ΔΙΑΤΜΗΜΑΤΙΚΟ ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
"ΕΡΕΥΝΑ ΚΑΙ ΕΚΜΕΤΑΛΛΕΥΣΗ ΥΔΡΟΓΟΝΑΝΘΡΑΚΩΝ"

DEEP WATER DRILLING

Master's thesis of

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ABSTRACT

The purpose of this thesis is to examine and present the technical challenges and solutions in drilling for exploration and production of hydrocarbons, in offshore environments under the presence of high sea water column. Additionally, we will try to give an answer whether and when it is economically and technically feasible to undertake such operations. The research was based on existing bibliography, articles and papers.

Two major categories of deepwater problems are considered. The first category is associated with the deepwater drilling facilities: platforms, drill ships, floating drilling, production, storage and offloading units (FDPSOs), and the subsea systems. The other category encompasses the challenges associated with operations, like: station keeping, drilling risers, subsea BOPs and wellheads, drilling operations (narrow drilling window, well control, drilling fluids, casing & cementing), as well as other technical challenges (high-pressure/high-temperature wells, salt drilling, remotely operated vehicles). Solutions to these problems adopted by the oil industry are also presented.

I would like to thank my supervisor, Sofia Stamataki, as well as Irene Dimitrellou (laboratory stuff), for their assistance and guidance on completing this thesis but also for their patience.

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CHAPTER 1

INTRODUCTION

The current thesis examines the technical challenges and solutions in deep and ultra-deep-water drilling. Demand for energy has led the industry to drill deeper and deeper, both on land and offshore, in order to get access to energy sources. Deepwater drilling is a quite demanding procedure for personnel and equipment. This thesis focuses mainly on technical challenges and solutions, but also gives information on physical/environmental challenges too and how they are dealt with.

Through the course of time, the industry has given many solutions to specific problems, regarding deep water drilling, from subsea systems, to floating drilling platforms. The variety of systems and solutions covers a quite wide aspect of conditions (physical and technical) around the world, in order to meet the goals of exploration and production in deep sea environments.

Two major categories of deepwater problems are considered. The first category is associated with the deepwater drilling facilities: platforms, drill ships, floating drilling, production, storage and offloading units (FDPSOs), and the subsea systems. The other category encompasses the challenges associated with operations, like: station keeping, drilling risers, subsea BOPs and wellheads, drilling operations (narrow drilling window, well control, drilling fluids, casing & cementing), as well as other technical challenges (high-pressure/high-temperature wells, salt drilling, remotely operated vehicles). Solutions to these problems adopted by the oil industry are also presented.

The current thesis is structured as follows:

Chapter 2 presents an historical review of deep-water drilling evolution. The definitions of deep-water drilling and why the oil industry undertakes such operations are also examined. Chapter 2 closes with an overview of the current status of deepwater operations around the world, focusing on the current situation in Greece regarding deep water activities.

Chapter 3 briefly presents the drilling facilities used in deepwater operations. Each type of facility is suitable for specific conditions. All together can cover a wide range of conditions, enough to meet the requirements of the industry in undertaking such demanding projects.

Chapter 4 examines the challenges in deepwater and ultra-deep water drilling operations. First, physical challenges, such as storms and currents are discussed, and, after that, the technical challenges are examined, in combination with the solutions adopted by the industry to overcome such problems.

Chapter 5 examines whether the existing technology is able to meet and deal with these challenges and the limitations of deep-water drilling.

CHAPTER 2

GENERAL OVERVIEW

2.1 Hydrocarbons: Past, Present, and Future

Oil constitutes one of the most important elements of modern civilization. Either as energy source, or a basis for producing other materials (etc. polymers), petroleum's impact on politics, society and technology since late 19th century is vast. The invention of the internal combustion engine was the major influence and key point in the rise in the importance of petroleum for modern societies.

Oil was known to ancient civilizations. According to Herodotus, more than four thousand years ago natural asphalt was used in the construction of the walls and towers of Babylon. Great amounts of asphalt were found on the sides of the Issus River, one of the tributaries of the Euphrates River, and this fact has been confirmed by Diodorus Siculus (Siculus, 1933). Herodotus also referred to a pitch spring on the island of Zakynthos in Greece. He also gave us a description of a well that produced bitumen, oil and salt near a place called Ardericca in the district of Cessia in Persia. The earliest known oil wells were drilled in China around 347 AD or even earlier. They reached depths of up to about 800 feet (240 m) and were drilled using bits connected to bamboo poles. The oil was burned to evaporate salt-water and produce salt. By the 10th century, widespread bamboo pipelines linked oil wells with salt springs (Ulrich Vogel, 1993).

