Fossil Fuels

Petroleum (rock oil), natural gas and coal have fueled the Industrial Revolution.

Exemplified by energy use in US — more than 50% from burning wood a century and a half ago

time of US Civil War

Now 90% from fossil fuels.

Questions:

(1) where do fossil fuels come from?

(2) when will we run out?

(3) environmental consequences of fossil fuel consumption

The source of oil is buried organic matter, mostly the remains of microscopic phytoplankton (algae)

70 GtC/yr is pre-industrial rate

Modern rate is ~ 90 GtC/yr

Photosynthesis of these microscopic plants fixes about 90 Gt of C per year (IPCC '94)

Holland & Petersen say 40–80 Gt/yr.

↑ phyto — Greek for plant

Phytoplankton are the bottom of the food chain in the ocean.

$$CO_2 + H_2O \xrightarrow{\text{sun}} \underset{\substack{\text{phytoplankton}\\\text{organic matter}}}{CH_2O} + O_2$$

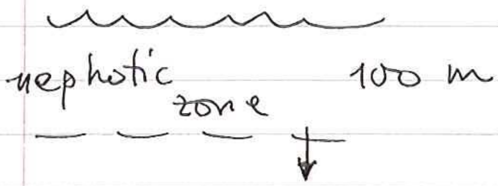
They are grazed & metabolized by a host of other organisms up to fish & whales.

All oceanic photosynthesis occurs in the upper 100 m of the ocean, where there is light.

0.2 Gt/yr

All but 0.1 – 0.2% of the organic C is consumed by other organisms.

Only 7–10% sinks to below 100 m



Oceanic NPP highly heterogeneous, needs nutrients (upwelling or streams)

7–10% fall to bottom – there most are eaten by bottom-dwelling organisms.

Sarmiento says 0.2 GtC/yr now accepted burial rate

Only 0.2 Gt of organic carbon (protein molecules, etc.) are <u>buried</u>. This 0.2 Gt of organic C / yr is the source of all oil & gas.

The amount buried depends on the flux into the sediments and on the fraction buried (the <u>burial</u> <u>efficiency</u>)

The flux is high in regions of high productivity, favoring coastal areas where rivers bring in nutrients needed for growth (fertilizers — phosphates & nitrates)

The burial efficiency depends on the sedimentation rate — fast rates favor burial (bury it before it gets eaten)

Burial rates very low in deep ocean. High on shelves in delta settings where sedimentation rates are high

Efficiency peaks at 20% – 30% for sedimentation rates exceeding [redacted]

[redacted]

burial efficiency is measured using sediment traps

1 m / 1000 yrs = 1 km / Myr very high

Rivers transport ~ [redacted] $2 \cdot 10^{13}$ kg of sediment per yr to the oceans

20 Gt seds/yr

The average organic content of [redacted] shales ~~deposited on continental~~ [redacted] should thus be

$$\boxed{\frac{0.2 \text{ Gt C/yr}}{20 \text{ Gt seds/yr}} \approx 1\%}$$

— average for all oceanic shales

↑ organic C — not C in $CaCO_3$

The range is high from $\overset{\text{deep-ocean}}{\uparrow}$ < 0.05 %
to > 5 %
↑ near-shore settings

<u>The average is indeed</u> 1 %.

Organic-rich (> 5 % organic C)
are <u>oil source rocks</u>.

Once the organic compounds are buried they can no longer be oxidized

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

No oxygen.

Bacteria can, however, consume them via reaction (in <u>simplified form</u>)

anerobic bacteria

$$2\,CH_2O \xrightarrow{\text{bacteria}} CH_4 + CO_2$$ biogenic methane

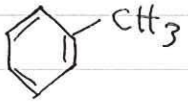
At greater depths and temperatures between 100°C – 200°C a complex set of reactions breaks the organic matter down into petroleum

~~The organic material prior to cooking is called kerogen~~

Petroleum consists of:

saturated hydrocarbons

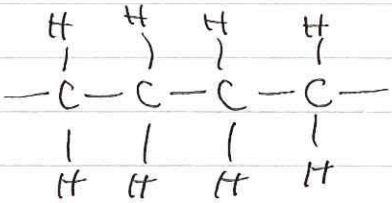
aromatic hydrocarbons



Details depend on the "cooking" history

asphaltenes

Mostly just



$$\begin{array}{ccccccccc} & H & & H & & H & & H & \\ & | & & | & & | & & | & \\ - & C & - & C & - & C & - & C & - \\ & | & & | & & | & & | & \\ & H & & H & & H & & H & \end{array}$$

Typical number of carbons per molecule
5 – 40.

The late stages of this breakdown process yield natural gas, mostly methane CH_4

Then ultimately graphite

The process is akin to baking a cake.

or grilling a steak

Everything must be just right to get petroleum. Not enough cooking — left with kerogen a waxy substance — much larger molecules

kerogen is what is found in ~~shale~~ oil shale — in addition to oil which cannot flow because of impermeability

120°C is optimum

The oil window 60° – 200°

Depths 2–7 km

The biogenic (bacterially produced) methane in the upper 1 km is mostly expelled by compaction of the sediment – expulsion of H_2O & reduction of pore space

Oil can remain in the source rocks "oil shales" or it can be mobilized into more permeable (sandier) formations.

There they can migrate – driven by buoyancy forces – oil floats on water

Much escapes in oil seeps such as the La Brea tar pits.

Tar has been used for centuries. Genesis – Noah caulked the arc with tar.

Collects in a wide variety of "traps"

← Wyoming – Montana border

Example: Elk Basin, studied in the lab – one of largest oil fields in US.

Madison formation

~~Talk about this on page 10 instead~~

Excellent book on the history of oil exploration — many colorful — characters

<u>The Prize</u> — Daniel Yergin 1991

First oil well — Drake's Folly
1861 Titusville, PA

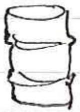
A few years later, hundreds of wells.

Many large oil fields in Middle East — though none in Israel, where Moses led the Israelites after wandering 40 years in the wilderness.

700 out of 2000 billion barrels of oil left in ground in Middle East: Saudi Arabia, Kuwait, Iran, Iraq

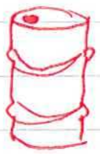
Burgan structure in Kuwait — a gently dipping anticlinal trap — second largest oil field in world

72 billion barrels



72 bbo

1 barrel = 1 bo [illegible] = 42 gallons



= 159 liters = 0.137 tons (metric)

1 bbo = 1 billion barrels of oil

Largest is in Siberia — a giant doubly plunging anticline 150 km long.

Most oil is relatively young rocks ← a few million years old

The longer it's been around, the more chance to escape

Current exploration in the US in the Gulf Coast — deep water.

Much oil associated with <u>salt diapirs</u>

KING COAL

<u>Coal</u> <u>formation</u> — <u>coal</u> is formed from large plant material that grows in swamps, often in slowly sinking coastal areas.

Trees, bushes & grass. Can be buried with very little oxidation
Some methane formed in freshwater swamps by

$$2CH_2O \xrightarrow[\text{bacteria}]{} CH_4 + CO_2$$

↑ hence "swamp gas"

With increasing burial, volatiles are removed

Main reaction is <u>dewatering</u>

$$CH_2O \rightarrow \underset{\uparrow \text{graphite}}{C} + H_2O$$

% C goes up & % H + % O go down.

Best coal — anthracite — is ~ 90% C
graphite

Coal formed in brackish swamps is high in H_2S due to the reaction (before burial)

$$2CH_2O + SO_4^{2-} \xrightarrow{\text{anerobic bacteria}} 2HCO_3^- + H_2S$$

sulfate in seawater

the hydrogen sulfide then reacts with Fe to form pyrite FeS_2

Such coal is "high sulfur"

Produces SO_2 sulfur dioxide "acid rain" upon combustion.

Land plants first appeared 450 my ago
Coal has formed continuously ever since

Two peak periods of coal (i.e. swamp) formation

ferns (gymnosperms) Carboniferous & Permian : 360 – 245 my
swampland much more extensive

Cretaceous : 144 – 66 my
angiosperms (flowering plants ~ today's swamps)

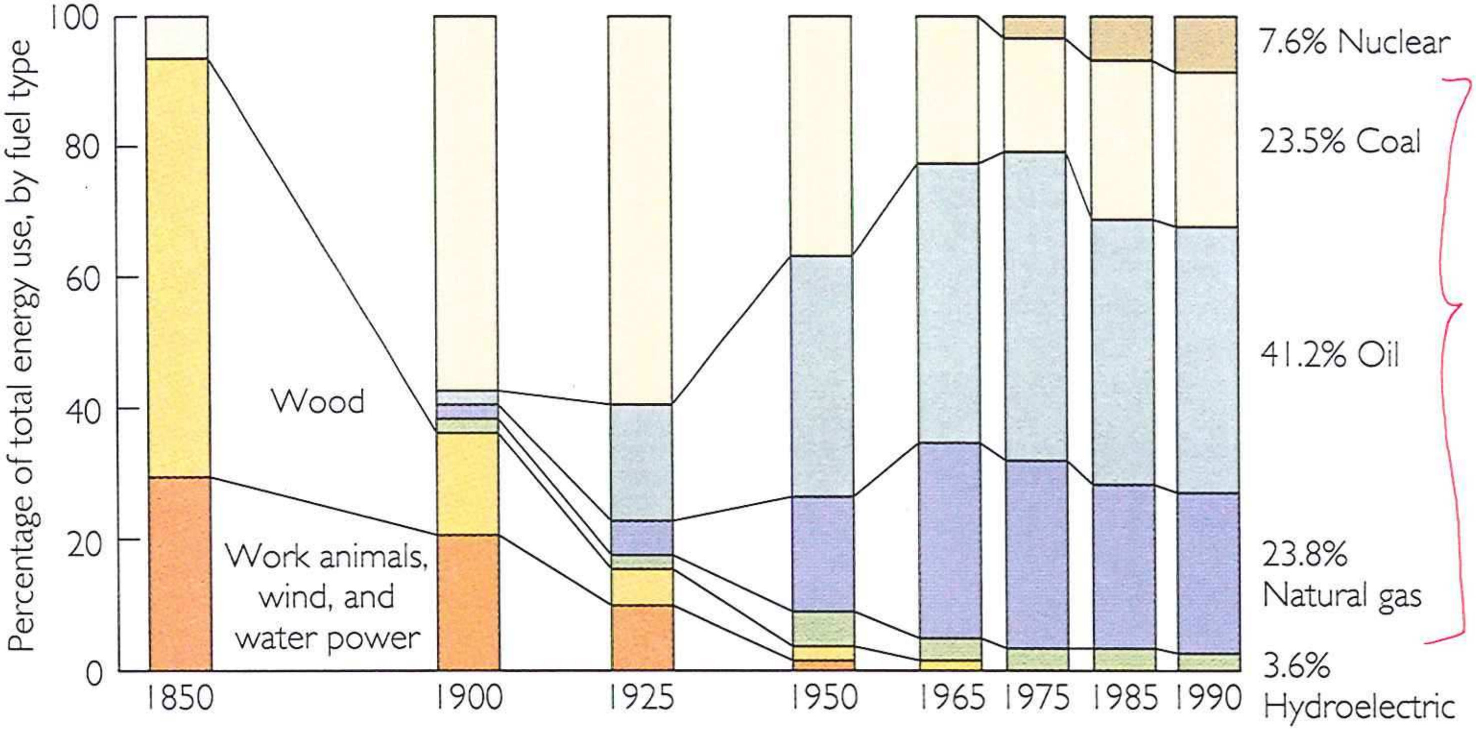


FIGURE 22.3 Percentages of various types of energy used in the United States from 1850 to 1990. (Data from U.S. Energy Information Agency, 1991.)

US 89% fossil fuel

post-industrial
92 GtC/yr
fixed
by phyto-
plankton

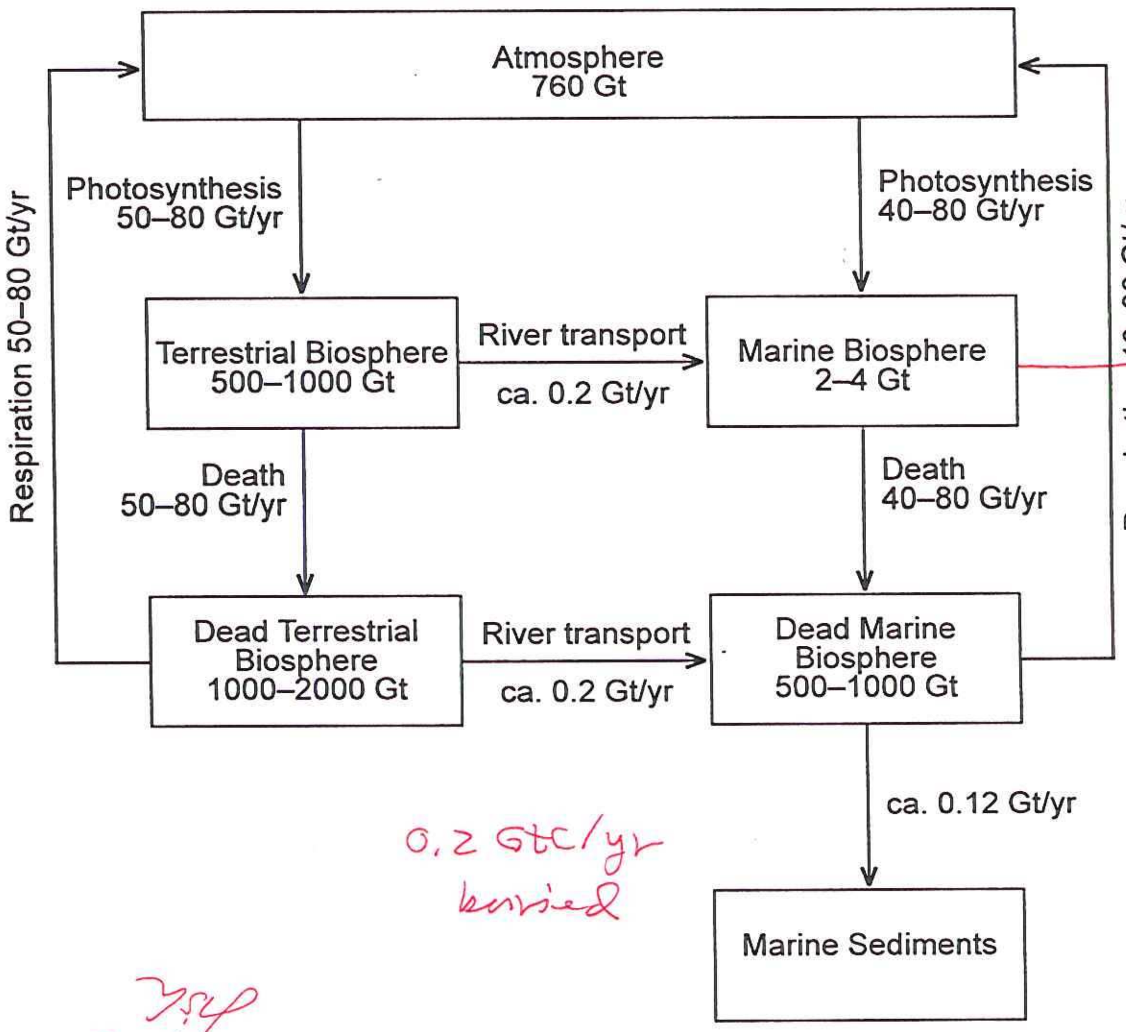


Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)

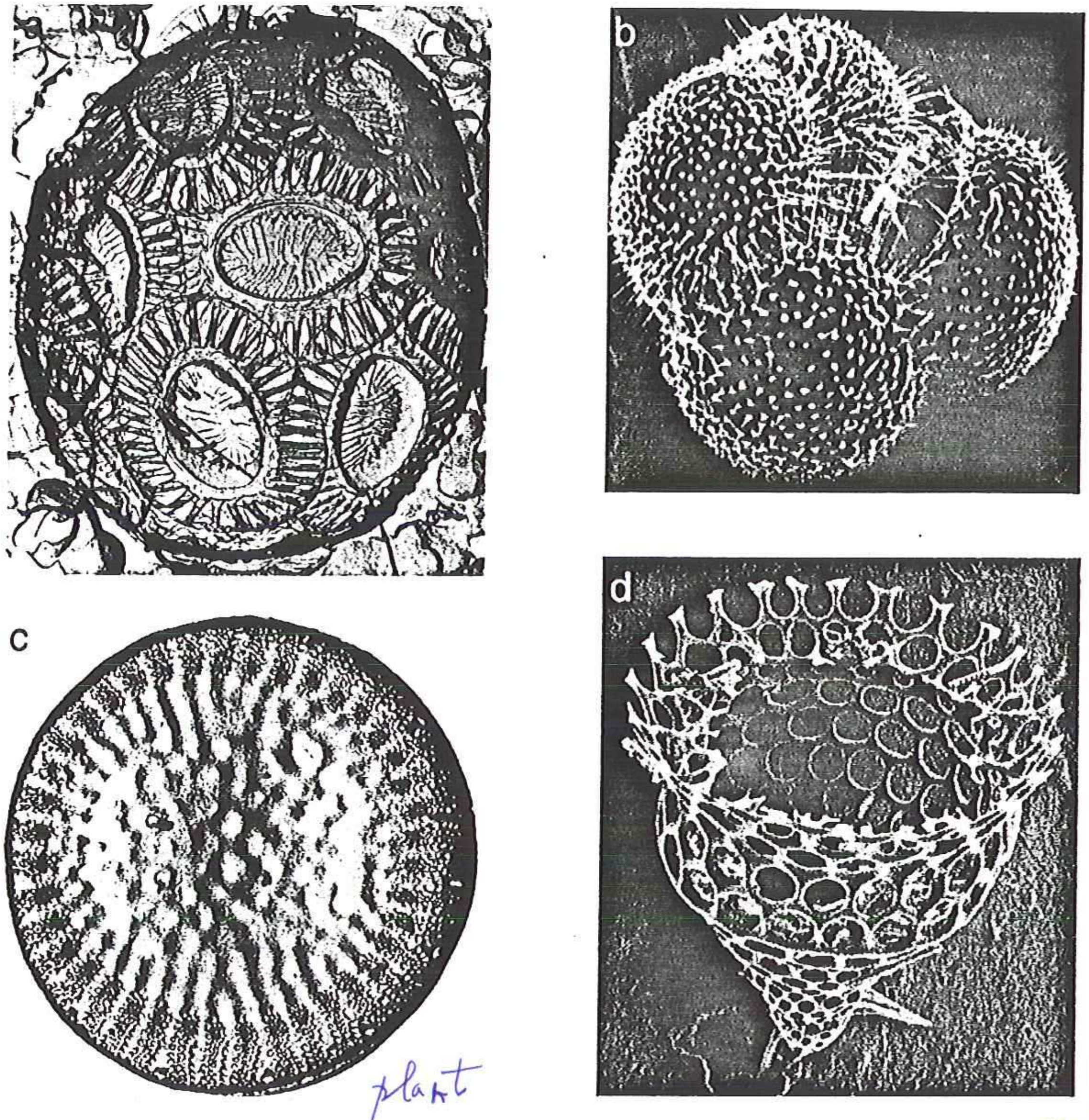
0.2 GtC/yr
buried

phytoplankton live in upper
100 m of ocean

note—trees are
heavier than
fish

plant

animal



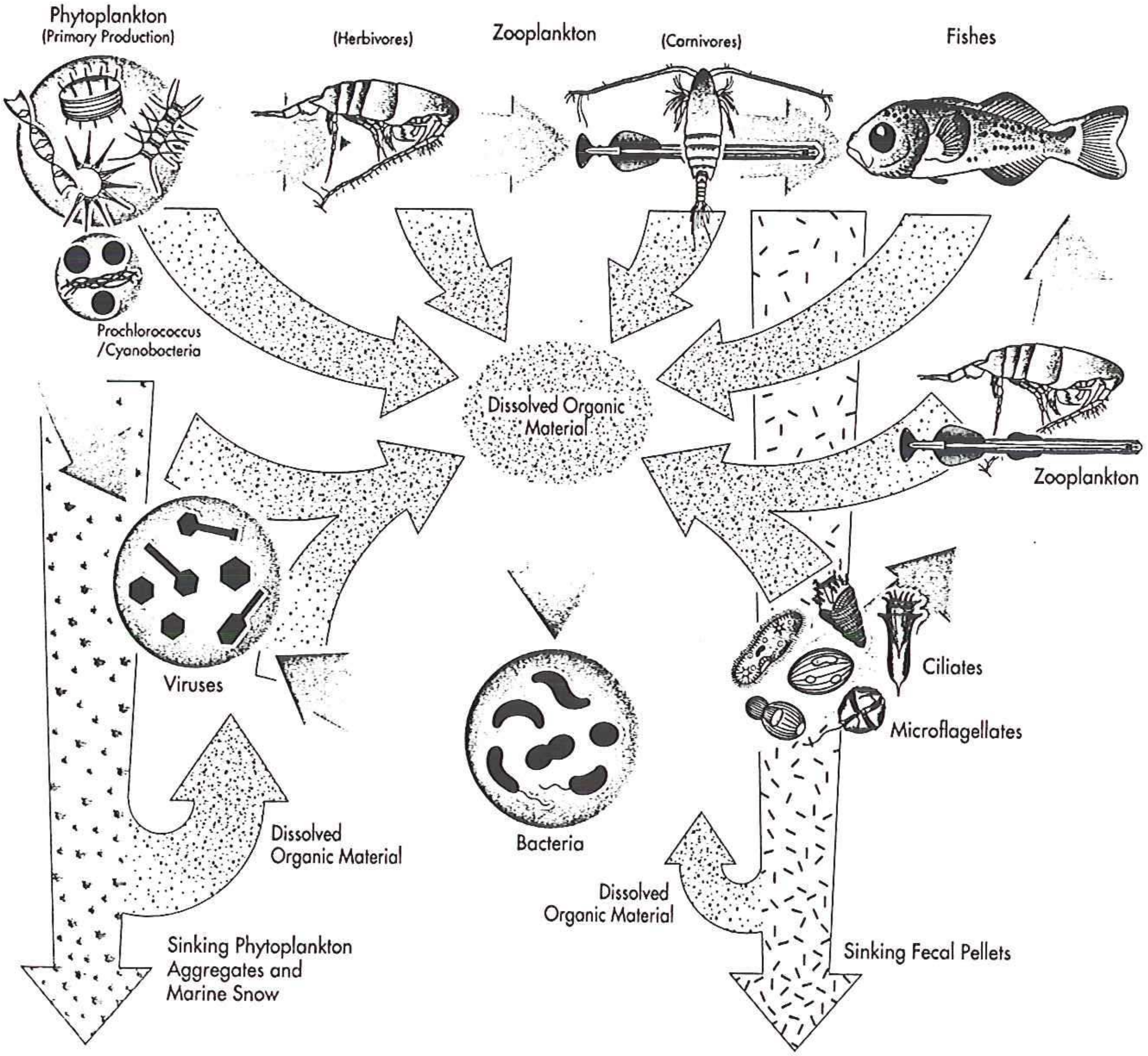
plant

animal

FIGURE 7–2 Planktonic organisms. Coccoliths (a) and foraminifera (b) deposit calcium carbonate tests. Diatoms (c) and radiolaria (d) deposit silica tests. The sizes range from 0.5 millimeters down. (Photos courtesy of A. McIntyre, E. Thomas, P. E. Hargraves and C. McClintock.)

The Marine Food Web:

This illustration shows the importance of bacteria in the marine food web. Phytoplankton convert carbon dioxide into organic material through photosynthesis. They are the primary food source and suppliers of carbon to the food web. Though it was long believed that the dominant pathway in the food web proceeded from phytoplankton to fishes, (left to right along the top) it is now well established that a major flux of carbon to bacteria also occurs through the pool of dissolved organic material. Bacteria are a critical link in returning some of this material back into the food web through a pathway known as the microbial loop (arrows to the right from bacteria). Bacteria may also be killed by viruses (arrow to the left) with much of their carbon returning to the dissolved organic material. As bacteria consume the dissolved material, they also release nutrients that facilitate the growth of phytoplankton. In another important role, bacteria not only consume dissolved organic material, they also further break it down with enzymes. Sinking aggregates and fecal pellets are the essential source of food for life in the dark depths of the ocean; however, they strip nutrients from the surface waters. By quickly dissolving some of these particles, bacteria help to keep nutrients in the upper layers of the ocean. In turn, these nutrients can be used by phytoplankton to create more food for the web. Without these salvage and recycling activities, the ocean would quickly become a vast desert.



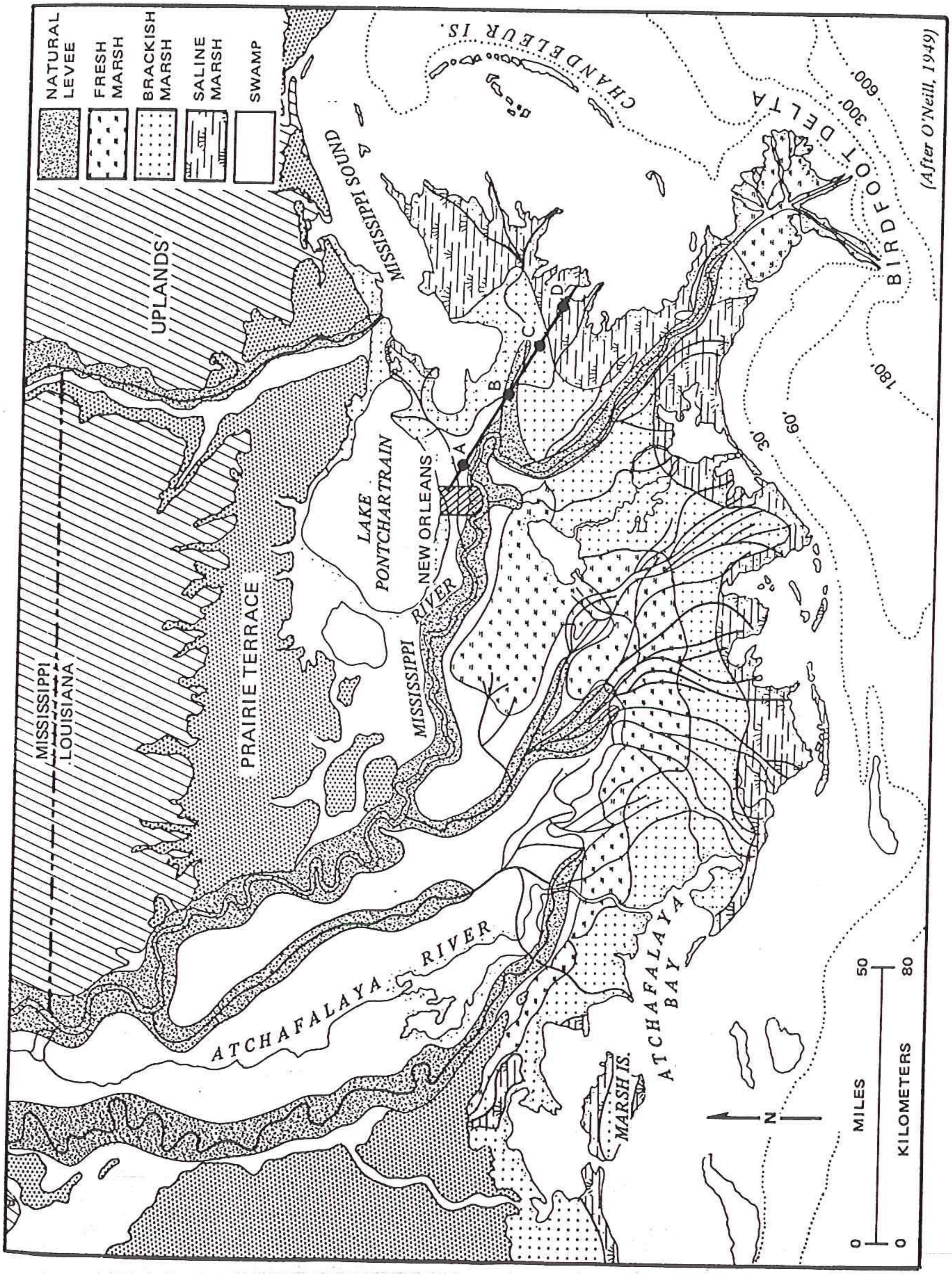


FIG. 8.—Distribution of swamp and marsh environments on Mississippi deltaic plain.

more than 100 km of sediment in less than 100 Myr
sedimentation rate exceeds 0.1 km/Myr

Evolution of the northern Gulf of Mexico

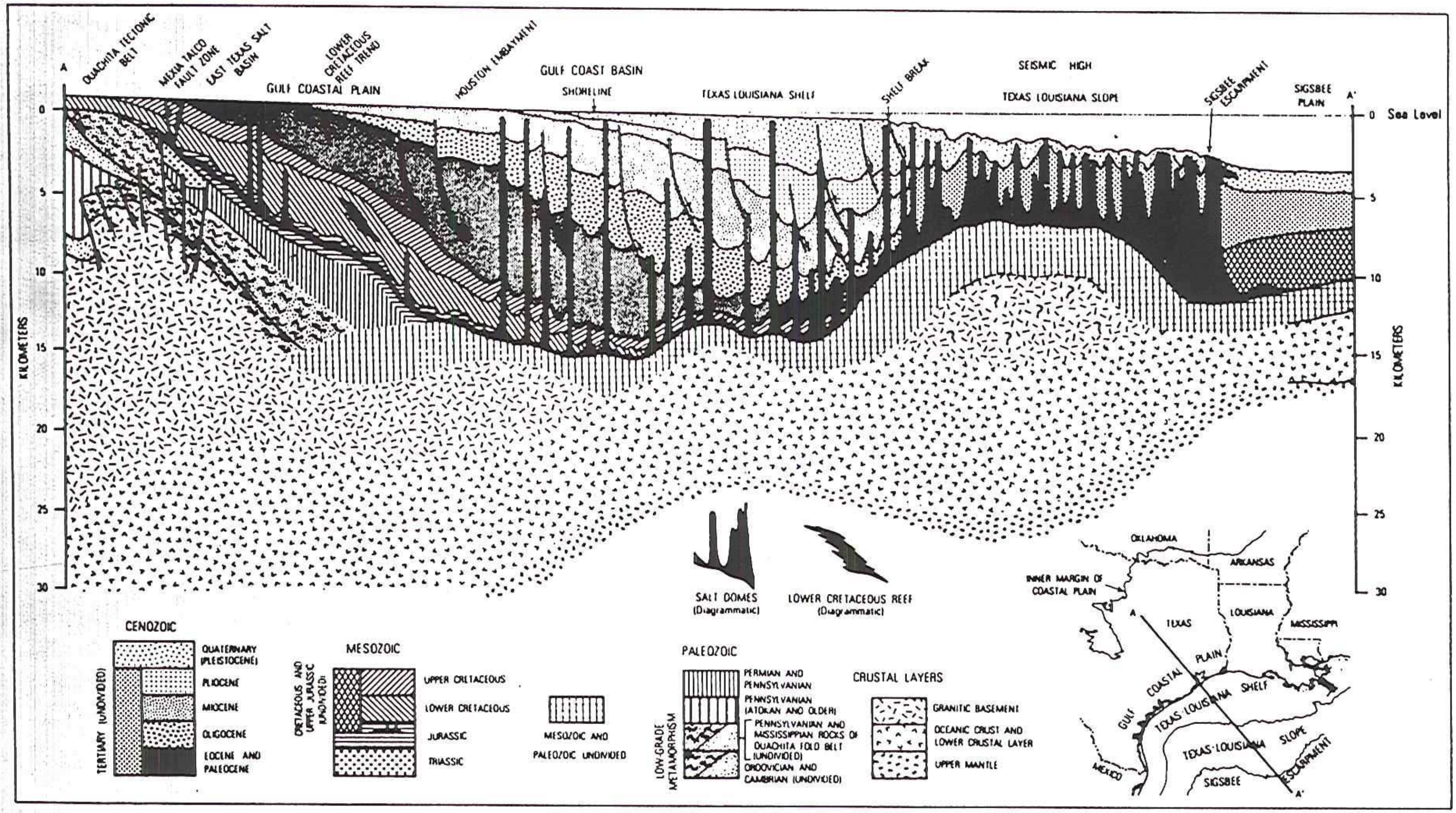


Figure 12. Generalized cross section of the northern Gulf of Mexico margin (from R. G. Martin, 1978, modified from earlier interpretations of Lehner, 1969; Dorman and others; 1972, Antoine and others, 1974; and Martin and Case, 1975).

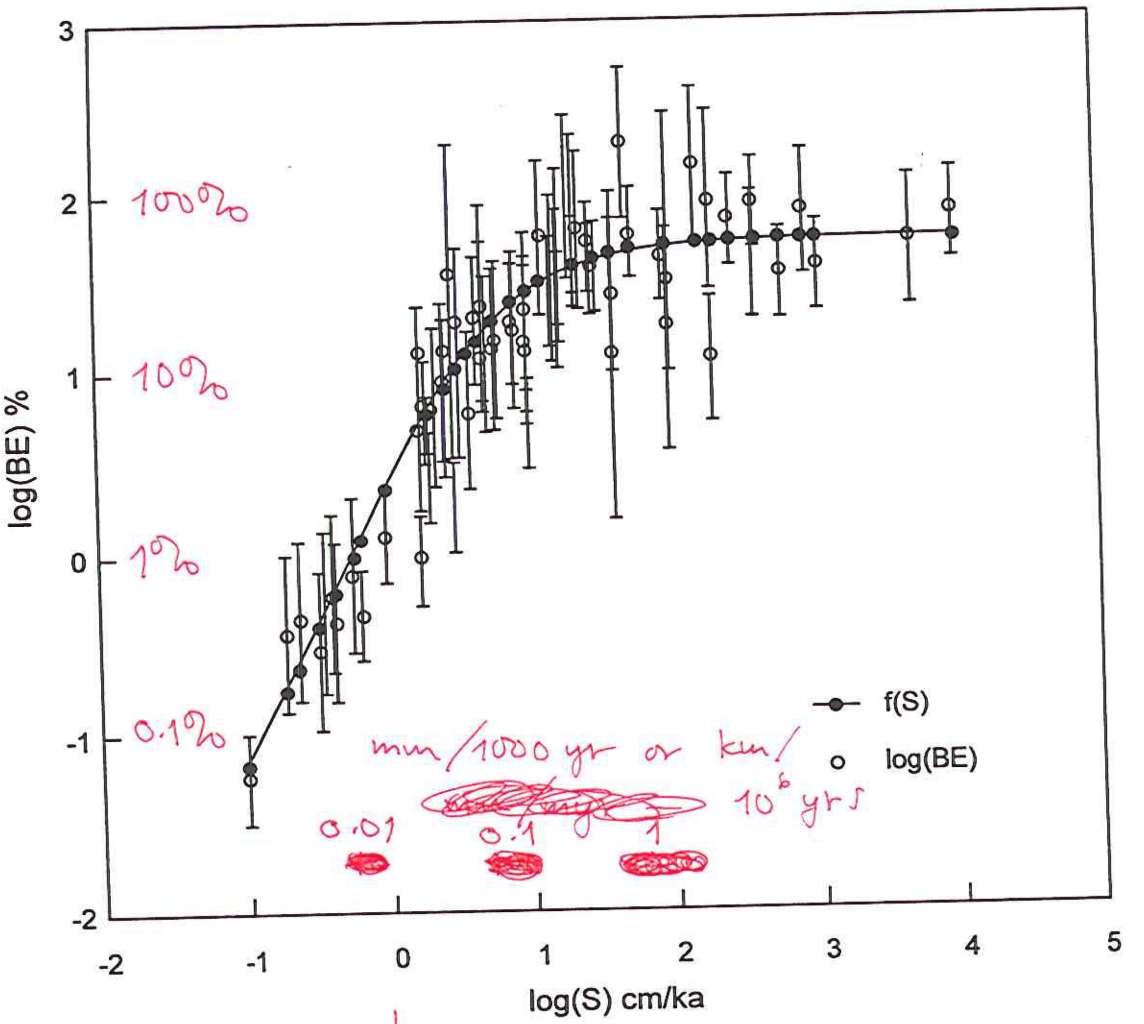


Figure 7.8. Plot of the burial efficiency, BE, of organic carbon with marine sediments vs. the sedimentation rate (S), in centimeters per 1,000 years. (Betts and Holland 1991)

these are fast sedimentation rates

TABLE 5.2 Suspended Sediment Carried by Rivers to the Ocean (in Metric Tons)

Continent	Drainage Area Contributing Sediment to Ocean (10^6 km^2)	Sediment Discharge (10^6 tons/yr)	Sediment Yield (tons/km^2/yr)	Mean Continental Elevation (km)
North America	15.4	1020	66	0.72
Central America[a]	2.1	442	210	—
South America	17.9	1788	97	0.59
Europe	4.61	230	50	0.34
Eurasian Arctic	11.17	84	8	~0.2
Asia	16.88	6349	380	0.96
Africa	15.34	530	35	0.75
Australia	2.2	62	28	0.34
Pacific & Indian Ocean Islands[b]	3.0	9000[c]	3000[c]	~1.0
World total	88.6	20,000[d]	226[d]	

[a] Includes Mexico.

[b] Japan, Indonesia, Taiwan, Phillipines, New Guinea, and New Zealand (Oceania).

[c] From Milliman and Syvitski (1992).

[d] From Milliman and Syvitski (1992). Data reflect greater sediment discharge from South America, the Alps-Caucusus Mountains, and northwest Africa, in addition to Oceania.

Sources: After Milliman and Meade (1983) and Milliman and Syvitski (1992), elevations from Fairbridge (1968).

