The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

The Status of North Ghawar

Posted by Stuart Staniford on April 7, 2007 - 10:49am
Topic: Supply/Production
Tags: ghawar, peak oil, saudi arabia [list all tags]

Oil saturation in reservoir simulation of all of Ghawar. Simulated date unknown but believed not later than 2004. Scale is not documented but presumably bright red is 100% water saturation and dark blue is 0% water saturation. Click to enlarge. Source: Figure 3 of Linux Clusters Driving Step Changes in Interpretation, Simulation.

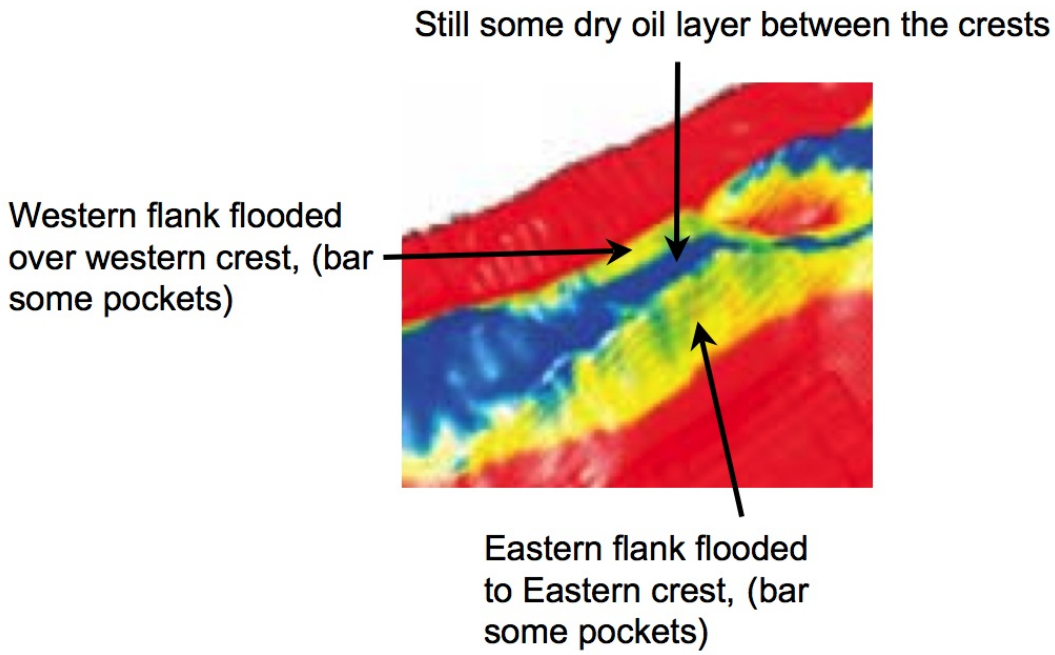
This post is not introductory (for which I apologize), but is instead intended to summarize the status of the overall hypothesis that watering out of North Ghawar is the main cause of declines in Saudi production in the last couple of years. Readers getting up to speed may want to read the following earlier posts which document most of "The Oil Drum Ghawar Project":

- Saudi Arabian Oil Declines 8% in 2006
- Saudi Arabia and that $1000 Bet
- A Nosedive Toward the Desert
- Saudi Production Laid Bare
- Of Oil Supply trains and a thought on Ain Dar
- Further Saudi Arabia Discussions

In many cases, the comments contain a great deal of additional analysis and value beyond the posts themselves.

In what follows, I'm deeply indebted to Fractional_Flow, Euan Mearns, Bob Shaw, GaryP, and others, for insights and references. However, the synthesis here is mine, and they might well disagree with it to varying degrees.

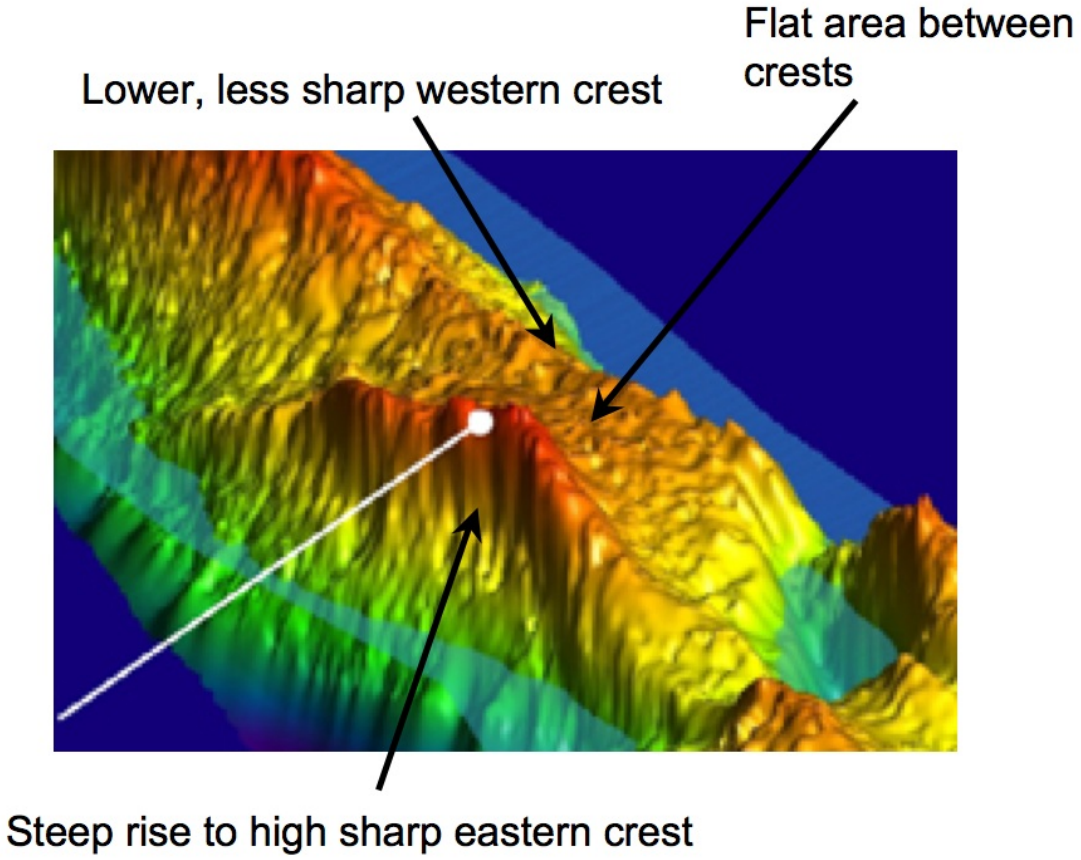
Ok, let's start in the middle with Uthmaniyah. Here's a blow-up of the Ghawar oil saturation plot. My interpretation of this plot is it represents the oil saturation *at the surface of the reservoir*. So it doesn't, by itself, tell us anything about the thickness of the oil layer, just that there is (or isn't) an oil layer at the surface of the reservoir. Ok, so here's Uthmaniyah:



Oil saturation in reservoir simulation of Ghawar - blowup of Uthmaniyah area. Simulated date unknown but believed not later than 2004. Scale is not documented but presumably bright red is 100% water saturation and dark blue is 0% water saturation. Click to enlarge. Source: Figure 3 of Linux Clusters Driving Step Changes in Interpretation, Simulation.

