

Chapter 12

FOSSIL FUELS

1. INTRODUCTION

1.1 I need not remind you that the modern world operates largely on fossil fuels, mainly coal and fluid petroleum hydrocarbons. For almost a hundred years much of the practice of geology has centered around exploration for such fossil fuels, as well as for the “hard” or metallic minerals. It seems important in a course like this to give some attention to the geology of fossil fuels.

2. COAL

2.1 Introduction

2.1.1 Have you ever had the opportunity to hold a lump of coal in your hand? The average person’s contact with coal has lessened greatly in the last fifty years, since the great increase in use of oil and natural gas in home heating. Only if you’re associated with the mining of coal or its use in industrial steam plants are you likely to have had hands-on experience with coal. But coal represents the world’s greatest remaining storehouse of energy—for better or for worse. Coal represents almost 90% of the world’s recoverable reserve of fossil fuels. The United States, with about 20% of the world’s coal supply, is well endowed. Figure 12-1 is a sketch map of the coal fields in the conterminous United States and adjacent parts of Canada.

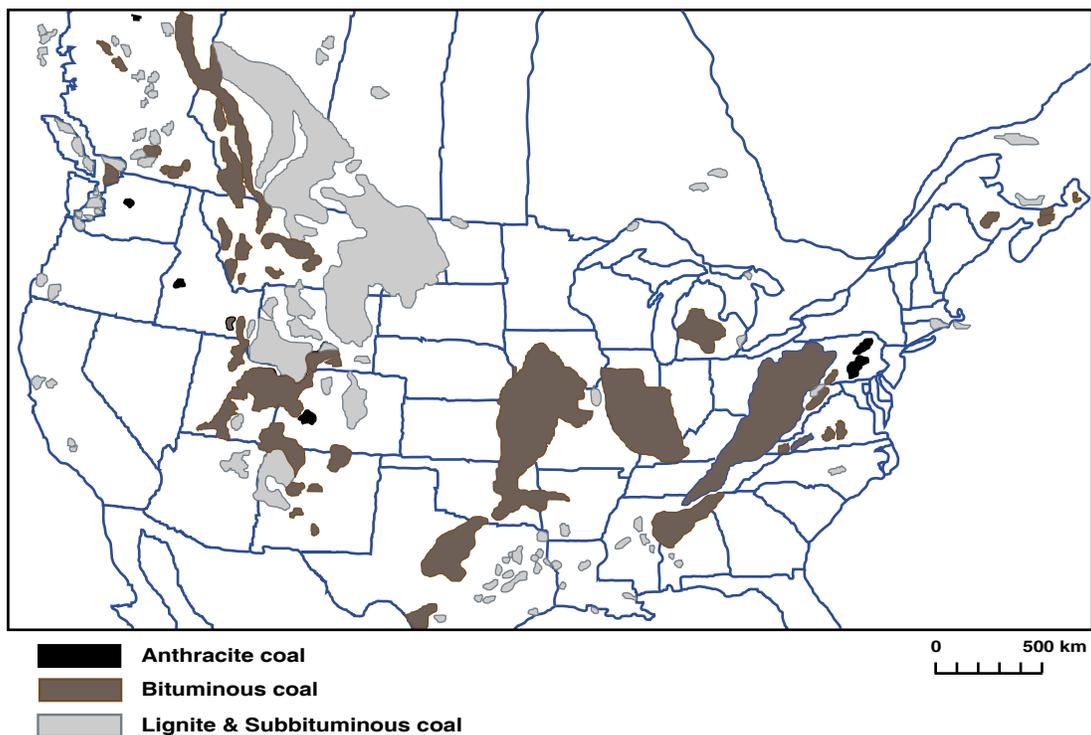


Figure 12-1: Sketch map of the coalfields of the United States and Canada

Figure by MIT OCW.

2.1.2 *Coal* is a sedimentary rock! It could be defined as *a combustible rock that had its origin in the accumulation and partial decomposition of vegetation*. That's okay as far as definitions go, but it's not very descriptive.

2.1.3 Coal is found to be *interbedded with other sedimentary rocks* you might consider to be ordinary rather than extraordinary: sandstones, shales, and limestones. Coal itself, however, should be viewed as a rare sedimentary rock, albeit widely distributed: even in the relatively few formations around the world in which it is found, coal constitutes only a small percentage of the stratigraphic section, rarely more than one or two percent and often much smaller. But in absolute terms, the quantity of coal remaining after centuries of mining is staggering: it has been estimated that there's something like 10^{15} to 10^{16} kilograms of coal locked up in the Earth's continental crust.

2.1.4 Coal is found in beds (or *seams*, in coal terminology) ranging in thickness from just millimeters to many meters. Typical thickness of coal beds is half a meter to a few meters.

2.2 Properties and Terminology

2.2.1 Coal varies greatly in its properties, depending in part upon its composition but for the most part in the degree of diagenesis or even metamorphism it's undergone. This degree of diagenesis is called the *rank* of the coal. In terms of extent of diagenesis, coal ranges from *low-rank* (brown, porous, semilithified, and of low density, something like 1.0 g/cm^3) to *high-rank* (jet black, hard, nonporous, hard, and much more dense, up to almost 2.0 g/cm^3). Figure 12-2 shows this spectrum, with conventional names along the way.