2 Gt seds per year

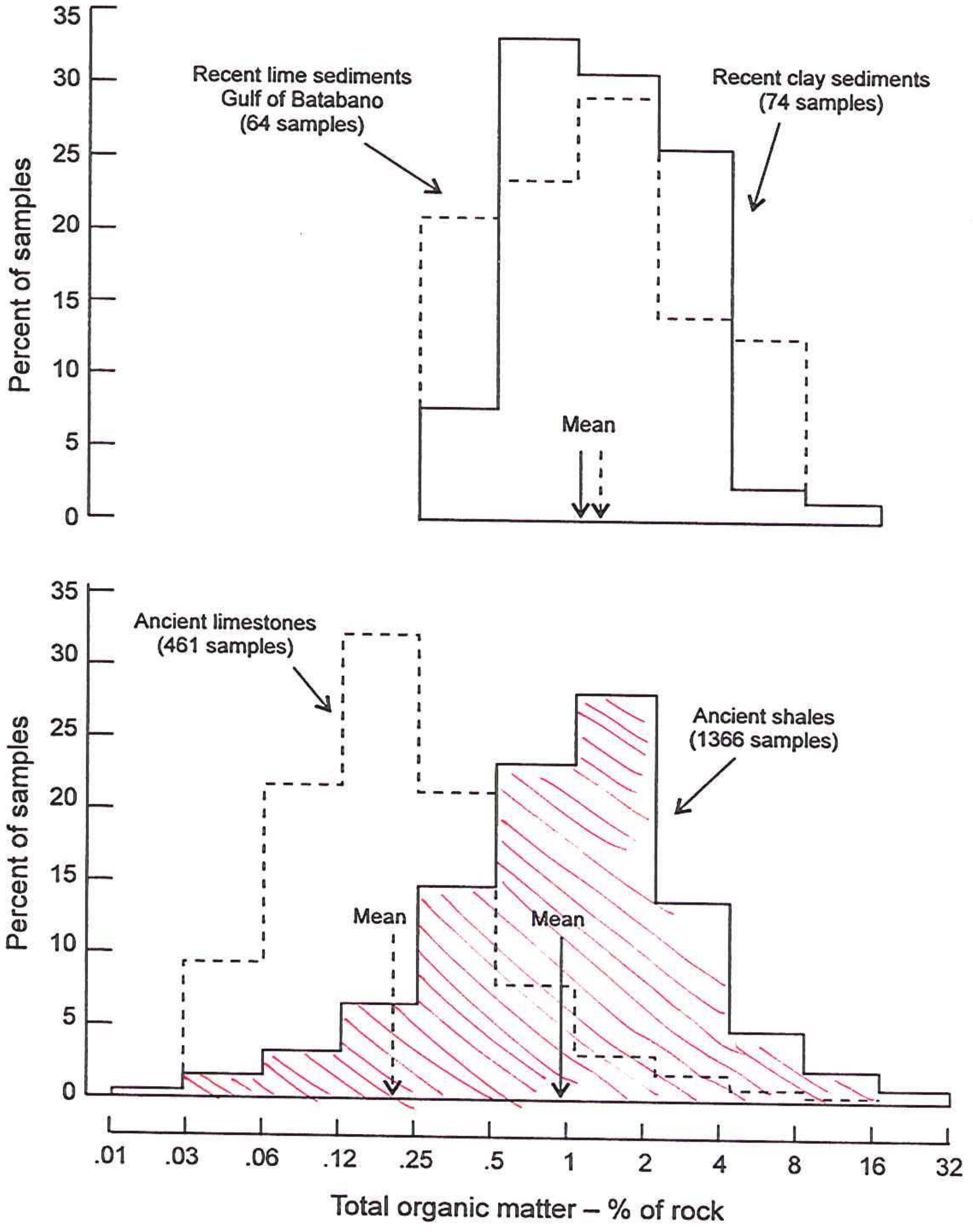


Figure 7.9. The total organic carbon content of recent and ancient limestones and shales. (Gehman 1962)

$2CH_2O \xrightarrow{\text{bacteria}} CH_4 + CO_2$

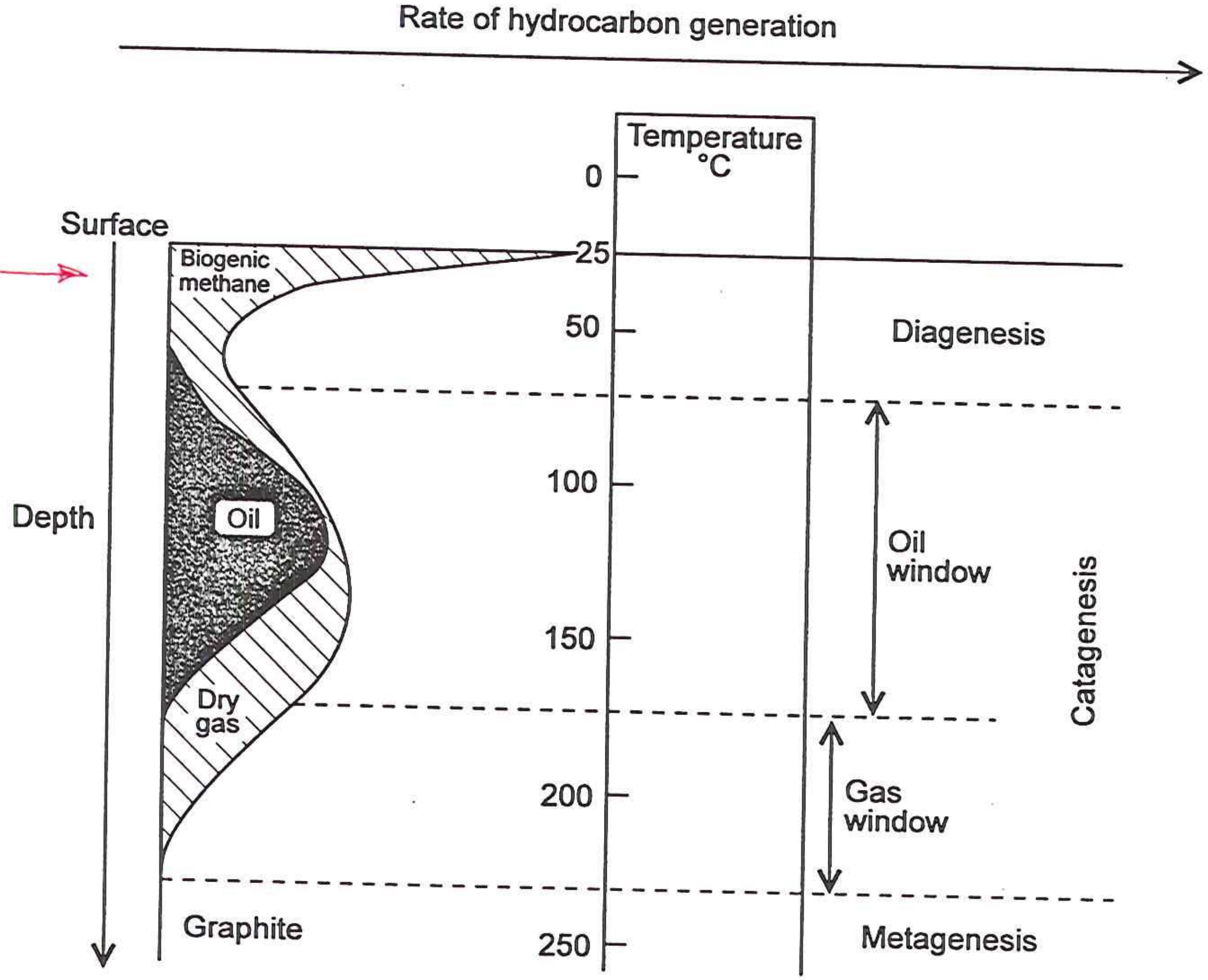
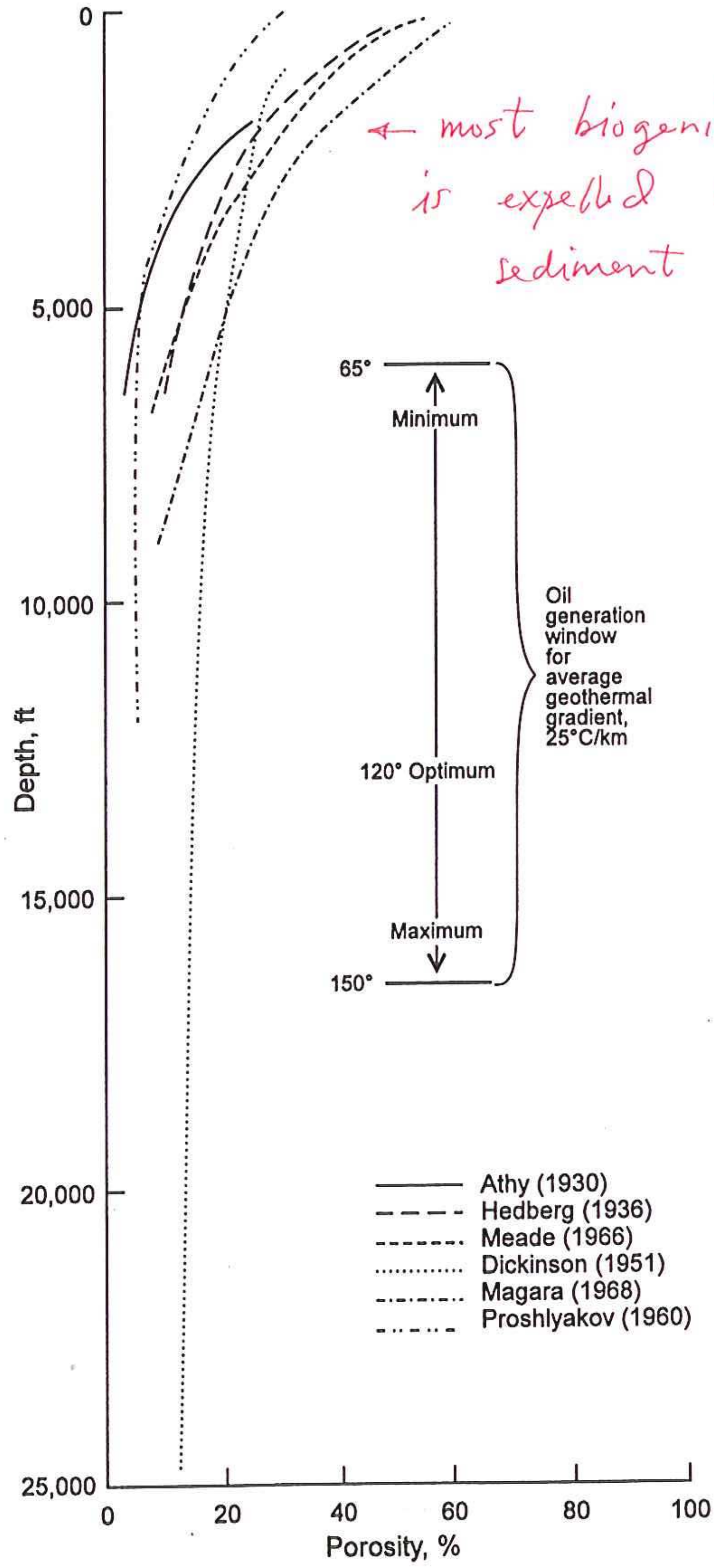
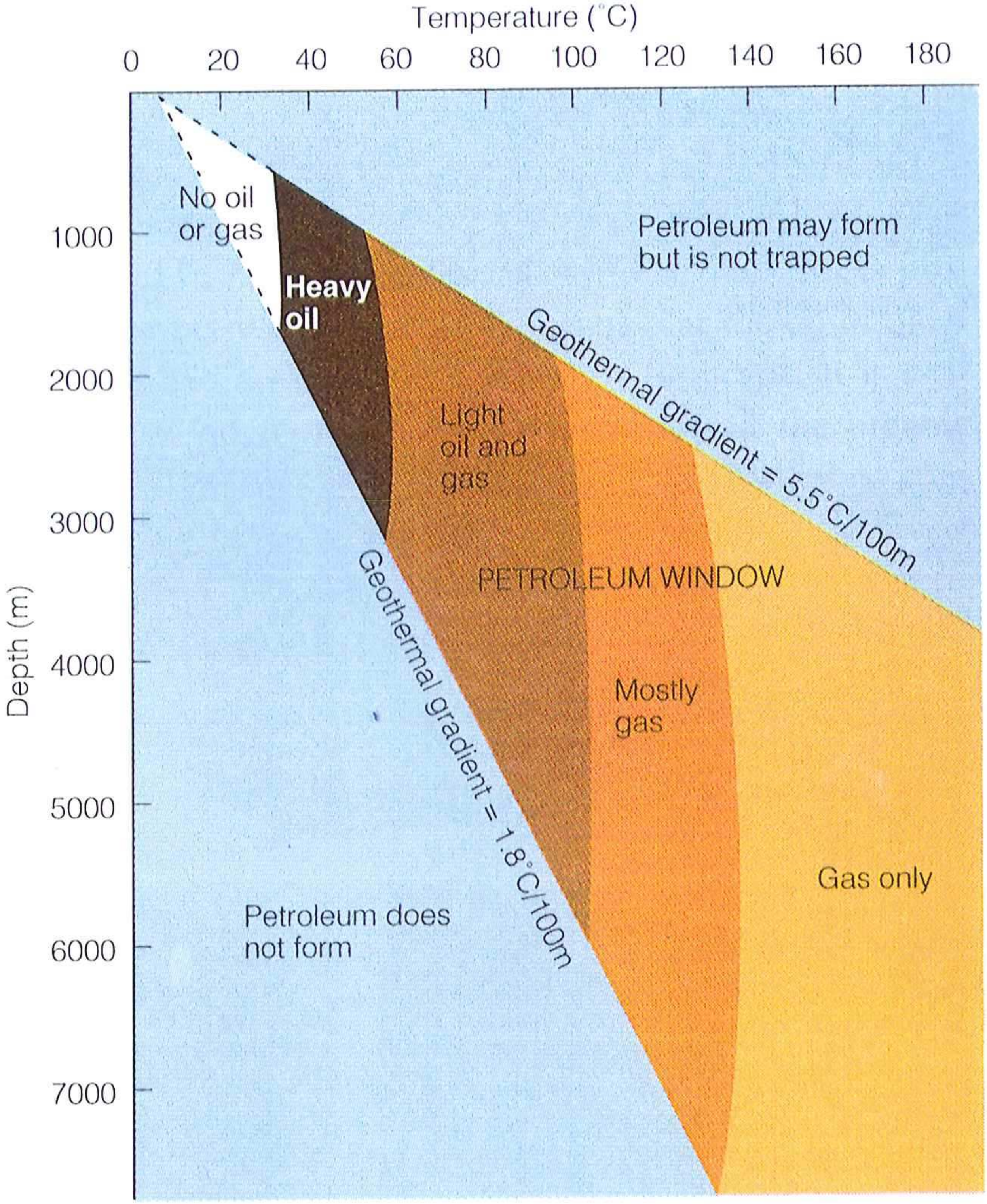


Figure 8.17. Correlation between temperature and the rate of hydrocarbon generation during the burial of organic matter in marine sediments. (Selley 1985)



← most biogenic methane is expelled during sediment compaction

Figure 8.18. Shale compaction curves from various sources. Note that there is only a small amount of water loss due to compaction over the depth range of the oil window.



▲ FIGURE 11.4

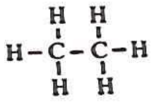
The "petroleum window" is the combination of depth and temperature within which oil and gas are generated and trapped.

Table 1.1. Names and Abbreviations for *n*-Paraffins

Name	Abbreviations		
Methane	CH_4	CH_4	None
Ethane	C_2H_6	CH_3CH_3	None
Propane	C_3H_8	$CH_3CH_2CH_3$	
Butane	C_4H_{10}	$CH_3(CH_2)_2CH_3$	
Pentane	C_5H_{12}	$CH_3(CH_2)_3CH_3$	
Hexane	C_6H_{14}	$CH_3(CH_2)_4CH_3$	
Heptane	C_7H_{16}	$CH_3(CH_2)_5CH_3$	
Octane	C_8H_{18}	$CH_3(CH_2)_6CH_3$	
Nonane	C_9H_{20}	$CH_3(CH_2)_7CH_3$	
Decane	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$	

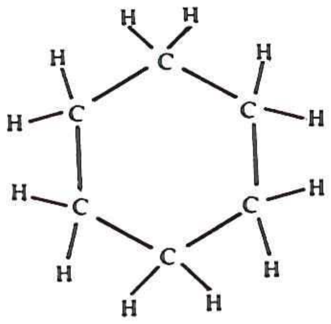
$$\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-H}$$

Methane

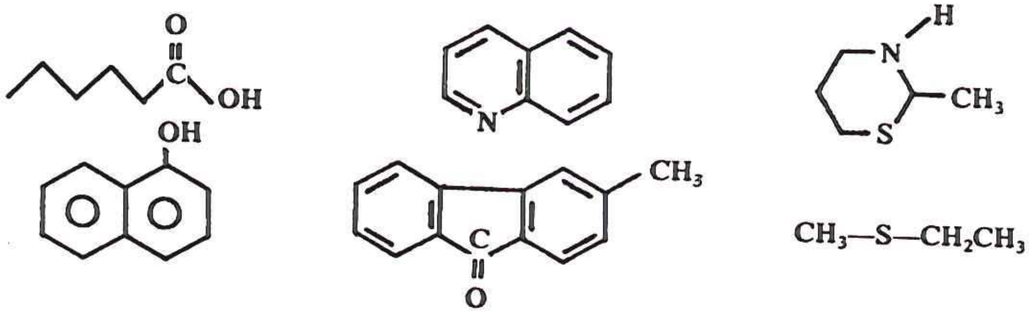


$$\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-H}$$

Ethane



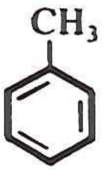
Cyclohexane



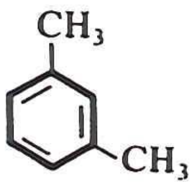
$CH_3—S—CH_2CH_3$

Examples of Resin Structures

Benzene

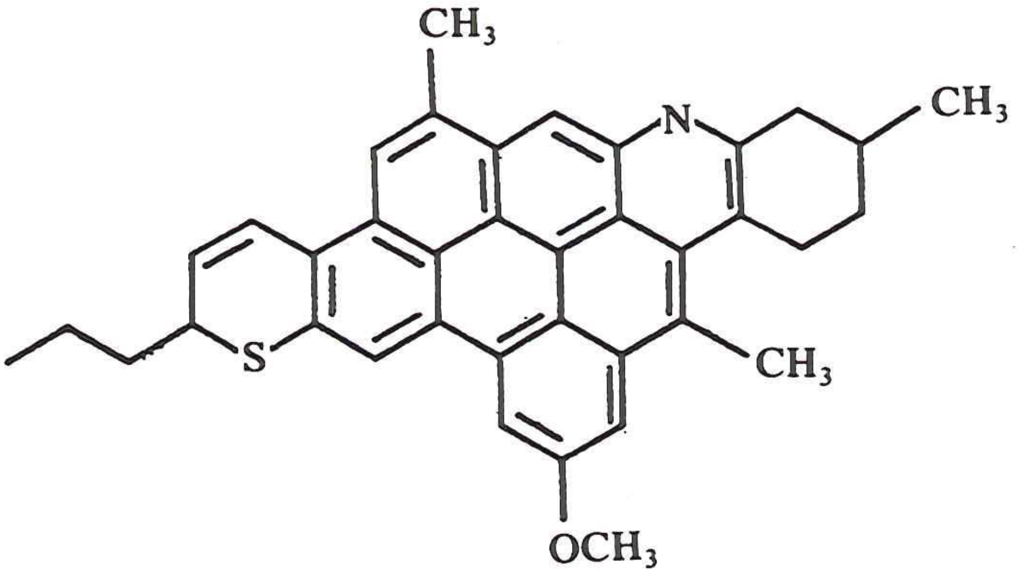


Toluene



m-Xylene

Naphthalene



Example of Asphaltene Structure

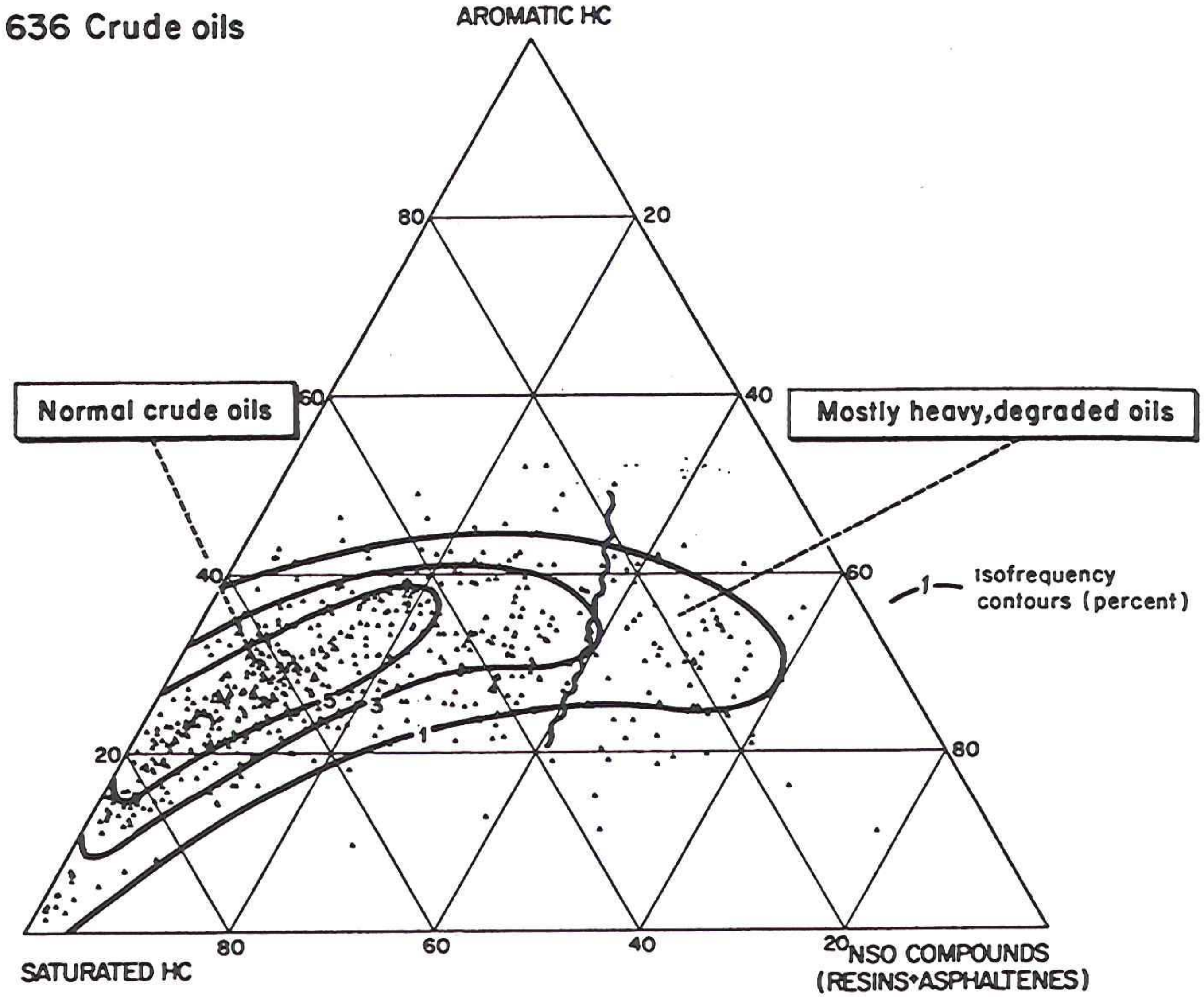


Figure 3.2. Ternary diagram showing the gross composition of 636 crude oils. (From Tissot and Welte, 1978: republished with permission of Springer-Verlag)

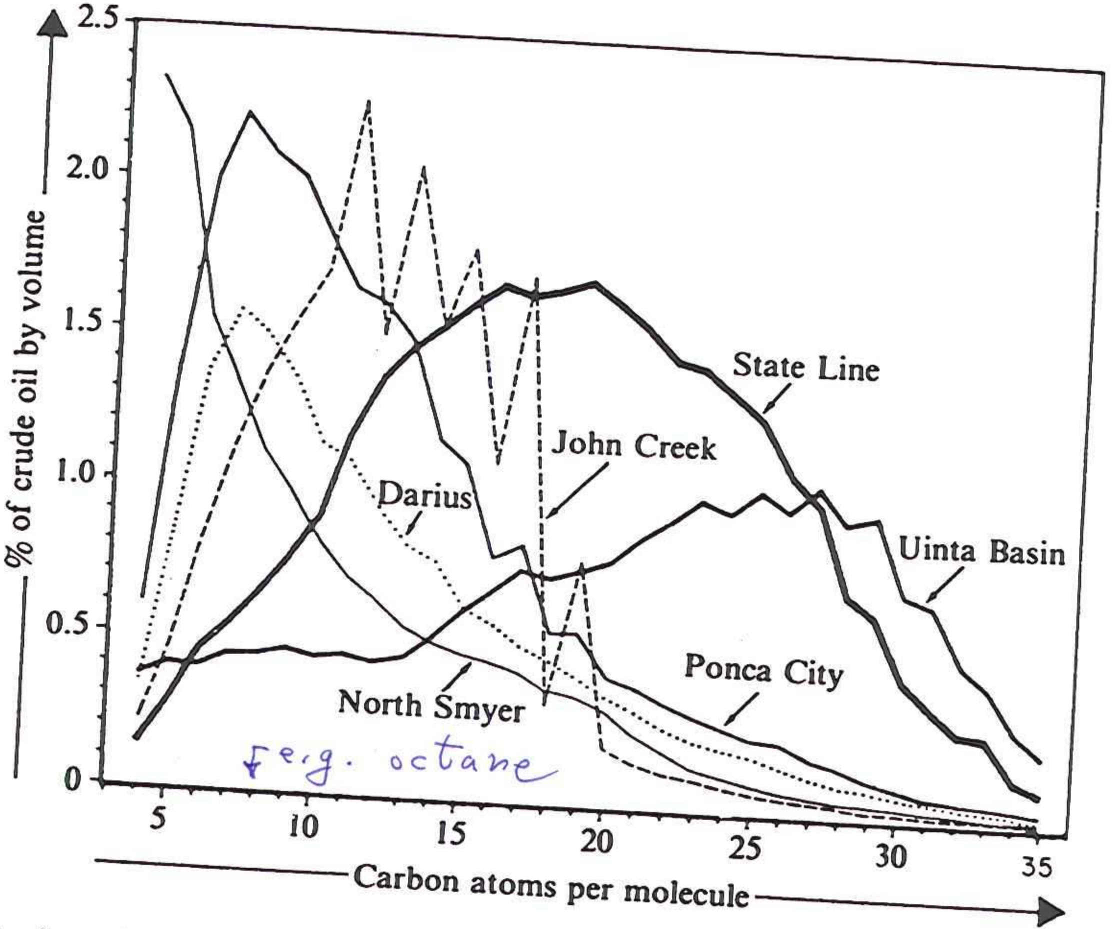
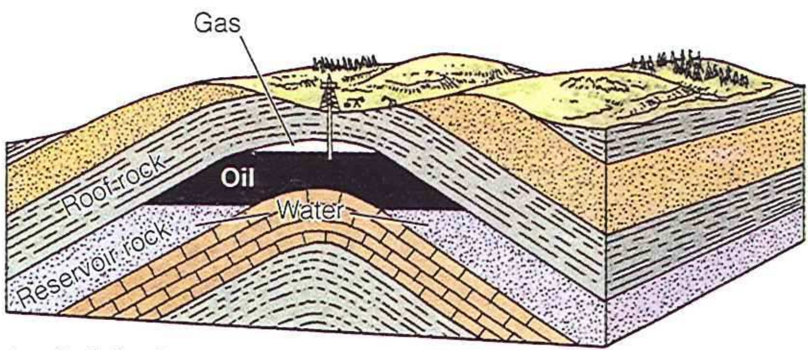
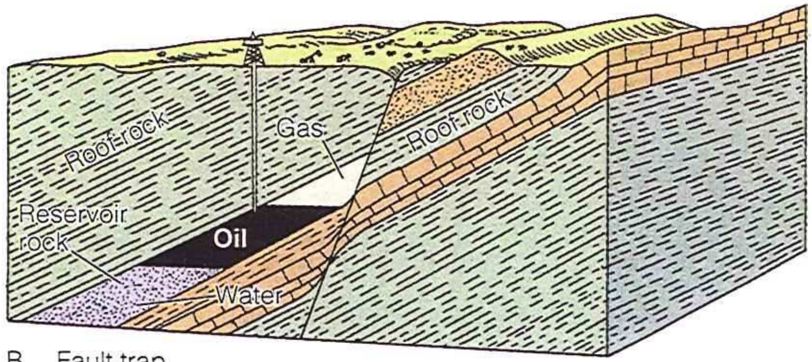


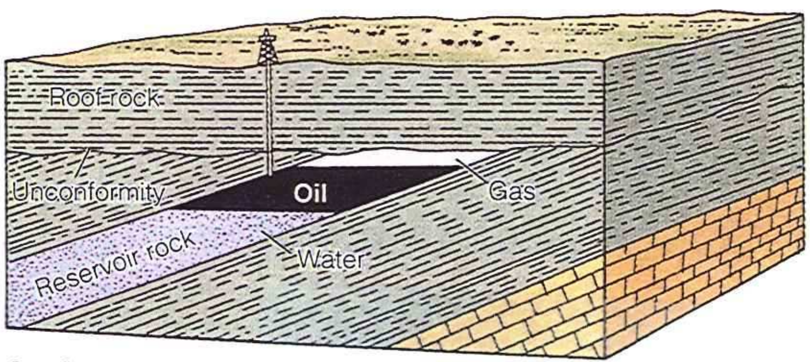
Figure 3.3. Distribution of *n*-alkanes in different types of crude oils. (From Martin et al., 1963; republished with permission of Nature)



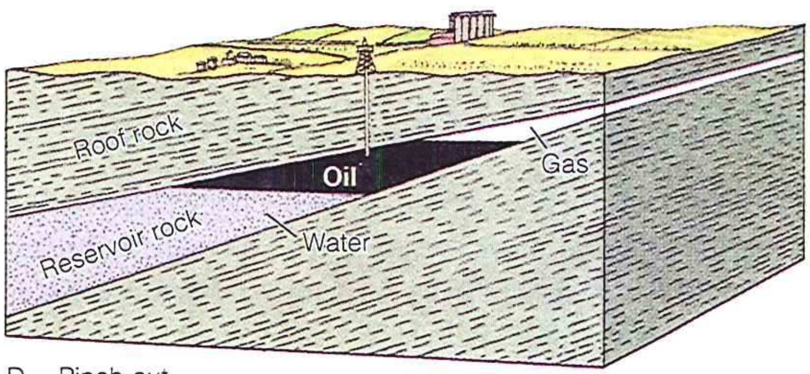
A. Anticlinal trap



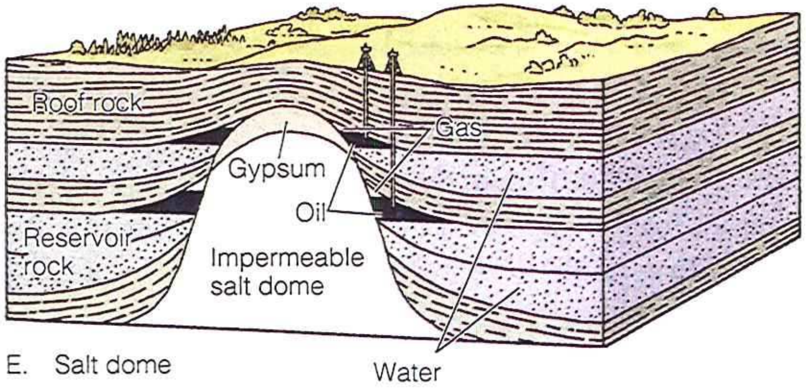
B. Fault trap



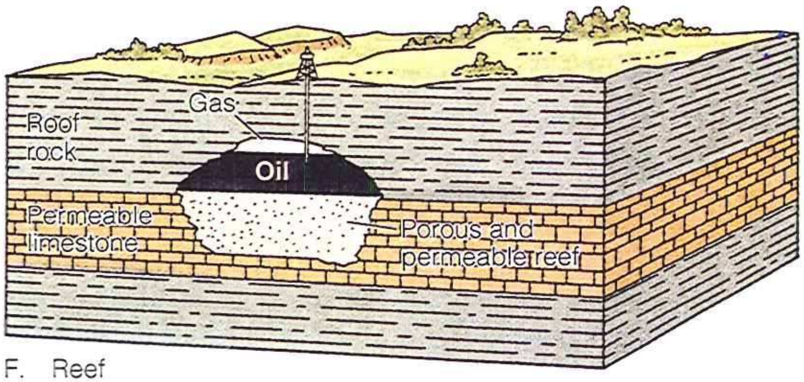
C. Stratigraphic trap



D. Pinch-out



E. Salt dome



F. Reef

GREYBULL SANDSTONE POOL — ELK BASIN

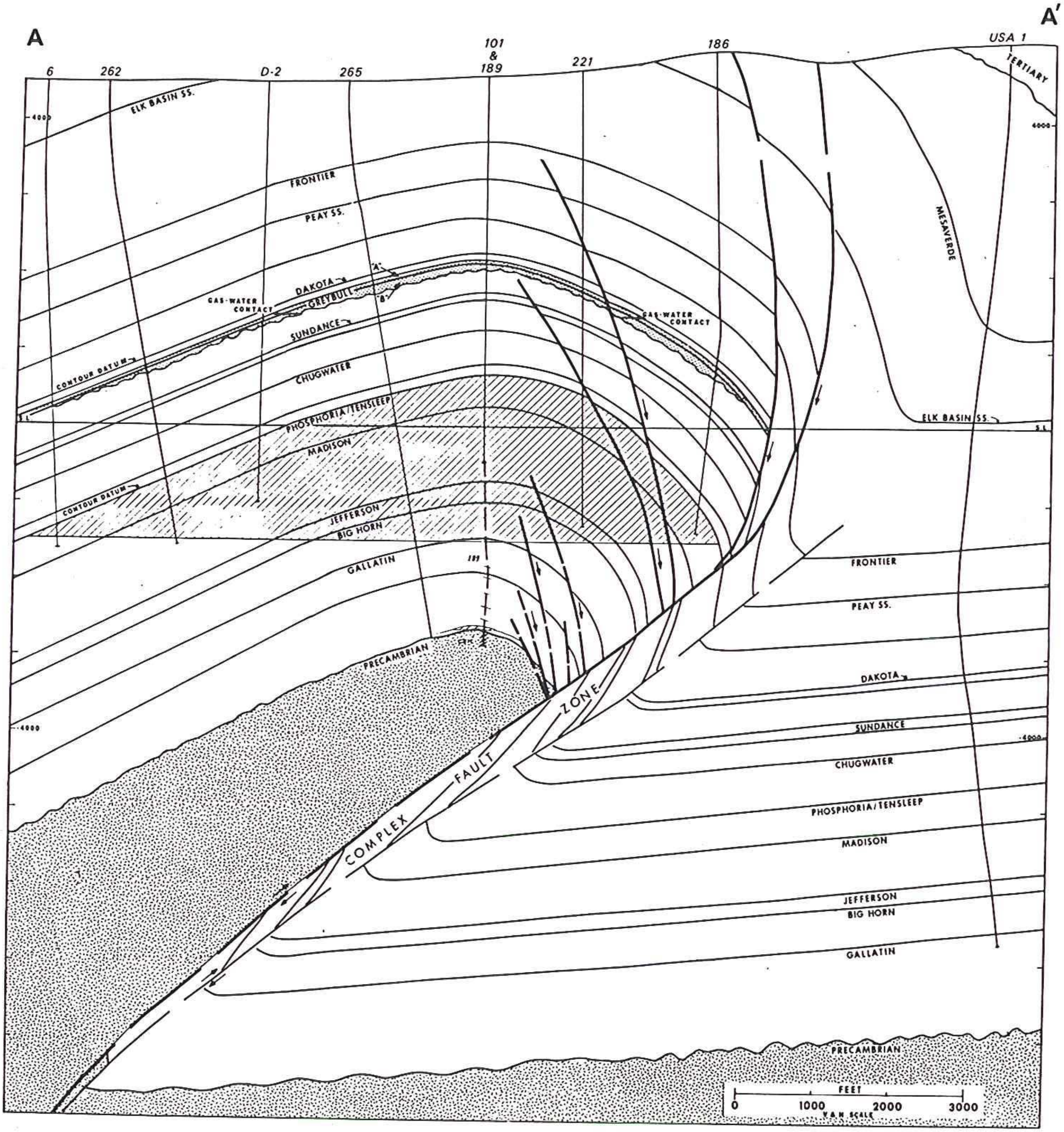


Figure 4. Northeast-southwest, true scale, structural cross section A-A′ through central Elk Basin field (location shown on Figs. 1, 2, 3, 7, and 8). Wells are identified by field numbers. Common pool Paleozoic accumulation is cross hatched.

1861 "Drake's Folly"

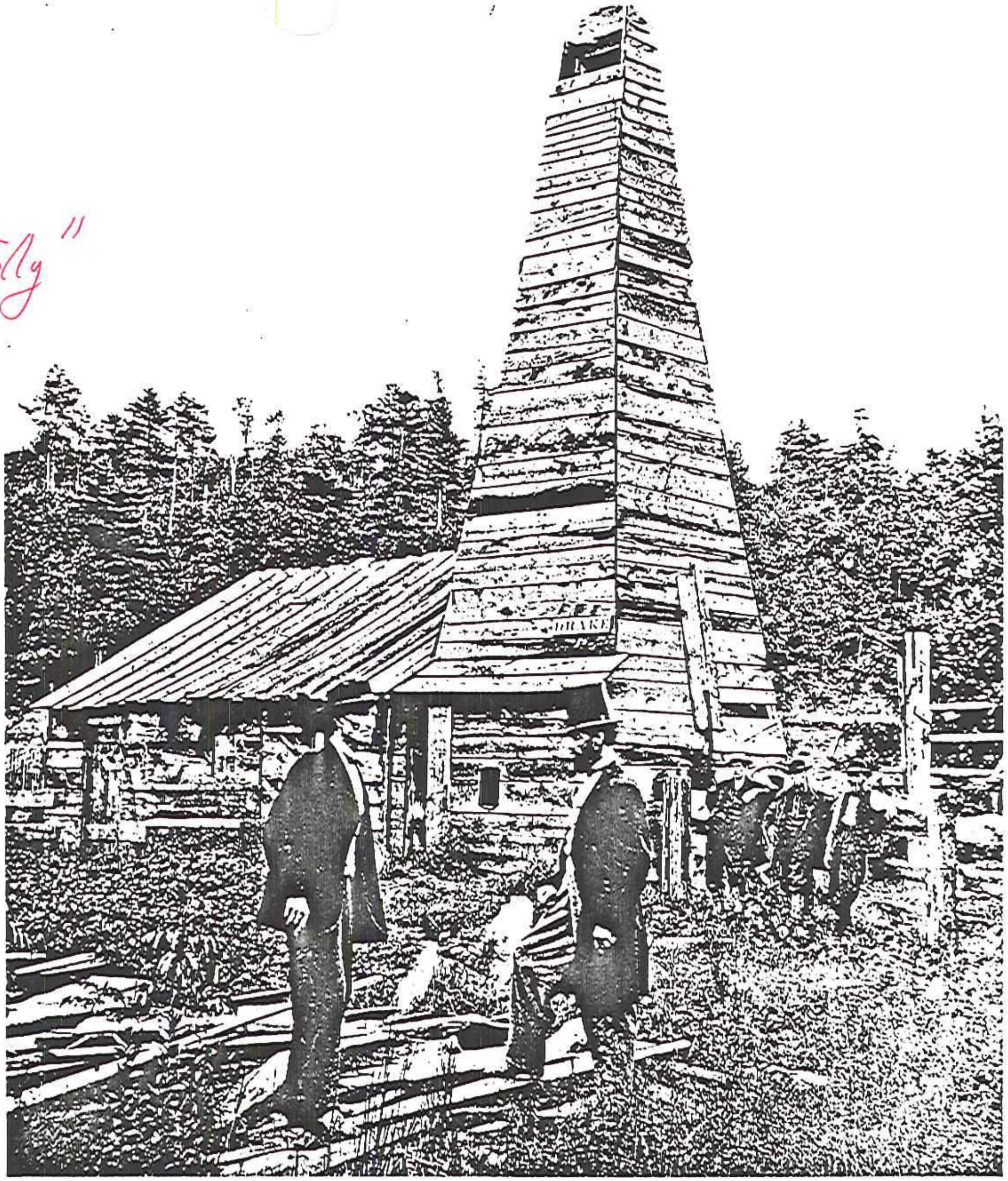
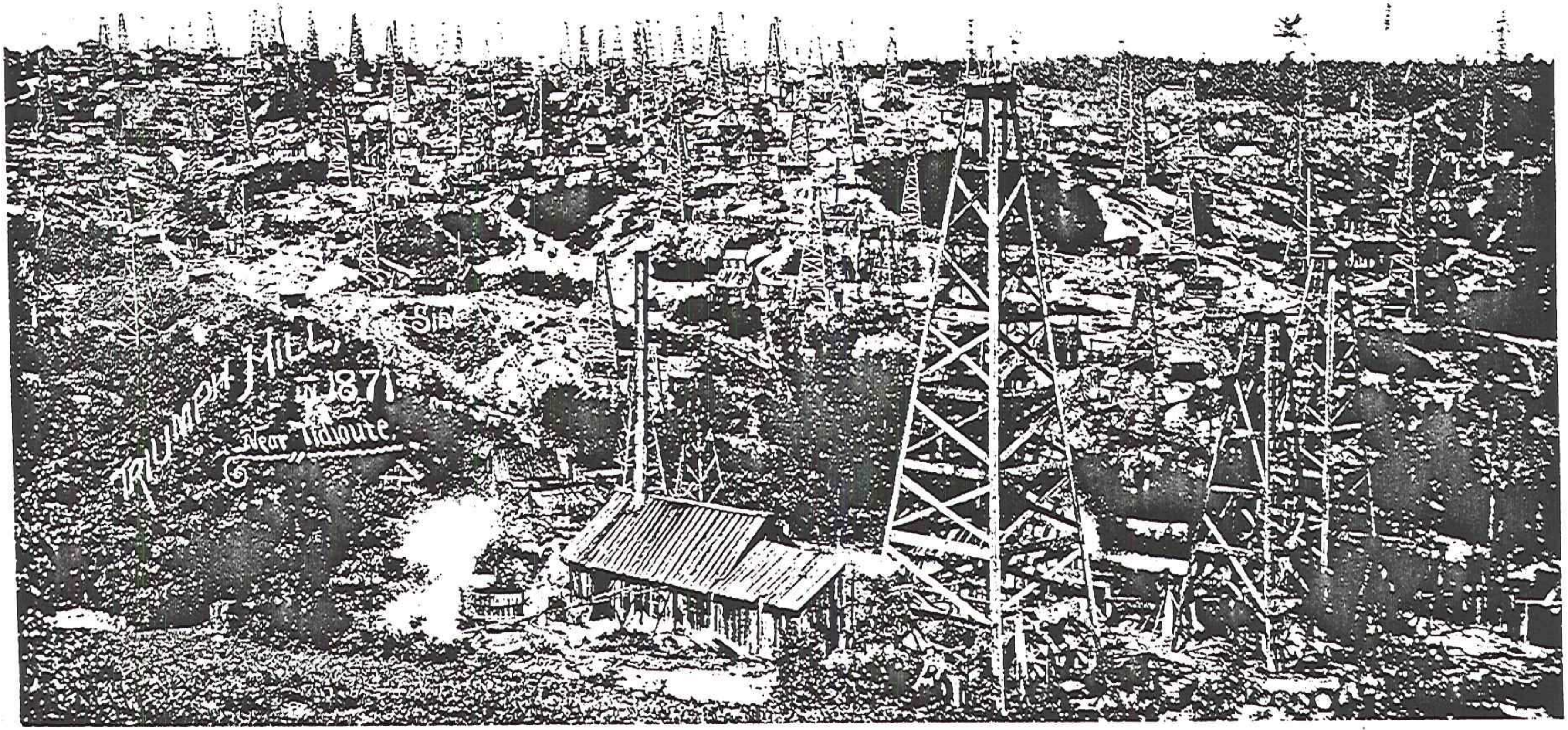


Figure 8.19. (a) Edwin Drake (*right*) in front of his oil well on the banks of Oil Creek in Titusville, Pennsylvania, in 1861; this well marked the beginning of the modern extraction of oil. (b, *on opposite page*) The success of Drake's first well resulted in the drilling of large numbers of closely spaced wells as shown here in 1861 on the Benninghoff Farm along Oil Creek. (Drake Well Museum, Titusville, Pennyslvania)



10 years later — 1871

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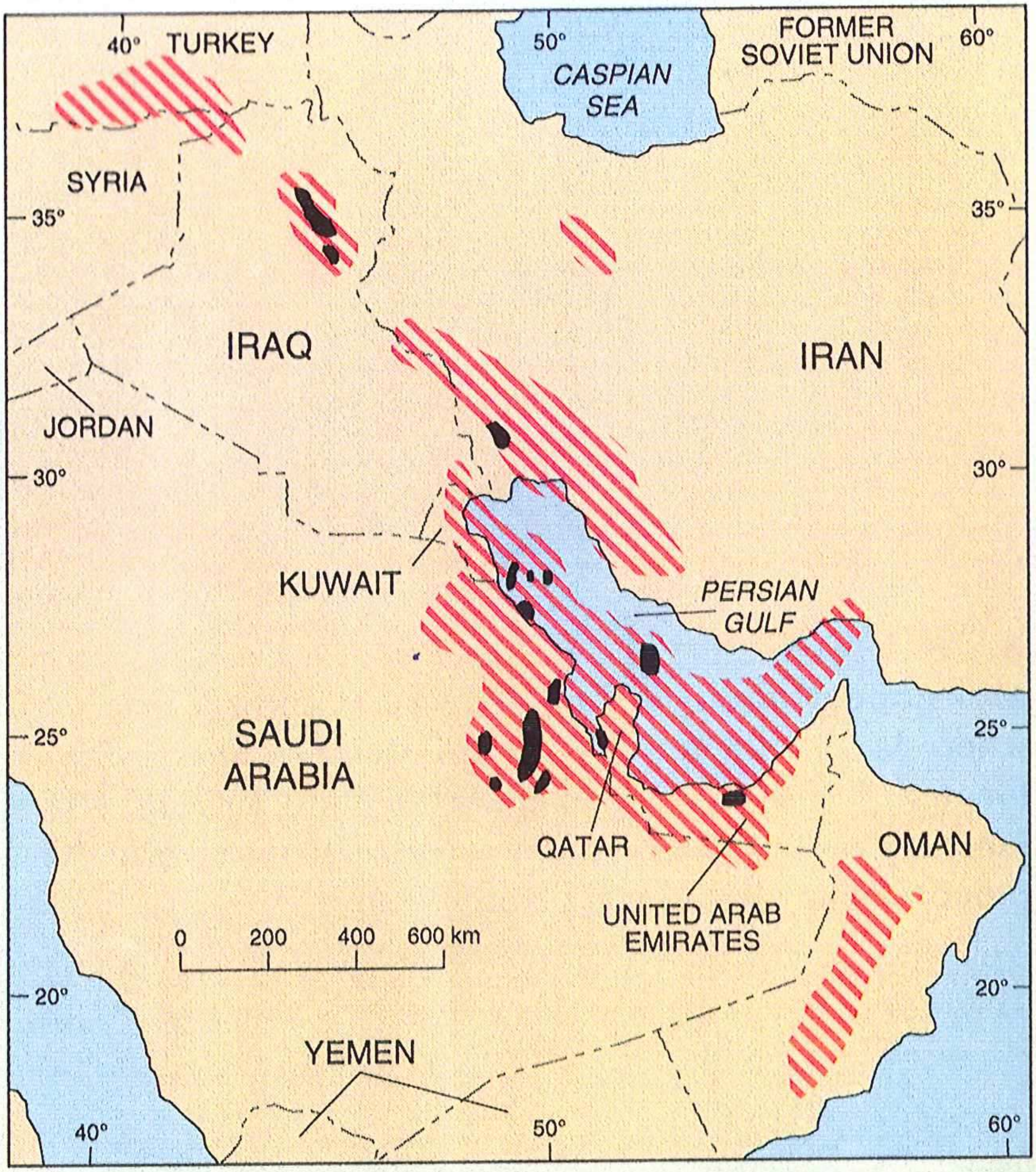
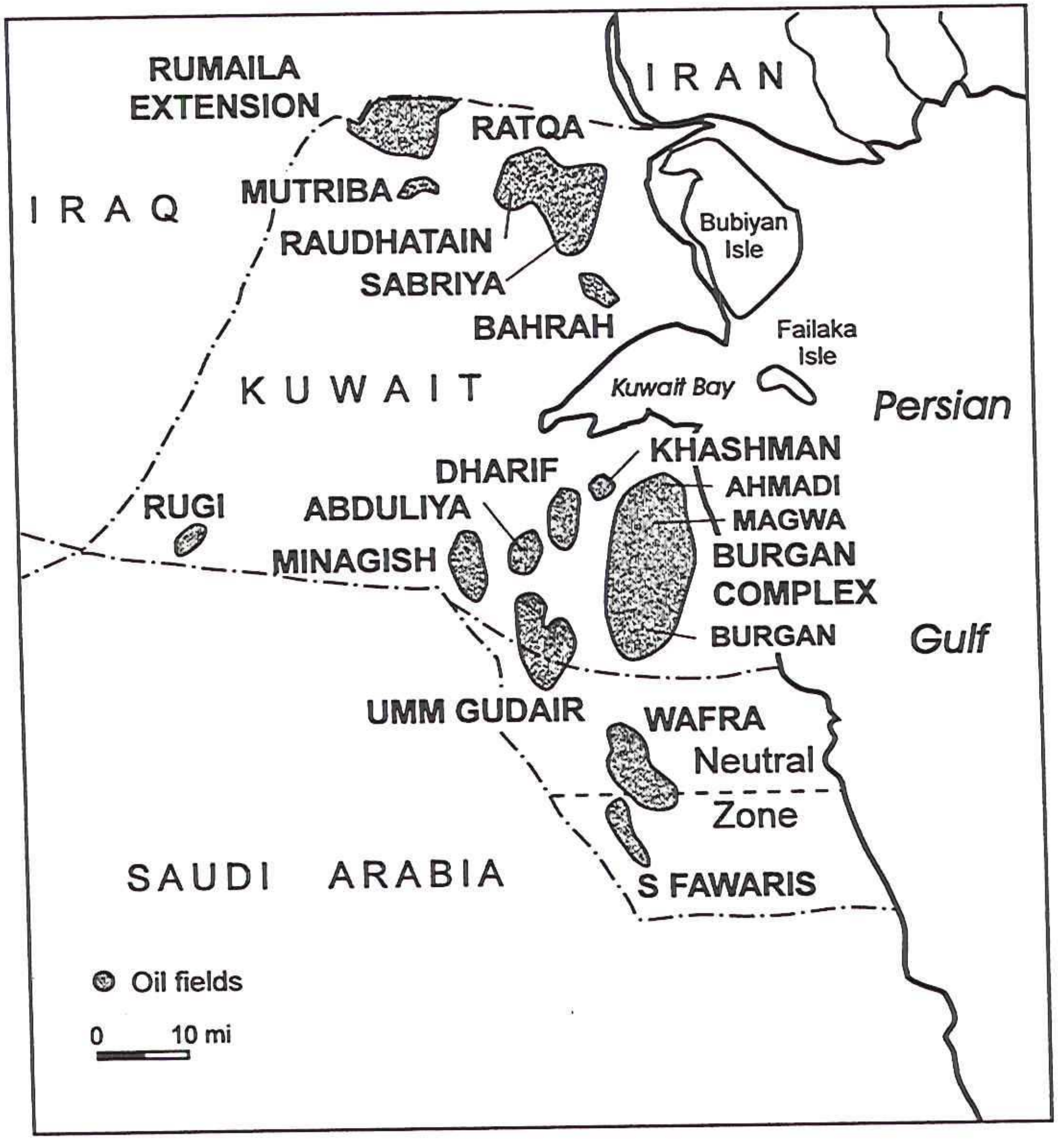


▲ FIGURE B1.1

Rocks containing oil and gas underlie large areas of the Middle East. The outlined areas enclose the more than 400 oil fields that have been discovered so far. The outlines of the largest individual fields are highlighted.

