CHAPTER 2

The Occurrence of Petroleum

Surface occurrences: seepages – mud volcanoes – disseminated deposits – vein deposits – kerogen shale. Subsurface occurrences: showings – pools – fields – provinces. Geographic location. Geologic age of reservoir rock.

THE OCCURRENCE of petroleum is widespread but very uneven. In some rocks it occurs only in infinitesimal amounts, measured in parts per million or even in parts per billion, whereas rocks of other areas contain enormous accumulations measured in billions of barrels. Petroleum occurs on all the continents of the world, although some continents are much richer in petroleum than others. And it occurs in all the geologic systems from Precambrian to Recent, though some systems are notably more prolific than others. The unevenness of the occurrence of petroleum, it should be remembered, is due in part to the unevenness of the exploration effort. This, in turn, depends on such variables as current geologic thought about the occurrence of petroleum, and on economic and political factors that either aid or hinder exploration.

Some petroleum occurrences are visible as outcrops at the surface of the ground. More important, however, from the standpoint of the petroleum geologist and the industry, are the underground or *subsurface* occurrences, exploited only as the result of drilling. Almost all of the world's commercial supply of oil and gas is produced from subsurface deposits.

The petroleum deposits of the world may be classified under several different categories. The most useful are these:

1. Mode of Occurrence

a. *Surface occurrences,* such as seepages, springs, exudates of bitumen, mud volcanoes, inspissated deposits, vug and vein fillings, and various kinds of "oil," kerogen, and bituminous shales.

b. *Subsurface occurrences,* including minor showings of oil and gas, pools, fields, and provinces.

2. Geographic Location

The distribution by countries, continents, and other geographic units.

3. Geologic Age of Reservoir Rock

MODE OF OCCURRENCE

The simplest classification of petroleum deposits is based on mode of occurrence; and on this basis the main division is into surface and subsurface occurrences. A deposit of either type may be of small magnitude and of only scientific interest, or may constitute a commercial deposit.*

Surface Occurrences

Petroleum occurs at the surface of the ground in a variety of ways. Some surface occurrences may be thought of as currently active, or "live," such as (1) those that form seepages and exudations of bitumen, and (2) those associated with springs and mud volcanoes and mud flows. Others may be considered as fossil, or "dead," occurrences, such as (3) bitumen-impregnated sediments, inspissated deposits, and dikes and vein fillings of solid bitumen; (4) vug and cavity fillings. Many surface deposits combine more than one of these types, and are therefore difficult to classify accurately. Another kind of surface occurrence takes the form of kerogen shales, or "oil shales." The substances that make up kerogen are a border class of hydrocarbon materials occupying a place in the chemical classification of hydrocarbons between the petroleum hydrocarbons and the coals. Although solid in the natural state, they decompose into gaseous and liquid petroleum hydrocarbons when heated to 350°C or more. They are called *pyrobitumens.* Free hydrocarbons are frequently closely associated with kerogen, but the association is thought to be due to the oil-wetting characteristics of the kerogen rather than to the kerogen as a source of the oil.

Seepages, springs, and bitumen exudates. Petroleum—whether gas, oil, or liquid asphalt—that exudes in the form of springs and seepages may reach the surface along fractures, joints, fault planes, unconformities, or bedding planes, or through any of the connected porous openings of the rocks. Some

* "Commercial deposit" is taken to mean an occurrence of a size and grade that warrant exploitation and sale of the product. The resulting operation may or may not be profitable. If it does not prove profitable, it probably will be abandoned, or its efficiency will be improved, or it will be continued in the hope that the economic situation improves and permits a profit.

of the more common types of seepage are shown diagrammatically in Figure 2-1. Most seepages are formed, presumably, by the slow escape of petroleum from fairly large accumulations that have been brought close to the surface and into the zone of fracturing by erosion, or that have been tapped by faults and fractures. Petroleum seepages are common in the sedimentary regions of the world, and many pools and producing regions have been discovered by drilling near seepages.[1] Occasionally a seepage and a pool are connected. More often there is no relationship that can actually be observed; the seepage merely furnishes direct evidence of the presence of petroleum in the area.

Surface seepages, either as oil or as gas, are frequently associated with water springs. The oil floats to the surface of the water, and the gas bubbles out and escapes into the atmosphere. If the water is stagnant, the oil may accumulate as a viscous-to-solid mass that remains after the water evaporates. If the oil-bearing water enters streams, the oil is carried along until it is either destroyed by oxidation or bacterial action or redeposited on the ocean floor. Oil films floating on water have a characteristic iridescent luster and are somewhat similar in appearance to films of iron oxide; but, unlike oxide films, they do not break when stirred. Gas seepages are more readily observed when they occur in swamps or bubble through water. Dry desert areas, for example, may have gas seepages that are not recognized.

Surface oil seepages may be of large dimensions. Some surface deposits of oil and asphalt, such as those in southern California, Venezuela, Trinidad, and the Baku region of the USSR, cover hundreds or even thousands of acres, and must be the residue from large oil pools. These deposits generally assume a viscous and semi-solid state, but they may become liquid and flow when warmed by the daily and seasonal rise in temperature. Earthquake activity

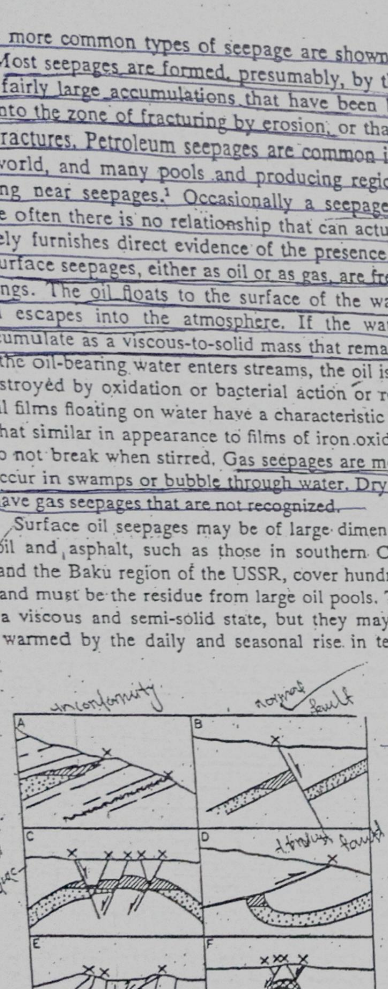

FIGURE 2-1

Sections showing the position of typical seepages with relation to the underlying structure. Seepages are marked x, and oil and gas pools are cross-hatched. The seepages in A are at the outcrop of the pool and at the outcrop of an unconformity; in B the seepage is along the outcrop of a normal fault; in C the seepages overlie a faulted anticline; in D the seepage is along the outcrop of a thrust fault; in E the seepages are associated with diapir folding; in F the seepages overlie a salt plug and are associated with the faults that occur above this intrusion.

may also account for unusually large flows from some seepages. Large seepages may consist of nearly pure oil, asphalt, or semisolid bitumens; more commonly these are mixed with varying amounts of sand, sticks, clay, leaves, peat, animal bones, and other debris.

Many of the larger seepages were once of considerable economic importance. Pitch Lake, in southwestern Trinidad near the shore of the Gulf of Paria, is one of the larger asphalt seepages and probably the most famous.[2] It lies in a nearly circular depression about 2,000 feet in diameter, and is over 135 feet deep near the center. It overlies a low structural dome containing heavy oil entrapped in Pliocene and Upper Miocene rocks. As the asphalt is mined near the center of the depression, the asphalt removed is continually replaced by what slowly wells up; so there is a slow motion outward toward the edges of the deposit. Gas accompanies the asphalt and bubbles up through the water that accumulates in the minor depressions at the surface. Many of these depressions are small synclines between folds in the asphalt surface, which has hardened as a result of exposure to the air. The gas causes the asphaltic material to assume a porous or honeycomb structure. It is believed that the lake will ultimately yield over 25 million tons of asphalt, of which more than half has been produced to date. The material mined is remarkably uniform in composition, and consists of asphalt, gas, water, sand, and clay.

Many other seepages occur in Trinidad[3] but are generally so mixed with detritus as to be of no commercial value. The seepages of the Trinity Forest Reserve, where it is possible to walk for miles without ever being out of sight of asphalt,[4] are especially noteworthy.

