Peak Oil, Peak Energy

Mother Nature Bats Last

Martin Sereno

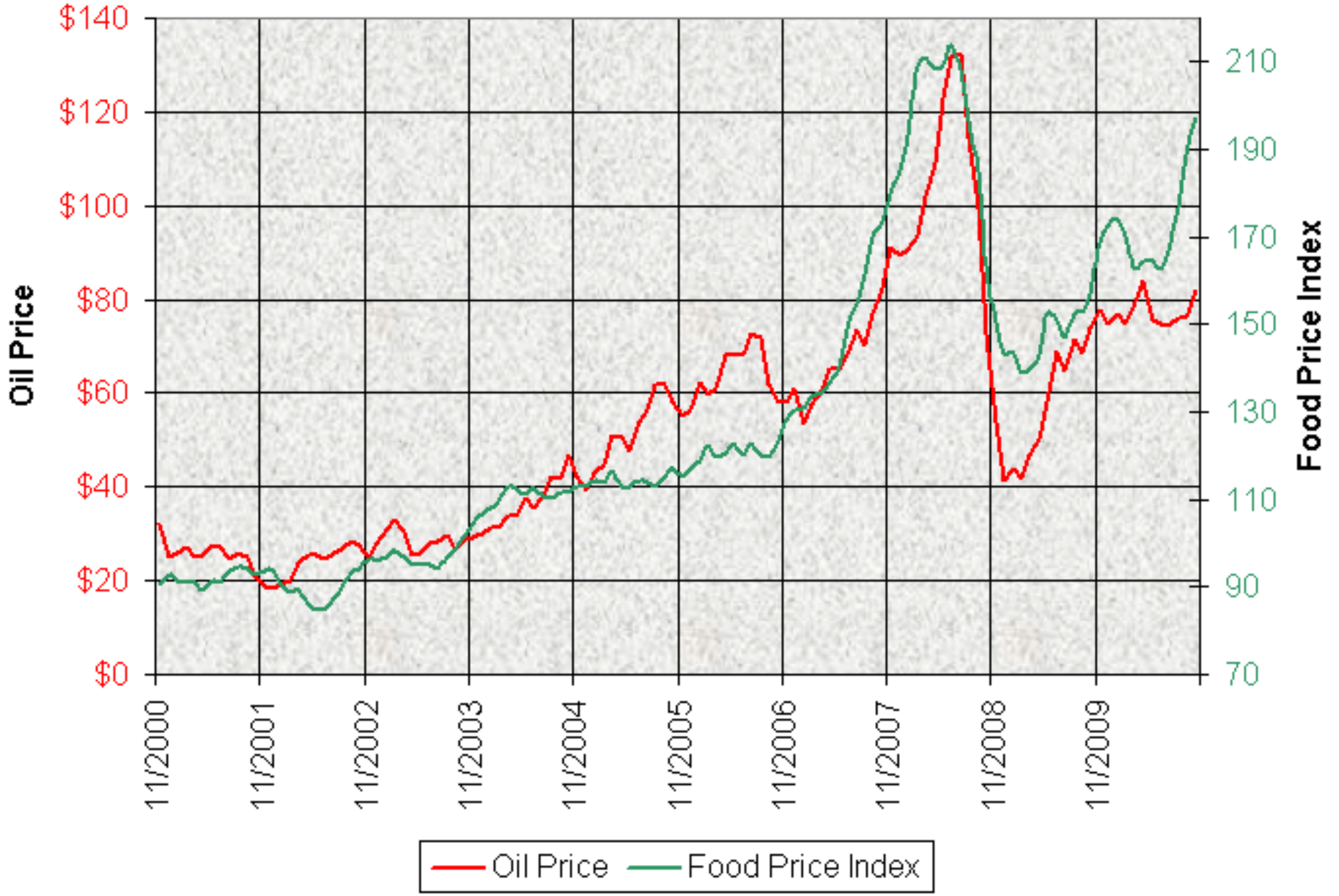
1 Feb 2011

(orig. talk: Nov 2004)

Oil is the Lifeblood of Industrial Civilization

- 80 million barrels/day, 1000 barrels/sec, 1 cubic mile/year
- highly energy-dense
- easy to transport, store
- moves goods and people
- allows us to fly (there will never be a battery-operated jet plane)
- digs huge holes and puts up huge buildings
- ballooned our food supply (fertilize, cultivate, irrigate, transport)
- our 'stuff' is made from it (iPods to the roads themselves)
- we're not "addicted to oil" -- that's like saying a person has an "addiction to blood"

Food Price vs. Oil Price



Where Oil Comes From

- raw organic material for oil (e.g., from plankton) is present in low concentrations in ‘all’ sedimentary rocks, but esp. from two warm periods 90 million and 140 million years ago

- temperature rises with depth (radioactivity, Kelvin’s mistake)

- oil is generated in rocks heated to 60-120 deg Celsius

- rocks at this temp. occur at different depths in different places (N.B.: water depth doesn't count)

- oil is ‘cracked’ to natural gas at higher temps (deeper)

- abiotic oil from “crystalline basement” is negligible, if it exists

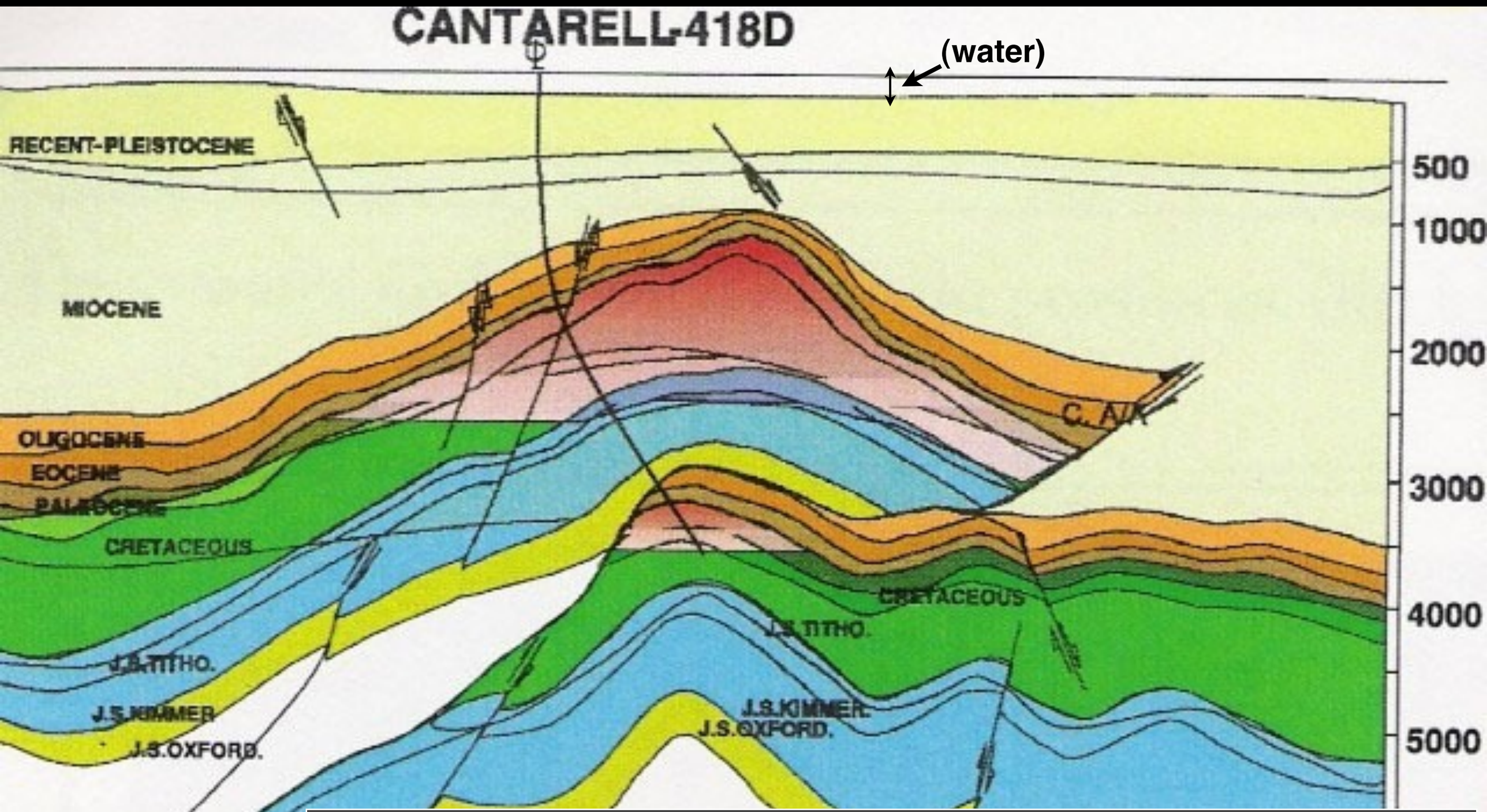
- exhausted oil fields do not refill

Recoverable Oil

- oil must collect in a “trap” to be practically recoverable
- a trap is a permeable layer capped by an impermeable one
- obvious traps: anticlines, domes (“oil in those hills”)
- less obvious traps found by seismic imaging: turned up edges of salt domes, near buried meteorite crater (Mexico)
- harder-to-get-at traps: shallow continental shelf (GOM)
- even-harder-to-get-at traps: edge continental slope (Macondo, resevoir pressure: 12,000 pounds [6 tons] per sq inch)
- essentially no oil in basaltic ocean floor or granitic basement

(Used to be!) Second Largest Oilfield

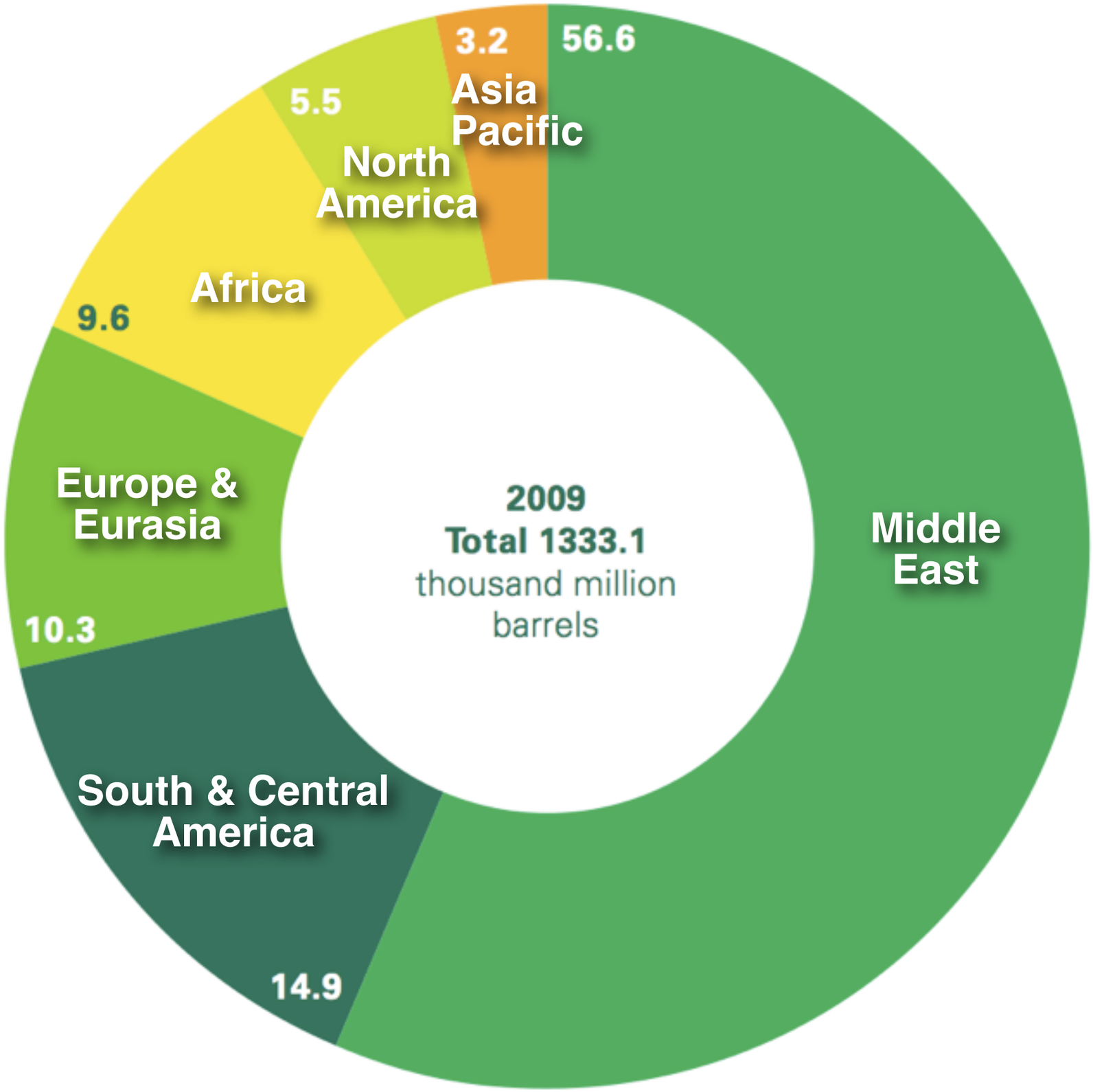
Cantarell used to supply 2% of world oil



Guzman, A.E. and B. Marquez-Dominguez (2001) The Gulf of Mexico basin south of the border: *The* petroleum province of the twenty-first century. In M.W. Downey, J.C. Threet, and W.A. Morgan, eds., *Petroleum Provinces of the Twenty-First Century*. Tulsa: AAPG, p. 346.

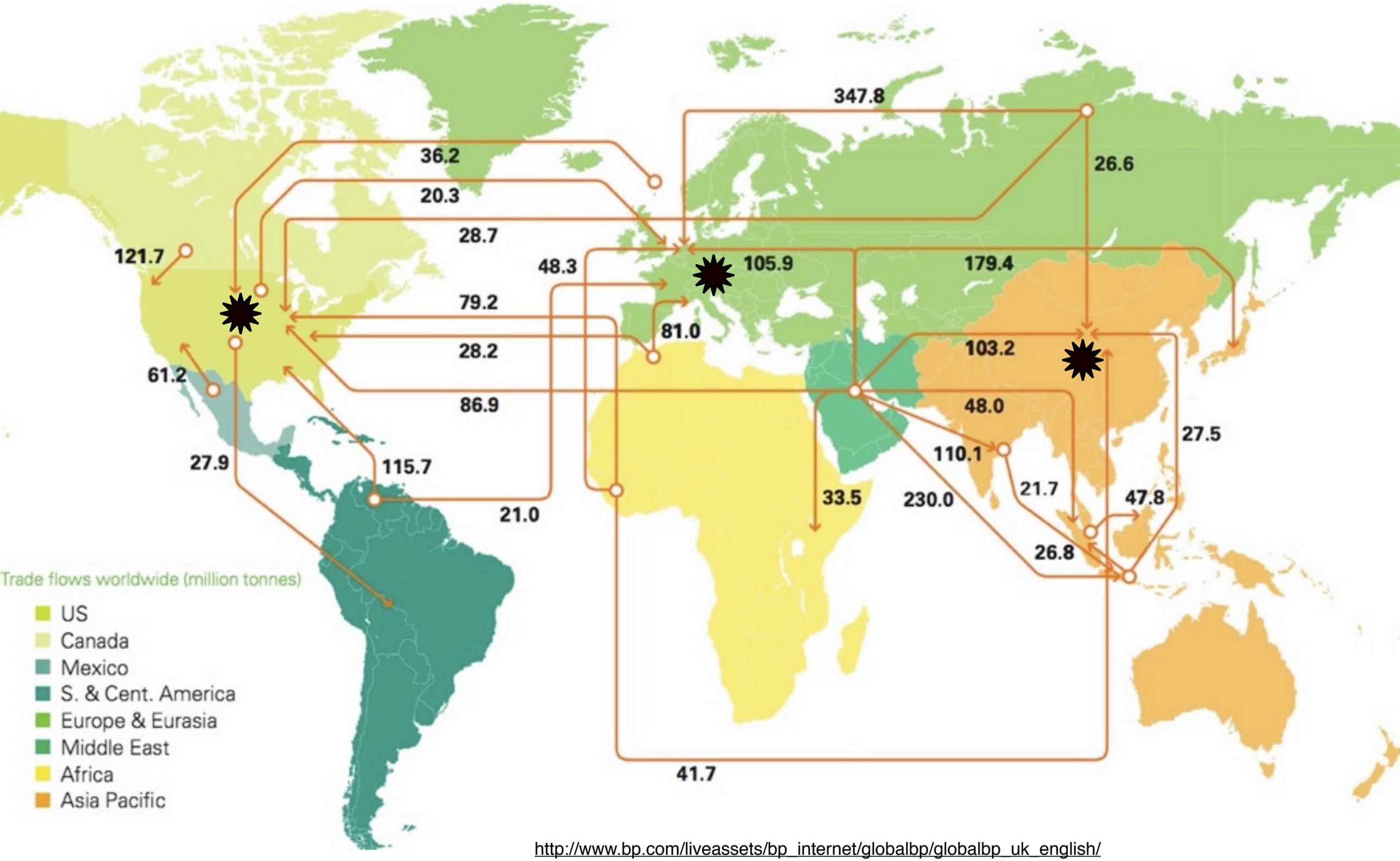
Recoverable Oil is Highly Localized in Space

(even more than this diagram implies)



BP 2010

World Oil Flows



http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2010_downloads/statistical_review_of_world_energy_full_report_2010.pdf

BP 2010

Significant traps are *extremely* localized in space

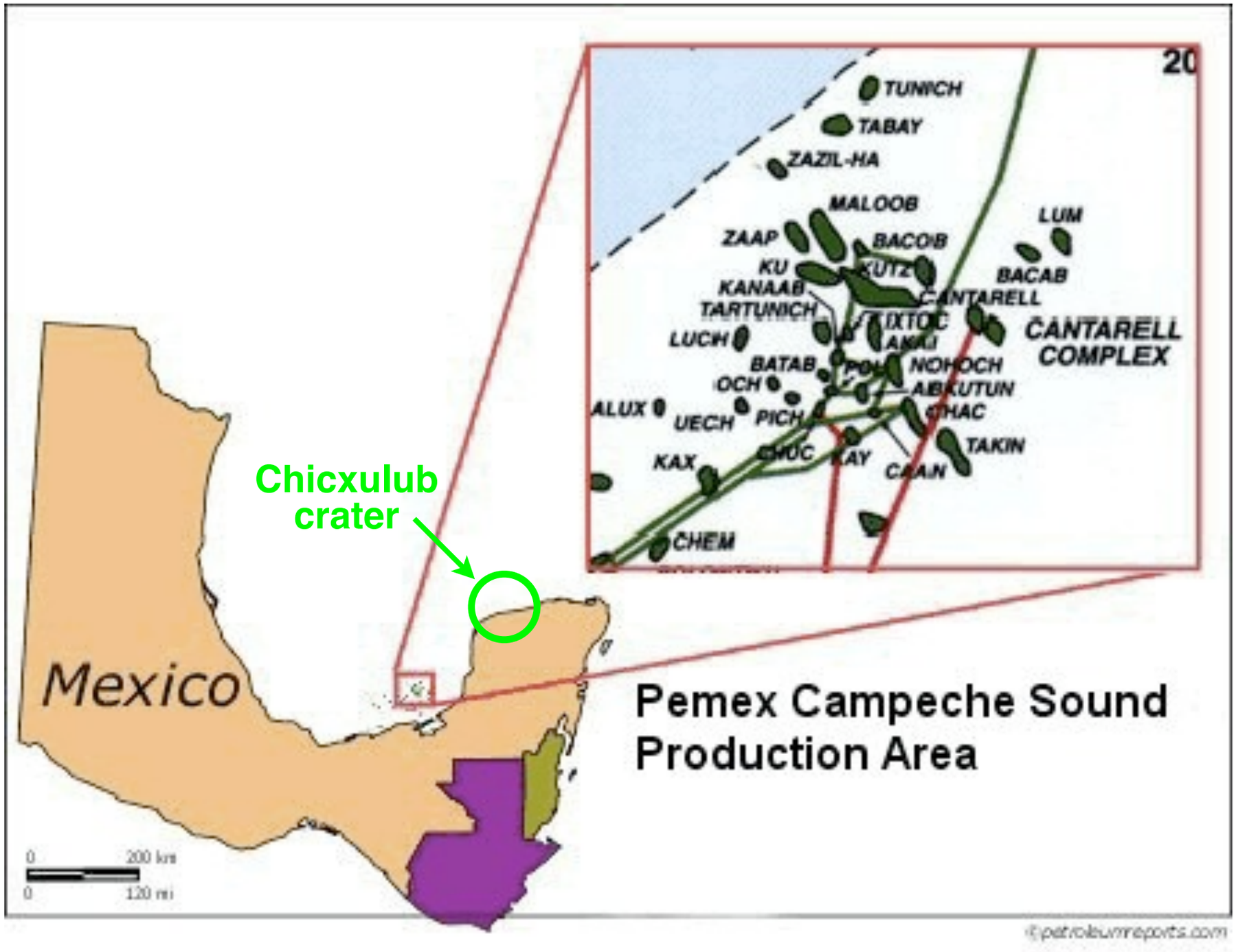
oil = red

largest: Ghawar

from Matt Simmons

~12% of remaining world oil

Cantarell Complex



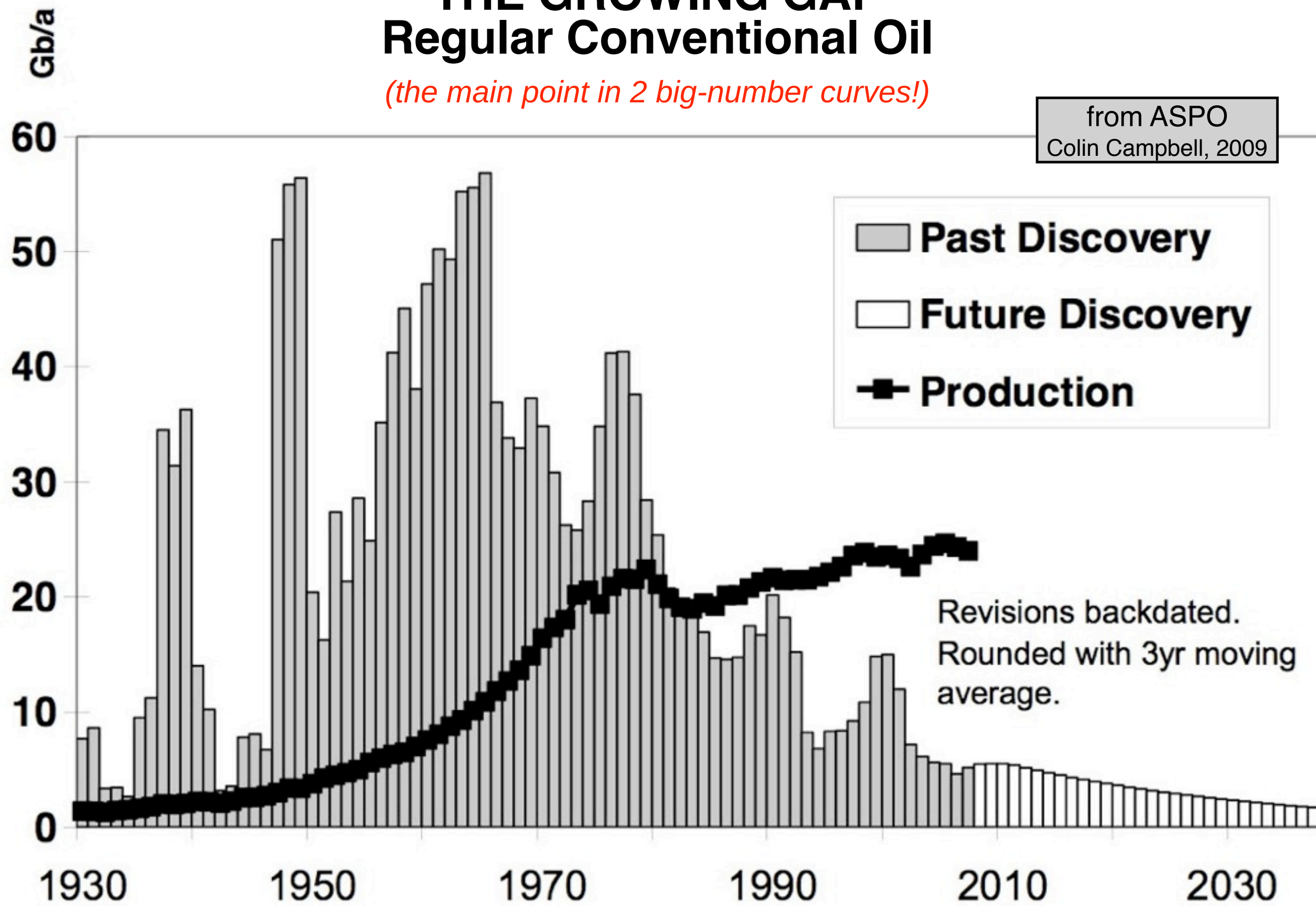
named after Yucatan fisherman Rudecindo Cantarell, who discovered an oil seep!

http://www.eia.doe.gov/emeu/cabs/Mexico/Oil.html

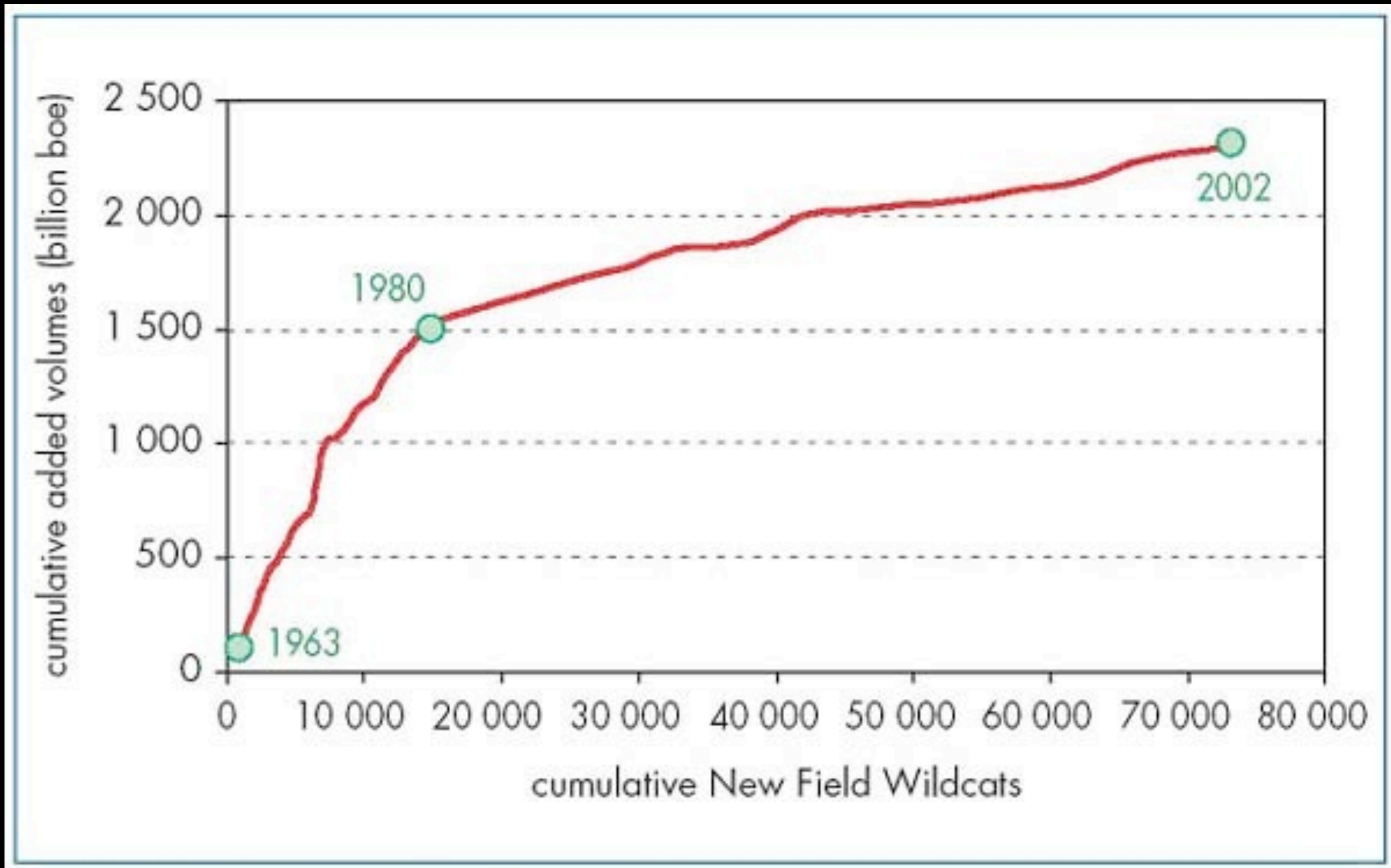
THE GROWING GAP
Regular Conventional Oil

(the main point in 2 big-number curves!)

from ASPO
Colin Campbell, 2009



World Creaming Curve



Source: IEA analysis based on IHS Energy database.