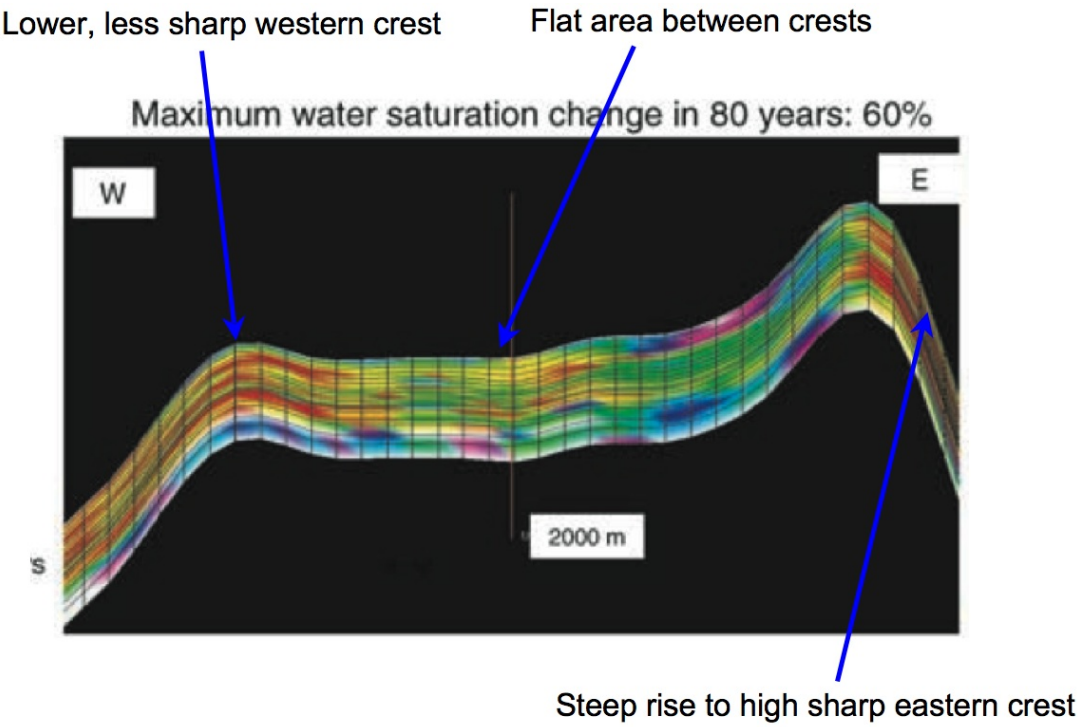
Before we go on, I'd like to stress, especially for Euan's benefit, that with all these visualizations: they have been scaled to fit on your computer screen. Ghawar is really much bigger than your computer screen. And in particular, the scaling in the horizontal direction is much more pronounced than the scaling in the vertical direction. That "cliff" on the eastern flank is really a slow rise that goes on for several miles at only a few degrees angle. However, it's very likely that even though the scales are adjusted, the **shape** is accurate, since it can be determined with great precision by seismic surveys.

Let's get a better sense of the shape of Uthmaniyah, running East-West. We can look at this other visualization:



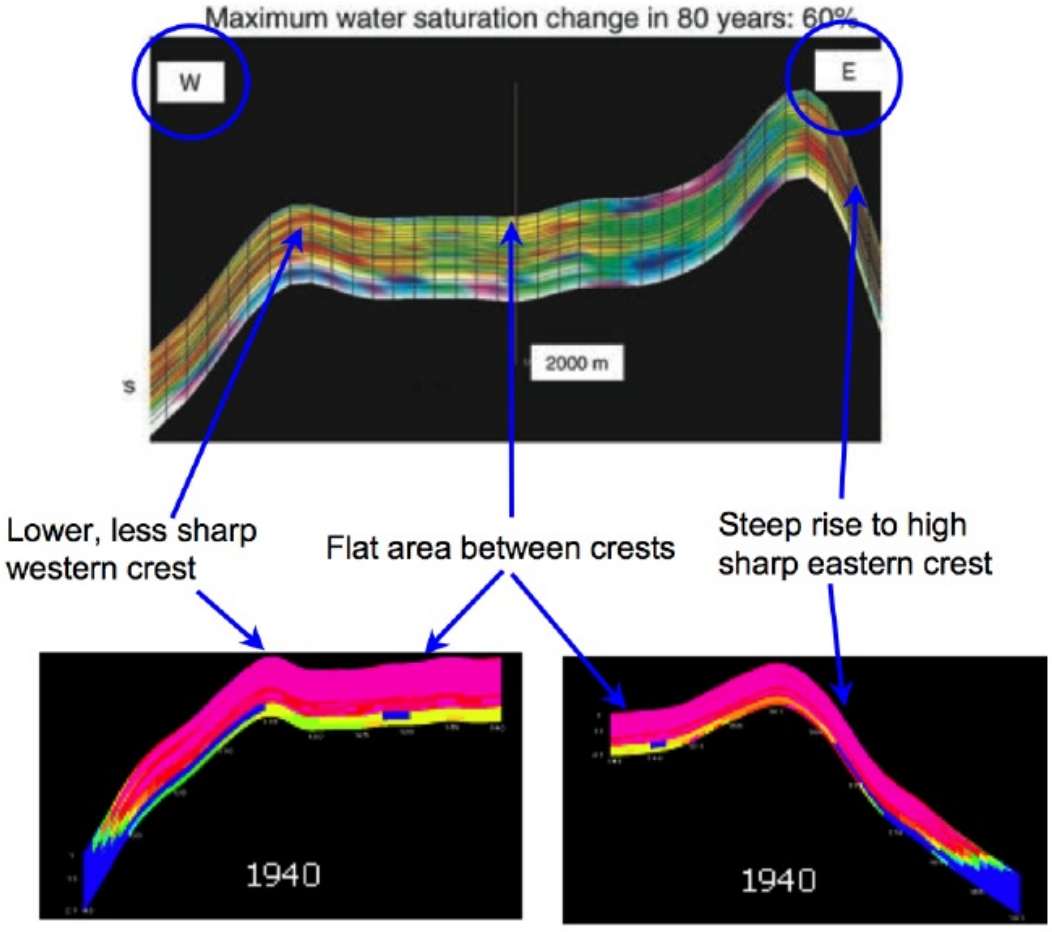
Topographical profile of Ghawar - blowup of Uthmaniyah area. Click to enlarge. Source: Figure 3 of Ghawar: The Anatomy of the World's Largest Oil Field.

