INTRODUCTION
TO PART TWO

THE PETROLEUM RESERVOIR is that portion of the rock that contains the pool of petroleum. The location of every oil and gas pool may be said to be the result of a complex of interrelated geologic conditions. Each reservoir is unique in its details, but general relations may be seen that permit broad classifications of the major elements that control a reservoir.

The petroleum reservoir consists of four essential elements, each of widely variable development, each with many gradations, and each of varying importance in the location and size of the pool of petroleum. They are:

1. The *reservoir rock*, or containing material. The composition and texture of the reservoir rock, and its continuity or lack of continuity, are of prime interest in the geology of petroleum. The edges of the reservoir rock may coincide with the edges of the petroleum pool, as where a lens is filled with oil and gas; or the reservoir rock, though extending through a large region, may become a petroleum reservoir only at locally favorable areas.

2. The *pore space*, or *void space*, sometimes called the *reservoir space*, is expressed as a fraction or percentage of the total volume of the rock (for example, 0.23 or 23%) and is called its *porosity*. The effective pore space is that portion of the reservoir rock that is available for the migration, accumulation, and storage of petroleum. The measure of the ease with which fluids may move through the interconnected pores of the rock is called its *permeability*. Porosity and permeability are properties that depend on the presence of pore space. They are of special interest because they determine the capacity of the reservoir rock both to hold and to yield petroleum.

3. The *fluid content* consists of the water, oil, and gas that occupy the effective pore space within the reservoir rock. Under favorable conditions the oil and gas are concentrated into pools, but most of the reservoir pore space outside the pools contains only water or water with petroleum measurable

in parts per million. The petroleum, then, occurs within an aquifer—within a water environment. The fluids may be in a state of either static or dynamic equilibrium; that is, at rest or in motion. During their geologic life they undoubtedly have been in motion at some time or even continuously because of changes brought about by erosion, deposition, and deformation, and any other changes that upset the equilibria of the fluid pressure, temperature, density, volume, and chemical characteristics. These changes cause the fluids to move along gradients from areas of higher energy potential toward areas of lower energy potential. Although the movements of the fluids cannot be observed directly, the concentrations of oil and gas into pools and the widespread evidence of fluid pressure gradients is evidence of such movement.

4. The *reservoir trap*, or the *trap*, is the element that holds the oil and gas in place in a pool. Most geologists think of the trap as the shape of the reservoir rock element that permits a petroleum pool to accumulate underground. As we shall see later (pp. 340–343) the trap may actually be due in part to the fluid pressure gradients that exist in the reservoir fluids. As considered here, the trap is the shape of the reservoir rock together with its pore space.

Rock traps are formed from a wide variety of combinations of structural and stratigraphic features of the reservoir rocks. A trap generally consists of an impervious cover—the *roof rock*—overlying and sealing a porous and permeable rock that contains the oil and gas. The upper boundary, as viewed from below, is concave; the top is generally arched, but it may form an angle or peak. In practice the term "trap" usually means any combination of rock structure and of permeable and impermeable rocks that will keep oil and gas from escaping, either vertically or laterally, because of differences in pressure or in specific gravity. Some petroleum reservoirs completely fill the trap, so that if any additional oil or gas were added it would spill out around the lower edges. Other reservoirs occupy merely a part of the apparent capacity of the trap.

The lower boundary of the reservoir is, either wholly or partly, the plane of contact of the oil and gas with the underlying body of water upon which the pool rests. It is known as the *oil-water contact* or *oil-water table*.* The water fills all of the pore space of the reservoir rock below the oil-water contact, and that portion of the reservoir pore space that is not filled with oil and gas. If the water is at rest, the contact plane is level or approximately level. But, if the water is in motion, because of a hydrodynamic fluid potential gradient parallel to the bedding and across the pool, the lower boundary of the reservoir may be an inclined plane, and the pool is said to have an *inclined* or *tilted oil-water table*. Occasionally the tilt of the oil-water table is enough to flush the oil and

gas out of a potential trap, in which case the rock trap is not effective, and there is neither reservoir nor pool.

These broad generalizations about the nature of a petroleum reservoir will apply to most of the known pools of petroleum in the world. The next five chapters are concerned with details of these elements as they combine in varying proportions to trap a pool of petroleum.

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Kashif

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* The oil-water table should be distinguished from the *water table*, which has had a long priority of usage in the geology of ground water to denote the surface below which all pores are filled with water. The ground-water table is, in effect, the *air-water table*, in contrast to the oil-water table of the petroleum geologist.

CHAPTER 3

The Reservoir Rock

Reservoir rock: classification – nomenclature – fragmental – chemical – miscellaneous. Well logs. Marine and nonmarine reservoir rocks.

BROADLY SPEAKING, any rock that contains connected pores may become a reservoir rock. As a matter of fact, however, nearly all reservoirs are in unmetamorphosed sedimentary rocks, and most of them in sandstones, limestones, and dolomites. Shales, slates, and igneous rocks are known to be reservoir rocks under exceptional conditions, but these conditions are rare and anomalous. A reservoir rock may be limited to the area of the pool of petroleum, or it may persist, with uniform lithological and physical characteristics, far beyond the pool.

CLASSIFICATION

Since nearly all petroleum reservoir rocks are of sedimentary origin, any classification of reservoir rocks is essentially a classification of sedimentary rocks. A number of classifications have been proposed,[1] some descriptive and some genetic, but most of them designed chiefly for the use of the specialist in sedimentary petrography.

Classifications of petroleum reservoir rocks for practical use should be as simple and broad as possible, for the petroleum geologist must keep his terminology understandable to the operator, driller, and engineer, who supply many of his basic data and to whom he has to convey his own ideas. Many terms that are perfectly good scientific descriptions, and that have clear and exact meanings for geologists, do not find much favor in the petroleum industry—such terms, for example, as "arenaceous" for "sandy," "argillaceous" for "shaly," and "rudaceous" for "conglomeratic." We need terms that are generally understood yet sufficiently definite.

A simple, broad, primary classification of reservoir rocks, based largely on the origin of the rock, divides them into three groups: (1) fragmental (clastic); (2) chemical and biochemical (precipitated); (3) miscellaneous. This may oversimplify a complex and difficult problem, but such a rough classification is useful in the geology of petroleum and is readily understandable. It is the system used here. The chief difficulty in applying any rock classification is that there are many gradational types that are hard to classify. Reservoir rocks, like all sediments, commonly grade into one another. Complex reservoir rocks are named according to their dominant constituent or rock characteristic, with an adjective to indicate the minor constituent, as in "limy sand" and "sandy lime."

It is sometimes useful to class a reservoir rock as of marine or nonmarine origin. This genetic classification may be combined with a lithologic classification, as in the terms "marine limestone," "continental sandstone," and "nonmarine conglomerate."

It is often useful, also, to place the rock in the standard geologic time scale and thereby classify it according to its geologic age. This can be done by combining an age term with other terms; we may speak, for example, of a "Permian dolomite" or a "nonmarine Oligocene sandstone" or "Devonian grit."

Nomenclature of Reservoir Rocks

A reservoir rock formation from which petroleum is produced is commonly given a specific proper name. Such names frequently begin at a well or pool during the early development stages, and, once started, they are difficult to change. A name that some driller or operator may casually give to a producing formation is first used in conversations, then in newspapers and trade journals, then in engineering and geological reports, and finally in legal contracts and scientific journals. One reservoir formation may come in this way to be called by many different names; but, as development proceeds and the continuity of the formation throughout the area becomes obvious to everyone, some names are dropped, and one name may come into general use.

The commonest names for reservoir rocks are "pay," "pay sand," "oil sand," "gas sand," "sand," and "lime," which are generally used by drillers and field men without much thought given to whether they are accurate rock names. Examples of names based on a more or less petrologic character are "Simpson sand," "McCloskey oolite," and "Welch chert." But many names have other bases. The depth relative to other pay formations is shown in such names as "First sand," "Third stray," "D-3 pay," and "First 'Wilcox.' " The relation to another reservoir is shown by "Squaw sand" for a lens detached from the "Big Injun" sand. The geologic name of the formation is used where it can be identified underground, as in "Berea sand," "Madison limestone," "Oriskany sand," and "Asmara limestone." A common method of naming a producing formation in the United States is to give it the name of the owner of the land on which the discovery well was drilled. Examples of such names are "Hoover sand" and "Jones sand."[1]

Sometimes the name of the producing formation is taken from the name of the pool in which it was first found, as "Mirando sand" from "Mirando pool." Another method is to name the producing formation after some characteristic fossil or fossil assemblage, as in "Nodosaria sand" and "Heterostegina sands." Sometimes the sand is named after the individual responsible for its discovery, or after the operator or the geologist. Examples are the "Wilcox" sand of Oklahoma, named after Homer F. Wilcox, who drilled the discovery well; the Dibblee sand of the Cuyama Valley of California, named after Tom Dibblee, a geologist who had much to do with the discovery; the Slick sand of central Oklahoma, named after Tom Slick, a famous wildcatter; and the Vedder sand of the San Joaquin Valley, named after the geologist Dwight D. Vedder, who also owned the land on which the discovery well was drilled.

Let us now return to the main kinds of reservoir rocks. These, as was said earlier, are fragmental (clastic), chemical (and biochemical), and miscellaneous.

FRAGMENTAL RESERVOIR ROCKS

Fragmental reservoir rocks are aggregates of particles, fragments of minerals, or fragments of older rocks. They are also called *clastic* or *detrital* rocks because they consist of mineral and rock particles washed from areas that have been eroded. Their character varies with such factors as the nature of the eroded material, the distance it is transported, the climate, the steepness of the gradients, the transporting agency (whether streams, waves, currents, or winds), the biochemical conditions of the area of deposition, the distance from shore, the agencies by which the particles are sorted, and the depth of the water.

The constituent particles of fragmental reservoir rocks range in size from colloidal particles up to pebbles and boulders.* The Wentworth grade scale[2] is commonly used to identify the texture of various clastic sediments and is also used to describe the texture of reservoir rocks. It is made up of a continuous series of size grades of particles, the median size in each grade being half as great as the median size in the next coarser grade. It is shown in Table 3-1. A useful but somewhat different classification is that of the Bureau of Soils (U.S. Department of Agriculture), shown in Table 3-2. The size distribution of clastic sediments may also be indicated by giving the logarithms of the diameters of the particles, as in Figure 3-1. Most typical sediments

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* A chart correlating the various grain-size definitions of sedimentary materials, prepared by Page E. Truesdell and David J. Varnes, and published in 1950, may be obtained from the United States Geological Survey, Washington 25, D.C.

TABLE 3-1 Particle Size Classification (Wentworth)

Classification	Grade Limits (Diameters in mm)	Microns	Retained on Mesh
Boulder	Above 256 mm		
Large cobble	256–128		
Small cobble	128–64		
Pebble			
Very large pebble	64–32		
Large pebble	32–16		
Medium pebble	16–8		5
Small pebble	8–4		6
Granule	4–2		
Sand			12
Very coarse sand	2–1		20
Coarse sand	1–1/2		
Medium sand	1/2–1/4		40
Fine sand	1/4–1/8		70
Very find sand	1/8–1/16	125–62.5	140
Silt			
Coarse silt	1/16–1/32	62.5–31.2	270
Medium silt	1/32–1/64	31.2–15.6	
Fine silt	1/64–1/128	15.6–7.8	
Very fine silt	1/128–1/256	7.8–3.9	
Clay			
Coarse clay	1/256–1/512	3.9–1.95	
Medium clay	1/512–1/1,024	1.95–0.975	
Fine clay	1/1,024–1/2,048	0.975–0.487	
Very fine clay	1/2,048–1/4,096	0.487–0.243	

are mixtures of sand, silt, and clay in varying proportions. A graphic method of showing the relations is given in Figure 3-2.[3]

Grain-size analyses of fragmental rocks offer valuable clues to the potential character of the fluid content. For example, most reservoir rocks of many analyzed from southern Trinidad, BWI, were found to be *graywackes,** which vary in grain size between 0.250 and 0.0625 mm.[4] The finer-grained rocks generally contained water, and the coarser-grained rocks carried gas or tar.

