Petroleum system

The petroleum system is a unifying concept that encompasses all of the disparate elements and processes of petroleum geology, including: the essential elements (source, reservoir, seal, and overburden rock) and processes (trap formation, generation-migration-accumulation) and all genetically related petroleum that originated from one pod of active source rock and occurs in shows, seeps, or accumulations; also called hydrocarbon system.

Practical application of petroleum systems can be used in exploration, resource evaluation, and research.

Elements and processes

The essential elements of a petroleum system include the following:

Source rock

Reservoir rock

Seal rock

Overburden rock

Petroleum systems have two processes:

A. Trap formation (A trap consists of a geometric arrangement of permeable (reservoir) and less-permeable (seal) rocks which, when combined with the physical and chemical properties of subsurface fluids, can allow hydrocarbons to accumulate.)

Three main trapping elements comprise every subsurface hydrocarbon accumulation:

1. Trap reservoir—storage for accumulating hydrocarbons and can transmit hydrocarbons.
2. Trap seal—an impediment or barrier that interferes with hydrocarbon migration from the reservoir
3. Trap fluids—physical and chemical contrasts—especially differences in miscibility, solubility, and density—between the common reservoir fluids (primarily water, gas, and oil) that allow hydrocarbons to migrate, segregate, and concentrate in the sealed reservoir.

B. Generation–expulsion–migration–accumulation of hydrocarbons

Generation

Deeper burial by continuing sedimentation, increasing temperatures, and advancing geologic age result in the mature stage of hydrocarbon formation, during which the full range of petroleum compounds is produced from kerogen and other precursors by thermal degradation and cracking (in which heavy hydrocarbon molecules are broken up into lighter molecules). Depending on the amount and type of organic matter, hydrocarbon generation occurs during the mature stage at depths of about 760 to 4,880 metres (2,500 to 16,000 feet) at temperatures between 65 °C and 150 °C (150 °F and 300 °F). This special environment is called the "oil window." In areas of higher than normal geothermal gradient (increase in temperature with depth), the oil window exists at shallower depths in younger sediments but is narrower. Maximum hydrocarbon generation occurs from depths of 2,000 to 2,900 metres (6,600 to 9,500 feet). Below 2,900 metres, primarily wet gas, a type of gas containing liquid hydrocarbons known as natural gas liquids, is formed.

Approximately 90 percent of the organic material in sedimentary source rocks is dispersed kerogen. Its composition varies, consisting of a range of residual materials whose basic molecular structure takes the form of stacked sheets of aromatic hydrocarbon rings in which atoms of sulfur, oxygen, and nitrogen also occur. Attached to the ends of the rings are various hydrocarbon compounds, including normal paraffin chains. The mild heating of the kerogen in the oil window of a source rock over long periods of time results in the cracking of the kerogen molecules and the release of the attached paraffin chains. Further heating, perhaps assisted by the catalytic effect of clay minerals in the source rock matrix, may then produce soluble bitumen compounds, followed by the various saturated and unsaturated hydrocarbons, asphaltenes (precipitates formed from oily residues), and others of the thousands of hydrocarbon compounds that make up crude oil mixtures.

At the end of the mature stage, below about 4,800 metres (16,000 feet), depending on the geothermal gradient, kerogen becomes condensed in structure and chemically stable. In this environment, crude oil is no longer stable, and the main hydrocarbon product is dry thermal methane gas.

Expulsion

Expulsion describes the movement of hydrocarbons from the petroleum source rock into the carrier bed or migration conduit. The expulsion event is driven by a combination of factors that include compaction, chemical reactions, source richness, kerogen type, and thermal expansion. Hydrocarbon generation causes pressure build-up in the source rock, exceeding the pore pressure of the adjacent carrier bed. Oil or gas is expelled or "squeezed" into the carrier bed due to the differential pressures between source rock and fluid in the carrier bed.