So if you stare at the shape of that field going from East to West, then I hope you'd agree with me that this next simulation profile of Uthmaniyah must be an East West cross section of the entire field:



East-West cross section of Uthmaniyah area of Ghawar. Click to enlarge. Source: Figure 5a of When 4D seismic is not applicable: Alternative monitoring scenarios for the Arab-D reservoir in the Ghawar Field.

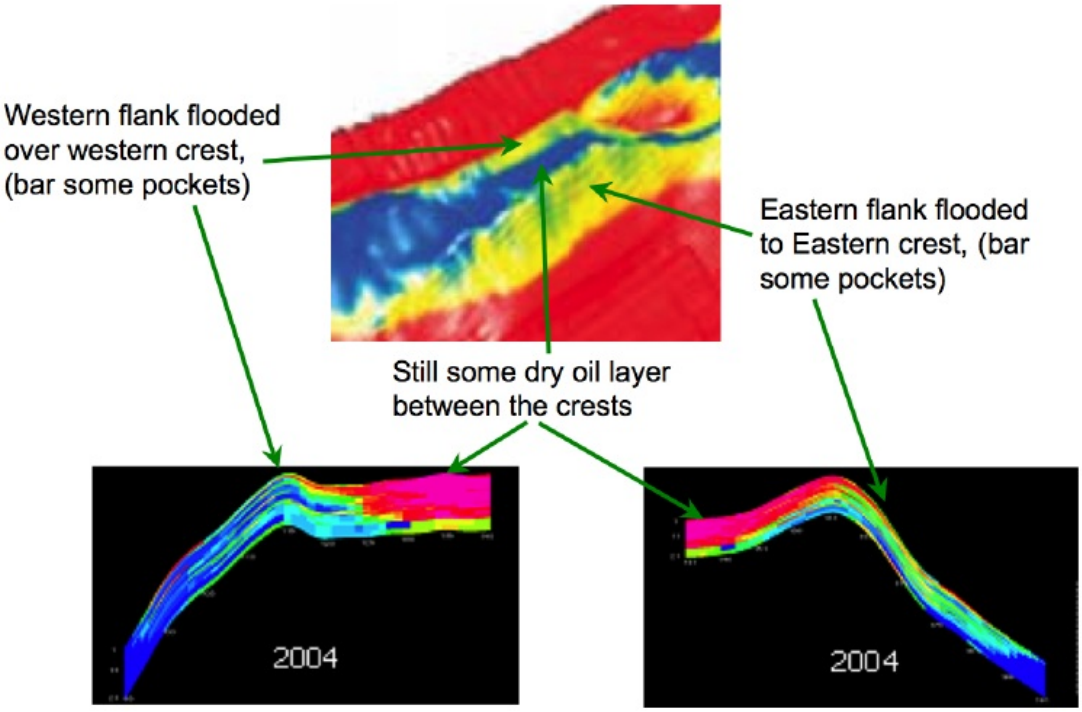
And if you agree with that, then I think you'd have to also agree that the profiles below are of the western and eastern flank and crest respectively, with each continuing to about the middle of the flat area between the dual crests:



Top: East-West cross section of Uthmaniyah area of Ghawar. (Figure 5a of When 4D seismic is not applicable: Alternative monitoring scenarios for the Arab-D reservoir in the Ghawar Field). Bottom: simulated 1940 water saturation for cross-sections of Uthmaniyah from Figure 12 of SPE 98847. Click to enlarge.

(NB: I'm not claiming the cross sections at bottom are in the exact same north-south position as the one at the top - clearly they aren't, nor do they have the same scalings. But I do claim that the bottom cross sections must be east-west cross sections that each include about half the structure (the west half and the east half respectively).)

And if you agreed to that, then it seems that the SPE 98847 cross sections from **2004** are telling a fairly similar story to the oil saturation picture from the Linux cluster paper:



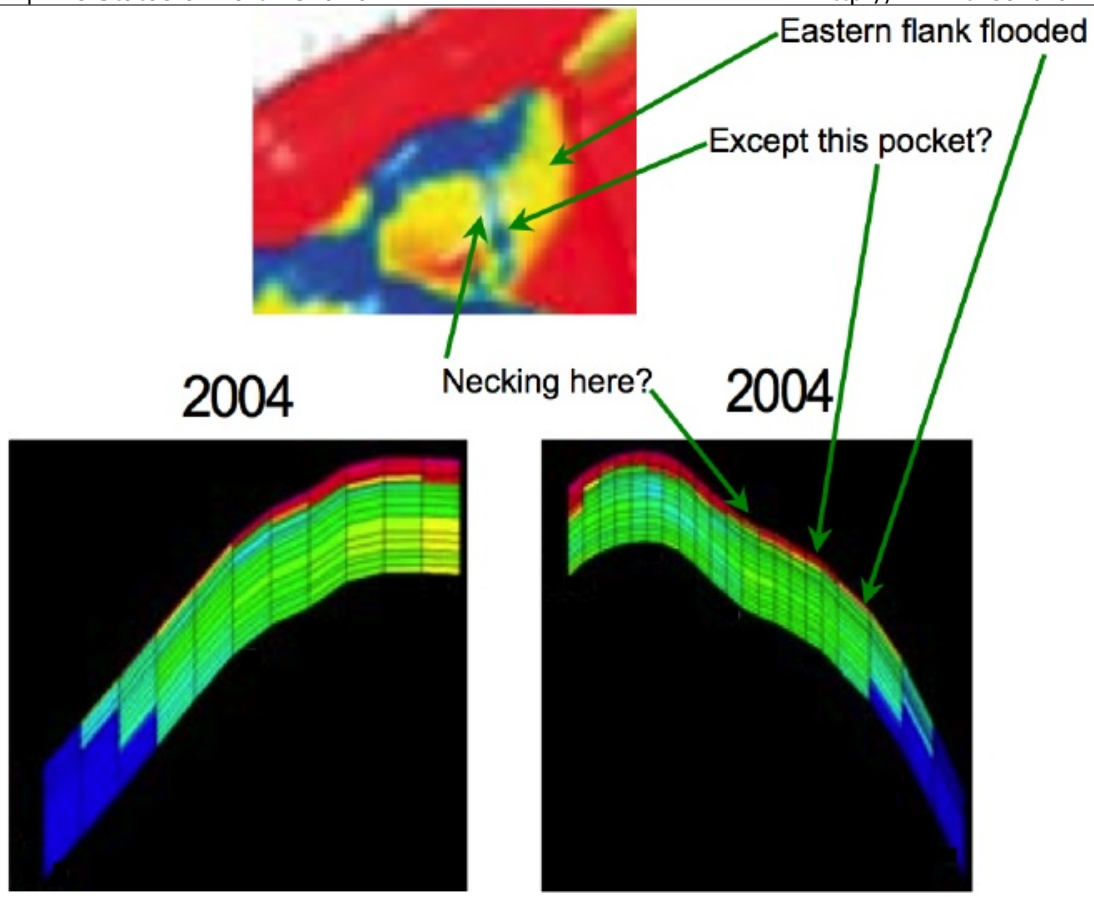
Top: Oil saturation in reservoir simulation of Ghawar - blowup of Uthmaniyah area. Simulated date unknown but believed not later than 2004. Scale is not documented but presumably bright red is 100% water saturation and dark blue is 0% water saturation. Click to enlarge. Source: Figure 3 of Linux Clusters Driving Step Changes in Interpretation, Simulation. Bottom: simulated 2004 water saturation for cross-sections of Uthmaniyah from Figure 12 of SPE 98847. Click to enlarge.

