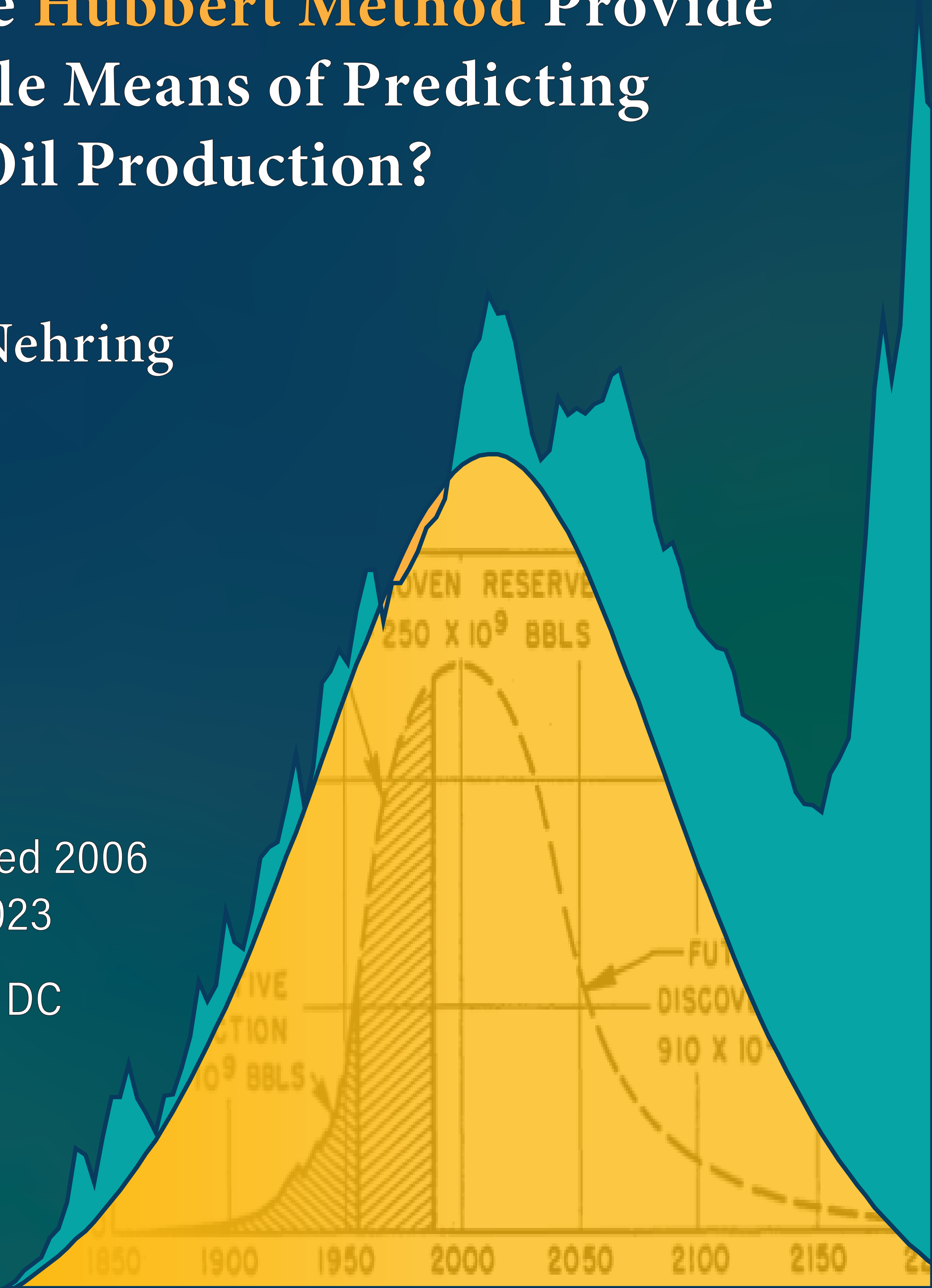
Report re-issue

Energy Policy Research Foundation

Does the Hubbert Method Provide a Reliable Means of Predicting Future Oil Production?

Richard Nehring



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About the Energy Policy Research Foundation

The Energy Policy Research Foundation was founded in 1944 and is a not-for-profit organization that studies energy economics and policy issues with special emphasis on energy security, including the role of oil, natural gas, and petroleum products in the national economy. It provides objective and technical analysis on a wide range of energy issues. It is funded by a variety of donors including foundations, the private sector, and occasional project specific research requested by the U.S. government. We frequently testify before the U.S. Congress. Through our newly established Darius W. Gaskins, Jr. Center for Energy Security Studies we are engaged in a long-term assessment of the costs, benefits, timing, and energy security implications of alternative pathways to a lower carbon energy system for the national economy. The institute's publications and workshops are available on our website: www.eprinc.org.

About the Author

On August 27, 2019, Richard D. Nehring, passed away at the age of 76 in Colorado Springs, Colorado. He was a good friend and routinely engaged with us a broad range of technical issues on long-term oil and gas supply. He was the founder of NRG Associates which maintained the Significant Oil and Gas Fields of the United States Database.

From 1973–1983 he was a fossil fuel supply analyst at The RAND Corporation. He was also chair of the organizing committee for AAPG Hedberg Research Conference on Understanding World Oil Resources. Richard was actively involved in the field of oil and gas resource/supply issues, serving on several professional and scientific committees of the National Petroleum Council and National Research Council. The American Association of Petroleum Geologists named him Haas-Pratt Distinguished Lecturer (1990-91), before he helped found AAPG's Committee on Resource Evaluation and organized the Hedberg Research Conference on Understanding World Oil Resources (2006).

Why Publish an Article from 2006?

What could we possibly learn from an article on oil supply published almost 20 years ago? Actually, quite a lot. At the time of publication in 2006, the revolution in technology and know-how that led to the rapid run up in oil and gas production from unconventional resources (commonly called the shale revolution) was still a few years away. Conventional wisdom at the time was that the U.S. could not "drill its way out of an energy crisis," and a well-established model of total resource recovery, the Hubbert Method, documented that we should prepare for and undertake costly initiatives to address a long period of declining oil and gas production.

Few expected the massive increase in U.S. oil and gas production that would emerge by 2010, stabilizing world oil prices and lifting the U.S. to the point where today it is the largest oil and gas producing country in the world. This was not the first-time technological advances had offered a surprise to conventional wisdom. In 1978, Congress passed the Fuel Use Act which prohibited the use of natural gas to generate electricity under assurances the country was running out of natural gas. Years later, the resulting surge in natural gas production from domestic reserves not only provided the world with reliable and growing supply of LNG but also played a major role in driving down U.S. carbon emissions as a substitute for coal combustion in the U.S. electric power system.

Of course, how could we ignore the Synthetic Fuels Corporation (established to build a financial bridge for the development and construction of commercial synthetic fuel manufacturing plants such as coal gasification) that would produce alternatives to imported fossil fuels? Congress authorized funding of $88 billion and a maximum of three hundred full-time professional employees over 12 years. The SFC's mandated goal was the production of at least 500,000 barrels of crude oil equivalent per day in synthetic fuels from domestic sources by 1987 and at least 2 million barrels per day by 1992. Over its six-year existence, the SFC spent approximately $960 million (barely five percent of its initial 1980 budget) to fund four synthetic fuels projects, none of which survive today. The corporation was abolished in April 1986.

What lessons should policy makers draw from Richard Nehring's analysis? Government energy policies are now directed at a specific set of technological pathways to reach net zero, i.e., the working assumption is that the future is known and we have a clear understanding of how to get there. Perhaps we would be better off if our policy makers recognize that the future faces a wide range of uncertainties, including the potential for good news.

Lucian Pugliaresi
President
Energy Policy Research

Introduction and Summary (2006)

The issue of whether world production is approaching a peak has been the subject of intense debate, particularly since 1997 with the publication of **The Coming Oil Crisis** by Colin Campbell who predicted at that time a peaking of production late in this decade.[1] Energy Policy Research has also taken a strong interest in this issue, co-sponsoring with the James A. Baker III Institute for Public Policy at Rice University, a conference in May 2000 entitled, **Running on Empty? Prospects for Future World Oil Supplies**.[2] Energy Policy Research is publishing this article by Richard Nehring in the interest of adding to the discussion of this critical issue.

Those who project a coming peak in oil production, rely on methodologies based on the pioneering work of M. King Hubbert published 40–50 years ago linking annual production levels to earlier discoveries and indicating that once annual discoveries decline, as they would once cumulative discoveries reached some share of ultimately recoverable resources, so too with a lag will production.[3] There is no question that on a worldwide basis, discovery rates have fallen back from their fabled levels in the first half of the last century when large US discoveries and even larger Middle East discoveries were made. With annual production generally exceeding new discoveries for many years, it would only be a matter of time before a production peak is reached and an inevitable decline sets in. Hubbert's analysis of U.S. discovery rates and cumulative discoveries versus estimated ultimate recovery led him to predict that U.S. oil production would peak in the early 1970s—a prediction which has proven correct. While the overall logic has a certain inevitability about it, the key elements involved in translating the broad logic into a reasonably reliable time profile for production have proven very elastic. In particular, estimates of amounts of recoverable oil associated with previous discoveries have tended to grow over time, thereby raising potential cumulative production available from the discoveries that in turn means a later, flatter rate of decline, or even upticks in annual production levels. PIRINC is publishing this article because of the light it sheds on the issues involved in assessing recoverable oil associated with originally announced discoveries and translating such assessments into production profiles.

The author focuses on two major US oil-producing basins, the San Joaquin Valley and the Permian Basin. Both have a very long history, with the first major discoveries beginning in 1887 in the San Joaquin Valley and in 1920 in the Permian Basin. The author applies Hubbert's methodology to these two basins to test its reliability as a predictor of ultimately recoverable reserves and of future time profiles of production. Both basins involved clearly defined areas and were mature by the early 1960s with the exploration process well advanced, and new discovery rates well below earlier peaks—all features favorable for testing the Hubbert method.

1 Colin J. Campbell, The Coming Oil Crisis, published by Multi-Science Publishing Company Ltd. 1997. In updated projections released in August 2006, Dr. Campbell projects a peak of "regular" oil production by 2010, where "regular" excludes heavy oils, deepwater and polar production, and NGLs, and a peak of total liquid petroleum production by 2020.

2 The conference report is available at: https://scholarship.rice.edu/bitstream/handle/1911/91547/study_14.pdf

3 M. King Hubbert (1903-1989) earned a Ph.D in geology from the University of Chicago. He worked as a geologist in the oil industry first for Amerada Hess and then for over 20 years for Shell. After retiring from Shell, he was for 12 years a senior research geophysicist for the USGS. He first publicly predicted a peaking in US oil production in the late sixties to early seventies in 1956.