Migration

The hydrocarbons expelled from a source bed next move through the wider pores of carrier beds (e.g., sandstones or carbonates) that are coarser-grained and more permeable. This movement is termed secondary migration and may be the result of rocks folding or raising from changes associated with plate tectonics. The distinction between primary and secondary migration is based on pore size and rock type. In some cases, oil may migrate through such permeable carrier beds until it is trapped by a nonporous barrier and forms an oil accumulation. Although the definition of "reservoir" implies that the oil and natural gas deposit is covered by more nonporous and no permeable rock, in certain situations the oil and natural gas may continue its migration until it becomes a seep on the surface, where it will be broken down chemically by oxidation and bacterial action.

Since nearly all pores in subsurface sedimentary formations are water-saturated, the migration of oil takes place in an aqueous environment. Secondary migration may result from active water movement or can occur independently, either by displacement or by diffusion. Because the specific gravity of the water in the sedimentary formation is considerably higher than that of oil and natural gas, both oil and natural gas will float to the surface of the water in the course of geologic time and accumulate in the highest portion of a trap. The collection under the trap is an accumulation of gas with oil and then formation water at the bottom. If salt is present in an area of weakness or instability near the trap, it can use the pressure difference between the rock and the fluids to intrude into the trap, forming a dome. The salt dome can be used as a subsurface storage vault for hazardous materials or natural gas.

Accumulation

A hydrocarbon accumulation forms when migrating hydrocarbon filaments encounter a zone (the seal), either laterally or vertically, with pore throat sizes smaller than the carrier bed. The seal pore throat breakthrough pressure or the distance to the spill point of the trap, whichever is less, determines the hydrocarbon accumulation column height.

Elements of petroleum system :

Source rock

A source rock is a rock that is capable of generating or that has generated movable quantities of hydrocarbons.

The first factor to be assessed in an exploration play in an area yet to be drilled is whether a source rock is present. If so, then we ask, "How good is it? Will it generate oil or gas? Has it generated hydrocarbons already?" To answer these questions, we must know the basics of what constitutes a source rock, how to classify source rocks, and how to estimate potential. This article provides a background in these fundamentals.

Source rock types: Based on kerogen type

- Type I source rocks are formed from algal remains deposited under anoxic conditions in deep lakes : they tend to generate waxy crude oils when submitted to thermal stress during deep burial.
- Type II source rocks are formed from marine planktonic and bacterial remains preserved under anoxic conditions in marine environments: they produce both oil and gas when thermally cracked during deep burial.
- Type III source rocks are formed from terrestrial plant material that has been decomposed bacteria and fungi under oxic or sub-oxic conditions: they tend to generate mostly gas with associated light oils when thermally cracked during deep burial. Most coals and coaly shales are generally Type III source rocks.

Source rock type: Based on generation of HC

- Potential source rock- Rocks which contain organic matter in sufficient quantity to generate and expel hydrocarbons if subjected to increased thermal maturation.
- Effective source rock- Rock which contain organic matter and is presently generating or expelling hydrocarbons to form commercial exploration.
- Relic effective source rock- An effective source rock which has ceased generating and expelling hydrocarbons due to a thermal cooling event such as uplift or erosion before exhausting its organic matter supply
- Spent source rock- An active source rock which had exhausted its ability to generate and expel hydrocarbons either through lack of sufficient organic matter or due to reaching an overmature stage.

Characterizing source rocks: To be a source rock, a rock must have three features:

Quantity of organic matter

Quality capable of yielding moveable hydrocarbons

Thermal maturity

Source rock characteristics

- The transformation of organic matter with increasing temperature is called maturation.
- During the course of diagenesis, catagenesis and metagenesis, organic matter converts into kerogen and further expel hydrocarbons.
- The assessment of any rock as a source rock is done based on the determination of the amount of organic matter, type of kerogen (insoluble organic matter) or bitumen and the level of maturity.
- The quantity of organic matter is commonly assessed by a measure of the total organic carbon (TOC) contained in a rock. Quality is measured by determining the types of kerogen. Thermal maturity is most often estimated by using vitrinite reflectance measurements and data from pyrolysis.
- The assessment of the rank or maturity is also done with the help of chemical parameters including volatile matter (daf basis) and carbon (daf basis).

