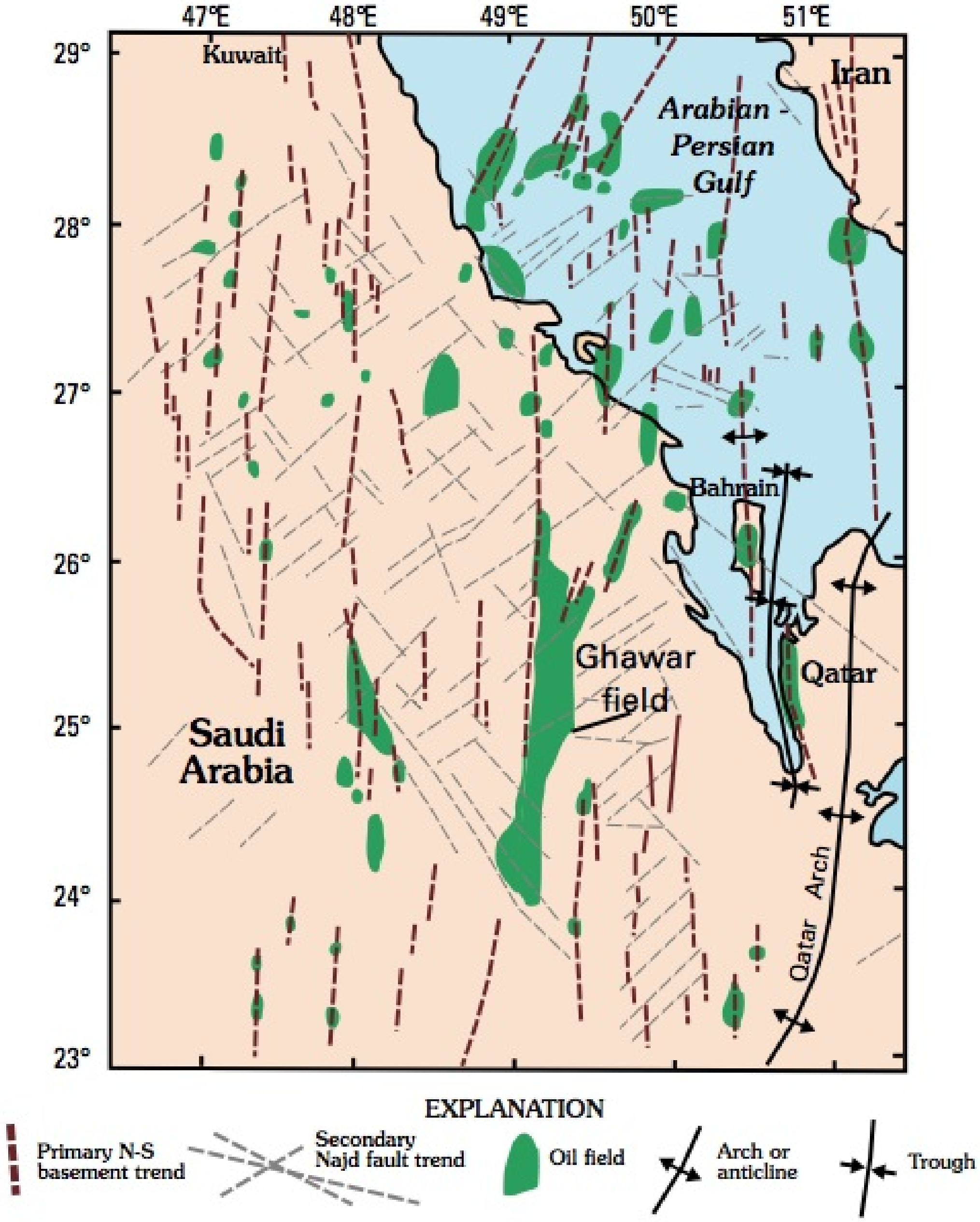

Figure 39. General structural trends of Greater Ghawar Uplift and surrounding area, showing primary north-south direction of basement and secondary trend due to Najd Fault system. Note how many of the major oil fields align with structures. Modified from Al Khatieb and Norman (1982) and Edgell (1992).

Figure 2. *The location of Ghawar in eastern Saudi Arabia showing main geological faults. This map contains latitude markers that point to the field being 162 miles long (SS). Map Source* ***[Total Petroleum Systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and Adjoining Provinces of Central Saudi Arabia and Northern Arabian-Persian Gulf.]*** *(large pdf).*

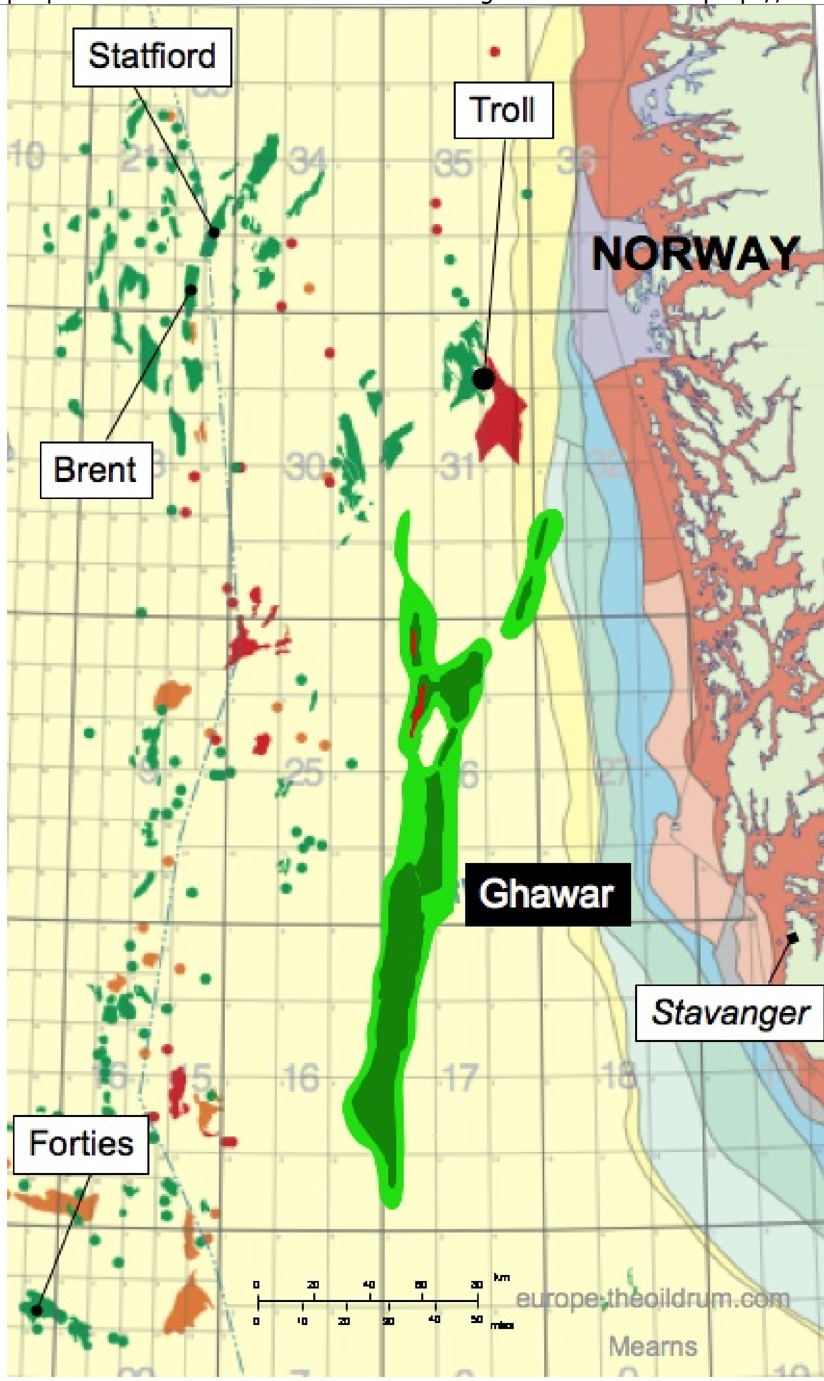

Figure 3. *Map comparing Ghawar to major North Sea oil and gas fields. Most North Sea fields have higher porosity than Ghawar, and many have stacked reservoirs (e.g. Brent Group lying above Statfjord Formation). Therefore, areal extent is not the only guide to reserves. But the scale of Ghawar is still immense. Note how the undrained crests of N and S Ain Dar are still comparable in area to giant North Sea fields. North Sea base map grabbed from* ***PESGB*** *Millennium atlas.*

The main oil bearing reservoir in Ghawar is the upper Jurassic Arab D limestone. This is of the order 250 to 300 ft thick and the depositional facies (geological type) of limestone varies both vertically and laterally across the structure (Fig 4). Superimposed upon this depositional variance is a network of fractures and combined these features influence the productivity and production problems from one area to the next.