Burgan : second largest oil field in world

Figure 8.21. The oil fields of Kuwait. (*World Oil*, January 1992)



Burgan Field
10 mi x 20 mi
70 bbo

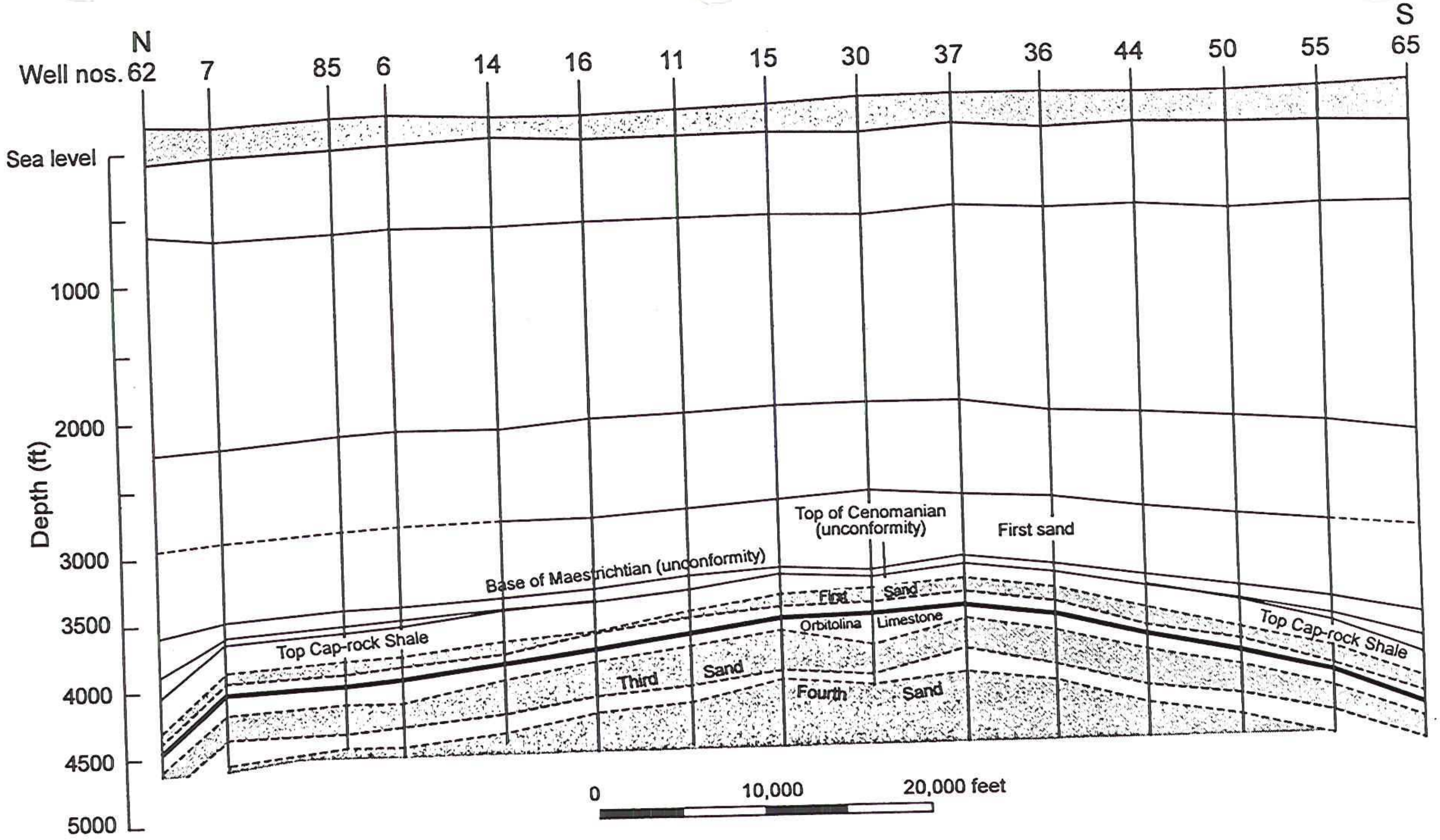


Figure 8.22. Geology of the Burgan structure, with eight times vertical exaggeration. (Jenyon 1990)

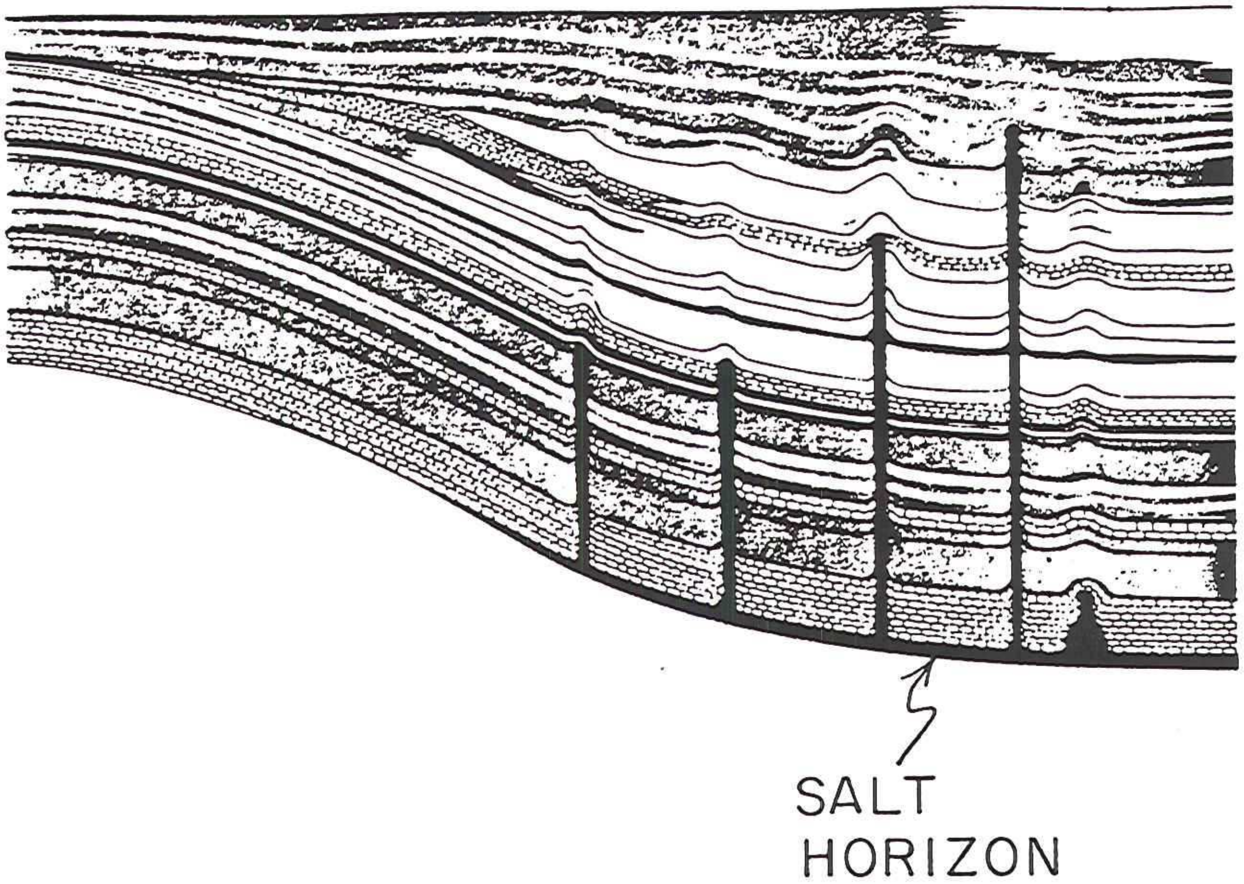


Figure 8-9. **Salt domes:** Narrow plug-like columns of salt are believed to "flow" upward through the more dense but mechanically weak overlying sediments, forming "salt domes." This geologic section of eastern Louisiana shows known salt domes that have risen through as much as 10,000 meters of overlying sediments.

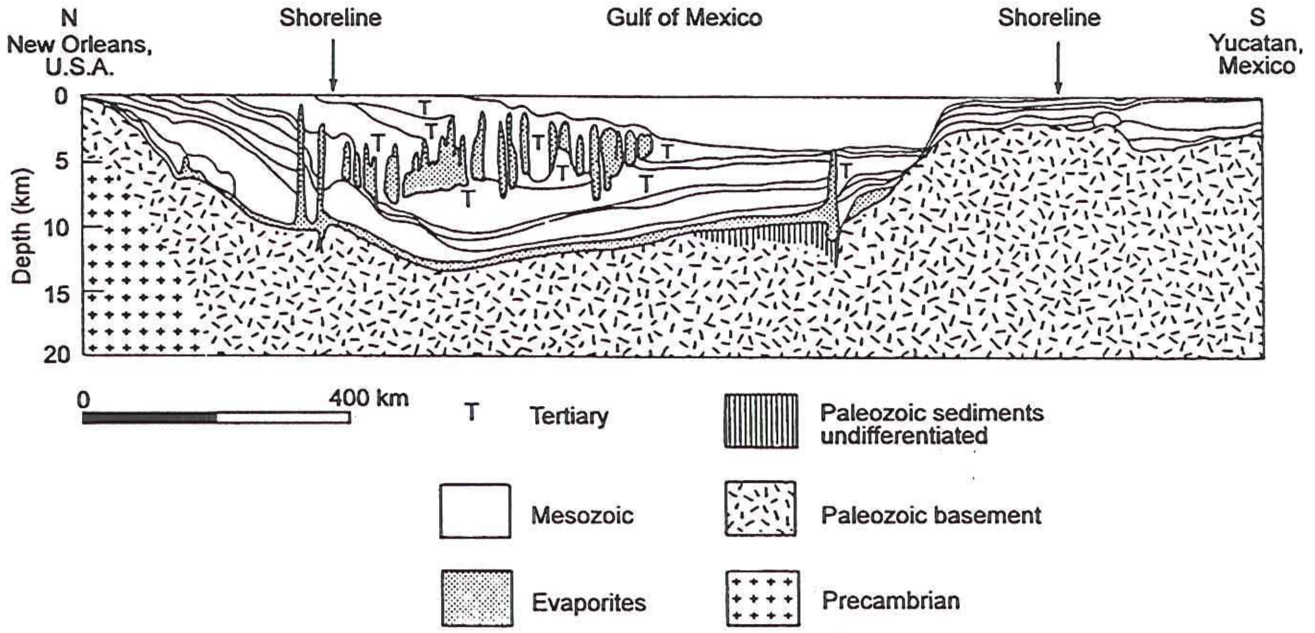


Figure 7.7. Geological cross section of the Gulf of Mexico; vertical exaggeration 20:1. (Bally 1979)

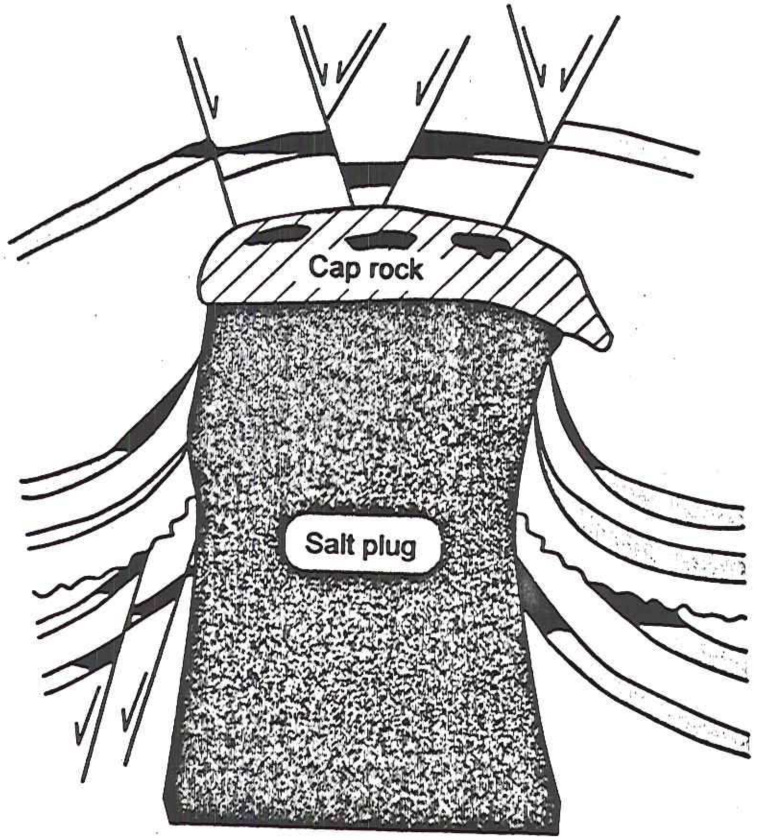


Figure 8.25. Schematic representation of a typical Gulf Coast salt dome, indicating various trap types, including leached secondary porosity traps in a cap-rock. (Jenyon 1990)

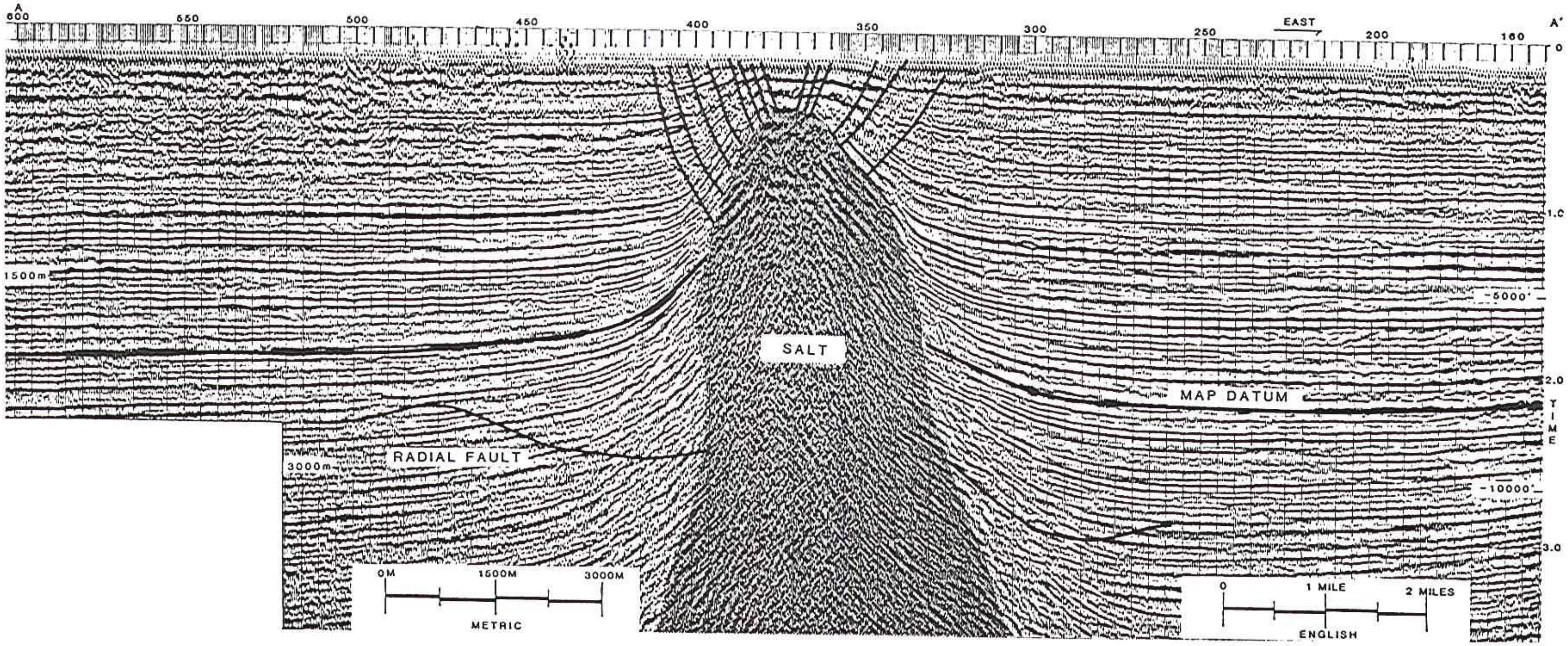
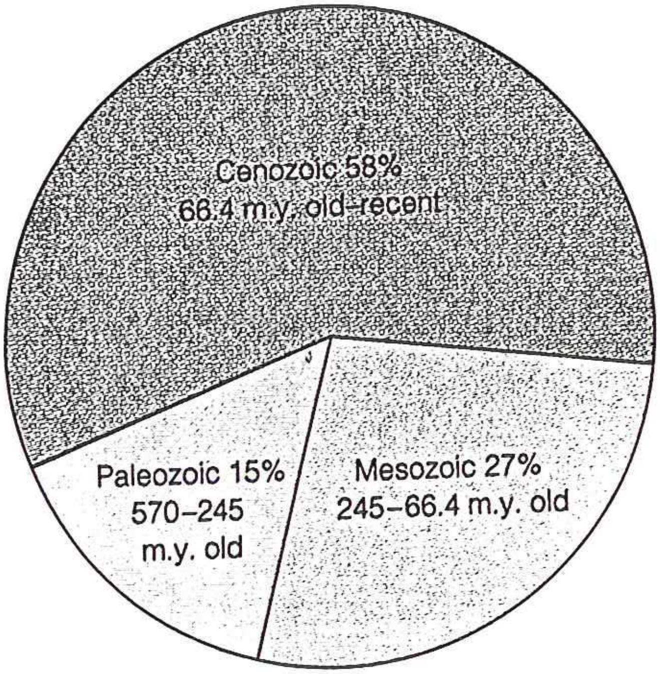
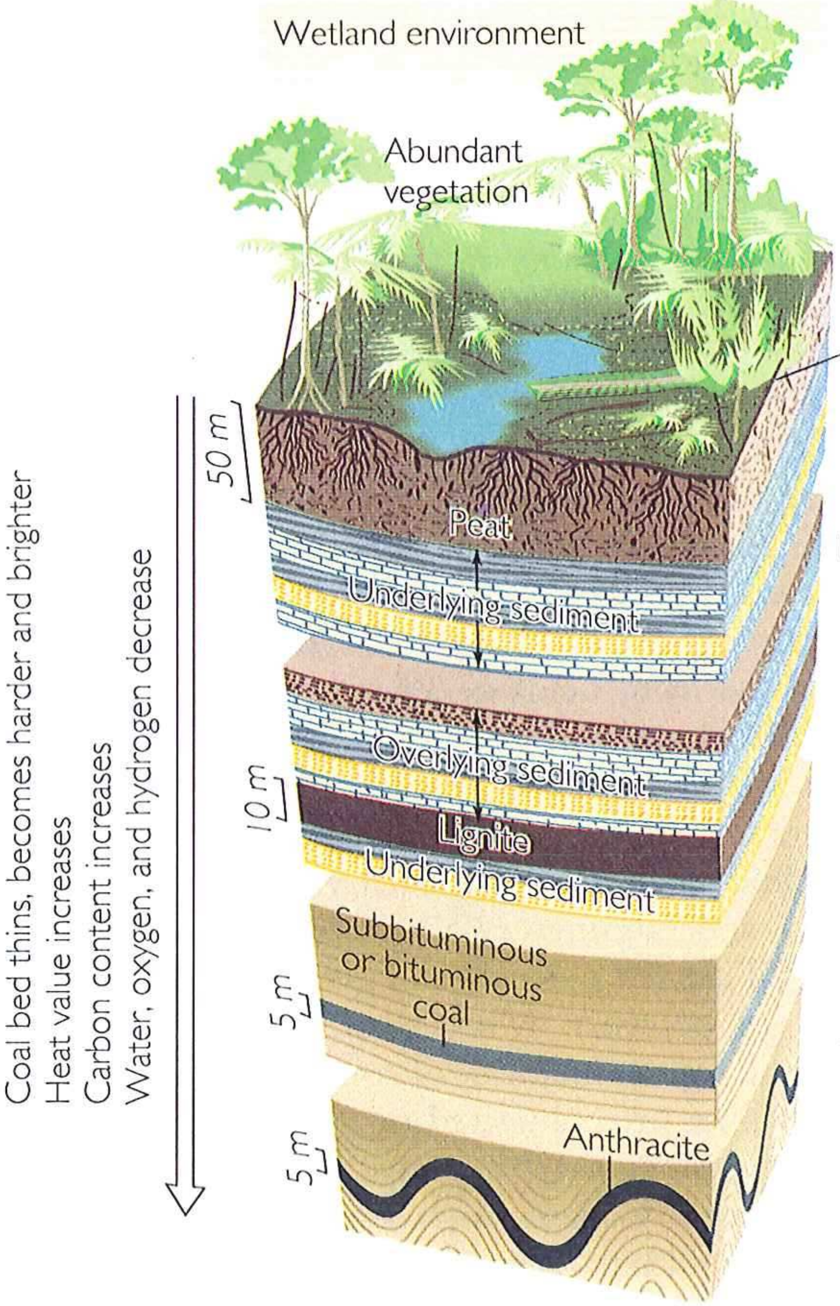


Fig. 8-31 (Sunwall et al., 1983)—Seismic line from offshore Louisiana, U. S. Gulf Coast, showing young salt diapir (characterized by reflection cut-outs) with superjacent normal faults and lower radial faults which strike parallel to seismic line. Salt configuration based on well control, gravity, and reflection and refraction seismic. Note that stratigraphic thinning toward diapir begins early (below 2 sec), but secondary rim synclines are not developed. Permission to publish by American Association of Petroleum Geologists.



▲ FIGURE 11.2
Percentages of total world oil production from rocks of different ages. (m.y. stands for million years.)



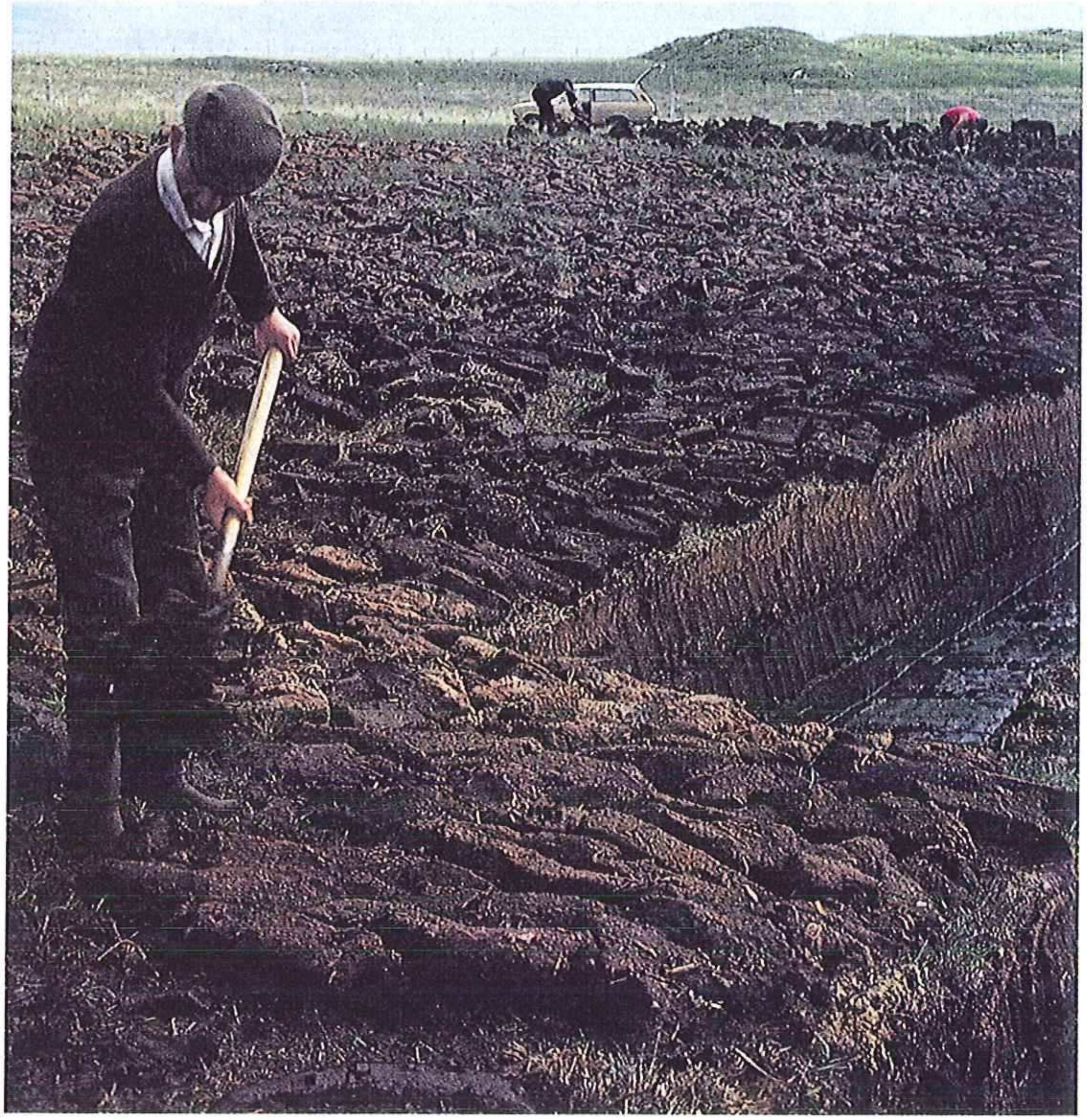
Surface accumulation of leaf litter, twigs, branches, and other fragments of vegetation

Lower buried swamp deposits partly decayed, compressed to **peat**

Shallow burial: transformation of peat to **lignite**

Further burial under hundreds to thousands of meters of sediment: transformation of lignite to **soft coal**

Continued burial and structural deformation: heat metamorphoses soft coal to **hard coal**



▲ FIGURE 11.8

A peat cutter harvests peat from a bog in western Ireland. The peat has formed in a cool moist climate that favors the preservation of organic matter in wet environments. When dried, the peat provides fuel for heat and cooking.

▲ FIGURE 11.10

Coal seams in a sequence of sedimentary strata, Healy, Alaska. Coal is a sedimentary rock; the sedimentary layers, once horizontal, have been tilted by tectonic forces.

▲ FIGURE 11.11 0.1 Gt coal /yr

On average, about 300,000 tons of coal per day are extracted from a seam 20 to 30 m thick in this strip mine at Wyodak, Wyoming.

this is $\frac{1}{10}$ of total US consumption (1 Gt coal/yr)

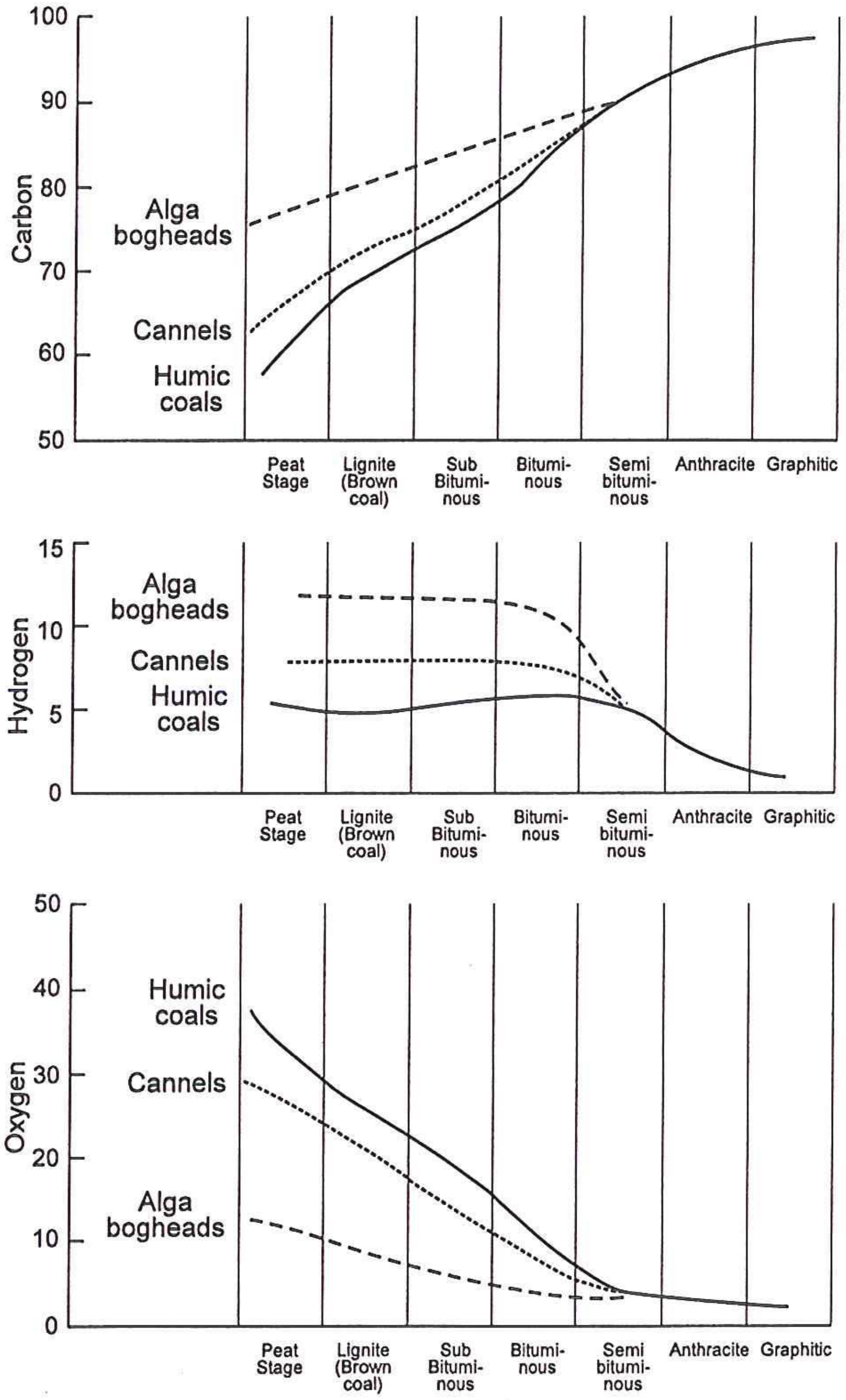


Figure 7.12. Changes in carbon, hydrogen, and oxygen content during the evolution of normal (humic) coals and algal (sapropelic) coals. (White 1925)

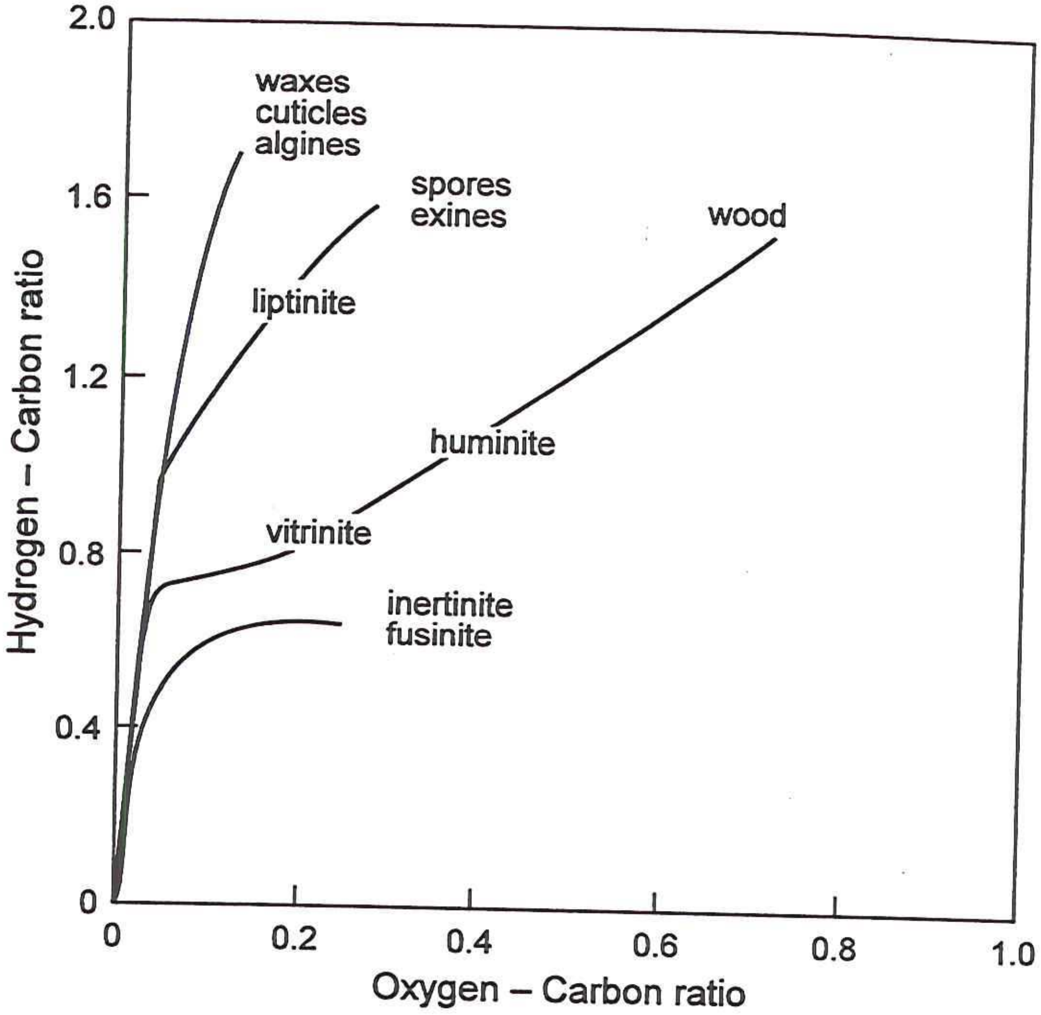
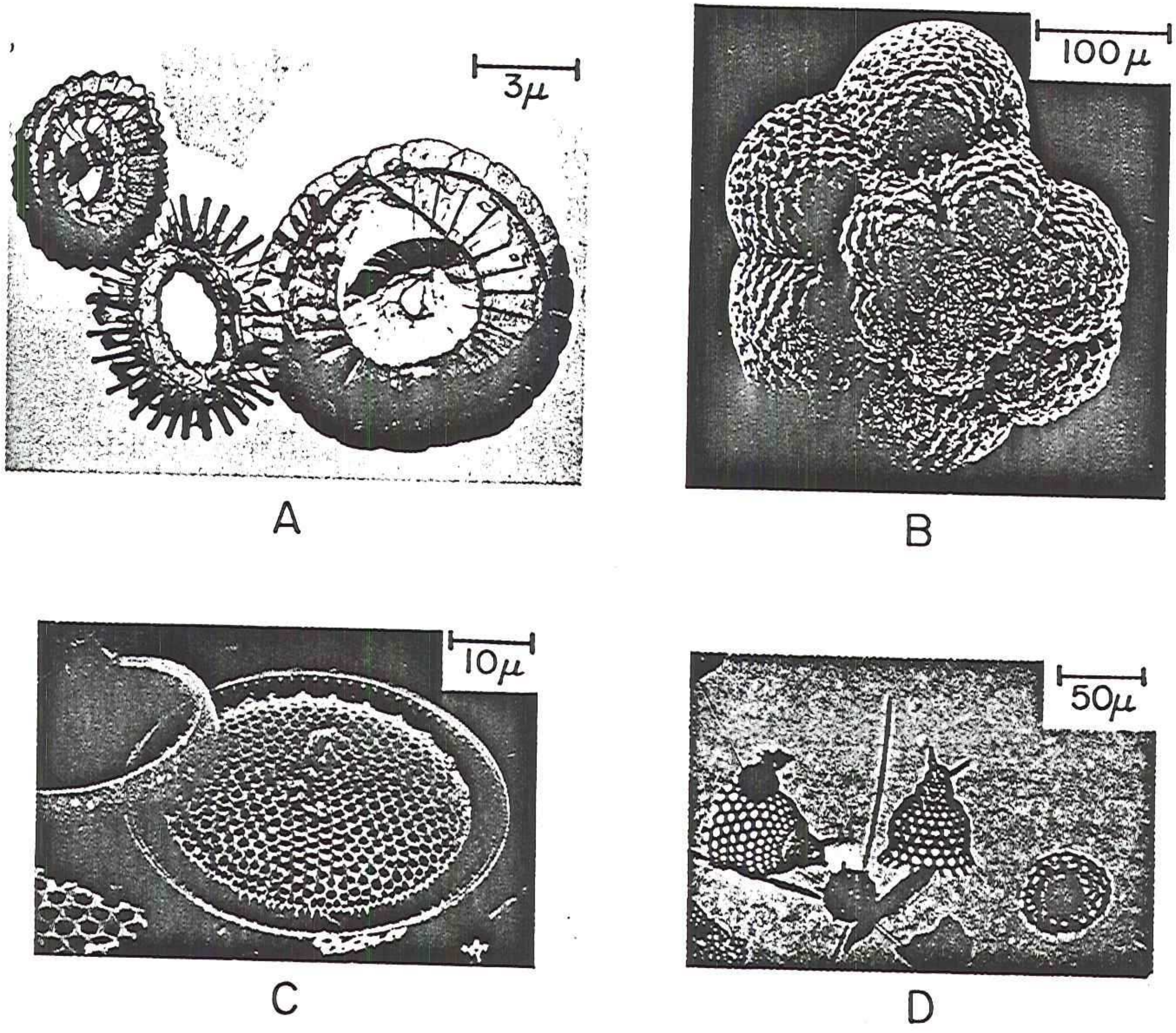


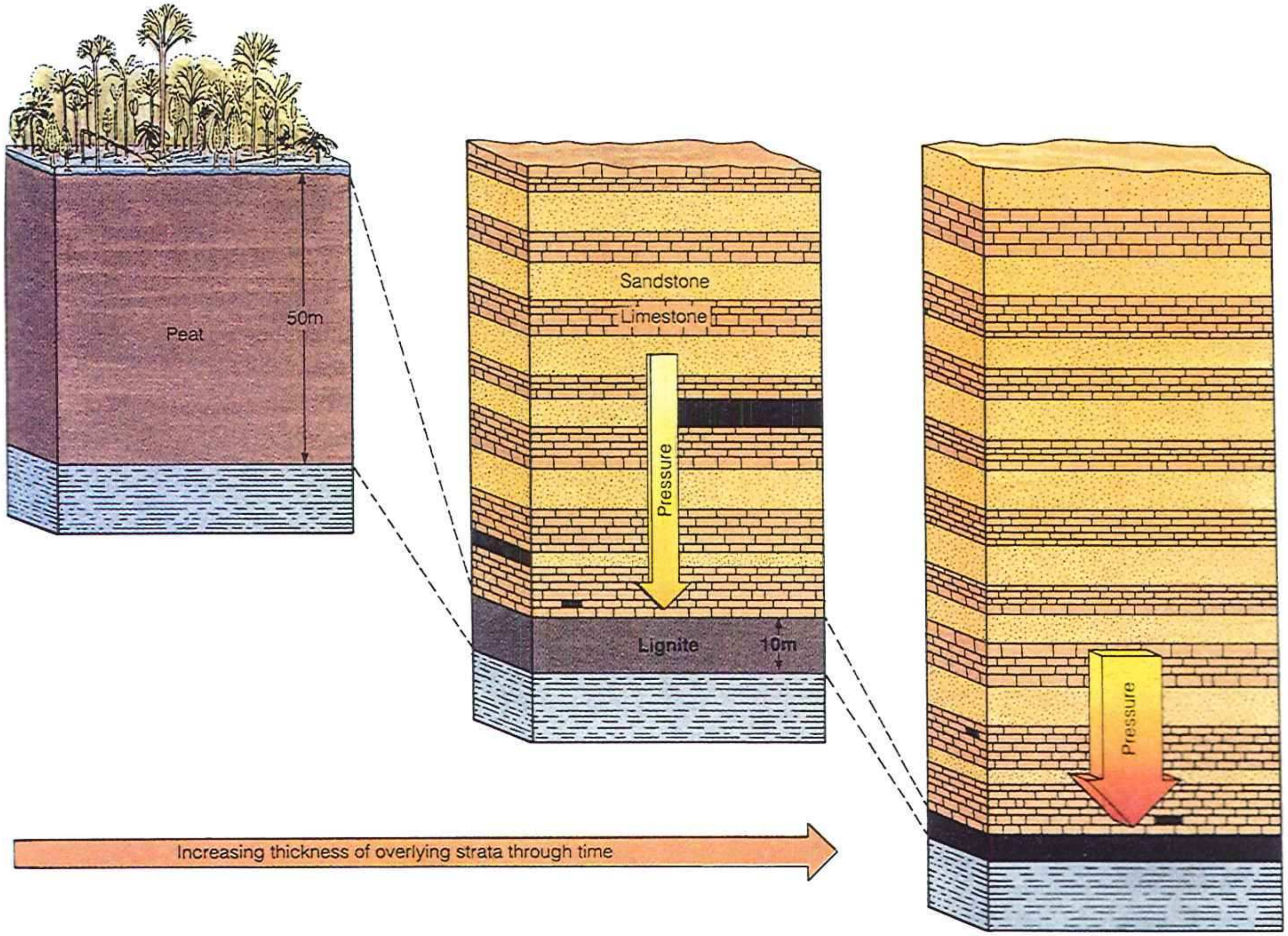
Figure 7.13. Van Krevelen diagram (H/C versus O/C atomic ratios) for the main components of coal and their predecessors with lines of dehydration, decarboxylation, demethanation, dehydrogenation, oxidation, and hydrogenation. (Modified after van Krevelen 1961; Tissot and Welte 1984; from Damberger 1991)



A B C D

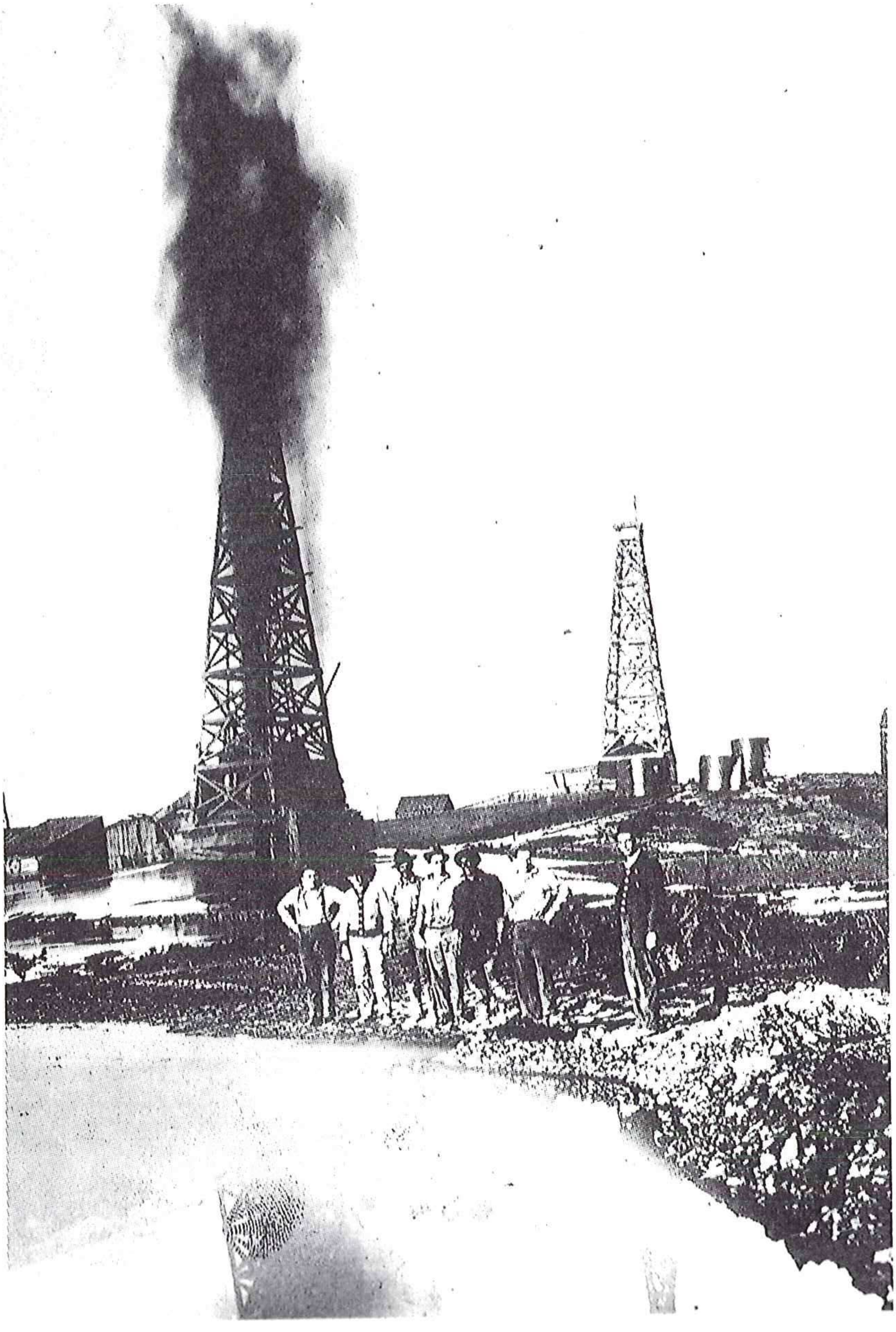
Figure 8-4. Calcite and opal houses made by marine microplankton: (A) Calcite cages which surround plants called coccolithophorida. (B) Calcite shell formed by foraminifera. (C) Opaline pillbox housing a diatom. (D) Opaline cages inhabited by radiolarians. These pictures were taken using a microscope; there are 10,000 microns in a centimeter.