The *matrix* of a clastic rock consists of particles, distinctly smaller than the average, that partially or entirely fill the interstices between the larger grains.[5] Such particles may consist of the same minerals as the larger grains, or of other minerals, or (as is usual) of both. The matrix differs from the *cementing*

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* Graywacke is a dark fragmental rock in which 20% or more of the constituent grains consist of other rock fragments.—Krynine.

TABLE 3-2 Particle Size Classification (U.S. Bureau of Soils)

Colloids	less than 0.001 mm	Fine sand	0.1 to 0.25 mm
Clay	0.001 to 0.005 mm	Medium sand	0.25 to 0.5 mm
Silt	0.005 to 0.05 mm	Coarse sand	0.5 to 1.0 mm
Very fine sand	0.05 to 0.1 mm	Fine gravel	1.0 to 2.0 mm

material, which is chiefly a chemical or biochemical deposit or clay that has infiltrated around both the larger particles and the matrix particles. The matrix and the cement may both be present in varying amounts, and either or both may be virtually absent from a sand. The relations of grains, matrix, and cement are graphically shown in Figure 3-3.

Among the fragmental rocks, sandstones, conglomerates, arkoses, graywackes, and siltstones are by far the most common reservoir rocks, and these sediments constitute nearly half of all reservoir rocks. Most of the fragmental reservoir rocks are siliceous, but many are fragmental carbonate rocks, such as oolites and coquinas, made up respectively of oöids and shell fragments that have been only slightly cemented or recrystallized. Shales are of only minor importance as reservoir rocks.

In some sandstones the grains are virtually all of quartz, with little or no cement. From this extreme there are all gradations, into sandstones that contain grains of other minerals in greater or lesser abundance, and into those that contain various kinds of matrix or cement, or both, in various quantities. Next to the pure-quartz type come sandstones that are highly siliceous but in which some of the grains consist of chert, fine-grained quartzite, and silicates, chiefly feldspar. Some sandy rocks contain feldspar, mica, and quartz in nearly the same proportion as the granites from which they are derived; these are the arkoses, or "granite washes."* Sandstones in which grains of dark, fine-grained igneous rocks are abundant are called graywackes. In all these rocks there is nearly always some matrix or cement, and usually both, between the larger grains. A reservoir rock may vary locally in texture and composition; either vertically because of bedding or laterally because of facies changes, or it may be essentially uniform throughout an entire region.

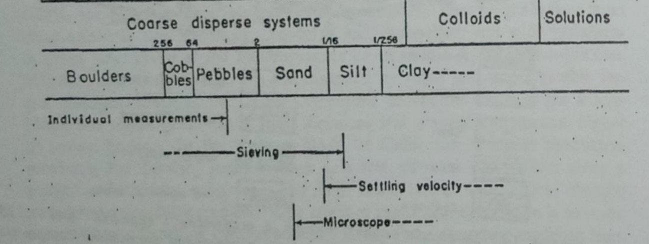

FIGURE 3-1 *Range of particle size in clastic sediments. [Redrawn from Krumbein and Sloss,* Stratigraphy and Sedimentation, *W. H. Freeman and Company (1963), p. 97, Fig. 4-2.]*

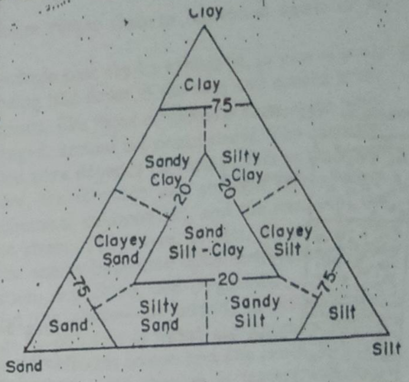

FIGURE 3-2

System used to classify sediments in terms of their content of sand, silt, and clay. [From Shepard, Jour. Sed. Petrol., Vol. 24 (1954), p. 157, Fig. 7.]

Sandstones vary from clean, well-washed quartz sandstone through all combinations produced by additions of silts and clays ("shaly," "muddy," "trashy," and "dirty" sandstones), of carbonates (limy, calcareous, and dolomitic sandstones), of silica (siliceous or quartzitic sands, volcanic ash), and of feldspars, micas, and rock fragments (arkose, granite wash, graywacke). The additions may come as primary constituents, as matrix, or as cement, and the variations in composition may be local or regionally uniform. Solution, redeposition, and recrystallization may become important in rocks containing soluble materials, especially in sandstones containing much calcite or dolomite, or rocks consisting chiefly of those minerals, as some of them do.

Clean, uniform, and continuous quartz sandstones may have been formed by the erosion of other sandstones, or they may consist of material that has been transported a long distance from the source, or been subjected to strong wave and current action during deposition, all of which make for thorough sorting and uniform texture. Where the sandstones contain abundant feldspars, micas, and other silicates, or clay or chert, they were probably derived from igneous and metamorphic rocks, from shales that had not been deeply weath-

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* An arkose is "a sandstone containing 25 or more percent of feldspar derived from the disintegration of acid igneous rock of granitoid texture" (Bull. 98, Committee on Sedimentation, Nat. Research Council, 1935).

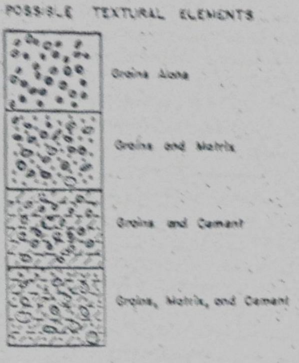

FIGURE 3-3

Possible textural elements of clastic rocks consisting of grains, cement, and matrix in varying proportions. [Redrawn from Krynine, Jour. Geol., Vol. 56 (March 1948), p. 139, Fig. 5.]

ered, or from shales and clays; the material may have been transported only short distances, or may have been deposited under such variable conditions as might prevail in deltas and flood plains. Clean, uniform sands, when continuous over wide areas, are sometimes called *blanket sands;* those containing much clay, shale, or other impurities are called *muddy* or *dirty sands* or, if they also contain fragments of other rocks, graywackes. A diagram showing the variable nature of a graywacke is shown in Figure 3-4. Graywacke reservoir rocks are found in the Bradford region of Pennsylvania and in the Gulf Coast region of Texas and Louisiana.[6]

There are more pools producing from sandstone reservoirs than from any other single rock type. The total production and ultimate reserves, however, are probably less than from carbonate reservoirs. Thousands of different pools might be mentioned, but only a few general references, where sandstone reservoir rocks are described, are listed below.

Tertiary sandstones contain most of the oil in California[7] and in the Gulf Coast region of Texas and Louisiana[8] and also many of the pools in Venezuela.[9]

Cretaceous sands are highly productive in the Burgan field of Kuwait, probably the largest single field in the world. The productive Burgan sands make up 800 feet of a total of 1,100 feet of section, and the pool is trapped in a large anticlinal fold.[10] Pools in the Baku, Maikop, and Grozny districts of the Caucasus region of the USSR—comprising some of the richest producing areas of the world—are nearly all in sandstone reservoirs.[11] The oil of the East Texas pool, the largest single pool in the United States, is found in the Woodbine sand (basal Upper Cretaceous). A structural map and a section of the East Texas pool are shown in Figure 8-3, page 351, and the location [illegible] shown in Figure 10-17, page 467.

Sandstones of Paleozoic age are the reservoir rocks in a great many pools through the eastern Mid-Continent and Rocky Mountain regions of the United States. The Devonian sands of the Bradford pool in Pennsylvania, because of the highly successful secondary recovery operations carried out there,[12] have probably been the most intensively studied reservoir rock in the world. A map of the region is shown in Figure 7-17, page 300. The "Wilcox" and Simpson sands (Middle Ordovician) of the Mid-Continent states of Kansas and Oklahoma are among the cleanest of the sandstone reservoir rocks and contain a large percentage of round, frosted sand grains. Most of the oil in the Oklahoma City pool is produced from Simpson sands. A map of the field and surrounding region is shown in Figure 14-6, page 643, and Figure 14-7, page 644.

Conglomerates, grits, and coarse sediments, chiefly composed of silica and silicates, are common reservoir rocks. Most are lenticular bodies, enclosed in finer-grained and more uniform sediments of similar composition—for example, the quartzose grits and conglomerates interbedded with the quartz sands and graywackes of the Devonian of northwestern Pennsylvania.[13] In the coarse and poorly cemented lenses of conglomerate (with pebbles up to two inches in diameter) and of grit, in the Haynesville field of Louisiana,[14] there are, because of the high permeability of these materials, many exceptionally

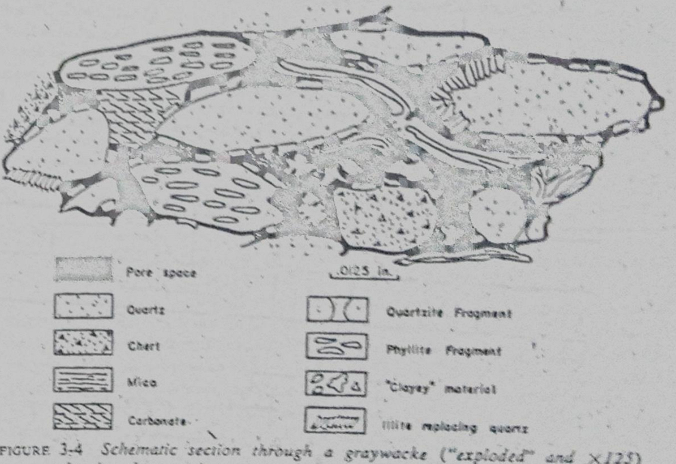

FIGURE 3-4 *Schematic section through a graywacke ("exploded" and ×125) showing the complex nature of the porosity and the mineral composition of a "dirty" sand. [Redrawn from Krynine, Jour. Geol., Vol. 56 (March 1948), p. 153, Fig. 13.]*

productive wells. The Big Injun sand (Lower Mississippian) of eastern Ohio and western West Virginia is a highly productive, massive, coarse, conglomeratic, and cross-bedded sandstone; where the same formation is thinner and consists of a more normal fine-grained sandstone, it produces only water.[15]

Basal Pennsylvanian conglomerates, composed of rounded pebbles and boulders of Mississippian chert, constitute the reservoir rock in a number of pools in Kansas;[16] and a basal conglomerate consisting mainly of schist rubble is the reservoir rock in the Playa del Rey field of California.[17] In a large area of the northern end of the East Texas field, a part of the pay zone is a conglomerate and gravel bed in the Woodbine producing formation (Upper Cretaceous), which consists mainly of normal sands, volcanic ash, and shales.[18]

Most sandstone reservoir rocks vary in texture and mineral composition, both vertically and laterally. For example, sandstone lenses and irregular patches of sand, interbedded with shale in siltstone, may thicken and thin, become shaly or clean, with no apparent reason. These sand lenses may be small and completely filled with oil or gas, and thus constitute both the reservoir rock and the trap, or they may extend continuously over larger areas and contain several pools at places where favorable trap conditions exist. When a reservoir formation that varies laterally in permeability becomes impermeable, it restrains or prevents the escape of any contained petroleum. Lateral variation in texture and mineral composition is consequently a favorable characteristic of a reservoir rock, for such a rock may trap petroleum whether deformed or not.

