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The evolution of giant oil field production behaviour

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Abstract

The giant oil fields of the world are only a small fraction of the total number of fields, but their importance is huge. Over 50% of the world oil production came from giants by 2005 and more than half of the world's ultimate reserves are found in giants. Based on this it is reasonable to assume that the future development of the giant oil fields will have a significant impact on the world oil supply.

In order to better understand the giant fields and their future behaviour one must first understand their history. This study has used a comprehensive database on giant oil fields in order to determine their typical parameters, such as the average decline rate and life-times of giants. The evolution of giant oil field behaviour has been investigated to better understand future behaviour. One conclusion is that new technology and production methods have generally lead to high depletion rate and rapid decline. The historical trend points towards high decline rates of fields currently on plateau production.

The peak production generally occurs before half the ultimate reserves have been produced in giant oil fields. A strong correlation between depletion-at-peak and average decline rate is also found, verifying that high depletion rate leads to rapid decline. Our result also implies that depletion analysis can be used to rule out unrealistic production expectations from a known reserve, or to connect an estimated production level to a needed reserve base.

Key words:

Giant oil fields, field behaviour, peak oil, depletion

Introduction

There are two main ways of defining a giant oil field. One system is based on ultimately recoverable resources (URR), defining a giant as a field with a URR more than 0.5 Gb. The American Association of Petroleum Geologists (AAPG) follows this definition and has published a series of memoirs about giant oil fields and their geology (AAPG, 1970; 1980; 1992; 2003; 2005). Other later studies have used basically the same definition system (Nehring, 1978; Robelius, 2007).

The other system is to use production level, where a giant is a field producing more than 100 000 barrels per day (bpd) for more than one year (Simmons, 2002). Based on this definition of giant oil fields, also fields with production over 100 000 bpd have been included in the data set used in this study, even though they are not giants with respect to URR. It should however be noted that there are only about 20 such fields in total. A more detailed discussion of the giant field data used in this study can be found in the thesis by Robelius (2007).

However, the discovery of giant fields is a thing of the past since a majority of the largest giant fields are over 50 years old and the discovery trend is clearly for fewer giant fields with smaller volumes (Figure 1). The production by subclass can be seen in Figure 2. Understanding of how each subclass behaves is essential for understanding and accurately depicts future oil production.

Figure 1: Discovery trend for giant oil fields. The discovered volume refers to the backdated ultimately recoverable resources. Modified from Robelius (2007)

Figure 2: The history of oil production from the world's giant oil fields. The rapid expansion of oil production from the 1950s to the 1980s chiefly came from increased production from Middle East giants. The Non-OPEC nation fields peaked in the 1980s and have been in decline since then. The small upturn after 2000 coincides with the revival of Russian oil production after the fall of the Soviet Union.

Giant oilfield data

The data for this study has been taken from the giant oil field database compiled by Robelius (2007). AAPG was the main source for information about discovery year, year of first oil production, URR and cumulative production (AAPG, 1970; 1980; 1992; 2003; 2005). Other sources such as James (2000), the UK department of Trade & Industry (DTI), IHS, the Norwegian Petroleum Directorate (NPD), Arab Oil & Gas Directory (1980-2008) have also been used in the data compilation. In order to minimize the dynamic aspect of URR estimates, proven plus probable (2P) reserves has been used (Robelius, 2007). The need to use 2P reserves is justified by Bentley et al. (2007).

Production data were obtained from petroleum related trade journals like AAPG Explorer, Offshore, Offshore Engineer, Petroleum Review, Petroleum Economist, Upstream and World Oil. Other sources included statistical yearbooks from NPD, DTI, Petróleos Mexicanos (PEMEX), Nigerian National Petroleum Company (NNPC) and similar sources. Closer description of the database and how it was compiled can be found in Robelius (2007).

Aim of this study

This study will use the production profiles of over 300 giant oil fields to determine their typical production behaviour. The approach is statistical analysis based on production data for individual fields to find the average values of giant oil fields. The fields will be divided into various subgroups to better reflect their different properties and driving forces.

Production behaviour parameters, such as decline and depletion rate, will be investigated in order to show differences in behaviour among the subgroups. We also intend to show that depletion can be a useful parameter for predicting the onset of decline. Also the impact from technology can be revealed by studying how these parameters have evolved over time within the giant oil field population. This is meant as a wider investigation of the results earlier obtained by Gowdy and Juliá (2007).

Finally some brief remarks of how the derived values and parameters can be used to model future oil production from giant fields will be made. Depletion rates are used in oil production forecasts (Mäkivierikko, 2007; Campbell and Heapes, 2008). A closer investigation of depletion on a field-by-field basis may therefore benefit depletion modelling.

The produced share of the ultimate reserves when the peak occurs is also a heavily debated topic. Hubbert (1956) originally stated that the peak would occur when approximately half the resource had been consumed. Campbell and Laherrere (1998) later agreed, while others disagreed (Lynch, 2004). By studying giant oil fields and the produced shares of URR at peak, the discussion can be brought down to a field-level and made clearer.

The decline analysis has been used to model decline in existing production in many cases. This study also uses a larger data set than Robelius (2007) in order to determine a reasonable decline rates for giant oilfields. The derived parameters for may also be used to better model how each subgroup behaves, i.e. better reflecting the differences between onshore and offshore production or between OPEC and non-OPEC fields. The findings will also be compared with the results of the field-by-field analyses performed by Cambridge Energy Research Associates (CERA, 2007) and International Energy Agency (IEA, 2008).