Given the general agreement, I think it is probable that the top picture is of the simulated reservoir as of 2004 (the source paper gives it as an example of the output of a super-computing cluster described as of 2004 - in principle it could have been of a year earlier than the end of the run, but that now seems unlikely).

So these sources are tolerably consistent, and what they say is that there is oil between the crests in Uthmaniyah still, but much less than there used to be. In these particular cross sections something like 1/4 of the original dry oil is left. Looking at the 3d visualization, we can see that the situation gets better to the south, and worse to the north, but overall it seems that Uthmaniyah will produce dry oil from horizontal wells for a few more years (even allowing for the three years that have passed since the time of these pictures).

I should note in passing that Fractional_Flow has a lot of issues with the left profile, in particular the extraordinarily low oil saturation left in some strata (less than 10% - much lower than 'Ain Dar). He also doesn't like the angle of the oil water contact - but a couple of hundred feet of rise in the OWC over several miles doesn't seem much worse than what we see in lots of these simulation pictures.

Ok. Let's now turn back to North 'Ain Dar. Here's the equivalent picture to the one we just looked at.



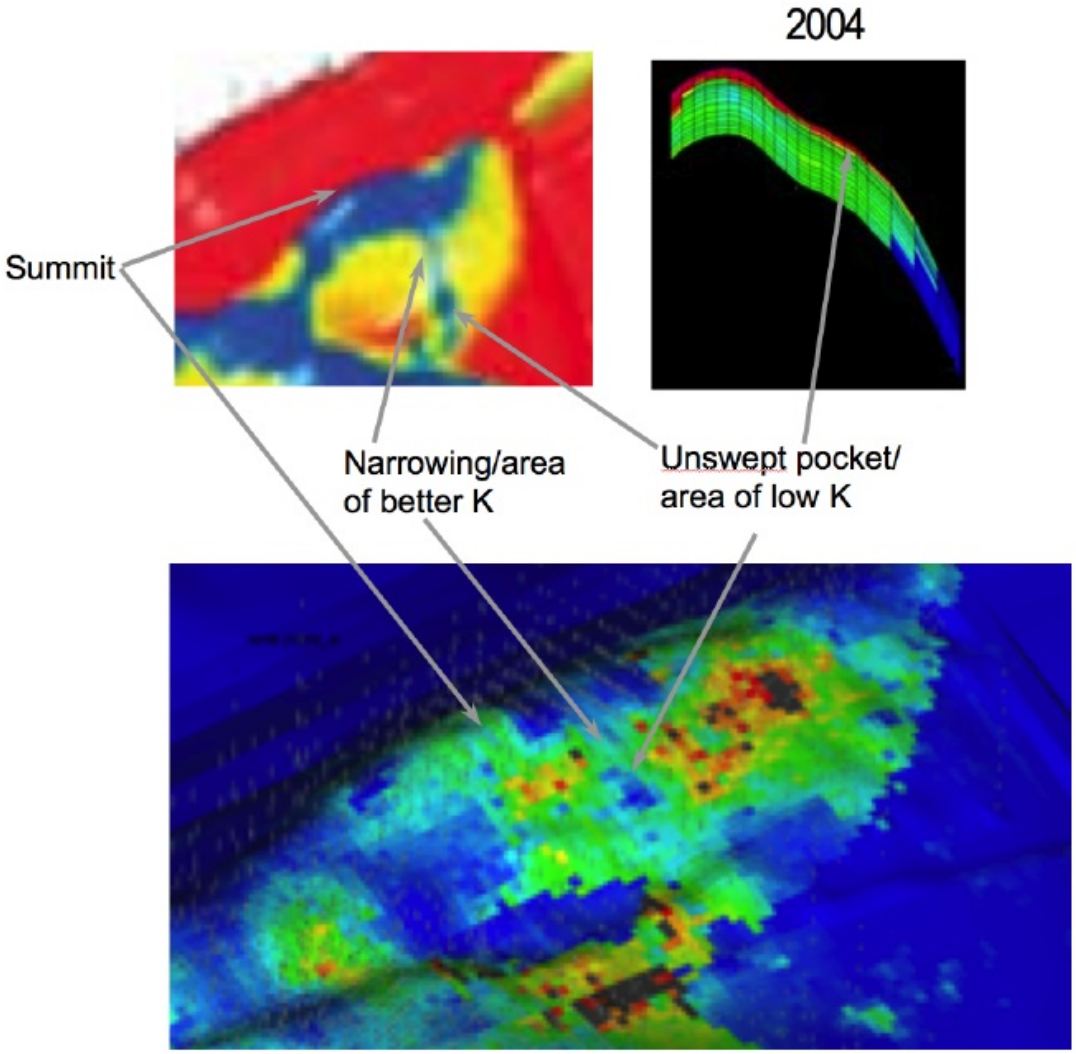
Top: Oil saturation in reservoir simulation of Ghawar - blowup of North 'Ain Dar area. Simulated date unknown but believed not later than 2004. Scale is not documented but presumably bright red is 100% water saturation and dark blue is 0% water saturation. Click to enlarge. Source: Figure 3 of Linux Clusters Driving Step Changes in Interpretation, Simulation. Bottom: simulated 2004 water saturation for cross-sections of North 'Ain Dar from Figure 9 of SPE 93439. Click to enlarge.

(And for those of you following the debate very closely - yes, I have become persuaded of GaryP's placement of the cross-section a few miles north of where I had it before, for reasons that will become clear).

Now, if you were a reasonable person, you **might** be inclined to accept that since Saudi Aramco in their paper on managing water in Uthmaniyah gave us a couple of cross sections that included each flank and the ridge, they likely are following the same practice in the North 'Ain Dar paper. And given that there is only one significant pocket of unswept oil in the 3D oil saturation visualization that comes more than a third of the way down from the ridge, you might be inclined to accept that the 9b) eastern cross section must be going through that pocket. If it was anywhere else, there could be no oil layer on the surface that far down the cross section. It's particularly striking that the oil layer in the cross-section weakens about 3/5 of the way up from the OOWC to the crest, just where the little unswept patch narrows on the 3d visualization.

But we have some folks who are still going to be claiming that Ghawar is fine as their rusty V8 engine blocks thump loudly to the floor, corroded from their vehicles by excessive attempts to drive with left-over injected sea water for fuel. So let me now proceed to beat this point into the ground with a 50lb mallet, and then pound it down some more with a 2 ton pile driver (solar powered, of course).

