**Unity University**
**Faculty of Engineering**

**Department of Mining Engineering**

# GENERAL GEOLOGY (Geol 2081)

## Chapter 6:

## MINERAL RESOURCES

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# 6. MINERAL RESOURCES

## 6.1. Introduction

How important is mining? Mining is the bedrock of civilization. Without mining there could be no modern agriculture, no production of energy, no factories or offices , no schools or hospitals, no transportation systems or communications networks and no weaponry or national defense. All of mankind's material needs must be dug from the earth, grown in the soil or taken from the sea. We must all remember that our horn of plenty begins with a hole in the ground."

A ***mineral resource*** is a volume of rock enriched in one or more useful materials. In this sense a mineral refers to a useful material, a definition that is different from the way we defined a mineral back in Chapter 3. Here the word mineral can be any substance that comes from the Earth. Mineral resources can be divided into three major categories – Metallic, Nonmetallic, and Energy. Metallic resources are things like Gold, Silver, Tin, Copper, Lead, Zinc, Iron, Nickel, Chromium, and Aluminum. Nonmetallic resources are things like sand, gravel, gypsum, halite, Uranium, dimension stone. Energy minerals like petroleum, coal and geothermal

Finding and exploiting mineral resources requires the application of the principles of geology that you we have discussed throughout this course. Some minerals are used as they are found in the ground, i.e. they require no further processing or very little processing. For example - gemstones, sand, gravel, and salt (halite). Most minerals must be processed before they are used. For example:

- Iron is the found in abundance in minerals, but the process of extracting iron from different minerals varies in cost depending on the mineral. It is least costly to extract the iron from oxide minerals like hematite ($Fe_2O_3$), magnetite ($Fe_3O_4$), or limonite [Fe(OH)]. Although iron also occurs in olivines, pyroxenes, amphiboles, and biotite, the concentration of iron in these minerals is less, and cost of extraction is increased because strong bonds between iron, silicon, and oxygen must be broken.
- Aluminum is the third most abundant mineral in the Earth's crust. It occurs in the most common minerals of the crust - the feldspars ($NaAlSi_3O_8$, $KalSi_3O_8$, & $CaAl_2Si_2O_8$, but the cost of extracting the Aluminum from these minerals is high. Thus, deposits containing the mineral gibbsite [$Al(OH)_3$], are usually sought. This

explains why recycling of Aluminum cans is cost effective, since the Aluminum in the cans does not have to be separated from oxygen or silicon.

Because such things as extraction costs, labor costs, and energy costs vary with time and from country to country, what constitutes an economically viable deposit of minerals varies considerably in time and place. In general, the higher the concentration of the substance, the more economical it is to mine. Thus we define an ***ore*** as a body of material from which one or more valuable substances can be extracted economically. An ore deposit will consist of ore minerals that contain the valuable substance. ***Gangue*** minerals are minerals that occur in the deposit but do not contain the valuable substance.

Since economics is what controls the grade or concentration of the substance in a deposit that makes the deposit profitable to mine, different substances require different concentrations to be profitable. But, the concentration that can be economically mined changes due to economic conditions such as demand for the substance and the cost of extraction.

For every substance we can determine the concentration necessary in a mineral deposit for profitable mining. By dividing this economical concentration by the average crustal abundance for that substance, we can determine a value called the ***concentration factor***. The table below lists average crustal abundances and concentration factors for some of the important materials that are commonly sought. For example, Al, which has an average crustal abundance of 8%, has a concentration factor of 3 to 4. This means that an economic deposit of Aluminum must contain between 3 and 4 times the average crustal abundance, which is between 24 and 32% Aluminum, to be economical.

| Substance | Average Crustal Abundance | Concentration Factor |
|---|---|---|
| Al (Aluminum) | 8.0% | 3 to 4 |
| Fe (Iron) | 5.8% | 6 to7 |
| Ti (Titanium) | 0.86% | 25 to 100 |
| Cr (Chromium) | 0.0096% | 4,000 to 5,000 |
| Zn (Zinc) | 0.0082% | 300 |
| Cu (Copper) | 0.0058% | 100 to 200 |
| Ag (Silver) | 0.000008% | ~1000 |
| Pt (Platinum) | 0.0000005% | 600 |
| Au (Gold) | 0.0000002% | 4,000 to 5,000 |
| U (Uranium) | 0.00016% | 500 to 1000 |

*Note that we will not likely ever run out of a useful substance, since we can always find deposits of any substance that have lower concentrations than are currently economical.*

*If the supply of currently economical deposits is reduced, the price will increase and the concentration factor will increase.*

## 6.2. Metallic Minerals

### 6.2.1. Origin of Metallic Mineral Resources

Mineral deposits can be classified on the basis of the mechanism responsible for concentrating the valuable substance.

- **Magmatic Ore Deposits** - substances are concentrated within a body of igneous rock by magmatic processes like crystal fractionation and crystal settling. Magmatic process such as partial melting, crystal fractionation or crystal settling in a magma chamber can concentrate ore minerals containing valuable substances by taking elements that were once widely dispersed in low concentrations in the magma and concentrating them in minerals that separate from the magma.

  Examples:

  - ***Pegmatites*** - During fractional crystallization water and elements that do not enter the minerals separated from the magma by crystallization will end up as the last residue of the original magma. This residue is rich in silica and water along with elements like the Rare Earth Elements (many of which are important for making phosphors in color television picture tubes), Lithium, Tantalum, Niobium, Boron, Beryllium, Gold, and Uranium. This residue is often injected into fractures surrounding the igneous intrusion and crystallizes as a rock called a pegmatite that characteristically consists of large crystals.

  - Crystal Settling. As minerals crystallize from a magma body, heavy minerals may sink to the bottom of the magma chamber. Such heavy minerals as chromite, olivine, and ilmenite contain high concentrations of Chromium, Titanium, Platinum, Nickel, and Iron. These elements thus attain higher concentrations in the layers that form on the bottom of the magma chamber.

- ***Hydrothermal Ore Deposits*** - Concentration by hot aqueous (water-rich) fluids flowing through fractures and pore spaces in rocks.