2.2.2 You can see from Figure 12-2 that the principal way-stations along this spectrum are *lignite* (brown coal) → *bituminous* (soft coal) → *anthracite* (hard coal). Lignite burns readily but with a smoky flame; anthracite is hard to ignite but burns with a clean, hot flame.

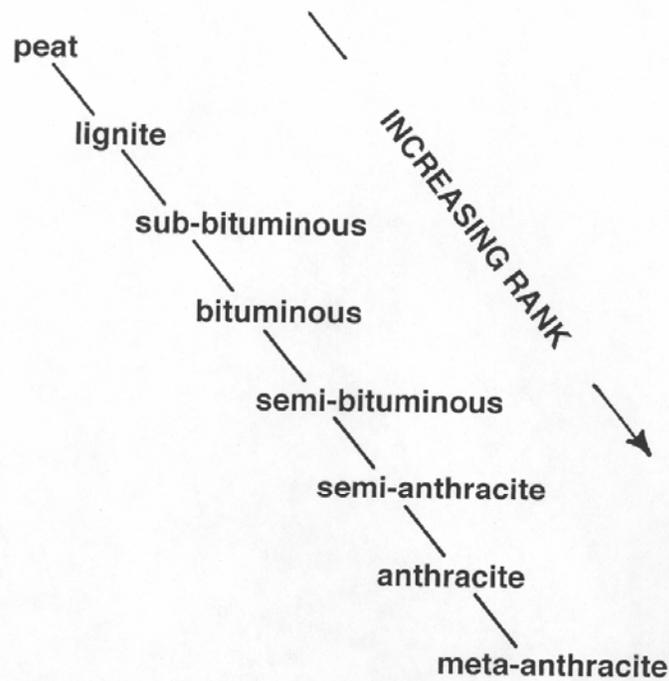


Figure 12-2. The spectrum of coal rank.

2.2.3 Material even less diagenetized than lignite is called *peat*, which is a porous aggregate of largely nondecomposed but stable plant residues. In some areas peat is mined as a domestic fuel, in addition to being ground up for agricultural and horticultural use. At the other end of the spectrum, under conditions of real metamorphism (the interbedded rocks then being metamorphic rather than sedimentary), anthracite coal is converted to meta-anthracite, and finally to graphite.

2.3 Composition

2.3.1 Almost by definition, coal consists mostly of carbon. The plant materials from which coal is derived are largely carbohydrates of various kinds, only the most resistant of which (mainly *cellulose* and *lignin*) remain after partial

decomposition after death of the plants. The initial plant residues that are buried to become coal therefore consist largely of carbon even at the very beginning. But coals—even lignites—contain appreciable percentages of *other constituents* as well. Here’s a list:

nitrogen: a couple of percent; doesn’t vary much. Probably from the organic matter itself, not from entrapped air.

sulfur: small percentages, a couple of percent, but undesirable because of production of sulfuric acid (the main constituent of acid rain) upon combustion.

water: varies with rank from a few percent to as much as 90% (conventionally measured after drying at a temperature a little greater than 100 °C, to get rid of liquid water in pore spaces).

gases: CO₂, O₂, N₂, CH₄, variable percentages.

“ash”: the solid residue upon combustion: sand, silt, and clay in variable proportions, either carbonate or siliciclastic (mostly the latter). From fractions of a percent in the cleanest coal to such large values that the rock should be called a *carbonaceous shale* or a *carbonaceous sandstone* rather than coal. Very impure coal is called *bone coal*.

2.3.2 Figure 12-3 shows one segment of a composition triangle whose end members are percent of carbon, hydrogen, and oxygen. Only the area nearest the carbon corner is occupied by rocks we would call coal. You can see that *the increase in rank is associated with a progressive decrease in the percentages of hydrogen and oxygen*, presumably owing to driving off of the volatile constituent water.

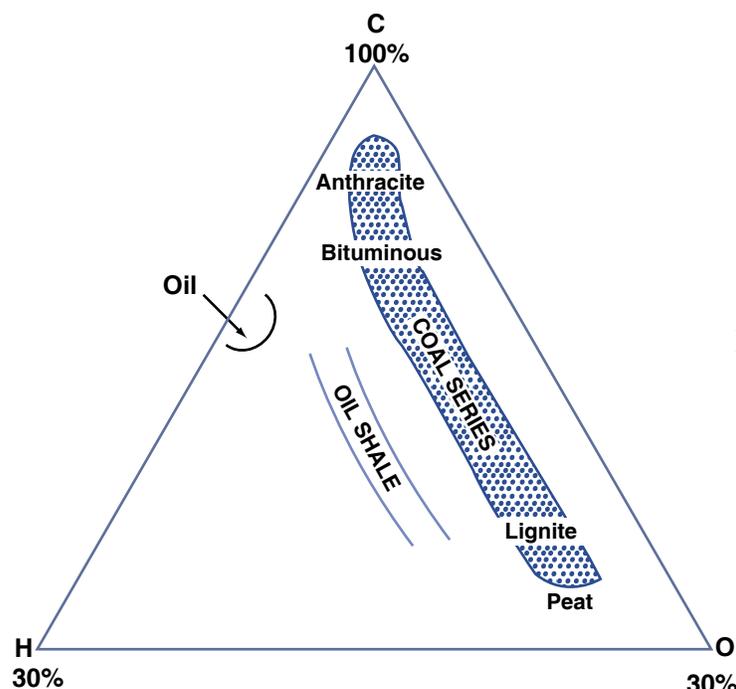


Figure by MIT OCW.