Methodology and definitions

The giant fields can sometimes be very well-behaved and follow a theoretical production profile quite closely (Figure 3). In some fields, production has been influenced by wars, sabotage and temporary shut-downs for political reasons. These fields are generally harder to analyze, as they do not display similarly clear trends or stages. Many fields within OPEC have been partly shut down for a few years, or even mothballed during long periods.

The production profile of a giant field generally has a long plateau phase, thus no clear “*peak*” can be found. Hirsch (2008) defined a 4% fluctuation band in order to define a plateau and the end of that stage has been used as the “*peak year*” in this study. However, some fields do have a clear and distinct peak in their production curves, especially smaller giants.

The decline rate, the average annual decrease in production after the plateau phase ends, is carefully analyzed. An average annual decline rate, corresponding to an exponential decline curve model, was fitted to actual production data for the post-peak region, using least square methods. The exponential decline curve model was first proposed by Arps (1945). Further development of this method was done by Fetkovich (1980) and Mueller et al. (1981).

Due to the simplicity of Arps empirical approach, the basic relations has remained as a benchmark for industry for analysis and interpretation of production data. Although, one should

note that the empirical relations has also been shown to be the physical long-term solutions for various cases, such as the exponential decline curve is the physical solution to the constant pressure case (Hurst, 1934; van Everdingen and Hurst, 1949). The advantage of the decline curve analysis is that it is virtually independent of the size and shape of the reservoir or the actual drive-mechanism (Doublet, 1994), avoiding the need for more detailed reservoir or production data.

Figure 3: *Theoretical production profile of an oilfield, describing various stages of development in an idealized case. Adapted from Feygin and Ryzhik (2001) and Robelius (2007)*

The exponential decline model has been shown to be in good agreement with actual field data, both for describing the past and forecasting the future (Höök and Aleklett, 2008). From the exponential decline model it naturally follows that fields show no major change in their decline behaviour over time, consequently there is no need to divide the decline phase into several stages. Despite this, other studies have chosen to split the decline phase into three substages (CERA, 2007; IEA, 2008). For a closer study of the decline rates of giant oil fields and what it means for future oil production a separate study has been performed (Höök et al., 2008).

The depletion rate, i.e. the amount of the remaining ultimate reserves that is extracted each year, is also analyzed. This parameter is calculated using URR and historical production data. The depletion rate when the field peaks or ends its plateau phase is here called *depletion-at-peak* and corresponds to the percentage of remaining reserve that is produced when the onset of decline starts. This parameter is essential for the maximum depletion rate model, which has been discussed in detail by others (Jakobsson et al., 2008). The decline rate, in comparison, is only derived from production data. Consequently, depletion can be seen as a parameter capable of bridging the gap between production and geology.

The cumulative amount of the URR that has been produced at the onset of decline, here called “*Cum.Prod/URR-at-peak*”, is also investigated. This parameter is derived from the historical production data and the URR estimate. It is useful for determining how much of the URR can be produced from a field before it will begin to decline. Figure 4, 5, 6 and 7 illustrate the concept with *depletion-at-peak* and *Cum.Prod/URR-at-peak*, both on a theoretical and empirical basis.

Naturally there is some uncertainty in the URR estimates, and this will influence both depletion rate and the share of URR produced at peak, as they are derived from both URR and production data. Hundreds of URR estimates for different giant oil fields have been compiled for this study. However, in many cases only one URR estimate per field was found and had to be used. Closer discussion of the spread in URR estimates can be found in Robelius (2007). A higher URR value will yield lower depletion and share of URR produced at peak, while a lower URR value will result in the opposite.

Also the time between discovery to first oil, called “*discovery-to-first oil*”, and from first oil to onset of decline, here called “*first oil-to-decline*” is determined for each field. These two parameters show how long it has taken from discovery to start of commercial oil production and for how long a field was in build-up or plateau phase before it started to decline. They can be calculated using the discovery year, year of first oil production and the peak year. These parameters provide information about the life time of a giant oil field.

Figure 4: A theoretical production profile of a giant oil field is used to show how the depletion rate and the produced share of the URR evolve as the field passes through various stages of its life. When the plateau ends the “peak” occurs and the depletion-at-peak and Cum-prod/URR-at-peak can be found. The Cum.Prod/URR-at-peak is expressed in percent and has been scaled with a factor 10 to fit in the same axis as depletion rate.

Figure 5: The actual production profile of the Norwegian giant oilfield Ula. The peak occurred in 1993 at a depletion rate of 16.4% with 53% of the URR produced, which is quite representative of many offshore giant fields in the North Sea region.

Figure 6: The famous giant oilfield Prudhoe Bay in the USA. The peak happened in 1988 at a depletion rate of 7.2% with 46% of the URR produced.

Figure 7: The production curve of the Nigerian giant field Jones Creek. This field peaked at a depletion rate of 7.0% with only 11.5% of the URR produced. Major disturbances, due to civil war, sabotage and rebel attacks, have greatly influenced production.

