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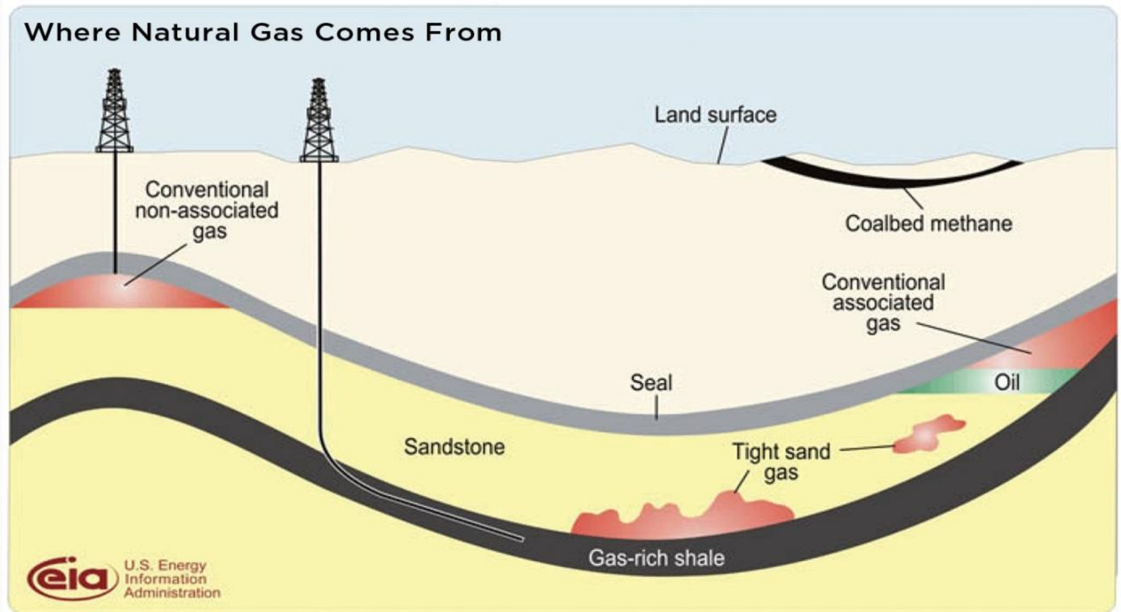
SCHOOL OF GEOLOGY

INTERSECTIONAL MASTER'S DEGREE PROGRAMME

"HYDROCARBON EXPLORATION AND EXPLOITATION"

UNCONVENTIONAL HYDROCARBON SYSTEMS – EXPLORATION AND EXPLOITATION

POSTGRADUATE DISSERTATION



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Ψηφιακή βιβλιοθήκη Θεόφραστος – Τμήμα Γεωλογίας – Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης

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UNCONVENTIONAL HYDROCARBON SYSTEMS – EXPLORATION AND EXPLOITATION

ΜΗ ΣΥΜΒΑΤΙΚΑ ΚΟΙΤΑΣΜΑΤΑ ΥΔΡΟΓΟΝΑΝΘΡΑΚΩΝ – ΈΡΕΥΝΑ ΚΑΙ ΕΚΜΕΤΑΛΛΕΥΣΗ

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UNCONVENTIONAL HYDROCARBON SYSTEMS – EXPLORATION AND EXPLOITATION – *Master Thesis*

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«The approval of the current dissertation by the members of the committee does not necessary mean the fully acceptance of author’s opinion»

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Η παρούσα Μεταπτυχιακή Διατριβή Ειδίκευσης (Μ.Δ.Ε.) εκπονήθηκε στα πλαίσια του Δι-ιδρυματικού προγράμματος μεταπτυχιακών σπουδών με τίτλο «Έρευνα και Εκμετάλλευση Υδρογονανθράκων» στο τμήμα Γεωλογίας της Σχολής Θετικών Επιστημών (Σ.Θ.Ε.) του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης (Α.Π.Θ.)

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1 Introduction

Despite the fact that the first oil reservoir was drilled two centuries ago from Edwin L. Drake in 1859 to Titusville, Pennsylvania, USA, today oil still remains the main energy source along with gas and coal. Oil and gas are natural resources which are being rapidly consumed and there are widespread efforts to seek possible substitutes for them. This means that the exploration and exploitation of new hydrocarbon fields are vital in order for the energy needs of the worldwide industries and people to be covered. During all these years, the easiest hydrocarbon deposits have been explored, exploited, and abandoned from the oil companies so new exploitation techniques are developed for the toughest and most demanding hydrocarbon fields.

This master thesis aims to present the newly unconventional hydrocarbon systems because more and more oil industries and governments across the world are investing in this kind of systems.

More specifically in the second chapter of this master thesis the main types of the unconventional hydrocarbon systems will be presented in contrast to the conventional hydrocarbon systems.

The third chapter concentrates in the most common type of shale gas and questions like how they form, why they are so important, where are the biggest deposits across the world, does Greece's territory host any type of unconventional hydrocarbon systems, will be answered.

The fourth chapter gives a short survey of the drilling methods that are needed and the characteristics of production technologies of unconventional hydrocarbon systems, mainly the process of hydraulic fracturing for shale gas and oil, are presented.

The fifth chapter presents the importance of production technologies from an environmental point of view. Specifically, the impacts of hydraulic fracturing for shale gas deposits will be presented along with impacts of open pit mines for other

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types of deposits. This chapter is focusing on the environmental and human health impacts.

The final chapter draws conclusions and gives recommendations on how to deal with the specific risks of the exploitation of unconventional hydrocarbon systems.

2 Hydrocarbon systems

The reserves of shale gas stand out as a very important source of substitutes for conventional oil and gas. General the hydrocarbon systems can be distinguished to conventional hydrocarbon systems and to unconventional hydrocarbon systems. The conventional hydrocarbon systems have been thoroughly studied all these years by oil and gas industries or governments in contrast with unconventional hydrocarbon systems which are yet to be studied thoroughly.

2.1 Conventional hydrocarbon systems

In general, the term conventional hydrocarbon system applies to oil and gas resources which can be extracted after the drilling operation just by the natural pressure of the wells and pumping or compression operations. After the depletion of mature fields, the natural pressure of the wells may be too low to produce significant quantities of oil and gas. Different techniques may be used to boost production, mainly water, and gas injection or depletion compression.

In order for any conventional hydrocarbon system to exist; it is necessary for some essential conditions to occur. These conditions are the source rock, the reservoir rock, the seal or cap rock, the petroleum trap, timing and maturing of the hydrocarbon in the sense of pressure and temperature, and final the migration of the hydrocarbons.

2.1.1 Source rocks

Source rocks, where oil and gas are formed, are organic-rich rocks capable of expelling hydrocarbon components. Generally, source rocks are nonpermeable rocks as clays and they are rich in organic matter and if they heated sufficiently oil or

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gas can be generated. Source rocks may have been deposited in a variety of environments including deepwater marine, lacustrine and deltaic. Typical source rocks are shales and limestones.

Depending on the environment where they have been formed, three types of source rocks exist.

- Type I source rocks are formed from algae deposited under nonoxidizing conditions in deep lakes. They tend to generate waxy crude oils.
- Type II source rocks are formed from marine planktonic and bacterial remains known as liptinitic kerogens that are preserved under anoxic conditions in marine environments. They produce both oil and gas.
- Type III source rocks are formed from terrestrial plant material that has been decomposed by bacteria and fungi under oxic or sub-oxic conditions. They tend to generate mostly gas. Most coals and coaly shales are generally Type III source rocks.

Fig. 2.1.1 Shale, a typical source rock (adopted from https://geology.com)

2.1.2 Reservoir rocks

Reservoir rocks are porous, permeable like sponge rocks, where hydrocarbons are stored. Reservoir rocks must have good porosity and permeability to accumulate and transmit fluids. All types of rock (igneous, sedimentary, metamorphic) can act as reservoir rocks if it can accommodate and drain hydrocarbons. But the most common reservoir rocks around the world are sedimentary rocks because generally,

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they have primary porosity. Igneous and metamorphic rocks can be reservoir if there are in fracturing state (secondary porosity). The most common reservoir rocks are sandstones and limestones. Sandstones have high porosity and permeability making them good reservoirs. In contrast carbonate rocks depending on how big fractures their structure have, can act as a good reservoir. It is believed that most of 60% of worldwide hydrocarbon reservoirs are consisted of sandstone formations with the remaining percentage consisted of carbonate formations. In general, every rock can act as a hydrocarbon reservoir if the following conditions exist: if it has sufficient porosity to retrain the hydrocarbons, if the permeability is sufficient to allow the fluids to flow to the surface and if the rock is able to contain hydrocarbon molecules in its pores.

Fig. 2.1.2 Sandstone, a typical reservoir rock (adopted from www.geo.auth.gr)

2.1.3 Seal or cap rocks

Hydrocarbon reservoirs are necessary to be sealed by a nonporous formation with low permeability in order fluids not to migrate beyond the reservoir upwards or lateral. This kind of formations called seal or cap rocks. So seal or cap rock is relatively an impermeable rock or very dense that forms a barrier above and around hydrocarbon reservoir. Buoyant, migrating fluids remain trapped in the reservoir by the cap rock unless deformation or erosion breaches the seal. For most of hydrocarbon basins across the world, cap rock could be shale, mudstone, halite, gypsum rock, dense limestone, evaporite, or volcanics (Fu et al., 2010). Klemme (1975, 1980) analyzed 334 oil fields around the world and found that shale cap rock

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accounted for 65%, evaporite for 33%, and limestone for only 2%. Evaporite deposits and permanently frozen ground are the only nonpermable to any liquid formations. A seal or cap rock is one of the most critical components of a complete hydrocarbon system.

Fig. 2.1.3 Evaporite deposits in the playa lakes of the American west (adopted from www.pitt.edu)

2.1.4 Hydrocarbon traps

When a permeable reservoir rock is sealed by some low permeability cap rock, a hydrocarbon trap is formed. A hydrocarbon trap prevents the upward migration of oil and natural gas up through the reservoir rock. Once oil and natural gas are in the reservoir rock, they continue to migrate upwards through the pore spaces of the rock until blocked by some sort of seal with a cap rock.

Three types of hydrocarbon traps exist based on their geological characteristics: structural traps, stratigraphic traps and a combination of traps. Structural traps are formed as a result of subsurface structural changes due to tectonic, diapiric, gravitational and compactional processes. These changes can block the upward migration of hydrocarbons so a hydrocarbon reservoir can be formed. Structural traps are the most important type of hydrocarbon traps as they represent the majority of the world's discovered hydrocarbon resources. The three basic forms of structural traps are the anticline trap, the fault trap and the salt dome trap with the majority of the world's hydrocarbon reserves belong to salt dome traps (fig. 2.1.4).

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Stratigraphic traps are formed as a result of the deposition in sedimentary rocks. When the sediment that creates the reservoir rock is deposited in a discontinuous layer, the seals are created beside and on top of the reservoir. In some cases, these seals are made of impermeable or low permeability shale deposited around the reservoir, blocking the oil and gas inside. The seals themselves may also be source rocks (fig. 2.1.4). The majority of hydrocarbon traps belong to structural traps and more specific to the anticline traps (up to 75%).

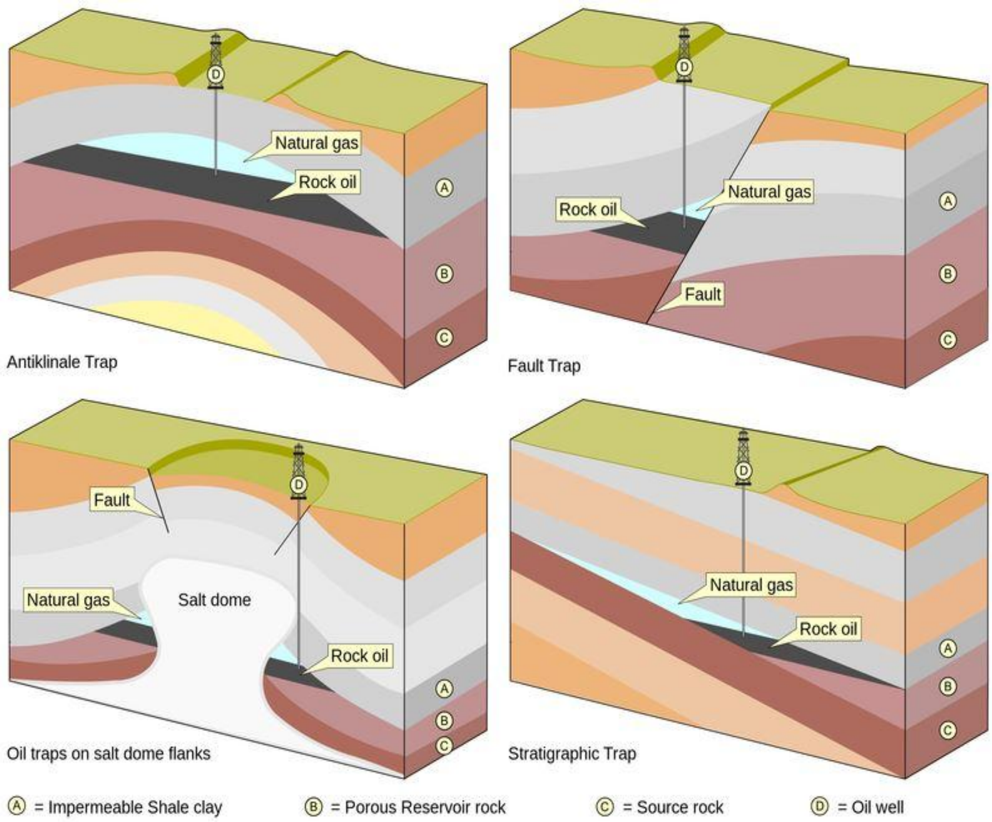

Fig. 2.1.4 Types of hydrocarbon traps (adopted from https://upload.wikimedia.org/wikipedia/commons/thumb/a/af/Oil_traps.svg/2000px-Oil_traps.svg.png)

2.1.5 Time and hydrocarbon maturation

The organic matter that exists in source rocks in order to be transformed to oil and gas is necessary for temperature and pressure to increase. This can happen only with the continuous precipitation of sediments. Hydrocarbons are generated in depths of 3 – 6 km below the surface of the earth, while temperature in order oil to be generated must range between 60°C to 160°C (oil window) and for gas generation temperature between 120°C to 200°C (gas window) is required. In environments

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where sedimentation is high and big amounts of organic matter are contained to the sediments, one main condition for hydrocarbon generation is fulfilled. Furthermore, nonoxidizing environment conditions along with the previous condition lead to the ultimate scenario for long-term hydrocarbon generation. Now only time in the sense of continuous compaction of the sediments is missing for hydrocarbon generation.

Oil and gas maturation contains the evaluation of the story the source rock is heated. Depending on the thermal value, different types of kerogen are generated. With the study of kerogen, essential conclusions came after, regarding the quantity and also the quality of generated hydrocarbons.

2.1.6 Hydrocarbon migration

As soon as oil and gas have been generated in source rock, less pore space remains of the source rock and a need for newly generated hydrocarbons to move into areas of less resistance, arises. This movement called expulsion. The expulsion of the oil out of the source rock is a dynamic process driven by the oil generation itself. Migration is a geological and geochemical process that takes place in the sedimentary basin where hydrocarbons are created. Migration is the 'movement' of hydrocarbons, in liquid or solid state, before their accumulation in a trap and the creation of a deposit in that place. Generally, migration occurs from places of high temperature and pressure in places of lower values of these parameters.

Three types of migration exist. Primary migration refers to the expulsion of hydrocarbons from the source rock into an adjacent permeable carrier bed. Secondary migration refers to the movement of hydrocarbons along a "carrier bed" from the source area to the trap. Migration mostly takes place as one or more separate hydrocarbons phases. Tertiary migration refers to hydrocarbon movements from one trap to another or to a seep that leads sometimes to the surface (oil seeps and gas chimneys).

As a conclusion for a conventional hydrocarbon system to exist is necessary for previous conditions to be applied at the same time (fig. 2.1.5). In order for conventional hydrocarbons to be produced a drilling well (a vertical hole) must be

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constructed, the productive interval of the borehole must be perforated and then hydrocarbons will flow to the surface and the production will begin. This exact procedure is required specifically for the conventional hydrocarbon systems.

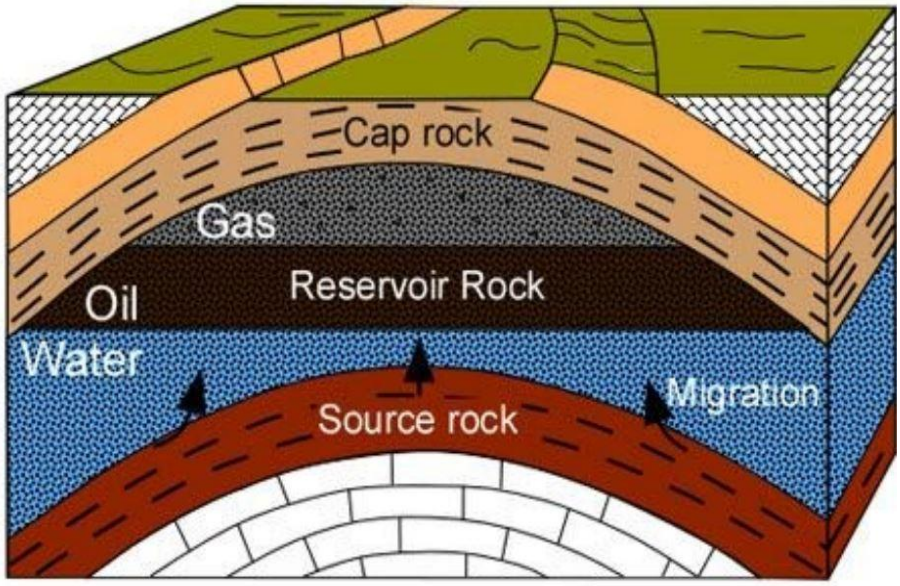

Fig. 2.1.5 A conventional hydrocarbon system (adopted from https://www.glossary.oilfield.slb.com/)

2.2 Unconventional hydrocarbon systems

2.2.1 General

By the term of unconventional is described a system of oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Unconventional hydrocarbon systems are oil and gas resources which are mainly created in the source rock and are maintained there without been migrated to reservoir rock. Unconventional oil or gas resources are much more difficult to be extracted compared to conventional reservoirs because of poor permeability and porosity values of the formation, meaning that it is extremely difficult or impossible for oil or gas to flow through the pores and into a standard well like conventional resources.

Generally speaking, unconventional hydrocarbons cannot be produced, transported, and/or refined using conventional (traditional) techniques. So, they require new,

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highly energy intensive production techniques and new processes to deal with their inaccessible placements or unusual compositions. To be able to produce from these difficult reservoirs, specialized techniques and tools are used. For example, unconventional resources can be extracted with the method of hydraulic fracturing of a rock formation in order to create cracks for the oil or gas to flow through. It is not oil or gases themselves that are calling unconventional, but the extraction methods are. Unconventional is a method that allows to drill down, drill horizontally, and fracking occurs. This allows oil and gas to be flowing from tight sands that we normally could not retrieve with conventional methods of drilling.

