MINING AND OIL EXPLORATION IN THE OCEANS AND SEAS

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1. Introduction

Earth is a dynamic planet in which geological processes and plate tectonics have acted, over geological time, to yield the present day shape and position of continents and oceans. Throughout geological time, depositional, igneous and metamorphic processes, coupled with tectonic forces have molded the shape of the subsurface, the types of rocks found at particular depths, and the fluids or minerals present. This chapter discusses the evolution of hydrocarbons and minerals in the subsurface, and briefly describes their occurrence and exploitation in the oceans of our Earth.

2. Occurrence of Hydrocarbons in Oceans and Seas

The most favorable geologic environments for offshore oil and gas are the sedimentary basins where the thickness of the stratigraphic assemblage exceeds 1000 meters. These basins are found on land as well as along the continental margin. Moreover, the size of the basin, geologic structure, and thickness varies considerably from one location to another. Within each ocean basin there may also be deltaic deposits of thickness in excess of 7620 meters caused by the erosion of continental land masses and deposition of detritus by major rivers. Figure 1 indicates on a worldwide basis the general distribution by thickness, of sediments adjacent to the continents—1000 to 3300 meters thick, over 3300 meters, and deltaic deposits within the basins that are more than 7000 meters thick.

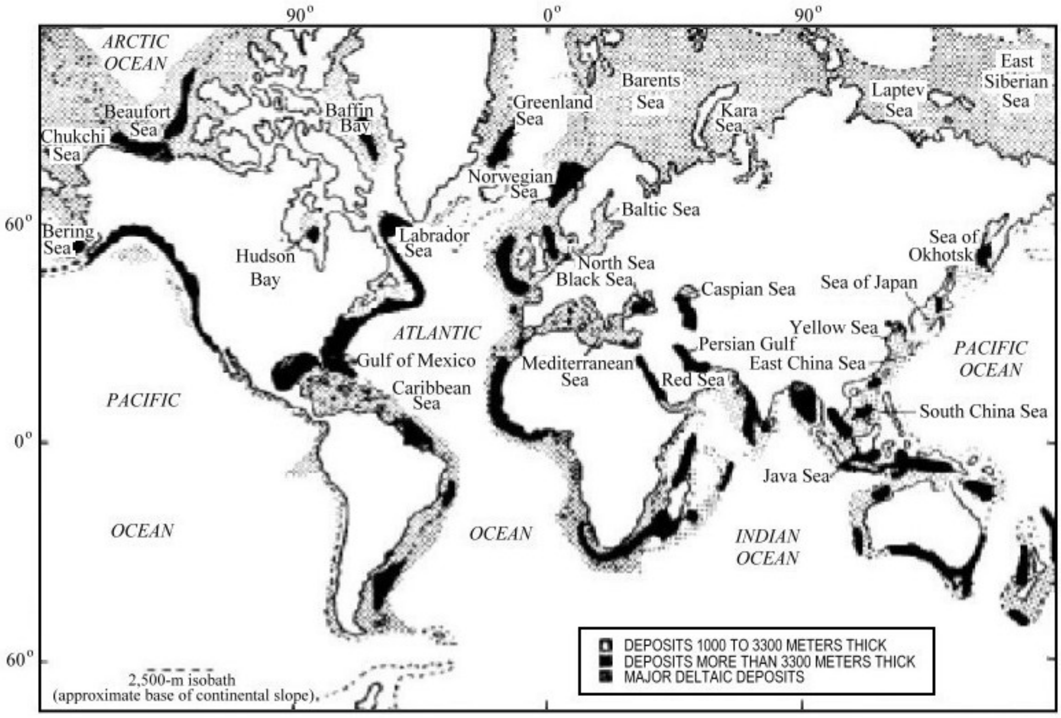

Figure 1. Distribution of sedimentary basins in the submerged continental margins (Ranney, 1979)

Oil and gas have been found in many of the sedimentary basins shown in Figure 1. Significant reserves have been located and developed in the US Gulf of Mexico, North Sea, Java Sea, Persian Gulf, Arabian Gulf, offshore Trinidad and Tobago, and off the coast of southern Brazil, Angola, Nigeria, and Newfoundland. More recently, production has also been proven in the South China Sea, Timor Sea, Caspian Sea, the Nile Delta, and offshore Viet Nam.

