INTRO TO ENVIRONMENTAL SCIENCE - E&ES 199

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OIL-GAS GEOLOGY

Oil or gas is found predominantly in sedimentary rocks and it is generally believed that it forms from organic precursor material. Requirements for oil/gas formation and accumulation are:

1. source rock
2. primary migration
3. reservoir rock - secondary migration
4. oil trap

Oil and gas are formed from organic material that is commonly present as finely dispersed "dark specks" in sedimentary rocks. This organic material can be the remains of small marine animals and plants, like forams, diatoms, and radiolarians, and such organic matter in rocks is labeled **sapropelic**. The remains of land plants are called **humic**, and are more a potential source of gas than oil. Oil source rocks contain at least 1% organic matter, but no excessive quantities of C_{org} are required for oil formation.

How do we get preservation of C in a marine environment and form a suitable source rock? (C is not stable in the atmosphere or in oxygenated water.)

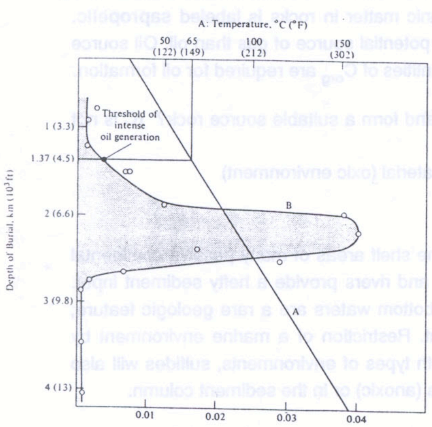
1. Rapid sedimentation and high productivity of organic material (oxic environment)
2. Anoxic environment - slow sedimentation.

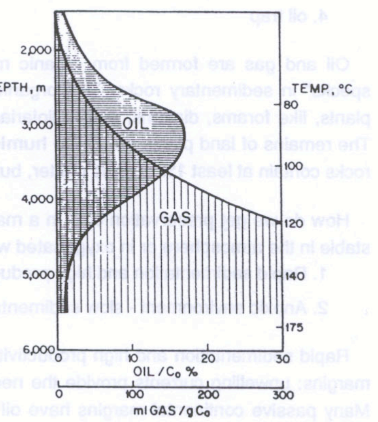
Rapid sedimentation and high productivity is common on the shelf areas of many passive continental margins: upwelling currents provide the neccessary nutrients and rivers provide a hefty sediment input. Many passive continental margins have oil potential! Anoxic bottom waters are a rare geologic feature; the Black Sea is a modern example of such an environment. Restriction of a marine environment by landmasses is required, which doesnot occur too often. In both types of environments, sulfides will also form as a result of sulfate reduction, either in the bottom waters (anoxic) or in the sediment column.

When such a C-rich horizon is subsiding in a sedimentary basin it will warm up and the oil is "cooked" from the organic remains. A black sticky substance is left behind, called kerobitumen. Oil exists of paraffins, waxes, fats, largely saturated chains of C, and some aromatic compounds. Nearly all oils have the same major constituents and variable minor organic compounds. Oil formation is not a 100% efficient process and takes long periods of time.

When a source rock is sinking with other sedimentary layers deeper into the basin sequence, and new layers of sediments are piled on top of it, the pressure of the fluids in the pores is initially **hydrostatic**, but changes to **lithostatic** during compaction. The change from hydrostatic to lithostatic results in expulsion of a large fraction of the pore fluids. If the oil had already formed, oil droplets are expulsed with the formation water, either as a separate phase, as an emulsion or in-solution. Since the expulsion process is P dependent, and the oil-cooking is T dependent, the **geothermal gradient** in the basin is of crucial importance. If oil has not yet formed, but fluid expulsion occurs already, the oil that forms later will become locked into the oil shales. Many formation waters on the Gulf coast contain high levels of dissolved gas (**geopressurized aquifers**), which is presumably the thermal breakdown product of oil that got trapped in a source rock. Most pore waters in source rocks are salty (trapped sea water), and oil is lighter than the water --> floating of oil. Many oil accumulations consist of a cap of gas, a layer of oil, underlain by a thick layer of salty water ("oil brines"). So primary migration is the removal of oil from the source rock by fluid expulsion, and floating of oil droplets through the water column. Usually, primary migration is upwards, although lateral flow also occurs.

The P-T conditions of oil formation are shown in figure 1; the sinking and warming of the organic remains and the slow conversion to oil is called the **maturation cycle** of the source rock. The time period of oil formation for a given temperature is shown in figure 2; oil forms more rapidly at higher temperatures, but if the temperature gets above 130 C, gas will start to form. The optimal conditions are called the *window of oil formation*, cross-hatched in figure 1.





SAPROPELIC H/C > 1

FATS, OILS, RESINS, WAXES, PIGMENTS

HUMIC H/C < 1

PRODUCTS OF PEAT FM. LIGNIN, CELLULOSE, TANNINS, CHARCOAL

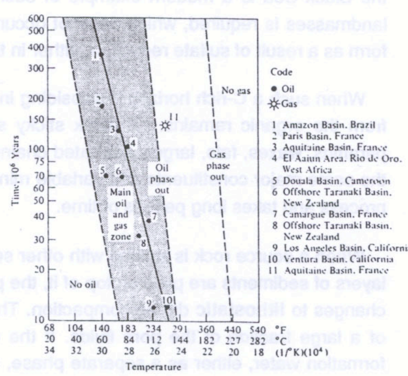


Figure 1: Conditions suitable for oil formation; most efficient ***window of oil formation*** is hatched; the timeperiod needed for oil formation at a given temperature is indicated on figure 2

Figure 2:

Many geologists accept the **biogenic** origin of oil as a fact; a small school of geologists thinks about **abiogenic** oil, involving the conversion of C-bearing substances in the mantle of the earth to methane. Arguments for a biogenic origin of oil are:

1. odd numbered chains of C compounds
2. optical activity
3. preference for a single isomer, e.g., the unique cholesterol isomer
4. a "light" $^{13}C/^{12}C$ signature

These features are characteristic for organic compounds that formed through a biological step (e.g., life).