Many examples of rapid lateral variation in reservoir sands might be cited. Tertiary formations, especially, are characterized by numerous unpredictable lateral changes in almost every place where they are productive. Sands come and go, and are commonly cross-bedded; their areal patterns, too, are irregular: they may be long and sinuous or broad and irregular. Nearly all of the Tertiary reservoir rocks of Rumania and of the Caucasus-Apsheron province of the USSR, for example, are characterized by rapid lateral change, gradations from clean sands to silts and shales, scouring and channeling, and wide variations in grain size. Many of the Pennsylvanian sands of the Appalachian–Illinois–Mid-Continent region also are characterized by rapid and unpredictable lateral changes. Many of the Upper Cretaceous productive sands of the Rocky Mountain region grade out in short distances and are replaced at some higher or lower horizon. In the Ventura Basin of California, a highly productive province, the Tertiary rocks thicken in a few miles to 40,000 feet along a trough or belt fifty miles long, and their rapid lateral and vertical changes have been intensively studied.[19] One effect of rapid lateral variation is to make correlations difficult or even impossible. Even where abundant evidence from samples, electric logs, pressure and production data, and fossil control is available, many wells must be drilled to establish the reservoir relations with any degree of confidence. And even when this has been done, the correlations may apply only to indefinite zones rather than to individual sands or to formations.

The variable deposits of the geologic past can be explained, in part at least, by a study of deposits that are being laid down in the seas and oceans at the present time.[20] The ancient sediments, like those of modern times, were probably zoned or concentrically arranged, around the ocean deeps. The character of the deposits in each depositional zone depends on such factors as the depth of water, the distance from shore, the direction and strength of the ocean currents, the biological and biochemical environment, and the nature of the material being brought down the rivers. They were, in fact, the sum of the source materials, together with the energy impressed upon them through such forces as weathering, transportation, deposition, and diagenesis.

The depositional zone nearest the shore—the strand, or littoral zone, known as the *neritic* environment (0–600 feet of water)—is characterized by wide variations in type of deposit; it contains coarse and fine sands, silts, coquinas, clays, and shales, all subject to rapid changes in texture and composition, both vertically and laterally. Chemical and biochemical activity is there at its highest so that shale and sand deposits are likely to be interbedded with fragmental rocks composed of organic remains. Most sandstone reservoir rocks were probably formed in this variable near-shore zone. Alternate advances and retreats of the sea caused sand formations to merge and various sediments to become re-sorted and redistributed, and continental conditions therefore interfinger with marine conditions. The Tertiary reservoir rocks bordering the Caribbean and the Gulf of Mexico, those occurring throughout the East Indies, and those of the USSR in the Middle East are especially characterized by conditions such as these.

Distributary channels of deltas and tidal-flat channels may fill with sand and clastic material and thus form branching channel sand deposits enclosed in shale. These may coalesce to form patchy sands or even sand formations that are continuous over considerable areas.[21] A sand deposit in which deltaic distributary channels have been recognized is shown in Figure 3-5, a map of the Booch producing sand (Pennsylvanian) in the Hawkins field, Oklahoma. The contours show the distribution of the high-potential wells in the pool (isopotential map), and, because of the wells' higher initial yields, they are also interpreted as giving a rough measure of the areas of high permeability. (See also Fig. 13-5, p. 597.)

Seaward the variable near-shore zone grades into or interfingers with the zone of muds, where conditions are more stable—the *bathyal environment* (600–6,000 feet of water); and this zone, in turn, grades into the pelagic zone of calcareous and siliceous oozes and red clays occupying the deep basins of the oceans—the *abyssal environment* (6,000–30,000 feet of water). The boundaries between the different zones are sharp in places, but more often they are gradational.

Layers of coarse, unsorted clastic deposits alternating with uniform fine-

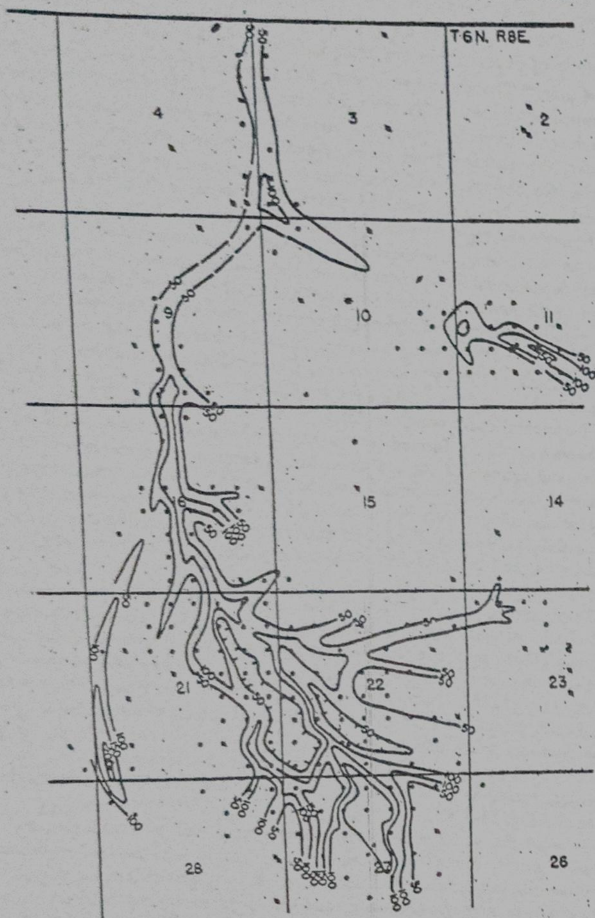

FIGURE 3-5 *Isopotential map showing the initial daily rate of oil production in the Hawkins field, Hughes County, Oklahoma. The contour interval is 50 barrels per day. Compare with Figure 13-5, an isopach map of the producing sand of the area.* [*By the courtesy of Daniel A. Busch.*]

grained deposits, and some graded bedding, are thought to be caused by high-density, or turbidity, currents that carry near-shore deposits far out into the ocean. They are called *turbidites*. Near-shore slumping or submarine landslides might start the movement, and the coarse material would then pass over older deposits without disturbing them, finally coming to rest in a sedimentary environment that was totally different from, and out of harmony with, the original sedimentary environment from which they began their journey.[22] That these phenomena may occur on a large scale was seen in the earthquake of 1929 off the Grand Banks of the Atlantic Ocean,[23] when material slumped off the continental slope traveled over 450 miles beyond the continental shelf and into the abyssal ocean plain, where many telegraph cables were cut. Kuenen[24] estimated the mass of moving mud to have contained 100 cubic kilometers of material, to have been about 270 meters (875 feet) thick and 350 kilometers (217 miles) wide, and to have moved over 1,000 miles from its point of origin. Coarse-grained, poorly sorted deposits, therefore, may not always indicate a near-shore environment.

Most cherts are composed of chalcedony (quartz fibers separated by films of opal), with minor impurities, such as quartz grains. Typical pure cherts have a massive, dense texture, a dull waxy luster, and conchoidal fracture. Terms such as *cherty shale, cherty limestone, cherty dolomite,* and *cherty sandstone* are applied to rocks that contain combinations of chert with other materials. All of these may form reservoir rocks. Some of them grade into rocks called *novaculite* or *porcellanite*, in which silica is the predominant material. Fragmental cherts, either produced by weathering in place, as a residual material, or transported and redeposited as clastic detritus, form reservoir rocks in some places. It is sometimes difficult to distinguish beds of a detrital chert, especially when recemented with silica, from the underlying, chemically precipitated chert, or from chert that has formed in place by weathering away of the original surrounding material. The relations are shown in Figure 3-6. A detrital chert, called "chat," forms a reservoir rock in the basal Pennsylvanian Sooy conglomerate[25] of Kansas; it is composed of boulders and smaller fragments of chert embedded in a red shale. This formation rests unconformably on the underlying Mississippian "lime," which is largely chert in its upper part and from which the chat presumably was derived. The upper part of the Mississippian limestone is weathered, fractured, and cherty, and closely resembles the overlying reworked material, especially when it is drilled up as well cuttings.

Varying amounts of feldspars are present in many sandstone reservoir rocks. As the feldspar content increases, the rock grades into an arkose, or granite wash. As with a chert reservoir rock, it is sometimes difficult to distinguish arkose from the underlying granite from which it is derived. (See Fig. 3-7.) Fresh granite may be distinguished from weathered granite by measuring the magnetic susceptibility of the well cuttings. The susceptibility of unweathered granite is generally several hundred to several thousand times

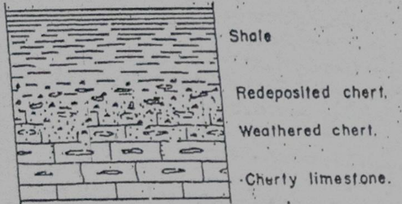

FIGURE 3-6 *Sketch showing nature of gradational contact between chert, weathered chert, and redeposited chert, any one or all of which may be the reservoir rock.*

that of weathered granite.[26] The residual, or remnant, magnetism of unweathered granite is likewise so much greater than that of weathered granite that the distinction between the two may be readily made. A striking example of arkose, or granite-wash, production is seen in the Panhandle fields of Texas. The lower part, of granite wash, contains an increasing amount of fresh granite boulders and fragments, until in places it becomes almost indistinguishable from the granite bedrock.[27] The reservoir rock is of Pennsylvanian-Permian age, and the granite basement is probably Precambrian. A section across the Texas Panhandle area is shown in Figure 3-8.

An arkosic reservoir rock, with its fresh or slightly weathered feldspars, suggests near-by mountain-building, block-faulting, or other strong deformation. It shows that basement granites have been exposed, and wedged-out sediments, including arkosic material, are likely to be found around the exposed cores. The arkosic material probably eroded rapidly, was not carried far, and was buried without extensive weathering. Of even greater importance is the fact that near-by diastrophism implies large-scale unconformities, overlaps, folding, and faulting—conditions that may form traps capable of holding large oil and gas pools. The Pennsylvanian and Permian arkoses of southern and western Oklahoma and the Panhandle of Texas are good examples. Arkoses that are free from clays and weathered debris, and that consist of permeable mixtures of quartz, feldspars, and mica, are especially good reservoir rocks. Such arkoses are said to have been "cleaned up" or "winnowed." Many arkoses, however, are so dirty with weathered fragments as to be impermeable.

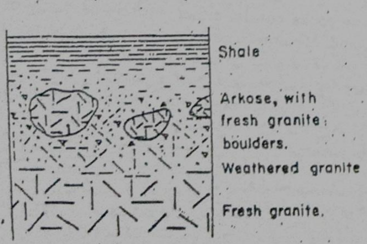

FIGURE 3-7 *Sketch showing the nature of the gradational contact between fresh granite, weathered granite, and reworked granite debris (arkose). Drilling into fresh granite boulders in the arkose may cause the premature abandonment of the well if they are thought to represent basement rocks.*

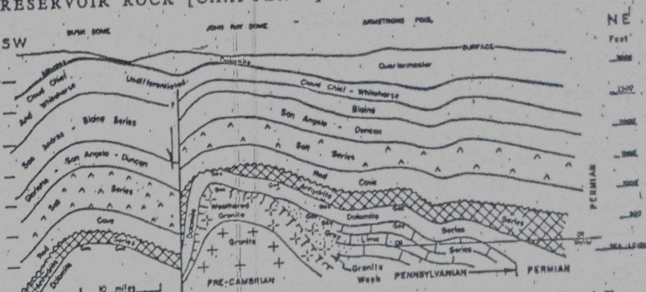

FIGURE 3-8 *Section across the buried Amarillo Arch in the Panhandle of Texas. The debris from a narrow mountain uplift several hundred miles long was deposited in the Pennsylvanian and early Permian seas along the north flank of the range. The granite core was finally buried, and the area was again folded, faulted, and eroded, with the final result that an interconnected zone of porosity, extending a distance of 125 miles, formed a trap in which over 31 trillion cubic feet of natural gas and over one billion barrels of recoverable oil accumulated. The reservoir rocks include granite wash, arkose, sand, limestone, and dolomite. An oil-water contact of nearly uniform level and a subnormal reservoir pressure characterize the field. This is but one of a number of oil and gas pools associated with the buried Wichita Mountains and Amarillo Arch.* [Redrawn from Cotner and Crum, Geology of Natural Gas, *Amer. Assoc. Petrol. Geol.* (1935), p. 388, Fig. 2.]