Another example of the petroleum seepage is the near-by Bermudez pitch lake, in eastern Venezuela. This is one of the largest deposits of pure asphalt yet discovered in the world.[5] It covers an area of over 1,100 acres and contains liquid asphalt to a depth of twenty feet, its average depth being five feet. The asphalt exudes from springs and remains soft and semiliquid under the hard crust that forms over the top. The top is covered with vegetation and pools of water, as the deposit has not been mined for many years.

Numerous tar and asphalt seepages, many of them large, are found throughout the Coast Ranges from Los Angeles to Coalinga, a distance of 140 miles. Probably the largest and most notable are those of the Ojai Valley–Sulphur Mountain district, which were described long ago by Benjamin Silliman, Jr., a professor of chemistry at Yale College. While visiting in California in 1864, he wrote back a description of the Rancho Ojai seepages: "The oil is struggling to the surface at every available point and is running down the rivers for miles and miles."[6]

The numerous surface occurrences of the Middle East are among the most famous in the world. They consist of oil and gas seepages, pitch lakes, bitumen deposits, and asphalt floating on the seas. The location of the best-known examples, as well as of the oil fields, is shown in Figure 2-2. The seepages are mentioned in many of the earliest writings, and from the beginning of recorded history down to the present time petroleum has exerted a profound influence on the lives of the peoples living in this area. Many descriptions of these ancient seepages have been recorded,[7] but only a few of the more striking examples will be mentioned here.

Probably the most famous seepage is at Hit,[8] in Iraq. (See Fig. 2-2.) Long before

FIGURE 2-2 *Map of the Middle East showing the location of some of the well-known oil and gas seepages and of the oil pools.*

the Christian era a bitumen industry had developed around this seepage, which, like many other seepages of the ancient world, acquired local importance from its reputed medicinal properties.[9]

The chief producing formation of the great Iranian oil fields is the Asmari limestone (Lower Miocene and Upper Oligocene). Where it crops out along the foothills to the northeast, many oil and gas seepages are found, either in the lime-

stone or closely associated with it.[10] Active seepages of oil and gas overlie the Quaiyarah, Kirkuk, Naft Khaneh, Naft-i-Shah, and Masjid-i-Sulaiman oil fields.

Many references to petroleum are found in the Old Testament. "The vale of Siddon was full of slimepits," or asphalt pits. (Genesis 14: 10). The builders of the tower of Babel used "oil out of the flinty rock" (Deuteronomy 32: 13). When Moses was three months old, and his mother "could no longer hide him, she took for him an ark of bulrushes, and daubed it with slime and with pitch, and put the child therein" (Exodus 2: 3). At one time the Dead Sea, around which many saturated sands, seepages, and bitumen deposits occur, was called "Lake Asphaltites."[11] Asphalt chunks are still found floating on it, but their source is unknown.

The numerous seepages of the region around the Caucasus Mountains, especially on the Apsheron Peninsula of the USSR, have also had a long history.[12] Many of them are associated with mud volcanoes (see pp. 21–23). Marco Polo, writing at the end of the thirteenth century, says of one seepage in the Baku area: "On the confines toward Geirgine there is a fountain from which oil springs in great abundance, inasmuch as a hundred shiploads might be taken from it at one time."[13] One of the gas seepages near Baku, known as the "Eternal Fires," was visited annually by thousands of fire-worshipers, many coming long distances.[14]

Marine seepages—oil and gas that escape under the ocean—occur at a number of places on the earth. The best-known are those near Santa Barbara, California;[15] off the south, east, and west coasts of Trinidad; in Consets Bay, Barbados, BWI;[16] off Yucatan in the Gulf of Mexico; southeast of Ancón, Ecuador,[17] where oil-stained spume is blown inshore from the ocean; and in the Caspian Sea off the Apsheron Peninsula. Such occurrences on the floor of the ocean are presumably associated, like land seepages, with fractures and openings leading to buried pools.

Mud Volcanoes and Mud Flows. Most mud volcanoes are caused by the diapiric intrusion of plastic clay. High-pressure gas-water seepages that often occur with them carry mud, sand, fragments of rock, and occasionally oil. Mud volcanoes are generally confined to regions underlain by incompetent softer shales, boulder and submarine landslide deposits, clays, sands, and unconsolidated sediments, such as are common in Tertiary formations.

The surface expression of a mud volcano is commonly a cone of mud through which gas escapes either continuously or intermittently. Single cones or groups of cones may cover an area of several square miles and extend more than a thousand feet in height, although they are more often measured in tens and hundreds of feet. Some mud volcanoes, however, may show at the surface either as basin-like depressions or as level stretches of ground strewn with erratic blocks of rock carried up from below. Mud volcanoes of these kinds generally occur where the rainfall is heavy, or at places on the seacoast where the tides and waves wash the soft muds away as fast as they are extruded but leave behind the erratic pebbles and boulders, many of them very large, that have been carried up from below by the mud stream. Erratic boulders have at times been encountered in drilling through subsurface unconformities. These deposits may be ancient mud volcanoes or mud flows, or they may be buried submarine landslide debris such as is thought to be the source material for many of the modern mud flows. Unless their occurrence is understood as erratic, they may cause a false interpretation of the stratigraphy and geologic history.

Flows of mud and breccia with little or no accompanying gas are often associated with mud volcanoes. The material may either come up through fractures and fissures or be squeezed out along bedding planes and faults by some diapiric folding mechanism. (See also pp. 250, 251.) The similarity of mud-volcano and mud-flow phenomena to igneous volcanism led Kugler[18] to use the term "sedimentary volcanism." The crusts of sticky mud frequently associated with the extrusions are sometimes explosively ruptured when the pressure of the gas accumulating underneath has become sufficiently high.

Many mud volcanoes, especially the larger ones, are associated with anticlines, faults, or diapiric folds. A mud volcano is especially likely to form on an anticline overlain by stiff, thick clay. During dry weather the clay becomes desiccated and cracked, and, if the cracks cut deep enough, a little of the gas manages to escape. Once an exit channel is formed, it is kept open by the escaping gas. As the gas rises, it mixes with the clay and ground water to form a mud, which erupts either steadily or spasmodically, depending on the local pressure, on the available amounts of gas, water, and mud, and on the size and shape of the opening. Mud volcanoes are most active after a long drought, probably because the desiccation cracks are then wider and penetrate deeper underground.[19]

As in igneous volcanism, auxiliary vents, from which mud flows, may open along the side of the cone when the main channel becomes clogged or when the cone grows large. In some mud volcanoes, from which large quantities of gas escape along with the mud, spectacular eruptions may occur.[20] The cone may consist in part of breccias, blocks, and fragments of rock, which are mixed with the mud. The breccias and erratic blocks that occur in some mud flows may have been picked up along the walls of the vent as the mud and gas rose to the surface. They are more likely, however, to be of shallow origin and to have come from "Wildflysch"—a buried layer of ancient submarine landslide material, such as erratic pebbles and boulders of all kinds, embedded in soft muds.* Such a mixture is incompetent when wet and charged with gas, and is easily squeezed out as folding occurs. The ascending gas and water readily pick up the soft mud with its erratic pebbles and boulders and carry it to the surface, where it is extruded as a mud flow.

The chief significance of mud volcanoes and mud-breccia flows to petroleum geologists is that they generally indicate the presence of gas. They also suggest that geologists need to be cautious in interpreting occurrences of unusual and anomalous rocks and fossils in subsurface stratigraphy, since these may come from erratic boulders contained in ancient mud flows; they may indicate

* H. G. Kugler in a personal communication.

the presence of near-surface, buried submarine landslip deposits. Since mud volcanoes are striking in appearance, the chances of finding new areas of mud-volcano and mud-flow activity are small, but new individual flows will undoubtedly continue to occur within the previously known areas.