  Hydrothermal deposits are produced when groundwater circulates to depth and heats up either by coming near a hot igneous body at depth or by circulating to great depth along the geothermal gradient. Such hot water can dissolve valuable substances throughout a large volume of rock. As the hot water moves into cooler areas of the crust, the dissolved substances are precipitated from the hot water solution. If the cooling takes place rapidly, such as might occur in open fractures or upon reaching a body of cool surface water, then precipitation will take place over a limited area, resulting in a concentration of the substance attaining a higher value than was originally present in the rocks through which the water passed.

Examples:

  - ***Massive sulfide deposits*** at oceanic spreading centers. Hot fluids circulating above the magma chambers at oceanic ridges can scavenge elements like Sulfur, Copper, and Zinc from the rocks through which they pass. As these hot fluids migrate back toward the seafloor, they come in contact with cold groundwater or sea water and suddenly precipitate these metals as sulfide minerals like sphalerite (zinc sulfide) and chalcopyrite (Copper, Iron sulfide).

  - ***Vein deposits*** surrounding igneous intrusions. Hot water circulating around igneous intrusions scavenges metals and silica from both the intrusions and the surrounding rock. When these fluids are injected into open fractures, they cool rapidly and precipitate mainly quartz, but also a variety of sulfide minerals, and sometimes gold, and silver within the veins of quartz. Rich deposits of copper, zinc, lead, gold, silver, tin, mercury, and molybdenum result.

  - ***Stratabound ore deposits*** in lake or oceanic sediments. When hot groundwater containing valuable metals scavenged along their flow paths enters unconsolidated sediments on the bottom of a lake or ocean, it may precipitate ore minerals in the pore spaces between grains in the sediment. Such minerals may contain high concentrations of lead, zinc, and copper, usually in sulfide minerals like galena (lead sulfide), sphalerite (zinc sulfide), and chalcopyrite (copper-iron sulfide). Since they are included within the sedimentary strata they are called stratabound mineral deposits.

- ***Sedimentary Ore Deposits*** - substances are concentrated by chemical precipitation from lake or sea water.

  Although clastic sedimentary processes can form mineral deposits, the term sedimentary mineral deposit is restricted to chemical sedimentation, where minerals containing valuable substances are precipitated directly out of water.

  Examples:

  - ***Evaporite Deposits*** - Evaporation of lake water or sea water results in the loss of water and thus concentrates dissolved substances in the remaining water. When the water becomes saturated in such dissolved substance they precipitate from the water. Deposits of halite (table salt), gypsum (used in plaster and wall board), borax (used in soap), and sylvite (potassium chloride, from which potassium is extracted to use in fertilizers) result from this process.

    - ***Iron Formations*** - These deposits are of iron rich chert and a number of other iron bearing minerals that were deposited in basins within continental crust during the Proterozoic (2 billion years or older). They appear to be evaporite type deposits, but if so, the composition of sea water must have been drastically different than it is today.

- ***Placer Ore Deposits*** - substances are concentrated by flowing surface waters either in streams or along coastlines.

  The velocity of flowing water determines whether minerals are carried in suspension or deposited. When the velocity of the water slows, large minerals or minerals with a higher density are deposited. Heavy minerals like gold, diamond, and magnetite of the same size as a low density mineral like quartz will be deposited at a higher velocity than the quartz, thus the heavy minerals will be concentrated in areas where water current velocity is low. Mineral deposits formed in this way are called placer deposits. They occur in any area where current velocity is low, such as in point bar deposits, between ripple marks, behind submerged bars, or in holes on the bottom of a stream. The California gold rush in 1849 began when someone discovered rich placer deposits of gold in streams draining the Sierra Nevada Mountains. The gold originally formed in hydrothermal veins, but it was eroded out of the veins and carried in streams where it was deposited in placer deposits.

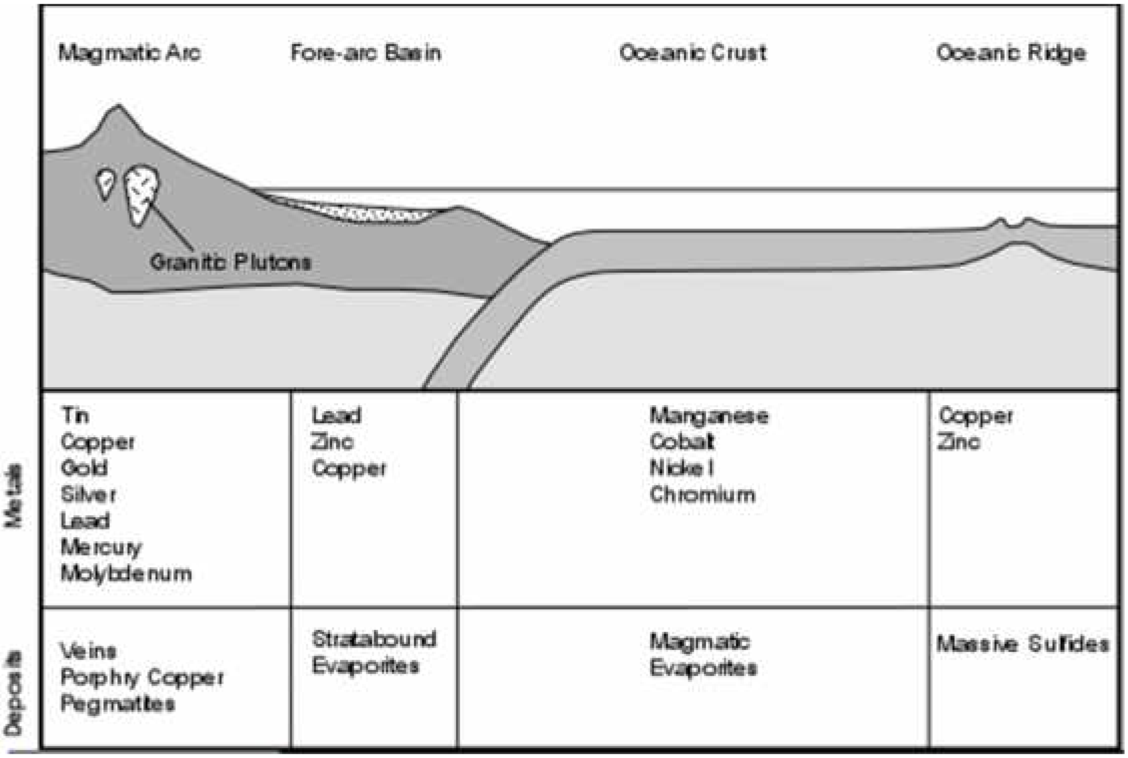
- ***Residual Ore Deposits*** - substances are concentrated by chemical weathering processes.