Figure 12-3: The rank of coal in relation to a carbon-hydrogen-oxygen composition triangle

2.3.3 The plant constituents of coal have been classified both macroscopically and microscopically. The basic idea is that all coal is composed of a small number of kinds of fragments of plant debris called macerals, which are analogous to the minerals of an ordinary sedimentary rock.

2.3.4 Macerals represent such things as branches, twigs, leaves, bark, interior tissue of various kinds, and pollen or spores, among many others. Study and classification of coal macerals is highly botanical and can be done only with the aid of a microscope.

2.3.5 The macroscopic study and classification of coals, on the other hand, while not as fundamental, is easier to deal with. Coal has long been recognized to consist of just a few macroscopic constituents, usually interlaminated. These constituents form strata that are typically from fractions of a millimeter to tens of millimeters thick.

vitrain: brilliant, vitreous (glassy-looking), jetlike coal with conchoidal (shell-like) fracture

clarain: coal layers that appear silky from the presence of very delicate internal lamination

durain: dull, lusterless, matte layers of coal with a close or dense texture, without internal lamination

fusain: friable and highly porous coal, usually appearing as irregular chips and wedges lying along the bedding; often called *mineral charcoal*.

2.4 Origin

2.4.1 Coal can form wherever growth of vegetation is abundant enough, and accumulation of the sediment is scanty enough, that plant material can accumulate in high concentrations and large quantities before complete decomposition. For this, one has to appeal to *extensive swamps*, usually termed *coal swamps*, either fresh water or sea water (probably mainly fresh water) in climatic conditions conducive to lush growth of vegetation and far from sources of siliciclastic sediments.

2.4.2 Most coal seems to have formed *in place, by gradual accumulation of plant material right where it grew*. You can imagine thick accumulations of earlier plant material into which the present crop puts down its roots, only to succumb eventually and form the substrate for yet another crop. Such coal is said to be ***autochthonous***. Some coal, however, seems to consist of plant fragments that were transported far from where they grew, presumably by flowing water, and deposited in some rather different sedimentary environment—but again one without an abundance of “ordinary” siliciclastic sediment. Such coal is said to be ***allochthonous***.

2.4.3 The overall association of other sedimentary facies with coals—mainly shallow marine and fluvial sediments—tells us that, broadly, *coal accumulates in coastal environments of one kind or other*. Perhaps the most common kind of environment of this kind could be termed *deltaic*. Imagine a broad river carrying mud and sand to the shoreline. The river flow in deltas tends to be well channelized, with strong flows carrying sand to the channel mouths. Mud carried by such channels is either spilled widely over the banks of the channels along the way or disgorged into the sea at the mouths of the channels. In certain settings, in between the channels are low-lying areas that receive little fluvial sediment and are conducive to dense vegetation. Such areas tend to experience slow subsidence, from compaction of earlier-deposited sediments; this subsidence makes room for further accumulation of plant materials. (Keep in mind that *there must be great compaction of the plant material as it's buried*.)

2.5 Cyclothem

2.5.1 The coastal nature of most coal is emphasized by the mode of occurrence of late Paleozoic coal. (You will see below that the Pennsylvanian was one of the great epochs of coal deposition around the world.) Most Pennsylvanian coal is found in distinctive cyclic units called ***cyclothem***. A cyclothem consists of *a systematic alternation or cycle of sedimentary deposits that represent a regular alternation of depositional environments*. Figure 12-4: Dunbar, C.O., and Rodgers, J., 1957, Principles of Stratigraphy: Wiley, 356 p. (Figure 52, p. 110) shows a schematic stratigraphic column of a cyclothem. The figure shows an idealized cycle, in that there's lots of variability in the real successions, but it gives you a good general idea of the typical succession.

2.5.2 Interpretation of a cyclothem like that shown in Figure 12-4 is clear: *there's a cyclic alternation of marine and nonmarine deposits*. The nonmarine part of the cyclothem extends from the disconformable base of the sandstone to the coal; the rest of the cyclothem represents shallow-marine deposition. We are forced to assume that *there was a cyclic rise and fall of sea level relative to land, to produce inward and outward migration of the shoreline* over the area where the deposits were accumulating. The lowest stand of sea level is represented by the sandstone at the base of the cyclothem, which by its features is best interpreted as fluvial or deltaic. The coal represents a time when the sea level was starting to rise again, and the flooding of the river system prevented extensive deposition of siliciclastic sediment and allowed development of coal swamps. Eventually the site of coal deposition was flooded by the sea, and limestone and shale was deposited. Then, as sea level fell again, the river was rejuvenated, and cut into previous sediments to lay down more fluvial sand.