Testing Hubbert-Method Predictions for Reserves and Production for San Joaquin Valley and Permian Basin: Billion Barrels Summary Data			
	1964	**1982**	**2000**
San Joaquin Valley			
Cumulative Discoveries	7.7	11.8	16.1
% Discovered by 1915	49%	69%	76%
Est. Ultimate Recoverable	8.0 – 9.5	11.9 – 12.1	16.1 – 16.2
Cumulative Production as of:	5.8	8.7	13.0
Year 2000 Production as projected in: (MB/D)	44 – 112	189	597 (act)
Permian Basin			
Cumulative Discoveries	17.6	27.9	35.2
% Discovered by 1950	85%	86%	84%
Est. Ultimate Recoverable	19 – 27.5	28.5 – 30.5	35.8 – 37.5
Cumulative Production as of:	10.5	22.4	30.2
Year 2000 Production as projected in: (MB/D)	162 – 479	326 – 479	910 (act)

Source: Author

The table below summarizes some of the key results of the author's analysis of the two basins. It shows for three benchmark years, 1964, 1982, and 2000, cumulative discoveries, the shares attributed to fields first discovered much earlier, and, using the Hubbert methodology, estimated ultimate recoverable reserves. The table also shows cumulative production and, in view of estimated ultimate recoverable reserves already produced by 1964 and 1982, projections based on data for those years of production in 2000. These projections can be compared with actual production.

In the San Joaquin Valley, cumulative discoveries amounted to 7.7 GB in 1964, 11.8 in 1982, and 16.1 in 2000. Of these growing cumulative discoveries, note that the share attributed to discoveries made by 1915 grows as well—from 49% in 1964 to 76% in 2000. In effect, appreciation of estimated recoverable resources in the older fields accounted for virtually the entire increase in discoveries. True new field discoveries within the basin were minimal, a result in line with the logic that the largest fields are discovered first. Ranges are shown for each period's estimate of ultimate recoverable reserves. The lower numbers make no allowance for the historic pattern of understatement of ultimate recoverable reserves in initial estimates of amounts discovered as recognized by Hubbert in his own work. The higher numbers incorporate Hubbert's growth factors derived from U.S. experience in the 1940s and 1950s. Note that the ranges tend to narrow as cumulative discoveries approach ultimate recovery estimates. For each of the years shown, cumulative discoveries account for well over 90% of estimated ultimate recoverable reserves, suggesting, as would be expected for a very mature basin, minimal prospects for future gains.

In 1964, cumulative oil production reached 5.8 GB, or 72% of unadjusted estimated ultimately recoverable reserves and 61% when adjusted for growth. In any case, the percentages for cumulative production are well above the approximate 50% threshold for share of ultimately recoverable reserves at which production peaks would occur. Indeed, by 1964, production had already been in decline for a number of years. Applying the Hubbert methodology to the 1964 data, the author estimates year 2000 production at 44 to 112 MB/D, corresponding to the actual and adjusted 1964 ultimate recovery estimates. Applying the methodology to the 1982 estimates results in a significantly higher estimate of 189 MB/D for 2000 production. The minimal range for ultimate recoverable reserves in 1982 results in the single point year 2000 production estimate. However, thanks to further substantial growth in discoveries, actual 2000 production at 597 MB/D is far higher than earlier projections—although below the historic peak of 745 MB/D achieved in 1985.

The figures for the Permian Basin show broadly similar results, with cumulative discoveries about doubling between 1964 and 2000, again driven primarily by appreciation of estimated reserves in fields initially discovered many years earlier. Year 2000 actual production at 910 MB/D is far above the 1964 and 1982 projections—although well below its historic peak of 2 MMB/D reached in 1974.

In his concluding notes, the author points out that Hubbert was developing his analysis in the 1960s, part of a long period of low oil prices and incremental technological advances. The much higher oil prices prevailing and technological advances since then have greatly expanded ultimate recovery and therefore production possibilities from older fields. Applications of advanced technologies to existing fields and to frontier areas have become the dominant sources of reserve additions and oil production in the Western hemisphere over the past three decades.

Production from nonconventional sources such as extra heavy oils are becoming more important. Under these conditions, a methodology based on U.S. conventional oil experience of the 1960s and before cannot offer reliable guidance in predicting oil's future.

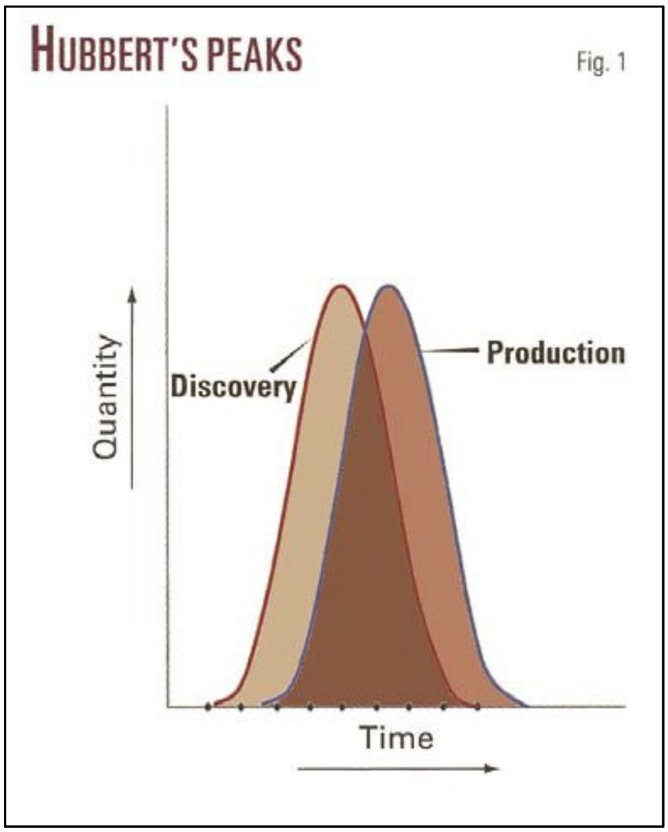
Does the Hubbert Method Provide a Reliable Means of Predicting Future Oil Production?

Richard Nehring

When will world oil production peak? This question, which only a few years ago was the concern of just several dozen specialists worldwide, is now a front-page issue. The obvious reason for its current salience is the recent doubling of crude oil prices, an increase that currently shows no signs of dropping back to its former level. Underlying the immediate causes of this increase is the nagging concern that the world oil resource base is inadequate for even sustaining, much less increasing, world oil production in the decades ahead.

Our opening question quickly leads to a second question: **Can we predict when world oil production will peak?** Do we know the key factors that determine world oil production? Do we understand how these factors behave and interact well enough to develop methods for predicting world oil production? Do these predictions provide a reliable foundation for decisions?

Discussion of a peak in world oil production, in both narrow technical circles and the broader public, has been dominated by one method of prediction: the method developed by M. King Hubbert in a series of articles 40-50 years ago. Hubbert based his analysis on deductions and extrapolations from two curves, one showing annual discoveries of oil, the other showing annual production of oil. Both discoveries and production begin at zero, grow to a peak, and subsequently decline to zero. The area under each of these curves equals ultimate recovery of oil. Production necessarily follows discovery. (Hubbert observed that in the United States the lag between discovery and production appeared to be 10 to 12 years.) Thus, once annual discoveries peak and begin to decline, the peak and subsequent decline of production can be predicted reliably. The peak in production has become popularly known as "Hubbert's Peak". It is more accurate to speak of Hubbert's Peaks (Figure 1)4. Both the annual discovery curve and the annual production curve with their respective peaks are essential to the Hubbert Method.



Hubbert argued that both the annual discovery and the annual production curves were **single-cy-**

cle curves, that is, they would only have one peak. Neither would be a multiple-cycle curve with two or more peaks substantially separated in time. Moreover, he argued that both curves were **horizontally symmetrical**, that is, the peaks in both the annual production and the annual discovery curves occurred when cumulative discoveries and cumulative production were approximately 50% of ultimate recovery.

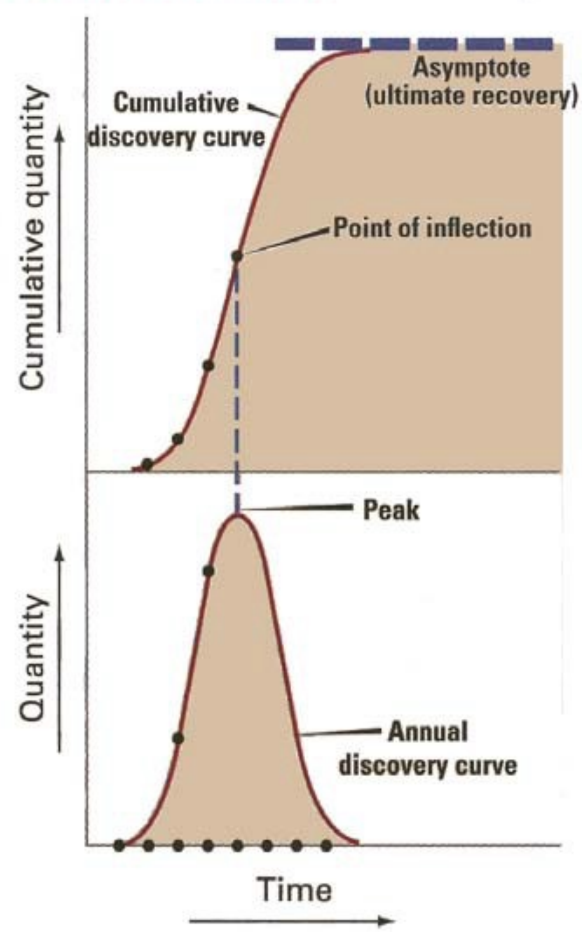
The key to predicting production accurately using the Hubbert Method is to have an accurate estimate of ultimate recovery. An accurate estimate of ultimate recovery is necessary because annual discovery curves, contrary to Hubbert's argument, tend to be highly irregular. Most have multiple peaks. The trick is thus to identify the true ultimate peak and not be misled by earlier peaks. If the observed peak in discoveries occurs when cumulative discoveries are approximately 50% of ultimate recovery, one can—at least according to Hubbert—confidently assume that the observed peak is the ultimate peak and proceed accordingly.

Hubbert struggled with several approaches to predicting ultimate recovery in his papers of the late 1950s and early 1960s. By 1965, following the peak and beginning of the decline he observed in annual oil discoveries in the United States, he concluded that ultimate recovery could be reliably determined using information intrinsic to his method. The cumulative discovery curve, constructed from the annual discovery curve, provides the means for estimating ultimate recovery. The cumulative discovery curve ultimately is an S-shaped curve. It begins at zero and accelerates its rise until annual discoveries reach their peak. As annual discoveries begin to decline, the cumulative discovery curve begins to flatten out, eventually approaching an asymptote as annual discoveries approach zero. The amount at this asymptote equals ultimate recovery (Figure 2).

This approach clearly has limitations. Its principal limitation is that it cannot be used until annual discoveries have clearly passed their peak. Hubbert never specified what the minimum ratio of cumulative discoveries to ultimate recovery had to be for this approach to yield reliable estimate of ultimate recovery. In his papers of the late 1960s (Hubbert, 1967 and 1969), the ratio of cumulative discoveries to his estimate of ultimate recovery was between 70 and 80%. Perhaps this ratio could be as low as 65%. At any point less than that, extrapolation of the cumulative discovery curve to its asymptote becomes increasingly uncertain.