  During chemical weathering and original body of rock is greatly reduced in volume by the process of leaching, which removes ions from the original rock. Elements that are not leached form the rock thus occur in higher concentration in the residual rock. The most important ore of Aluminum, ***bauxite***, forms in tropical climates where high temperatures and high water throughput during chemical weathering produces highly leached lateritic soils rich in both iron and aluminum. Most bauxite deposits are relatively young because they form near the surface of the Earth and are easily removed by erosion acting over long periods of time.

  In addition, an existing mineral deposit can be turned in to a more highly concentrated mineral deposit by weathering in a process called ***secondary enrichment***.

## Mineral Deposits and Plate Tectonics

Because different types of mineral deposits form in different environments, plate tectonics plays a critical role in the location of different geological environments. The diagram to the right shows the different mineral deposits that occur in different tectonic environments.



| | Magmatic Arc | Fore-arc Basin | Oceanic Crust | Oceanic Ridge |
|---|---|---|---|---|
| Metals | Tin<br>Copper<br>Gold<br>Silver<br>Lead<br>Mercury<br>Molybdenum | Lead<br>Zinc<br>Copper | Manganese<br>Cobalt<br>Nickel<br>Chromium | Copper<br>Zinc |
| Deposits | Veins<br>Porphry Copper<br>Pegmatites | Stratabound<br>Evaporites | Magmatic<br>Evaporites | Massive Sulfides |

## 6.2.2. Mineral Exploration and Production

Ores are located by evidence of metal enrichment. Geologists look for hints in rocks exposed near the surface, for example, the enrichment process often results in discoloration of the soil and rock. When such hints are found, geophysical surveys involving measuring gravity, magnetism, or radioactivity are conducted. Geochemical surveys are conducted which analyze the composition of water, sediment, soil, rocks, and sometimes even plants and trees. Once it is determined that a valuable material could be present, the deposit is assessed by conducting core drilling to collect subsurface samples, followed by chemical analysis of the samples to determine the grade of the ore If the samples show promise of being economic to mine, then plans are made to determine how it will me mined.

If the ore body is within 100 meters from the surface, open-pit mines, large excavations open to the air are used to extract the ore before processing. Open pit mines are less expensive and less dangerous than tunnel mines, although they do leave large scars on the land surface. If the ore body is deeper, or narrowly dispersed within the non-ore bearing rock tunneling is necessary to extract the ore from underground mines. Mine tunnels are linked to a vertical shaft, called and adit. Ores are removed from the walls of the tunnels by drilling and blasting, with the excavated ores being hauled to the surface from processing. Underground mines are both more expensive and dangerous than open pit mines and still leave scares on the landscape where non-ore bearing rock are discarded as tailings. .

## Global Mineral Needs

Because the processes that form ores operate on geologic time scales, the most economic mineral resources are essentially nonrenewable. New deposits cannot be generated in human timescales. But, as mentioned previously, as the reserves of materials become depleted it is possible to find other sources that are more costly to exploit. Furthermore, mineral resources are not evenly distributed. Some countries are mineral-rich; some are mineral-poor. This is a particular issue for strategic mineral resources. These strategic metals are those for which economical source do not exist in the U.S., must be imported from other potentially non-friendly nations, but are needed for highly specialized applications such as national security, defense, or aerospace applications. These metals include, Manganese, Cobalt, Platinum, and Chromium, all of which are stockpiled by the U.S. government in case supplies are cut off.

How long current mineral resources will last depends on consumption rates and reserve amounts. Some mineral resources will run out soon, for example global resources of Pb, Zn, and Au? will likely run out in about 30 years. U.S. resources of Pt, Ni, Co, Mn, Cr less than 1 year. Thus, continued use of scarce minerals will require discovery of new sources, increase in price to make hard-to-obtain sources more profitable, increased efficiency, conservation, or recycling, substitution of new materials, or doing without.

## Environmental Issues

Extraction and processing has large environmental impacts in terms of such things as air quality, surface water quality, groundwater quality, soils, vegetation, and aesthetics. Acid mine drainage is one example; Sulfide minerals newly exposed to Oxygen and water near the surface create sulfuric acid. Rainwater falling on the mine tailings becomes acidified and can create toxic conditions in the runoff. This can mobilize potentially dangerous heavy metals and kill organisms in the streams draining the tailings.

## 6.3. Energy Resources

### 6.3.1. Fossil Fuels

To produce a fossil fuel, the organic matter must be rapidly buried in the Earth so that it does not oxidize (react with oxygen in the atmosphere). Then a series of slow chemical reactions occur which turn the organic molecules into hydrocarbons- Oil and Natural Gas, together called Petroleum. ***Hydrocarbons*** are complex organic molecules that consist of chains of hydrogen and carbon.