Among the largest and most spectacular mud volcanoes in the world are those of the Baku region, USSR, which is part of the Apsheron Peninsula. (See Fig. 2-3.) These have been described by many writers[21] since the time of the first recorded history of the area. Here the mud volcanoes are generally associated with diapiric folding in the soft Tertiary rocks. In some places mud and mud breccias ooze without the aid of free gas from cracks in the rocks, as toothpaste oozes from a tube. The cones of the Touragai, Kinzi Dag, and Kalmes mud volcanoes rise to heights of over 1,200 feet (400 meters) above the adjacent Caspian Sea, and many lesser cones are found throughout the region. Eruptions containing great quantities of gas are frequent, and these are very spectacular when the gas catches fire. When an eruption on Opman-Box-Dag caught fire in 1922, the smoke rose to a height of 14 kilometers; and the flames from the Touragai eruption could be seen from a distance of 700 kilometers. The heat from the burning gas bakes and fuses the clays and muds into dark porous slags and porcellanites. Intraformational breccias that may be ancient mud flows or submarine landslide debris are found by drilling, and these often make subsurface

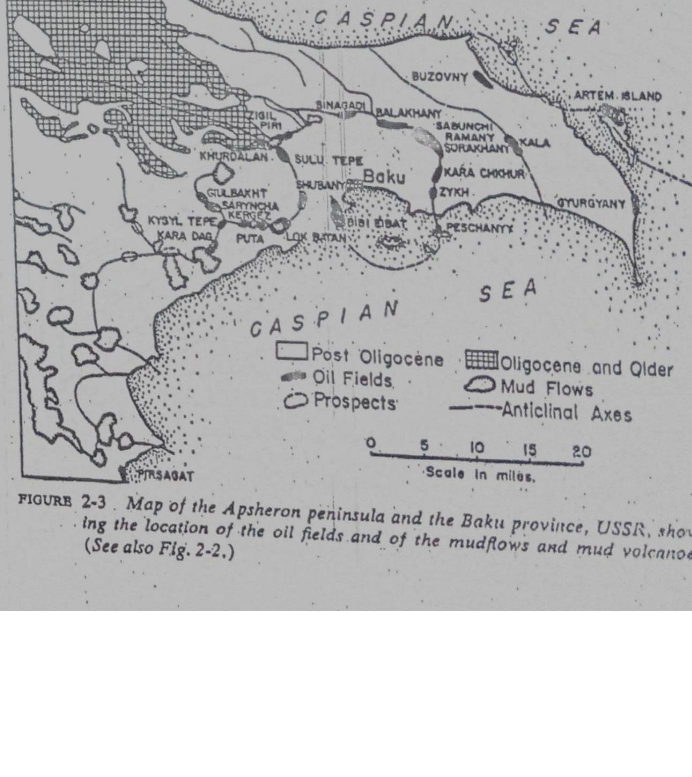

FIGURE 2-3. *Map of the Apsheron peninsula and the Baku province, USSR, showing the location of the oil fields and of the mudflows and mud volcanoes (See also Fig. 2-2.)*

correlations difficult. A section through a fossil mud flow or mud volcano of the Bibi-Eibat field is shown in Figure 2.4.

The mud volcanoes in Burma have long been known.[22] The most famous are on the Arakan Coast.[23] Those on the island of Cheduba and at Mimbu have at times erupted with startling violence, and the eruptions have been accompanied by burning gas. An eyewitness to the eruption in Cheduba says: "I saw what at first I took for a black cloud, but which was no doubt mud, shoot far above the trees, followed a moment afterward by very dark red flames and dense black smoke, which looked to me to shoot right up to the clouds." The Mimbu volcanoes lie along an important fault and are about two miles south of a group of oil-producing wells at the north end of the Mimbu field. There are seven or eight vents. Although some of them are mounds of pale-gray mud that reach 100 feet in height, others

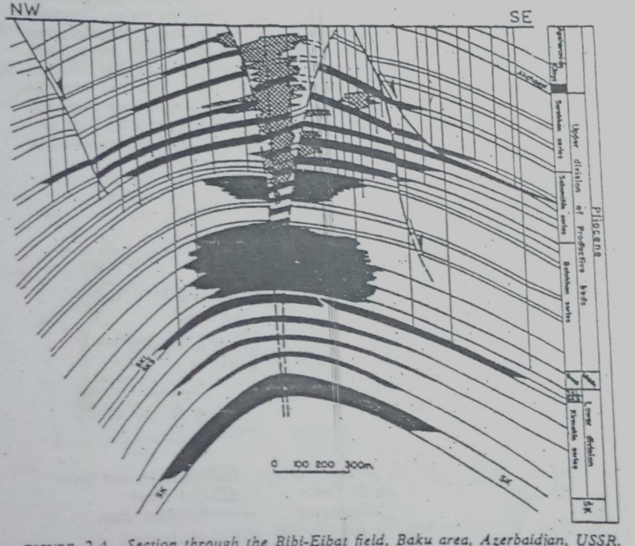

FIGURE 2-4 *Section through the Bibi-Eibat field, Baku area, Azerbaidjan, USSR. (For location see Fig. 2-3.) The top of the field is cut by an ancient or fossil mud volcano (cross-hatched). This is one of many multiple-reservoir fields in the Baku region. The structure is a large elongated dome with minor faulting. Oil pools are in black.* [Redrawn from Trust "Stalinneft," XVIIth Int. Geol. Cong., Moscow, USSR, Vol. 4 (1940), p. 120, Fig. 12.]

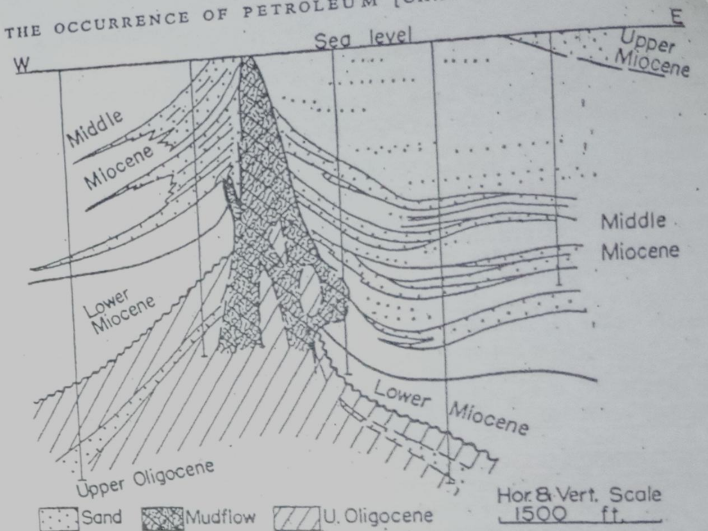

FIGURE 2-5 *Section through the Barrackpore oil field, Trinidad, showing a diapiric anticline with a mudflow core (shaded).* [Redrawn from Suter, Colonial Geology and Mineral Resources, *Vol. 3, No. 1 (1952), p. 18, Fig. 13.*]

are simply broad pools of fluid mud, through which huge bubbles of gas rise and burst every ten or fifteen seconds.

Many mud volcanoes and mud flows occur south of the Central Range on the island of Trinidad.[24] Here the volcanoes are mostly small and cone-shaped, and the eruptions are of the typical mud-and-gas variety. Along the southern coast of Trinidad, between Palo Seco and Erin, the beach is strewn with erratic blocks of calcareous sandstone. One block is about ninety cubic feet in volume, and many measure several cubic feet. These erratic blocks are left behind on the beaches, where the waves erode the mud cones and wash the mud away. Weeks[25] described one of these cones erupting nine or ten feet above sea level and throwing water six or eight feet into the air. A mud flow associated with an oil field is shown in Figure 2-5, a section through the Barrackpore field in the Digity region of Trinidad.

Occurrences of Solid Petroleum. Petroleum is also found in forms popularly regarded as solid, although, strictly speaking, some of them are highly viscous liquids. These include "tar,"* asphalt, wax, and pyrobitumen.[26] Outcrops

* "Tar" is a distillation product, and not a naturally occurring substance, although it is frequently spoken of as such.

of solid petroleum are found in two general forms: (1) disseminated deposits and (2) veins or dike-like deposits filling cracks and fissures.

Disseminated Occurrences. Sediments containing petroleum in the form of asphalts, bitumen, pitch, or thick, heavy oil, disseminated through the pore spaces of the rock either as a matrix or as the bonding material, are common throughout the world. They are generally called *bituminous sands* or *bituminous limestones*, depending on the nature of the host rock. Both bituminous limestones and bituminous sandstones are often quarried for direct use as road metal and paving. Their asphalt content may be as much as 25 percent but is usually between 8 and 12 percent.