Location of Source Rocks

1. Marine Environments

- Deep marine basins with restricted circulation (low oxygen).
- **Example**: Kimmeridge Clay Formation (UK), Monterey Shale (California, USA).

2. Lacustrine Environments

- Freshwater lake basins with algal blooms and anoxic bottom water.
- **Example**: Green River Formation (USA), Songliao Basin (China).

3. Deltaic/Swampy Environments

- Organic matter from plants, deposited in deltas and swamps.
- **Example**: Carboniferous coal beds, West Siberian Basin.

4. Restricted Basins

- Partially enclosed seas with limited oxygen, such as ancient epicontinental seas.
- **Example**: La Luna Formation (Venezuela), Bakken Formation (USA/Canada).

How to Recognize a Good Source Rock:

- **High TOC** ($\geq$ 2%)
- **Kerogen type I or II**
- **Rock is thermally mature** (within oil/gas window)
- **Anoxic depositional setting** (e.g., laminated black shale)

- **Pyrolysis data (e.g., S1+S2, HI values)** support high generation potential
- **Note:** Pyrolysis is a process that uses high temperatures in an environment without oxygen to decompose materials without combustion

Reservoir rocks

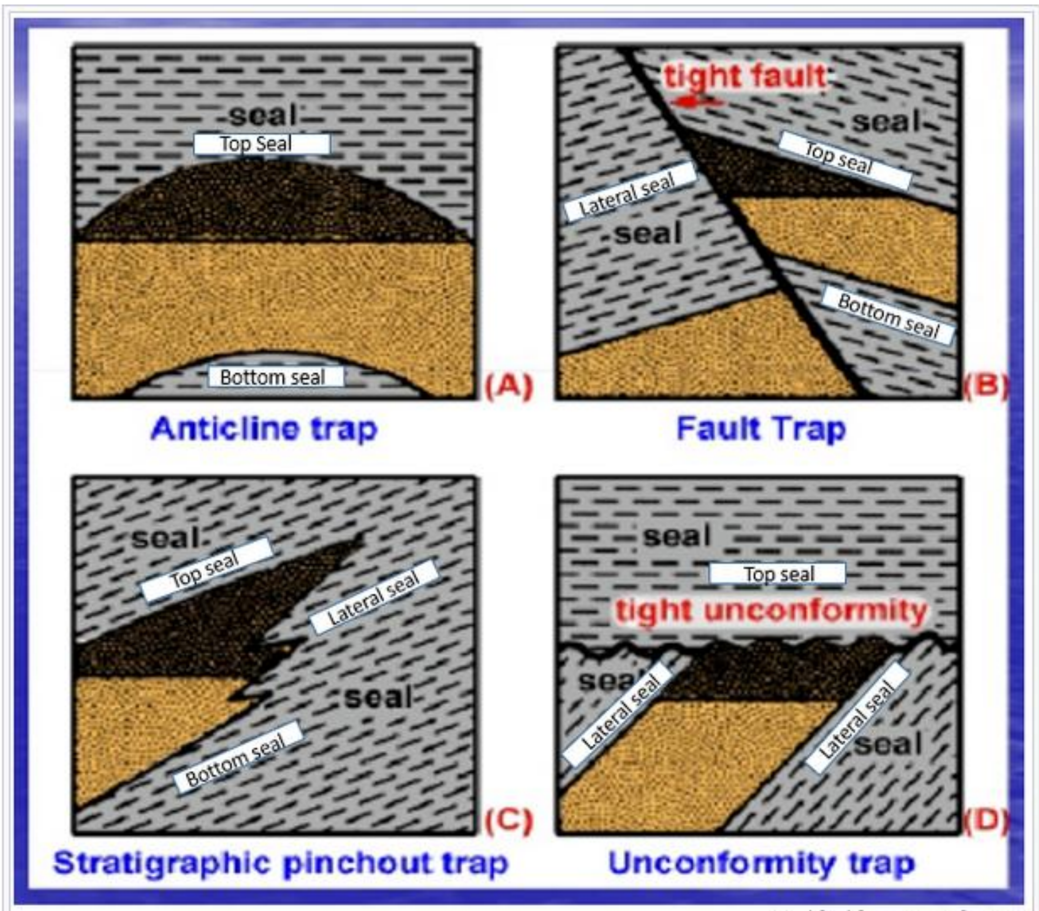
Reservoir rocks are rocks that have the ability to store fluids inside their pores, so that the fluids (water, oil, and gas) can be accumulated. In petroleum geology, reservoir is one of the elements of petroleum system that can accumulate hydrocarbons (oil or gas). Reservoir rock must have good porosity and permeability to accumulate and drain oil in economical quantities.