Clay

Clay is of great importance in the geology of petroleum. It is present in most reservoir rocks in varying amounts, it enters into many problems connected with the porosity and permeability of the reservoir, it influences greatly the production of oil and gas in many pools, and it is especially important in the water-injection programs of secondary recovery. Most of the compaction and compressibility of sediments is due to the squeezing of water out of clay minerals; the high mineral content of oil-field waters is probably largely due to the freeing of salts adsorbed onto the clay minerals; and clays form the bulk of most drilling muds. Because of the many later references to clays, it is worthwhile to give some attention to them now. The reader is referred to the many articles on the role of clays and clay minerals in the geology of petroleum and the production of oil and gas.[28]

The clay minerals* present in nearly all reservoir rocks may be dispersed through the sandy rocks as individual grains, may fill interstices between sand grains and thus serve as a cement, or may be in thin laminae interbedded with layers of sand or carbonate. Since many of the clay minerals are platy, small amounts may be plastered over the surface of sand grains in thin films, and thus a very small amount of clay may have a surprisingly large effect on such phenomena as adhesion, adsorption, interfacial tensions, capillarity, and wettability. Some clay minerals are oleophyllic and some are hydrophyllic.

Clay minerals, when present, have much the same effect on chemical reservoir rocks as on fragmental reservoir rocks. Clay minerals occur in carbonate rocks as partings at the bedding planes, and elsewhere as thin shale laminae.[29] Such partings may consist of flocculated colloidal clay material carried to the areas of deposition, for such material will generally be flocculated (collected into small soft lumps or flakes) when it comes in contact with sea water. Styolites are common in limestones, and the material along their boundaries may consist of colloidal clay. The major Paleozoic limestone and dolomite formations of Illinois, for example, all contain clay, which is chiefly in the form of illite, but partly in that of kaolinite. The illite is considered to be authigenic (to have originated in place), since illite weathers readily into other constituents and is unstable under weathering conditions. The kaolinite is probably detrital.

Analyses of clays by x-rays and optical and electron microscopes show them to consist of aggregates of extremely minute crystalline particles of clay minerals. These clay minerals tend to be platy or lath-shaped. The smallest particles consist of a single crystal; the larger particles may contain connected groups of crystals. Individual crystals are composed of what are known as building units, which in turn make up the atomic lattices or sheets of the molecule, and are nearly identical.

Two reasons largely account for the importance of clay in reservoir studies: (1) the smallness of the individual crystal particles, many being less than two microns (8×10^{-5} inch) in diameter and some of the most active being less than 8×10^{-6} inch; (2) the chemical and physical activity of the clay minerals, especially of the montmorillonite group. The small size means a proportionately large surface area, which means a larger than normal effect on the surface phenomena of the reservoir. The chemical activity is chiefly due to the presence of loosely attached exchangeable cations, or the power of *ion-exchange*—that is, an exchange of ions of a solution for those of a solid when they are in contact. The character of both the solution and the solid undergoes a change as a result of the base-exchange. Most of the ion-exchange properties of the sediments, including reservoir rocks, are due to their clay content.[31] The physical activity of the clay minerals is due to their

lattice, or accordion-like molecular structure, which permits the entry of water between the lattices, thereby greatly changing their volume. This permits fluid continuity, even across thick, fine-grained shales, and allows the shales to act as semipermeable membranes. Substantially large fluid pressure gradients may thus form across the shale bedding planes because of osmotic phenomena coupled with differences in the salinity of waters above and below the shale layers.

Clays that have developed fissility are called shales. Shales are not ordinarily considered reservoir rocks, but in a few places they have produced considerable oil and gas, probably contained in fractures and in films along bedding planes. The Florence pool in Colorado[32] occurs in shale of Cretaceous age, and there are gas pools in the Cherokee (Pennsylvanian) shales of eastern Kansas[33] and the Chattanooga (Mississippian-Devonian) shales of eastern Kentucky.[34] Oil production has also been found in the shales above the main pay sands in the Salt Creek and Tow Creek fields of Wyoming and in the shales above the pay formation at Rangeley, Colorado.* Production has been obtained from the shales as well as from the limestones in the shale-limestone section west of Lake Maracaibo in Venezuela.* Large quantities of oil have also been produced in the Santa Maria field, California,[35] where the reservoirs are chiefly siliceous shales, from the sandy siliceous shales of the Stevens zone in the Elk Hills field, California;[36] from the shales, siltstones, and sandy shales of the Spraberry field, Texas.[37]

Volcanic ash is sometimes an important though generally a minor constituent of producing sands. Its effect, like that of shales and the clay minerals, is to reduce permeability. The Woodbine sand of the East Texas field contains large amounts of volcanic ash:[18] the content of shale and volcanic ash together in the producing formation ranges from 30 percent in the northern part of the pool to 70 percent in parts of the southern end of the pool. The interbedding and lateral variations of the sand, shale, and volcanic ash make detailed correlations from one well to the next extremely difficult.

Cementation of Fragmental Reservoir Rocks

Some sandstone reservoir rocks consist either entirely or partly of loose, uncemented sand grains, and at times loose sand grains come up in large quantities along with the oil. The sand grains in most reservoir sandstones, however, are held together by various kinds of cementing material, chiefly carbonates, silica, or clays. Some of the cementing material may be primary, having been deposited along with the sand grains, and then precipitated chemically around and between them by a diagenetic† process. Sandstones

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* The chief clay minerals are kaolinite [$(OH)_8Al_4Si_4O_{10}$], illite [$(OH)_4K_y(Al_4 \cdot Fe_4 \cdot Mg_4 \cdot Mg_6)(Si_{8-y} \cdot Al_y)O_{20}$] ($y = 1$–$5$), and montmorillonite [$(OH)_4Al_4Si_8O_{20}$]. [From R. E. Grim, in *Recent Marine Sediments* (reference note 28), pp. 475–477.]

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* Herman Davies in a personal communication.

† "Diagenesis denotes the processes leading to the lithification of a rock, or the conversion of newly deposited sediments into an indurated rock." (F. J. Pettijohn, *op cit.* in reference note 1, p. 476.)

cemented by primary silica are called *orthoquartzites*, as distinguished from metaquartzites, or quartzite of metamorphic origin. Other cementing material may be secondary, having been precipitated from water solutions that entered the formation after it was deposited (see also pp. 128–130).

As the proportion of cement increases, a clastic rock may be gradually changed to a chemical rock. By increase in amount of dolomitic cementing material, for example, a sandstone—within a few miles, or, even more abruptly, within a few hundred feet—may change from a clean quartz sand to a dolomitic sand, and finally to a sandy dolomite. By increase in the silica cement, a friable sand may grade into a quartzitic sand and finally into a sandy quartzite.

Different lateral aspects of equivalent sedimentary rocks that are essentially contemporaneous give rise to what are termed *facies*. These may be either local or regional in extent. Different lithologic aspects are called *lithofacies*, and different biologic aspects are called *biofacies*. Lithofacies maps are discussed on pages 600–602. The most significant lithofacies changes in reservoir rocks occur where a permeable rock grades into a less permeable rock. Such changes are of great importance in relation to the production of oil and gas from pools, the localization of traps, and the regional movement of fluids through the reservoir rock.

Clastic limestones and dolomites—the former are sometimes called calcarenites—consist of grains of calcite and dolomite that have been transported and redeposited just as grains of quartz are. The carbonate grains may consist largely of shells, shell fragments, coquina, and oolites. Rocks thus formed are always more or less recemented with recrystallized calcite and, when the process has gone far, may resemble a chemically deposited limestone or dolomite. Cross bedding may often be seen, however, on the weathered surfaces of clastic carbonate rocks, and the outlines of clastic grains may occasionally be recognized under the microscope. Carbonate rocks formed in this way are likely to be porous and therefore to be good reservoir rocks, and they probably form a larger proportion of the carbonate reservoir rocks than is generally realized.

CHEMICAL RESERVOIR ROCKS

Chemical reservoir rocks are those that are predominantly composed of chemical or biochemical precipitates. They consist of mineral matter that was precipitated at the place where the rocks first formed, and not transported as clastic grains, although clastic grains may have originated as chemically precipitated rock before being formed into grains. The dominant chemical reservoir rocks are carbonate sediments, mostly limestones and dolomites.[38] The relations may be graphically shown, as in Figure 3-9.

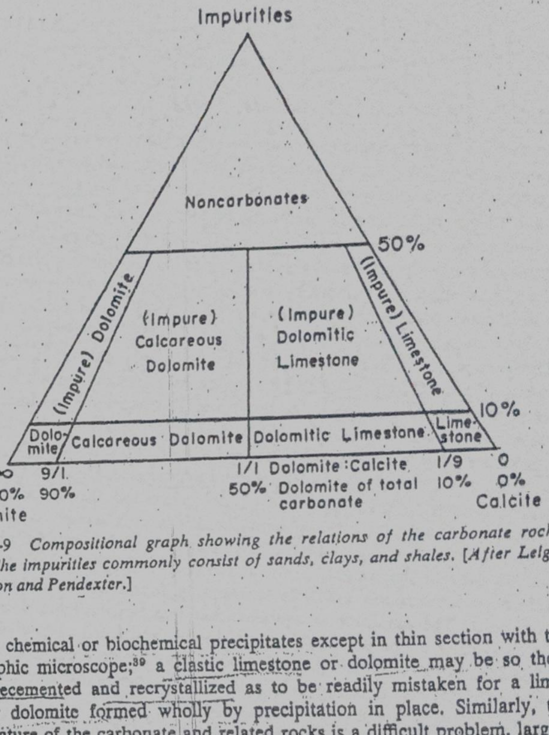

FIGURE 3-9 *Compositional graph showing the relations of the carbonate rocks. The impurities commonly consist of sands, clays, and shales. [After Leighton and Pendexter.]*

It is hard to tell how large a proportion of the carbonate reservoir rocks are truly chemical or biochemical precipitates except in thin section with the petrographic microscope;[39] a clastic limestone or dolomite may be so thoroughly recemented and recrystallized as to be readily mistaken for a limestone or dolomite formed wholly by precipitation in place. Similarly, the nomenclature of the carbonate and related rocks is a difficult problem, largely because of the gradational boundaries of the various types of carbonates. Usage is generally in the direction of compositional and structural characteristics rather than genetic.[40] Recementation and recrystallization may be considered as chemical processes in place, and a rock formed by these processes would still properly be classified as a chemical reservoir rock if it appeared as predominantly chemical in origin even if a part of it was originally clastic grains. Some chemically precipitated rocks consist wholly, or almost wholly, of silica, in the form of chert, novaculite, or orthoquartzite, but in some of these there has been a certain amount of secondary cementation with silica. Such rocks are quite common, but, compared with the carbonate rocks, they contain few reservoirs. In some reservoir rocks carbonate and siliceous precipitates may be mixed to form cherty or siliceous limestones and dolomites.

Chemically Precipitated Carbonate Rocks

The chemically precipitated carbonate reservoir rocks are usually crystalline limestones and dolomites, but sometimes consist of marl and chalk. When they consist predominantly of carbonate, their textures are generally crystalline, and they may be coarse-, medium-, or fine-grained. The relatively pure carbonate rocks may grade into more or less siliceous rocks. The siliceous components may be precipitated chert, siliceous fossils, clastic grains of quartz or chert, or shaly material more or less intimately mixed with the carbonate. As the siliceous components increase, we get such things as sandy, cherty, or shaly limestones and dolomites.