Let's investigate that little patch of unswept oil on the eastern flank for a minute. In particular, I'm going to look at it on the permeability visualization:



Top left: Oil saturation in reservoir simulation of Ghawar - blowup of North 'Ain Dar area. Simulated date unknown but believed not later than 2004. Scale is not documented but presumably bright red is 100% water saturation and dark blue is 0% water saturation. Click to enlarge. Source: Figure 3 of Linux Clusters Driving Step Changes in Interpretation, Simulation. Top right: simulated 2004 water saturation for east-flank cross-section of North 'Ain Dar from Figure 9 of SPE 93439. Bottom: Blow up of North 'Ain Dar region of permeability visualization from IPTC 10395 Click to enlarge.

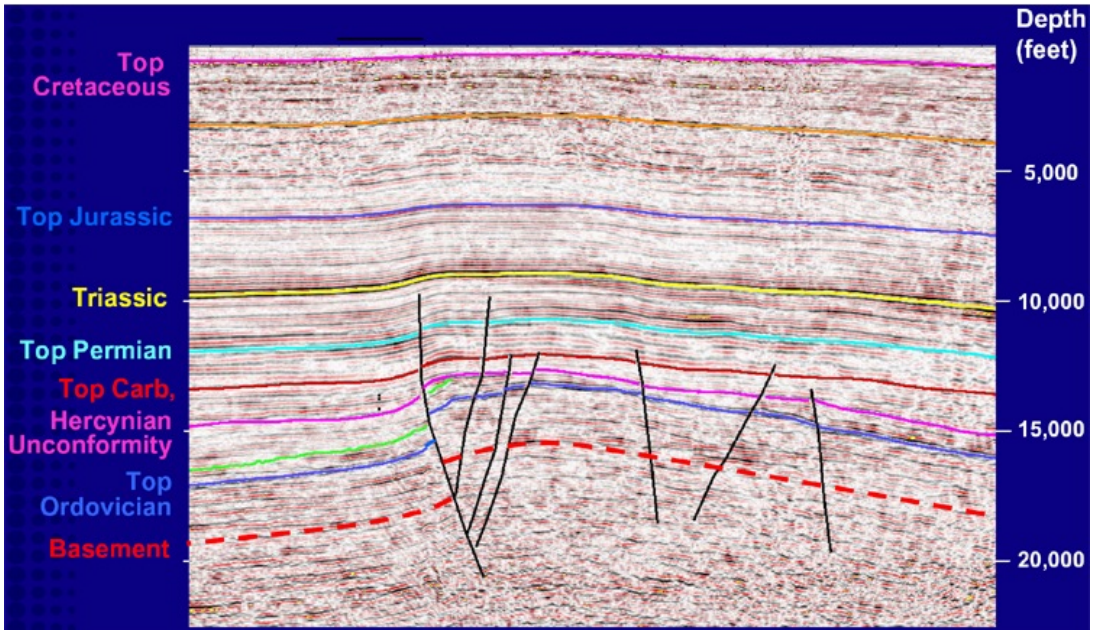
Nice, huh? It's pretty clear why that patch of unswept oil is there. And that helps us to locate on a slightly less blurry picture where we need the 9b) eastern cross section to go. In a few minutes we'll take this to our best topographical visualization. But first we need to talk about the thickness of the Arab-D reservoir in North 'Ain Dar so we can do the best possible job of establishing the vertical scale here. We know the average thickness of the oil layer from Greg Croft (204'), but it's not quite clear where in the simulation picture we should consider the bottom of the oil layer to be. There are also questions about whether the reservoir (and the layer) are reasonably uniform or not.

Overall we don't expect radical changes change in the strata thickness. From this extensive survey of Middle East geology, we learn:

> South of the 'Gotnia Rim', four shoaling cycles of interbedded calcarenite and anhydrite units developed. They are the A to D Members of the Arab Formation. Throughout the 250-km-wide Arabian Basin, they show a remarkably uniform development in fabric

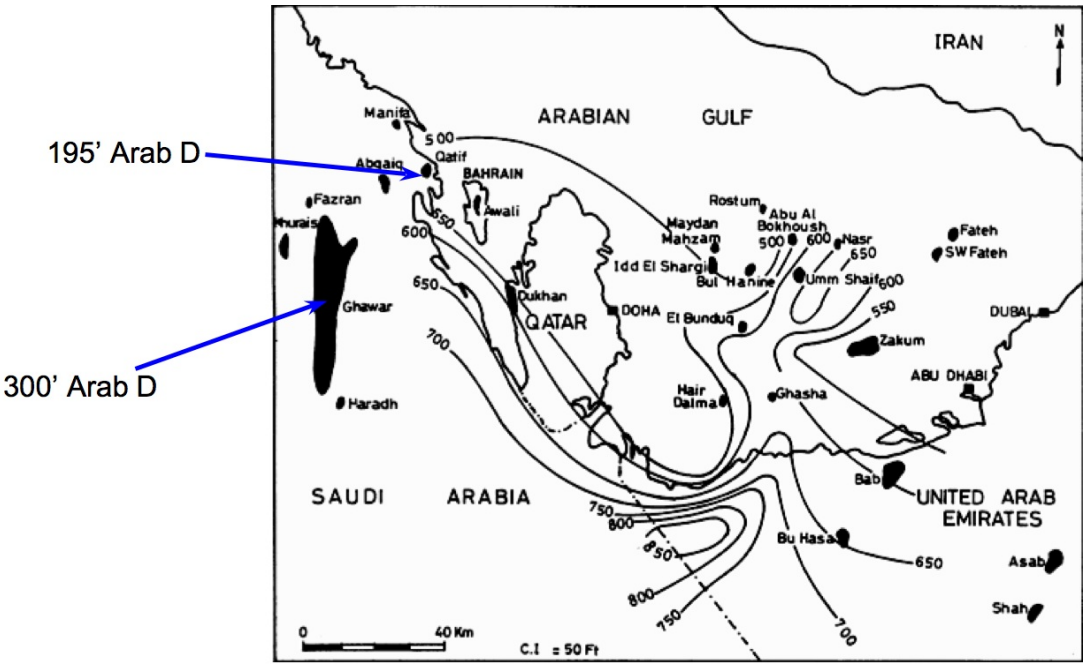
and thickness.

You get the idea from this east-west cross section of a seismic picture of the strata in the area:



Picture of geological strata and faults forming Ghawar anticline. Click to enlarge. Source: Figure 9 of [Ghawar: The Anatomy of the World's Largest Oil Field](#).

However, I have come to the view that there is likely some North-South variation of the reservoir thickness through the length of Ghawar. The best map I've been able to find doesn't nail it, but hints at what to think:



Map of isopachs (lines of constant thickness) for Arab formation near Ghawar. Click to enlarge. Source: Figure 6 of [Carbonate-Evaporite Sequences of the Late Jurassic, Southern and Southwestern Arabian Gulf](#). Two known measurements of Arab-D thickness are marked.