The modern history of petroleum exploitation, in terms of extraction from seeps, began in the 19th century with the refining of paraffin from crude oil. Breakthroughs in petroleum exploration and production from oil wells during the latter half of the 19th century, and the early 20th, placed the foundations for modern petroleum industry (upstream, midstream and downstream) (Russell, 2003).

During the 20th century, oil had become the driving force behind any activities around the globe. Its significance is better understood if we think about the number of conflicts, major or minor, that occurred because of petroleum.

Until the mid-50s, petroleum had bypassed coal as the main energy source. Soon after that, major concerns occurred on the fact that oil is a limited resource, and it will soon "run out". The oil crises in 1973 and 1979 contributed to this opinion. Although demand for oil and gas, increases continuously, scientific and engineering breakthroughs, have helped the industry, to transform non-exploitable reserves, into fully operational and exploitable oil and gas fields.

Today, oil and gas combined, cover 54% of the global energy demand (ourworldindata.org). Even though, there is a trend in the developed countries for a more environmental-friendly mix of energy sources, the upcoming and continuously growing middle classes in China and India, with their ever growing "thirst" for energy, will be the most important factor in the next decades that will lead any breakthrough and advancement in oil industry (Figures 2-1 & 2-2).

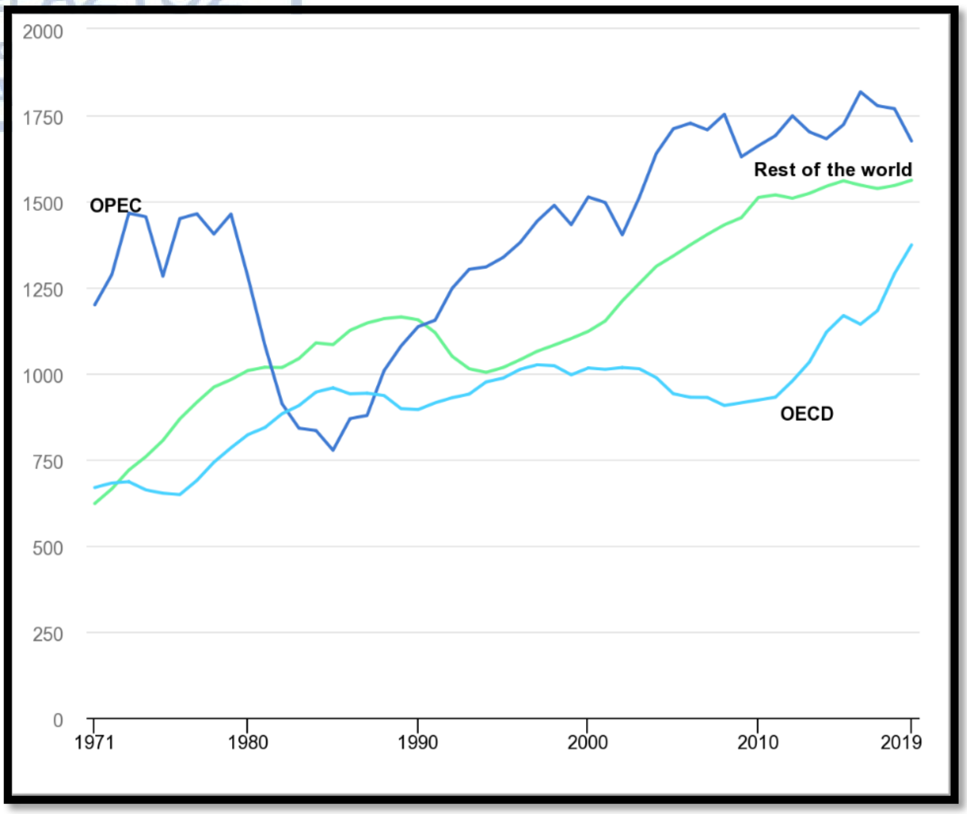

Figure 2-1. World oil production by region 1971-2020 (IEA, 2021)