Stages of production

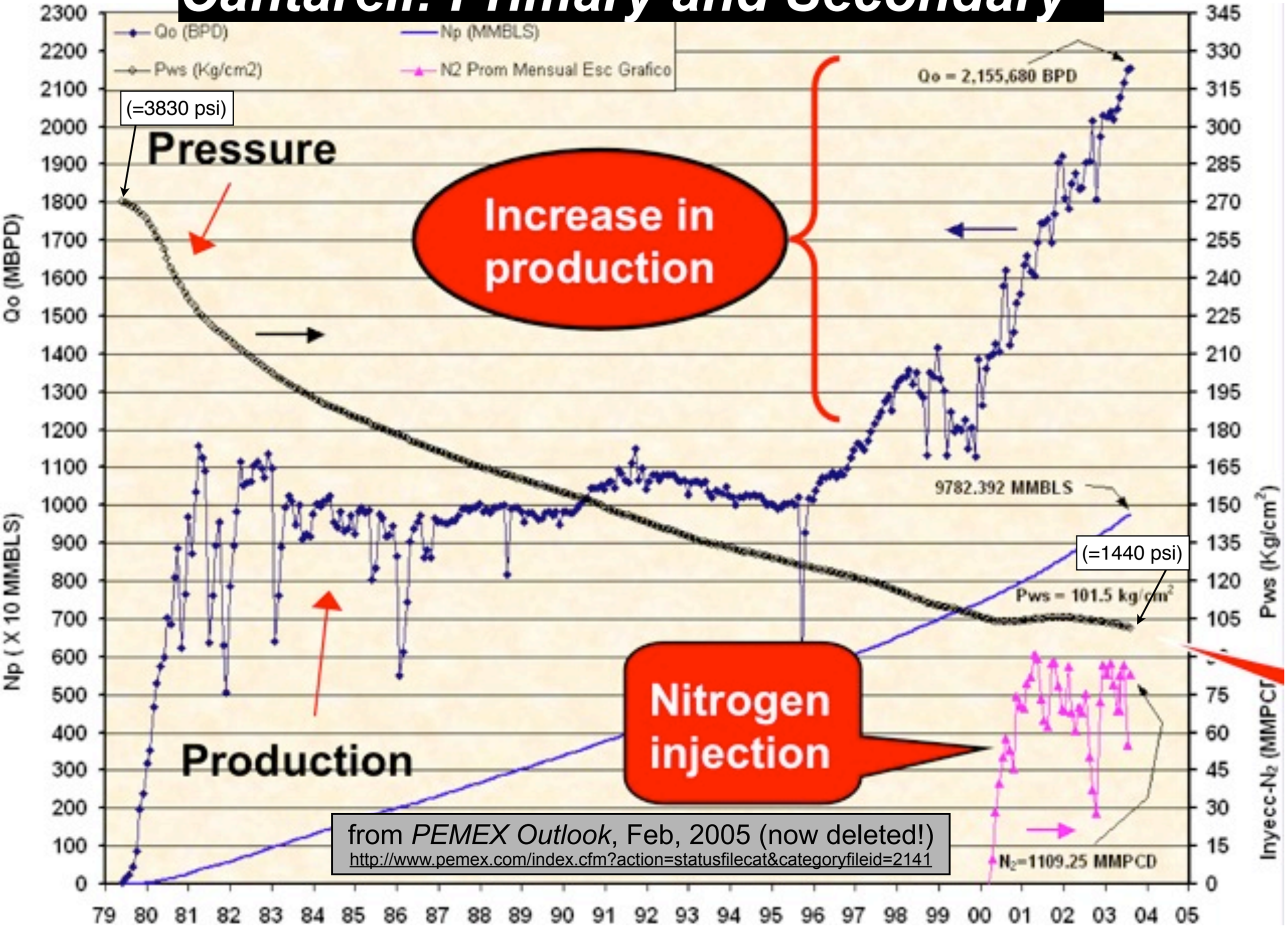
- ***Primary production*** (just produce -- real wells aren't pumped)
  - – initially, oil blasts out under own pressure (e.g., 3500 psi)
  - – main productive run as pressure slowly drops (2000 psi)
  - – as pressure drops, dissolved gas comes out of solution

- ***Secondary production*** (reinstate pore pressure by injection)
  - – pump water down underneath oil (Ghawar, Saudi Arabia)
  - – pump nitrogen down above oil (Cantarell, Mexico)
  - – pump natural gas (or CO_2) down above oil (US)

- ***Tertiary production*** (extreme measures)
  - – underground pumps, detergents, explosions, "proppants"
  - – inject oil-eating bacteria (repressurize with bacterial gas)

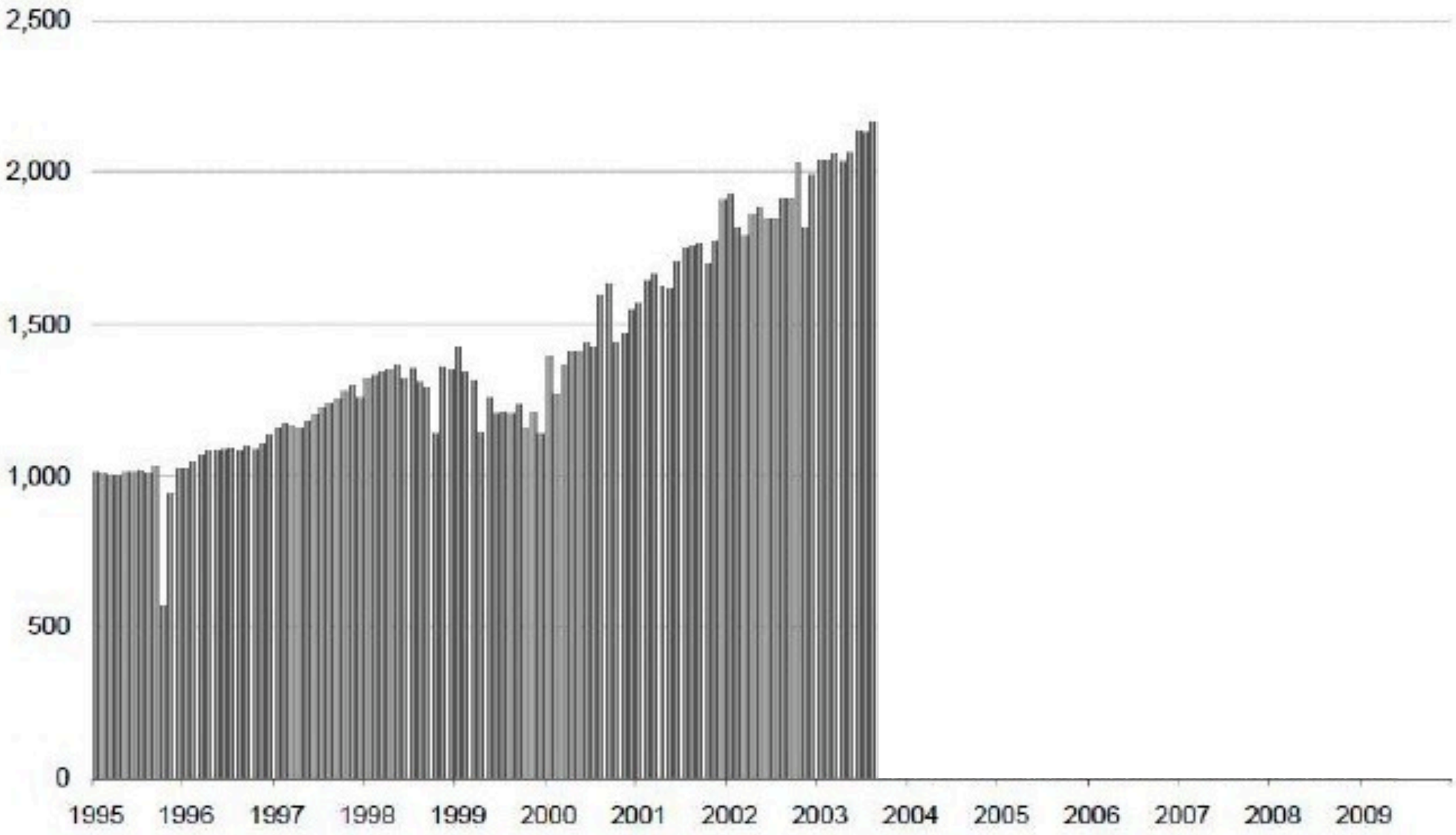
- ***EROEI*** (energy return on energy investment)
  - – EROEI decreases with each successive stage until < 1.0

Cantarell: Primary and Secondary



from *PEMEX Outlook*, Feb, 2005 (now deleted!)
http://www.pemex.com/index.cfm?action=statusfilecat&categoryfileid=2141

MEXICO: DAILY PRODUCTION FROM ONE-TIME SUPER-GIANT "CANTARELL" OILFIELD
000 b/d



Source: Energy Information System, Federal Government of Mexico
Printed: 27/07/2009

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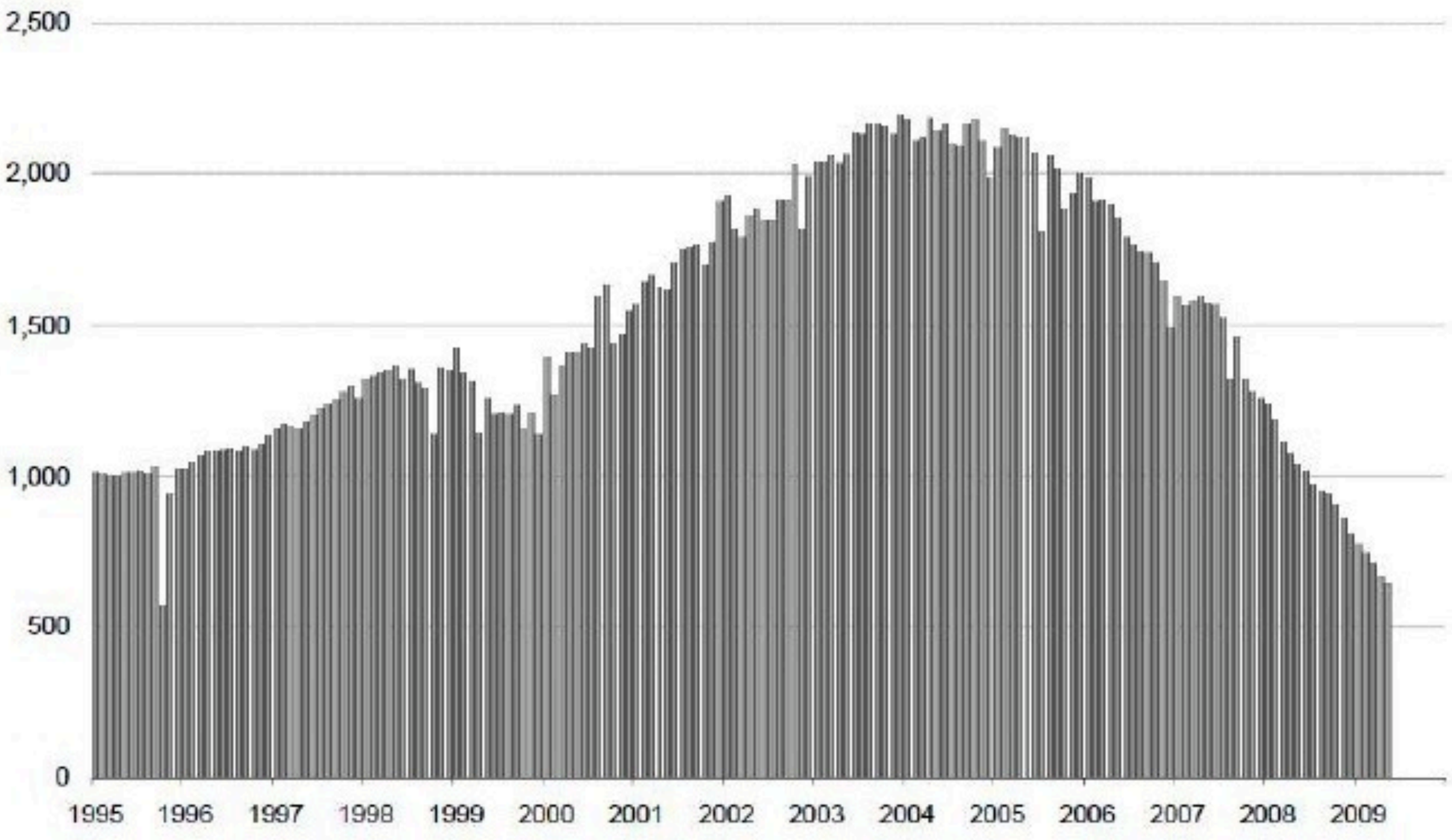
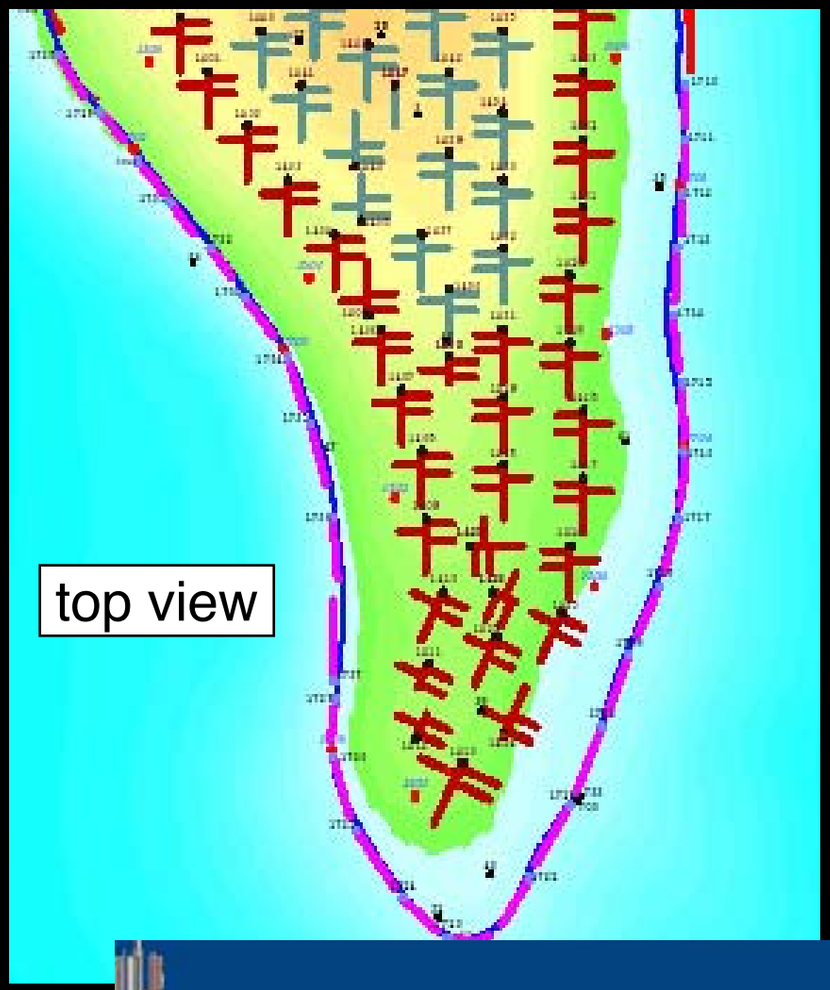


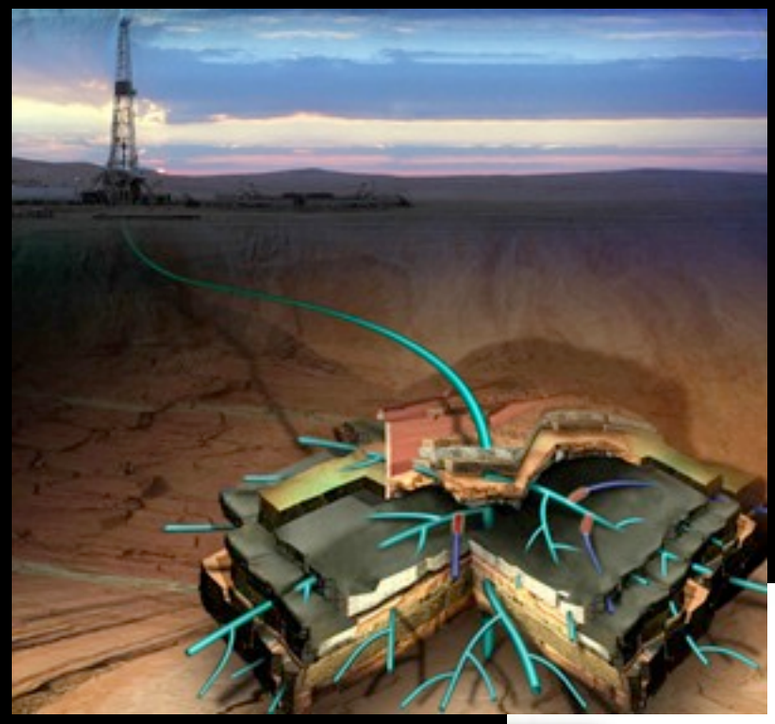
Source: Energy Information System, Federal Government of Mexico
Printed: 27/07/2009

Sideways Drilling – e.g., Ghawar

(increases flow by exposing longer length of borehole to oil floating on injected water)



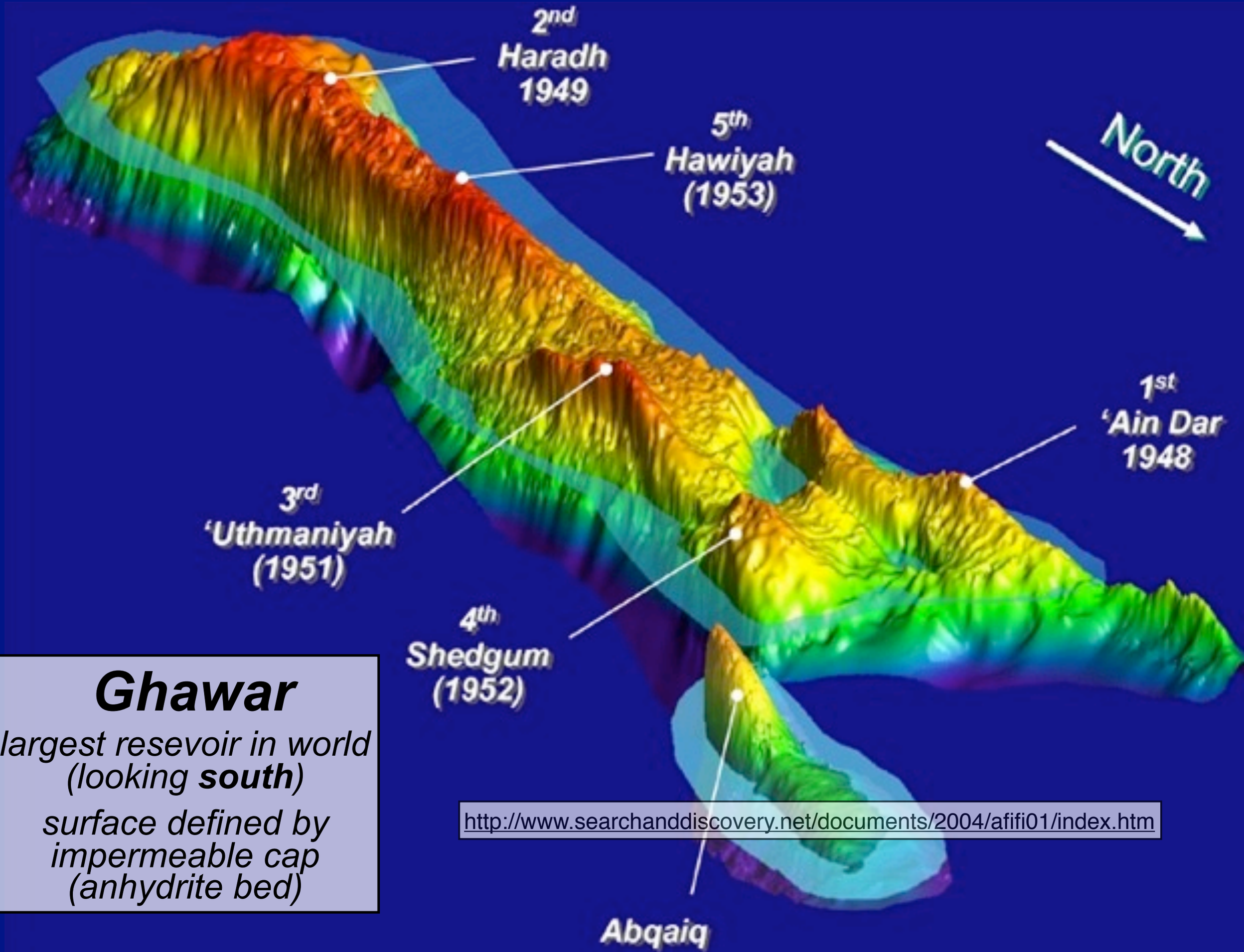
from Matt Simmons



3-D views of "bottle-brush" well completion

Greatly increases flow rate from single wells

(e.g., 10,000 barrels/ day vs. 300 barrels/day)



Ghawar

largest resevoir in world
*(looking **south**)*

surface defined by impermeable cap (anhydrite bed)

http://www.searchanddiscovery.net/documents/2004/afifi01/index.htm

Rock permeability is critical -- and spatially complex

(model of 'Ain Dar and Shedgum, northern Ghawar)

(a)

(b)

North

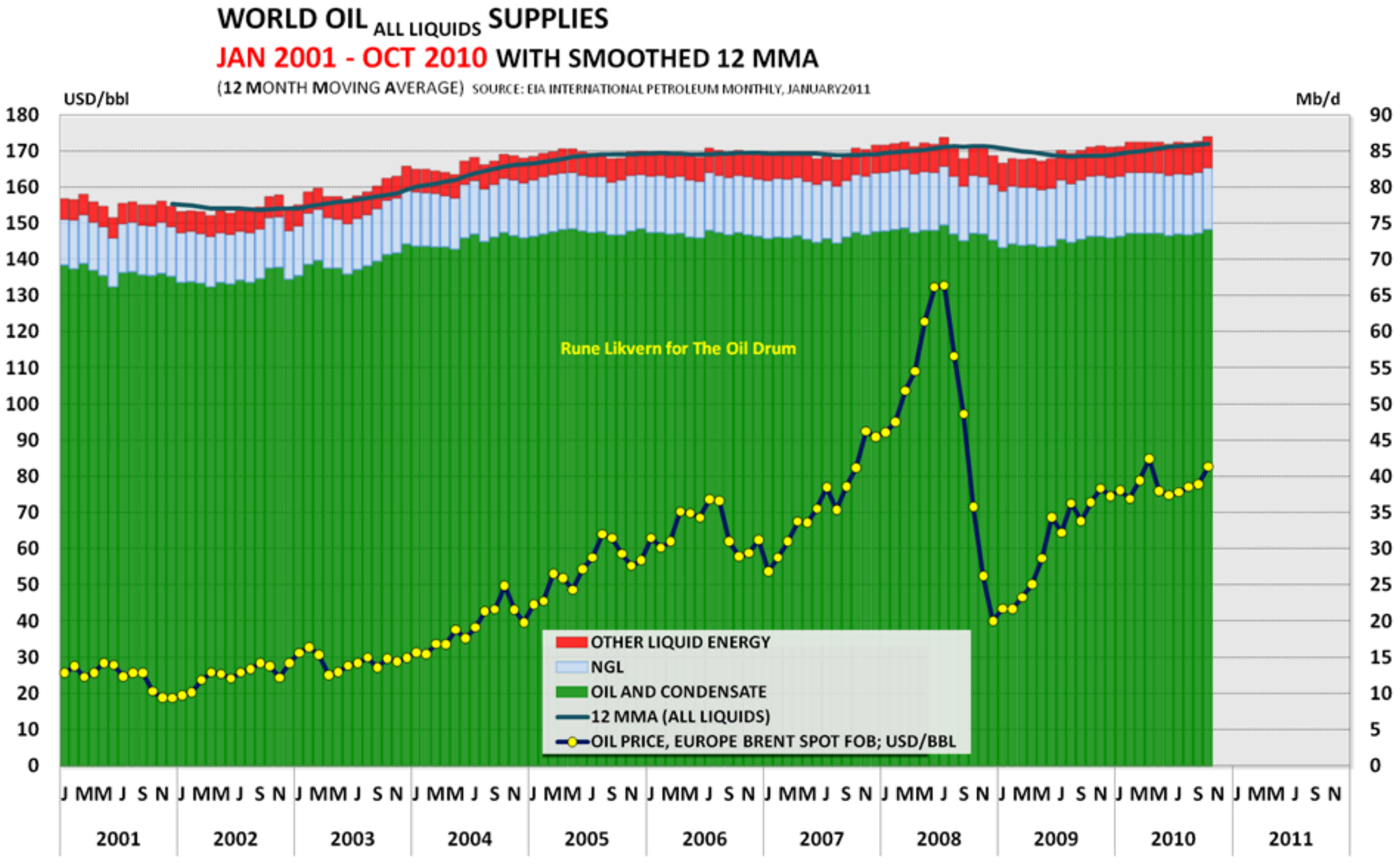
http://www.theoildrum.com/node/2393

http://www.spe.org/elibinfo/eLibrary_Papers/iptc/2005/05IPTC/IPTC-10395-MS/IPTC-10395-MS.htm

Natural Gas Liquids (NGL's)

- Don't confuse these with "liquified natural gas" (LNG), which is cooled, compressed methane
- "Natural gas liquids" (NGL's) are short chain hydrocarbons (e.g., pentane) extracted from deep, hot (e.g., 180 deg C) natural gas wells with (N.B.: *75% energy density of crude*)
- NGL's are gases *in situ* but some condense to liquids when brought to the surface and cooled
- NGL's and "condensates" are divided into immediately separated "lease condensates" (e.g., pentane) and later stage "natural gas plant liquids" (e.g., propane, butane)
- 75% of US 'oil' production is now "natural gas liquids"!
- finally, "all liquids" adds together crude oil, NGL's, and "other liquids" (mainly ethanol, a little biodiesel)

The Undulating Plateau of Peak Oil



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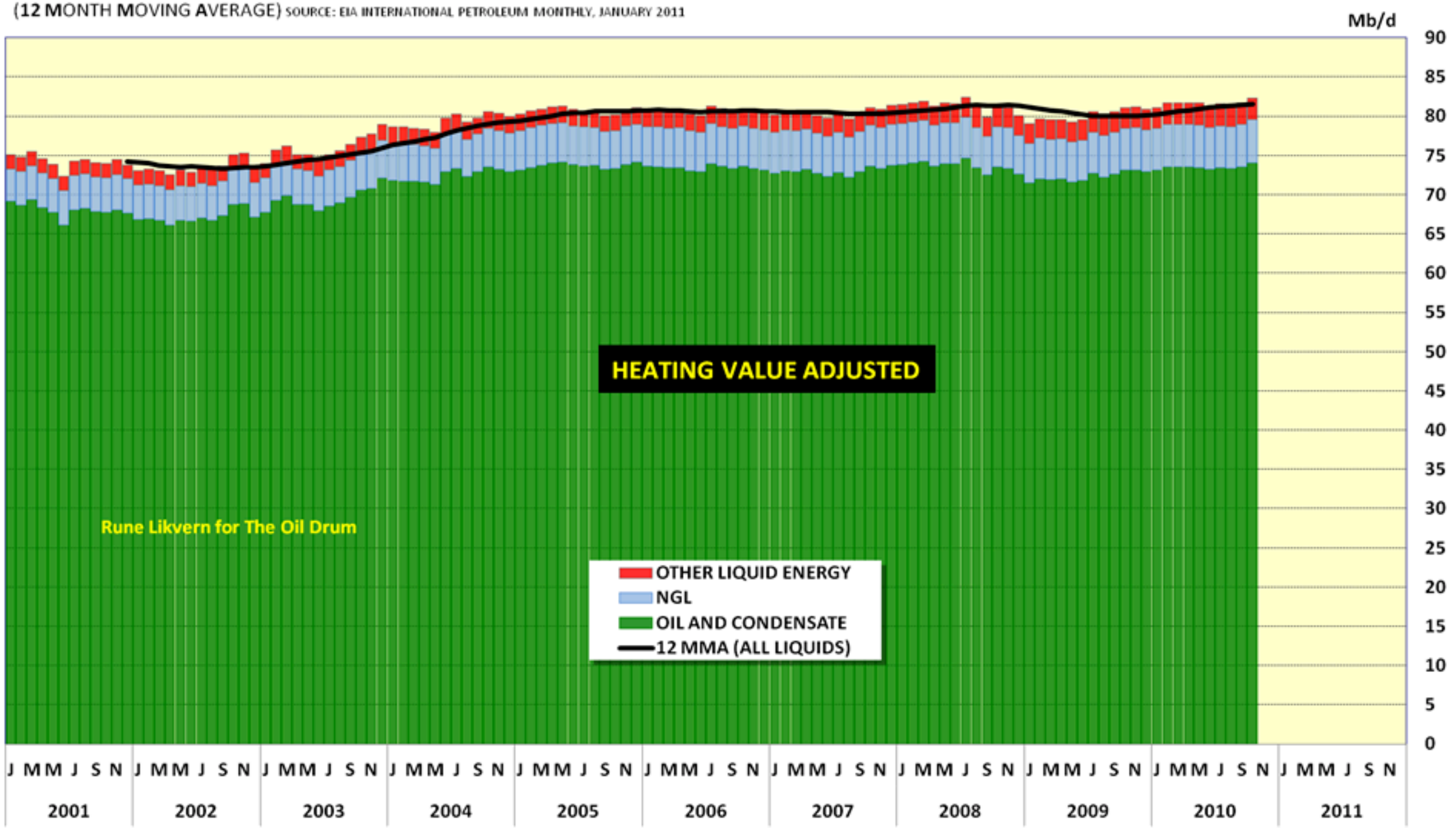
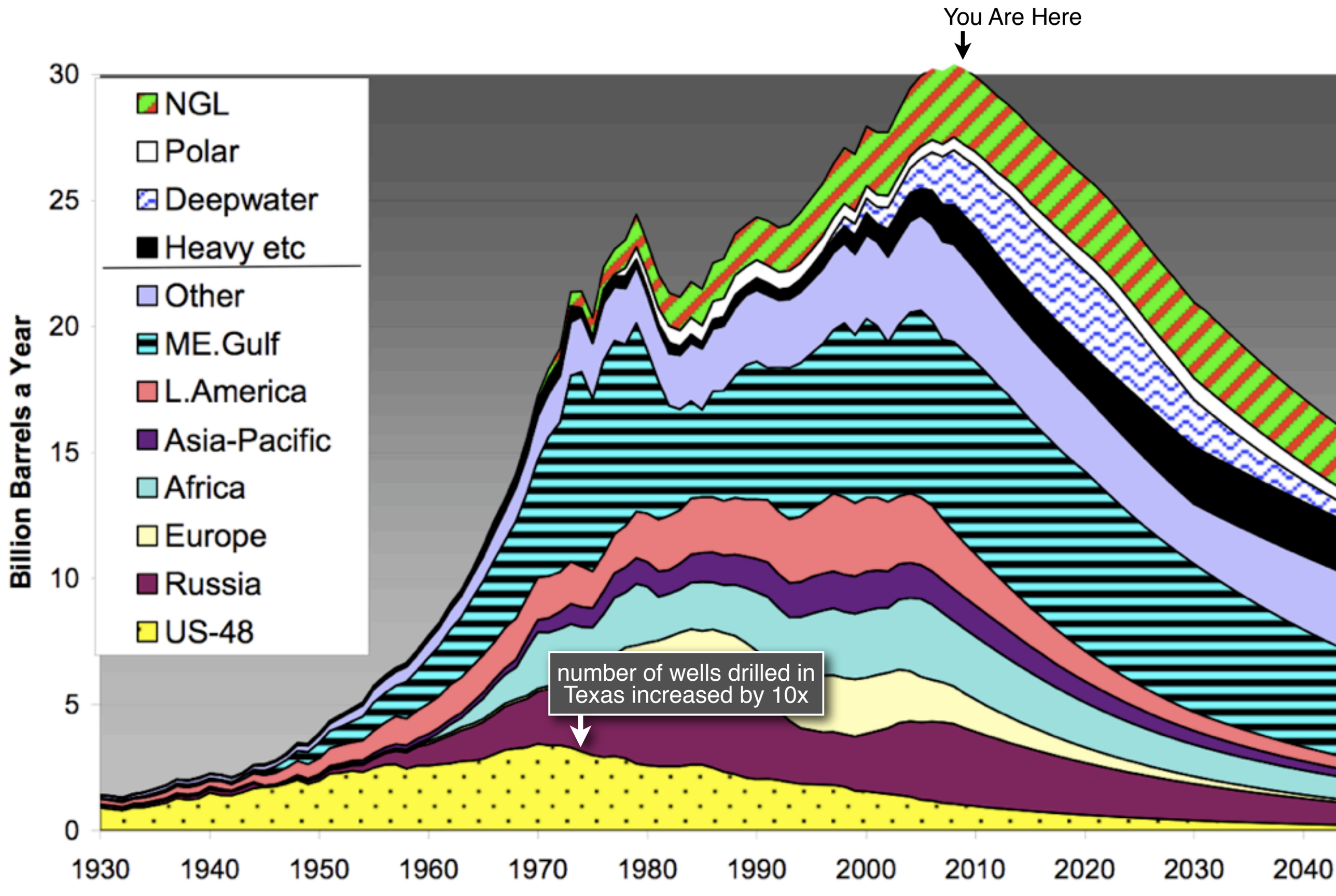


Most of the World has Already Peaked

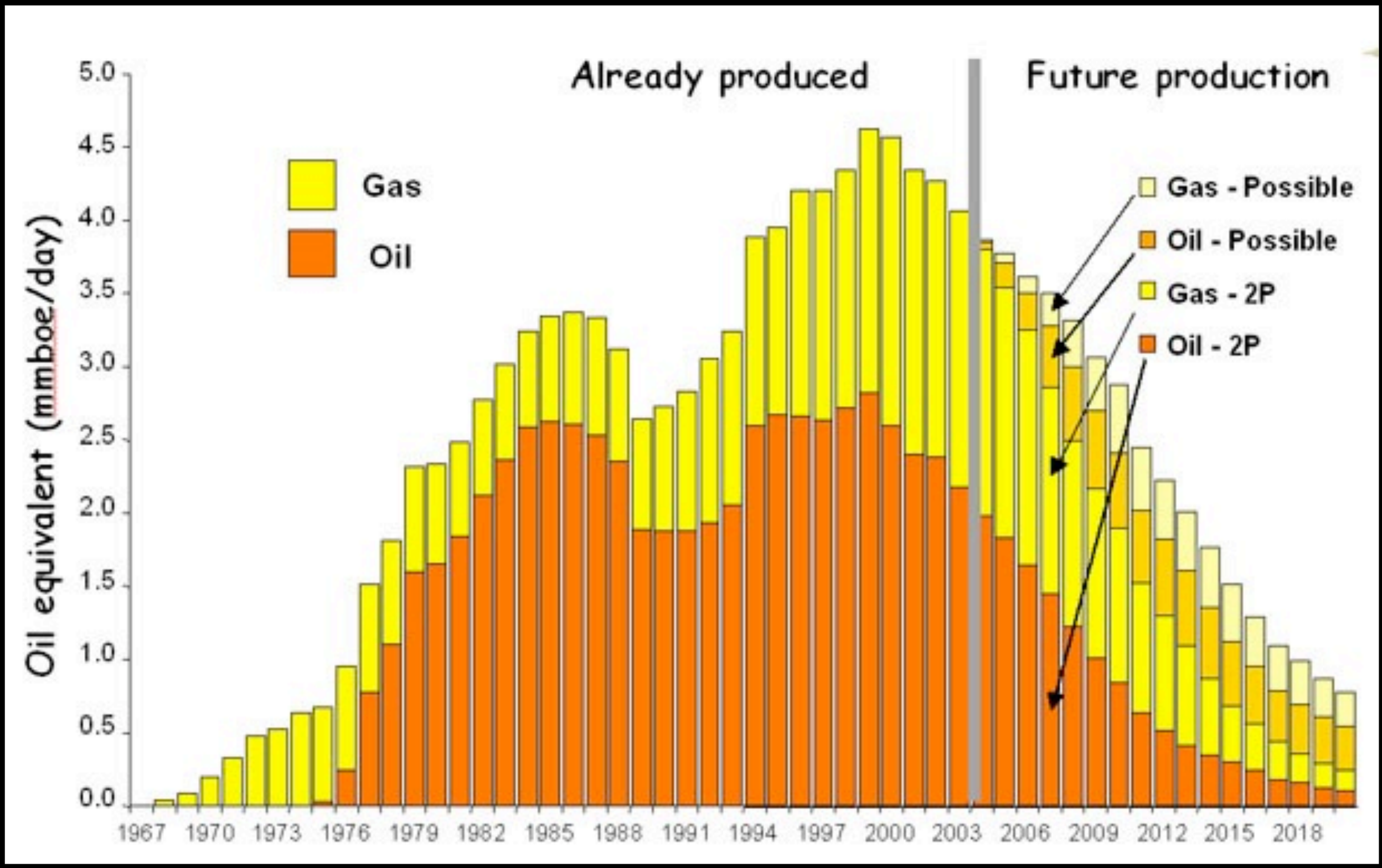
- Only producers that have *not* peaked are OPEC and FSU
- This is called “depletion”
- Depletion is occurring despite widespread use of secondary methods in mature fields
- Since world demand is growing, depletion means that the non-peaked countries need to increment production to: (1) offset *depletion*, (2) meet new *external* demand, and (3) meet new *internal* demand
- Price increases may make companies return to previously unprofitable/abandoned fields
- But higher prices cannot make fields re-fill with easy-to-get oil, or make remaining oil with EROEI<1.0-2.0 an energy ***source***