The carbonates in these rocks are almost wholly calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$], and the carbonate in a particular rock is likely to be almost wholly of one species or the other. The two are often intermingled, however, in various ways. Dolomitic and calcitic rocks may be interbedded, or dolomite may form irregular bodies that stand out in slight relief on weathered surfaces and give them a patchy appearance. Or the rock may have reached a certain uniform degree of dolomitization throughout, owing to replacement of calcium by magnesium, and it is then classed as a magnesian or dolomitic limestone—or in the final stage, as a dolomite in which more than 50 percent, by weight, is the mineral dolomite.[38, 41] Both patchy and uniform dolomitization are most commonly found in the older Paleozoic formations. The extensive recrystallization that accompanies dolomitization destroys many of the primary textures, fossils, and fossil casts of the original limestone. Limestones and dolomites are approximately equal in importance as reservoir rocks, differing chiefly in their permeability; the dolomites are generally more permeable.

Some carbonate rocks have closely spaced bedding planes, which may grade into massive, virtually unbedded rocks. It is rather difficult to identify bedding planes in well cuttings, but modern continuous-coring devices obtain nearly complete core recoveries, and these generally show the bedding. The massive, nonbedded rocks are usually found in organic reef deposits, and a lack of bedding is sometimes indicative of such an origin.

Limestone and dolomite reservoir rocks of biochemical origin have been identified in all terranes from Pliocene to Cambrian. Rocks of biochemical origin contain significant quantities of biologic remains along with the normal chemically precipitated material. Biochemical processes have been especially active in the organic reefs (bioherms, biostromes), which have become increasingly important as reservoir rocks; but lime-secreting organisms have contributed variable amounts of material to most carbonate rocks. (See pp. 315–316.) The main biochemical agents in forming limestones are the algae, bacteria, foraminifera, corals, bryozoa, brachiopods, and mollusks. Of these the algae are the most important as rock-builders; they have, in fact, been considered by some geologists as among the chief agents of lime secretion and deposition.[42] The carbonate secreted by living organisms is mostly $CaCO_3$, in the form of either aragonite or calcite. Magnesium carbonate as well as calcite is secreted by some organisms, but is thought to be of minor importance. Some rocks of biochemical origin were formed where the organisms lived and died, the shell fragments having later been consolidated more or less in place; others consist of shells and skeletal remains that were transported by winds and currents and concentrated into clastic deposits. The change from shell fragments to a rock results partly from the growth of algae, such as *Lithothamnium*, which filled in and solidified the loose fragments, and partly from cementation, packing, and precipitation of carbonate. After the material has been solidified and buried, the entire mass may be again dolomitized and recrystallized, leaving little or no trace of the parent material. The resultant rock is therefore a variable combination of fragmental shell debris and biochemical and chemical precipitates, localized by an environment that permitted the lime-secreting organisms to flourish and to be deposited and then modified after burial by various processes of solution and redeposition.

By increase in the proportion of insoluble clastic materials, limestones and dolomites may grade imperceptibly into shaly limestones and sandy dolomites, and from them into calcareous shales and dolomitic sandstones. The clastic sand grains, chert fragments, and other insoluble materials were probably enclosed in the carbonate material while it was being deposited. Some fragments are set in the carbonate rock like plums in a pudding, without touching one another; others make up thin laminae, lenses, or patches.

Limestones and dolomites are by far the most important of the chemical reservoir rocks; in fact, they contain nearly half of the world's petroleum reserves. The shift in importance from predominantly sandstone reservoirs to carbonate reservoirs has been a development of recent years, brought about by the discovery and development of the great oil fields of the Middle East, western Texas, and western Canada, in much of which oil is produced from limestone and dolomite reservoir rocks. Some of the more important oil-bearing carbonate formations of the world are briefly described below.

The greatest concentration of large oil fields in the world is in the Middle East, chiefly in Iran, Iraq, Kuwait, and Saudi Arabia. (See Fig. 2-2, p. 18.) Much of the production is obtained from limestone reservoir rocks, which are folded into large anticlines. Several pools contain 5 billion barrels or more each. The reservoir rock in Saudi Arabia is chiefly of the Arab zone (Upper Jurassic), consisting of several limestone and dolomite formations, each 20–200 feet thick, separated by anhydrite layers.[43] The chief producing limestone formation of Iran is the Asmari limestone (Oligocene and Miocene), 700–1,500 feet thick, which underlies a large area and has reef characteristics in places.

Prolific oil production is obtained from several pools in thick, dense, Cretaceous limestones in western Venezuela.[44] (See Fig. 14-12.) The oil is found on large, faulted anticlines; a section across one of them, the Mara field, is shown in Figure 6-31 on page 263. Cretaceous limestones also form the reservoir rock in most of the great Mexican oil fields. Many of these discoveries were made as a result of drilling near surface seepages. A structural map showing one such pool in Mexico, the Poza Rica pool, is shown in Figure 8-10, page 356.

Devonian limestone and dolomite reef deposits form the reservoir rocks of most of the large oil pools of western Canada. (See also pp. 327–329 and Fig. 7-48.) Niagaran (Silurian) limestone reef rocks form the reservoir rock of many pools, mostly small, in Ontario, Indiana, Kentucky, and Illinois.[45] (See Fig. 7-35, p. 319.)

The Kansas City–Lansing group (Pennsylvanian) of limestones, with interbedded thin shale members, ranges from 200 to 400 feet in thickness and constitutes one of the important producing sections over a large area in central Kansas.[46] The pools are localized by variations in the porosity and permeability of the limestones, together with local structural anomalies. The Kansas City–Lansing group truncates and rests unconformably on all the older formations down to the Cambro-Ordovician Arbuckle limestone on the broad, low Central Kansas Uplift.

The Arbuckle-Ellenburger group (Cambro-Ordovician)[47] contains many important pools in the Mid-Continent region of Kansas, Oklahoma, and Texas. It is also the oldest, geologically, among the major producing formations of the world. It consists predominantly of dolomite and limestone, with minor amounts of chert, sand, and shale, and ranges in thickness from about 1,000 feet near El Paso to more than 7,000 feet in the Arbuckle Mountains of Oklahoma. The limestone and dolomite members are alternately thin- and thick-bedded, and their texture varies from coarsely granular to microgranular. Many siliceous and sandy layers occur locally in the upper part in northeastern Oklahoma, where the formation is called the "siliceous lime." Most of the pools in the Arbuckle-Ellenburger rocks are trapped in folds and faulted anticlines. As the oil production declines, they produce water freely, suggesting a more than local permeability. The oil is generally of high quality, and many wells have an initial producing capacity of several thousand barrels a day.

The region of western Texas and southeastern New Mexico, also known as the Permian Basin, is one of the richest producing areas in North America. (See Fig. 3-10.) It accounts for about 17 percent of the production of the United States.[48] With the exception of the sand-trend pools (AA′ in Fig. 3-10), practically all of the pools of the region are in Paleozoic limestone and dolomite reservoir rocks. In fact, all ages from Permian to Cambro-Ordovician are productive in a wide variety of traps. (See also Fig. 6-16, p. 25.)

Siliceous Reservoir Rocks

FIGURE 3-10 *Map showing the oil pools in western Texas and southeastern New Mexico.*

Chemically precipitated silica is common as an accessory constituent of many carbonate reservoir rocks,[49] and in places it becomes the predominant or sole constituent of the rock. The siliceous material is most often found as chert,[50] in the form of nodules, interbedded layers, and minute fragments embedded in the limestone or dolomite. It is difficult in wells to distinguish precipitated primary chert from eroded chert fragments later cemented by silica.

The Monterey formation (Miocene), a reservoir rock in California, consists of several kinds of siliceous rocks, classified as porcellanite, porcellanous shale, cherty shale, and chert. Bramlette[51] believes they were formed by alteration of diatomaceous rocks through solution of the delicate opaline diatom shells and reprecipitation of the silica as a cementing material. Other theories suggest that the Monterey cherts were derived from a silica gel material. Their permeability is due to cracks and fractures. (See also pp. 119–121.)

The reservoir rock of some pools in western Texas consists of a dense, hard, brittle, white-to-buff, opaque, and very fine-grained sedimentary siliceous rock that closely resembles the Caballos novaculite (Devonian), which crops out in the nearby Marathon region. As with most dense and brittle rocks, the porosity is thought to be caused by fractures, which have been enlarged in places into solution cavities and cavernous voids.[52]

MISCELLANEOUS RESERVOIR ROCKS

Miscellaneous reservoir rocks include the igneous and metamorphic rocks, mixtures of both frequently forming the "basement complexes." [53] These are interesting geologically but rarely important commercially. Where commercial production is obtained from igneous and metamorphic rocks, the reservoir is generally located up-dip from overlapping or buttressing sediments, from which the petroleum is thought to have migrated. Bedding and unconformity planes in sediments appear to have provided permeable paths for migration, and the reservoir space is usually in fractures in the brittle basement rocks.

The igneous rocks of the great volcanic fields of the earth present some rather special exploration problems, and their effect on the accumulation of oil and gas has not been fully evaluated. These volcanic fields include the Columbia Plateau of Washington and Oregon; the volcanic deposits extending up the Rocky Mountains, through British Columbia, and into Alaska; the Mexico-Arizona volcanic field; the Deccan traps of India; the volcanic deposits of the Pacific; the Paraná basin of South America; and the region comprising Iceland, North Ireland, and the Hebrides. The presence of artesian ground water in many igneous flows, and in weathered intrusive igneous rocks, shows permeability through interconnected pore spaces, which suggests that oil and gas might be found in both extrusive and intrusive igneous rocks under special conditions. The presence of lava flows does not preclude the presence of petroleum in the underlying and interbedded sediments. These sediments may well produce like any other sediment, once the hard, brittle, overlying volcanic series has been penetrated.

Igneous and metamorphic rocks from which commercial oil production has been obtained include the basalt flows, pyroclastics, and intrusive basalt and andesite dikes, known as the "Conejo volcanics" (Miocene), in the Conejo oil field of Ventura County,[54] the granitic and metamorphic basement complex (Jurassic?) in the Edison field of San Joaquin Valley,[55] and the Franciscan (Cretaceous-Jurassic?) or older schist in the El Segundo field south of Los Angeles,[56] all in California. Production is obtained from fifty or more widely scattered wells in the fractured, Precambrian, quartzite hills or knobs of central Kansas[57] and from the granite basement cores of the Mara and La Paz oil fields of western Venezuela. (See p. 125.) Commercial gas has been found in the Rattlesnake Hills field of Washington from one or two porous zones of basalt, overlain by lake clays intercalated between the igneous flows.[58] "Serpentines" are the reservoir rocks in a number of pools of central Texas.[59] (See pp. 305–306.)

The main producing formation of the Tupungato field, in Mendoza Province, Argentina, was formerly thought to be a sandstone but is now known to consist of a series of hard, volcanic tuffs, interbedded with shales through a thickness of 300 meters. The porosity is high, but the permeability is low; there is much pore space, but the pores are not well interconnected. The formation has been intensely fractured, and cores show that the openings that have not been filled with calcite or zeolites contain oil.[60]

WELL LOGS

Well logs are used to identify and correlate underground rocks and to determine the porosity of potential reservoir rocks and the nature of the fluids they contain. Since the petroleum geologist's chief area of interest is below the surface, we will refer to well logs and well data in every chapter that follows; it is desirable, therefore, that we now discuss briefly some of the different kinds of well logs, with their uses and limitations. A complete discussion of all of them is beyond the scope of this book, but the reader is referred to the many articles about and descriptions of various logging methods, a few of which are listed in the reference notes.[61]

The common types of well logging are (1) drillers' logs; (2) sample logs: (a) lithologic, and (b) paleontologic; (3) electric logs; (4) radiation logs: (a) gamma ray, and (b) neutron; (5) drilling-time logs; (6) core and mud analyses; (7) caliper logs; (8) temperature logs; (9) sonic logs; (10) dipmeters. A brief discussion of the manner in which they are made and of their uses follows.

