Fossil fuels

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

Exemplified by US energy use — more than 50% from burning wood at time of Civil War — now 90% from fossil fuels

Oil and natural gas:

Source is buried organic carbon, mostly the remains of microscopic oceanic phytoplankton (algae)

↑ "phyto" = Greek for plant

Photosynthesis of these microscopic plant fixes 70 GtC/yr (pre-industrial). This oceanic NPP ≈ terrestrial NPP.

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

The phytoplankton are grazed & metabolized by a host of respiring organisms:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

All oceanic photosynthesis occurs in uppermost 100 m — photic zone.

Only 7-10% sinks to below 100 m.

Only 0.2 GtC/yr escapes consumption and is buried.

This 0.2 GtC/yr of buried organic carbon is the source of all oil and gas.

The amount buried depends on the flux into the sediment top and the efficiency of burial.

The flux is high in regions of high productivity — coastal regions where rivers supply needed nutrients (nitrate and phosphate)

The burial efficiency is highest in regions of high sedimentation rate (deltas)

The efficiency peaks at 20% — 30% for sedimentation rates exceeding
1 m/1000 yrs = 1 km / Myr

Rivers transport $2 \cdot 10^{13}$ kg = 20 Gt of sediments to the ocean each year.

The average organic C content of oceanic shales should therefore be

$$\boxed{\frac{0.2\ \text{GtC/yr}}{20\ \text{Gt seds/yr}} = 1\%}$$

← recall this is organic C, not C in $CaCO_3$

The measured range is

$$\underset{\text{deep ocean}}{0.05\%} - \underset{\text{near shore}}{5\%}$$

$$\boxed{\text{measured mean } 1\%}$$

The small fraction with organic C exceeding 5% are petroleum source rocks.

Once the organic compounds are buried they can no longer be oxidized (no O_2)

Anerobic bacteria can, however, consume them via the reaction

$$2CH_2O \xrightarrow[\text{bacteria}]{} \underbrace{CH_4}_{\text{biogenic methane in uppermost 1-2 km}} + CO_2$$

Most of this biogenic methane is expelled by compaction during further burial

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

Typically 5–40 C atoms per molecule of petroleum.

The late stages of this process yield natural gas, mostly methane CH_4. The ultimate product is graphite

The "oil window" 60°–200° C occurs at depths 2–7 km, depending upon the geothermal gradient

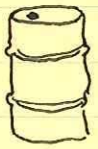
Oil can [illegible] remain in the source rocks ("oil shales") or it can be mobilized into more permeable (sandier) formations.

Once there it can migrate — much escapes in oil seeps such as the La Brea tar pits in LA. Also collects in a wide variety of "traps" where it can be drilled and pumped.

The first well — Drake's folly — was drilled in 1861 in Titusville, PA.

Traditional unit of oil measurement:

1 barrel = 42 gallons
= 159 liters
= 0.137 metric tons



1 bbo = 1 billion barrels of oil

Most oil is found in relatively young rocks — ~~a few million years old~~ tens of Myr old. The longer it has been around, the more chance it has had to escape.

King Coal:

Coal is formed from large leafy plants growing in swamps, often in slowly sinking coastal areas.

The swampy conditions can lead to burial of almost pristine organic matter with very little oxidation

Some methane is found in freshwater swamps due to

$$2CH_2O \xrightarrow[\text{anerobic bacteria}]{} \overset{\text{"swamp gas"}}{CH_4} + CO_2$$

Increasing burial leads to devolatilization. Main reaction is <u>dewatering</u>:

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

The %C goes up and the %O and %H go down. The highest-grade coal (anthracite) is ~90% C.

Organic matter in brackish swamps is high in H_2S due to reaction

$$2CH_2O + \underset{\text{sulfate ion in seawater}}{SO_4^{2-}} \xrightarrow[\text{bacteria}]{\text{anerobic}} 2HCO_3^- + \underset{\text{hydrogen sulfide}}{H_2S}$$

The H_2S then reacts with Fe to form pyrite FeS_2.

Such coal is "high sulfur" — produces SO_2 sulfur dioxide — acid rain — upon combustion.

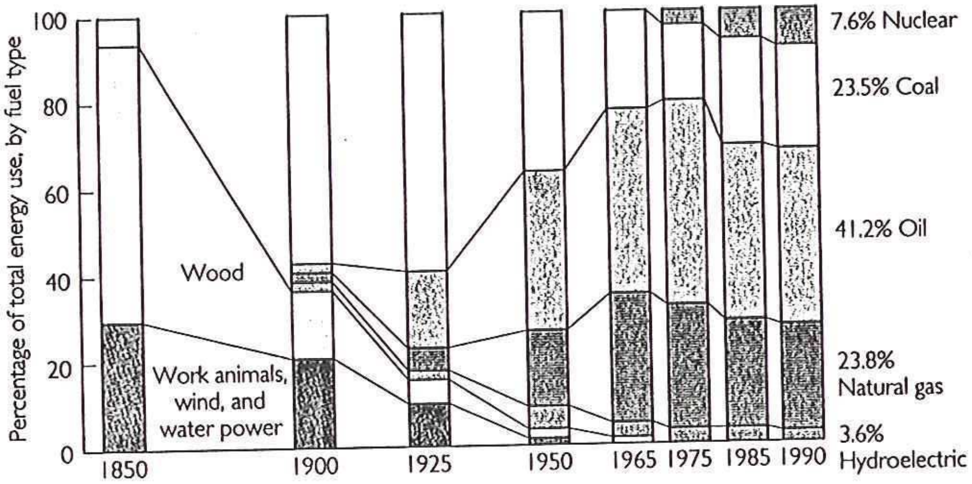


FIGURE 22.3 Percentages of various types of energy used in the United States from 1850 to 1990. (Data from U.S. Energy Information Agency, 1991.)

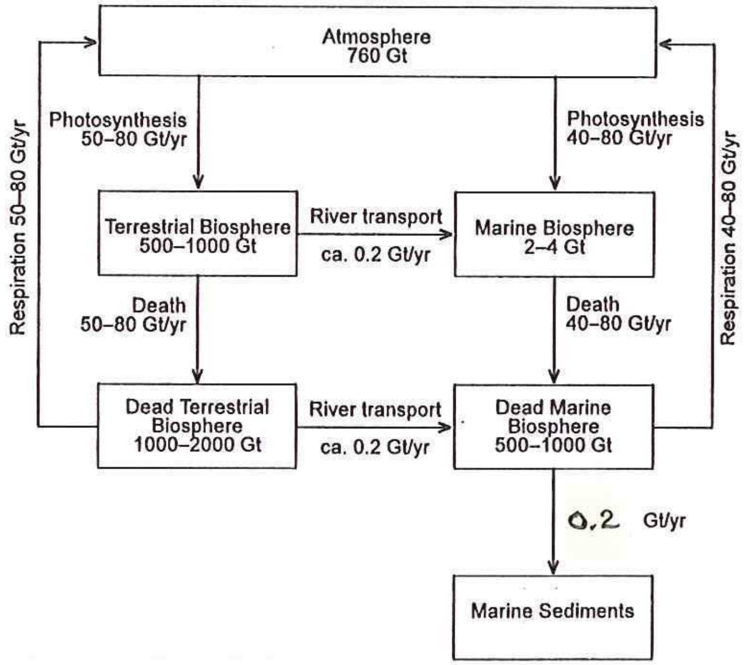


Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)

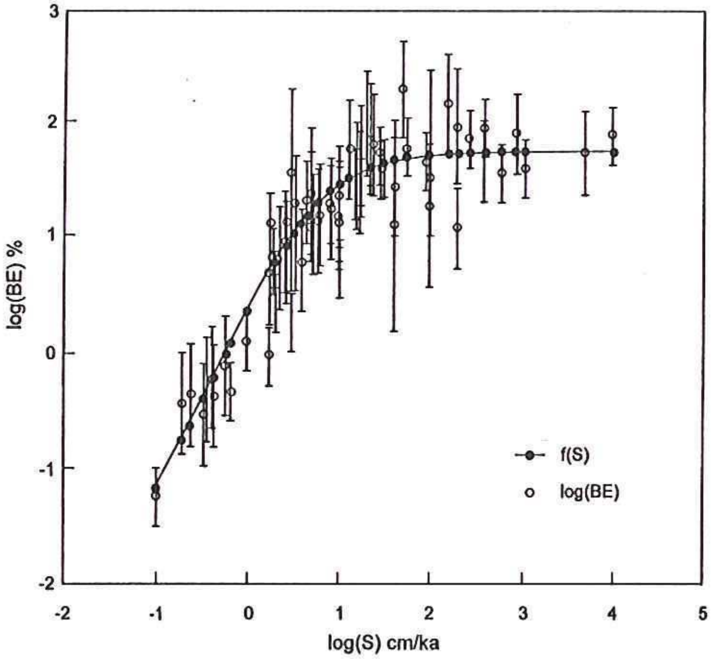


Figure 7.8. Plot of the burial efficiency, BE, of organic carbon with marine sediments vs. the sedimentation rate (S), in centimeters per 1,000 years. (Betts and Holland 1991)

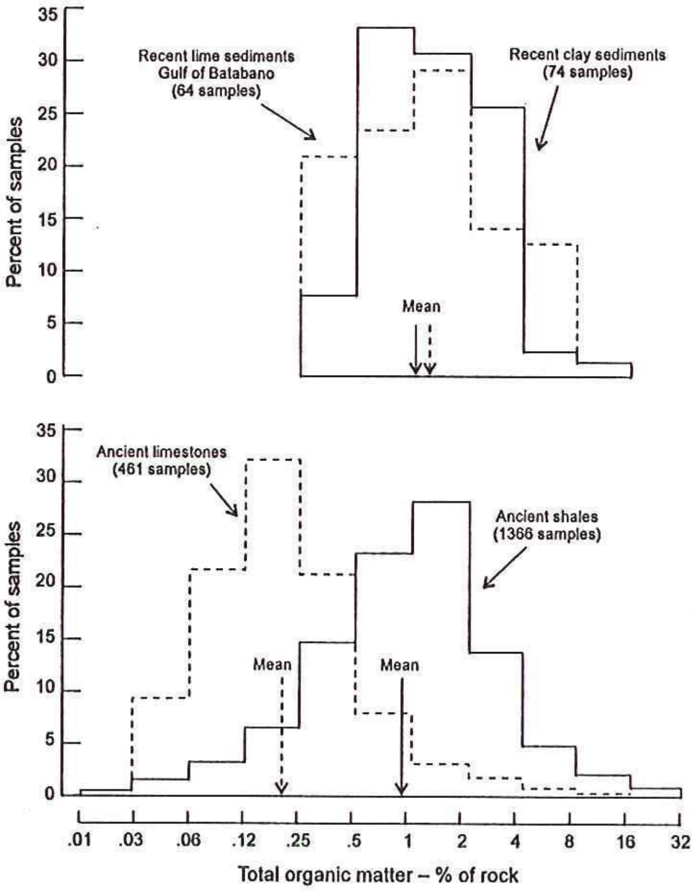


Figure 7.9. The total organic carbon content of recent and ancient limestones and shales. (Gehman 1962)

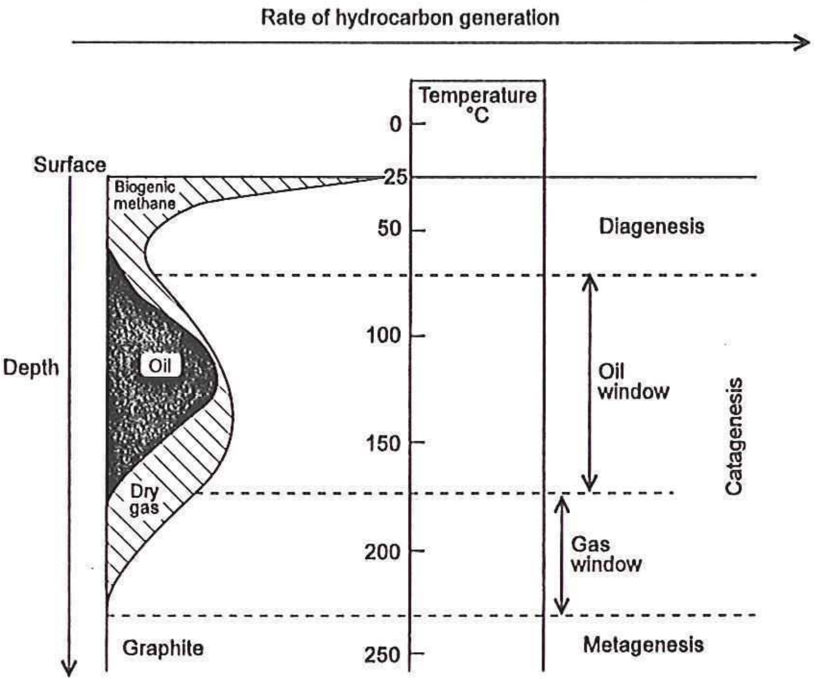


Figure 8.17. Correlation between temperature and the rate of hydrocarbon generation during the burial of organic matter in marine sediments. (Selley 1985)

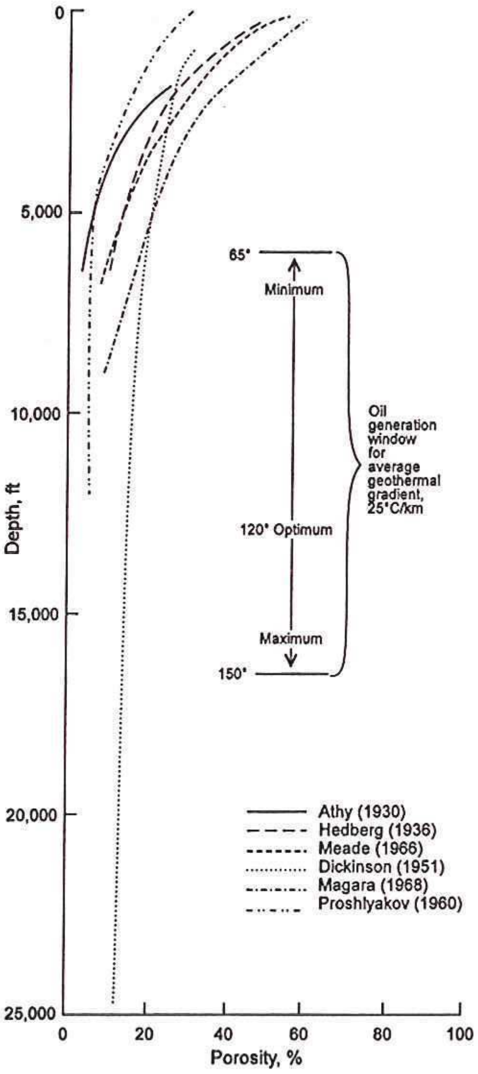


Figure 8.18. Shale compaction curves from various sources. Note that there is only a small amount of water loss due to compaction over the depth range of the oil window.

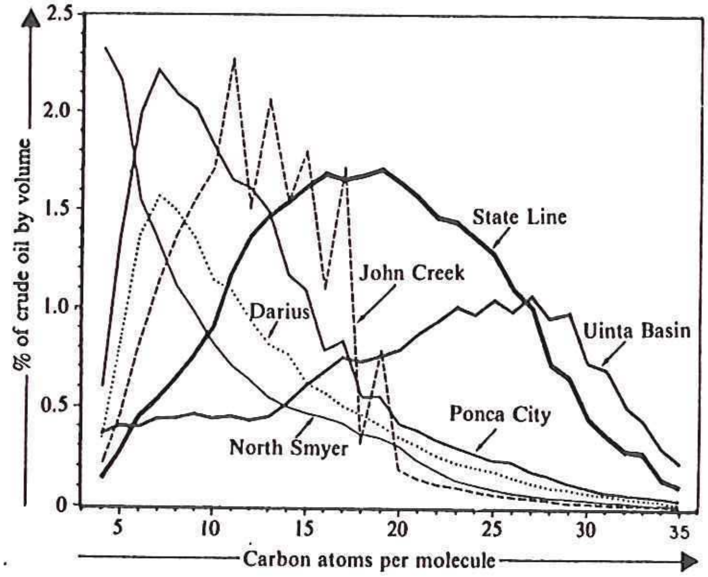
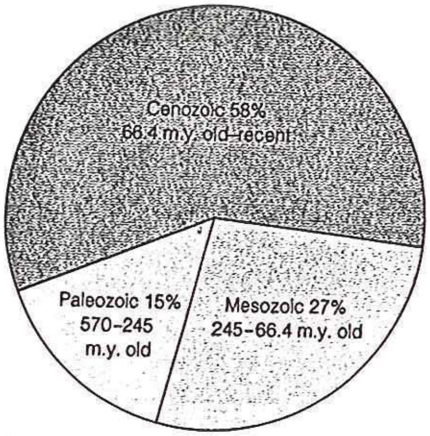


Figure 3.3. Distribution of *n*-alkanes in different types of crude oils. (From Martin et al., 1963; republished with permission of Nature)



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

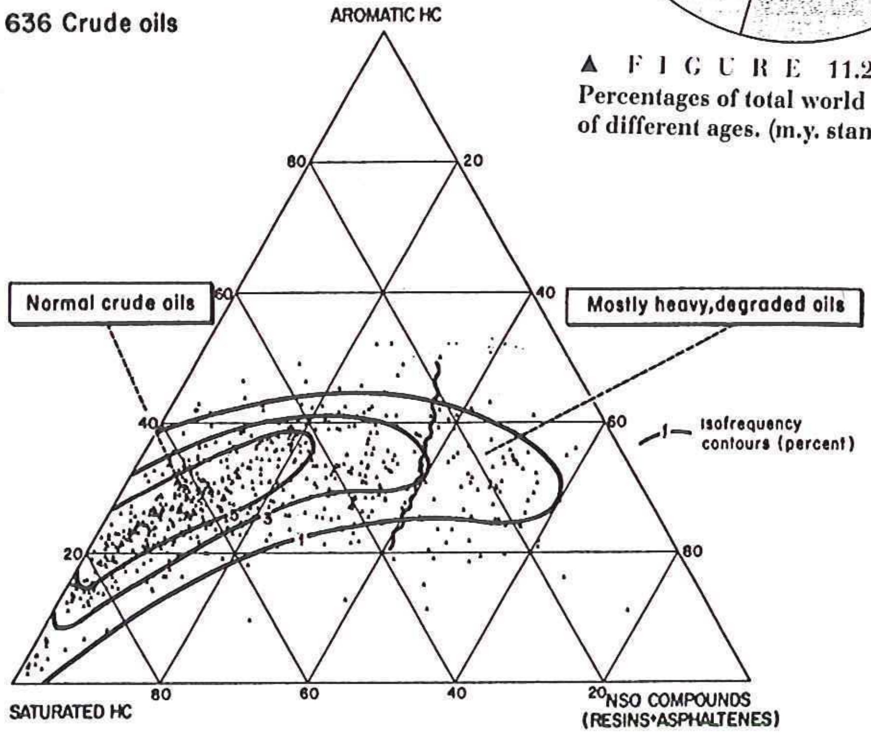


Figure 3.2. Ternary diagram showing the gross composition of 636 crude oils. (From Tissot and Welte, 1978: republished with permission of Springer-Verlag)

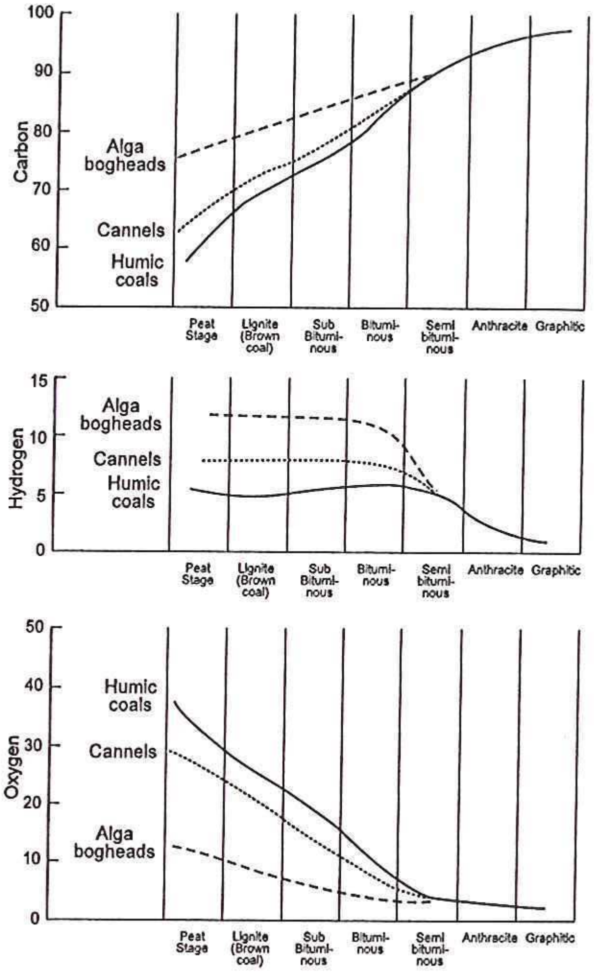


Figure 7.12. Changes in carbon, hydrogen, and oxygen content during the evolution of normal (humic) coals and algal (sapropelic) coals. (White 1925)

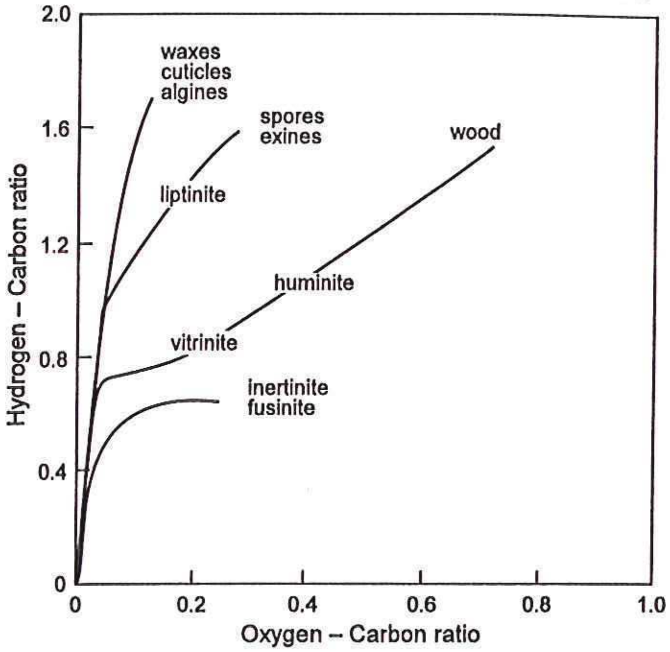


Figure 7.13. Van Krevelen diagram (H/C versus O/C atomic ratios) for the main components of coal and their predecessors with lines of dehydration, decarboxylation, demethanation, dehydrogenation, oxidation, and hydrogenation. (Modified after van Krevelen 1961; Tissot and Welte 1984; from Damberger 1991)