2.5.3 The origin of the fluctuations in sea level were controversial for a long time. It's now generally agreed that *the sea-level fluctuations were not tectonic but eustatic*: the late Paleozoic was by good evidence a time of widespread continental glaciation, which would have produced substantial and cyclic fluctuation of sea level worldwide.

2.5.4 The variability in the nature of the cyclothem from place to place provides further evidence for coastal deposition during eustatic fluctuations in sea level. At points on the continent that were at lower elevations and therefore closer to the ocean on average, a greater percentage of the cyclothem are represented by marine deposits, whereas at points that were at higher elevations, farther from the ocean, a greater part of the cyclothem are nonmarine. Coals are most abundant in the cyclothem that were intermediate in position; in the US, the Pennsylvanian cyclothem richest in coal are found in Illinois.

2.6 Coal Through Geologic Time

2.6.1 Coal was not common before the spread of plants from the oceans onto the land, in the Silurian. For this reason, the earliest extensive coal deposits date from the Devonian. Since then, the times of most abundant coal deposition were in the Pennsylvanian, the Jurassic, the Cretaceous, and the earlier part of the Tertiary—most especially in the Pennsylvanian. Since the Devonian the time of scantiest coal, by far, was the Triassic. The reasons for such a grossly uneven distribution of coal deposition through time are not entirely clear: it must have had to do with the extent of climatic and tectonic settings around the world favorable to coal deposition.

2.6.2 But it might surprise you to learn that *there is some coal even as far back as the Early Proterozoic!* Proterozoic coal, minor in extent and volume, was formed by accumulation and appropriate coalification of algae in certain marine environments.

3. PETROLEUM

3.1 Introduction

3.1.1 Petroleum is in so many ways the cornerstone of modern life. Even those of us who bemoan our overdependence on petroleum find ourselves using it in so many ways. How many environmentalists refuse to drive or ride in petroleum-powered motor vehicles?

3.1.2 Fluid petroleum hydrocarbons, crude oil and natural gas, began to be exploited on a large scale near the end of the last century. Up until a few decades ago, supplies seemed limitless. Now we know that they are limited, although we are not about to run out. It's more a matter of how much we are willing to pay to extract petroleum as the more readily recoverable reserves dwindle in the coming decades. More on that later.

3.1.3 Here's a nutshell prelude to this section: petroleum in all its forms is derived almost entirely from organic matter left over from death and decay of plant and animal microorganisms, mostly marine, and deposited along with sediments. As the sediments are buried and subjected to increased temperatures and pressures, those organic matter undergo complex chemical changes, leading in some situations but not all to mobile fluid hydrocarbons, which, being less dense than aqueous pore solutions, tend to rise buoyantly, eventually leaking to the surface to be reoxidized. In some places this rising fluid is trapped by geological structures to form concentrated fields, which can be tapped by deep drilling.

3.2 Organic Matter in Sediments

3.2.1 In geology the term *organic matter* is generally used for *material composed of organic molecules derived directly or indirectly from the organic part of organisms*. Mineralized skeletal materials, like shells or bones, are by convention not included. Such organic matter is synthesized by living organisms and then, upon the death of the organisms, is either oxidized back to its simple inorganic constituents (mainly CO₂ and water) or in part deposited along with inorganic sediments, in usually small but sometimes surprisingly large concentrations.

3.2.2 Because of the relatively high concentrations of oxygen in the atmosphere (about 20% by weight) and the relatively low concentrations of oxygen in the oceans (a few milliliters per liter), organic matter produced subaerially is much more susceptible to oxidation before preservation than is organic matter produced subaqueously. Only in the case of lush woody plant growth (with its abundant hard-to-destroy constituents cellulose and lignin) and rapid burial can organic matter be abundantly preserved on land (see the earlier section on coal).

3.2.3 In the oceans, oxygen-poor bottom environments are common. Closed basins, deep or shallow, large or small, tend to have stable density stratification, usually because waters are warmer near the surface than near the bottom, and vertical circulation is virtually nonexistent. In such conditions the rain of organic matter to the bottom outstrips the supply of oxygen to oxidize the organic matter, and there's not accumulation of non-decayed organic matter in anoxic conditions. The organic-matter content of sediments deposited in such environments can be as high as 5%. The Black Sea is an excellent modern example, and is widely used as a model for organic-matter-rich anoxic basins by petroleum geologists.

3.2.4 But even ordinary dark shales, so abundant in the sedimentary record, contain on average a substantial fraction of one percent organic matter. A good way to explain this is that even in a sea-floor setting that's well oxygenated, any organic matter that escapes decay before burial will soon be comfortable as it finds itself below the sediment-water interface, because the permeability of muds is so small that the subsurface sediment is effectively sealed off from access to oxygen upon burial of just a few centimeters.

3.2.5 *The great bulk of organic matter is produced in the oceans by single-celled microscopic organisms of various kinds.* You can forget about clams and snails, to say nothing of fish or whales; they play a minor part on the organic-matter budget of the oceans and their sediments. The microorganisms that are the most important producers of organic matter are *planktonic*—that is, they float passively, mostly in the near-surface waters of the oceans. Most such organisms are much less than one millimeter in size, and the bulk of the organisms are a small fraction of a millimeter in size, often no larger than several micrometers. Some are soft bodied; others secrete stiffening material consisting of either amorphous silica or calcium carbonate.

