A new mission for geologists as oil production peaks

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A new mission for geologists as oil production peaks

with 6 figures and 2 tables

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Abstract

So far, geologists have worked to find new mineral and energy resources for the benefit of Mankind. They have been only too successful finding an abundant flow of crude oil that has stimulated economic growth and trade, allowing the population of *Hydrocarbon Man* to expand six-fold. Now, geologists face a new mission to explain that discovery peaked in the 1960s due to the constraints of Nature, and that production must inevitably also peak because you cannot produce oil without having found it. The trend of the past 150 years is about to change. Geologists, who know more about the Earth than economists and politicians, have an obligation to make their voices heard.

Zusammenfassung

Bis heute war die Aufgabe der Geologen vor allem, die Menschheit mit Bodenschätzen und Energie zu versorgen. Sie waren damit nur zu erfolgreich, denn der überreiche Fluss von Erdöl stimulierte ein Wirtschaftswachstum, welches der „Erdölmenschheit“ erlaubte, sich sechsfach zu vermehren. Der neue Auftrag an die Geologen besteht nun darin, der Öffentlichkeit klarzumachen, dass der Kulminationspunkt der Erdölfundraten naturgegeben bereits 1960 überschritten worden ist. Die Produktionsraten werden in der Folge unausweichlich kleiner werden, da man nicht produzieren kann, was man nicht gefunden hat. Der Aufwärtstrend der letzten 150 Jahre ist endgültig vorbei. Geologen, die unsere Erde besser kennen als Wirtschaftsfachleute und Politiker sollten deshalb ihren Stimmen Gehör verschaffen.

1. Introduction

Swiss oil geologists are world famous, and have made an enormous contribution to humanity. My own career opened under the inspiring tutelage of Hans Kugler from Basel and ended with the wise counsel of Walter Ziegler from Chardonne, as we laboured in vain to build a now deservedly defunct oil company. In the same way as they led in the past, Swiss geologists now have a new mission which will perhaps make an even greater contribution.

Man swung down from the trees some four million years ago. For most of this time, he lived sustainably on the planet. At first, he met his minimal energy needs by wind, water, muscle and biomass before turning to coal, as iron-making used up his supply of firewood. By 1850, his numbers had grown to about one billion.

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Then came a new sub-species, *Hydrocarbon Man*, whose population grew six-fold over a period of 150 years, exactly in parallel with the growth of a new supply of cheap and convenient energy – oil. Today, *Hydrocarbon Man* is the sole surviving human subspecies. It is time to ask about his future, and the supply of the fuel that feeds him.
Before you can produce oil, you have to find it. Even the flattest of the "flat-earth" economists can agree with that proposition. It is therefore right to ask two questions of the geologists, who were the people that found it: How much did you find ? and When did you find it ?
They sound simple questions, but they are difficult to answer because the public database of past production and reserves is atrocious. The many different hydrocarbon categories – each with its own characteristics and depletion profile – are not properly distinguished; reserve definitions are ambiguous; reporting procedures are lax and subject to distortion by vested interests; and there is no audit.
It means that we have to use geological skills and understanding of the resource in Nature to interpret the public data as well as possible. We need to remove the worst anomalies to present a rational answer to the two questions. The implications are extremely serious, spelling the extinction of our very subspecies by the end of the next century. It is by all means an important subject.

2. Data Sources

The three main sources of public data on world production and reserves are:

- Oil & Gas Journal,
- World Oil,
- BP's Statistical Review of World Energy, which can however be ignored because it simply reproduces the Oil & Gas Journal reserve data not contributing any of the company's own knowledge.

The two journals have compiled information from government and industry sources for many years in a similar manner. It is remarkable therefore that the reports should be so different. In 1998, the Oil & Gas Journal reports a world reserve total of 1034.7 Gb (billion barrels) whereas World Oil reported 974.1 Gb, in both cases for what are described as *Pro ed Reser es*. The range for individual countries is in many cases much greater. Furthermore, in 1997 World Oil retroactively revised downwards its 1996 estimate by as much as 11 %. It is difficult to imagine how genuine *Pro ed Reser es* can be reduced. Also noteworthy is the fact that 60 of the countries listed by the Oil & Gas Journal show unchanged estimates in 1998, some having done so for several years. It is implausible because production eats into reserves unless exactly matched by upward reserve revision or new discovery. In short, we have to reject the data sets as unreliable.

A better source of information is the industry database maintained by Petroconsultants in Switzerland. It carries detailed information on 18 000 fields worldwide as well as comprehensive drilling statistics, but it is not in the public domain.

3. Categories of Oil and Gas

It is important to recognize at the outset that the family of hydrocarbons is a large one: each having its own endowment in nature, characteristics, costs and above all depletion profile. Some members are easy, cheap and fast to produce; others are difficult, expensive and slow. It has been common practice to describe the former group as *Con entional* oil without applying any clear definitions of the boundary. The data published by the above journals generally refer to *Con entional* oil only but there are two main difficulties. The first is the inclusion or exclusion of natural gas liquids, which are often metered with oil, but belong to the gas domain. The second is the practice of reporting all production, no matter from what source, whereas defining reserves more restrictively, which makes it impossible to sum production and reserves to obtain a value for the total discovered.

Some definitions define *Con entional* oil on economic criteria, so as to cover all oil that is perceived to be commercially producible on any given date, but for the purpose of understanding the general endowment and depletion, it is better to apply physical attributes. Thus in this study, the following categories are treated as *Non-con entional:*

- Extra-Heavy oil (< 10°API); bitumen; heavy oil (10 - 17.5°API); "shale oil",
- Deepwater oil (> 500 m water depth),
- Polar oil,
- Enhanced Recovery (re-visiting an old field to change the characteristics of the oil in the reservoir by steam injection etc.),
- Synthetic oil derived from heavy oil, bitumen,
- Also to be excluded are Condensate, Natural Gas Liquids and synthetic oil from gas, all of which belong to the gas domain, as already noted.

4. Reserve Definition

The term *Reser es* is variously defined. Lying far underground, reserves can be estimated but not measured. Reserve estimates, like all estimates, are subject to degrees of probability, which in some way have to be quantified, but there are no international standards on how to do so. Here, the term *Reser es* is taken to mean the estimated amounts of oil that remain to be produced from known fields at the reference date under current or prospective technology and oil prices (see IEA, 1998). To simplify, three probability rankings may be identified:
- Low Case (with a probability of, say, 90% - P_{90}); often termed *Pro ed (P)*
- Median Case (with a probability of 50% - P_{50}); often termed *Pro ed & Probable (2P)*
- High Case (with a probabiliy of say 10% - P_{10}); *Pro ed, Probable & Possible (3P)*

The best estimate of what a field will have delivered on abandonment is the Median Case. (Strictly speaking, the Mean Case is the more correct; but the term Proved & Probable is in wider usage, and in practice P_{50} is close enough). P_{50} estimates are naturally subject to revision, but the results should be statistically neutral, with as many down as up. Systematic upward revision speaks of systematic under-reporting.

Table 1 shows the self-evident spurious reports from the main OPEC countries which competed with each other for quota based on reported reserves.

