Shale Gas and Nonconventional Resources
Geology is the science concerned with the study of the solid Earth, its constituent rocks and the processes by which they change.

Rocks are important in this story and we will therefore briefly review the basic types
• Igneous
• Sedimentary
• Metamorphic
Igneous rock is formed through the solidification of magma or lava.
• This process may or may not involve crystallisation.
• It may occur below the surface (intrusive rocks) or on the surface (extrusive or volcanic rocks).
• This magma can be derived from partial melts of pre-existing rocks in either the Earth’s mantle or the crust.
• Melting is typically involves one or more of the following processes: an increase in temperature, a decrease in pressure, or a change in composition. Over 700 types of igneous rocks have been described, most of which were formed beneath the surface of the Earth’s crust.
• Examples of igneous rock include granite (intrusive) and basalt and obsidian (extrusive).

http://www.mycenae-excavations.org/citadel.html
Sedimentary rocks are formed by the deposition of material at the Earth’s surface or within bodies of water.
• The process involves mineral and/or organic particles.
• The particles may be formed by weathering and erosion of pre-existing rocks or through the sedimentation of smaller units.
• Classic sedimentary rocks, are subdivided according to the dominant particle size.
• Examples of sedimentary rocks include conglomerates (dominantly composed of rounded gravel), sandstone (composed of sand-sized mineral grains) mudrocks (composed of at least 50% silt/clay-sized particles) and limestone (frequently composed of the skeletal fragments of marine organisms such as coral).
Metamorphic rocks arise from the transformation of pre-existing rock types as a consequence of heat and pressure. The initial rock may be igneous, sedimentary or another older metamorphic rock.

Examples of metamorphic rock include slate (formed from shale) and marble (formed from limestone).
Origins of Oil and Gas

• Numerous theories have been proposed to account for the existence of oil and gas, which draw upon various terrestrial and extra-terrestrial observations.

• The existence of organic molecules, notably methane, on other planets has been used to justify the notion that the terrestrial equivalent did not originate from “decayed fish” (Sir Fred Hoyle).

• The existence of organic molecules in igneous rock clearly precludes their production from sedimentary processes, demonstrating that *abiogenic* routes must also exist.

• Nevertheless, the dominant production routes are now accepted to be related to the thermal “*maturation*” of organic matter.
The major groups of organic molecules found in plants and animals are:

- **Proteins**
- **Carbohydrates**
- **Lipids**
- **Lignin**

These are composed of hydrogen, carbon, oxygen and nitrogen.
The production of oil begins with the sedimentation of organic-rich deposits to the floor of the ocean or freshwater lakes. On land, significant preservation of organic matter is less likely, except under swampy conditions.

The extent to which this occurs depends on the rate of sedimentation compared with the rate at which organic debris is consumed. For example, preservation of organic molecules is favoured under conditions of water stratification, where life thrives in the warmer, oxygenated upper zones compared to the relatively cold, dark, anaerobic conditions in deep water.
Formation and Maturation of Kerogen

As time passes, the organic matter described above becomes buried through further sedimentation processes and the burial depth progressively increases. The consequences of this have been discussed in terms of three steps:

**Diagenesis**: Shallow burial; involves both biological and non-biological processes; evolution of methane, CO$_2$ and H$_2$O; production of complex hydrocarbon molecules in which the C:H ratio is comparable to that in the starting material but where the O content is reduced; this material is termed *kerogen*.

Selley “Elements of Petroleum Geology” p203

![Diagenesis diagram](image)

**FIGURE 5.12** The molecular structure of (A) type I, or algal, kerogen, (B) type II, or liptinitic, kerogen; and (C) type III, or humic, kerogen. (Reprinted from J. Geochim. Explor., Vol. 7, Dow, pp. 79–100, 1977, with kind permission of Elsevier Science, The Netherlands.)

Liptinitic – from plankton; humic – from land plants
Formation and Maturation of Kerogen

**Catagenesis**: Deeper burial; increased temperature and pressure; the C:H ratio increases; C:O ratio remains constant; petroleum release from kerogen begins; initial production of oil, then gas.

**Metagenesis**: Deep burial involving high temperatures and pressures; production of CH₄; C:H ratio increases further; finally, only graphitic carbon remains.

Practically, these *maturation catagenesis/metagenesis* phases is critical since:
- If the kerogen is immature, no petroleum will have been generated
- If the kerogen is overmature, no petroleum will remain.