3.2.7 Systematic consideration of the various kinds of planktonic microorganisms today and in the geologic past would be out of place here; suffice it to say that the greater part are **autotrophic** (they produce their own food, mainly by photosynthesis) and thus should be considered *plants*. They are termed **phytoplankton**. The main kinds are **diatoms**, **algae** of various kinds, and **nannoplankton** (extremely small). Also important, however, are *planktonic animals*, termed **zooplankton**, which feed on smaller plankton, mainly phytoplankton. **Foraminifera** are the most important kind of zooplankton. Figure 12-5: Tissot, B.P., and Welte, D.H., 1984, *Petroleum Formation and Occurrence*, Second Edition: Springer-Verlag, 699 p. (Figure 1.3.1, p. 22) shows the kinds of plankton most important in the generation of petroleum. The kinds and relative percentages of plankton have varied through geologic time, but because of the varying preservability, it's difficult to know much about the relative importance of the various kinds of planktonic organisms in the past. It's reasonable to assume, however, that they've been abundant throughout the latter part of geologic time, at least since the Precambrian.

3.2.8 All organisms are composed of the same groups of chemical constituents: **proteins** (highly ordered polymeric molecules built of amino acids), **carbohydrates** (basically monomeric and polymeric sugars: monosaccharides and polysaccharides), and **lipids** (organism-produced organic compounds insoluble in water: fats, oils, and waxes). With respect to generation of petroleum, lipids are by far the most important, because they are much less susceptible to decay by oxidation before, during, or immediately after sedimentation. In addition, **lignin** (a high-molecular-weight aromatic polymer that acts as a structural stiffener in higher plants) is an important and readily preservable kind of organic matter, but does not figure prominently in the generation of petroleum.

3.3 Organic Matter to Petroleum

3.3.1 The conversion of organic matter to petroleum is a complex process of chemical change during burial of the sediment that contains the organic matter. These changes can be viewed as a series of phases that begin immediately after burial and continue to the point of true metamorphism of the sediment, at depths of many kilometers. Broadly speaking, the depth of burial at which most fluid petroleum hydrocarbons are generated ranges from about a thousand meters to a few thousand meters.

3.3.2 The series of chemical changes in organic matter upon burial of a sediment is conventionally subdivided into three stages:

diagenesis, catagenesis, and metagenesis. (Figure 12-6: Tissot, B.P., and Welte, D.H., 1984, *Petroleum Formation and Occurrence*, Second Edition: Springer-Verlag, 699 p. Figure II.1.1, p. 70) shows schematically the course of petroleum evolution during these three stages.) Remember two things, however:

- This is a largely arbitrary subdivision, for convenience in thinking and communication, and doesn't reflect any sharp breaks in the nature of the process
- This use of the term diagenesis is narrower than the way sedimentologists in general use the term, for all the changes that happen in a sediment upon burial, all the way to what should better be termed metamorphism.

3.3.3 Diagenesis acts during shallow burial, down to a few hundred meters; perhaps a good albeit arbitrary lower limit would be 500 m. Temperatures rise to not much more than 50°C.

3.3.4 Early on in diagenesis, the activity of living microbes of various kinds, buried along with the sediment, are the main agents of chemical transformation of organic matter. These are mainly bacteria.

3.3.5 If the sediment was deposited in an oxygenated environment, then the earliest stage of microbial decomposition proceeds aerobically, using up all the free oxygen. Then, at greater depths, anaerobic sulfate-reducing bacteria extract oxygen from sulfates (SO_4^{--}) and reduce the sulfur to sulfide ions (S^{--}). The sulfide ions then combine with ferrous iron to form various iron sulfides, which are slowly converted to pyrite after further burial. Finally, by fermentation, certain other anaerobic bacteria feed on oxidized forms of organic matter, mainly carbohydrates, generating methane.

3.3.6 In the later stages of diagenesis, upon burial to tens to a few hundreds of meters, the organic matter remaining after microbial activity is progressively converted or synthesized into higher-molecular-weight organic compounds that are more stable and less water-soluble. The details of chemistry of these reactions is much beyond the scope of this course.

3.3.7 The compounds resulting from diagenesis are lumped together under the term **kerogen**. Kerogen is a kind of wastebasket term for *all of the immobile and insoluble organic compounds found in shallowly buried sediments* (or, because other things have been happening to the sediment in the meantime, *sedimentary rock*). This term kerogen is one of the most important in petroleum geology, because it's the raw material for synthesis of mobile liquid hydrocarbons during further burial (see below). Also by this stage, certain organic compounds have been produced that are soluble in organic solvents and can therefore be extracted commercially. Such material is called **bitumen**. It's the material for which **oil shales** can be mined.

3.3.8 Finally, during catagenesis, fluid hydrocarbons are formed by various organic chemical reactions from some of the kerogen that was produced at earlier stages of diagenesis. The amount and composition of these hydrocarbons changes progressively toward lower-molecular-weight hydrocarbons. By the time the stage of metagenesis is reached, only methane, the lightest hydrocarbon, is produced.