KEY TO HUBBERT METHOD

Fig. 2



The use of this method also requires careful interpretation of the annual discovery curve. Hubbert, on the basis of research published by the National Petroleum Council in the late 1950s and early 1960s, recognized that the initial reports of the amounts discovered in recent finds persistently understated the amounts that would ultimately be discovered from these fields. Thus these initial reports had to be adjusted upwards using empirically derived growth factors. Failure to make this adjustment results in an unduly pessimistic estimate of ultimate recovery and thus an erroneously low prediction of future production.

Testing the Hubbert Method

This paper systematically and rigorously tests the Hubbert Method as a tool for predicting future oil production. Its basic approach is a simple one. It applies the method to two major oil-producing basins in the United States: the San Joaquin Valley in California and the Permian Basin in west Texas and southeast New Mexico. It applies the method to each of these two basins as of three different reference years: 1964, 1982, and 2000. It uses the fundamental components of the method to predict production to 2020 for each basin from each of these three years and then compares these predictions with actual production through 2004.

The fundamental components of the Hubbert Method examined for each basin for each of these three years are annual discoveries, annual production, and the cumulative discovery curve. Annual discovery and annual production curves were constructed from the beginning of discovery and production through each specified year. Because annual discovery curves are highly irregular, the discovery curves presented were constructed using a trailing five-year moving average of actual discoveries. (Because discoveries were few and far between in the San Joaquin Valley before 1920, a trailing ten-year moving average was used to construct the discovery curves for that period in that basin.) The use of moving averages begins to approximate the derived smooth curves that Hubbert used in his analysis.

Because the peaks of the annual discovery and production curves are central to Hubbert's method, each is noted and discussed. Cumulative discoveries and production at each peak in annual discoveries and production are explicitly noted. Because the annual discovery curves provide the foundation of Hubbert's method, the key factors shaping them, namely the timing and then-current size of world-class giant discoveries (those with 500 million barrels or more ultimate recovery), are indicated as well.

The most recent thirty years of each annual discovery curve is also adjusted for future growth resulting from full development of the more recent discoveries. The growth factors used are taken from Hubbert (1967). This adjustment is made to correct the observed sizes of the more recent discoveries to their ultimate potential. The growth factors used by Hubbert were derived from U.S. experience in the 1940s and 1950s. Because it is uncertain whether this particular past growth experience is relevant to future growth, these adjustments are noted as "corrected" estimates.

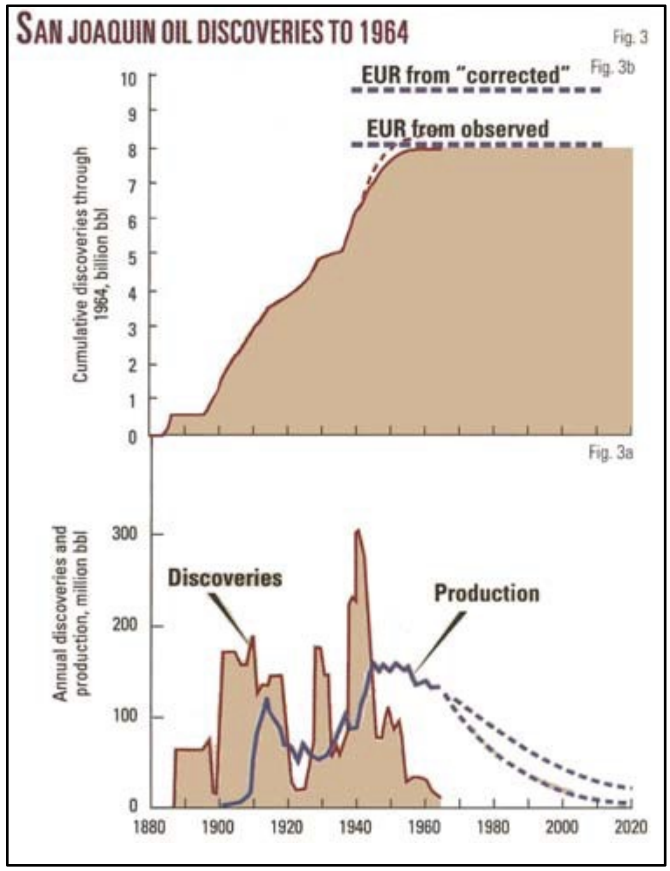
Cumulative discovery curves were then derived for each basin as of each year from both the actual and the "corrected" annual discovery curves. Ultimate recovery (EUR) was then estimated for each basin according to the information available for each of the specified years by extending both the actual and the "corrected" cumulative discovery curves to their asymptotes. Because each of these basins was at a high degree of exploration maturity for each of the three reference years (in all cases, cumulative discoveries exceed 80% of estimated ultimate recovery and in most cases they exceed 90% of estimated ultimate recovery), there was negligible uncertainty associated with estimating ultimate recovery. Cumulative production as of each year was then subtracted from estimated ultimate recovery to obtain ultimate remaining reserves.

Production was then projected for each basin from each reference year and for each estimate of ultimate recovery out to 2020. These projections assumed, following Hubbert, that annual production peaks when cumulative production is approximately half of ultimate recovery. The projections assume a gradually increasing rate of production decline from observed recent rates of decline, with an upper limit on the basin decline rate of no more than 10% per year.

Each basin discussion concludes with a comparison of the cumulative discovery curves and the associated estimates of ultimate recovery for all three years. Projected production as of 1964, 1982, and 2000 is also compared with actual production through 2004.

San Joaquin Valley

Geographically, the San Joaquin Valley is the southern half of the great Central Valley of California. For the past century, it has been an important center of U.S. oil production, being one of only eight major oil provinces in the United States (major provinces are those with an ultimate oil recovery of at least eight billion barrels).



Oil exploration and discovery in the San Joaquin Valley has a long history, going back to the late nineteenth century. The first discovery in the basin was the world-class giant **Coalinga** field (610 million barrels ultimate recovery as of 1964) in 1887. (This was the first giant oil field discovered in any of the major oil provinces of the United States.) The other known giant fields in the basin as of 1964 were discovered in the next quarter century, beginning with **Midway-Sunset** (1100 million barrels) in 1901 and concluding with **Buena Vista** (615 million barrels) in 1909.

After this brief spurt in discovery, exploration in the basin dwindled to negligible levels in the early 1920s, resumed at a healthy rate during the late 1920s, plunged again in the early years of the Great Depression, and reached their peak of 303 million barrels per year in 1941 (based on a five-year moving average). From that peak, discoveries plummeted. By 1964, average annual discoveries for the five years from 1960 to 1964 had dropped to 15 million barrels, only 5% of the 1941 peak (Figure 3A)

Reflecting the annual rate of discoveries, cumulative crude oil discoveries grew rapidly through 1915, leveled off for a decade, then grew rapidly again for the next quarter century before flattening out in the 1950s (Figure 3B). By 1964, 7745 million barrels had been discovered in the San Joaquin Valley. Nearly half (48.5%) of this amount had been discovered by 1915. If Hubbert's correction factors are applied to San Joaquin Valley discoveries, cumulative discoveries through 1964 increase modestly. The corrected known recovery as of 1964 is 8655 million barrels, 11.7% more than the observed amount (Figure 3B).

The correction factors have a substantial effect on the estimates of ultimate recovery derived from the cumulative discovery curve. Using only the observed discovery rate with its rapidly declining discovery rate from 1950 to 1964, estimating ultimate recovery for the San Joaquin Valley beyond 8.0 billion barrels would have no justification in the historical discovery record. The "corrected" discovery rate, which has substantial year-to-year fluctuations and depends heavily on a handful of moderately-sized discoveries, suggests an estimated ultimate recovery around 9.5 billion barrels, nearly 20% higher.

Crude oil production in the San Joaquin Valley grew slowly in its first twenty years before taking off in 1910 (Figure 3A). By 1914, it hit its first peak of 124 million barrels (340,000 b/d). Production subsequently declined to only 49 million barrels in 1928–1929. From that low, production grew steadily to its historic peak of 161 million barrels (440,000 b/d) in 1945. Production subsequently stayed at a high plateau through 1956 before beginning to decline slowly in the early 1960s. By 1950, annual production exceeds annual discoveries for good.

Although the annual discovery and production curves for the San Joaquin Valley do not follow the smooth single-peak curves that Hubbert postulated, they clearly illustrate two key points of his analysis. First, **production closely follows discovery**. The two peak years of production (1914 and 1945) follow peaks in discovery by five to ten years. Secondly, **peak production occurs when cumulative production is at or near the midpoint of ultimate recovery**. Cumulative oil production in 1945 was 3003 million barrels, 37.5% of the estimated ultimate of 8000 million barrels. By 1956, the end of the peak plateau in production, cumulative oil production was 4677 million barrels, 58.5% of the estimated ultimate. If the estimated ultimate recovery of 9500 million barrels is used instead, cumulative production in 1956, the last year of the peak plateau in production, was 4678 million barrels, 49.2% of the corrected estimated ultimate.

The historic discovery and production data for the San Joaquin Valley thus appears to provide a solid basis for accurately predicting future oil production. By 1964 the San Joaquin Valley was clearly a highly mature oil province. Between 91% to 97% of all the oil estimated to be ultimately recoverable in the basin had been discovered. Cumulative production of 5759 million barrels was between 60.6% and 72.0% of ultimate recovery. Moreover by 1960–1964, production was clearly exceeding the rate of discovery. The decline in production that had begun in the 1950s was thus destined to continue. The only remaining uncertainty was which ultimate recovery estimate and thus which decline rate to use in projecting production.

With an estimate ultimate recovery of 8000 million barrels, only 2241 million barrels remained to be produced after 1964. Projected production thus declines rapidly to only 16 million barrels in 2000 and less than 3 million barrels in 2020. By that year San Joaquin Valley would be close to total depletion, having produced 99.7% of its ultimate recovery. With an estimated ultimate recovery of 9500 million barrels, 3741 million barrels remained to be produced after 1964. Projected production thus declines more slowly to 41 million barrels in 2000 and 18 million barrels in 2020. By then, the basin would have produced 96.7% of its ultimate recovery.

The San Joaquin Valley as of 1982

Moving forward to 1982, what was then known about the San Joaquin Valley had changed substantially from the situation as of 1964. Cumulative crude oil discoveries as of 1982 were 11,770 million barrels, 52% more than cumulative discoveries as of 1964. Corrected cumulative discoveries were 11,944 million barrels, 38% more than Corrected cumulative discoveries as of 1964.