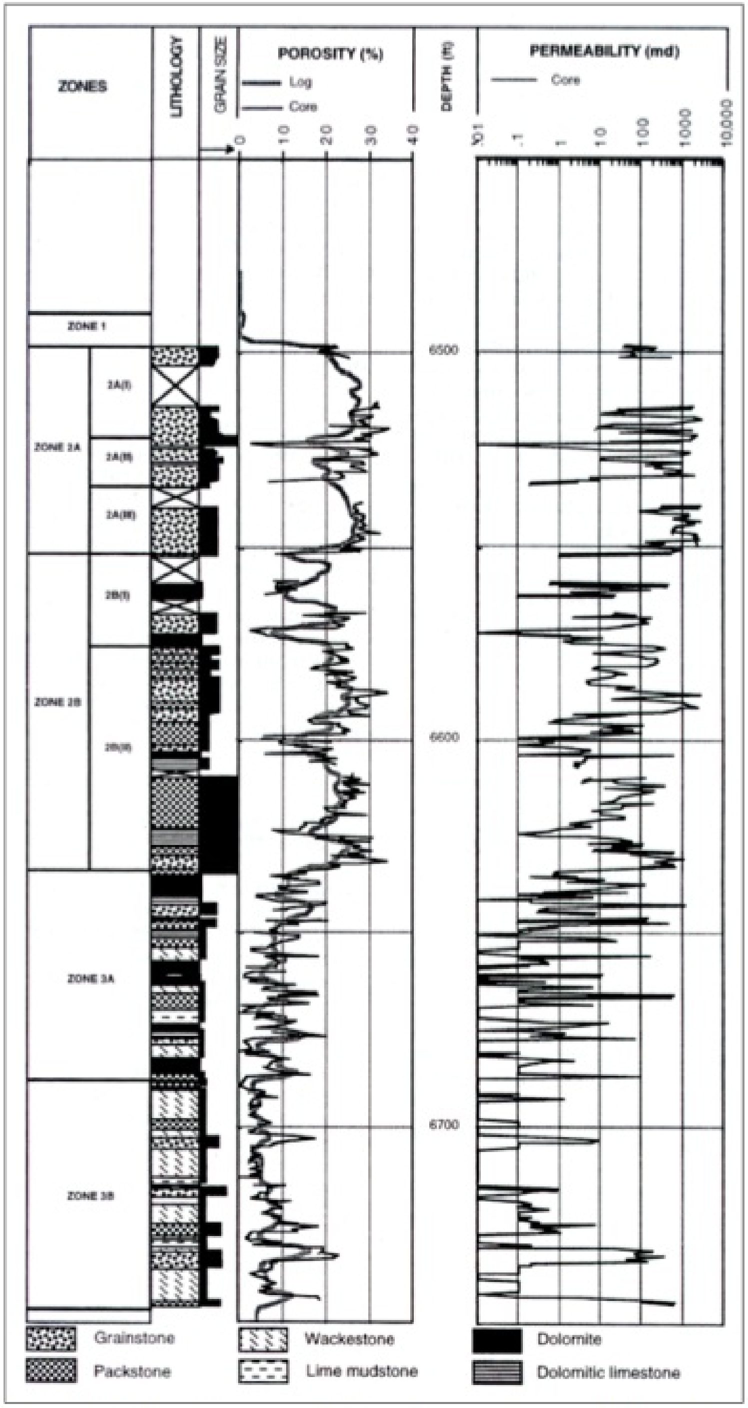

Fig. 5.1: Typical Arab-D permeability and porosity vertical distribution[45]

Figure 4. *Stratigraphic section for the Arab D. The reservoir comprises those beds with significant porosity and permeability. Reservoir beds are separated from each other by low porosity / permeability beds that are non-reservoir (Saner and Sahin (1999) Lithological and Zonal Porosity-Permeability Distributions in the Arab-D Reservoir, Uthmaniyah Field, Saudi Arabia. AAPG Bulletin v83, p230-243).*

Zone 1 is transitional between reservoir limestone and the anhydrite (calcium sulphate) top seal and has poor / non-reservoir qualities. The reservoir section in this well is around 250 feet thick and divided into zones 2A, 2B, 3A and 3B. Note how the upper section, Zone2, has significantly better reservoir quality than the underlying Zone 3.

Greg Croft provides average net reservoir thickness values. These net thicknesses are presumed to be for the producible reservoir and not for the gross Arab D section.

The gross thickness of the reservoir is small compared to the scale of the structure and in the various 3D renderings of Ghawar (e.g. Figure 5) the reservoir should be viewed as a thin skin coating the surface of the structure.

Ghawar may be sub-divided into 6 main production areas defined by structural closures (structural relief) and reservoir properties. From north to south (Figure 5):

North ‘Ain Dar
South ‘Ain Dar
Shedgum
Uthmaniyah
Hawiyah
Haradh

In general terms, reservoir quality and hence productivity decreases from north to south. The key parameter that varies is permeability – 700 mD average in the north, 100 mD average in the south. As we shall see, the highly productive north will shortly be fully depleted and most of the remaining reserves are in the south and this will inevitably mean lower production rates during the final chapter of Ghawar’s history.

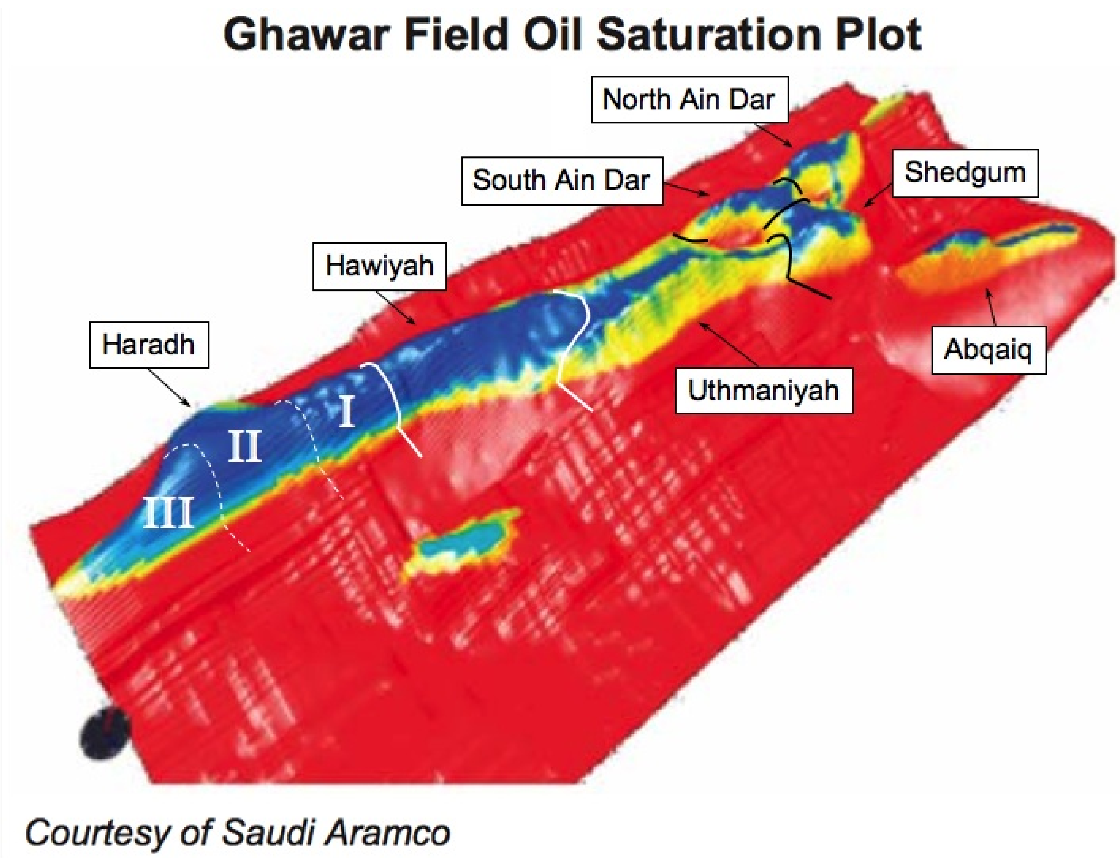

Figure 5. *The "Linux" map showing oil saturations in Ghawar (hat tip Bob Shaw). The blue areas are interpreted to represent dry oil at the top of Arab D Zone 2. The yellow areas are interpreted to be swept, water wet at the top of Arab D Zone 2. The effects of 50+ years production in northern Ghawar are there for everyone to see* ***(Linux Clusters driving step changes in interpretation simulation. (pdf)****.*