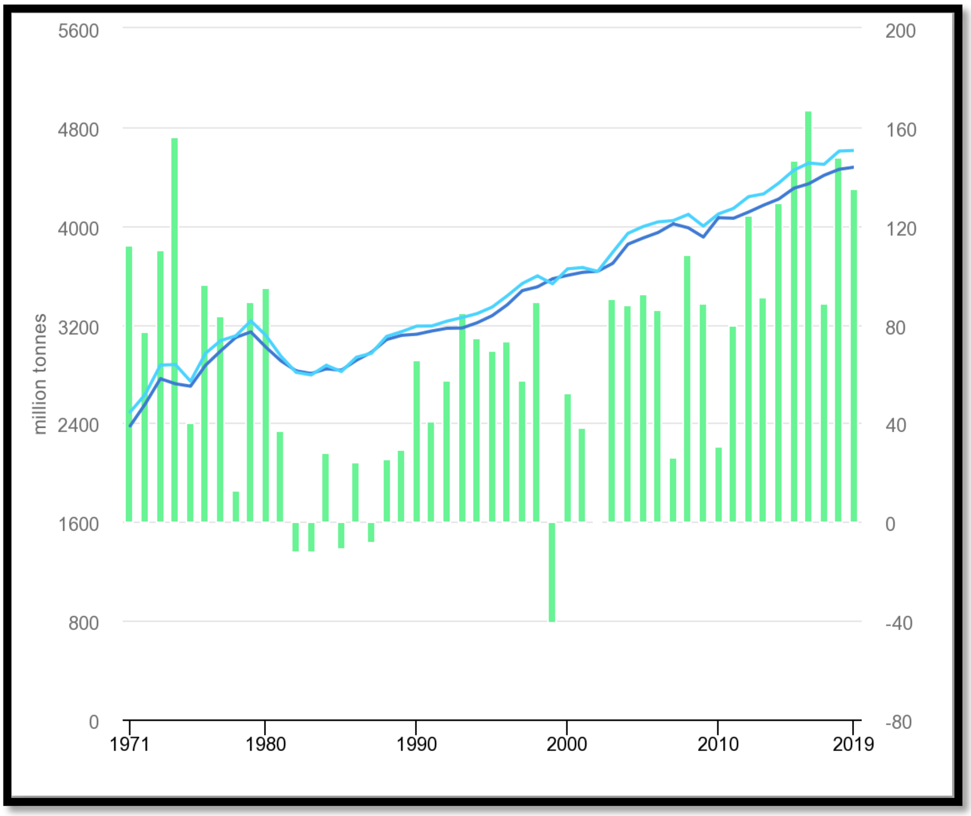

Figure 2-2. Global oil supply and demand, 1971-2020 (IEA, 2021)

As we can see from the figures above, global oil production, supply, and demand, follow an ever-increasing trend. 2020 has been a devastating year for the oil industry, because of the covid-19 pandemic, and the subsequent decrease on oil demand. "The combination of the COVID-19 pandemic demand disruption, and a supply glut has generated an unprecedented crisis for the industry", "Under most best-case scenarios, oil prices could recover in 2021 or 2022 to precrisis levels of $50/bbl to $60/bbl." (Barbosa, 2020). There are high expectations, that in the next 2 or 3 years, the oil industry will recover from the impact of the covid-19 pandemic.

2.2 Offshore Drilling Operations: Definition and Historical Background

The only way to get to the place where oil "lies" is by drilling. Drilling for oil and/or natural gas takes place both onshore and offshore. The quantity of recoverable oil and natural gas worldwide has been swiftly expanding, thanks to the above sophisticated drilling practices. But what is the difference between them?

In short, onshore drilling refers to drilling deep under the earth's surface whereas offshore drilling relates to drilling below the seabed. These drilling practices are used to obtain natural resources – usually oil and gas – from the depths of the earth. While obtaining oil from underneath the surface of the ocean or of other water bodies, had, at first, more difficulties than the traditional onshore well drilling process, offshore drilling has evolved through time into an easier practice due to the innovations that have emerged such as the floating or fixed platforms on the seabed to support drilling.

In general, the equipment used in both offshore and onshore drilling presents many similarities. Both practices require the use of tools and equipment like drill strings, drill bits, blowout preventers, drilling fluids, wastewater/oil separators, pumps, pipelines, etc.

Offshore drilling is a mechanical procedure where a wellbore is drilled underneath the seabed to extract petroleum and natural gas from reservoirs located beneath the Earth's oceans instead of from those located on the mainland (Lamb, 2016). It is typically carried out to explore for and afterward extract hydrocarbons that lie within sedimentary formations deep beneath the seabed. Most commonly, the term is used to describe drilling activities on the continental shelf, though the term can also be applied to drilling in lakes, inshore waters, and inland seas.