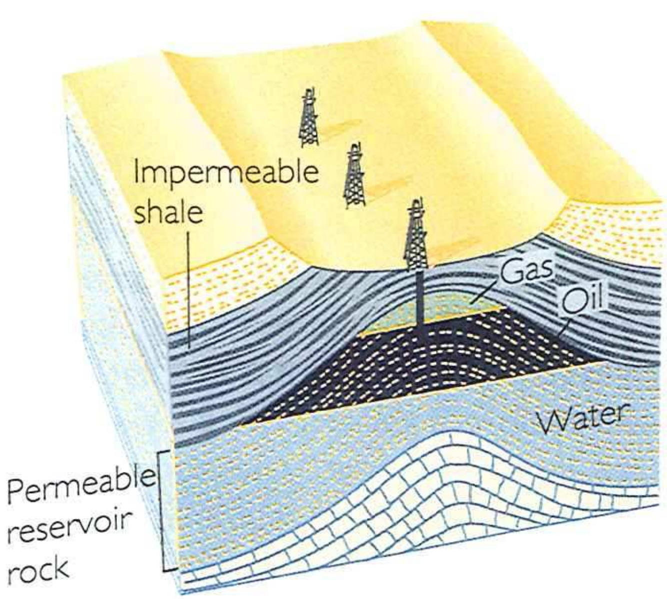
extra
from
here



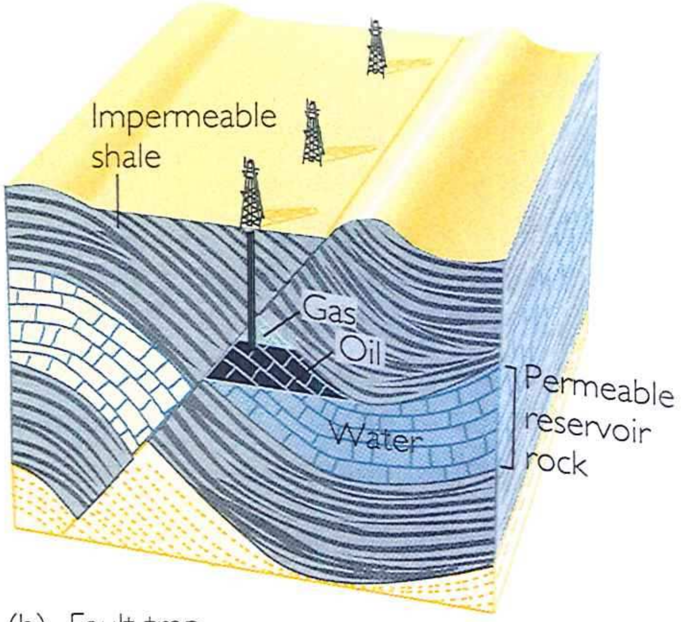
▲ FIGURE 11.9

Plant matter in peat is converted into coal by decomposition, coupled with increased pressure and temperature as overlying sediments build up. By the time a layer of peat 50 m thick has been converted to bituminous coal, its thickness has been reduced by 90 percent. In the process, the proportion of carbon has increased from 60 to 80 percent.

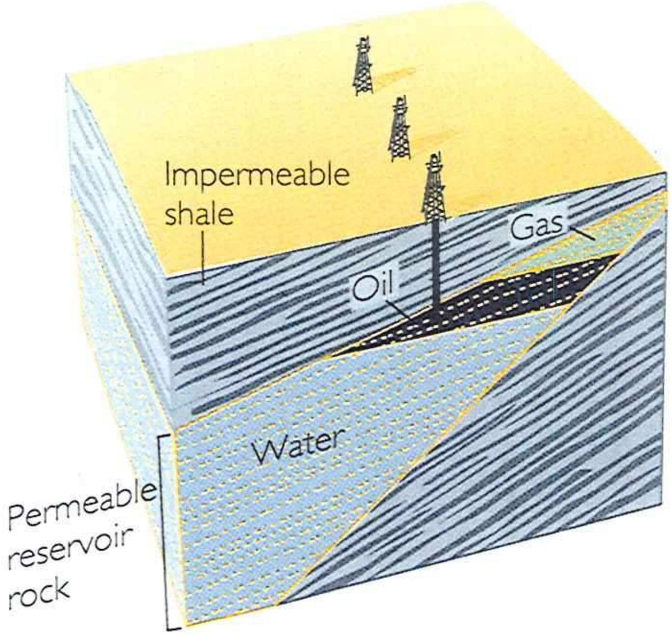




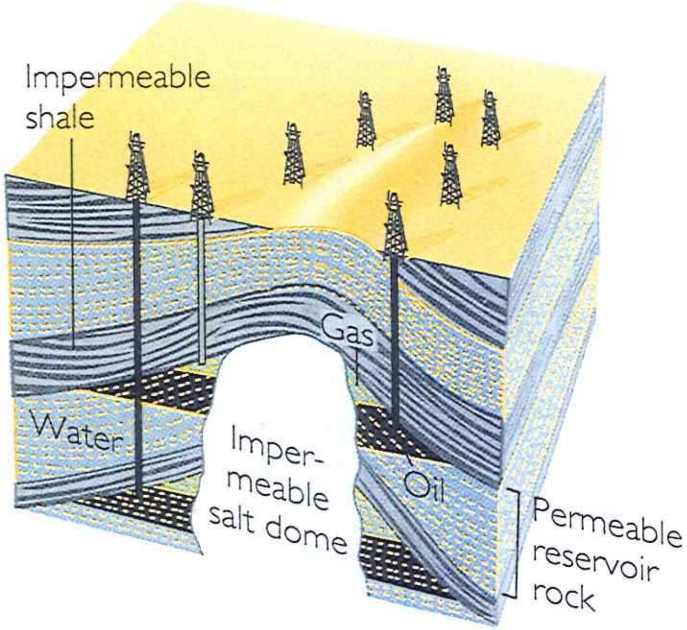
(a) Anticlinal trap



(b) Fault trap



(c) Stratigraphic trap



(d) Salt dome trap

[redacted]

DEMAND & SUPPLY

So, how much have we used and how much is left?

Consumption best viewed in context of energy use as a whole.

Units — simplest to convert everything to energy units.

Some conversion factors are handy:

1 BTU = energy required to raise one pound of water 1°F — quaint

1 BTU = 1055 J

1 quad = 1 quadrillion BTU

$$= 10^{15}\ \text{BTU} = 1.055\ \text{EJ}$$

exajoule

$$= 1.055 \cdot 10^{18}\ \text{J}$$

$$\approx 1\ \text{EJ}$$

unit commonly used for global accounting

Oils differ but we adopt a nominal average

1 bl oil (upon burning) = 5.8 MBTU
= 6.1 GJ

10 1/2

1 bbo ≈ 6 quads

To make matters more confusing:
Natural gas resources measured in
tcf = trillions of cubic ft!

1000 cu ft = 1 MBTU = 1 GJ
so 1 tcf = 1 quad

Finally, coal consumption is measured
in tons

1 Gt = 27.8 quads

A typical electrical power plant has
a full capacity of ~ 1 GW

Typically operate at ~ 60%
capacity, producing ~ 0.6 GW

World consumption currently (1996)

350 quads/yr ← 87% fossil fuel

Increasing at 2.7% / year — almost
twice (1.7 times) as fast as
world population

$\boxed{\text{NPGL = natural gas pressurized liquid (propane, etc.)}}$

One more source of confusion — utility companies charge by the kilowatt-hr

$$\boxed{1\ \text{kWh} = 3.6\ \text{MJ} = 3412\ \text{BTU}}$$

So 1 barrel oil produces 1700 kWh

A coal-burning power plant requires ~ 10,000 BTU to produce 1 kWh
⇒ efficiency of electrical conversion about 33%

~~[illegible]~~

$\boxed{\text{Current US consumption rate 82 quads/yr}}$

Fossil fuels ~ 90%

Coal & nuclear are the fastest growing

$\boxed{\text{World consumption rate} \sim 350\ \text{quads/yr}}$

~~this in 1992 — now 350 quads/yr~~

Oil 21 bbl/yr = 120 quads/yr
137 in 1992

~~[illegible] .7 [illegible] Gt/yr~~

88 in 1992
Coal 2.7 Gt/yr = 75 quads/yr

gas 60 tcf/yr = 60 quads/yr
74 in 1992

not same as Fig. 8.31 (1992)

Problems :

1. How does fossil fuel consumption compare to food consumption?

fossil fuel

$(350 \cdot 10^{18}\ \mathrm{J})$ (85% fossil fuel)

$3 \cdot 10^{20}$ J/yr

this is 10^{13} W ≈ $\frac{1}{4}$ × heat flow from $\oplus$

2. food

(2700 kcal/day)(365 days/yr)

× (4184 J/kcal)($\cancel{5}\cancel{7}^{6} \cdot 10^9$ people)

$= 2.4 \cdot 10^{19}$ J/yr $= 8 \cdot 10^{11}$ W

12 times as much fossil fuel (nonrenewable) as food (renewable)

terrestial NPP is $8 \cdot 10^{13}$ W

This makes sense : fossil fuel consumption release 6 Gt C/yr into atmosphere

This 12% of NPP and human food consumption is about 1% of NPP
↑ terrestial

NPP is ~ twice × heat flow from $\oplus$ so fossil fuel consumption is ~ $\frac{1}{8}$ NPP — checks ↗

Great inequities —

US : 5% of population
20% of energy consumption

per capita
US ≈ 8× China

China : 20% of population
< 10% of energy

US oil "production" (funny word — nature produced it)

18 quads /yr

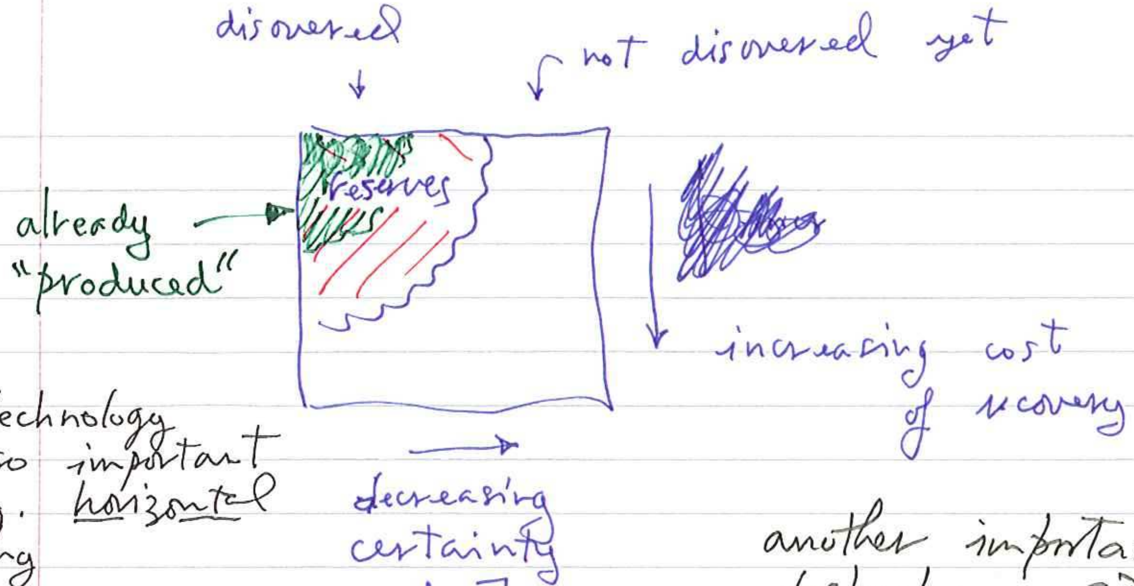
Consumption 33 quads /yr
24% of world total

Produces only ~ half of what it consumes.

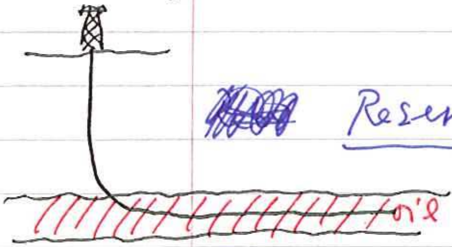
So, how much is left?

Very difficult to estimate — not a strictly scientific question

As with any nonrenewable resource:



New technology also important e.g. horizontal drilling



another important technology: 3D seismic

Reserves : a floating target

US reserves relatively well known (well explored) but small

Original 226 bbl
Already consumed 142 bbl
Remaining 84
Estimated undiscovered 46 } 130 total
↑
2 estimates in Holland & Petersen say ~155 bbl

Have consumed ~3/4 of all pumpable oil in ground in US since time of Drake's folly — 130 years ago

World reserves more uncertain

About 1200 bbl — out of 1900 original

About 3/4 of known reserves in the Middle East — reason for US interest in political & economic stability of this region

Total reserves, including undiscovered, could be up to 2000 bbl = 12,000 quads

Current production 20 bbl / yr ⇒

About 100 more years

But remember that consumption is increasing at 3% per year

World reserves of natural gas:

World-wide 8100 tcf = 8100 quads

Also about 100 years supply at current rates

Coal: even greater reserves

US riches in this case

Fig 8.37 adds to 1100 Gt but could be as high as 3000 Gt

some estimates of "ultimately recoverable" coal as high as 6700 Gt

3000 Gt coal = 80,000 quads

Bodansky says 10,000 – 12,000 quads

Most coal in Russia, US, China
(in that order)

At current consumption rate will last

$$\frac{3000}{5.2} = \underline{500-600 \text{ years}}$$

For US alone (~ 1/4 – 1/5 of world supply)

Proven reserves

$$\frac{276 \text{ Gt}}{\cancel{0.7}\ \overset{}{\underset{0.9}{}} \text{ Gt/yr}} \sim \overset{300}{\cancel{400}} \text{ years}$$

Subeconomic sources — petroleum that has not been cooked enough to be pumped.

Too viscous, or may be trapped in original impermeable shale source rock.

Tar sands, oil shales, heavy oils

New extraction techniques required

But reserves are huge.

Current production rates miniscule because of expense.

But will become more important in future

Estimates vary — but maybe as high as

20,000
[illegible] bbl oil equivalent

This 10 times [illegible] times as much as pumpable oil = [illegible] 120,000 quads

Total remaining — all sources:

oil	12,000	quads
gas	8,000	quads
coal	80,000	quads ← some say its 4 x this
other	120,000	quads
	220,000	quads

Current consumption rate

350 quads / yr ⇒ 600 [illegible] years

So — the bottom line — are we about to run out of fossil fuel energy?

No, though projections are uncertain

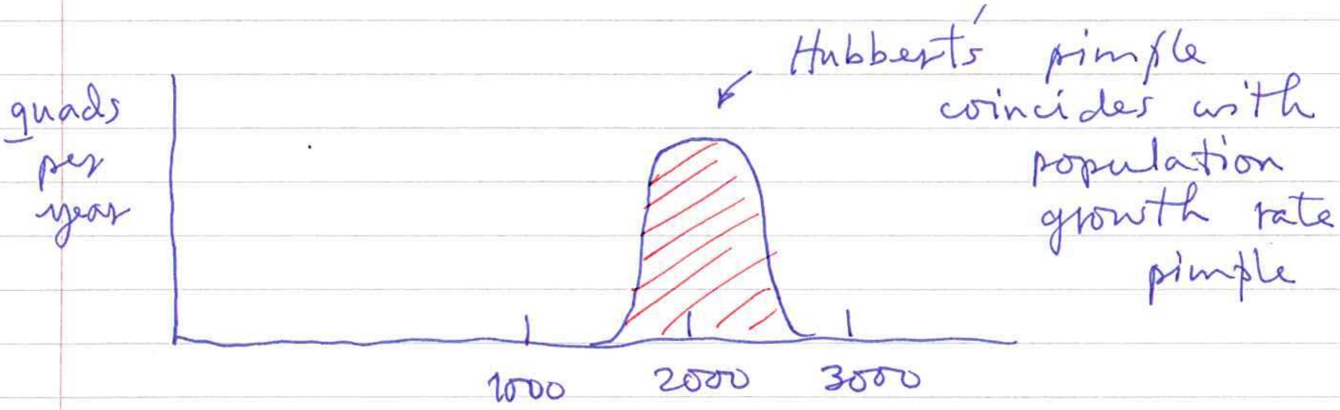
220,000
~~130,000~~ ← both uncertain

350 ← may increase due to rising GNP
or decrease by conservation measures

16.1

A few years ago, projections (by environmentalists) were much more dire.

M. King Hubbert — plot of energy consumption



Hubbert's pimple coincides with population growth rate pimple

Hubbert thought the peak would be before now — writing in 1976. He thought would peak at $55 \cdot 10^{12}$ kW/yr = 190 quads/yr. Now known that we have a few hundred years to adapt to a non-fossil-fuel world.

He thought oil consumption would peak at more than 40 bbo/yr about now — in fact demand has stayed at 1976 levels 22 bbo/yr

From a geological perspective Hubbert's pimple is a reality

In a few hundred years we will completely deplete the fossil fuel resources that the ⊕ took 1 billion years to produce

16.2 ~~[illegible]~~

In fact Hubbert made a much more pessimistic estimate.

He based his analysis on the recovery cost per barrel.

On this basis he thought the oil production was showing signs of decline in 1974 - 76 when he did his work

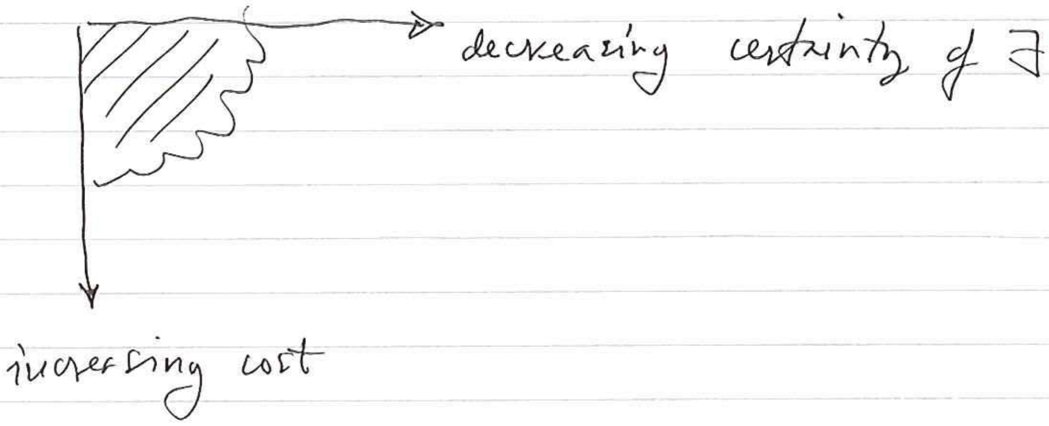
He thought the maximum production rate would bend over in 1995

Thought we would "run out" in 2025 - 2050.

Total supply remaining in 1996, according to his analysis, ~ 1000 bbls

More recent estimates ~ 2000 bbls.

It all depends on where you draw the line "recoverable resources"



Oil shale — again it all depends on how much effort it is to recover.

Yields — using retort methods (heat the shale and extract the organic component in liquid form in an above-ground retort — also can heat in situ) range from 5 – 100 gallons of oil per ton of shale

the extraction process — we simply cook it some more

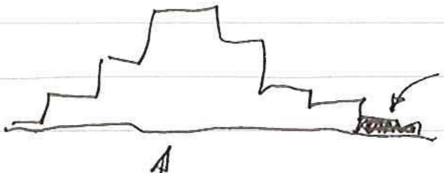
The US is rich in these shale oil resources

Most intensively explored is Green River Formation in Colo, Utah, Wyoming

Show Table 4 & Table 5 from article by Hinman

If it could be extracted shale oil in US reserves could supply US needs for centuries

25 gallons of oil / ton of shale
⇒ 8% organic matter by weight



just this — about 1% of total

mean 1%

Let's view this — in closing — in the context of the global C cycle as a whole.

At present ~ 65 Gt of C fixed / yr

0.1 – 0.2 Gt of C buried per year

Total amount of <u>organic C</u> in shales:

× 75% ← % of organic matter that is C – rest is mostly H

1% × total mass of shales
= $2 \cdot 10^7$ Gt

By comparison $CaCO_3$ in limestones ~ $5 \cdot 10^7$ Gt

↑
inorganic carbon

$CaCO_3 = 40 + 12 + 3(16) = 100$

C is 12% of $CaCO_3$

<u>Shales are ~ 95% of all sediments</u>

$(0.95)(0.01)(\frac{2}{7})$

↑ $\frac{2}{7}$ of C in shale

3% of all seds are limestone + dolomite

$\approx (0.03)(.12)(5/7)$

↑ $\frac{5}{7}$ of all C in carbonates

Not bad!

According to [illegible] Sarmiento & Siegenthaler the repository of buried carbon in the ⊕'s crust is:

organic C (coal + oil $\overset{\text{mostly}}{\text{shale}}$) $2 \cdot 10^7$ GtC

$(Ca, Mg)CO_3$ (limestone + dolomite) $5 \cdot 10^7$ GtC

See the calculation on page 18 showing that this checks

How much total C in oil shale (and coal)?

$$\text{Total} = 2 \cdot 10^7 \text{ GtC} = \frac{2}{0.75} \cdot 10^7 \text{ Gt oil}$$

$$= 2.7 \cdot 10^7 \text{ Gt oil}$$

$$= \underline{2 \cdot 10^8 \text{ bbo}}$$

1 barrel = 0.137 ton

$$= 2 \cdot 10^{17} \text{ barrels}$$

top 1% in grade amounts to $2 \cdot 10^6$ bbl

Conventional estimates of the amount that can be exploited commercially more like

20,000 bbl — with ~3000 in NAM

$2 \cdot 10^4$ bbl

↑ only about 1% of the top 1%

Present-day erosion — and thus organic C burial — rates are ~~probably~~ higher [illegible] than in the past due to anthropogenic effects — recall study of Huang He River in China.

But if today's rate were typical, it would have taken

$$\frac{2 \cdot 10^7 \text{ GtC}}{0.2 \text{ GtC/yr}} = 100 \text{ million years}$$

(Jorge says this better

this is the residence time

to bury all the organic C at today's rates

also some of it must be <u>unburied</u>: oil seeps, etc.

Today's erosion rates ~ twice pre-human rates ⇒ 200 million years — consistent with Fig. 11.2 showing age distribution of oil-bearing rocks 58% are Cenozoic (< 70 m.y. old)

This looks about right — if today's rates are a factor of 10 higher than pre-human we get 1-2 billion years.

<u>Roughly</u>:

- $\frac{1}{\text{every } 500}$ C atoms fixed by phytoplankton each year are buried
- $\frac{1}{\text{every } 100{,}000}$ of those get "cooked" just right and are trapped in <u>pumpable</u> reservoirs of oil
- however $\frac{1}{\text{every } 10{,}000}$ reside in commercially exploitable oil shale

Energy units

Table 1. Conversion of units.[a,b]

General

1 short ton (ton) = 2000 lb = 0.907185 tonne
1 metric ton (tonne) = 1000 kg
1 barrel = 42 U.S. gallons = 159.0 litres

1 Btu (British thermal unit) = 1055 J (Joules)
1 kWh (kilowatt hour) = 3.6 MJ = 3412 Btu
1 kWh of electricity requires on average 10,253 Btu to produce, corresponding to a mean thermal efficiency of 33% (1988 U.S. fossil-fuel average)

Large units

1 quadrillion Btu = 10^9 MBtu = 10^{15} Btu
1 exajoule (EJ) = 10^3 PJ = 10^{12} MJ = 10^{18} J
1 terawatt-yr (TWyr) = 10^9 kWyr
= 8.76×10^{12} kWh

	Quad	EJ
1 Quad	1.000	1.055
1 EJ	0.948	1.000
1 TWyr (100% conversion)	29.89	31.54
1 TWyr (33% efficiency)	90.6	95.6
10^9 tonne coal equiv (Gtce)	27.76	29.29
10^9 barrel oil equiv (bboe)	5.80	6.12
10^9 tonne oil equiv (Gtoe)	42.43	44.76
10^9 tonne oil equiv (Gtoe)[c]	39.69	41.87

Fuel values

1 barrel of crude oil = 0.137 metric ton
1 million barrels per day of crude oil
= 2.12 quad/yr = 2.23 EJ/yr

	MBtu	GJ
Nominal or standard equivalents:		
1 barrel of crude oil (boe)	5.8	6.12
1000 cu. ft. of natural gas	1.000	1.055
1 short ton of coal	25.18	26.57
Average heat content (U.S. 1988):		
1 barrel of petroleum products	5.408	5.705
1000 cu. ft. of natural gas	1.029	1.086
1 short ton of coal	21.53	22.72
1 cord of dry wood (1.25 ton)	21.5	22.7
1 barrel of natural gas liquids	3.812	4.022
1 barrel of aviation gasoline	5.048	5.326
1 barrel of motor gasoline	5.253	5.542
1 barrel of distillate fuel oil	5.825	6.145
1 barrel of residual fuel oil	6.287	6.633

---

a. Adopted from Ref. 1.

b. Based on *Annual Energy Review* 1988 (Ref. 2), *Monthly Energy Review* (Ref. 3), and IIASA report (Ref. 4).

c. Alternate equivalent, used by OECD (Ref. 5).

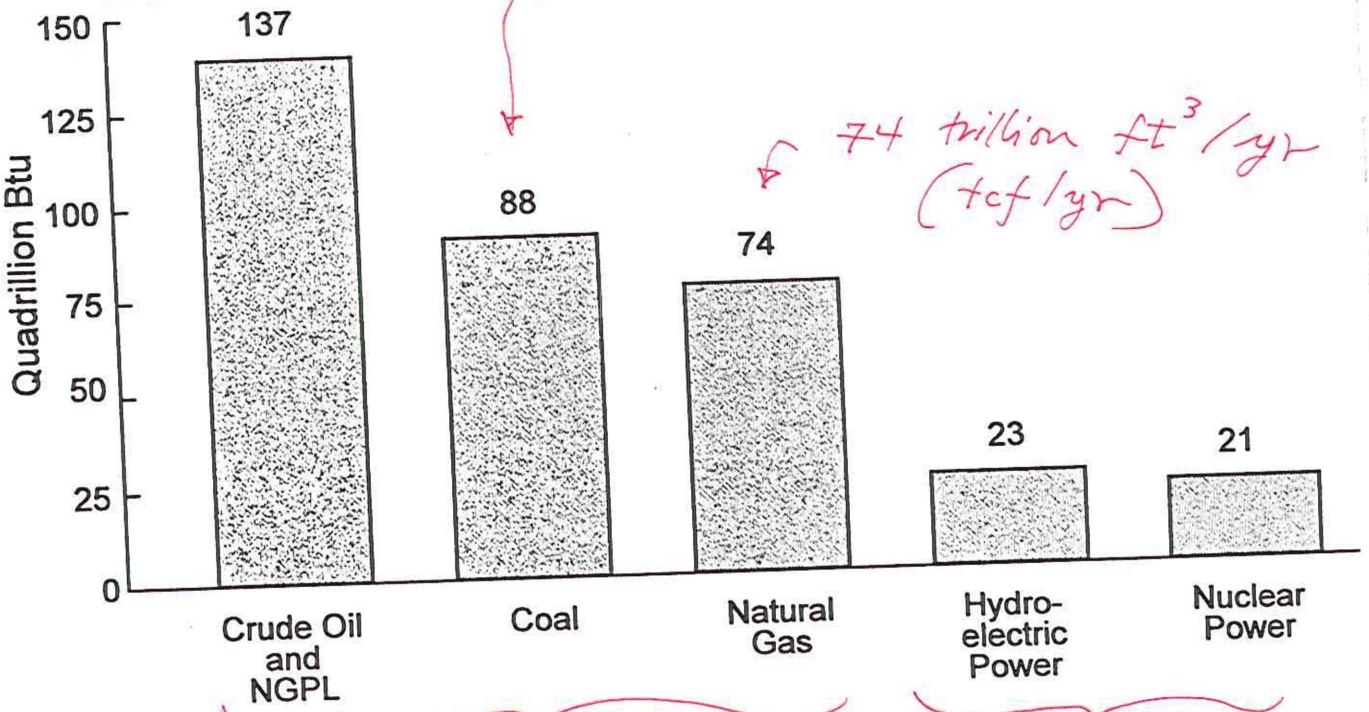


Figure 8.31. The major sources of world energy in 1992. (*Annual Energy Review 1993*)

22 billion oil barrels/yr (22 bbl/yr)

3 Gt coal/yr

74 trillion ft^3/yr (tcf/yr)

87% fossil fuel

13% hydroelectric & nuclear

sum to 343 quads/yr

increasing at 2.7% / yr

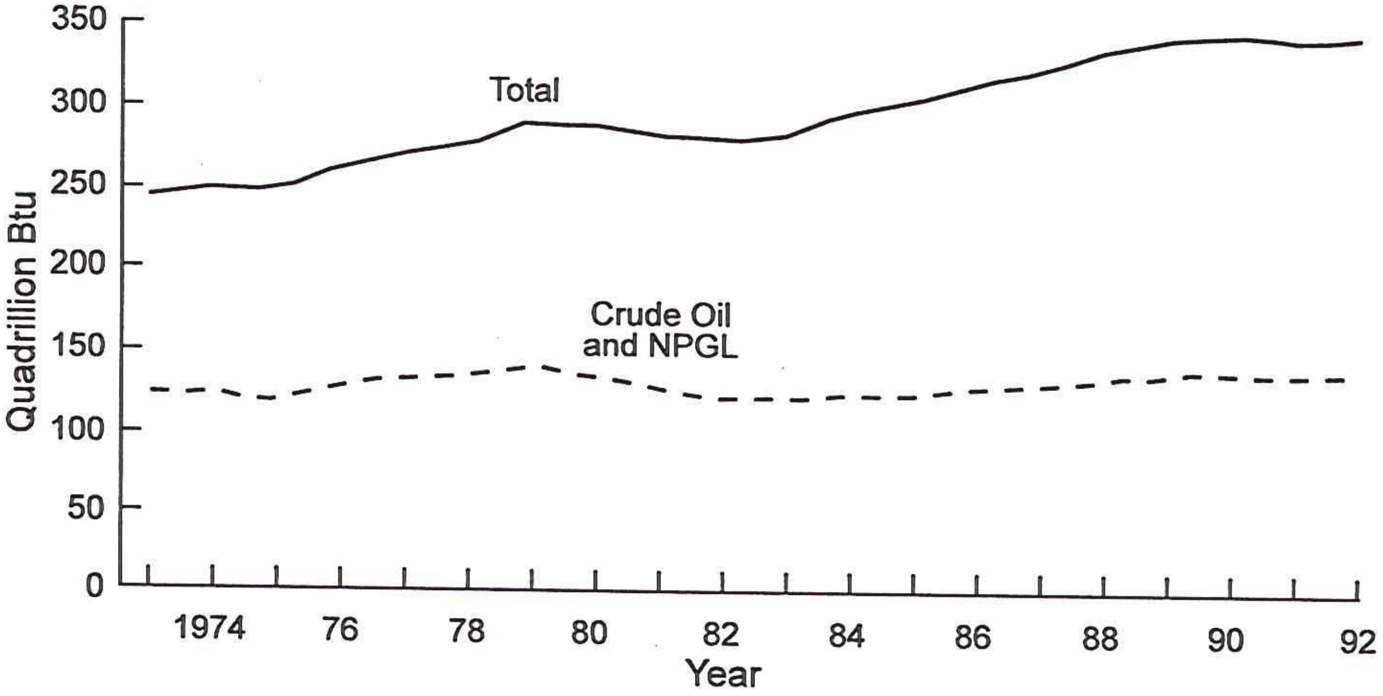


Figure 8.30. World primary energy production between 1973 and 1992. (*Annual Energy Review 1993*)

nuclear power is the fastest growing world-wide — slowed to a standstill in US.