Two different types of disseminated occurrences are found: (1) *inspissated deposits* and (2) *primary mixtures* of rock and bitumen.

Inspissation means "drying up." An inspissated deposit is *in situ* (in place), was probably once a pool in liquid and gaseous form, and now consists of only the more resistant and heavier residues, the lighter fractions having been lost. An inspissated deposit, then, may be thought of as a fossil oil field. As erosion gradually removes the overburden and brings the surface closer to the petroleum pool, the pressure on the fluids in the rocks is reduced. The lowering of pressure causes the gases and lighter oil fractions to come out of solution and expand, leaving the heavier hydrocarbon fractions behind. As the zone of weathering approaches the pool, the opening of incipient fractures allows the gases to escape more readily. Oxidizing agencies probably aid in solidifying the heavier oils that remain behind. Such a deposit, typical of many in California and Utah, is shown in Figure 2-6. An inspissated deposit in a fossil stream channel is described on pages 303 and 304.

Inspissated deposits occur in southern Oklahoma, in and around the Ouachita and Arbuckle Mountains. These are among the richest deposits of disseminated asphalt in the United States.[27] In this area the asphalt is generally viscous or

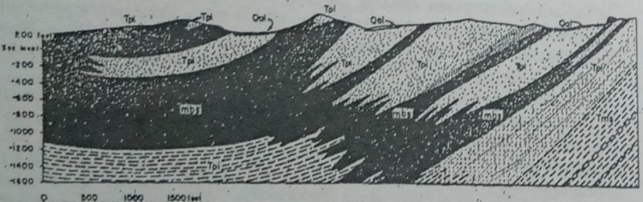

FIGURE 2-6 *Section through a bituminous black sandstone deposit* (mbs) *in the Pismo formation* (Tpi), *Pliocene-Miocene, near Edna, San Luis Obispo County, California. The asphaltic sands are underlain by the Monterey shales* (Tms). [*Redrawn from Page, Williams, Hendrickson, Holmes, and Mapel, U.S. Geol. Surv., O. & G. Investig., Prelim. Map 16 (1944).*]

semisolid, and occurs in rocks ranging from the Ordovician to the Cretaceous in age. The numerous buried oil pools in the region suggest that many of the surface deposits are inspissated pools that have been exposed by erosion. Some of these deposits consist entirely of sand grains held together by asphalt, which commonly constitutes 5–17 percent of the quarried rock.[28] Estimates of the total amount of asphalt in this region have run as high as 13 million tons.

The second type of disseminated deposit is one in which the sediments were mixed with the oil, asphalt, or bitumen during their deposition, the whole deposit having later been buried by younger sediments and then exposed by erosion. Such a deposit might be thought of as primary. It is hard to distinguish from an inspissated deposit, as is clearly shown by the long controversy over the origin of the Athabaska oil sands (Cretaceous) of Alberta, Canada.[29] These sands constitute the largest known single deposit of oil in the world, being estimated to contain over 600 billion barrels of oil in place, of which more than half is estimated to be recoverable. This deposit, therefore, has received a great deal of attention from geologists and engineers, and theories of its origin have passed through many cycles. Some believe in a Cretaceous oil source; others believe that a pre-Cretaceous oil came in along the unconformity separating the Cretaceous sediments (including the reservoir rock) from the truncated edges of the Paleozoic sediments.[30] It is possible that these oil sands might be considered a primary disseminated deposit in which the sand was deposited in or with the oil.

Another example of a deposit believed to be contemporaneous with the deposition of the rock is the Anacacho limestone (Cretaceous) of Uvalde County, Texas. This material, which underlies an area of many square miles, consists of limestone grains loosely cemented with asphalt. When it is treated with carbon tetrachloride, only the loose limestone grains remain.[31] The asphalt is hard and has a brilliant luster and conchoidal fracture. The asphalt content ranges from 10 to 20, and averages 15, percent.

Oil from offshore seepages, or oil carried into the ocean from land seepages, may be blown against the shore and be mixed with the sand to form bituminous sands. Some of the Pliocene to Recent oil and "tar" sands in southwest Trinidad appear to have been formed in some such manner.

Bituminous Dikes, Solid or Semisolid. A group of related bitumens occur as solid vein fillings in many places throughout the world. Although these substances are almost all very similar to one another, they are variously called asphalt, grahamite, uintaite, gilsonite, manjak, albertite, wurtzlite etc. Most of the names are derived from geographic or personal names. (See the Appendix for definitions of many of the solid bitumens.) Nearly all these solid bitumens are characterized by conchoidal-to-hackly fracture, a black or dark streak, and an appearance that somewhat resembles that of cannel coal. Some are soluble in carbon disulfide, and all require heating to free their oil content. These hydrocarbons occur as vein fillings that vary from a few inches to twenty-five feet in width. Sections through several vein deposits of solid bitumen are shown in Figure 2-7.

Occurrences of solid petroleum may be regarded as fossil or dead seepages from which the gaseous and liquid fractions have been removed, leaving only the solid residues behind. In the inspissated deposits the separation of the lighter constituents occurred in place in the rock. In the deposition of sedimentary petroleum the separation of the gas from the liquid took place before

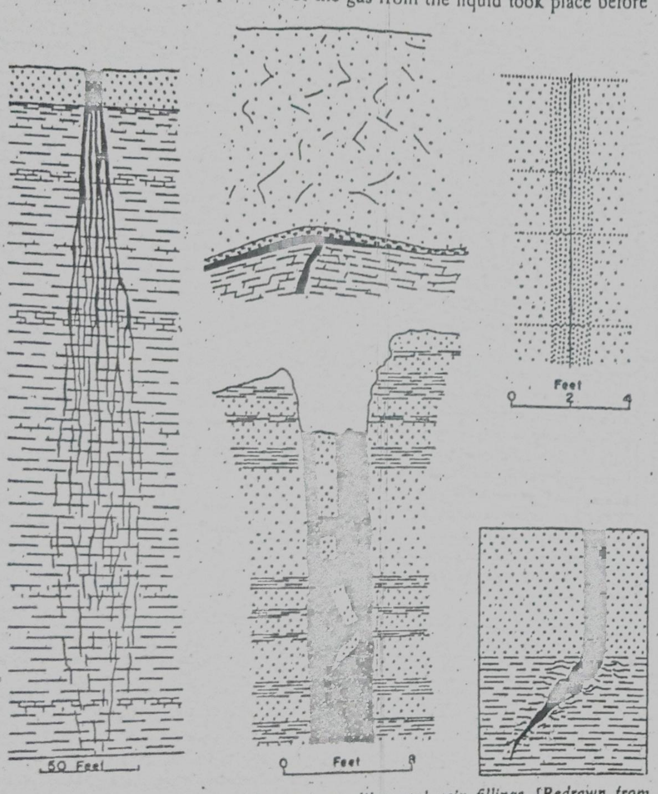

FIGURE 2-7 *Sketches of solid petroleum dikes and vein fillings. [Redrawn from Eldridge, U.S. Geol. Surv., 22nd Ann. Rept. (1901).]*

the contemporaneous deposition of the oil and asphalt with the enclosing sediments. In the solid vein and dike fillings the loss of the gaseous and liquid fractions probably occurred while the petroleum was filling the opening. Most geologists would not consider occurrences of solid petroleum in a prospective region quite as favorable an indication of oil and gas pools as a live and active seepage. Solid petroleums do have significance, however, and should not be overlooked as evidence of the presence of source rocks somewhere within the region.

Miscellaneous Surface Occurrences. Liquid and solid petroleums are frequently found in fossil casts, in vug openings, in the central cavities of geodes,* and in the nuclei of concretions.[32] The oil sometimes completely fills the cavity, but generally it occupies only a portion of it. Commonly only a few of the concretions or fossil casts present contain bitumen. Since the surrounding rocks generally do not contain any visible petroleum hydrocarbons, these occurrences present a problem. How did the material get into the cavity without leaving some trace in the surrounding rock? If the cavity is lined with crystals of calcite or quartz, the petroleum presumably came in with the solutions that deposited these minerals. Other concretions may have formed around organic nuclei, which later became transformed into petroleum hydrocarbons that remain inside the cavity. More probably the concretion furnishes a small low-pressure space within an environment in which the fluid pressure would steadily increase with depth (such as would be expected with continued burial) and the few parts per million of hydrocarbons within the surrounding shales found their way into the lower-pressure space.