World Crude + NGL Production



Past/Predicted Production, North Sea

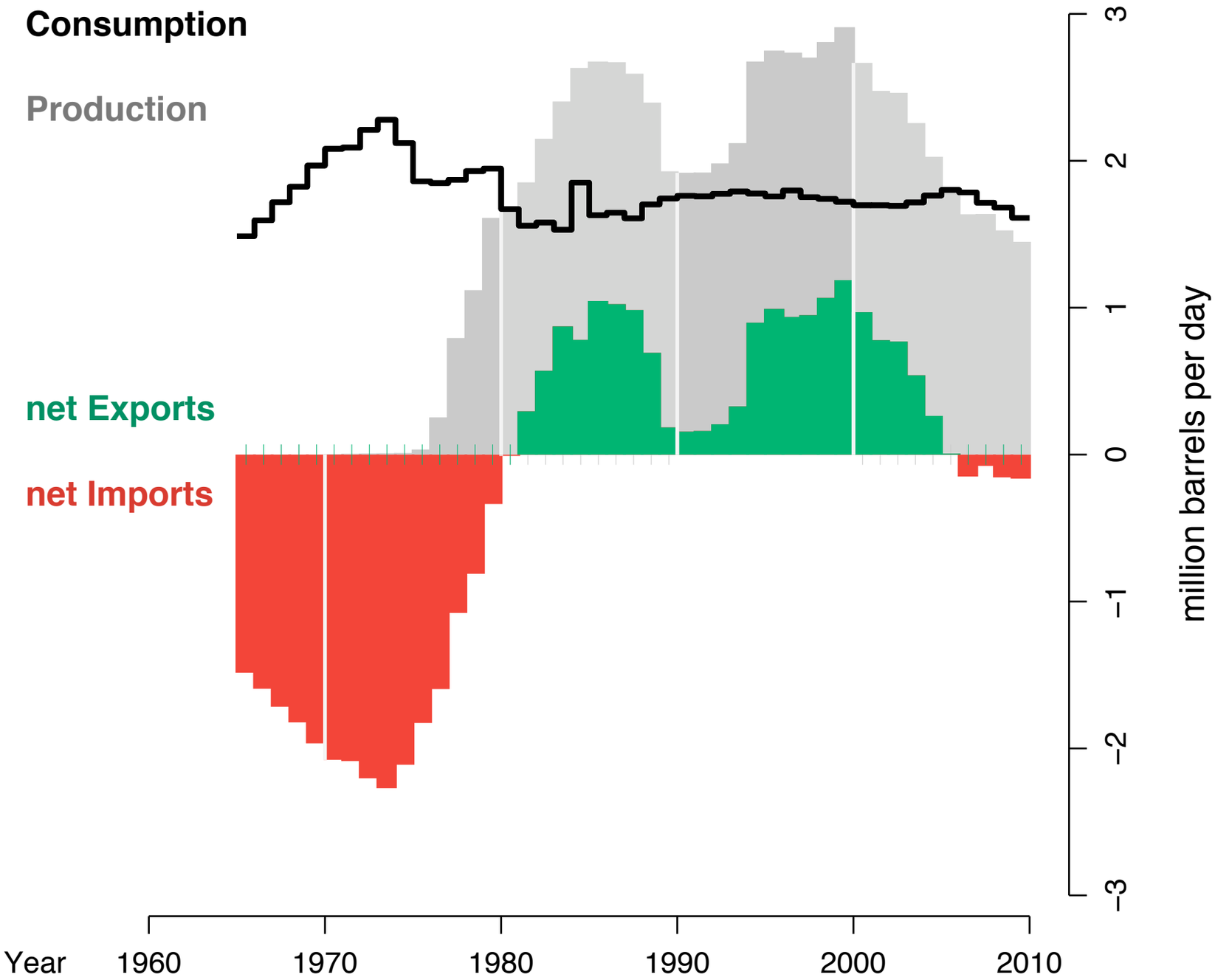
(already discovered sites) from a 2004 report



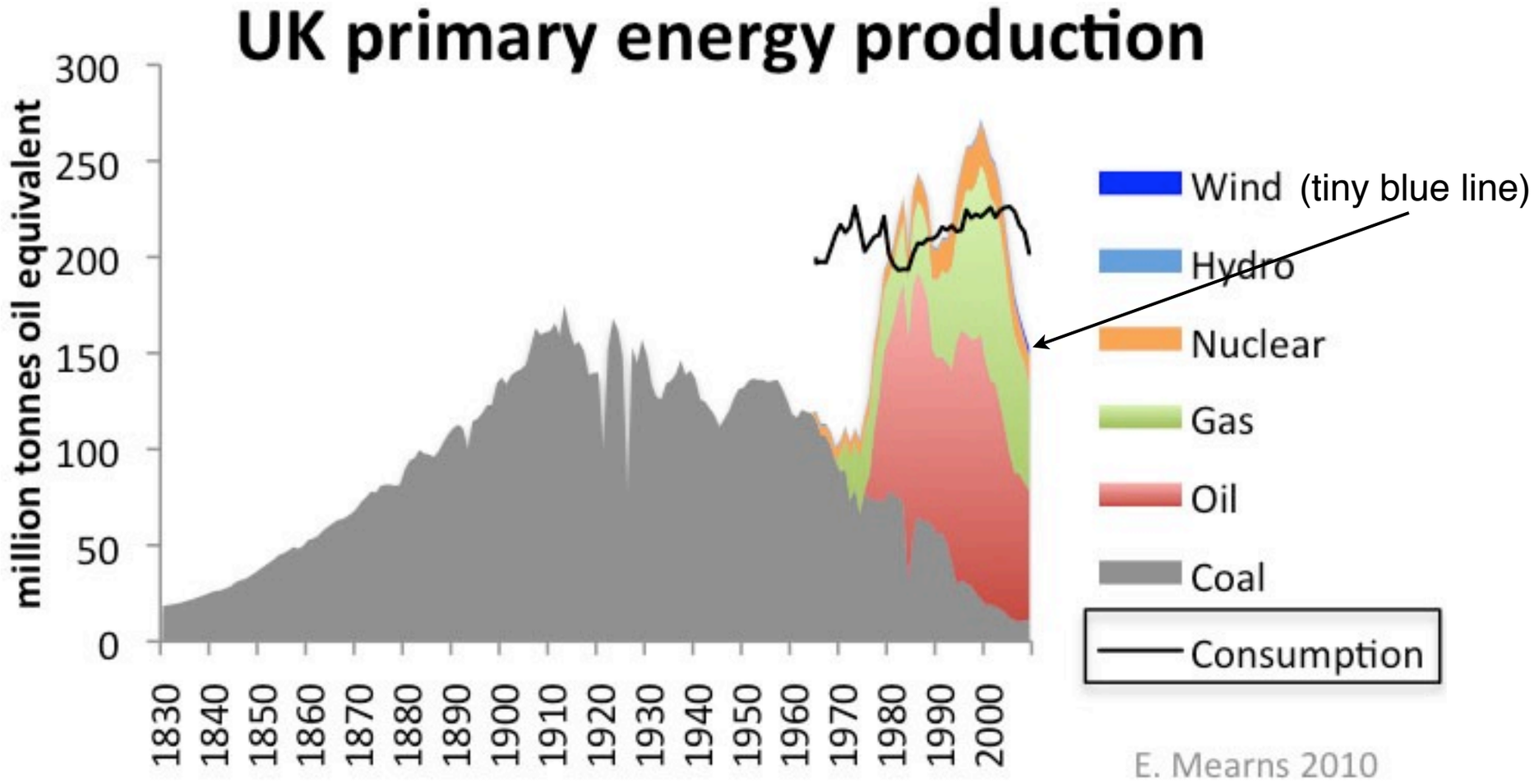
Peter Haile, UK Dept Trade & Industry

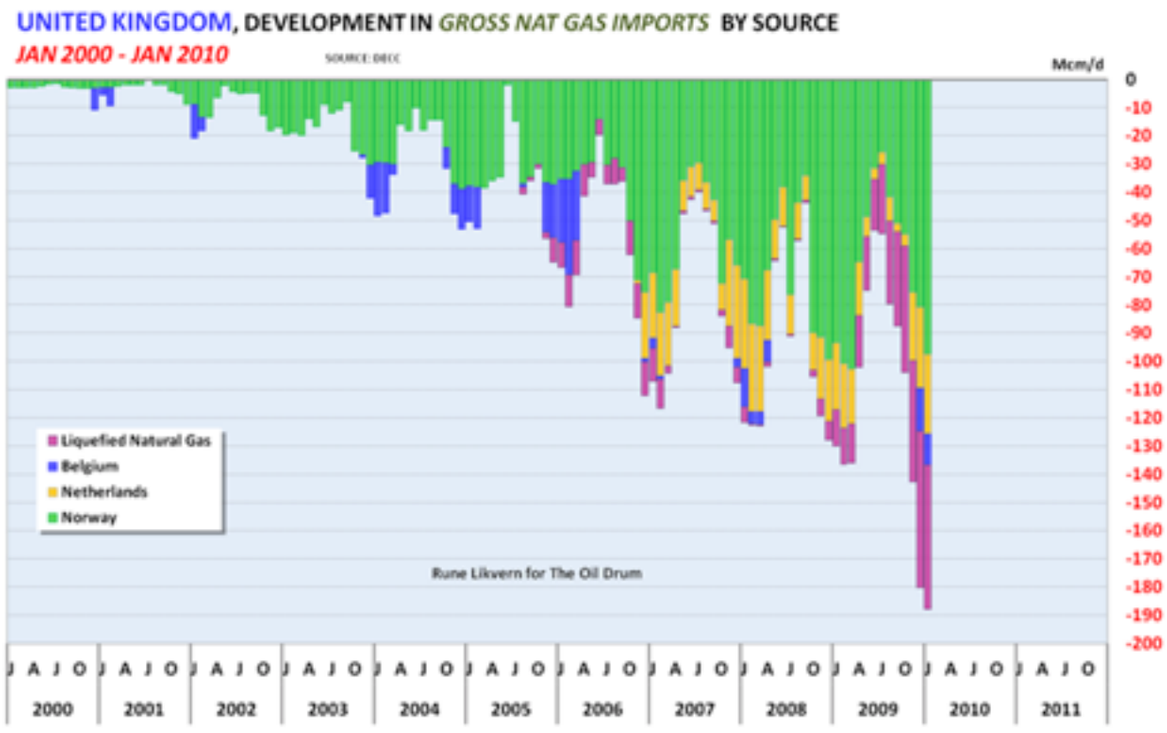
United Kingdom : Oil

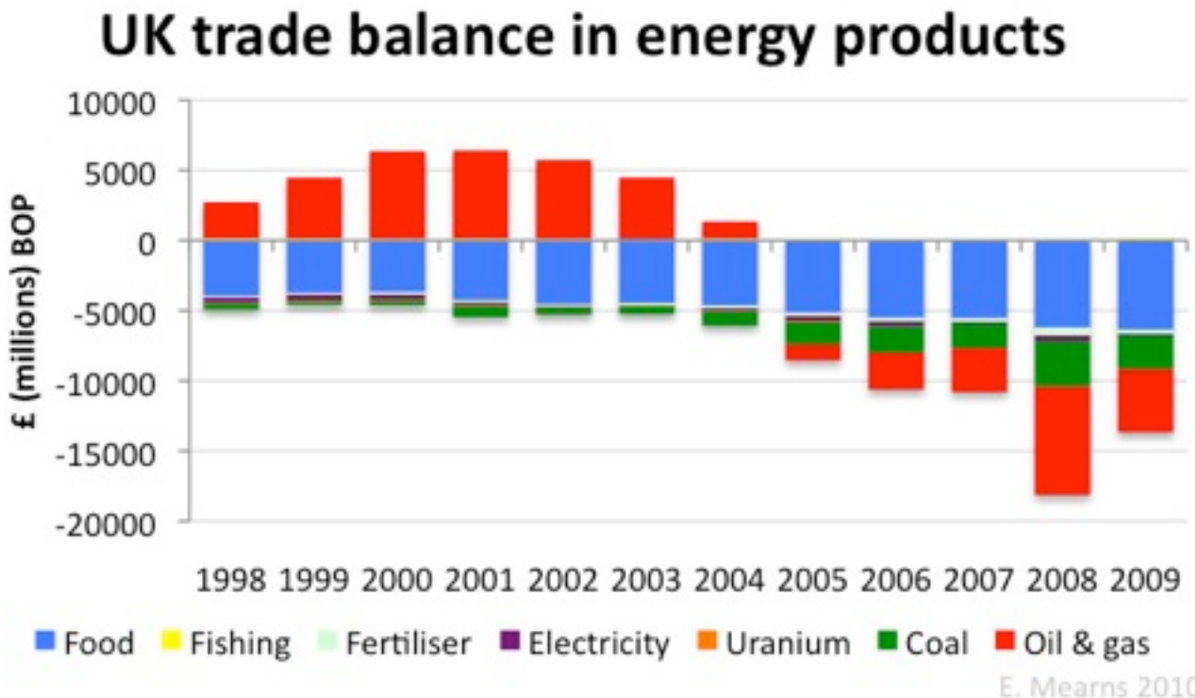
2009 imports increased by 5.4 %



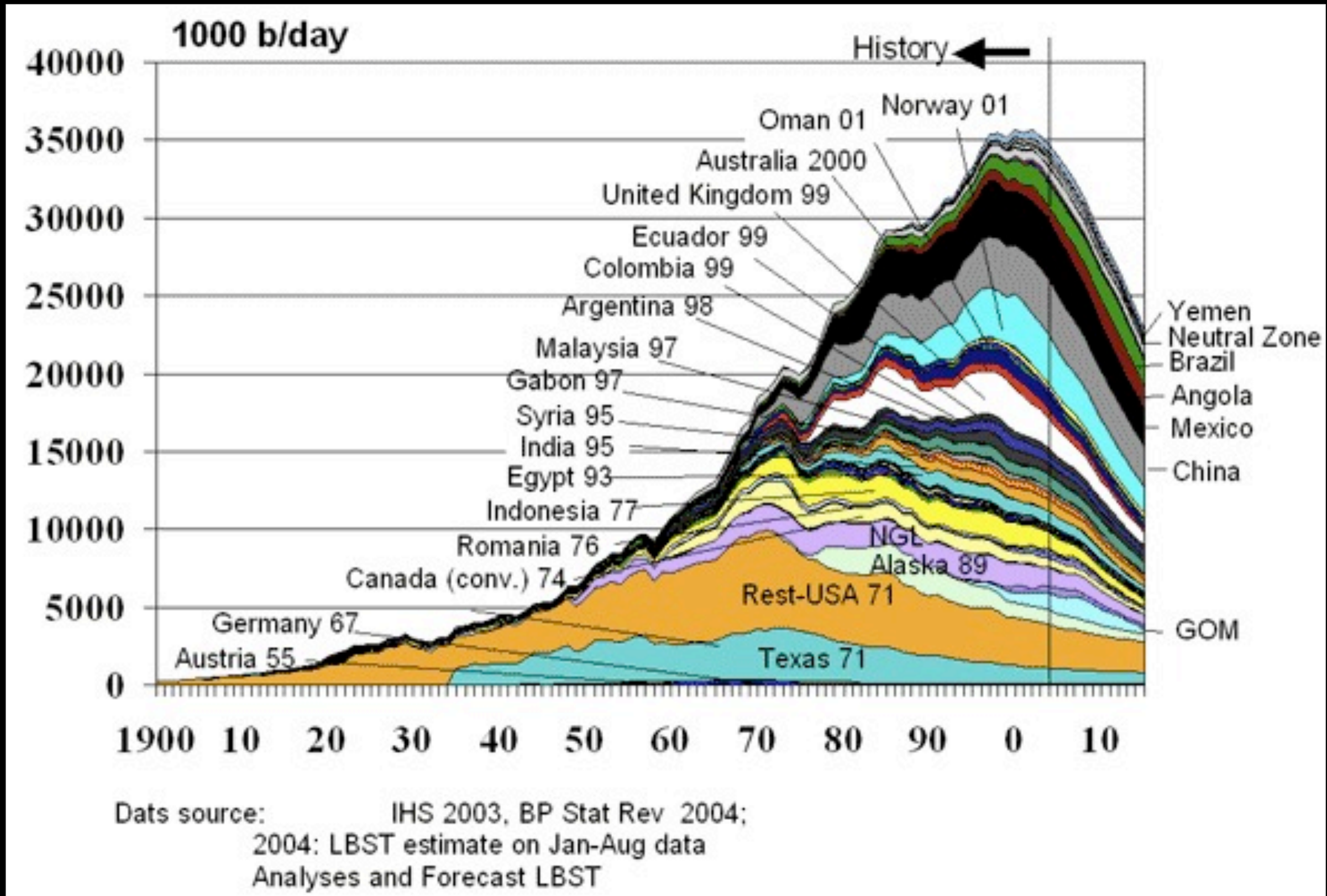
Data: BP Statistical Review 2010 Graphic: mazamascience.com


UK primary energy production
million tonnes oil equivalent
300
250
200
150
100
50
0
1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
Wind (tiny blue line)
Hydro
Nuclear
Gas
Oil
Coal
Consumption
E. Mearns 2010


UNITED KINGDOM, DEVELOPMENT IN GROSS NAT GAS IMPORTS BY SOURCE
JAN 2000 - JAN 2010
SOURCE: DECC
Mcm/d
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
Liquefied Natural Gas
Belgium
Netherlands
Norway
Rune Likvern for The Oil Drum
J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011


UK trade balance in energy products
£ (millions) BOP
10000
5000
0
-5000
-10000
-15000
-20000
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Food
Fishing
Fertiliser
Electricity
Uranium
Coal
Oil & gas
E. Mearns 2010

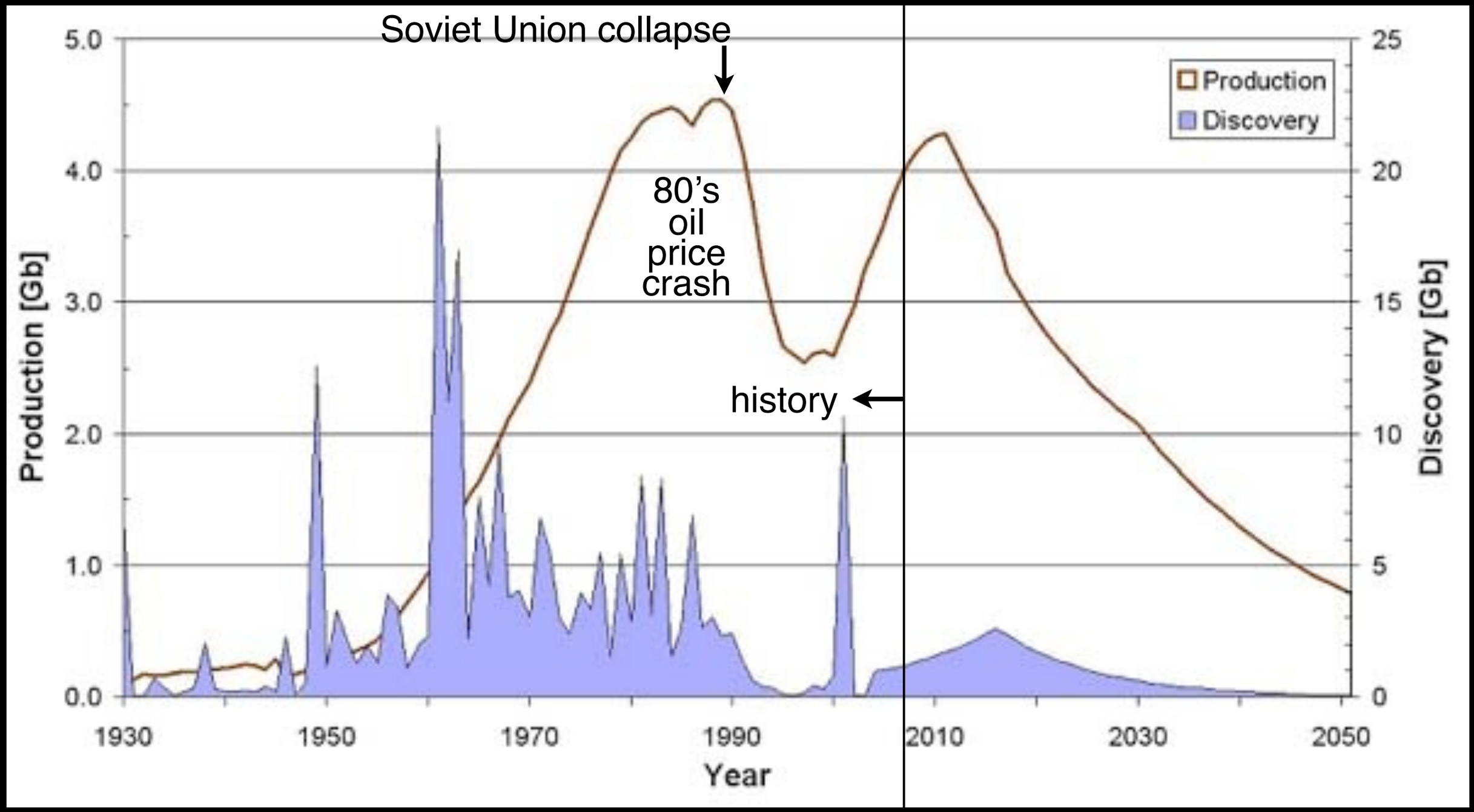
World Production Excluding OPEC, FSU



Dats source: IHS 2003, BP Stat Rev 2004;
2004: LBST estimate on Jan-Aug data
Analyses and Forecast LBST

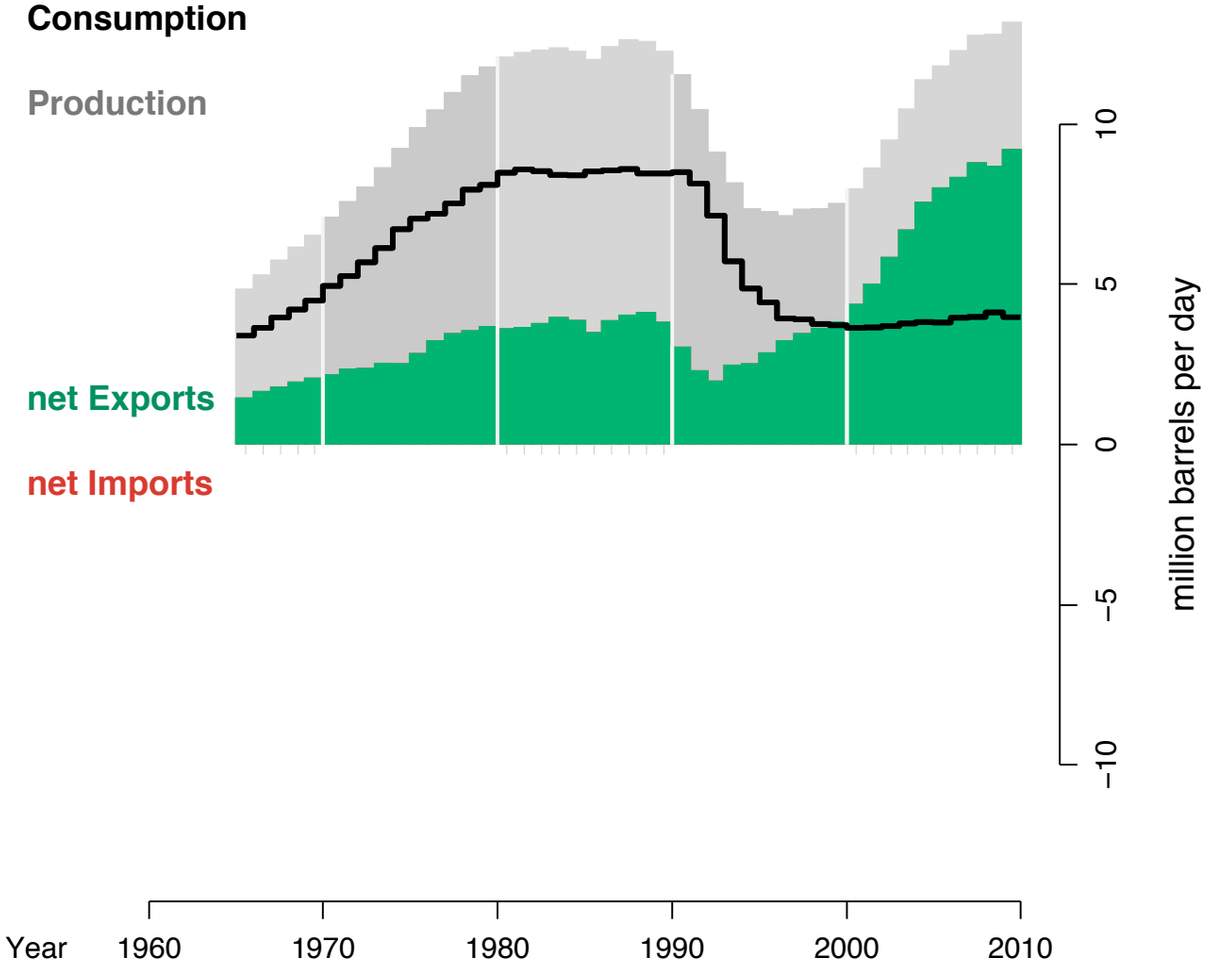
http://www.odac-info.org/links/documents/LBST_Countdown_2004-10-12.pdf

Past/Predicted (2006) Discovery, Production FSU (former Soviet Union)



Former Soviet Union : Oil

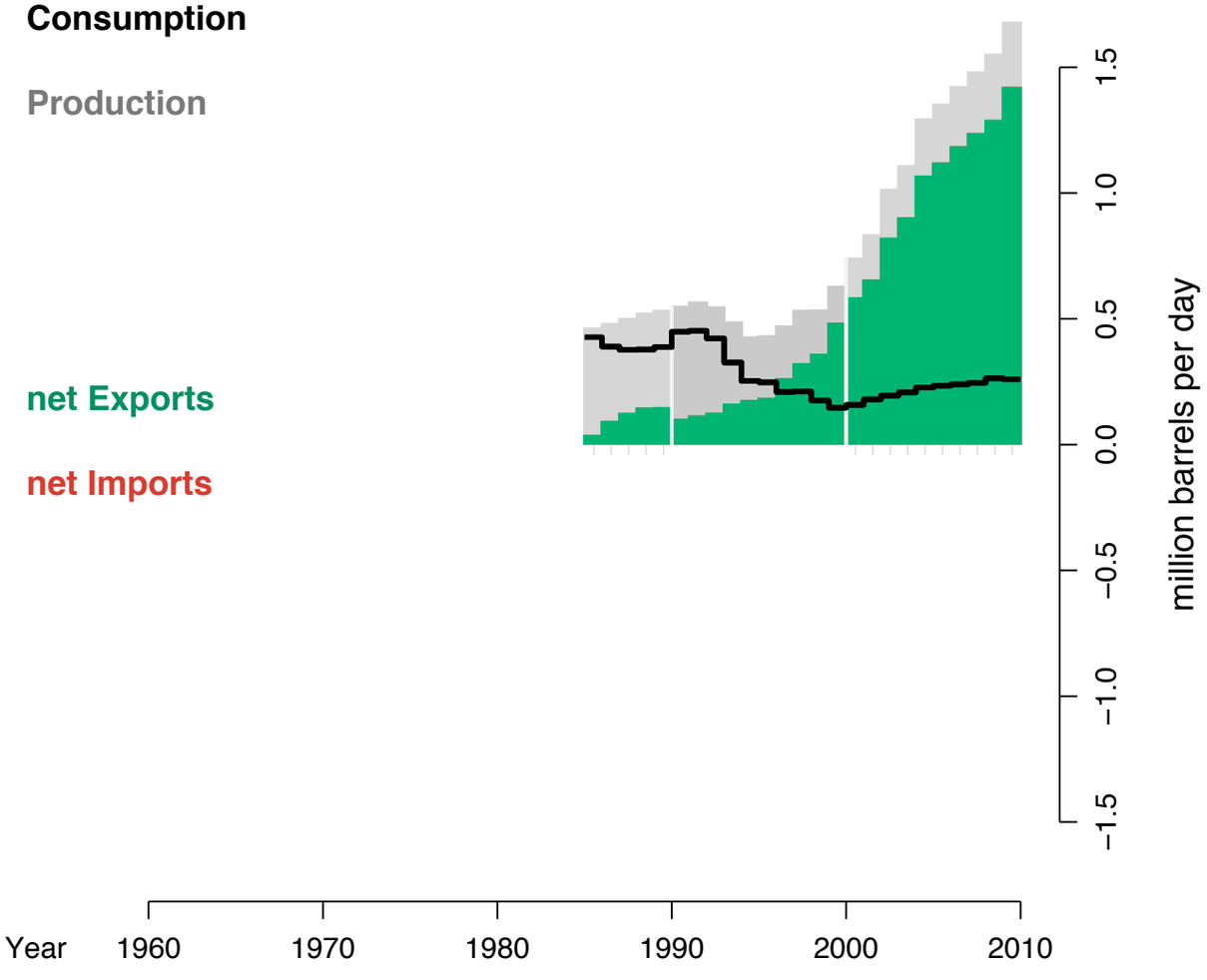
2009 exports increased by 6.0 %



Data: BP Statistical Review 2010 Graphic: mazamascience.com

Kazakhstan : Oil

2009 exports increased by 10.1 %

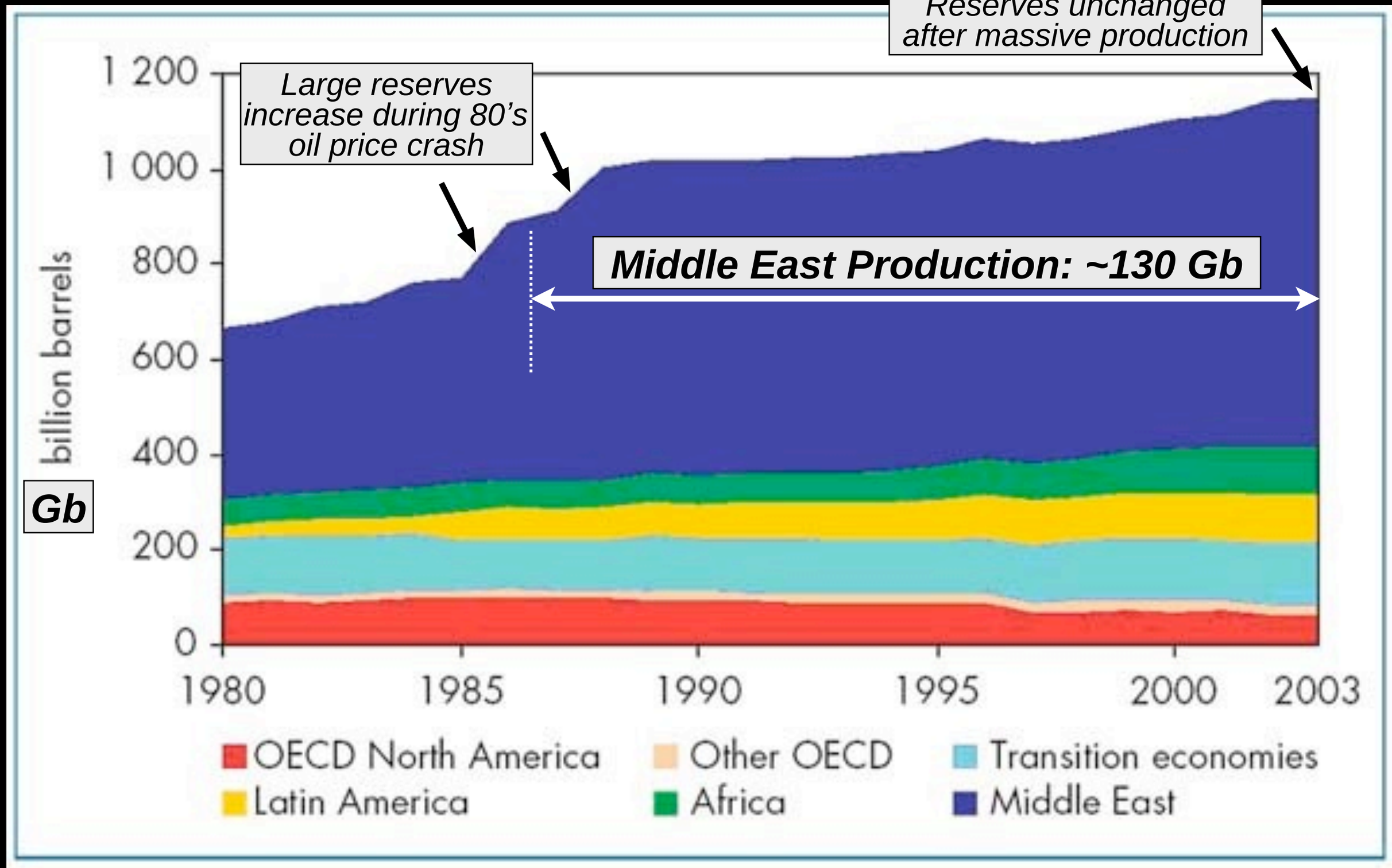


Data: BP Statistical Review 2010 Graphic: mazamascience.com

Reserve Estimates Unreliable, Semi-Secret

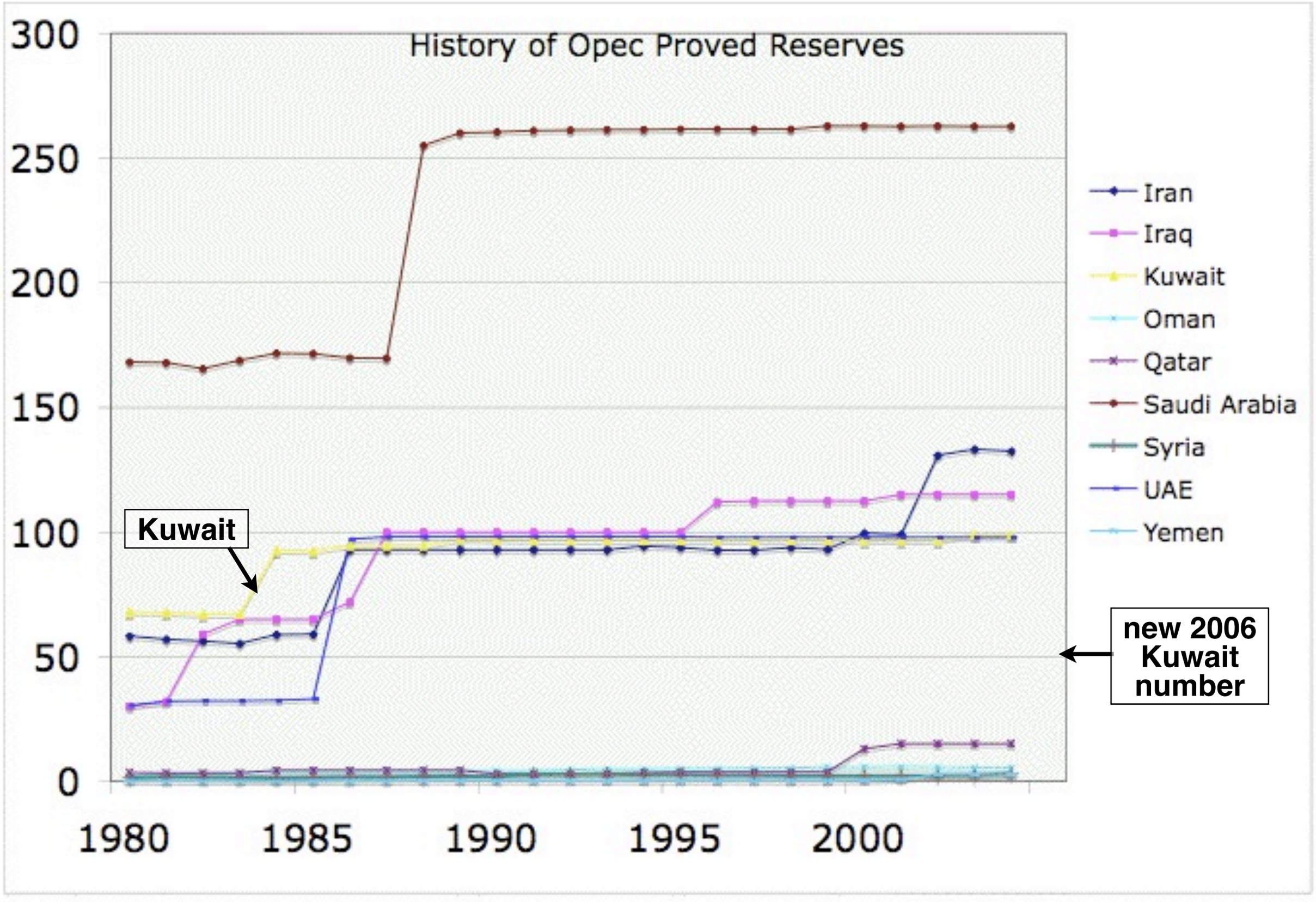
- Several major oil companies recently downgraded reserves
- OPEC countries all doubled reserves estimates in mid 80's
- OPEC reserves have remained unchanged after strong 90's production despite absence of new discoveries
- Secondary production can end with sharp drops (sharp late 1990's North Sea peak *versus* shallower US peak) when water reaches borehole, or sidesteps left-behind oil
- In newer fields, primary and secondary production are being done sooner (e.g., Cantarell), or from beginning
- Kuwait halved stated reserves in 2006 (~100 Gb to ~50 Gb)

World Reserves Estimates Through Time



Source: BP (2004).