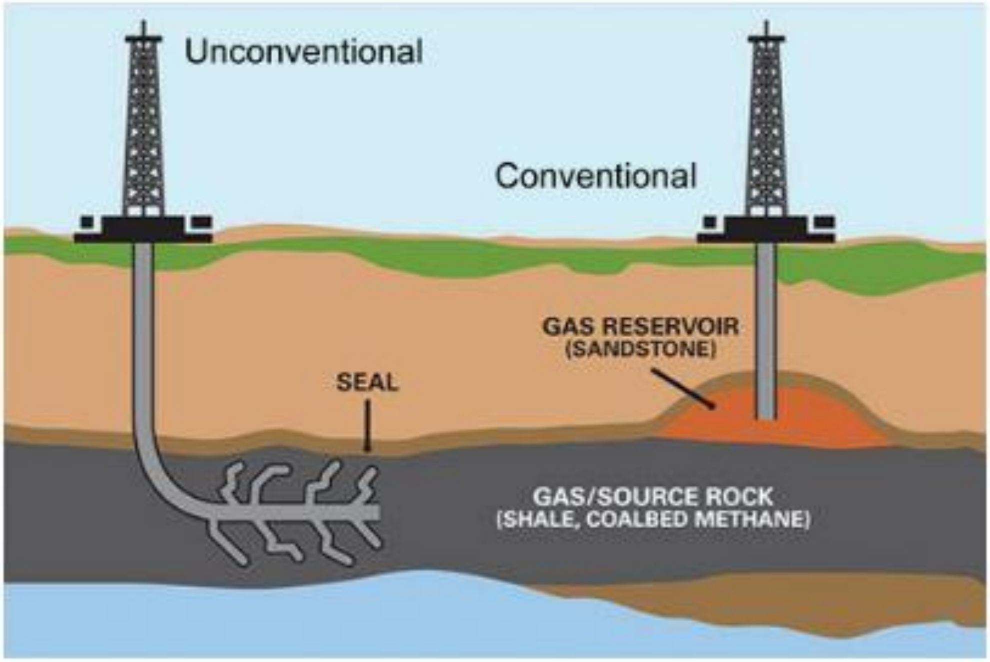

Fig. 2.2.1 Conventional versus unconventional extraction methods (adopted from http://worldinfo.org/2012/01/point-of-view-unconventional-natural-gas-drilling)

Unconventional extraction methods are costing more than those used to produce hydrocarbons from a traditional reservoir, but this stimulation allows the production of oil and gas from resources that were previously not economic viable. These methods need sophisticated technologies, lots quantities of water and the injection of additives, which may be harmful to the environment. There are many types of unconventional hydrocarbon systems which are presented to the following chapter.

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2.2.2 Types of unconventional deposits

Unconventional hydrocarbon systems include many different types of deposits. The most important types are shale gas, shale oil, coalbed methanes, tight gas, oil sands or tar sands, heavy oil, gas hydrates, and other low-permeability tight formations. Shale gas and shale oil are the most well studied of all. Following this chapter, the meanings of these types will be explained along with the main characteristics of them, while shale gas will be presented to the third chapter.

The following picture concentrates all the main types of unconventional deposits that exist and the way they are exploited nowadays, along with the conventional deposits.

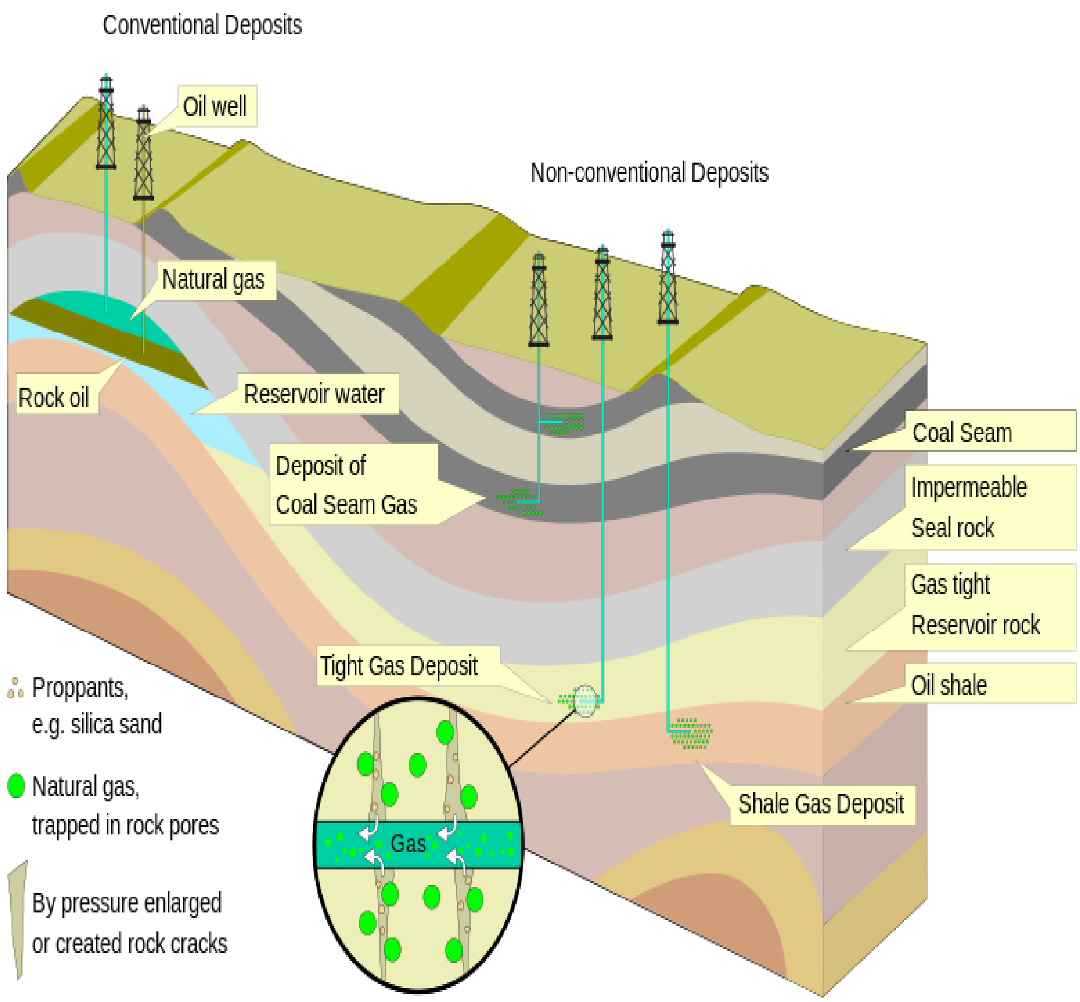

Fig. 2.2.2 Scheme of petroleum or natural gas extraction in conventional and unconventional deposits (adopted from Magenta Green 2014)

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2.2.3 Shale gas

Shale gas is a natural gas that is found trapped within shale formations. The natural gas is still within the source rock, not having migrated to a porous and permeable reservoir. Shales are fine-grained sedimentary rocks that can be rich sources of petroleum and natural gas. Shale gas is the term often used to describe both tight gas and shale gas resources. The main difference between tight gas and shale gas, however, is that tight gas can be found in low permeability sedimentary rocks, such as sandstones, while shale gas rocks are usually impermeable. Usually the shale rock is both the source of the gas and the means of trapping it. Shale gas resources are referred to as "plays" rather than fields and they generally cover large geographical areas. Both shale and tight gas are dispersed over much wider areas than conventional gas and that means many more wells need to be drilled to extract the same amount of gas as from conventional resources.

Because shale formations have very low values of permeability is necessary for an advanced technique to be developed in order for gas to start to flow. The process to extract natural gas from shale formations is called hydraulic fracturing or "fracking". With this process a combination of water, proppants and chemical additives called “fracking fluid” are pumped with high pressure to shale formations in order to create fractures. The combination of horizontal drilling and hydraulic fracturing has allowed access to large volumes of shale gas that were previously uneconomical to produce.

Today, shale gas is the fastest growing natural gas resource in the United States and worldwide as a result of several recent developments. United States of America are leading the production of natural gas from shale formations during the last decade and other countries are about to follow. Advances in horizontal drilling technology allow a single well to pass through larger volumes of a shale gas reservoir and thus produce more gas. Shale gas deposits are about to be presented in the following chapter more detailed.

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2.2.4 Oil shale

Oil shale is defined as a fine-grained sedimentary rock that contains a high proportion of endogenous organic matter (kerogen) mostly insoluble in ordinary petroleum solvents, from which substantial amounts of synthetic oil can be extracted. Through advanced processing methods oil shale can be converted into shale oil and other hydrocarbons. This can be accomplished by heating oil shale to a sufficiently high temperature and this process is called retorting. Retorting is the cracking process used in shale oil refining where firstly the kerogen is broken down to release hydrocarbons, and then further cracks the hydrocarbons into lower weight products.

Oil shale was formed millions of years ago by the deposition of organic debris and silt on lake beds or on the bottom of the sea. By years passing heat and pressure have transformed these materials into oil shale in a process similar to conventional oil formation. However, heat and pressure were not great enough to mature the kerogen and for this reason, oil shale is "immature oil" that has not been in the ground long enough to form oil.

Fig. 2.2.3 Oil shale formation (adopted from www.geology.com)

Based on the environment where the initial organic matter was deposited Adrian C. Sutton distinguished the following categories: i) terrestrial, ii) lacustrine (lake bottom depositions) and iii) marine (ocean bottom depositions).

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Oil shale formations consist mainly of organic matter and inorganic matter. The organic matter consists of three maceral types the telalginite, the lamalginite, and the bituminite. The inorganic matter consists of carbonate minerals such as calcite, dolomite, siderite, quartz, feldspar, clay minerals such as illite and chlorite. Some oil shale formations may contain metals such as vanadium, iron, uranium, nickel, molybdenum, etc.

Based on the mineral content of oil shales three categories are recognized:

- <u>Carbonate-rich oil shales</u>

  This type of oil shales contains a large number of carbonate minerals such as calcite and dolomite that are mixed with oil shale. The organic-rich layers usually exist between the carbonate-rich layers. One characteristic of these shales is the intense hardness that makes them impossible for exploitation.

- <u>Siliceous oil shales</u>

  They are usually dark brown or black shale formations that they contain more siliceous minerals, such as quartz, feldspar, clay, chert, and opal, than carbonates. They are not as hard as carbonate-rich shales, so they are more suitable for exploitation.

- <u>Cannel oil shales</u>

  These shales are dark brown or black and they consist of organic matter that completely encloses other mineral grains. This type of oil shales is the most suitable for exploitation.

Oil shale is an example where a thermally immature source rock has not generated and expelled hydrocarbons. The Native Americans called oil shale as “the rock that burns” because of it’s easy to catch fire and they used it as a source of energy.

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Fig. 2.2.4 Oil shale “the rock that burns” (adopted from Energy.gov Office of Fossil Energy)

Oil shale can be extracted in two ways:

- by mining the oil shales either underground or in open pits, crushing them and collecting them to a treatment area where the separation of kerogen from shale takes place and turning the kerogen to crude oil
- by in-situ processing, involving drilling into the oil-shale unit, fracturing it to increase its permeability, igniting the shale, and recovering the oil thus generated through other wells.

Shell oil is developing an in situ retorting process known as thermally conductive in-situ conversion (ICP). By this process oil shale is heating underground over a period of 2 – 4 years and after the released product is pumping and refining in conventional ways. This process has many advantages compared to open pits mining such as no piles of taling are left over, the unwanted products are minimized, the quantities of the water that is used are also minimized and deeper formations can be approached by this process.

Oil shale is a hugely untapped resource that has been mined and processed since the 1800s. Despite oil shale is related to conventional oil the production quantities have been very low because of the fact that oil extraction from oil shale formations is a more complex and more expensive procedure than from conventional oil drilling wells. The great amount of oil shale reserves found all over the world lead to the exploitation of these reserves ignoring the cost. According to the International

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Energy Agency, [(2010), World Energy Outlook 2010] there are about 1 trillion barrels of economically recoverable shale oil resources, compared to 1.3 trillion of recoverable conventional oil reserves. However, with ex-situ technology being the only economically viable method of recovering shale oil, even with government subsidies, shale oil is not expected to account for more than 1 million barrels of oil per day (mb/d) by the year 2035. The main worldwide reserves are found in the western United States with the Green River deposits, in Queensland in Australia with the Tertiary deposits and in Europe in Sweden and Estonia. Other significant oil shale deposits found in Russia, France, and Germany in Europe, in Jordan with the El-Lajjun deposits, and finally deposits in Brazil and China.

2.2.5 Coalbed methane

Coalbed methane (CBM or coal-bed methane) is natural gas that is produced as organic material and turned into coal. It is then stored on the many surfaces of the coal. Gas contained in coal bed methane is mainly methane and trace quantities of ethane, nitrogen, carbon dioxide, and few other gases. It is called 'sweet gas' because of its lack of hydrogen sulfide. Methane, CH_4, is a naturally occurring gas and it is the major component (95%) of natural gas. It can be produced in a variety of ways.

Coalbed methane originates from buried organic matter in an environment free from oxygen. Biogenic methane is produced during the transformation process. With deeper burial, carbon-carbon bonds break up generating gas as well as liquid hydrocarbons. More deeply buried bituminous coals crack generating thermogenetic methane. Coalbed methane is a form of natural gas extracted from coal beds. Some methane is trapped inside coal and is produced during the coal formation process and gets trapped on the surface of the coal in tiny pores and fractures by a process called adsorption. Coalbed methane generally contains methane, but carbon dioxide CO_2, nitrogen N_2, ethane C_2H_5, hydrogen sulfide H_2S, and hydrogen H_2 can also be contained to them.

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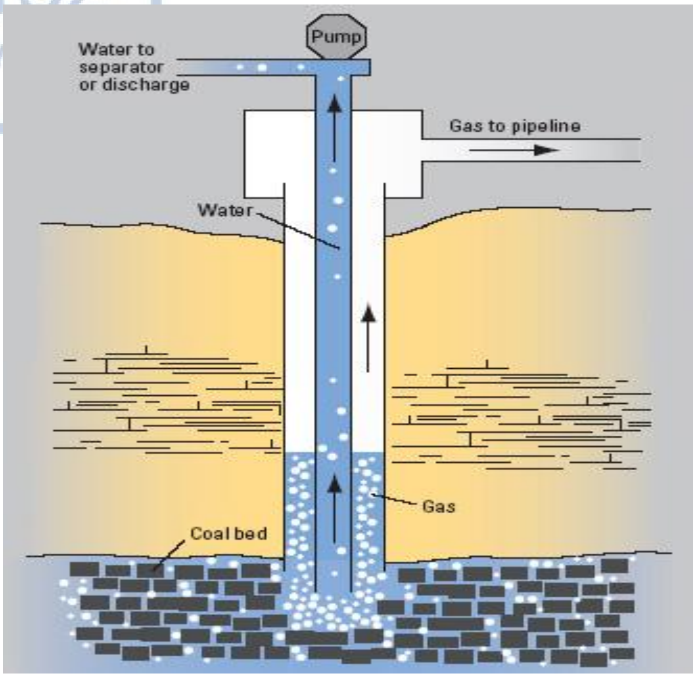

Fig. 2.2.5 Diagram of coalbed methane recovery (adopted from USGC courtesy: http://serc.carleton.edu/research_education/nativelands/crow/coalbedmethane.html)

Coalbed methane wells often produce at lower gas rates than conventional reservoirs and can have large initial costs. Also with methane, coalbeds contain large amounts of water. The existence of water increases the pore pressure and the methane is kept in place. By pumping out the water, the reservoir pressure drops and the methane can detach from the coal surface and flow out into the well. Methane tends to follow the water as it is pumped to the surface, where it is captured and transported through pipelines to storage facilities or shipped. The production profiles of CBM wells are typically characterized by a "negative decline" in which the gas production rate initially increases as the water is pumped off and gas begins to desorb and flow as described below.

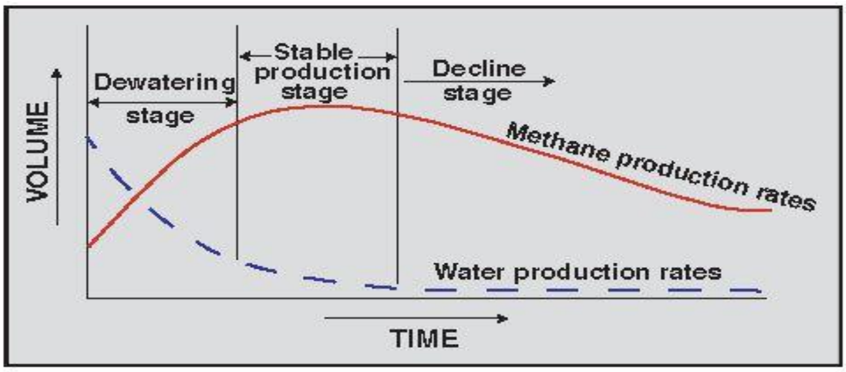

Fig. 2.2.6 Production curve of coalbed methane (Modified from Kuuskraa and Brandenberg 1989)

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The environmental issues of coalbed methane production refer to the disposal of water and to greenhouse gas emissions. The water that has been firstly drawn of the drilling wells must be disposed of in an environmentally acceptable manner. This water is commonly saline but in some areas can be drinking water. Surface disposal of large volumes of potable water can affect streams and other habitats. If this water is reinjected subsurface the production will cost even more. In addition, methane is a greenhouse gas that is acting as a trap heat and thus contributes to global warming.

It is only during the last two decades that it was realized that coalbed methane could be used as a resource. The inexpensive and straightforward procedure of coalbed methane recovery has made coalbed methane a useful, easily accessible form of energy. Coalbed methane producing areas are found in Australia (Queensland and New South Wales) where 10% of gas production produced, in Canada (British Columbia, Alberta), in the United Kingdom, in United States (Rocky Mountain states of Colorado, Wyoming, and New Mexico), in Kazakhstan and in India. Generally, methane from coal is thus an attractive resource.

2.2.6 Tight gas

Different countries and regions have varying amounts of tight sandstone gas resources, as well as technological expertise and economic conditions, and there is currently no uniform standard for the definition of tight gas. Tight gas is natural gas which is contained in reservoir rocks with such low permeability that massive hydraulic fracturing is necessary to produce the well at economic rates. The reservoir rocks where the tight gas existed are extraordinarily impermeable hard rock formations making the underground formation extremely "tight."