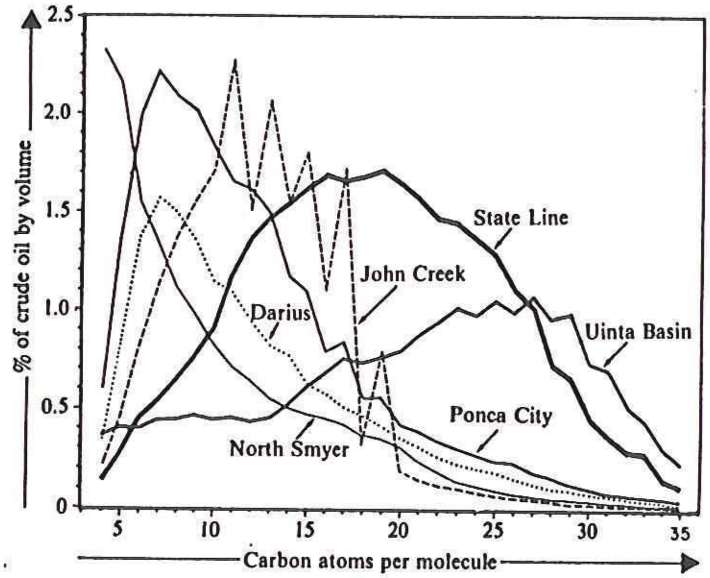
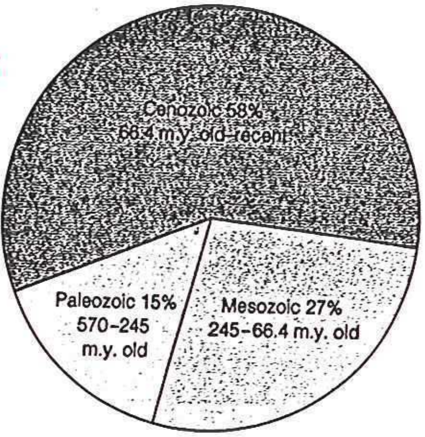


Figure 3.3. Distribution of *n*-alkanes in different types of crude oils. (From Martin et al., 1963; republished with permission of Nature)

Cenozoic rocks
≈60%



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

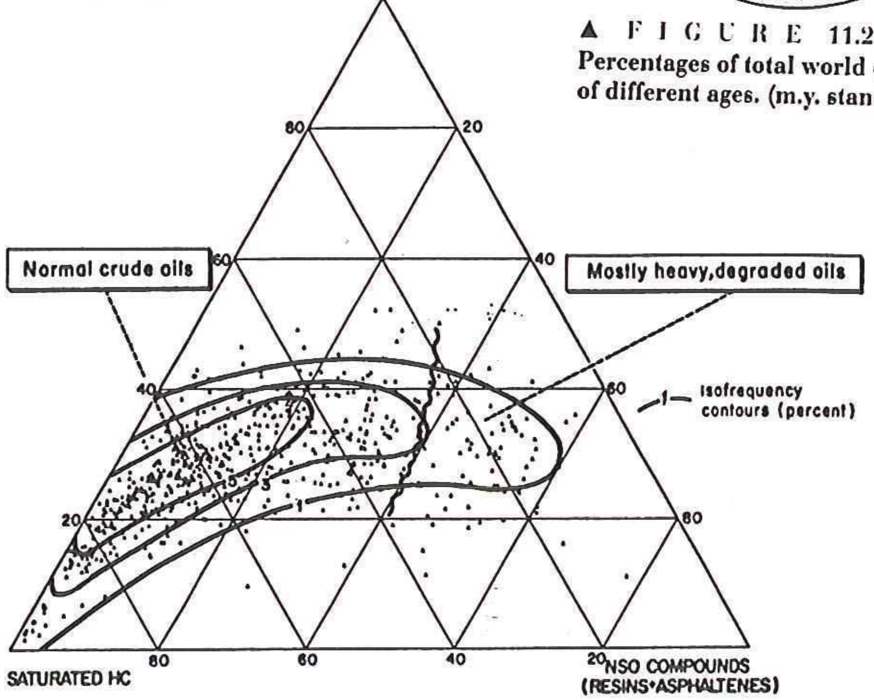


Figure 3.2. Ternary diagram showing the gross composition of 636 crude oils. (From Tissot and Welte, 1978: republished with permission of Springer-Verlag)

Fossil fuel consumption: best viewed in context of energy use as a whole.

Simplest to convert everything to energy units.

Some conversion factors are handy:

1 BTU (British Thermal Unit) = energy required to raise 1 lb of water 1°F.

1 BTU = 1055 J

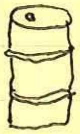
$$1 \text{ quad} = 1 \text{ quadrillion BTU}$$
$$= 10^{15} \text{ BTU} = 1.055 \cdot 10^{18} \text{ J}$$
$$\approx 1 \text{ EJ (exajoule)}$$

unit commonly used for global accounting

Oils differ but it is conventional to adopt a nominal average:

1 barrel of oil (upon burning)

= 5.8 MBTU = 6.1 GJ



so... 1 bbo (billion barrels of oil) ≈ 6 quads

To make matters more confusing:

Natural gas resources are commonly measured in tcf = trillions of cubic feet

1000 cu ft = 1 MBTU ≃ 1 GJ, so

$$\boxed{1 \text{ tcf} \approx 1 \text{ quad} \simeq 1 \text{ EJ}}$$

Finally, coal consumption is measured in <u>tons</u>.

$$\boxed{1 \text{ Gt coal} = 27.8 \text{ quads} = 27.8 \text{ EJ}}$$

↑ nominal average

Current world-wide energy consumption (1996):

$$\boxed{350 \text{ quads / yr} \leftarrow 87\% \text{ fossil fuel}}$$

World-wide is increasing at 2.7% per year — almost twice as fast as population

More confusion — electrical utility companies charge by the kilowatt-hour (kWh)

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

A typical electrical power plant has a <u>full</u> capacity of ~ 1 GW. Typically operates at ~ 60% capacity, producing 0.6 GW.

Burning 1 barrel of oil produces 1700 kWh

A typical coal-burning plant requires ~ 10,000 BTU ~ 0.3 tons of coal to produce 1 kWh. Efficiency of electrical conversion ~ 33%

How does fossil fuel consumption compare to food consumption?

$$\left(350 \cdot 10^{18} \text{ J/yr}\right) \quad (.85)$$

energy use × ~ 85% fossil fuel

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

$$= 10^{13} \text{ W} \approx \tfrac{1}{4} \times \text{heat flow from the } \oplus$$

Food consumption, as [redacted] we have seen, amounts to $2.4 \cdot 10^{19}$ J/yr $= 8 \cdot 10^{11}$ W

Humans consume 12 times as much fossil fuel (a nonrenewable resource) as food (a renewable resource)

Terrestrial NPP by photosynthetic plants is ~ $8 \cdot 10^{13}$ W, so

fossil fuel consumption is ~ 12% of terrestrial NPP

[redacted]

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

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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).

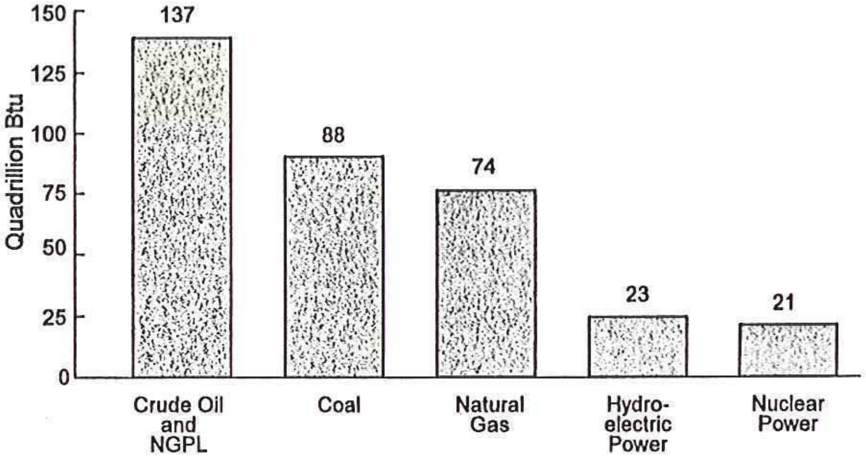


Figure 8.31. The major sources of world energy in 1992. (*Annual Energy Review 1993*)

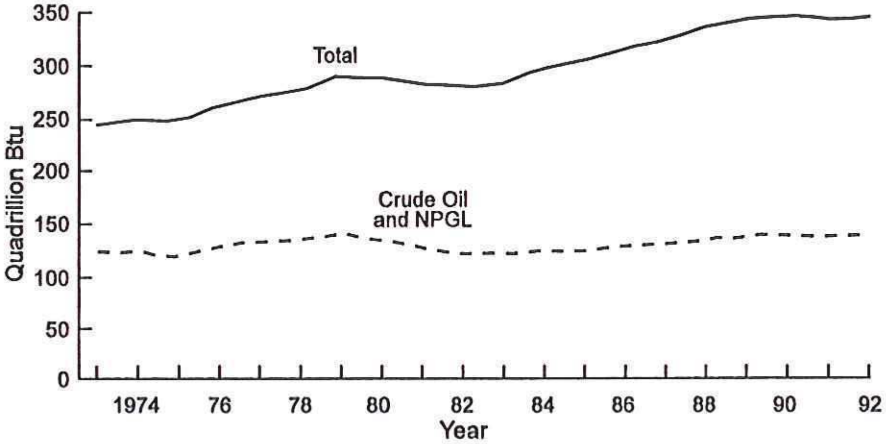


Figure 8.30. World primary energy production between 1973 and 1992. (*Annual Energy Review 1993*)

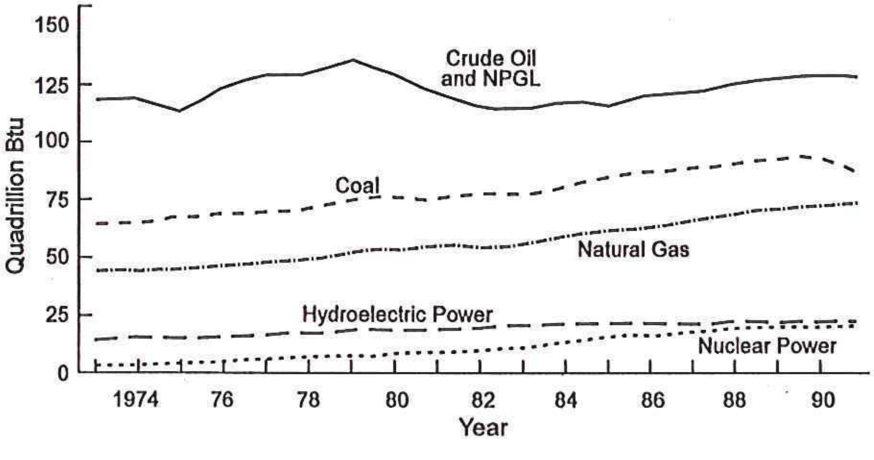


Figure 8.32. World primary energy production by source between 1973 and 1992. (*Annual Energy Review 1993*)

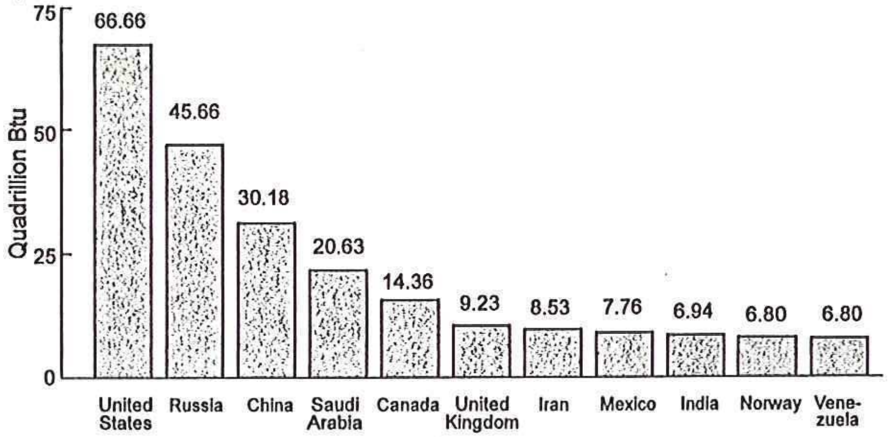


Figure 8.33a. The eleven major primary energy-producing countries in 1992. (*Annual Energy Review 1993*)

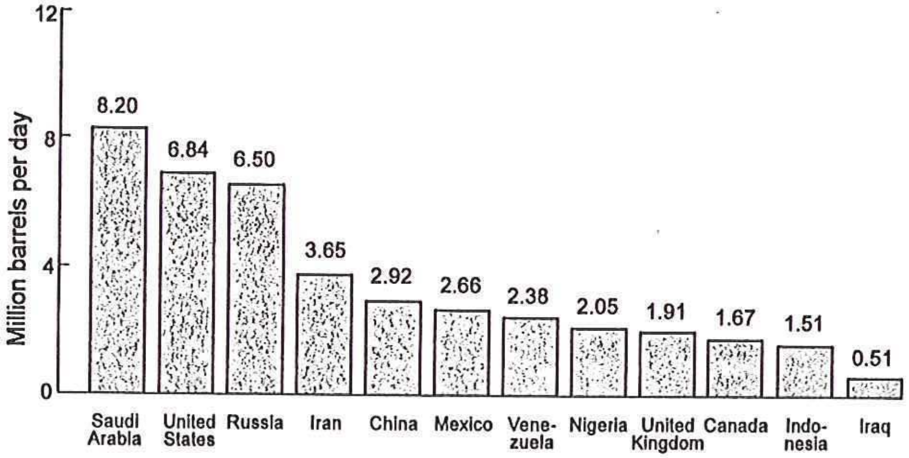


Figure 8.40. 1993 oil production by the twelve most important oil-producing countries. (*Annual Energy Review 1993*)

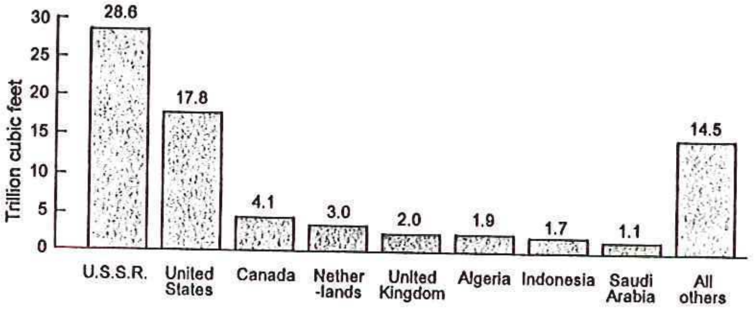


Figure 8.42. The major producers of natural gas in 1991. (*Annual Energy Review 1993*)

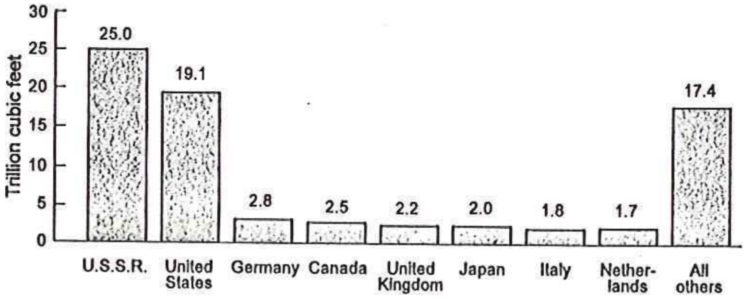


Figure 8.43. The major consumers of natural gas in 1991. (*Annual Energy Review 1993*).

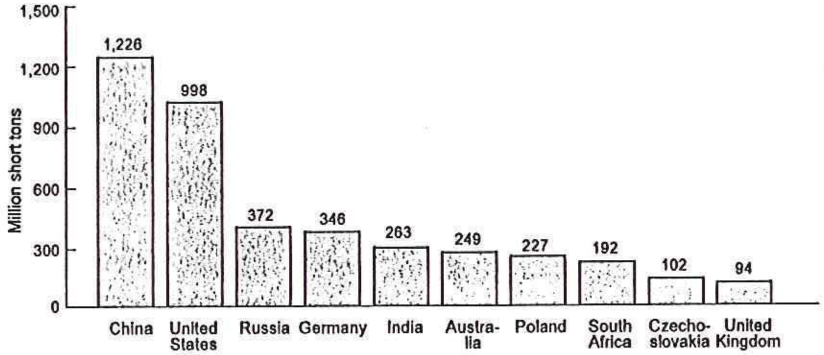


Figure 8.34. 1992 production of coal in the ten leading countries. (*Annual Energy Review 1993*)

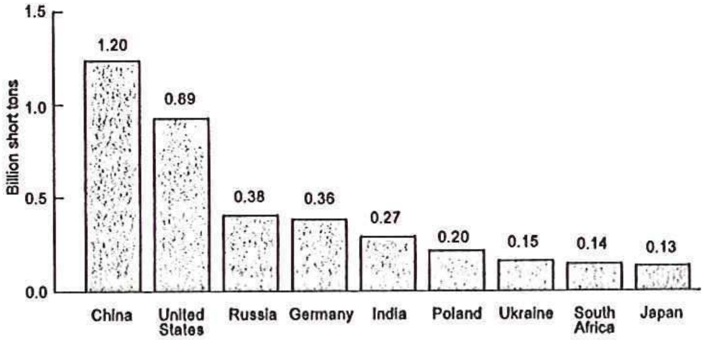


Figure 8.35. 1992 consumption of coal in the nine most coal-consuming countries. (*Annual Energy Review 1993*)

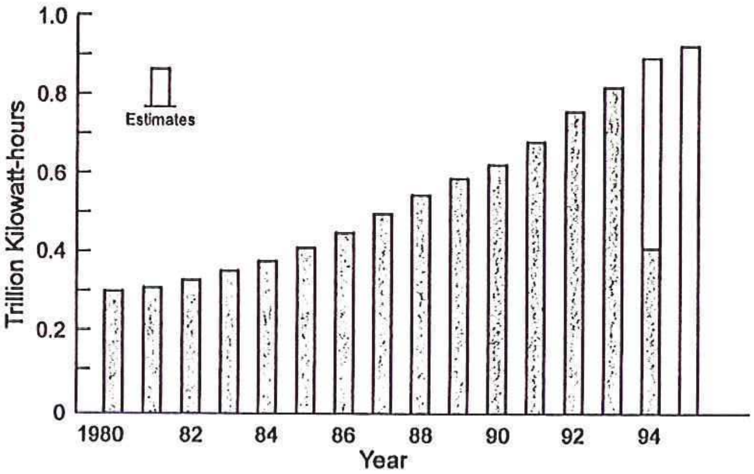
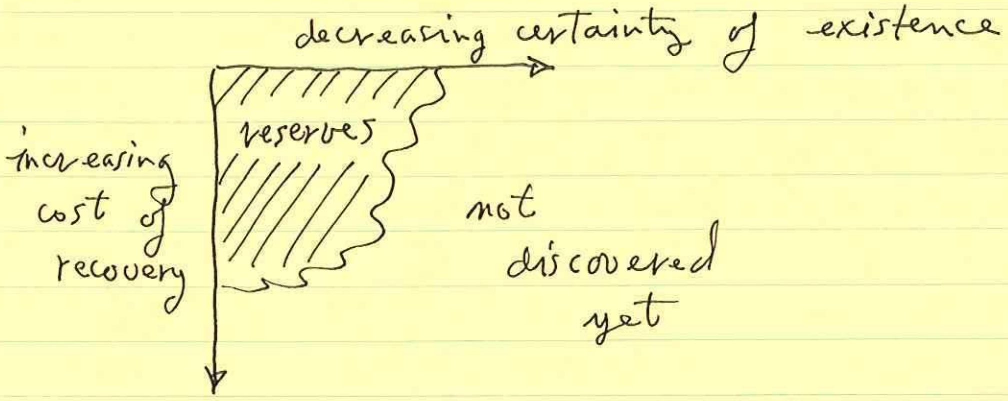


Figure 8.33b. Electricity generation in China since 1980. (*New York Times*, November 7, 1994)

So... how much is left?

Not easy to estimate — economic as well as scientific questions are relevant

The reserves of any nonrenewable resource are a floating target:



US — intense oil exploration — reserves are relatively well known

About 300 bbo pumpable oil in ground. We have already consumed ~ 50% of all pumpable oil in US since time of Drake's folly — 135 years ago.

World reserves are more uncertain. Total reserves, including undiscovered oil, could be as high as 2000 bbo = 12,000 quads

Current consumption rate 20 bbo/yr ⇒ 100 years' supply left.

Remember, however, that world-wide consumption is increasing at 3% per year

World reserves of natural gas estimated to be 8000 tcf = 8000 quads (about 100 years' supply at current consumption rates)

Coal is even more plentiful. Some estimates as high as 3000 Gt = 80,000 quads!

US very rich in coal: 1/4 – 1/5 of world reserves.

Subeconomic sources (tar sands, oil shales) — oil that has not been cooked enough to be pumped.

New extraction techniques are required.

Current production rates are minuscule because of expense — but potential reserves are huge — may be as high as 20,000 bbo equivalent = 120,000 quads (10 times as much as pumpable oil reserves)

Total remaining — all sources:

oil — 12,000 quads
gas — 8,000 quads
coal — 80,000 quads
other — 120,000 quads
total — 220,000 quads

$$\frac{220{,}000 \text{ quads}}{350 \text{ quads/yr}} \approx 600 \text{ years}$$

But both numerator & denominator are uncertain

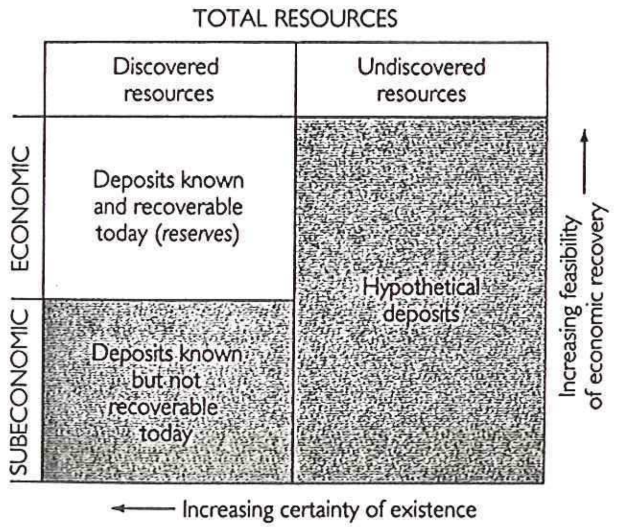


Table 1. United States oil resources (in billions of barrels).

Orignal proven conventional recoverable resources	226
Already produced	142
Remaining	84
Estimated undiscovered resources	46
Domestic production (per year)	3
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.

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.