SPURIOUS RESERVE REVISIONS

	Abu Dhabi	Dubai	Iran	Iraq	Kuwait	Neutral Zone	Saudi Arabia	Venezuela
1980	28.0	1.4	58.0	31.0	65.4	6.1	163.4	17.9
1981	29.0	1.4	57.5	30.0	65.9	6.0	165.0	18.0
1982	30.6	1.3	57.0	29.7	64.5	5.9	164.6	20.3
1983	30.5	1.4	55.3	41.0	64.2	5.7	162.4	21.5
1984	30.4	1.4	51.0	43.0	63.9	5.6	166.0	24.9
1985	30.5	1.4	48.5	44.5	90.0	5.4	169.0	25.9
1986	30.0	1.4	47.9	44.1	89.8	5.4	168.8	25.6
1987	31.0	1.4	48.8	47.1	91.9	5.3	166.6	25.0
1988	92.2	4.0	92.9	100.0	91.9	5.2	167.0	56.3
1989	92.2	4.0	92.9	100.0	91.9	5.2	170.0	58.1
1990	92.2	4.0	92.9	100.0	91.9	5.0	257.5	59.1
1991	92.2	4.0	92.9	100.0	94.5	5.0	257.5	59.1
1992	92.2	4.0	92.9	100.0	94.0	5.0	257.9	62.7
1993	92.2	4.0	92.9	100.0	94.0	5.0	258.7	63.3
1994	92.2	4.3	89.3	100.0	94.0	5.0	258.7	64.5
1995	92.2	4.3	88.2	100.0	94.0	5.0	258.7	64.9
1996	92.2	4.0	93.0	112.0	94.0	5.0	259.0	64.9
1997	92.2	4.0	93.0	112.5	94.0	5.0	259.0	71.7
1998	92.2	4.0	89.7	112.5	94.0	5.0	259.0	72.6
	P50 Estimates by Petroconsultants							
1996	57.7	1.0	64.7	77.4	52.0	8.2	222.6	27.4
	Annual production Gb							
1998	0.69	0.11	1.31	0.77	0.66	0.20	2.95	1.13

Anomalous increase underlined. Note also implausible unchanged estimates.

Tab. 1: Spurious reports from main OPEC countries 1980 - 1998

5. Interpreting Published Reserve Data

To answer the question of how much has been found, posed earlier, we need to know past production and P_{50} Reserves, which are not directly available in the published data. Accordingly, we have to interpret. The procedure adopted here to produce the estimates given in Table 2 is as follows:

CONVENTIONAL OIL ENDOWMENT

1998

Ref. date end 1998 — Revised 01/05/99 — Gb (billion barrels)