Tight gas can also be trapped in sandstone or limestone formations that are typically impermeable or nonporous, also known as tight sand. These reservoirs are generally defined as having less than 0.1 millidarcys (mD) matrix permeability and less than ten percent matrix porosity (Law and Spencer, 1993). Though natural gas is available in these reservoirs, extracting the gas out of them is a difficult process because these reservoirs are impermeable and non-porous so heavy investment for gas development is needed. Specifically, large hydraulic fracture treatments, a horizontal

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drilling well, or multilateral drilling wells must be used to stimulate flow rates and increase the recovery efficiency in these reservoirs. Types of tight gas reservoirs are mainly sandstones while significant quantities of tight gas been produced from low permeability carbonates, shales, and coal seams. Generally tight gas is formed in the same way as conventional natural gas deposits with the main difference been the age of the deposits. Conventional gas is relatively young in contrast to tight gas that formed around 248 million years ago in Palaeozoic formations. Over this long period of time, a conventional gas reserve was changed by cementation and recrystallization. This led to reduced permeability of the rock and natural gas being trapped tightly within rock formations. Most tight gas formations are found mainly onshore while tight sand reservoirs produce dry natural gas.

Tight reservoirs are not typical and their characteristics are not specific. They can be:

- Deep or shallow
- High pressure or low pressure
- High temperature or low temperature
- Blanket or lenticular
- Homogeneous or naturally fractured
- Single layered or multilayered

As technology has developed, the permeability guidelines for tight gas have changed onshore from less than 0.1 mD in the 1970s to less than 0.01 mD today, and less than 0.001 mD in the United States. These guidelines lead many countries to develop extraction activities of tight gas. Large hydraulic fracture treatments are being used more commonly around the world to stimulate gas flow from low permeability reservoirs. Countries, where tight gas is extracted, are Canada, Australia, Argentina, Venezuela, Saudi Arabia, Mexico, China, Indonesia, Egypt, and Russia. In Europe, the presence of huge natural gas reserves has resulted in tight gas not receiving the same attention as in the United States. However, this is changing due to technology developments and the continuing need for energy.

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2.2.7 Oil sands or tar sands

Oil sands or tar sands are either loose sands or partially consolidated sandstone containing a naturally occurring mixture of quartz sand, clay, water, trace minerals, and a small share of bitumen (10% - 18%). Bitumen is made up of organic components ranging from methane—the simplest organic molecule—to large polymeric molecules. Bitumen is thick, sticky, black oil that can form naturally in a variety of ways, usually when lighter oil is degraded by bacteria. This extremely complex hydrocarbon mixture can be synthetically processed into oil. Most of the bitumen produced from tar sands is refined and mixed with lighter oils to produce synthetic crude oil that can be further refined and used in much the same way as typical crude oil. In general oil sands or tar sands occur where conventional crude oil has failed to be trapped at depth and has migrated near to the surface and has become degraded by evaporation, biodegradation and water washing to produce a viscous heavy oil residue.

Fig. 2.2.7 Tar sandstone from Monterey Formation, Miocene, 10-12 Ma; southern California, USA

Natural bitumen deposits are reported in many countries, but in particular, are found in extremely large quantities in Canada (Alberta). Other large reserves are located in Kazakhstan, Russia, and Venezuela. Bitumen can't be pumped out through wells like conventional oil because bitumen is very thick and also it sticks to the sand and clay, so does not flow easily. So, it is necessary for new extract methods to be found by oil companies in order to obtain bitumen from tar sands. Tar sands are mined in two main ways:

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- **Open-pit mining** – if tar sands are found near the surface, as in Alberta, Canada, they can be mined directly – much like open-pit coal mining – and then transferred to an extraction plant where the bitumen can be separated from the sand, clay, and water.

Fig. 2.2.8 an aerial view of the Alberta tar sands (adopted from Green Peace/Eamon MacMahon)

- **In-situ mining** – if tar sands are too deep to dig up, the bitumen can be extracted by injecting hot steam or solvents to loosen up the bitumen and allow it to flow through a well to the surface.

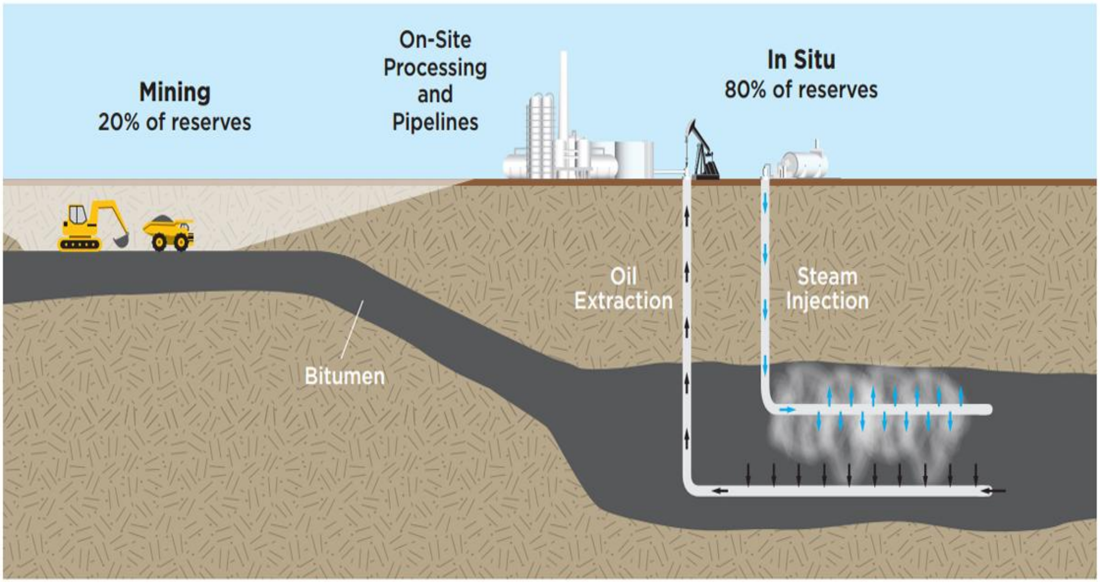

Fig. 2.2.9 Open pit mining versus in situ tar sands extraction (adopted from Union of Concerned Scientists)

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The estimated worldwide deposits of oil coming from oil sands are more than 2 trillion barrels (320 billion cubic meters); the estimates include deposits that have not been discovered. Proven reserves of bitumen contain approximately 100 billion barrels and total natural bitumen reserves are estimated at 249.67 Gbbl (39.694×109 m^3) worldwide.

Despite the great quantities of tar sands deposits the extraction of bitumen from tar sands and the refining into products like gasoline requires significant amounts of water, energy, and land (for open pit mines) compared to other energy resources. Open-pit mining also produces a lot of waste (leftover sand, clays, and contaminants contained within the tar sands) that may pose a risk to nearby water supplies. Some attempts to mitigate the environmental impacts of mining tar sands include using non-potable and recycled water, moving to in-situ rather than open-pit mining to decrease land use and waste, and using carbon capture and storage to reduce greenhouse gas emissions from the extraction and use of oil from tar sands because according to researches a gallon of gasoline that made from tar sands produces about 15% more carbon dioxide emissions than one made from conventional oil.

2.2.8 Heavy oil

Heavy oil is highly-viscous oil that cannot easily flow to production wells under normal reservoir conditions. It is a type of crude oil characterized by an asphaltic, dense, viscous nature (similar to molasses), and its asphaltene content. It is called as "heavy" because density or specific gravity has higher values than that of light crude oil. Heavy crude oil has been defined as any liquid petroleum with less than 20° API gravity. According to American Petroleum Institute "API gravity" is a standard to express the specific weight of oils, computed as (141.5/sp g) - 131.5, where sp is the specific gravity of the oil at 60 degrees Fahrenheit. The lower the specific gravity value, the higher the API gravity will be.

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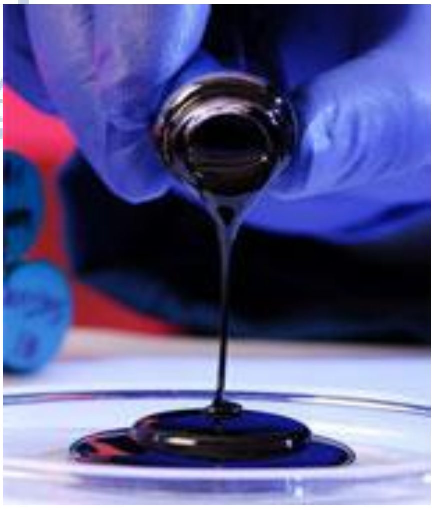

Fig. 2.2.10 Heavy crude oil with API gravity less than 20° (adopted from https://www.glossary.oilfield.slb.com/en/Disciplines/Heavy-Oil.aspx)

Physical properties that differ between heavy crude oils and lighter grades include higher viscosity and specific gravity, as well as heavier molecular composition. In comparison with heavy oil, light oil (conventional) flows naturally and can be pumped without being heated or diluted. Light oil is characterized by an API gravity of at least 22°, and extra-heavy oil has an API gravity of less than 10°. Natural bitumen, also known as oil sands, shares the characteristics of heavy oil but is even more dense and viscous - with a viscosity greater than 10,000 cP. Natural bitumen and extra-heavy oil differ in the degree by which they have been degraded from the original conventional oils by bacteria.

Related to API gravity the types of crude oil can be distinguished as follows:

Type	**API gravity**	
	from	to
Light oil	45.4°	31.1°
Medium	30.2°	22.3°
Heavy oil	21.5°	10°
Extra heavy oil	6.5°	0.1°

Table 1: Crude oil classification by the National Petroleum Agency of America (Adapted from ANP, 2000)

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Heavy oils are unconventional deposits and typically are not recoverable in their natural state through a well or by ordinary production methods. It is necessary to be heated or to be diluted in order to flow into a well or through a pipeline. Production, transportation, and refining of heavy crude oil acquire special challenges and techniques compared to light crude oil. Heavy oil's quality is lower than the quality of light oil. The quality can increase either by increasing the number of hydrogen atoms or decreasing the number of carbons in the structure.

The resources of heavy oil on worldwide scale are more than twice those of conventional light crude oil. The largest heavy crude oil reserves are located in the Orinoco Belt in Venezuela and the oil sands in Alberta Canada. High viscosity and low specific gravity of heavy oil increase the cost and the environmental impact for the production, transportation, and refining compared to light crude oil. Especially environmental impact is significant due to contamination of heavy oil with sulfur and heavy metals, both of which must be removed. Heavy metals are often toxic and their removal from crude oil presents disposal issues. Moreover, carbon dioxide output of heavy oil can be as much as three times that of light crude oil of the same quantity. There are two reasons for this. Firstly compared to light oil, the production of the same quantity for heavy oil requires more energy. This means more carbon dioxide is released for the same amount of useable energy produced. Secondly, heavy oil has a higher carbon to hydrogen ratio than light crude, so it contains less hydrogen per carbon than does light crude, which means that when it is burned, more carbon dioxide is created.

2.2.9 Gas hydrates

Gas hydrates are solid ice-like forms of water that contain gas molecules, mostly methane, in their molecular cavities. Hydrate deposits generally occur in two types of settings: on submarine continental slopes and in deep ocean floor sediment where temperature and pressure conditions are suitable for their formation. Generally, gas hydrate occurs at high pressure and low temperature in the Arctic, below permafrost as "boulders" on the sea floor and beneath the ocean floor at a

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water depth greater than 500 meters. Hydrate deposits can be several meters thick. If these occur in sedimentary rocks, the value of hydrate saturation and rock permeability for future production is very important. Methane that forms hydrate can be both biogenic that is created by biological activity in sediments and thermogenic that is created by geological processes deeper within the earth.

Fig. 2.2.11 Hydrate Plug Formed in a Subsea Hydrocarbon Pipeline (adopted from https://www.uio.no/studier/emner/matnat/math/MEK4450/h11/undervisningsmateriale/modul-5/MEK4450_FlowAssurance_pensum-2.pdf)

There are two types of hydrates:

1. Hydrate crystal type I:

   There are 6 medium and 2 small voids. Water moles are 46. If all voids are filled by smaller molecules (CH4, H2S, CO2, etc.), the general formula is 8M46 H2O. If only large voids are filled, the general formula is M72/3 H2O

2. Hydrate crystal type II:

   This hydrate crystal forms if the number of water moles is 136 and there are 16 small and 8 large voids. Its formula is 8M136 H2O or M17 H2O

The methods that gas hydrates can be released are:

- By heating the hydrates using hot water, steam, electromagnetic radiation or electricity. These methods would raise the temperature so that the hydrates would melt, releasing the natural gas.

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- By lowering the pressure of the hydrates, they can melt so the natural gas can be released
- By injecting chemical inhibitors prevent hydrates from forming or cause hydrates that have formed to "melt."

Gas hydrates can cause problems to the petroleum industry, because they can form inside gas pipelines – plug the line-, often resulting in obstructions. The gas hydrate crystallization in pipeline is first appeared in arctic area because the temperature is very low that the hydrate phase can be stabilized due to such a low temperature and low pressure. Such a context occurs in arctic area but in Siberia and south of Argentina too. As the oil exists to the well head, it is at a high temperature corresponding to the temperature of the sediment in which the well has been drilled. But, as the flow moves along the pipe, its temperature decreases because of the low temperature of the wall. Finally, the oil is at the same temperature as the surrounding and the gas hydrate crystallization becomes possible. The temperature is not low, but the pressure can be very high and sufficient to stabilize the hydrate phase.

Gas hydrates can be found on the seabed, in ocean sediments, in deep lake sediments as well as in the permafrost regions. The amount of methane potentially trapped in natural methane hydrate deposits may be significant which makes them of major interest as a potential energy resource. A catastrophic release of methane from the decomposition of such deposits may lead to a global climate change because CH_4 is more of an efficient greenhouse gas than CO_2.

In 2017, both Japan and China announced that attempts at large-scale resource extraction of methane hydrates from under the seafloor were successful. However, commercial-scale production which is the important fact is not yet accomplished.

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3 Shale gas

3.1 General

As mentioned above shale formations can contain gas that is natural gas, mostly methane. Natural gas is produced from shale formations and is trapped there without been migrated to other more permeable formations. So a shale formation acts as both the source rock and as the reservoir. This gas can be stored interstitially within the pore spaces between rock grains or fractures in the shale or can be absorbed to the surface of organic components contained within shale. Shale gas is the most common unconventional source of energy. Because of the large quantities that shale gas is found around the world and with the advance of extraction technologies, shale gas production has led to a new abundance of natural gas supply especially in the United States over the past decade. Shale gas is expected to continue to be the main natural gas supply for the foreseeable future because of the benefits it has.

3.1.1 Shale formation

Sedimentary rocks are the weathering products of preexisting rocks with the main channels of weathering been wind and water. Based on grain size the sedimentary rocks can be divided into breccia, conglomerate, sandstone, siltstone, and shale or clay/ mudrock. Shale is a fine-grained sedimentary rock that is formed from the compaction of silt and clay-size mineral particles that are commonly called "mud". Shale is the most abundant sedimentary rock on Earth, 55% of which is made up of sedimentary rock. Shale is a fissile, terrigenous sedimentary rock in which particles are mostly of silt and clay size (Blatt and Tracy, 2000). In this definition, fissile refers to the ability of the shale to split into thin sheets along the bedding and terrigenous refers to the origin of the sediment. Shale formations are the most common sedimentary rock and often are considered as a natural barrier to the migration of oil and gas and they act as a cap rock for conventional hydrocarbon reservoirs. When they act as a reservoir where gas remains trapped, they form an extremely tight

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reservoir where the extraction of gas is a difficult process and special methods are developed to making it possible.

Shale is composed of quartz and feldspar and major minerals such as kaolinite, illite, and smectite. Other minor constituents are organic carbon, carbonate minerals, iron oxide minerals, sulfide minerals, and heavy minerals. The typical color of shale formations is grey but depending on whether they contain minor constituents, the color of shales can differ. Organic-rich shale is the major rock type for the formation of shale gas, which includes black shale and carbonaceous shale. Black shale includes large amounts of organic matter, fine and scattered pyrite, and siderite, where TOC is usually 3%-15% or more with extremely laminated bedding. Carbonaceous shale contains large amounts of fine and scattered carbonaceous organic matter (usually TOC is 10%-20%), which is characterized by black color staining and large amounts of fossil plant. Regardless of the kind of shale, their antiweathering capacity is weak, where low mountains and valleys were usually formed in natural topography (Jiang, 2003; Zhang et al., 1987; Qian and Zhou, 2008). Red, brown and green colors indicate a ferric oxide (hematite – reds), an iron hydroxide (goethite – browns and limonite – yellow), or some micaceous minerals (chlorite, biotite, and illite – greens).

Fig. 3.1 A Typical sample of shale and an outcrop laminated shale formation (adopted from www.geology.com)

The accumulation of mud begins with the chemical weathering of rocks. As a result of the weathering, the rocks break down into clay minerals and other small particles which often become part of the local soil. A rainstorm might wash tiny particles of

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soil from the land and into streams, giving the streams a "muddy" appearance. When the stream slows down or enters a standing body of water such as a lake, swamp, or ocean, the mud particles settle to the bottom and the sedimentation begun. If the sedimentation continues undisturbed and buried deeper, this accumulation of mud might be transformed into a sedimentary rock known as "mudstone." This is how most shale formations are formed.

Shales are mainly deposited in very slow moving water and are often found in lakes and lagoonal deposits, in river deltas, on floodplains and offshore from beach sands. They can also be deposited in sedimentary basins in the continental shelf in relatively deep and quiet water. As soon as sediments are deposited, their burial begun and a process called compaction took place. The continuous burial leads to temperature and pressure increase and to the maturation of the organic material.

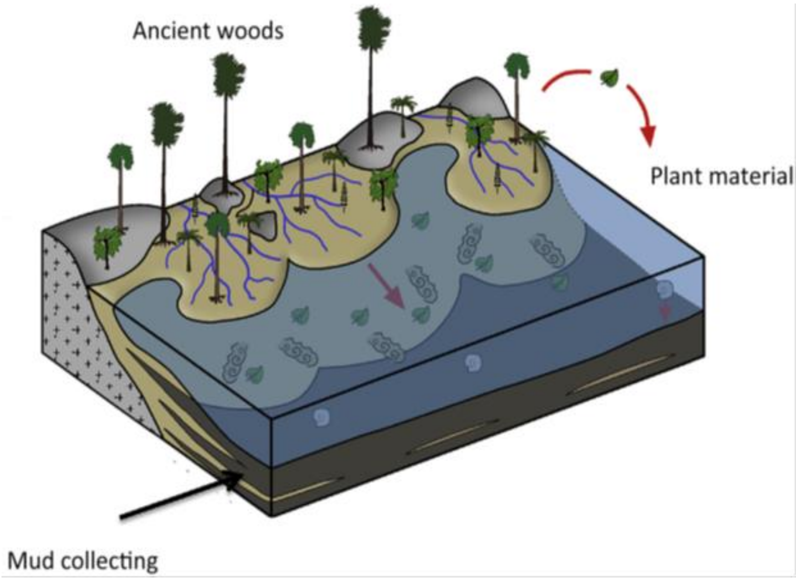

Fig. 3.2 Organic material collects with the mud that eventually hardens into shale (adopted from Könitzer 2013)

In general, shale formations considered as important resources because of their properties, with the most important property been for black shales the content of organic material from which under certain circumstances oil or gas can be formed. Other shales can be crushed and mixed with water to produce clays that can be made into a variety of useful objects.