Characteristic behaviour

The first and most necessary division one must do is to split the giant fields into two subclasses, land-based and offshore fields. Because of the financial and practical differences between these two types of installations, this division is needed to establish a comprehensive picture of how each subclass behaves. A further division into OPEC-fields and non-OPEC fields has also been made. This is to reflect better the potentially different behaviour of giants with no political restrictions on production and those limited by quota systems. There is a significant difference in the actual production strategy between the quota-restricted fields in OPEC and those fields outside that organization's control.

This study covers 331 giant oil fields, with a combined URR of over 1100 Gb, based on the most optimistic URR estimations available in the database. The estimates for some fields vary significantly in some cases. For example, URR-estimates for Ghawar range from 66-150 Gb. Closer discussion of the URR estimates can be found in Robelius (2007).

A total of 214 (~65%) fields are land-based, while 117 (~35%) are offshore installations. 261 fields (~79%) have been classified as post-plateau and in decline and of these 170 (~65%) are land-based and 91 (~35%) are offshore. OPEC controls or has controlled 143 (~43%) of the fields. Gabon are no a longer member of OPEC, but was formerly a part of the organisation; consequently their fields are therefore classified as OPEC-fields because they have been

subjected to the quota system. Same applies to Ecuador, which suspended its OPEC membership in 1992 and rejoined in 2007. In total the OPEC class includes 104 (~73%) fields on land and 39 offshore (~27%). Outside OPEC, 190 fields have been studied with 110 fields (~58%) onshore and 78 (~42%) offshore. The North Sea, Russia and the US can perhaps be seen as the most important regions within the non-OPEC group.

Based on their production curves some parameters can be calculated for each field. The number of fields is also large enough to provide reasonable statistics and form a sound mean value of the giant oil fields as a group. These values were also weighted against the peak/plateau production to provide an alternative view. Table 1 shows the values of all analyzed giant fields, regardless of their geographical location or which nation controls them. It should be noted that such a wide group is likely to miss the details and differences between, for instance, land and offshore fields.

The mean value was calculated as the arithmetic mean. The median value was defined as the common median, i.e. the value that separated the lower half of the population from the upper half. The standard deviation was defined as in Equation 1. The production-weighted average was defined as Equation 2. The reason for weighting against the peak/plateau production level was to find a suitable way of giving greater weight to fields which play a larger role in the production. This means that a 1 Mbpd field will be regarded as more important than a 100 000 bpd field. We believe that this weighting is better than using the cumulative production, since high production flows matter more to the oil market than modest flows under longer times. However, no weighting method can be seen as optimal, our choice will also be a complement to IEA (2008), which weighted against cumulative production.

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{(n-1)}} \quad \text{Equation (1)}$$

Where n = sample size, $\bar{x}$ = arithmetic mean of sample

$$\text{PW-decline} = \frac{\sum D_i * P_i}{\sum P_i} \quad \text{Equation (2)}$$

Where D_i = decline for individual fields according to the exponential decline curve model,

P_i = peak or plateau production level of individual fields

From Table 1 it can be seen that there is a significant spread in the data and simple calculations, without taking the special properties of various subgroups into account, does not give very trustworthy numbers. Figure 8, 9, 10 and 11 gives a better example of the spread in some of the data.

Table 1: Characteristic parameters of giant fields. Fields that have not yet reached their decline phase (as of 2005) are excluded. In total the post-plateau behaviour of 261 giant oil fields, distributed all over the world, is summarized here.

All Giant Fields	Mean	Median	Prod. weight	Std. dev.
Depletion-at-peak	8.1%	7.2%	7.2%	4.3%
Decline rate	-6.5%	-5.3%	-5.5%	4.9%
Cum. Prod./URR-at-peak	38.6%	38.3%	36.8%	16.9%
Discovery-to-First Oil	5.2 years	3.0 years	4.2 years	5.7 years
First Oil-to-Decline	17.7 years	13.0 years	18.7 years	16.1 years

An analysis of giant oil fields divided into onshore and offshore fields yields the results displayed in Table 2. Both land and offshore fields enter the decline phase when about 40% of the URR have been produced, but offshore fields tend to extract the oil at a higher rate than land-based fields. This also explains why the average lifetimes of offshore fields are shorter than for land-fields and why they decline faster. Unsurprisingly, one can also, see that offshore fields require more time from discovery to the start of commercial oil production. All this is logical due to the higher investments required for offshore installations.

Figure 8: Histogram of the depletion-at-peak of the 170 post-plateau giant fields located on land. A small spread occurs, but the vast majority is centered in the 5-10% interval. Despite the fact that all the studied field are widely different, in terms of reservoirs, production strategies and much more, the actual difference in behavior seems small.

Figure 9: Histogram of the depletion-at-peak of the 91 post-plateau giant fields located offshore. The spread is somewhat larger than for land fields, but once again the majority is located in a relatively narrow interval.

Figure 10: Histograms of the share of URR produced at the onset of decline for giant oil fields located on land. The fields with over 55% of URR produced at peak are almost solely the American giants that were revived during the oil crisis in the 1970-1980s.

Figure 11: Histograms of the share of URR produced at the onset of decline for giant oil fields located offshore.

Table 2: Characteristic behaviour of land and offshore fields. The land group include 170 post-plateau fields and the offshore group 91 post-plateau fields. Fields that have not yet ended their plateau phase or are in build-up phase are excluded (as of 2005).