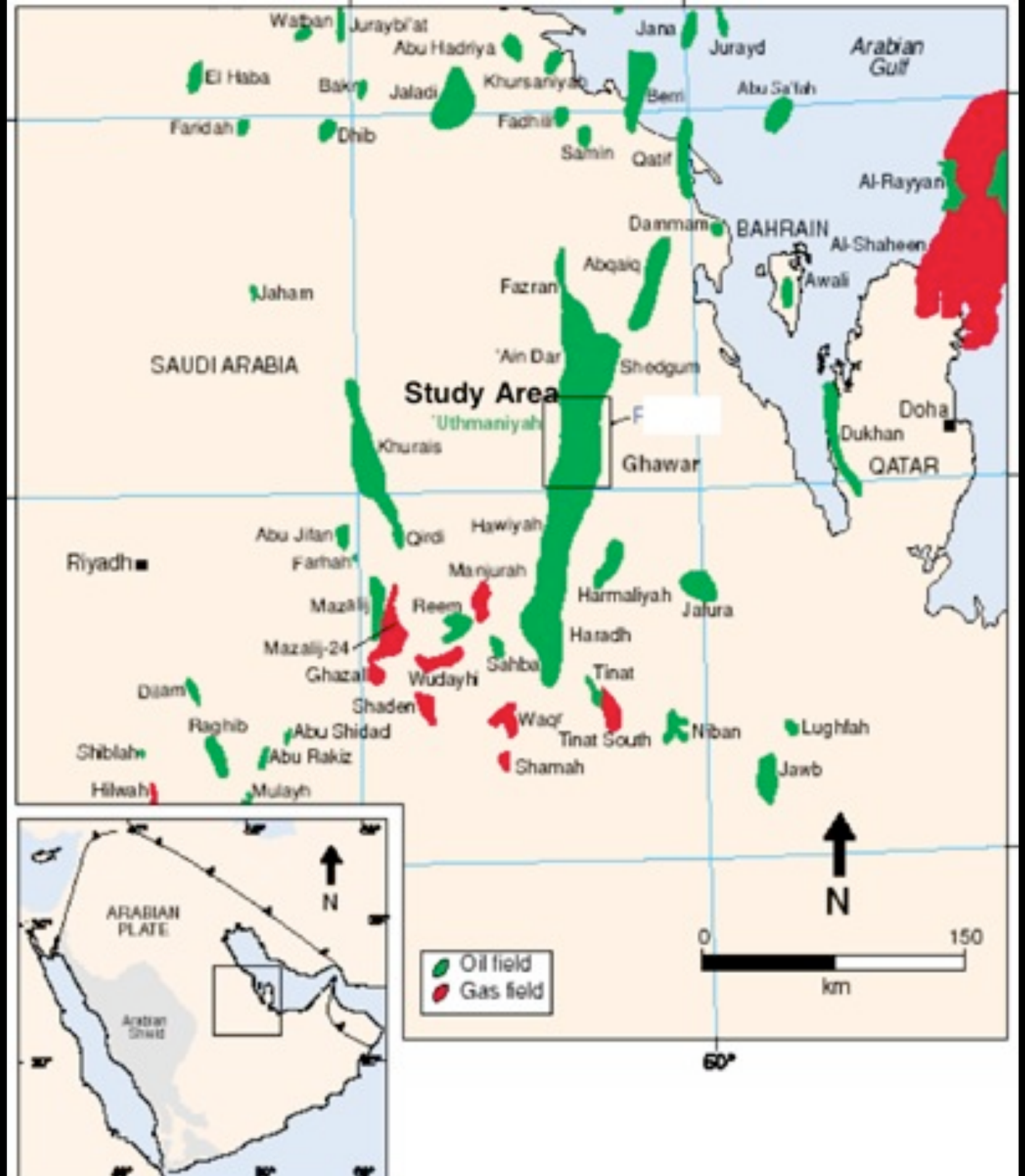
OPEC proved reserves – details



http://www.bp.com/genericsection.do?categoryId=92&contentId=7005893

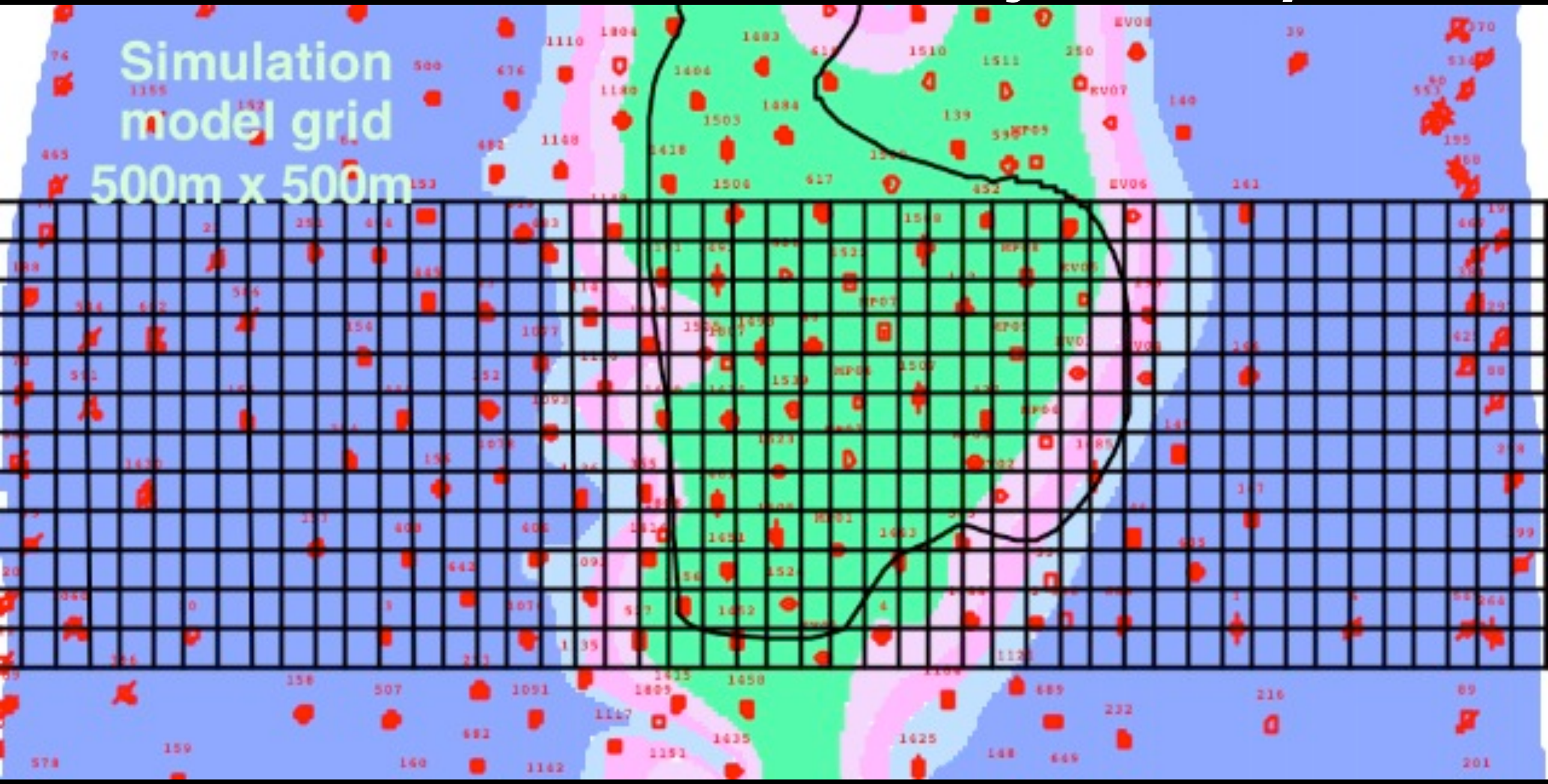
A Closer Look at Ghawar

The Largest Oilfield (~5% world production for past 3 decades)



(from reference on next slide)

Ghawar 3D Seismic Survey Closeup



Oil column thickness *(orig:* ***1300 feet****)*

blue **0-30 feet**

green more than **120 feet**

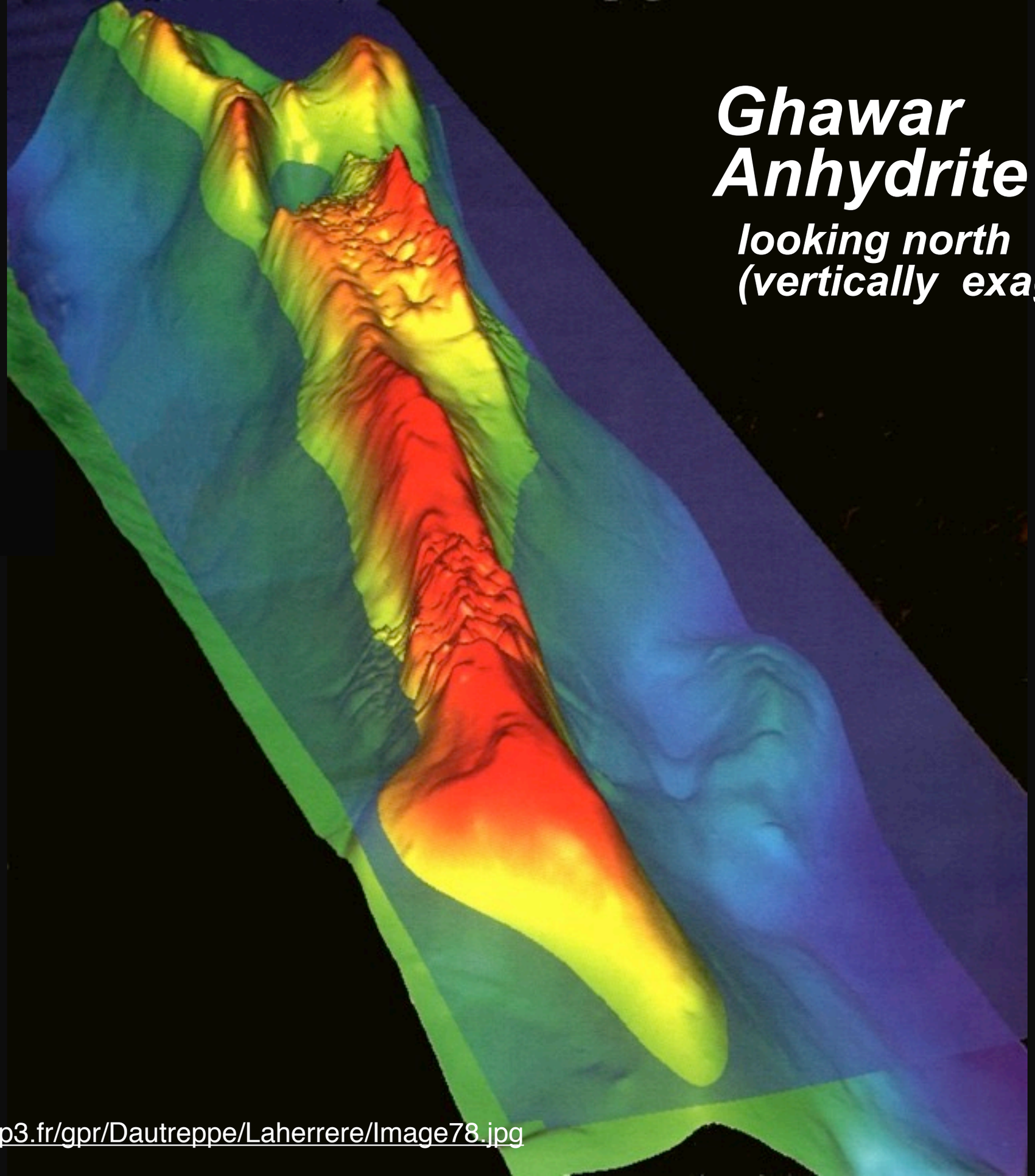
red boreholes (most now used for water injection)

Shiv Dasgupta, “Reservoir monitoring with permanent borehole sensors: Ghawar Arab D reservoir”, 74th SEG Conference, 2004

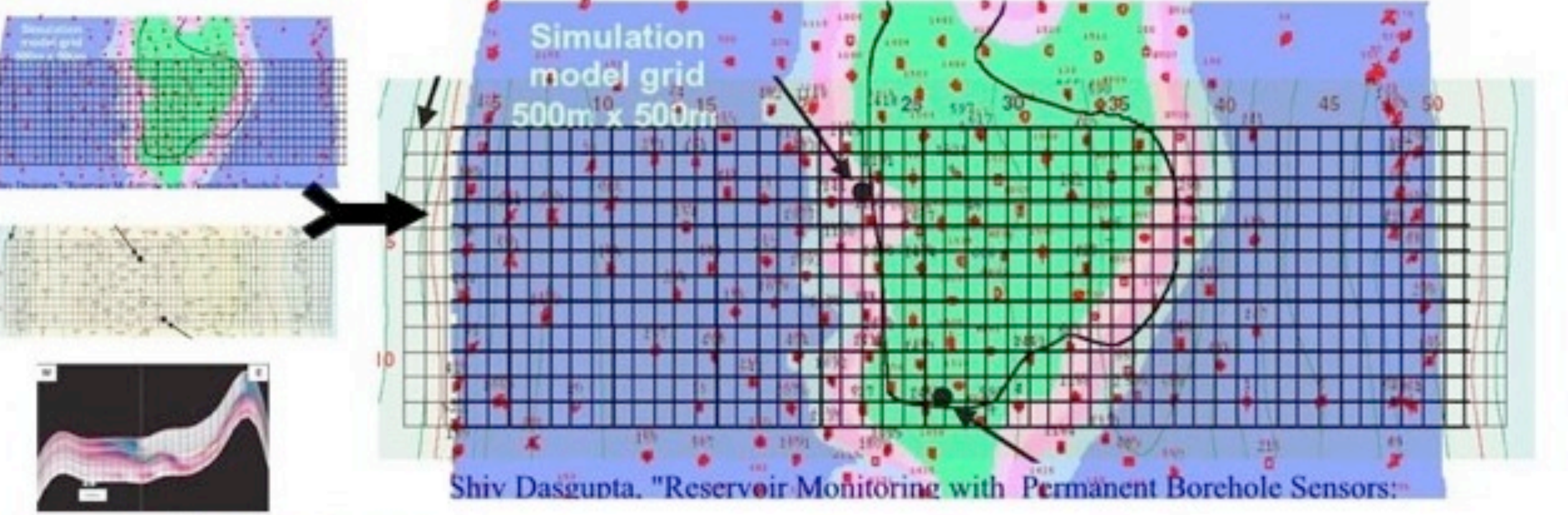
http://abstracts.seg.org/ease/techprog/downloadpaper?paper_id=817&assigned_num=762

Ghawar Anhydrite Cap

looking north
(vertically exaggerated)



http://lpsc.in2p3.fr/gpr/Dautreppe/Laherrere/Image78.jpg

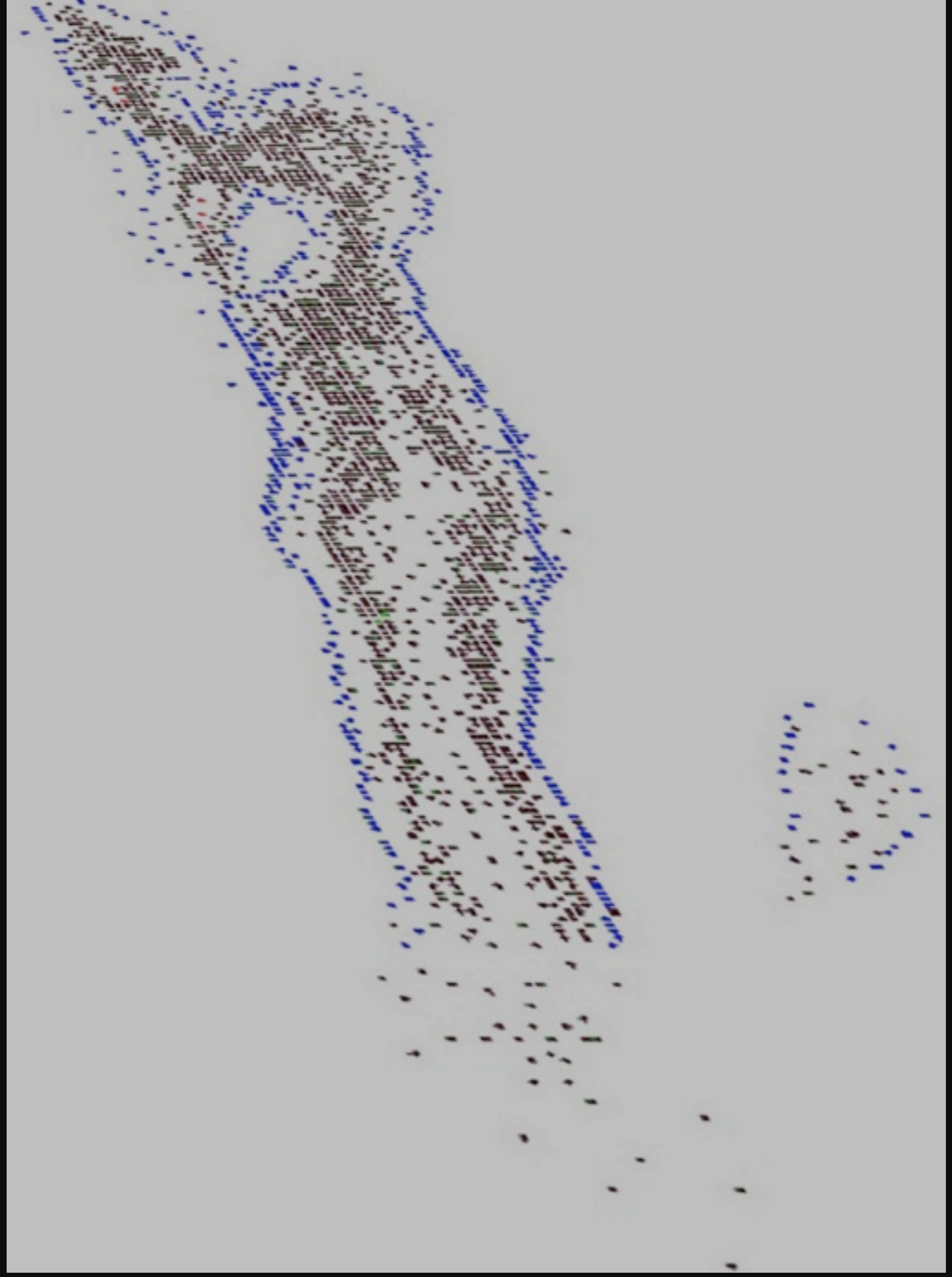


Shiv Dasgupta, "Reservoir Monitoring with Permanent Borehole Sensors:

possible location of traverse on 3D reconstruction

from garyp

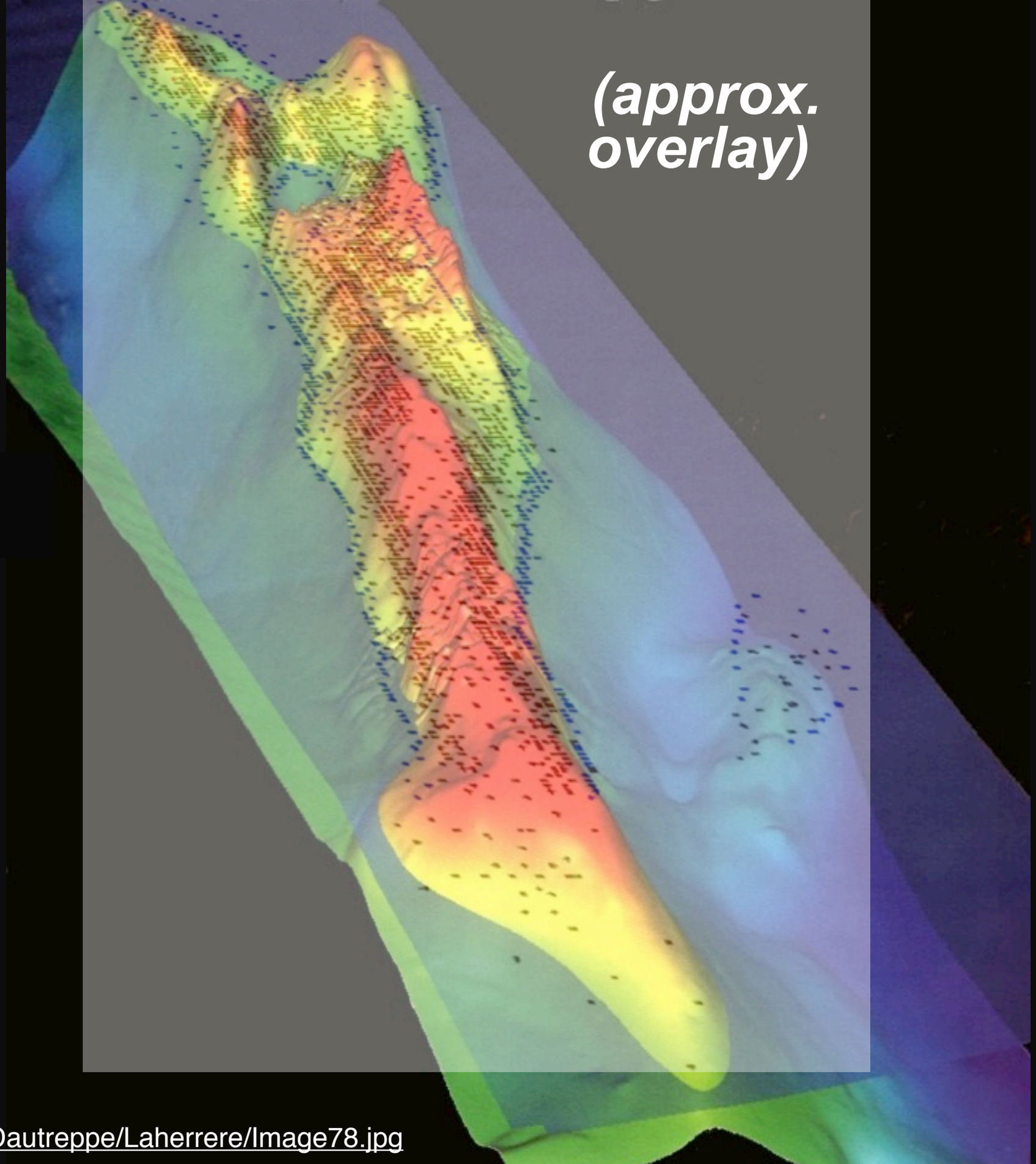
http://www.theoildrum.com/node/2441#comment-177244



Ghawar Boreholes

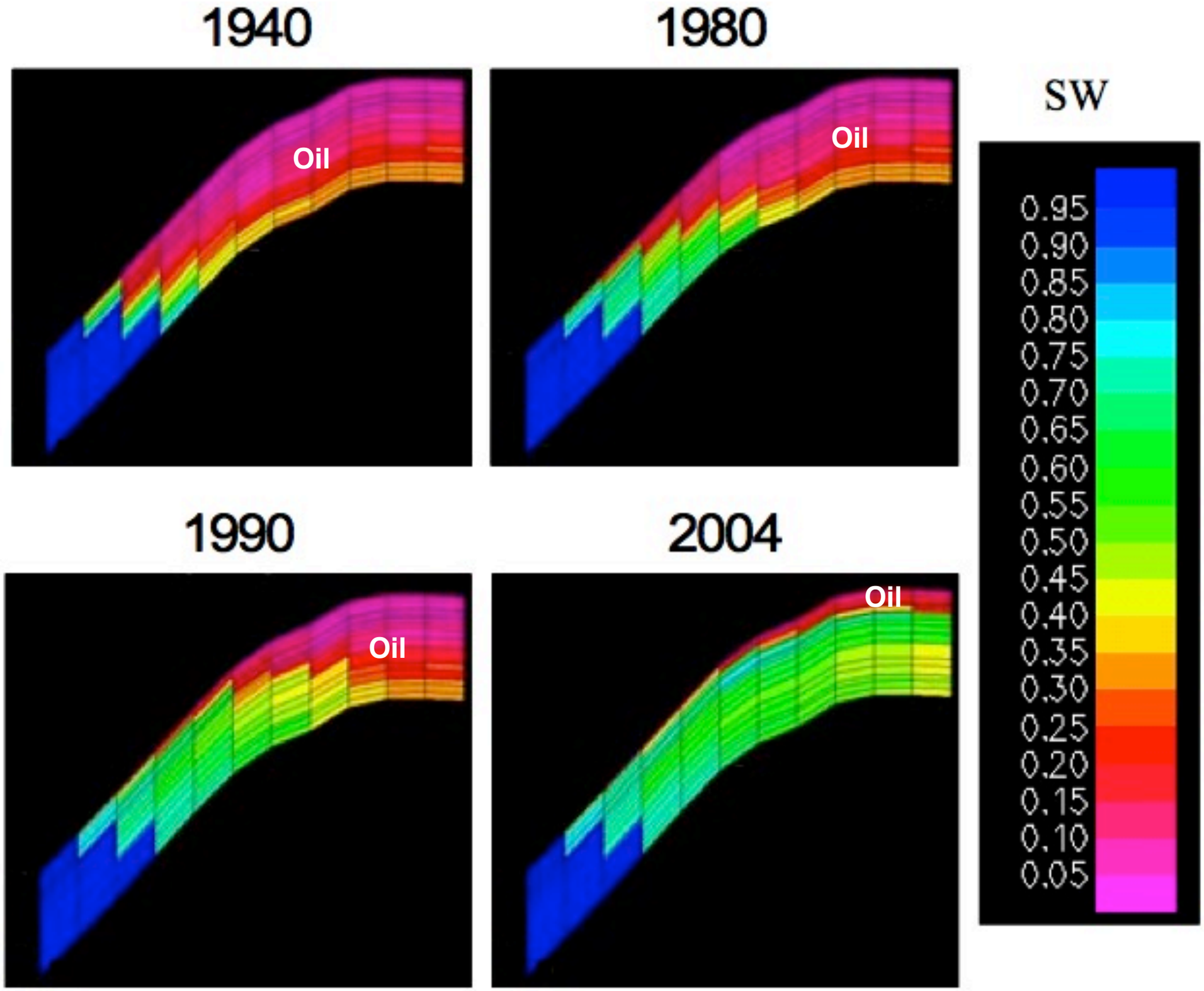
brown: oil
blue: water inj

http://pangea.stanford.edu/~jcaers/theses/thesisJoeVoelker.pdf



http://lpsc.in2p3.fr/gpr/Dautreppe/Laherrere/Image78.jpg

Depletion of North 'Ain Dar



http://www.theoildrum.com/node/2441 **from Stuart Staniford**

http://www.spe.org/elibinfo/eLibrary_Papers/spe/2005/05MEOS/SPE-93439-MS/SPE-93439-MS.htm

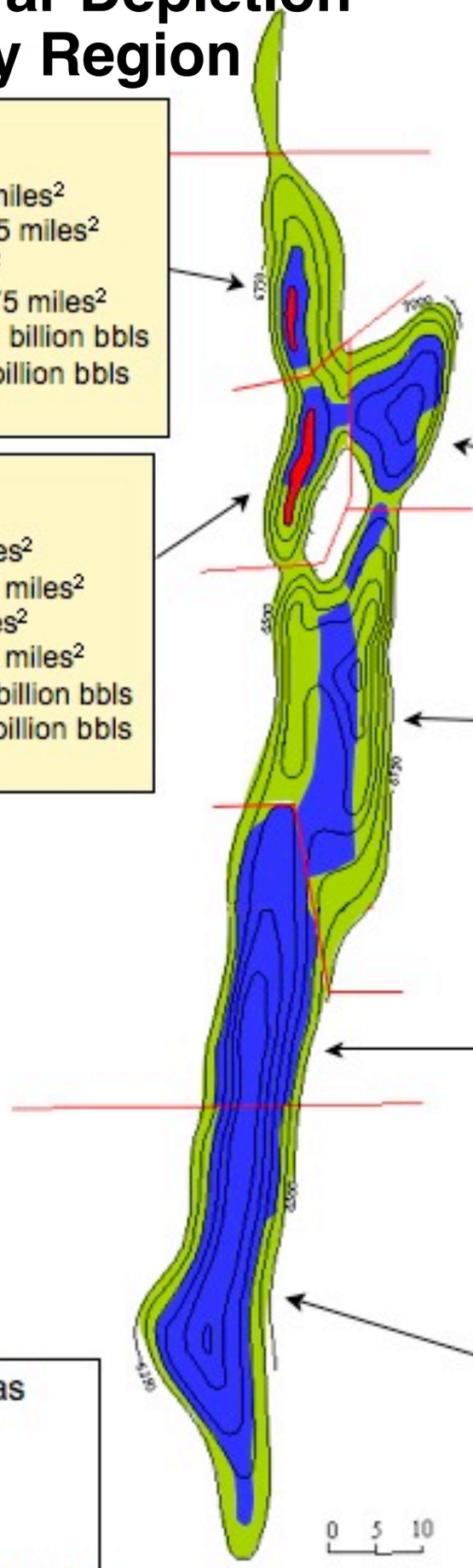
Ghawar Depletion by Region

N

Base Case Scenario
2004 Whole Field Reserves:
34.3 billion bbls

North Ain Dar
Area: 149.5 miles²
Swept Area: 120.75 miles²
Un-swept Area: 28.75 miles²
Area of Oil: 23 miles²
Area of Gas Cap: 5.75 miles²
Initial Reserves: 12.1 billion bbls
2004 Reserves: 1.5 billion bbls
% Depletion: 88

South Ain Dar
Area: 120 miles²
Swept Area: 79.5 miles²
Un-swept Area: 40.5 miles²
Area of Oil: 25.5 miles²
Area of Gas Cap: 15 miles²
Initial Reserves: 9.7 billion bbls
2004 Reserves: 1.7 billion bbls
% Depletion: 83



Shedgum
Area: 163.5 miles²
Swept Area: 70.5 miles²
Un-swept Area: 93 miles²
Initial Reserves: 11.3 billion bbls
2004 Reserves: 5.4 billion bbls
% Depletion: 55