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3.2 Origin of shale gas

Gas from shale formations is generated in two different ways, although a mixture of gas types is possible: (i) thermogenic gas is generated from thermal decomposition of organic matter or the secondary thermal decomposition of any liquid products—oil, and (ii) biogenic gas that is generated from microbes in areas of freshwater recharge (Martini et al., 1998, 2003, 2004). Thermogenic gas is associated with a mature organic matter that has been subjected to relatively high temperature and pressure in order to generate hydrocarbons. Subjected to high pressures, thermogenic gas would naturally seek pathways to lower pressure environments. Shale gas is such a gas that has been trapped in shale formations that are replete with fissures arising from their laminate and fissile structures, these pathways culminating in dead-ends owing to the classic low porosity and permeability characteristics of shale formations.

Typically, shale formations in which thermogenic gas has been trapped occur up to 2 to 3km below the Earth's surface, although this can vary widely according to geological exigencies and influences. Black organic-rich shale is mainly developed in depositional environments that are oxygen poor and H_2S rich, such as closed bay, lagoon, deep lake, under-compensation basin, and deep shelf (Jiang, 2003; Zhang et al., 1987). As soon as shales that contain organic material buried and compacted by other sediments the temperature and pressure increased relative to depth, so from the organic material, hydrocarbons can be generated if they heated properly. Whether these shales are capable of producing hydrocarbons and whether they generate oil or gas, only depends on the amount and the type of organic material they contain. Organic matter is composed of carbohydrates, proteins, and lipids, of which the lipids are the most resistant to the sedimentary degradation processes. In case those hydrocarbons can migrate from the source rock to a porous formation where they can be storage then a conventional hydrocarbon system is formed. In case those hydrocarbons can't migrate and stay to the source rock where the pore spaces are so tiny that hydrocarbons are difficult to move through the shale and into the well, an unconventional hydrocarbon system is formed.

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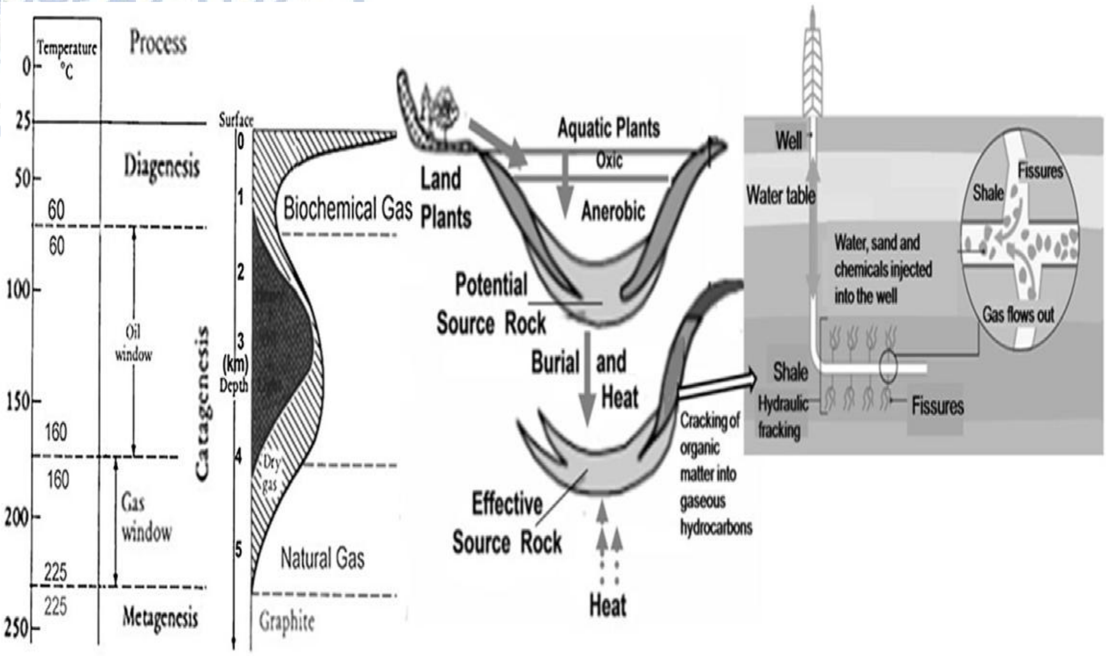

Fig. 3.3 Production, deposition, preservation, and maturation of organic matter in shale gas plays. Modified after Mani, D., Patil, D.J., Dayal, A.M., 2015a.

In general, natural gas has formed through the thermogenic processing of carbonaceous material many millions of years old found at a significant depth in the Earth's crust, where higher temperature and pressure have transformed that material into gas. Natural gas consists primarily of methane, together with other hydrocarbons such as carbon dioxide, nitrogen, and heavier hydrocarbons such as ethane and propane. The methane component is typically 80 percent or more. The proportion of higher hydrocarbons is influenced mainly by the type of organic matter within the geologic formation from which the gas is derived, and by the level of thermal maturity. With its high methane content, natural gas is an excellent energy source for heating.

3.3 Shale gas reservoir

A shale gas reservoir (gas shale) is an organic-rich and fine-grained shale that contains natural gas (Bustin, 2006; Bustin et al., 2008). Gas is stored in shale in three different ways: (i) adsorbed gas, which is physically attached (adsorption) or chemically attached (chemisorptions) to organic matter or to clay, (ii) free gas (also referred to as non associated gas (Speight, 2014), which occurs within the pore spaces in the rock or in spaces created by the rock cracking (fractures or micro

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fractures), and (iii) solution gas (also referred to as associated gas (Speight, 2014), which exists in solution in liquids such as petroleum and heavy oil. The amount of adsorbed methane usually increases with an increase in organic matter or surface area of organic matter and/or clay.

The most important properties for each shale gas play are the following: (i) the type of gas generated and stored in the reservoir—biogenic gas or thermogenic gas, (ii) the total organic carbon (TOC) content of the strata (iii) the maturity of the organic matter and (iv) the permeability of the reservoir. The total organic content (TOC) is the total amount of organic material present in the rock, expressed as a percentage by weight. Generally, the higher the total organic content is, the better the potential for hydrocarbon generation. The thermal maturity of the rock is a measure of the degree to which organic matter contained in the rock has been heated over time, and potentially converted into liquid or gaseous hydrocarbons. Total organic content is a fundamental attribute of gas shale and is a measure of organic richness.

For the economic viability of a shale gas play the total organic content, the thickness of organic shale and thermal maturity of the rock are the key attributes to be taken over consideration with no unique combination or minimum amount of these factors to be needed for reservoir description. The factor of shale thickness refers to the size of the area the shale is expanded. Generally the thicker the shale reservoir is the better target constitutes.

However, the presence of sufficient quantities of gas does not guarantee economic success, since shale has very low permeability and the withdrawal of gas is a difficult proposition that depends largely upon efficient drilling and completion techniques.

The main difference between a conventional and an unconventional hydrocarbon play is that in an unconventional system, hydrocarbons remain where they have been generated. So, in gas shales, the gas is generated in shales which act as the source rock and as the reservoir rock. According to the US Geological Survey (USGS), shale gas is produced from continuous gas accumulations. In order for continuous accumulations of shale gas to be formed, the US Geological Survey (USGS) proposes a list of the most important traits. These traits are: regional extent, absence of an

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obvious seal and trap, absence of a well-defined gas/water contact, natural fracturing, estimate ultimate recovery (EUR, it describes the amount of oil and gas expected to be economically recovered from a reservoir or field by the end of its producing life) is lower compared to conventional accumulation and really low permeability are all parts of the list. When some of these characteristics occur, a shale gas deposit has probably been formed and has to be explored.

3.4 Worldwide shale gas plays

According to Bp's Energy Outlook of 2017 natural gas as a fuel oil grows faster than both oil and coal, growing by 1.6% p.a. between 2015 and 2035. Around sixty percent of the increase in gas supplies is due to shale gas production, driven by the United States where shale gas production increased dramatically during the last decade. The United States is now the number one natural gas producer in the world and, together with Canada, accounts for more than 25% of global natural gas production (BP Statistical Review of World Energy, June 2012). This fact leads many countries to spread their interest to explore potential shale gas deposits. US Energy Information Administration estimates the quantity of technically recoverable shale gas for 41 countries. Nevertheless, only the United States, Canada, and China produce shale gas in commercial quantities with the United States and Canada to have significant shale gas production. All the other countries are yet to produce gas from shale formations due to environmental reasons especially the European countries and due to technical reasons for the other countries despite the fact that their territories contain subsurface shale gas deposits.

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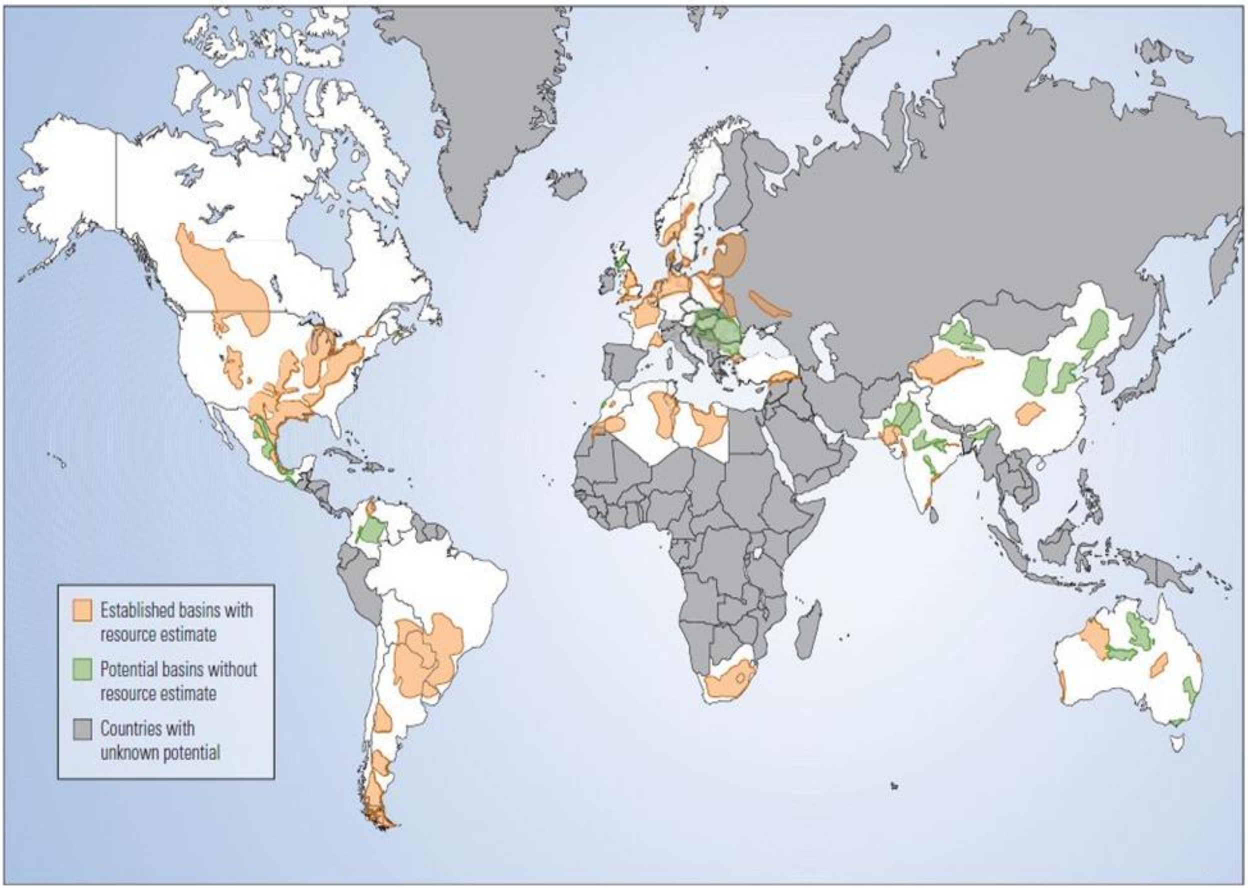

Fig. 3.4 Global shale gas resources (adopted from US EIA)

USA

The United States have firstly produced shale gas after a long-term effort by the natural gas industry in partnership with the Department of Energy to improve drilling and extraction methods while increasing exploration efforts. Energy Information Administration agency of the United States Department of Energy estimates that the United States has about 308 trillion cubic feet of proved shale gas resources while 623 trillion cubic feet of additional unproved technically recoverable shale gas resources added to previous. During 2005 the Barnett Shale formation was drilled horizontal and the economic results were remarkable. Since then all the shale gas plays in the US were drilled horizontal and the shale gas revolution took place as the following picture describes.

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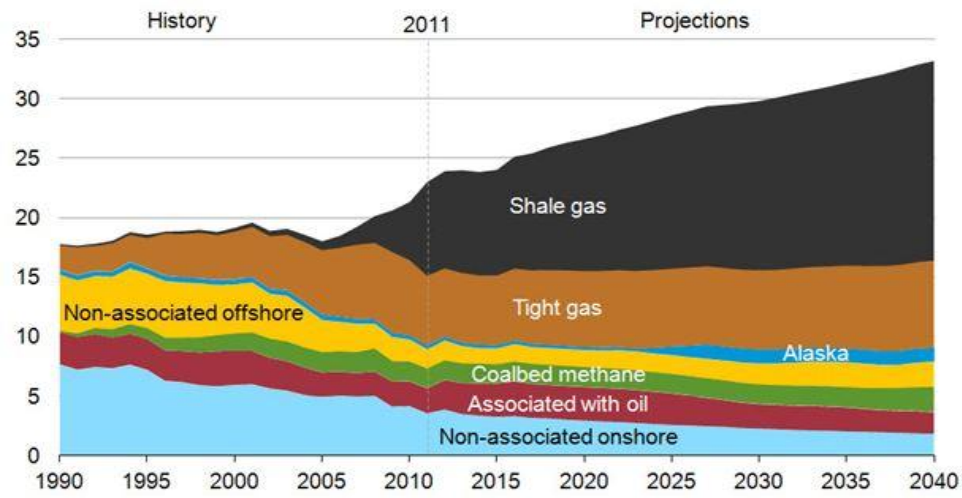

Fig. 3.5 US dry natural gas production in trillion cubic feet (adopted from US Energy Information Administration)

The most important shale gas formations across US are the Marcellus shale in West Virginia, Pennsylvania, and New York which is estimated to hold 168 to 516 trillion cubic feet, the Barnett Shale located in the Bend Arch-Fort Worth Basin Province in North Central Texas and southwestern Oklahoma which from 2002 to 2010 was the most productive source of shale gas in the US. The Barnett shale has been called the largest natural gas field onshore in the United States and has acted as a source and sealing cap rock for more conventional oil and gas reservoirs in the area. Other important shale gas formations are Utica shale in the northeastern United States, Haynesville Shale in northwest Louisiana, Fayetteville shale located in Arkansas, Collingwood-Utica shale located in Michigan, the Eagle Ford shale in southern Texas and many others.

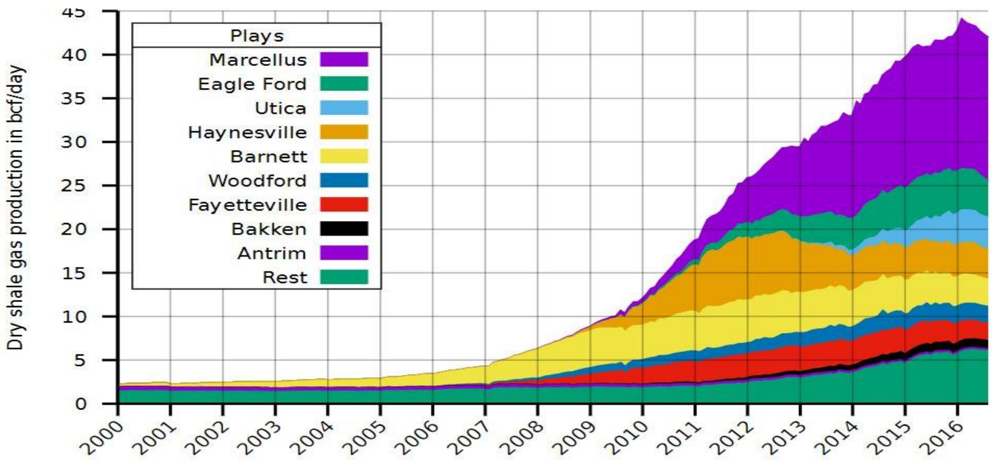

Fig. 3.6 Shale gas production in US by shale formation (adopted from US Energy Information Administration)

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CANADA

Along with the United States, Canada also produces dry gas from shale formations and sees large-scale development of shale resources. There are a number of prospective shale gas targets that located in British Columbia, Alberta, Saskatchewan, Ontario, Quebec, New Brunswick, and Nova Scotia. The most important shale gas formations are the Montney Shale in east-central British Columbia, and the Duvernay Shale in central Alberta. Together these two shale gas formations are estimated to hold about 388 trillion cubic feet of natural gas. Other important shale formations are Muskwa shale in northeast British Columbia, Horton Bluff shale in Nova Scotia and Frederick Brook Shale New Brunswick.

CHINA

China has produced during 2017 9 bcf (billion cubic feet) of shale gas and is planning to double this amount in 2020. It is believed that China holds the world’s largest recoverable shale gas resources but the shale formations tend to be deeper, more fractured and located in densely populated mountainous terrains, leading to higher costs and complications in drilling comparing with US shale gas formations. So it is necessary for all the shale gas sectors from exploration to exploitation to be developed in order for the goals of China government to be accomplished. The majority of Chinese shale reserves located in Sichuan basin, in the Tarim basin, and in Yangtze Platform, accounting for 89% of the estimated national reserves.

SOUTH AMERICA

In South America, Argentina has by far the largest resource potential of gas shale that is estimated around 774 Tcf and is technically recoverable. In Neuquen basin, the Vaca Muerta Shale formation is located along with the Los Molles formation. In these two shale formations, the most of the oil and gas fields are sourced. Brazil has 906 Tcf of technically recoverable shale gas while Chile, Paraguay, and Bolivia have some sizable resources of shale gas.

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EUROPE

Europe as a continent has also many sedimentary basins with shale gas prospects. Eastern Europe may hold as much as 250 Tcf of shale gas, with the Silurian Shale gas resource holding as much as 187 Tcf of that total. These shale gas resources could reduce Europe's dependence on natural gas imports and will give Poland (Baltic, Podlasie, Lublin Basins) a strong claim to energy independence as its projected reserves equate to approximately 300 years of domestic consumption. In France, it is believed that 180 Tcf of shale gas can be produced from formations that Paris and Southeast basins host. Toarcian shale formation and Permian – Carboniferous shale are organic-rich shales that found in Paris basin. The North Sea German basin that includes also fields from North Belgium and Netherlands includes a number of potential shale gas formations such as the Posidonia shale, the Wealden shale, and the Carboniferous Namurian shale but in general with low potential in terms of quantity. In Hungary, Romania, and Slovakia the Pannonian – Transylvanian basin can host shale formations with organic material but more researches must be made. Ireland and the United Kingdom are also two additional areas for shale exploration because of their conventional hydrocarbon history.