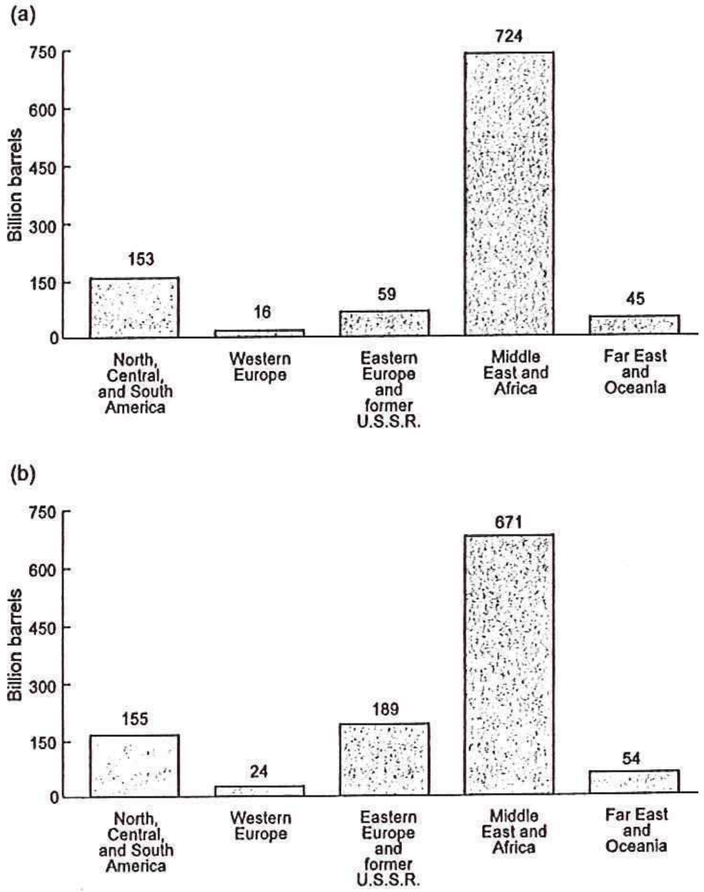


Figure 8.41. The distribution of world oil reserves in 1993. Sources (a) *Oil and Gas Journal*; (b) *World Oil*. (*Annual Energy Review 1993*)

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

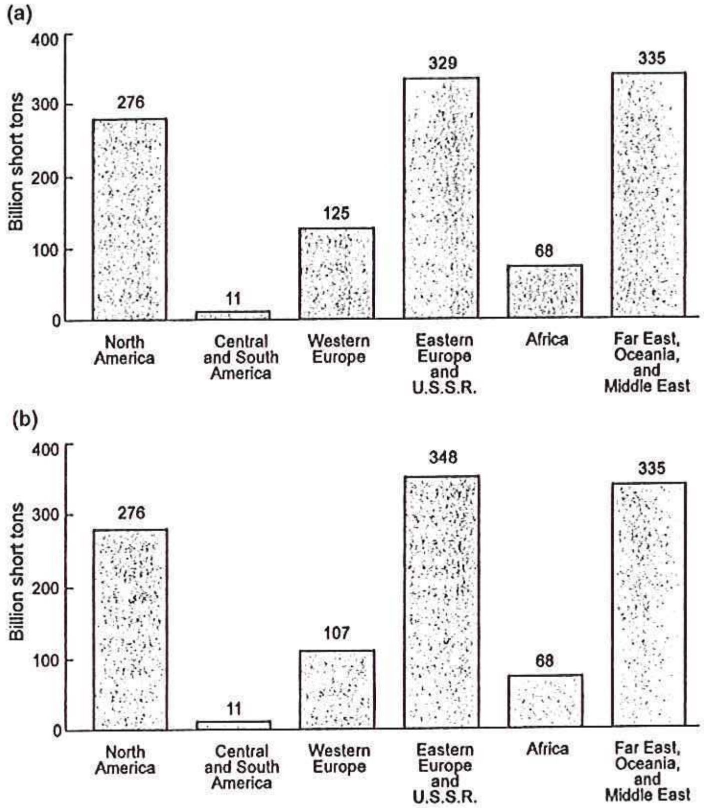


Figure 8.37. World reserves of coal estimated by (a) the World Energy Council, 1991; (b) British Petroleum, 1992. (*Annual Energy Review 1993*)

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

	Range of shale oil yields (gallons per ton[a])		
Location	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 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

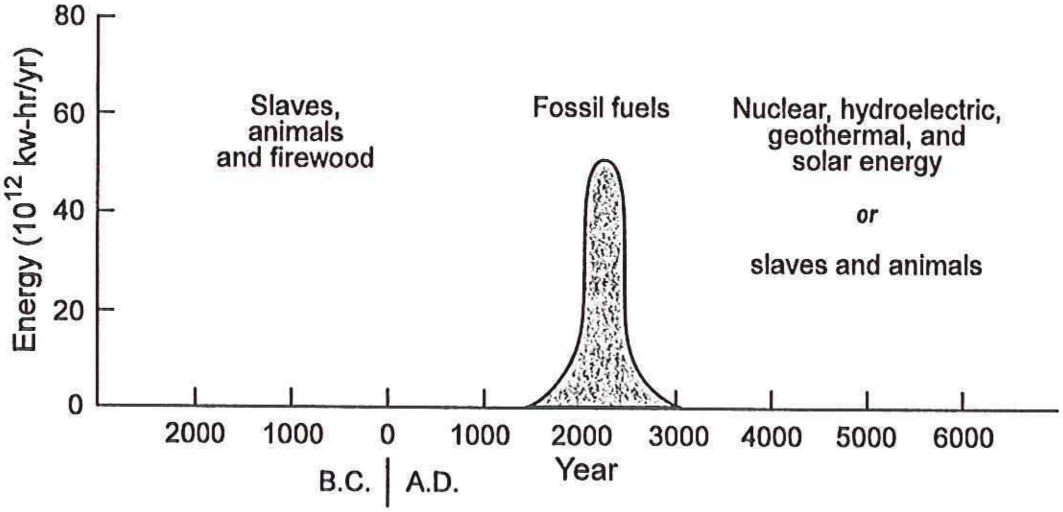
	Billion Barrels		
	Measured Resources	*Speculative Resources*	*In-Place Resources*
United States	21	41	~60
Canada			~1,700
Venezuela			~700
World total			~4,000

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.



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.

$$CO_2 + H_2O \xrightarrow{sun} CH_2O + O_2$$

phytoplankton
organic matter

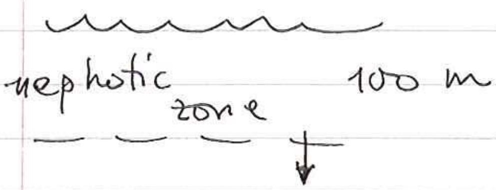
They are grazed & metabolized by a host of other organisms up to fish & whales.

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

$\boxed{0.2\ Gt/yr}$

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 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]

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

burial efficiency is measured using sediment traps

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

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

— average for all oceanic shales

organic C — not C in $CaCO_3$

deep-ocean
↓
The range is high from < 0.05 %
to > 5 %
↑ near-shore settings

The average is indeed 1%.

Organic-rich (> 5% [redacted] organic C)
are oil source rocks.

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

CH_2O [redacted] $+ O_2 \rightarrow CO_2 + H_2O$

No oxygen.

Bacteria can, however, consume
them via reaction (in simplified form)

anerobic
bacteria

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

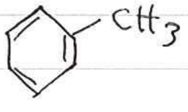
At greater depths and temperatures
between 100°C – 200°C a complex
set of reactions breaks the organic
matter down into petroleum

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

Petroleum consists of:

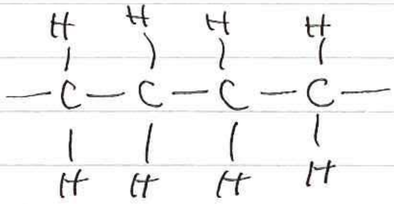
saturated hydrocarbons

aromatic hydrocarbons



Details depend on the "cooking" history

asphaltenes

Mostly just 

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 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. [redacted] Genesis – Noah caulked the arc with tar.

Collects in a wide variety of "traps"

Example: Elk Basin ← Wyoming – Montana border, 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

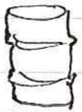
A few years later, hundreds of wells.

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 = 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.

a few million years old

Most oil is relatively young rocks

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 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"

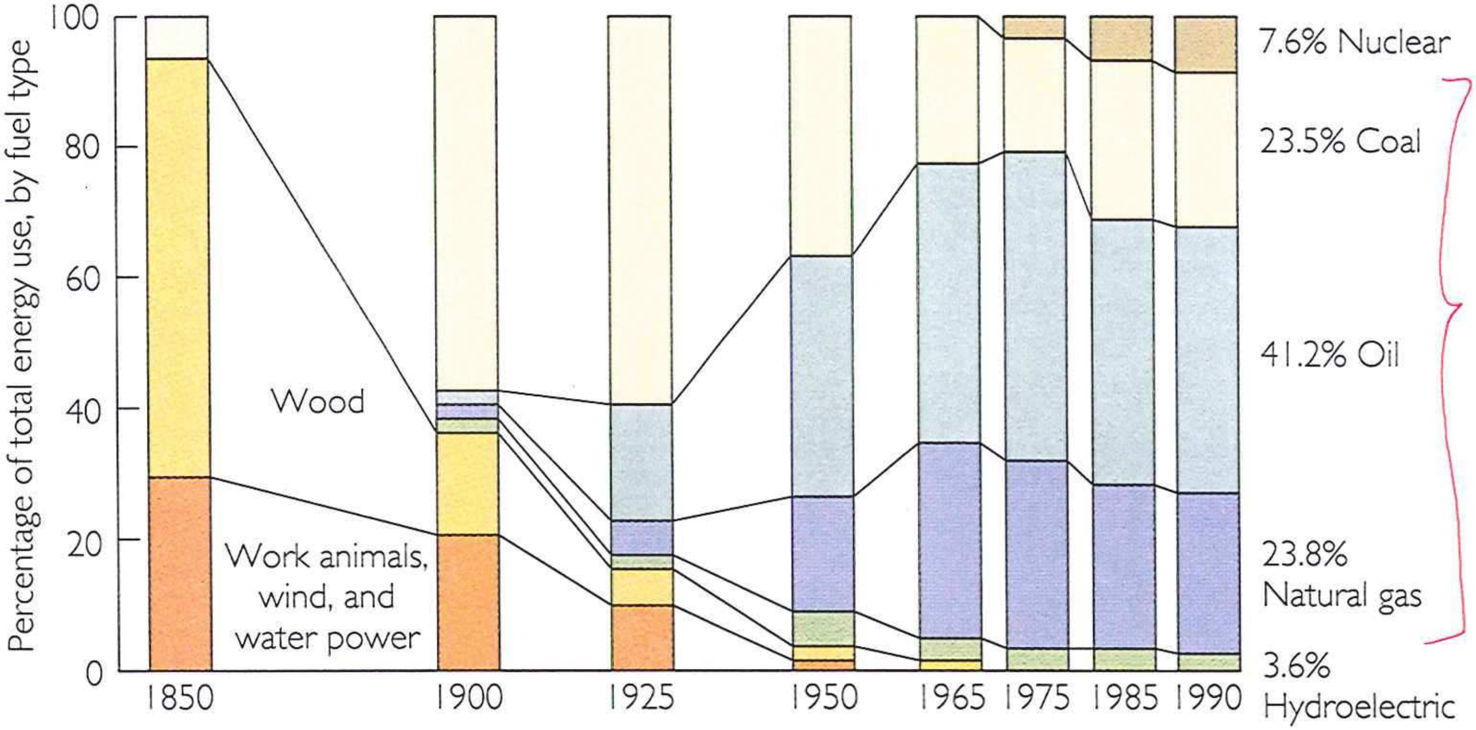
Produces SO_2 sulfur dioxide "acid rain" upon combustion.

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

i.e. swamp
Two peak periods of coal formation

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

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



US 89% fossil fuel

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.)

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

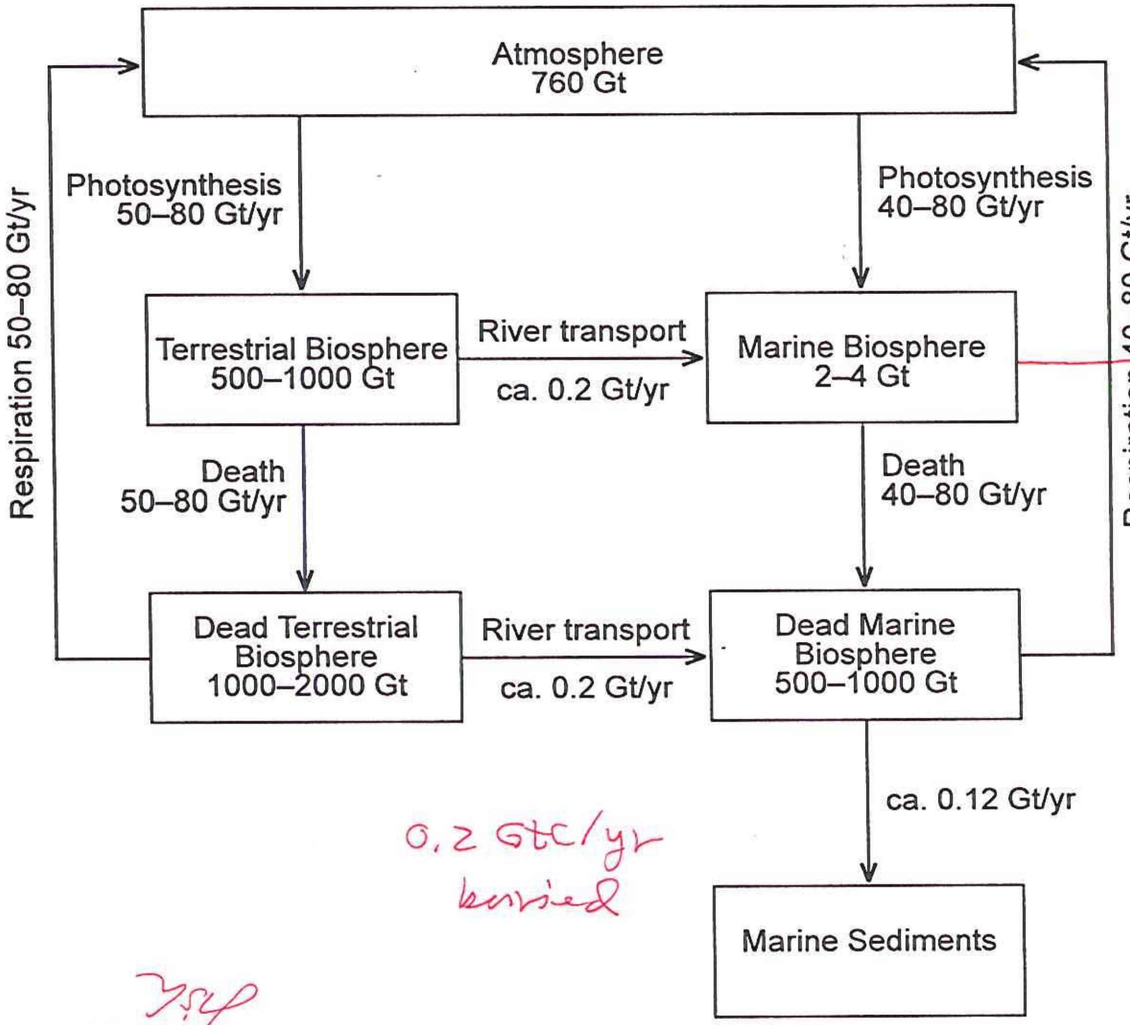


Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)