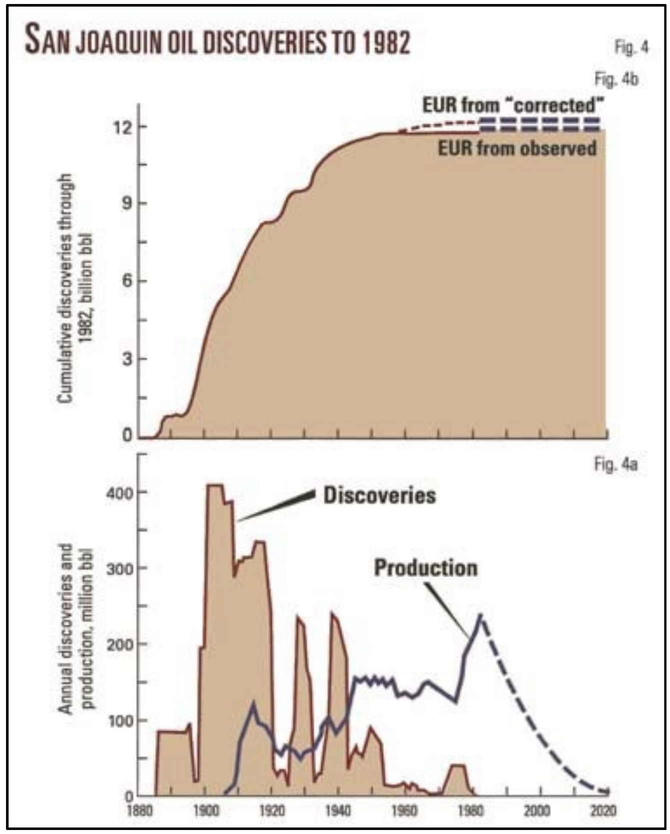
This increase was not primarily the result of major new discoveries during the 1960s and 1970s. Rather, by 1982 seven fields in the basin were now recognized as world-class giant fields, with all but one discovered by 1911. These included **Coalinga**

(785 million barrels known recovery as of 1982) in 1887, **Kern River** (1750 million barrels) in 1899, **Midway-Sunset** (2090 million barrels) in 1901, **Buena Vista** (657 million barrels) in 1909, **South Belridge** (750 million barrels) and **Elk Hills** (1300 million barrels) in 1911, and **Coalinga East Extension** (505 million barrels) in 1938. Together, these seven fields accounted for two-thirds of the observed cumulative discoveries in the basin.

Because of the concentration of giant discoveries between 1899 and 1911, the peak discovery period as of 1982 has shifted to the first decade of the century, peaking (using a 10-year moving average) at 405 million barrels per year from 1901 to 1905. As before, two lesser peaks in discovery occur in the late 1920s and late 1930s. Except for two major discoveries—**Tule Elk** in 1973 and **Yowlumne** in 1974, the first new field discoveries exceeding 50 million barrels in the San Joaquin Valley since 1944, discoveries since 1964 were minimal, with no new field discoveries in 11 of the 18 years from 1965 to 1982. Consequently, the application of correction factors to the discoveries of the past thirty years has a minor effect, increasing known recovery as of 1982 by only 174 million barrels (1.5% of the observed total) (Figures 4A and 4B)

The cumulative discovery curve reflects these changes in the annual pattern of discoveries. Cumulative discoveries soar from 1895 to 1915, reaching 69.4% of 1982 known recovery by 1915. By 1940, cumulative discoveries have reached 90.7% of 1982 known recovery. After 1950, cumulative discoveries inch up at a barely perceptible rate. The flattening of annual discovery rates after 1950 leave very little room for future discoveries. Consequently, ultimate recovery for the San Joaquin Valley is estimated as of the end of 1982 to be between 11.9 billion barrels and 12.1 billion barrels.

The changing patterns of peak discoveries alter the relationships between discovery and production substantially. More importantly, crude oil production in the San Joaquin Valley, after declining to 123 million barrels in 1974, suddenly takes off,



nearly doubling to 245 million barrels in 1982. That year becomes the new historic peak in San Joaquin Valley crude oil production, exceeding the previous peak of 1945 by 52%. More importantly this sudden increase is inexplicable according to the Hubbert model.

If one applies the principles of the Hubbert model to this situation, one can only conclude that this sudden increase in production was a totally aberrant situation. By 1982, cumulative crude oil production of 8692 million barrels was 72–73% of estimated ultimate recovery. Average annual production from 1978 to 1982 was more than two orders of magnitude greater than average annual discoveries during the same five years. Remaining ultimate reserves were less than 14 times 1982 production. An immediate and rapid decline in production thus is clearly indicated. By 2000, production is projected to be only 69 million barrels. By 2020, production will have declined to only 13 million barrels, just 5% of the 1982 peak. Cumulative production that year will have reached 98% of ultimate recovery (Figure 4A).

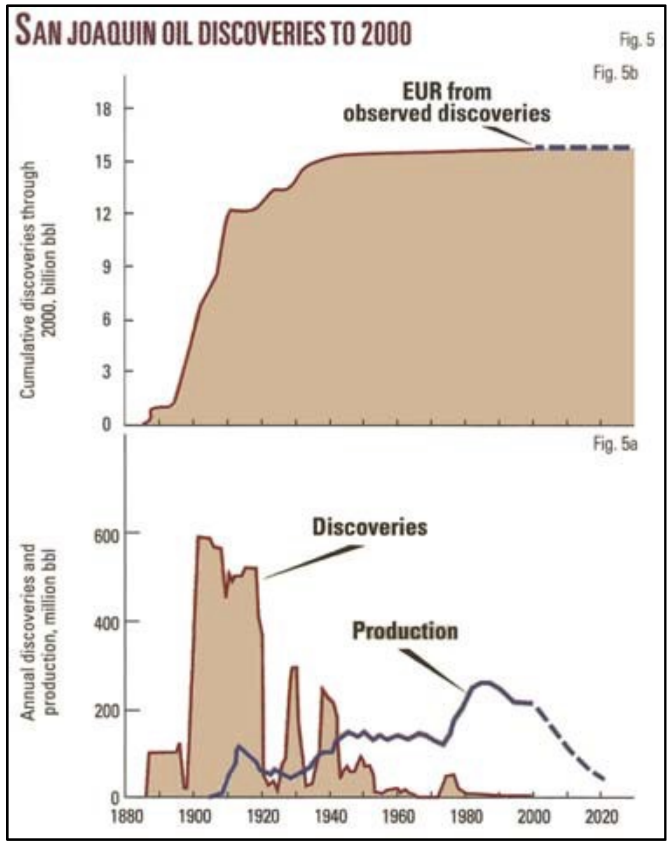
The San Joaquin Valley as of 2000

From 1982 to 2000, known oil recovery in the San Joaquin Valley again increased substantially. As of 2000, cumulative crude oil discoveries in the basin were 16,068 million barrels, 107% more than cumulative discoveries as of 1964 and 37% more than cumulative discoveries as of 1982. Corrected cumulative discoveries were 16,111 million barrels, 86% more than corrected discoveries as of 1964 and 35% more than corrected discoveries as of 1982.

New discoveries from 1983 to 2000 were a trivial part of the 4300 million-barrel increase in cumulative discoveries from 1982 to 2000. Only 31 million barrels (0.7%) of this increase came from new field discoveries in the basin after 1982. Nearly all of the increase occurred in the giant fields discovered by 1911, including **Coalinga** (965 million barrels known recovery as of 2000), **Kern River** (2300 million barrels), **Midway-Sunset** (3596 million barrels), **Buena Vista** (674 million barrels), the newly recognized giant 1909 discovery **Cymric** (500 million barrels), **South Belridge** (1860 million barrels) and **Elk Hills** (1383 million barrels). (An eighth field, **Lost Hills**, discovered in 1910, was growing rapidly and appears likely to reach world-class oil giant status before 2010.) These eight fields contained 72.8% of cumulative discoveries as of 2000. With **Coalinga East Extension** (505 million barrels), a 1938 discovery, the world-class giants accounted for 76.5% of all the basin's oil.

Because of the increasing concentration of known recovery in the giant discoveries made between 1899 and 1911, the peak discovery period is even more prominent during this period. (Figure 5A) Using the ten-year moving average, the peak discovery rate occurred from 1901 to 1905 at 590 million barrels per year. As before, lesser peaks in discovery occur in the late 1920s and late 1930s. After 1975, new field discoveries in the basin dwindle to insignificant levels, exceeding ten million barrels in only one year and being nothing in 18 of the 25 years.

As of 2000, cumulative discoveries are even more concentrated from 1895 to 1915, reaching 76.1% of known recovery as of 2000 by 1915. (Figure 5B) By 1940, cumulative discoveries were 92.2% of 2000 known recovery. The nearly flat cumulative discovery curve after 1975 provides no encouragement for meaningful future discoveries. Consequently, ultimate recovery for the San Joaquin Valley estimated from the 2000 data is between 16.1 billion barrels and 16.15 billion barrels.



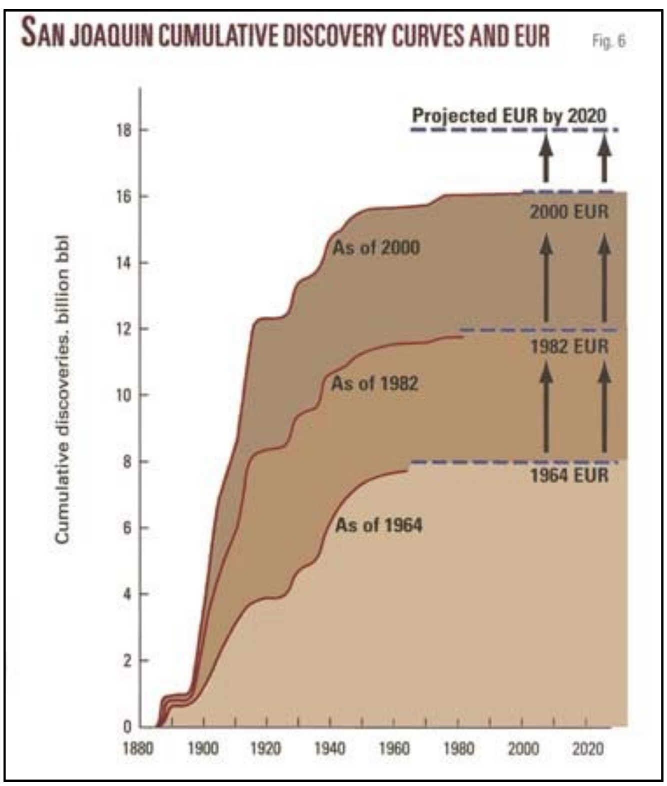
For a few years after 1982, crude oil production in the San Joaquin Valley continued to defy Hubbert's principles, reaching its peak in 1985 at 272 million barrels (745,000 b/d). Cumulative crude oil production that year was 9473 million barrels, 58% of the estimated corrected ultimate. Following this peak, normality finally prevailed and production began a more or less steady decline to 218 million barrels in 2000 (Figure 5A). From 1980 to 2000, production exceeded discoveries by more than two orders of magnitude.

