PETROLEUM (OIL AND GAS) GEOLOGY AND RESOURCES

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Contents

Summary

Petroleum, including oil and natural gas, is a critical component of the world economy. It is widely used, not only in transportation but also in power generation, heating, fertilizer, and as petrochemical feedstock.

Large volumes of petroleum exist in the earth’s crust, but only a fraction of that volume is recoverable and relevant to current and future supply. Current technological means of extraction require the petroleum to be concentrated in reservoir rocks with suitable

characteristics before it can be considered a resource. Economic constraints further limit the volume that may be relevant to supply. Very large amounts of unconventional petroleum exist, however, that may become relevant to supply with the development of appropriate technology.

Projections of the future role of petroleum in the world economy are conditional not only on the volumes of resource available, but also on economic, social, and political factors and availability of alternate fuels. Much misunderstanding about the volumes of resource potentially available in the future comes from misunderstanding the quantitative estimates of resources and reserves. These estimations of the volumes of petroleum resource involve increasing amounts of uncertainty as one goes from the category of produced volumes to that of undiscovered volumes.

1. Introduction

Petroleum consists of a wide variety of naturally occurring chemical compounds of carbon and hydrogen (and often other elements). This elemental composition is reflected in another commonly used term, hydrocarbons. Most commonly, petroleum exists in nature as a mixture of several to many of these compounds. Natural gas consists of simple compounds of low density (“lighter”) that are normally in a gaseous state. Oil consists of more complex compounds of higher density (“heavier”) that are normally in a liquid state.

Petroleum can exist in a gaseous, liquid, or solid state and the state at surface conditions may be different from the state in the subsurface at reservoir depths. An oil accumulation includes some amount of natural gas dissolved within the oil at subsurface reservoir conditions. Some of this gas, termed dissolved gas, will separate from the oil when brought to the surface. An oil accumulation may also include some natural gas in the gaseous state at reservoir conditions which is termed associated gas. The associated gas normally exists as a gas cap floating on top of the oil because of its lower density.

Gas accumulations are those deposits with either relatively small amounts of oil or no oil. The gas in these accumulations is termed non-associated gas. Both non-associated gas and associated gas may include varying amounts of natural gas liquids (NGL). These NGL are low-density petroleum liquids that occur in gaseous form in the reservoir but condense into liquid form when brought to the surface.

2. Importance of Petroleum

Petroleum has been used since prehistoric times. Oil and tar from surface seeps have been used as waterproofing for baskets and boats, as mortar, and as medicine. Natural gas was first produced in China several thousand years ago in Sichuan Province from wells drilled with tools and pipes made of bamboo. The gas was burned to evaporate brine to produce salt.

The modern era of petroleum is commonly dated to 1859 with the first successful oil well in Pennsylvania, U.S.A. Actually, some drilling and production, especially for natural gas used for lighting, had already taken place in several areas of the world since the early part of the nineteenth century. Nevertheless, use of petroleum, particularly the use of petroleum-derived kerosene for lighting, increased rapidly in the late nineteenth century. In the early twentieth century, increasing use of electric lights and a large increase in number of motorized vehicles shifted much of the use of petroleum from lighting to transportation.

Although most people think of petroleum as a transportation fuel, as of 1999 that only accounted for about 50 percent of world oil usage and only a very small portion of world natural gas usage. Other uses of petroleum are for power generation, fertilizer, and as petrochemical feedstocks for plastics.

Oil and natural gas provided 63 percent of the energy used worldwide as of 1999 (figure 1). Because of this, petroleum is a major factor in the world economy. Higher or lower petroleum prices have a direct effect on far more than just the prices paid at the gasoline pump, but are closely linked to economic productivity and unemployment rates.