Generally, the development of unconventional gas in Europe is likely to be a long-term story and is unlikely to become a sudden gas revolution as in the US. There will be no significant production before at least 2020 due to specific reasons.

ASIA

India is believed to host 500 to 2.000 Tfc of recoverable shale gas in shale formations of sedimentary basins. The continuous tectonic activity in India makes the geological basins more complex. Indonesia has proven shale gas resources of 574.07 Tcf in Sumatra Island, in Kalimantan Island, in Papua Island, in Java Island, and in Sulawesi Island. Pakistan has a sedimentary basin with a future prospect and the technically recoverable shale gas deposits are about 51 Tcf.

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AUSTRALIA

Australia has a long history in the production of unconventional reservoirs such as tight gas and coalbed methane (CBM). Canning, Cooper, Perth and Maryborough basins are considered for shale gas development. These basins hold an estimated 396 Tcf of technically recoverable shale gas deposits with the Canning basin being the biggest and the most interesting of all. The Goldwyer formation of Canning basin has the greatest estimated recoverable resource.

AFRICA

One of the most plentiful sources of shale gas in the world is in South Africa and more specifically in the Karoo Supergroup. The area is constituted mainly of shale and sandstone and underlies more than two-thirds of the entire area of South Africa and contains an estimated 485 Tcf of technically recoverable gas. Shale gas could reduce the country's dependence on coal, to fuel 85% of the energy needs.

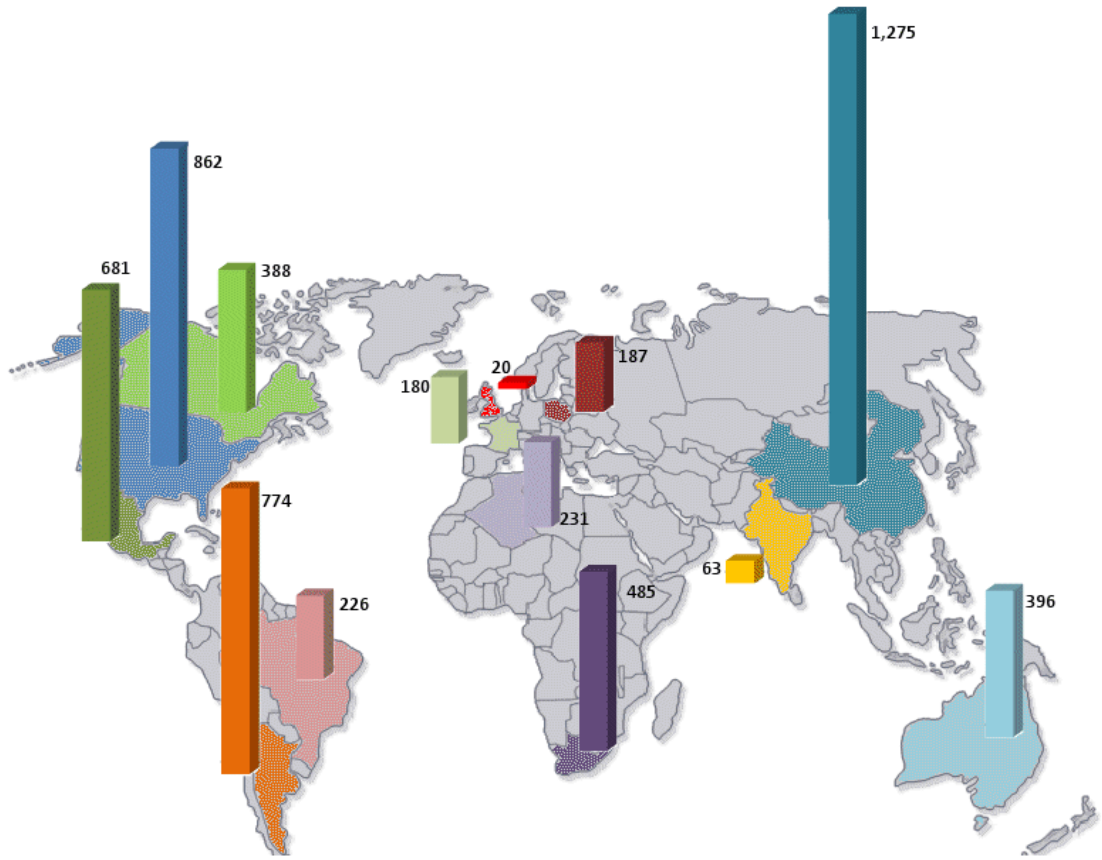

Fig. 3.7 Technically Recoverable World Shale Gas Resources estimated in trillion cubic feet, TCF (adopted from US Energy Information Administration)

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3.5 Shale gas in Greece

In Greece, the possibilities of finding gas in shale formations are limited because of the geological processes that have occurred. The sedimentary basins which are necessary for the shale formations to be formed have not grown enough in Greek territory and also the intense tectonics that occurred are the main reasons for the limited possibilities.

Generally, in Greek sedimentary basins, several gas occurrences are detected which is important for understanding the geology of these basins. More specific gas appearances distinguished as follows:

- The appearance of gas in the surface
- The appearance of gas in small depth drilling wells
- The appearance of hydrocarbon gas in exploration wells
- The appearance of gas in hydrocarbon fields (Prinos field)

Gas evidence in these occasions denotes that petroleum production has taken place in these regions along with the primary migration of hydrocarbons. Also, the petroleum system of these regions can be studied in the sense of hydrocarbons creation, migration and maturation.

Based on the chemical analysis of these gases, they are classified into three categories relative to their origin:

- Biogenic gas from corrosion of organic matter
- gas mainly derived from petroleum production called catagenetic
- the post-gas derived from other trapped gases in cracking.

However, according to recent studies, Greek territory contains some areas with potential shale gas formations. The areas in the order of greatest probabilities are:

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- Thrace (Alexandroupoli basin - Orestiada basin) and Limnos basin

  This area contains a large basin with a significant cover of sediments and for this area, borehole data exist for biogenetic gas production. Also in neighboring areas of the east Thrace, already corresponding geological forms are exploited.

  During Tertiary, the main sedimentation took place in Evros delta, where the environment deposit was a shallow marine and deltaic while lignite deposits and shales rich in organic material follow. At the end of Oligocene, a general rise and erosion phenomena took place. The organic-rich formations are covered by Miocene – Pleistocene clastic sediments such as sandstone, sand, rough ground sediments and unconnected conglomerates. In this basin, exploration drills have been made for hydrocarbons with the depth of them to range from 2752 m to 3702m and natural methane gas of biogenic origin was found. In Evros delta near to Oligocene lignite horizons, great presence of methane gas was found. Similar formations have been deposited in east Thrace where research and exploitation of shale gas have started.

  Limnos basin was formed during middle Eocene when first sediments were deposited. In the beginning, the depositional environment was terrestrial and then become shallow with deposits of limestone, which develops into a pelagic environment. During late Eocene – early Oligocene in the area typical continental decline deposits was deposited such as thick sandstones, microencapsulation, and conglomeration, with interference clay-sandstone in the form of turbidite. To the south of Limnos, an offshore drill was made and the typical continental decline deposits were drilled without any data on geochemical and stages evolution of organic matter to be published.

- Area of Kavala – Prinos basin

  In this area, hydrocarbon exploitation is taking place and the presence of natural gas is typical without having been proven its connection to the hydrocarbon deposits.

  The taphrogenetic Prinos basin is located at the southern edge of the pre-alpidic Rhodope massif. The gas deposit is located between the two

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evaporitic horizons and is consisted of fine to coarse sands, microencapsulation in alternations with clays, marls, and conglomeration with shale matrix. The gas deposit is at depth of 1656 m, it has a net thickness of 10 meters, and it has porosity from 10% to 24% and permeability greater than 400 md.

- <u>Axiou - Thermaikos basin</u>

  According to researches, this area can host two reservoirs one at the beginning of the molassic period and the other in the upper limestones of Mesozean limestone Jurassic - Lower Cretaceous.

  During the decade of 1980 two exploration drills were made in the area of Epanomi and a natural gas deposit was discovered. It is believed that the feeding of gas deposit is made laterally by Eocene source formations. The reservoir formation is a Mesozoic limestone of late Jurassic – early Cretaceous age, with low porosity but with a significant crack system that creates the active porosity of the reservoir. According to studies, it comes as a conclusion that both gas and hydrocarbons have the same source of origin: the Eocene shale formations and a deeper formation horizon due to a high level of maturation of organic matter in gas.

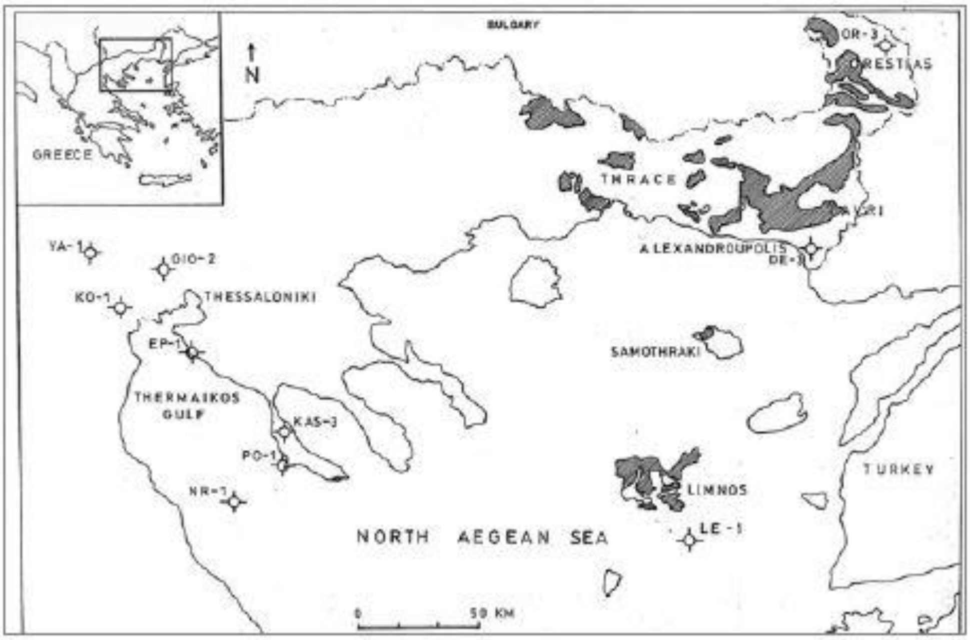

Fig. 3.8 Rock formations that can host gas on North and east Greece and drilling points (Roussos 1993)

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- Western Greece (Epirus, Katakolon, Akarnania)

  The significant presence of biogenic gas and of mature gas, contained in the flysch or in the carbonate rocks of Eocene - Mesozoic.

  In Katakolon, drills have made as part of exploration project for hydrocarbons. The results showed that a small gas field is located in Katakolo, while hydrocarbon gases were found to the most drilling wells in Northwest Peloponnese. These concentrations of gases, mainly methane, are trapped in clastic horizons of Upper Neogene age and in carbon formations of Mesozoic age.

- Meso Hellenic Grove (Grevena)

  Exploration wells were drilled as part of an exploration project in Meso Hellenic Grove. After the data collection, the Tsotylian sandstone formation of Aquitaine – Bourguignon age has significant signs for natural gas. Also, other promising source rocks are recognized for large quantities of hydrocarbon accumulation.

4 Exploitation of shale gas

4.1 Hydrocarbon exploration

Every drilling process which is the most important stage of exploration phases must begin as soon as the chances of finding oil or gas are high. These possibilities came after long term exploration processes that include topographic survey, aerial survey, and geological survey. When the appropriate area is found, then the geophysical exploration methods took place. These methods include magnetic, gravity, seismic and well logging. The goal for every geophysical method is to identify potential hydrocarbon bearing traps. The most important geophysical tool is by far the seismic surveys because they can perform the underground structures with great detail. The next stage for hydrocarbon exploration contains the exploration drilling wells constructed in the targets the previous searches indicate. This kind of drilling wells aims to supply data about the potential reservoir with rock sampling and analysis of

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reservoir size and quality. The last step of the exploration process is the evaluation of the resource that will indicate if the extraction of the resource can be economically profitable or not. If the hydrocarbon system is profitable, is necessary for the hydrocarbon system to be produced. In order for every hydrocarbon system, conventional or unconventional, to become productive is necessary for productive drilling wells to be constructed. With the productive drilling wells, the production of hydrocarbons begins until the depletion of the deposit and program is terminated. Hydrocarbon field is abandoned with all the safety measures be taken. All the exploration and exploitation phases are concentrated to the following diagram.

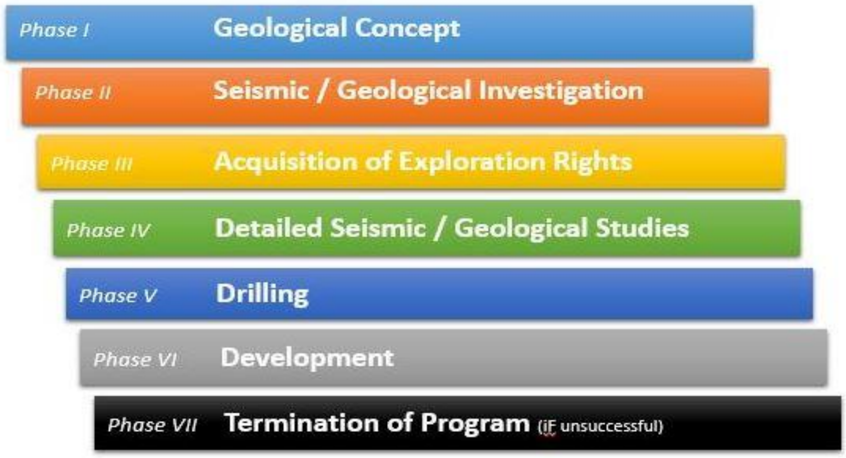

Fig. 4.1 Typical exploration-exploitation stages (adopted from https://www.glossary.oilfield.slb.com)

4.2 Drilling Rigs

Every drilling well is constructed by drilling rigs. Every drilling well is constructed for a specific reason and depending on this reason different types of drilling rigs are used for the drilling well construction. The drilling rig is a facility that can open holes in the earth's subsurface either onshore or offshore. Drilling rigs can be used to construct production boreholes for water, oil or natural gas extraction wells. Drilling rigs can also be used for core sampling subsurface mineral deposits, for geotechnical reasons such testing physical properties of rock and soil formations. Drilling rigs are necessary for installing sub-surface fabrications, such as underground utilities, instrumentation, tunnels or wells. Drilling rigs can be mounted on trucks, tracks or trailers so they called automotive or they can be permanent structures on land or marine-based structures and they called onshore oil rigs or offshore oil rigs.

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The deeper the hole has to be drilled the more powerful the drill rig has to be. There are different types of drilling rigs available, relative to the area and the target that has to be drilled for the exploration phase.

Fig. 4.2 Typical onshore drilling rig courtesy of Energy CG (adopted from https://www.petroprophet.com)

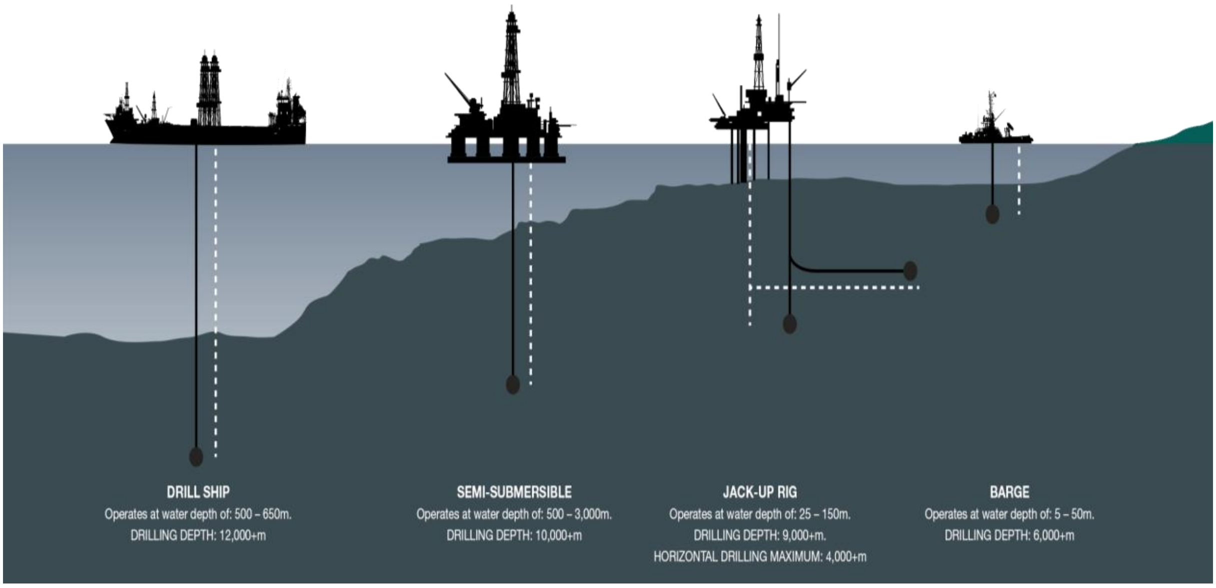

Fig. 4.3 Different types of offshore drilling rigs (adopted from MAERSK Drilling)

With the development of drilling techniques have been made during last decades, areas where it was impossible for drilling exploration; now drilling wells are constructed and new hydrocarbon fields are discovered. The only way to confirm

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whether a geological structure contains oil or gas is to drill an exploration drilling well. An exploration drilling well apart from the confirmation of hydrocarbon existence provides also information for further exploration and future field development.

4.2.1 Parts of a drilling rig

A facility of an oil drilling rig consists of many function systems which are presented below:

<u>The Hoisting System</u>

The hoisting system is used to raise or lower and to suspend the drilling equipment such as the drillstring, the casing etc. The hoisting system consists of the derrick, some draw works, the block and tackle system and finally of the miscellaneous hoisting equipment such as hooks, elevators, and weight indicator.

<u>The Rotary System</u>

Rotating equipment is used for rotary drilling and includes the following components:

- Swivel: a big handle that holds the weight of a drill string and allows the string to rotate, making a pressure-tight seal on the drilling hole.
- Drill String: made up of the drill pipe (normally sections of drill pipe are about 30 feet and are connected together) and drill collars which fit around the pipe in order to put weight on the drill bit.
- Drill Bit: the very end of the drill which is capable of cutting through rock. Bits can come in many different sizes and shapes and can be made of various materials including diamond and carbide steel. Drill bits are specialized for different types of rock formations and drilling tasks.
- Rotary or Turntable – the component that drives rotating motion by utilizing power from electric motors.
- Kelly – a four or six-sided pipe that will transfer the rotary motion to the rotary table and drill string.