Indirect evidence of petroleum is sometimes given by areas of burnt clay found at various places where exuding oil or gas has caught fire and been burned up. Generally the clay burns to a red color, and it often fuses into a porcellanite or lava-like rock. Such occurrences have been found in California,[33] in Northwest Territory, Canada,[34] in Trinidad, at Burnt Hill on Barbados Island, and along the Yorkshire and Dorsetshire coast of England.[35]

Petroleum is occasionally associated with metal ores. In many quicksilver mines, for example, and some vanadium, lead, and zinc mines, asphalt and bitumen are mixed or associated with the vein material,[36] and small but measurable amounts of mercury are being brought up along with the oil in the Cymric pool of California.[37] The Black Band shale, which overlies the Freeport coal (Ohio No. 7) of the Conemaugh (Pennsylvanian) in Ohio, contains both iron ore and enough petroleum distillate to make it potentially an important commercial oil shale. The iron ore is partly a kidney ore and partly a ferruginous limestone called "mountain ore," and is thought to be a sedimentary bog-iron deposit laid down in a swamp.[38] Disseminated solid bitumen has also been found in the copper-bearing Nonesuch formation of the Keweenawan series (Precambrian) of

* Willard D. Pye, in a personal communication, describes oil-filled geodes in the Kaibab limestone (Permian) of the San Rafael Swell, Utah, and in the Mississippian chert of the Tri-State mining district of Oklahoma, Missouri, and Kansas.

northern Michigan.[39] Recent analyses of the shales of the Nonesuch formation show the presence of several hydrocarbons typical of those found in crude oil.* More than a hundred barrels of oil have been recovered in the Minerva fluorite mine in southern Illinois, from the fractured fluorite-bearing rocks of Chester age (Upper Mississippian). Another example is the famous Kolm black shale (Middle Cambrian) of Sweden,[40] which is mined for both oil and radioactive mineral content. Uranium is the radioactive element, and is believed to have been deposited with the shales. The Kolm shale is a low-grade "oil shale" with approximately 35 percent ash.

"Oil Shale," or Kerogen Shale. "Oil shales" are widely distributed throughout the world and throughout the geologic column.[41] They become of considerable economic interest from time to time—especially during periods when there is a fear of oil shortage—because large amounts of oil may be derived from them and may become a substitute for naturally occurring liquid petroleums.

The term "oil shale" is applied to several kinds of organic and bituminous shales, most of which consist of varying mixtures of organic matter with shale and clay. The organic matter is chiefly in the form of a mineraloid, called *kerogen*, which is of indefinite composition, insoluble in petroleum solvents, and of uncertain origin. For this reason these shales are better called *kerogen shales*. A small part of the oil recovered from kerogen shales occurs as oil in the shale; most of it is formed from the kerogen by heating. The distillation of the kerogen vapors begins at temperatures around 350°C (662°F); the kerogen in the shale is a *pyrobitumen*. Yields of up to 150 gallons of oil per short ton of shale have been encountered, but most commercial grades are on the order of 25–50 gallons per ton. Kerogen shales are neither petroleum nor coal, but rather an intermediate bitumen material with some of the properties of each. Geologists have long believed that kerogen is the primary source material of crude oil and natural gas. Modern analytical methods have shown, however, a widespread presence of small amounts of petroleum hydrocarbons; consequently, most geologists now look upon kerogen as merely a pyrobitumen with little or no genetic relation to petroleum.

Most oil shales contain free petroleum, which is recoverable by ordinary oil solvents, such as petroleum naphthas, ether, chloroform, and carbon tetrachloride. The petroleum in these shales usually occurs in fractures, fissures, bedding planes, and microscopic openings in the rock. Shales containing free oil, generally a few parts per million, may grade into fractured siltstone reservoir rocks, such as the Spraberry formation of western Texas (described on p. 121).

Kerogen, under a microscope, is seen to consist of masses of almost completely macerated organic debris, chiefly plant remains, algae, spores, spore cases, pollen, resins, waxes, and the like. In some of the richer layers it makes up 50 percent or more of the shale. Kerogen also contains yellow or reddish-yellow subspheroidal bodies and irregular streaks of reddish-yellow, dark-brown, and black material. This latter material may be the source of the oil obtained when the rock is distilled, but before distillation the oil is probably not any natural form of petroleum, for only small amounts can be extracted from the shale by ordinary solvents of petroleum.[42] As the kerogen content increases, the kerogen shales grade imperceptibly through torbanites and boghead coals into cannel coal, which might be termed "kerogen coal" to distinguish it from coals of the peat-to-anthracite series.[43] The frequent and often complete transitions from kerogen shales to cannel coal suggests a common mode of origin.[44]

* John M. Hunt, personal communication.

The kerogen of the average rich kerogen shale is extremely fine-grained and is intimately mixed with inorganic clays, sands, and carbonates. The layers rich in kerogen break with a smooth conchoidal fracture and have a dull or satiny luster. The material in them burns readily and resembles cannel coal. Kerogen varies in chemical composition, by weight percentage, within the following ranges:

Carbon	69–80
Hydrogen	7–11
Nitrogen	1.25–2.5
Sulfur	1–8
Oxygen	9–17

It differs chemically from crude oil in its high content of oxygen and nitrogen, both of which must be removed in some manner before kerogen can become petroleum.

Subsurface Occurrences

Underground, or subsurface, petroleum occurrences may be broadly divided according to their size as (1) minor showings of oil and gas, (2) oil and gas pools, fields, and provinces.

Minor Showings. Some natural gas and crude oil are found in most wells drilled in sedimentary rocks, especially within the known producing regions, where nearly every exploratory well finds some indication of gas or oil, even though it may be so slight that the well is abandoned as a dry hole. Two questions are raised by any minor showing in a well: (1) "Is this a large enough showing to indicate a commercial well?" (2) "Is it at the edge of a pool?" Naturally there is no problem in deciding that a well is commercial when it "blows in" and starts to produce oil and gas at the surface, or when the core is found by analysis to be well saturated with gas and oil and capable of giving them off. A core that bubbles oil and gas at its surface as it is removed from the well is called a "live" showing, in contrast to the dull, asphaltic staining of the "dead" showing.

Many well showings, however, are on the borderline between commercial and noncommercial, and how to distinguish between commercial and noncommercial showings is one of the problems confronting every petroleum geologist and engineer concerned with drilling exploratory wells.

Oil and gas showings may be observed directly and also, by means of tests for various physical properties during the drilling of a test well, indirectly. These properties are discussed under Logging in Chapter 3. In fact, field and laboratory techniques have been developed to such a point that well data can yield fairly reliable information as to a reservoir's gas, oil, and water content, its thickness, and its porosity and permeability—its capacity, in short, to produce oil and gas. Whether the evidence obtained from any particular well will justify testing the well further, or justify an attempt to produce oil from it, immediately becomes a matter for individual judgment.

Pools, Fields, and Provinces. Commercial petroleum deposits are classified as *pools, fields,* and *provinces.*[45] Terms such as "pool," "field," "province," and "subprovince" are useful in describing and locating the various oil and gas accumulations and occurrences. They combine both geographic and geologic factors that are commonly understood by the geologists, geophysicists, and engineers of the petroleum industry. But these terms, like many others in geology, grade into one another, which makes it difficult, at times, to define their exact meaning. Local usage generally prevails eventually, even though it may not reflect the best or most accurate scientific classification and terminology.