Transferring the data from this 3D image onto the 2D Croft map is subject to considerable uncertainty. On the large scale, the Linux map illustrates gravitational equilibrium, i.e. the undrained areas lie in the structure highs. However, on the smaller scale there is evidence for gravitational dis-equilibrium with areas of water lying above areas of oil on the flanks of Shedgum and S Ain Dar. This may reflect local geology, faults, Super K zones and variations in reservoir quality etc.

In transferring the Linux data into 2D I have in many cases simply contoured unswept areas – presuming overall gravitational control. Note the presence of oil in the saddle between Shedgum and S Ain Dar.

The date of this image is uncertain. It was published in 2006 and refers to a simulation run in 2004. It is possible, however, that the data used pre-dates 2004 which may be significant with respect to any debate about the timing of production decline.

Ghawar has been developed using a large number of oil production and water injection wells (Figure 6). The principal reason for injecting water is to maintain reservoir pressure above bubble point. Formation of secondary gas caps in N and S 'Ain Dar are most likely due to re-injection of produced gas.

The principal production problem in Ghawar is premature water break through whereby seawater injected down the flanks is prematurely conducted to production wells up the flanks via fracture networks. This creates a variety of problems discussed later in this article.

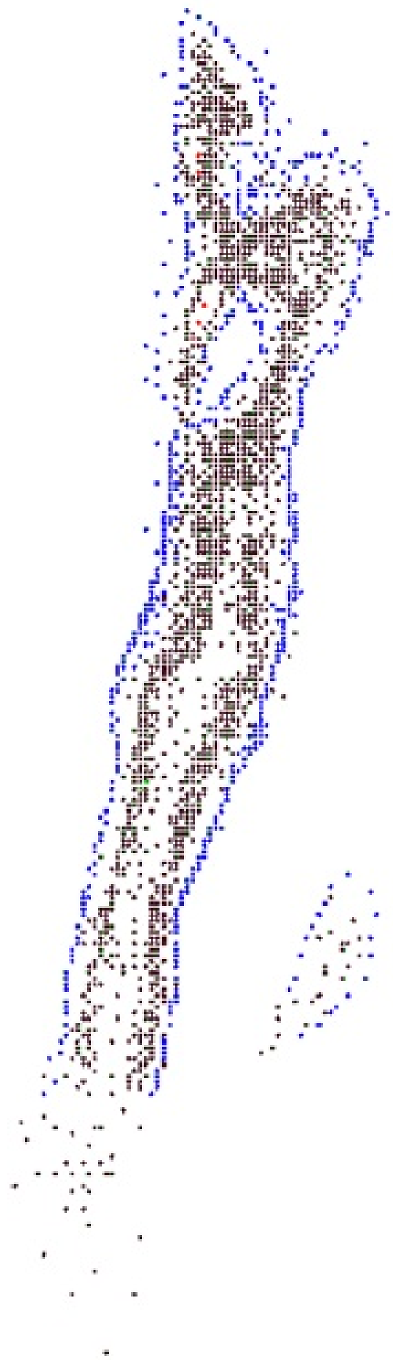

Figure 6. *Map showing the distribution of water injection wells (blue) production wells (black) and gas injection wells (red). (Source is Voelker, J. PhD thesis 2004). The small number of wells in southern Haradh suggests this map pre-dates the Haradh II and III GOSP developments (Figure 5), which came on stream 2003 and 2006 respectively.*

Note that Hawiyah has been fully developed along the flanks, presumably using vertical wells and this ties in with OWC movement observed in Figure 5. It is also worth noting that that the tongue of oil in Uthmaniyah (Figure 5) lies in an area that lacks wells on this map. The crest of Shedgum and S Ain Dar and the ridge axis of Hawiyah and Haradh are essentially undrilled.

Data sources

The main data sources used in compiling the reserves estimates and production model are:

Greg Croft Inc web site

Linux super cluster 3D rendering of produced zones (pdf)

Water Management in North 'Ain Dar, Saudi Arabia, SPE 93439, March 2005.

Water Production Management Strategies in North Uthmaniyah Area, Saudi Arabia, SPE 98847, June 2006.

Optimizing Maximum Reservoir Contact Wells: Application to Saudi Arabian Reservoirs, SPE 10395, Nov 2005.

A large number of ancillary data sources have also been used.

Greg Croft provides a contoured map of the Ghawar structure that dates from 1959. This map provides a scaled area of the structure. Croft also provides average net reservoir thickness and petrophysical data for the reservoir in the various producing regions, described below, including average porosity and formation volume factor. All this information is used in compiling the reserves estimates and it is therefore assumed that the information is broadly reliable. Croft's map would appear to be based upon a map published by "Arabian American Oil Company Staff" in the Bulletin of The American Association of Petroleum Geologists; vol 43, no 2, 1959 (Figure 7). This map, is produced by company professionals, is published in a reputable journal, but is inevitably based on old and perhaps out dated data.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 43, NO. 2 (FEBRUARY, 1959), PP. 434-454, 8 FIGS.

GHAWAR OIL FIELD, SAUDI ARABIA[1]

ARABIAN AMERICAN OIL COMPANY STAFF[2]
New York, New York

442 *ARABIAN AMERICAN OIL COMPANY STAFF*

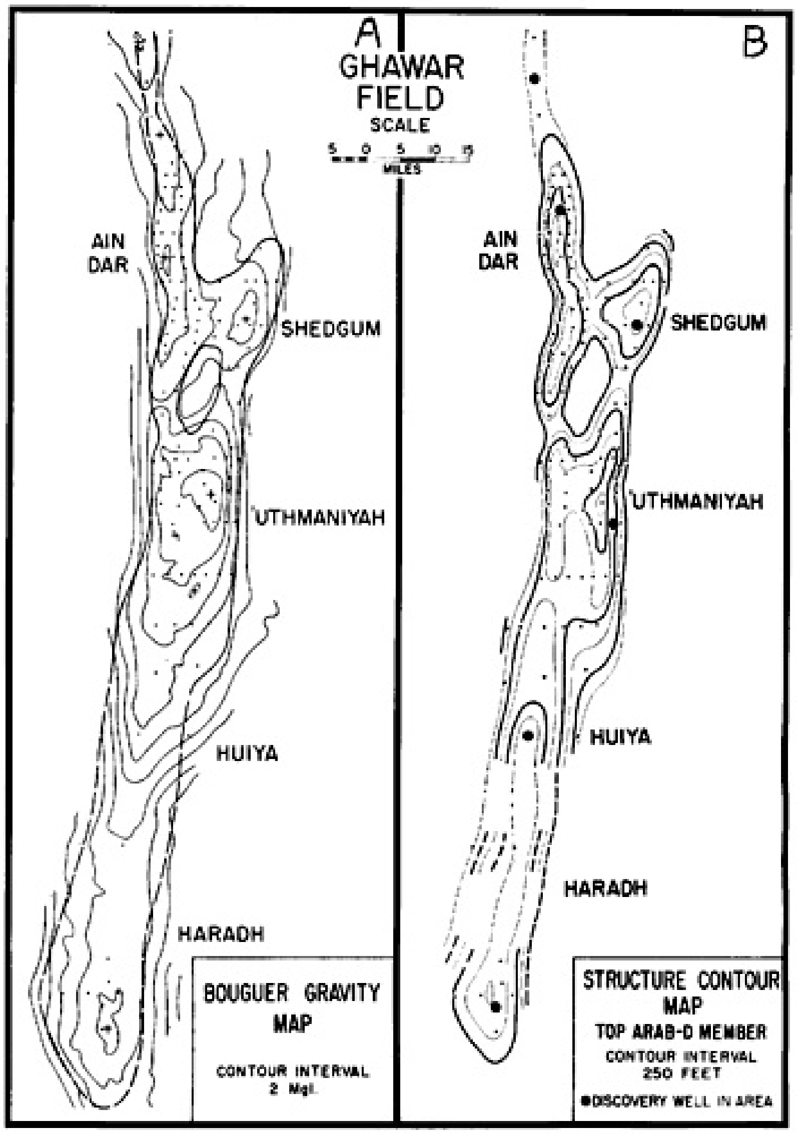

FIG. 3a.—Bouguer gravity map of Ghawar showing outlines of field determined by drilling.
FIG. 3b.—Structure contour map of top of Arab-*D* member.