Thus, during the kerogen maturation process, desirable petroleum products are formed, which subsequently migrate along with water through surrounding *permeable rocks*. Numerous theories have been proposed to account for the various mechanisms that must be involved in this but, for our purposes, it is sufficient to note that migration occurs.
Conventional Oil and Gas

The search for oil and gas is now a highly sophisticated process involving a wide range of techniques, but it was not always so. According to Selley early attempts were rather less scientific. In the US the following was tried:

Selley “Elements of Petroleum Geology”
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• “Creekology” – drilling in river beds.
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• Drilling in ancient Indian graves
• Riding a horse wearing a hat until it dropped off
• “Creekology” – drilling in river beds

The origin of creekology is now known to be based on sound principles, as evinced by the anticline theory of oil entrapment first expounded by Hunt in 1861.

Selley “Elements of Petroleum Geology”
Structure/property Relationships in Rock

In general, the physical properties of materials is determined by their composition and structure. In this case, an important property is permeability. That is, the property of a rock that is an indication of the ability for gases or fluids to flow through it.

Although the SI unit for permeability is m², a practical unit is the darcy (D), or more commonly the mD (1 darcy 10⁻¹² m²). The unit is derived from the French Engineer Henry Darcy who first described the flow of water through sand filters for water purification.

\[ \kappa = v \frac{\mu \Delta x}{\Delta P} \]

where:
\( v \) is termed the superficial fluid flow velocity through the medium (i.e., the average velocity calculated as if the fluid were the only phase present in the porous medium)
\( \mu \) is the dynamic viscosity of the fluid
\( \Delta P \) is the applied pressure difference
\( \Delta x \) is the thickness of the porous medium
Rock Diagenesis

As in the case of the production of oil and gas themselves, which is a consequence of complex processes, the rocks which act as reservoirs also evolve with time; these various processes are collectively referred to as diagenesis. Consider the case of sandstone.

- Compaction of the structure over time results in a progressive reduction in the porosity and permeability of the rock.

- Cementation – this is the process by which new minerals crystallise in the porosity between the sand grains during burial. This results in a progressive reduction in the porosity and permeability of the rock.

- Dissolution of soluble minerals. This results in a progressive increase in the porosity and permeability of the rock.

The porosity of a recently deposited sand may be 40-50% and it may exhibit a permeability ~10 D; a mature sandstone has a porosity ~10-20% permeability ~10 mD.
Rock Permeability

\[ \kappa = \nu \frac{\mu \Delta x}{\Delta P} \]

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Pervious</th>
<th>Semi-Pervious</th>
<th>Impervious</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconsolidated Sand &amp; Gravel</td>
<td>Well Sorted</td>
<td>Well Sorted</td>
<td>Very Fine Sand, Silt, Loess, Loam</td>
</tr>
<tr>
<td>Unconsolidated Clay &amp; Organic</td>
<td>Gravel</td>
<td>or Sand &amp; Gravel</td>
<td></td>
</tr>
<tr>
<td>Consolidated Rocks</td>
<td>Highly Fractured</td>
<td>Oil Reservoir</td>
<td>Fresh Limestone, Dolomite</td>
</tr>
<tr>
<td></td>
<td>Rocks</td>
<td>Rocks</td>
<td></td>
</tr>
<tr>
<td>(\kappa ) (cm²)</td>
<td>(10^{-8})</td>
<td>(10^{-7})</td>
<td>(10^{-10})</td>
</tr>
<tr>
<td>(\kappa ) (milidarcy)</td>
<td>(10^7)</td>
<td>(10^6)</td>
<td>(10^3)</td>
</tr>
</tbody>
</table>

- \(\kappa\): Permeability coefficient
- \(\nu\): Fluid viscosity
- \(\mu\): Fluid dynamic viscosity
- \(\Delta x\): Distance
- \(\Delta P\): Pressure difference
In structural geology, an **anticline** is a folded structure that is convex up and which has its oldest rocks beds at its core. On the ground or on geological maps, anticlines are characterised by a sequence of rock layers that are progressively older toward the centre of the fold because the uplifted core of the fold is preferentially eroded to a deeper stratigraphic level relative to the topographically lower flanks. The strata dip away from the centre, or **crest**, of the fold.
Anticlines, Traps and Reservoirs

The significance of an anticline is that it has the potential to trap mobile material, provided the lower levels are permeable and the upper levels are not. This leads immediately to the concept of a reservoir, which needs to exhibit the following characteristics:

• There must be an organic-rich source rock from which oil and gas can form.
• The conditions in the source rock must have been suitable for the correct degree of maturation to occur.
• There must be a reservoir within which the oil and gas can reside, where the rock is characterised by porosity, to contain the oil, and permeability to allow fluid flow.
• The reservoir must be sealed by an impermeable cap rock to prevent petroleum escape to the surface.
• The stratigraphy must be such that the petroleum is trapped.