<u>Land Fields</u>	Mean	Median	Prod. Weight	Std. Dev.
Depletion-at-peak	6.8%	6.1%	5.8%	3.5%
Decline rate	-4.9%	-4.4%	-3.9%	3.5%
Cum. Prod. / URR at peak	38.1%	36.2%	34.1%	17.5%
Discovery-to-First Oil	4.6 years	3.0 years	3.7 years	5.4 years
First Oil-to-Decline	21.4 years	16.0 years	21.0 years	17.9 years
<u>Offshore Fields</u>	Mean	Median	Prod. Weight	Std. Dev.
Depletion-at-peak	10.4%	9.4%	11.0%	4.8%
Decline rate	-9.4%	-9.0%	-9.7%	5.8%
Cum. Prod. / URR at peak	39.4%	40.3%	44.0%	15.7%
Discovery-to-First Oil	6.3 years	5.0 years	5.3 years	6.0 years
First Oil-to-Decline	10.8 years	8.0 years	12.4 years	8.3 years

Table 3: Characteristic behaviour of non-OPEC fields. In total 164 fields are analysed, of which 67 fields are offshore and 97 are located on land. Fields that have not yet ended their plateau phase or are in build-up phase are excluded (as of 2005). In total 87% of all giants outside OPEC can be classified as post-plateau, this corresponds to having 83% of all the URR in giant oil fields outside OPEC located in post-plateau fields.

<u>All Non-OPEC fields</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	9.1%	8.0%	8.7%	4,7%
Decline rate	-7.5%	-6.3%	-7.1%	5,0%
Cum. Prod. / URR at peak	42.2%	41.4%	40.7%	16,7%
Discovery-to-First Oil	5.0 years	3.0 years	3.8 years	5,1 years
First Oil-to-Decline	19.1 years	14.0 years	17.9 years	17,6 years
<u>Non-OPEC land</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	7.5%	6.5%	6.8%	3,7%
Decline rate	-5.7%	-4.7%	-5.2%	3,6%
Cum. Prod. / URR at peak	42.8%	40.5%	37.4%	18,0%
Discovery-to-First Oil	4.0 years	2.0 years	2.6 years	4,9 years
First Oil-to-Decline	25.0 years	19.0 years	21.2 years	19,7 years
<u>Non-OPEC offshore</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	11.5%	10.6%	11.8%	4,9%
Decline rate	-10.0%	-9.4%	-10.3%	5,6%
Cum. Prod. / URR at peak	41.3%	41.6%	46.2%	14,7%
Discovery-to-First Oil	6.3 years	5.0 years	5.7 years	5,2 years
First Oil-to-Decline	10.4 years	9.0 years	12.6 years	8,0 years

From Table 2 it can be seen that the actual difference in behaviour for land and offshore fields is significant. This division also reduces the dispersion in the data and yields a more reliable result.

The results of the non-OPEC fields can be seen in Table 3. Once again the high depletion, high decline rates and short lifetimes of offshore fields compared to land fields can be seen. The average decline rate of all non-OPEC giant fields is above 7%, indicating that non-OPEC production will be dropping relatively fast, especially in offshore regions.

Many of the low decline rates can be found in fields from the USA that peaked prior to the 1970s. In fact, most of the non-OPEC land group is dominated by the USA and its giant fields. The non-OPEC offshore group is mostly dominated by giant fields in the North Sea. Many fields, both giant fields and smaller ones, in the North Sea show a high decline rate (Höök and Aleklett, 2008; Zittel, 2001).

Table 4: *Characteristic behaviour of OPEC-fields. In total 97 fields, of which 24 fields are offshore and 73 are located on land. Fields that have not yet ended their plateau phase or are in build-up phase are excluded (as of 2005). In total 67% of all OPEC giant fields can be classified as post-plateau, which corresponds to having 48% of all URR in OPEC giants in post-plateau fields.*

<u>All OPEC fields</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	6.3%	5.9%	5.3%	2,8%
Decline rate	-4.8%	-4.1%	-3.4%	4,2%
Cum. Prod. / URR at peak	32.4%	31.6%	31.5%	15,3%
Discovery-to-First Oil	5.6 years	3.0 years	4.7 years	6,3 years
First Oil-to-Decline	15.6 years	12.0 years	19.8 years	13,1 years
<u>OPEC land</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	5.9%	5.4%	4.9%	2,7%
Decline rate	-3.8%	-3.8%	-2.8%	2,8%
Cum. Prod. / URR at peak	31.8%	31.2%	31.0%	14,6%
Discovery-to-First Oil	5.3 years	3.0 years	4.8 years	6,3 years
First Oil-to-Decline	16.7 years	12.5 years	20.8 years	13,9 years
<u>OPEC offshore</u>	Mean	Median	Prod. weight	Std. Dev.
Depletion-at-peak	7.5%	7.7%	7.5%	2,8%
Decline rate	-7.7%	-6.1%	-7.5%	6,1%
Cum. Prod. / URR at peak	34.1%	33.8%	34.8%	17,6%
Discovery-to-First Oil	6.4 years	4.0 years	3.9 years	7,5 years
First Oil-to-Decline	12.0 years	7.0 years	12.0 years	9,3 years

In comparison to the non-OPEC group one can see that the OPEC group generally has lower depletion rates and decline rates, as seen in Table 4. One quite intriguing detail is that OPEC fields tend to exit the plateau phase at a lower percentage of the URR as produced volumes. This is in many ways an explanation for the lower decline rate. Instead of a prolonged plateau, a

longer decline phase with less annual decrease has generally been favoured as a production strategy compared to the non-OPEC fields.