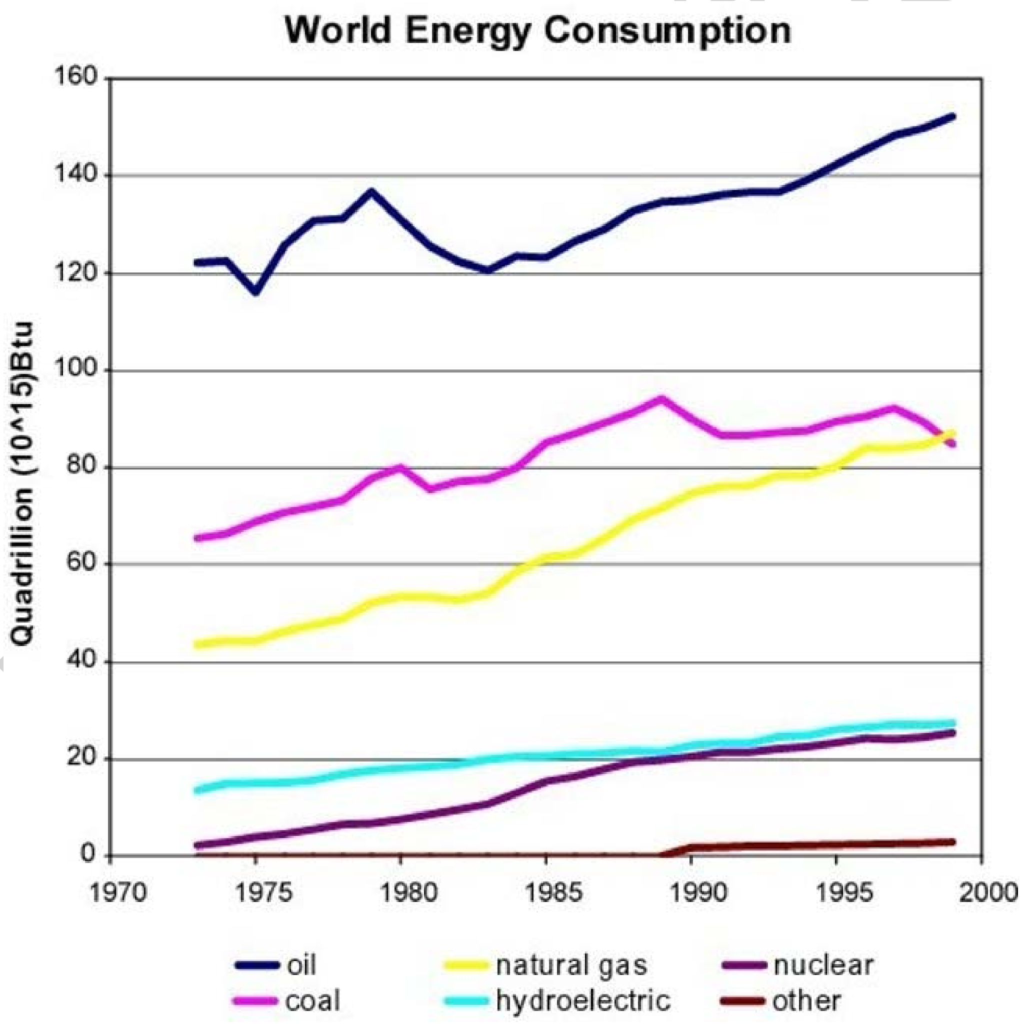

Figure 1: Energy use by fuel type, 1973 to 1999
(data from U.S. Energy Information Administration)

Petroleum has advantages and disadvantages when compared to other sources of energy.

It is fairly compact in that a large amount of energy can be derived from a small volume of the resource. It is relatively clean burning, compared to wood or coal, leaving little to no solid residue (especially important to internal combustion engines). Oil is very transportable, by either pipeline or ship. Natural gas is somewhat less transportable in that transportation of large quantities by ship requires that it be converted to a liquid. These more expensive liquefication procedures include liquefied natural gas (LNG) or gas to liquids (GTL) technologies. Most natural gas is therefore transported by pipeline, except in East Asia where tanker transport of LNG is important.

3. Origin of Petroleum

3.1. Petroleum Geochemistry

The study of organic geochemistry has revealed much about petroleum formation. There are many types of organic matter that are sources of petroleum. Algae, especially marine algae but also lacustrine algae, are a primary source of oil. Since the Devonian (during the last 400 million years), terrestrial woody organic material has been an important source material, especially for natural gas. Organic material from animals is of such a small volume as to be insignificant.

Organic matter in rocks undergoes chemical changes as it is buried deep in the earth and heated. Large organic molecules are broken into smaller molecules as they are heated. At higher temperatures of deeper burial, these smaller molecules may be further broken into even smaller molecules. Methane (CH_4), the smallest of these hydrocarbon molecules, is the major component of natural gas. These chemical changes have been confirmed by laboratory experiments involving the heating of organic-rich rocks and study of the generated fluids.