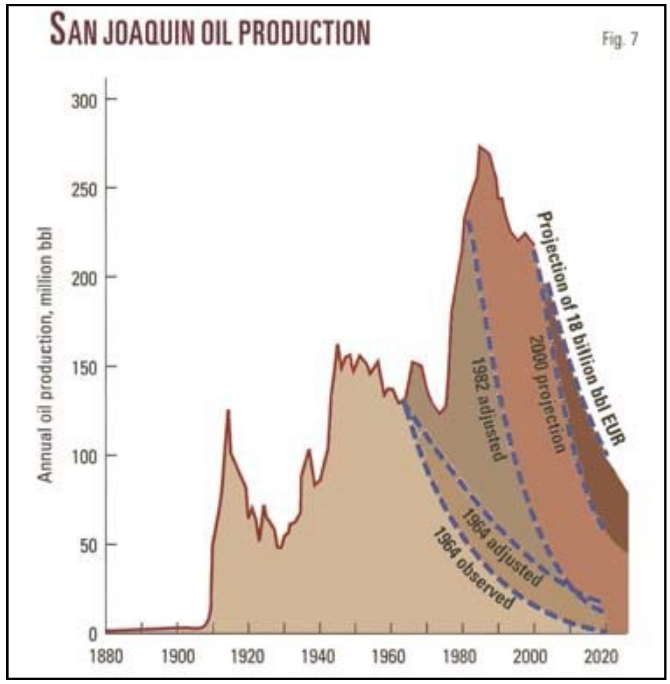
With cumulative production in 2000 at 13,031 million barrels, 80.7% of the estimated ultimate recovery of 16,150 million barrels, it seems an absolute certainty that oil production will continue to decline. By 2020, oil production is expected to drop to 57 million barrels, only 21% of the 1985 peak.

San Joaquin Valley Summary

From 1964 to 2000, the cumulative discovery curves for crude oil in the San Joaquin Valley change dramatically (Figure 6). Observed cumulative discoveries increase from 7745 million barrels in 1964 to 11,770 million barrels in 1982 to 16,068 million barrels in 2000, an increase of 107.5%. Corrected cumulative discoveries increase from 8655 million barrels in 1964 to 11,944 million barrels in 1982 to 16,111 million barrels in 2000, an increase of 86%.

Because of these increases, the projected ultimate recovery levels, as determined by the asymptotes indicated by the cumulative discovery curves, change as well. Using asymptotes based on the observed discovery curves, estimated ultimate recovery increases from 8.0 billion barrels as of 1964 to 11.9 billion barrels as of 1982 to 16.1 billion barrels





as of 2000, an increase of 101%. Using asymptotes based on the corrected discovery curves, estimated ultimate recovery increases from 9.5 billion barrels as of 1964 to 12.1 billion barrels as of 1982 to 16.15 billion barrels as of 2000, an increase of 70%.

The estimates based on the observed discovery curves appear to have greater historical verification. The correction factors used were based primarily on observed increases in size of the giant and large discoveries of the 1920s, 1930s, and 1940s. They appear to overstate increases in size over time of the much smaller discoveries of the 1950s and 1960s. Consequently, estimates of future discoveries based on the corrected discovery curves overstate future discoveries. For example, the estimates of ultimate recovery made using data as of 1964 suggest future discoveries of 255 million barrels (using the observed data) and 845 million barrels (using the corrected data). Actual new field discoveries from 1965 to 2000, with none after 1989, totaled 287 million barrels as of 2000, only 12.5% more than the estimate from the observed data.

Despite an increase of 8.1 billion barrels in estimated ultimate recovery from 1964 to 2000, the San

Joaquin Valley is not yet finished as an oil province. Reserve additions from 2001 to 2004 totaled 466 million barrels, raising known recovery to 16,534 million barrels. Propelled by the impetus of higher prices that began in 2004, increases in known recovery to at least 18 billion barrels by 2020 appear highly probable. With an original oil-in-place of at least 38–40 billion barrels in the San Joaquin Valley, a known recovery of 20 to 22 billion barrels by 2050 is a distinct possibility.

Because ultimate recovery based on the 1964 and 1982 data is grossly underestimated, future production projected from this data is grossly under-estimated as well. For example, actual production of 218 million barrels in 2000 was 13.7X the projected production of 16 million barrels for 2000 from the 1964 observed EUR, 5.3X the projected production of 41 million barrels from the 1964 corrected EUR, and 3.15X the projected production of 69 million barrels from the 1982 corrected EUR (Figure 7). Assuming the ultimate recovery in the basin by 2020 will be at least 18 billion barrels only widens this discrepancy.

Permian Basin

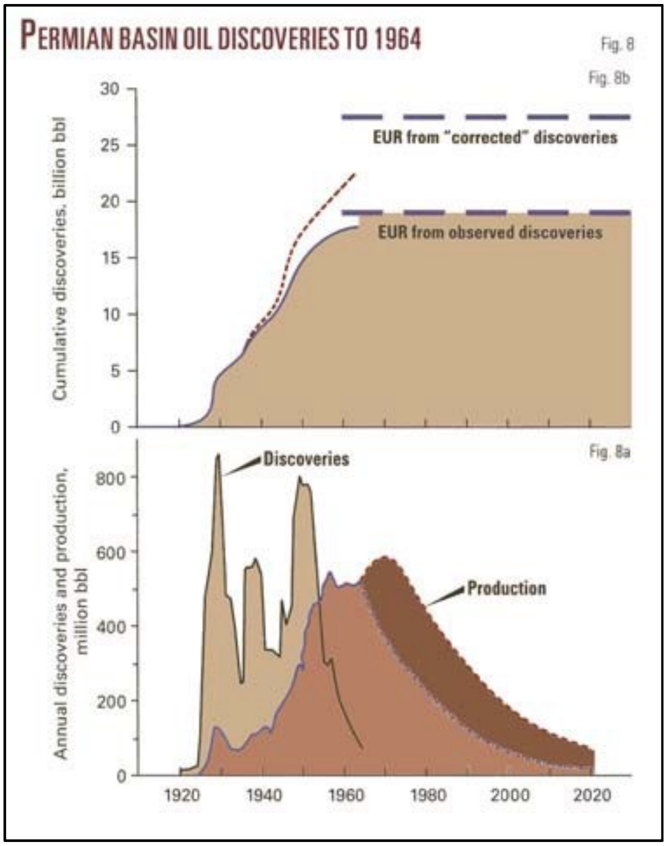
Geographically, the Permian Basin consists of west Texas and southeast New Mexico. For purposes of this analysis it will be defined as Texas Railroad Commission Districts 7C, 8, and 8A, together with Chaves, Eddy, Lea, and Roosevelt counties in southeastern New Mexico. (The standard geological definition of the Permian Basin also includes several counties in Districts 7B and 9. They are excluded here because they add only small additional amounts of oil, just 3% of the basin total—while vastly complicating data compilation.)

The Permian Basin has become recognized as one of the great oil provinces of the world, being one of only two oil superprovinces in the United States. (There are only a dozen oil superprovinces in the world, a superprovince being defined as one with at least 25 billion barrels ultimate recovery.)

Because of the remote location of the basin and a lack of major surface structures, the first discovery in the Permian Basin did not occur until 1920 (**Westbrook**). Following the application of early geophysical methods in the mid-1920s, the world-class giant fields on the Central Basin Platform were quickly discovered, beginning with **McElroy-Dune** (500 million barrels known recovery as of 1964), **South Sand Belt** (825 million barrels), and **Yates** (650 million barrels) in 1926, **Eunice Area** (685 million barrels) in 1929, and **Goldsmith-Andector** (570 million barrels) in 1934. Because of these giant discoveries the annual discovery rate (using five-year moving averages) reaches its all-time peak of 860 million barrels in 1930, just ten years after the initial discovery in the basin (Figure 8A).

Discoveries in the Permian Basin dropped off sharply in the early 1930s following plummeting oil prices during the early years of the Great Depression. With the geographical expansion of exploration onto the North Basin Platform in the late 1930s, discoveries rebounded with two giant fields, **Slaughter-Levelland** (690 million barrels) and **Wasson** (660 million barrels), being discovered there in 1936. After a minor decline during World War II, exploration expanded into the Midland Basin in the late 1940s and discoveries approached record heights. Another giant, **Scurry** (1240 million barrels), in 1948—was the most prominent discovery during this period. Following this last peak, discoveries declined steadily and rapidly throughout the 1950s and into the early 1960s. Observed 1961–1964 discoveries, averaging 60 million barrels per year, were more than an order of magnitude less than average discoveries during the 1948–1952 peak, only twelve years earlier.

Reflecting the annual rate of discoveries, cumulative crude oil discoveries grew rapidly in the late



1920s and from 1936 to 1950 (Figure 8B). After 1950, the cumulative discovery curve flattens markedly. By 1964, cumulative discoveries in the Permian Basin totaled 17,589 million barrels. Nearly 28% of this amount was discovered by 1930; nearly 50% by 1940; and 85% was discovered by 1950. The decade from 1941 to 1950 was thus clearly the most prolific decade for basin discoveries.

Because of the large amounts of oil discovered from 1936 to 1955 in the Permian Basin, applying Hubbert's correction factors to observed discoveries from 1935 to 1964 has a substantial effect on estimated cumulative discoveries. The corrected cumulative discoveries as of 1964 are 22,194 million barrels, 26.2% more than the observed discoveries as of 1964 (Figure 8B). Moreover, the peak period of discovery shifts from 1929–1930 to 1949–1952, average "corrected" discoveries being 1045 million barrels annually during this latter period. Discoveries still drop after this peak, but to a substantially lesser degree.

The application of the correction factors has an even greater effect on the estimates of ultimate recovery derived from the cumulative discovery curve. With only the observed cumulative discovery curve to go by, it is difficult to see how ultimate crude oil recovery in the Permian Basin could ever exceed 19.0 billion barrels. Using the "corrected" cumulative discovery curve, an estimated ultimate recovery of 27.5 billion barrels (45% more) seems likely.

Following the giant discoveries of 1926, crude oil production in the Permian Basin soared, reaching a peak of 135 million barrels (370,000 b/d) in 1929. The combined effects of flush **East Texas** field production and declining Depression demand cut production by more than half to only 63 million barrels in 1934, just five years later. From this low point, production grew more or less steadily to a peak of 550 million barrels (1.5 million b/d—21.5% of U.S. crude oil production) in 1957. Following this peak, production stayed at a high plateau, fluctuating by between 90% and 95% of the peak rate. As Hubbert observed, production in the Permian Basin clearly followed discovery, usually with only a five to ten year lag. (Figure 8A). Annual production finally exceeded the moving average of annual discoveries only in 1954.