Petroleum (oil and natural gas) consists of many different such hydrocarbons, but the most important of these are a group known as the paraffins. ***Paraffins*** have the general chemical formula:

$$C_nH_{2n+2}$$

As the value of n in the formula increases, the following compounds are produced:

| n | Formula | Compound | Use |
|---|---|---|---|
| 1 | $CH_4$ | methane | Natural Gas |
| 2 | $C_2H_6$ | ethane | |
| 3 | $C_3H_8$ | propane | |
| 4 | $C_4H_{10}$ | butane | |
| 5 | $C_5H_{12}$ | pentane | Gasoline |
| 6 | $C_6H_{14}$ | hexane | |
| 7 | $C_7H_{16}$ | heptane | |
| 8 | $C_8H_{18}$ | octane | |
| 9 | $C_9H_{20}$ | nonane | |
| >9 | various | various | Lubricating Oils, Plastics |

When we extract petroleum containing these compounds and add oxygen to it, either in furnaces, stoves, or carburetors the following reaction takes place:

$$\underset{\text{Hydrocarbon}}{C_nH_{2n+2}} + \underset{\text{Oxygen}}{\frac{3n+1}{2}O_2} \longrightarrow \underset{\text{Carbon Dioxide}}{nCO_2} + \underset{\text{Water}}{(n+1)H_2O} + \text{Energy}$$

**Formation of Petroleum**

The process of petroleum formation involves several steps:

- Organic matter from organisms must be produced in great abundance.
- This organic matter must be buried rapidly before oxidation takes place.
- Slow chemical reactions transform the organic material into the hydrocarbons found in petroleum.

The organic matter that eventually becomes petroleum is derived from photosynthetic microscopic organisms, like plankton and bacteria, originally deposited along with clays in the oceans. The resulting rocks are usually black shales that form the petroleum source rock. As the black shale is buried to depths of 2 to 4 km it is heated. This heating breaks the organic material down into waxy kerogen. Continued heating breaks down the kerogen with different compounds forming in different temperatures ranges -

Oil and gas – 90° to 160°C.
Gas only – 160° to 250°C.
Graphite – >250°C.

If temperatures get higher than the petroleum forming window (90 to 150 °C ) then only graphite forms, which is not a useful hydrocarbon. Thus oil is not formed during metamorphism and older rocks that have been heated will also lose their oil forming potential. Most oil and gas is not found in the source rock. Although black shales (oil shales) are found, it is difficult to extract the oil from such rock. Nature, however, does separate the oil and gas. As a result of compaction of the sediments containing the petroleum, the oil and natural gas are forced out and migrate into a reservoir rock.

**Petroleum Reservoirs**

Reservoir rock contains pore space between the mineral grains (this is called ***porosity***). It is within this pore space that fluids are stored. Sands and sandstones are the best reservoir rocks because of the pore space left around the rounded sand grains. Highly fractured rock of also a good reservoir rock, because the fractures provide lots of open space. Limestone, if it has often been partially dissolved, also has high porosity.

Another essential property of reservoir rock is that it must have good permeability. ***Permeability*** is the degree of interconnections between the pores. Low permeability means that the fluids cannot easily get into or out of the pore spaces. Highly cemented sandstones, unweatherd limestones, and unfractured rock have low permeability.

Since oil and natural gas have a density lower than that of water, the petroleum migrates upward. It would continue upward and seep out at the surface where it would oxidize, if it were not for some kind of trap that keeps it in the Earth until it is extracted.

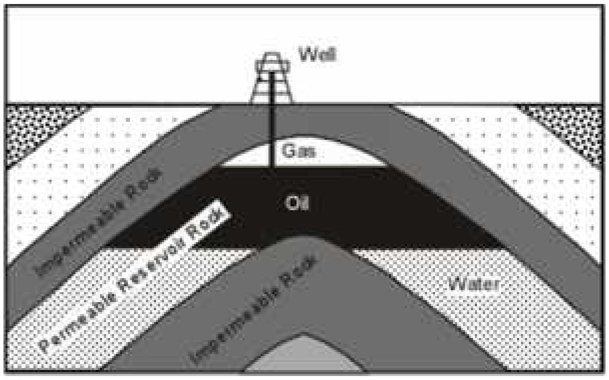
## Oil Traps

An oil or gas reserve requires trapping in the reservoir. A trap is a geological configuration that holds oil and gas. It must be overlain by impermeable rock called a seal or cap rock, which prevents the petroleum from migrating to the surface. Exploration for petroleum reservoirs requires geologists to find trap and seal configurations where petroleum may be found.

Oil traps can be divided into those that form as a result of geologic structures like folds and faults, called ***structural traps***, and those that form as a result of stratigraphic relationships between rock units, called ***stratigraphic trap****s*. If petroleum has migrated into a reservoir formed by one of these traps, note that the petroleum, like groundwater, will occur in the pore spaces of the rock. Natural gas will occur above the oil, which in turn will overly water in the pore spaces of the reservoir. This occurs because the density of natural gas is lower than that of oil, which is lower than that of water.

### ***Structural Traps***

Anticlines - If a permeable reservoir rocks like a sandstone or limestone is sandwiched between impermeable rock layers like shales or mudstones, and the rocks are folded into an anticline, petroleum can migrate upward in the permeable reservoir rocks, and will occur in the hinge region of the anticline.

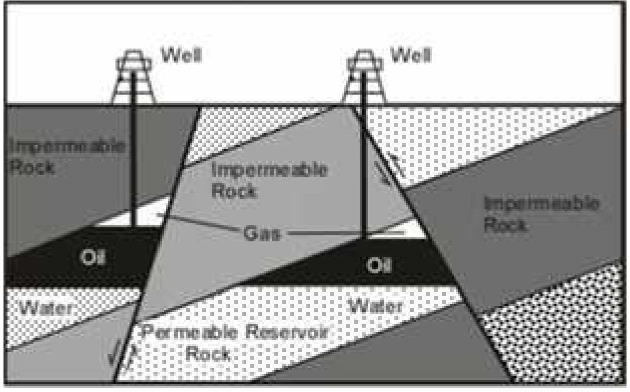


Since anticlines in the subsurface can often be found by observing the orientation of rocks on the surface, anticlinal traps were among the first to be exploited by petroleum geologists.