Figure 7. *The Arabian-American map of Ghawar dating from 1959. The contour map looks like it is the base map used by Croft and has a better scale bar. Measuring four easily identifiable dimensions on this map gave the exact same lengths as Croft's map indicating that the scale bars on these two maps are compatible with each other – but both may be wrong. Note that Arabian American Oil Company was the predecessor to Saudi Aramco.*

The Linux 3D rendering of Ghawar (hat tip Bob Shaw) is believed to show areas of the reservoir that have been produced and are now water wet (coloured yellow in Figure 5) versus those that have not been produced (coloured blue). This 3D image is not an official Aramco data release and was published (by accident?) in an obscure source. Furthermore, what this image shows is subject to conjecture.

The Linux image looks highly plausible from geological and engineering perspectives and it is possible to cross link observations from this image to other more reliable sources. For example, the elongate tongue of oil in Uthmaniyah (Figure 5) can be correlated with unswept oil zones in oil saturation profiles published in SPE papers and other sources (Figure 8). Furthermore, zones of unswept oil correlate with zones that lack production wells (Figure 6), e.g. The crests of Shedgum and S ‘Ain Dar and the unswept tongue of Uthmaniyah.

My interpretation of the Linux super cluster image is that yellow areas are swept, and will have high water saturation. With respect to primary and secondary (water drive) oil production, these areas are now essentially dead, though they may continue to produce oil with very high water cut for decades. The blue areas I interpret to be essentially dry oil at top reservoir (accept Ain Dar). As we shall see in the story of the 10 ft oil column, top reservoir is the top of Zone 2 that is not the top of the Arab D (see below).

Gas caps in N and S ‘Ain Dar (Figure 11, hat tips to Stuart Staniford and Fractional_Flow) means that gas replaces dry oil in the crest of these structures and this is taken into account in the reserves estimates.

Should this interpretation of the Linux Super cluster visualisation be incorrect then it will render as meaningless all estimates produced in this report.

SPE papers provide information on oil and water saturations in the vicinity of the water flood front. This provides insight to recovery mechanism, controlling the flows of produced water and to recovery factor.

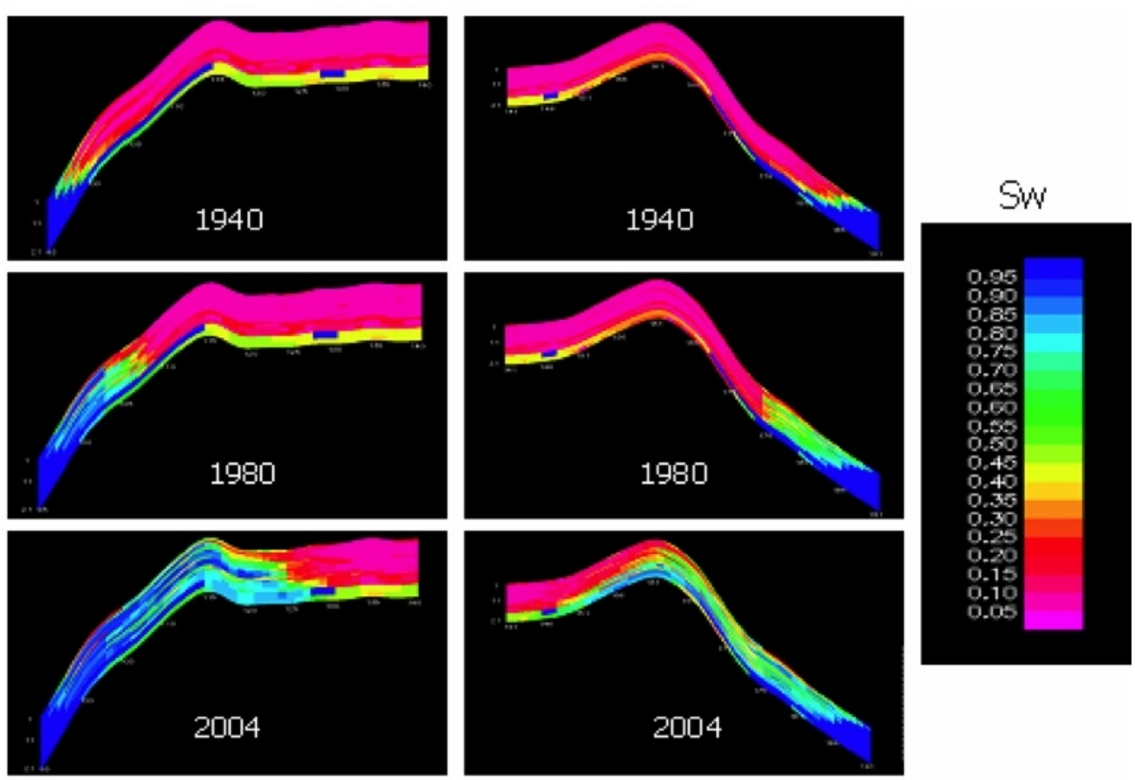

Figure 8. *Time-lapse series of oil saturation profiles, east and west Uthmaniyah. Image source:* ***Water in the gas tank by SS****, original source is:* ***Water Production Management Strategies in North Uthmaniyah Area, Saudi Arabia, SPE 98847, June 2006.****. Ghawar was discovered in 1948 and production began in 1951 so the provenance of the 1940 vintage data is dubious and is presumed to denote pre-production data. The 1980 profiles show a zone of low oil saturation along the base of the profile (yellow colour) which may reflect poor quality zone 3 reservoir.*

The 2004 profiles show the east and west flanks are swept and that water is climbing over the east ridge leaving a tongue of dry oil in the saddle axis that corresponds with the tongue of oil observed in the Linux visualisation (Figure 5).

The preponderance of dark blue colours along the west flank in 2004 suggests a very high recovery factor in this area that translates to high recovery factors being used for Uthmaniyah in the reserves presented below.