#	Country	PRODUCTION kb/d 1998	PRODUCTION Cum. Prod.	PRODUCTION 5yr Trend	RESERVES Reported World Oil	RESERVES Reported O&GJ	RESERVES Adjust +/-	RESERVES Factor	RESERVES Median Prob. (P50)	DISCOVERED	YET-TO-FIND	YET-TO-PROD.	ULTIMATE	Disc. in Giants	Peak Disc/Prod Lag	Pk/Ult	% Prod	Dep. Rate	MP Dep	Peak Prod
1	Saudi Arabia	8058	83.23	0%	261.50	259.00	-14.47	0.85	207.85	291.08	18.92	226.77	310.00	85%	60	1.7%	27%	1.3%	2015	2008
2	FSU*	7021	133.13	-2%	63.07	57.00	-22.64	2.3	77.31	210.44	19.56	96.87	230.00	47%	24	2.0%	58%	2.6%	1991	1988
3	USA-48	4544	163.76	-3%	21.69	22.55	-8.50	1.2	16.86	180.62	9.38	26.24	190.00	26%	41	1.8%	86%	5.9%	1970	1971
4	Iraq	2114	23.96	74%	99.67	112.50	-0.77	0.80	89.38	113.34	16.66	106.04	130.00	52%	80	1.9%	18%	0.7%	2019	2008
5	Iran	3597	49.14	-0%	89.70	89.70	0.00	0.70	62.79	111.93	8.07	70.86	120.00	63%	13	1.9%	41%	1.8%	2006	1974
6	Kuwait	1796	28.37	1%	91.18	94.00	-4.24	0.60	53.86	82.23	2.77	56.63	85.00	95%	70	1.5%	33%	1.1%	2011	2008
7	Abu Dhabi	1893	15.40	1%	62.82	92.20	-5.47	0.70	60.71	76.12	3.88	64.60	80.00	70%	44	1.8%	19%	1.1%	2018	2008
8	Venezuela	2331	37.75	7%	45.50	72.60	-44.00	1.0	28.60	66.35	8.65	37.25	75.00	73%	29	1.3%	50%	2.2%	1998	1970
9	Mexico	3048	25.52	3%	40.82	47.82	-25.00	1.0	22.82	48.34	6.66	29.48	55.00	53%	23	2.2%	46%	3.6%	2000	2000
10	China	3196	23.77	2%	34.00	24.00	-1.78	1.1	24.44	48.21	2.79	27.23	51.00	45%	40	2.4%	47%	4.1%	1999	1999
11	Libya	1395	20.90	0%	26.90	29.50	-1.54	0.85	23.77	44.66	3.34	27.10	48.00	62%	9	2.6%	44%	1.8%	2003	1970
12	Nigeria	2080	19.43	2%	21.23	22.50	-1.00	0.85	18.28	37.71	2.29	20.57	40.00	22%	7	2.1%	49%	3.6%	1999	1974
13	Caspian*	200	1.82	4%	*In FSU				5.00	6.82	23.18	28.18	30.00	0%	20	3.0%	6%	3.0%	2029	2030
14	U.K.	2660	16.06	8%	5.19	5.19	0.00	2.5	12.98	29.03	0.97	13.94	30.00	43%	24	3.2%	54%	6.5%	1997	1998
15	Norway	3049	11.71	7%	11.69	10.91	0.00	1.3	14.19	25.90	3.10	17.29	29.00	45%	21	4.2%	40%	6.0%	2000	2000
16	Algeria	818	10.96	2%	13.80	9.20	-2.60	2.00	16.04	24.17	2.83	16.04	27.00	50%	22	1.7%	41%	1.8%	2005	1978
17	Indonesia	1289	18.04	-1%	9.09	4.98	-0.97	2.0	8.02	26.06	0.94	8.96	27.00	44%	22	2.3%	67%	5.0%	1989	1977
18	Canada	850	15.26	-1%	5.48	4.93	0.00	1.4	6.90	22.16	2.84	9.74	25.00	46%	14	1.4%	61%	3.1%	1990	1972
19	N.Zone	547	5.78	10%	4.60	5.00	-1.17	2.00	7.66	13.44	0.56	8.22	14.00	68%	48	1.5%	41%	2.4%	1999	1999
20	Egypt	842	7.52	-1%	3.72	3.50	0.00	1.25	4.38	11.90	1.10	5.48	13.00	35%	30	2.6%	58%	5.3%	1995	1995
21	Oman	895	5.66	3%	3.76	5.28	0.00	1.3	6.87	12.52	0.39	7.34	13.00	32%	27	2.6%	44%	4.3%	1999	1999
22	India	659	4.63	5%	3.51	3.97	0.00	1.5	5.96	10.59	0.41	6.37	11.00	27%	25	2.3%	42%	3.6%	1999	1999
23	Colombia	743	4.76	13%	2.60	2.58	0.00	2.0	5.15	9.91	1.09	6.24	11.00	37%	9	2.7%	43%	4.2%	2000	2000
24	Argentina	848	7.15	9%	2.62	2.62	0.00	1.1	2.88	10.03	0.47	3.35	10.50	30%	38	2.9%	68%	8.4%	1991	1998
25	Qatar	664	5.79	12%	4.15	3.70	-0.96	1.4	3.83	9.62	0.38	4.21	10.00	68%	58	2.4%	58%	5.4%	1994	1998
26	Malaysia	731	4.25	3%	3.51	3.90	-0.27	1.1	4.00	8.25	0.75	4.75	9.00	12%	26	3.1%	47%	5.3%	1999	1999
27	Australia	592	4.88	4%	2.23	2.90	0.00	1.2	3.47	8.36	0.64	4.12	9.00	29%	34	2.4%	54%	5.0%	1996	1998
28	Brasil	457	3.96	2%	7.11	7.11	-5.00	1.0	2.11	6.06	0.94	3.04	7.00	0%	14	2.8%	57%	5.2%	1995	1989
29	Angola	726	3.46	8%	3.90	5.41	-4.16	2.00	2.51	5.97	1.03	3.54	7.00	19%	27	3.8%	49%	7.0%	1998	1998
30	Romania	135	5.57	-0%	0.93	1.43	0.00	0.7	1.00	6.57	0.18	1.18	6.75	12%	119	4.0%	83%	4.0%	1969	1976
31	Syria	555	3.03	0%	2.35	2.50	-0.84	1.5	2.49	5.52	0.48	2.97	6.00	33%	29	3.7%	50%	6.4%	1998	1995
32	Ecuador	383	2.71	3%	2.60	2.12	-0.42	1.6	2.71	5.42	0.58	3.29	6.00	38%	28	2.4%	45%	4.1%	1998	1997
33	Dubai	315	3.33	-2%	1.02	4.00	-1.30	0.4	1.08	4.41	0.34	1.42	4.75	63%	21	3.3%	70%	7.5%	1990	1991
34	Gabon	360	2.40	3%	2.67	2.50	-1.13	1.20	1.64	4.05	0.45	2.10	4.50	40%	11	3.0%	53%	5.9%	1997	1996
35	Brunei	136	2.73	-3%	1.06	1.35	-0.45	1.6	1.44	4.17	0.08	1.52	4.25	74%	13	2.1%	64%	3.2%	1989	1978
36	Trinidad	121	3.02	-0%	0.53	0.53	0.00	1.1	0.59	3.61	0.14	0.73	3.75	16%	22	2.3%	81%	5.7%	1978	1981
37	Peru	110	2.18	-3%	0.81	0.77	0.00	1.0	0.77	2.96	0.54	1.32	3.50	38%	122	2.1%	62%	3.0%	1988	1983
38	Yemen	382	1.08	14%	3.10	4.00	-0.94	0.5	1.53	2.61	0.39	1.92	3.00	17%	23	5.4%	36%	6.8%	2001	2001
39	Congo	238	1.14	6%	1.62	1.51	-0.26	1.10	1.37	2.51	0.24	1.61	2.75	18%	16	3.5%	41%	5.1%	2000	2000
40	Germany	58	1.84	-1%	0.39	0.39	0.00	1.3	0.51	2.34	0.16	0.66	2.50	0%	15	2.3%	74%	3.1%	1976	1967
41	Denmark	235	0.83	8%	0.98	0.64	0.00	1.6	1.03	1.86	0.24	1.27	2.10	0%	29	4.5%	39%	6.3%	2000	2000
42	Vietnam	226	0.46	17%	0.82	0.60	-0.15	2.3	1.02	1.47	0.33	1.34	1.80	28%	28	5.9%	25%	5.8%	2003	2003
43	Tunisia	79	1.09	-4%	0.33	0.31	-0.06	1.75	0.44	1.53	0.22	0.66	1.75	46%	14	2.6%	62%	4.2%	1991	1985
44	Italy	109	0.75	5%	0.62	0.63	0.00	1.0	0.63	1.38	0.27	0.90	1.65	0%	19	2.7%	46%	4.2%	2000	2000
45	Cameroon	125	0.91	1%	0.61	0.40	-0.48	-4.00	0.31	1.23	0.27	0.59	1.50	0%	10	4.4%	61%	7.2%	1994	1986
46	Bahrain	102	1.08	-1%	0.22	0.16	0.00	1.2	0.19	1.27	0.23	0.42	1.50	67%	62	2.6%	72%	8.2%	1985	1993
47	Turkey	64	0.75	-3%	0.32	0.32	0.00	0.9	0.29	1.03	0.17	0.45	1.20	0%	22	2.6%	62%	4.9%	1992	1991
48	Netherlands	57	0.77	2%	0.13	0.13	0.00	1.2	0.15	0.92	0.08	0.23	1.00	0%	6	3.3%	77%	8.2%	1987	1987
49	Sharjah	70	0.40	12%	0.38	1.50	-0.16	0.3	0.40	0.81	0.19	0.60	1.00	0%	21	3.0%	40%	4.1%	2001	2001
50	Papua	79	0.24	-8%	0.30	0.33	0.00	1.3	0.43	0.68	0.27	0.71	0.95	0%	6	4.9%	26%	3.9%	2004	1993
51	France	34	0.68	-8%	0.11	0.11	0.00	1.5	0.16	0.84	0.06	0.22	0.90	0%	30	2.8%	76%	5.4%	1987	1988
52	Austria	21	0.75	-2%	0.09	0.09	0.00	1.0	0.09	0.84	0.06	0.15	0.90	57%	7	2.8%	83%	4.8%	1970	1955
53	Hungary	26	0.67	-11%	0.05	0.13	0.00	0.5	0.07	0.74	0.16	0.23	0.90	0%	20	2.8%	74%	4.0%	1983	1984
54	Thailand	84	0.27	12%	0.30	0.30	0.00	1.5	0.44	0.71	0.19	0.63	0.90	0%	22	4.3%	30%	4.6%	2003	2003
55	Albania	5	0.53	-10%	0.13	0.17	-0.03	1.1	0.14	0.67	0.13	0.27	0.80	0%	55	3.6%	66%	0.7%	1986	1983
56	Pakistan	55	0.38	-2%	0.20	0.21	-0.04	1.2	0.20	0.59	0.11	0.32	0.70	0%	9	3.9%	55%	6.0%	1996	1992
57	Bolivia	28	0.38	6%	0.14	0.13	-0.02	1.5	0.17	0.54	0.16	0.32	0.70	0%	8	2.5%	54%	3.1%	1996	1974
58	Philippines	1	0.05	-18%	0.31	0.23	0.00	1.5	0.34	0.39	0.21	0.55	0.60	0%	13	5.2%	8%	0.1%	2010	2010
59	Chile	9	0.41	-7%	0.08	0.15	-0.00	0.9	0.13	0.54	0.15	0.19	0.60	0%	22	2.5%	68%	1.7%	1983	1982
	REGIONS																			
1	ME Gulf	18005	205.88	2.7%	609.47	652.40	-26.12	0.77	482.26	688.13	50.87	533.12	739.00	75%	60	1.7%	28%	1.2%	2014	2008
2	Eurasia	10583	165.49	-1.0%	98.18	82.72	-24.45	1.85	107.96	273.45	46.00	153.96	319.45	41%	37	1.1%	52%	2.4%	1996	2001
3	N.America	5394	179.02	-2.5%	27.16	27.48	-8.50	0.00	23.76	202.78	12.22	35.98	215.00	29%	42	1.8%	83%	5.2%	1972	1972
4	L.America	8078	87.82	4.9%	102.81	136.43	-74.45	1.06	65.93	153.76	19.29	85.23	173.05	75%	23	1.7%	51%	3.3%	1998	2000
5	Africa	6664	67.81	1.8%	74.77	74.82	-11.21	1.04	65.90	133.71	11.79	77.69	145.50	42%	36	1.7%	47%	3.0%	2000	1997
6	W.Europe	6222	33.39	6.9%	19.18	18.08	0.00	0.00	29.72	63.11	4.94	34.66	68.05	39%	24	3.3%	49%	6.1%	1998	1998
7	East	3852	35.93	1.8%	22.80	18.76	-1.87	1.50	25.33	61.26	3.94	29.27	65.20	34%	30	2.2%	55%	4.6%	1996	1997
8	ME.Other	3046	21.12	3.8%	15.29	21.46	-4.21	0.97	16.68	37.80	2.65	19.33	40.45	43%	35	2.7%	52%	5.4%	1997	1998
9	Other	380	3.36	4.5%	0.00	2.12	1.10	1.10	3.54	6.90	1.10	4.64	8.00							
10	Unforeseen	0	0.00	0.0%	0.00	0.00	0.00	0.00	0.00	0.00	26.30	26.30	26.30							
	Non-Swing	44218	594	1.6%	360.19	381.88	-123.6	1.31	339	933	128	467	1061	39%	37	1.5%	56%	3.3%	1994	1997
	WORLD	62223	816	1.9%	969.66	1034.3	-149.7	0.93	821	1637	163	984	1800	54%	40	1.3%	45%	2.3%	2002	2005

Tab. 2: Conventional oil endowment. Conventional Oil excludes: heavy, tar, deepwater (> 500 m WD), polar, enhanced, NGL. Values shown as computed but should be generously rounded.
ME Gulf: Abu Dhabi, Iran, Iraq, Kuwait, Saudi Arabia; Eurasia: FSU, E. Europe, China; N. America: Canada, USA-48; W. Europe: Norway to Italy

- Take the Oil & Gas Journal value,
- remove the cumulative production for any period of unchanged reports, as well as any identifiable non-conventional oil, and list in the column entitled "Adjust",
- compare the adjusted number with World Oil and any other available data, proprietary or otherwise, and apply a factor to convert the reported *Pro ed* to a best estimate of the P_{50} value.