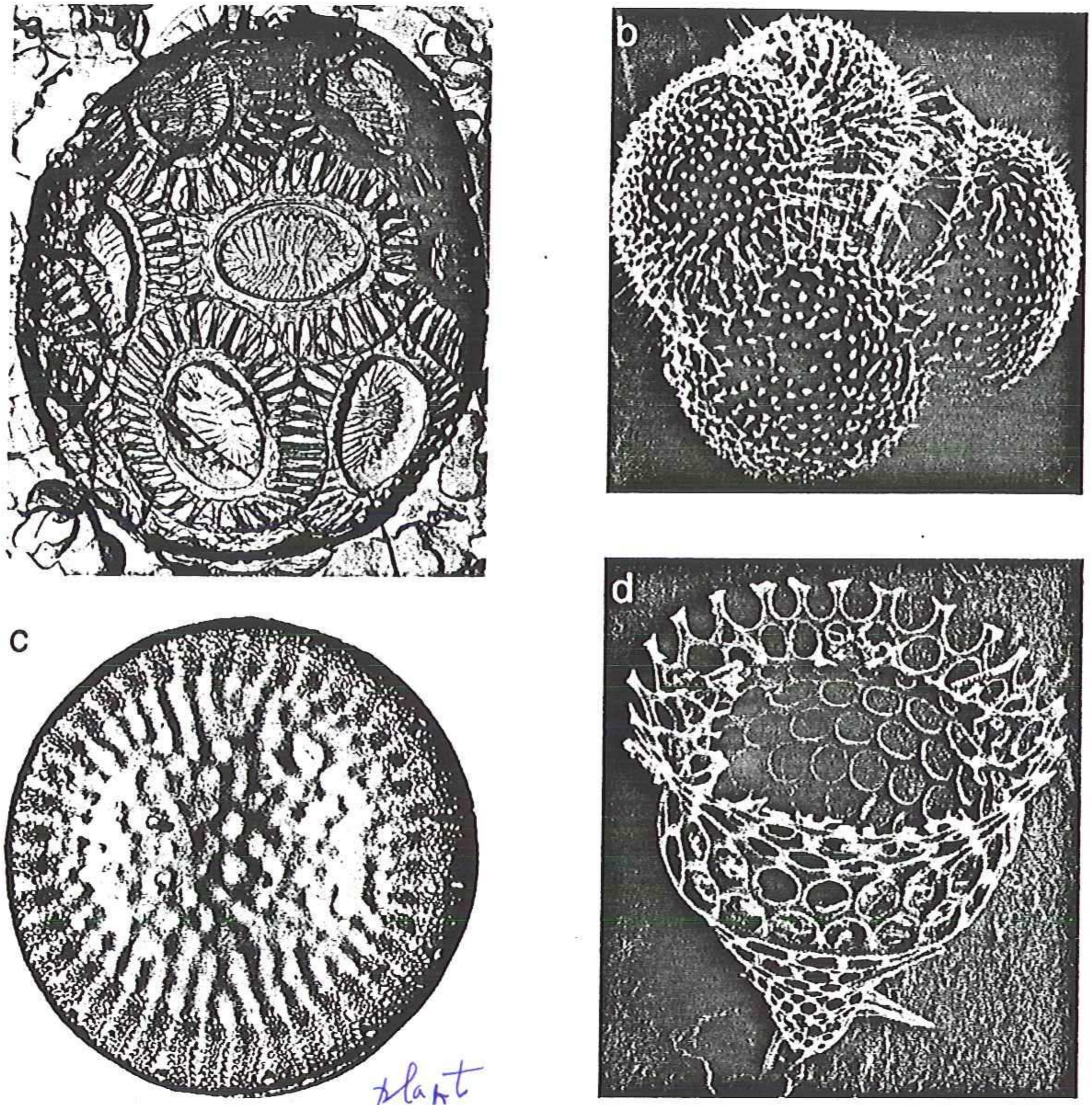
0.2 GtC/yr
buried

note — trees are
heavier than
fish

phytoplankton live in upper
100 m of ocean

plant

animal



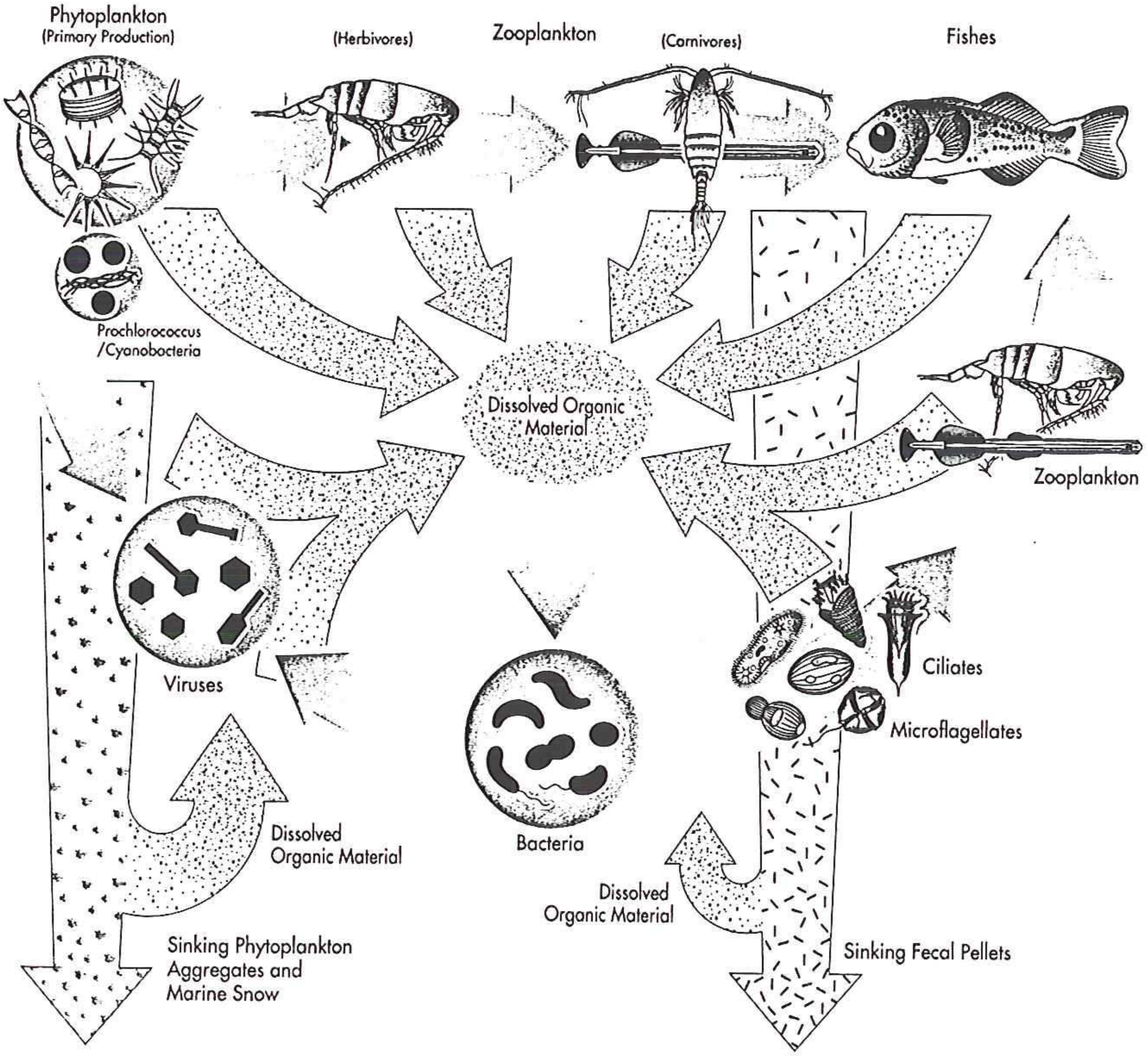
plant

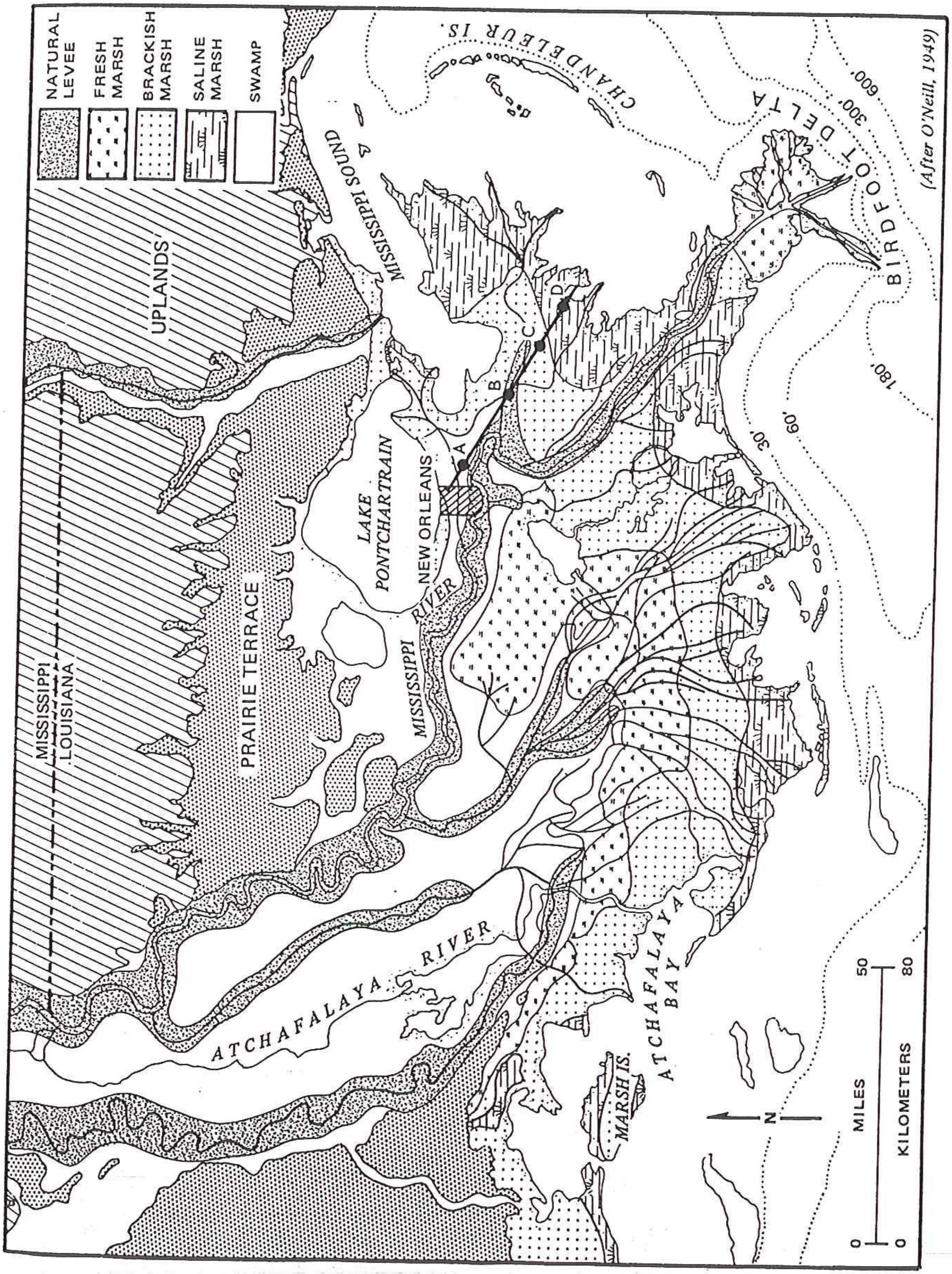
animal

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.





(After O'Neill, 1949)

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

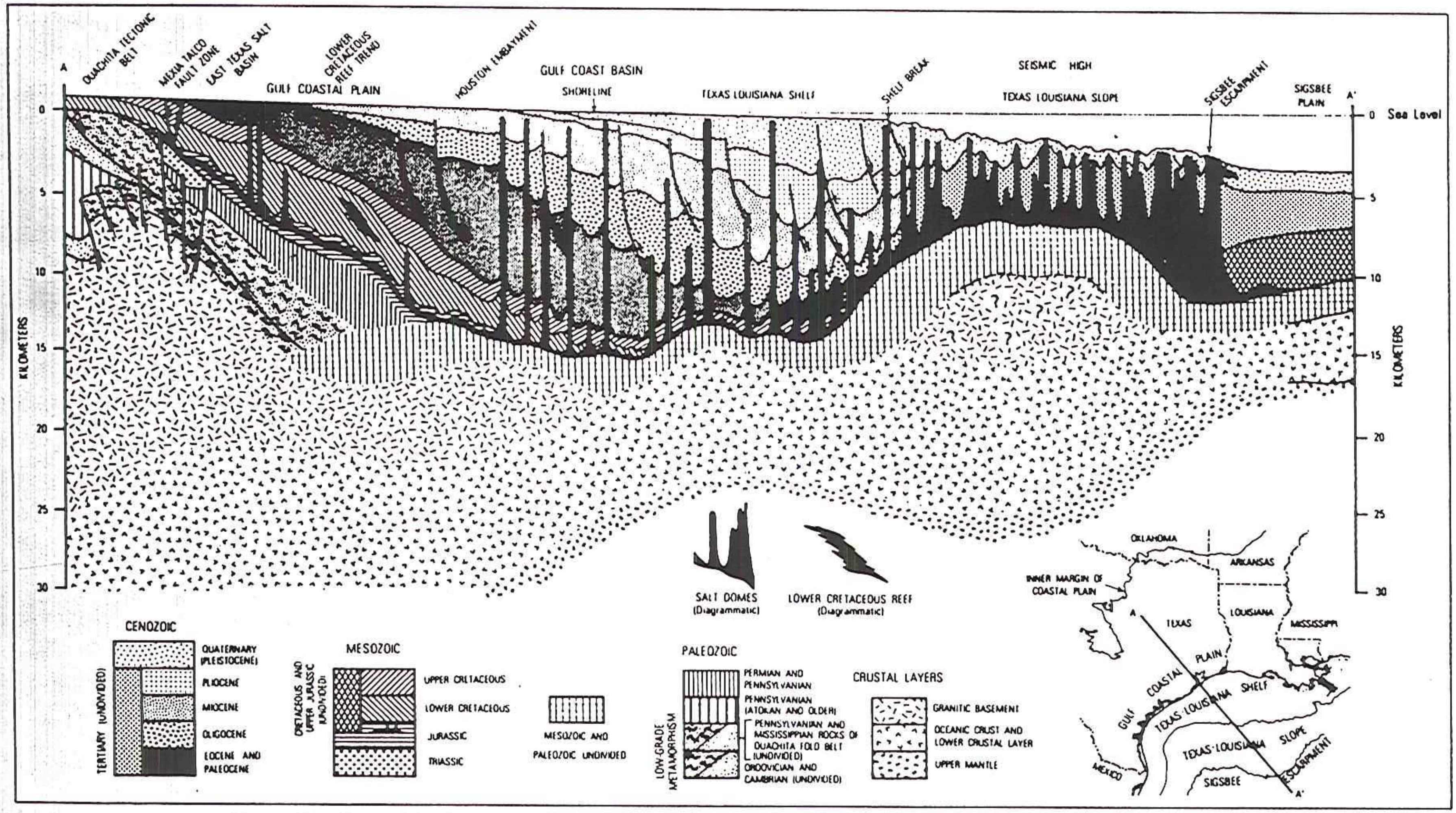


Figure 12. Generalized cross section of the northern Gulf of Mexico margin (from R. G. Martin, 1978, modified from earlier interpretations of Lehner, 1969; Dorman and others; 1972, Antoine and others, 1974; and Martin and Case, 1975).

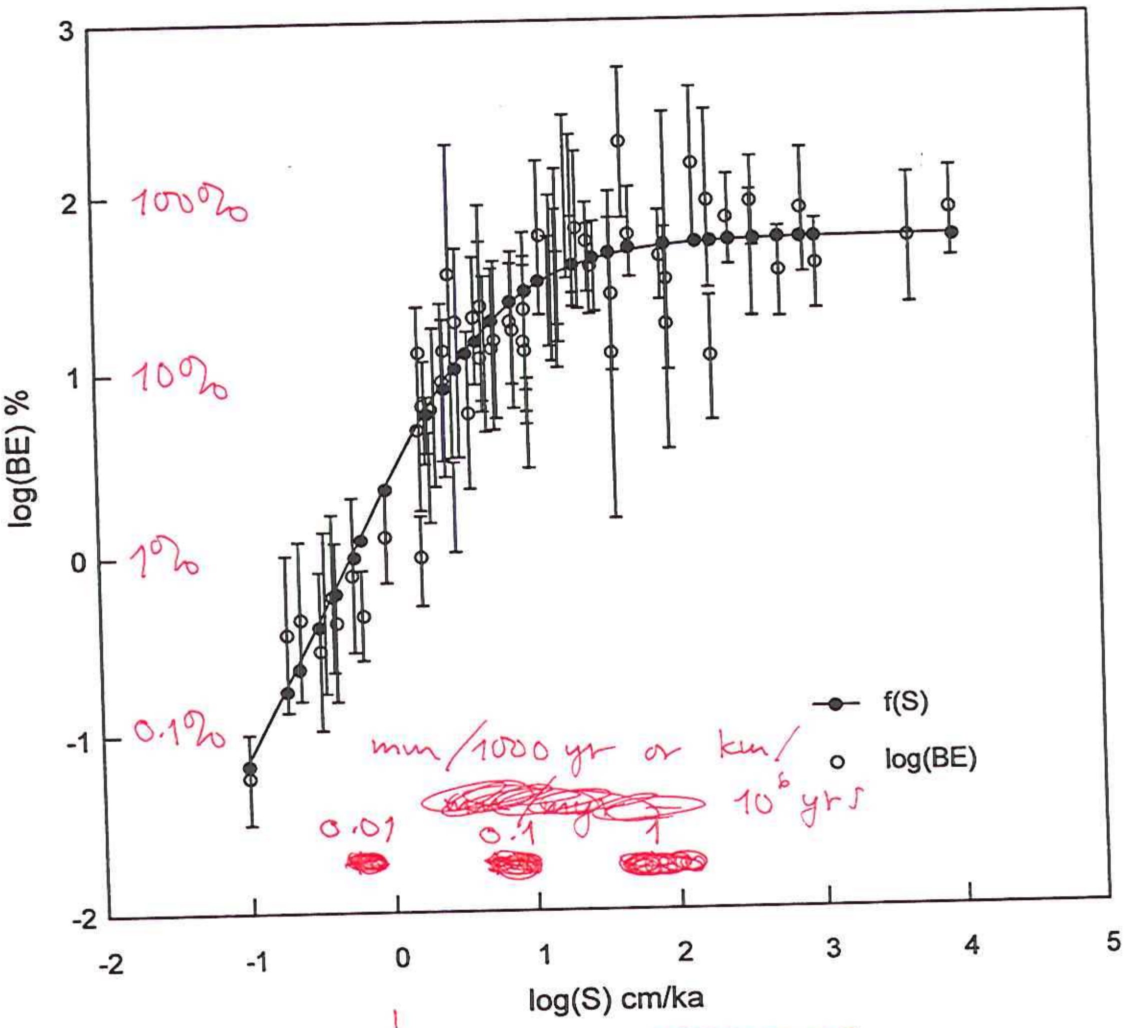


Figure 7.8. Plot of the burial efficiency, BE, of organic carbon with marine sediments vs. the sedimentation rate (S), in centimeters per 1,000 years. (Betts and Holland 1991)

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

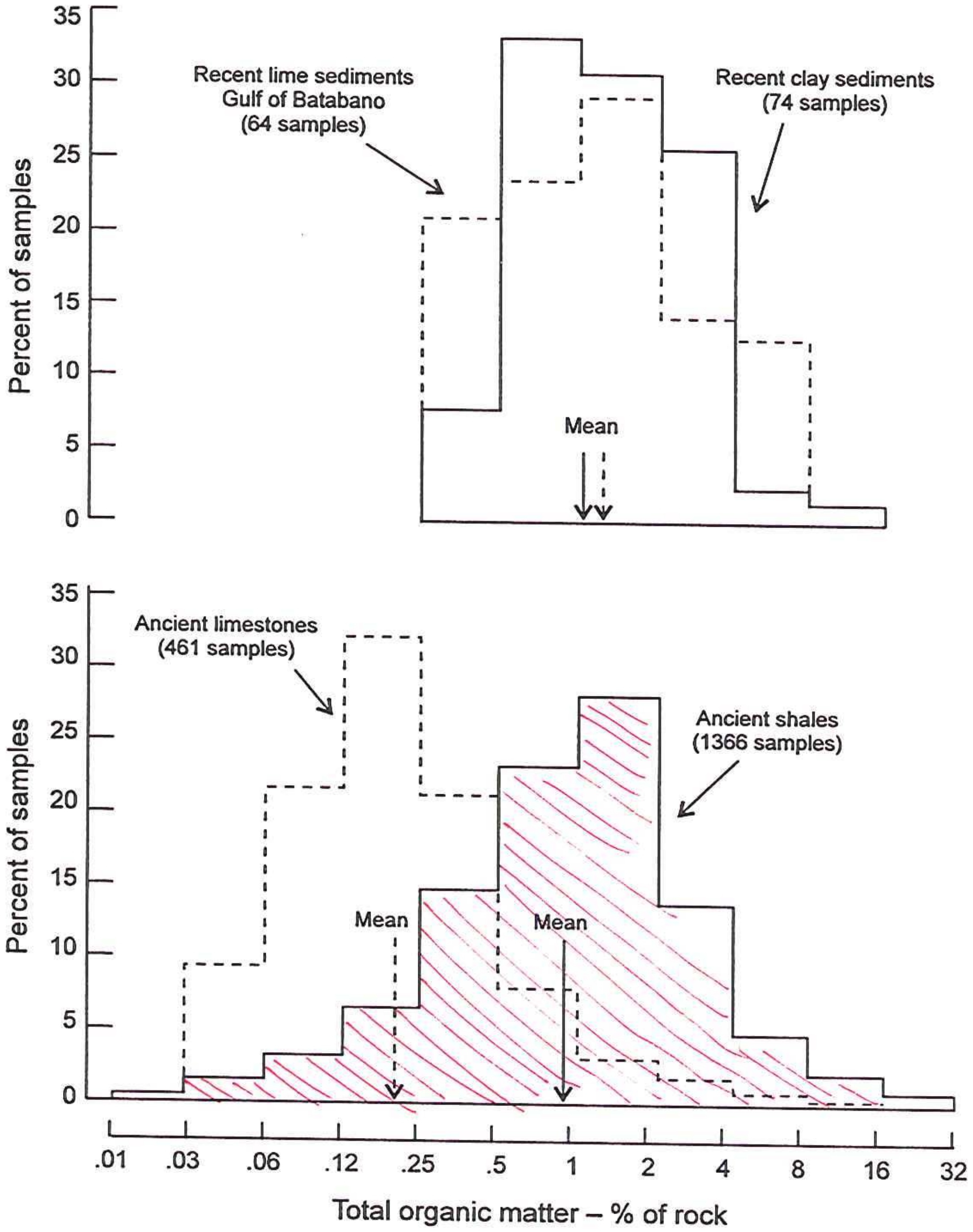


Figure 7.9. The total organic carbon content of recent and ancient limestones and shales. (Gehman 1962)

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

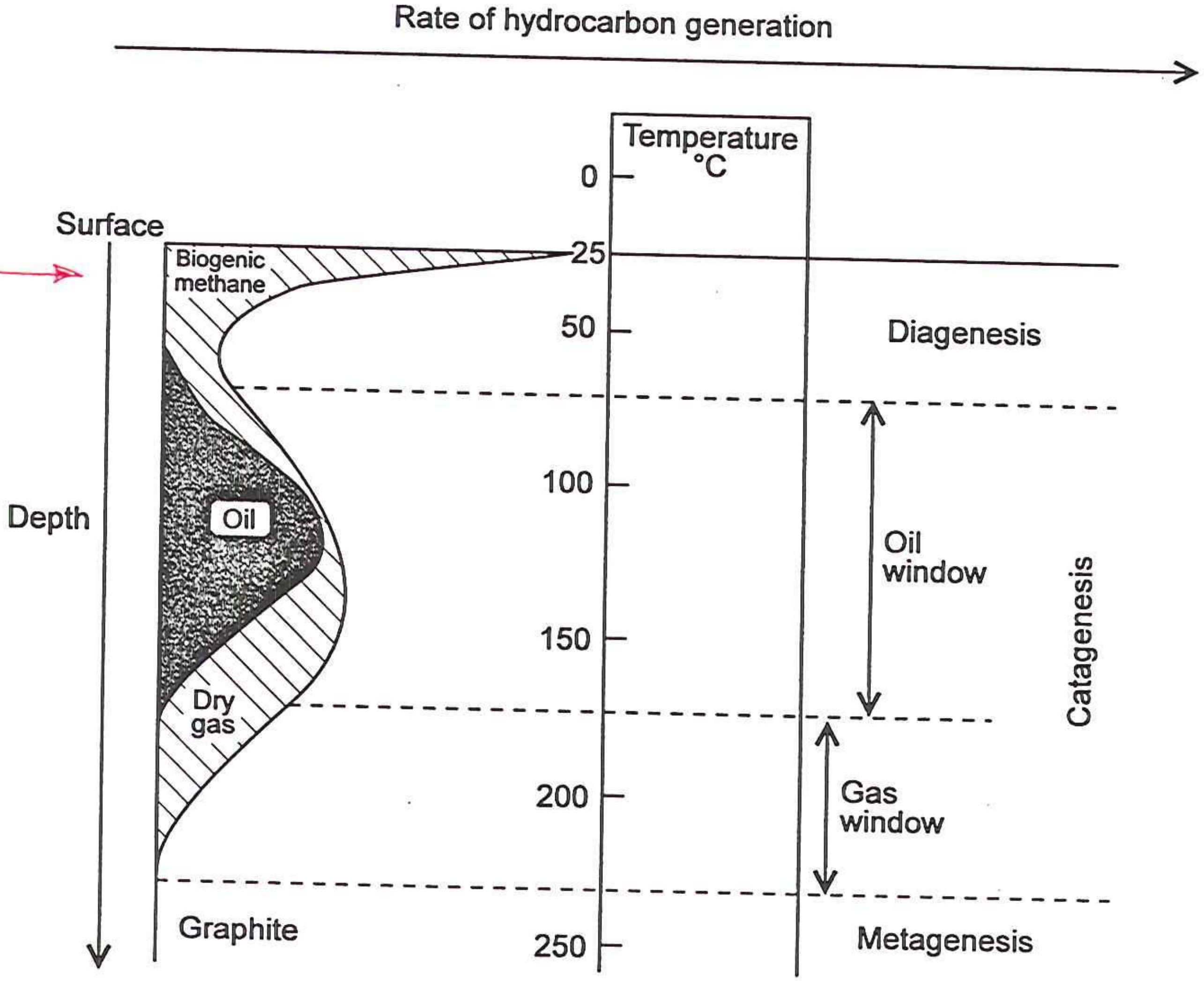
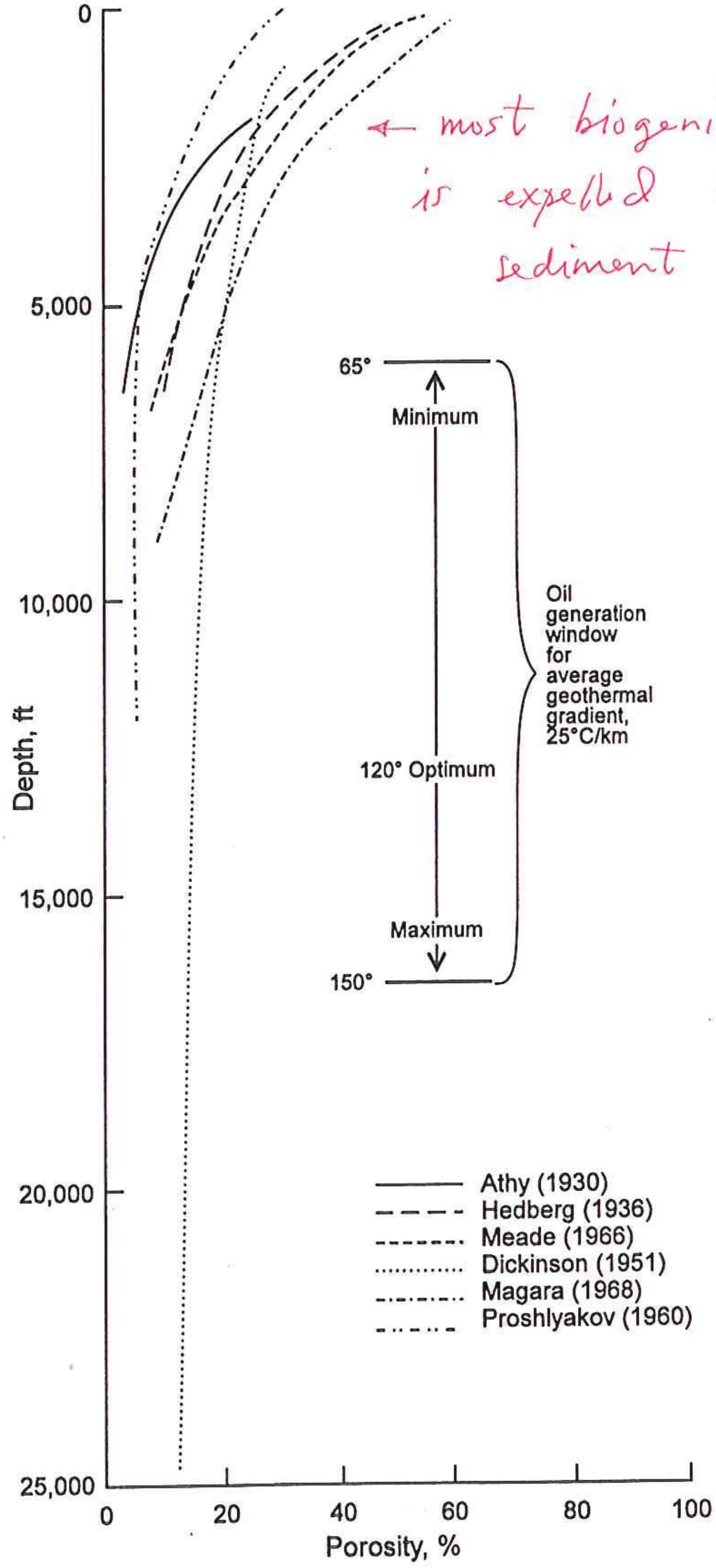
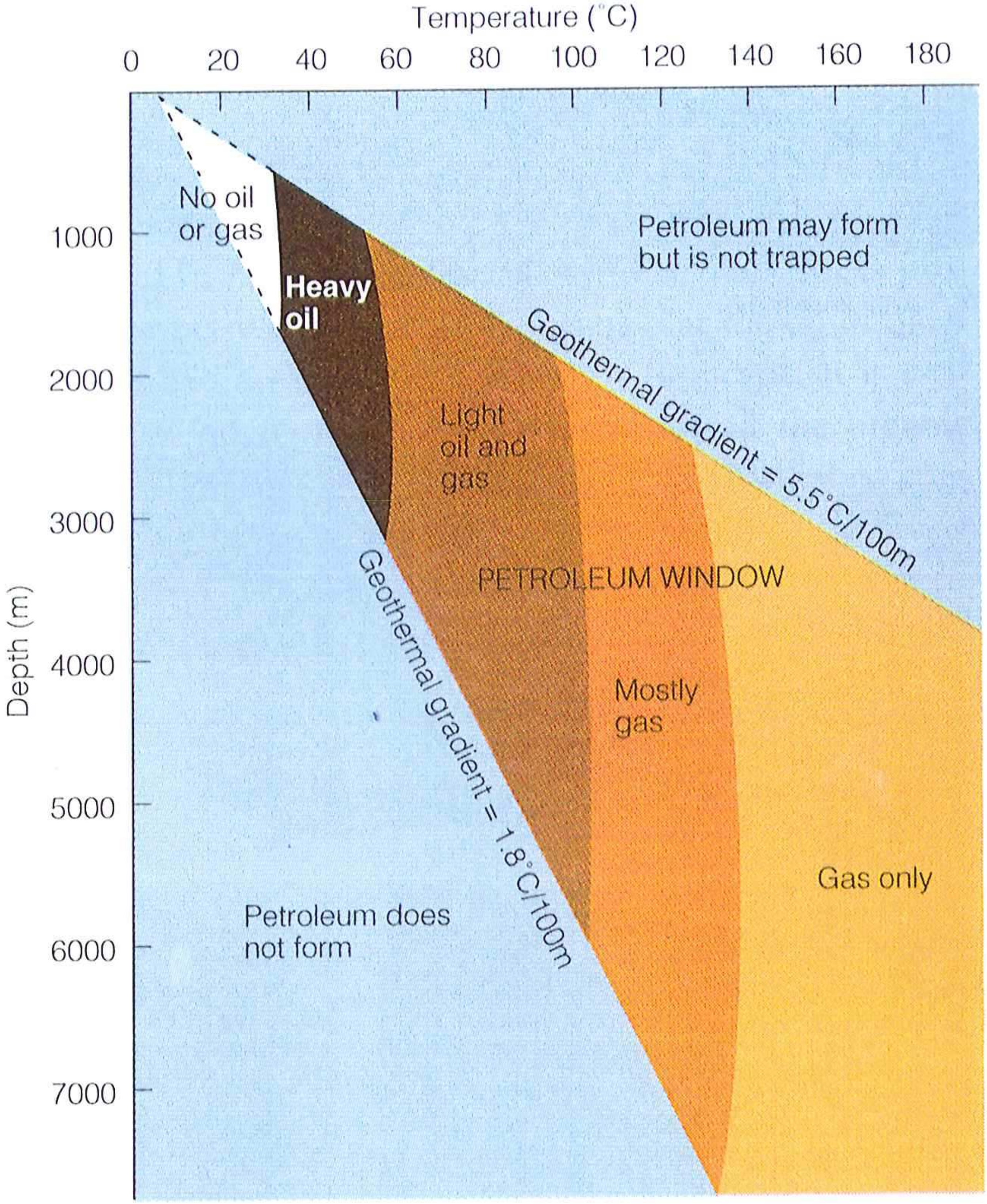