Pool. The simplest unit of commercial occurrence is the pool.* It is defined as the body of oil or gas or both occurring in a separate reservoir and under a single pressure system. A pool may be small, underlying only a few acres, or it may extend over many square miles. Its content may be entirely gas, or it may be entirely or mainly oil. The term *major pool* is arbitrarily taken to mean a pool that will ultimately produce 50 million barrels or more of oil.†

Field. When several pools are related to a single geologic feature, either structural or stratigraphic, the group of pools is termed a *field.* The individual pools comprised in a field may occur at various depths, one above another, or they may be distributed laterally throughout the geologic feature. Geologic features that are likely to form fields are salt plugs, anticlinally folded multiple sands, and complex combinations of faulting, folding, and stratigraphic variation. Many examples may be seen in the maps and sections in Chapters 6, 7, and 8, on traps. The amount of oil that a pool or a field will produce is not a distinguishing characteristic. In the East Texas pool and in many of the Middle East pools, for example, the oil is obtained from a single reservoir; yet the ultimate production of each of these pools will be greater than that of many fields or even provinces. Since a field may contain several closely related pools, the terms "pool" and "field" are often confused, especially during the early development stages.

* Each year maps, production figures, and geologic data for all oil and gas pools in the world are published in July by World Oil, Houston 1, Texas, and in December by the Oil and Gas Journal, Tulsa, Oklahoma. In addition, both journals publish a Review and Forecast issue in January or February of each year, giving a detailed statistical summary of exploration and production throughout the world during the previous year. The Petroleum Division of the American Institute of Mining and Metallurgical Engineers, New York 18, publishes an annual list of the pools in the world, with many production and geologic data for each pool.

† The size of an oil pool is generally given as the number of barrels of crude oil that may be produced and recovered at the surface of the ground. This is but a fraction of the crude oil in place underground, usually ranging from one-quarter to three-quarters of the total amount. The oil left behind is called the *nonrecoverable* oil; the oil produced, the *recoverable* oil. The total, original amount of oil in the pool underground is called the *in-place* oil.

Province. A petroleum province is a region in which a number of oil and gas pools and fields occur in a similar or related geologic environment. Since the term is loosely used to indicate the larger producing regions of the world, the boundaries of a so-called province are often indistinct. The Mid-Continent province of the south-central United States, for example, has definite regional characteristics of stratigraphy, structure, and oil and gas occurrence. Consequently, the term has a specific meaning for geologists and the petroleum industry. Subprovinces may occur within provinces; within the Mid-Continent province, for example, we find the Cherokee sand subprovince of southeastern Kansas and northeastern Oklahoma, the Anadarko Basin subprovince of western Oklahoma and northwestern Texas, the Reef subprovince of west-central Texas, the Panhandle subprovince of northwestern Texas, and many others.

The Importance of Minor Occurrences. Although an understanding of the geology of petroleum must be based on a study of the large, commercial deposits, the minor, or noncommercial, occurrences are frequently of great importance to the exploration geologist. The significance of the minor occurrences is twofold:

1. Minor occurrences often furnish clues that lead to the discovery of commercial deposits. Nearly every producing region (*petroleum province*) was discovered as the result of drilling prompted by the recognition of a nearby surface or subsurface showing of gas, oil, or asphalt. Visible surface evidences, or outcrops of petroleum, have often furnished the only reason for drilling an exploration well, especially in the early days of the industry.

Minor subsurface showings have also proved valuable exploration guides. As more drilling was done and as more well logs and records became available, the geologist's explorations were guided more and more by subsurface evidences and showings of petroleum in wells. Confronted by a minor subsurface showing of oil or gas, no matter how small, the petroleum geologist must always ask himself, "Is this showing located at the edge of a pool?" The evaluation of minor subsurface showings, in fact, constitutes a large part of the work of the modern petroleum geologist.

2. Minor occurrences indicate the presence of a "source rock." Although the origin of petroleum is not known, most geologists believe that it comes from some kind of source rock or source environment. They do not agree, however, on just what a source rock is. But when an area contains petroleum in any natural form, either at the surface or underground, and in either commercial or noncommercial quantities, it is evident that petroleum was formed in some way within that par-

similar area, or tributary to it, and that a source rock, whatever its character, is or has been present. As we shall see later, this evidence becomes important when the geologist is considering the oil and gas possibilities of a new and partially explored region. When the presence of a source rock is demonstrated only by a minor occurrence, the smallness of the occurrence may reflect the size of the trap, a lack of favorable local conditions of concentration, or a location at the edge of a pool. Even a minor accumulation, therefore, generally encourages the prospector to keep searching for larger traps and more favorable conditions.

GEOGRAPHIC LOCATION

Petroleum deposits are unevenly distributed throughout the world. Large areas in Asia, Australia, and Africa, for example, are nonproductive or only slightly productive, so far. This seeming scarcity may be due only to the lack of drilling and exploration in these areas. Other areas in each of these continents are productive and as the nonproductive areas contain large volumes of untested sediments, they too must be considered as potentially favorable for petroleum accumulation. Some large areas, on the other hand, have been found to be exceptionally rich in petroleum. The two outstanding areas, or regions, which have been termed the "oil axis" or the "oil poles" because they are on opposite sides of the earth,[46] are the Middle East region and the Gulf of Mexico–Caribbean region. The Gulf of Mexico–Caribbean pole includes the Gulf Coast province of the United States and the provinces in Mexico, Colombia, Venezuela, and Trinidad. The Middle East pole includes the provinces in Iran, Iraq, Kuwait, Saudi Arabia, and the Trans-Caucasus–Apsheron of the USSR. Two-thirds of the known reserves of the world have been found in these two regions, and future discoveries there give promise of being proportionately large. Lesser but important major productive regions in North America include the Mid-Continent province, the Appalachian province, the Illinois basin province, the Rocky Mountain province, California, the prairie provinces of Canada (especially Alberta), and the Tampico province of Mexico. In Europe the principal petroleum-bearing regions are the Polish province; the North German plains province; the Carpathian plains–Rumania–Ploesti province; the North Sea province; the Transylvanian basin province; and the Emba salt-dome province, the Perm basin province, the Fergana Valley, and the Ural-Volga province of the USSR. The Far East includes major producing areas in Ceram, Java, Borneo, Sumatra, New Guinea, Burma, and the Japanese islands. The reserves and current rates of production of each of the countries of the world are shown in Table 2-1. The growth of the world's crude-oil production may be seen in Figure 2-8.

Because of the varying political climates, the geographic situation of any petroleum prospect is extremely important in considering an exploration program.[47] In strongly nationalistic countries, such as the USSR, Mexico, Brazil,

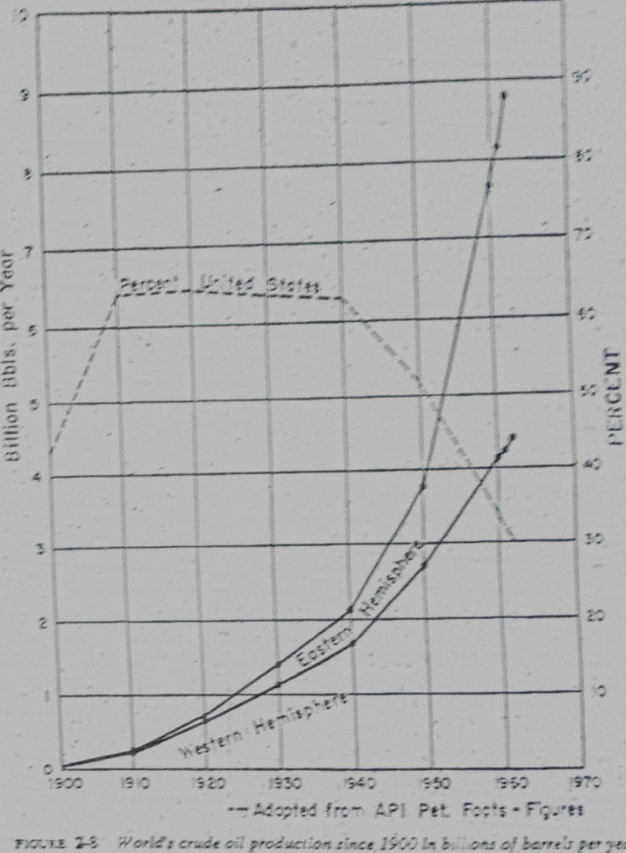

FIGURE 2-8 *World's crude oil production since 1900 in billions of barrels per year.*

and Argentina, the petroleum industry and exploration activities are closely controlled by the government itself or by government-owned companies. In less nationalistic countries, such as most European countries, Venezuela, Colombia, Peru, and the United States, the government owns some or all of the mineral rights but gives concessions or leases to companies or individuals to explore certain areas under rigid rules and regulations. This situation also