Evidently, it is not a strictly scientific exercise, but relies on judgment, experience and the study of many complex relationships depicted in the individual country analyses. Anomalies ring alarm bells that call for reconsideration in an effort to come up with the most plausible interpretation. No apology need be made for successive annual revisions and re-evaluations as new information comes in.

6. Reserve Revisions

In general, companies have initially understated the size of discoveries for a host of good commercial and political reasons, quoting a so-called *Pro ed* value. It may be as little as half that estimated by the explorers prior to drilling the discovery well on the basis of volumetric mapping and an assumed recovery factor.

It is obvious that this Low Case value grows over the life of the field to approach a Median (P_{50}) value, which, as noted, is the best estimate of what the field will have delivered on abandonment. Accordingly, reserve revisions have to be backdated to the discovery of the fields containing them, save for such fraction as is due to some demonstrable new technological and economic dynamic at the date of the revision. Since reserves are defined to include *prospecti e* oil price and technology, current revision should apply only some totally unforeseen developments. The genuine contribution of technology is small except in special circumstances.

This has been the cause of colossal confusion and misunderstanding. BP's Statistical Review, for example, publishes reserves with successive annual revisions taken on a current basis, which has misled many analysts to assume much higher discovery than has actually been the case. Backdating is an absolutely fundamental issue.

It is widely claimed that advances in technology will recover more oil from known fields. This is unfortunately largely an illusion. The explorers determine *oil-in-place* from volumetric mapping to which they apply a notional recovery factor to calculate how much is producible. Later, recovery is determined from the performance of the wells themselves, and no one knows or cares what fraction that might be of a notional amount of *oil-in-place*, which cannot be measured accurately anyway because much of it remains forever in the ground. Reported improvements in recovery commonly mean that the estimate of *oil-in-place*, upon which it is based, is also due for upward revision taking into account new information from drilling. The main impact of technology is on production rate, which yields profit but accelerates depletion. Figure 1 plots the depletion of the giant Prudhoe Bay Field in Alaska, which is an instructive and typical example. The operator internally estimated reserves of 12.5 Gb in 1977 but prudently announced 9 Gb for commercial and regulatory reasons. The depletion plot has been as straight as an arrow since 1991, show-

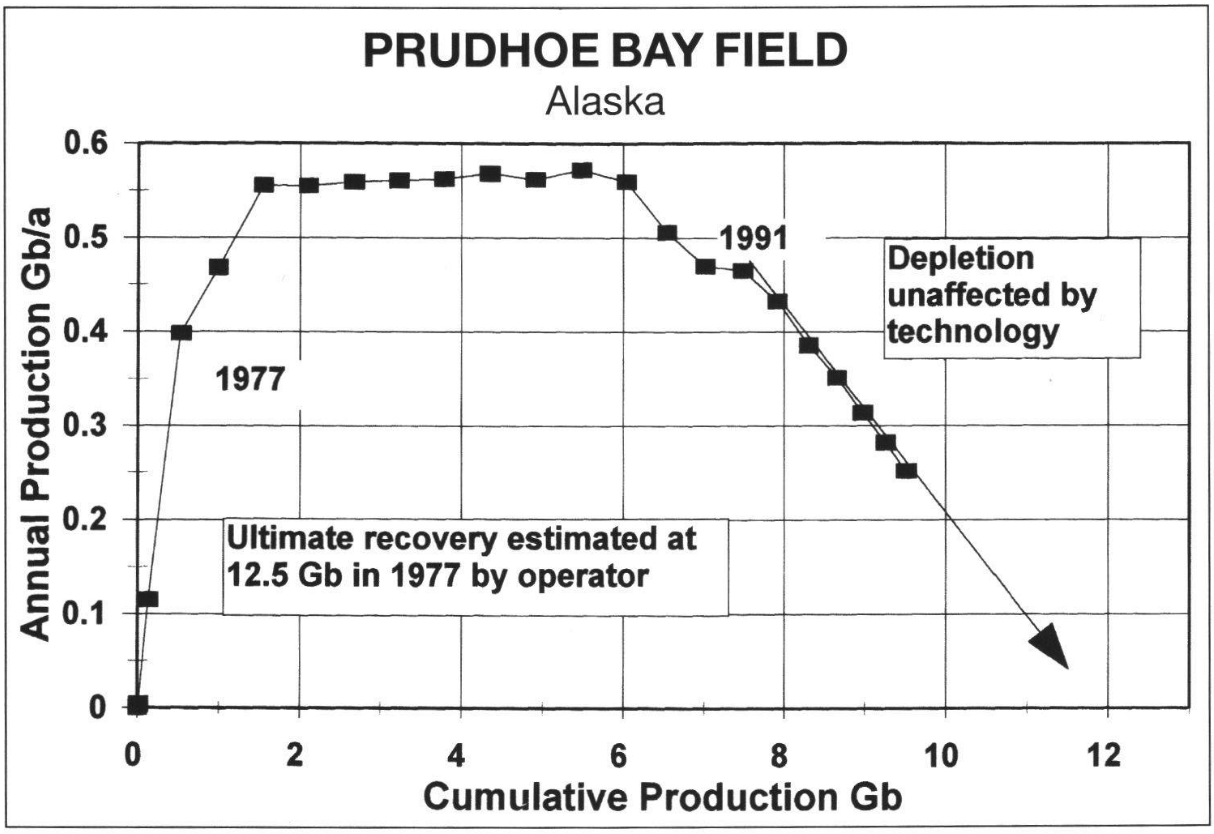

Fig. 1: Production in America's largest field shows the minimal impact of technology on reserves.

ing that the company will barely make its own original estimate, despite the vigorous application of all available technology and the benefit of every economic incentive.

7. How much has been found and when it was found

Figure 2, which is based on confidential Petroconsultants' properly backdated data, demonstrates unequivocally that discovery peaked in the 1960s. My present interpretation, as given in Table 2, is that a total of **1637** Gb have been found, made up of 816 Gb already produced and 821 Gb remaining to produce from known fields.

Having answered, albeit within the limitations of the data, the first two questions, it is time to ask two more: How much is Yet-to-Find ? and How fast are we finding it ?