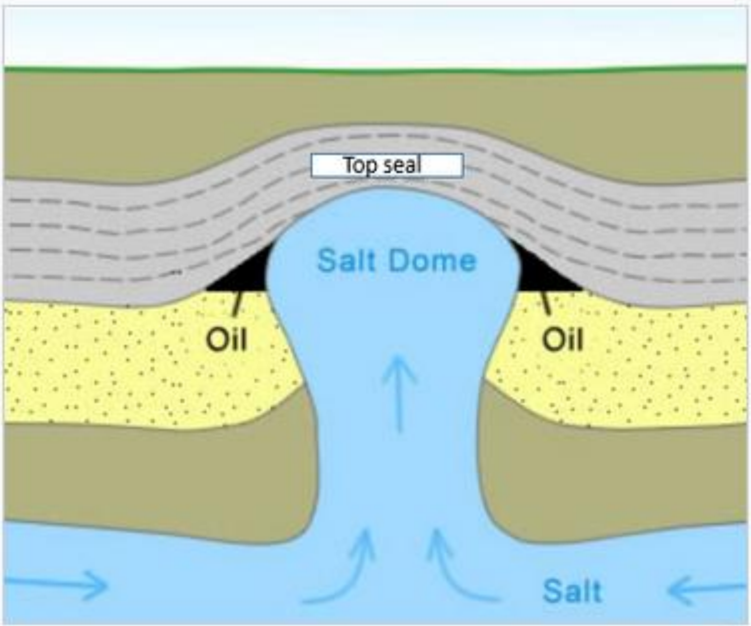
Type of Reservoir Rocks: Siliciclastic reservoir and carbonate reservoir.

Seal rocks

A seal is a relatively impermeable, a seal is a layer of rock that forms a barrier or cap above and around a reservoir rock. Commonly composed of shale, chalks, clays, anhydrite or salt, a seal helps prevent fluids from migrating beyond the reservoir. It is sometimes also referred to as a cap rock.

Seals are closely associated with the traps they surround. Some common traps associated with petroleum systems include structural traps such as folds, anticlines, faults, and diapirs (Figures 1, 2, & 3). Stratigraphic pinchout traps are also common in petroleum systems as well (Figure 1(c)). Traps can have top, lateral and bottom seals. In figure 1 (a), the hydrocarbons are trapped in an anticline and sealed with a top, lateral and bottom seal. Figure 1 (b) shows hydrocarbons trapped by a fault, surrounded by top, lateral, and bottom seals again. Figure 1 (c) shows hydrocarbons trapped in a stratigraphic pinch-out, completely surrounded by the seal. Figure 1 (d) depicts hydrocarbons trapped by a tight unconformity, incased by top and lateral seals. Figure 2 represents a salt diaper trap, in which hydrocarbons are trapped against the salt dome and beneath the overlying top seal. Similarly, Figure 3 represents a shale diaper trap in which hydrocarbons within a heavily fractured shale dome migrate up and are trapped by the overlying top and lateral seals.