The sedimentary basins that have become repositories of oil and gas were formed by a broad scope of tectonic processes that have affected the Earth throughout time. The relationship of large oil and gas fields to generalized orogenic or tectonic regions, as shown in Figures 1 and 2, indicates that large hydrocarbon deposits may be found in both currently mobile zones and quiescent zones, and that the major causal factor in localization is the accumulation of sedimentary rocks. The factors leading to the local accumulation of oil and gas are considered here.

2.1. Occurrence of Hydrocarbons Reservoirs

Hydrocarbon reservoirs are associated with (a) the existence of a source rock which generated the oil over geologic time, (b) a trap having sufficient closure to contain the oil, and (c) reservoir rock of sufficient quality to produce the fluids.

2.1.1 Source Rocks and the Generation of Hydrocarbons in the Subsurface

Hydrocarbons are complex mixtures of hydrogen and carbon, which sometimes also contain impurities such as nitrogen or sulfur. When the chemical mixture is composed of small molecules (e.g. CH_4, C_2H_6) it is a gas at normal temperature and pressure. When the mixture contains larger molecules (C_5-C_{38}), it is a liquid. Crude oils are classified chemically according to the structures of the larger molecules and have widely varying characteristics. Some are black, heavy and thick (like tar) while others are brown or nearly clear with low viscosity and low specific gravity.

The exact means of oil generation in the subsurface is not absolutely certain, but evidence strongly suggests that during sedimentary processes, organic material is deposited along with the rocks. This organic material decays and is transformed into humin through biochemical degradation (rotting). Humin transforms to kerogen by insolubilization, a process whereby anything that is soluble in the subsurface is dissolved and eliminated. Hence, kerogen is essentially an insoluble residue. It is believed to be the precursor to virtually all oil, and most natural gas.

The generation of oil from kerogen requires heat. Most scientists today feel that oil is generated at rates approximated by the Arrhenius Equation,

$$K = Ae^{-Ea/RT}$$

where K is rate, A is a constant, E_a is the activation constant, R is the gas constant, and T is temperature. Subsurface temperatures between 100 ^oC and 200 ^oC provide the most favorable thermal conditions for the generation of oil. Higher subsurface temperatures typically result in the formation of natural gas.

Rocks containing large amounts of kerogen (organic-rich shales and evaporites) act as source rocks, where the oil is first generated. As these shales and evaporites in the subsurface become buried and compacted through sedimentary processes, they expel water, gas and oil. All of these fluids escape into available pore spaces (voids) in adjacent rock and are free to move through adjacent formations.

Oil and gas and can migrate great distances from the point of origin. The fluids migrate through the subsurface until reaching a point where there is an impermeable barrier, referred to as a ‘trap’.

2.1.2 Reservoir Rocks, Depositional Systems and Hydrocarbon Traps

Virtually all oil and gas reservoirs are found in sedimentary rock. There are four different classifications of rocks that are of interest with respect to subsurface

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hydrocarbons production. These are sandstones, carbonates (limestones and dolomites), evaporites and shales.

Sandstones are rocks comprised predominately of quartz, or silicon dioxide (SiO_2), and are noted for being a collection of grains. The grain size may range from very small (silts of 5 microns) to very large (the size of a small pea). The grains fit together to form a matrix, that has some void space for fluids. The sandstone typically also contains other minerals, such as clay, pyrite, calcite, dolomite, and other materials in various amounts. These minerals act as cement, and aid in holding the sand grains together. Some cementation is critical to formation strength. However, excessive amounts of silts tend to reduce the pore space available in the rock, and can also reduce the permeability.

Carbonate rocks are accumulations of calcium carbonate particles, that are typically deposited or formed in marine systems. The $CaCO_3$ appears as various forms depending on the depositional environment. For example, fossiliferous limestone is composed of fossil fragments cemented by coarsely crystalline calcites; while cemented, inorganic or biochemical rounded masses (ooliths) make up oolitic limestone.

Regardless of the origin and texture, $CaCO_3$ is the major component in a carbonate rock. Because calcite is never compositionally pure, small amounts of magnesium, iron, manganese, barium and strontium may be found in a carbonate rock. Magnesium is the most abundant of these and if MgO exceeds over 1% wt., the limestone may convert to domomite ($CaMg(CO_3)_2$). When dolomite forms, a chemcial process involving the substitution of magnesium for part of a calcium in the carbonate structure may create vugs and natural fractures in the rock.