In earlier years, exploration was a hit or miss affair, as geologists armed with little more than a hammer and a hand lens combed the world for prospects, being drawn mainly to areas with natural seepages. Even so, they had managed to find most of the prolific onshore basins and many of the giant fields. Then came geophysics to investigate the subsurface, which has been progressively refined until to-day it provides amazing resolution capable of revealing the smallest and most subtle trap. Even more important was the geochemical breakthrough of the 1980s that made it possible to identify the source- rocks, and map where they had been heated sufficiently to give up their hydrocarbons.
In short, the planet has now been explored from end to end with advanced technol-

WORLD DISCOVERY

Conventional Oil

CONVENTIONAL OIL ENDOWMENT

Ref. date end 1998 — Revised 01/05/99 — Gb (billion barrels)

		PRODUCTION			RESERVES					DISCOVERED	YET-TO-FIND	YET-TO-PROD.	ULTIMATE	Disc. in Giants	Peak Disc/Prod Lag	Pk/Ult	% Prod	Dep. Rate
	Country	kb/d 1998	Cum. Prod.	5yr Trend	Reported World Oil	Reported O&GJ	Adjust +/-	Factor	Median Prob. (P50)									
1	Saudi Arabia	8058	83.23	0%	261.50	259.00	-14.47	0.85	207.85	291.08	18.92	226.77	310.00	85%	60	1.7%	27%	1.3%
2	FSU*	7021	133.13	-2%	63.07	57.00	-22.64	2.3	77.31	210.44	19.56	96.87	230.00	47%	24	2.0%	58%	2.6%
3	USA-48	4544	163.76	-3%	21.69	22.55	-8.50	1.2	16.86	180.62	9.38	26.24	190.00	26%	41	1.8%	86%	5.9%
4	Iraq	2114	23.96	74%	99.67	112.50	-0.77	0.80	89.38	113.34	16.66	106.04	130.00	52%	80	1.9%	18%	0.7%
5	Iran	3597	49.14	-0%	89.70	89.70	0.00	0.70	62.79	111.93	8.07	70.86	120.00	63%	13	1.9%	41%	1.8%
6	Kuwait	1796	28.37	1%	91.18	94.00	-4.24	0.60	53.86	82.23	2.77	56.63	85.00	95%	70	1.5%	33%	1.1%
7	Abu Dhabi	1893	15.40	1%	62.82	92.20	-5.47	0.70	60.71	76.12	3.88	64.60	80.00	70%	44	1.8%	19%	1.1%
8	Venezuela	2331	37.75	7%	45.50	72.60	-44.00	1.0	28.60	66.35	8.65	37.25	75.00	73%	29	1.3%	50%	2.2%
9	Mexico	3048	25.52	3%	40.82	47.82	-25.00	1.0	22.82	48.34	6.66	29.48	55.00	53%	23	2.2%	46%	3.6%
10	China	3196	23.77	2%	34.00	24.00	-1.78	1.1	24.44	48.21	2.79	27.23	51.00	45%	40	2.4%	47%	4.1%
11	Libya	1395	20.90	0%	26.90	29.50	-1.54	0.85	23.77	44.66	3.34	27.10	48.00	62%	9	2.6%	44%	1.8%
12	Nigeria	2080	19.43	2%	21.23	22.50	-1.00	0.85	18.28	37.71	2.29	20.57	40.00	22%	7	2.1%	49%	3.6%
13	Caspian*	200	1.82	4%	*In FSU				5.00	6.82	23.18	28.18	30.00	0%	20	3.0%	6%	3.0%
14	U.K.	2660	16.06	8%	5.19	5.19	0.00	2.5	12.98	29.03	0.97	13.94	30.00	43%	24	3.2%	54%	6.5%
15	Norway	3049	11.71	7%	11.69	10.91	0.00	1.3	14.19	25.90	3.10	17.29	29.00	45%	21	4.2%	40%	6.0%
16	Algeria	818	10.96	2%	13.80	9.20	-2.60	2.00	16.04	24.17	2.83	16.04	27.00	50%	22	1.7%	41%	1.8%
17	Indonesia	1289	18.04	-1%	9.09	4.98	-0.97	2.0	8.02	26.06	0.94	8.96	27.00	44%	22	2.3%	67%	5.0%
18	Canada	850	15.26	-1%	5.48	4.93	0.00	1.4	6.90	22.16	2.84	9.74	25.00	46%	14	1.4%	61%	3.1%
19	N.Zone	547	5.78	10%	4.60	5.00	-1.17	2.00	7.66	13.44	0.56	8.22	14.00	68%	48	1.5%	41%	2.4%
20	Egypt	842	7.52	-1%	3.72	3.50	0.00	1.25	4.38	11.90	1.10	5.48	13.00	35%	30	2.6%	58%	5.3%
21	Oman	895	5.66	3%	3.76	5.28	0.00	1.3	6.87	12.52	0.39	7.34	13.00	32%	27	2.6%	44%	4.3%
22	India	659	4.63	5%	3.51	3.97	0.00	1.5	5.96	10.59	0.41	6.37	11.00	27%	25	2.3%	42%	3.6%
23	Colombia	743	4.76	13%	2.60	2.58	0.00	2.0	5.15	9.91	1.09	6.24	11.00	37%	9	2.7%	43%	4.2%
24	Argentina	848	7.15	9%	2.62	2.62	0.00	1.1	2.88	10.03	0.47	3.35	10.50	30%	38	2.9%	68%	8.4%
25	Qatar	664	5.79	12%	4.15	3.70	-0.96	1.4	3.83	9.62	0.38	4.21	10.00	68%	58	2.4%	58%	5.4%

Fig. 2: Backdating reserve revisions is critically important to give a valid picture of discovery.

ogy and the benefit of vastly improved knowledge. This effort shows that virtually all the productive basins with significant conventional oil potential have been found. To give a sense of proportion, it may be noted that the North Sea with an ultimate recovery of almost 60 Gb is the largest to be found in 50 years, adding enough to supply the world for less than three years at current rates of consumption.

Exploration follows a natural cycle. First comes a learning period as a new area is investigated by seismic surveys and boreholes to secure the necessary information. At the moment of truth, it may prove to be barren, lacking one or more of the essential geological ingredients, of which source is the most important. In that case, it will remain forever barren no matter how much technology or investment may be thrown at it. But if it is productive, the larger, easier fields will be found first, being too large to miss. They are highly profitable, and both company and host government have every incentive to produce them as fast as possible. They give rise to a natural peak in discovery which is barely affected by economics or technology. Peak is followed by ever smaller and more difficult finds largely financed by the proceeds of the large early fields under the tax regime. Advanced technology becomes more important as the fields become smaller and more difficult. At the end of the day, an economic cutoff brings exploration to a halt, leaving some oil behind.

It is evident that most of the world's *Yet-to-Find* lies in ever smaller fields in the existing basins. This means that the past discovery trend can be extrapolated to indicate what remains to be found down to a certain economic cutoff. There are two main statistical approaches. One is the so-called creaming curve which plots cumulative discovery against cumulative wildcats (or over time), as shown in Figure 3.