TABLE 2-1 Production and Reserves of Crude Oil

	Daily Production Est. 1963 1,000 bbl/day	Reserves Est. 1963 1,000,000 bbl
NORTH AMERICA		
Canada	717	5,675
United States	7,537	34,272
Mexico	320	2,500
Total	8,574	42,447
SOUTH AMERICA		
Argentina	262	2,300
Bolivia	9	200
Brazil	92	300
Chile	36	200
Colombia	167	900
Ecuador	7	25
Peru	5	380
Trinidad	134	500
Venezuela	3,246	17,000
Total	4,010	21,805
EUROPE		
Austria	49	240
France	50	235
Germany (West)	142	650
Italy-Sicily	34	300
Netherlands	42	250
United Kingdom	2+	1 1/2
Yugoslavia	30	250
Total	349	1,926
MIDDLE EAST		
Abu Dhabi	49	7,500
Bahrein	45	243
Iran	1,470	37,000
Iraq	1,120	25,500
Israel	3	25
Kuwait	1,930	63,500
Neutral Zone	306	10,000
Qatar	193	2,950
Saudi Arabia	1,618	60,000
Turkey	14	350
Total	6,748	207,068

called the *in-place* oil.

	Daily Production Est. 1963 1,000 bbl/day	Reserves Est. 1963 1,000,000 bbl
AFRICA		
Algeria	502	7,000
Angola	14	200
Congo	2	10
Egypt	113	1,500
Gabon	17	150
Libya	470	7,000
Morocco	3	15
Nigeria	71	500
Total	1,192	16,375
ASIA–PACIFIC		
Australia	—	50
Burma	11	35
Formosa	—	.3
India	33	750
Indonesia	452	10,000
Japan	16	50
Malaysia	67	600
New Guinea	3	10
Pakistan	8	25
Philippines	—	.5
Total	590	11,520.8
USSR–CHINA		
USSR and controlled areas	4,121	29,500
China (estimated)	125	300
Total	4,246	29,800

SUMMARY

	Daily Production Est. 1963 1,000 bbl/day	Reserves Est. 1963 1,000,000 bbl	Reserves (Percent)
North America	8,574	42,447	12.6
South America	4,010	21,805	7.0
Europe	349	1,926	0.6
Middle East	6,748	207,068	62.5
Africa	1,192	16,375	5.0
Asia–Pacific	590	11,521	3.5
USSR–China	4,246	29,800	9.0
World total	25,709	330,942	100+%

Source: From O. & G. Jour., December 30, 1963. Most trade journals give production and reserve figures annually in December or January issues. Nearest whole numbers used.

prevails in the prairie provinces of Canada—Alberta, Saskatchewan, and Manitoba—except that the provincial government rather than the Canadian government controls most of the mineral rights, and each province sets up its own rules and regulations on exploration. The extreme opposite of the nationalistic system prevails in most of the oil-producing states of the United States, where the underground minerals are owned by the surface or fee owner of the land. There the wildcatter deals directly with the individual landowner, and both have a share in the oil and gas production.

The most advanced exploration practices have been developed in areas where the individual owns the minerals and the land. In these areas the tracts of land are generally small, and exploration becomes extremely competitive. Strong competition gives rise to new ideas and new methods, which increase production and profit. In those countries, on the other hand, in which great tracts of land are held by the government and competition is nonexistent, there is less incentive to undertake expensive and time-consuming test drilling, which is the best source of information on the many ever-present geologic variables, and is what ultimately results in the discovery of petroleum. In such countries, therefore, fewer wells are drilled, more variables remain unknown, fewer prospects are located, and less oil is discovered. This condition is less obvious, of course, in such prolific regions as the Middle East and northern Venezuela, where great pools are discovered with a minimum of exploration drilling. Yet even in these regions the proportion of oil that will ultimately be discovered is probably much less than it would be if there were a more competitive incentive for drilling.

The occurrence of petroleum is not confined to the land areas of the world. Discoveries of large deposits along the coast of southern California, along the

FIGURE 2-9 *Map showing the areas of continental shelf in the world (black).* [*Redrawn from Petroleum Press Service, London (January 1951)*.]

shores of Louisiana and Texas in the Gulf of Mexico (see Figs. 6-33 and 6-35), in the North Sea, and in the Persian Gulf (see Fig. 2-2) point to the vast potential source of petroleum underlying the shallow waters that border the continents. These submerged lands, sloping down to a depth of 100 fathoms (600 feet) below sea level, are known as the *continental shelves*. Their distribution is shown in Figure 2-9. The area of the continental shelves, which are mostly under water less than 300 feet deep, has been estimated as 14 million square miles.[48] The geologic conditions prevailing on these continental shelves should be similar to those that prevail on the neighboring land areas. Exploration and development problems, however, will be quite different, because of the varying depths of water, soft bottoms, storms, uncertain ownership of the minerals, higher costs, and underwater pipe-line transportation.[49] Consequently, exploration will be much more expensive than on nearby land, and therefore slower and more cautious.

GEOLOGIC AGE OF RESERVOIR ROCK

The geologic age of the reservoir rock is a useful means of classifying a group of pools and fields or a province or subprovince, since it fits into a pre-existing classification.[50] It also serves in some cases as a descriptive classification, for the reservoir rocks of different ages frequently have different petroleum characteristics and productivity. The producing characteristics of the Permian reef limestone reservoirs of western Texas, for example, are different from those of the Ordovician limestones of the same area. The term "Miocene," applied to the Asmari limestone of the Middle East, quickly classifies the formation and brings to mind the differences between it and the Devonian limestone of the Ural-Volga region of the USSR. It is frequently desirable, therefore, to state the geologic age of a reservoir rock, for that is one means of identifying it and indicating something of its character. The age of the reservoir rock, however, does not necessarily indicate the time at which the petroleum accumulated in it. As will be pointed out later, the petroleum may have accumulated into a pool at any time subsequent to the original formation of the reservoir rock.

Two parallel classifications are used to identify (1) the time necessary to form the rock and (2) the rock units of the earth, termed geologic-time units and time-stratigraphic units, respectively. The time-stratigraphic units differ fundamentally from the descriptive classifications in that the rock boundaries are based on geologic time. That is, they are bounded by isochronous surfaces. The most commonly recognized ranks of geologic-time units and their corresponding time-stratigraphic units, in the order of descending magnitude, are:

GEOLOGIC-TIME UNITS	TIME-STRATIGRAPHIC UNITS
Era	
Period	System
Epoch	Series
Age	Stage

Thus we say "Devonian period" when considering the geologic time, but "Devonian system" when discussing the Devonian rocks. Similarly, we may speak of the Canadian series of the Ordovician system when referring to the rocks, but of the Canadian epoch of the Ordovician period when referring to the time.

The geologic time scale based on the geologic-time classification is given in Table 2-2. If the rocks of these units were being classified, the headings would be "system," "series," and "stage" instead of "period," "epoch," and "age." An estimate of the age in years is given for each of the major time boundaries.

Available evidence indicates that rocks of certain geologic ages are much richer in petroleum than those of other ages. Precambrian, Cambrian, and Triassic rocks, for example, have each produced less than 1 percent of the world's oil, and Pleistocene rocks have produced practically none. Rocks of Tertiary age, on the other hand, account for 58 percent, Cretaceous rocks for 18 percent, and Paleozoic rocks for 15 percent, of the estimated recoverable oil content of the earth. Details of the past production and the known reserves of oil, as related to geologic age, are shown in Table 2-3.

Only minor amounts of commercial oil have been found in rocks of definite Pleistocene age. The reason for this has been the subject of considerable speculation. The apparent lack of petroleum in the youngest rocks of the geologic column may be attributed, in whole or in part, to the general lack of drilling and exploration in these rocks. But it may be due in greater part to several other factors: the short time that the exposed sediments have had to form and to accumulate petroleum, the general lack of an impervious cover to create trap conditions, and the general nonmarine character of the sediments.