Chalk formations may be almost pure calcium carbonate. They are relatively soft rocks (low compressive strength) that have high pore space but relatively low flow capacity. The North Sea contains chalk formations. One field in the North Sea, the Ekofisk Field, has experienced significant subsidence during fluid withdrawal due to compaction of the chalk.

The third formation of interest is shale. These formations are laid down from very small particles (poor sorting) that are mixed with organic material. The organic material is often in layers, pools or ebbs. The shales may accumulate in deep marine environments (high energy) or in lagoon environments (low energy). Shales typically have little porosity, and fluid cannot flow through a shale. Hence, shales often serve as a seal for permeable formations. Shales are also important as source rocks.

Evaporites are deposits that are formed by the evaporation of water. Deposits such as anhydrite are usually accumulations produced in dried inland seas. They serve as extensive geologic markers and sealing formations. They are extremely dense, but can contain fractures.

Sandstones and carbonates are formed in a variety of depositional environments that determine the initial sediment/rock properties. The depositional environment is simply what type of surroundings and forces shaped the deposits. Forces may be 'high' or 'low' depending on wind, wave and current actions in the environment as the sediements are

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deposited. High energy environments have wind or currents capable of moving large pieces of sediments while lower energy environments move only the smaller particles. The energy of the depositional environment is important because it determines grain sorting and average size of the grain.

There are two classification of depositionsal systems—clastic and carbonate. 'Clastic' refers to fragments of pre-existing rock. Clastic depositional systems include alluvial fans, braided streams, meandering streams, lakes, deltas and tidal flats. Sandstone is the predominate type of clastic reservoir rock.

Carbonate depositional systems are those in which limestone is deposited. This may be a carbonate ramp sequence, laid close to sea level by carbonates precipitating on the sea floor. Alternatively, carbonate reefs and banks may develop as organic buildups, on the sea floor. Carbonate depositional systems often undergo tectonic, solution or other processes that induce secondary porosity, fractures or dolomitization.

The depositional environment is important in producing offshore oil and gas because it influences the quality of the reservoir rock, the extent of the reservoir and the nature of the hydrocarbons accumulated.

Regardless of the type of depositional system in which the hydrocarbon reservoir is formed, there must be a trap within the subsurface formation, to prevent the upward migration of oil. Hydrocarbon traps are divided into two broad classifications—structural and stratigraphic traps.