Besides formation by thermal breakdown of organic matter (thermogenic formation), petroleum can also be formed by biologic processes (biogenic formation). Bacteria in the subsurface can break down organic molecules by digestion, yielding methane as the primary product. These methanogenic bacteria are the origin of most “swamp gas.” In general, organic matter that is buried less than about one kilometer can generate some amount of natural gas by biogenic means. At greater depths with correspondingly higher temperatures, the methanogenic bacteria die out and most of the generation is thermogenic.

From some types of organic source material, both oil and some natural gas are generated. With other types of organic material, mainly natural gas is generated. At even higher temperatures, the generated oil molecules themselves begin to further break down and more natural gas is generated. Specific depths and temperatures for these chemical changes depend on the type of organic matter and the rapidity with which temperature increases with depth.

3.2. Petroleum from Non-Organic Sources?

It has been suggested that much of the earth’s petroleum is of inorganic origin. Inorganic methane is found in many planetary atmospheres. The major hypothesized sources of inorganic methane are either migration of primordial methane from the earth's mantle or methane formed by hydrolysis of ultramafic and mafic igneous rocks in the earth's crust. Some fraction of the methane found at depth is probably of such inorganic origin.

Organic geochemical experiments show that organic-rich sedimentary rocks, at temperatures and pressures comparable to those found at one or more kilometers depth, yield petroleum fluids. Details of the geochemical and isotopic compositions commonly allow fluids to be matched with specific source rocks. Many such studies matching source rocks and petroleum fluids geochemically have been accomplished around the world. These relationships between petroleum fluids and source rocks are explainable only by organic processes.

Geochemical relations between source rocks and fluids have been established in many parts of the world, but no substantial petroleum accumulations from inorganic sources have ever been definitively identified. It is also unclear how these simple molecules (methane) would be converted into the more complex molecules of other petroleum components. Thus, almost all of the petroleum produced for consumption is probably of organic origin.

4. Formation of Petroleum Accumulations

Not all the petroleum within the earth's crust is a usable resource. The petroleum resource is that part that is sufficiently concentrated such that economic extraction is currently or potentially feasible. In order to be part of the resource, petroleum must be concentrated into an accumulation with characteristics that allow it either to be produced by wells or to be mined at the surface. Petroleum dispersed at low concentrations is not a viable resource because of the high cost of extraction. Three processes are required in order to have such a petroleum accumulation: generation, migration, and accumulation.

4.1. Generation

Oil and gas generation requires a source rock of adequate organic content that has undergone an appropriate thermal (or biologic) history to generate significant hydrocarbons. Most good source rocks have an organic-matter content of at least two percent by weight. These concentrations generally require that they be deposited in areas with both high organic productivity and good preservation of the organic matter. Most organic matter in sediments is consumed by a variety of organisms, from bacteria to grazing animals. Low oxygen content in the sediments may reduce the population of organic-matter consumers and increase the preservation of organic matter. These low oxygen conditions are often caused when the water bodies (seas or lakes) have geometries that result in restricted circulation.

A rock with concentrations of preserved organic matter will not generate large volumes of thermogenic petroleum until buried deep enough to heat the source rock to the point at which hydrocarbons are generated. The required depth for peak petroleum generation depends primarily on the geothermal gradient, the rate at which temperature increases with depth. It also depends to a lesser degree on the particular type of source organic material. With insufficient heat, even a rich source rock can only generate a relatively small amount of biogenic gas.

4.2. Migration

Source rocks generally are fine-grained shales and do not have the characteristics suitable for production at economic volumes or rates. Their volume of pore space (porosity) may be adequate to store significant volumes of fluids. However, the ability of fluids to flow through the rock (permeability) is commonly so low as to be insufficient to provide fluid movement into a well at economic flow rates. To be economically recoverable, the fluids must migrate to a reservoir rock with better production characteristics.

The main cause of migration is the difference between the densities of formation water and of petroleum fluids. Oil (except for some extremely heavy oils) and natural gas are lighter than water and thus float on water. This causes the petroleum to be buoyant and to move upwards until it reaches an obstruction.