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Power Systems

The power systems of a rig are the main source of power for running all equipment and include the following components:

- Electric Generators: generators that are powered through diesel engines in order to provide electrical power to the rig.
- Diesel Engines: very large engines that burn diesel fuel in order to provide the main source of power on the rig.

The Circulation System

With circulation system the drilling cuts are pumped out of the drilling hole (to the surface). This is accomplished by the use of drilling mud which is consisted of water mixed with various chemicals and clays. The drilling mud is also used for cooling and lubricating the drill bit and for preventing the caving of loose formations. The drilling mud is circulated through many different components of the circulating system.

The circulation system consists of the following:

- Pipes & Hoses – various parts that are used to connect a pump to the drilling apparatus.
- Pump – equipment that works to suck mud so it can be pumped into the drilling apparatus.
- Shale Shaker: a sieve that has the ability to separate cut up rock from mud.
- Mud Return Line: a line used to return mud from the mud pit.
- Shale Slide: a slide that transfers cut rock to the reserve pit.
- Mud Pit: the area where drilling mud is not only mixed but also recycled.
- Mud Mixing Hopper: the apparatus used to mix new mud after which it is sent to the mud pits.

Mechanical System

The mechanical system of a drilling rig is run by electric motors and consists of the following components:

- Turntable: a piece of the drilling apparatus.

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- Hoisting System: a system that is used to lift heavy loads. It consists of a mechanical winch with a block and tackle pulley and big steel cable spool along with a receiving storage reel for the cable.

The Safety System

The main safety system that is used during the drilling procedure is called the blowout prevention system. This system aims to prevent the uncontrolled and high pressure escape of oil and gas during drilling. The blowout prevention system is consisted of a series of hydraulically operated valves and rams. During drilling, these are left open to allow drilling mud to circulate. In case of excessive pressure enters the well the valves can quickly be closed. If excessive pressure from the formation suddenly enters the borehole, commonly referred to as a kick, pipe rams are closed to prevent overpressure reaching to the surface. As the last line of defense in an emergency shear rams are activated which cut through the drill string and seal the well completely.

Along with the systems and apparatuses listed above, a drilling rig will also have casing pipes. The casing is a concrete pipe with a large diameter that essentially lines the drill hole in order to prevent it from collapsing. The casing also allows the drilling mud to easily circulate. The drilling rig will also have a derrick which is the supporting structure responsible for holding the drilling apparatus. It is important for the derrick to be long enough to allow new sections to be added to the drilling apparatus once the oil drilling progresses. Another important component of a drilling rig is a blowout preventer.

While the above equipment is used for land-based oil drilling, some of the same components are used for offshore drilling as well. Drilling for hydrocarbons is a difficult process that incorporates numerous different pieces of equipment and a crew that specializes in setting up and running the drilling equipment.

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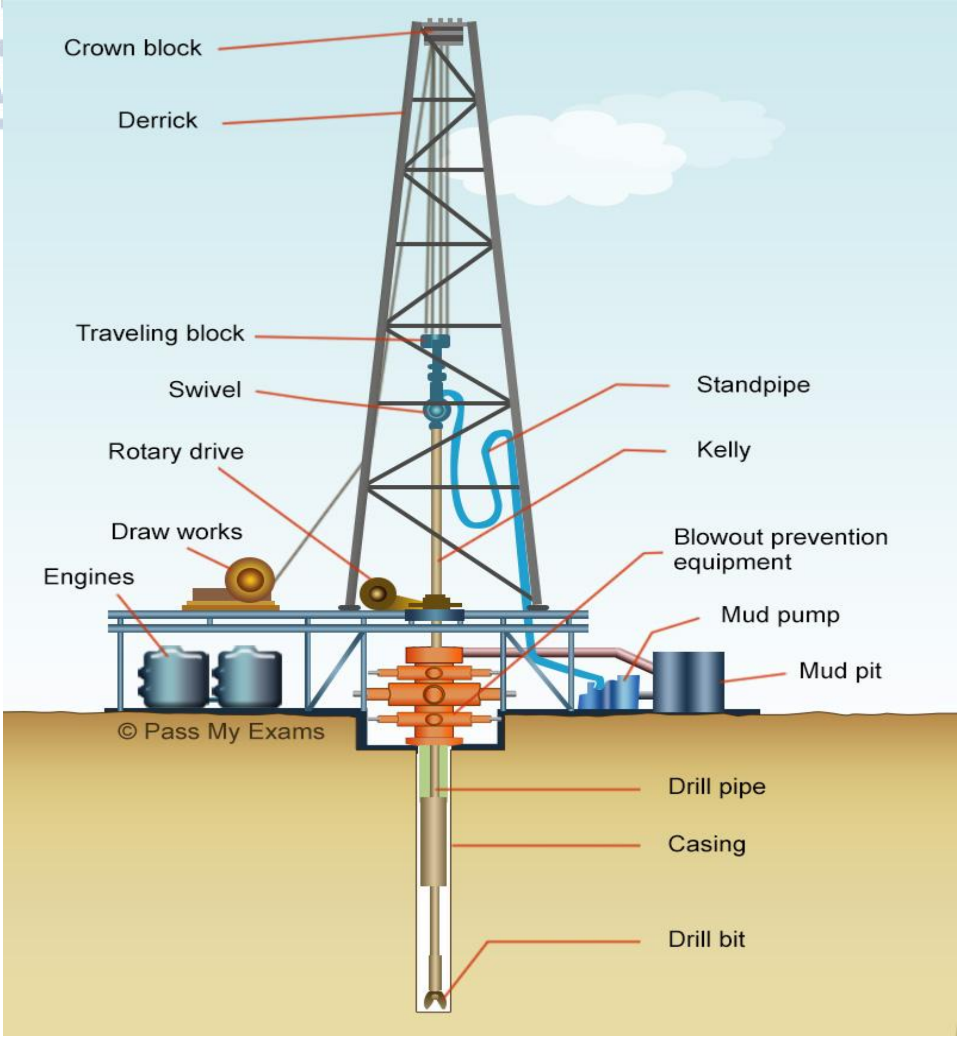

Fig. 4.4 Scheme of the most important parts of a drilling rig (adopted from http://www.passmyexams.co.uk/GCSE/chemistry/drilling-crude-oil-1.html)

4.3 Types of drilling wells

Depending on the stage of hydrocarbon exploration and exploitation different types of drilling wells exist. There are four types of drilling wells which are presented below:

1. **<u>Exploration drilling wells</u>**

   Exploration drilling wells (wildcats) drill possible geological prospects after research of previous stages (seismic – geological investigation, detailed seismic – geological studies). With the exploration drilling well, geological data are collected such as rock sampling – rock properties – reservoir fluids and if positive conclusions come then a new hydrocarbon field is discovered.

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2. **Appraisal drilling wells**

   This type of drilling wells follows exploration wells after the hydrocarbon field discovery. Appraisal wells provide additional data for reservoir characteristics such as estimation of hydrocarbon reserves, estimation of the size of the reservoir, etc. and help to confirm the economic potential of hydrocarbon discovery.

3. **Development drilling wells**

   These types of drilling wells are part of the Field Development Plan (FDP) and they constructed at selected points in the reservoir to optimize oil or gas production. They can also be constructed in order for fluids to be injected in the reservoir so hydrocarbons can flow easier. With these wells, the production rate is defined in order the hydrocarbon field production to be stable.

4. **Workover and interventions drilling wells**

   These types of drilling wells are constructed during hydrocarbon field production in order for some repairs to be made, for new reservoir data to be obtained, for safety reasons and for completion reasons.

4.4 Drilling procedures

For the construction of a drilling well many steps are required. Before the construction of a drilling well, a drilling program has already been made and every drilling step is already been planned for better, safer and quicker construction. The first step is the installation of the conductor pipe which is a large diameter pipe usually 30'' to 36'' that is set into the ground to provide the initial stable structural foundation for the oil well. So a large diameter hole (bigger than the pipe diameter) is drilled to a shallow depth and the conductor pipe is installed. Before the main drilling procedures begin a hole called 'mouse hole' is drilled near to the main borehole which is used for the temporary storage for every one drill pipe that has to be used. After the installation of the conductor pipe the drilling rig and all the drilling equipment installed to the borehole.

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Next stage is the installation of the surface casing. In order for the surface casing to be installed a bigger hole is drilled to the programmed depth. The surface casing has many purposes such as the aquifers protection which may contain freshwater, the supply of mounting place for the installation of the blowout preventer and can support the appropriate hatch for the installation of production casing. The surface hole is usually a hundred or thousand feet deep. To the top of the surface casing, an important device is installed the blowout preventer. This device is required to control the well in the event that abnormal pressures of drilled formations come into the well which could not be controlled by drilling fluid – mud. In case high-pressure gas or liquid blows the drilling fluid out of the wellbore, the blowout preventer can be closed so gas and fluids cannot escape to the surface.

Drilling operations resume until the well has been drilled to the total depth decided upon. If it is required another string of casing is installed which called intermediate casing and provides protection against caving of weak or abnormally pressured formations and enables the use of drilling fluids of different density necessary for the control of lower formations. Intermediate casing is installed before the production casing.

As drilling operations continue a geologist examines drill cuttings that came up to the surface with mud, for oil and gas signs. In some cases new technology logging tools LWD (Logging While Drilling) are used for oil or gas detection. The examination of drill cuttings declines the type of rock the drill bit is penetrating and the geologic formation from which the cuttings are coming from. When geologists detect oil or gas traces a Drill Stem Test is performed. Drill Stem Test helps to determine productive capacity, pressure, permeability or the extent of an oil or gas reservoir. The testing equipment is run into the well and the zone of interest is isolated using compression-set packers. If the quantity of liquids existed in the zone is tested, then the liquids can rise to the surface. If gas existed it is burned at the surface as a flare. During the Drill Stem Test, the amount of fluids and the pressure of fluids are measured, in order petrophysical properties of the reservoir such as porosity, permeability and the nature of the fluids or gas contained, to be estimated.

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After drill stem testing and well logging operations are completed and the results have been analyzed it has a decision to been made by the managers whether the well must be completed to become productive if oil or gas presented or to be plugged and abandoned if no hydrocarbons presented in the reservoir. For the well completion, some operations are necessary. Firstly is necessary for the production tubing to be installed. Production tubing works as a passage for hydrocarbons from the reservoir to transport to the surface. Production tubing starts from the tubing hanger at the top of the wellhead down to a point generally just above the top of the production zone. One crucial operation is to make a connection between the wellbore and the formation. This is made by perforations guns which blast holes to production casing or liner so a perforation tunnel is created that provides a pathway for fluid flow from the reservoir to the wellbore. General completions can be divided into three categories: open-hole completions, liner completions, and perforated casing completions. A perforated casing completion is the most commonly used completion technique today. Finally, at the surface, a wellhead is installed which is used to control the flow of oil or gas from the well through valves. This device is known as “Christmas tree”. Eventually, after all these procedures, a hydrocarbon reservoir becomes productive until the definitive depletion of the reserves.

4.5 Horizontal drilling wells

Shale formations have very low values of permeability and low porosity but in some cases, they have their pores filled with gas so shale gas reservoirs are formed. For gas production of these plays, is important for new methods of drilling to be developed in order gas to flow in the borehole. Apart from drilling methods development is crucial for new techniques of well completion to be developed. So for gas production from shale formations horizontal drilling wells is necessary to be constructed and fracking techniques to be applied.

Horizontal drilling is the intentional deviation of the wellbore from the path it would naturally take. Horizontal drilling wells are high-angle wells (with an inclination of generally greater than 85°) drilled to enhance reservoir performance by placing a

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long wellbore section within the reservoir. Horizontal lateral sections can be drilled to intersect natural fractures or simply to contact more of the productive formation.

Horizontal drilling is accomplished through the use of sophisticated devices - tools such as whipstocks, bottom hole assembly (BHA) configurations, instruments to measure the path of the wellbore in three-dimensional space, data links to send the measurements that were taken downhole to the surface, mud motors and special BHA components, including rotary steerable systems and drill bits. All these devices are used in order a horizontal drilling well to be constructed.

Most horizontal wells begin at the surface as a vertical well and the general idea for horizontal drilling is the following: Drilling progresses until the section where the target rock unit is located a few hundred feet above. At that point, the pipe is pulled from the well and a hydraulic motor is attached between the drill bit and the drill pipe. The hydraulic motor can rotate the drill bit without rotating the entire length of drill pipe between the bit and the surface. This allows the bit to drill a path that deviates from the orientation of the drill pipe. After the motor is installed, the bit and pipe are lowered back down the well and the bit drills a path that steers the wellbore from vertical to horizontal over a distance of a few hundred feet. Once the well has been steered to the desired angle, straight-ahead drilling resumes and the well follows the target rock unit. Keeping the well in a thin rock unit requires careful navigation. Downhole instruments are used to determine the azimuth and orientation of the drilling. This information is used to steer the drill bit. Rotary steerable tools allow steering while rotating, usually with higher rates of penetration and ultimately smoother boreholes. Horizontal drilling is common in shale reservoirs because it allows drillers to place the borehole in contact with the most productive reservoir rock.

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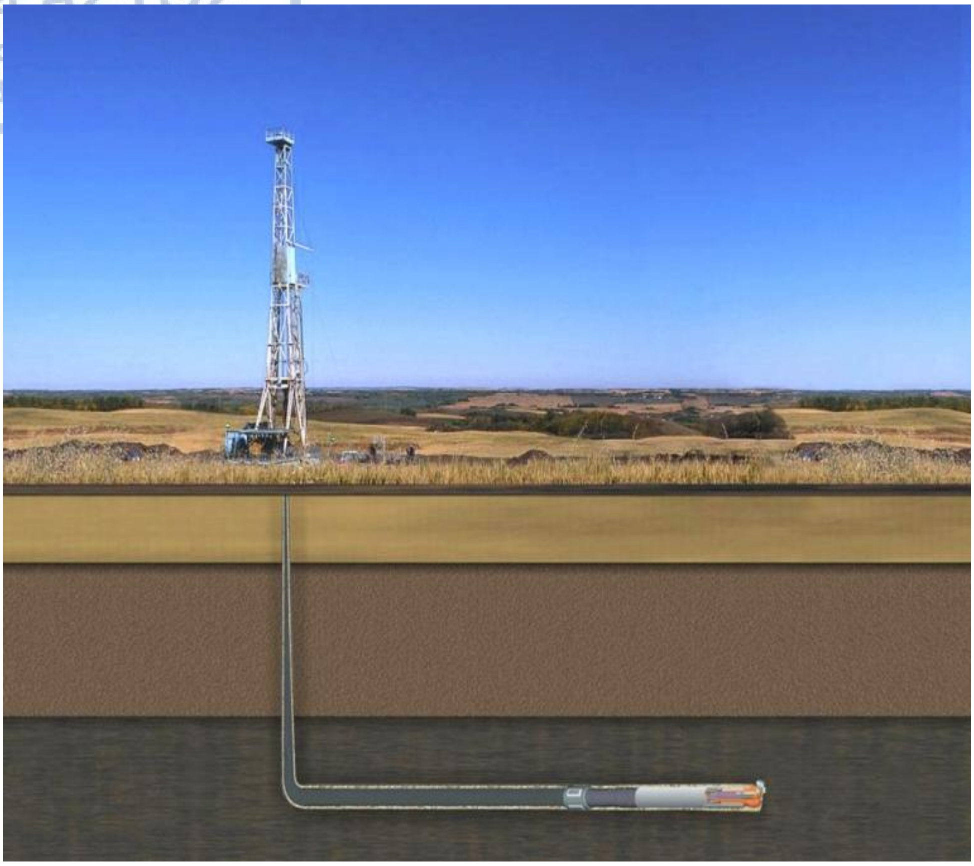

Fig. 4.5 Scheme of horizontal drilling (adopted from U.S. Department of Energy)

Drilling horizontal wells have many advantages versus traditional vertical drilling wells. The benefits of horizontal drilling are presented below:

- The length of the "pay zone" within the target rock unit is increased
  By drilling horizontally a formation which is fulfilled with gas but the thickness of this formation is short, the productivity of this formation will increase dramatically. So horizontal drilling increase the distance of penetration within the pay zone (reservoir) and if it is combined with hydraulic fracturing, unproductive shales can be transformed into fantastic reservoir formations.
- The productivity of wells in a fractured reservoir is improved.
  This is done by drilling in a direction that intersects a maximum number of fractures. The drilling direction will normally be at right angles to the dominant fracture direction. Geothermal fields in granite bedrock usually get nearly all of their water exchange from fractures. Drilling at right angles to the dominant fracture direction will drive the well through a maximum number of fractures.

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- A broad area can be drained by single drilling well

  From a single drill pad, many wells can be drilled in different directions so the surface footprint of drilling operations can significantly be reduced. It is estimated that horizontal drilling reduces the size of the drilling area above ground by as much as 90 percent.
- Targets that cannot be reached by vertical drilling can eventually be drilled

  Horizontal drilling can reach reservoirs which can be located in places where drilling is forbidden such as a city or a park etc. and now these reservoirs can be drilled.
- An "out-of-control" well can be sealed or relieved

  If a well has a problem and is out of control, it must be sealed at depth or the pressure must be relieved. In this situation, a "relief well" can be drilled from a nearby site. The relief well will be a directionally drilled well that intersects the bore of the problem well to drain off some of the pressure or to plug the well by pumping cement into the bore.

Perhaps the most important role that horizontal drilling has played is in the development of the natural gas shale plays. These low-permeability rock units contain significant amounts of gas and can become productive with horizontal drilling.

4.5.1 Pad drilling

In some cases multiple wells can be drilled from the same pad and it is often referred to as pad drilling. From the same pad as many as six to eight horizontal wells can be constructed. “Pad” is called the cleared land where the rig operates and it can be covered with swamp matting, rig matting or gravel to provide a steady base for the rig.

Typically, the well pad drains an area which is usually about one half mile wide by two miles long with the pad itself positioned at the center of the rectangle. Pad drilling may be accomplished through the use of a movable flex or suitable-for-the-purpose drilling rigs with the intent to drill as many wells on a pad as are

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economically feasible. By drilling more boreholes from one pad the environmental impact is minimized.