Figure 8.17. Correlation between temperature and the rate of hydrocarbon generation during the burial of organic matter in marine sediments. (Selley 1985)



← 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.



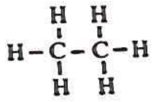
▲ FIGURE 11.4

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

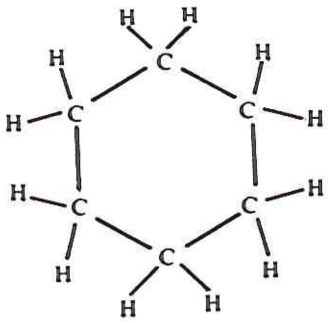
Table 1.1. Names and Abbreviations for *n*-Paraffins

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	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$	

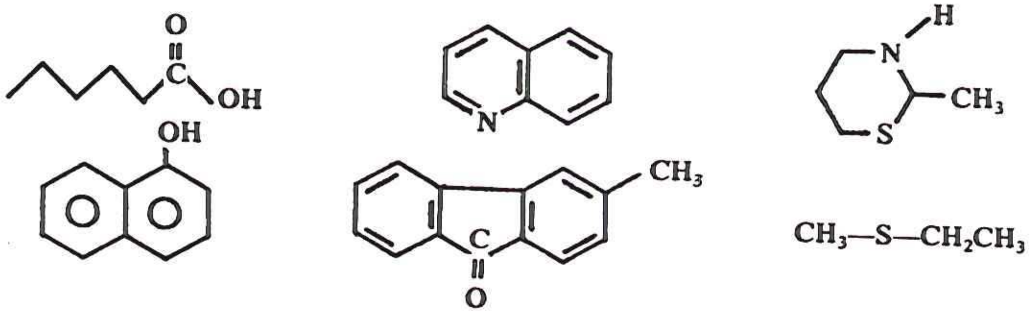
Methane



Ethane

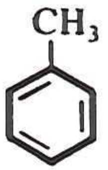


Cyclohexane

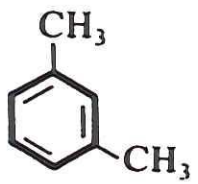


Examples of Resin Structures

Benzene

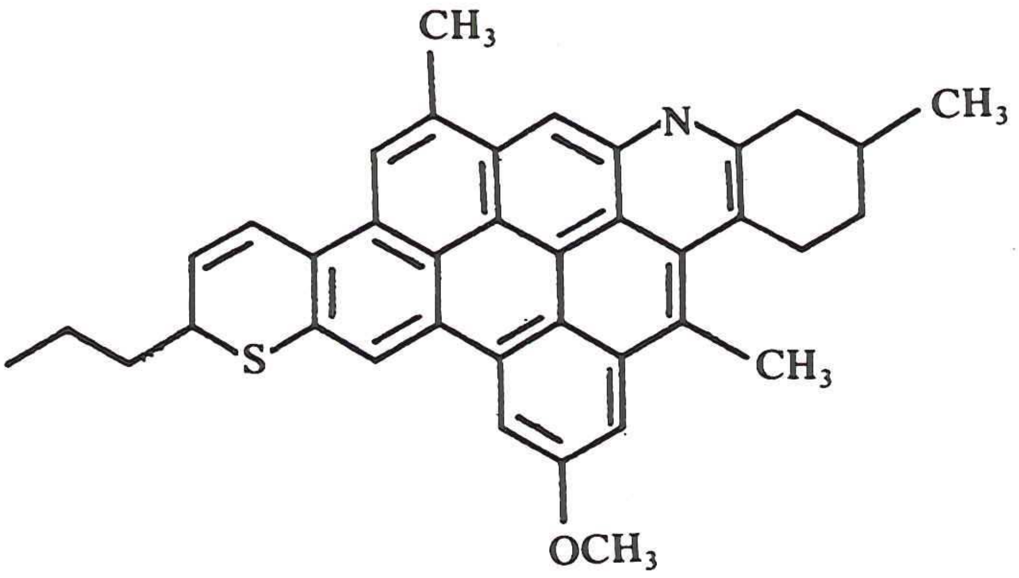


Toluene



m-Xylene

Naphthalene



Example of Asphaltene Structure

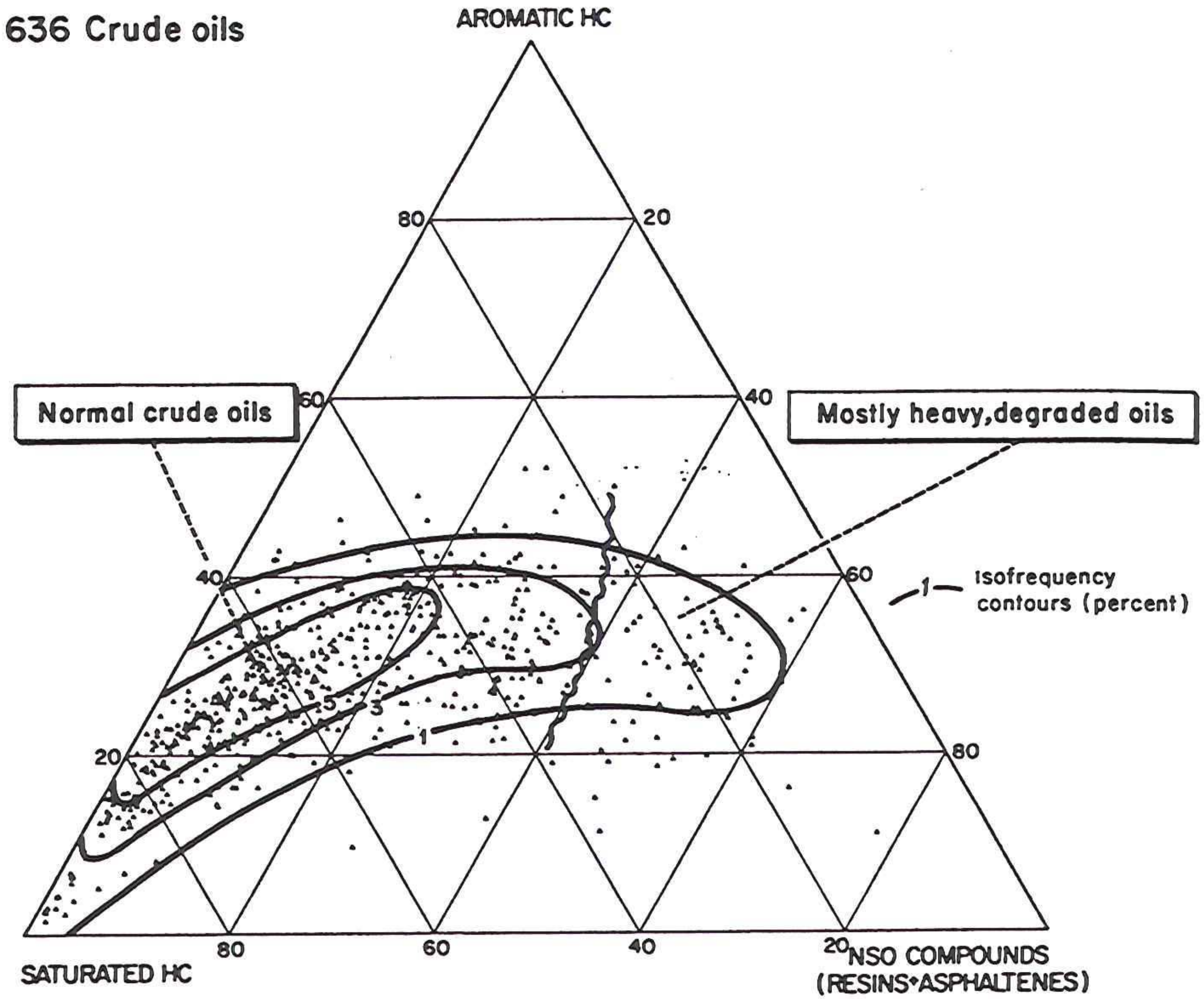


Figure 3.2. Ternary diagram showing the gross composition of 636 crude oils. (From Tissot and Welte, 1978: republished with permission of Springer-Verlag)

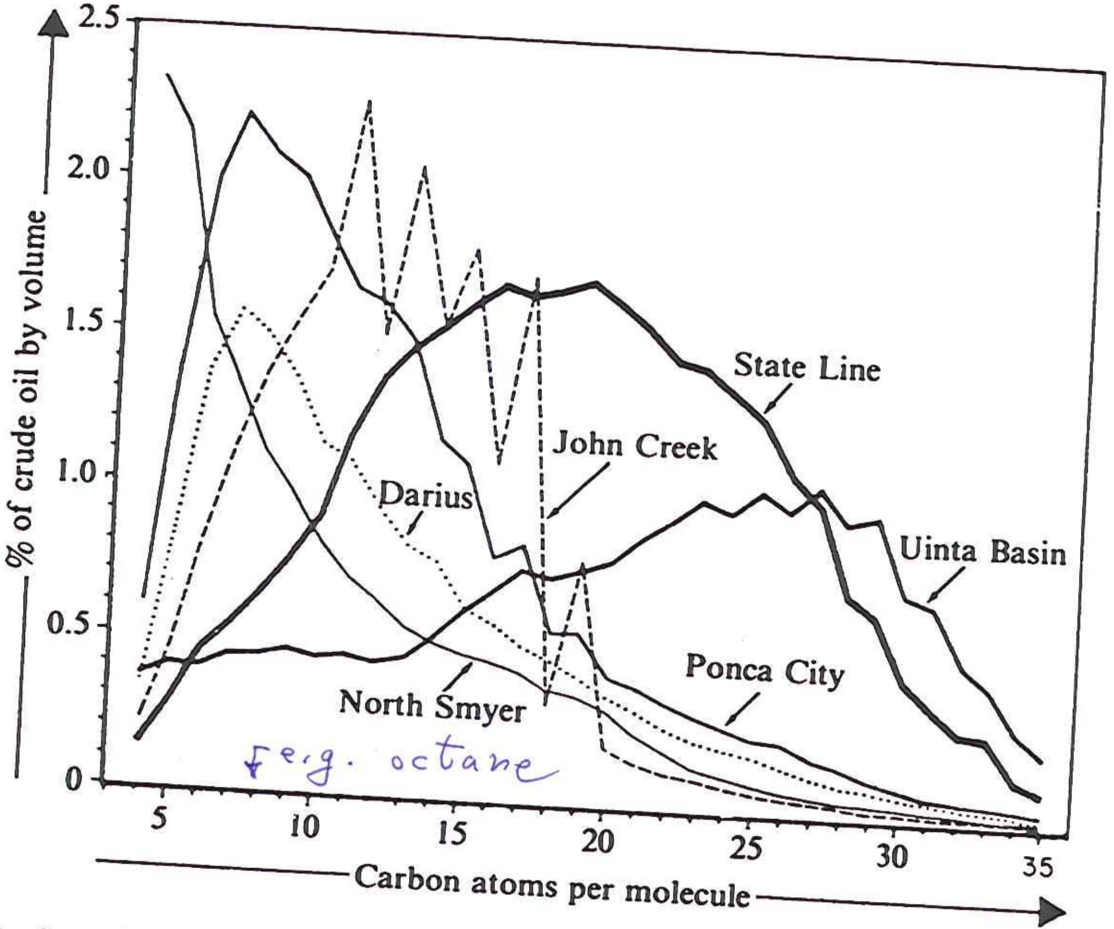
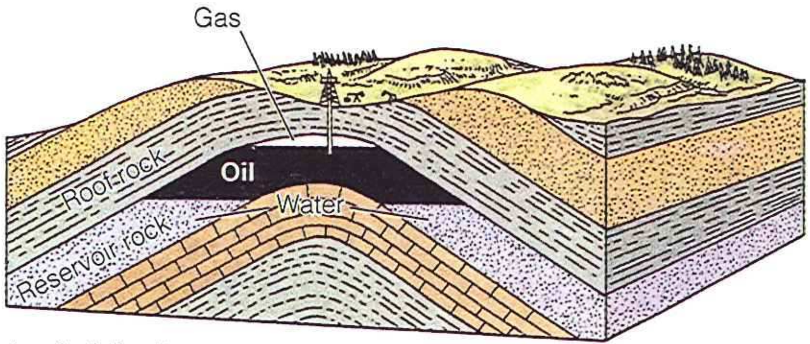
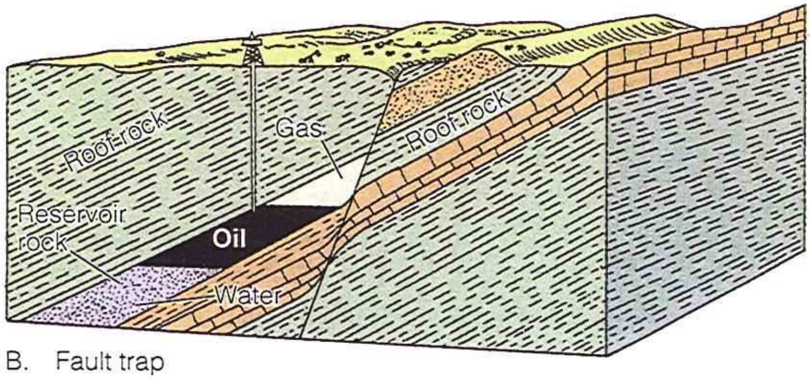


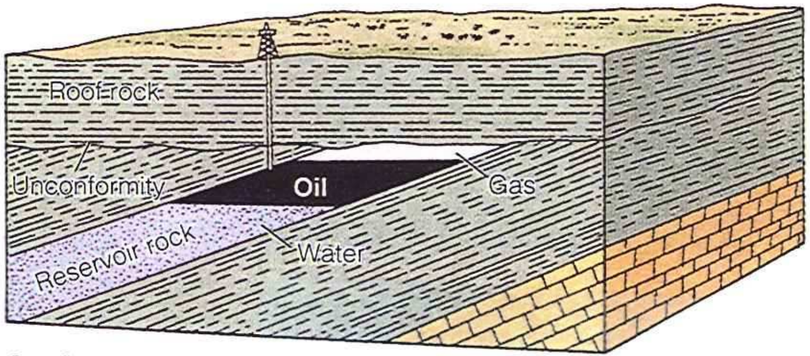
Figure 3.3. Distribution of *n*-alkanes in different types of crude oils. (From Martin et al., 1963; republished with permission of Nature)



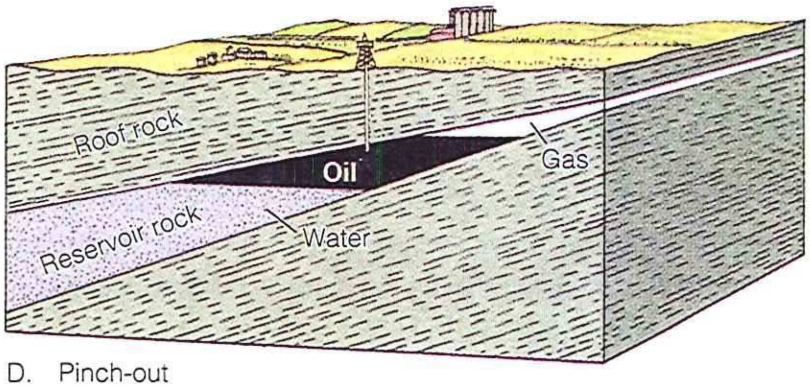
A. Anticlinal trap



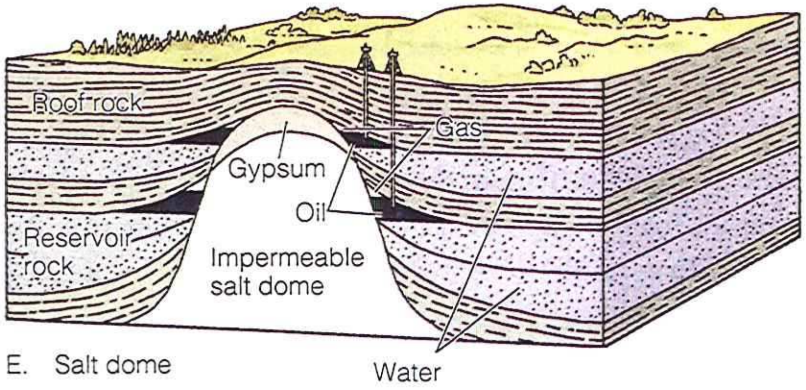
B. Fault trap



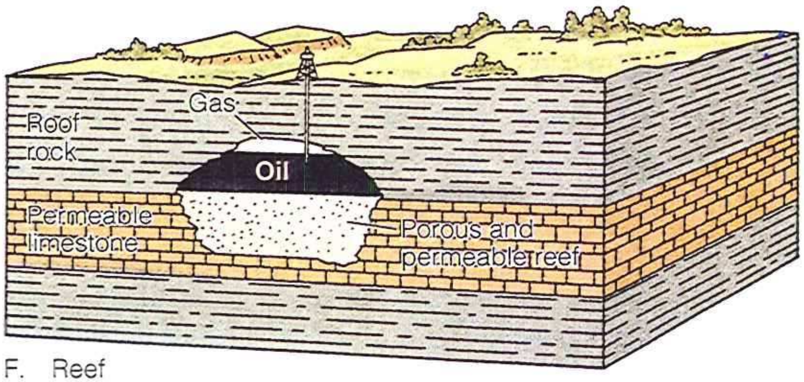
C. Stratigraphic trap



D. Pinch-out



E. Salt dome



F. Reef

GREYBULL SANDSTONE POOL — ELK BASIN

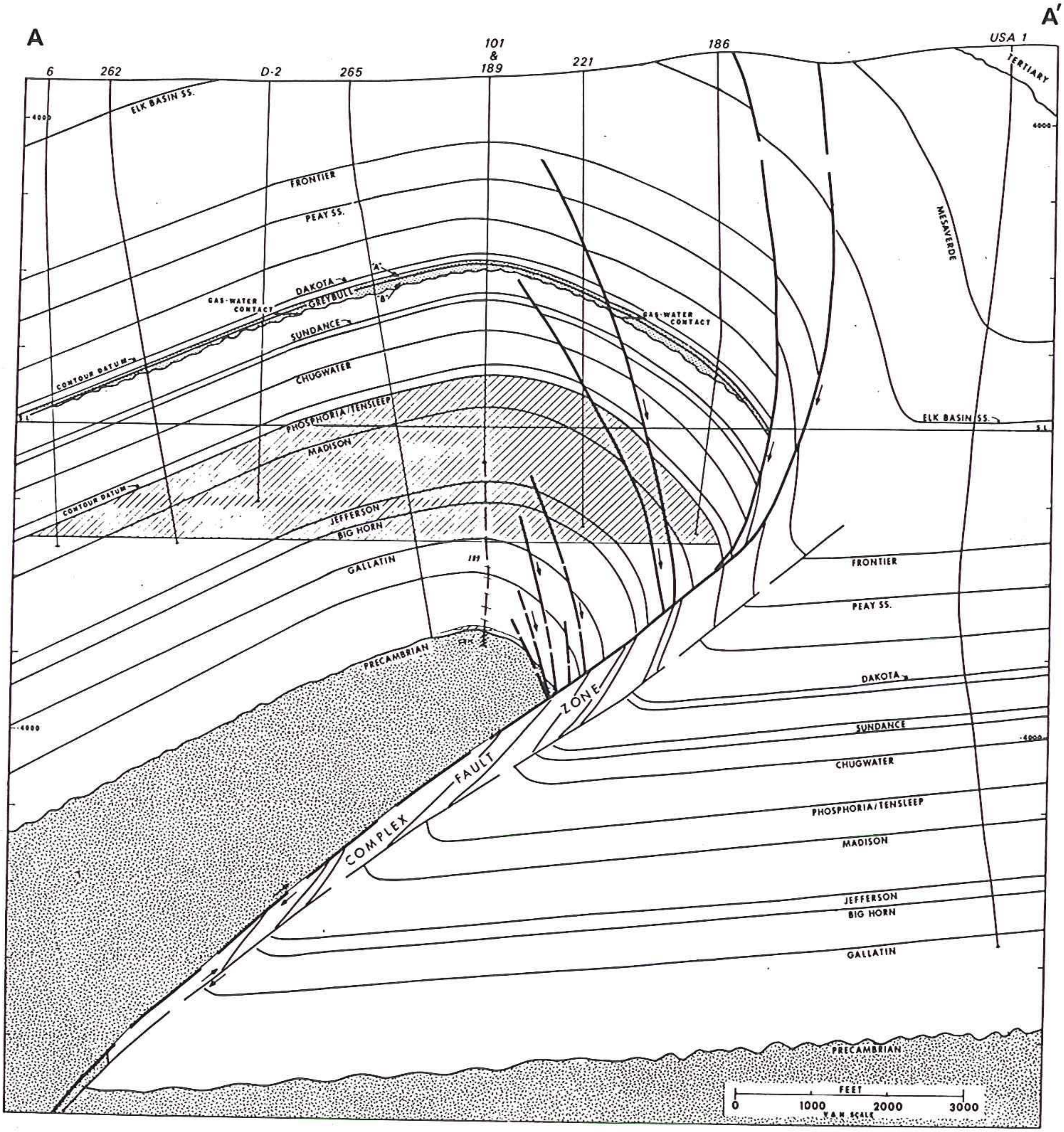


Figure 4. Northeast-southwest, true scale, structural cross section A-A′ through central Elk Basin field (location shown on Figs. 1, 2, 3, 7, and 8). Wells are identified by field numbers. Common pool Paleozoic accumulation is cross hatched.