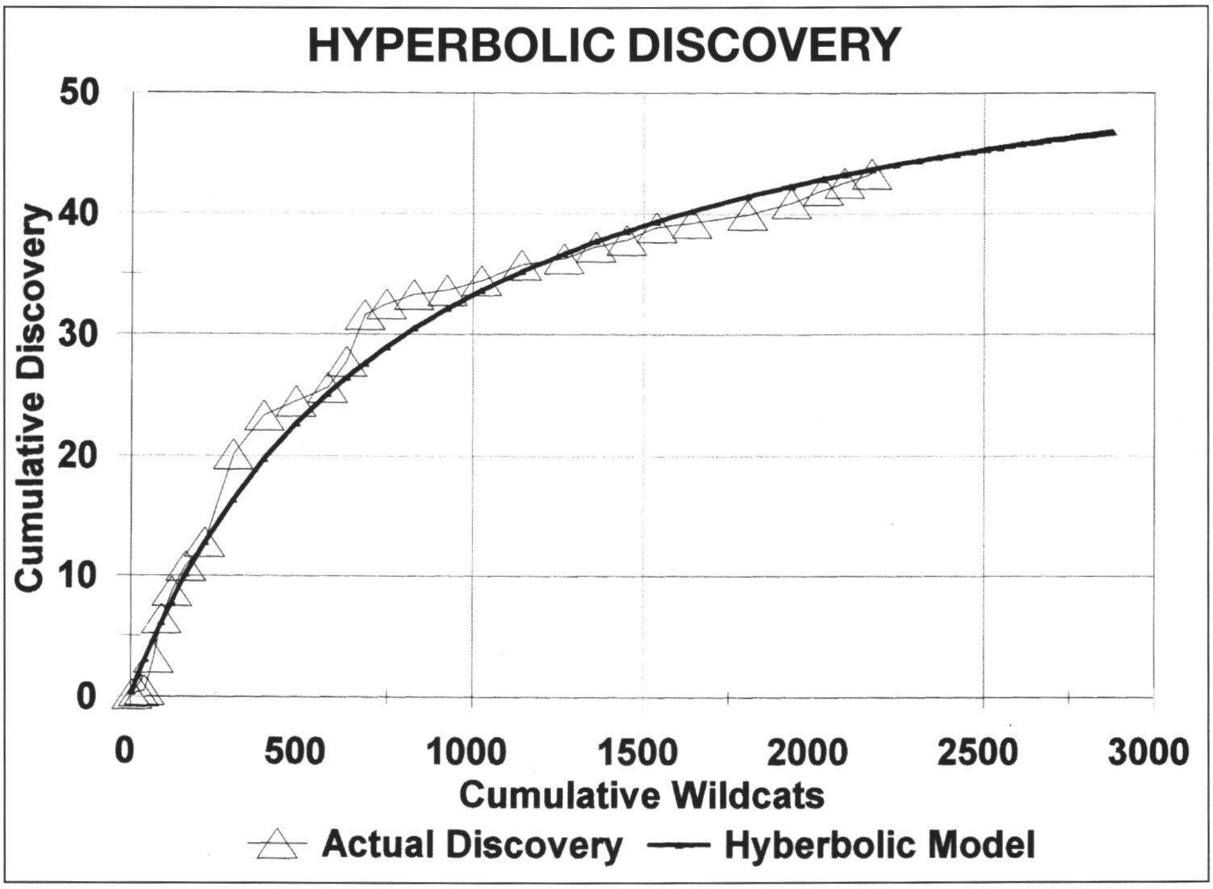

Fig. 3: Cumulative discovery against cumulative wildcats is hyperbolic.

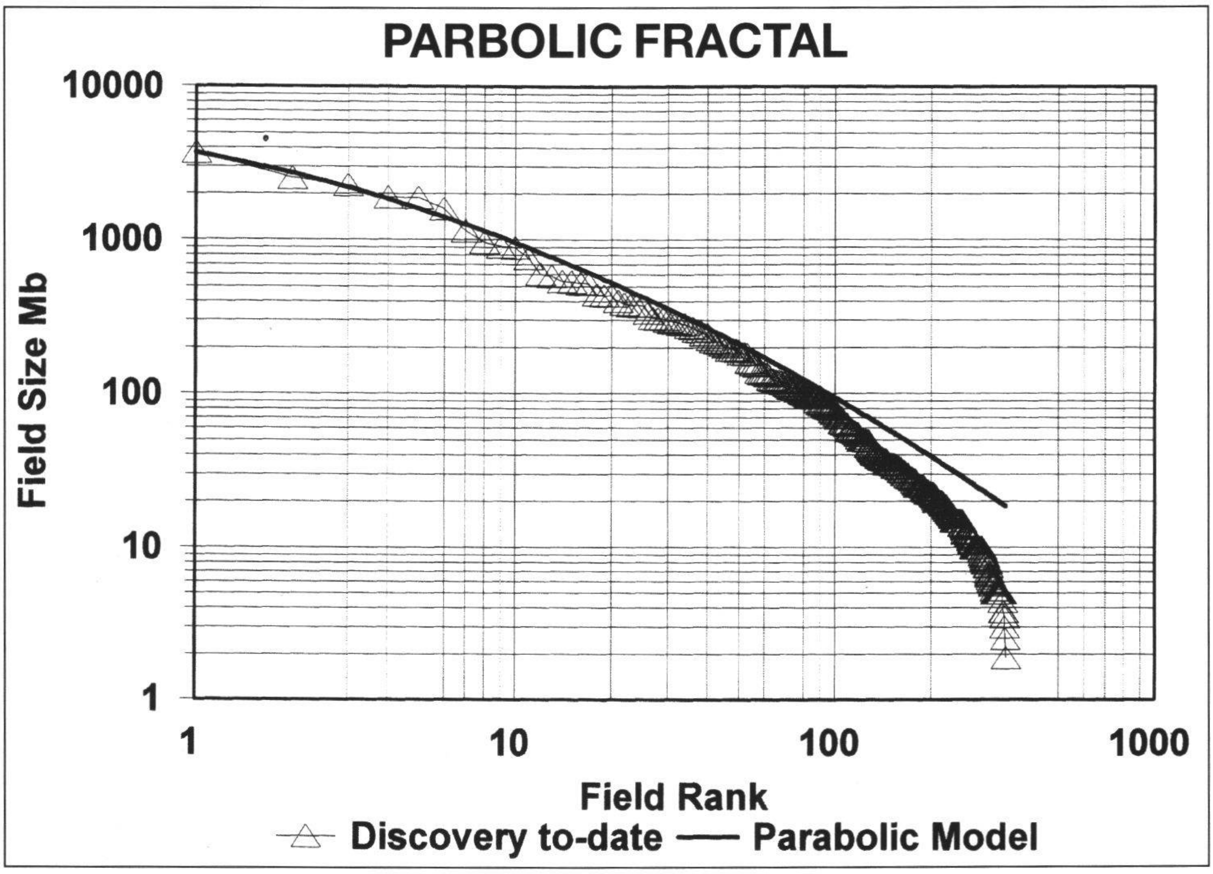

Fig. 4: The parabolic fractal plots size against rank showing the distribution in Nature.

The result is a normally a hyperbola, whose asymptote equates with ultimate recovery. The other is the parabolic fractal (Figure 4), plotting log-size against log-rank, which models as a parabola under a law of nature described by Laherrère. These and other statistical techniques, together with old-fashioned judgement, can be used to make reasonable estimates of the *Yet-to-Find*, which under this assessment amounts to **163** Gb.
Discovery rate has been falling since it peaked in the 1960s, and is now down to about 6 Gb a year, with a current wildcat drilling rate of 3000 a year. It means that even if the downward trend were to be arrested, it would still take 27 years and 80 000 wildcats to find the indicated *Yet-to-Find*. It is difficult to propose a higher number, especially in relation to the contribution discovery could make to peak.

In short, we find one barrel for every four we produce, as we continue to consume our natural inheritance at a prodigious rate.

8. Modelling Depletion

Having now estimated, as well as we can, how much has been found and how much remains to find, we can turn to consider the *Yet-to-Produce,* and evaluate how it may be depleted. Table 2 shows that it amounts to **983** Gb, being the sum of the *Reser es* and the *Yet-to-Find.* Depletion Rate is defined as the percentage that annual production bears to the *Yet-to-Produce* on any given date. The rate at which it can be extracted is determined primarily by the immutable physics of the reservoir, giving limited discretionary options.

Being a finite resource, we may be sure that production in any geological basin or country starts and ends at zero, with peak coming somewhere in between. In an unfettered environment, as represented for example by the USA or FSU, peak comes around the midpoint of depletion. The OPEC countries are however characterised by twin peaks separated by a saddle due to quota restrictions, and the world as a whole is a composite, being heavily influenced by the OPEC contribution.

Depletion Rate increases to depletion midpoint but then stabilizes. With the exception of the five Middle East producers which own about half the *Yet-to-Produce,* most countries are now either just past peak or close to it.