Both land and offshore fields within OPEC tend to have much softer decline rates than their non-OPEC counterparts. The general conclusion from this is that the OPEC quota system has been quite efficient in restricting production levels and maintaining the longevity of fields rather than extracting the oil faster, with the accompanying high decline rates.

Evolution of the field behaviour

Many of the giant fields are old and had their plateau phases before much of the modern technology utilized today was implemented and standardized. Therefore it can be useful to study the evolution of field behaviour and how this has changed over time, due to the introduction of new technology and production methods.

The year that a field left plateau production will be used to form subgroups. For instance if a field started to decline sometime between 1950-1959 it will be sorted into the 1950s group and so on. The same subdivisions as previously will be used here to present a comprehensive picture of how the behaviour has changed from group to group. It should however be noted that in some cases the available statistics are poor, especially in the 2000s due to the low number of fields that started to decline in this decade.

Results for land and offshore fields can be seen in Tables 5 and 6 respectively. The trends are clear and a tendency towards higher depletion, decline rate and share of URR produced when the plateau phase is over can be seen for the giant oil fields. Also the time from first commercial oil production to the onset of decline has considerably increased, as has the proportion of URR produced before a field enters the decline phase. All this can be summarized as a generally prolonged plateau phase compared to further back in time.

One can therefore conclude that average decline rates for the giant oil fields as a group are increasing with time, even though individual field decline rates are constant once the field has left plateau production. This is in agreement with CERA (2007). The important conclusion CERA fails to draw from the historical trends in oil field behaviour is that the fields that are declining now or will begin to decline in the near term will do so with an average decline rate generally higher than the fields that left plateau level earlier in history.

New technology and the introduction of new production methods have greatly altered decline behaviour and the typical parameters for the 1960s are not valid today. Effectively this means also that one must apply a generally higher decline rate to the giant fields in the future. The low average value of -6% annually is not representative for the giant fields that are about to leave the plateau level in the near and medium term. Prolonged plateau level and increased depletion, made possible by new technology, result in a generally higher decline rate. New technology has made it possible to extract oil from fields faster and to keep flow rates high for an extended period of time, but once production starts to fall it falls more rapidly. This is in good agreement with another study on technology and exhaustion (Gowdy and Juliá, 2007).

Table 5: *Evolution of the behaviour of land-based giant fields. The decade that the fields left plateau production is used to form the different subgroups. The standard deviation is given based on the sample.*

# fields	Depletion-at-peak	Mean	Median	Prod. weight	Std. Dev.
23	Pre 1960	6,2%	4,7%	6,6%	3,3%
19	1960s	7,3%	6,8%	8,7%	2,5%
72	1970s	6,4%	5,6%	4,9%	3,4%
25	1980s	6,3%	6,1%	5,6%	1,9%
28	1990s	7,8%	7,0%	6,9%	4,5%
4	2000s	11,6%	11,0%	12,1%	4,8%
# fields	Average Field Decline	Mean	Median	Prod. weight	Std. Dev.
23	Pre 1960	-4,2%	-4,4%	-4,2%	1,6%
19	1960s	-5,1%	-5,5%	-5,9%	3,0%
72	1970s	-4,2%	-3,9%	-3,0%	3,1%
25	1980s	-4,4%	-4,1%	-3,9%	2,6%
28	1990s	-6,9%	-5,6%	-5,6%	4,8%
4	2000s	-10,7%	-9,8%	-10,1%	3,5%
# fields	Cum./URR at Peak	Mean	Median	Prod. weight	Std. Dev.
23	Pre 1960	37,5%	36,1%	31,1%	13,9%
19	1960s	35,1%	30,0%	34,0%	18,4%
72	1970s	36,3%	34,2%	31,1%	19,3%
25	1980s	37,2%	31,6%	33,6%	14,7%
28	1990s	44,9%	40,2%	44,7%	16,4%
4	2000s	46,2%	45,2%	46,5%	15,7%
# fields	Discovery-to-First Oil	Mean	Median	Prod. weight	Std. Dev.
23	Pre 1960	2,4	1,0	2,3	3,3
19	1960s	1,7	1,5	2,0	1,6
72	1970s	4,1	3,0	4,4	4,6
25	1980s	4,7	2,0	3,2	6,2
28	1990s	5,2	3,0	3,9	5,7
4	2000s	1,5	1,5	1,5	1,7
# fields	First Oil-to-Decline	Mean	Median	Prod. weight	Std. Dev.
23	Pre 1960	18,2	17,0	38,3	10,4
19	1960s	17,0	8,0	12,4	19,4
72	1970s	19,9	14,0	19,8	15,6
25	1980s	23,6	16,0	22,1	18,8
28	1990s	27,8	21,5	28,9	24,2
4	2000s	26,3	25,5	25,9	23,5

Table 6: *Evolution of the behaviour of offshore giant fields. The decade that the fields left plateau production is used to form the different subgroups.*