seal
Top Seal
Bottom seal
(A)
Anticline trap
tight fault
seal
Top seal
Lateral seal
seal
Bottom seal
(B)
Fault Trap
seal
Top seal
Lateral seal
seal
Bottom seal
(C)
Stratigraphic pinchout trap
seal
Top seal
tight unconformity
Lateral seal
Lateral seal
seal
(D)
Unconformity trap


Top seal
Salt Dome
Oil
Oil
Salt
Figure 2

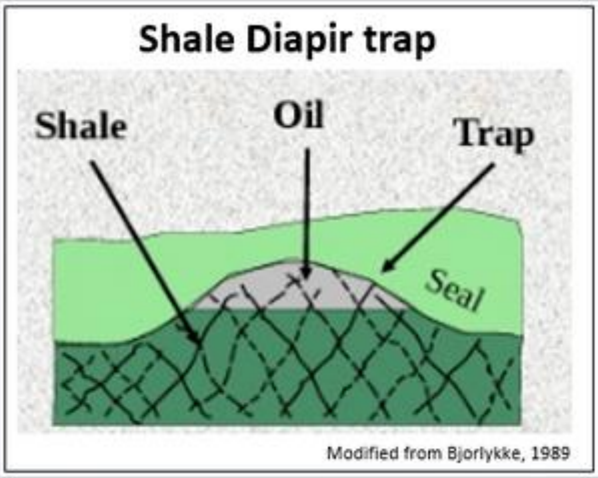


Figure 3

Overburden rocks:

The overburden pressure (OBP) is the stress due to the weight of overlying rock. This is calculated through integration of density, either via analytic extension of logs (1D well calibration mode) or a transform of velocity volume (3D model building mode).

Kerogen: The Source of Hydrocarbons

Kerogen is the solid, insoluble organic matter in sedimentary rocks that generates hydrocarbons when subjected to heat during burial (thermal maturation). It is the precursor to oil and gas. (kerogen, complex waxy mixture of hydrocarbon compounds that is the primary organic component of oil shale. Kerogen consists mainly of paraffin hydrocarbons, though the solid mixture also incorporates nitrogen and sulfur. Kerogen is insoluble in water and in organic solvents such as benzene or alcohol. Upon heating under pressure, however, the large paraffin molecules break down into recoverable gaseous and liquid substances resembling petroleum. This property makes oil shale a potentially important source of synthetic crude oil.)

Formation of Kerogen:

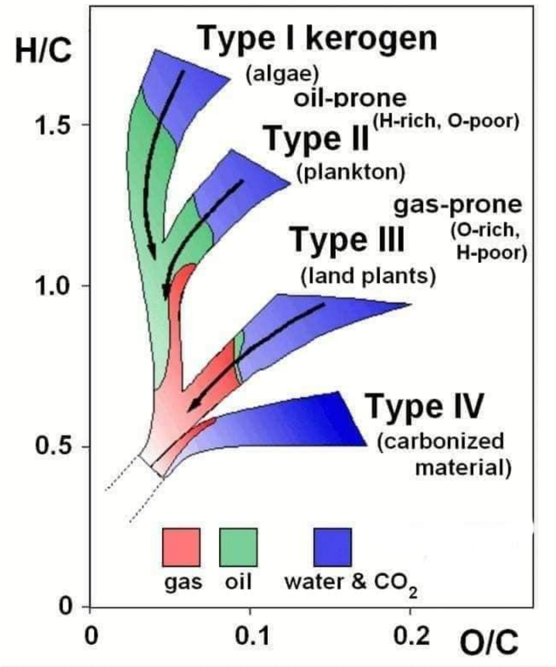
Derived from the accumulation of organic material (plant, plankton, bacteria) in anoxic (low oxygen) environments.

Undergoes diagenesis (early sediment transformation), catagenesis (oil formation), and metagenesis (gas formation).