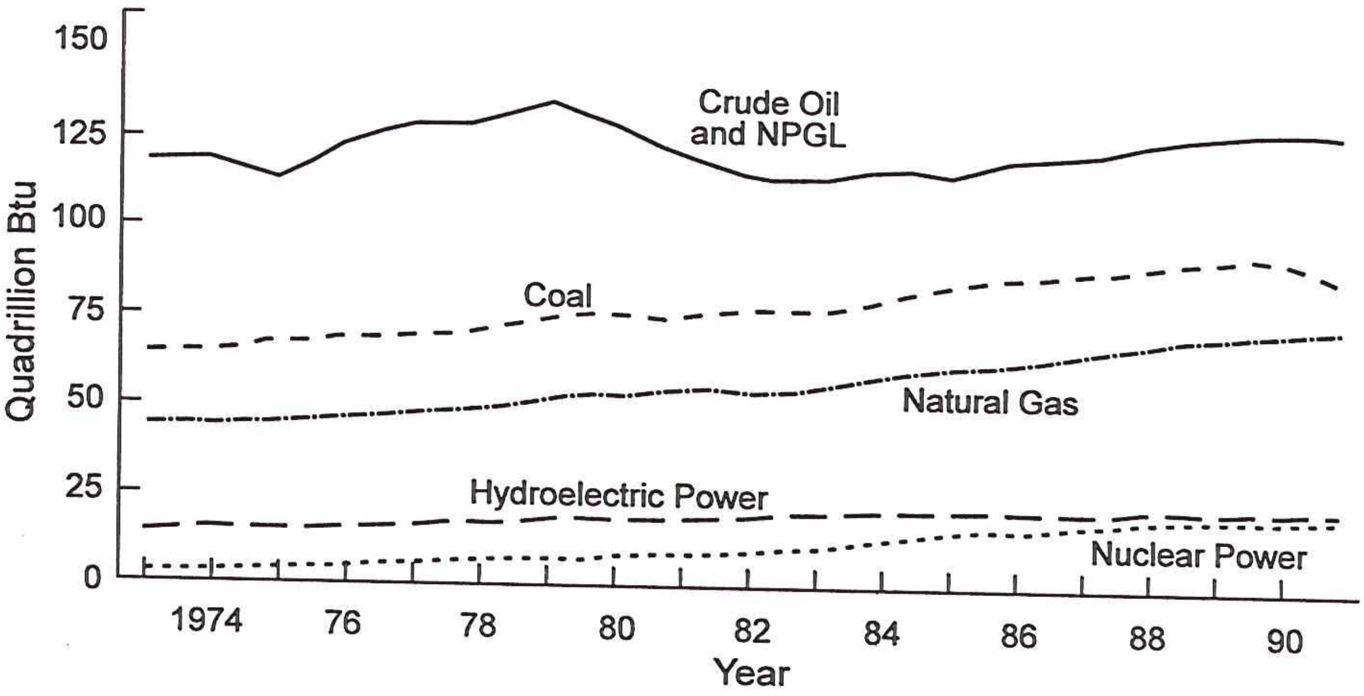


Figure 8.32. World primary energy production by source between 1973 and 1992. (*Annual Energy Review 1993*)

US with 5% of population consumes 20% of world's energy

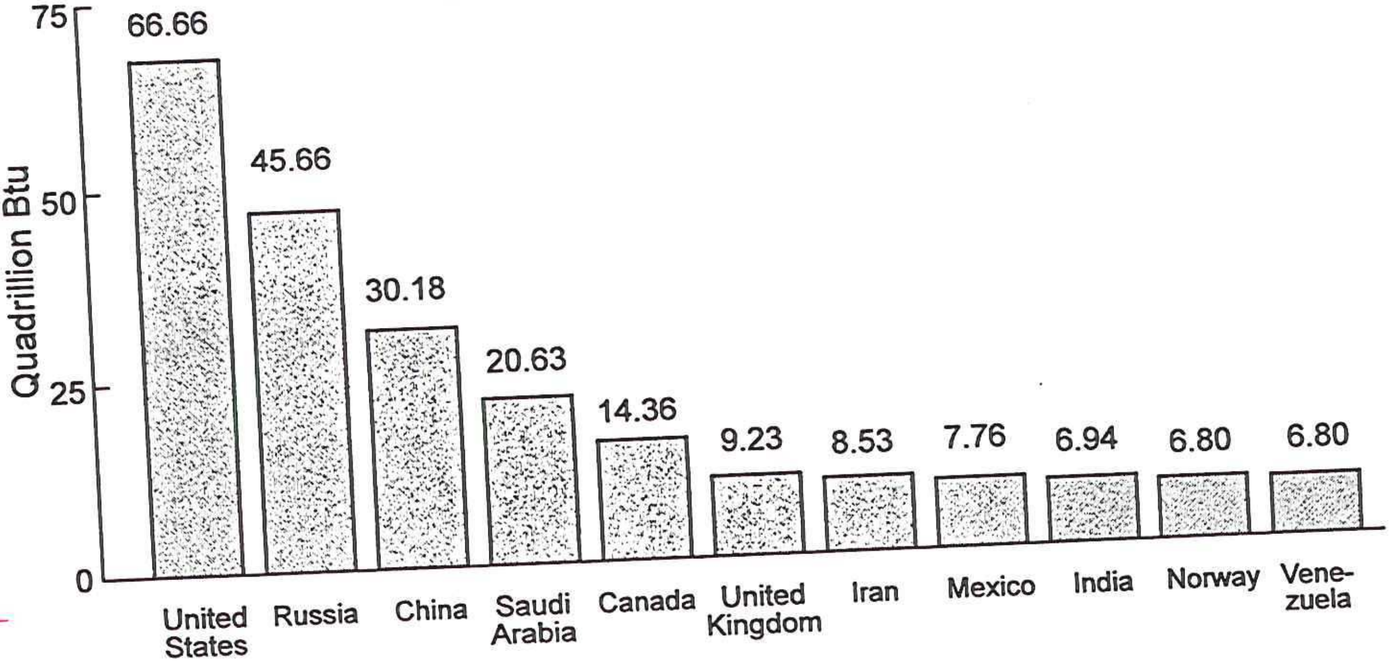


Figure 8.33a. The eleven major primary energy-producing countries in 1992. (*Annual Energy Review 1993*)

China 20% of world's population only 10% of world's energy — but increasing rapidly

US consumption of energy exceeds "production"

effect of oil embargo

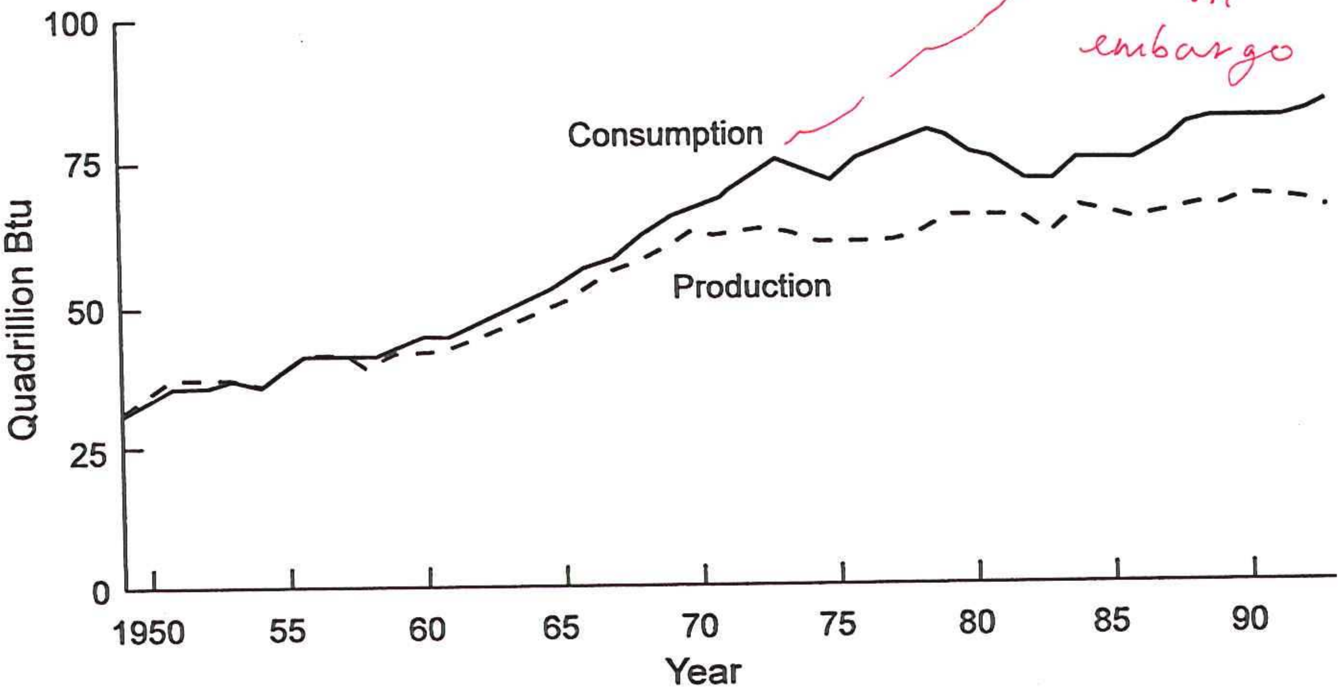
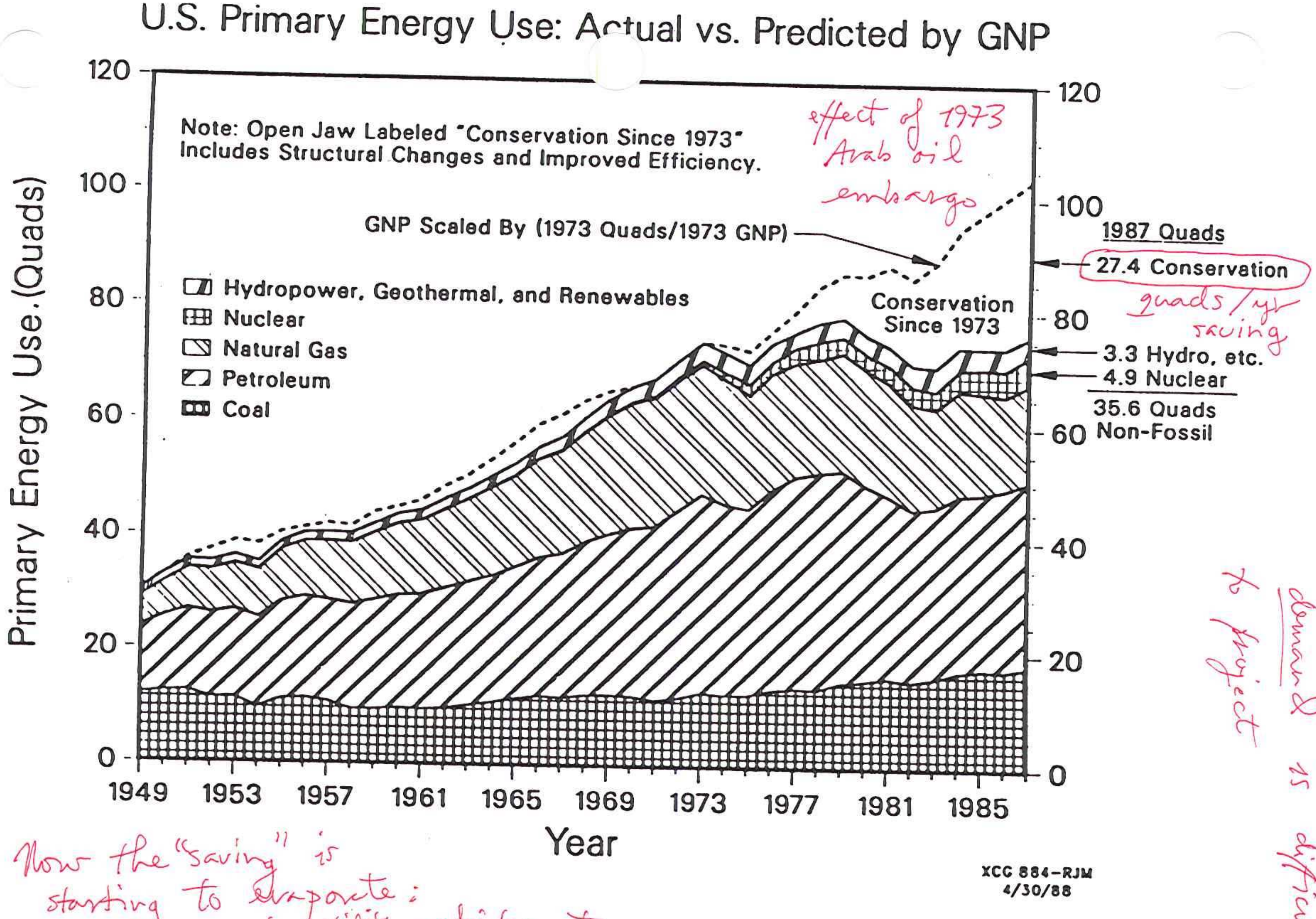


Figure 8.26. The production and consumption of energy in the United States between 1949 and 1993. (*Annual Energy Review 1993*)



Now the "saving" is starting to evaporate: sports utility vehicles, etc.

This shows that future demand is difficult to project

Source: *Economic Report of the President*, Council of Economic Advisors, January 1988, and *Annual Energy Review 1987*, EIA.

Figure 1. U.S. primary energy use: Actual vs predicted by GNP. (Source: Economic Report of the President, Council of Economic Advisors, January, 1988, and Annual Energy Review 1987, EIA. Figure courtesy of Lawrence Berkeley Laboratory, LBL.)

← US oil consumption is twice this:
27% of world total

6.9 · 10^6 barrels /day
= 2.5 billion barrels /year ← call this $\boxed{3 \text{ billion}}$
= 15 quads/yr produced

↙ Saudi Arabia major supplies of oil

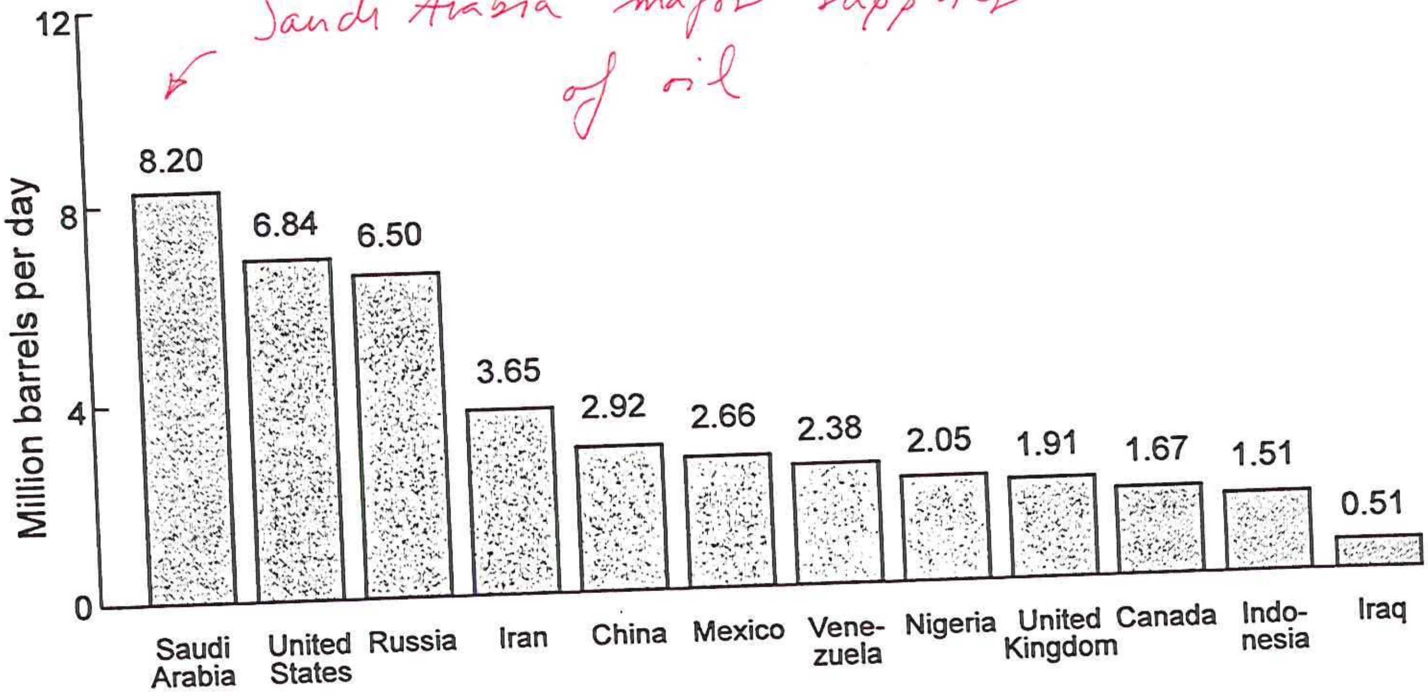


Figure 8.40. 1993 oil production by the twelve most important oil-producing countries. (*Annual Energy Review 1993*)

Most natural gas is consumed locally

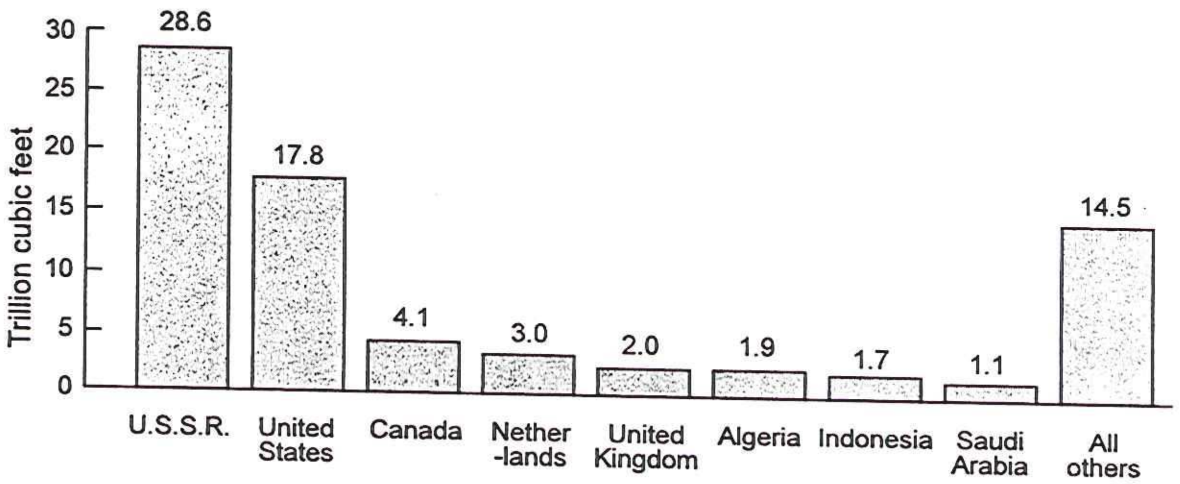


Figure 8.42. The major producers of natural gas in 1991. (*Annual Energy Review 1993*)

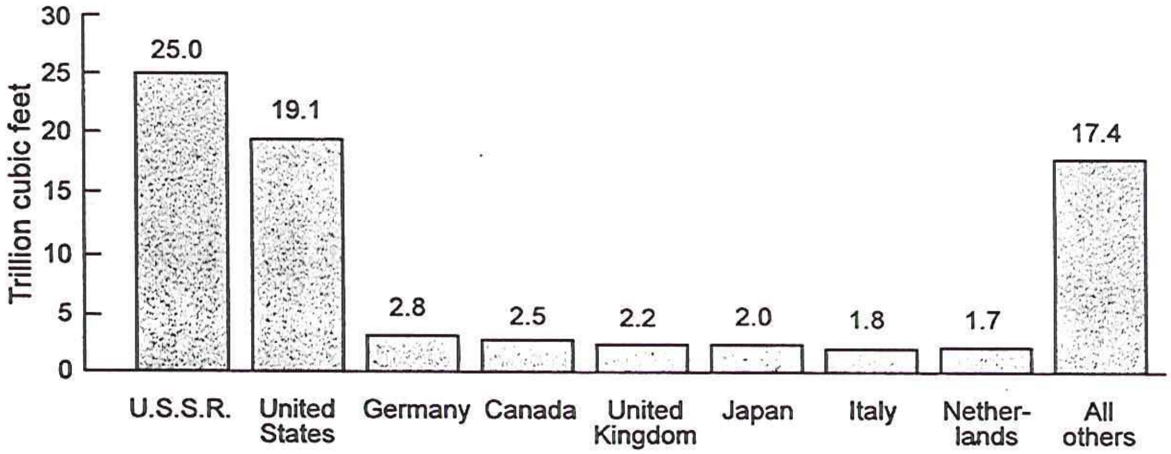


Figure 8.43. The major consumers of natural gas in 1991. (*Annual Energy Review 1993*).

ditto coal

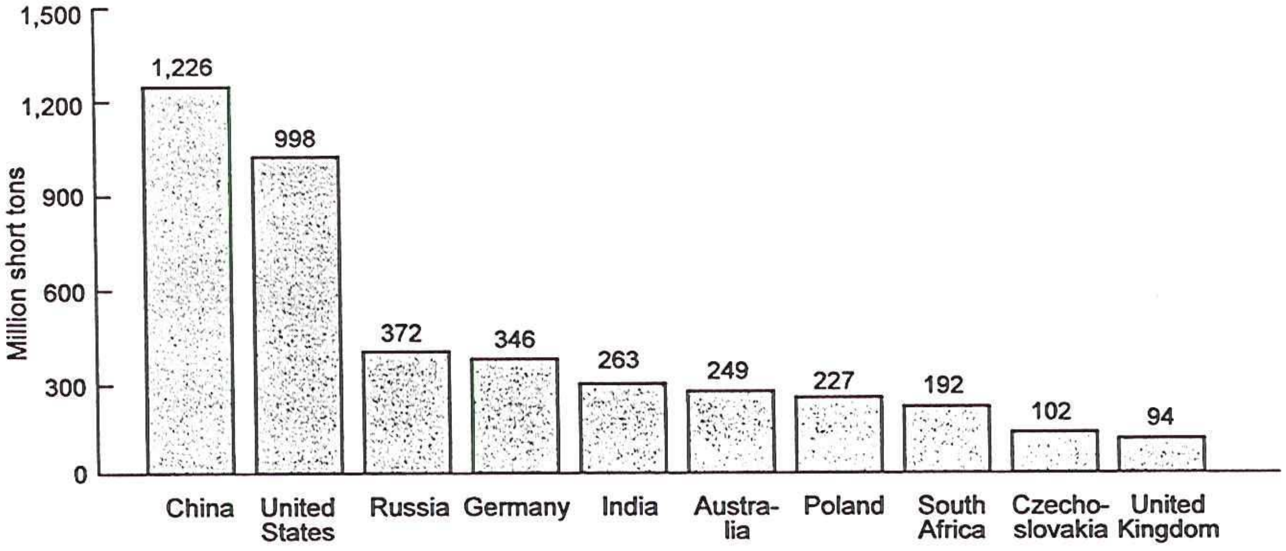


Figure 8.34. 1992 production of coal in the ten leading countries. (*Annual Energy Review 1993*)

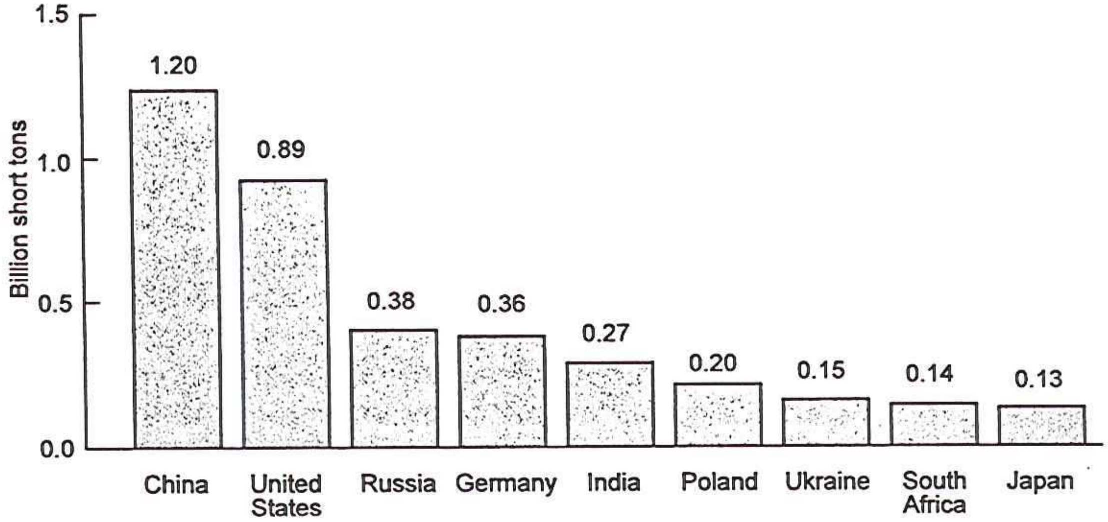


Figure 8.35. 1992 consumption of coal in the nine most coal-consuming countries. (*Annual Energy Review 1993*)

China is using its plentiful coal reserves to fuel its industrial expansion

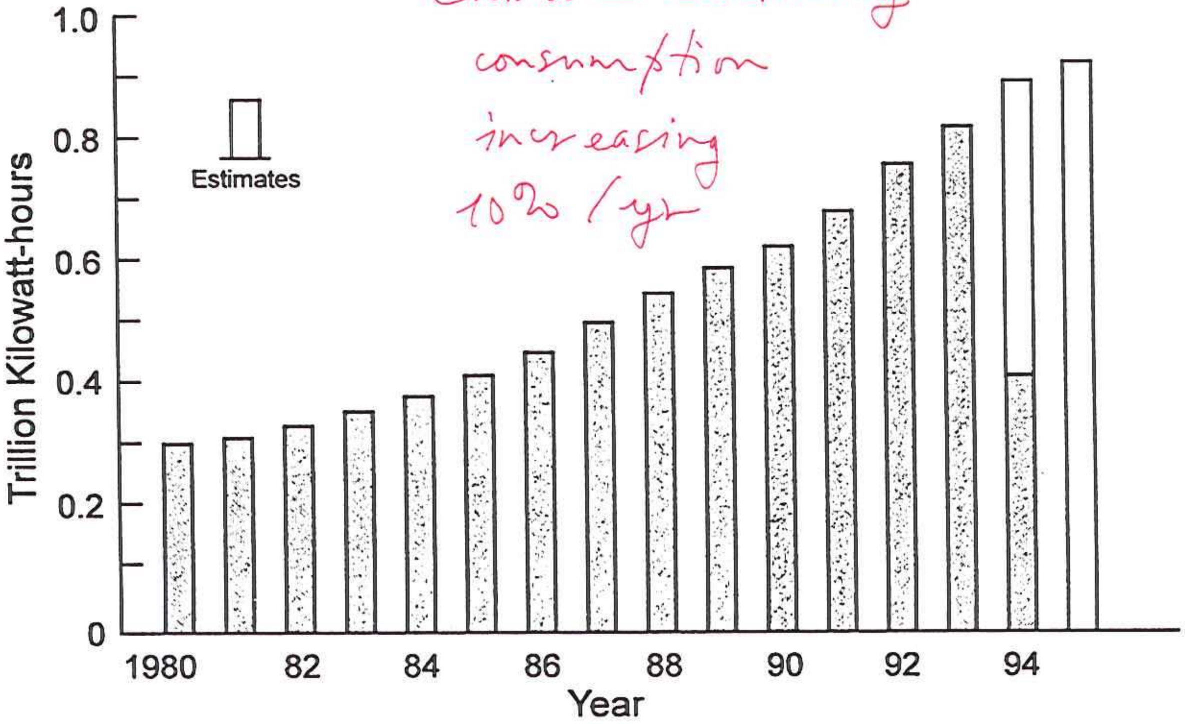
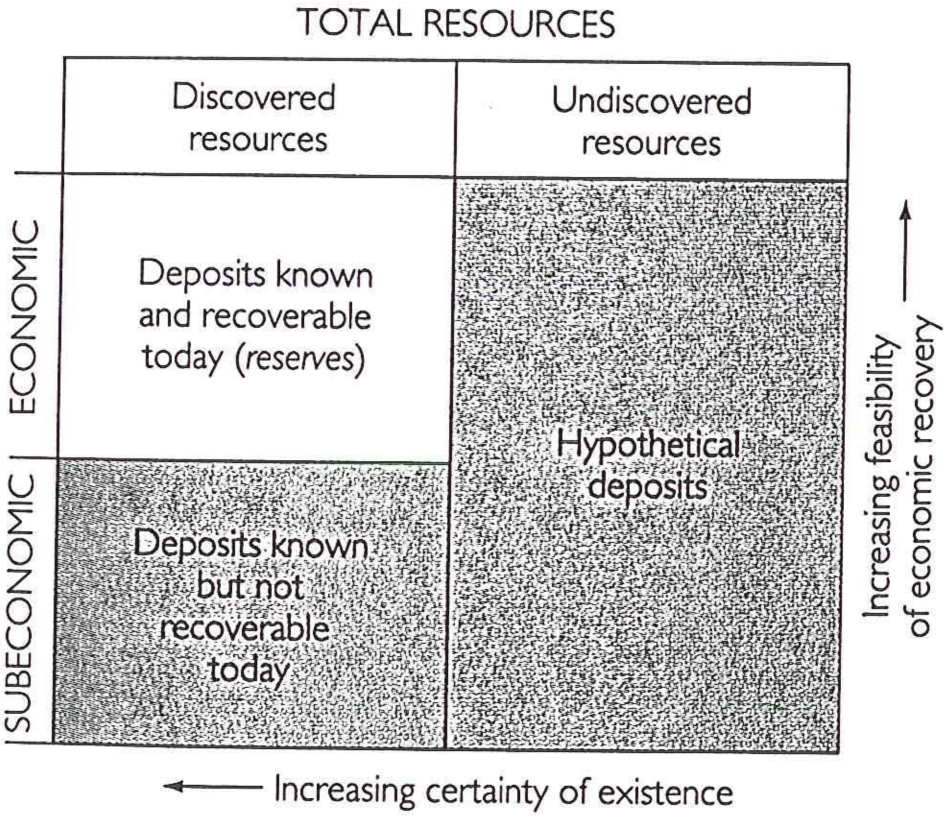


Figure 8.33b. Electricity generation in China since 1980. (*New York Times*, November 7, 1994)

China — electricity consumption increasing 10% / yr


TOTAL RESOURCES
Discovered resources
Undiscovered resources
ECONOMIC
SUBECONOMIC
Deposits known and recoverable today (*reserves*)
Deposits known but not recoverable today
Hypothetical deposits
Increasing feasibility of economic recovery
Increasing certainty of existence

THE NEW YORK TIMES, FRIDAY, NOVEMBER 22, 1996

US consumes 5 bbo/yr

Petrobrás Finds Big Deep-Water Oilfield

By AGIS SALPUKAS

Petrobrás, the state-owned Brazilian oil company, said yesterday that an oilfield in very deep water contained reserves of about 1.3 billion barrels of oil, more than double previous estimates, making it one of the largest discoveries in recent years.

"This is a major field," said Mary Quinn, an analyst who follows the oil industry in Latin America for SBC Warburg Inc.

She said that if the field was brought into production, this could further help cut Brazil's need to import oil. That, in turn, would add to world supplies. But she noted that the field was beneath about 6,100 feet of water, so pumping oil to the surface would pose a major technological challenge.

Petrobrás, however, has been a pioneer in producing oil from deep water off the coast of Brazil and has teamed up with the Shell Oil Company, a pioneer in deep-water development and a unit of the **Royal Dutch/Shell Group**, to meet the technolgical challenges.

The increasing flow of oil from Latin America, particularly from Venezuela and Colombia, has blunted efforts by the Organization of Petroleum Exporting Countries to keep up the price by keeping its production quota at 25 million barrels a day.

Latin America has become increasingly important as a supplier to the United States, whose dependence on imports has been rising as domestic production, particularly from Prudhoe Bayin Alaska, has been declining.

The Petrobrás field is about 80 miles off the coast of the state of Rio de Janeiro.

With an estimated 1.3 billion barrels in reserves, the Petrobrás field is the largest discovery since the Cusiana and Cupiagua fields were discovered in Colombia in 1991. That find, in turn, was the largest since Prudhoe Bay in 1968.

Petrobrás, whose formal name is Petróleo Brasiliero S.A., had estimated last month that the field could hold reserves of 400 million to 600 million which it now has more than doubled.

"This is a new frontier for Petrobrás," said Daniel Oliveira, the financial manager in New York of the oil company. He said it was too early to say whether Petrobrás would go ahead with the huge costs and technical challenges of bringing the field into production.

"The prospects are very good," he said, since the oil is of much higher quality than the heavy crude oil from neighboring fields in the Campos Basin, where Petrobrás has brought up oil from wells deep under water.

The higher-quality oil commands a higher price in world markets, providing an added incentive for Petrobrás to make the investment needed to bring the field into production.

Table 1. United States oil resources (in billions of barrels).

Orignal proven conventional recoverable resources	226	
Already produced	142	
Remaining	84	
Estimated undiscovered resources	46	
Domestic production (per year)	3	note imbalance
Domestic consumption, including imports (per year)	5.5	
Years left. under current production conditions, and no increase in imports	28–43	

Note 1: If imports decrease or use increases, the number of years left will be smaller.

Note 2: As supplies shrink, increasing costs will decrease use, so reserves will increase number of years left.

rate at which US is finding new gas "plays"

Table 2. United States natural gas resources (in trillions of cubic feet).

Proven conventional recoverable resources (including Alaska, and at less than $5 per thousand cubic feet)	384
Production rate (per year)	17
Recent yearly addition to proven recoverable resources	14–15
Estimated total remaining conventionally recoverable resources (lower 48)	400–900
Estimated unconventional recoverable resources (price of recovery not determined, but probably high)	140–700
Total estimated resources	540–1600
Years left at current rate	35–95
Years left at double current rate	17–47

Note: Current cost of natural gas is about $1.70 per thousand cubic feet.

Table 3. Global resources.

Oil (in billions of barrels)		
Original resources		1900
Produced	Many say 2000 bbo	673
Remaining	(12,000 quads) left →	1227
Production (per year)		21
Years left at current rate		60
Note: Undiscovered and unconventional resources could approximately double the total supplies, but at undetermined cost.		
Natural gas (in trillion of cubic feet)	Many say more than	
Estimated remaining resources	10,000 tcf (10,000 quads) →	8100
Production rate (per year)	left	
Years left at current rate		120

Table 3. Global resources.

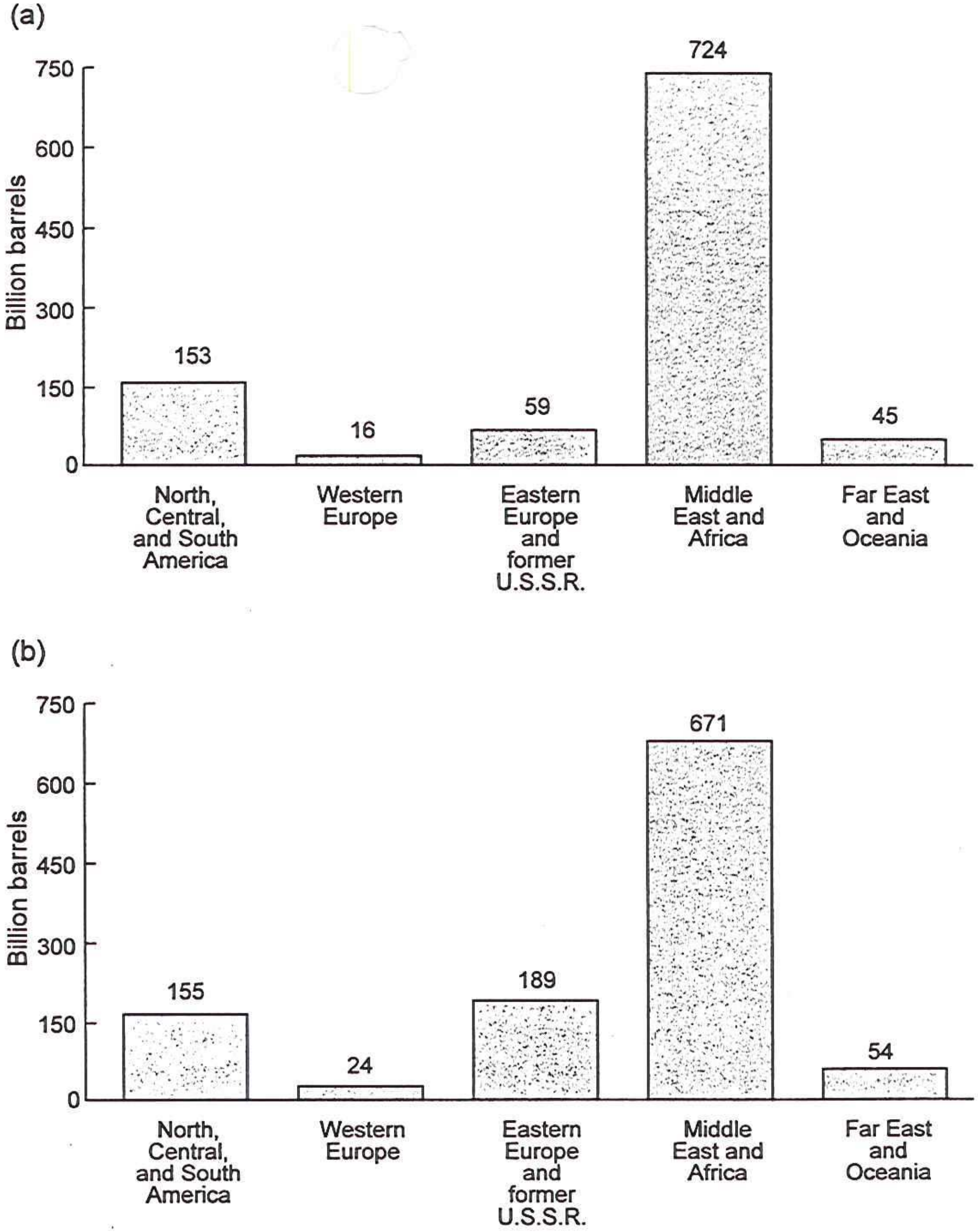
Natural gas (in trillion of cubic feet)	
Estimated remaining resources	8100
Production rate (per year)	
Years left at current rate	120

Table 3. Global resources.

Oil (in billions of barrels)	
Original resources	1900
Produced	673
Remaining	1227
Production (per year)	21
Years left at current rate	60

Note: Undiscovered and unconventional resources could approximately double the total supplies, but at undetermined cost.

Figure 8.41. The distribution of world oil reserves in 1993. Sources (a) *Oil and Gas Journal*; (b) *World Oil*. (*Annual Energy Review 1993*)



The New York Times

Founded in 1851

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America's Energy Independence

The worldwide scramble to develop new and existing energy sources has become a driving force in contemporary foreign policy. The Clinton Administration, building on America's dual role as the world's largest energy producer and largest energy consumer, has made itself a main player in this new world energy game, promoting increased production at home and abroad. Its sensible goal is to lessen the country's vulnerability to pressures from energy exporters and protect Washington's freedom to make foreign policy based on larger American and global interests.

Global energy supplies are not tight now, but demand is rising quickly, especially in areas of robust economic growth, like the United States, China and Southeast Asia. Last year, the world consumed just over 70 million barrels of oil every day. That is projected to rise to nearly 105 million barrels by 2015. Proven worldwide reserves are now about one trillion barrels, a figure that tends to rise over time with new exploration, cheaper extraction methods and changes in price.

America's daily oil consumption was just over 18 million barrels last year, up nearly 10 percent from 1991. Without significant new gains in conservation and efficiency, the United States can be expected to consume more than 22 million barrels by 2015. Imports have been rising even more sharply, and now account for just over half the oil the country uses.

NYT data
1997
70x365=
26 bbo/yr
US alone
7 bbo/yr
proven
reserves
1000 bbo

The Administration is right to emphasize developing new low-cost foreign sources. The United States learned the perils of overdependence on Persian Gulf supplies during the 1970's Arab oil embargo.

But there is no strategic justification for the favors, like reduced royalty payments, that the Administration and Congress have been lavishing on domestic producers. The United States can retain its energy independence while relying on foreign sources of supply, leaving much of its own untapped wealth in the ground as a strategic reserve. The Administration has also failed to focus on more efficient use of existing energy supplies and on stronger conservation efforts, whether through taxes, regulation or market-based incentives.

Diversification is not the only motive behind the race for new supplies. There is worry that prices will rise if global consumption grows as rapidly as predicted. Meanwhile, the investment climate has been transformed by political changes in oil regions, like the collapse of Communism in Russia and the Caspian Basin and Latin America's more welcoming attitude toward foreign investment.

The Administration's policies have produced good results in Venezuela, from which the United States now imports more oil than it does from Saudi Arabia. Since 1995, American companies have helped Venezuela sharply increase its production capacity. Washington has promoted business partnerships with Russia's oil and gas industry, in the hope that American technology will help Russia pump more energy at lower cost from aging wells.

Washington has also been wooing the newly independent governments of the Caspian Basin, like Azerbaijan, Georgia, Kazakhstan and Turkmenistan, all of which sit astride rich energy deposits or vital pipeline routes. Rightly, it has pressed the case of American companies seeking a share of Caspian energy rights, encouraged the removal of regulatory obstacles and sought consistent standards for cross-border pipeline routes.

But except for Georgia, Caspian area governments have shown scant tolerance for democracy and human rights and have tried to use their leverage with Washington to deflect American pressures on these issues. The Administration should be cautious about the tradeoffs it makes to smooth access to oil. One aim of energy independence is to gain more freedom to pursue larger national goals. Washington should not subordinate these goals to a mindless rush for new energy suppliers. □

US has $\frac{1}{4}$ to $\frac{1}{5}$ of world's supply

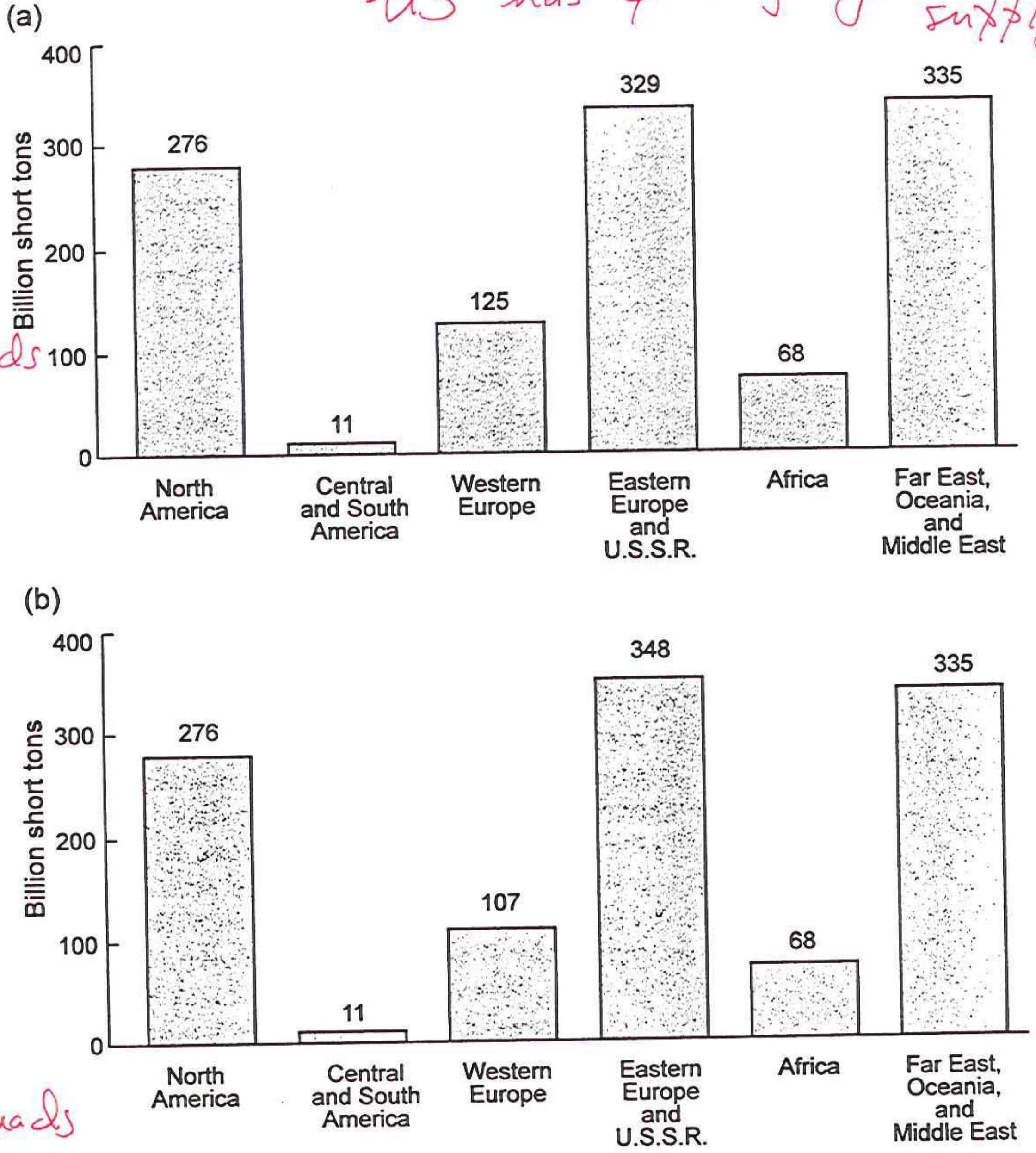


Figure 8.37. World reserves of coal estimated by (a) the World Energy Council, 1991; (b) British Petroleum, 1992. (*Annual Energy Review 1993*)

← 30,000 quads

adds to 1100 Gt of coal but some estimates of "ultimately recoverable" coal are as high as 3000 – 4000 Gt of coal

⇒ 80,000 – 110,000 quads

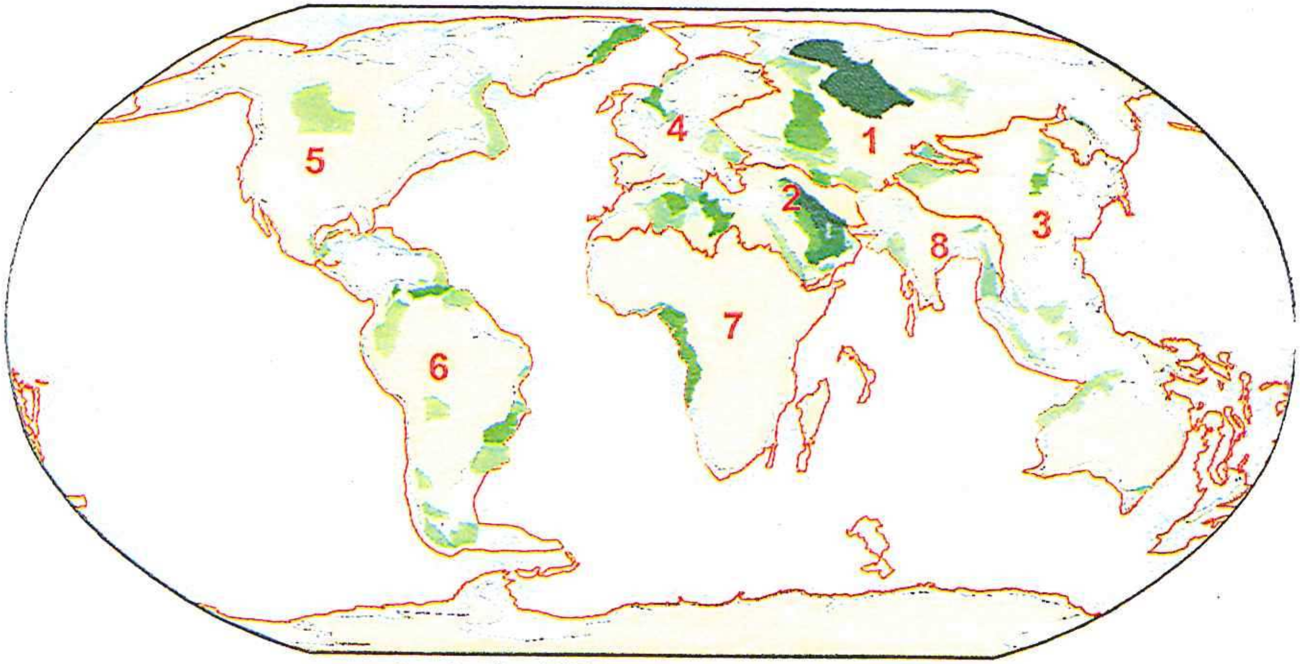
World Petroleum Assessment 2000:

Excluding the United States, the estimated mean (expected) volumes of undiscovered resources are 649 billion barrels of oil (BBO), 778 billion barrels of oil equivalent (BBOE) or 4,669 trillion cubic feet of gas (TCFG), and 207 billion barrels of natural gas liquids (BBNGL).