1861 "Drake's Folly"

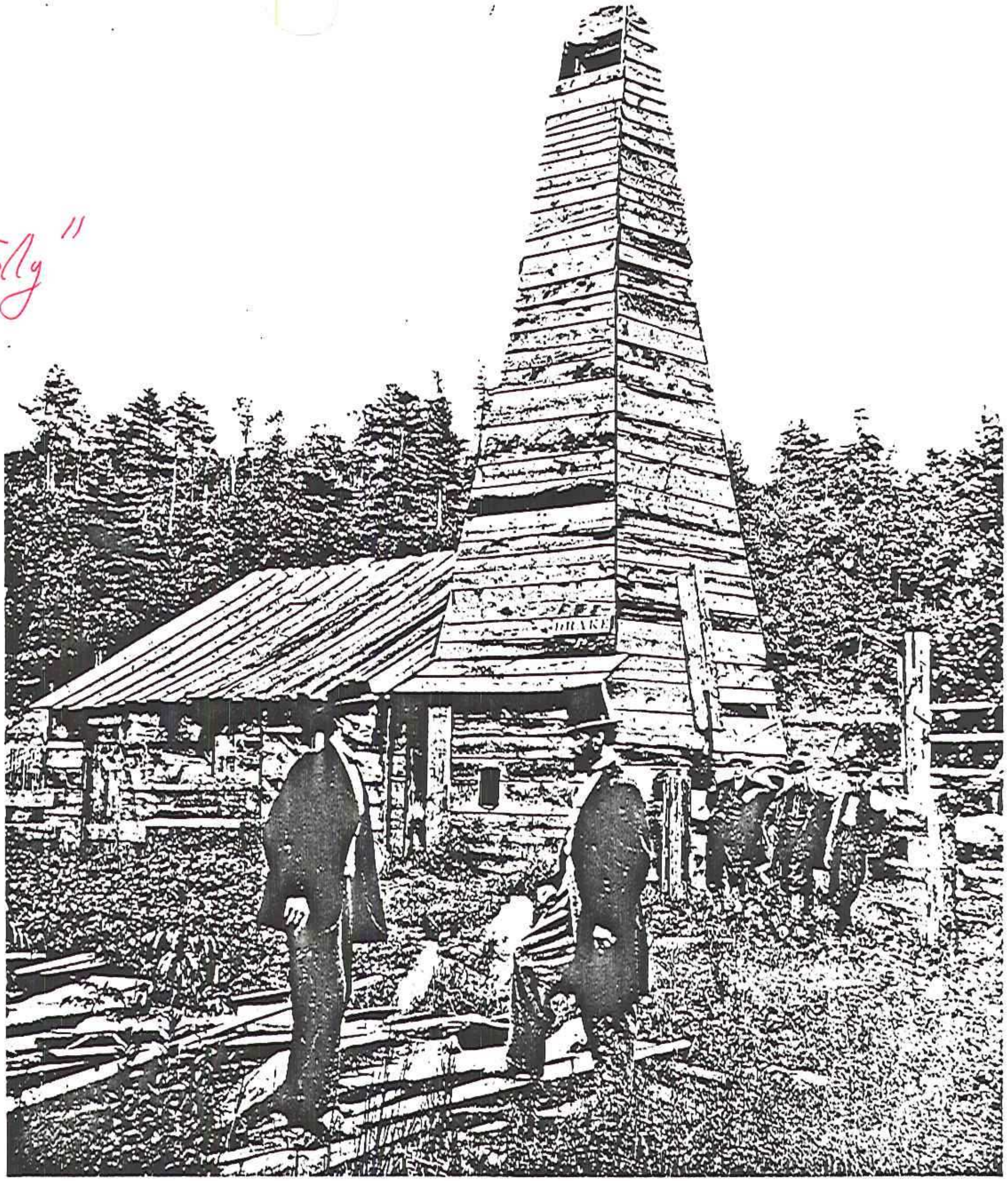
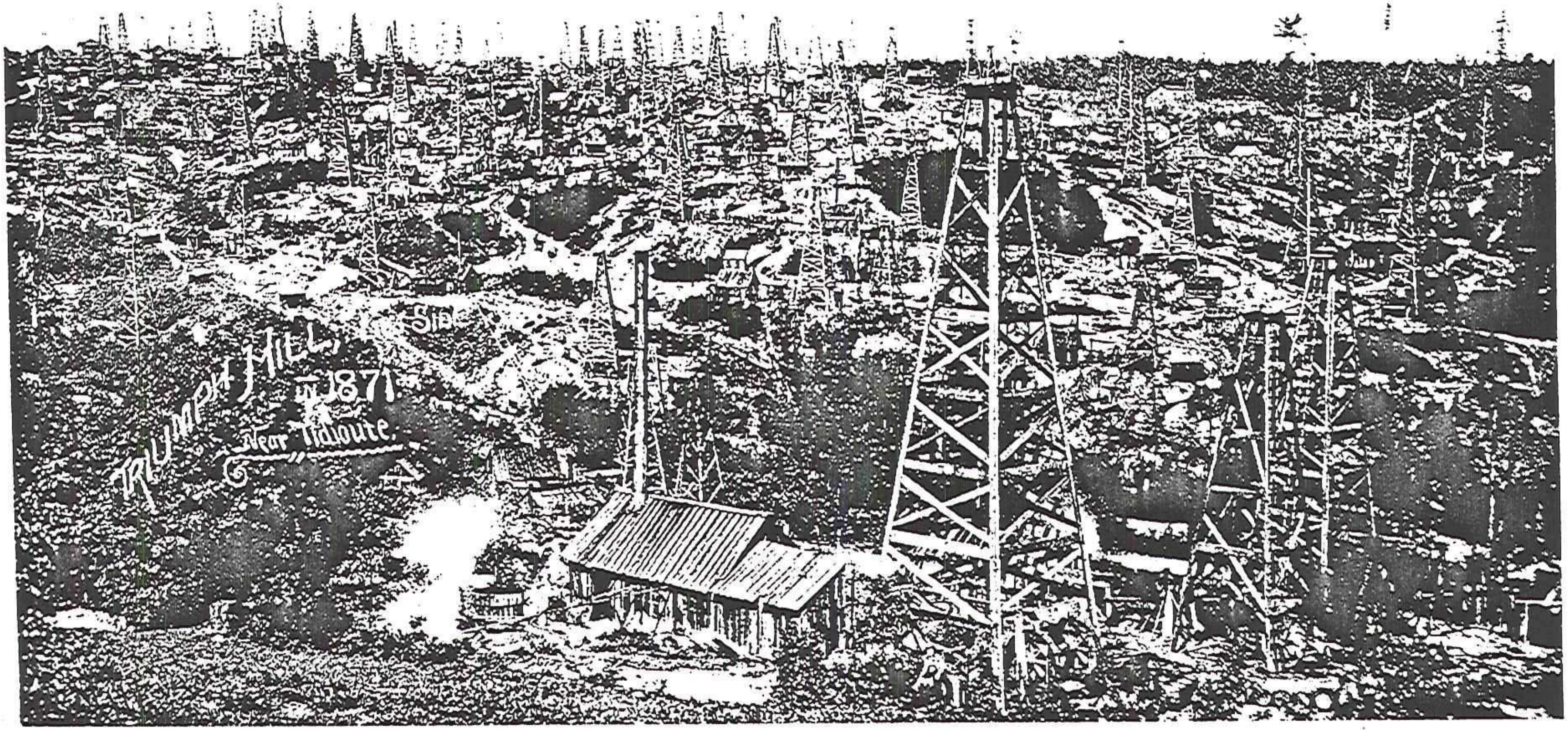


Figure 8.19.
(a) Edwin Drake (*right*) in front of his oil well on the banks of Oil Creek in Titusville, Pennsylvania, in 1861; this well marked the beginning of the modern extraction of oil. (b, *on opposite page*) The success of Drake's first well resulted in the drilling of large numbers of closely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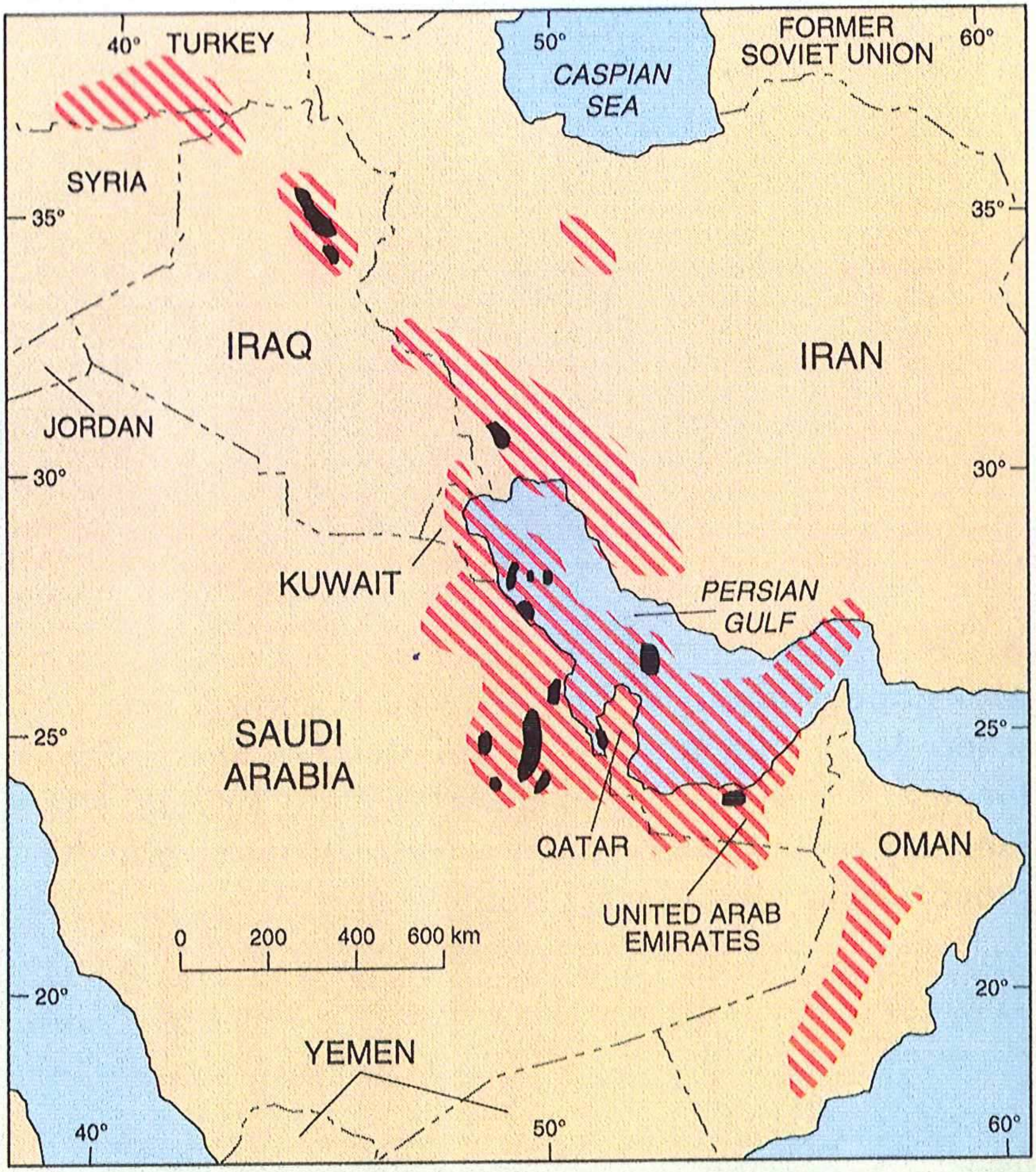


▲ FIGURE B1.1

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

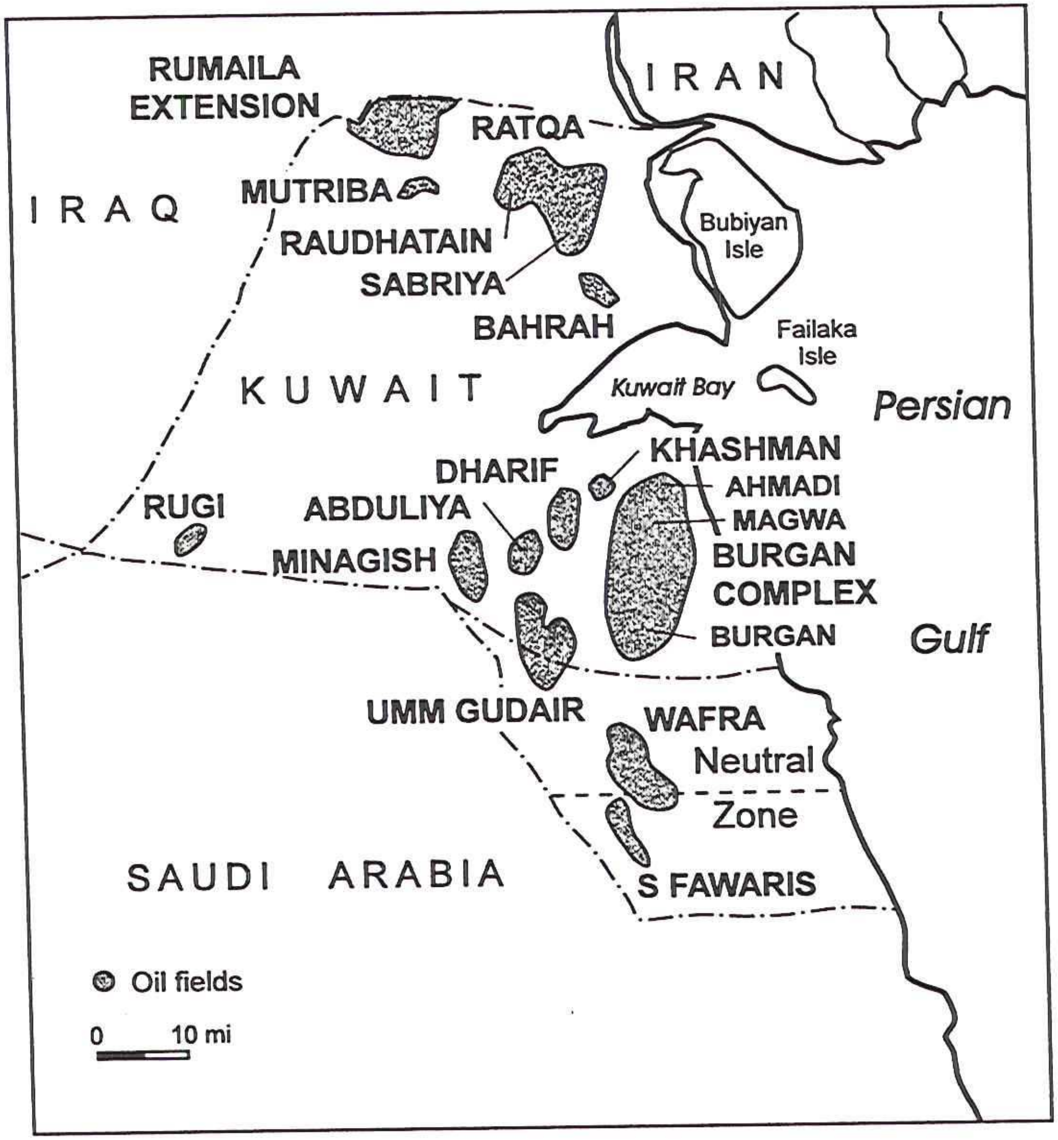


Figure 8.21. The oil fields of Kuwait. (*World Oil*, January 1992)

Burgan Field
10 mi x 20 mi
70 bbo

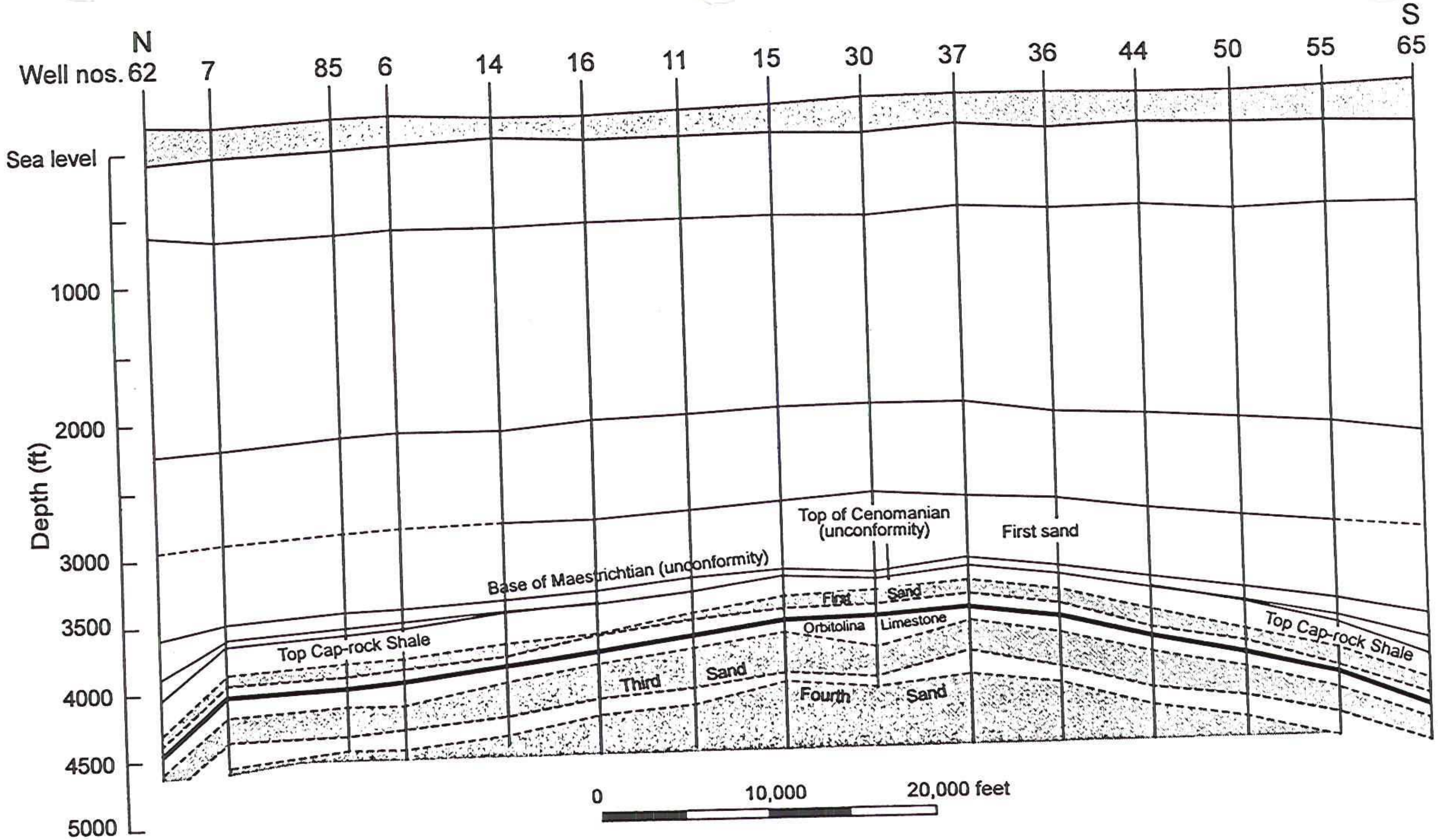


Figure 8.22. Geology of the Burgan structure, with eight times vertical exaggeration. (Jenyon 1990)