Petroleum is also rarely found in Precambrian rocks. Some commercial occurrences have been described,[51] but the general metamorphism and lack of permeability of most Precambrian rocks preclude them from being considered as potential reservoirs. Most of the Precambrian occurrences are found in fractures and secondary openings resulting from weathering and deformation. Significantly, these occurrences are usually associated with nearby petroleum-bearing younger sediments—which suggests a handy source of the petroleum. Oil and gas in the Precambrian rocks must be considered abnormal, and the upper surface of the Precambrian generally marks the lower limit of exploratory drilling.

The presence of organic carbon, however, has been demonstrated in rocks of Precambrian age. Rankama[52] found that the ratio of the carbon isotopes C^{12} and C^{13} in ten samples of Precambrian rocks from Finland, as measured by a

Turkey 6,748
Total

TABLE 2-2 The Geologic Time Scale

Era	North America: Period	North America: Epoch	North America: Age	Europe: Period	Europe: Epoch	Europe: Age	Age, millions of years (approx.)
Cenozoic	Quaternary	Recent Pleistocene		Neogene	Holocene Pleistocene		1
	Tertiary	Pliocene Miocene			Pliocene Miocene		25
		Oligocene Eocene Paleocene	Jacksonian Claibornian Wilcoxian Midwayan	Paleogene	Oligocene Eocene Paleocene		63
Mesozoic	Cretaceous	Upper	Montanan Coloradoan	Cretaceous	Upper	Senonian Turonian Cenomanian	
		Lower	Comanchean Coahuilian		Lower	Albian Aptian Barremian Neocomian	135
	Jurassic	Upper Middle Lower		Jurassic	Upper Middle Lower	Malm Dogger Lias	181
	Triassic	Upper Middle Lower		Triassic		Keuper Muschelkalk Bunter	
Paleozoic	Permian	Upper Middle Lower	Ochoan Guadalupian Leonardian Wolfcampian	Permian		Tartarian Kasanian Kungurian Artinskian Sakmarian	280
	Pennsylvanian	Upper Middle Lower	Virgilian Missourian Desmoinesian Morrowan	Carboniferous	Upper	Stephanian Westphalian Dinanthian	
	Mississippian	Upper Middle Lower	Chesterian Osagean Kinderhookian		Lower	Visean Tournasian	345
	Devonian	Upper	Chautauquan Senecan	Devonian	Upper	Famennian Frasnian	
		Middle	Erian Ulsterian		Middle	Givetian Eifelian	
		Lower	Oriskanian Helderbergian		Lower	Coblenzian Gedinnian	405
	Silurian	Upper Middle Lower	Cayugan Niagaran Alexandrian	Silurian	Gotlandian	Ludlovian Wenlockian Llandoverian	
	Ordovician	Upper Middle Lower	Cincinnatian Mohawkian Chazyan Canadian		Ordovician		500
	Cambrian	Upper Middle Lower	St. Croixan Albertan Waucoban	Cambrian	Upper Middle Lower		600±
Precambrian	Proterozoic Archeozoic						

TABLE 2-3 World Production and Reserves (December 31, 1947)

Geologic Age	Total Cumulative Production to Date		Total Reserves		Total Ultimate Production	
	Billion Bbl	%	Billion Bbl.	%	Billion Bbl	%
Tertiary	32.0	58.1	40.2	58.0	72.2	58.0
Cretaceous	10.8	19.6	11.7	17.0	22.5	18.3
Jurassic-Triassic	2.4	4.3	9.2	13.0	11.6	8.6
Paleozoic	9.9	18.0	8.3	12.0	18.2	15.0
Totals	55.1	100.0	69.4	100.0	124.5	100.0

Source: Adapted from G. C. Gester, World Oil, November 1948.

mass-spectroscopic assay, varied between 90.2 and 92.9. This ratio is nearly the same as that found in bituminous sediments, petroleum, and vegetable carbon material, including coal, where it ranges between 90.1 and 94.1. The ratio in inorganic material, such as graphite, diamond, calcite, and chalk, ranges between 87.9 and 90.2. Algae as old as Archean have been described by Gruner,[53] who also found evidence of Upper Huronian algae, bacilli, and iron bacteria.[54] He concluded that the iron and silica of the great Minnesota iron deposits were carried to the sea by rivers rich in organic matter. The disseminated bitumen found in the late Precambrian Nonesuch formation of northern Michigan[39] also suggests the possible presence of organic hydrocarbons in Precambrian time.

About the only regions of the earth in which there are virtually no prospects of future commercial petroleum discovery are those where Precambrian igneous rocks are exposed at the surface or are under the shallow cover of alluvium, glacial debris, or continental sands and gravels. The largest of these regions occur in the great shield areas of the earth—northeastern North America, Siberia, the Brazilian shield, much of central and southern Africa, and the Scandinavian countries.

As petroleum exploration expands over the world, it is becoming apparent that rocks of all geologic ages are potentially productive; the most important factor is the presence of connected porosity (*permeability*) in a manner that will trap and retain a pool of oil or gas. Lack of drilling and testing is probably the chief reason why geologists have a low opinion of rocks of some geologic ages, notably the Cambrian and the Triassic. Now that rocks of these ages have been found to be productive in various parts of the world, it is difficult to predict which rocks will eventually prove to be the most productive per unit of volume.

Nevertheless, rocks of Tertiary age continue to dominate in total productivity, and several reasons may be suggested to account for this:

1. The Tertiary contains thick sequences of unmetamorphosed marine sediments, characterized by lateral gradation, permeable reservoir rocks, adequate impervious cover, numerous traps (both local and regional), and an adequate supply of petroleum hydrocarbons.
2. Since the Tertiary system is late in the geologic time scale, only a minor part of it has been removed by erosion. Erosion attacks the topographically high rocks first and, as these normally are structurally high as well, destroys many traps filled with petroleum. A high percentage of pools, consequently, is preserved in Tertiary rocks.
3. Tertiary rocks consist largely of material eroded from pre-Tertiary anticlines, and this material may have included some of the oil that seeped out from the larger oil pools in the eroded rocks. Much of this eroded oil must, of course, have been evaporated, oxidized, destroyed by bacteria, or otherwise lost, but some of it, at least, may have been carried along with the sediments and redeposited with them.

Since the age classification of a reservoir rock offers a rough index, historically, of its potential productivity, it should be taken account of in any estimate of the chances of finding oil in a prospective region. Tertiary rocks, for example, are more likely, by and large, to contain oil pools than Triassic rocks are, because much more oil has been found in the Tertiary than in the Triassic. (It must not be forgotten, however, that some good pools have been found in Triassic rocks.) This, of course, is merely an indication of what the mathematical chances are of finding oil in a rock of a certain age at a specific place. Circumstances may occasionally justify hopes for oil in rocks belonging to systems that have yielded little oil in the past; whenever such hopes are fulfilled, there is renewed reason for believing that other areas, hitherto unproductive, have not, perhaps, been adequately tested.

CONCLUSION

Petroleum occurs in a variety of ways; some deposits are quite obvious at the surface of the earth, and others are buried at varying depths. While we are most concerned with the buried deposits, some of the large occurrences at the surface may become of first importance as our technology continues to develop. The smaller occurrences at the surface are chiefly important for the direct evidence they give of the presence of petroleum accumulations in the rocks of the area, and this is used to evaluate the prospects for deep-lying pools. If we are to include the lesser petroleum deposits, petroleum occurs in most of the countries of the earth and also in strata of all geologic ages. This is not to say that petroleum originated in each age, for the origin and the accumulation may be in separate episodes, as we shall see later. The chief interest of the petroleum geologist, however, is in knowing where petroleum is now; and one of the best places to look for new pools is the vicinity of known occurrences, irrespective of their size.

Selected General Readings

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Sir Boverton Redwood, *Petroleum*, 4th ed., 3 vols., Charles Griffin & Sons, London (1922). Vol. 1 contains a detailed historical review and a discussion of petroleum occurrences throughout the world as of 1922.

A. E. Dunstan (managing editor) and many contributors, *The Science of Petroleum*, 6 vols., Oxford University Press, London and New York (1938–1953). This is a standard work of reference. The titles of the six volumes give an indication of the scope of the subject matter:

I. Origin and Production of Crude Petroleum
II. Chemical and Physical Principles of the Refining of Mineral Oils
III. Refining
IV. Utilization, Detonation and Combustion, and Bituminous Materials
V. Crude Oils
VI. The World's Oil-Fields

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