The estimated mean additions to reserves from discovered fields (potential reserve growth) are 612 BBO, 551 BBOE or 3,305 TCFG, and 42 BBNGL. Compared to the 1994 USGS world petroleum assessment, undiscovered volumes from the 2000 assessment are 20 percent greater for oil, 14 percent smaller for gas, and 130 percent greater for natural gas liquids. This study offers the first USGS assessment of large estimated volumes of oil, gas, and natural gas liquids from reserve growth at the world level.

The estimated volume of undiscovered oil is more than that of the 1994 assessment, due in part to larger estimates for the Middle East and Atlantic offshore portions of South America and Africa. However, in some areas the estimated volumes of undiscovered oil were smaller, particularly for Mexico and China.

World Oil Assessment 2000

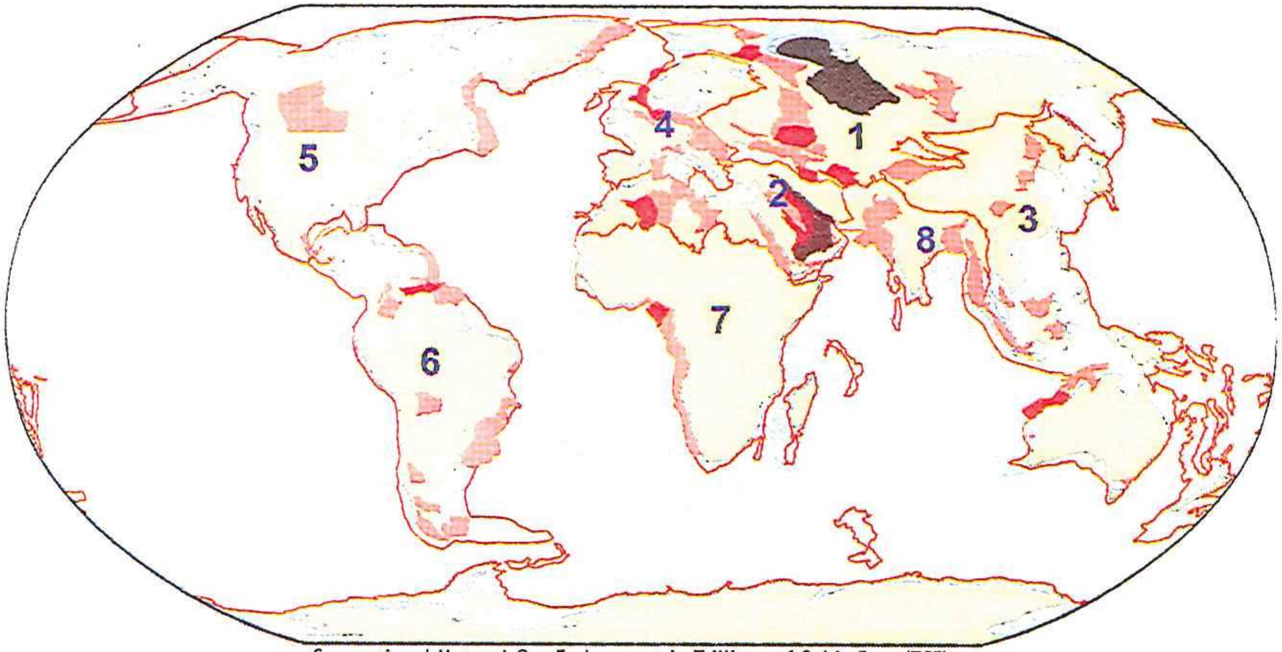


Conventional Natural Oil Endowment in billions of barrels of oil (BBO)

🟩 Less than 1 BBO
🟩 6-20 BBO
🟩 20-40 BBO
🟩 40-80 BBO
🟩 80-160 BBO

World Gas Assessment 2000

1 Former Soviet Union
2 Middle East and North Africa
3 Asia Pacific
4 Europe
5 North America
6 Central and South America
7 Sub-Saharan Africa and Antarctica
8 South Asia



Conventional Natural Gas Endowment in Trillions of Cubic Feet (TCF)

Less than 6 TCF
6-120 TCF
120-240 TCF
240-480 TCF
480-960 TCF
Greater than 960 TCF

Table 6. Composition and pyrolysis products of typical Colorado oil shale.[a]

Mineral constituents

Mineral	Weight percent of minerals
Dolomite	32
Calcite	16
Quartz	15
Illite	19
Low-albite	10
Adularia	6
Pyrite	1
Acalcime	1
Total	100

Ultimate analysis of organic constituent

Element	Weight percent of organics
Carbon	76.5
Hydrogen	10.3
Nitrogen	2.5
Sulfur	1.2
Oxygen	9.5
Total	100.0

Yields from Fischer assay pyrolysis

Decomposition product	Weight percent of organic constituent in raw shale	Weight percent of total raw shale
Oil	63	10.4
Noncondensable gas	15	2.5
Fixed-carbon residue	13	2.2
Water vapor	9	1.4
Total	100	16.5

15% organic matter by weight

[a] Pyrolyzed by the standard Fischer assay at 932 F: oil yield = 26.7 gal/ton.

Source: T.A. Sladek, "Recent Trends in Oil Shale—Part 1," *Mineral Industries Bulletin,* Vol. 17, No. 6, November, 1974, pp. 4–5. As reported in Reference 10, Table 16.

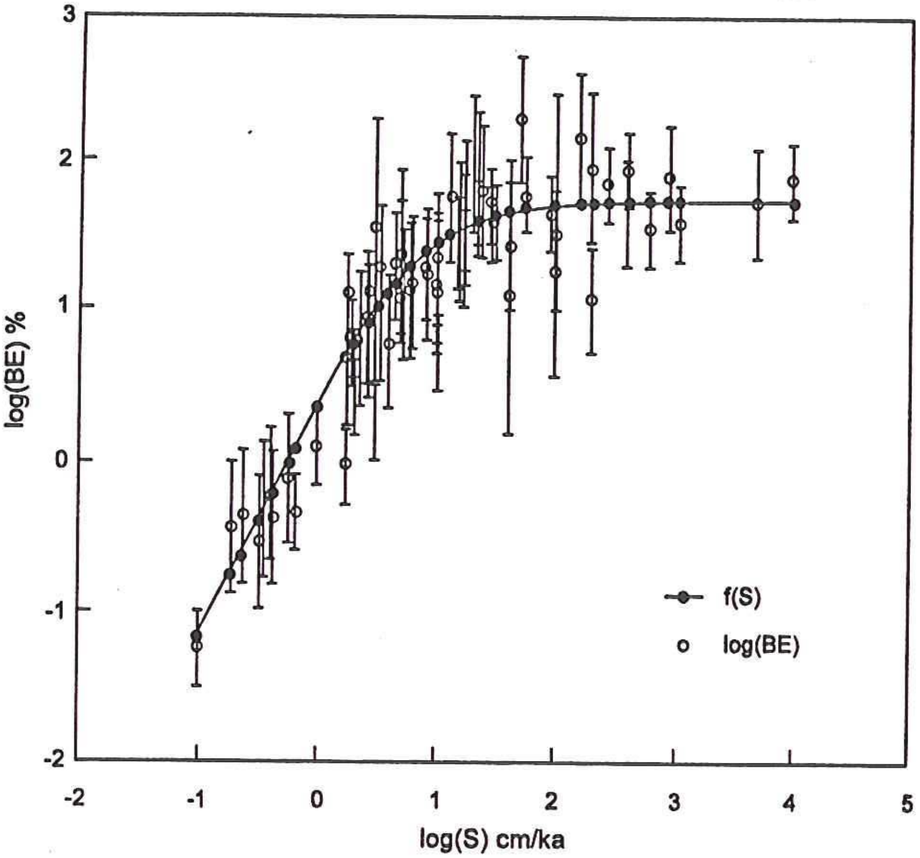
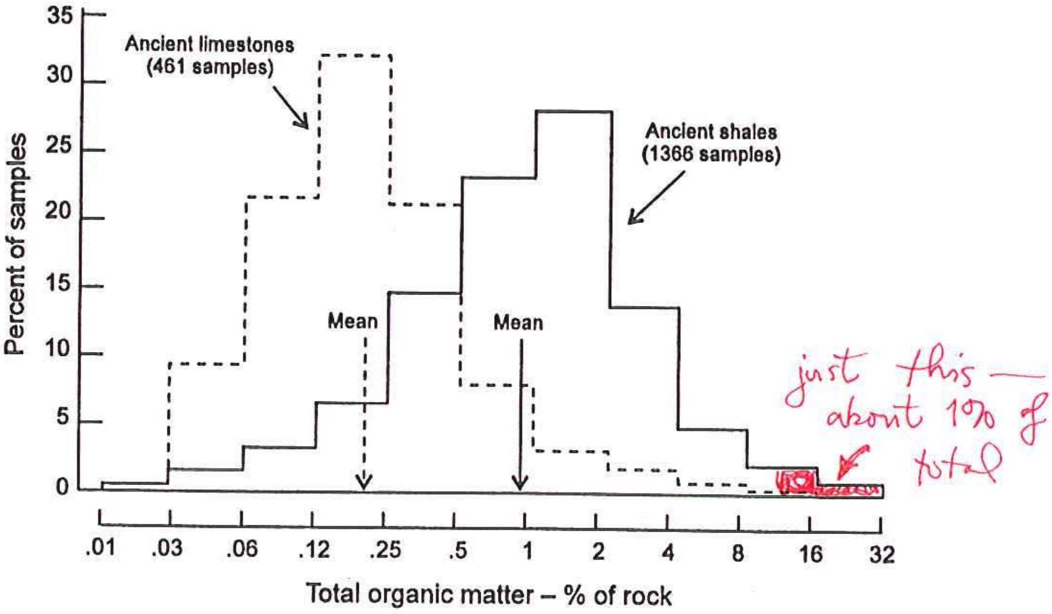


Figure 7.8. Plot of the burial efficiency, BE, of organic carbon with marine sediments vs. the sedimentation rate (S), in centimeters per 1,000 years. (Betts and Holland 1991)



just this — about 1% of total

Figure 7.9. The total organic carbon content of recent and ancient limestones and shales. (Gehman 1962)

Table 4. Potential shale oil in place in the oil shale deposits of the United States (billions of barrels).

Location	Range of shale oil yields (gallons per ton[a])		
	5–10	10–25	25–100
Colorado, Utah, and Wyoming (the Green River formation)	4,000	2,800	1,200
Central and eastern states (includes Antrim, Chattanooga, Devonian, and other shales)	2,000	1,000	(?)
Alaska	Large	200	250
Other deposits	134,000	22,000	(?)
Total	140,000+	26,000	2,000(?)

[a] Order of magnitude estimate. Includes known deposits, extrapolation and interpolation of known deposits, and anticipated deposits.

Source: Reference 1 as reported in Reference 2.

Table 5. Potential shale oil resources of the Green River formation (billions of barrels).

Location	Resource class[a]				
	1	2	3	4	Total
Piceance basin (Colorado)	34	83	167	916	1200
Uinta basin (Colorado & Utah)	. . .	12	15	294	321
Wyoming basins	. . .	. . .	4	256	260
Total	34	95	186	1466	1781

[a] 1 Deposits at least 30 ft thick and average 35 gal/ton.
2 Deposits at least 30 ft thick and average 30 gal/ton.
3 Similar to 1 & 2 but less well defined and not as favorably located.
4 Poorly defined, ranging down to 15 gal/ton.

Source: "An Initial Appraisal by the Oil Sale Task Group 1971–1985." U.S. Energy Outlook—An Interim Report, The National Petroleum Council, Washington, DC, 1972. Reported in Reference 2.

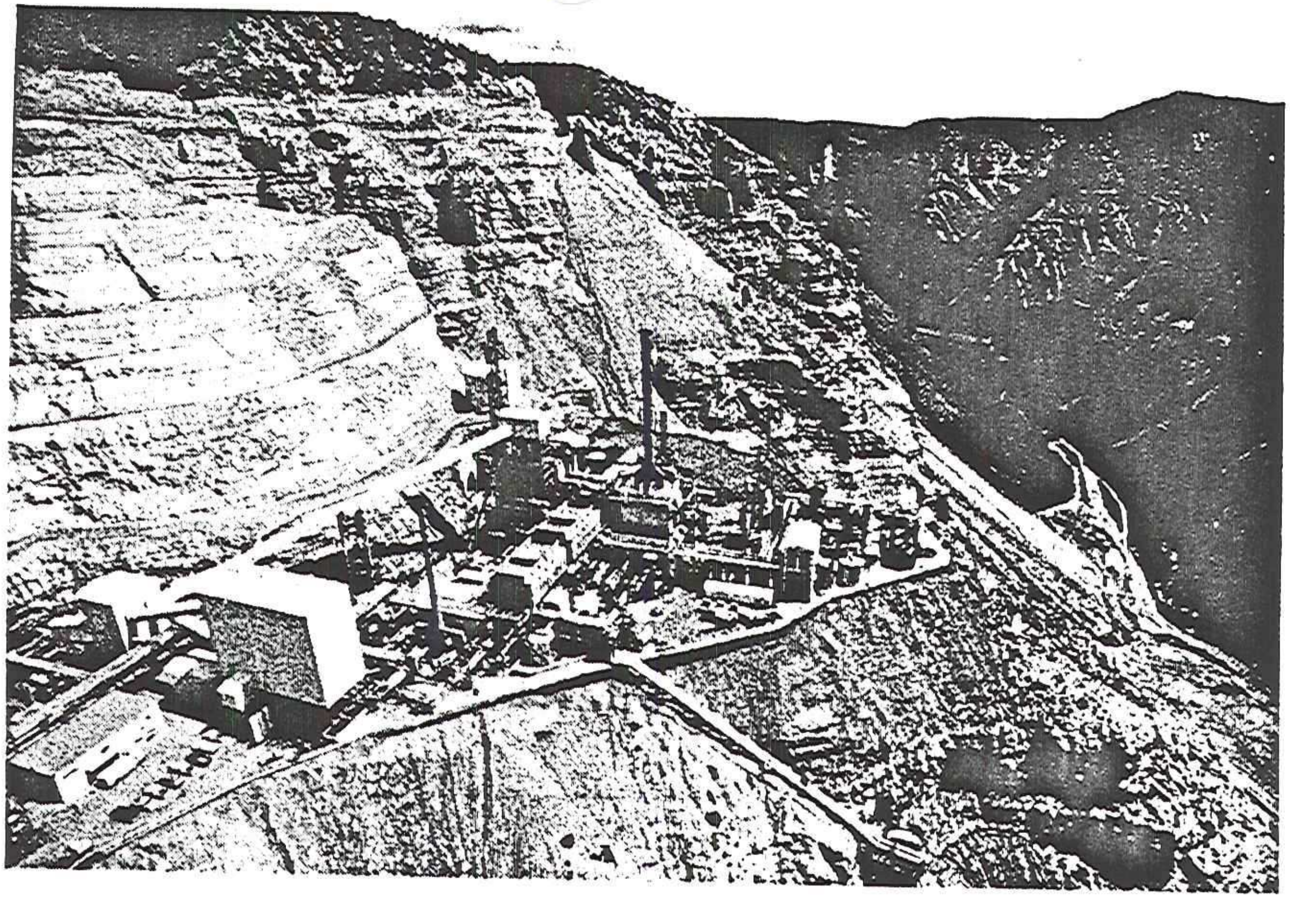


Figure 3. Photograph courtesy of Unocal.

Oil field of the future
Strip mine → above ground retort

Table 8.2.
World Resources of
Heavy Oil, Tar Sands,
and Oil Shale, 1990

Heavy Oil

	Billion Barrels		
	Proved Reserves	*Undiscovered Resources*	*Total Recoverable*
North America	23	30	65
Central and South America	280	16	309
Western Europe	8	0	9
USSR and Eastern Europe (former)	7	21	33
Africa	4	1	5
Middle East	115	22	169
Far East and Oceania	13	4	19
World total	450	94	609*

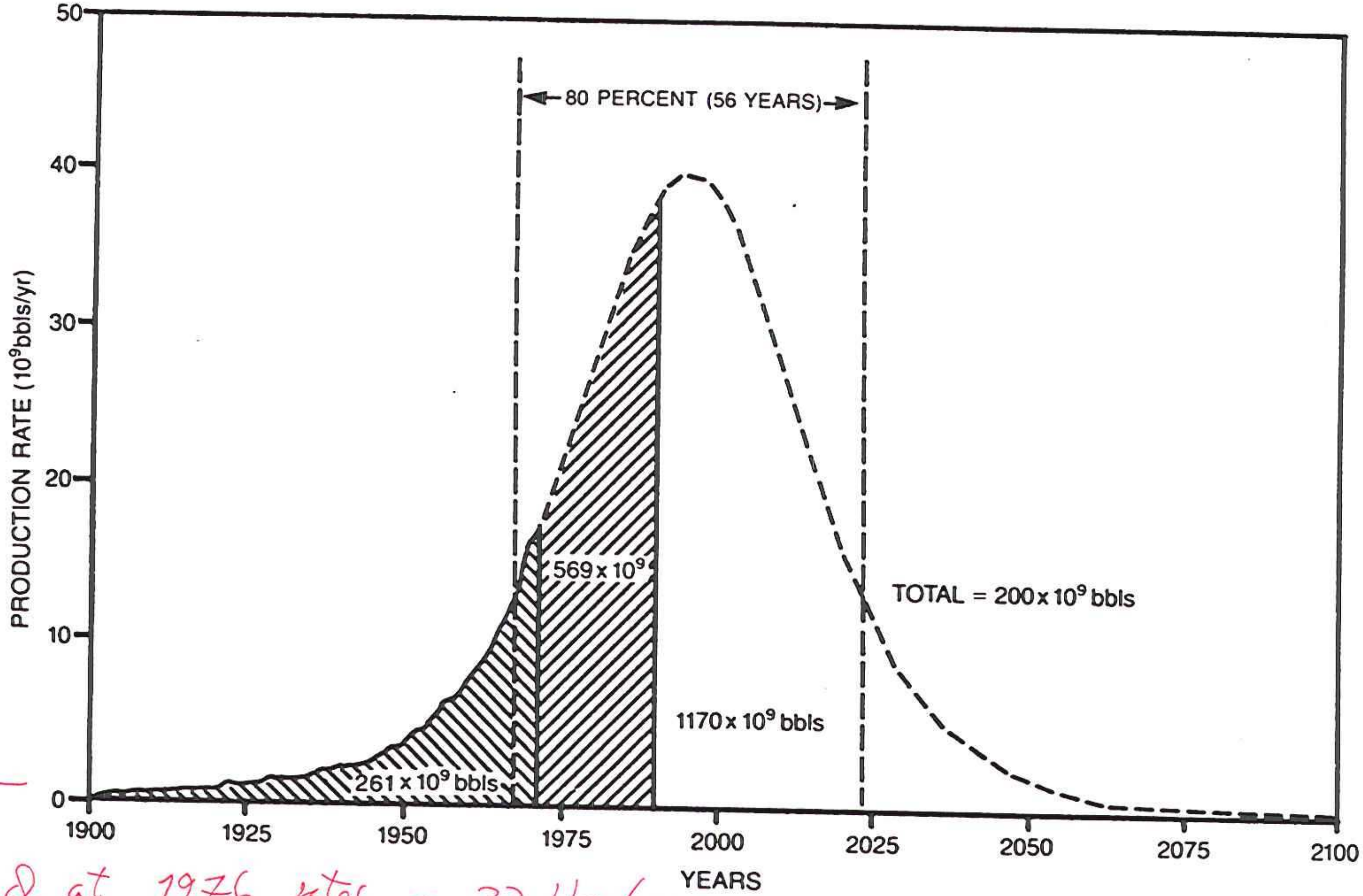
Tar Sands

	Billion Barrels		
	Measured Resources	*Speculative Resources*	*In-Place Resources*
United States	21	41	~60
Canada			~1,700
Venezuela			~700
World total			~4,000

Oil Shale

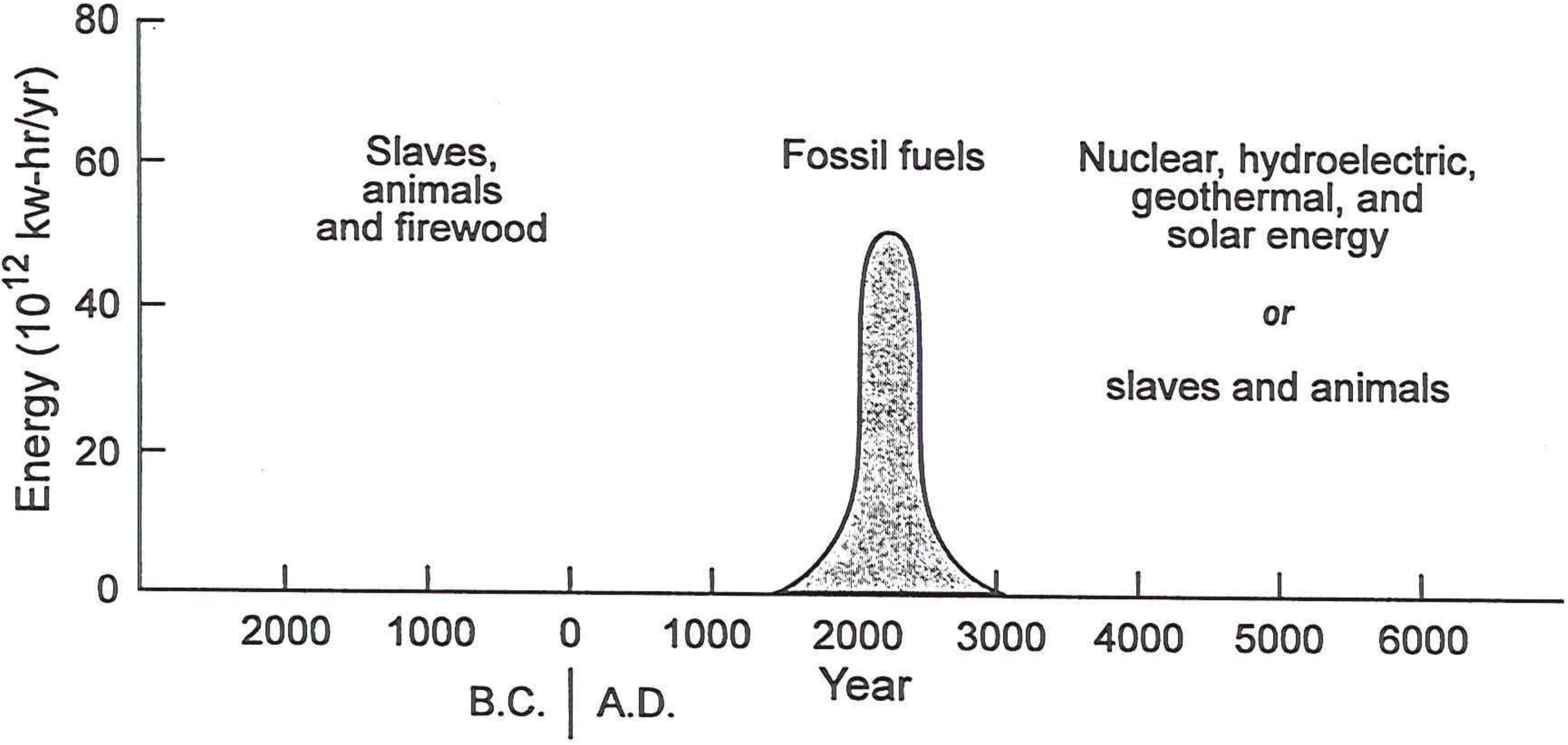
		*Billion Barrels of Oil**
United States		630
Western	460	
Eastern	170	
South America (Brazil)		300
USSR (former)		40
Africa (Zaire)		40

Source: Data from compilation by Kulp 1990.
* Recovery = 38% of estimated in-place resource.



Hubbert thought consumption would peak at more than 40 bbo/yr about now— in fact has remained at 1976 rates ~ 22 bbo/yr

Figure 14-1. Complete lifetime curve for world petroleum "production." (After Hubbert, 1974.)

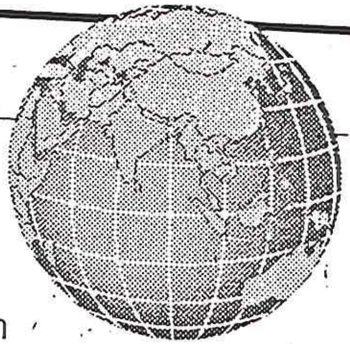


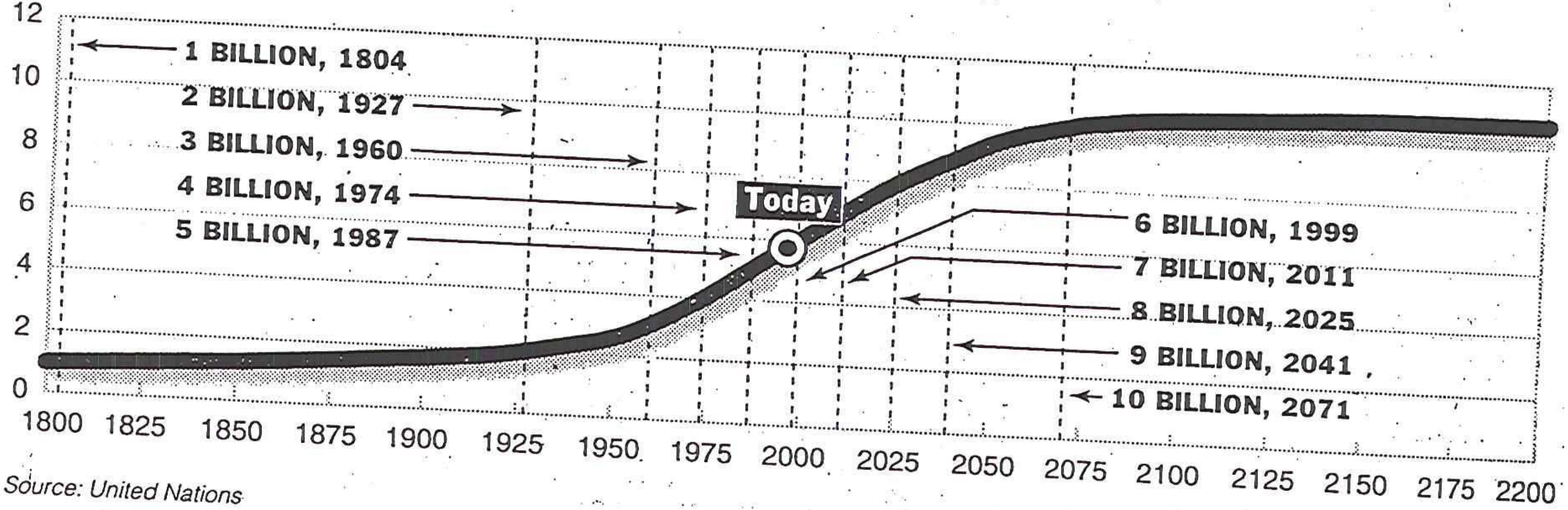
Energy (10^{12} kw-hr/yr)
80
60
40
20
0
Slaves,
animals
and firewood
Fossil fuels
Nuclear, hydroelectric,
geothermal, and
solar energy
or
slaves and animals
2000
1000
0
1000
2000
3000
4000
5000
6000
B.C. | A.D.
Year

STATUS REPORT

The Population Explosion Slows Down

A new United Nations study has found that the world's population is growing more slowly than was expected. This suggests that the world's population, now 5.77 billion, will stabilize just after the year 2200 at 10.73 billion. Shown is the world population from 1800 to stabilization based on United Nations projections, in billions.





Source: United Nations

The New York Times

from John's lecture when I was at AGU

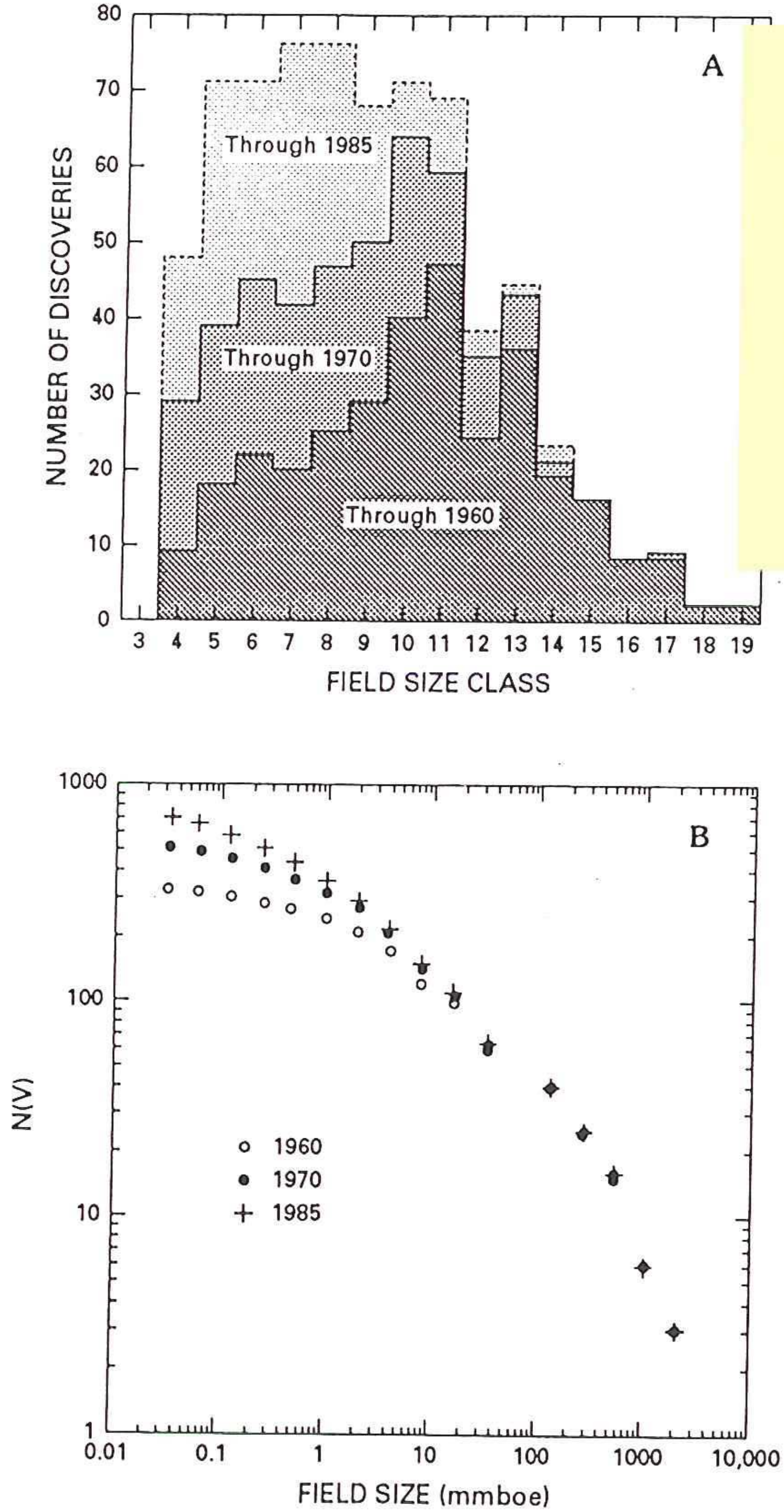


FIGURE 2.2. Observed field size distribution for oil and gas in the Frio Strand Plain exploration play, onshore Texas during three time periods; through 1960, through 1970, and through 1985. (a) The distribution's three discovery segments over time, when added, show the cumulative number of fields of a given size discovered through the specified year. (Taken from Drew, 1990, Fig. E.4). (b) Log-log plot by time segments of cumulative frequency of oil and gas fields, *N*(*V*), versus field size.

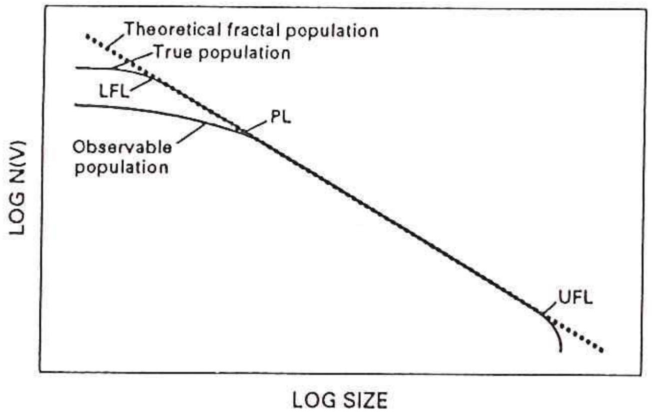
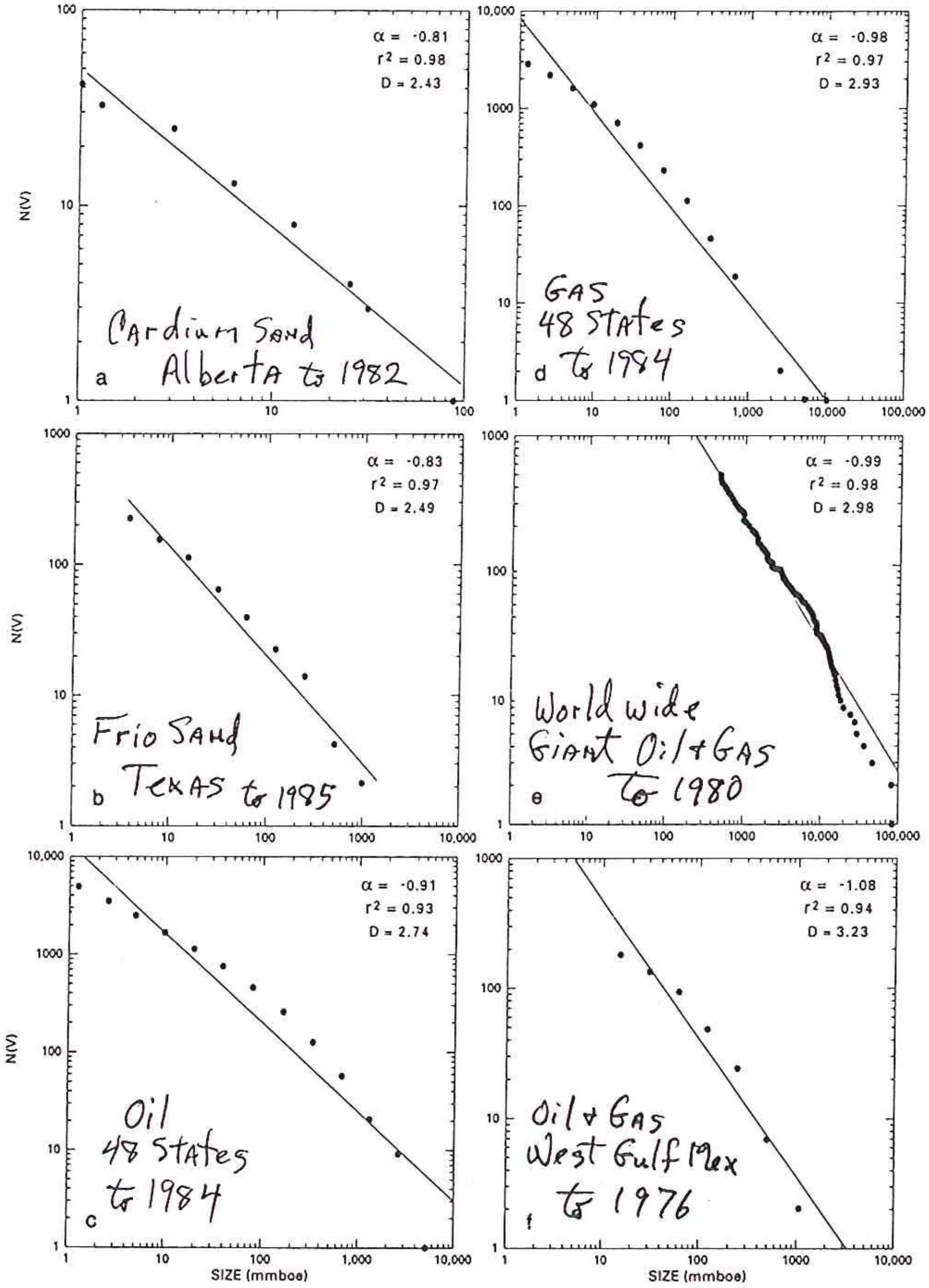


FIGURE 2.1. Schematic diagram, a log-log plot of cumulative frequency versus size, illustrating the differences between a theoretical fractal distribution (dashed line), a true fractal population, between upper and lower fractal limits (UFL and LFL), and an observable population, that is truncated by a perceptibility limit (PL).