Drillers' Logs. Most logs of wells drilled before 1930 were prepared by the drillers of the wells; the geologist has no other well data than drillers' logs in many large areas, and is forced to use and interpret them as best he can. Cable-tool drillers' logs proved relatively satisfactory, for the driller is fairly sure of the depth to the tops of the formations, of the character of the rocks, and of their content of oil, gas, or water at all times. He determines sand by the wear on his bit, and shale and limestone by the jerk on the drilling line. He knows how much water is placed in the hole and how much comes out; therefore he knows the water content of every permeable formation. In fact, the rate at which water is produced is a good measure of the permeability of a rock. He also knows immediately when small amounts of gas and oil show in the well. He describes the rocks as hard, soft, or sticky, and as red, blue, black, gray, or brown. His measurements are accurately checked each time a string of casing is run in the hole, and generally a steel-line measurement is taken at the top of the producing formation. Errors in depth, which are common, are absorbed in the last steel-line measurement. If such errors are large, they throw the log off, and a geologist generally distributes the correction up to the next check point above.

Drillers' logs of rotary-drilled holes are not nearly as dependable or usable as the cable-tool drillers' logs; in fact, rotary drillers seldom make logs any more. Rotary drillers are able to tell change in color from the cuttings that come up in the mud, and they are able to tell hard and soft formations. Since most of the early drilling, at least, was in the areas of soft formations, many of their shales and clays were described as "gumbo" or "sticky clay." "Rock" is any hard formation; "boulders" are alternating hard and soft formations; "heaving sand" is sand that is forced into the hole from the bottom; "quick sand" is sand that caves and settles rapidly; "water sand" is sand in which the cuttings come clean and bright, or sand that dilutes the drilling mud.

Sample Logs. These logs, prepared by geologists and based on an examination of the well cuttings and cores, began to be made in the period from 1920 to 1925, and have increased steadily ever since. Sample logs are made now of practically every wildcat well and of a great many production wells. The sample logs may be made from the surface of the ground to the bottom of the hole, or they may be prepared for only particularly important portions of the section.

Samples of drill cuttings from cable-tool holes are collected each time the hole is bailed, or approximately every five or ten feet, and are dried and placed in cloth sacks. As they come from the well they are generally clean and require no additional treatment. The drill cuttings are examined under a binocular microscope, at powers ranging between 12 and 24 times, and the log is then compiled, either at the well or in a laboratory.

Samples from rotary holes, called "ditch samples," are obtained from the return mud stream that comes from the well and carries the cuttings from the bottom of the hole to the surface. Well samples are collected at every five, ten, or twenty feet of drilling, and they represent the material drilled during this penetration. They are washed in water until the fine, colloidal mud material is removed, then dried and placed in sacks. The samples, together with rock fragments and cores, are examined under a binocular microscope either at the well or at the laboratory, and a lithologic log of the well is prepared. The geologist at the well is called a *well-site geologist*, and while he is there he is said to be *sitting on the well*.

Lithologic logs prepared from well cuttings, either from cable-tool holes or from rotary holes, are logs that describe the physical properties of each formation penetrated by the well. Characteristics commonly noted for each sample include the character of the material, whether it is limestone, dolomite, sandstone, silt, clay, conglomerate, anhydrite, salt, or chert; its color, its luster, whether greasy, dull, or shiny; its content of fossils; its porosity, if any, and whether the porosity is intergranular, vuggy, pin-point, or characterized by primary or secondary crystallinity; evidences of oil, gas, or solid bitumen; evidence of fracturing or slickensiding; whether the sand is loose and friable or cemented together; and the character of the cement; whether the material breaks across individual grains or whether the cuttings are clusters of sand grains cemented together; and any other physical property that may help to identify it. The time it takes for the mud stream to carry the samples from the bottom of the hole to the surface* must be considered in

making a lithologic log from well cuttings from a rotary hole; it may take several hours for the fragments to rise from the bottom of deep holes to the surface.

Paleontologic logs, as the name implies, are logs in which the emphasis is on stratigraphy and fossil content, the fossils being chiefly the smaller forms such as foraminifera and fusilinids.

Electric Logs. An electric log is a continuous record of the electrical properties of the formations and the fluids penetrated in a well. (See Fig. 3-11.) The measurements are made in the uncased portion of the well, and are commonly made of formations in holes drilled with rotary tools while they are still full of drilling mud. Electric logs are made by passing electrodes, encased in an insulated tube called a *sonde*, down the well hole. A generator at the surface sends electric energy down

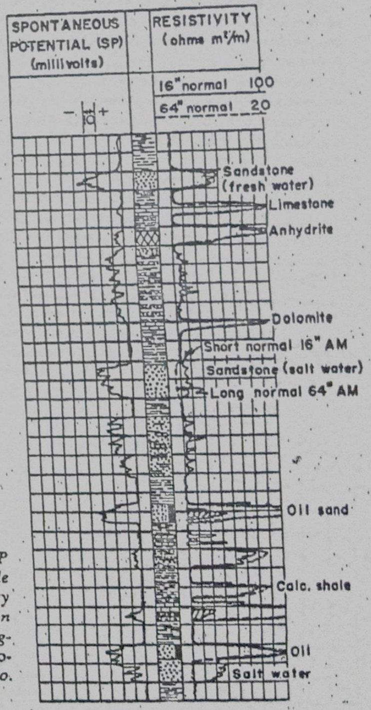

FIGURE 3-11

Typical electric log, showing the SP curve at the left, a lithologic sample log in the center, and the resistivity log at the right. [*Redrawn from Stratton and Ford, "Electric Logging," in L. W. LeRoy (ed.), Subsurface Geologic Methods, Colo. Sch. Mines, p. 365, Fig. 152.*]

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* This time may be roughly estimated by calculating the number of strokes the mud pumps require to displace the mud in the hole and dividing by the strokes per minute. A better way is to chart the time for each well, using as control points the time it takes for a sudden change in rock material to reach the surface after recording a sudden change in drilling time rate. Rice or corn may also be added to the mud stream at the top of the drill pipe; the time it takes to make the round trip to the shale shaker is approximately twice the lag time. A rough measure is that for seven- or eight-inch holes: it will take cuttings about ten minutes per 1,000 feet to return from the bottom. [See Hiestand and Nichols, Bull. Amer. Assoc. Petrol. Geol., Vol. 23 (1939), p. 1824, and John M. Hills, *loc. cit.* in reference note 60, pp. 348–349.]

one cable and out into the rock through its electrode, while other electrodes attached to other cables pick up the charge and carry it to the surface, where it is recorded on sensitized paper synchronized with the movement of the electrode along the hole. The spacing of the receiving electrodes along the sonde varies for different areas and different stratigraphic conditions.[62]

Electric logs[63] were first studied in the small French oil fields of Pechelbronn. The method was applied in Venezuela in 1929 and later in the USSR, where it rapidly became widely used. It was introduced into Romania in 1931 and since then has spread to all oil-producing regions of the world. The present standard practice is to make an electric log of every rotary well drilled. Some wells are logged at different stages in the drilling, and others are logged after the completion of the hole, depending on the immediate needs of the situation. Logging is commonly done by commercial service companies, which charge a fee for the work done.

Electric logs have become a most effective geologic tool; they are so widely understood by petroleum geologists and engineers that cross sections and correlation charts are commonly prepared with only data from electric logs to indicate the stratigraphy and structure. (See Fig. 3-12.) An electric log does not displace a lithologic log or a paleontologic log, but it furnishes added information on the rocks penetrated by the drill and their fluid content, and each kind of log supplements the data of the other. Electric logs are used chiefly for correlation purposes and for identifying and measuring porosity and reservoir fluids; their interpretation has progressed from an art to a technique to a science in the short time since they were first used.

Two values of the electrical properties of the formations and fluids drilled are determined, the electric potential and the resistivity.

Electric Potential. The log of the electric potential of a formation in a well hole is variously called the *spontaneous potential log*, the *self-potential log*, or the *S.P. log*. The S.P. log is commonly placed on the left track of the printed record. The measurement is expressed in millivolts, starting from a base line near the center of the record. Formations of higher electric potentials are shown as curves extending varying distances to the left on the millivolt scale. The electromotive forces which generate the S.P. current that is measured in the S.P. log are thought to be the result of two types of phenomena, electrofiltration and electro-osmosis. The potentials produced by both of these phenomena are cumulative, for the most part, and consequently accentuate the amplitude of the S.P. curve. (See Fig. 3-11.)

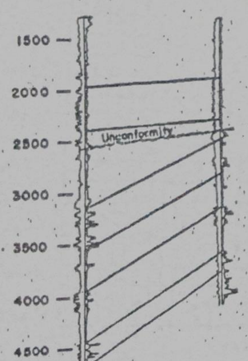

FIGURE 3-12

Section showing how electric logs may be used in correlating formations between wells. [Redrawn from Stratton and Hamilton, in L. W. LeRoy (ed.), Subsurface Geologic Methods, *Colo. Sch. of Mines (1951), p. 638, Fig. 336.]*

The electromotive forces caused by electrofiltration have been considered electrokinetic in nature. They are directly proportional to the pressure and electrical resistivity of the liquid, and are inversely proportional to its viscosity. The liquid is the water of the mud in the drill hole, which is an electrolyte, and is caused to flow through a pervious solid dialectric into the porous formations of the wall rock. The hydrostatic pressure of the mud is generally greater than the pressure in the permeable formations; therefore, some water filters through the mud cake into the permeable bed. The electromotive forces appear primarily where the pressure difference is the maximum, or opposite the permeable formation. The flow from the well into the formation produces a negative potential, whereas flow from the formation into the well produces a positive potential; the greater the rate of flow, the greater the potential difference. Where the pressure in the formation is the same as the pressure in the well, no current due to electrofiltration will be observed, and the recording will be zero even opposite a porous formation. Flow from the well into the formation is commonly found in practice, and the electric potential is therefore commonly negative.

The second cause of spontaneous electric potential, concentration cell potential, is thought to be electrochemical. When two electrolytes come in contact with each other, an electromotive force is generated. The electrolytes in a drill hole are the drilling mud of the well and the salt water of the formation. Below varying depths, most formation waters contain salts in variable amounts. The solution-concentration difference between the drilling mud and the formation water generates the electromotive force. If the concentration of salts, or the salinity of the water, in the formation is higher than that of the drilling mud, the electric current enters the formation, and a negative reading with respect to shale is observed opposite the porous zone. This is the common relationship found in practice. If the salinity of the mud is equal to that of the water in the formation, no potential due to electro-osmosis is generated; if the mud is more saline than the formation water, as after drilling through a salt layer, the current enters the hole, and a positive reading with respect to shale is observed opposite the porous zone.

A lesser cause of the electric potential of the formations may be the selective polar adsorption of charged ions by certain minerals within the formations, particularly clays.

The self-potential diagram of an electrical survey of a well is the resultant of the combined phenomena of electrofiltration, electro-osmosis, and ion adsorption. The common practice is to maintain the hydrostatic pressure of the fluid in the well higher than in the formation; since the concentration of salts in the formation waters is commonly higher than the concentration or salinity of the drilling-mud water, the two causes are cumulative, and the resultant is the algebraic sum of the two components. Exceptions occur occasionally, as when drilling through a salt section, where the mud becomes salty and of higher concentration than the formation water. The self-potential effect may then become positive. Shallow fresh-water sands may give a similar or negligible self-potential measurement. It may also happen that a high-pressure formation, ready to blow out from a deep sand, will give little or no self-potential effect, for the fluid from the sand enters the hole and reduces the electrofiltration effect. Occasionally, in shallow depths where there is an artesian sand, water flows into the well, and the electrofiltration effect may be reversed.

Resistivity. Rocks differ greatly in their electric conductivity and, conversely, their resistivity. The differences depend chiefly on the fluids, such as water, oil, and gas, that are in the porous and permeable portions of the rocks, for dry rocks are nonconductors. The fluids contained within the rocks are: (1) adsorbed or connate water that is present in the minute interstitial spaces of shales and clays and is incapable of circulation because the enclosing formation is not permeable; (2) fresh or salt water, that is present in permeable formations, and is free to circulate (dense rocks, such as granites, quartzites, gneisses, marbles, gypsum, anhydrite, rock salt, and coal, have so little interstitial space, and therefore so little moisture, that they are very poor conductors of electricity; they have a high resistivity); (3) oil and gas that occupy varying portions of the porosity.