3.3.9 The hydrocarbons of relatively high molecular weight are in liquid form both in the subsurface and when they are pumped (or flow naturally) to the surface. In a general way, the higher the molecular weight of the hydrocarbon mix in the petroleum, the more viscous the liquid. The hydrocarbon with lowest molecular weight, methane, CH_4 , is a gas even at the high pressures of petroleum-forming depths. The hydrocarbons with slightly greater molecular weights (ethane, C_2H_6 ; propane, C_3H_8 ; and butane, C_4H_{10}), are liquid under the great pressures of petroleum-generating depths but undergo a change of state from liquid to gas on the way to the surface, as the pressure decreases.

3.3.10 Natural gas is composed predominantly of methane, with much smaller percentages of ethane, propane, and butane. Natural gas also contains variable percentages of carbon dioxide, hydrogen sulfide, nitrogen, hydrogen, helium, and argon; these are largely of inorganic origin, and are included in the natural gas basically because they were there. Liquid petroleum consists mainly of a mixture of **alkanes** of various molecular weights (alkanes are organic compounds with chains of single-bonded carbon, with hydrogens bonded to the carbons along the chains) and **aromatics** (aromatic compounds are those with benzene rings in their structures). This may not mean much to you unless you have had some organic chemistry, but don't worry about it.

3.4 The Migration of Petroleum

3.4.1 Consider a sedimentary rock that started out at the depositional interface with a substantial content of appropriate organic matter, some of which during burial has been converted to liquid or gaseous hydrocarbons. These hydrocarbons are present as *tiny fluid masses in the pores or interstices among the mineral constituents of the rock*. Keep in mind that their concentration is small: the initial concentration of organic matter might have been of the order of a percent or two, and only a fraction of that ends up being converted to fluid hydrocarbons.

3.4.2 Since the concentration of organic matter is appreciable only in the finer-grained rocks—shales, in a general way—it's accurate to say that *most petroleum is produced in shales*. The fine-grained rocks in which petroleum is generated in nonnegligible concentrations are called **source rocks** or **source beds** for the petroleum.

3.4.3 But once the petroleum is produced in the rock, it tends to *migrate*. The migration of petroleum is a critically important topic in petroleum geology, because in order for the petroleum to be present in a rock in concentrations great enough to be tapped by wells, it must migrate from the source rocks, in which it's present in very small concentrations, into much more porous rocks from which it can be extracted in large quantities at practical rates.

3.4.4 The basic pore fluid in all subsurface sedimentary rocks is, of course, *water*, with various dissolved constituents. At the depths of petroleum generation, such pore waters (called **formation waters** at that stage) are usually very *salty*, to the point where they are best described as **brines**. As it's produced, the petroleum exists as *little globules within and immiscible with the aqueous pore solutions*.

3.4.5 All mobile petroleum hydrocarbons are of lower density than water. So the little globules of petroleum tend to *make their way buoyantly upward through the rock*. That's a slow process, both because of the relatively *high viscosity* of the liquid petroleum (the natural gas component moves faster) and because of the *low permeability* of shales. In turn, shales are of low permeability for two reasons: low porosity, and small size of the passageways that connect that porosity. *The largely upward migration of newly generated petroleum* is termed **primary migration**. (The movement isn't necessarily strictly upward: the liquid moves in the direction of most rapidly decreasing pressure, which for various reasons may be at some angle to the vertically upward direction.)

3.4.6 If the slowly migrating petroleum encounters much more porous rock in its travels, it collects in such rocks in much greater concentrations—in some cases up to volume concentrations approaching 30%, the porosity of poorly cemented and well sorted siliciclastics—and it travels much faster. Such *migration in more porous rock* is called **secondary migration**.

3.5 Petroleum Traps and Petroleum Reservoirs

3.5.1 If not detained somehow, the upward-migrating petroleum ultimately reaches the Earth's surface, as **oil seeps**. Natural oil seeps can be seen in many places in the world today. Oil seeps on the sea floor can be detected by the occasional release of a large glob or drop of oil from the sediment-water interface, from which it rises to the sea surface. If you are a diver, you can even collect the petroleum by inverting a bucket over the seep. On land, the lighter and more volatile fraction of the oil that seeps out the land surface tends to evaporate away, leaving only the more viscous bituminous components, which then act as **tar pits**, perhaps to trap unsuspecting animals feeding at the edge of the tar.

3.5.2 For the upward-migrating petroleum to be retained in large concentrations in the subsurface, it must encounter a *petroleum trap* of some kind. A **petroleum trap** is an arrangement of effectively impermeable rocks above permeable rocks in a geometry such that the boundary surface or zone between the permeable rock below and the impermeable rock above has upward convexity. Then there is a non-negligible volume of the permeable rock in which the petroleum is detained or trapped (Figure 12-7).