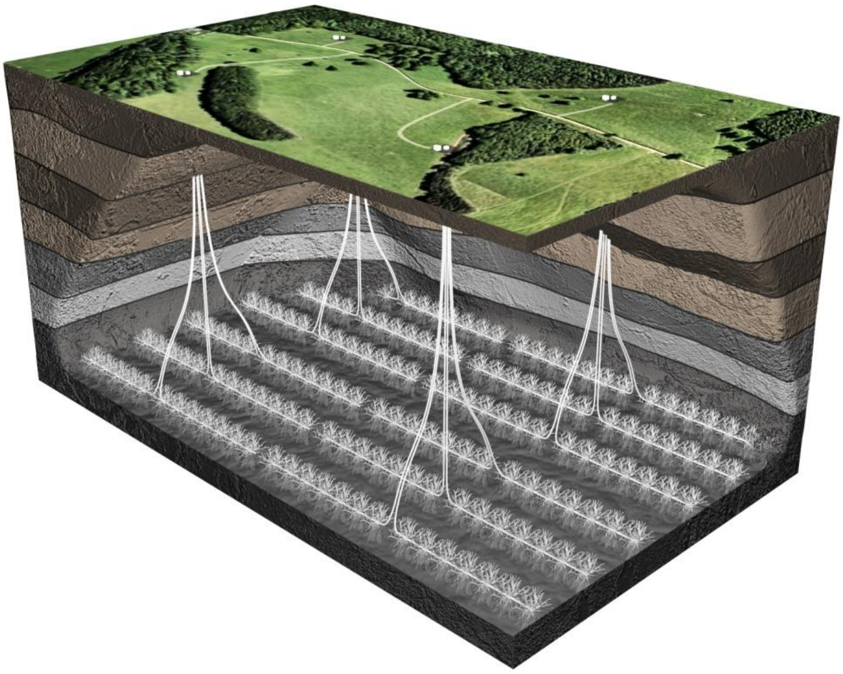

Fig. 4.6 Scheme of pad drilling (adopted from U.S. Department of Energy)

Especially in shale drilling it is becoming increasingly common to use a single drill pad to develop as large an area of the subsurface as possible. A number of horizontal drilling wells can be constructed from a single location with minimal impact on the surface. The scope of these horizontal wells from one pad can be so far reaching that multiple formations can be targeted from the same location. Pad drilling increases the operational efficiency of gas production and reduces infrastructure costs and land use. Any negative impact upon the surface environment is therefore mitigated. Such technologies and practices developed by industry serve to reduce environmental impacts from shale gas operations.

4.6 Hydraulic fracturing

In order for hydrocarbons to be produced is necessary to be able to flow to the borehole. Low values of permeability along with low values of porosity make impossible any gas to flow because resistance to fluid flow is high. So it is necessary for reservoir rocks to be fractured in order gas to flow through paths which are

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created by fractures. It was necessary for a new technique to be developed in order to achieve this kind of fluid flow. This new method is called hydraulic fracturing. Hydraulic fracturing is a well stimulation technique in which rock formation is fractured by liquids which are intensive pressured through the wellbore. By this technique the 'fracking fluid' which is mainly water that contains sand or other chemical proppants suspended with the aid of thickening agents, is pressured into the wellbore to create cracks in the deep-rock formations. Through these cracks, natural gas, petroleum, and brine will flow easier and more freely. During injection the resistance of liquids to flow in the rock formation increases and also the pressure in the wellbore increases to a value called the break-down pressure that is the sum of the in-situ compressive stress and the strength of the formation. Once the formation “breaks down,” a fracture is formed, and the injected fluid flows through it. As soon as the 'fracking fluid' is removed from the well, small grains of hydraulic fracturing proppants hold the fractures open. By the technique of hydraulic fracturing we achieve good flow rates in shale gas formations, tight gas formations, tight oil formations, and coal seam gas wells which means that these unconventional hydrocarbon systems can be productive and profitable, while before the development of hydraulic fracturing these kinds of hydrocarbon systems remained undeveloped. The following picture shows the types of unconventional deposits with their permeability values and the need for hydraulic fracturing.

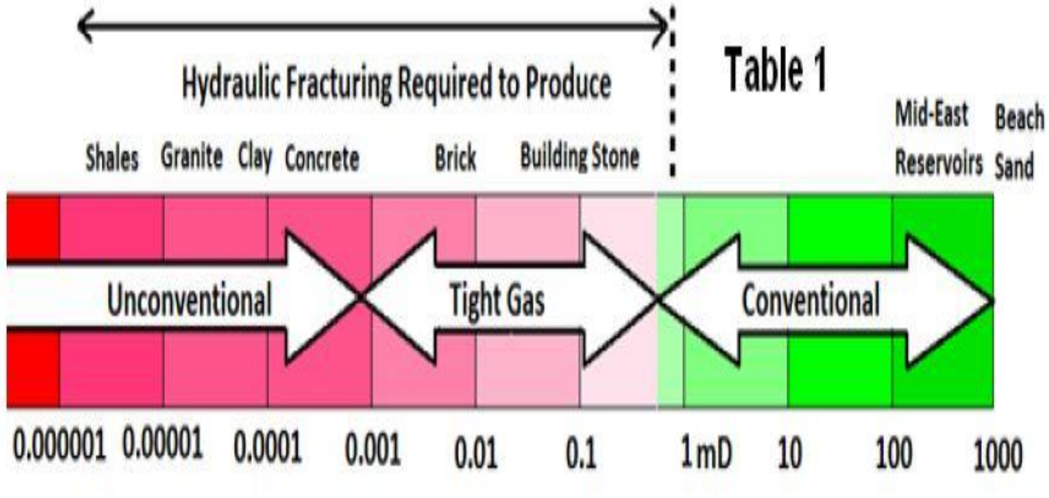

Fig. 4.7 Comparison of permeability in oil and gas reservoirs utilizing permeability values for typical rock types and common building materials (adopted from King 2012)

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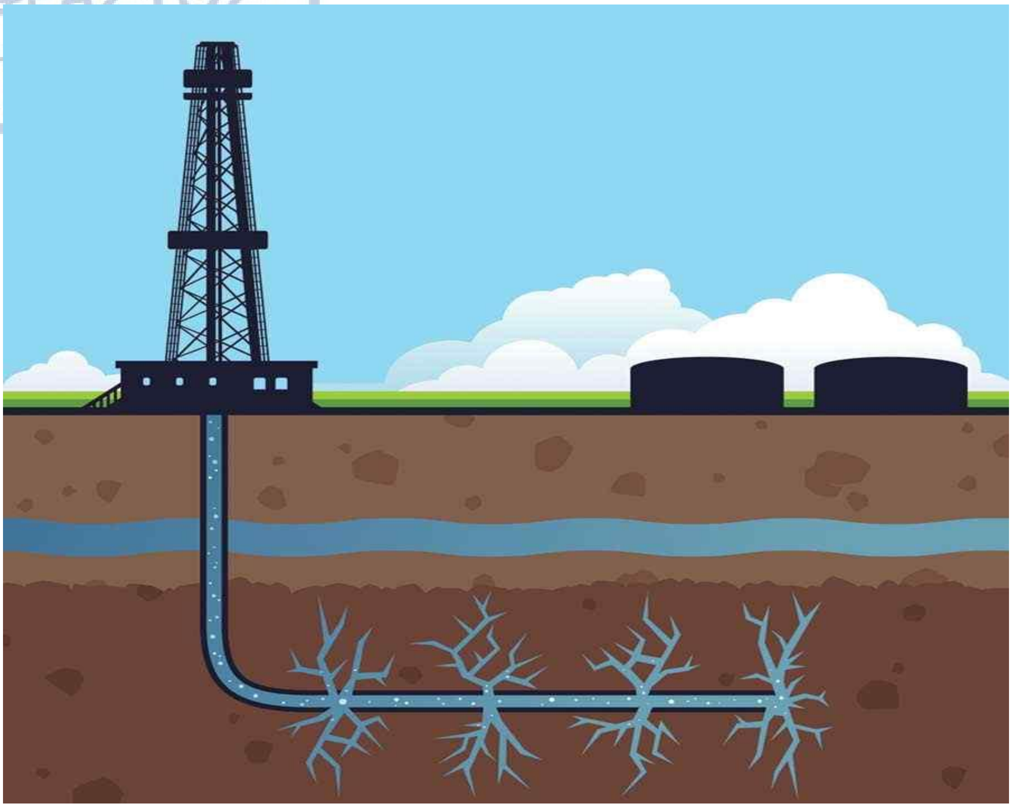

Fig. 4.8 Scheme of hydraulic fracturing (adopted from Huffington Post)

In general, hydraulic fracturing is used to increase the productivity index of a producing well or the injectivity index of an injection well. The productivity index defines the rate at which oil or gas can be produced at a given pressure differential between the reservoir and the wellbore, while the injectivity index refers to the rate at which fluid can be injected into a well at a given pressure differential.

There are many applications for hydraulic fracturing. Hydraulic fracturing can:

- Increase the flow rate of oil and/or gas from low-permeability reservoirs
- Increase the flow rate of oil and/or gas from wells that have been damaged
- Connect the natural fractures and/or cleats in a formation to the wellbore
- Decrease the pressure drop around the well to minimize sand production
- Enhance gravel-packing sand placement
- Decrease the pressure drop around the well to minimize problems with asphaltene or paraffin deposition
- Increase the area of drainage or the amount of formation in contact with the wellbore

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- Connect the full vertical extent of a reservoir to a slanted or horizontal well.

In order for better results, it is important the most suitable drilling wells to be selected for hydraulic fracturing. The most critical parameters which have to be considered for hydraulic fracturing are:

- The formation permeability
- The in-situ stress distribution
- The reservoir fluid viscosity
- The skin factor
- The reservoir pressure
- The reservoir depth
- The condition of the wellbore

The skin factor refers to whether the reservoir is already stimulated or is damaged. If the skin factor is positive, the reservoir is damaged, and the well could be an excellent candidate for stimulation.

In general, a hydrocarbon reservoir with the following characteristics is the most suitable for hydraulic fracturing treatments. The characteristics are:

- A thick pay zone
- Medium to high pressure
- In-situ stress barriers to minimize vertical height growth
- Either a low-permeability zone or a zone that has been damaged - high skin factor

In contrast, hydrocarbon reservoirs with the following characteristics are not suitable for hydraulic fracturing treatments. The characteristics are:

- Thin reservoir
- Low reservoir pressure
- Small areal extent

If a hydrocarbon reservoir has the upper characteristics plus very low values of permeability, hydraulic fracturing may not be succeeded to pay all the drilling and completion costs. So such reservoirs would not be good choices for stimulation.

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In new fields or reservoirs as part of reservoir investigation logs are running, cores are cutting, and well tests are running to determine important factors such as the in-situ stress and the permeability of the reservoir layers. With such data, along with fracture-treatment and production records, accurate data sets for a given reservoir normally can be compiled. These data sets can be used in the following wells to optimize the fracture treatment designs. Eventually, the process of hydraulic fracturing is ready to be achieved based on the characteristics of the reservoir and the data that already have been collected with previous tests.

4.6.1 The process of hydraulic fracturing

The entire process of hydraulic fracturing is analyzed step by step as follows. In the beginning, the wellbore is drilled until the depth where the reservoir rock is found. Thus, once the vertical wellbore is a few hundred feet above the reservoir rock, the bore slowly changes the angle of drilling until the bore accesses the reservoir rock horizontally. At this point, drilling continues horizontally for several hundred feet along the hydrocarbon deposit. All the necessary casings have been installed and cemented for safety reasons and the integrity of the wellbore is tested. Then perforating guns are inserted to the wellbore and the horizontal section of the wellbore is perforated. Now the rock formation is ready to be fractured. All casing, tubing, wellheads, valves, and weak links, such as liner tops, should be tested thoroughly before starting the fracturing treatment. Mechanical failures during treatment can be costly and dangerous. All mechanical problems should be discovered during testing and repaired before pumping the fracture treatment. Various surface facilities and mobile equipment including fracture fluid storage tanks, and storage units, chemical trucks, blending equipment and pumping equipment surround the wellhead on the lease. The hydraulic fracturing process is monitored from a single truck often referred to as the Data Monitoring Van.

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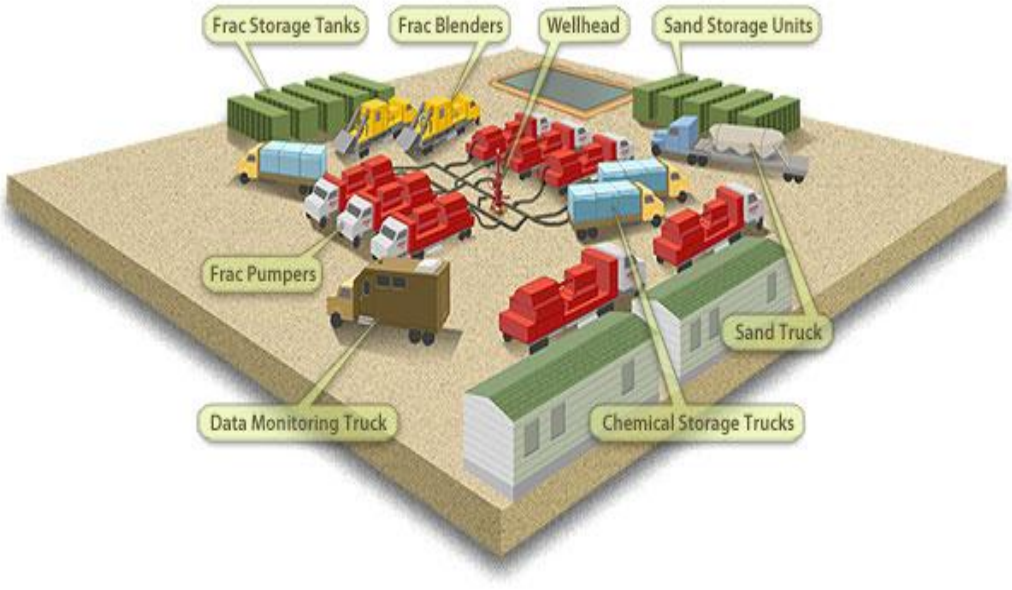

Fig. 4.9 Scheme of surface facilities and mobile equipment for hydraulic fracturing (adopted from Hydraulic Fracturing & How it works?, FracFocus. Chemical Disclosure Registry)

High volumes of fracturing fluids, commonly consisted of 90% of water, 9.5% of proppant (sand) and 0.5% of chemicals additives, are pumped deep into the wellbore at pressures sufficient to create or restore the small fractures in the reservoir rock needed to make production possible. The fracturing fluids that are pumped into the well are pressurized only to the portion of the well where the fractures are desired. This portion of the well is isolated by using some plugs and only this section of the well receives the full force of pumping. As pressure builds up in this portion of the well, water opens fractures, and the driving pressure extends the fractures deep into the rock unit.

The sand in fracking fluid keeps the fractures open after the pressure is released, and the chemicals are chiefly agents to reduce friction and prevent corrosion. The types of proppants are silica sand, resin-coated sand, bauxite, and man-made ceramics, while the choice of the most suitable in any case proppant depends on the type of permeability of the formation or the size of the grain that is needed. In some formations, where the pressure is great enough to crush grains of natural silica sand, higher-strength proppants such as bauxite or ceramics may be used. The most

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commonly used proppant is silica sand, though proppants of uniform size and shape, such as a ceramic proppant, are believed to be more effective.

The most common chemical additives are described above.

CHEMICAL ADDITIVES	PURPOSE
Acids (hydrochloric acid or acetic acid)	Dissolve minerals and initiate fissure in rock (pre-fracture)
Sodium Chloride	Allows a delayed breakdown of the gel polymer chains
Polyacrylamide	Minimizes the friction between fluid and pipe
Ethylene Glycol	Prevents scale deposits in the pipe
Borate Salts	Maintains fluid viscosity as temperature increases
Sodium / Potassium Carbonate	Maintains effectiveness of other components, such as crosslinkers
Glutaraldehyde	Eliminates bacteria in the water
Guar Gum	Thickens the water to suspend the sand
Citric Acid	Prevents precipitation of metal oxides
Isopropanol	Used to increase the viscosity of the fracture fluid

Table 4.1 Main chemical additives

Not all of the additives are used in every hydraulically fractured well with the exact mixture and proportions of additives will vary based on the site-specific depth, thickness and other characteristics of the target formation. In United States, during 2005 – 2009 the most common chemicals that were used for hydraulic fracturing was methanol, while some other most widely used chemicals were isopropyl alcohol, 2-butoxyethanol, and ethylene glycol.

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Fig. 4.10 Sand proppant and chemical additive for hydraulic fracturing
(Adopted from https://geology.com)

Generally, a typical hydraulic fracture program will follow the stages below:

- **Acid stage:** this stage refers to several thousand gallons of water mixed with a dilute acid such as hydrochloric or muriatic acid that helps to clear debris that may be present in the wellbore providing a clear pathway for fracture fluids to access the formation.
- **Pad stage:** this stage refers to approximately 100,000 gallons of slickwater without proppant material which is filled to the wellbore and is used to break the formation and initiate the hydraulic fracturing of the target formation. For slickwater fluids the use of sweeps is common which are helping the borehole not to be overwhelmed with proppant.
- **Proppant stage:** During this stage, a mixture of water and sand (i.e. proppant) is fed into the wellbore. The proppant is composed of non-compressible material, such as sand, that will be carried by the fracture fluid into the formation and deposited. The proppant will remain in the formation once the pressure is reduced and 'prop' opens the fracture network. Thus, maintaining the enhanced permeability created by the hydraulic fracture program.
- **Flush stage:** A volume of fresh water is pumped down the wellbore to flush out any excess proppant that may be present in the wellbore. Some but not all of the injected fluid is recovered. The recovered fluid is managed by several methods, including underground injection control, treatment, discharge, recycling, and temporary storage in pits or containers.

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After the process of hydraulic fracturing natural gas and oil from the reservoir rock start to flow from fissures into the drilling well along with "flowback fluid" – consisting of varying proportions of the injected fluids, and other liquids such as salt-saturated water, drilling muds, or brine. These fluids are pumped into a waiting pool or in closed storage tanks where the liquid waste will be either recycled and used at another site or disposed of according to regulatory standards specific to the state in which they are disposed of. Mainly gas is treated in gas processing equipment where oil, water, elements & carbon dioxide, and natural gas liquids are removed. Afterward, gas can be transported either by truck or pipeline to the gas processing facility.

4.7 Hydraulic fracturing in shale formations

4.7.1 General

The first use of hydraulic fracturing to stimulate oil and natural gas wells in the United States was done over 60 years ago. Haliburton Oil Well Cementing Company has issued a patent for the procedure in 1949. The method successfully increased well production rates and the practice quickly spread. It is now used throughout the world in thousands of wells every year.

The first economical shale fracture has achieved in 1998 using slick-water fracturing by Mitchell Energy. Mitchell Energy realized that gas in the Barnett Shale play was trapped in tiny pore spaces that were not interconnected. There was pore space to the rock formation but permeability was zero. Wells drilled through the Barnett Shale would usually have a show of gas but not enough gas for commercial production. Mitchell Energy solved this problem by hydraulic fracturing the Barnett Shale to create a network of interconnected pore spaces that enabled a flow of natural gas to the well. Since then, natural gas from shale has been the fastest growing contributor to total primary energy in the United States and has led many other countries to pursue shale deposits.

Hydraulic fracturing development combined with horizontal drilling development has turned previously unproductive organic-rich shales into the largest natural gas

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fields in the world. Generally, horizontal wellbores allow greater production rates to a formation comparing to conventional vertical wellbores.

4.7.2 The process of hydraulic fracturing

As soon as the shale reservoir is drilled horizontally, is then completed and is fractured in order for gas to be produced. The methods by which the fractures are placed along the rock formation are most commonly achieved by one of two methods, known as "plug and perf" and "sliding sleeve".