The uneven distribution of oil means that we can treat the five Middle East countries (ME Gulf on Table 2), as swing producers around midpoint, having the ability in resource terms to make up the difference between world demand under alternative scenarios and what the other countries can produce under their depletion profiles.

Figure 5 depicts three such scenarios which may span the spectrum of what is likely to happen over the next decade or so. The Base Case assumes that the demand for oil grows at 1.5% a year until the swing share has risen to 35% which is taken to be the threshold when their control is sufficient to impose radically higher prices, meaning perhaps something in the \$30 - \$50/b range. This price rise dampens demand giving a plateau of production until share has risen to 50 %, and the swing countries too approach their depletion midpoints. Production thereupon declines at the then depletion rate of about 3% a year.

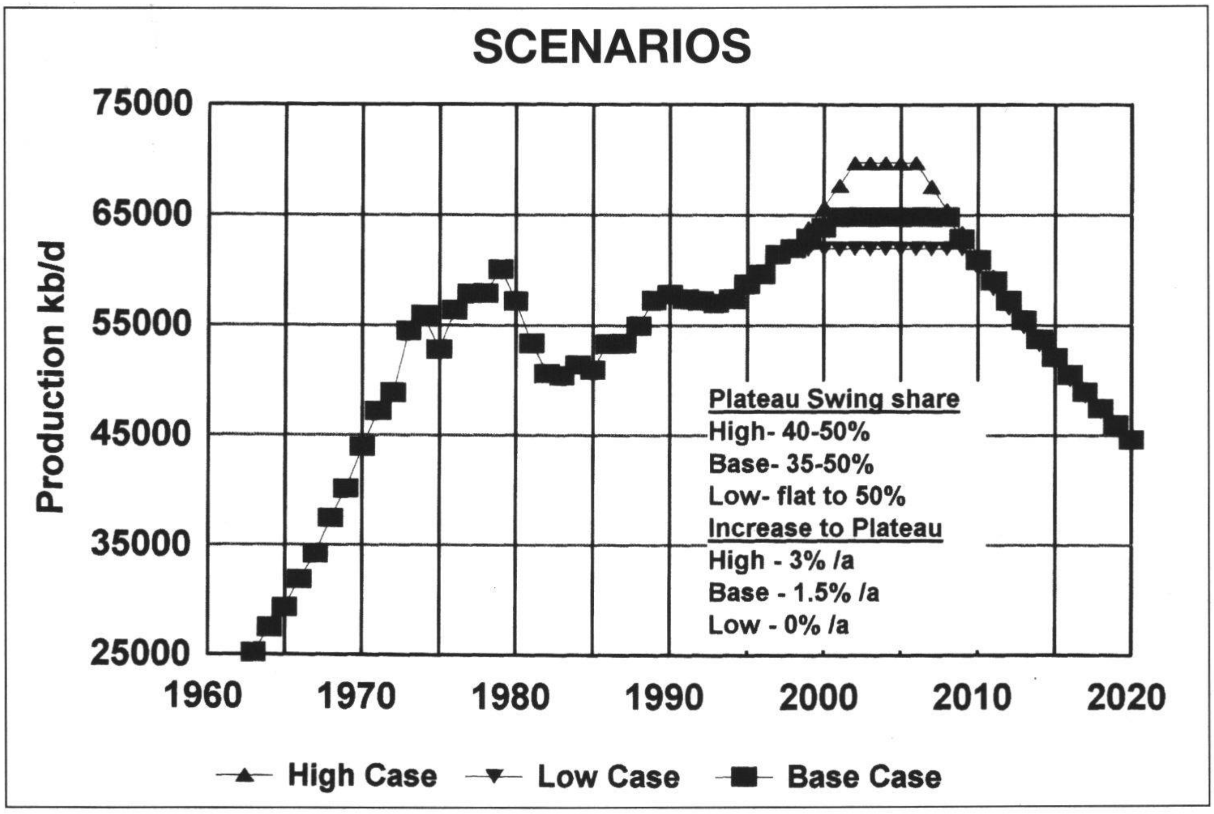

Fig. 5: Scenarios of future production respecting resource constraints

Naturally, other scenarios can be pictured, but given the resource base described in Table 2, a permanent chronic shortfall in supply will in all cases have to develop around the end of the first decade of the 21st Century. This is in accord with the recent findings of the International Energy Agency, the world's premier authority on the subject. Its *World Energy Outlook* depicts a non-Middle East peak by 2000 and a shortfall of conventional oil of 19 Mb/d by 2020. It further shows the share of Middle East supply rising to 52 % by 2010 which implies sufficient control to impose much higher prices.

9. After Peak

The peak of conventional oil production will be an historic turning point marking the decline of *Hydrocarbon Man*, who by any reasonable reckoning will be close to extinction by the end of the 21st Century. As of to-day, we have no idea who his successor may be. The impact of declining oil supply on the latter half of his life-span will clearly be enormous, and it is worth considering some of the more immediate consequences.

9.1 Non-conventional production

Some 2 Mb/d of *Non-con entional* oil is already in production, although largely dependent on favourable fiscal treatment. No doubt production will be stepped up in the aftermath of conventional peak.

There is scope to increase production of heavy oil and bitumen from the huge deposits of Eastern Venezuela and Canada. They are however far from homogenous, and only the most favourable locations within them are presently viable. It means that to bring in more becomes exponentially more difficult, costly and perhaps unlikely. The energy equation is poor, much being consumed in the extraction process. It is reasonable to anticipate production rising to a long low plateau at a level not more than two or three times current production. The IEA's estimate of a ceiling of 2.4 Mb/d is in the right order of magnitude.

Deepwater production can be stepped up. Most of the deepwater areas are definitely non-prospective for well understood geological reasons, but there are prospective tracts in the Gulf of Mexico, bordering the South Atlantic and in a few other places. These areas are characterised by very unusual oceanic geology, and successful exploration depends on finding unique combinations of circumstances where source trends are in juxtaposition with reservoirs, often in rather remarkable ways. For example, some of the finds off West Africa rely on huge rafted blocks of platform carbonate that slid down the slope to come to rest above narrow generating grabens. Off Brazil, the reservoirs are Tertiary turbidites that were re-worked by longshore currents, forming huge dune-like deposits with excellent characteristics. In some cases, the reservoirs develop in sediments that were ponded behind sea-bed topographic irregularities due to salt and clay diapirism.

The technology of deepwater operations is impressive, but even so is viable only with high productivity per well, which severely limits the number of prospects that can be developed. To attribute about 85 Gb to the deepwater domain, to be produced in a series of rather short and sharp bursts, is quite optimistic, adding some three years of world supply.

Polar exploration can be stepped up. Antarctica is closed by agreement for environmental reasons and is not in any event very promising to judge from the other segments of Gondwanaland with which it is related. The Arctic is more prospective with some huge shelves overlying sedimentary basins. It has delivered Alaska, but generally appears to be gas prone, due probably to the effects of substantial vertical movements of the crust under fluctuating ice caps in the geological past.

9.2 Gas and Gas Liquids

Gas was more widely generated in nature than was oil, but it needs better seals to hold it in the reservoir. The two factors tend to cancel each other out, meaning that the world's gas endowment in calorific terms is about the same as its conventional oil endowment, and much less on a value basis given the high cost of transporting gas. Nevertheless, it is at a much earlier stage of depletion, not being expected to peak until around 2020, following the construction of new pipelines to the Middle East and other areas remote from market, such as Nigeria.

The increasing supply of gas will yield large amounts of natural gas liquid and synthetic fuel, as technology advances and as rising prices make the processing economically viable. It promises to be a valuable fuel for the future.