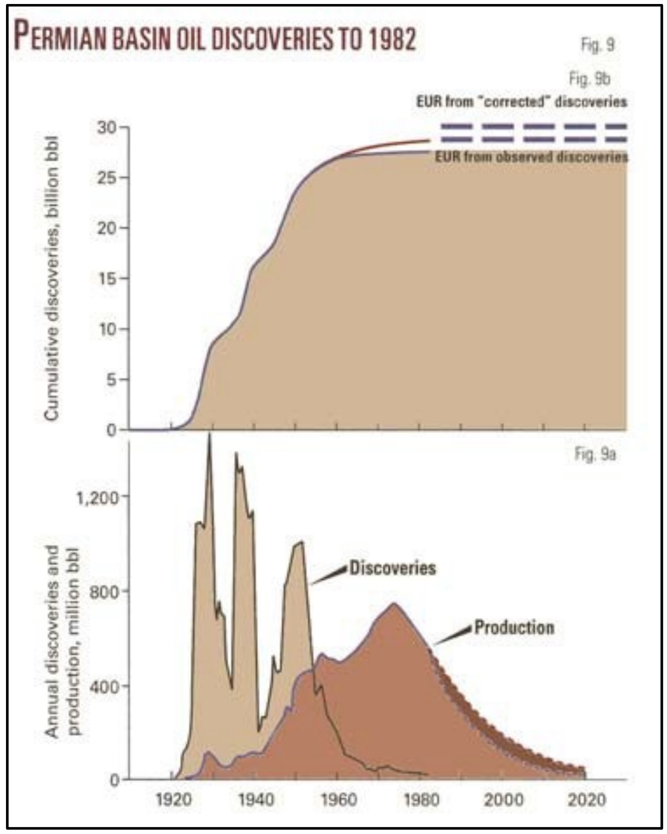
Projections of future Permian Basin production after 1964 depend heavily on the choice of estimates of estimated ultimate recovery. If one uses the estimate of 19.0 billion barrels (derived from the observed discovery rates), the outlook for future production is rather bleak. The Permian Basin is a highly mature province from this perspective. Cumulative discoveries are already 92.6% of the estimated ultimate recovery. Cumulative production as of 1964 (10,496 million barrels) is 55.3% of the estimated ultimate. Production from 1960 to 1964 exceeded discoveries more than seven-fold. Remaining ultimate reserves are only sixteen times current production. These key indicators strongly suggest an imminent and rapid decline in annual production to an estimated 59 million barrels in 2000 and only 9 million barrels in 2020 (Figure 8A). By 2020, the province is projected to be essentially depleted, cumulative production having reached 99.5% of the estimated ultimate recovery.

The use of the estimate of 27.5 billion barrels ultimate recovery derived from the "corrected" discovery rates suggests a much brighter future. The "corrected" cumulative discoveries are only 80.7% of the estimate of ultimate recovery. Cumulative production as of 1964 is only 38.2% of estimated ultimate recovery. Recent production only exceeds recent discoveries by 150%. Remaining ultimate reserves are 32 times current production. These indicators suggest that Permian Basin production could still increase, reaching a peak of 583 million barrels in 1970 (with a cumulative production that year at 50.5% of the estimated ultimate). After this peak, production will decline at a slowly increasing rate, dropping to 175 million barrels in 2000 and 63 million barrels in 2020. By that year, cumulative production will have reached 96.2% of the estimated ultimate recovery.

The Permian Basin as of 1982

The annual discovery rates for the Permian Basin as of 1982 are an amplified version of those as of 1964. Discoveries (again, using five-year moving averages) peaked in 1929–1930 at a rate of nearly 1500 million barrels per year (Figure 9A). All told, eight world-class giant fields were discovered on the Central Basin Platform from 1926 to 1934, beginning with **McElroy-Dune** (690 million barrels as of 1982), **South Sand Belt** (899 million barrels) and **Yates** (2000 million barrels) in 1926, and continuing with **Eunice Area** (830 million barrels) and **Vacuum** (550 million barrels) in 1929, **North Cowden** (515 million barrels) in 1930, **South Cowden** (535 million barrels) in 1932, and **Goldsmith-Andector** (870 million barrels) in 1934.

With the giant discoveries on the North Basin Platform in 1936—**Seminole** (500 million barrels), **Slaughter-Levelland** (1900 million barrels), and



Wasson (2050 million barrels), the discovery rate rebounded from its Great Depression low. After an early World War II low, discoveries hit their third peak with the discoveries of **Scurry** (1610 million barrels) in 1948 and **Spraberry Trend** (717 million barrels) in 1949. Together, the thirteen world-class giant fields discovered in the Permian Basin from 1926 to 1949 had 13.67 billion barrels known recovery as of 1982, 49% of the basin total.

After 1950, discoveries in the Permian Basin declined rapidly. From 1952 to 1962, the five-year moving average of discoveries declines by an order of magnitude. From 1962 to 1982, it drops another 80%. This reflects the disappearance of giant and large discoveries during this period. After 1957, no large field (at least 50 million barrels known recovery) was discovered in the Permian Basin.

The cumulative discovery curve for the Permian Basin reflects these patterns in the annual rate of discoveries. By 1982, cumulative discoveries in the Permian Basin were 27,943 million barrels (Figure 9B). The bulk of these discoveries occurred in the late 1920s, the late 1930s, and the late 1940s. By 1930, 31.5% of these cumulative discoveries had already occurred. By 1940, cumulative discoveries had reached 58.8% of 1982 ultimate recovery and by 1950 they were up to 86.0%. The flattening of the cumulative discovery curve becomes particularly pronounced after 1965. Only 2.2% of the cumulative discoveries in the Permian Basin occur from 1966 to 1982.

Because of the low annual rates of discovery in the Permian Basin in the 25 years from 1958 to 1982, the application of correction factors has little effect on cumulative discoveries. "Corrected" cumulative discoveries as of 1982 are estimated at 28,845 million barrels, only 3.2% more than the observed amount.

Estimates of ultimate recovery for the Permian Basin derived from observed and "corrected" cumulative discovery curves thus do not differ substantially. The estimate from the observed curve is 28.5 billion barrels. The estimate from the "corrected" curve is 30.5 billion barrels, only 7.0% higher.

Crude oil production in the Permian Basin grew steadily from 1964 to 1974. In 1966, the previous peak of 550 million barrels was easily exceeded, production reaching 588 million barrels. At the ultimate peak in production of 746 million barrels in 1974 (2.04 million b/d), the Permian Basin was providing nearly a fourth (24.6%) of all U.S. crude oil production. Cumulative production at this peak was 17,902 million barrels, 64.1% of observed cumulative discoveries as of 1982 and 62.1% of corrected cumulative discoveries as of 1982. Following the 1974 peak, production in the basin dropped nearly 25% to 561 million barrels in 1982.

It is obvious that production would continue to decline after 1982. Cumulative discoveries as of 1982 were between 94.6% and 98.0% of estimated ultimate recoveries. Cumulative production as of 1982 (at 22,385 million barrels) was between 73.4% and 78.5% of estimated ultimate recoveries. Annual production, though declining, was more than twenty times the rate of annual discoveries. Ultimate remaining reserves were only 10.9 to 14.5 times 1982 production. Given this universally depressing combination of indicators, the only remaining uncertainty was whether production would decline rapidly or very rapidly.

If the estimated ultimate recovery is only 28.5 billion barrels, production is halved in less than every nine subsequent years, dropping to 119 million barrels in 2000 and only 16 million barrels in 2020. By 2020, the Permian Basin would be effectively depleted, as cumulative production has reached 99.5% of ultimate recovery. The decline in production is slower, but only relatively, if ultimate recovery is 30.5 billion barrels. Production declines to 175 million barrels in 2000, and 39 million barrels in 2020 (only 7% of 1982 production). Even with this more optimistic projection, cumulative production has reached 98.3% of ultimate recovery by 2020.

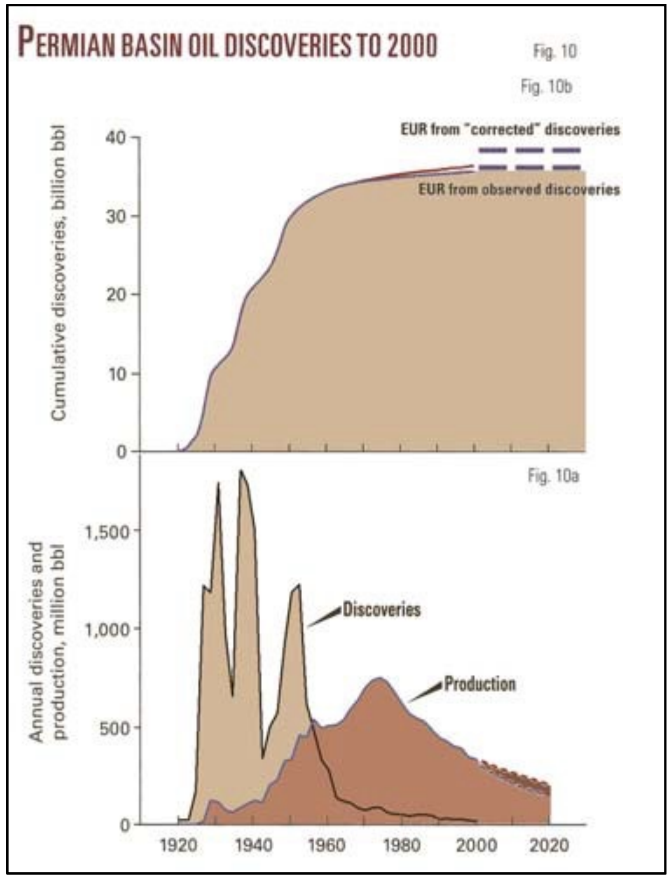
The Permian Basin as of 2000

The annual discovery curve for the Permian Basin from 1920 to 2000 maintains the basic pattern of the discovery curves as of 1964 and 1982, but with a few significant changes. Discoveries still grew rapidly in the late 1920s, bolstered by the concentration of giant discoveries during this period. These include the newly recognized giant **Howard-Glasscock** (514 million barrels known recovery in 2000) in 1925, **McElroy-Dune** (861 million barrels), **South Sand Belt** (989 million barrels), **Yates** (2000 million barrels), **Eunice Area** (1065 million barrels), **Vacuum** (748 million barrels), **North Cowden** (770 million barrels), **South Cowden** (653 million barrels), and **Goldsmith-Andector** (1022 million barrels). Four other fields discovered from 1923 to 1934 appear likely to eventually join the ranks of world-class giant oil fields, including **Artesia-Maljamar** in 1923 (463 million barrels), **Penwell-Waddell** in 1926 (423 million barrels), **Hobbs** in 1928 (425 million barrels), and **Means-McFarland** in 1934 (391 million barrels). These discoveries pushed average discoveries up to more than 1.7 billion barrels per year in 1929–1930 (Figure 10A).

This peak however was quickly exceeded in 1936 with the discoveries of **Seminole** (720 million barrels), **Slaughter-Levelland** (2457 million barrels), and **Wasson** (2660 million barrels). Another emerging giant - **Robertson-Flanagan** (455 million barrels) was also discovered that year. Despite the discovery of a recently recognized giant in 1941, **Fullerton Area** (560 million barrels), discoveries dropped during the early 1940s, only to soar again in the late 1940s as **Scurry** (1650 million barrels), **Spraberry Trend** (1303 million barrels), and another emerging giant (**Salt Creek** in 1950 with 435 million barrels) were discovered. The fifteen recognized giant fields provided 17,972 million barrels (51%) of Permian Basin cumulative discoveries as of 2000. The six emerging giants added another 2,592 million barrels, 7.4% of cumulative discoveries.

Following this third and last peak, discoveries in the Permian Basin begin a steady decline throughout the latter half of the twentieth century. After 1985, annual discoveries never exceed 50 million barrels.

The cumulative discovery curve for the Permian Basin reflects these changing annual patterns of discovery. By 2000, cumulative discoveries in the Permian Basin were 35,242 million barrels. By 1930, only a decade after the first discovery in the basin, 29.7% of these discoveries had already occurred. By 1940, 57.6% of 2000 cumulative discoveries had been made. By 1950, 83.8% had been discovered. By 1960, the midpoint in time of exploration to date, 94.0% of known recovery as of 2000 had already been discovered. Conversely, only 1.7% of the cumulative discoveries occurred after 1980 (Figure 10B).