Water containing one or more soluble salts is an electrolyte and electrically conductive. Oil and gas are not conductive, are highly resistive. Electric resistivity, as logged, is dependent on the relative saturations by gas, oil, and water, the concentration of the salt in the water, and the character of the rock, especially its porosity. (See also pp. 157–160 for a discussion of the formation factor.) In former years several separate resistivity logs were recorded simultaneously for different electrode spacings. These logs generally included a "short-normal" type with an electrode spacing of 10 to 20 inches, a "long-normal" type with an electrode spacing of 20 inches to 7 feet, and a "lateral" type with an electrode spacing of 15 to 20 feet. The wider spacing sent the current deeper into the surrounding formation so that it would pass through rock uncontaminated by drilling-mud filtrates. The induction log (see below) has been introduced in recent years and has supplanted the long-normal and lateral resistivity logs. The standard electric log today is an "induction-electric" log that consists of (1) a plotted log of conductivity and its reciprocal, resistivity, as determined by the induction measurement; (2) a short-normal resistivity log (16-inch electrode spacing); and (3) a self-potential (S. P.) log.

Induction Logging. Induction logs measure the resistivity (or its reciprocal, conductivity) of the strata traversed by energizing them with an induction current sent out from coils set in a sonde; no contact is made with the drilling mud. The alternating magnetic fields generated by the coils create a secondary magnetic field in a receiver coil located in the sonde. If the transmitter current is maintained at constant strength, the variations in the receiver coil are proportional to the conductivity of the strata.[64] Induction logs can be run in any uncased hole regardless of the type of fluid medium that is present. This log was first developed to measure the conductivity in wells drilled with oil-base mud where conventional resistivity determinations could not be obtained. Induction logging has since demonstrated its general superiority over conventional deep-penetration resistivity logs in holes drilled with water-base mud. Induction logs have a greater radius of investigation than either long-normal or lateral resistivity logs and, because of their superior focusing capability, determine more accurately the resistivity of thin beds.

MicroLog. Where the resistivity of the formations is much greater than that

of the drilling mud (as in limestone formations, for example), the S.P. currents are short-circuited along the mud cake that forms on the well wall, and the details of the permeability are missed. The MicroLog[65] is a resistivity log in which the electrodes are spaced only one or two inches from each other and are encased in an insulated pad that is pressed against the walls of the hole. The close spacing permits the current to enter the rocks for only a short distance. Microresistivities are high opposite impermeable beds because the resistivity of such beds is approximately fifty times that of mud, and the mud cake is thin; microresistivities are low opposite permeable beds because the mud enters the formation to varying depths and forms a thick mud cake. (See Fig. 3-13.) Two different electrode spacings commonly are run. In porous and permeable zones the resistivity determined by the wide spacing is commonly higher than that determined by the short spacing. This difference is due to the relative depth of investigation of the two spacings. The short spacing measures principally the resistivity of the drilling mud; the wide spacing measures to a greater degree the resistivity of the rock formations and their fluids. Opposite permeable zones the wide spacing records the presence of high-resistivity drilling-mud filtrate that has invaded the zone; opposite zones of low permeability the resistivity measurement for the same wide spacing is commonly low because of the presence of low-resistivity formational waters with their high ion content.

Laterolog. Where the drilling mud becomes very salty, its high conductivity overshadows the effects of the conductivity of the formations. In a method known as Laterolog[66] the drilling mud is first highly charged with electricity, and this permits focusing the current laterally so that it enters the rocks. (See Fig. 3-14.)

Microlaterolog is a combination that uses the focusing feature of the Laterolog and the close spacing of the MicroLog and in certain areas gives more detailed information on the character of the reservoir than any other electric log.

Radiation Logs. Radiation logging is of two general types, one that measures the natural radioactivity of the formations, known as the *gamma-ray log*, and one that measures the effect of the bombardment of the formations by neutrons from an artificial source, known as the *neutron log*.[67] Both gamma-ray and neutron logs are

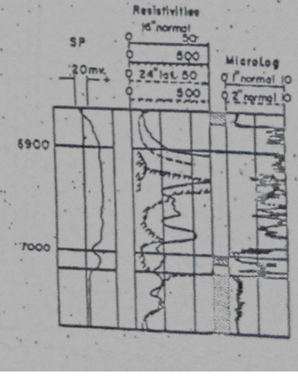

FIGURE 3-13

Typical MicroLog, in comparison with electric log, showing the differences between permeable formations (cross-hatched) and impermeable formations (blank). [Redrawn from Doll, Trans. Amer. Inst. Min. Met. Engrs., Vol. 189 (1950), p. 159, Fig. 9.]

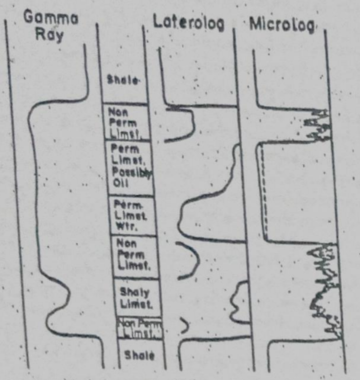

FIGURE 3-14

Gamma-ray log, Laterolog, and Micro-Log of same section of rocks. [Redrawn from Ford, Tulsa Geol. Soc. Digest (1952), p. 98.]

run simultaneously, or the gamma-ray log may be run simultaneously with the resistivity log. A sonde containing the measuring equipment is lowered into the hole at the end of an electrically conducting cable fastened to a drum at the surface and synchronized with a recording drum. The radioactivity of the strata is measured by the variations in conductivity produced by gamma rays emitted by the rocks and penetrating the gas in an ionization chamber contained in the sonde as it is passed down the well bore. Some rocks radiate more gamma rays than others, as is seen in Figure 3-15, and these differences form the basis of the gamma-ray log. (See Fig. 3-16 and also Fig. 3-14.) Its chief use is for the correlation of formations, especially in wells where the casing has been set.

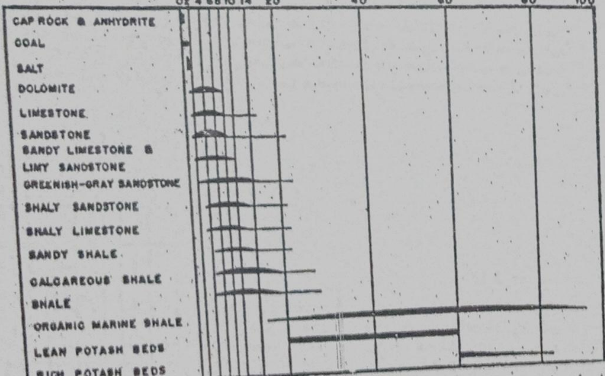

FIGURE 3-15 *Relative radioactivities of various sedimentary rocks associated with petroleum pools. Radioactivity increases to the right in units of measurement of 10^{-12} gram of radium equivalent per gram of rock. [Redrawn from Russell, Bull. Amer. Assoc. Petrol. Geol., Vol. 25 (1941), p. 1775.]*

The neutron survey is obtained when a capsule containing a radium-beryllium mixture, which acts as a source of neutrons, is added to the sonde. The ionization chamber in neutron logging is affected by the gamma rays induced by the action of the neutrons on the formation, the gamma radiation emitted by the source capsule, and the natural gamma radiation of the formations, the latter being small compared with the other two radiations.

Hydrogen has a greater effect on the neutron logs than any other element, the effect being proportional to the number of hydrogen atoms per unit volume. Since hydrogen is a constituent of water, oil, and gas, the chief use of the neutron log is to locate porous zones in the formations, the interpretation being based on the fact that all porosity will be filled with one or more of the hydrogen-bearing fluids. The determinations are more accurate in limestones and dolomites than in shales and sandstones, probably because the clastic rocks generally contain elements other than hydrogen that may affect the log.[68] By calibrating neutron logs with known petrophysical data from the locality of the survey, it is possible to make reasonably accurate determinations of porosity in carbonate formations.[69]

Drilling-time Logs. This standard procedure on most rotary wells consists of measuring the time required to drill a unit depth, as the time in minutes for each foot, five feet, or ten feet of penetration, or the number of feet drilled per unit of time, as feet per hour.[70] When plotted on log strips, the change in the rate of penetration in the drilling-time logs is interpreted as a change in the lithology of the formations drilled. A geologist at the well can tell before seeing the samples the exact depth at which a change occurs, and this offers a check on his sample log and on the electric log. (See Fig. 3-17.)

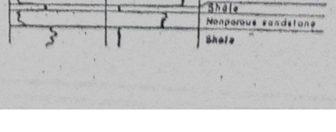

FIGURE 3-16

Typical expressions of the various rock types on gamma-ray and neutron logs. [Redrawn from Russell, Bull. Amer. Assoc. Petrol. Geol., Vol. 36 (1952), p. 327, Fig. 3.]

Core and Mud Analyses. These are made during drilling, especially of wildcat or exploratory wells. The chief purpose is to detect minute quantities of gas or oil entrained in the mud stream as it comes from the hole. Well cuttings are also tested for gas and oil.[71] The method is to pass a part of the mud stream or some of the well cuttings to a trap, where they are mixed with air and the gas separated from the mud. The air-gas mixture is passed over a "hot-wire" gas-detector instrument, where the percentage of combustible gas is measured, the temperature at which ignition occurs giving the amount of methane and the total of all hydrocarbon gases present. One improvement is a steam distillation method, which extracts the hydrocarbon gases quantitatively, and another is the gas chromatograph, which permits analysis for individual hydrocarbons. Minute showings of oil are seen when the drilling fluid is viewed under ultraviolet rays, the amount of fluorescence giving the magnitude of the showing. Logs showing drilling-mud and cuttings analyses are generally made in truck-mounted laboratories driven to the well. A part of a typical log is shown in Figure 3-17.

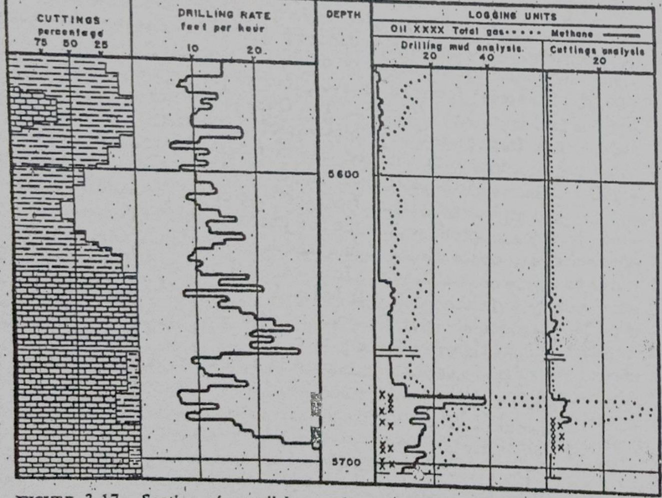

FIGURE 3-17 *Section of a well log made at the well as it was being drilled. [Redrawn from a Baroid Well Log Service log.]*

Caliper Logs. These show a continuous record of the diameter of the well bore. A caliper consisting of four spring-actuated arms, which when open contact the sides of the hole, is pulled through the hole. The arms are connected to a rubber, oil-filled chamber, which in turn is connected to a rheostat that measures the changing resistance. As the pressure from the arms on the chamber changes with the varying diameter of the hole, the potential drop across the rheostat is measured and recorded as the caliper log.[72] Caliper logs are chiefly used to calculate the amount of cement necessary to fill up the annular space between the casing and the well, to select packer seats, and to determine accurately hole diameters for quantitative use in interpreting various electrical and radioactivity logs. These logs are also useful in locating porous zones and sometimes are helpful in identifying and correlating various lithologic types.