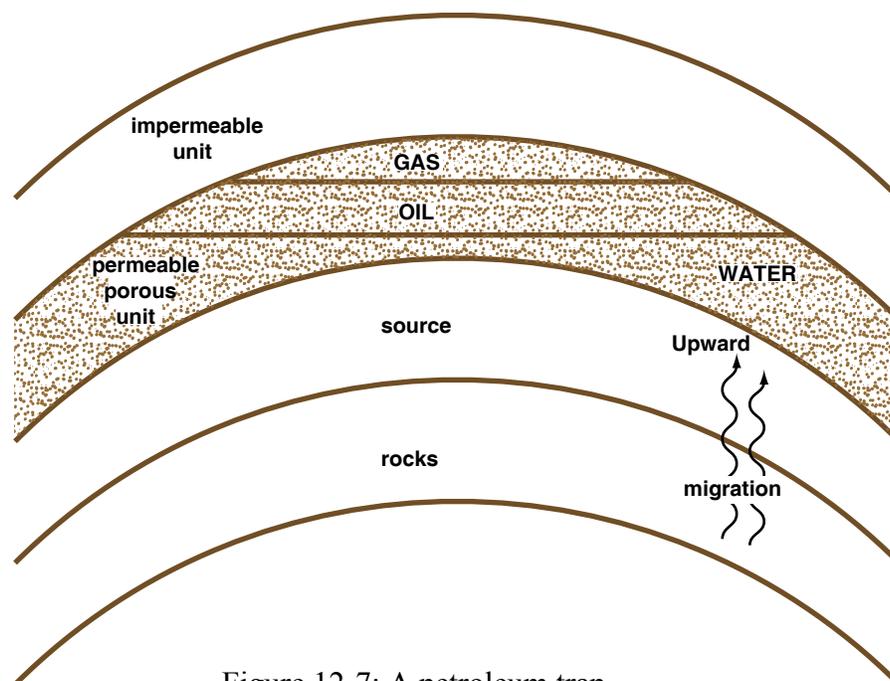


Figure 12-7: A petroleum trap

Note that I have shown the gas above the petroleum, which in turn lies above the water; you should expect this stable density stratification of the three different and immiscible materials. All you have to do then is drill downward through the roof of impermeable rock to tap the detained petroleum. Such a detained mass of petroleum is called a *reservoir* or a *pool*. A pool is the smallest and simplest unit of commercial petroleum production: it's *a single and connected body of oil and/or gas that under a single fluid-pressure system*. In horizontal area, a single reservoir might cover anywhere from an acre to many square miles. The *closure* (the vertical distance between the roof of the pool and the lowest level of detention) could be anywhere from a few meters to hundreds of meters. A major pool might contain 50 million barrels of oil.

3.5.3 Traps vary enormously in their nature. They might best be classified as *structural traps* and *stratigraphic traps*. A **structural trap** is a trap whose geometry originates by deformation. Figure 12-8 shows three classic examples. In Figure 12-8A, a doubly plunging or canoe-shaped anticline in a stratigraphic succession with an impermeable unit overlies a mass of reservoir rock, which in turn overlies source rocks. In Figure 12-8B, a fault has placed reservoir rock below impermeable rock not only in its own fault block but in the adjacent fault block. If the fault is later sealed by healing, so the petroleum can't leak upward along the fault zone, a trap is formed. In Figure 12-8C, a salt diapir has slowly punched its way up through a sedimentary sequence. If an impermeable unit overlying a permeable unit is in that sequence, a crudely doughnut-shaped trap around the salt dome can be formed.

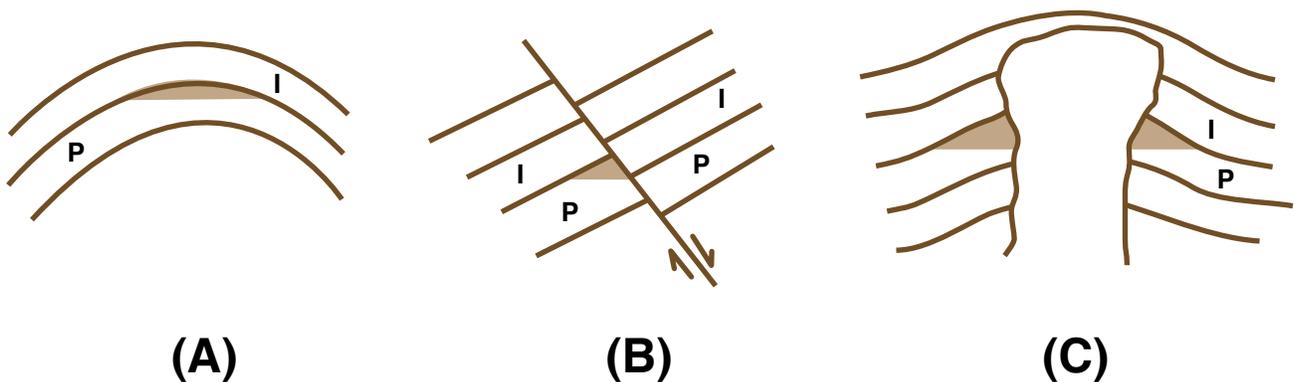


Figure 12-8: Some kinds of structural traps

Figure by MIT OCW.

3.5.4 Stratigraphic traps owe their arrangement to sedimentary rather than structural processes. Figure 12-9 shows two examples. In Figure 12-9A, in a stratigraphic succession with some non-negligible regional dip, a permeable unit

lying below an impermeable unit undergoes lateral facies change from permeable to impermeable rock in the up-dip direction, thus creating a trap. In Figure 12-9B, an isolated reef developed and was then eventually mantled by fine sediment. Reef carbonates are among the most permeable of sedimentary rocks, and since they're often in close proximity to fine sediment, this kind of situation makes for important reservoirs. Stratigraphic traps are not usually as voluminous as structural traps, and they tend to be harder to find.