While the anticline potentially meets all of these criteria, numerous other structures do too ……
The above diagram shows structural trap, where the origin of the reservoir is a fault. The oil, which is shown in red, accumulates against the seal, to the depth of the base of the seal. Capping rocks may take many forms, but common systems include:

- **Evaporites**: these are layered crystalline sedimentary rocks that form by the evaporation of water from mineral-rich solutions. Although almost 100 varieties of these minerals are possible, only ~10 are volumetrically important and include carbonates (e.g. especially calcites and dolomites), sulphates (e.g. gypsum), etc.

- **Shales**: fine-grained, sedimentarey rock composed of a mix of flakes of clay and small fragments of other minerals, notably quartz and calcite.
Reservoir rocks are characterised by porosity and permeability. Although Selley estimated that 90% of the world’s conventional oil and gas occurs in sandstone of carbonate reservoirs (typical reservoirs), many other rocks can also act as a reservoir (untypical reservoirs). Examples include:

- **Fractured shales – the fracturing leads to permeability.**
- Weathered multicomponent rocks in which the unstable minerals are weathered out. Granites can undergo such a process, whereby the feldspars are leached out to leave an unconsolidated quartz sand.

Selley “Elements of Petroleum Geology”
Oil and Gas Production

Once a reservoir containing oil and gas has been located production can begin.

• The oil well is initially created by drilling into the earth, whereupon a steel pipe (*casing*) is placed in the hole, to provide structural integrity to the newly drilled well bore.
• Holes in the base of the well then enable oil to pass into the bore and a collection of valves at the top regulate pressures and control flow.

Extraction occurs in three phases:
• Primary
• Secondary
• Tertiary
During the *primary recovery stage*, extraction occurs as a result of natural mechanisms whereby the pressure in the reservoir is sufficient to force the oil and gas to the surface. These include:

- Water displacing oil into the well.
- Expansion of the natural gas at the top of the reservoir.
- Expansion of gas initially dissolved in the crude oil.
- Drainage resulting from the movement of oil within the reservoir from the upper to the lower parts where the wells are located.

As the initial high pressure falls, down-well pumps may be used to enhance extraction. The recovery factor during the primary recovery stage is typically 5-15%.
Secondary and Tertiary Recovery

*Secondary recovery* methods rely on the supply of external energy into the reservoir in the form of injecting fluids to increase reservoir pressure, hence replacing or increasing the natural reservoir drive with an artificial drive. Secondary recovery techniques include increasing the reservoir's pressure through injection of, for example:

- Water
- Natural gas
- Air
- *Anything else .....?*

The typical recovery factor from water-flood operations is about 30%, depending on the properties of the oil and the characteristics of the reservoir rock.

*Tertiary, or enhanced oil recovery* methods involve increasing the mobility of the oil in order to increase extraction.

- Thermally enhanced oil recovery methods (TEOR) are tertiary recovery techniques that heat the oil, thus reducing its viscosity and making it easier to extract. Steam injection is the most common; the steam is generated by using waste heat resulting from burning oil in a gas turbine (electricity generation).
- In-situ combustion is another form of TEOR, in which some of the oil is burned to heat the surrounding oil.
- Alternatively, chemicals can be injected to alter the physical conditions in the system (e.g. surfactants to reduce surface tension between the water and oil).

Tertiary recovery allows another 5% to 15% of the reservoir's oil to be recovered. However, significant costs can be involved so the use of technologies such as those described above is a economic one.
Oil Production and Consumption

Top World Oil Producers, 2012
(Thousand Barrels per Day)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia</td>
<td>11,726</td>
</tr>
<tr>
<td>United States</td>
<td>11,115</td>
</tr>
<tr>
<td>Russia</td>
<td>10,397</td>
</tr>
<tr>
<td>China</td>
<td>4,416</td>
</tr>
<tr>
<td>Canada</td>
<td>3,856</td>
</tr>
<tr>
<td>Iran</td>
<td>3,589</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>3,213</td>
</tr>
<tr>
<td>Iraq</td>
<td>2,987</td>
</tr>
<tr>
<td>Mexico</td>
<td>2,936</td>
</tr>
<tr>
<td>Kuwait</td>
<td>2,797</td>
</tr>
<tr>
<td>Brazil</td>
<td>2,652</td>
</tr>
<tr>
<td>Nigeria</td>
<td>2,524</td>
</tr>
<tr>
<td>Venezuela</td>
<td>2,489</td>
</tr>
<tr>
<td>Norway</td>
<td>1,902</td>
</tr>
<tr>
<td>Algeria</td>
<td>1,875</td>
</tr>
</tbody>
</table>

Data through 2012 by country, region, and commercial group (OECD, OPEC) for 217 countries including total and crude oil production, oil consumption, natural gas production and consumption, coal production and consumption, electricity.