Because recent discoveries have been both so small and relatively few, application of the correction factor does little to change cumulative discoveries. The "corrected" cumulative discoveries as of 2000 are 35,748 million barrels, only 1.4% more than the observed cumulative discoveries.

Although the use of the correction factor has only a small effect on cumulative discoveries, it modestly increases the estimate of future discoveries. Without the correction factor, ultimate recovery in the Permian basin as of 2000 could be no more than 35.75 billion barrels. Average observed discoveries were dropping around 30% every five years after 1985. With the correction factor, average discoveries decline only 10–15% every five years after 1985. This suggests an ultimate recovery around 37.5 billion barrels for the Permian Basin. Either way, the annual discovery curves and the ensuing estimate for ultimate recovery indicates that the Permian Basin had reached a high level of exploration maturity. Between 95.3% and 98.6% of all the oil likely to be discovered in the Permian Basin had already been discovered by 2000.

The record of crude oil production in the Permian Basin from 1982 to 2000 is essentially one of steady decline, occasionally interrupted by a few minor upward ticks in production (Figure 10A). Overall, production declines from 561 million barrels (1.54 million b/d) in 1982 to 333 million barrels (0.91 million b/d) in 2000, a decline of 40.6%. By 2000, cumulative production in the basin was 30,235 million barrels, 84.6% to 85.8% of cumulative discoveries. The role of the Permian Basin as a major oil-producing province thus appears to be largely past.

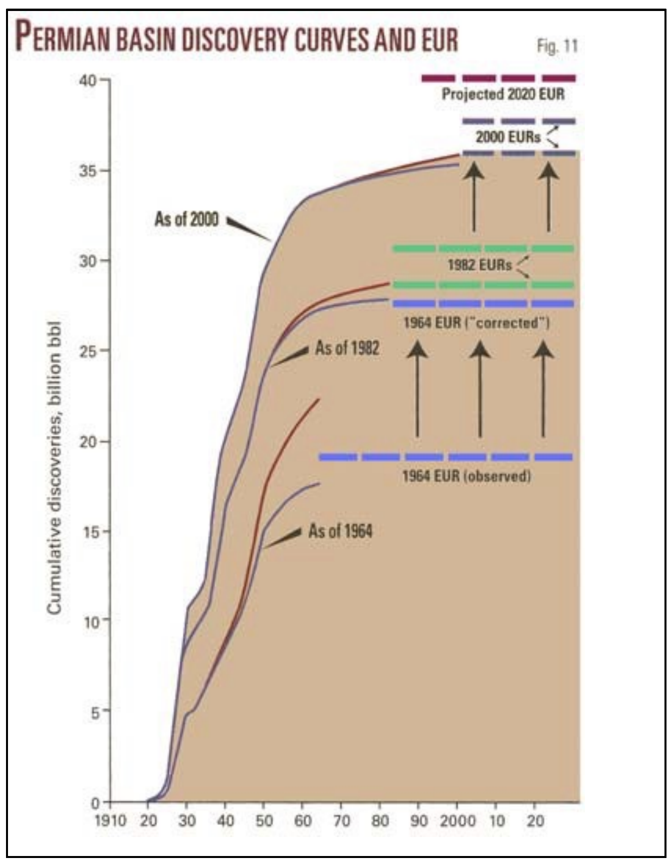
The future of crude oil production in the Permian Basin can thus be only one of continued decline. Here too, the only uncertainty is the rate of decline. Recent annual production is more than twenty times the observed rate of discovery. Ultimate remaining reserves (as calculated from the observed rate of discovery) are only 16.6X 2000 production. Under this scenario, crude oil production in the basin declines to only 99 million barrels in 2020, a decline of 70% from the 2000 level. Cumulative production by 2020 reaches 34,432 million barrels. 96.3% of the estimated ultimate recovery of 35,750 million barrels.

With the “corrected” discovery curve, recent annual production is approximately seven times the rate of recent discoveries. Ultimate remaining reserves are 21.8X 2000 production. Even under this more optimistic scenario, crude oil production in the Permian Basin falls to 155 million barrels in 2020, only 46.5% of 2000 production. Cumulative production by 2020 is 34,954 million barrels, 93.2% of the ultimate recovery of 37,500 million barrels.

Permian Basin Summary

Cumulative discoveries in the Permian Basin increase substantially from 1964 to 2000 (Figure 11). That cumulative discoveries increase in a super-province such as the Permian Basin over a period exceeding a third of a century is not surprising. A universal characteristic of super provinces is that they have a sizeable number of prospects of diverse characteristics and thus require several decades to be explored and developed adequately. What is surprising about this increase is both its magnitude and its composition. First of all, cumulative discoveries double during what is clearly the second and clearly lesser half of exploration in the basin, a period where few giant and large discoveries remained to be made. More importantly, relatively little of this increase comes from recent discoveries. Only 9.3% (1642 million barrels of the 17,653 million barrel increase in cumulative discoveries) comes from new field discoveries from 1965 to 2000. Conversely, 82.6% of this increase (14,583 million barrels) occurs in fields discovered from 1920 to 1950.

Because the cumulative discoveries increase substantially, estimated ultimate recovery for the Permian Basin increases substantially as well. The ultimate recoveries (as asymptotes tied to the observed discovery curves) increase from 19.0 billion

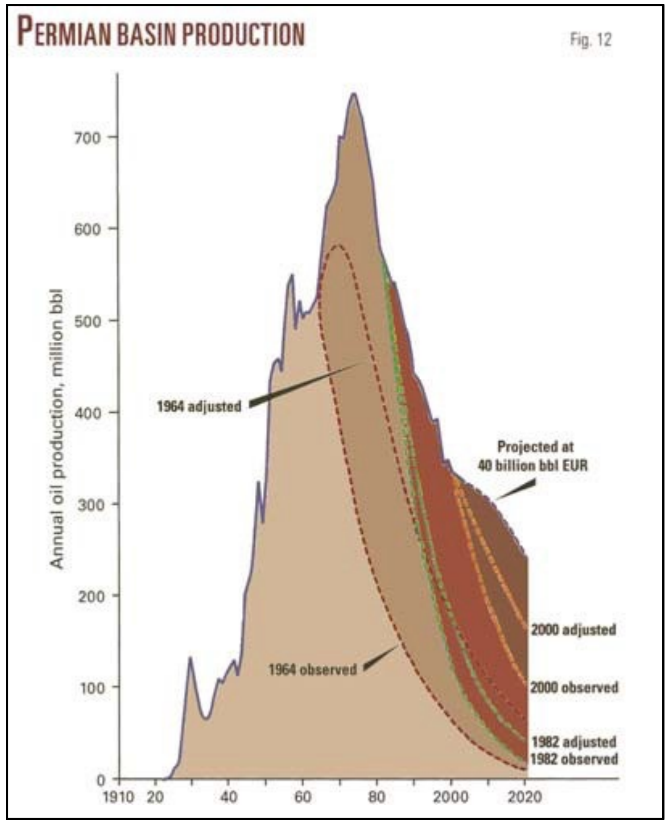


barrels as of 1964 to 28.5 billion barrels as of 1982 to 35.75 billion barrels as of 2000, an 88% increase (Figure 11). The ultimate recoveries (as asymptotes tied to the "corrected" discovery curves) increase from 27.5 billion barrels as of 1964 to 30.5 billion barrels as of 1982 to 37.5 billion barrels as of 2000, a 36% increase.

The use of the correction factors clearly results in an overestimation of future discoveries for the Permian Basin. As of 1964, future discoveries in the Permian Basin were estimated to be 1411 million barrels (using the observed discovery curves) and 5306 million barrels (using the "corrected" discovery curves). By comparison, observed discoveries from 1965 through 2000 were 1642 million barrels, only 16.4% more than the observed prediction but 61.9% less than the corrected prediction. As of 1982, future discoveries were estimated at 557 million barrels (observed) and 1655 million barrels ("corrected"). Observed discoveries from 1983 through 2000 were only 498 million barrels.

Because ultimate recovery for the Permian Basin as estimated from the 1964 and 1982 data proved to be substantially understated already by 2000, projected production based on these estimates of ultimate recovery fall well below actual production from 1965 to 2000 (Figure 12). Both projections as of 1964 miss the 1974 peak in production. Both the pre-peak projections of 1964 and the post-peak projections of 1982 overstate the rate of decline and thus understate 2000 production. Actual production in 2000 was 1.9X both the 1964 and 1982 adjusted projections, 2.8X the 1982 observed projection and 5.6X the 1964 observed projections. Even the projections made from the data through 2000 are already diverging substantially from actual production through 2004.

The divergence between actual and projected production after 2000 suggests that cumulative discoveries (known recovery) in the Permian Basin should be at least 40 billion barrels by 2020, an increase of 4758 million barrels from 2000 to 2020. By comparison, total reserve additions in



the Permian Basin in the four years from 2001 to 2004 were 856 million barrels, even after a 375 million barrel reserve reduction in the giant **Yates** field following a transfer of ownership. (With these additions, cumulative discoveries as of 2004 were 36,098 million barrels, a level already greater than the observed EUR as of 2000.) At this level of ultimate recovery, Permian Basin oil production in 2020 would be between 3.7X and 26X the amounts projected for 2020 production as of 1964 and 1982. Looking further ahead, cumulative discoveries (known recovery) of 45 to 50 million barrels for the Permian Basin as of 2050 seem quite possible, given the basin's original oil-in-place of at least 95 billion barrels as of 2000.

Conclusion

This paper addresses the question: Does the Hubbert Method provide a **reliable** means of predicting future oil production? The key word in this question is "reliable." We are not asking whether the Hubbert Method has provided a few valid predictions in the past, such as Hubbert's own often cited prediction that U.S. oil production would peak around 1970. We are asking whether the method is **sufficiently robust** to provide **consistently valid** predictions across a diverse range of circumstances. Validity in predicting production has two dimensions: (1) predicting when and at what level production will peak and (2) predicting the post-peak rate of decline. As Hubbert clearly recognized, valid predictions of future production depend on valid estimates of ultimate recovery.

For the two basins examined in this paper, **the Hubbert Method clearly fails to predict future production accurately**. All six predictions made prior to the actual peak in production fail to forecast the peak. Five of these six even indicate that the peak had already occurred. All predictions, whether pre-peak or post-peak, consistently overstate the rate of decline. Moreover, the divergence between actual and predicted production is very large. Only two of the eight predictions as of 1964 and 1982 are even barely within 50% of actual production as of 2000.

This consistent underprediction of future production occurs even in the half of the predictions that use the sophisticated version of the Hubbert Method, namely one in which recent discoveries are adjusted for the future growth in their sizes that is likely to occur as these discoveries are fully developed. Predicted production from the adjusted data is more accurate than predicted production made from the unadjusted data. But it is still significantly less than actual production.