Now, I think the isopachs on the map (in feet with fifty foot contour interval) must be for the full

Arab A-D sequence, whereas the actual reservoir only consists of Arab D. And the contours don't go as far as Ghawar. But the picture does suggest that we might expect the rock to get thicker as we go south, and that it probably doesn't vary rapidly in the region of the North end of Ghawar.

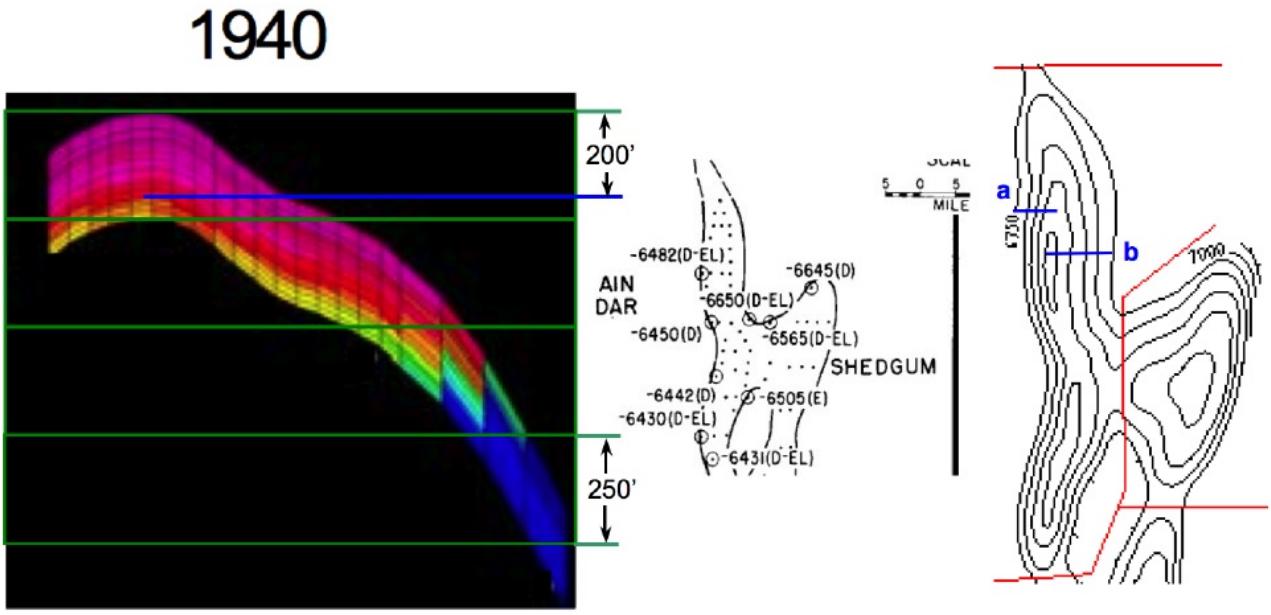
To get any further with this, we have to resort to point observations. A very extensive USGS survey of the area's petroleum geology tells us that

> For example, the Arab D reservoir at the 'Uthmaniyah substructure (fig. 10) field of Ghawar is a 91-m thick carbonate rock sequence consisting of various carbon- ate rock types that exhibit an overall stratigraphic downward decrease in porosity with a corresponding increase in dolomite content.

91m is 300 feet. Then, this paper reports that the original Dammam-7 well (which is the tip of the other blue arrow above) found 58.5m (or 195') of Arab D reservoir.

So looking at the map overall, one would assume that 'Ain Dar has something like 250' of reservoir (with a possible error of a few tens of feet either way). Furthermore, it's not very plausible that there's radical variations in reservoir thickness **within** 'Ain Dar.

The reason this is important is it allows us to construct a reasonably reliable vertical scale for the 9b) eastern cross section. Under the assumption that there's 200' of pay in 250' of reservoir, the picture has to look fairly close to this:

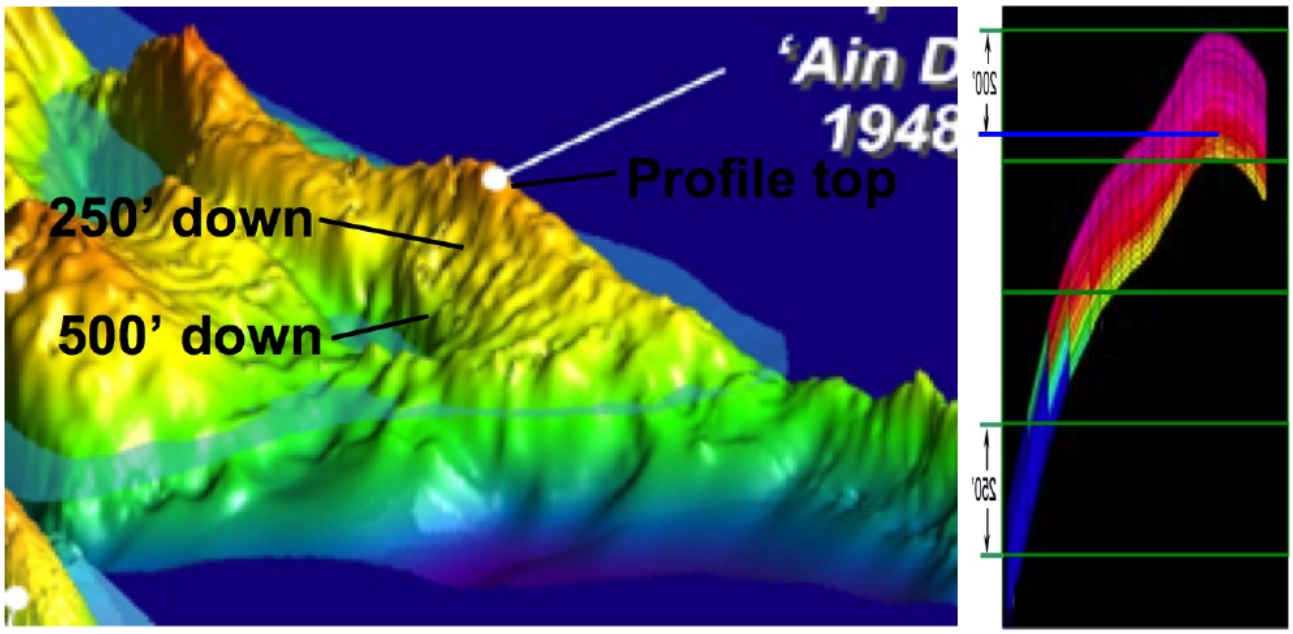


Left: 9b) cross section with green lines every 250 feet. Center: Fractional_Flow supplied map of OOWC measurements. Right: Greg Croft contour map of the area.