# fields	Depletion-at-peak	Mean	Median	Prod. weight	Std. Dev.
0	Pre 1960	-	-	-	-
2	1960s	5,3%	5,3%	5,9%	2,4%
17	1970s	7,7%	7,9%	8,1%	3,0%
16	1980s	9,8%	9,9%	10,5%	3,4%
35	1990s	10,9%	9,6%	11,2%	5,2%
19	2000s	13,0%	12,3%	12,4%	5,0%
# fields	Average Field Decline	Mean	Median	Prod. weight	Std. Dev.
0	Pre 1960	-	-	-	-
2	1960s	-2,8%	-2,8%	-3,7%	3,3%
17	1970s	-5,9%	-6,1%	-6,3%	3,5%
16	1980s	-7,9%	-7,5%	-8,9%	4,1%
35	1990s	-10,4%	-11,4%	-10,6%	6,6%
19	2000s	-12,5%	-12,6%	-10,8%	5,1%
# fields	Cum./URR at Peak	Mean	Median	Prod. weight	Std. Dev.
0	Pre 1960	-	-	-	-
2	1960s	29,8%	29,8%	33,4%	13,7%
17	1970s	29,1%	25,1%	28,5%	14,9%
16	1980s	39,3%	39,6%	40,4%	12,5%
35	1990s	43,8%	44,8%	46,3%	14,9%
19	2000s	41,2%	40,4%	49,8%	17,3%
# fields	Discovery-to-First Oil	Mean	Median	Prod. weight	Std. Dev.
0	Pre 1960	-	-	-	-
2	1960s	3,5	3,5	3,0	2,1
17	1970s	3,8	3,0	3,2	1,9
16	1980s	3,9	3,5	3,8	2,8
35	1990s	5,7	5,0	5,2	3,9
19	2000s	9,4	7,5	6,9	7,1
# fields	First Oil-to-Decline	Mean	Median	Prod. weight	Std. Dev.
0	Pre 1960	-	-	-	-
2	1960s	13,0	13,0	14,1	4,2
17	1970s	9,2	7,0	7,4	8,5
16	1980s	8,3	8,0	8,1	4,3
35	1990s	12,4	11,0	13,0	9,2
19	2000s	11,0	8,0	15,8	9,2

The land and offshore division is useful to show the general behaviour of giant oil field, but it does not distinguish between fields subjected to the OPEC quota-system with its political restrictions and those producing under more “free market”-conditions. It is especially evident in Table 5 that some unusual behaviour occurred during the 1970s and 1980s. This is very likely connected to the oil crises at that time and the large number of OPEC-controlled land fields that behaved unnaturally for political reasons.

By applying the OPEC and non-OPEC division one can better see how the differences in behaviour have evolved for the two groups (Table 7 and 8). Especially in the OPEC-group the oil crisis in the 1970s can clearly be seen, with a large number of fields starting to decline prematurely at a small percentage of the URR produced compared to those non-OPEC fields that reached the onset of decline in the same decade. This also means that the OPEC fields peaked at lower depletion values, hence showing low average decline rates.

Table 7: *Evolution of the behaviour of non-OPEC giant fields. The decade that the fields left plateau production is used to form the different subgroups.*

# fields	Depletion-at-peak	Mean	Median	Prod. weight	Std. Dev.
13	Pre 1960	6,4%	4,3%	6,9%	4,2%
12	1960s	6,3%	6,5%	6,8%	1,7%
46	1970s	7,9%	6,8%	7,5%	4,0%
33	1980s	8,2%	7,2%	8,2%	3,1%
40	1990s	10,9%	9,5%	10,1%	5,6%
20	2000s	13,3%	12,4%	12,3%	4,9%
# fields	Average field decline	Mean	Median	Prod. weight	Std. Dev.
13	Pre 1960	-4,2%	-3,8%	-4,3%	1,7%
12	1960s	-4,9%	-4,9%	-6,0%	2,5%
46	1970s	-5,8%	-4,7%	-4,9%	3,1%
33	1980s	-6,3%	-5,3%	-4,6%	3,6%
40	1990s	-10,2%	-9,5%	-6,5%	6,6%
20	2000s	-11,7%	-11,8%	-9,9%	4,3%
# fields	Cum./URR at Peak	Mean	Median	Prod. weight	Std. Dev.
13	Pre 1960	37,3%	31,9%	28,2%	16,0%
12	1960s	40,9%	42,8%	37,8%	18,0%
46	1970s	42,8%	43,9%	38,5%	20,6%
33	1980s	38,4%	37,7%	33,3%	14,3%
40	1990s	45,6%	44,8%	46,8%	14,9%
20	2000s	44,3%	43,6%	53,2%	15,6%
# fields	Discovery-to-First Oil	Mean	Median	Prod. weight	Std. Dev.
13	Pre 1960	2,3	0,0	1,7	3,8
12	1960s	2,1	2,0	2,4	1,9
46	1970s	3,2	2,5	2,5	3,0
33	1980s	4,5	3,0	2,3	5,6
40	1990s	6,1	5,5	4,2	4,9
20	2000s	8,6	6,0	0,9	7,4
# fields	First Oil-to-Decline	Mean	Median	Prod. weight	Std. Dev.
13	Pre 1960	18,3	16,0	12,1	11,6
12	1960s	23,9	18,0	20,0	20,8
46	1970s	22,8	23,5	21,9	16,0
33	1980s	17,1	9,0	18,1	17,2
40	1990s	18,0	12,0	29,8	21,7
20	2000s	13,5	11,0	36,2	12,3