The examples used were ones that should be considered favorable for the Hubbert Method. Both the Permian Basin and the San Joaquin Valley were clearly mature basins by 1960. The exploration process was highly advanced in each, discoveries being well past their peak. Neither incurred a subsequent expansion in area, a problem that historically has bedeviled the Hubbert Method.

Moreover, neither basin can be considered a trivial example. These two basins are among the five largest oil provinces in the United States. As of 2000, the Permian Basin contained 17.8% and the San Joaquin Valley contained 8.2% of the known recovery of 196.5 billion barrels of crude oil in the United States. The two combined provided an even greater share of U.S. oil production in 2000, the Permian Basin providing 333 million barrels (17.7%) and the San Joaquin Valley providing 215 million barrels (11.4%) of the 1880 million barrel national total.

Why the Hubbert Method Fails

Why does the Hubbert Method fail to predict future oil production accurately? The answer is simple. The method consistently underestimates future production because it consistently underestimates ultimate recovery. It underestimates ultimate recovery because it is incapable of estimating the appreciation (growth) in ultimate recovery that occurs in older fields. Even the use of the correction factors (which focus on the growth that occurs in recently discovered fields until they become fully developed) provides no mechanism within the Hubbert Method for accurately estimating growth in older fields.

The magnitude of this omission becomes clear when we consider the composition of the increase in ultimate recovery in both the Permian Basin and the San Joaquin Valley from 1964 to 2000. In the Permian Basin, observed cumulative discoveries grew by 17,653 million barrels. Of this amount, 14,583 million barrels (82.6%) occurred in fields discovered by 1950. Use of the correction factors predicted 2,227 million barrels of this pre-1951 appreciation, leaving 12,356 million barrels (84.7% of the increase during this period) unexplained. In the San Joaquin Valley, observed cumulative discoveries grew by 8323 million barrels. Growth in fields discovered by 1950 was 8190 million barrels, 98.4% of this total. The appreciation factors predicted 461 million barrels of this amount, leaving 7729 million barrels (92.9%) unexplained by the Hubbert Method.

The Hubbert Method assumes, as did all the thinking of his time and still too much of the thinking of our own, that future additions to reserves come wholly from new discoveries and from the gradual completion of the development of recent discoveries. The history of reserve additions in the United States since 1970 clearly indicates that this assumption is no longer valid.

Appreciation (growth) in the ultimate recovery of older fields not only invalidates the basic assumption of the Hubbert Method; it also eviscerates its vital parts. If the Hubbert Method is to forecast production accurately, his argument that production follows discovery with a relatively short lag time (5 to 15 years) needs to be valid. For both the Permian Basin and the San Joaquin Valley, this relatively short lag time appeared to be correct as of 1964 (Figures 3A and 8A). By 2000, it was clearly wrong in both basins (Figures 5A and 10A). In each basin, the peak in discovery had moved to the left (backward in time), while the peak in production had moved to the right (forward in time). The resulting lag between the two peaks thus increased to 40–80 years, a span of time that makes the temporal linkage between discovery and production so tenuous that it renders this linkage useless for predicting future production.

When the Hubbert Method is employed at the basin level (or used for even smaller levels of analysis), this is likely to be a universal problem. Hubbert, especially in his later papers, argued that both the annual discovery and the annual production curves are **horizontally symmetric**. Yet on the basin and smaller level, the discovery curve will invariably be **asymmetric** to the left. That this is so stems from two of the few firm conclusions of petroleum resource assessment. The first of these is that the petroleum resources of a basin are concentrated in a relatively small number of giant and large fields. The second is that most, if not all, of these giant and large fields are discovered early in the exploration of the basin. A necessary corollary of these two conclusions is that the annual discovery curve in a mature developed basin will be highly asymmetric to the left.

On the other hand, the shape of the annual production curve could easily be symmetric, asymmetric to the right, or asymmetric to the left, depending on how a variety of economic, technological, and political factors shape production over its history. Peak annual oil production in the San Joaquin Valley occurred in 1985 when cumulative production was 9.47 billion barrels. This cumulative is 57.3% of known recovery as of 2004. In other words, the currently observed annual production curve for the San Joaquin Valley is somewhat asymmetric to the right. As known recovery continues to grow, the peak on the annual production curve moves to the left. (The San Joaquin Valley is clearly a special case. Its shallow heavy oil fields were discovered early, but these fields could not be produced economically until after 1975.) Peak annual oil production in the Permian Basin occurred in 1974 when cumulative production was 17.90 billion barrels, 49.6% of 2004 known recovery of 36.10 billion barrels. As recovery continues to grow in the Permian Basin, this cumulative at the peak of production will also move to the left. These two limited examples suggest that ultimate annual production curves are likely to be slightly to moderately asymmetric to the left. More provinces need to be examined however to validate this tentative conclusion.

Hubbert argued explicitly that both the annual discovery and the annual production curves were **horizontally symmetric**, that is, that their peaks would occur at the midpoint of ultimate recovery. He also suggested (as in the precursors to Figure 1) that the two curves were also **vertically symmetric**, that is, they peaked at approximately the same amount. Both the evidence from these two basins and general theoretical considerations regarding the discovery process indicate that this suggestion is clearly false. The annual peaks in discovery (without being dampened by the use of moving averages) are very high in both the San Joaquin Valley and the Permian Basin. The three peak years of discovery in the San Joaquin Valley as of 2000 account for 22.5% (1901), 20.2% (1911), and 14.3% (1899) of 2000 known recovery. The three peak years of discovery in the Permian Basin as of 2000 account for 19.0% (1936), 12.6% (1926) and 7.5% (1929) of 2000 known recovery. The high concentration of discovered amounts in just a few years is the consequence of the concentration of ultimate resources in a few giant fields and the early discovery of these fields in the exploration history of a basin.

By comparison, peak annual production in the San Joaquin Valley is only 1.69% of known recovery as of 2000. Peak annual production in the Permian Basin is 2.12% of 2000 known recovery. As known recovery increases in each basin, the percentage of the peak in production to known recovery can only decrease, possibly to as low as 1.25% in the San Joaquin Valley and 1.50% in the Permian Basin. The order of magnitude difference between the percentage of ultimate recovery in the peak discovery year and the percentage of ultimate recovery in the peak production year is typical of most productive basins worldwide. Ultimate annual discovery curves are thus highly **vertically asymmetric** to the annual production curves.

The only way Hubbert discussed estimating ultimate recovery that is intrinsic to his method is to use the cumulative discovery curve. Once a basin has entered the phase of exploration maturity, the cumulative discovery curve begins to flatten out, indicating an asymptote that cumulative discoveries will gradually approach. This asymptote provides the estimate of ultimate recovery. One consequence of growth in the ultimate recovery in older fields is that the cumulative discovery curve moves upward over time (see Figures 6 and 11). This continuous upward movement in the cumulative discovery curve makes this curve useless as a tool for predicting ultimate recovery. Estimates of ultimate recovery derived from cumulative discovery curves are only valid if one can guarantee that there will be no further increases in the ultimate recovery of discovered fields (other than those predicted by a correction factor for recent discoveries). In the present circumstances, especially when we appear to be entering a permanent realm of higher oil prices, no such guarantee can credibly be made.

Attempted Rebuttals

Growth in the ultimate recovery of older fields creates a backbreaking challenge to proponents of the Hubbert Method. Beginning with Hubbert himself, these proponents have been aware of this challenge. Their responses fall into three basic categories.

The first response has been one of **denial**. Growth simply does not occur, or as Hubbert (being a more careful thinker than his current disciples) would argue, major growth is very unlikely. In the 1960s, when Hubbert was formulating his arguments, such an argument was clearly viable. In an environment of low, stable prices with only slow, incremental improvements in exploration and production technology—conditions which essentially characterized the quarter century from 1946 to 1970 in the upstream petroleum industry, growth in old fields was at most a minor component of reserve additions. The experience of the industry since 1970, in a different economic and technological environment, provides overwhelming evidence that massive growth does occur. As Figures 6 and 11 clearly demonstrate, what Galileo allegedly muttered after being forced to recant his argument that the earth rotated around the sun (Eppur si muove! Yet it moves!) applies with equal force to the asymptote indicating ultimate recovery.

The second response is that growth does occur, but that it can be accommodated by **backdating** all growth to the year of field discovery. Backdating growth clearly helps the Hubbert Method **explain** past production. Yet it does not help it **predict** the future. Sound predictions of future production require accurate predictions of future growth. Backdating is a technique that only helps us understand what has already happened; it provides no clues as to what will happen.

Moreover, backdating creates its own problems for the Hubbert Method. As noted earlier, growth (backdated to the year of field discovery) increases the lag between discovery and production. As this lag lengthens, the causal linkage between discovery and production weakens, gradually rendering one of the key components of the Hubbert Method useless for guiding predictions.

The third and final response is that growth occurs, but since it is mostly **unconventional**, it can be ignored. If we could apply the Hubbert Method to only conventional oil resources, it works quite well in predicting future oil production. This response does indeed save the method. If one could delete growth from infill drilling, advanced secondary recovery, and enhanced oil recovery in the Permian Basin and growth from heavy oil reservoirs through the application of thermal recovery methods in the San Joaquin Valley (and the associated production from each), the Hubbert Method would have provided fairly accurate estimates of future conventional production in each basin after 1964.

This tactic however is one of desperation. It only saves the method by destroying its relevance. What has been considered the near non-conventional oil resources, whether defined by liquid quality (heavy oil and natural gas liquids), recovery method (advanced secondary and enhanced), or geographic location (Arctic and deepwater), have become the dominant sources of both reserve additions and oil production in the Western Hemisphere over the past three decades. The more distant non-conventional resources, such as extra heavy oils (like those in the Orinoco region in Venezuela) and tar sands (such as those in Alberta) will be prominent oil resources throughout the 21st century. The response of any knowledgeable student of world oil resources to the argument that the Hubbert Method still accurately predicts future conventional oil production is simply "So what?" with an accompanying shrug of the shoulders. The problem we face is that of accurately predicting the resources and production of all types of liquid hydrocarbons, not simply predicting a steadily diminishing component of world oil such as the so-called conventional resources.

Closing Thoughts

We develop our methods and models to help us understand the world. Yet paradoxically our methods and models are also limited by those same understandings. At best, methods and models provide a systematic and logical rendition of our current knowledge. Often, the process of putting what we know in a systematic and logical form helps us to understand more fully the implications of our current knowledge.

As our knowledge changes, particularly in substantial ways, our methods and models need to change as well. Unfortunately, there is often a substantial lag between changes in our knowledge and changes in our methods and models. Methodologists and modelers become so enamored with the aesthetic properties of their creations that they focus all their attention and effort on polishing existing methods and models, instead of developing new and more relevant ones.

When Hubbert developed his method between 1955 and 1965, it was an accurate reflection of how the process of petroleum discovery and development and their implications for production were understood at the time. His work clearly laid out the implications of that understanding. In the four decades since, our knowledge of petroleum discovery and development has changed significantly. We now recognize the existence and importance of recovery growth, especially in older and larger fields. The task facing us now is not to continue to use an obsolete and increasingly irrelevant method, but to develop further our understanding of recovery growth and create new methods and models of estimating ultimate petroleum recovery and forecasting production that incorporate that improved understanding.

References

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