The point here is that 9b) cross section is 900' tall (measured at the top of the Arab-D) and still descending. Thus, to fit on the Greg Croft map, which has about 1000' of spacing shown, it has to be not too far from the crest, and it has wrap over the main ridge. If it was going over some subridge on the side of the eastern flank, but not going over the main ridge, it's very difficult to make the height work.

To attack the same issue from a fourth (and final, I promise) angle, we can look at the topographic visualization. After reflection, I decided I could live with GaryP's solution, and I liked it because of

the match up with the visible unswept oil on the oil saturation visualization. I've marked off how I think the heights work.



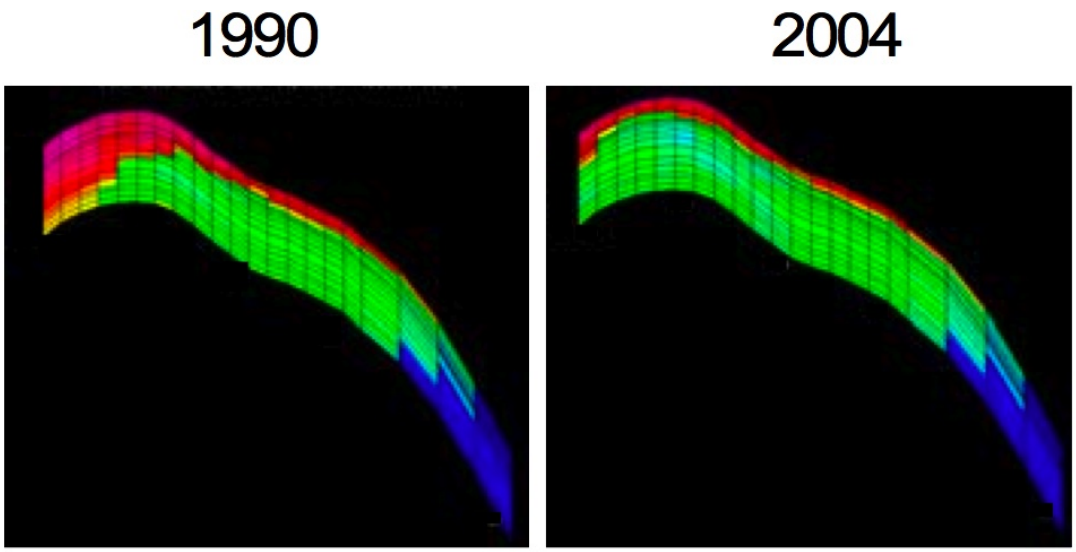
Right: 9b) cross section with green lines every 250 feet, mirrored and laterally compressed. Left: Visualization, showing where profile would fit, with heights matched to 250' intervals.

To me, this meets all the requirements in a way that only a handful of spots (all close together) do:

- A visible shoulder in the profile at the right height.
- Around 600' from the ridge top to the OOWC
- Steepening into the water.
- Room to continue for a few hundred feet down under the water.

I haven't seen anywhere very far from the crest that can meet those requirements.

So given all that, the implications for North 'Ain Dar are pretty clear:

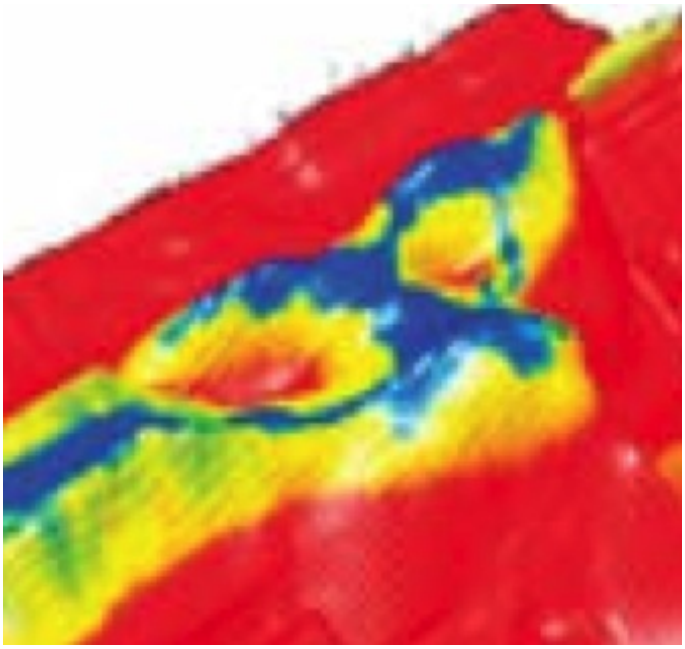


East flank cross section in reservoir simulation of the northern portion of the 'Ain Dar region of Ghawar. Blow-

up of 1990 and 2004 only. Source: Figure 9 of Alhuthali et al, Society of Petroleum Engineers Paper #93439, March 2005.

> Layer counting here says that 6-9 layers of red/pink have been reduced to 1 layer over the same 14 years, suggesting a similar pace. So, overall, we lose a layer about every 21 months, and there were 1-2 layers left at the time of the 2004 simulation. Now, we do not know for sure whether this simulation means by "2004", "2004.0" -- the beginning of the year, or the end of the year. However, labels on simulation visualizations in other papers shows annual data with a ".0", suggesting that is the convention. If so, then we would expect the green area to reach the top of the reservoir in some places in North 'Ain Dar in mid-late 2005, and in most places there by the middle of 2007. Thus in timing, this phenomenon would be consistent with the decline in output across production zones E-I (mid 2005 through the present).

But what we now have is a much stronger argument for extrapolating this conclusion to south 'Ain Dar and Shedgum:



East flank cross section in reservoir simulation of the northern portion of the 'Ain Dar region of Ghawar. Blow-up of 1990 and 2004 only. Source: Figure 9 of Alhuthali et al, Society of Petroleum Engineers Paper #93439, March 2005.

Eyeballing the picture, they are at about the same stage of depletion as North 'Ain Dar, or maybe a fraction behind. Assuming the flood has been done in a similar manner, there will have been a similar thinning out of the oil layer, with perhaps only the saddle between 'Ain Dar and Shedgum being left with a thicker oil layer.

Finally, I have come around to Fractional_Flow's position that the wet area production in Figure 10 of SPE 93439 is that it is coming from wells with both oil and water coming in different zones, but that in any given zone, pretty much either water or oil flows - breakthrough is close to a binary affair. Two lines of argument support this (in addition to FF's reasoning). One is the well profile data that Euan highlighted the other day:

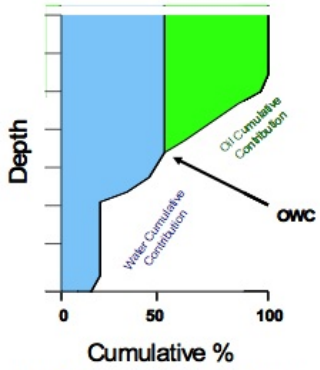


Fig. 7-Flow-meter profile schematic.