9.3 Enhanced recovery

Enhanced recovery is here defined as re-visiting an old field and changing the characteristics of the oil in the reservoir by steam injection and other methods. It applies mainly to the onshore United States and former Soviet Union, where some of the fields were developed long ago with rather primitive technology. About one-tenth of the US fields are susceptible and yield up to 10% more oil. Infill drilling can be considered as a related activity.

Enhanced recovery is not to be confused with so-called Improved Recovery, which is now routinely applied to all modern fields. Its proceeds are to be included in the P_{50} reserve estimates.

Figure 6 gives an approximate profile of the production of all hydrocarbon based on present knowledge. As any explorer will confirm, more knowledge does not necessarily improve a prospect, and there is no reason to assume that the resource base will grow simply because we come to know more about it.

9.4 Other consequences

It is quite evident that the supply of hydrocarbons will be incapable of meeting an extrapolation of past demand growth. It is evident that the United States, Europe and the Asian countries will be on a collision course for access to Middle East oil, and that there will be further pressures from an impoverished Third World. There

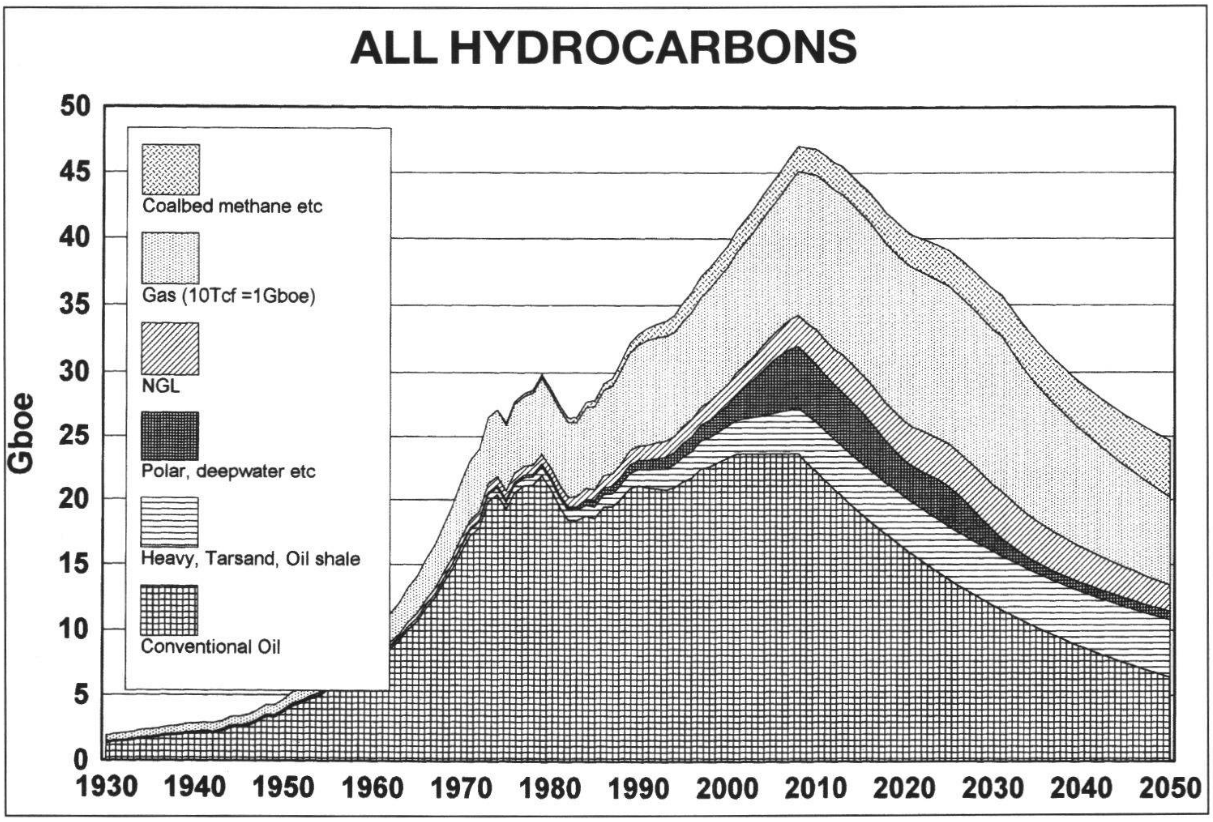

Fig. 6: Tentative estimate of the production of all hydrocarbons.

are grave dangers that the control by the Middle East will be taken as a hostile political act giving rise to highly misjudged military actions. While there may be indeed political overtones, the control of oil by the Middle East is due ultimately to geological factors, which are not affected by military intervention or changing ownership.

Other solutions have to be found. Nuclear energy is an option, given that the intractable problems of waste disposal can be solved, and coal can be rediscovered provided that the emissions can be managed. There is obvious scope for stepping up renewable energy from a wide range of sources, and even more scope for energy savings. But these things take time to achieve and will not happen until there is a fiscal or market incentive.

It is worth commenting on the recent low oil price which is imposed by the open market that values the marginal barrel but makes no charge for natural depletion. Oil is a liquid not an ore: it is either there in abundance or not there at all. This has made it naturally subject to feasts or famines, unless the market is controlled in some way, as it has been in the past by Standard Oil, the Texas Railroad Commission, the hegemony of the "Seven Sisters" or OPEC.

Since the Gulf War, the market has benefited from the embargo on Iraq, which has acted as a sort of swing producer of last recourse, keeping over 2 Mb/d off the market. Last winter, when prices were rising uncomfortably, it was decided to relax the embargo for "humanitarian" reasons, but the export quota was set in dollars not barrels. When a combination of warm weather and the Asian recession led to a fall in demand, prices fell, and Iraq was able to export more oil exacerbating the situation.

Low oil price is a critically serious situation for the Middle East governments who rely almost exclusively on oil revenue. It has led already to the premature abandonment of wells, reducing the reserves. It is an absurd way in which to manage the supply and pricing of a commodity as important as oil. We can anticipate how the market will over react in the other direction once marginal shortages begin to appear as they undoubtedly will in the near future.

What is needed is a new international protocol whereby production and imports are limited to Depletion Rate. Such a proposal has already been published by the Centre for Global Energy Studies and is attracting attention, being seen as a useful complement to the Kyoto climate accords.

10. The New Geological Mission

Without realising it, geologists have had a profound impact on humanity: indeed their efforts have led to an entirely new subspecies called *Hydrocarbon Man*. Before you can produce oil, you have to find it – that is geological business. So far, the exploration community's mission has been to find mineral resources and essential energy supplies for the benefit of Mankind. He has been only too successful. Now, he has a new mission, which is to describe just how finite those resources are and to warn of the impacts of depletion : it is geological not economic or political business.

The abundance of mineral resources and especially cheap energy from oil have set the world on an unsustainable path of rampant consumerism as the rich get richer and the poor get poorer in an increasingly uncontrolled global economy, hanging on a delicate financial structure. It is time to change direction.

Institutions are designed to serve the epochs that created them and are incapable of dealing with historic discontinuities. Geologists by contrast are used to unconformities and plate-collisions. Their knowledge, experience and insight are vital if the world is to ameliorate the tensions that must inevitably accompany the transition as the 150 year trend of rising production comes to an end giving way to increasing shortage and high price. They have a right to intervene beyond their strictly professional domain. The politicians need their advice.

In the same way as Swiss geologists were some of the most famous pioneering oil explorers, they now have a more important role to play in a new mission of explaining what the true situation is. In the course of doing so, they might have a word with their cousins in the banks to help them avoid the financial meltdown that an oil crisis might otherwise trigger.

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ERRATA CORRECTION

In vol. 4/1 of the Bulletin for applied Geology, the article of C.J. Campbell contains a incorrect figure 2 on page 26. Attached you find a new and corrected version. Please attach this page to your corresponding volume.

In the same article in all italic texts the letter "v" is missing, due to a printing problem.

We apologize for this mistakes.