Table 8: *Evolution of the behaviour of OPEC giant fields. The decade that the fields left plateau production is used to form the different subgroups.*

# fields	Depletion-at-peak	Mean	Median	Prod. weight	Std. Dev.
10	Pre 1960	5,8%	5,5%	6,1%	1,8%
8	1960s	8,3%	7,9%	10,2%	3,1%
43	1970s	5,3%	4,9%	4,2%	2,1%
8	1980s	5,5%	5,2%	3,4%	2,3%
24	1990s	7,3%	7,1%	6,3%	3,0%
4	2000s	10,2%	8,3%	14,1%	4,6%
# fields	Average field decline	Mean	Median	Prod. weight	Std. Dev.
10	Pre 1960	-4,3%	-4,7%	-4,0%	1,5%
8	1960s	-4,9%	-5,5%	-5,9%	3,9%
43	1970s	-3,2%	-3,1%	-2,2%	2,6%
8	1980s	-3,7%	-4,1%	-1,9%	3,2%
24	1990s	-6,6%	-5,7%	-4,0%	4,5%
4	2000s	-14,7%	-12,2%	-10,2%	7,5%
# fields	Cum./URR at Peak	Mean	Median	Prod. weight	Std. Dev.
10	Pre 1960	37,7%	36,9%	36,1%	11,4%
8	1960s	25,1%	24,4%	30,5%	13,4%
43	1970s	26,5%	24,1%	28,2%	13,0%
8	1980s	36,7%	35,1%	34,6%	12,1%
24	1990s	42,0%	42,8%	41,1%	16,3%
4	2000s	30,7%	28,9%	40,6%	20,4%
# fields	Discovery-to-First Oil	Mean	Median	Prod. weight	Std. Dev.
10	Pre 1960	2,6	1,5	3,4	2,6
8	1960s	1,6	1,5	1,7	1,2
43	1970s	4,9	3,0	5,2	5,3
8	1980s	3,9	4,5	6,2	2,6
24	1990s	4,3	3,0	3,5	4,2
4	2000s	5,5	4,5	2,1	5,6
# fields	First Oil-to-Decline	Mean	Median	Prod. weight	Std. Dev.
10	Pre 1960	18,1	17,0	17,2	9,1
8	1960s	5,6	4,5	5,4	3,9
43	1970s	12,8	7,0	19,0	12,6
8	1980s	20,0	16,0	34,1	15,0
24	1990s	21,1	21,5	27,4	13,3
4	2000s	14,0	5,5	17,0	20,1

Discussion

The historical evolution of depletion-at-peak values for giant fields is of great interest, as depletion-at-peak can be used to make crude estimates of when a field will enter the decline phase. When a field is in plateau production it is possible to estimate when onset of decline will occur, using depletion analysis. The narrow spread in depletion-at-peak for giant oil fields (Figure 8), provides a reasonable ground for estimating the peak years of giant fields currently in build-up or plateau phase. A production peak occurring at too low depletion rate can therefore be regarded as a production disturbance, due to non-geological reasons, rather than the onset of depletion-driven decline. This is obvious in the case of many Middle East fields that peaked in the 1970s, in the wake of the oil crises at that time.

The depletion-at-peak may also be used to control URR-estimates using production curves. If a field is reasonably well-behaved and has reached the onset of decline, one can assume that approximately the same depletion-at-peak was reached as for similar giants. For field on plateau level, one can assume that the depletion rate must be lower than the typical depletion-at-peak levels, otherwise the field would have begun to decline. This can be used to rule out some URR estimates. The enormous Cantarell field of Mexico is estimated to contain ultimate reserves of 11-20 Gb (Robelius, 2007), corresponding to depletion-at-peak values of 66.2-7.5%. It is only the depletion-at-peak values between 5-15% that are reasonable, if Cantarell is assumed to behave similar as other giant oilfields (Figure 8), so the URR-estimates giving depletion levels outside this interval may be regarded as unrealistic. Consequently, depletion connects production output to reserve base, since only some depletion rates are possible for a given reserve base without reaching a peak production.

Alternatively the depletion-at-peak can be used as a reasonable value for the maximum depletion rate in a maximum depletion rate model in order to forecast future oil production (Jakobsson et al., 2008). Understanding depletion and its impact on decline is also vital for determining how the future will unfold. The depletion rate of a region is limited by the depletion rates of the individual fields that make up the region. Further studies of the connection between depletion rates of oil fields and regions should be undertaken to better establish the actual relationship. Depletion models have been used by Campbell and Sivertsson (2003), Mäkilä (2007), Campbell and Heapes (2008). It is our hope that the derived depletion behaviour of giant oil fields can benefit depletion modelling of future oil production. Field-by-field analysis shows a narrow distribution of depletion rates in giant oil fields, justifying the use of depletion as a tool for production forecasting.

The produced share of URR at the onset of decline can also be used in the same way to make crude estimates of when a field will reach the onset of decline. On average, about 40% of the URR has been produced for the world's giant oil fields when they leave plateau production and enter the decline phase. Looking at the cumulative production and URR it is then possible to estimate how long a field can remain on plateau production.