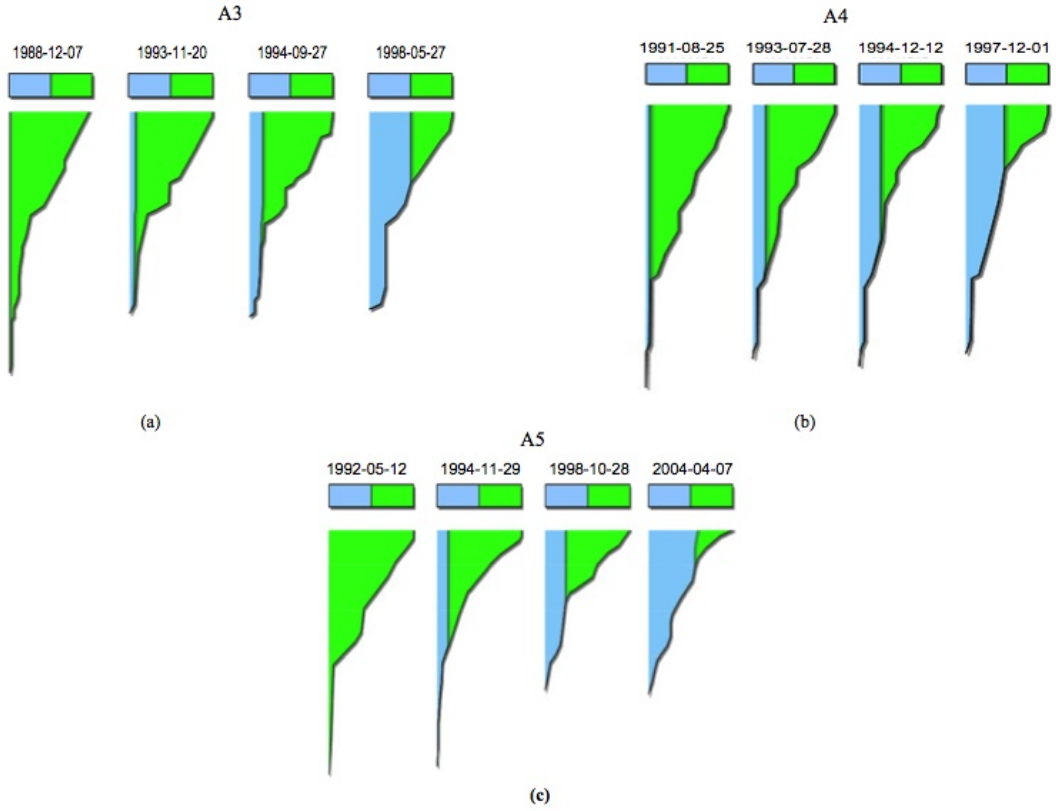
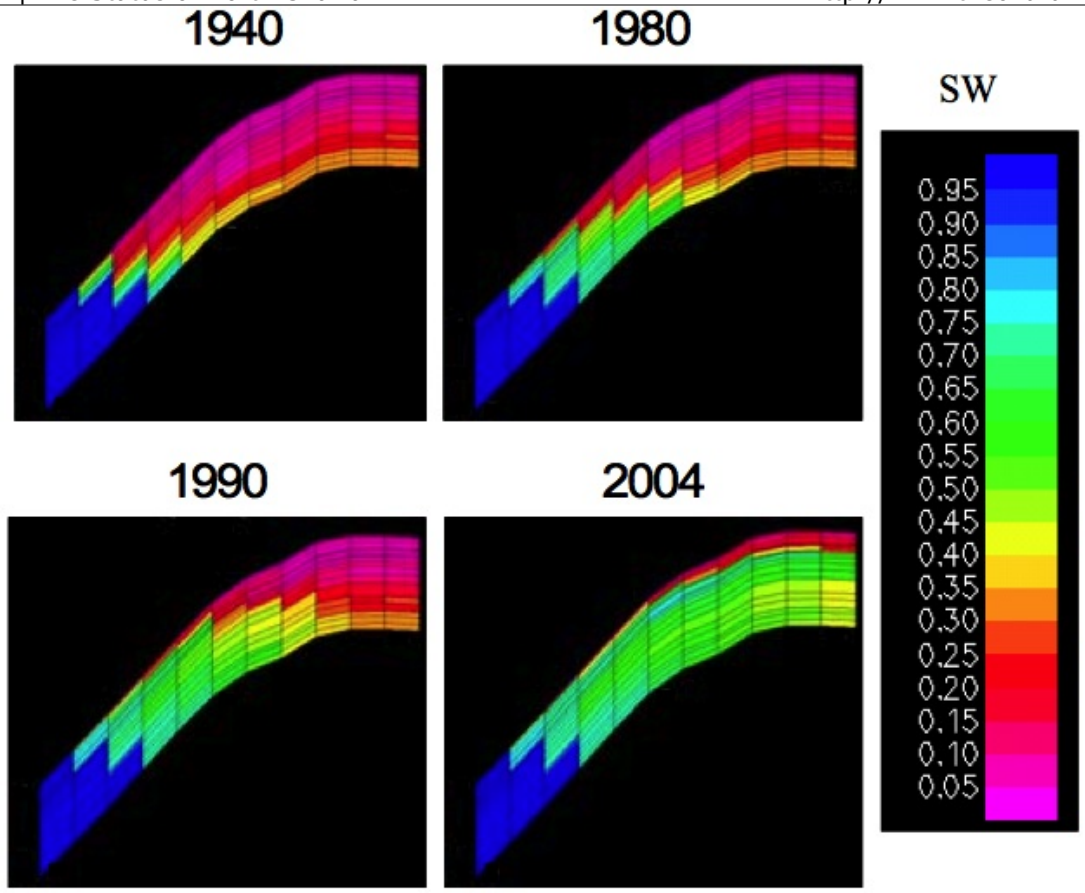


Fig. 8-Time-lapse flow-meter profiles for three wells.

Well profile data for three vertical wells. Source: Figure 8 of Alhuthali et al, Society of Petroleum Engineers Paper #93439, March 2005.

The line between the blue and the green zone in each case is very close to vertical all the way up the join between the two colored regions. That means hardly any water came out where oil was coming out, and hardly any oil came out where water was coming out.

Additionally, we can see in these pictures:



Western flank cross section of North 'Ain Dar. Source: Figure 9 of Alhuthali et al, Society of Petroleum Engineers Paper #93439, March 2005.

Once a given cell turns green or pale blue early on, it never changes again. Clearly no meaningful amount of oil is coming out of there.

This, finally, implies that I'm now willing to accept Fractional_Flow's idea that:

- 90% or so of 'Ain Dar/Shedgum's 2mbpd could water out over the course of a few years.
- We are likely somewhere in the midst of that process.
- That is likely the explanation for most of the Saudi production declines we have seen since June 2005 (including the failure of Haradh III and Qatif/Abu Safah to raise production)..