## Fault Traps

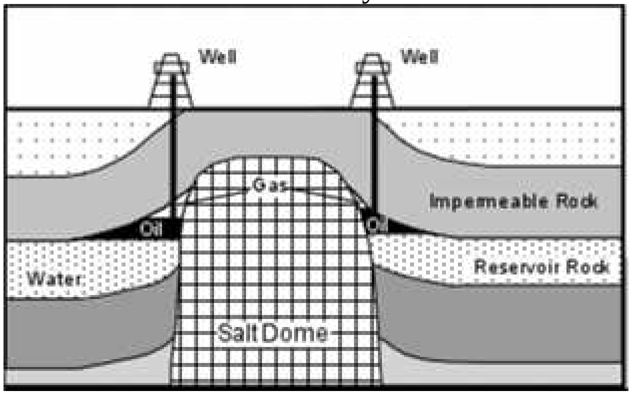
If faulting can juxtapose permeable and impermeable rocks so that the permeable rocks always have impermeable rocks above them, then an oil trap can form. Note that both normal faults and reverse faults can form this type of oil trap.

Since faults are often exposed at the Earth's surface, the locations of such traps can often be found from surface exploration.



Salt Domes - During the Jurassic Period, the Gulf of Mexico was a restricted basin. This resulted in high evaporation rates & deposition of a thick layer of salt on the bottom of the basin. The salt was eventually covered with clastic sediments. But salt has a lower density than most sediments and is more ductile than most sedimentary rocks.

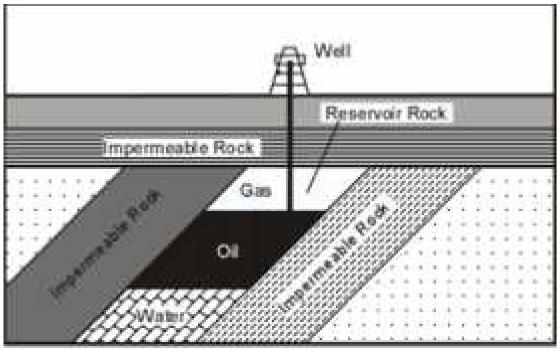
Because of its low density, the salt moved upward through the sedimentary rocks as salt domes. The intrusion of the salt deforms the sedimentary strata along its margins, folding it upward to create oil traps. Because some salt domes get close to the surface, surface sediments overlying the salt dome are often domed upward, making the locations of the subsurface salt and possible oil traps easy to locate.



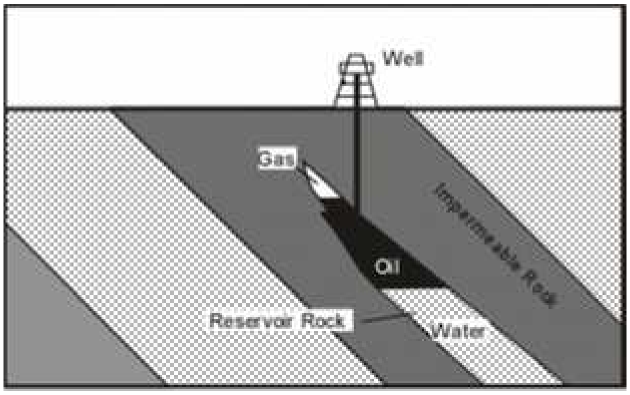
## Stratigraphic Traps

- Unconformities - An angular unconformity might form a suitable oil trap if the layers above the unconformity are impermeable rocks and permeable rocks layer are sandwiched between impermeable layers in the inclined strata below the unconformity.

This type of trap is more difficult to locate because the unconformity may not be exposed at the Earth's surface. Locating possible traps like this usually requires subsurface exploration techniques, like drilling exploratory wells or using seismic waves to see what the structure looks like.



- Lens Traps
  Layers of sand often form lens like bodies that pinch out. If the rocks surrounding these lenses of sand are impermeable and deformation has produced inclined strata, oil and natural gas can migrate into the sand bodies and will be trapped by the impermeable rocks.



This kind of trap is also difficult to locate from the surface, and requires subsurface exploration techniques.

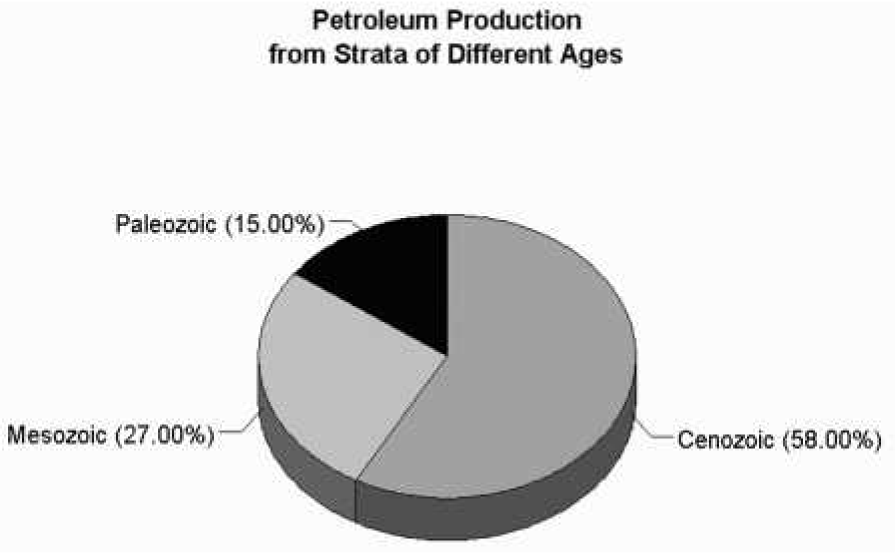
### Petroleum Distribution

As we have seen, in order to form a petroleum reserve, the development of four features is necessary:

1. Formation of a source rock.
2. Formation of a migration pathway so that the petroleum can move upwards
3. Filling a suitable reservoir rock with petroleum.
4. Development of an oil trap to prevent the oil from migrating out of the reservoir.

Because these features must develop in the specified order, development of an oil reserve is geologically rare. As a result, petroleum reserves are geographically limited. The largest known reserves are currently in the Persian Gulf.