There are many different types of installations from which offshore drilling activities occur. These include bottom-founded drilling rigs (jackup barges and swamp barges), combined drilling and production facilities on either bottom-founded or floating platforms, and deepwater mobile offshore drilling units (MODU) including semi-submersibles and drill ships. According to the type of installation, the water depth that can be handled rises to almost 9000ft (3000m). In shallower waters the mobile units are moored to the bottom of the sea, however, in deeper water (more than 1,500 meters - 4,900 ft) the semi-submersibles or drill ships are maintained at the required drilling location using dynamic positioning systems (Figure 2-3).

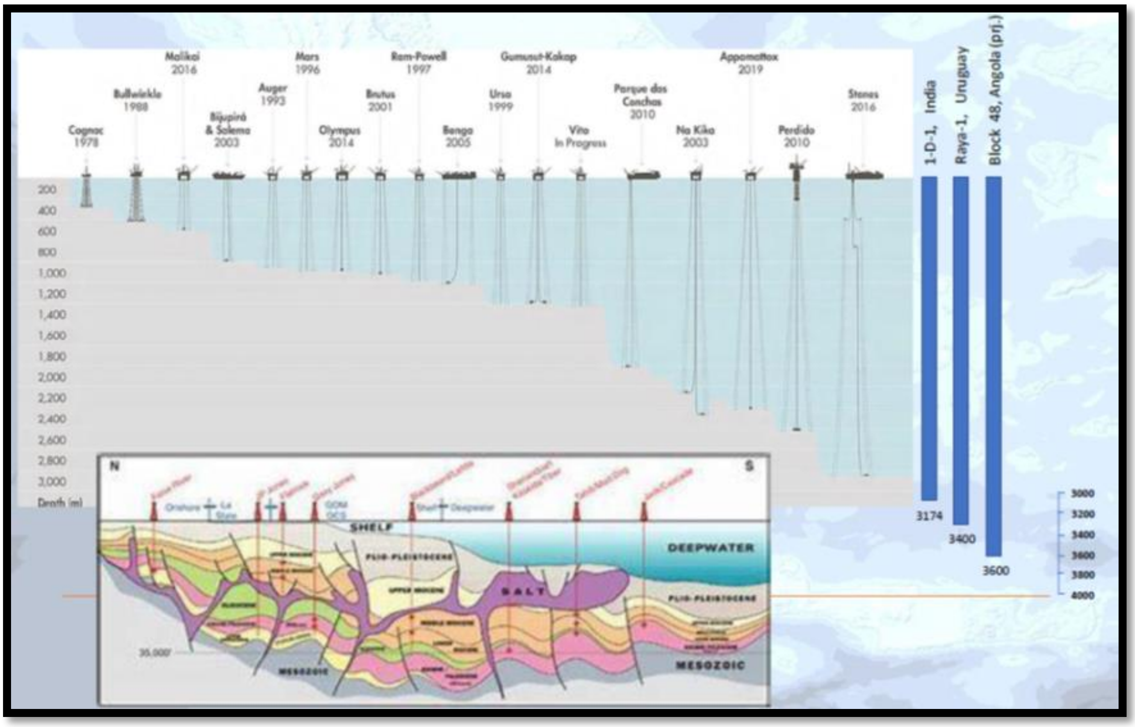

Figure 2-3. Different types of drilling rigs including land rigs and offshore rigs. Possible water depth for offshore drilling is increasing from drilling barge to drillship (Μπασιάς, 2020)

Around 1891, the first underwater oil wells were drilled from installations built on piles in the fresh waters of the Grand Lake St. Mary's in Ohio. These particular oil wells were drilled by small local enterprises such as Bryson, Riley Oil, German American, and Banker's Oil (Energy Global News, 2019).

In 1896, the first offshore oil wells in salt water were drilled in the portion of the Summerland field extending under the Santa Barbara Channel in California. The wells were drilled from installations extending from land out into the sea (Figure 2-4) (National Oil Industries Association (NOIA), 2010).