Once the oil has formed, and droplets have accumulated outside the source rock, we need a **reservoir rock**. Reservoirs are highly porous units usually sandstone, and water with oil can easily move through them, usually upwards. If the reservoir rock is outcropping, an oil seep occurs, and no accumulation will form. Most oil has escaped through geologic history in seeps. If all light oil compounds evaporate in a seep, a tar pit is formed. Geologic conditions where a "clean" porous sandstone overly a C-rich clay bed sequence are commonly present on passive continental margins during a period of **lowering of sealevel**, a so called **regression.** Sea level fluctuations are either the result of large scale tectonic processes (changes in spreading rate at the MOR's) or a result of changes in the water volume of the oceans (Ice ages, water stored on the continents as ice). When the sea retreats, a formerly coastal environment with sedimentation of C-rich clays will be superceded by a shallow environment with coarser (e.g., beach sand) sand deposits. Such **regressive depositional cycles** provide good conditions for the formation of an oil reservoir above an oil source rock.

To form an oil accumulation in a reservoir, an **oil trap** is needed, so that the process of **secondary migration** (movement of the oil with water through the reservoir rock) is stopped. The oil is usually trapped in the reservoir under an impermeable horizon (clay layer) in a suitable structure.

Oil traps are of different types:

1. structural traps
2. stratigraphic traps
3. combination traps

Structural traps are either related to folding or faulting on a regional scale (100 of miles) or to local structures. Rocks can be folded in **anticlines** and **synclines**, and oil present in a folded reservoir will migrate up to the crest of the anticline. If the crest of an anticline is undulated, a series of dome structures occur, with oil accumulating in the top of the dome.

Faults can offset a reservoir against an impermeable horizon, forming a trap. Many complicated structures can function as oil traps. Local structures are salt diapirs, with sedimentary beds domed up above the diapir, and beds ending laterally against the dome, all forming oil traps (see the handout with the cartoons).

Stratigraphic traps are isolated sand bars, changes in porosity or clay content of the reservoir, buried reefs etc. Combination traps are erosional surfaces that cut off older structures, with sediments commonly on top of that surface. **Growth faults** are faults that are active while sedimentation is ongoing, and may lead to a complex diversity of structures that may also serve as combination traps. A famous type of structure is the **baldheaded dome**, where the crest of the undulation has been removed by erosion and the whole structure is subsequently covered by younger sediments.

Oil exploration occurs with conventional mapping techniques, subsurface mapping (seismic) and drilling. Drilling is expensive, so exploratory wells are kept at a minimum. Once a hole has been drilled, it will be **logged** with a logging tool. Well logging involves determination of the character of the penetrated strata, (nuclear logs, electrical logs) especially the porosity.

Texas oil occurs commonly in salt dome structures, Oklahoma oil in large regional structures, whereas in California, much of the oil occurs in the source rock (Monterey formation), which also serves as the reservoir.

How to decide where to drill for oil? On land we can study the rocks at the earth's surface and try to surmise what the rocks at depth look like, but we do not have this possibility at sea, where all rocks are covered with water. We also do not have this possibility where rocks at the surface are not exposed. Therefore we have to use "remote sensing" techniques to infer the character of rocks invisible to the eye.

Oil only occurs in specific rocks and in specific geologic settings. An **oil reservoir** is a rock that contains many spaces that are filled with water and oil. To find a reservoir, we have to search for rock units with a high **porosity** and high **permeability**. The mass of porous rock must be covered in some way, to prevent the oil from escaping to the surface of the earth, and getting out in oil seeps. Therefore the porous rock must be covered with a non-permeable material (also called cap rock). Finally, the structure of the rock layers must be so that the oil cannot escape by following the layers to the surface. For instance, the layers of porous rock covered by non-porous rock can be domed, so that the oil can migrate to the top of the dome (from where it can not escape). So to find oil we must know the nature of the rocks and their structure hundreds of meters below the surface. This is not possible by just using remote sensing techniques, but we can use these techniques in combination with drilling. Once we know what we found in one hole, we can use our remote techniques to predict what we will find over large areas without having to drill more holes.

Methods used routinely include SEISMIC or ACOUSTIC techniques, in which shock waves (from explosions or loud sound) map rocks below the surface. The simplest acoustic equipment is the ECHO SOUNDER, used to find out how deep water below a ship is. It works as follows: a device in the bottom of the ship produces sound, which travels to the bottom of the water, where it is reflected back by the rocks on the bottom. There is a receiver in the ship that records how long it takes the sound to travel to the bottom and come back to the ship. If we know how fast sound travels through water, we can calculate the water depth from the travel time of the sound: 2 x depth = travel time x velocity of sound in water. The speed of sound in sea water is about 1500 m/s, with variations depending on the temperature and salinity of the water and corrections must be made to find the depth precisely. The frequency of the sound used in echo sounders is usually 12 kHz (kiloHertz).

We can use a similar technique to study rocks and their structures on land or on sea: sound waves can travel through the rocks. The source of the sound waves can be explosives, but at sea usually AIRGUNS are used (not so dangerous, and not so bad for the fish in the area). In an airgun, air is