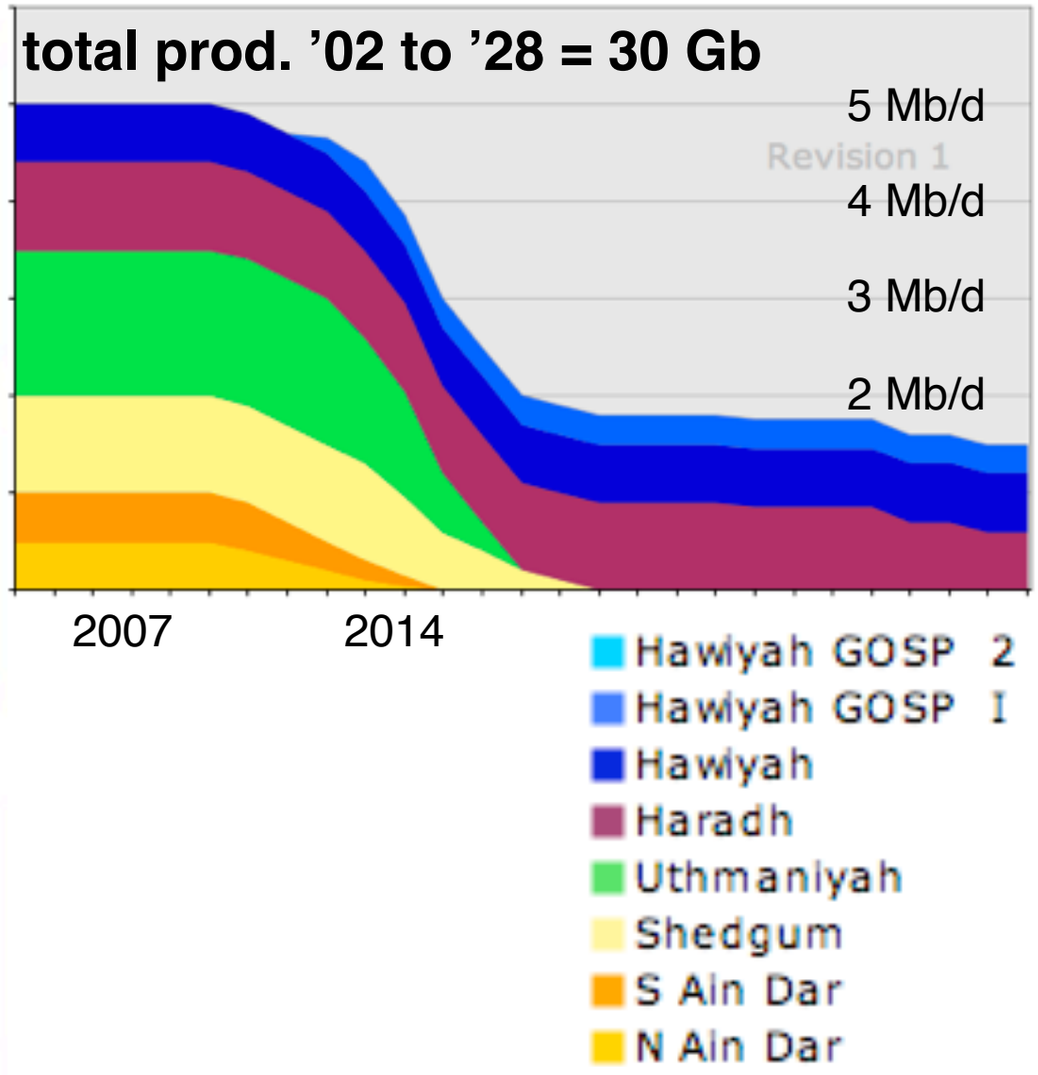
Uthmaniyah
Area: 461.75 miles²
Swept Area: 327.5 miles²
Un-swept Area: 134.25 miles²
Initial Reserves: 29.3 billion bbls
2004 Reserves: 6.5 billion bbls
% Depletion: 78

Hawiyah
Area: 293.75 miles²
Swept Area: 56 miles²
Un-swept Area: 237.75 miles²
Initial Reserves: 13.8 billion bbls
2004 Reserves: 11.1 billion bbls
% Depletion: 19

Haradh
Area: 436 miles²
Swept Area: 161.75 miles²
Un-swept Area: 274.25 miles²
Initial Reserves: 14.4 billion bbls
2004 Reserves: 8.4 billion bbls
% Depletion: 42

Measurement of Areas
SHEDGUM
5X5 mile square grid

Ghawar Base Case Production Model



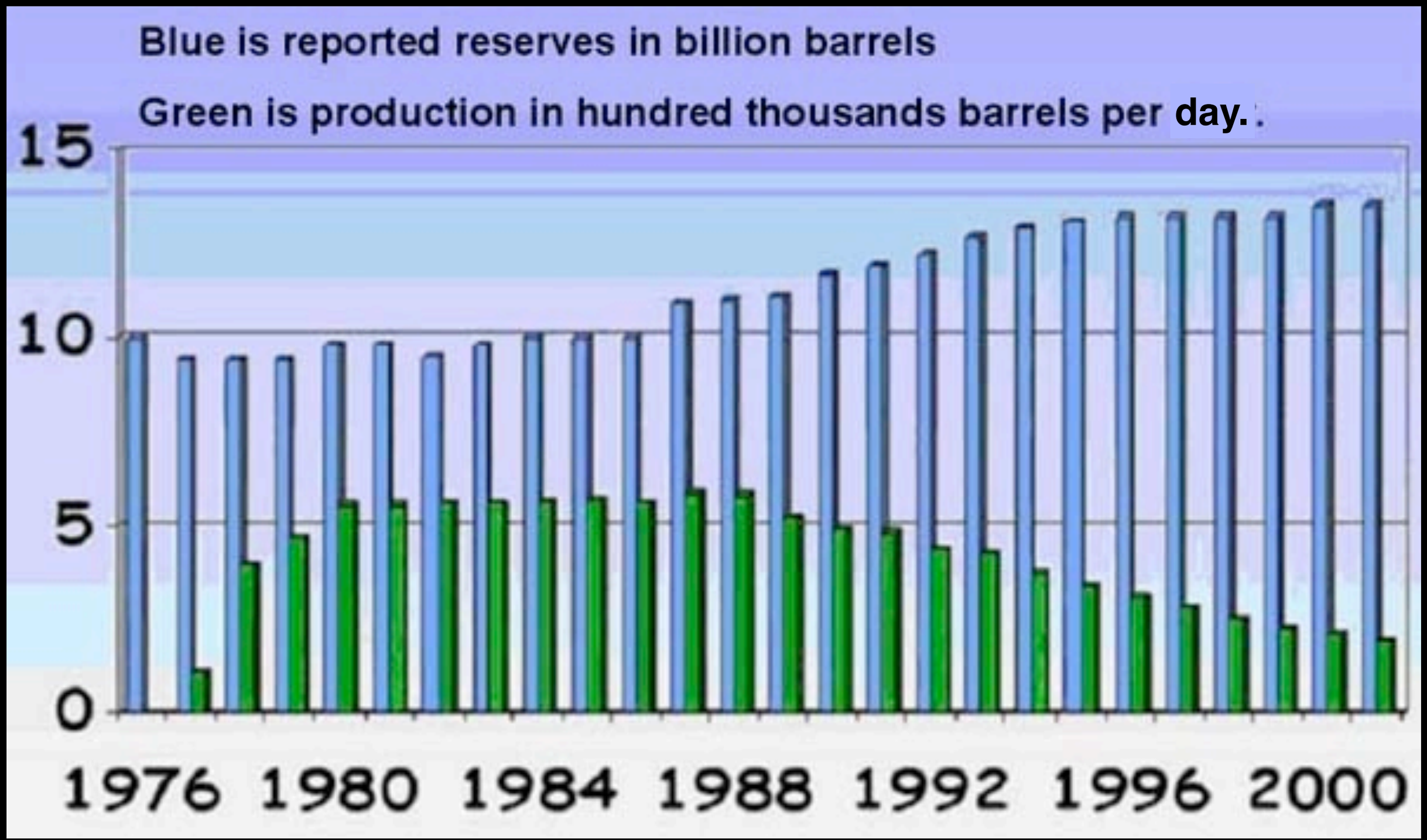
from Euan Mearns

http://europe.theoildrum.com/node/2507

http://europe.theoildrum.com/node/2494

Prudoe Bay, Alaska – Production/Reserves

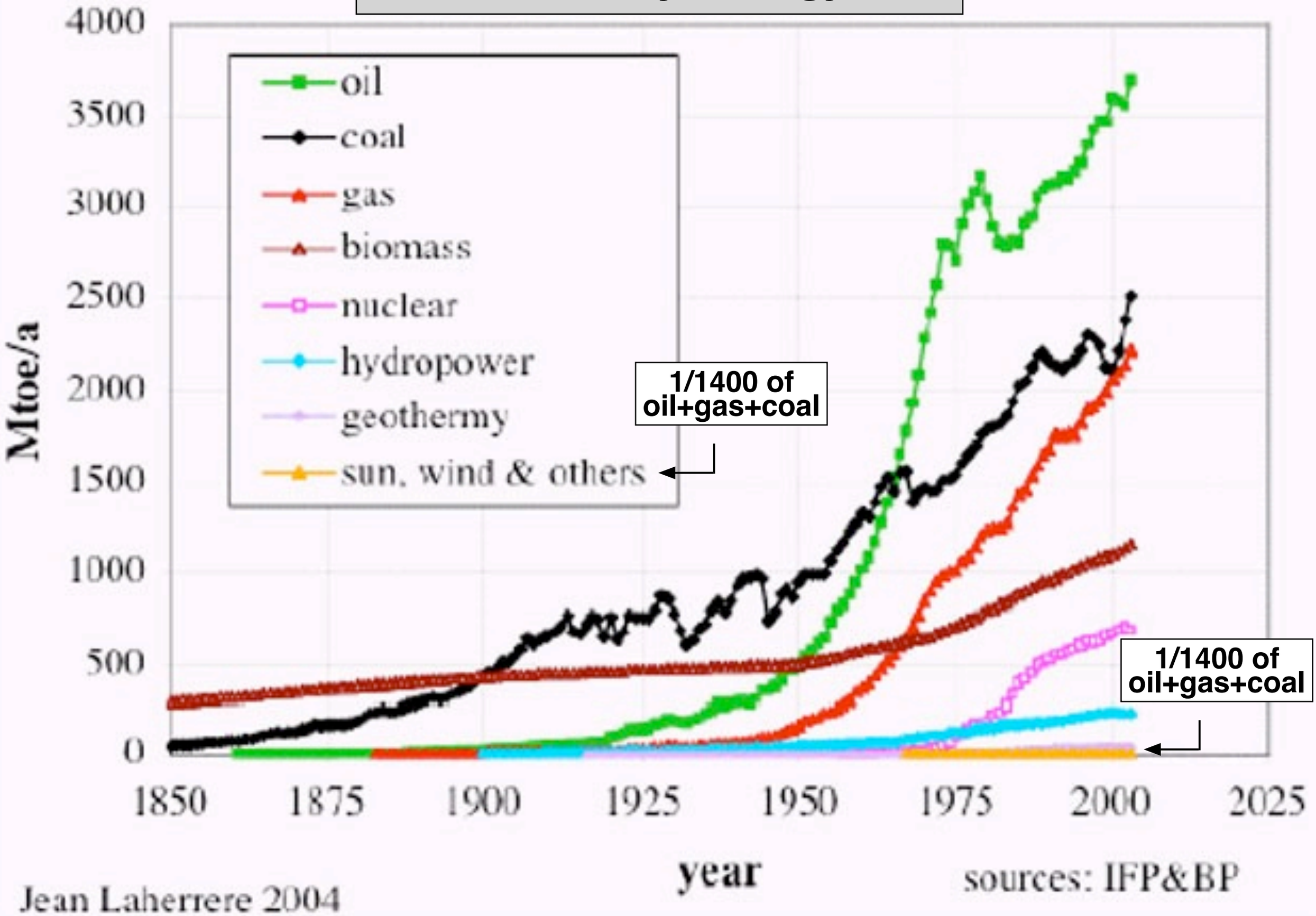
largest North American oil field (discovered 1968) 'reserves' increase but production continues to drop



Extreme Danger Ahead

- we have merely been ***adding*** energy sources, not transitioning
- other main energy types are themselves depleting
- demand is growing as rest of world imitates US/EU/UK
- a bicycle is a 100-watt device
- a car is a 100,000-watt device
- 1 google search (0.1 kWh) equals pedaling a bike for 1 hour
  (est. kWh/search: ~1 million Google servers × ~1 kW each ÷ 10 million searches/hour)

World Primary Energy Mix



First, A Basic Energy Facts Review

- oil and gasoline are extremely energy-dense & convenient
- a car is a ***100,000 watt device*** (accelerating a 130 hp car is like turning on 1,000 one-hundred-watt light bulbs)
- there will ***never be a 100 mpg car*** (4 upright people, 65 mph) because of weight, wind and rolling resistance, engine size
- one gallon of gas (2.84 kg) contains ***36 kW-hours*** of energy (before losses), a Tour de France cyclist generates ***0.2 kW***
- ***one barrel*** of oil = ***one year*** hard physical labor by a human (25%-efficiency petrol *vs.* 6 hours 128 watts continuous/day)
- batteries have low energy-density (Prius NiMH battery is 0.07 kWh/kg – ***1/45*** of 25%-efficiency-gasoline) (Li battery=1/26)
- solar radiation is ubiquitous but has ***very*** low energy density
- the deployed military is ***70% fossil fuel by weight***
- current per capita US energy use: ***250 kWh/day***
- current per capita UK/EU energy use: ***125 kWh/day***
- current per capita India energy use: ***20 kWh/day***
- pre-industrial per capita energy use: ***20 kWh/day (wood)***

Distribution of World Primary Energy Use

Population in %

Total Primary Energy consumption per country or region in %

Energy Consumption in equiv. Watts of power per capita

Annual GDP per capita in US$ (●○)

Population in Millions

- Biomass & waste
- Hydro
- Nuclear
- Coal
- Natural Gas
- Oil

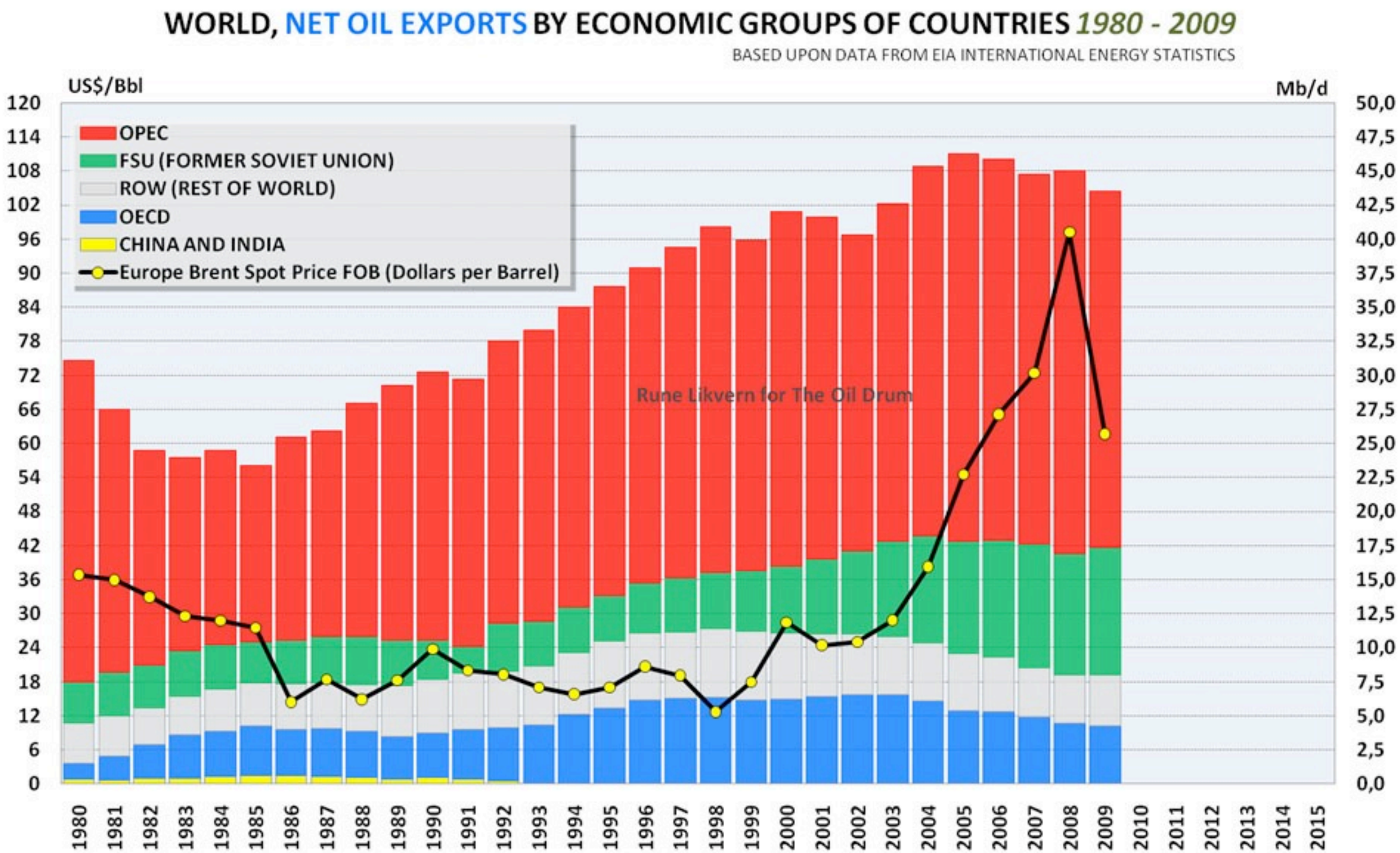
World average energy. consumption

Preindustrial energy needs

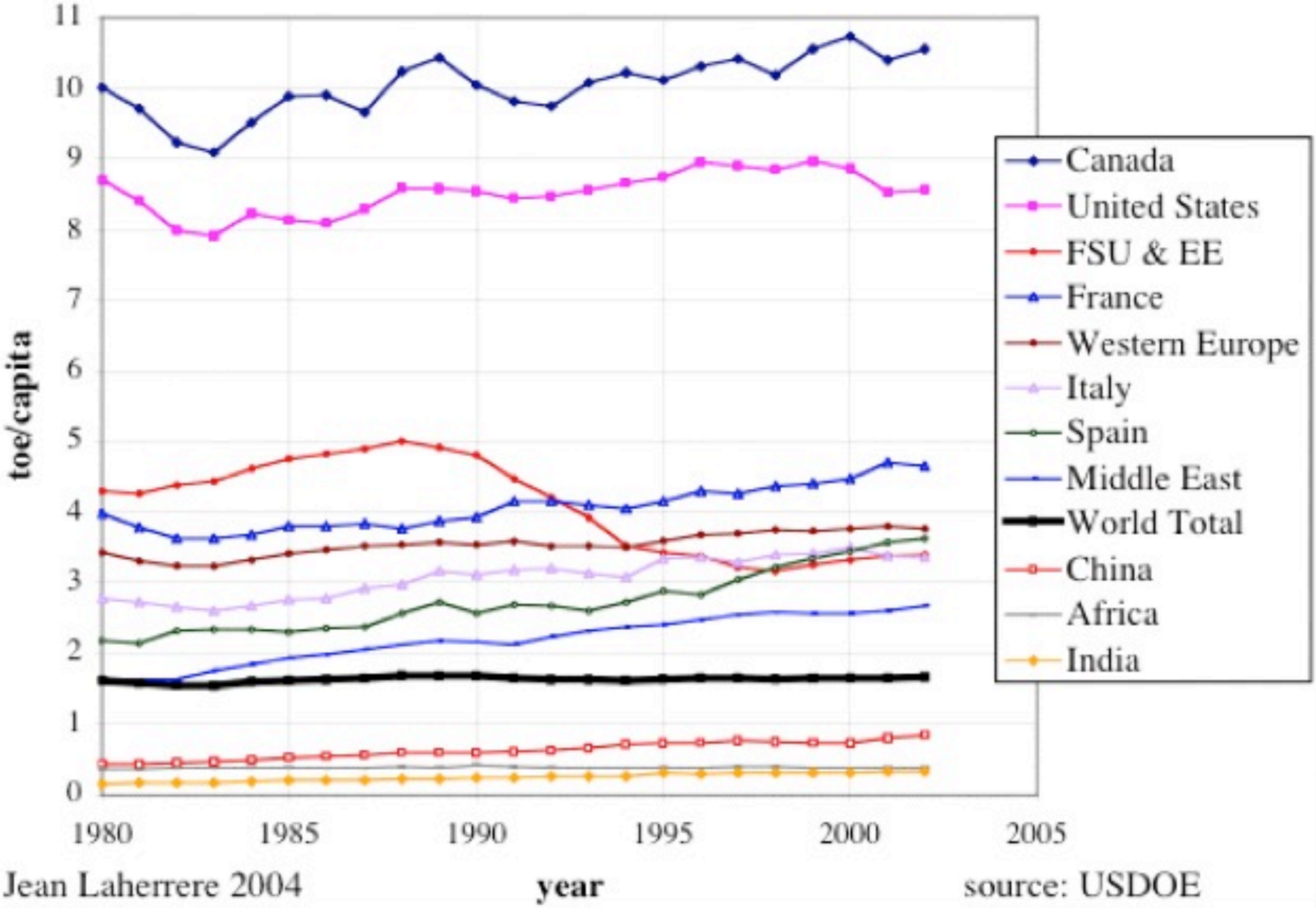
Metabolic energy needs

	Population	Energy
USA + CANADA	5.0%	23%
JAPAN	1.9%	4.6%
EU 15	5.8%	13.3%
RUSSIA	2.1%	5.9%
MIDDLE EAST	2.4%	4.6%
EU 16 to 27	1.4%	2.3%
OTHERS EX USSR	2.4%	2.9%
LATIN AMERICA	7.8%	6.5%
CHINA	20.0%	16.0%
REST OF ASIA	18.0%	9.4%
REST OF EUROPE +TURKEY	3.7%	1.9%
AFRICA	12.5%	4.7%
INDIA	17.0%	4.7%