World Liquid Fuels Production and Consumption Balance

Source: Short-Term Energy Outlook, October 2015

http://www.eia.gov
Natural gas is a naturally occurring hydrocarbon gas mixture consisting primarily of CH₄, but commonly includes varying amounts of other higher alkanes and plus other compounds such as CO₂, N₂, H₂S, .......

- The above map shows an evaluation of global production in m³ per year.
- The tables show more detailed data for selected geographical areas
Nonconventional Petroleum Resources

Conventional resources of oil and gas have been described above and are broadly characterised by their properties, their locations and the means used to extract them. However, in energetic terms, vast petroleum resources are locked up in different forms and in different locations and accessing these is largely a matter of economic viability.

As conventional resources dwindle, their cost increases and nonconventional supplies become more attractive. Nonconventional resources take many forms and include:

• Plastic and solid hydrocarbons (e.g. asphalt)

• Tar sand

• Oil shale

• Shale gas
Shale Oil and Gas

Table 5. Top 10 countries with technically recoverable shale oil resources

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Shale oil (billion barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Russia</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>U.S.</td>
<td>56 (48)</td>
</tr>
<tr>
<td>3</td>
<td>China</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Argentina</td>
<td>27</td>
</tr>
<tr>
<td>5</td>
<td>Libya</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>Australia</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Venezuela</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>Mexico</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td>Pakistan</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>Canada</td>
<td>9</td>
</tr>
</tbody>
</table>

World Total: 345 (335)

Table 6. Top 10 countries with technically recoverable shale gas resources

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Shale gas (trillion cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>China</td>
<td>1,115</td>
</tr>
<tr>
<td>2</td>
<td>Argentina</td>
<td>802</td>
</tr>
<tr>
<td>3</td>
<td>Algeria</td>
<td>707</td>
</tr>
<tr>
<td>4</td>
<td>U.S.</td>
<td>665 (1.161)</td>
</tr>
<tr>
<td>5</td>
<td>Canada</td>
<td>573</td>
</tr>
<tr>
<td>6</td>
<td>Mexico</td>
<td>545</td>
</tr>
<tr>
<td>7</td>
<td>Australia</td>
<td>437</td>
</tr>
<tr>
<td>8</td>
<td>South Africa</td>
<td>390</td>
</tr>
<tr>
<td>9</td>
<td>Russia</td>
<td>285</td>
</tr>
<tr>
<td>10</td>
<td>Brazil</td>
<td>245</td>
</tr>
</tbody>
</table>

World Total: 7,299 (7,795)

Figure 1. Map of basins with assessed shale oil and shale gas formations, as of May 2013

Source: United States basins from U.S. Energy Information Administration and United States Geological Survey, other basins from ARI based on data from various published studies.

http://www.eia.gov/analysis/studies/worldshalegas/
Proven Oil Reserves

Data through 2012 by country, region, and commercial group (OECD, OPEC) for 217 countries including total and crude oil production, oil consumption, natural gas production and consumption, coal production and consumption, electricity generation and consumption, nuclear energy, energy intensity, CO2 emissions, and intensity and assets for all fuels.
## All Sources of Oil and Gas

<table>
<thead>
<tr>
<th></th>
<th>Crude oil (billion barrels)</th>
<th>Wet natural gas (trillion cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outside the United States</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale oil and shale gas unproved resources</td>
<td>237</td>
<td>6,034</td>
</tr>
<tr>
<td>Other proved reserves</td>
<td>1,617</td>
<td>6,521</td>
</tr>
<tr>
<td>Other unproved resources</td>
<td>1,230</td>
<td>7,250</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5,474</td>
<td>20,451</td>
</tr>
<tr>
<td>Increase in total resources due to inclusion of shale oil and shale gas</td>
<td>10% 46%</td>
<td></td>
</tr>
<tr>
<td>Shale as a percent of total</td>
<td>9% 32%</td>
<td></td>
</tr>
</tbody>
</table>