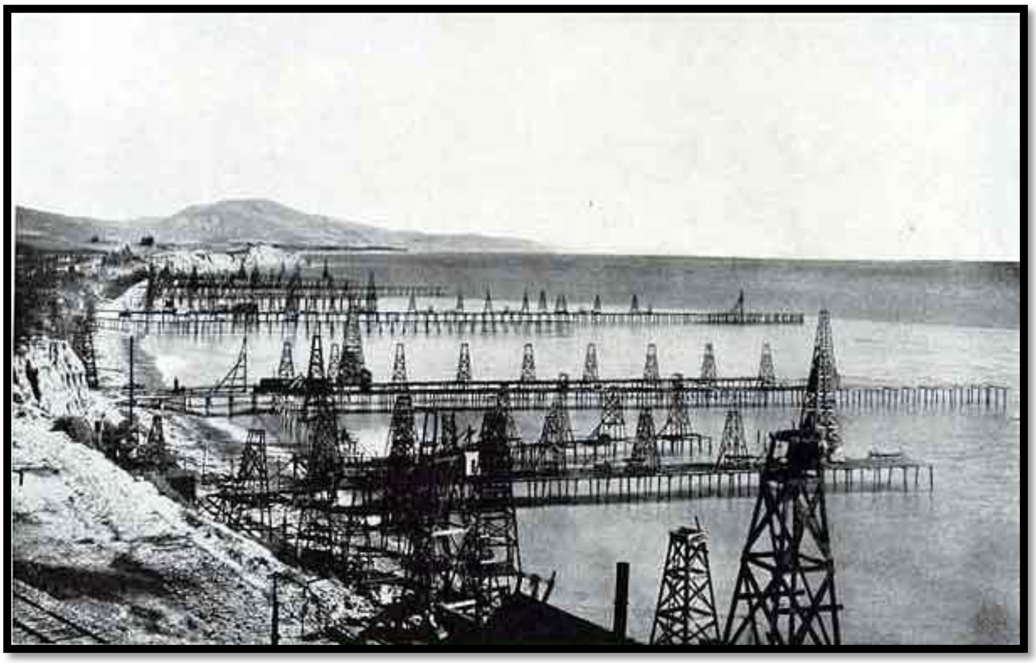

Figure 2-4. Many of the earliest offshore oil wells were drilled from piers at Summerland in Santa Barbara County, California. Circa 1901 photo by G.H. Eldridge courtesy National Oceanic & Atmospheric Administration (Wells & Wells, 2021)

Other important early underwater drilling efforts took place on the Canadian side of Lake Erie in the 1900s and the Caddo Lake in Louisiana in the 1910s. Shortly thereafter wells were drilled in tidal flats along the Texas and Louisiana coasts on the Gulf of Mexico. The Goose Creek Oil Field near Baytown, Texas is one such example. In the 1920s drilling activities took place from concrete installations in Venezuela's Lake Maracaibo (Engenya GmbH, 2021).

The Bibi Eibat well is one of the oldest underwater wells, which was drilled in 1923 in Azerbaijan. The well was drilled on a man-made island in a shallow section of the

Caspian Sea. In the early 1930s, the Texas Co., later Texaco (now Chevron) constructed the first mobile metal barges for drilling in the salty coastal regions of the Gulf of Mexico (Morton, 2016).

In 1937, Pure Oil (now Chevron) and its partner Superior Oil (now ExxonMobil) used a fixed platform to exploit an oil field 1 mile (1.6 km) offshore of Calcasieu Parish, Louisiana at a water depth of 14-feet.

In 1938, Humble Oil constructed a mile-long wooden framework with railway tracks into the sea at McFadden Beach on the Gulf of Mexico, setting a derrick at its end - this was later damaged by a hurricane (Morton, 2016).

In 1945, the pressure from domestic oil interests regarding the exploitation of American offshore oil reserves incited President Harry Truman to issue an Executive Order unilaterally extending US jurisdiction over all natural resources (petroleum, natural gas, minerals, etc.) on the edge of American continental shelf. This act efficiently brought to an end the 3-mile limit "freedom of the seas" doctrine. Other nations soon followed suit.

In 1946, Magnolia Petroleum (now ExxonMobil) made a well at a distance of 18 miles (29 km) off the coastline, setting up a platform at a water depth of 18 feet (5.5 m off St. Mary Parish, Louisiana.

Early next year (1947), Superior Oil constructed a drilling and production platform at a water depth of20 feet (6.1 m), about 18 miles (29 km) off Vermilion Parish, Louisiana. But it was Kerr-McGee Oil Industries (now Occidental Petroleum), acting as operator for Phillips Petroleum (ConocoPhillips) and Stanolind Oil & Gas (BP) partnership, that completed the historic Ship Shoal Block 32 well in October 1947, months before Superior drilled an exploration well from their Vermilion platform farther offshore. In any case, that made Kerr-McGee's well the first to discover oil drilled offshore at a distance actually out of sight of land (Offshore Energy, 2010).