Where Oil Exports Currently Come From



Primary energy per capita



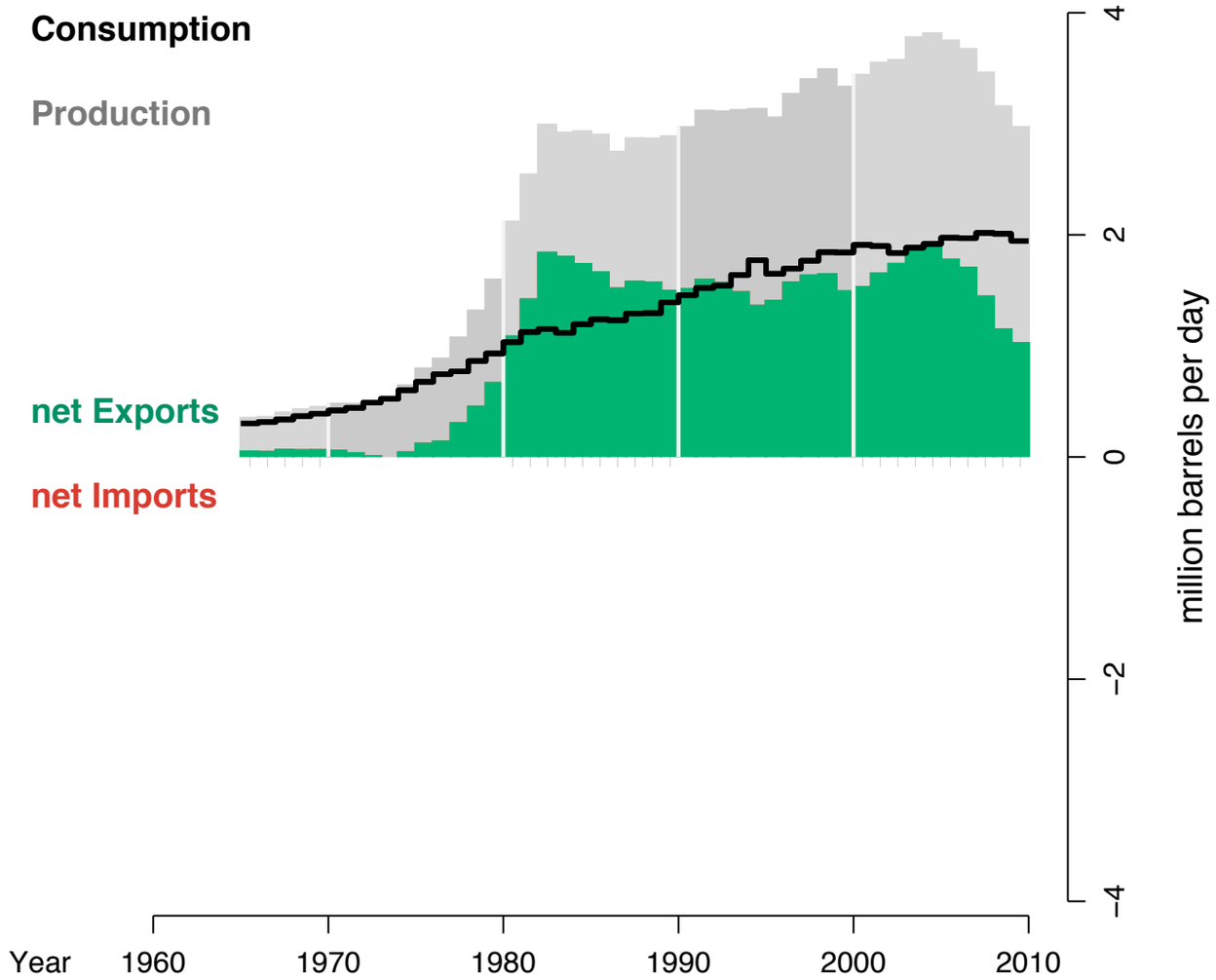
Jean Laherrere 2004

source: USDOE

Exporting Countries Have Growing Internal Demand

Mexico : Oil

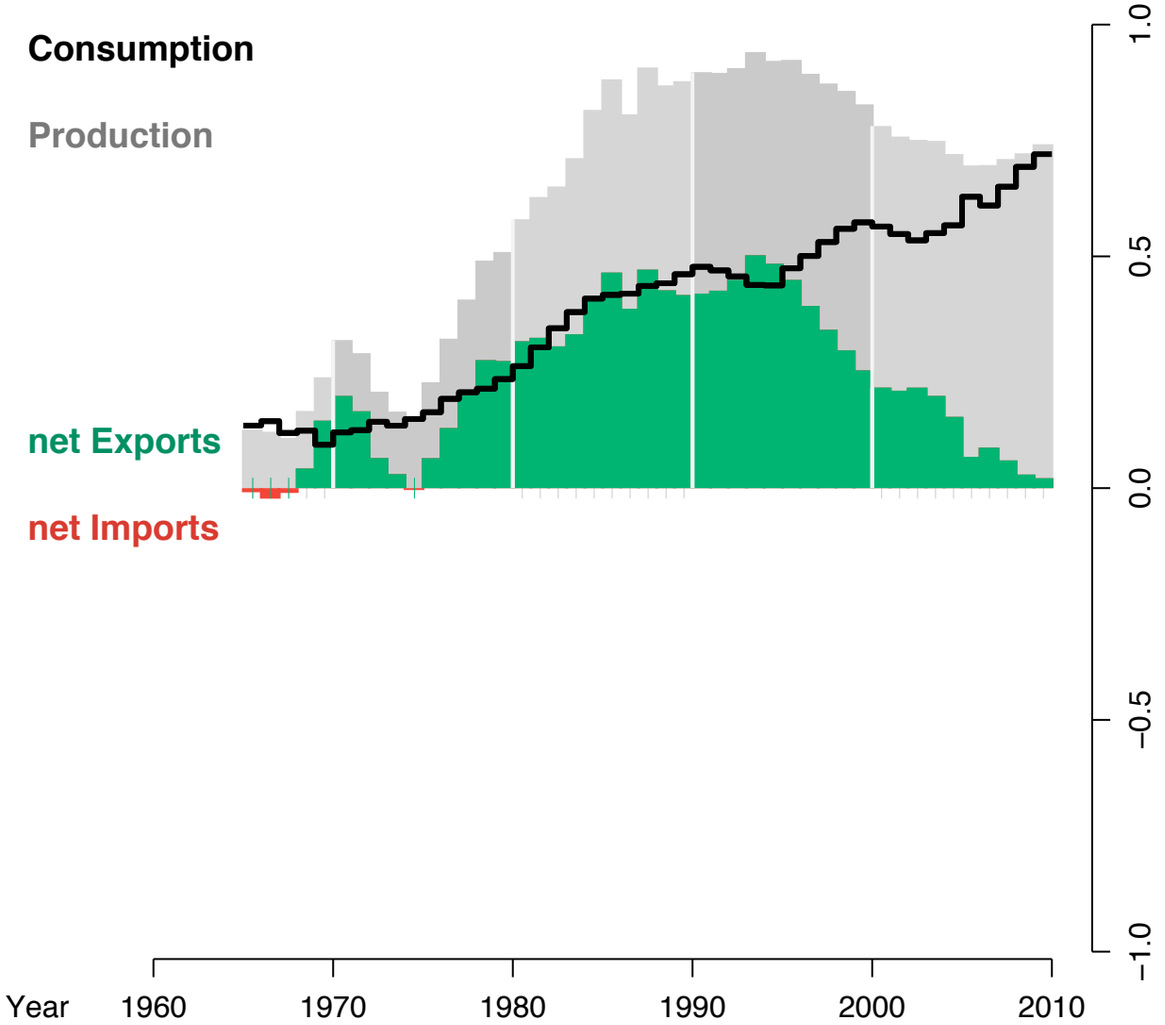
2009 exports decreased by 10. %



Data: BP Statistical Review 2010 Graphic: mazamascience.com

Egypt : Oil

2009 exports decreased by 26. %

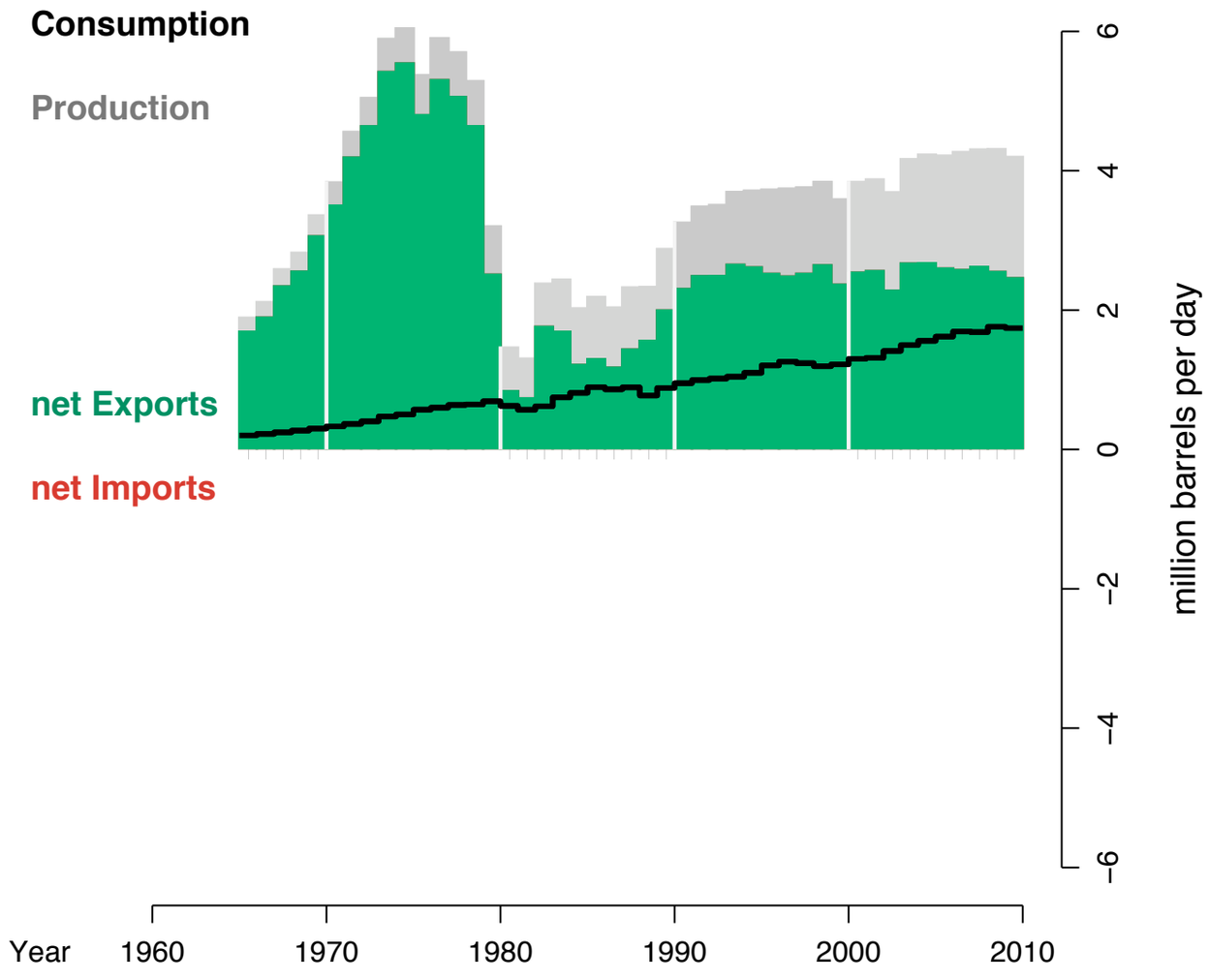


Data: BP Statistical Review 2010 Graphic: mazamascience.com

Even the "biggies" have similar issues

Iran : Oil

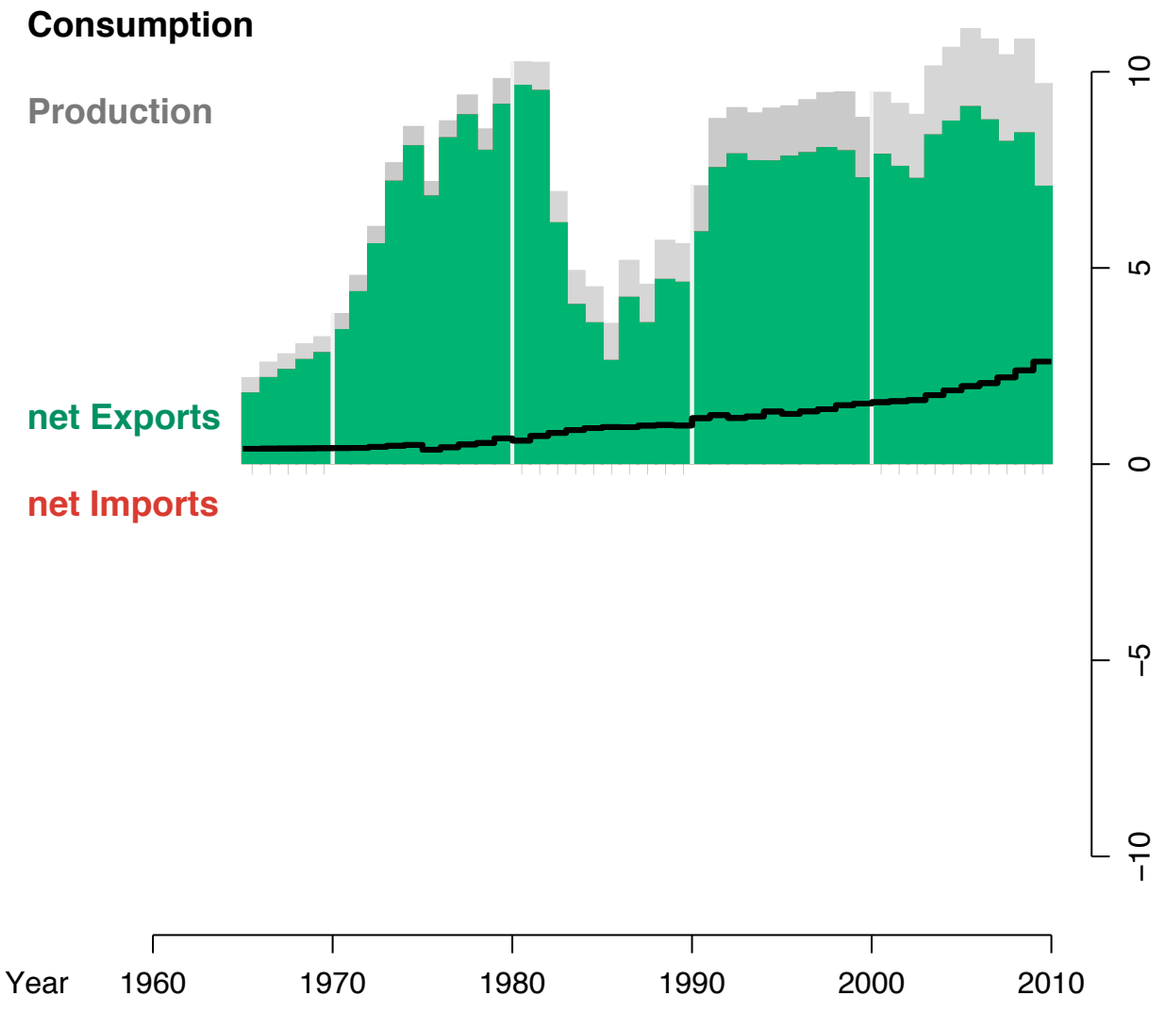
2009 exports decreased by 3.5 %



Data: BP Statistical Review 2010 Graphic: mazamascience.com

Saudi Arabia : Oil

2009 exports decreased by 16. %

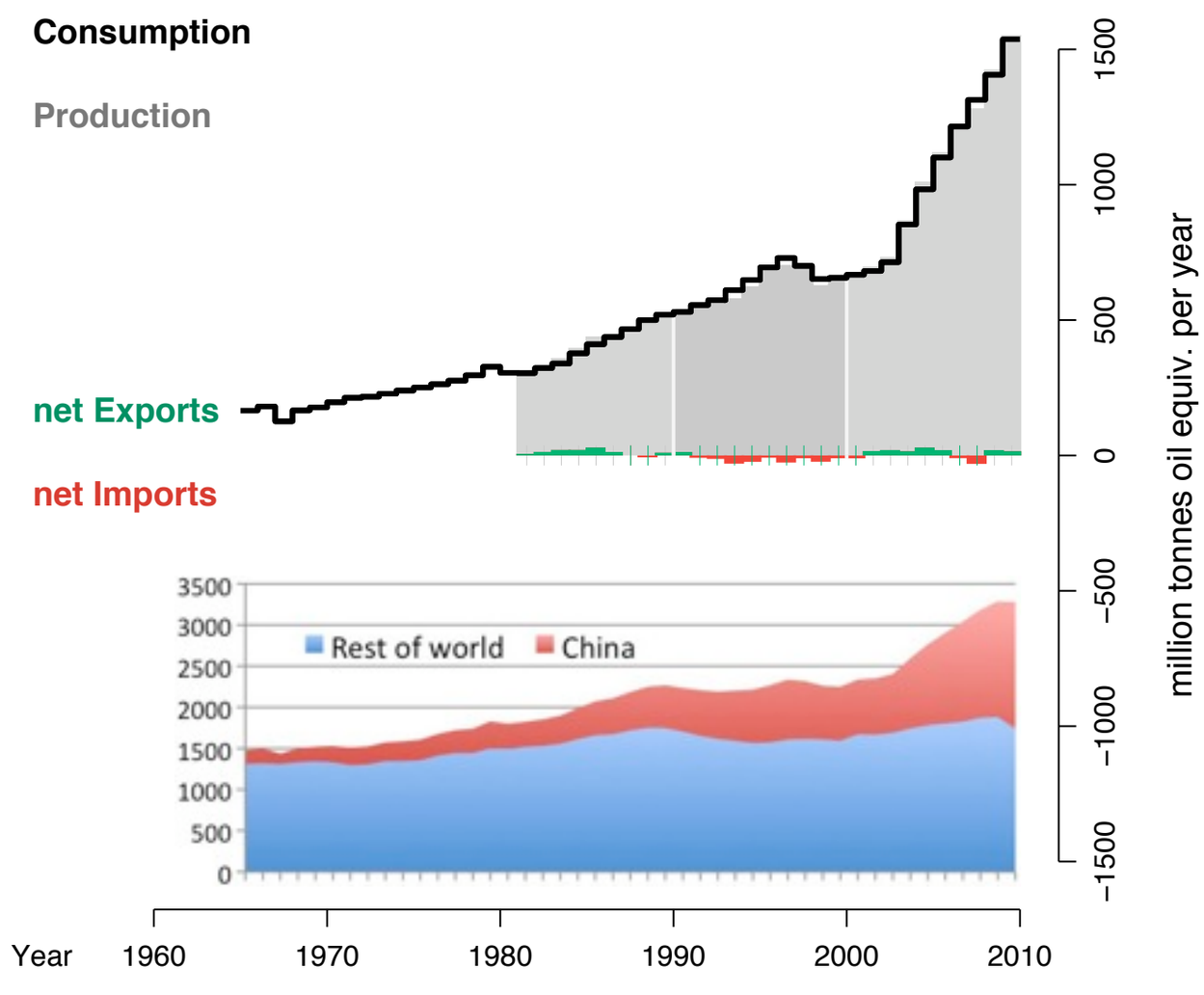


Data: BP Statistical Review 2010 Graphic: mazamascience.com

At prev. decade growth rate, China will consume all world exports of oil and coal in 15 years

China : Coal

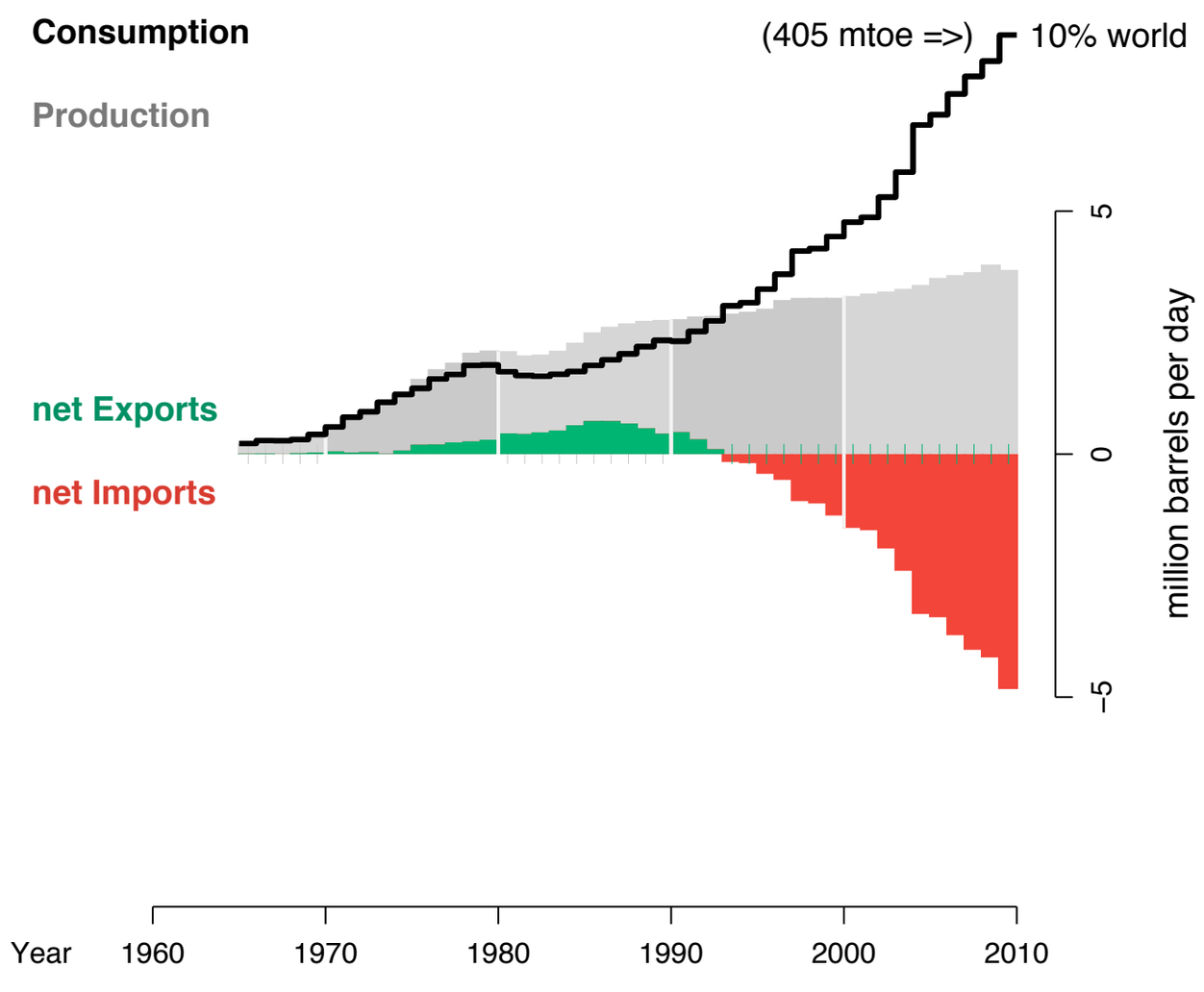
2009 exports decreased by 20. %



Data: BP Statistical Review 2010 Graphic: mazamascience.com

China : Oil

2009 imports increased by 15. %

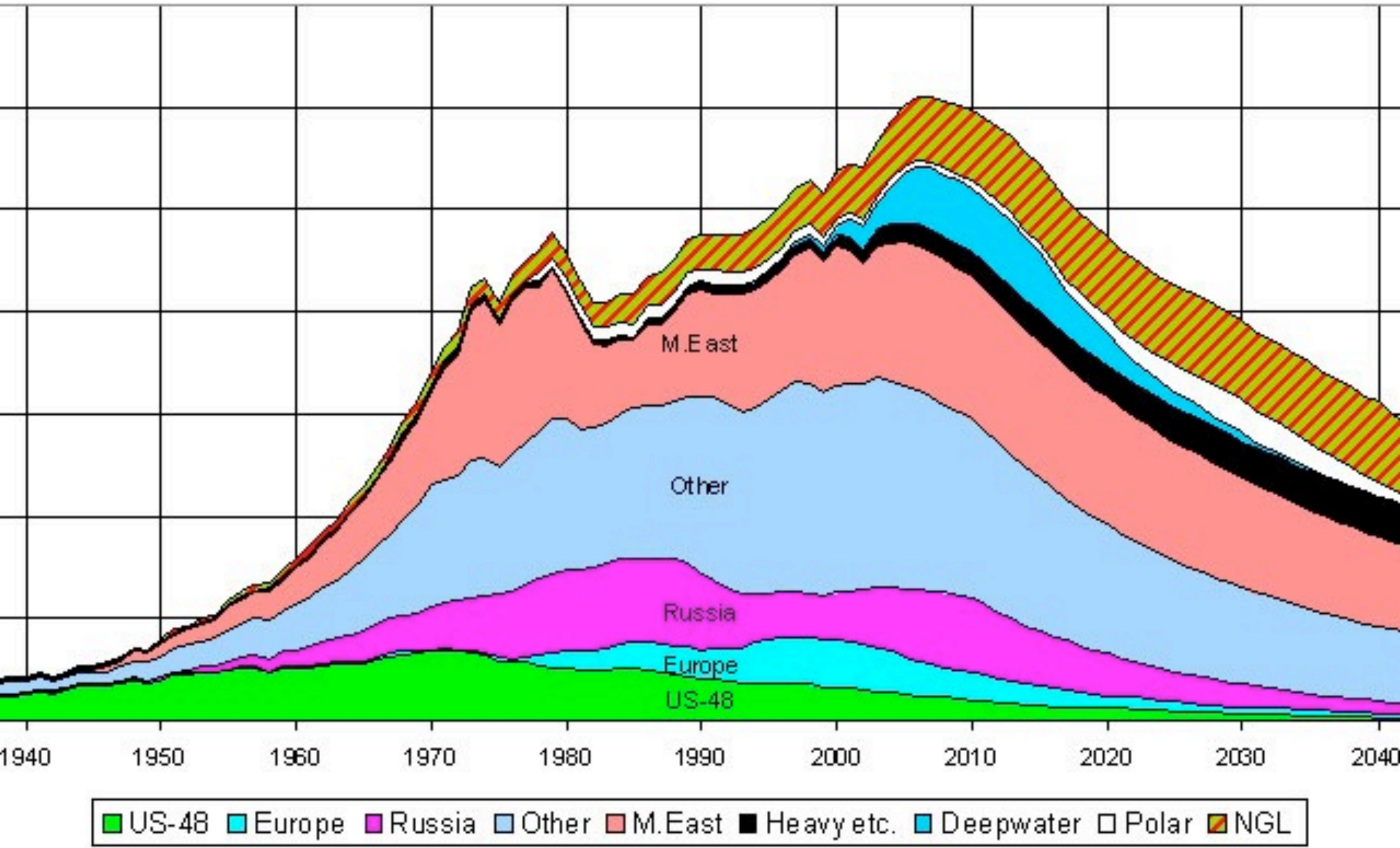


Data: BP Statistical Review 2010 Graphic: mazamascience.com

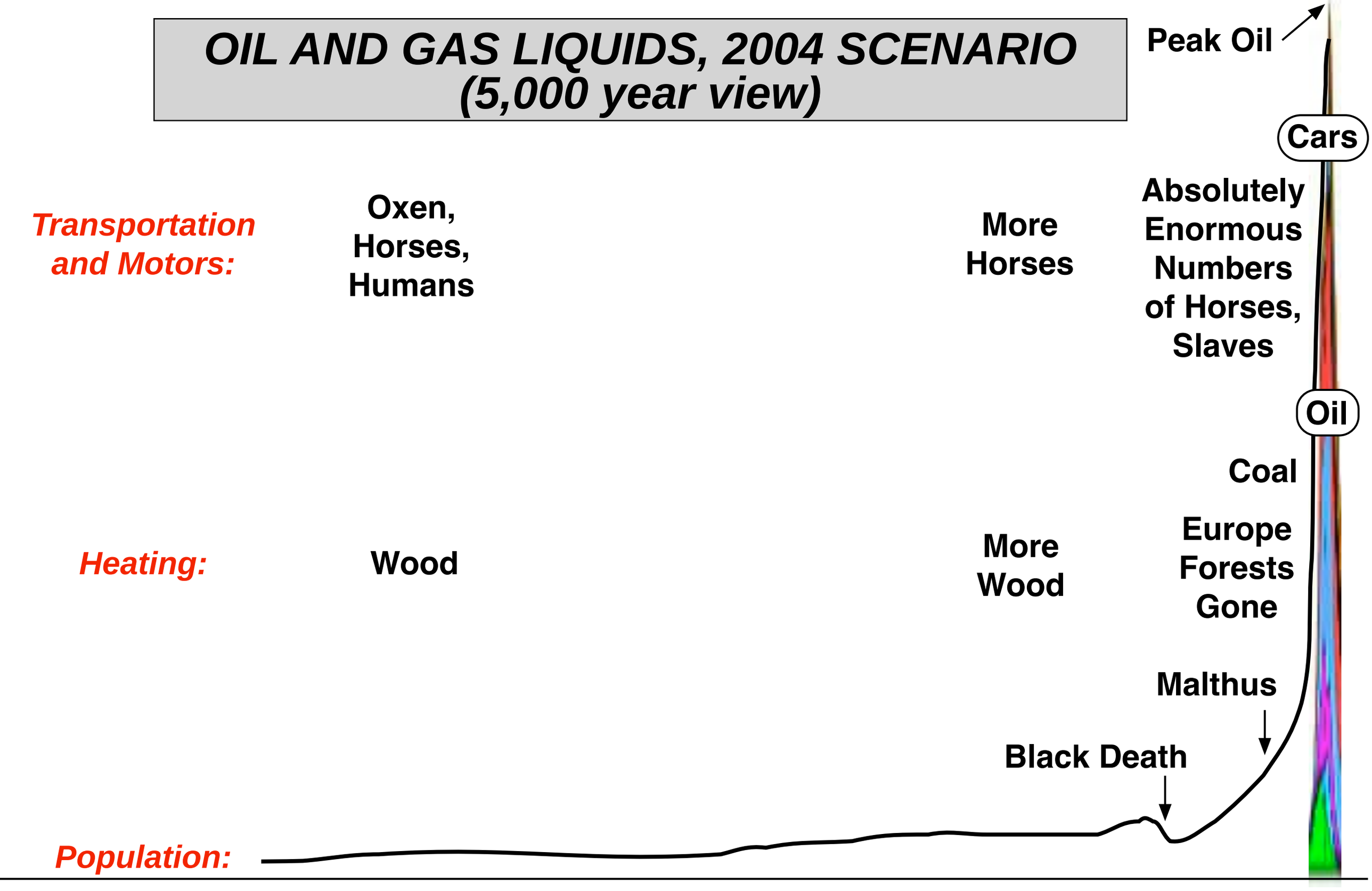
Let's Take a Longer-Term View

- too doomer-ish?
- perhaps the 'cornucopians' are correct

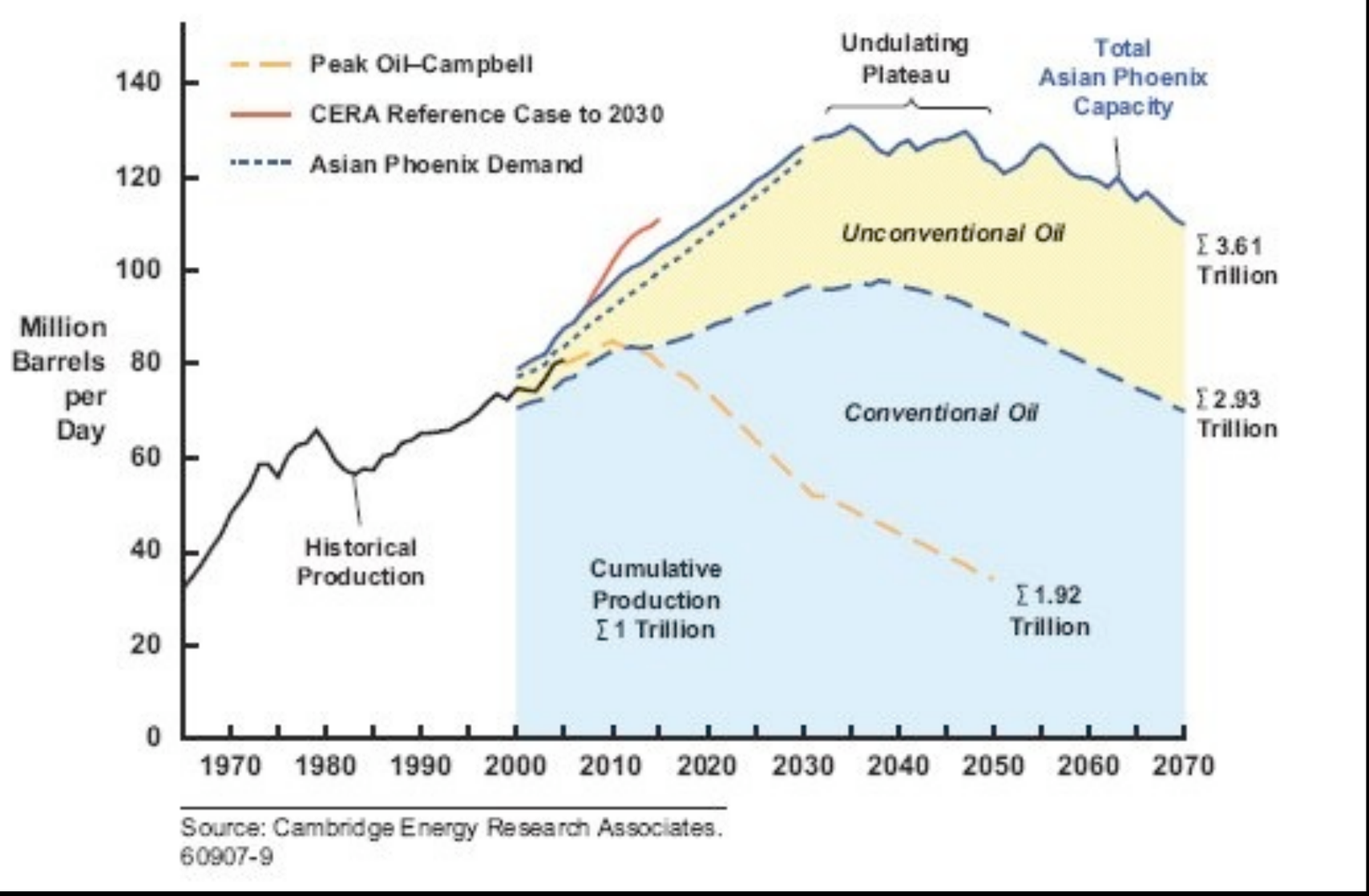
OIL AND GAS LIQUIDS, 2004 SCENARIO (100 year view)



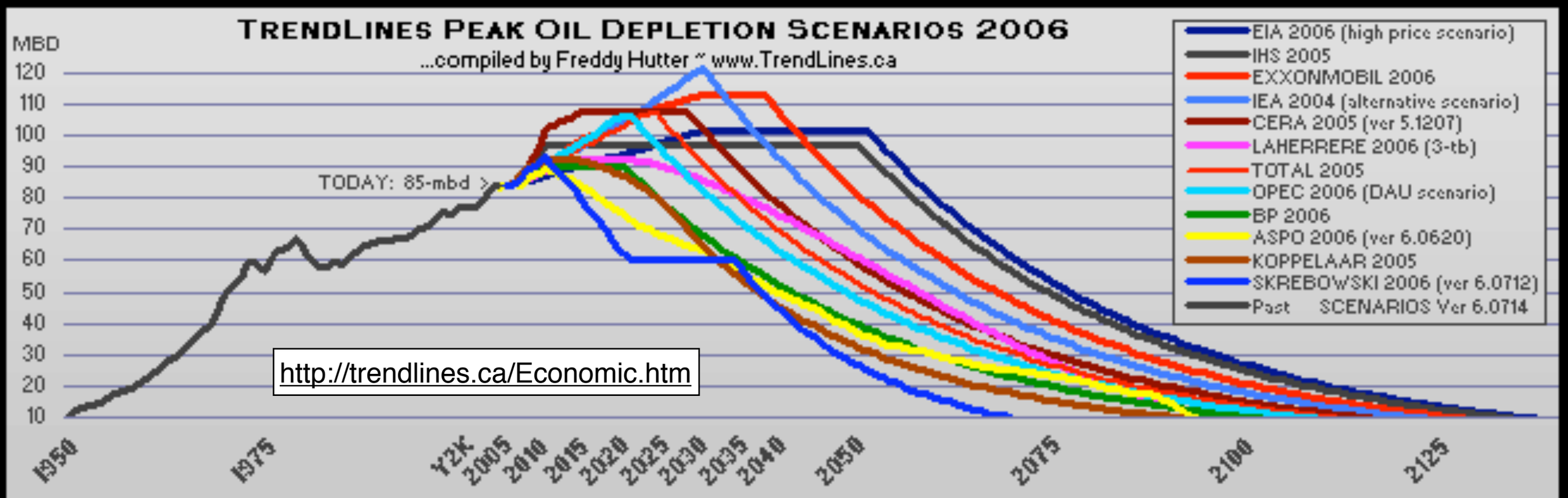
OIL AND GAS LIQUIDS, 2004 SCENARIO (5,000 year view)



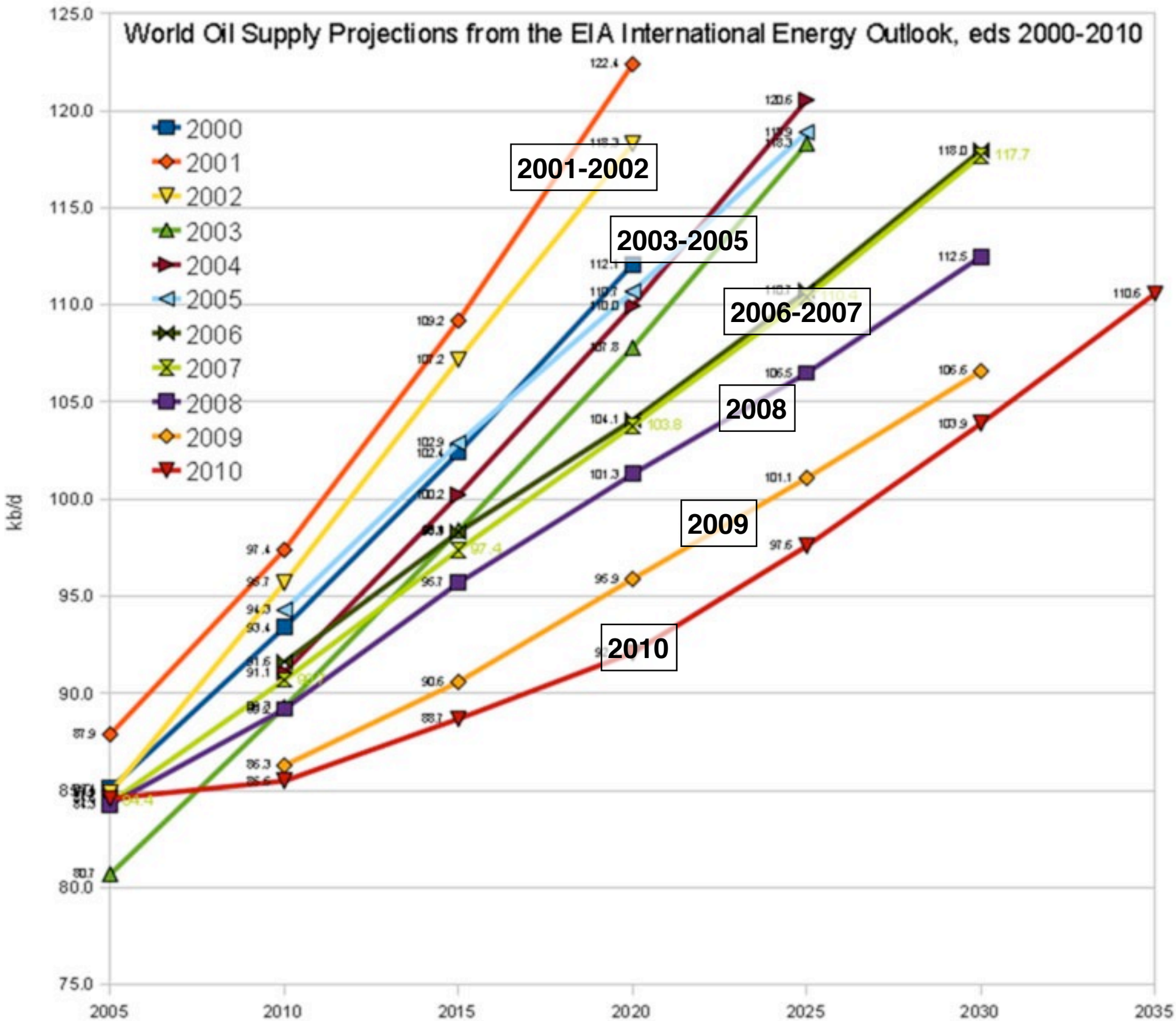
Other Scenarios Are More Optimistic



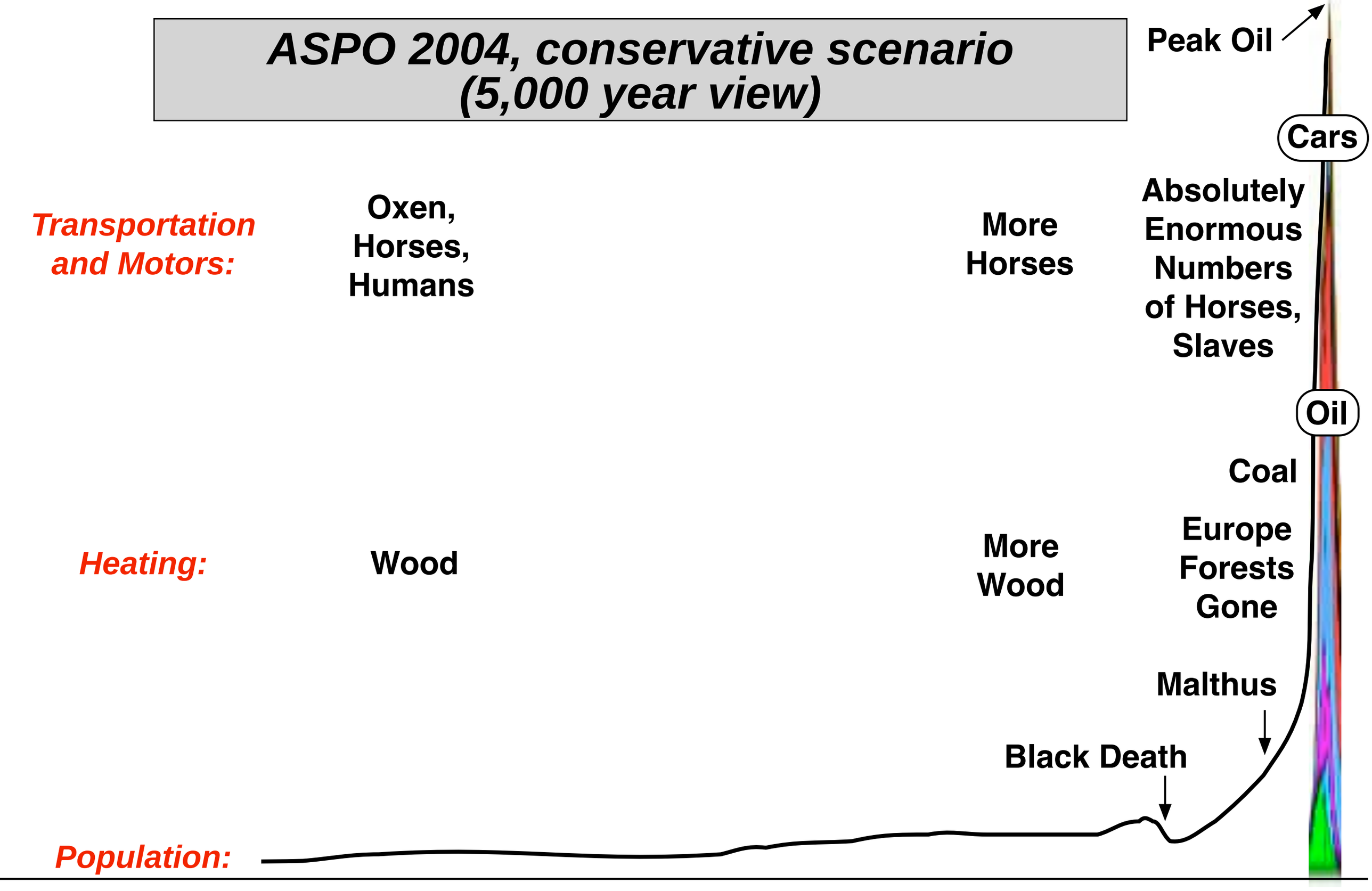
Source: Cambridge Energy Research Associates.
60907-9



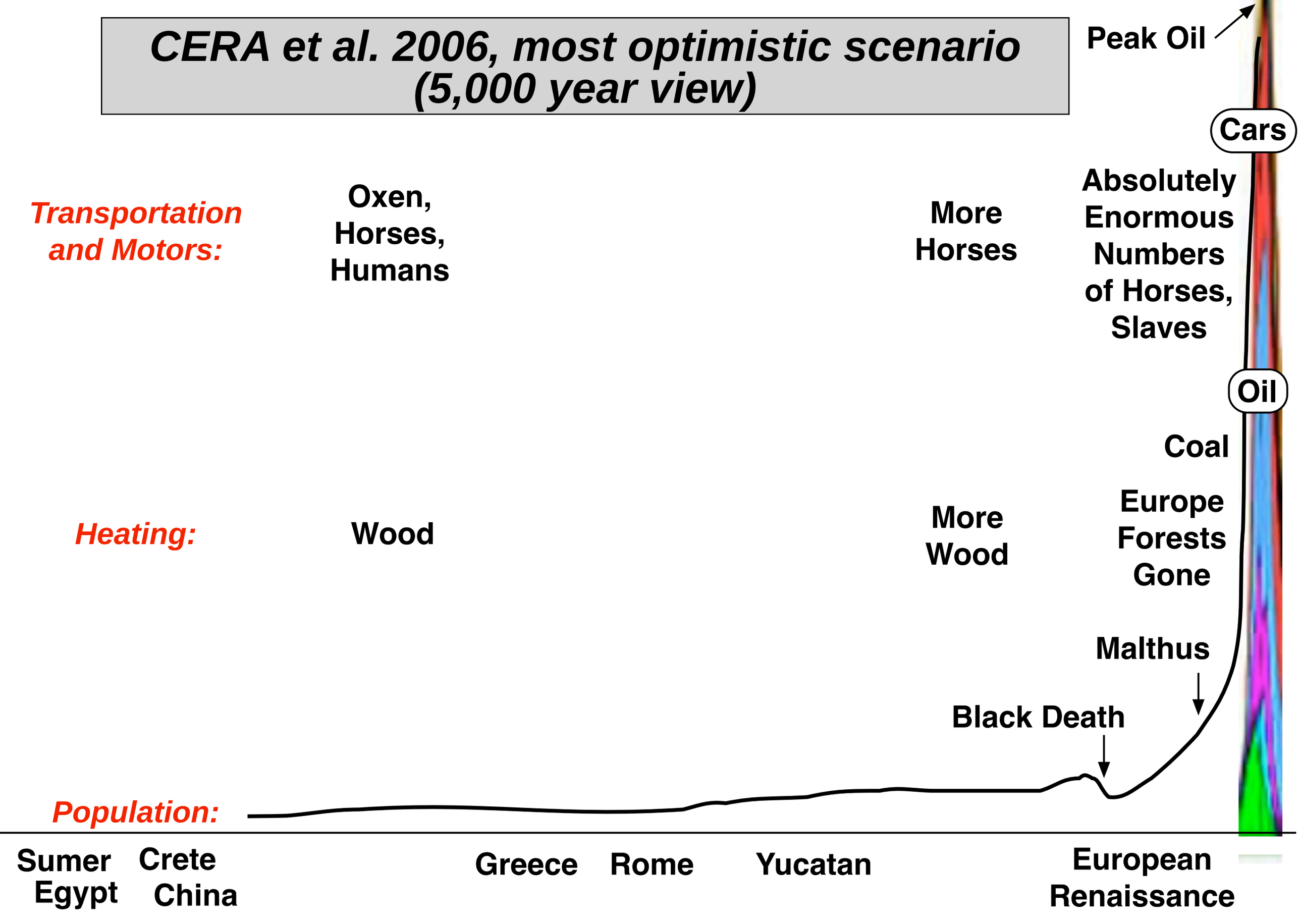
For Public Consumption
(ridiculous projections reset each year by reality)