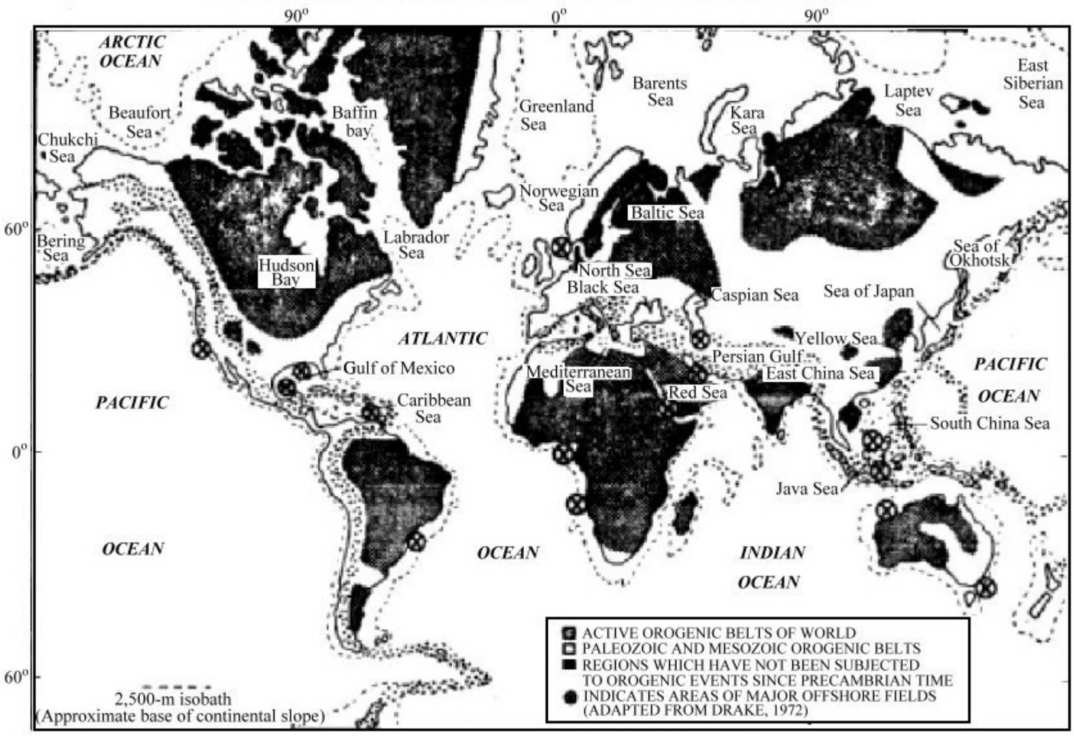

Figure 2. Relationship of large oil and gas fields to tectonic regions (Ranney, 1979)

Structural traps are geological features that provide an impermeable seal beyond which the oil cannot migrate. One important structural trap is the dome or anticline (Figure 3). As shown, the anticline provides a structural high, overlain by an impermeable seal, such as a shale or evaporite. The oil migrates to the crest of the structural feature and is trapped at that point, forming an oil reservoir.

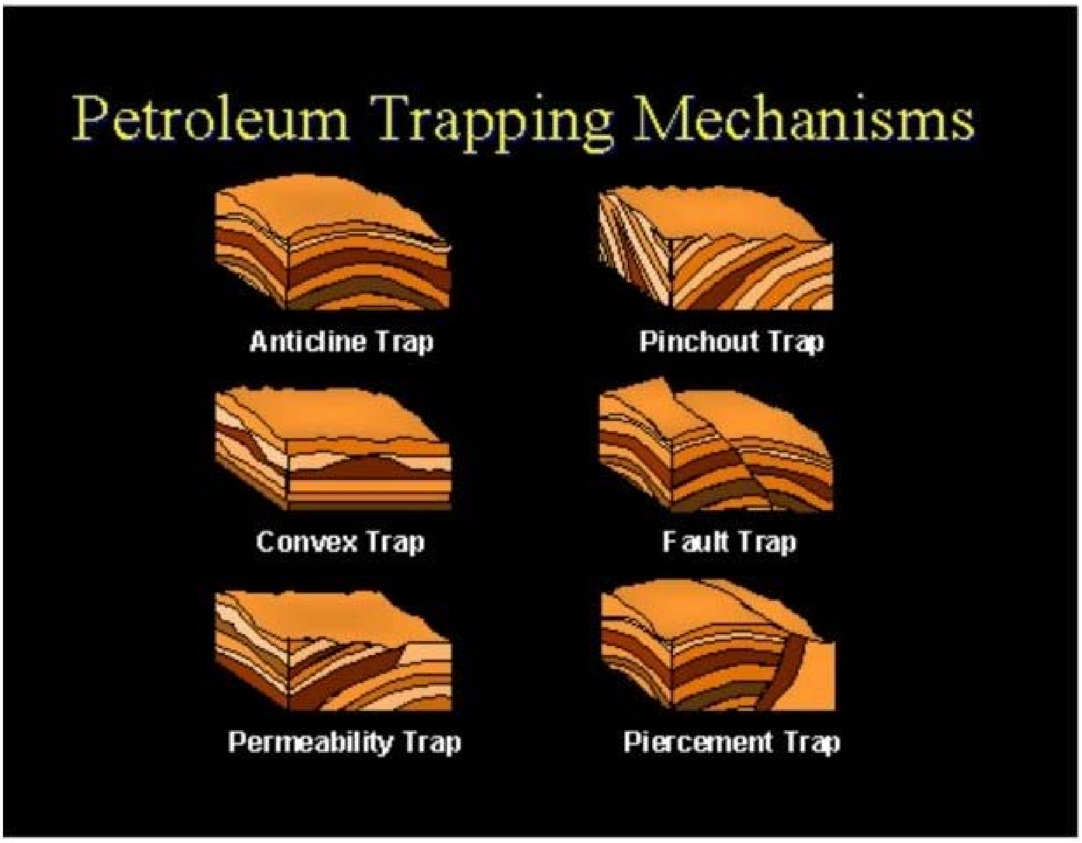

Figure 3. Petroleum traps (Economides *et al*, 1996)