Temperature Logs. These are made by passing a temperature electrode down the hole. The electrode contains a twenty-inch length of platinum wire that quickly assumes the temperature of the fluids in the hole. Changes in temperature produce changes in resistance; these changes are detected at a bridge circuit in the electrode and recorded at the surface.[73] The temperature electrode measures the temperature of the drilling fluid. If the measurement is made as soon as drilling stops, the fluid will show little change from top to bottom of the hole. Most anomalies show up between twenty-four and thirty-six hours after circulation has ceased, the cooling or warming of the drilling fluid depending on the thermal conductivity of the formations penetrated and the size of the hole. Temperature logs are used chiefly to determine the height of cement in the hole by measuring the heat generated by the cement as it sets. They are also used to locate gas entering the hole, for, as it enters, it expands and cools. Formation water leaking through the casing and the position of zones where mud circulation is lost may also be determined by temperature surveys.

Sonic Logs.[74] Sonic logs are a continuous record of the time required for a sound wave to traverse a definite thickness of subsurface formation. The reciprocal of the speed of sound through the differing sediments is measured. Sound velocities vary from around 5,000 feet per second for clay to around 25,000 feet per second for dense dolomite. This corresponds to 200 microseconds per foot of clay to 40 microseconds per foot of dolomite. These logs are useful for porosity determinations, for detecting hydrocarbon-bearing zones, for determining various lithologic and stratigraphic correlations, for locating fractures, and for obtaining more accurate travel-time determinations for seismological interpretations.

Nuclear Magnetism Logs.[75] This type of log offers a direct measurement of the hydrogen in the formation and not of the rock matrix. This permits the interpretation of the results in terms of the fluids in the porous and permeable sections of the rocks and permits one to determine the water and the hydrocarbon content. It is the only log that responds solely to the formation fluids.

Dipmeters. The dip of a formation across a well bore may be measured electrically by passing three MicroLogs down the hole set 120° apart. The difference in the time at which each MicroLog passes the same formation boundary is recorded at the surface, thereby giving the angle of dip. Orientation of the instrument and its deflection from vertical are also measured at the same time so that the correct formation dip may be plotted at its exact position. Dipmeters are used, or have been used, where other types of logs are used, such as the Microlaterolog, self-potential logs, and short-normal resistivity logs.

MARINE AND NONMARINE RESERVOIR ROCK

Sedimentary reservoir rocks may be subdivided into those of marine origin and those of nonmarine, or continental, origin, but between these classes there are many gradations and intermixtures. Most petroleum is found in rocks believed to have been deposited under marine conditions, a belief that greatly influences the current ideas on its origin. Substantial deposits of petroleum have been found, however, in rocks of undoubted nonmarine origin, and it is likely that a good many more will be discovered in the future. Perhaps one reason why so few have been discovered hitherto is that many petroleum geologists are prejudiced against continental deposits as source rocks of petroleum and are consequently preoccupied with exploring in the marine sediments.

It is often difficult to determine whether a particular sediment is marine or nonmarine. The distinction is much easier at the surface, however, where depositional features such as bedding, cross-bedding, and lateral gradation can be seen in outcrops, than it is below the surface, where the evidence is all contained in well cuttings and cores. Some rocks, moreover, may be of mixed origin; the rock particles, such as those from wind-blown sands or terrace deposits, may have been originally distributed by nonmarine agencies, and the final burial may have been under marine conditions. Criteria that have been applied include:[76]

1. Marine or nonmarine fossil content.
2. Well-formed euhedral crystals of feldspar (marine).
3. New growth of secondary feldspar around nuclei of clastic feldspar (marine).
4. Aggregates of feldspar and quartz grains cemented by secondary feldspar (marine).
5. Widespread, uniformly bedded "blanket" sands (marine).
6. Thick sequences of interbedded, nonfossiliferous, unsorted fragmental rocks commonly forming lenses (nonmarine).
7. Tillites, coarse grits, and erratics (nonmarine, possibly glacial, although some may be submarine landslip debris).
8. Coal beds, formations with bone fragments, and lenticular sands (nonmarine).
9. Channel-deposited shoestring sands (probably nonmarine).

The Capitan, South Mountain, Shiells Canyon, and Bardsdale pools in the Ventura region of California[77] all produce from the continental red-bed facies of the Sespe formation, a group of sediments up to 7,500 feet thick that are widely distributed in the Ventura basin of southern California. These sediments range in age from Upper Eocene to Lower Miocene, and the proportion of marine deposits in them increases westward. They consist chiefly of red or maroon, fine-grained, arkosic sandstones, more or less silty shales and mudstones, and poorly sorted sandy conglomerates.

In northwestern Colorado the highly lenticular sand bodies of the Hiawatha member of the continental Wasatch formation (Eocene) produce oil and gas. The reservoir rocks are extremely lenticular sandstone beds, highly cross-bedded and ripple-marked, interbedded with variegated mudstones and clay shales and with thin beds of coal, all containing bone fragments. The Wasatch formation is mostly of fluviatile origin, but includes occasional deposits laid down in shallow lakes. The producing formations are of fresh-water origin.[78] The oil and gas are believed to be indigenous to the Wasatch formation, for there are no marine formations within a reasonable distance that might be the source material. Farther southwest, in Utah, the interbedded sands of the Wasatch formation have also been found to contain petroleum.

Several oil pools have been found in the Uinta basin of northeastern Utah in the Green River formation (Middle Eocene), which consists of lacustrine marls, limestones, and siltstones reaching a thickness of 7,000 feet.[79] Oil-saturated sandstones occur around the margins of the basin, and numerous gilsonite veins and fracture fillings occur throughout the eastern part, where the rocks are chiefly shales In fact, the Uinta basin has long been noted for the wide variety and abundance of hydrocarbons at the surface.

Nonmarine clastic rocks of the continental Quirequire formation (Plio-Pleistocene) form the reservoir rock of the highly productive Quirequire oil field in eastern Venezuela. The Quirequire reservoir pinches out within the field from a maximum thickness of 1,600 feet. It consists of "sandy clays interbedded with unsorted clastics ranging in size from silty sands to conglomerates to boulder beds. Thin beds of lignite, lignitic clay, tufa, travertine, and asphalt are present from the base of the formation to the surface." [80]

The reservoir rock in the San Pedro oil field of Argentina[81] is the Tupambi formation, consisting of fine sandstones, siltstones, coarse grits, and tillites, all chiefly of glacial origin. It is the basal member of the Permo-Carboniferous group. In this pool, it is believed but unproved, the source beds for the oil are the underlying Devonian shales, and the first folding to form the trap occurred in early Tertiary time.

In Romania, oil is produced in a number of pools in the Meotian (Pliocene) sediments, which consist of alternating sands, marls, sandstones, and limestones. These sediments are generally considered to be of continental, fresh-water origin.[82]

The Productive series (Miocene-Pliocene) of the rich Apsheron Peninsula (Baku area), USSR, consists of 9,500 feet or more of alternating lenticular sands, intercalated clays, and silt, which grade out into a fanglomerate. It contains many fresh-water fossils. The sediments are believed to have been deposited by the ancient Kura and Volga rivers at the places where they entered estuaries and muddy marine deltas.[83] The rich "red-bed series" of the Turkmen Republic, USSR, is equivalent in age, lithology, depositional environment, thickness, and productivity to the Productive series of the Baku area. In the South Kahetia region of Georgia, USSR,[84] numerous oil showings and some oil production have been found in the Pliocene and Miocene clays, sands, and conglomerates of continental origin.

The two large oil fields in China, Laochunmaie, near Yumen in Kansu Province, and Tsupinkai, near Wusu in Sinkiang Province,[85] both produce from Tertiary continental sandstones. Minor oil occurrences in nonmarine sediments have been described from a number of areas. One of these is in the Shensi series (Jura-Triassic), in North Shensi, China. The Shensi series is about 2,000 meters (6,600 feet) thick and of continental origin, being partly fluvial and partly lacustrine. A number of oil seepages and one pool, called the Yenang pool, have been found in it. In the Szechuan region of China some oil seepages occur in the Tzuliuching limestone (Lower Cretaceous), which is of lacustrine origin.

On the western side of the island of Madagascar, numerous oil seepages and tar springs occur in the continental Karro formation (from Upper Carboniferous to Middle Lias) and in the shallow-water fluviatile deposits of the Ankavandra Beds (Lower Lias and Triassic). The sediments are fine-to-coarse sands, conglomerates, clay shales, and micaceous sands, with a total thickness of 2,400 feet.[86]

In Pakistan, formerly northwestern India, numerous seepages occur in the lower part of the fresh-water Nimadric series (from Oligocene to Pleistocene), along and above the unconformable contact with the underlying marine nummulitic sediments (Eocene). The Nimadric series consists of over 20,000 feet of alternating sandy and silty beds, with some conglomerates, and appears to be partly of fluviatile and partly of eolian origin.[87] A somewhat similar relationship exists in Assam, where the thick nonmarine Tipam sands and clays (Miocene) unconformably overlie marine sediments (from Oligocene to Eocene) and all contain numerous oil seepages.[88]

In summary, we see that oil does occur commercially in rocks of continental, or nonmarine, origin.[89] We may conclude, then, that nonmarine sediments with porosity, permeability, adequate impermeable cover, and favorable trap conditions should not be overlooked as potentially favorable reservoir rocks. Geologists generally try to explain away the occurrence of oil in nonmarine sediments as being due to migration along fractures, faults, or bedding planes from adjacent marine sediments, even though there may be no direct evidence of such movement. The lack of exploration of nonmarine sediments has been largely due to the prevalent belief that all petroleum is of marine origin. Whether the oil originated within the nonmarine sediments or migrated into them from some neighboring marine sediment is not of practical importance; the main problem is to locate the place where it has accumulated. The evidence of existing oil and gas fields in nonmarine sediments in different parts of the world indicates that petroleum does migrate through nonmarine rocks and will accumulate into a pool where there is a trap. With a more aggressive exploration of nonmarine sediments, there seems to be every reason to expect that many more pools will be discovered in them.

CONCLUSION

The reservoir rock is the material in which oil and gas are found; it consists chiefly of sandstones, limestones, and dolomites. No one of these rocks seems to be favored ahead of the others, for large pools are found in each and in all combinations of them. Not only is the reservoir rock one of the essential elements of the single reservoir, but, as we shall see later (Chap. 14), the volume, character, and variableness of the sediments in a prospective producing region form an essential element in the judging of its petroleum possibilities. The presumption is that, if large volumes of sediments are present, they will somewhere contain potential reservoir rocks. Reservoir rocks, in fact, include so many sedimentary rock types that it is doubtful if any sedimentary basin will prove to be without some kind of rock that could become a reservoir rock.

Selected General Readings

Studies for Students: The Classification of Sedimentary Rocks, Jour. Geol., Vol. 56 (March 1948), pp. 112–165, contains the following articles: F. J. Pettijohn, "A Preface to the Classification of the Sedimentary Rocks," pp. 112–117; Robert R. Shrock, "A Classification of Sedimentary Rocks," pp. 118–129, with 55 references; Paul D. Krynine, "The Megascopic Study and Field Classification of Sedimentary Rocks," pp. 130–165. These three articles summarize many fundamental ideas on the classification and nomenclature of the sediments.

Gordon Rittenhouse, "Interpretive Petrology of Sedimentary Rocks," World Oil, October 1949, pp. 61–66. A lecture showing the deductions that may be made from studies of the composition, texture, and structure of sedimentary rocks.

F. J. Pettijohn, *Sedimentary Rocks*, 2nd ed., Harper & Brothers, New York (1957), 718 pages. A standard reference book.

Parker D. Trask, "Dynamics of Sedimentation," in *Applied Sedimentation*, John Wiley & Sons, New York (1950), pp. 3–40. 100 references. A summary of sedimentary processes.

Ph. H. Kuenen, *Marine Geology*, John Wiley & Sons, New York (1950), 568 pages, Chap. 5, "Formation of Marine Sediment," pp. 302–413. 101 references listed. Discusses phenomena related to marine sedimentation.