**United States**

<table>
<thead>
<tr>
<th></th>
<th>Crude oil (billion barrels)</th>
<th>Wet natural gas (trillion cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIA shale / tight oil and shale gas proved reserves</td>
<td>n/a</td>
<td>97</td>
</tr>
<tr>
<td>EIA shale / tight oil and shale gas unproved resources</td>
<td>58</td>
<td>687</td>
</tr>
<tr>
<td>EIA other proved reserves</td>
<td>25</td>
<td>220</td>
</tr>
<tr>
<td>EIA other unproved resources</td>
<td>130</td>
<td>1,546</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>223</td>
<td>2,431</td>
</tr>
<tr>
<td>Increase in total resources due to inclusion of shale oil and shale gas</td>
<td>30% 36%</td>
<td></td>
</tr>
<tr>
<td>Shale as a percent of total</td>
<td>24% 27%</td>
<td></td>
</tr>
</tbody>
</table>

**Total World**

<table>
<thead>
<tr>
<th></th>
<th>Crude oil (billion barrels)</th>
<th>Wet natural gas (trillion cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale / tight oil and shale gas proved reserves</td>
<td>n/a</td>
<td>97</td>
</tr>
<tr>
<td>Shale / tight oil and shale gas unproved resources</td>
<td>345</td>
<td>7,201</td>
</tr>
<tr>
<td>Other proved reserves</td>
<td>1,642</td>
<td>6,741</td>
</tr>
<tr>
<td>Other unproved resources</td>
<td>1,370</td>
<td>8,842</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3,357</td>
<td>22,882</td>
</tr>
<tr>
<td>Increase in total resources due to inclusion of shale oil and shale gas</td>
<td>11% 41%</td>
<td></td>
</tr>
<tr>
<td>Shale as a percent of total</td>
<td>16% 33%</td>
<td></td>
</tr>
</tbody>
</table>
Secondary and Tertiary Recovery

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- Air
- *Anything else .....?*

The typical recovery factor from water-flood operations is about 30%, depending on the properties of the oil and the characteristics of the reservoir rock.

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- In-situ combustion is another form of TEOR, in which some of the oil is burned to heat the surrounding oil.
- Alternatively, chemicals can be injected to alter the physical conditions in the system (e.g. surfactants to reduce surface tension between the water and oil).

Tertiary recovery allows another 5% to 15% of the reservoir's oil to be recovered. However, significant costs can be involved so the use of technologies such as those described above is a economic one.
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- Air
- **Carbon dioxide**
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Carbon capture and storage (CCS)

The world’s first commercial coal-fired power plant that can capture its CO₂ emissions was officially launched in Canada in October 2014.

The Boundary Dam project, in Saskatchewan, aims to capture and sell around 1 million tonnes of CO₂ - up to 90% of the emissions of one of its refitted power units (Unit #3) - to oil company Cenovus Energy, which will use the compressed gas to extract oil reserves.

Unsold gas will go to the Aquistore CO₂ storage research project.

The Boundary Dam refit cost US$1.3 billion ($800 million for the CCS process) and, economically, relies critically on government subsidies.

In 2009, the IEA published a road map calling for 100 large CCS projects by 2020, but in July 2013 the lack of projects led it to downgraded that to just 30.

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Unsold gas will go to the Aquistore CO\textsubscript{2} storage research project.

The Boundary Dam refit cost US$1.3 billion ($800 million for the CCS process) and, economically, relies critically on government subsidies.

In 2009, the IEA published a road map calling for 100 large CCS projects by 2020, but in July 2013 the lack of projects led it to downgraded that to just 30.

120 megawatts (MW)
Biomass

Our biomass plans

In July 2012, Drax confirmed that it plans to transform itself into a predominantly biomass-fuelled generator through burning sustainable biomass in place of coal. Initially, Drax plans to convert three of its six generating units to run on sustainable biomass.

The first unit was converted in the second quarter of 2013. From May 2014, a second unit ran as an enhanced co-firing unit, burning at least 85% biomass, until it was fully converted in the fourth quarter of 2014. The third unit is expected to be converted in 2015/16.

We are also evaluating the option to convert a fourth unit.

According to last year’s WWF report Europe’s Dirty 30, which used emissions data from 2013, Drax is by far the biggest emitting power plant in the UK, with nearly twice the CO2 count as next-worst offender Eggborough.

Since then, however, Drax has cut emissions by 18% — and that’s largely down to their move to biomass. In any case, it’s still the country's largest emitter by a long way.

There is also a fight over the climate merits of burning biomass.

According to a study from the Spatial Informatics Group, which used DECC’s biomass model (BEAC), Drax’s net emissions will be four times higher than the required standard of 285 kilogrammes of CO2 per 1MWhe of power.

Biomass

- Drax: 4 GW
- Eggborough: 2 GW

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