When offshore drilling proceeded into greater water depths of up to 30 meters (98 ft), fixed platforms were built, until the need for drilling equipment at water depths of 100 ft (30m) up to 390 ft (120m) in the Gulf of Mexico emerged. Soon after that, the first jack-up rigs appeared from specific offshore drilling contractors (Wikipedia, 2021).

The first semi-submersible rig aroused from an accident observed in 1961. At that time Blue Water Drilling Company operated a four-column submersible rig in the Gulf of Mexico for Shell Oil Company (Figure 2-5). As the pontoons were not sufficiently buoyant to sustain the weight of the rig, it was towed between sites at a draught midway between the top of the pontoons and the underside of the deck. It was observed that the changes at this draught were very small, and Blue Water Drilling and Shell agreed to try operating the rig in a floating way. While the idea of an anchored, stable floating deep-sea platform had been conceived and tested way back in the 1920s by Edward Robert Armstrong to use it as a base for aircraft (his invention was known as the 'seadrome'), the first semi-submersible rig, the Ocean Driller, was launched in 1963. Since then, many semi-submersibles rigs have been purpose-designed for the offshore drilling industry (Wikipedia, 2021).

Figure 2-5. The Blue Water 1, the industry's first semisubmersible drilling rig. (All photos courtesy Ronald L. Geer) (Priest, 2014)

At about the same time the first drillship was developed for the Project Mohole launched in 1961 to drill down into the Earth's mantle. It was the drilling barge CUSS 1, named after the oil companies that had developed it, Continental, Union, Shell, and

Superior. Within four years of the project's proposal, propellers had been installed on the side of CUSS 1 and a system developed that allowed these to keep the ship in position (Ildefonse, 2015).

Nowadays, one of the world's deepest hubs is the Perdido rig in the Gulf of Mexico, floating at a water depth of 2,438 meters (Figure 2-6). It is operated by Royal Dutch Shell and was constructed for $3 billion. The deepest operational platform is the Petrobras America Cascade FPSO (Floating, Production, Storage and Offloading), in the Walker Ridge 249 field at a water depth of 2,600 meters (Hays, 2010) (Figure 2-7).

Figure 2-6. The Shell Perdido deepwater offshore production platform in the Gulf of Mexico (Shell Global, 2010)

Figure 2-7. The Petrobras FPSO in the Gulf of Mexico (Offshore staff, 2020)

Offshore oil and gas exploration and production are more challenging than onshore because of the harsh conditions and remoteness of the marine environment. A great proportion of the innovation in the offshore petroleum industry is about overcoming these challenges and difficulties of the marine environment, along with the demand to deliver very large production facilities.

Offshore platforms may float with the proper mooring system to assist in keeping them on a fixed location. While a floating platform may have a lower cost in deeper waters than a fixed platform, there are many difficulties for the drilling and production installations to dynamically maintain the proper position.

The water column at sea can add up several thousand meters or more to the column of fluid. This effectively increases the equivalent circulating density and downhole pressures when drilling a well, as well as the energy needed to bring up the produced fluids for separation on the platform.

That's why the trend in recent years is to perform more of the production processes subsea, such as separating water from oil and re-injecting it rather than pumping the produced fluids up to a platform, or by transporting them onshore via pipelines, with no visible installations above the sea level. Subsea installations help to exploit resources at deeper waters—locations that had been unreachable—and overcome challenges presented by sea ice such as in the Barents Sea. Another challenge in such an icy environment, even in shallower water, is seabed gouging by drifting ice features (protection of offshore installations against ice action includes the burial of them in the seabed).

Human resources and logistics are very important challenges in offshore manned installations. An offshore oil platform is a small remote society with a cafeteria, sleeping quarters, administration and other support services. In the North Sea, staff members are transported by helicopter for a two-week shift. They usually have higher salaries than onshore workers. Supplies and wastes are carried by ship and deliveries of supplies must be carefully planned because there of the limited storage space on the platform. Today, a significant effort is being made into moving as many of the personnel as possible onshore, where administration and technical experts are in touch with the platform by video conferencing. An onshore job is also more appealing for the older workers in the petroleum sector. The ever-increasing use of subsea installations helps to achieve the objective of keeping more workers onshore. Subsea installations are also easier to modify, with new separators or different components for different oil types and can be laid to an extent not limited by the narrow floor space of an offshore platform.