ASPO 2004, conservative scenario (5,000 year view)



CERA et al. 2006, most optimistic scenario (5,000 year view)

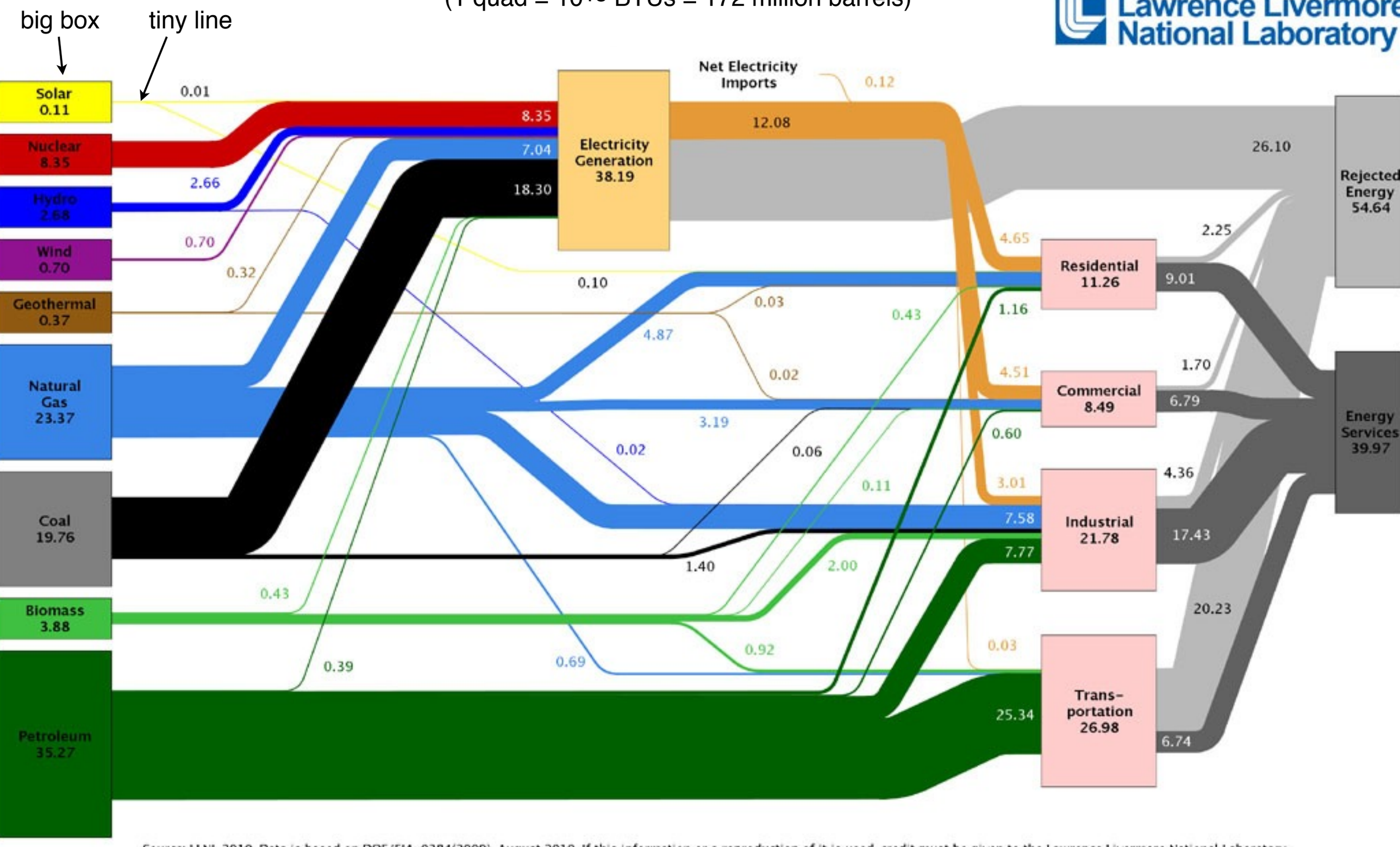


OK, Let's Look At Other Energy Sources

Estimated US Energy Use 2009: 94.6 Quads

(1 quad = 10^{15} BTUs = 172 million barrels)

Lawrence Livermore National Laboratory



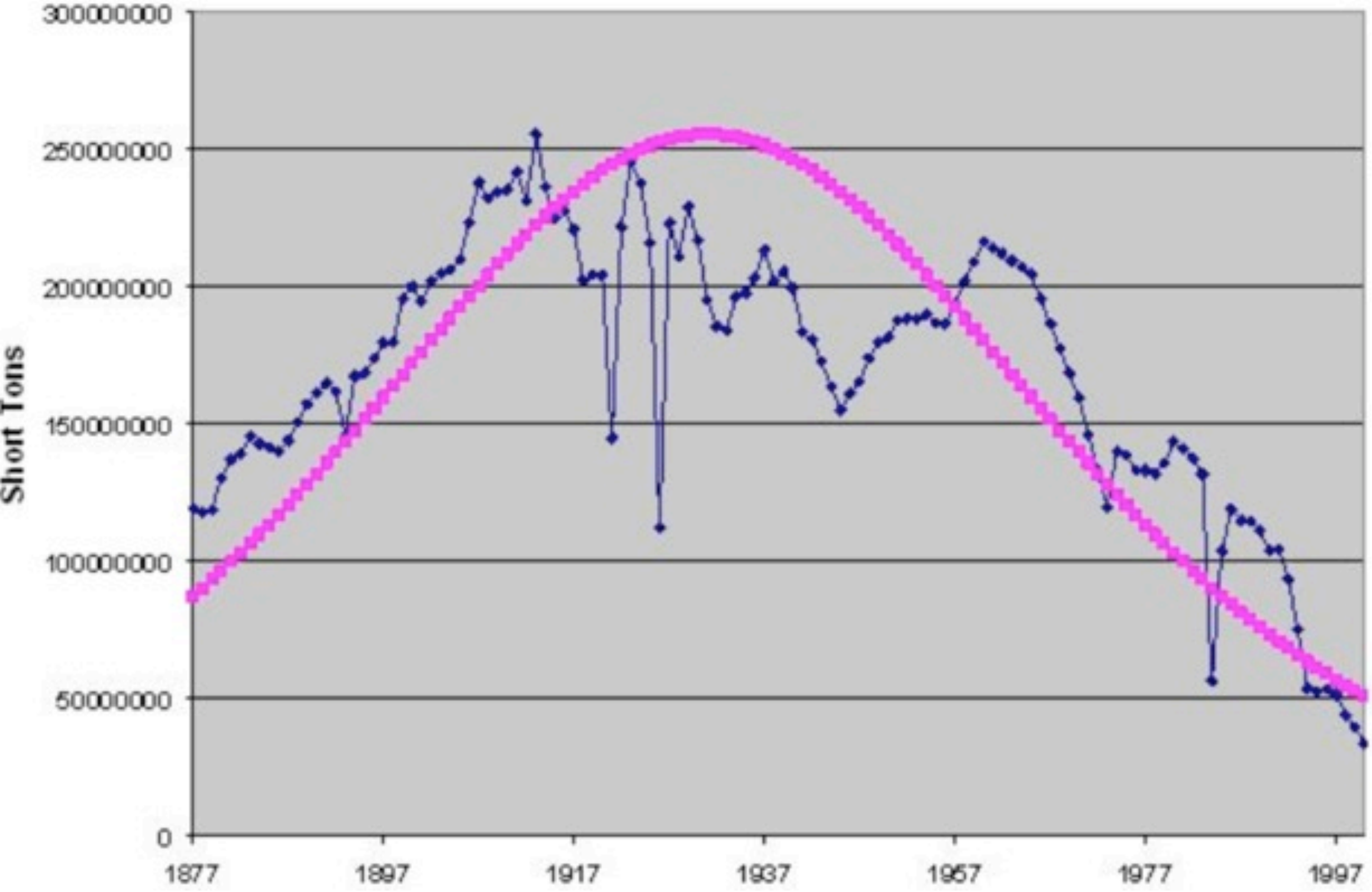
Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Possible Replacements – Fossil Fuel Sources

- ***oil*** *(currently: 40% US energy)*
- ***coal*** *(currently: 22% US energy)*
  - – may peak 2030, then reach EROEI=1.0 long before all gone
  - – mercury in fish is from burning coal; 2x CO_2 of oil/gas
  - – coal bed methane production growing but water intensive
- ***natural gas*** *(currently: 23% US energy)*
  - – world peak later than oil, but North American peak passed
  - – requires energy-intensive cooling/liquification to transport
- ***oil/tar sands*** *(currently: small portion of oil imports)*
  - – two tons *best* sand make 1 barrel oil (14:1 weight ratio)
  - – sands must be dug, heated, washed (EROEI 1.0-3.0)
- ***oil shale*** *(currently: 0%)*
  - – EROEI worse than oil/tar sands, maybe below 1.0
- ***methane hydrates*** *(currently: 0%)*
  - – reserves unknown, extraction methods unknown
  - – may outgas on their own with arctic melting

UK Coal Production

(why Newcastle has to have coal carried to it)

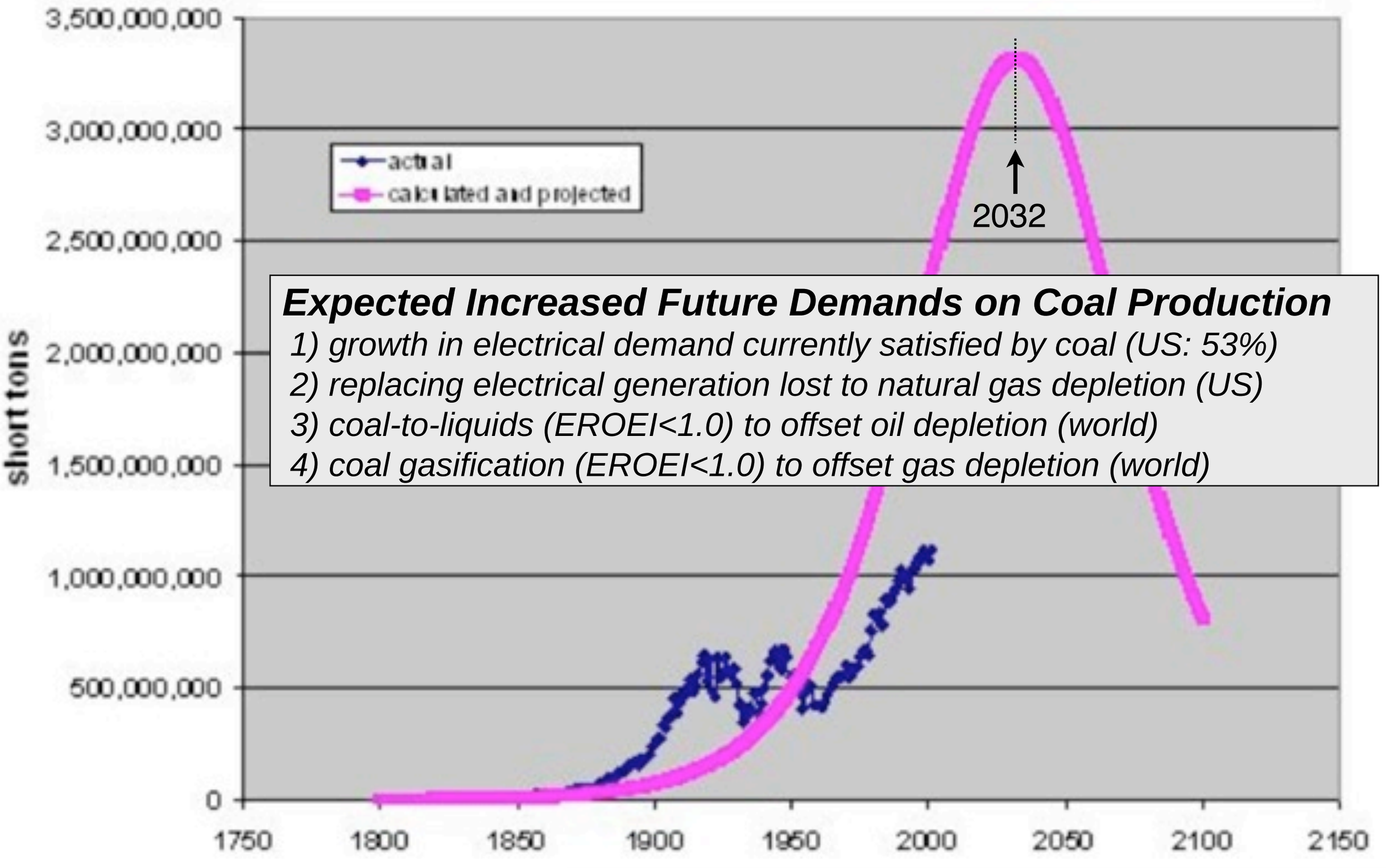


From Gregson Vaux

http://www.fromthewilderness.com/free/ww3/052504_coal_peak.html

World Coal Production

Hubbert curve using (generous) EIA reserves estimates



Expected Increased Future Demands on Coal Production

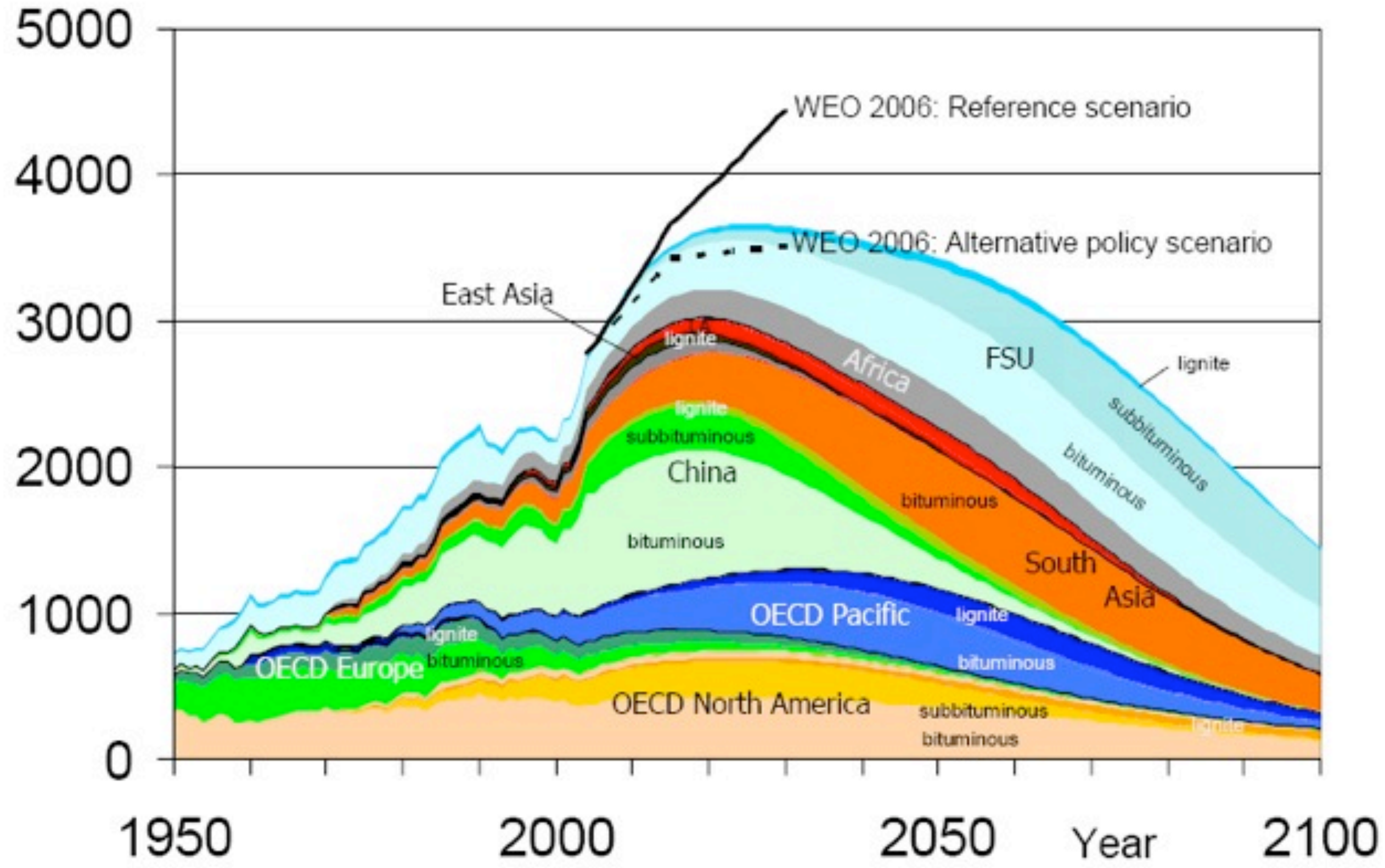
1) growth in electrical demand currently satisfied by coal (US: 53%)
2) replacing electrical generation lost to natural gas depletion (US)
3) coal-to-liquids (EROEI<1.0) to offset oil depletion (world)
4) coal gasification (EROEI<1.0) to offset gas depletion (world)

From Gregson Vaux (2005)

http://www.fromthewilderness.com/free/ww3/052504_coal_peak.html

World Coal Production

a 2020 peak from the Energy Watch Group (2007)



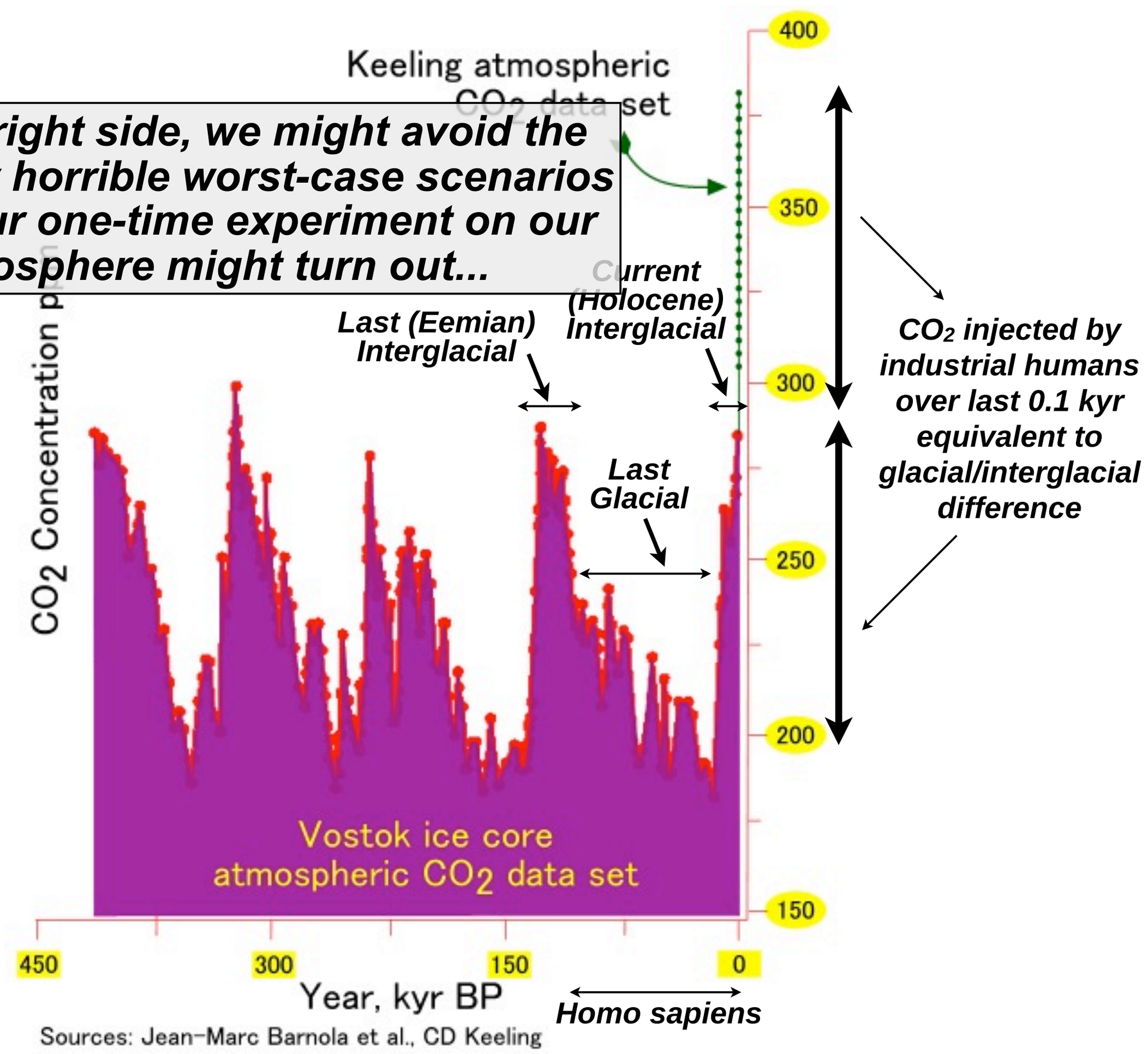
http://www.energywatchgroup.org/files/Coalreport.pdf

World Coal Production
(this estimate is 1/4 of EIA)

Region	Current production Mt	Cumulative production Gt	Long-term production estimate Gt	Reserves + cumulative Gt	Long-term production estimate/ (reserves + cumulative)	Long-term production estimate range Gt	Regression t90
Australia	414	10	50	87	57%	28 - 53 (51%)	2076
China	3,050	51	139	162	86%	107 - 201 (68%)	2051
Africa	253	8	18	40	45%	18 - 27 (49%)	2048
Europe	731	83	134	193	70%	134.1 - 134.4 (0.2%)	2078
Russia	445	28	65	225	29%	40 - 65 (40%)	2101
Western United States	568	17	45	160	28%	42 - 49 (14%)	2054
Eastern United States	404	48	82	137	60%	82 - 99 (21%)	2084
Canada	63	3	4	10	45%	4 - 5 (22%)	2030
South Asia	895	15	86			78 - 113 (40%)	2072
Latin America	94	2	22			12 - 24 (53%)	2088
World coal (with mature regions)	6,941	309	680	1,163	58%	653 - 749 (14%)	2070

Table 3. Comparisons between the historical long-term production estimates and reserves for the active regions and the world (WEC, various years, EIA, 2009). The numbers for the Eastern United States are without Pennsylvania anthracite. The ranges for the historical estimates are for the years 1995 through 2009. The calculations for Europe, Russia, Eastern United States, Canada, South Asia, and Latin America are available on line (Rutledge, 2010).

On the bright side, we might avoid the absolutely horrible worst-case scenarios of how our one-time experiment on our atmosphere might turn out...



Sources: Jean-Marc Barnola et al., CD Keeling

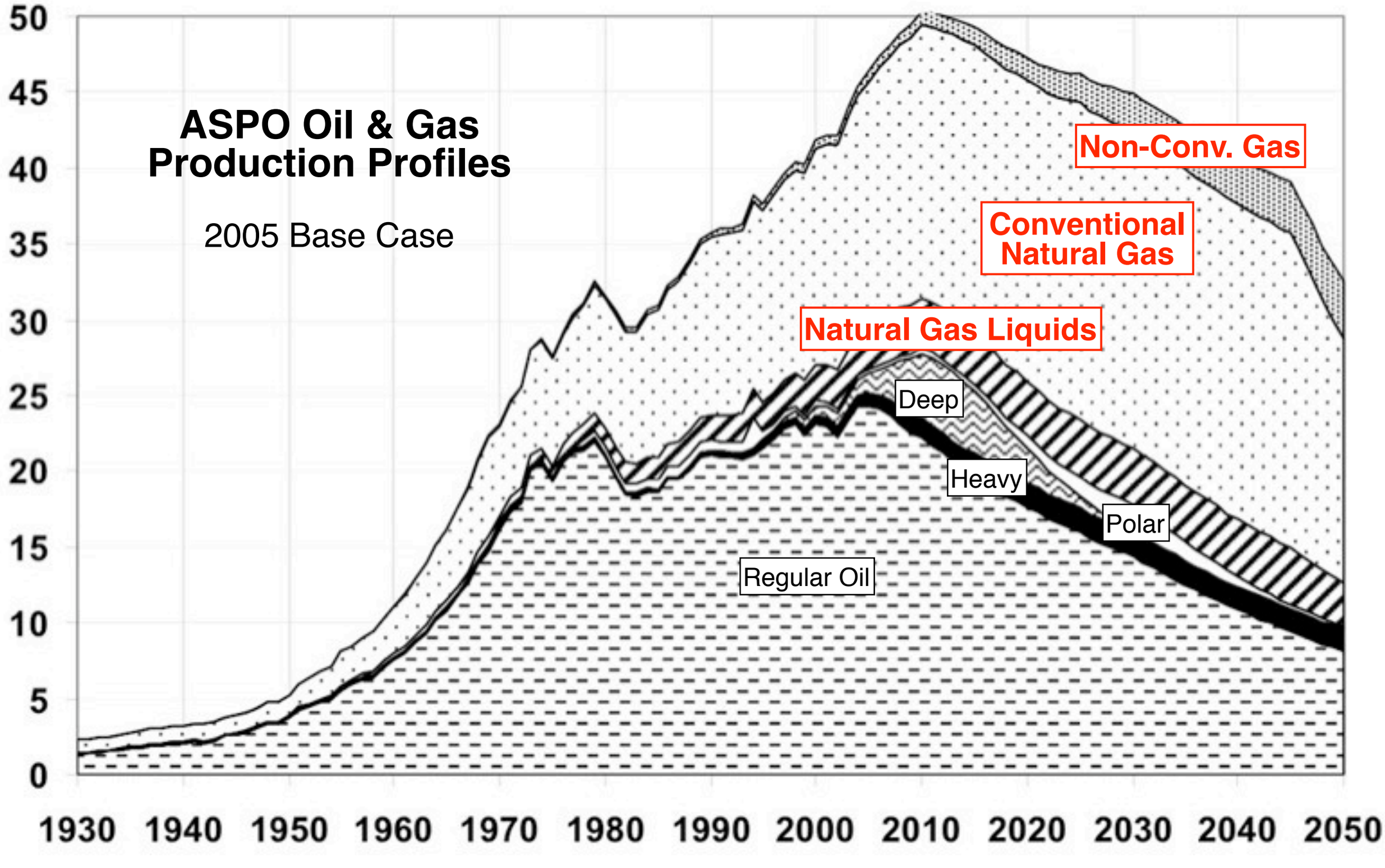
Coal Mining & Burning *(curr: 22% total US energy)*

- burning coal (without carbon sequestration) generates 2X as much CO_2 per unit energy as burning oil or natural gas
- coal-to-liquids and coal gasification generate more CO_2 than burning the coal directly (EROEI<1.0 for both)
- carbon and mercury sequestration requires additional energy and will speed approach to EROEI=1.0
- a large number of new coal electric and coal-to-liquids plants are currently being commissioned and planned, virtually all without sequestration

45,000 ton Krupp earth-mover crossing a highway in Germany en route to an open-pit coal mine

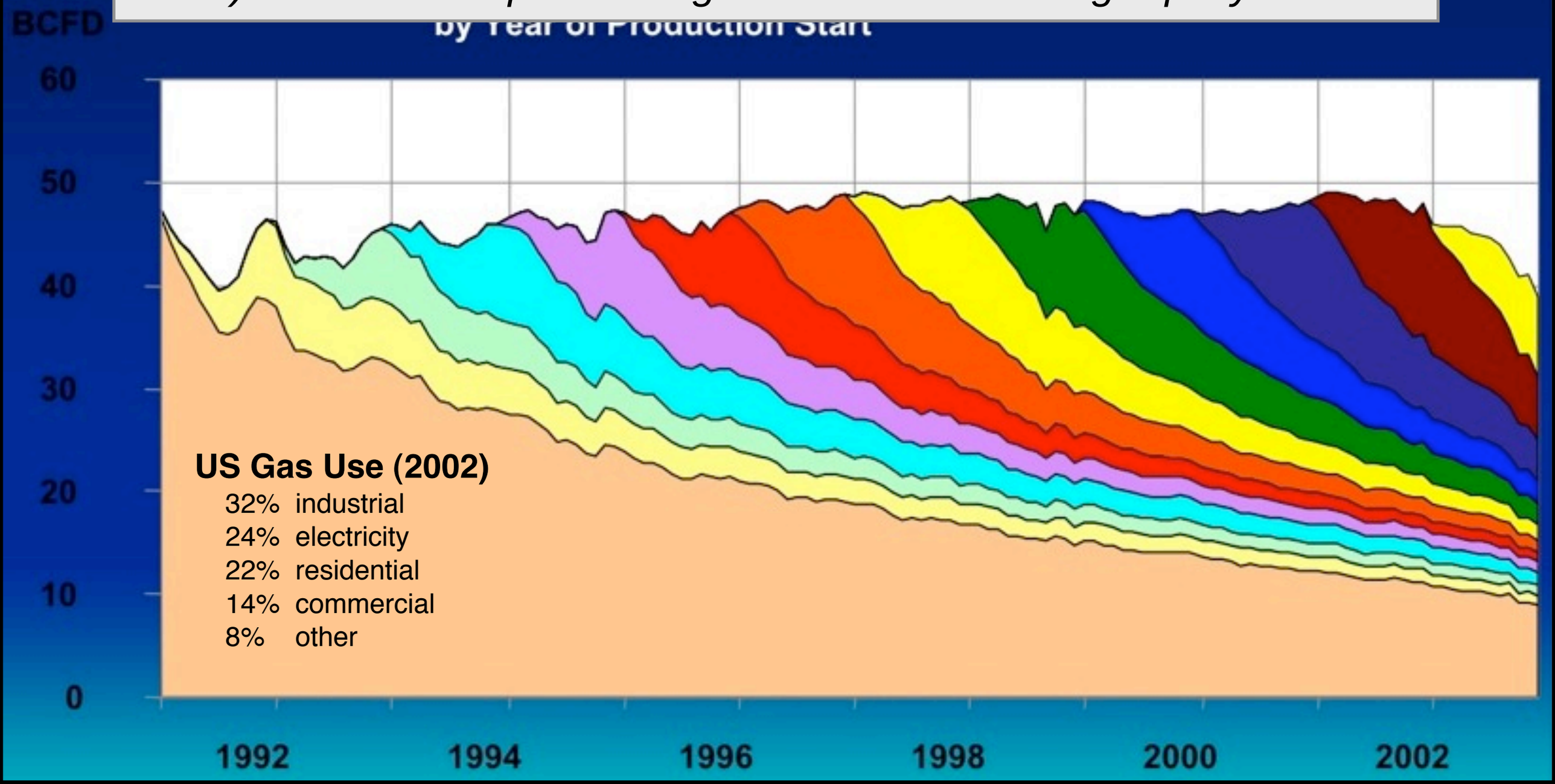
World Gas Production

Total gas peak is later than oil (~2030)
*but **combined** gas+oil peak **around now***



Depletion of US Gas Wells in the Lower 48 States (wet gas by year of start)