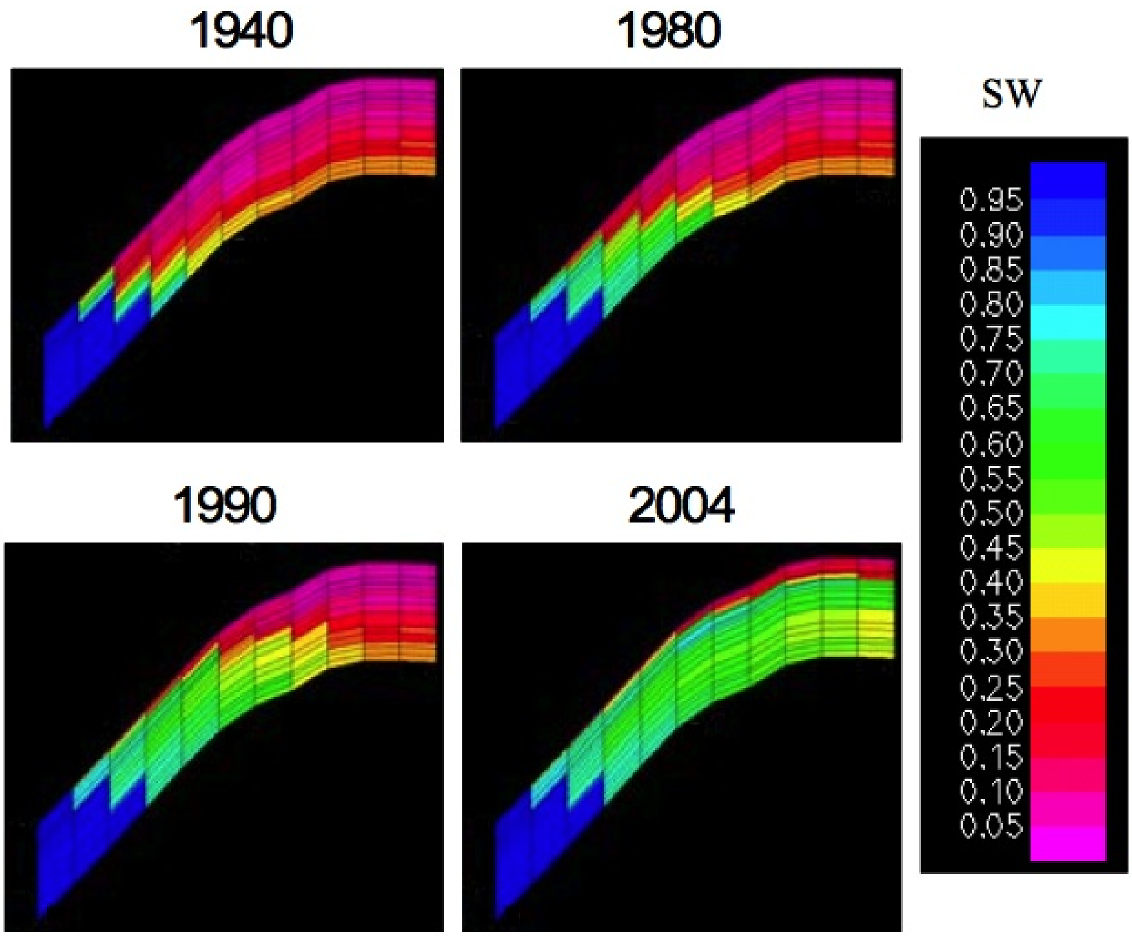

Figure 9. *Oil saturation profiles from the flank of N ‘Ain Dar. Image source:* ***Water in the gas tank by SS****, original source is:* ***Water Management in North 'Ain Dar, Saudi Arabia, SPE 93439, March 2005.****. These profiles are believed to lie just to the N of the small crest illustrated in Figure 5 of this SPE paper. They are therefore believed to mount the ridge well below the crest area of N Ain Dar.*

The 10 foot oil column

In the period March – April 2007, there was much debate on TOD about the significance of water saturation profiles for N ‘Ain Dar showing a single 10 ft layer of oil at the top of a predominantly water swept section (**Water Management in North 'Ain Dar, Saudi Arabia, SPE 93439, March 2005.**, Figure 9). Many argued that these sections showed only 10 ft of oil remaining at the crest of the S ‘Ain Dar structure. The position I adopted was that these profiles were from the flanks of the structure and said nothing about the height of the oil column at the crest (this conservative point of view did not receive much support).

Hat tip to F_F who dug up SPE paper 81567 (**Asphaltene Precipitation in High Gas-Oil Ratio Wells, SPE 81567, June 2003.**) showing gas caps at the crest of N and S ‘Ain Dar.

(Figure 11). Transferring this data and that contained in SPE 81567 onto Croft's contoured map suggests that the secondary gas caps are in excess of 100 ft thick. So much for the 10 ft oil layer and I hope this data lays this debate to rest once and for all.

Further to the above, SS has described via e.mail that the uppermost layer(s) of the Arab D are a transitionl depositional facies between the limestone reservoir (highly permeable) and the overlying anhydrite (calcium sulphate) seal that has virtual zero permeability. This transitional boundary layer (about 10 ft thick) has low permeability and porosity. The buoyancy pressure produced by a 1300 ft + oil column has been sufficient to force oil into this boundary layer, but extreme poor reservoir quality means that this layer is by passed by the water flood front (see Figures 10). So there is a default tendency for the uppermost 10 ft layer to remain oil saturated.

This is significant for the interpretation of the Linnux Supercluster 3D visualistaion. My interpretation is that this shows top reservoir (Top Zone 2) and not top Arab D – as the uppermost layer is non-reservoir. Others may choose too interpret this differently.

The water / oil saturation profiles from Shedgum (Figure 10) and Uthmaniyah (Figure 8) are useful in providing an indication of oil column thickness. However, I have tended to use these in conjunction with contour intervals on Croft's map to guide guesswork about oil column height.

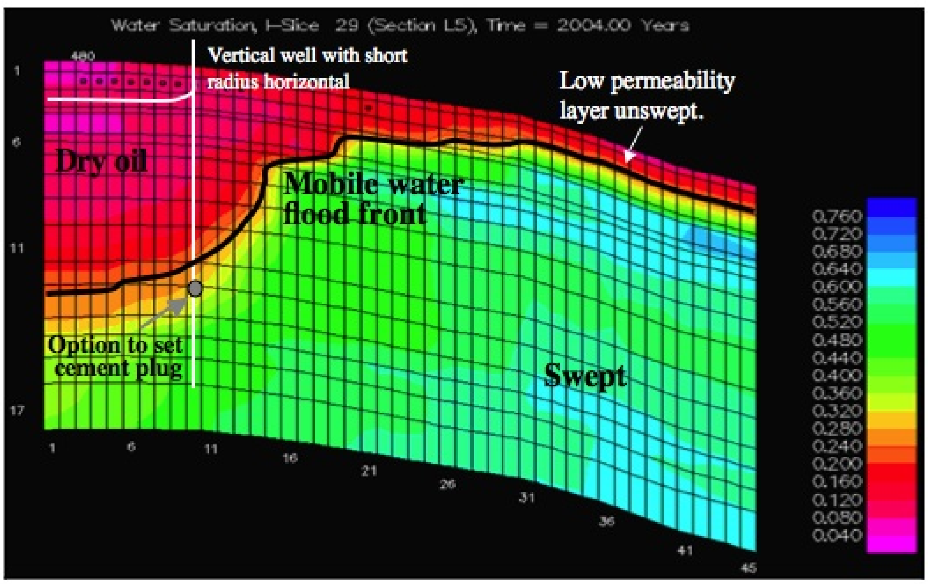

Figure 10. *Oil saturation profile for Shedgum used in estimation of recovery factor. The annotations illustrate water control strategies described in the text. Image source:* [***Optimizing Maximum Reservoir Contact Wells: Application to Saudi Arabian Reservoirs, SPE 10395, Nov 2005.***]() *The profile is presumed to be from the flanks, and contouring the dry oil areas from the Linux map onto Croft's map would suggest a full oil*

reservoir still exists on the crest of Shedgum that in Figure 6 still had a small number of wells. Modelling the geometry of mobile contacts is problematic and subject to uncertainty. In the Base Case reserves model, oil column thickness is reduced by 20% across the whole dry oil area to account for contact geometry along the flood front.

Water flood, secondary recovery, water handling strategies

The natural aquifer under Ghawar is not sufficiently active to provide pressure support to production. Producing oil, therefore, causes the reservoir pressure to drop. In the early 1960s, a program of peripheral water injection was initiated to maintain reservoir pressure above bubble point – the pressure at which solution gas comes out of the oil which has negative impact upon reservoir productivity.

The distribution of peripheral water injection wells is shown in Figure 6 and the movement of the mobile oil water contact resulting from oil production is illustrated for Shedgum in Figure 10.

We have had some debate about the dynamics of flow in this reservoir. Some have argued for a purely gravity driven system – water floating on oil with vertical movement of the flood front. However, the Arab D reservoir is layered (it is not a uniform tank) and contains low permeability horizons that inhibit vertical flow (Figure 4). These impermeable baffles may be kilometres across but lack the extent and geometry to form actual seals within the reservoir. Furthermore, production pressure gradients tend to be horizontal with higher pressure around the periphery related to water injection draining laterally towards the low-pressure sinks associated with producing wells. Layering, and pressure gradients therefore in my opinion give rise to a strong lateral flow component.