Factors other than buoyancy also affect the movement of petroleum. Differential pressure can cause petroleum to move even in a direction contrary to buoyancy. Because petroleum fluids take up more space than the original organic matter from which they are derived, pressure builds up in source rocks. This pressure can force the petroleum into lower-pressured rock. Capillary forces can also affect petroleum migration.

4.3. Accumulation

With few exceptions, oil and gas pools do not occupy underground caverns. Instead, petroleum occupies microscopic holes or pores (porosity) within rocks. To have economic production volumes and rates, rocks must have sufficient porosity (volume of pore space) and permeability (connections among the porosity that allow fluid flow).

Sandstones are the most common reservoir rock type, but other rocks (such as dolomites and limestones) also form reservoirs. Fractures can cause even the least porous and permeable rock types (like igneous rocks) to be good reservoirs.

Once petroleum has migrated to a reservoir rock with good production characteristics, it can form an accumulation only if a barrier impedes further migration. These impediments to flow are called seals and the geometric configurations are called traps. Seals impede migration by providing a barrier of impermeable rock. The resulting trap can be formed of structural configurations of rocks caused by folding or faulting (figure 2). It can also be caused by stratigraphic changes in rock characteristics laterally (figure 3) or from some combination of both structural and stratigraphic elements.

As oil migrates toward the surface, it may lose some of its lighter molecular components through biodegradation. The remaining fluids are more viscous and, having a density closer to that of water, less buoyant. In extreme cases, the oil may be degraded to immobile tar, which can itself be a seal for additional petroleum.