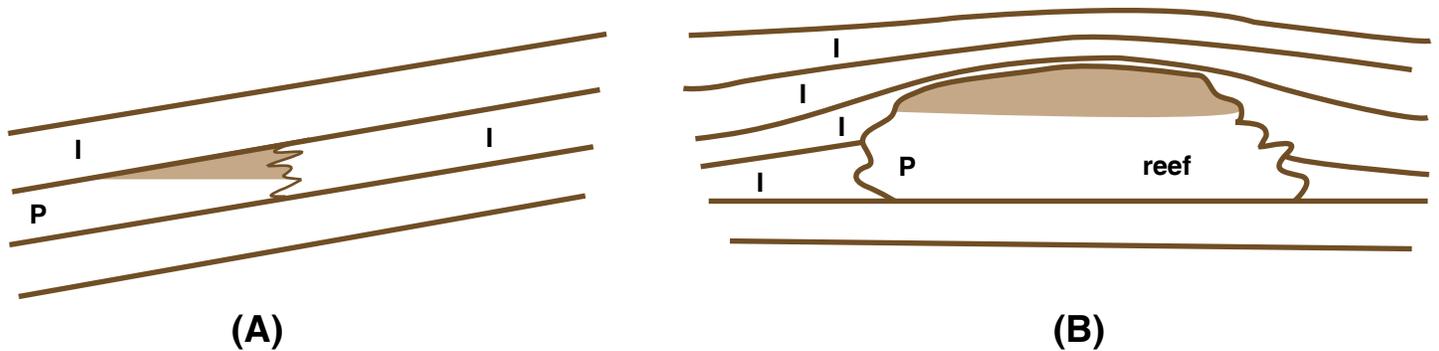


Figure 12-9: Some kinds of stratigraphic traps

Figure by MIT OCW.

3.5.5 *An area where a number of pools are related to a single geologic setting, structural or stratigraphic, is called a **petroleum field**. In a looser way, a large area where a number of pools and/or fields are found in a broadly related setting is called a **petroleum province**.*

3.6 Petroleum Distribution and Reserves

3.6.1 Most of the world's easy-to-find fields have already been found and exploited. Present exploration focuses on major fields in previously unexplored areas, which of course are now few and far between, and minor fields and pools in already exploited areas.

3.6.2 Is the world running out of petroleum? That continues to be a hotly debated issue. In a broad way the answer has to be **yes**, in that much of the world's readily extractable fluid hydrocarbons have already been extracted. Proven reserves of such readily extractable petroleum are sufficient to last for some decades (although how many decades isn't entirely clear). But keep in mind

that *easily extractable petroleum represents only a tiny fraction of all the petroleum hydrocarbons residing in sedimentary rocks around the world*. In an important sense, it's not so much a matter of running out of petroleum as having to *pay more and more to extract the more and more difficulty extractable petroleum*.

3.6.3 This is a good point to mention two other major sources of petroleum: *tar sands* and *oil shales*. In some places there are enormous reserves of essentially solid petroleum (actually, very high-viscosity liquids which have no appreciable tendency toward migration). These materials are described as *asphalt* or *bitumen*. They are of two kinds:

- *inspissated (dried-up) deposits* left over in rock that was once a pool but from which most of the hydrocarbons have drained away, leaving only immobile residues in the pore spaces
- *primary (disseminated) deposits* in which sediments were mixed with oil or bitumen during deposition, buried and then later exposed by erosion.

The very best example of a primary deposit is the Athabasca tar sands of Alberta. It's the largest known single deposit of oil in the world, something like a few hundred billion barrels! The oil seeped up from Devonian organic-rich limestones and then was redeposited in the Cretaceous along with sand, in various protected nearshore marine environments.

3.6.4 The other alternative source, oil shales, are widely distributed around the world in both time and space. They are of potentially great commercial importance. These involve several kinds of organic-rich or bituminous shales, with varying mixtures of organic matter with the mineral matter of the shales. The organic matter is mainly *kerogen* (see an earlier section) which never made it to the stage of petroleum generation or was left over after petroleum generation and migration out of the shale. One has to mine the shale (usually by surface mining) and then distill the kerogen out of the rock to obtain mobile hydrocarbons. As with tar sands, there are enormous reserves of oil shale, especially in the western US. Of course, there's an environmental cost to the exploitation of oil shales.

3.6.5 One final comment seems in order: **How long the supply of petroleum lasts depends on how our consumption grows in the future.** This seems obvious, doesn't it, but differing assumptions about growth can lead to spectacularly different estimates. The most important point to be made has to do with *the difference between arithmetic growth and exponential growth*. A.A. Bartlett, in a thought-provoking paper in the Journal of Geological Education

(1980, vol. 28, p. 4-35) makes a revealing computation in this regard. We paraphrase the key passage:

If the Earth were a spherical tank of oil, the oil would last for 4×10^{11} years at the 1970 rate of consumption but only 342 years at a 7.04% annual rate of growth [the rate that prevailed during the century before 1970].