Another important example of a structural trap is a subsurface fault (see Figure 3), of which there are many types (e.g. normal, growth, thrust, strike-slip). The formation displacement due to faulting results in a permeable reservoir being shifted and positioned opposite an impermeable bed and perhaps also truncated by an impermeable fault. This seal prevents the oil from migrating and forms an oil reservoir.

Stratigraphic traps are features characterized by discontinuous reservoir rock such as channel sandstones, a barrier island sandstone, or carbonate reef or bank. Figure 3 depicts a pinchout, where the reservoir sand is absent, and a permeability trap where the quality of the reservoir rock degrades and forms a seal. Stratigraphic traps such as these are formed as a function of depositional processes.

In some hydrocarbon reservoirs, only one sealing mechanism is found. However, many reservoirs include more than one type of trap.

2.1.3 Characterisitcs of Reservoir Rocks

For a subsurface formation to be a hydrocarbon reservoir, the rock within the formation must provide sufficient 'porosity', or void space. This porosity is expressed as a fraction or percent of the total bulk volume of the rock. Porosity is an important property of the rock because it defines the reservoir storage capacity.

In most unconsolidated formations, porosity depends upon the grain size distribution; not on the absolute size of the grain itself. Porosity can be in the order of 35 to 40% if all grains are close to the same size but very low (<15%) where grains vary in size. The average porosity of producing reservoirs ranges from about 5 to 15% in limestones and dolomites and 10 to 25% in sandstones. Chalk formations can have a porosity as high as 30%.

Rocks are also described on the basis of their permeability. Permeability is the measure of the conductance of the formation (rock) to flow of a fluid. The higher the permeability, the easier it is (takes less driving force or pressure) for a fluid to flow through the rock matrix. Permeability depends on the absolute grain size, how well the sediments are sorted, presence of fractures, and how much chemical modification has occurred to the matrix. Flowing and bound fluid properties also affect the permeability of a particular rock.

Large grained sediments with a minimum of fine particles usually have high permeability, whereas fine-grained sediments with small pores have lower permeability. However, porosity does not always relate to permeability. Some shales and chalks may have high porosity but essentially no permeability because there is no inter-connection of the pores.

Reservoir permeability is measured in a unit referred to as the Darcy (D) or millidarcy (mD). Typically, reservoir permeability can range from as low as 0.5 mD in a tight gas well to 5 Darcies (5000 mD) in the vugular dolomites and limestones found in reservoirs in the Arabian Gulf.

The depositional processes and the type of rock (sandstone, siltstone, limestone) determine the degree of granular compaction at the time the rock was formed. This determines the primary porosity and permeability of the rock. Secondary porosity may be induced by tectonic forces, which created fractures in the rock. These fractures act as permeable conduits for hydrocarbon flow through the rock and greatly enhance production from some reservoirs offshore.

Fluids in the pore space of the rock generate 'pore pressure'. This pressure, combined with the overburden of sediments laid down after the reservoir is formed, define a reservoir pressure within the rock containing hydrocarbons. This pressure acts as the driving force that enables oil and gas to be produced through a wellbore.

In oil and gas reservoirs found offshore, reservoir porosity, permeability and initial reservoir pressure must all be highly favorable for a well to flow at sufficient rates to justify the expense of an offshore development.

3. Exploiting Hydrocarbon Resources in the Oceans and Seas

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Developing hydrocarbon resources offshore requires the collective effort of geologists, geophysicsists, engineers (typically employed by oil companies) and large offshore service companies. The following details major steps in the process of finding and developing oil and gas reserves offshore.

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Biographical Sketch

Shari Dunn-Norman is Associate Professor of Petroleum Engineering at the University of Missouri – Rolla. She has over 25 years of combined academic, industrial and consulting experience in well design and well completion technology. She has co-authored and co-edited a textbook on well construction. Dr. Dunn-Norman teaches courses in offshore oil technology, petroleum design, production engineering, and environmental applications.

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