Although the distribution of petroleum reserves is widespread, the ages of the petroleum and the reservoirs is somewhat limited. Since older rocks have had more time to erode or metamorphose, most reservoirs of petroleum occur in younger rocks. Most petroleum is produced from rocks of Cenozoic age, with less produced from rocks of Mesozoic and Paleozoic age**.**



## Oil Shale and Tar Sands

- *Oil shale* is shale that contains abundant organic matter that has not decomposed completely to produce petroleum. Oil can be extracted from oil shales, but they must be heated to high enough temperatures to drive the oil out. Since this process requires a lot of energy, exploitation of oil shales is not currently cost-effective, but may become so as other sources of petroleum become depleted. Known deposits of oil shale are extensive.

- ***Tar Sands*** are sandstones that have thick accumulations of viscous oil in their pore spaces. Extraction of this oil also requires heating the rock and is therefore energy intensive and not currently cost effective.

## Coal

***Coal*** is a sedimentary rock produced in swamps where there is a large-scale accumulation of organic matter from plants. As the plants die they accumulate to first become peat. Compaction of the peat due to burial drives off volatile components like water and methane, eventually producing a black- colored organic- rich coal called ***lignite***. Further compaction and heating results in a more carbon- rich coal called ***bituminous coal***. If the rock becomes metamorphosed, a high grade coal called ***anthracite*** is produced. However, if temperatures and pressures become extremely high, all of the carbon is converted to graphite. Graphite will burn only at high temperatures and is therefore not useful as an energy source. Anthracite coal produces the most energy when burned, with less energy produced by bituminous coal and lignite.

Coal is found in beds called ***seams,*** usually ranging in thickness from 0.5 to 3m, although some seams reach 30 m. The major coal producing period in geologic history was during the Carboniferous and Permian Periods, the continents were apparently located near the equator and covered by shallow seas. This type of environment favored the growth of vegetation and rapid burial to produce coal. Known reserves of coal far exceed those of other fossil fuels, and may be our best bet for an energy source of the future. Still, burning of the lower grades of coal, like lignite and bituminous coal produces large amounts of waste products, like $SO_2$ and soot that pollute the atmosphere. This problem needs to be overcome before we can further exploit this source of energy.

Mining of coal is still a problem from an aesthetic point of view. Seams near the surface are often strip mined and backfilled, leaving temporary scars on the landscape. Deep coal seams have to be mined through tunnels, which often collapse, catch fire, or explode as a result of ignition of coal dust or methane released from the coal. Coal miners often suffer from black-lung disease from years of breathing coal dust.

### 6.3.2. Geothermal Energy

**Geothermal energy** is thermal energy generated and stored in the Earth. Thermal energy is the energy that determines the temperature of matter. The Geothermal energy of the Earth's crust originates from the original formation of the planet (20%) and from radioactive decay of minerals (80%). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. The adjective *geothermal* originates from the Greek roots *γη (ge)*, meaning earth, and *θερμος (thermos)*, meaning hot.

At the core of the Earth, thermal energy is created by radioactive decay and temperatures may reach over 5000 degrees Celsius (9,000 degrees Fahrenheit). Heat conducts from the core to surrounding cooler rock. The high temperature and pressure cause some rock to melt, creating magma convection upward since it is lighter than the solid rock. The magma heats rock and water in the crust, sometimes up to 370 degrees Celsius (700 degrees Fahrenheit).

## NATURE OF GEOTHERMAL RESOURCES

The *geothermal gradient* expresses the increase in temperature with depth in the Earth's crust. Down to the depths accessible by drilling with modern technology, i.e. over 10,000 m, the average geothermal gradient is about 2.5-3 °C/100 m. For example, if the temperature within the first few metres below ground-level, which on average corresponds to the mean annual temperature of the external air, is 15 °C, then we can reasonably assume that the temperature will be about 65°-75 °C at 2000 m depth, 90°-105 °C at 3000 m and so on for a further few thousand metres. There are, however, vast areas in which the geothermal gradient is far from the average value. In areas in which the deep rock basement has undergone rapid sinking, and the basin is filled with geologically 'very young' sediments, the geothermal gradient may be lower than 1 °C/100 m. On the other hand, in some 'geothermal areas' the gradient is more than ten times the average value.

The difference in temperature between deep hotter zones and shallow colder zones generates a conductive flow of heat from the former towards the latter, with a tendency to create uniform conditions, although, as often happens with natural phenomena, this situation is never actually attained. The mean *terrestrial heat flow* of continents and oceans is 65 and 101 $mWm^{-2}$, respectively, which, when areally weighted, yield a global mean of 87 $mWm^{-2}$ (Pollack *et al.*, 1993). These values are based on 24,774 measurements at 20,201 sites covering about 62% of the Earth's surface. Empirical estimators, referenced to geological map units, enabled heat flow to be estimated in areas without measurements. The heat flow analysis by Pollack et al. (1993) is the most recent in print form. The University of North Dakota is currently providing access via internet to an updated heat flow database comprising data on oceanic and continental areas.

The temperature increase with depth, as well as volcanoes, geysers, hot springs, etc., are in a sense the visible or tangible expression of the heat in the interior of the Earth, but this heat also engenders other phenomena that are less discernible by man, but of such magnitude that the Earth has been compared to an immense 'thermal engine'. We will try to describe these phenomena, referred to collectively as the *plate tectonics* theory, in simple terms, and their relationship with geothermal resources.

Our planet consists of a *crust*, which reaches a thickness of about 20-65 km in continental areas and about 5-6 km in oceanic areas, a *mantle*, which is roughly 2900 km thick, and a *core*, about 3470 km in radius. The physical and chemical characteristics of the crust, mantle and core vary from the surface of the Earth to its centre. The outermost shell of the Earth, known as the *lithosphere*, is made up of the crust and the upper layer of the mantle. Ranging in thickness from less than 80 km in oceanic zones to over 200 km in continental areas, the lithosphere behaves as a rigid body. Below the lithosphere is the zone known as the *asthenosphere*, 200-300 km in thickness, and of a 'less rigid' or 'more plastic' behaviour. In other words, on a geological scale in which time is measured in millions of years, this part of the Earth behaves in much the same way as a fluid in certain processes.