As an example consider Ghawar, the world's largest oil field. By 2005 its cumulative production was around 61 Gb and we will make the optimistic assumption of a URR of 150 Gb. Assuming that the production was constant at around 5 Mbpd for 2006 and 2007 the produced share of URR by end of 2007 was 43%. This is in line with the 48% of reserves produced as stated by Saudi-Aramco (2004). This is just about the typical share of URR produced at the onset of decline and can be seen as an indication that the peaking of Ghawar is not very far away. As Ghawar is already subject to extensive water-injection and other secondary measures a high

decline rate seems likely once the onset of decline begins. As Simmons (2005) pointed out, “Twilight in the Desert” is likely not far in the future.

Prolonging plateau production and increasing production levels is equivalent to increasing the depletion of the field. Most of the world’s giants have also reached maturity and many of these fields are subject to measures to increase recovery (Babadagli, 2007). Drilling of new wells and installation of more equipment can delay the actual onset of decline for some years, but once that oil field starts to decline the decline is faster. Studies have shown that production technology seldom increases the ultimate recovery, rather, only masks increasing resource exhaustion by increasing the depletion rate (Gowdy and Juliá, 2007).

A strong correlation between depletion-at-peak and average decline rate is also found. The correlation coefficient is calculated to be 0.74. Unsurprisingly, this can be seen as verification of the ironic nature of depletion of finite resources such as oil: *“the better you do the job; the sooner it ends”*.

Conclusions

The characteristic behaviour of giant oil fields has been carefully examined in this study to establish statistically reasonable parameters. With a large database covering the world’s giant oil fields that were responsible for well over 50% of total oil output in 2005, it has been possible to characterise the typical behaviour of giant oil fields.

The evolution of the parameters has shown that fields leaving plateau production in the future will decline more rapidly than fields from further back in history. A larger share of the URR will also be produced before the field reaches the onset of decline. The increased depletion of the fields, made possible by new technologies, can be seen as the main explanation for this.

The non-OPEC group contains mostly giant oil fields that have reached decline phase. In total 87% of all giant oil fields in this group can be classified as post-plateau and 84% of the non-OPEC giant oil field URR is located in declining fields. Most of the non-OPEC fields have already shown the typical behaviour for this group and the small share that remain to show this behaviour will have a relatively small impact on the world supply situation.

Regarding OPEC, more than 50% of all URR in their giant fields is also located in fields that have not yet reached the onset of decline. They still have plenty of oil left in fields that have not begun to decline, so the future production strategy and the resulting decline rates of OPEC giant oil fields will be very influential on the future world oil supply. The prolonged plateau production and higher depletion of those fields will mean that their decline will be fast once they leave their plateau phases.

From our study of the evolution of field behaviour, one can see that the average values found in Table 1 are not applicable to the giant fields that are about to leave the plateau stage in the near and medium term. More reasonable values can be obtained by treating the different subgroups separately (Table 2, 3 and 4) and combining them with the historical trends in giant oilfield behaviour. When it comes to the average decline rates of giant oilfields, our results end up in the same range as CERA (2007) and IEA (2008). This is discussed in more detail in Höök et al. (2008). Our results may also be useful in all forms of decline modelling of oil production.

Calculating general mean values of all giants, regardless of when in time they reached the onset of decline, is interesting, but do not properly reflect the behavioural changes imposed by new technology and production methods. Therefore those mean values should not be used as representative values for future decline in fields that will leave their plateau levels in the near or medium term future. To find realistic values for fields that are about to reach the onset of decline

the effects of technology must be included. With the introduction of new technology and production methods the behaviour has changed dramatically over the decades. Prolonged plateau production with its corresponding high decline rates has been favoured compared to the behaviour of the 1960s and before. Based on the historical trend in giant oilfield behaviour it is reasonable to assume that future fields will decline and be depleted faster than fields from before.

The introduction of new technology and production methods has greatly enhanced depletion and made it possible to extend plateau production and prevent the onset of decline for some time, but once the decline starts its rate is higher. In many ways the use of technology to extend plateau production will disguise increasing scarcity, as earlier pointed out by Gowdy and Juliá (2007). Production management may therefore chose between a relatively shorter plateau phase and gentle decline or a longer plateau stage with generally higher decline.

Furthermore, we propose depletion as a useful parameter to bridge the gap between production and geology. Depletion analysis can be used to rule out unrealistic production expectations from a known reserve, or to connect an estimated production level to a needed reserve base. Depletion analysis can also rule out unreasonable URR estimates for individual oilfields or be utilized to obtain basic estimates of the URR from production figures. The narrow spread in depletion-at-peak provides a solid ground for depletion modeling of oil production (Figure 8). From a physical point of view, it is the extent of depletion that is the governing factor of giant oil field behavior. As expected, we also found a strong correlation between depletion and decline.

Finally we can conclude that the peak usually occurs before half the ultimate reserves have been produced in giant oil fields. From a large field-by-field analysis of the largest contributing group to the world oil production, it cannot be claimed that the peak would occur after more than half of the ultimate reserves have been produced. This result brings strength to the original assumption by Hubbert (1956), but more comprehensive analysis of the connection between individual fields and regions are encouraged to better illuminate this topic.

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