2.3 Deep- and Ultra Deep-water Drilling

2.3.1 Definitions

The definition of deep and ultra-deep water drilling varies depending on county and/or company. There are different versions on the definitions of deep water and ultra-deep water drilling. Most companies and organizations converge to the following definition: deepwater drilling, or deep well drilling, refers to the process of drilling wells at sea depths above 1219 meters (4000ft). Ultra-deep-water drilling refers to depths above 2134 meters (7000 ft) (Enhanced Drilling, 2021). On this thesis, this definition will be used.

Deep water and ultra-deep water drilling has not been technically and economically viable for many decades, but with rising oil prices and growing consumption in emerging economic powers such as China and India, more companies are investing in this field. Major oil industry companies working in this field include Halliburton, Diamond Offshore, Transocean, Geoservices, and Schlumberger. The deepwater gas and oil market is back on the rise after the 2010 Deepwater Horizon disaster.

In the Deepwater Horizon oil spill of 2010, a large explosion took place resulting in the death of many workers and the leaking of high quantity of oil into the Gulf of Mexico, while a BP oil rig was drilling the Macondo well in deep waters (Figure 2-8).

Figure 2-8. The Deep Water Horizon catastrophe (The Editorial Team, 2018)

Despite the risks and the high costs, deep water and ultra-deep-water activities are on the rise in eastern Mediterranean and off the cost of East Africa, where huge discoveries of natural gas reservoirs have taken place. It is said by analysts that the driving force behind the resumption of such activities is the continuing demand for energy worldwide.

2.3.2 Drill deeper! "Why?"

The endless and ever-growing need for energy and specifically oil and natural gas has forced the oil industry to drill into ultra-deep waters (water depths greater than 2134 m) with the wells reaching depths of more than 7500 m under the seabed. The process of drilling and completing these wells is very expensive, with costs rising to almost $100 million per well. Pore pressures exceeding 138MPa and extreme temperatures pose challenges that threaten the integrity of the well.

In 2007 a report entitled "Facing the Hard Truths about Energy" was published by the United States' National Petroleum Council (NPC). This specific report estimated the future oil and natural gas supply and demand up to 2030. The participation in this study has been broad - more than 350 contributors with various backgrounds have been engaged from within the NPC and beyond. In addition, over 1000 other individual persons and associations involved in the energy sector contributed their ideas and opinions. The outcome of the report was that the total demand for energy worldwide will increase by 50–60% up to 2030 as a result of the increase in world population and higher average living standards in many of the developing countries in Asia, Africa and Latin America (National Petroleum Council, 2007).

The following Figure 2-9 presents the consumption of primary energy worldwide by type of source:

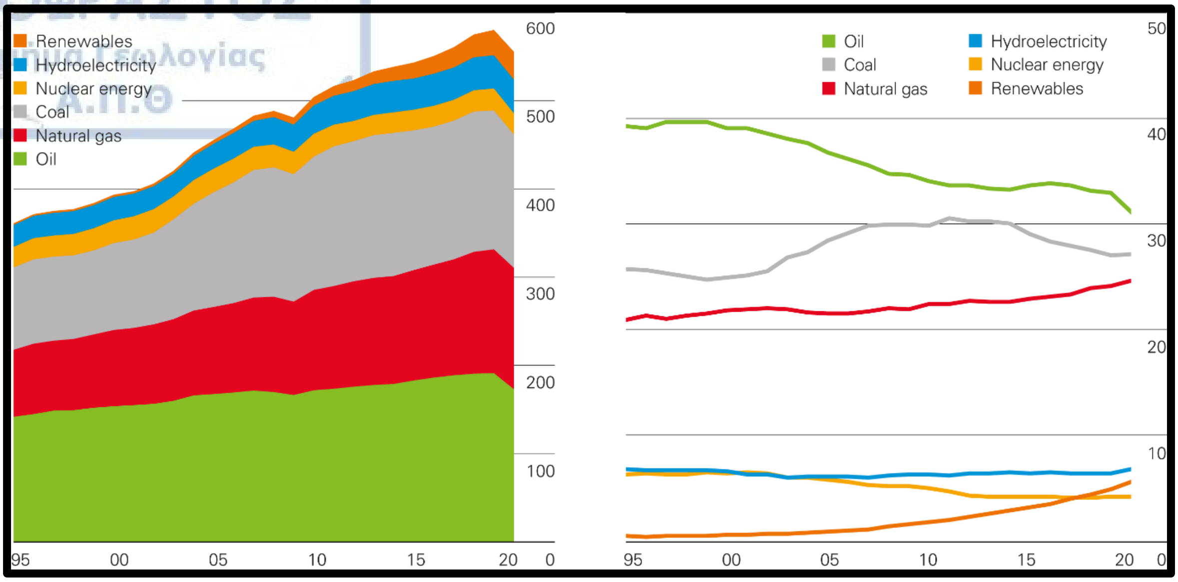

Figure 2-9. Participation of different energy sources in world primary energy consumption (BP p.l.c., 2021)

As seen on the above graph, although renewables play an ever-growing role in world energy consumption, still they cannot follow the growth rate on worldwide energy demand. This is the main reason why fossil fuels and especially oil and natural gas, remain the key players in the global energy market.