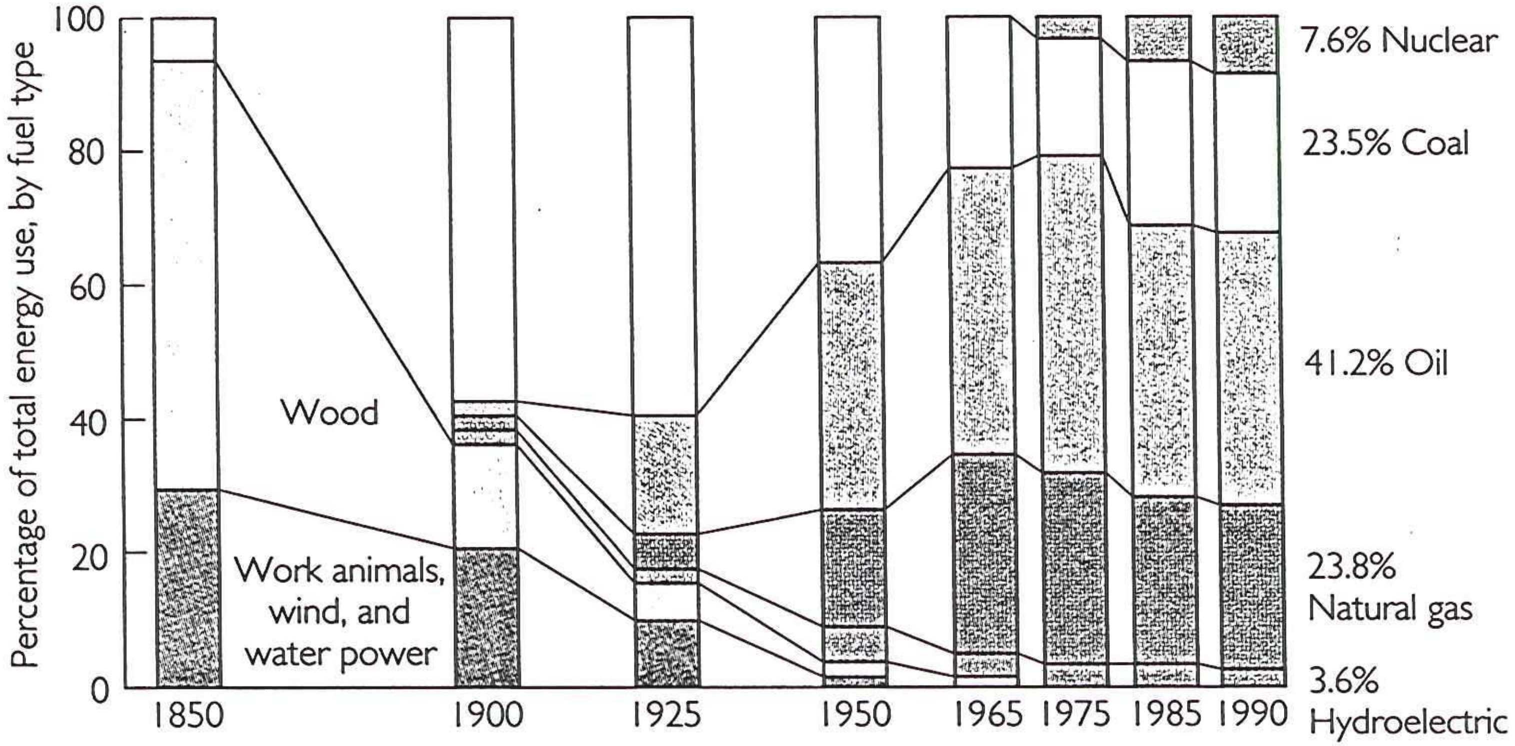


FIGURE 22.3 Percentages of various types of energy used in the United States from 1850 to 1990. (Data from U.S. Energy Information Agency, 1991.)

extra
beyond
here

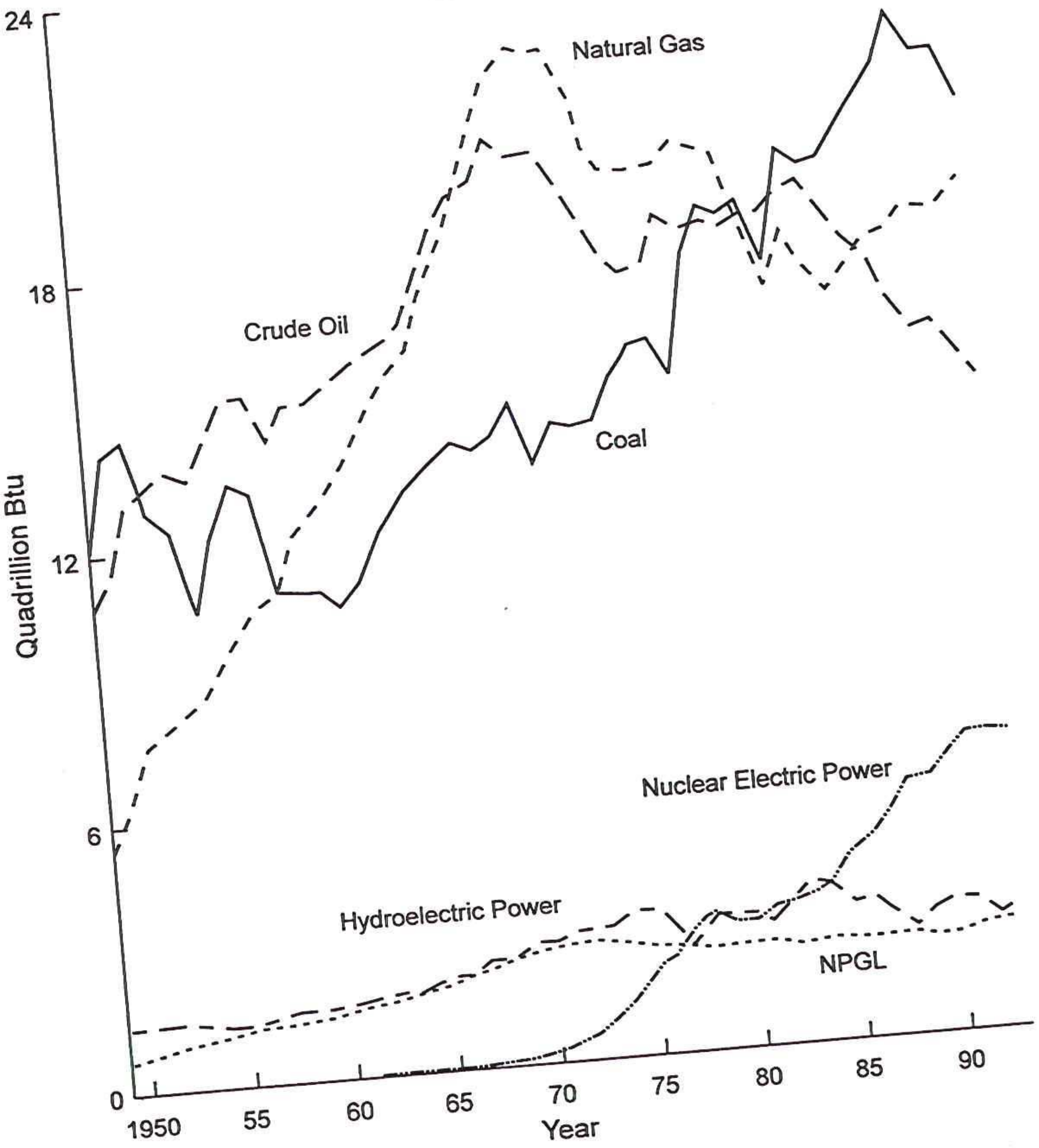
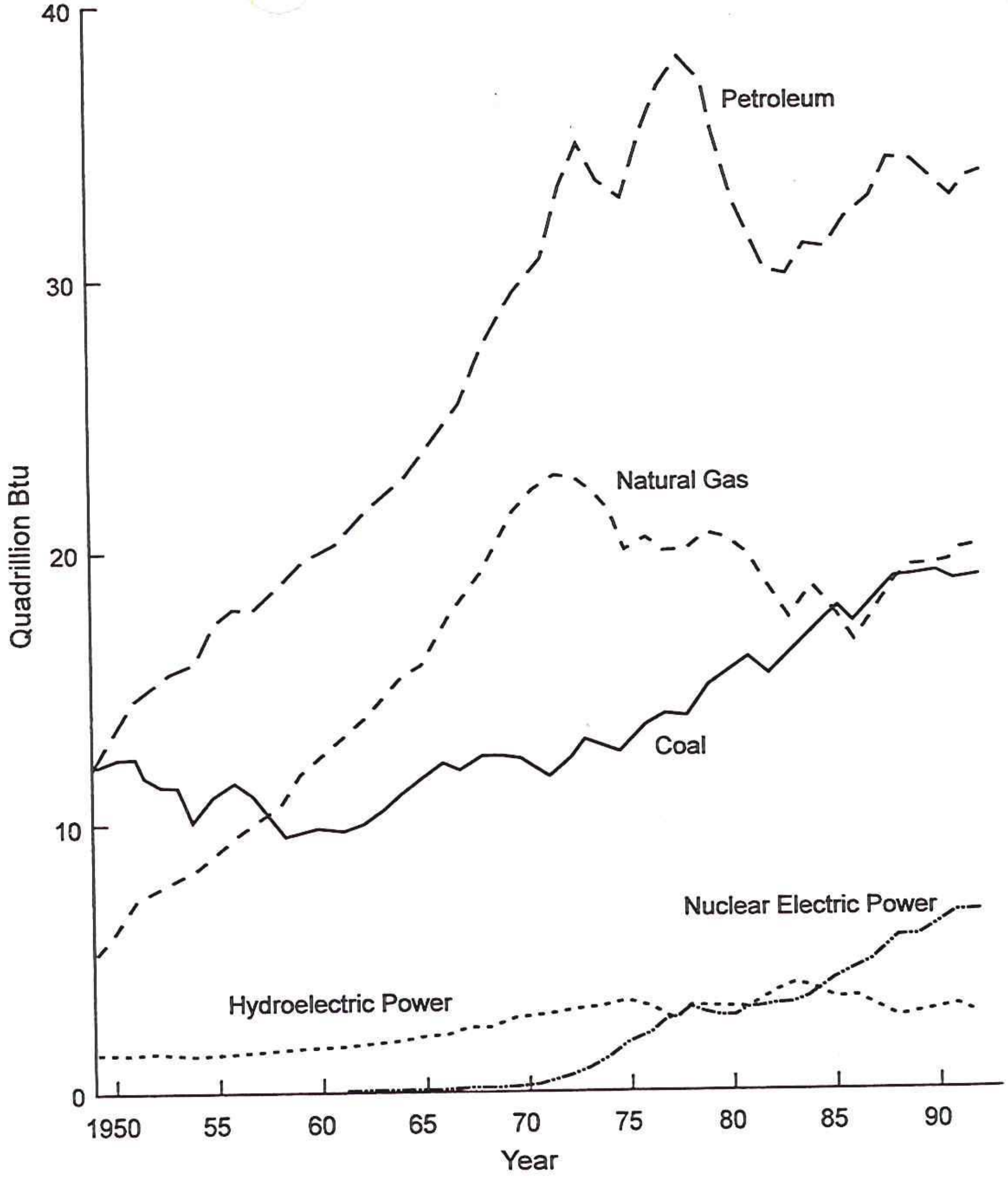


Figure 8.27. The major sources of energy produced in the United States between 1949 and 1993. NPGL = natural pressurized gas liquid. (*Annual Energy Review 1993*)

Figure 8.29. The major sources of energy consumed in the United States between 1949 and 1993. (*Annual Energy Review 1993*)



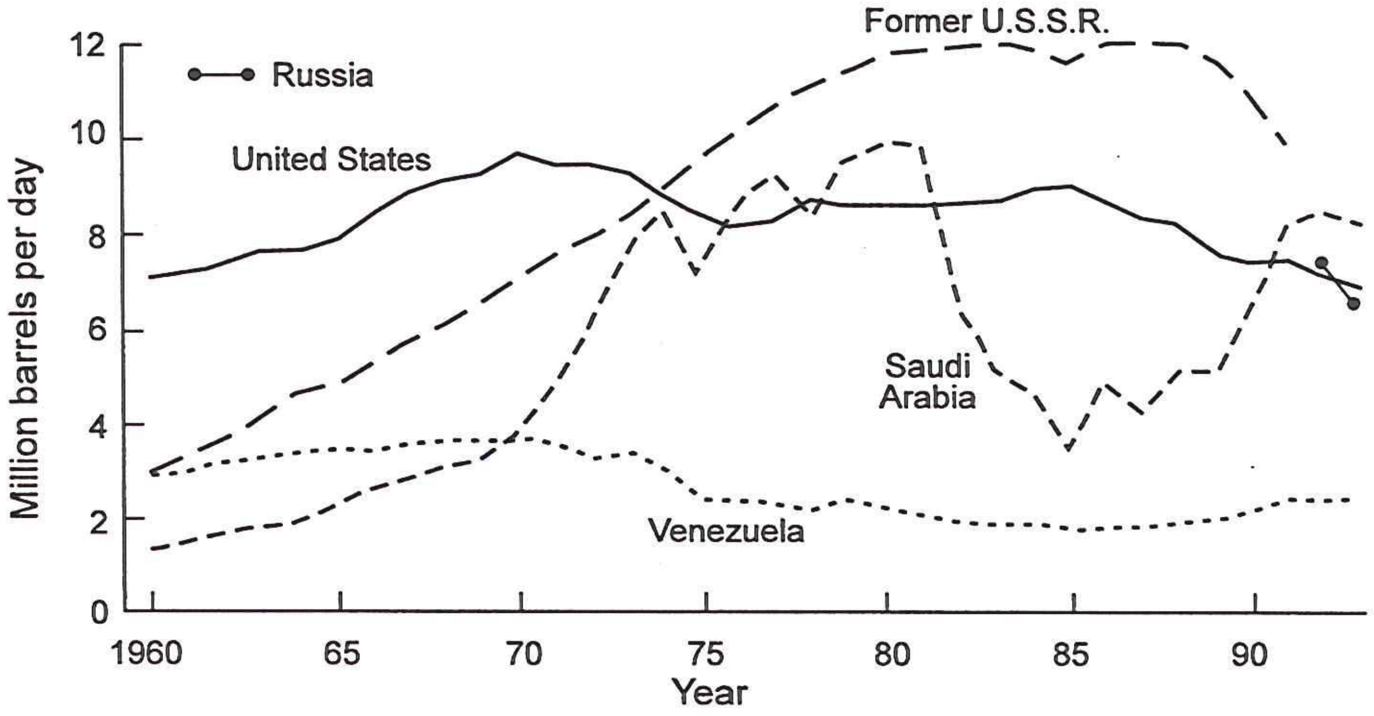


Figure 8.39. Production by the leading crude oil producers, 1960–93. (*Annual Energy Review 1993*)

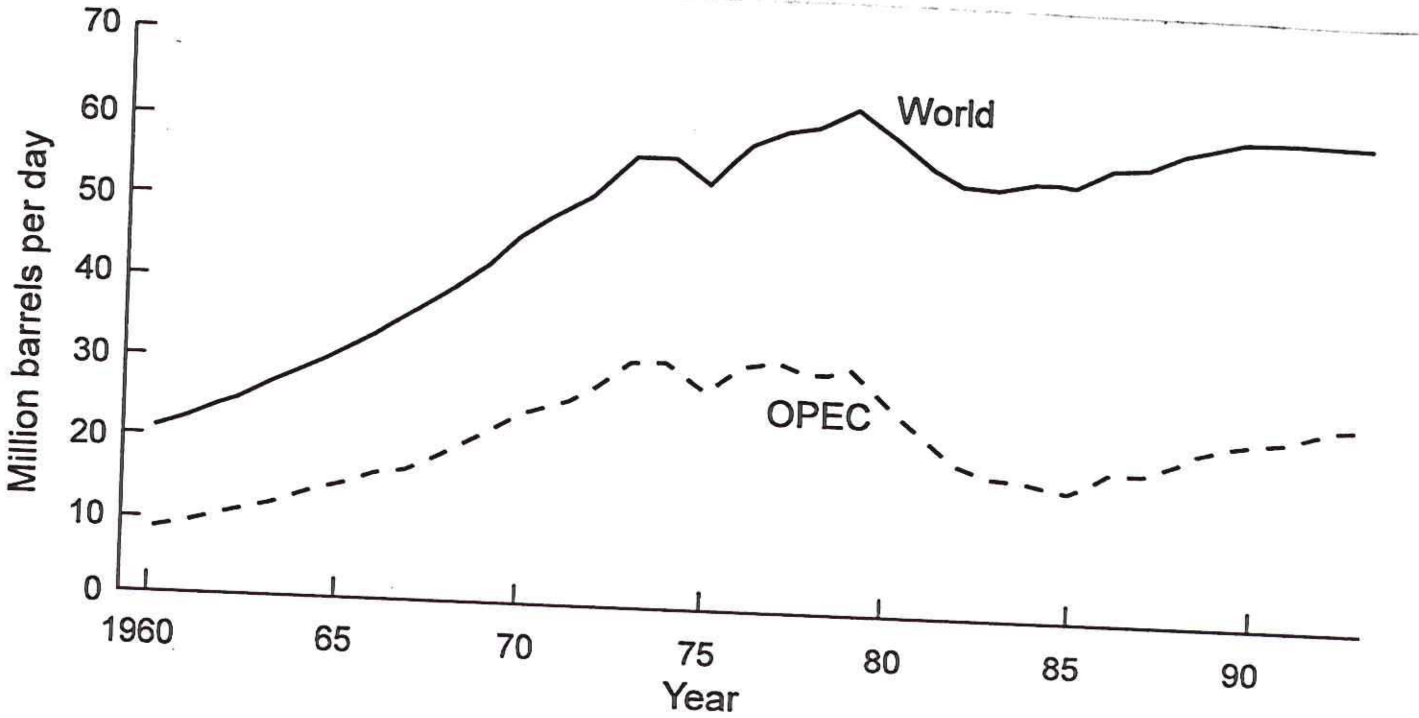
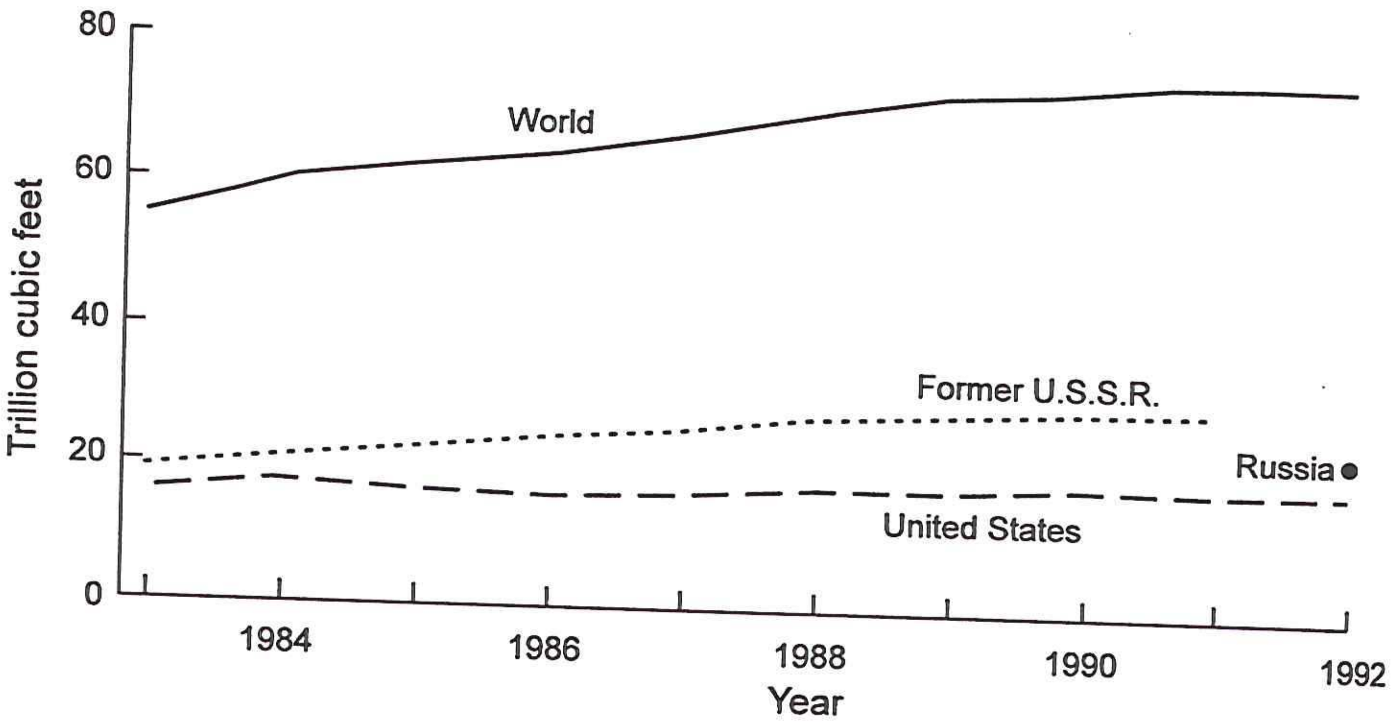
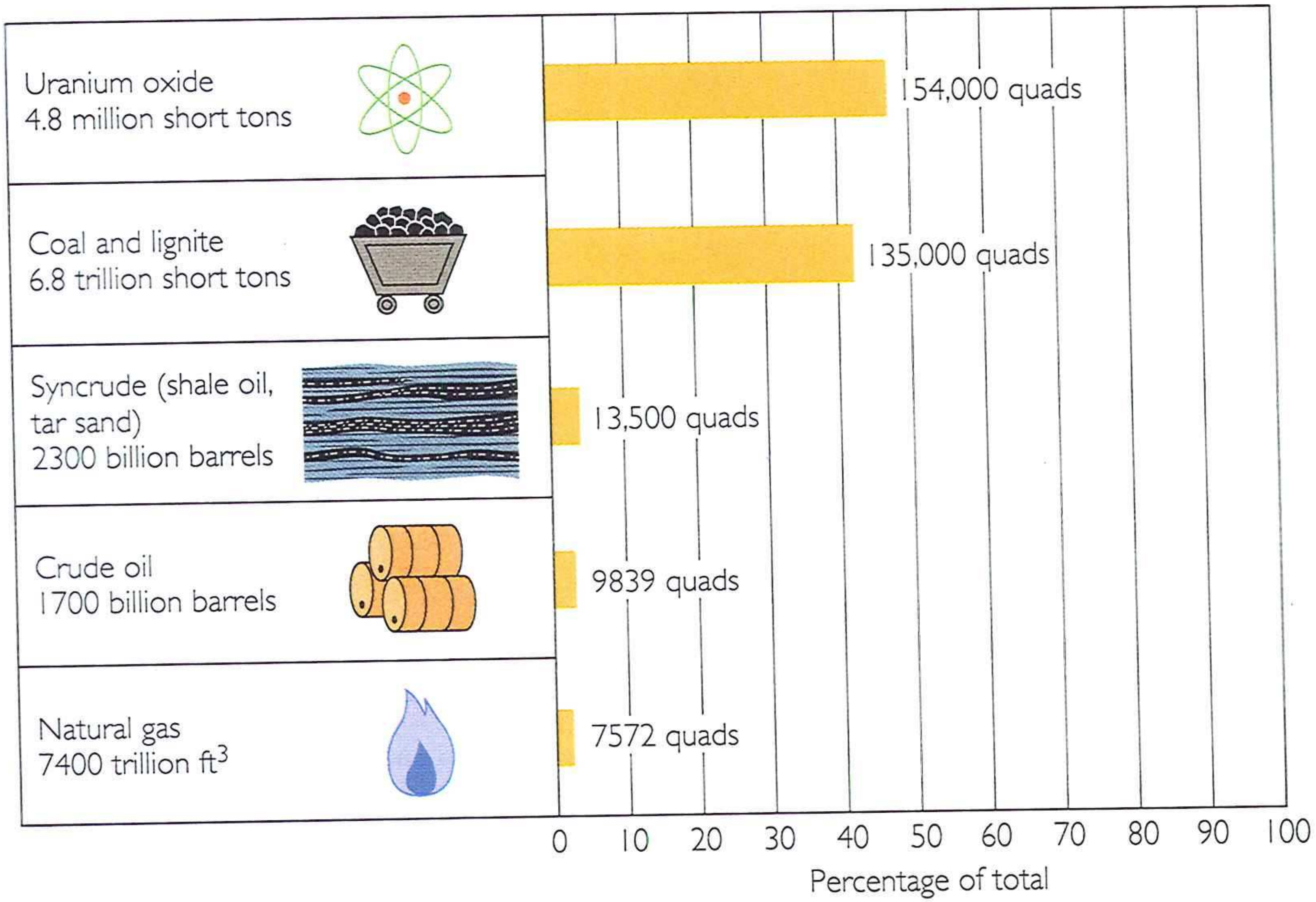


Figure 8.38. Crude oil production, 1960–93; the world and OPEC. (*Annual Energy Review 1993*)

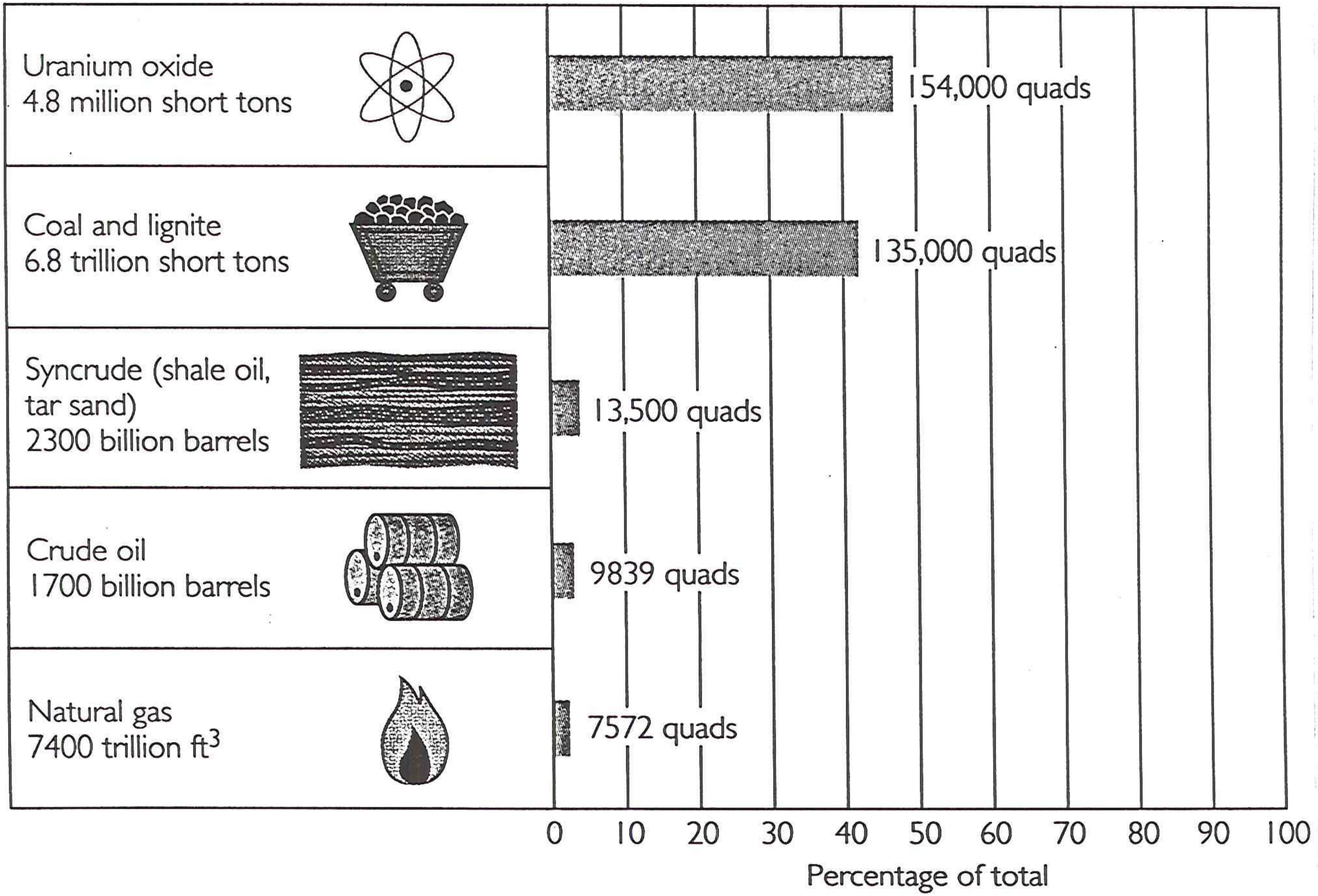
Figure 8.44. Natural gas production in the United States, the former USSR, and the world as a whole between 1983 and 1992. (*Annual Energy Review 1993*)



TOTAL WORLD RESOURCES



TOTAL WORLD RESOURCES



In 1949, I was at Raffles College (now the University of Singapore) when their new library, not yet built, received a complete set (1662–1930's) of the *Philosophical Transactions of the Royal Society of London*. I took the beautiful calf-bound volumes into protective custody and set them in ten-year piles on the bedside bookshelves. For a year I read them cover to cover, thereby getting my initial education as a historian of science. As a side product, noting that the piles made a fine exponential curve against the wall, I counted all the other sets of journals I could find and discovered that exponential growth, at an amazingly fast rate, was apparently universal and remarkably long-lived.

Derek de Solla Price
1983

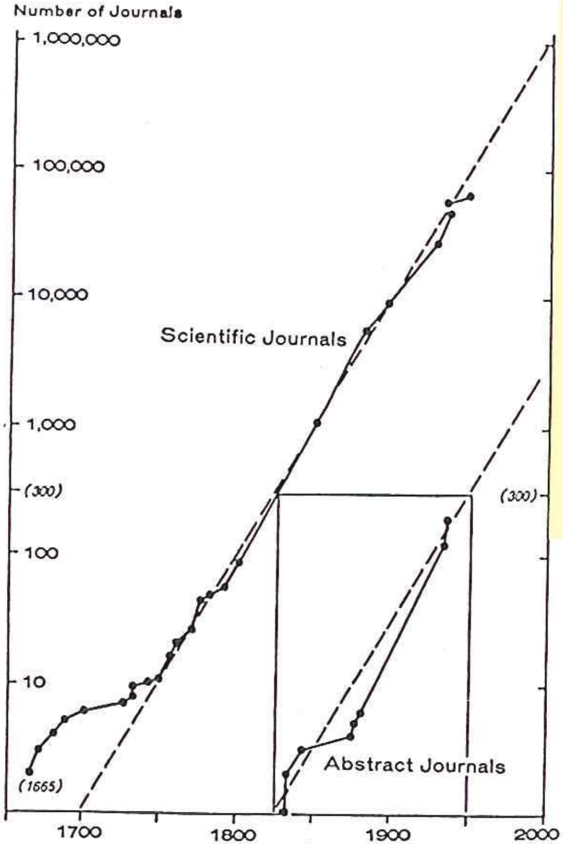
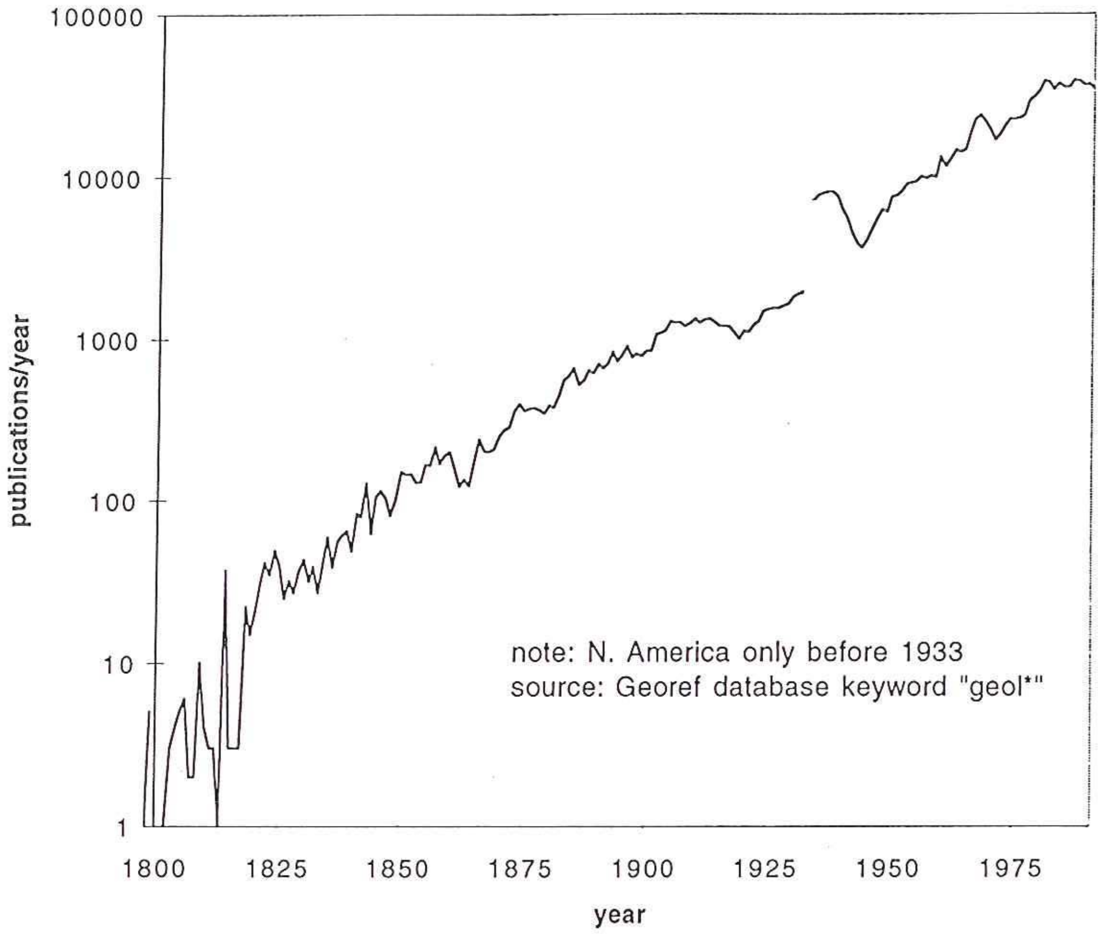


Figure 8.1
Number of journals founded (*not* surviving) as a function of date. The two uppermost points are taken from a slightly differently based list.

John on
growth
of science

Derek de Solla Price,
1961, Science
Since Babylon,
Yale Univ Press



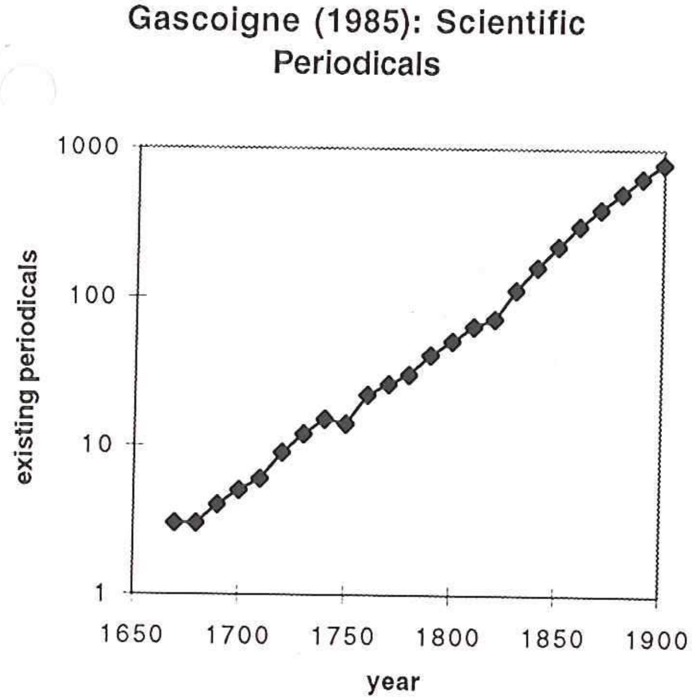
"Geology" Publication Rates

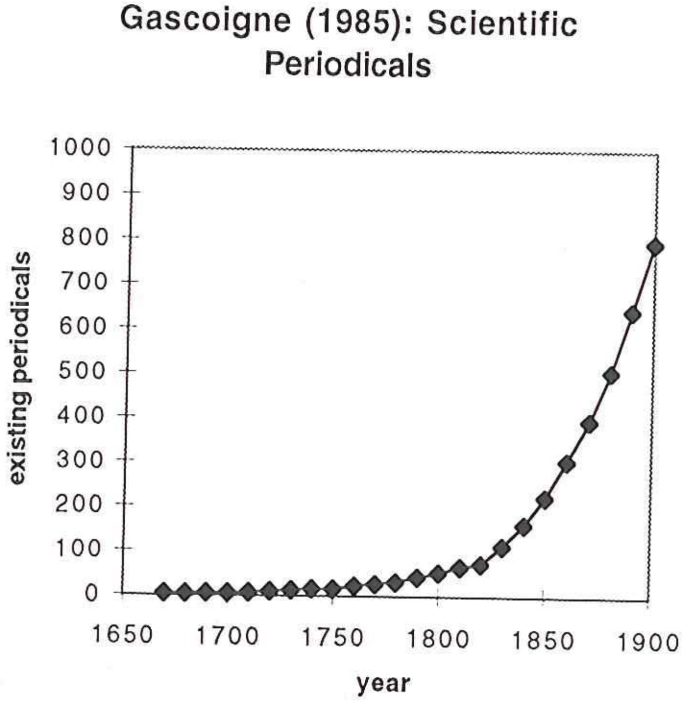
note: N. America only before 1933
source: Georef database keyword "geol*"

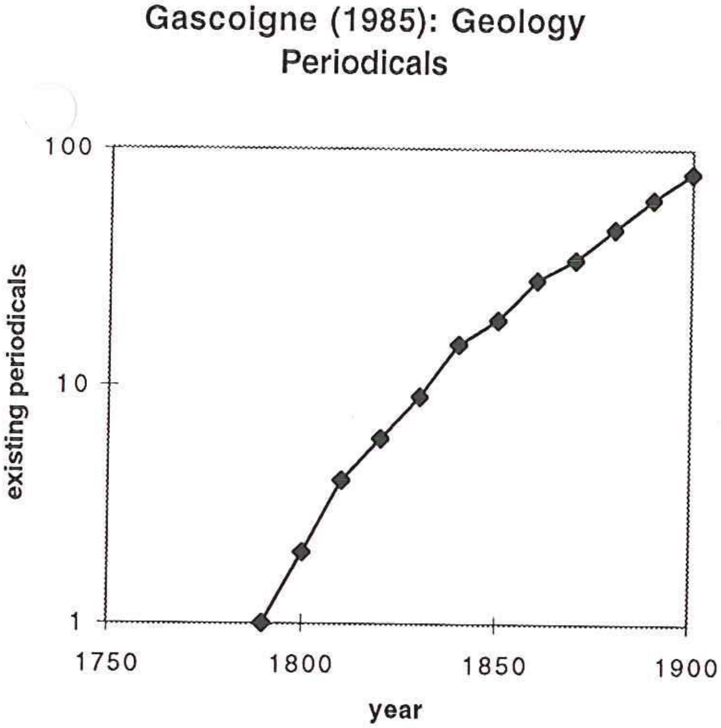
Table 1: The Doublings of North American & World Geologic Literature since 1818.

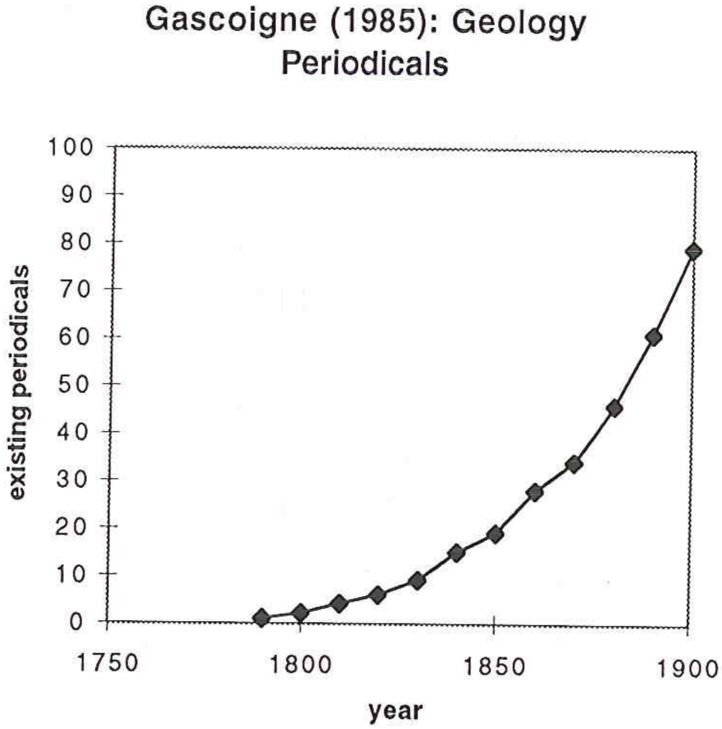
date	cumulative publications	cumulative percent
1818	134	0.01%
1823	277	0.02%
1830	530	0.04%
1840	999	0.08%
1850	2,012	0.16%
1863	3,961	0.32%
1878	8,306	0.65%
1892	16,155	1.3%
1909	33,219	2.6%
1932	65,479	5.2%
1941	131,362	10%
1959	261,893	21%
1974	530,291	42%
1990	1,066,976	84%
1998	1,270,537	100%

*Based on references to 'geology' in the comprehensive *Georef* digital database, published by the American Geological Institute. This database covers North American literature from 1785 until 1933, at which point it expands to worldwide coverage.


Gascoigne (1985): Scientific Periodicals

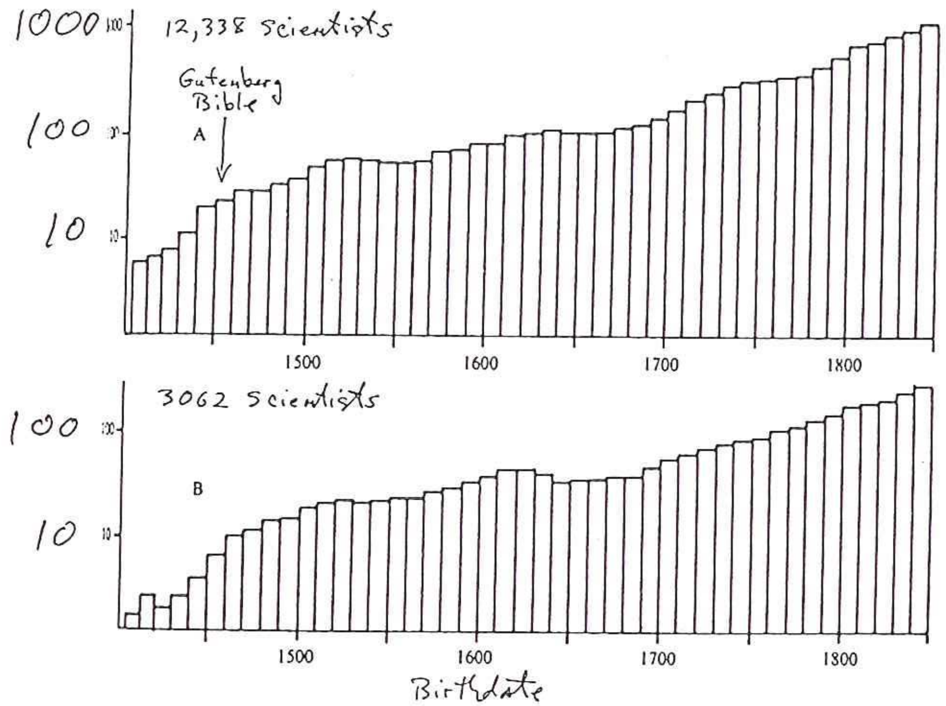

Gascoigne (1985): Scientific Periodicals


Gascoigne (1985): Geology Periodicals

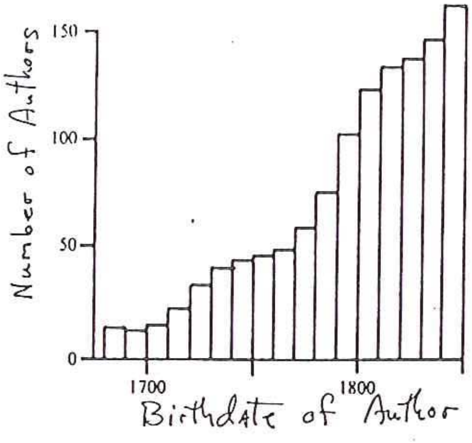

Gascoigne (1985): Geology Periodicals

Gascoigne, R.M., 1985, A Historical Catalogue of Scientific Periodicals, 1665-1900. Garland, New York.

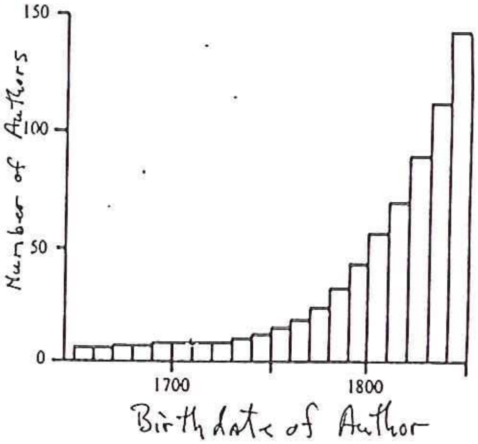
All Countries (Logarithmic Scale)
A: Data from *HCS* B: Data from *DSB*
(Hist Cat Sci + Sci Books) (Dict. Sci - Biography)



Geology: Data from *HCS*
(Historical Catalogue of Scientists and Scientific Books)



United States: Data from *HCS*



Robert Gascoigne, 1992,
"The historical demography
of the scientific Community,
1450–1900"
Social Studies of Science,
v. 22, p. 545-573.