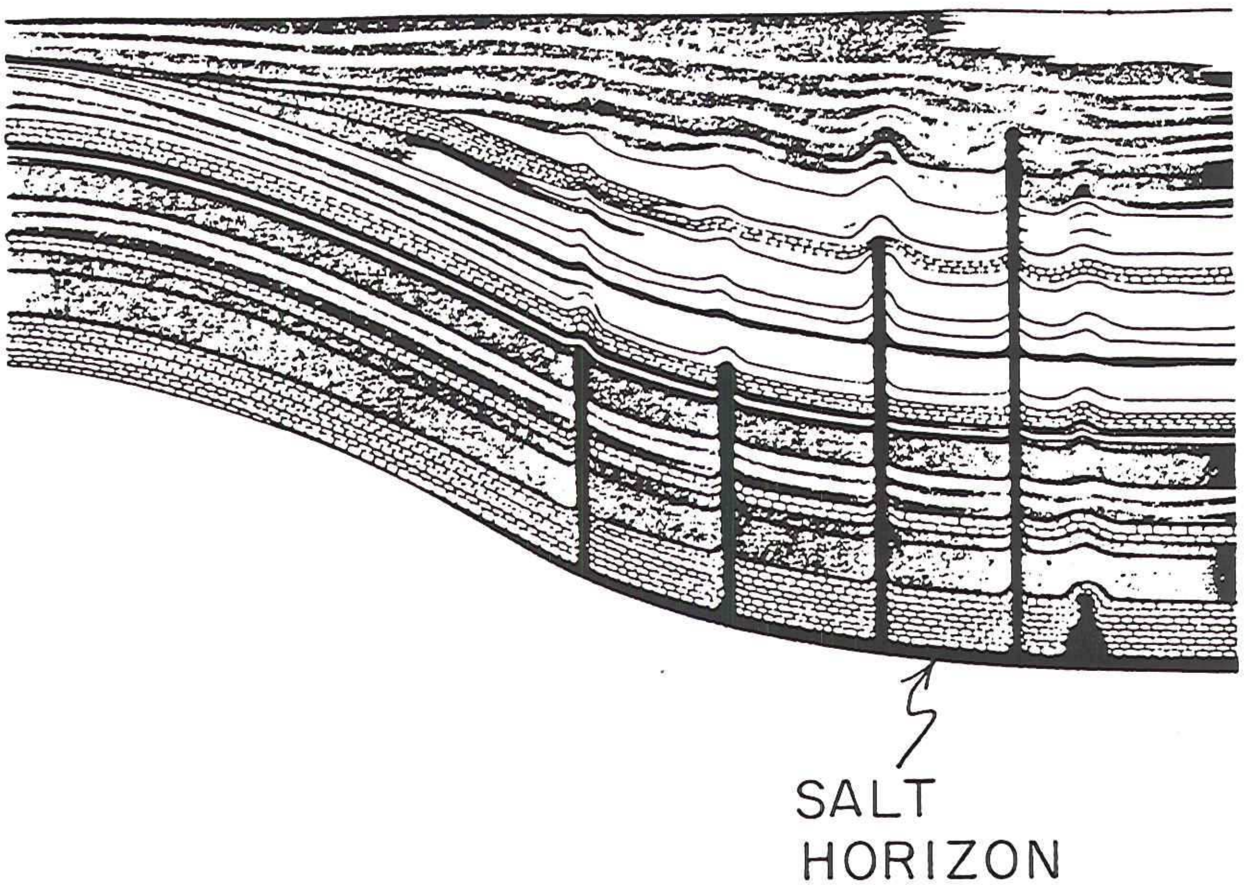


Figure 8-9. **Salt domes:** Narrow plug-like columns of salt are believed to "flow" upward through the more dense but mechanically weak overlying sediments, forming "salt domes." This geologic section of eastern Louisiana shows known salt domes that have risen through as much as 10,000 meters of overlying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

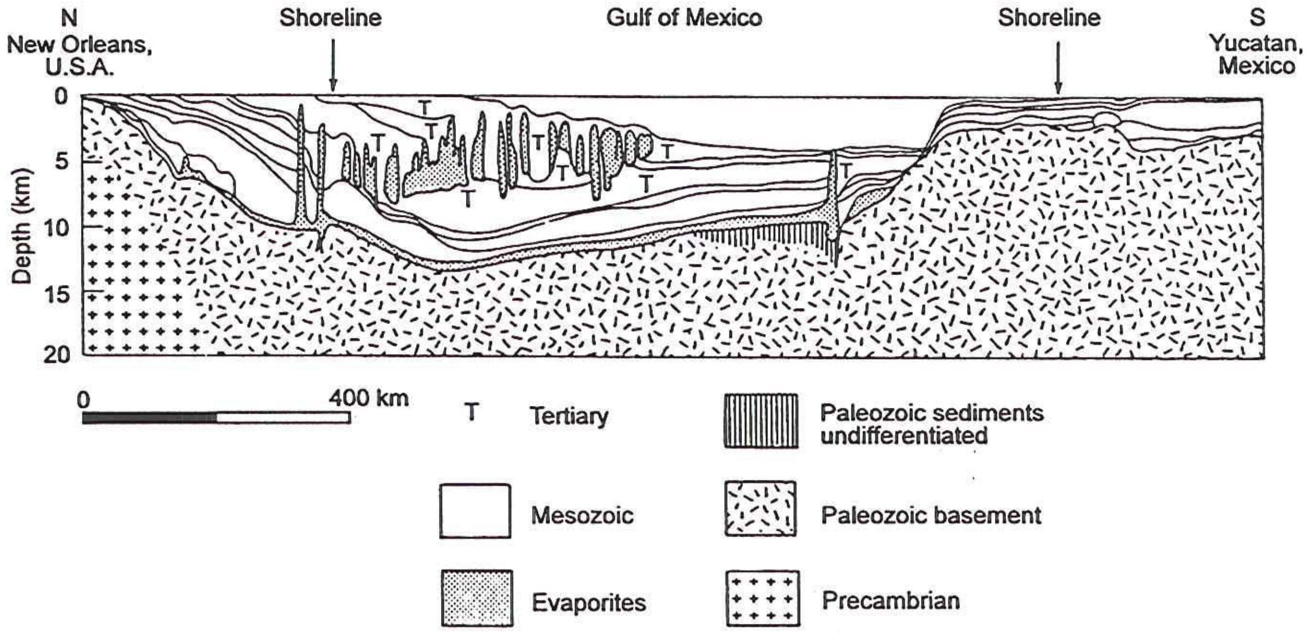


Figure 7.7. Geological cross section of the Gulf of Mexico; vertical exaggeration 20:1. (Bally 1979)

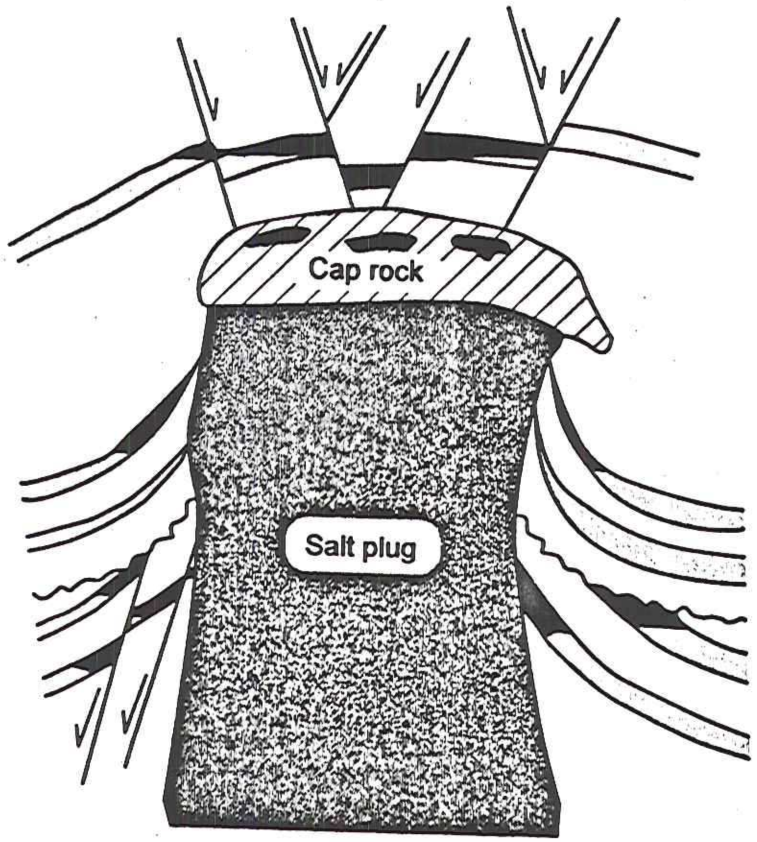


Figure 8.25. Schematic representation of a typical Gulf Coast salt dome, indicating various trap types, including leached secondary porosity traps in a cap-rock. (Jenyon 1990)

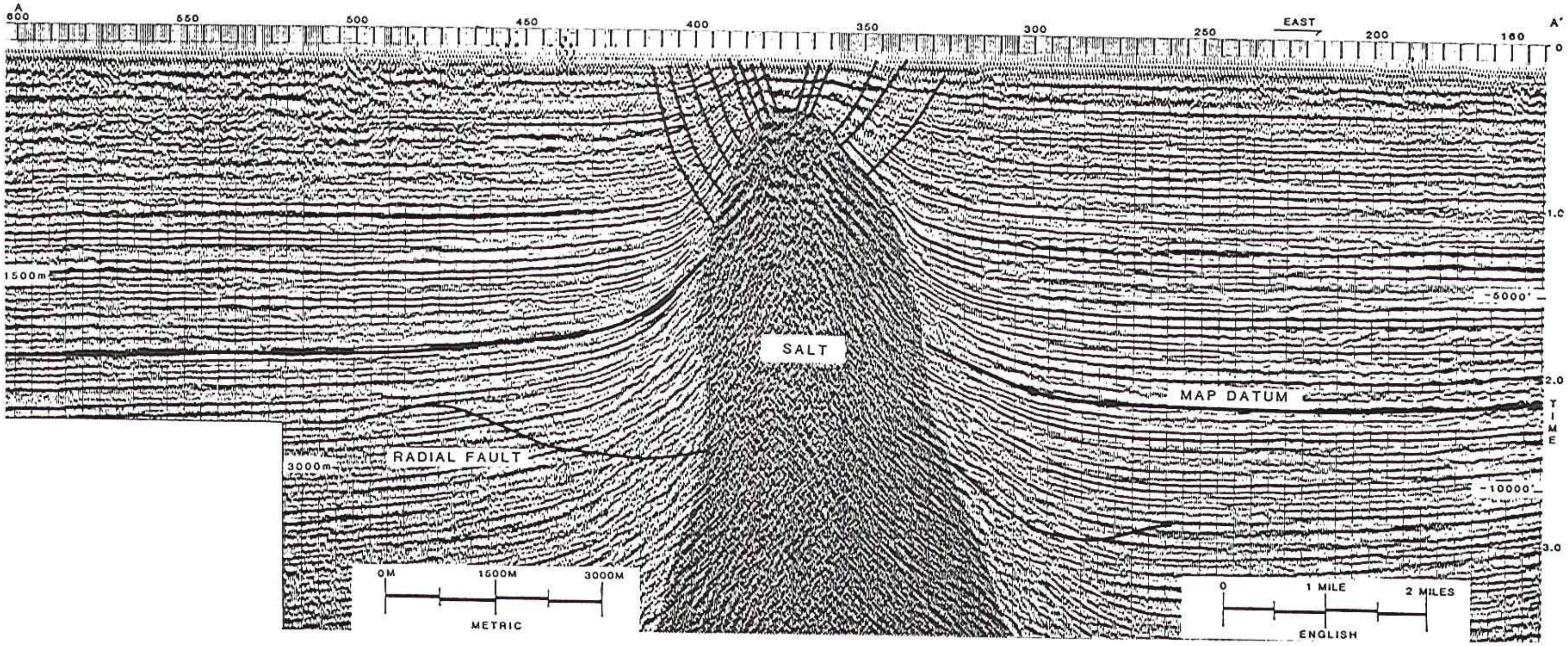
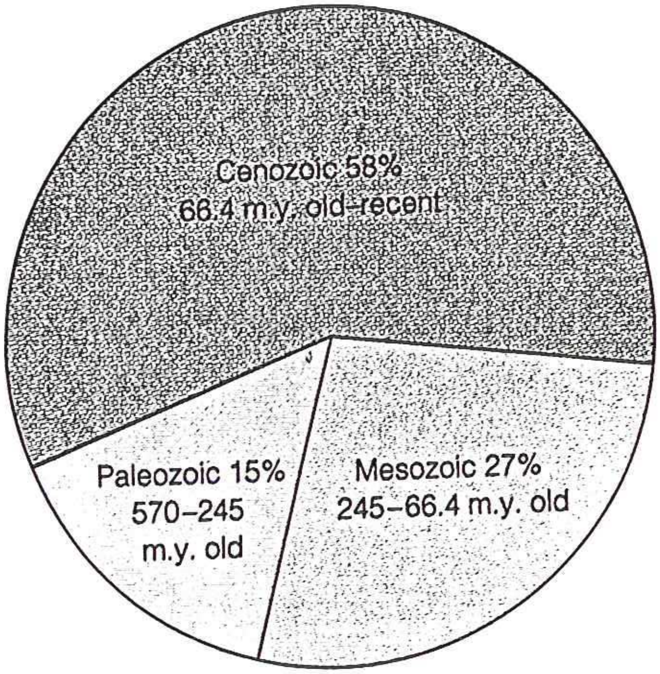
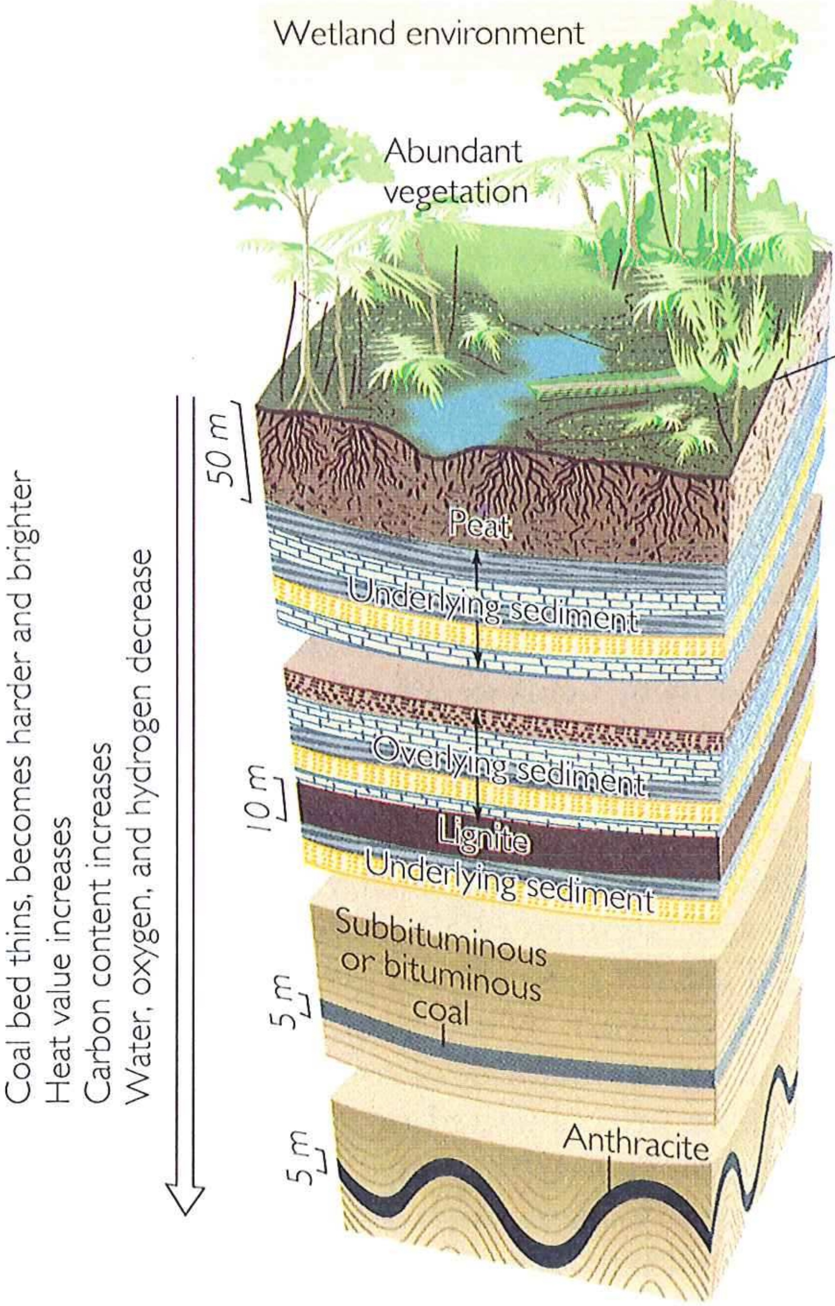


Fig. 8-31 (Sunwall et al., 1983)—Seismic line from offshore Louisiana, U. S. Gulf Coast, showing young salt diapir (characterized by reflection cut-outs) with superjacent normal faults and lower radial faults which strike parallel to seismic line. Salt configuration based on well control, gravity, and 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.)



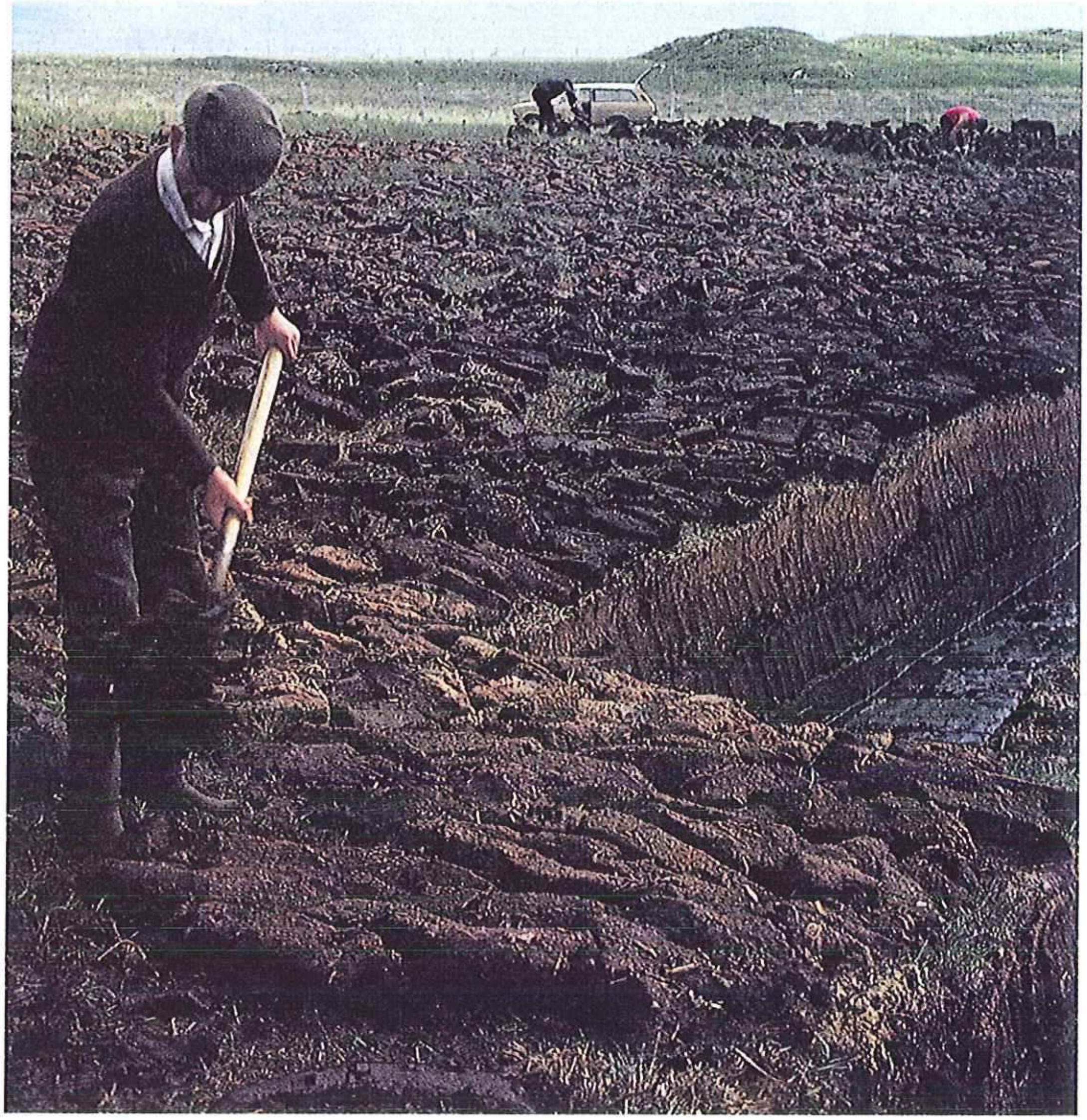
Surface accumulation of leaf litter, twigs, branches, and other fragments of vegetation

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)

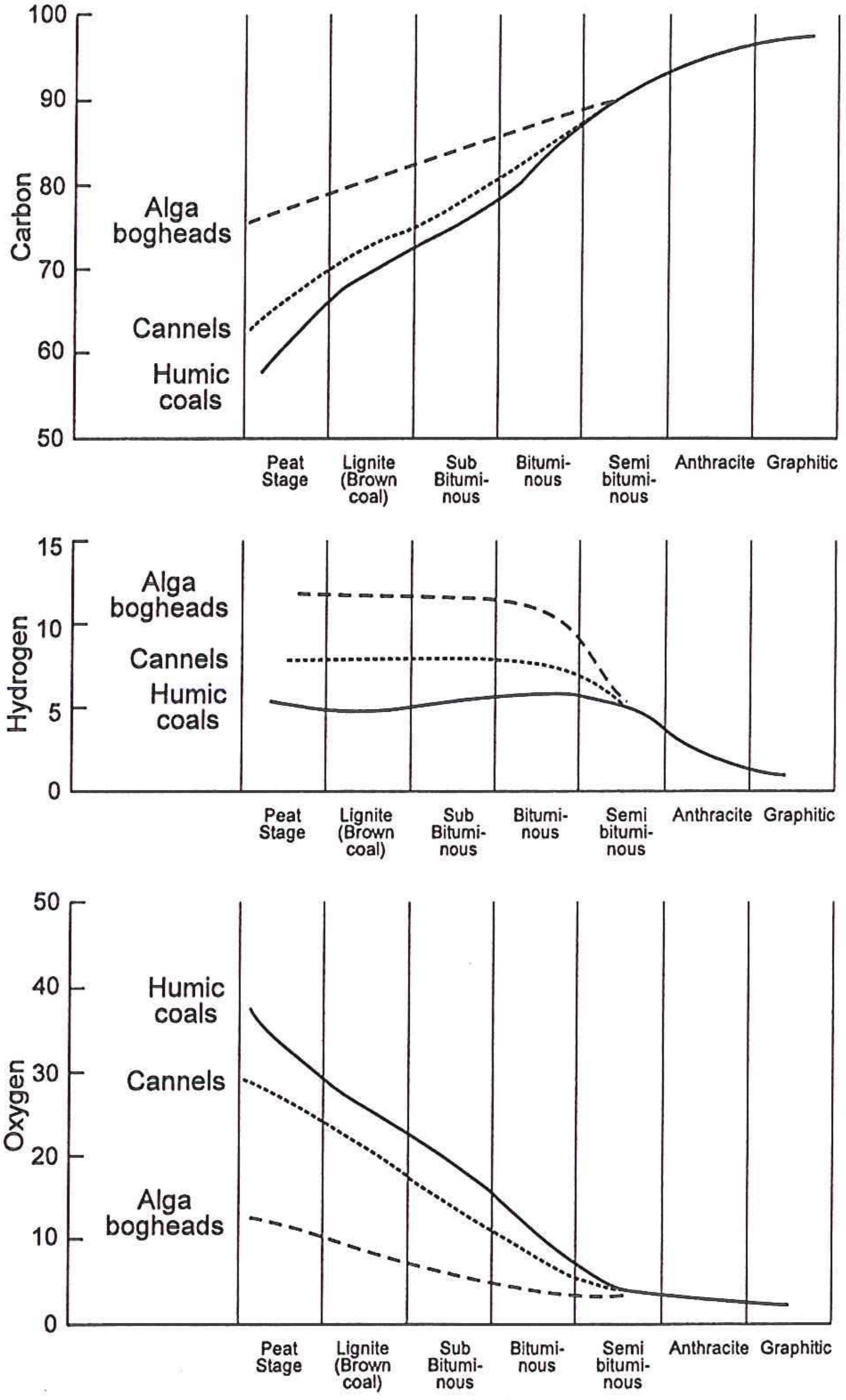


Figure 7.12. Changes in carbon, hydrogen, and oxygen content during the evolution of normal (humic) coals and algal (sapropelic) coals. (White 1925)