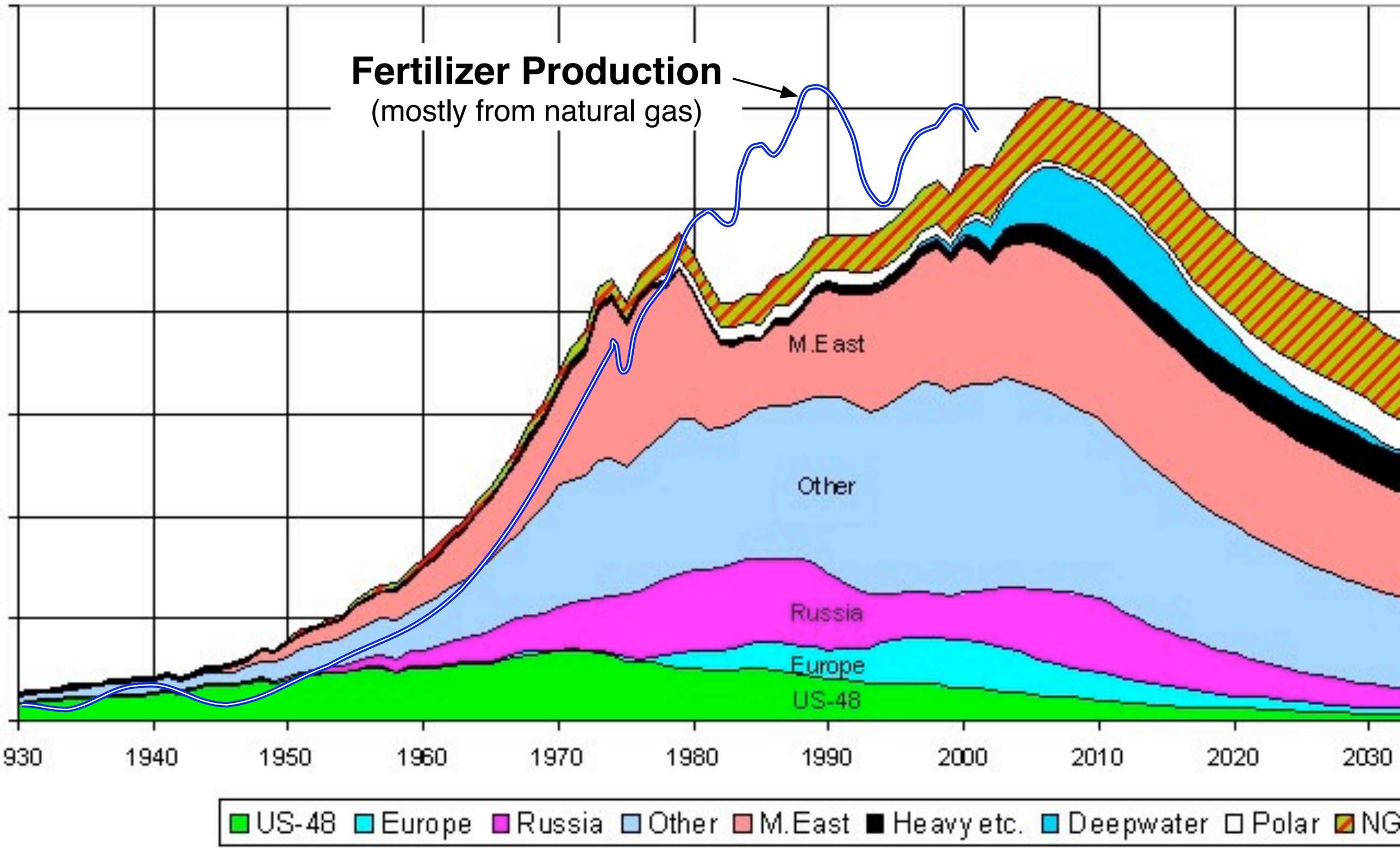
1) gas wells deplete more rapidly than oil wells
2) the rate of depletion of gas wells is increasing rapidly



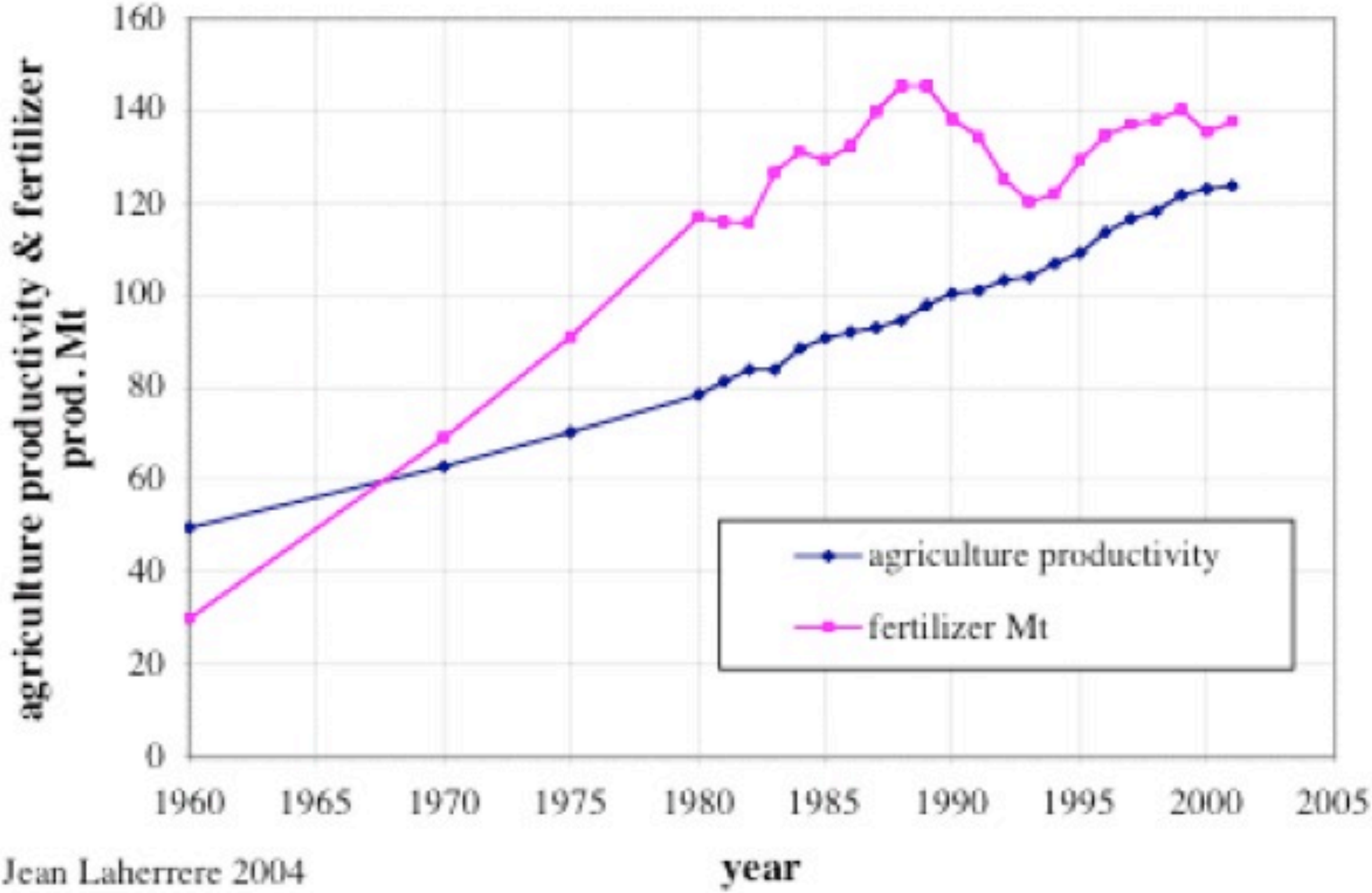
from David Maul

http://www.energy.ca.gov/papers/2004-10-27_MAUL_GASOUTLOOK.PDF

Oil and Natural Gas are Critical to Current World Food Production



World agriculture productivity & fertilizer production



Jean Laherrere 2004

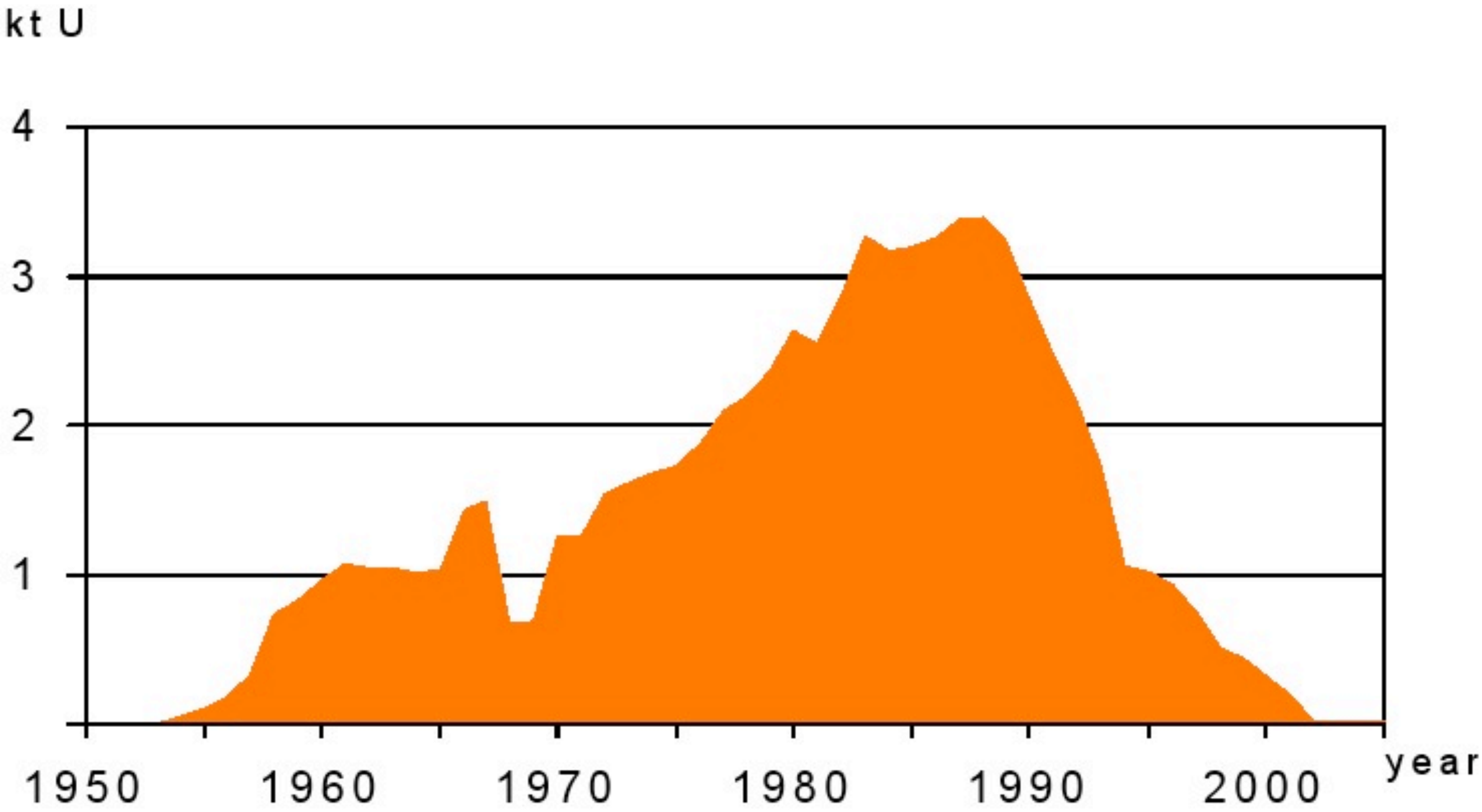
Hydrogen is Not an Energy Source

- more energy used in making hydrogen than you get out of it
- currently made from natural gas (50% loss chemical energy)
- can be made from oil (>50% loss)
- can be made (along with CO) from coal ("town gas": 65% loss)
- compression to 12,000 psi uses additional energy (15% loss)
- energy density still 1/3 that of gasoline (remember Avogadro)
- tanks leak rapidly (H is tiny); unburnt hydrogen greenhouse gas
- 4x as much energy needed to pump hydrogen vs. natural gas
- can be stored as metal hydride, but with 70% loss of energy
- fuel cells use expensive metals and have reliability problems
- **Concl.: hydrogen is a bad choice, even as energy carrier**

Possible Replacements – Nuclear Sources

- ***nuclear fission*** *(currently: 7.5% total US energy)*
  - making fuel is energy-intensive (5% French nuclear electric power used in gas diffusion fuel production step [Eurodif])
  - 1960's EROEI for fissionable uranium < 1.0 (because of weapons diversion and nuclear reactor fuel sales)
  - uranium a non-renewable resource and in scarce supply
  - breeder reactor tech still not viable after 40 yrs (thorium?)
- ***nuclear fusion*** *(currently: 0%)*
  - current test beds demonstrating magnetically confined plasma fusion require ***helium*** for superconducting coils
  - helium comes from oil and gas wells and cannot be made now (though some could be made in a hypothetical continuously running fusion reactor of the future)
  - a practical continuous-energy-generating fusion demo still several decades away (same prediction in 1980!)

Uranium production in France
(produces majority of its electricity from uranium)

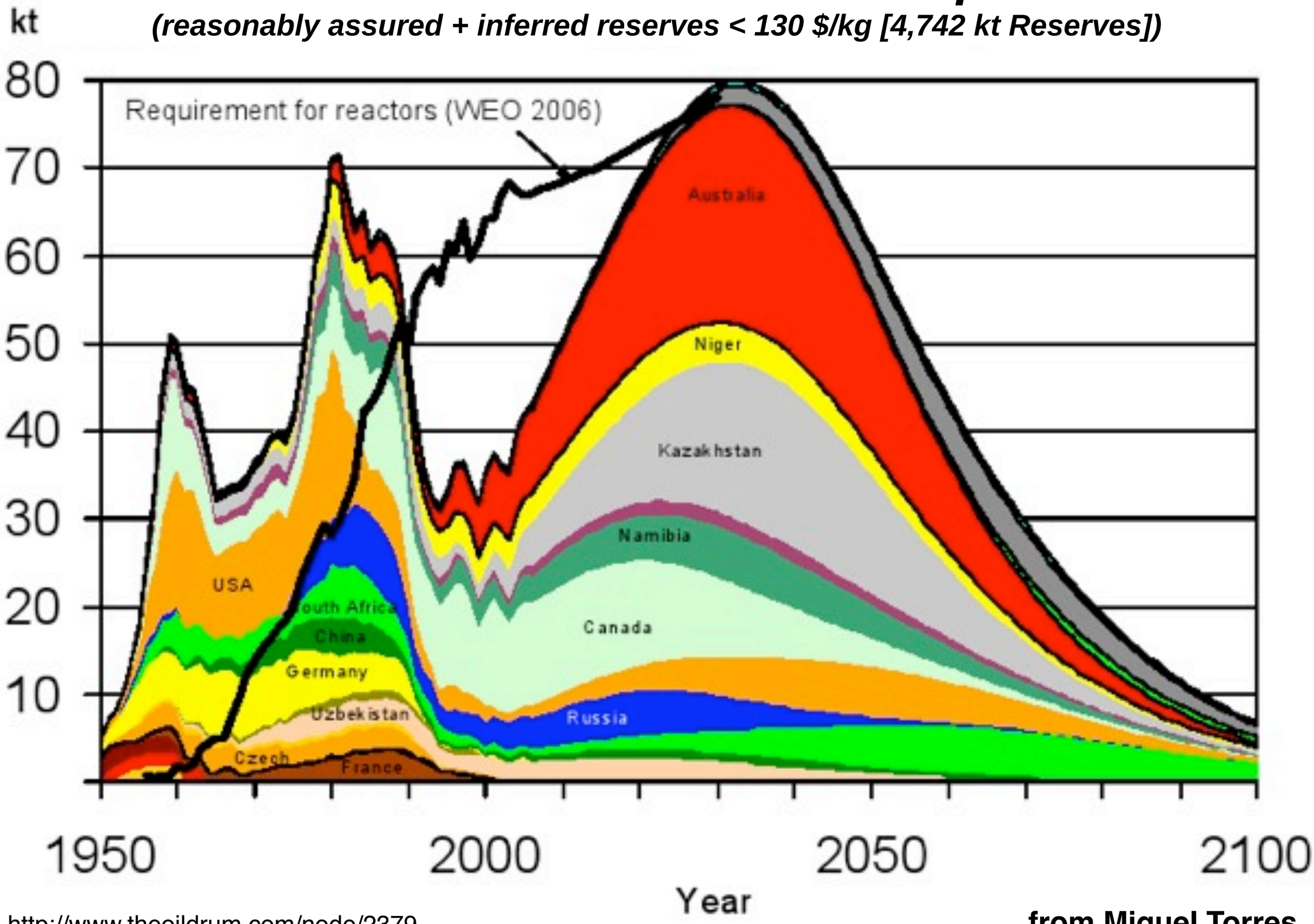


http://www.theoildrum.com/node/2379

from Miquel Torres

World Uranium Production and Requirements

(reasonably assured + inferred reserves < 130 $/kg [4,742 kt Reserves])



http://www.theoildrum.com/node/2379

from Miquel Torres

Possible Replacements – Renewable Sources

- ***hydroelectric*** *(currently: 2.3% total US energy)*
  - – substantially tapped out, few new sites available
- ***wind*** *(currently: 0.07% total energy, 3% Calif. electrical)*
  - – substantial growth possible in windy areas
- ***solar photovoltaic*** *(currently: US 0.01% total, 1% CA electr.)*
  - – costly, large: 20 kWh/day syst. is $50,000 and 500 sq ft
- ***solar heat-concentrating steam/Stirling systems***
  - – possible replacement for centralized power generation
- ***local solar passive heating***
  - – solar water heating systems common in 1900 before gas
- ***tides***
  - – small demo tidal barrage systems have existed for years
- ***solar from space, wires into space, cold fusion***
  - – among other possibilities, none with practical demo

Photovoltaic array capable of (intermittently) generating power used by average European (=1/2 American), in a sunny place!

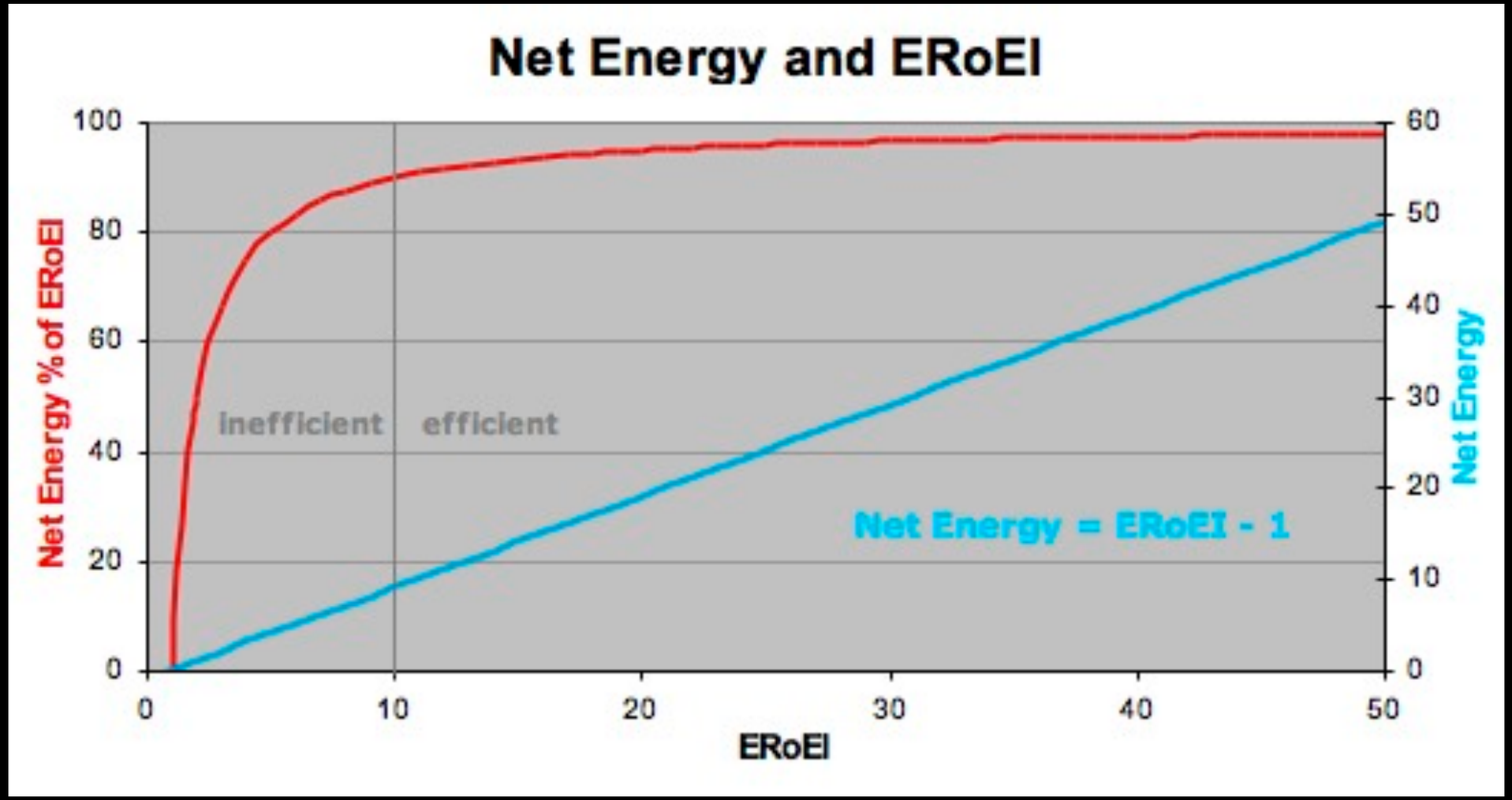
solar conc., 25% efficient
std. 10% efficient => same area

Energy Scavenging/Conversion

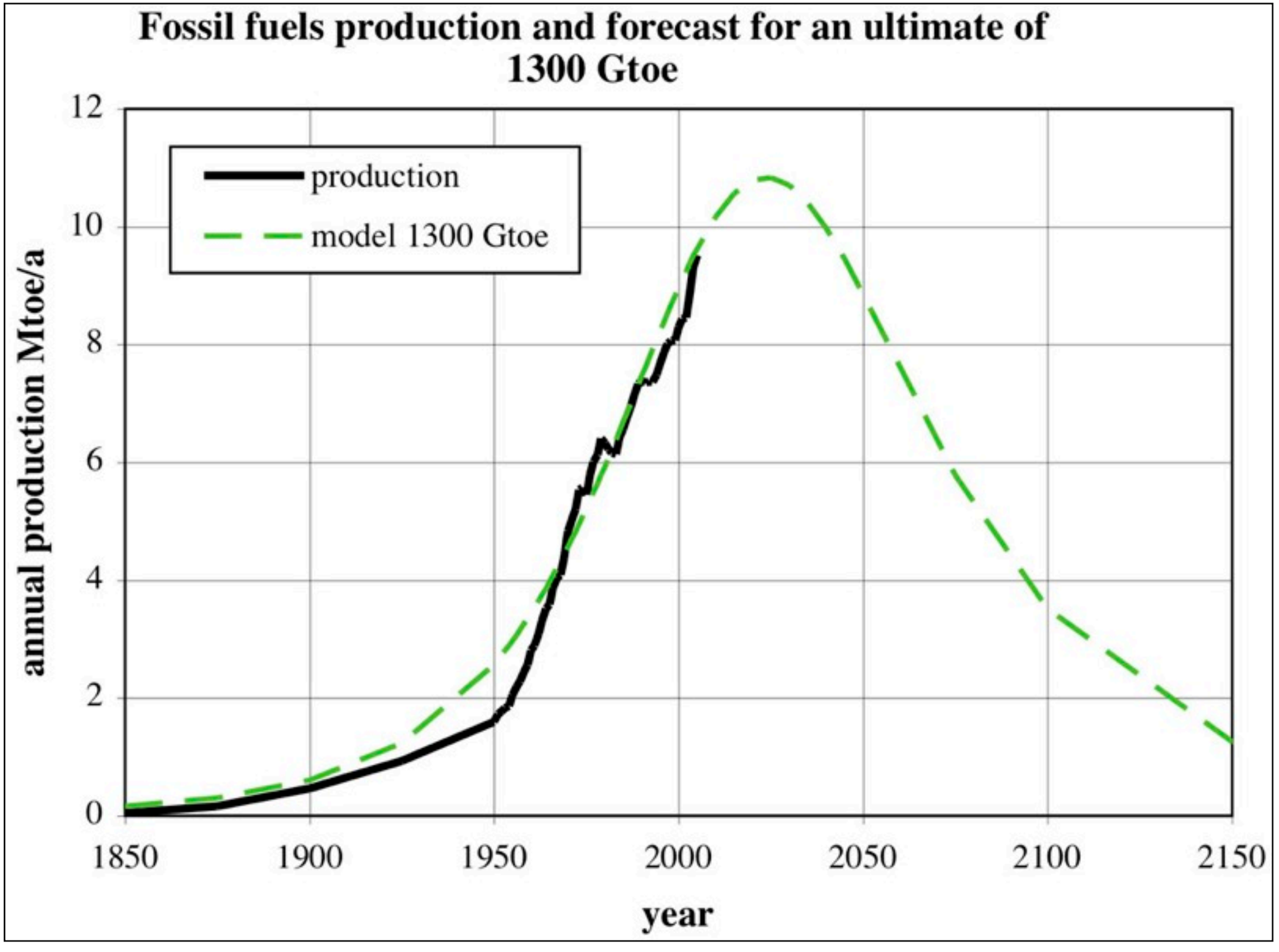
- ***biogas*** (anaerobic digestion of animal manure)
  - in small scale use for decades (esp. the Netherlands)
  - recovers some fossil fuel input to growing food/animals
- ***biodiesel*** (chemically modify plant vegetable oil w/10% alc.)
  - better EROEI and energy density than ethanol
  - water immiscible (no distilling step)
  - biodiesel for UK would require >100% of UK arable land
  - biodiesel for developed world would require all of Africa
- ***thermal depolymerization*** (cook tires, animal tissue waste)
  - currently: US 0.0002% (500 barrels/d vs. 20 million/d used)
  - EROEI < 1.0 (recovers 85% of energy of inputs)
  - can recover part of fossil fuel inputs to tires, chickens
- ***ethanol*** (from fermentation of corn, switchgrass, sugar cane)
  - must be distilled from initial raw water-ethanol mixture
  - distillation step alone uses 40% of energy in final product
  - w/farming, an energy-neutral (EROEI 0.8–1.25) disaster

Real energy sources must have EROEI >5-10

- crude oil (e.g., EROEI=10) means 1 unit of energy expended (e.g., from other oil) to produce 9 units of net energy
- ethanol at EROEI=1.2 means 5 units of energy (e.g., coal and methane) expended to produce 1 unit of net energy
- e.g., start with 1 unit ***net*** oil and 1 unit ***net*** ethanol energy
  --oil: 1=>2 net units requires ***using*** an extra 1/9 energy unit
  --eth.: 1=>2 net units requires ***using*** 5 extra units (extra is 45x!)



Peak Everything



Summary of the Main Difficulties

- total oil used since 1850 – ***about 1000 billion barrels (1 Tb)***
- total world oil reserves left – ***about 1000 billion barrels***
- percent oil currently in use discovered before 1973 – ***70%***
- time left, current world usage (30 billion/year) – ***about 30 years***
- time left, whole world uses oil at US's current rate – ***6 years***
- percent US oil used in food production (*not* including packaging, refrigeration, trucking, cooking) – ***25%***
- physical human work equivalent of energy used to generate US diet for 1 person, 1 day – ***about a month***
- oil in US strategic reserves (< 1 billion) – ***about a month***
- peak ***methane, coal, and uranium*** are closer than you think

Suggestions

- *reduce* oil production/use now (so coming fall less steep)
- expand, electrify rail (4-6x efficient as trucks, cars)
- US: more people rail, UK/EU: more freight rail
- personal transportation by small electric cars, bicycles, carts
- intermittent wind excellent for charging batteries (dual grid)
- better insulation, more solar heating, use heat pumps
- recycle nitrogen, phosphorus, rare earths
- more nuclear
- utilize fossil fuel to construct renewables *while we still can*
- have less kids
- "the market" will not save us:
  - it won't trump geology, it can't change Maxwell's equations, make hydrogen more compressible, make fusion work next year, or contract gracefully
  - it doesn't look far enough into the future (it decided to *disinvest* in renewables from late 80's until 2004!)
  - *it can fail industrial civilization and its human population*
- *time is short*: technological-demographic collapse of Rome, Maya took centuries, but there are *many* more people now

Oil and World Population
(since 1900)

Billions of People

Millions of Barrels Oil/Day

1 2 3 4 5 6 7

0 10 20 30 40 50 60 70 80 90

1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000

Oil and World Population
(last 2000 years)

0 1 2 3

0 200 400 600 800 1000 1200 1400 1600 1800 2000

http://canada.theoildrum.com/node/2516

from Paul Chefurka

Usually not mentioned in polite company

- one entire new UK+ (80,000,000) worth of people are added to the globe every year
- China's draconian one-child policy begun around 1980 slowed population growth to 'just' 300,000,000 more people (another entire US)
- less numerous rich western children consume more total resources than more numerous 3rd world children
- bringing the entire world through a US/EU 'demographic transition' would deplete fossil fuels in 10 years (would not even possible to get them out that fast)
- we should retool human society before Mother Nature does it for us

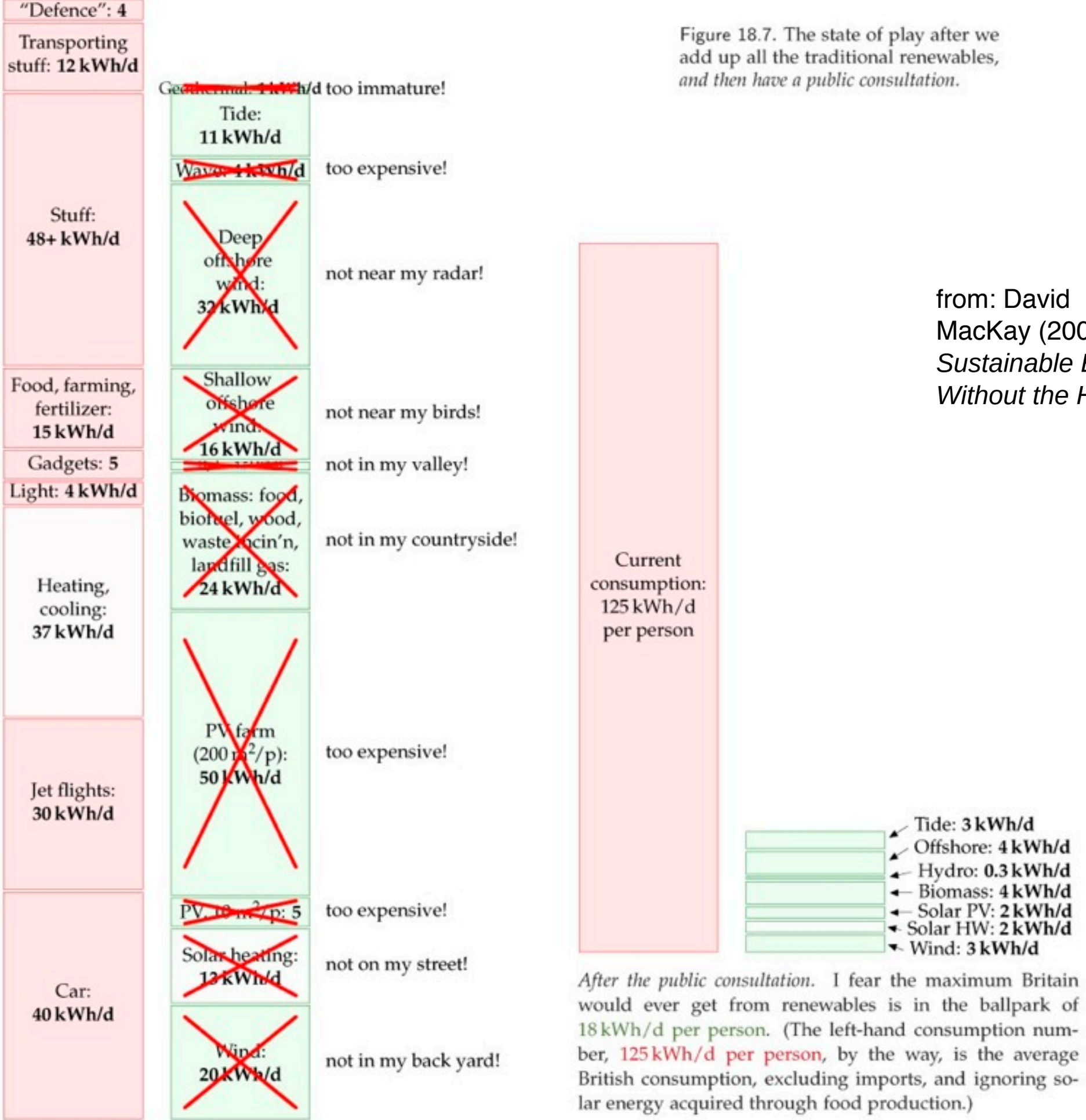


Figure 18.7. The state of play after we add up all the traditional renewables, *and then have a public consultation.*

After the public consultation. I fear the maximum Britain would ever get from renewables is in the ballpark of 18 kWh/d per person. (The left-hand consumption number, 125 kWh/d per person, by the way, is the average British consumption, excluding imports, and ignoring solar energy acquired through food production.)

from: David MacKay (2008) *Sustainable Energy Without the Hot Air*.

plan D	plan N	plan L	plan G	plan E
Clean coal: **16 kWh/d**	Solar in deserts: **20 kWh/d**	Solar in deserts: **16 kWh/d**	Solar in deserts: 7	Nuclear: **44 kWh/d**
Nuclear: **16 kWh/d**	Clean coal: **16 kWh/d**	Clean coal: **16 kWh/d**	Tide: **3.7**	
Tide: **3.7**	Nuclear: **10 kWh/d**	Tide: **3.7**	Wave: 3	
Wave: 2	Tide: **1 kWh/d**	Wave: 2	Hydro: **0.2**	Tide: **0.7**
Hydro: **0.2**	Hydro: **0.2 kWh/d**	Hydro: **0.2**	Waste: **1.1**	Hydro: **0.2**
Waste: **1.1**	Waste: **1.1 kWh/d**	Waste: **1.1**	Pumped heat: **12 kWh/d**	Waste: **1.1**
Pumped heat: **12 kWh/d**	Pumped heat: **12 kWh/d**	Pumped heat: **12 kWh/d**	Wood: **5 kWh/d**	Pumped heat: **12 kWh/d**
Wood: **5 kWh/d**	Wood: **5 kWh/d**	Wood: **5 kWh/d**	Solar HW: **1**	Wood: **5 kWh/d**
Solar HW: **1**	Solar HW: **1 kWh/d**	Solar HW: **1**	Biofuels: **2**	Solar HW: **1**
Biofuels: **2**	Biofuels: **2 kWh/d**	Biofuels: **2**	PV: **3**	Biofuels: **2**
PV: **3 kWh/d**	Wind: **2 kWh/d**	PV: **3**	Wind: **32**	Wind: **4**
Wind: **8 kWh/d**		Wind: **8**		

from: David MacKay (2008) *Sustainable Energy Without the Hot Air*

Recycling

Car pool

Train pool

Bicycle Trailer

Innovative Method for Transport of Stolen Methane