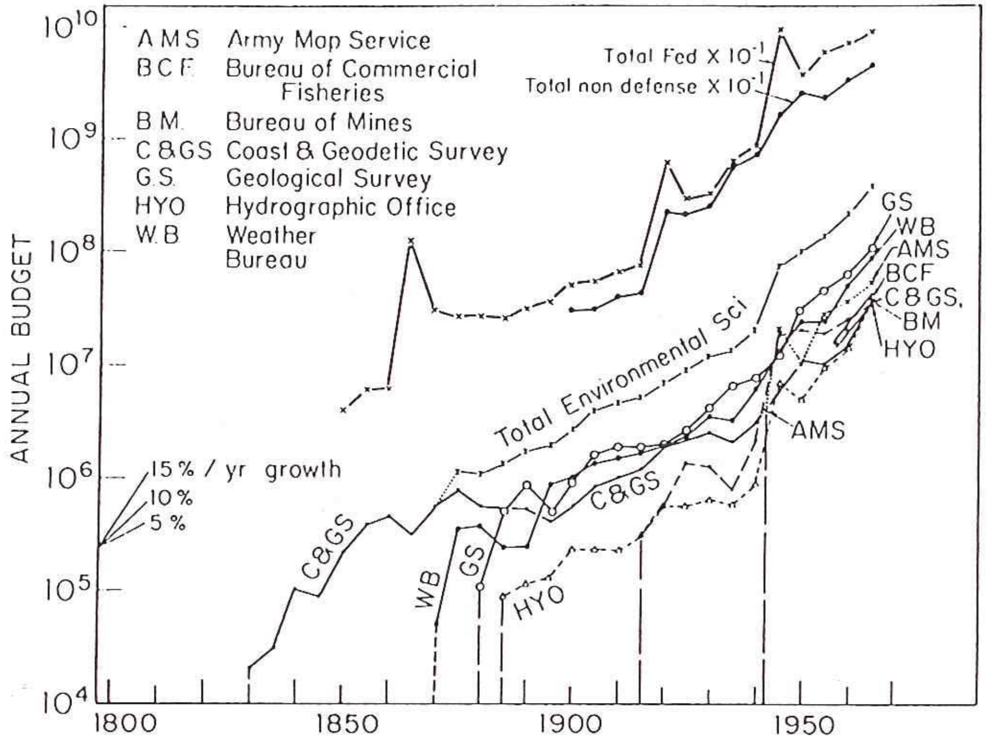
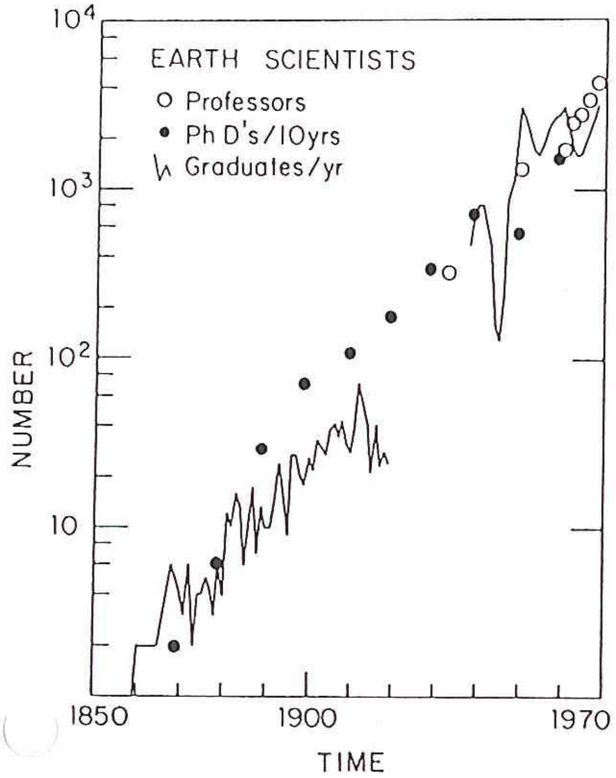
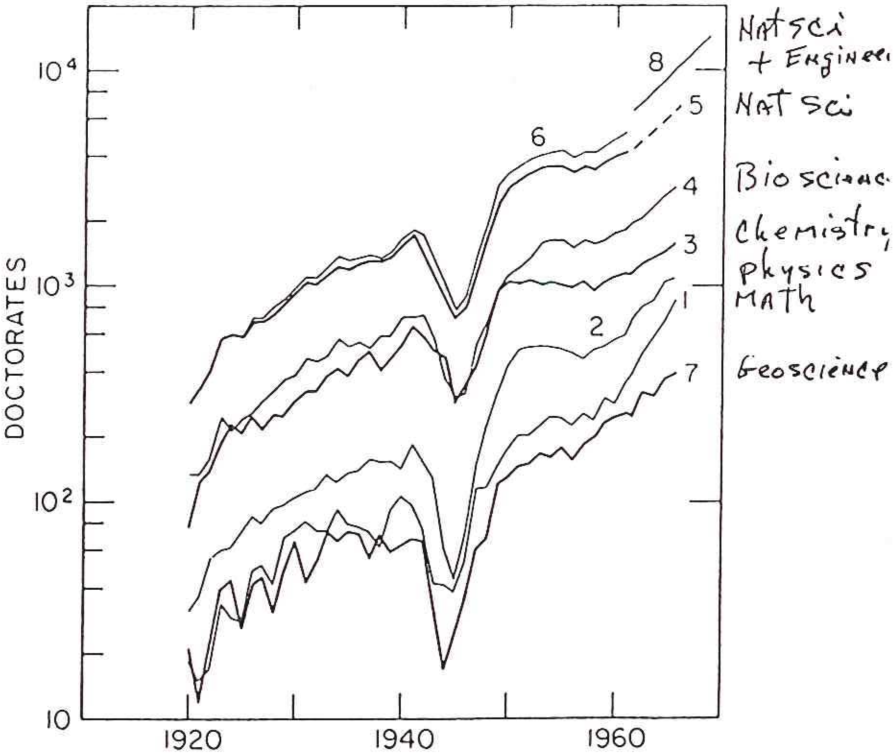


Fig. 8.1 Annual budgets of federal agencies concerned with the environmental sciences compared with the nondefense and total federal budget.





Menard, H., 1971, Science: Growth and Change. Harvard U. Press

Knowledge begets knowledge as money bears interest.

—A. CONAN DOYLE, *The Great Keinplatz Experiment*

1. ADAMS' LAW

By the end of the nineteenth century no clear-eyed observer could fail to remark the striking pace of scientific advance. But among the first to detail this phenomenon in exact terms—indeed to give it mathematical formulation—was Henry Brooks Adams (1838–1918), the American scholar, historian, and student of cultural affairs. (He was a grandson of John Adams, George Washington's successor as President.) Noting that scientific work increased at a rate fixed by a constant doubling-time—so that science has an *exponential* growth-rate—Adams characterized this circumstance as a "law of acceleration" governing the progress of science. He wrote:

> Laplace would have found it child's play to fix a ratio in the progression in mathematical science between Descartes, Leibnitz, Newton and himself. . . . Pending agreement between . . . authorities, theory may assume what it likes—say a fifty or even a five-and-twenty year period of reduplication . . . for the period matters little once the acceleration itself is admitted.[1]

[1] *The Education of Henry Adams* (Boston, 1918; privately printed already in 1907), chapter 34 (see p. 491). This chapter was written in 1904. The earliest anticipation of Adams' principle of exponential growth that I know of occurs in an *obiter dictum* in the 1901 Presidential Address to the British Association for the Advancement of Science by William Thomson (Lord Kelvin):

> Scientific wealth tends to accumulate according to the law of compound interest. Every addition to knowledge of the properties of matter supplies the naturalist with new instrumental means for discovering and interpreting phenomena of nature, which in their turn afford foundations for fresh generalizations. (Reprinted in G. Basalla, William Coleman, and R. H. Kargon [eds.], *Victorian Science: A Self-Portrait Through the Presidential Addresses of the British Association for the Advancement of Science* [New York, 1970], pp. 101–128 [see p. 114], and compare p. 488.)

The idea occurs in embryonic form in A. Conan Doyle's 1894 short story *The Great Keinplatz Experiment*, in whose opening paragraph the professorial protagonist is described as follows:

> As . . . the worthy professor's stock of knowledge increased—for knowledge begets knowledge as money bears interest—much which had seemed strange and unaccountable began to take another shape in his eyes. New trains of reasoning became familiar to him, and he perceived connecting links where all had been incomprehensible and startling.

Rescher, Nicholas, 1978,
Scientific Progress.
Univ. Pittsburgh Press

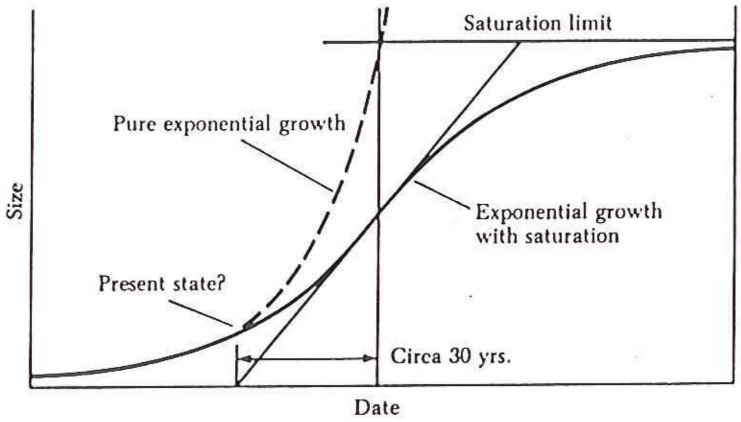


Figure 1.5. General Form of the Logistic Curve

From Derek J. de Solla Price, *Science Since Babylon* (New Haven, Yale University Press, 1961).

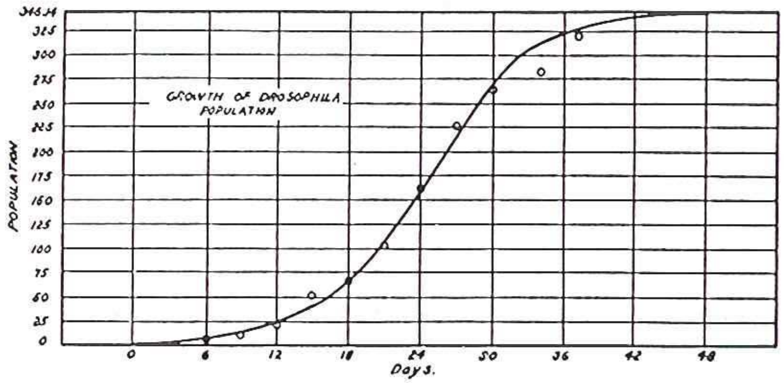


FIG. 5. GROWTH OF A POPULATION OF DROSOPHILA (FRUIT FLIES) UNDER CONTROLLED EXPERIMENTAL CONDITIONS, ACCORDING TO PEARL AND PARKER

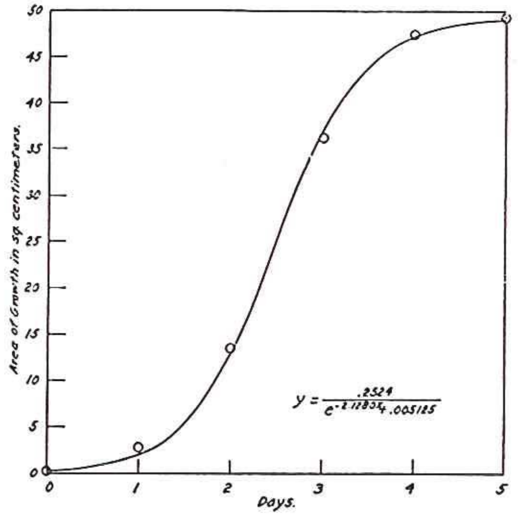


FIG. 6. GROWTH OF A BACTERIAL COLONY (B. DENDROIDES)
Observations by H. G. Thornton

Extrapolation of logistic Curves

$$X = \frac{\frac{a}{b}}{1 + e^{-at'}} \qquad (12)$$

the symbol t' denoting time reckoned from the origin indicated.[5]

Population of United States. Formula (12) has been applied by Pearl and Reed[6] to the population growth of the United States.[7] The calculated curve for the number N of the population fits the observed data over a long period of years (1790 to 1910) with remarkable faithfulness, as will be seen from table 2 and the graph shown in figure 4. Numerically the formula (12) here takes the form

$$N = \frac{197,273,000}{1 + e^{-0.03134t'}} \qquad (14)$$

and the time t' (in years) is dated from April 1, 1914 (t', being negative for dates anterior to this). This epoch is one of peculiar interest. It represents the turning point when the population passed from a progressively increasing to a progressively diminishing rate of growth. Incidentally it is interesting to note that if the population of the United States continues to follow this growth curve in future years, it will reach a maximum of some 197 million souls, about double its present population, by the year 2060 or so. Such a forecast as this, based on a rather heroic extrapolation, and made in ignorance of the physical factors that impose the limit, must, of course, be accepted with reserve.

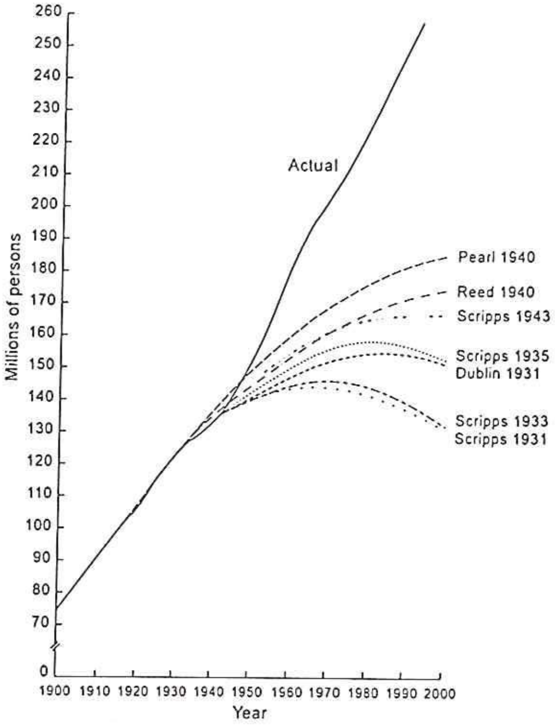


Figure 5.13. U.S. population forecasts made between 1931 and 1943, and the actual population increase during the twentieth century.

TABLE 2

Results of fitting United States population data 1790 to 1910 by equation (14)

YEAR	OBSERVED POPULATION	CALCULATED POPULATION BY EQUATION (14)	ERROR
1790	3,929,000	3,929,000	0
1800	5,308,000	5,336,000	+28,000
1810	7,240,000	7,228,000	−12,000
1820	9,638,000	9,757,000	+119,000
1830	12,866,000	13,109,000	+243,000
1840	17,069,000	17,506,000	+437,000
1850	23,192,000	23,192,000	0
1860	31,443,000	30,412,000	−1,031,000
1870	38,558,000	39,372,000	+814,000
1880	50,156,000	50,177,000	+21,000
1890	62,948,000	62,769,000	−179,000
1900	75,995,000	76,870,000	+875,000
1910	91,972,000	91,972,000	0

Lotka Elements of
Mathematical Biology
1st pub 1923

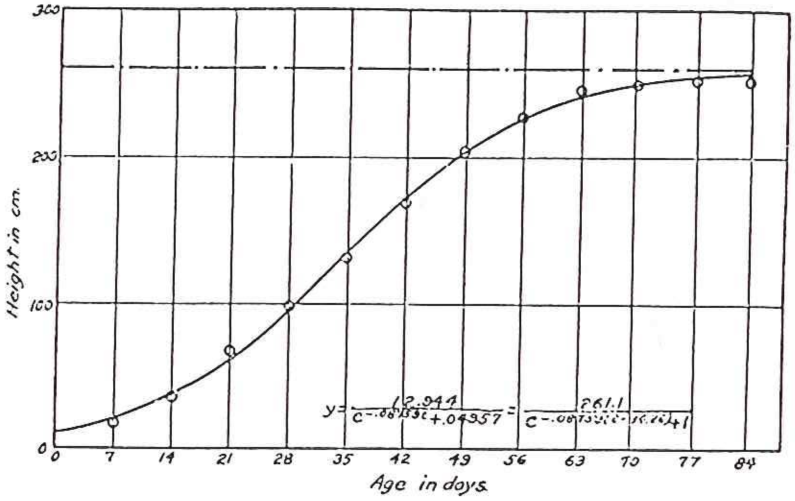


Fig. 8. Growth of Sunflower Seedlings According to H. S. Reed and R. H. Holland; Computed Curve by L. J. Reed

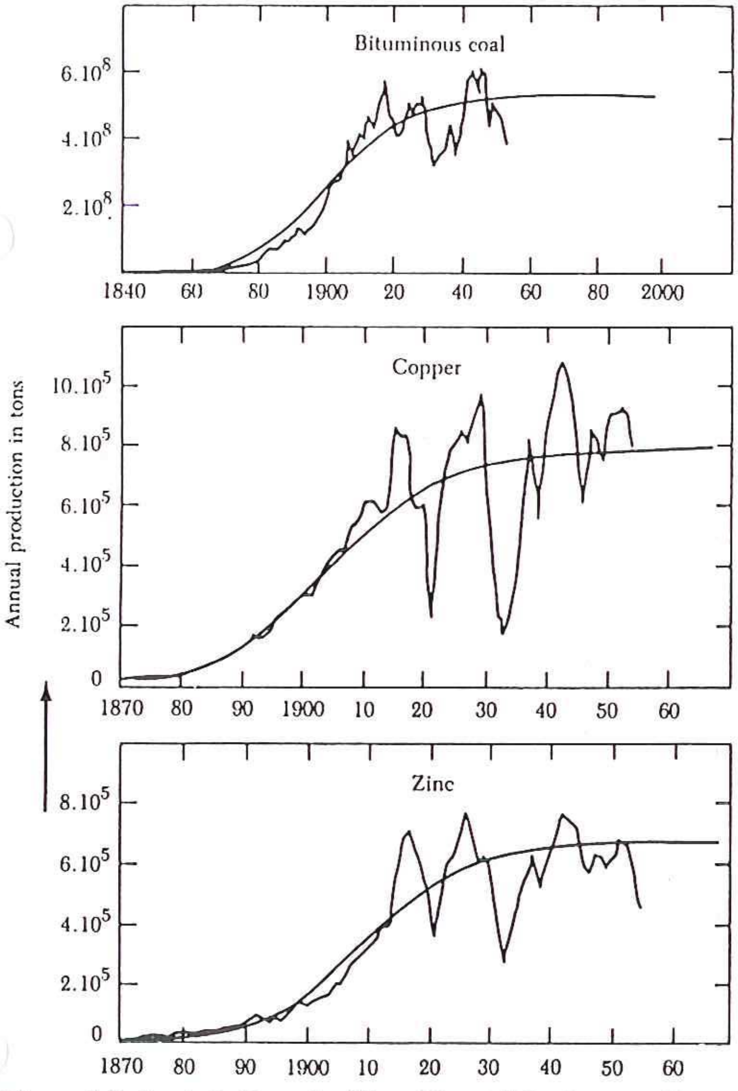


Figure 1.8. Logistic Growth of Raw Material Production, Showing Oscillation on Attaining Ceiling Conditons

Adapted from S. G. Lasky, "Mineral industry futures can be predicted," *Engineering and Mining Journal* (September 1955), Vol. 15b.

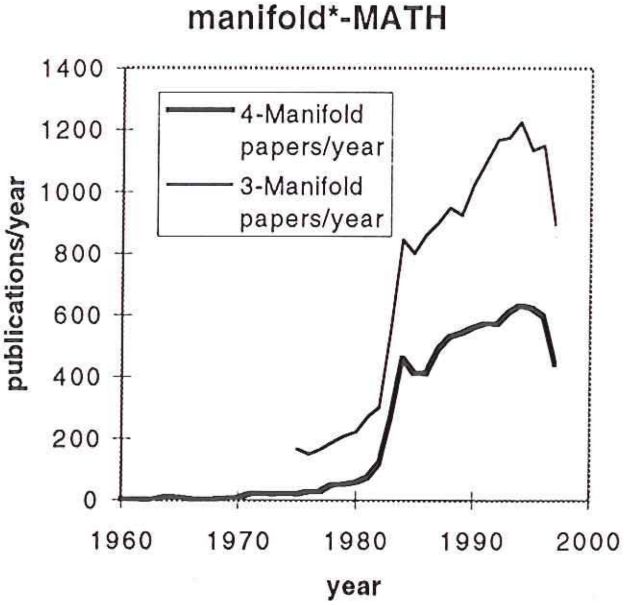
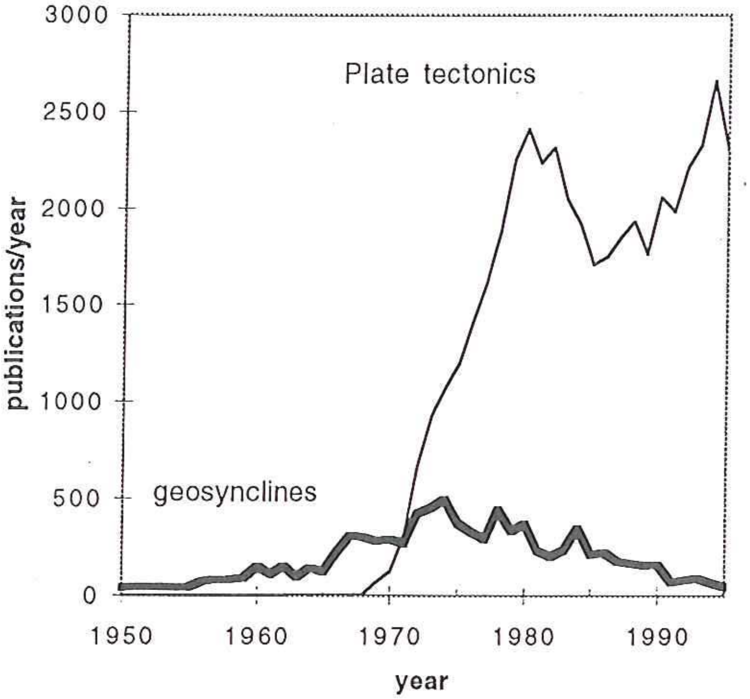
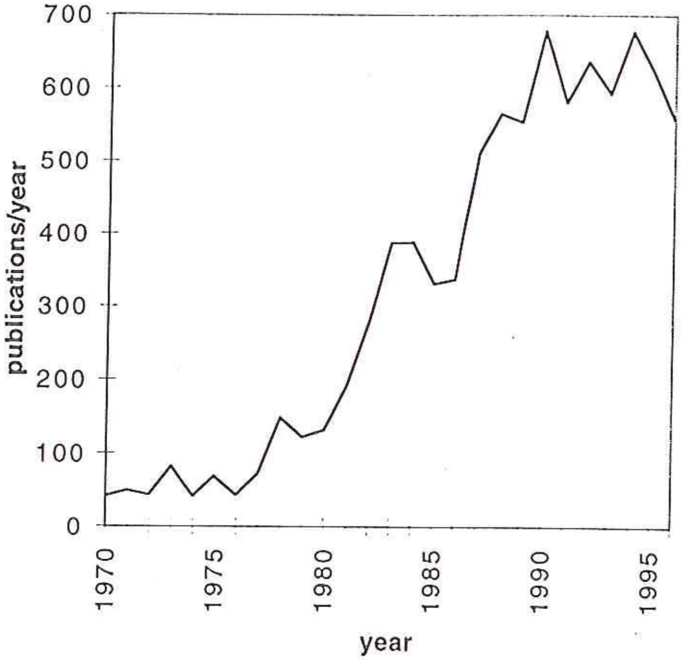
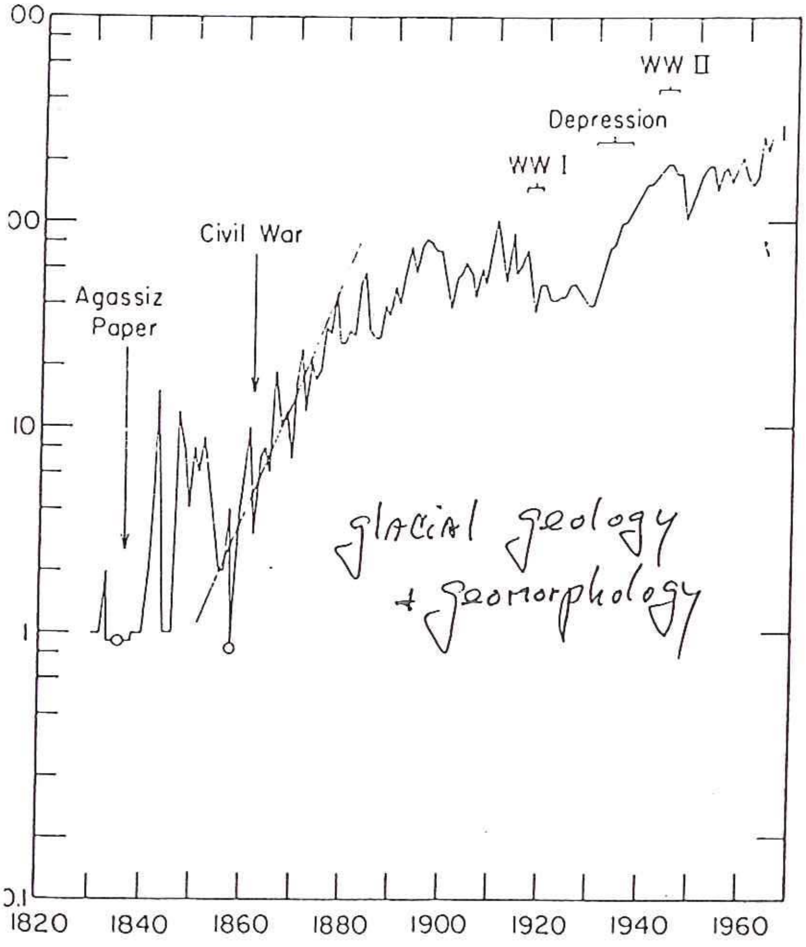


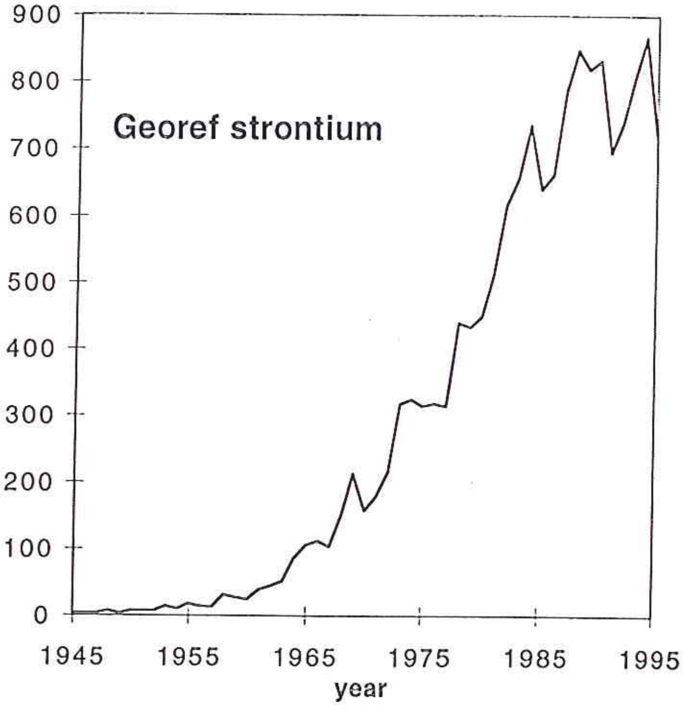
Plate tectonic revolution



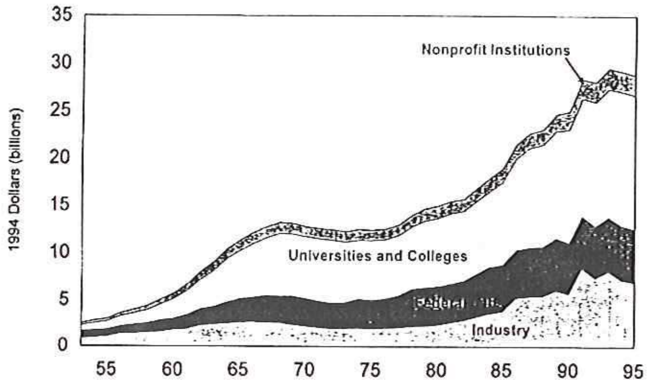
Neodymium georef citations

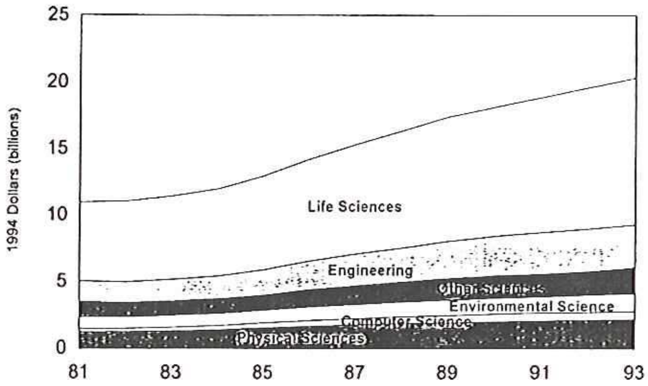


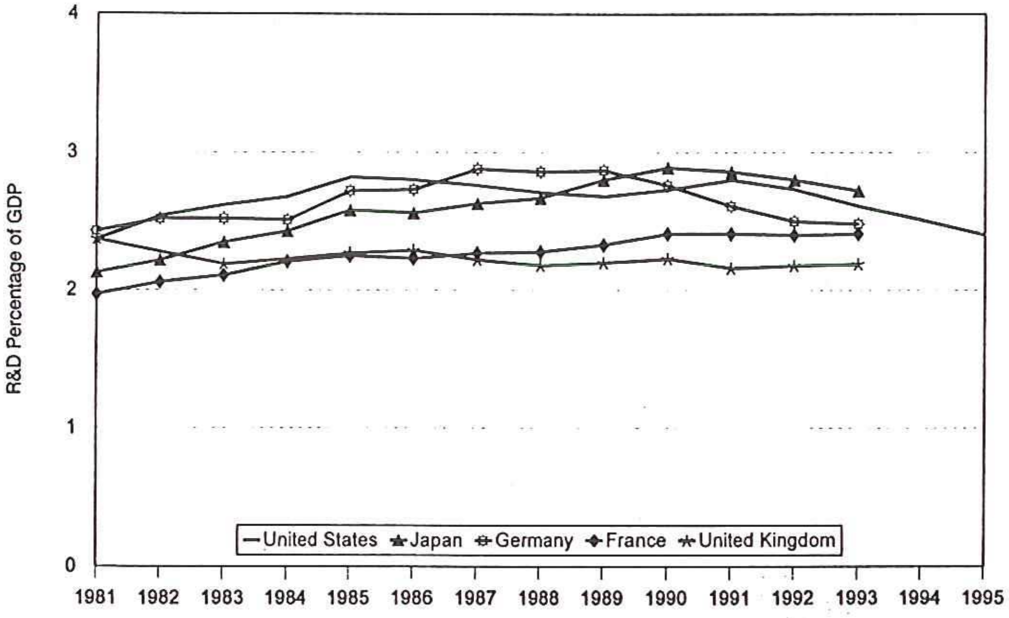




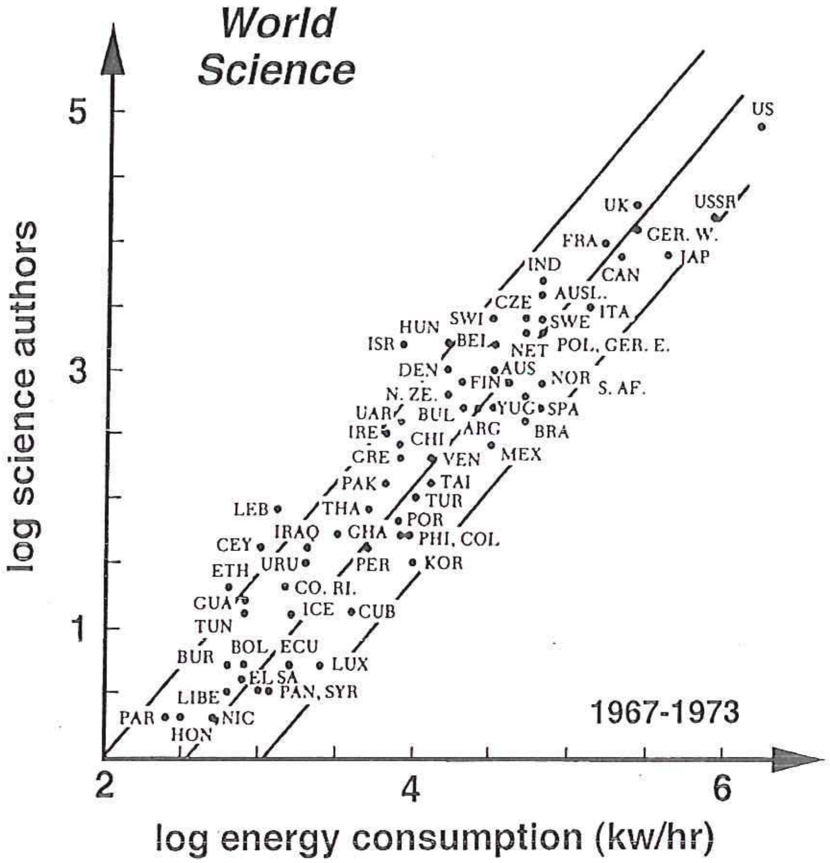
NATIONAL ACADEMY OF SCIENCES COLLOQUIUM:







SCIENCE, TECHNOLOGY AND THE ECONOMY



Derek J. de Solla Price, 1986

Do major discoveries in science grow linearly?

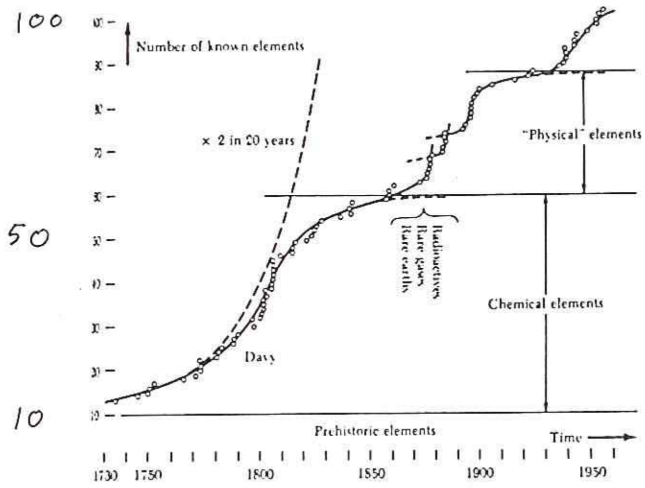


Figure 1.11. Number of Chemical Elements Known as a Function of Date

After the work of Davy there is a clear logistic decline followed by a set of escalations corresponding to the discovery of elements by techniques that are predominantly physical. Around 1950 is the latest escalation produced by the manufacture of transuranic elements

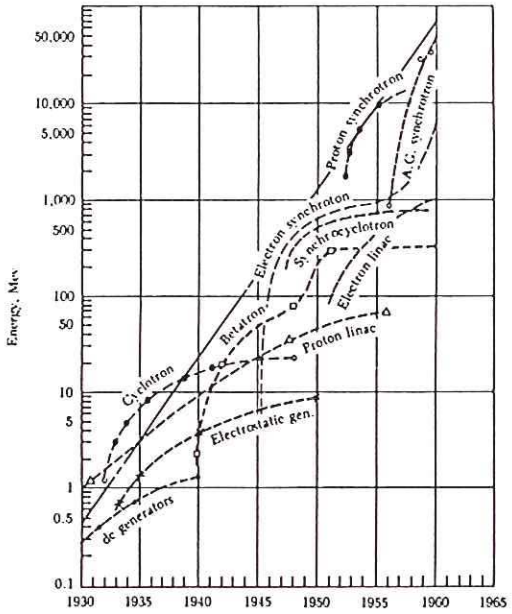
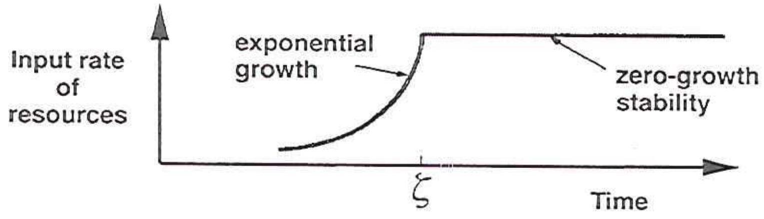


Figure 1.10. The Rate of Increase of Operating Energy in Particle Accelerators

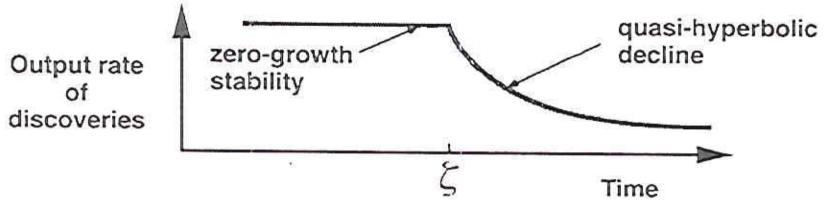
From M. S. Livingston and J. P. Blewett, *Particle Accelerators* (New York: McGraw-Hill, 1962), p. 6, figure 1.1, used by permission.

The Transition from Exponential Growth to Zero Growth in Resources for Scientific Discovery

A. Input History



B. Output History



after Rescher , 1978

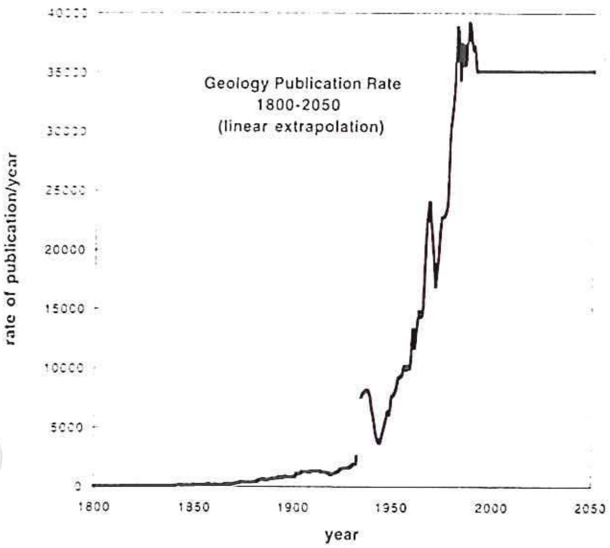
Observed

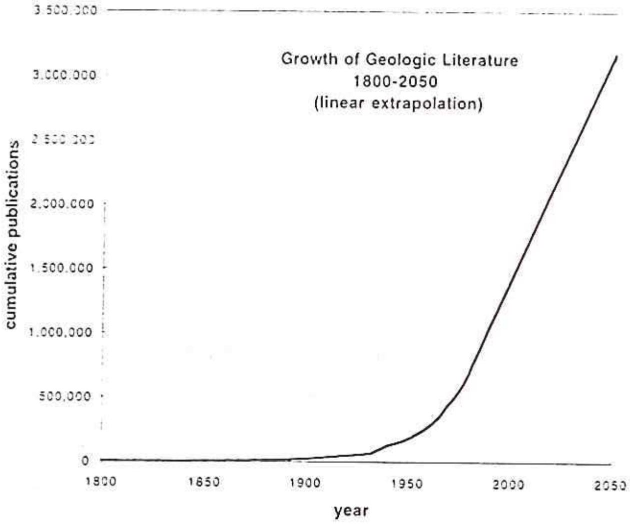
rate ordinary science $\propto$ rate of resources

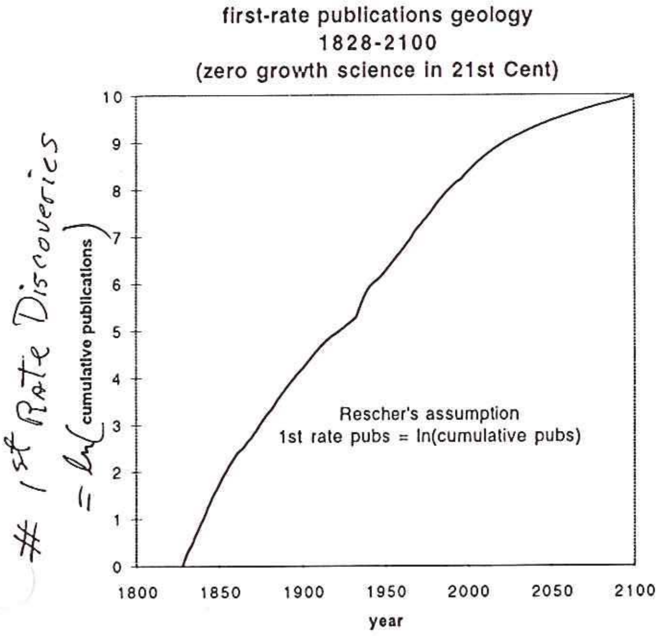
Idea (unsubstantiated)

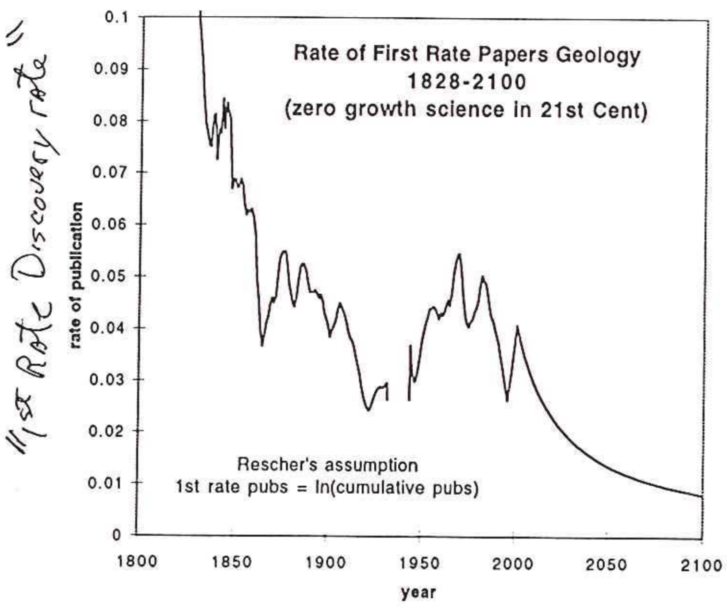
First-Rate Discoveries $\propto$ ln cumulative resources

$\propto$ ln cumulative ordinary science









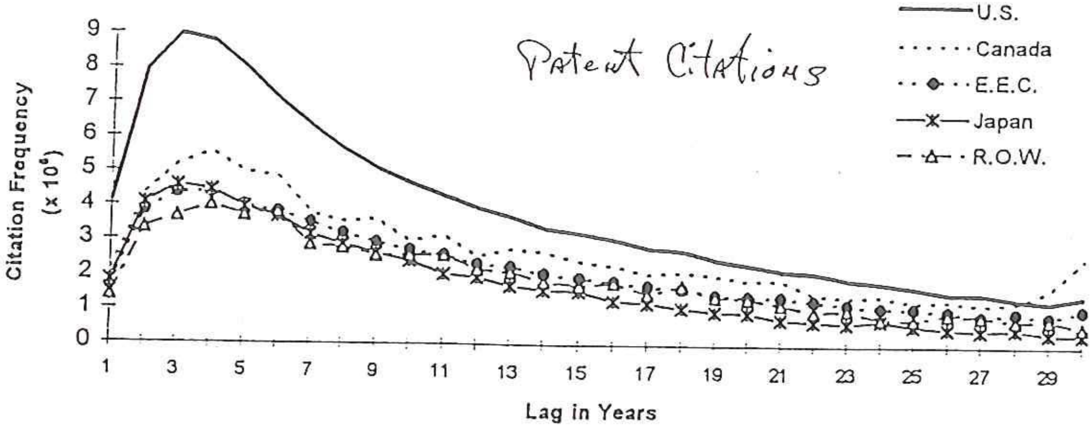
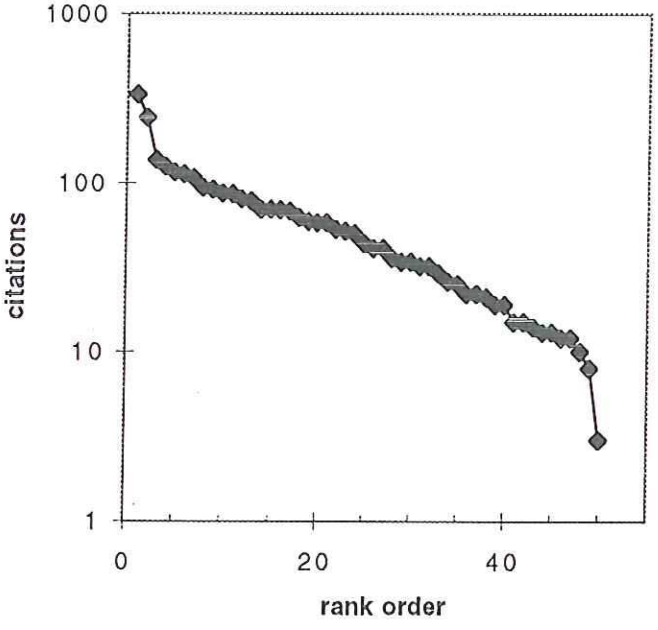


FIG. 1. Plot of the average citation functions for each of five geographic regions (citation frequency as a function of time elapsed from each potentially cited patent).

Citations to 1984 Nd isotope papers



pub/yr (years = 83, 84, 85, 90)