The effect of layering on channelling flow can bee seen in Figure 10 where step changes in oil saturation occur across some but not all layer boundaries. These step changes are associated with high water saturation layers down dip. The flood front is neither horizontal (gravity driven) nor vertical (piston layer driven) but has a shape consistent with a dynamic equilibrium between these two processes.

Figure 10, will show only a tiny segment of the Shedgum reservoir. You can imagine that a few years ago the whole section would be coloured red and in a few years time it will be coloured green and blue. As the flood front passes through a vertical production well, it will start to produce water from the base of the well. As water begins to replace oil throughout the oil column (fractional flow) the water cut increases due to increasing ingress of swept reservoir at the base and progressively higher water cuts above the mobile flood front. Eventually, as the flood front passes through, the water cut will get too high and the well may be retired or abandoned altogether.

Handling water production on Ghawar is one of the greatest challenges facing Aramco today. Various strategies have been deployed to manage water cut. In the early years, they could simply go and drill new wells in dry areas and balance wet area with dry area production. In more recent years, they have deployed two strategies in the wet areas to reduce water cut in wet area production. One has been to set cement plugs in the well to cut off water production from the base (Figure 10). The other has been to drill short radius horizontal wells at the top to increase the well contact area with dry oil (Figure 10, **Water Management in North 'Ain Dar, Saudi Arabia, SPE 93439, March 2005.**). Both of these are temporary measures because once the flood front passes through, the well will be “totally watered out”. When this happens, it is time to drive a few miles up the road and drill new wells in dry areas.

As the areas of dry production shrink in Northern Ghawar, the ability to maintain water cut at the target 40% will become increasingly difficult – and this may be significant in determining oil flow rates in the immediate future. High contact area horizontal wells will be deployed to counter this problem – but this represents the final roll of the dice in Northern Ghawar.

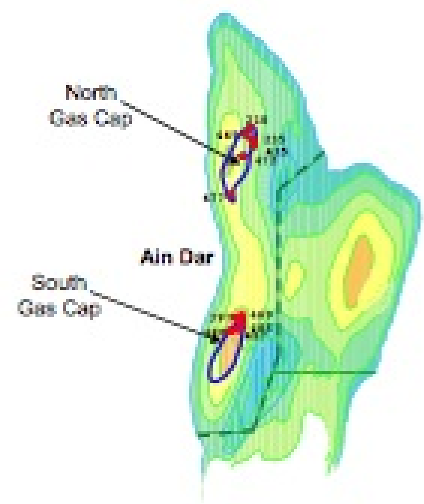

Figure 11. *N and S Ain Dar have secondary gas caps formed as a result of gas injection aimed at improving reservoir sweep. The presence of gas caps gives rise to a complex geometry for the remaining oil reservoir in these areas (Figure 14). Westexas has on very many occasions mentioned on these pages thinning oil columns sandwiched between oil-water and gas-oil contacts. In N and S 'Ain Dar this is indeed the case. These thin (50 to 200 ft thick?) oil horizons will lend themselves ideally to production via multi-lateral horizontal wells in a manner analogous to that used in the W Troll Field, Norway (see Figure 3). At the time SPE 93439 was written, only one such well had been drilled on N 'Ain Dar and Aramco said they were planning to drill more. This will be the last roll of the dice for dry oil production in the Ain Dar area.*

Image source: **Asphaltene Precipitation in High Gas-Oil Ratio Wells, SPE 81567, June 2003.**

Methodology

The Arab D and net reservoir

The Arab D section shown in Figure 4 has a gross thickness of around 250 ft (Uthmaniyah) for Zones 2 and 3 combined. The average net reservoir thickness for Uthmaniyah given by Croft is 180 feet. The net reservoir only includes producible beds and the cut off between producible and non-productive layers can be somewhat arbitrary. Figure 4 shows that the best quality reservoir is Zone 2 and the 180 feet of pay in Figure 4 is most likely distributed as 150 feet in Zone 2 (near 100% pay) and 30 feet distributed throughout Zone 3.

Zones 2 and 3 have very different reservoir qualities. It is to be expected that Zone 2 should be uniformly swept and more efficiently swept than Zone 3. Zone 3, on the other hand should experience uneven sweep owing to inter-bedded good and poor quality reservoir.

The saturation profiles for N Ain Dar (Figure 9) and Shedgum (Figure 10) do not display the variability expected if these represented full Zone 2 + 3 sections and it is considered more likely that they portray Zone 2 only, which is expected to have a uniform sweep.

The saturation profiles for Uthmaniyah (Figure 8) exhibit more heterogeneity, and in particular, the 2004, W flank section appears less well swept in the lower half, suggesting these profiles may represent the full Zone 2 and 3 interval.

In summary, the net reservoir figures from Croft are interpreted to represent producible beds from Zones 2 and 3 with the producible beds concentrated in Zone 2.

One of my reviewers pointed out that with the advent of horizontal drilling over the last 25 years, many companies view of net pay has become more generous. This is because horizontal wells allow greater recovery from poor permeability rock. It is possible, therefore, that horizontal wells may allow greater recovery from Zone 3 than assumed at the time Croft's figures were compiled. This will be booked as one possible source of underestimation in my reserves figures.

Scaling factors

All the volumetric calculations presented here hinge on the accuracy of Croft's map and the scale bar on that map which is best described as a bit scrappy. Measuring the length of Ghawar from the tip of Fazran to the toe of Haradh yields a length of 164 miles using Croft's scale bar. However, in his text Croft says that Ghawar is 174 miles long and this raises concern about the reliability of that scale bar.

SS sourced a second map produced by "Arabian American Oil Company Staff" (Fig 7) that had a better scale bar attached and measuring 4 easily identifiable dimensions on this map yielded the exact same dimensions as Croft. It would seem that the "Arabian American Oil Company Staff" map was probably the base map used by Croft, so this agreement is not surprising. What it does show is that the scale bars on these two maps are compatible with each other – but they may both be wrong.

A second contoured map came to light from a confidential industry report. On this map, Ghawar is 181 miles long and is proportionally wider in the north relative to Croft. This map therefore has a significantly larger surface area than Croft's map – very approximately 24% larger area. This would clearly have a significant impact upon volumetric calculations.

The Ghawar wells map (Figure 6) showing the distribution of oil production and water injection wells was overlaid on both of these maps. This provides a good fit with the Croft map, the injectors fit snugly around the map outline in Haradh, Hawiyah, Uthmaniyah and N Ain Dar (Figure 12). The fit is less good to the east of Shedgum and to the west of South Ain Dar and in the large saddle area between Ain Dar, Shedgum and Uthmaniyah.

The fit of the injector well profile to the confidential map was good in Uthmaniyah and Hawiyah but it was not good in the north with most injector wells lying inside the structure outline.