Types of Kerogen

Type	Origin	Hydrocarbon Potential	Typical Environment
Type I	Algal	High (oil-prone)	Lacustrine (lake)
Type II	Planktonic	Moderate (oil/gas-prone)	Marine
Type III	Terrestrial plants	Low (gas-prone)	Swamps/Deltaic
Type IV	Reworked/oxidized	None (inert)	Oxidized environments

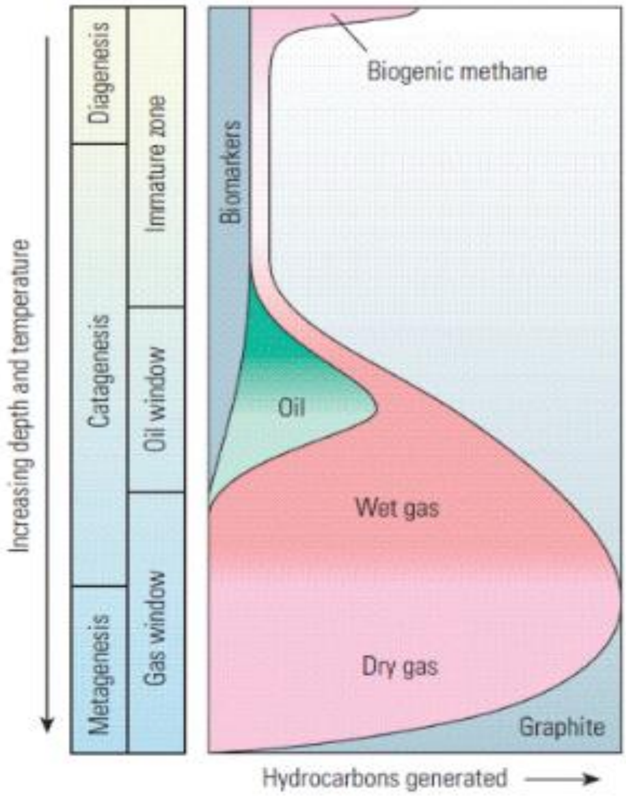
Environment	Kerogen Type	Kerogen Form	Origin	HC Potential
Aquatic	I	Alginite	Algal bodies	Oil
		Amorphous Kerogen	Structureless debris of algal origin	
	II		Structureless planktonic material, primairly of marine origin	
Terrestrial		Exinite	Skins of spores and pollen, cuticle of leaves and herbaceous plants	
	III	Vitrinite	Fibrous and woody plant fragments and structureless, colloidal humic matter	Gas, some oil
				Mainly gas
	IV	Inertinite	Oxidized, recycled woody debris	None



Diagenesis, Catagenesis and Metagenesis of Organic Matter

Diagenesis

The physical, chemical or biological alteration of sediments into sedimentary rock at relatively low temperatures and pressures that can result in changes to the rock's original mineralogy and texture. After deposition, sediments are compacted as they are buried beneath successive layers of sediment and cemented by minerals that precipitate from solution. Grains of sediment, rock fragments and fossils can be replaced by other minerals during diagenesis. Porosity usually decreases during diagenesis, except in rare cases such as dissolution of minerals and dolomitization. Diagenesis does not include weathering processes. Hydrocarbon generation begins during diagenesis. There is not a clear, accepted distinction between diagenesis and metamorphism, although metamorphism occurs at pressures and temperatures higher than those of the outer crust, where diagenesis occurs.



Catagenesis

Catagenesis involves heating in the range of 50 to 150 degC [122 to 302 degF]. At these temperatures, chemical bonds break down in kerogen and clays within shale, generating liquid hydrocarbons. At the high end of this temperature range, secondary cracking of oil molecules can generate gas molecules.

Metagenesis

The last stage of maturation and conversion of organic matter to hydrocarbons. Metagenesis occurs at temperatures of 150 to 200 degC [302 to 392 degF]. At the end of metagenesis, methane, or dry gas, is evolved along with nonhydrocarbon gases such as CO_2, N_2, and H_2S, as oil molecules are cracked into smaller gas molecules.