Because of the difference in temperature between the different parts of the asthenosphere, convective movements and, possibly, convective cells were formed some tens of millions of years ago. Their extremely slow movement (a few centimetres per year) is maintained by the heat produced continually by the decay of the radioactive elements and the heat coming from the deepest parts of the Earth. Immense volumes of deep hotter rocks, less dense and lighter than the surrounding material, rise with these movements towards the surface, while the colder, denser and heavier rocks near the surface tend to sink, re-heat and rise to the surface once again, very similar to what happens to water boiling in a pot or kettle.

In zones where the lithosphere is thinner, and especially in oceanic areas, the lithosphere is pushed upwards and broken by the very hot, partly molten material ascending from the asthenosphere, in correspondence to the ascending branch of convective cells. It is this mechanism that created and still creates the *spreading ridges* that extend for more than 60,000 km beneath the oceans, emerging in some places (Azores, Iceland) and even creeping between continents, as in the Red Sea. A relatively tiny fraction of the molten rocks upwelling from the asthenosphere emerges from the crests of these ridges and, in contact with the seawater, solidifies to form a new oceanic crust. Most of the material rising from the asthenosphere, however, divides into two branches that flow in opposite directions beneath the lithosphere. The continual generation of new crust and the pull of these two branches in opposite directions has caused the ocean beds on either side of the ridges to drift apart at a rate of a few centimetres per year. Consequently, the area of the ocean beds (the oceanic lithosphere) tends to increase. The ridges are cut perpendicularly by enormous fractures, in some cases a few thousand kilometres in length, called *transform faults*. These phenomena lead to a simple observation: since there is apparently no increase in the Earth's surface with time, the formation of new lithosphere along the ridges and the spreading of the ocean beds must be accompanied by a comparable shrinkage of the lithosphere in other parts of the globe. This is indeed what happens in *subduction zones*, the largest of which are indicated by huge ocean trenches, such as those extending along the western margin of the Pacific Ocean and the western coast of

South America. In the subduction zones the lithosphere folds downwards, plunges under the adjacent lithosphere and re-descends to the very hot deep zones, where it is "digested" by the mantle and the cycle begins all over again. Part of the lithospheric material returns to a molten state and may rise to the surface again through fractures in the crust. As a consequence, *magmatic arcs* with numerous volcanoes are formed parallel to the trenches, on the opposite side to that of the ridges. Where the trenches are located in the ocean, as in the Western Pacific, these magmatic arcs consist of chains of volcanic islands; where the trenches run along the margins of continents the arcs consist of chains of mountains with numerous volcanoes, such as the Andes.

Spreading ridges, transform faults and subduction zones form a vast network that divides our planet into six immense and several other smaller lithospheric areas or *plates* (Figure below). Because of the huge tensions generated by the Earth's thermal engine and the asymmetry of the zones producing and consuming lithospheric material, these plates drift slowly up against one another, shifting position continually. The margins of the plates correspond to weak, densely fractured zones of the crust, characterized by an intense seismicity, by a large number of volcanoes and, because of the ascent of very hot materials towards the surface, by a high terrestrial heat flow. As shown in Figure below, the most important geothermal areas are located around plate margins.

## GEOTHERMAL SYSTEMS

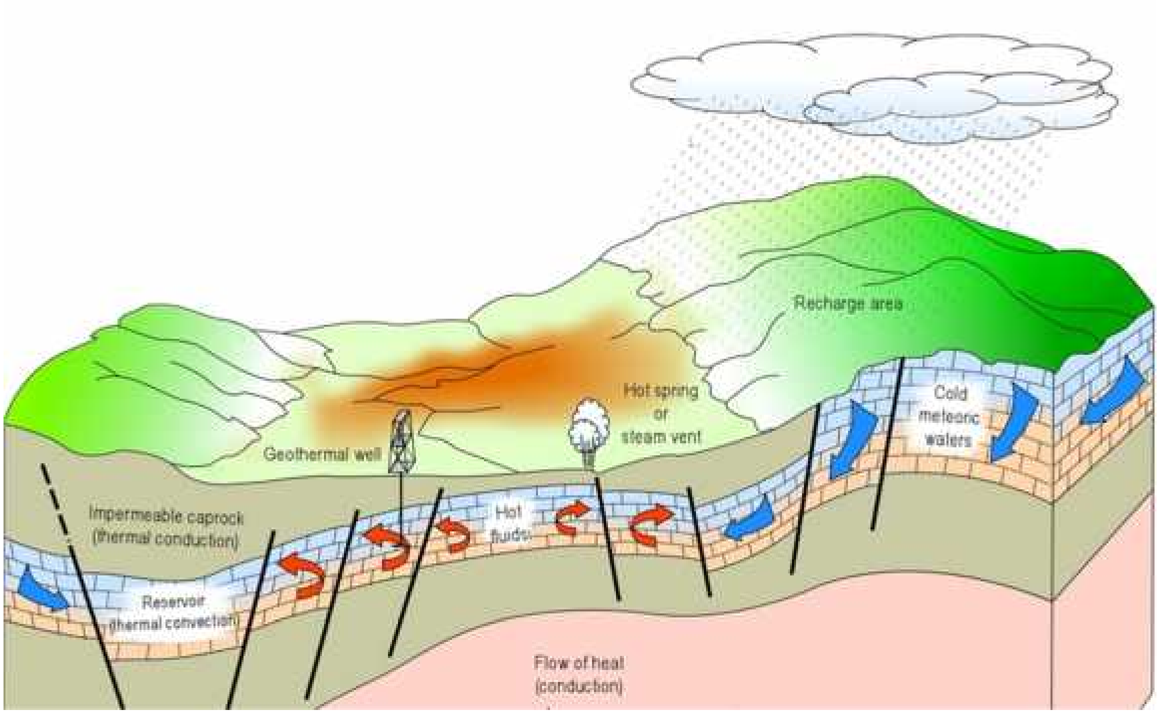
Geothermal systems can therefore be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case the systems will be characterised by low temperatures, usually no higher than 100 °C at economic depths; in the second case the temperatures could cover a wide range from low to very high, and even above 400 °C.