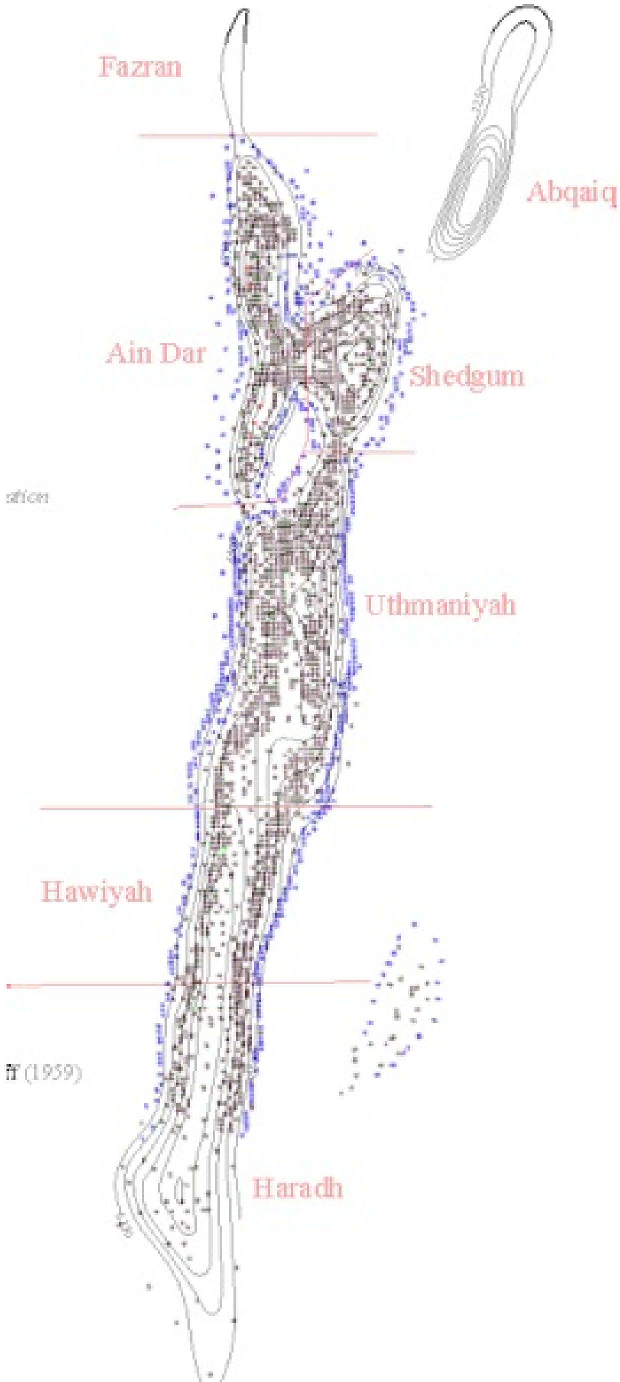

Figure 12. *Wells map (Figure 6) overlaid upon Croft's map (Figure 16). The wells map had to be rotated anti-clockwise and rescaled (constant x-y axes scaling) to produce the fit of water injectors around the peripheral contour on Crofts map believed to be the oil water contact. The fit is excellent around Haradh, Uthmaniyah, N Ain Dar and the northern rim of Shedgum. The fit is not so good down the W margin of S Ain Dar and the E margin of Shedgum or in the large saddle area suggesting that Croft's map may be a bit narrow across S Ain Dar – Shedgum.*

Working in 2D

The main uncertainty working in 2D arises from what are known as edge wedge effects. Where the reservoir plunges through the OWC working with 3D cubes breaks down as shown in Figure

13. On Ghawar, these edge wedge effects are estimated to penetrate about 1.1 miles from the edge of the structure (300 ft thick Arab D section, 2.8 degrees dip) and this will result in overestimation of reserves working in 2D.

In the Arab D reservoir the upper Zone 2 has superior reservoir quality to the underlying Zone 3 (Figure 4) and as illustrated in Figure 13, the overestimation resulting from the edge wedge is mainly the poorer quality Zone 3 reservoir. Very roughly the edge wedge comprises 25% Zone 2 and 75% Zone 3. This will significantly reduce errors arising from ignoring the edge wedges where this has been done in calculating initial reserves and the remaining reserves in South Ghawar.

In the Base Case scenario, edge wedge effects, and contact dip effects have been accounted for by reducing column height by 20% in Ain Dar and Shedgum. In Uthmaniyah, owing to the unpredictability of the underlying shape of that tongue of oil, oil layer heights have been reduced by 33% in both Base and High Cases to account for this and for edge wedges.

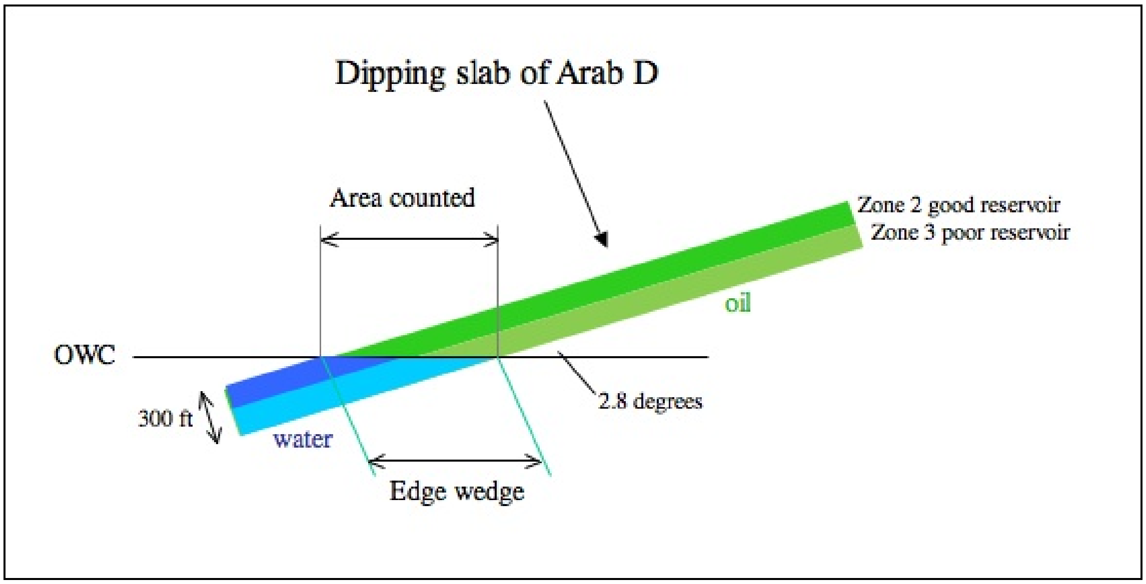

Figure 13. *Diagram illustrating errors arising from edge wedge effects at the OWC whilst working in 2D. The area counted will tend to overestimate reserves. However, in the Arab D reservoir, good quality productive horizons are concentrated in the top half of the reservoir and this tends to reduce errors arising from edge wedges as illustrated.*

Secondary gas caps in N and S 'Ain Dar

The presence of secondary gas caps in N and S 'Ain Dar has a significant impact upon the volume of reservoir that is now occupied by oil. These gas caps have formed as a result of re-injection of produced gas. This is an efficient way of displacing oil and is a commonly used secondary recovery mechanism.

Figure 14 illustrates how the gas caps and volume of underlying oil rim has been modelled in North and South Ain Dar. This exercise is subject to large uncertainties. 200 ft thick gas caps have been assumed leaving a complex oil volume geometry as illustrated in Figure 14. Modelling this as cubes will tend to underestimate oil remaining oil volumes. Note that thin oil layers below gas in N and S 'Ain Dar occur in poorer quality Zone 3 reservoir and present ideal drilling targets for high contact area horizontal wells.

Note also, that the model for S 'Ain Dar actually shows gas on water at the south end of the closure (Figure 16) – indicating how close we may be to the final stages of primary oil production in this area.