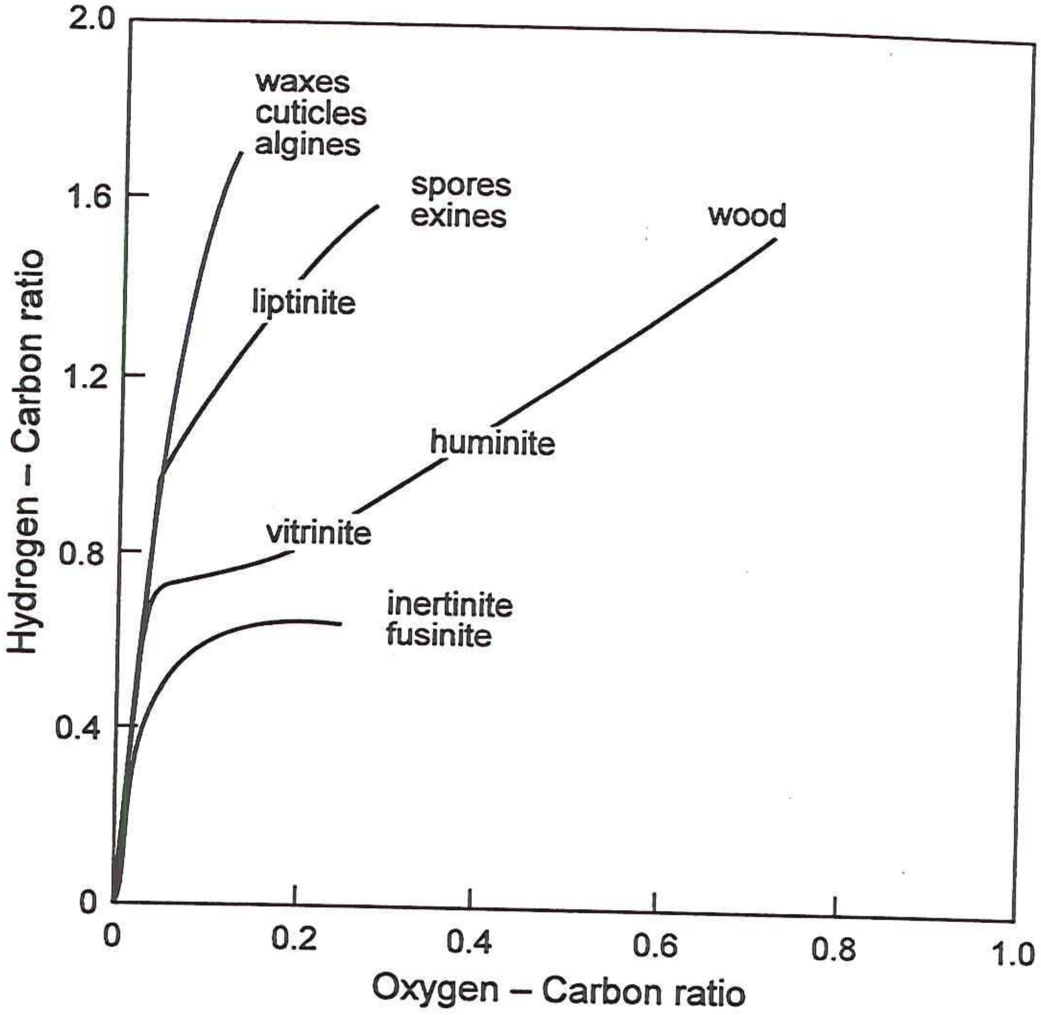


Figure 7.13. Van Krevelen diagram (H/C versus O/C atomic ratios) for the main components of coal and their predecessors with lines of dehydration, decarboxylation, demethanation, dehydrogenation, oxidation, and hydrogenation. (Modified after van Krevelen 1961; Tissot and Welte 1984; from Damberger 1991)

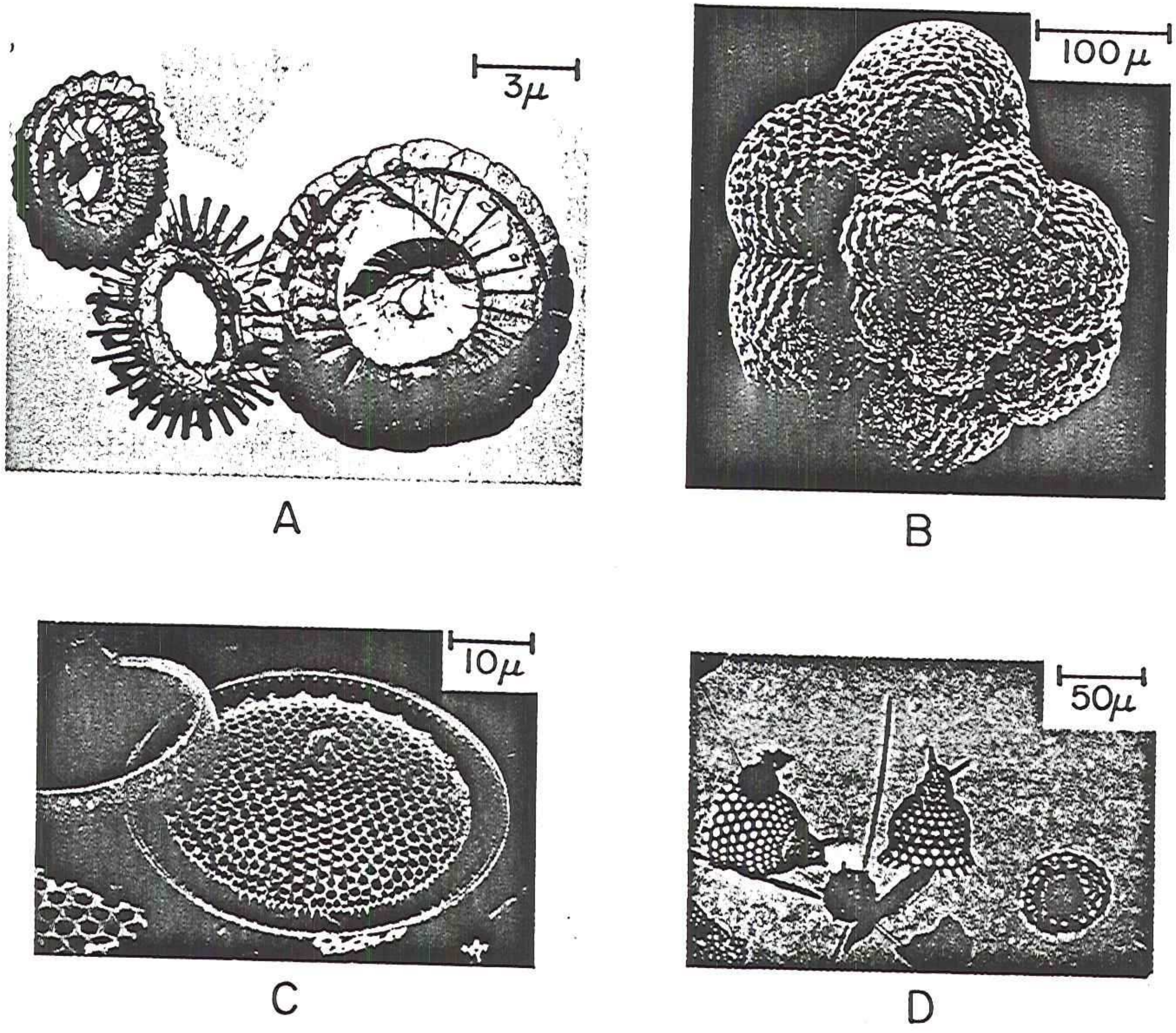


Figure 8-4. Calcite and opal houses made by marine microplankton: (A) Calcite cages which surround plants called coccolithophorida. (B) Calcite shell formed by foraminifera. (C) Opaline pillbox housing a diatom. (D) Opaline cages inhabited by radiolarians. These pictures were taken using a microscope;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

extra
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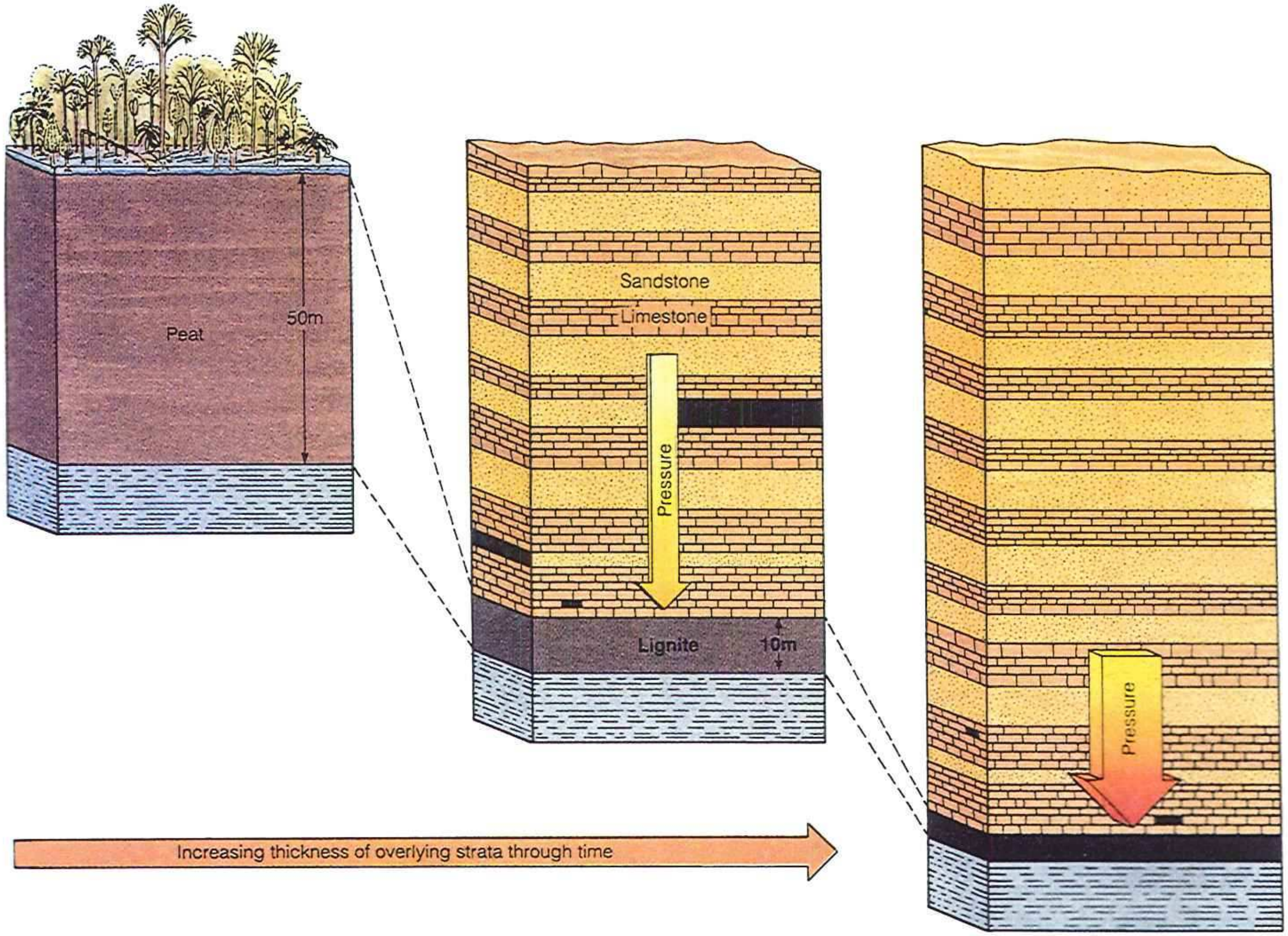
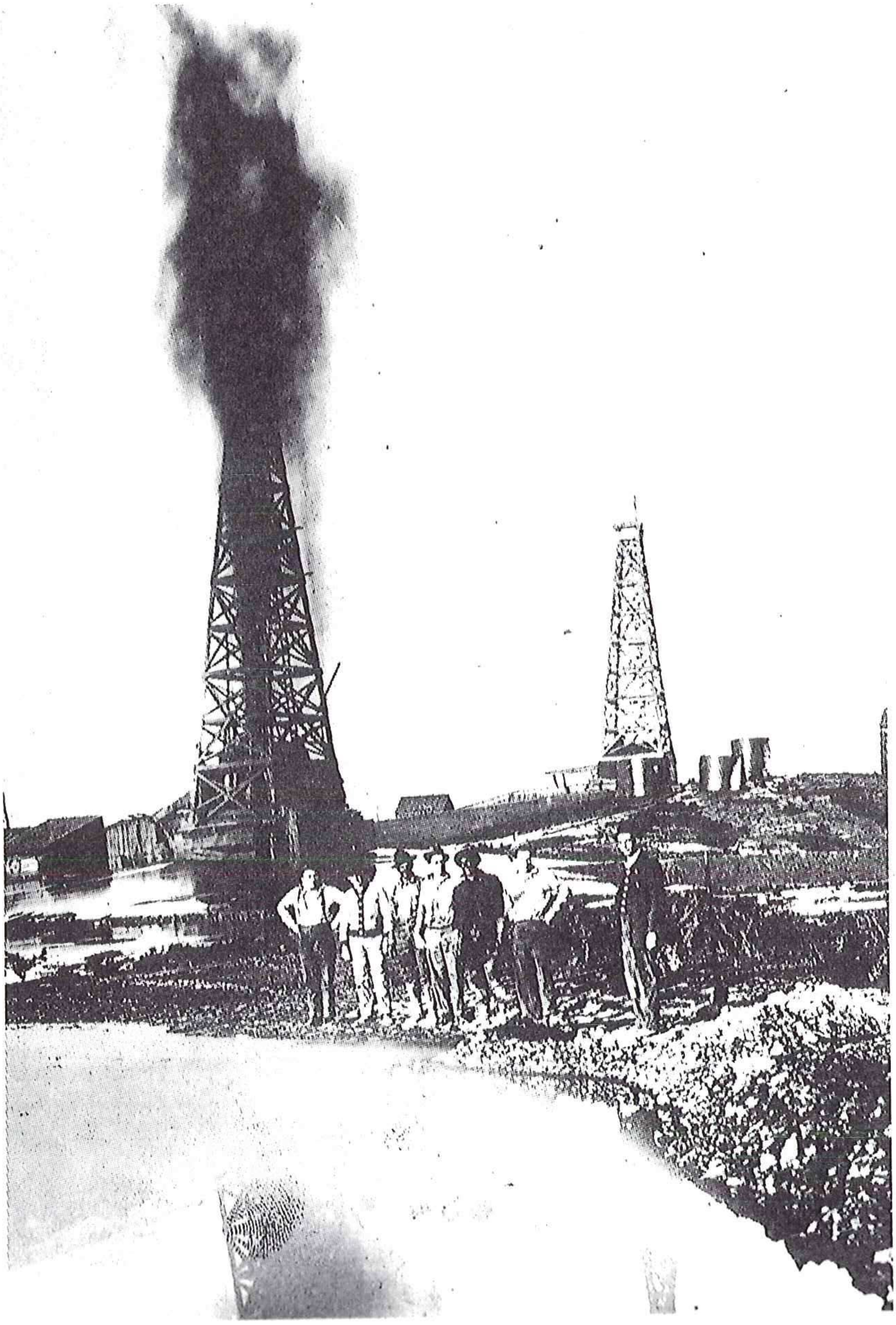
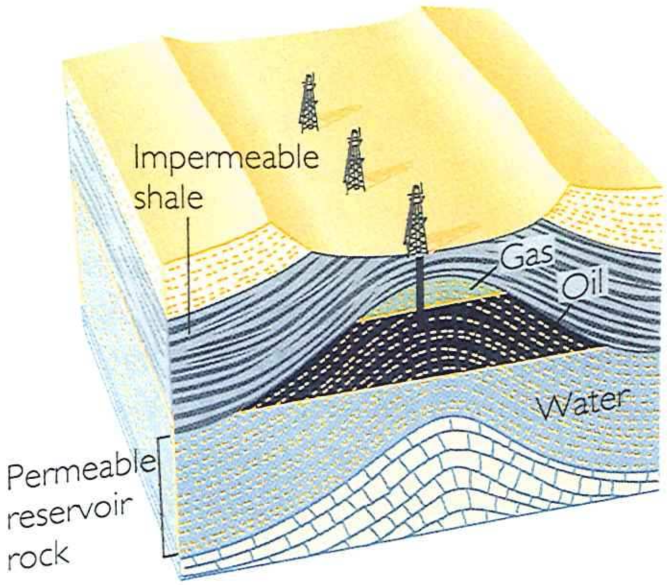
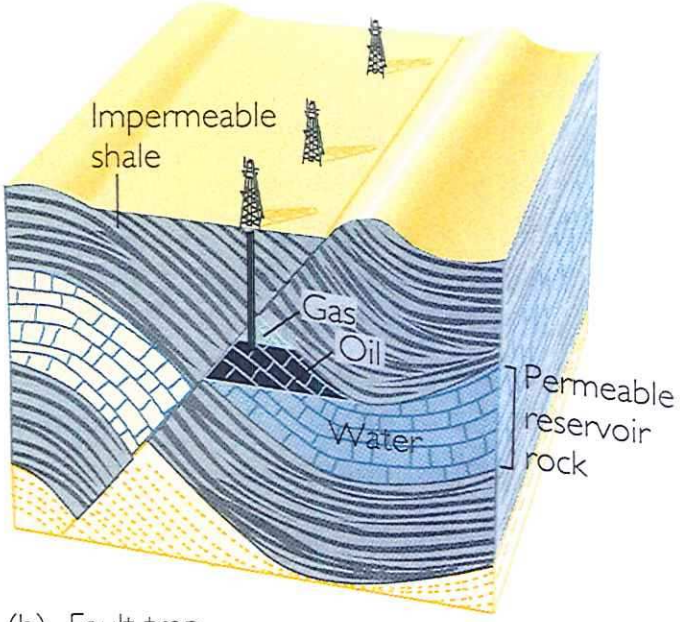


▲ FIGURE 11.9
Plant matter in peat is converted into coal by decomposition, coupled with increased pressure and temperature as overlying sediments build up. By the time a layer of peat 50 m thick has been converted to bituminous coal, its thickness has been reduced by 90 percent. In the process, the proportion of carbon has increased from 60 to 80 percent.

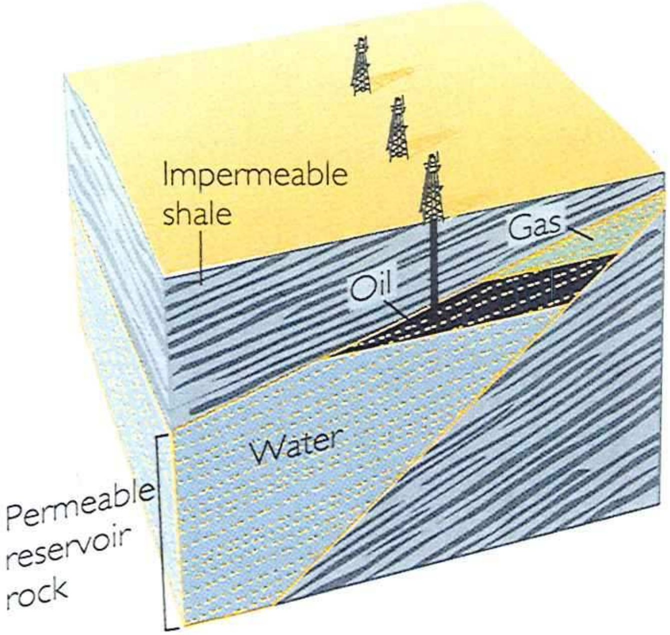




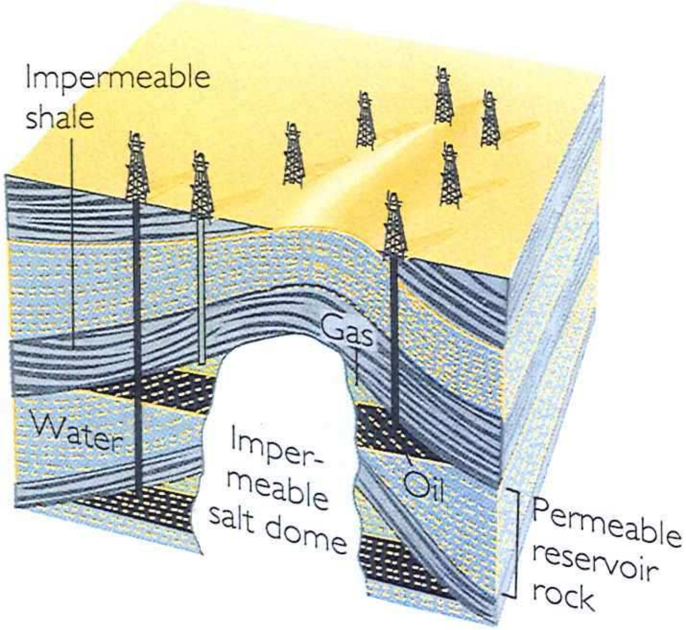
(a) Anticlinal trap



(b) Fault trap



(c) Stratigraphic trap



(d) Salt dome trap