What is a *geothermal system* and what happens in such a system? It can be described schematically as '*convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface*' (Hochstein, 1990). A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid*, which is the carrier that transfers the heat. The heat source can be either a very high temperature (> 600 °C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, as in certain low-temperature systems, the Earth's normal temperature, which, as we explained earlier, increases with depth. The reservoir is a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is generally overlain by a cover of impermeable rocks and connected to a surficial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir through springs or are extracted by boreholes. The geothermal fluid is water, in the majority of cases meteoric water, in the liquid or vapour phase, depending on its temperature and pressure. This water often carries with it chemicals and gases such as $CO_2$, $H_2S$, etc. Figure 6 is a greatly simplified representation of an ideal geothermal system. The mechanism underlying geothermal systems is by and large governed by *fluid convection*. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. The phenomenon we have just described may seem quite a simple one but the reconstruction of a good model of a real geothermal system is by no means easy to achieve. It requires skill in many disciplines and a vast experience, especially when dealing with high -temperature systems. Geothermal systems also occur in nature in a variety of combinations of geological, physical and chemical characteristics, thus giving rise to several different types of system.

Of all the elements of a geothermal system, the heat source is the only one that need be natural. Providing conditions are favourable, the other two elements could be 'artificial'. For example, the geothermal fluids extracted from the reservoir to drive the turbine in a geothermal power-plant could, after their utilization, be injected back into the reservoir through specific *injection wells*. In this way the natural recharge of the reservoir is integrated by an artificial recharge. For many years now re-injection has also been adopted in various parts of the world as a means of drastically reducing the impact on the environment of geothermal plant operations.

Artificial recharge through injection wells can also help to replenish and maintain 'old' or 'exhausted' geothermal fields. For example, in The Geysers field in California, USA, one of the biggest geothermal fields in the world, production began to decline dramatically at the end of the 1980s because of a lack of fluids. The first project of this type, the Southeast Geysers Effluent Recycling Project, was launched in 1997, to transport treated wastewater for 48 km to the geothermal field. This project has led to the reactivation of a number of power plants that had been abandoned because of a lack of fluids. In the second system, the Santa Rosa Geysers Recharge Project, 41.5 million litres per day of tertiary treated waste-water will be pumped from the Santa Rosa regional sewage treatment plant and other cities through a 66-km pipeline to The Geysers field, where it will recharge the reservoir through specially drilled boreholes.

In the so-called *Hot Dry Rock* (HDR) projects, which were experimented for the first time at Los Alamos, New Mexico, USA, in 1970, both the fluid and the reservoir are artificial. High-pressure water is pumped through a specially drilled well into a deep body of hot, compact rock, causing its *hydraulic fracturing*. The water permeates these artificial fractures, extracting heat from the surrounding rock, which acts as a natural reservoir. This 'reservoir' is later penetrated by a second well, which is used to extract the heated water. The system therefore consists of (i) the borehole used for hydraulic fracturing, through which cold water is injected into (ii) the artificial reservoir, and (iii) the borehole used to extract the hot water.



*Schematic representation of an ideal geothermal system.*

## UTILIZATION OF GEOTHERMAL RESOURCES

Electricity generation is the most important form of utilization of high-temperature geothermal resources (> 150 °C). The medium-to-low temperature resources (< 150 °C) are suited to many different types of application. The classical Lindal diagram (Lindal, 1973), which shows the possible uses of geothermal fluids at different temperatures, still holds valid (Figure 10, derived from the original Lindal diagram, with the addition of electricity generation from binary cycles. Fluids at temperatures below 20 °C are rarely used and in very particular conditions or in heat pump applications. The Lindal diagram emphasises two important aspects of the utilization of geothermal resources (Gudmundsson, 1988): (a) with cascading and combined uses it is possible to enhance the feasibility of geothermal projects and (b) the resource temperature may limit the possible uses. Existing designs for thermal processes can, however, be modified for geothermal fluid utilization in certain cases, thus widening its field of application.

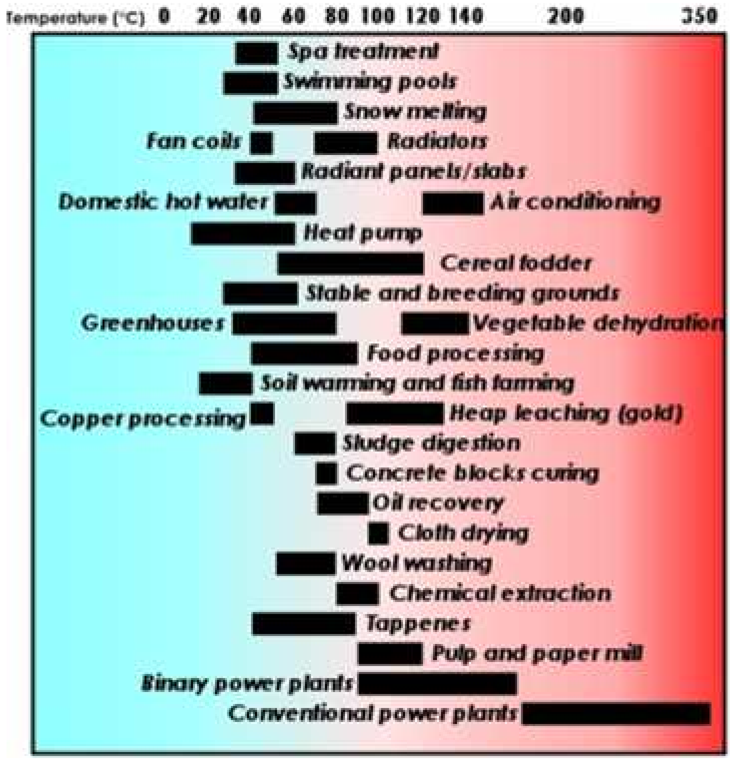


*Diagram showing the utilization of geothermal fluids (derived from Lindal, 1973)*