“Plug and perf” method

This operator sets the plug at a horizontal location near the well toe, and the zone is then perforated. Next, the tools are removed from the well, and the fracture stimulation treatment gets pumped in. A ball-activated plug diverts fracture fluids through the perforations and into the formation. As the operator repeats the “plug and perf” process for each stage, the downhole tools move from the end of the wellbore back to the beginning until each stage has been completed. With this method, every zone of the drilling well can be perforated many times at varying distances.

One disadvantage this method has is that since multiple perforation clusters are stimulated simultaneously, there is no control over the size of each fracture. Some clusters are not stimulated at all, while others receive varying amounts of treatment. The result is gaping areas of the formation that remain unstimulated.

"Sliding sleeve" method

The sliding sleeve method refers to sleeves that are included at set points in the steel casing at the time casings are installed. During the casing installation the sliding sleeves are all closed. When the well is due to be fractured, the bottom sliding sleeve is opened using one of several activation techniques and the first stage gets pumped. Once finished, the next sleeve is opened, concurrently isolating the previous stage, and the process repeats. For the sliding sleeve method, wireline is usually not required and also the sleeves are pre-perforated sleeves so that a perforating gun or system is not needed.

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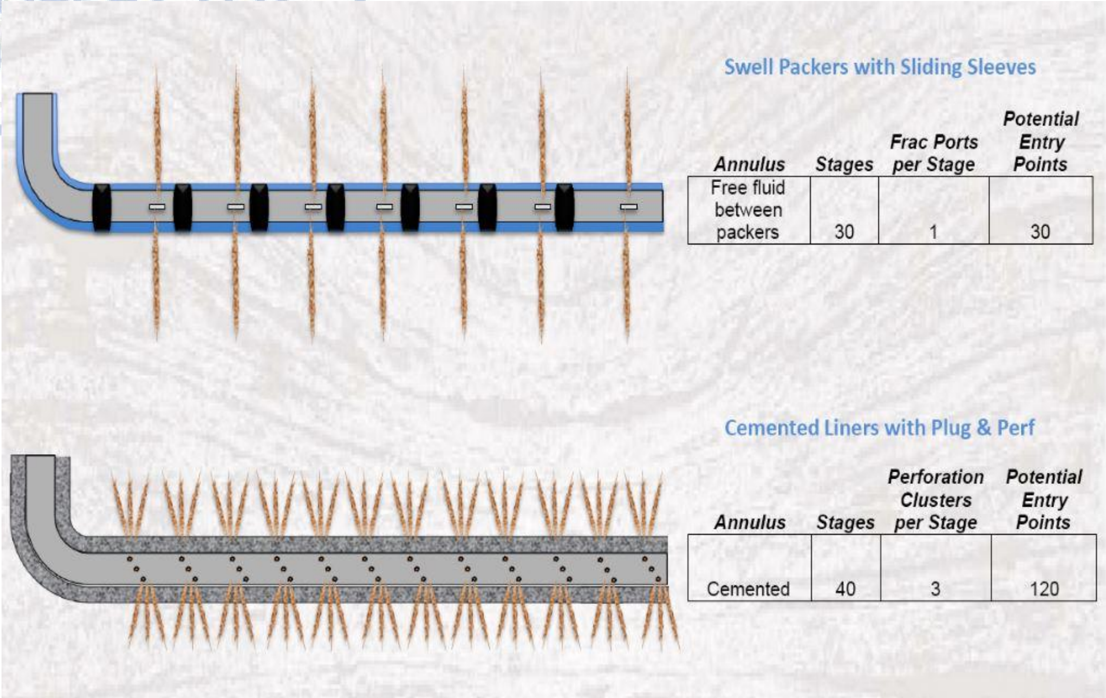

Fig. 4.11 Sliding sleeve method vs. cemented liner with Plug & Perf method (adopted from Fidelity exploration & production)

Approximately 1,000 feet of the wellbore is hydraulically fractured at a time, so each drilling well must be hydraulically fractured in multiple stages, beginning at the furthest end of the wellbore. These completion techniques may allow for more than 30 stages to be pumped into the horizontal section of a single drilling well, if it is required. The number of the stages that are pumped in horizontal well is greater than the number of the stages that are pumped into a vertical well that had far fewer feet of producing zone exposed. Thus, while the stimulation process in fracking is similar to the process used in many conventional drilling operations, the scope and size of the fracturing are much larger in shale plays (PIOGA, 2013).

After the shale formation is fractured, the gas production is started and gas that is recovered from the drilling well is sent to small-diameter gathering pipelines that connect to larger pipelines that collect gas from a network of production wells. Once a well no longer produces at an economic rate, the wellhead is removed, the wellbore is filled with cement to prevent leakage of gas into the air, the surface is reclaimed and the site is abandoned to the holder of the land's surface rights.

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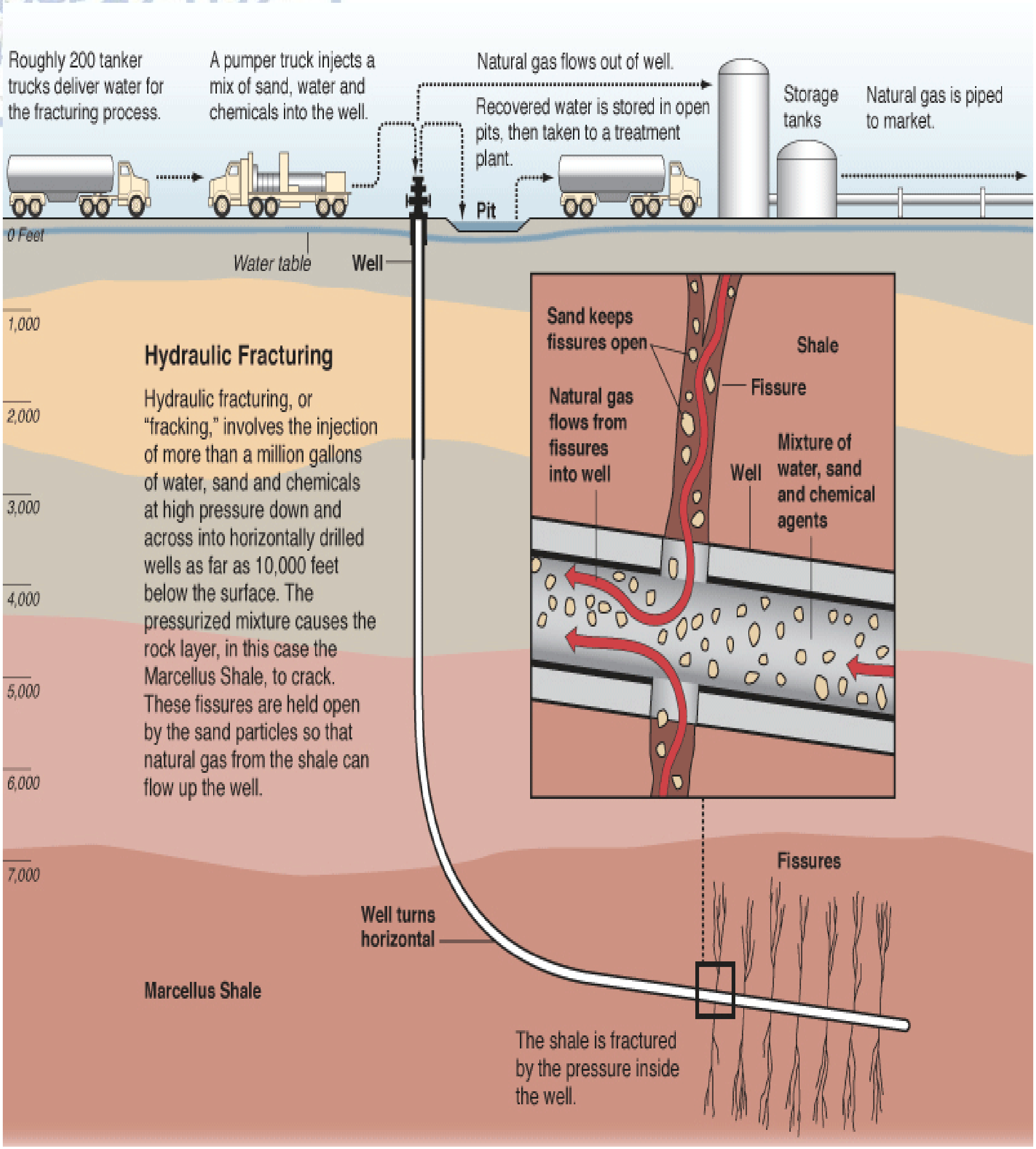

Fig. 4.12 The process of hydraulic fracturing in Marcellus Shale (adopted from Granberg/ProPublica)

Because production of gas from shale formations is very recently occurred, it is too early for conclusions to be made about the duration for this kind of production. Generally is observed that shale gas drilling wells experience quicker production declines than conventional natural gas production.

As a conclusion, hydraulic fracturing can significantly increase the potential of drilling well. When it is combined with horizontal drilling, unprofitable rock formations such as shales are often converted into productive natural gas fields. The hydraulic fracturing process and the chemicals used with it cause the greatest amount of concern to environmental issues which will be presented to the following chapter.

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5 Environmental concerns of unconventional plays

5.1 Environmental impacts of shale gas production

Exploitation of unconventional reservoirs and especially of shale formations with the method of hydraulic fracturing creates some environmental impacts at global and local levels. These include impacts on climate change, local air quality, water availability, water quality, seismicity, and local communities. Apart from environmental impact air pollution and water can also create impacts on human's health.

Air pollution

The primary concern for air pollution is the leakage of methane (CH4), a potent greenhouse gas, that is a natural gas primary constituent. Methane (CH4) is 25 times more powerful in trapping heat at the atmosphere than carbon dioxide, so any possible leakage of it is very dangerous. After the well completion of hydraulic fracturing is necessary the flow back water to be removed from the drilling well in order gas to start to flow. Flow back water that contains natural gas can be vented to the atmosphere over the course of several days so methane is also vented to the atmosphere.

Apart from methane a number of other air contaminants are released during the various drilling procedures at local level, including construction and operation of the well site, transport of the materials and equipment, and disposal of the waste water. Some of the pollutants that are released by drilling include: benzene, toluene, xylene and ethylbenzene (BTEX), particulate matter and dust, ground-level ozone, or smog, nitrogen oxides, carbon monoxide, formaldehyde and metals contained in diesel fuel combustion. The exposure to these pollutants is known to cause short-term illness, cancer, organ damage, nervous system disorders and birth defects or even death.

Another local air pollutant of growing concern is crystalline silica dust, which can be generated from the sand proppant. Silica dust can be generated in the mining and transporting of sand to the well site and in the process of moving and mixing sand into the hydraulic fracturing fluid on the well pad. Crystalline silica dust within the respirable size range (<4 microns) is considered a HAP and a carcinogen.

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Water consumption

Water consumption for hydraulic fracturing is estimated about 4.500m^3 to 13.200m^3 per drilling well, while large projects of hydraulic fracturing demand up to 19.000 m^3. During the lifetime of a drilling well 11.000 m^3 to 30.000 m^3 of water are required. Generally, the deeper the shale formation is the more quantity of water is required. Despite the fact that water is also needed in many stages for the drilling well construction, the large quantity is used during the gas production. It should be mentioned that after fracturing a well, anywhere from 5% to 20% of the original volume of the fluid will return to the surface within the first 10 days as flow back water. An additional volume of water, equivalent to anywhere from 10% to almost 300% of the injected volume, will return to the surface as produced water over the life of the well (Mantell 2010). By using this produced water again for new processes of hydraulic fracturing, the total amount of used water is lowered while the need of wastewater disposal after use is also reduced. On the other hand this technique of water processing is relatively expensive, the water must be treated before each reuse and the life of some types of equipment can be shortened. For these reasons is common fresh water to be used for hydraulic fracturing. Using large volumes of water for most common hydraulic fracturing methods have raised concerns especially for arid regions and drought-prone areas.

Water quality

Concerns over water quality focus on potential drinking water contamination by methane or fluids from fracturing activities. This potential contamination may occur in many different manners. During the drilling well construction chemical additives are used for the drilling mud while also for hydraulic fracturing in many cases chemical additives are required for better fracture results. These chemical additives came to the surface with flowback water and produced gas. Generally, each well produces millions of gallons of toxic fluid that contains not only the added chemicals, but other naturally occurring radioactive material, liquid hydrocarbons, brine water, and heavy metals. Many efforts have been made for flow back water treatment processes in order the water contamination to be reduced. The most common processes are: underground injection, municipal and commercial wastewater

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treatment and discharge, self-contained systems at well sites or fields, and recycling flow back water to fracture future wells.

Fissures that are created by hydraulic fracturing process can also create underground pathways for gases, chemicals and radioactive material that may insert to water shallow aquifers and pollute them. Another scenario for potential contamination to occur is by a faulty drilling well design or by faulty construction of the cement well casings. If any of these faults occur the results will be disastrous.

Seismicity

Shale gas production has been proven that it is responsible for induced seismicity called microseismic events or microearthquakes. Generally, induced seismicity can be caused by two processes which are referred to as shale gas production: hydraulic fracturing and water disposal in drilling wells. USGS's studies suggest that increased injection of gas-well wastewater into disposal wells is the favorite cause for induced seismicity in shale gas production regions and also in areas with the conventional method of production. Recent researches suggest that disposal wells for hydraulic fracturing wastewater do not pose a hazard for induced seismicity and also the process of hydraulic fracturing itself does not pose a high risk for inducing felt seismic events.

Noise

Exploring and developing a hydrocarbon field requires a large geographic area with many construction activities which in many cases is near to residential areas. Increases in noise can cause areas that are not typically proximate to industrial activities and associated noise to be disturbed. Various studies have indicated that noise from traffic negatively affects property values (e.g., Wilhelmsson, 2000).

Human health

Besides the environmental impacts of hydraulic fracturing, also some potentials impacts in human health may exist. All the chemical additives which are used during the exploration and exploitation stages of shale gas formations may cause some hazards to human health in continuous presence. It is believed that a continuous use of chemical additives could affect the skin, eyes and other sensory organs, along with the respiratory and gastrointestinal system. Also many chemical additives could

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affect the brain - nervous system, immune and cardiovascular systems, the endocrine system while some chemicals are related to cancer and mutations.

5.2 Environmental impacts of oil shale production

For oil shale production two methods for mining exist the open pit mining and the in – situ mining. Each type of mining causes negative impacts on the environment. The main problems refer to the following categories:

Surface disturbance

For open pit mining, extended areas are occupied in order to extract the oil from shale formations. In huge open-pit or underground operations, large amounts of rock material have to be moved in order to provide shale for surface retorting. Such operations can cause problems to the integrity of the land, to agricultural activities around the mines, and to local fauna and flora.

Waste management

By heating to a sufficiently high-temperature shale formation which has previously been mined, oil or/and can be extracted. This process called retorting. Oil shales generally have a low calorific value and high ash and mineral content. After retorting the remaining of mining waste along with the remaining ashes have to be deposited in other areas. Generally, the waste material occupies a greater volume than the material previously has been extracted so it cannot be placed the whole waste material underground. The most important aspect of the waste material is that it may consist of several pollutants including sulfates, heavy metals, and polycyclic aromatic hydrocarbons with some of them being toxic and carcinogenic. An open dump is necessary to be created in order to avoid contamination of the groundwater, so waste management is crucial for open pits mining.

Water management

For open pits mining is crucial for the aquifer level to be lowering below the level of extracted shale formations which may have harmful effects on the surrounding area. Apart from that water is necessary for retorting quenching hot products and controlling the dust. A great amount of water is necessary to be consumed for oil/gas production from shale formations.

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Greenhouse gas pollution - Air pollution

Oil shale production is responsible for carbon dioxide (CO_2) emission which is the most common greenhouse gas. Carbon dioxide can come of different sources such as: during heating methods carbon dioxide is released due to decomposition of kerogen, also from the energy supply for shale heating (power plants nearby), from other oil and gas processing operations and also from fuels that consumed for mining processes and for the disposal of the waste materials.

Air pollution comes from the oil shale-fired power plants which produce emissions consisted of nitrogen oxides, sulfur dioxide, and hydrogen chloride and the airborne particulate matter.

Fig. 6.1 A typical open pit mining of oil shale formations

Other unconventional types of plays such as tar sands and tight gas are exploited mainly with the same methods as oil shale formations by open pits mining. The environmental concerns for these types of plays are the same as oil shale production which has previously been described.

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6 Conclusions

Since the first oil reservoir discovered and produced in the United States many decades have passed. The continuous development of hydrocarbon exploration and exploitation methods has leaded to the easiest approachable and recoverable hydrocarbon reservoirs to be totally produced and abandoned. So types of hydrocarbon plays which are produced with unconventional methods are necessary to be explored and exploited. These types of hydrocarbon deposits form the unconventional hydrocarbon plays.

The main types of unconventional hydrocarbon deposits are shale gas, shale oil, coalbed methanes (CBM or coal-bed methane), tight gas, oil sands or tar sands, heavy oil, gas hydrates, and other low-permeability tight formations.

The main differences between conventional and unconventional plays are presented to the following table.

Conventional plays	Unconventional plays
Accumulations in medium to highly porous reservoir with sufficient permeability to allow gas to flow to wellbore	Deposits of natural gas found in relatively impermeable rock formations (tight sands, shale and coal beds)
Vertical or horizontal completions	Key technologies are horizontal drilling and modern fracking techniques
Production from formation matrix, natural flow	Production from natural and induced fractures (e.g. shales are the source rock)
Permeability and porosity determine production rates and estimated ultimate recoveries	Total organic carbon, thermal maturity and mineralogy determine reservoir and ultimate completion
Development plans on a field basis	Development plans on a well by well basis

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Table 6.1 Main differences between conventional and unconventional plays

The continuous increase in world energy demands that is mainly driven by the economic development and the dramatic population growth recorded in recent decades has caused the decline of the availability of petroleum resources that are characterized by efficient production and refining. These resources were composed mainly of conventional oil reserves with high market value and whose production and processing is consisted of simple and technically well-established methods. Forecasts predict that a continuous expansion in world energy consumption will extend at least until 2035, as indicated by the U.S. Energy Information Administration. The search for new types of hydrocarbon plays along with the need for cleaner energy fuels has led a number of oil and gas companies to explore new potential areas with unconventional types of hydrocarbons. Especially shale gas that is massively produced in the United States thanks to new and advanced recovery techniques has led a considerable number of regions around the world to focus their interest for their shale potential—in fact, 48 major shale basins are identified in 32 countries around the world that are prospects for development (EIA, 2011).

In an era of declining conventional gas production and increasing energy demands, economically producing gas from unconventional sources represents an unavoidable alternative. Unconventional shale gas has thus become a topic that is increasingly being debated. During their exploitation unconventional hydrocarbons cause many environmental and public issues especially those where hydraulic fracturing is necessary. With adequate safeguards in place, shale gas can be exploited responsibly in ways that protect both the environment and human health so it eventually substitutes the conventional types of hydrocarbons.

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