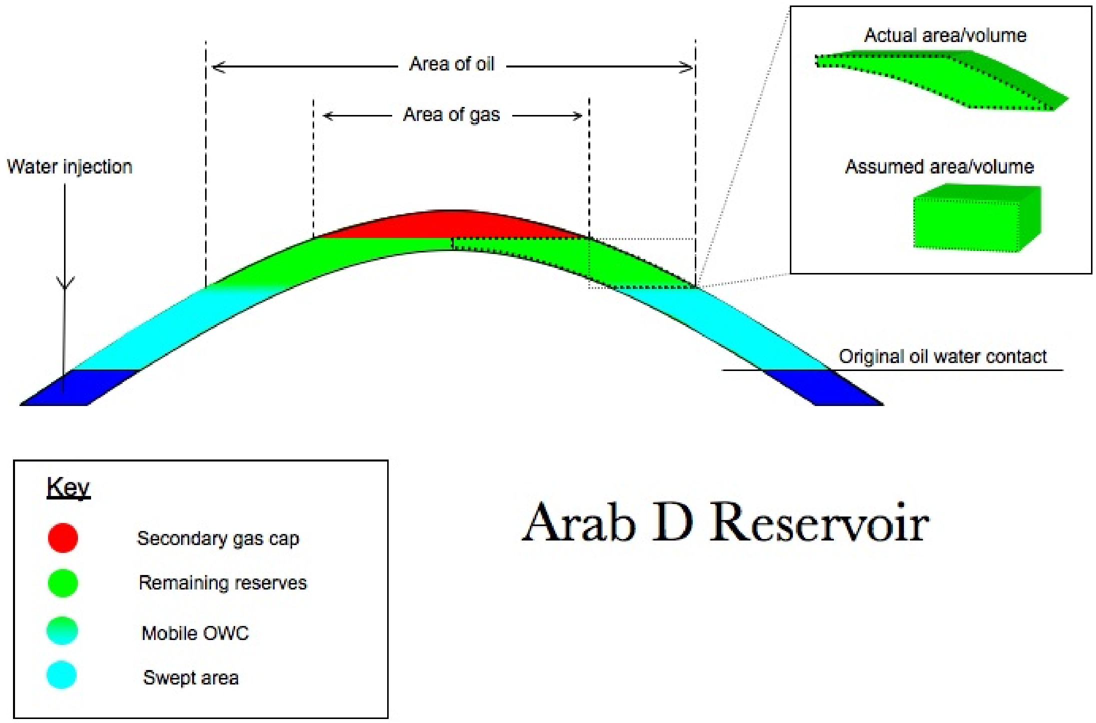

Figure 14. *Diagram illustrating errors arising from measuring oil rims below the gas caps of N and S Ain Dar. In these structures, the area of gas has been deducted form the area of oil and a "cuboid" volume of oil determined on that basis. In reality, the oil volume has complex geometry with larger volume than the cuboid.*

Recovery factor

The recovery factor is the percentage of the initial oil in place that may be recovered.

Recovery factors have been estimated from the published water saturation sections for N 'Ain Dar, Shedgum and Uthmaniyah (Figures, 8, 9 and 10).

The procedure followed is to estimate the initial oil saturation (Soi) and the minimum final residual oil saturation (Sor). Note that water saturation Sw = 1 – So. This allows a value to be calculated for the mobile oil that is recovered. The recovery factor then equals Soi-Sor / Soi. (Figure 15).

This provides an estimate for optimum recovery in the most efficiently swept zones, and not all zones will be swept by this optimum efficiency. Thus the recovery factor is multiplied by an efficiency factor. In the base case scenario a sweep efficiency of 80% has been assumed whilst for the high case a sweep efficiency of 95% has been assumed.

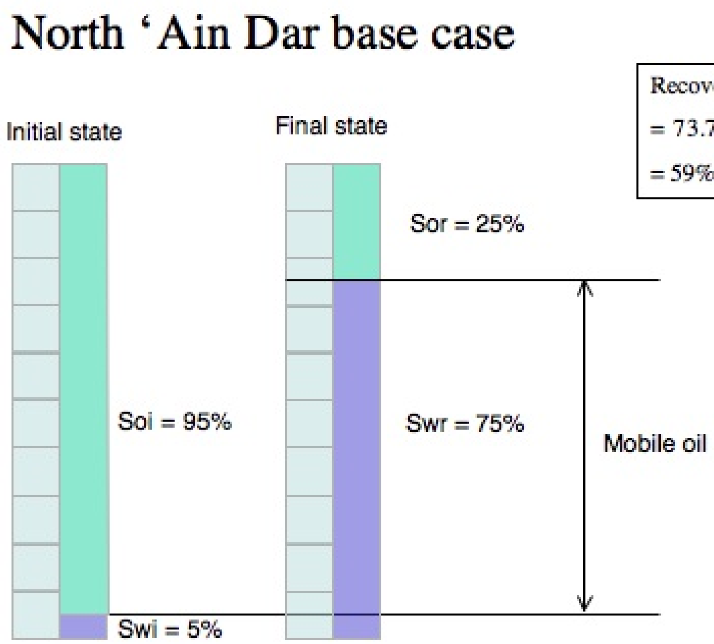

Figure 15. *Diagram illustrating how recovery factors have been estimated. The recovery factor = mobile oil / initial oil * a sweep efficiency factor. Mobile oil = the residual water saturation (Swr) minus the initial water saturation (Swi). Minimum Swi and maximum Swr have been estimated from the saturation profiles in N Ain Dar, Shedgum and Uthmaniyah (Figures 8, 9 and 10). This provides a picture of optimum recovery that will not likely be achieved throughout the whole reservoir owing to uneven sweep. The base case model uses a sweep efficiency factor of 0.8 and the high case model a sweep efficiency factor of 0.95.*

Reserves Calculation

The following methodology was used to obtain a Base Case and High Case for the remaining recoverable oil reserves in Ghawar. The Base Case is based on what are considered to be conservative assumptions. The High Case is based on more optimistic assumptions that are more closely aligned with Aramco's input data.

Step 1

The oil saturation data on the Linux visualisation was transferred by hand onto the 2D Greg Croft map (Figure 16). No bias between base case and high case.

Step 2

The total areas of N 'Ain Dar, S 'Ain Dar, Shedgum, Uthmaniyah, Hawiyah and Haradh were measured by counting squares on a square mile grid overlaid on the map. The process was repeated for the unswept areas (Figure 16). No bias between base case and high case. The total map area determined in this way is 1625 square miles. Stuart S has made the same measurement using computer code and got 1663 square miles. This is considered to be extremely good agreement.

Step 3

Oil rock volumes were determined for initial and remaining reserves. The details are on the spreadsheet. In short, the main difference between high and base cases is that thinner oil layers have been used in the latter, especially in N and S 'Ain Dar and Shedgum.

Step 4

Oil rock volumes calculated in cubic feet are converted to barrels by dividing by 5.615.

Step 5

Hydrocarbon pore volumes are calculated using the average porosity data for each area provided by Greg Croft (no bias between high and base case) and oil saturation data. Initial oil saturation data has been estimated from the published saturation profiles for the North. In the south, with the absence of independent data, the 89% So values from Croft have been used. These seem appropriately lower for the poorer reservoir quality in the southern area.

The initial oil saturations used are as follows (no bias between high and low case):

N Ain Dar 95%
S Ain Dar 95%
Shedgum 95%
Uthmaniyah 96%
Hawiyah 89%
Haradh 89%

Step 6

Dividing the hydrocarbon pore volume by the formation volume factor yields stock tank barrels in place (STOIP). Note that the volume of oil shrinks under surface conditions owing to degassing and cooling. No bias between high and base cases.

Step 7

Recoverable reserves are determined by multiplying STOIP by a recovery factor (see above). In the North, recovery factors are based on the published saturation profiles using methodology described above (Figure 15). In Haradh, High Case recovery factor is calculated using 900,000 bpd for 30 years as a percentage of STOIP yielding 53%. This factor is then applied to Hawiyah. The Base Case recovery factor in the south has been assumed to be 45%. In summary, the net recovery factors are as follows:

	Base Case	High Case
N Ain Dar	59%	70%
S Ain Dar	59%	70%
Shedgum	54%	64%
Uthmaniyah	67%	80%
Hawiyah	45%	53%
Haradh	45%	53%

The recovery factors calculated for Uthmaniyah are very high. The saturation profiles (Figure 8) suggest very high recovery and in the absence of other evidence this has been accepted at face value. Note that a sweep efficiency of 95% is assumed for the High Case and 80% is assumed for the Base Case.

The main differences between high and base cases are:

	Base Case	High Case

Oil coulmn thickness	reduced in north	full reservoir (accept Uthmaniyah)
Recovery factor	lower	higher

And that brings us to the end of the background and methodology section. Part 2 - results will be along very shortly.

Full acknowledgements will be included at the end of Part 2. However, at this point I feel obliged to point out that Stuart Staniford (in conjunction with certain posters) provided most of the reference material used in this article and he provided the images for Figures 2, 4, 6, 7, 8 and 9.

Recent Oil Drum articles on Saudi Arabia:

by Stuart Staniford

The Status of North Ghawar

Further Saudi Arabia Discussions

Water in the Gas Tank

Saudi Aramco's Astrologers

A Nosedive Toward the Desert

Saudi Arabian oil declines 8% in 2006

by Euan Mearns

Saudi production laid bare

Saudi Arabia and that $1000 bet

by Heading Out

Simple mathematics - The Saudi reserves, GOSPs and water injection

Of Oil Supply trains and a thought on Ain Dar

by Ace

Saudi Arabia's Reserve "Depletion Rates" provide Strong Evidence to Support Total Reserves of 175 Gb with only 65 Gb Remaining

Further Evidence of Saudi Arabia's Oil Production Decline