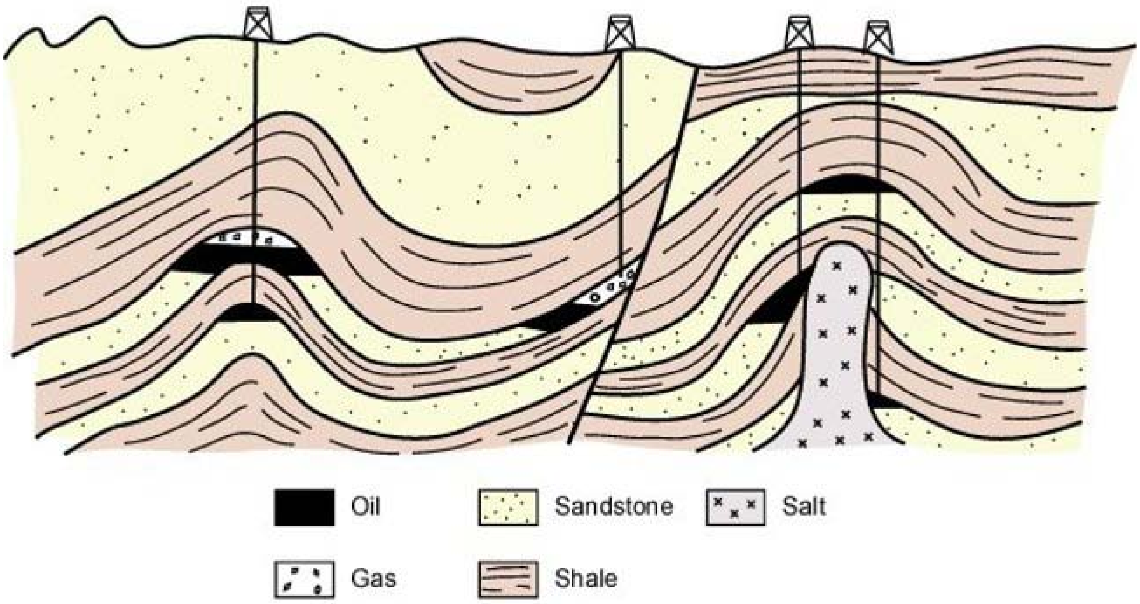

Figure 2: Examples of structural trapping configurations

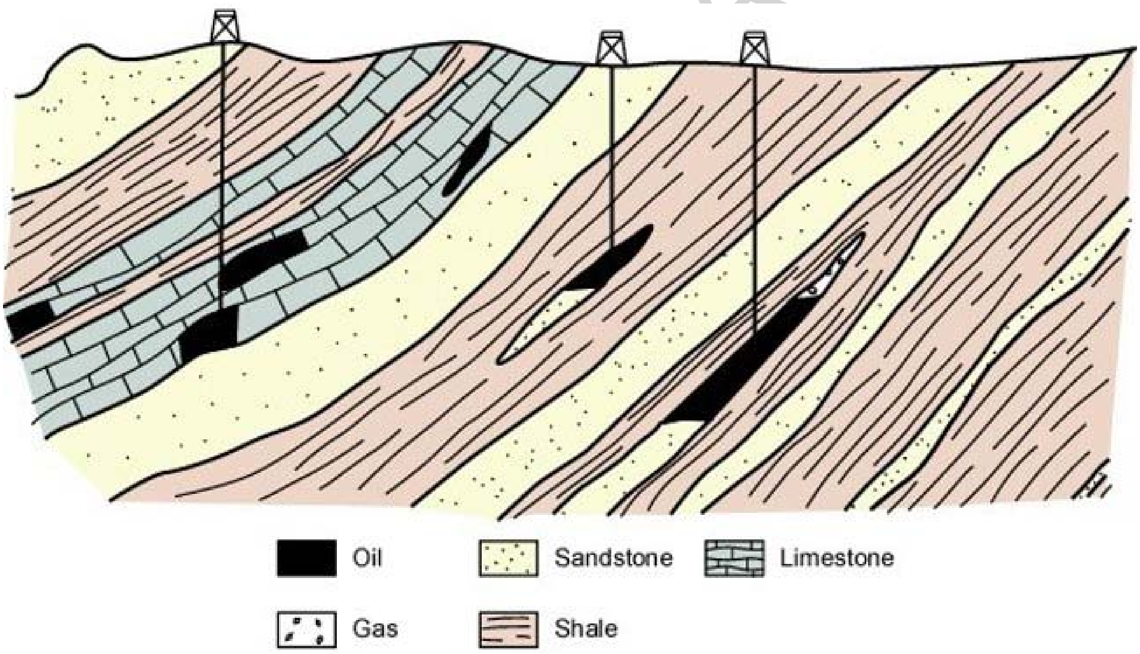

Figure 3: Examples of stratigraphic trapping configurations

The relative timing of geologic events in an area is an important consideration. If generation and migration from a source rock took place before the creation of appropriate traps, the petroleum may be leaked to the surface and lost.

The ultimate fate of most petroleum is to leak to the surface and be either degraded or vented to the atmosphere. Natural seeps of oil and natural gas are common in petroleum-producing areas and have been used as an exploration tool. Geochemical studies of petroleum generation, migration, and accumulation have strongly suggested that the volumes of generated hydrocarbons are far greater than what can reasonably be accounted for in discovered and undiscovered traps. Some of the remaining petroleum stays in the source rock or is dispersed in low concentrations. Most petroleum generated throughout geologic history, however, seems to have leaked to the surface.

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Recommended Websites

http://energy.usgs.gov/ [A U.S. Geological Survey website with links to many energy-related reports, especially several assessments of undiscovered petroleum resources in the U.S. and around the world]

http://www.eia.doe.gov/ [The website of the Energy Information Administration of the U.S. Department of Energy with a very large amount of data on energy demand and production of all types worldwide]

http://www.iea.org/ [The website of the International Energy Agency]

http://www.api.org/ [The website of the American Petroleum Institute]

http://www.bp.com/centres/energy/index.asp [The website with BP's Statistical Review of World Energy]

Biographical Sketches

Ronald R. Charpentier is a research geologist with the U.S. Geological Survey in Denver, Colorado specializing in the assessment of potential for undiscovered oil and natural gas worldwide. He received a B.S. in geology from the University of Kansas and both an M.S. and a Ph.D. in geology from the University of Wisconsin/Madison. Since 1979 he has worked with the U.S. Geological Survey on assessments of oil and natural gas resource potential both for the U.S. and internationally. During that time he has developed and improved methodology for making such assessments, both for conventional and unconventional accumulations.

Thomas S. Ahlbrandt received his B.A. (1969) and Ph.D. (1973) in geology from the University of Wyoming. He currently serves as the World Energy Project Chief for the U.S. Geological Survey in the Central Energy Team in Denver, Colorado. He has nineteen years of petroleum industry exploration and production experience in addition to nearly 20 years of service at the USGS. He has held several management positions within the USGS in Denver, Colorado and Reston, Virginia.