Undoubtedly, the world can make use of all the energy the industry can deliver from oil, natural gas, coal, nuclear energy, and renewable energy resources, such as wind, sun, biofuels, and hydroelectric power. It is also clear that oil, natural gas, and coal will remain the main energy sources for the next few decades. The energy industry will have to continue enhancing the production and supply of hydrocarbon fuels to meet the global energy needs.

There are enough oil and natural gas reserves to meet the demands of the 21st century. Unconventional reservoirs, such as heavy oil reservoirs, oil shales, tight gas reservoirs, gas shales, and coal seams, contain large volumes of oil and natural gas, much greater than the volume of oil and natural gas that has been produced so far, mainly from conventional reservoirs. Also, conventional reservoirs, which lie below many hundreds or even thousands of meters of seawater and bedrock are a topic and issue which will concern the oil industry in the coming years. The key to the future will be the development and promotion of new technology that will allow the industry to produce oil and gas from these unconventional and deep-water reservoirs, in an environmentally compatible and safe approach.

However, some other issues will also have an impact on both the supply and demand of oil and gas in the upcoming decades. One very important factor is the growing environmental concern. As such, CO_2 geological sequestration and new environmentally friendly operations will provide a great opportunity of developing new resources. Other factors, such as technology innovations in nuclear power, biofuels, or solar energy, can be expected to adjust the demand for energy from fossil fuels. The process and development of new materials, particularly those that can resist high-pressure, high-temperature, and high-stress environments, will be crucial for the petroleum industry.

The following Figures 2-10 up to 2-13 present the production of oil and gas depending on the sea depth.

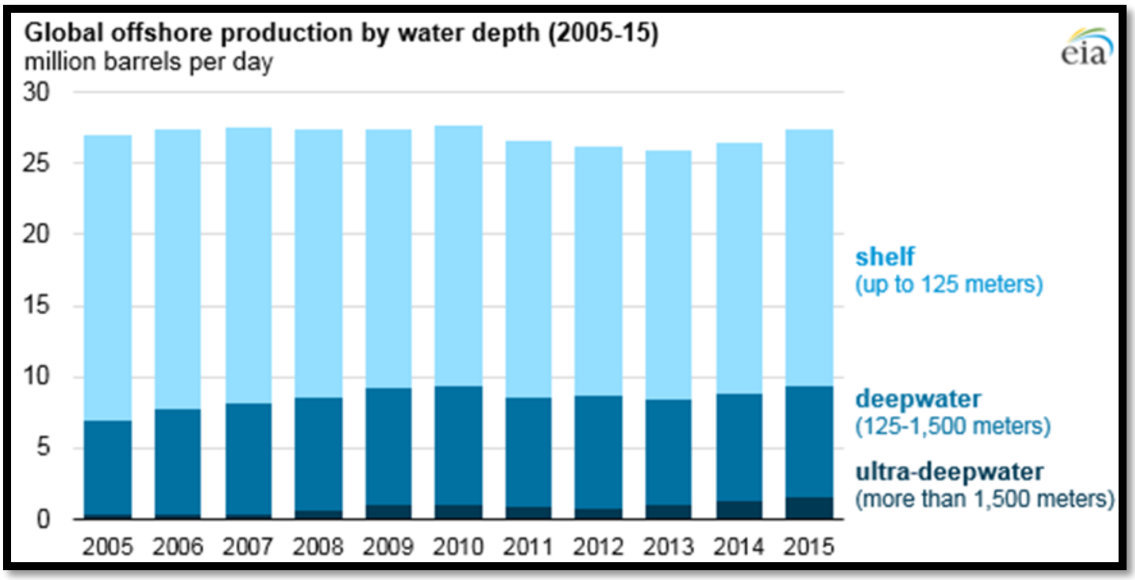

Figure 2-10. Global offshore oil production by water depth (US Energy Information Administration, 2016)

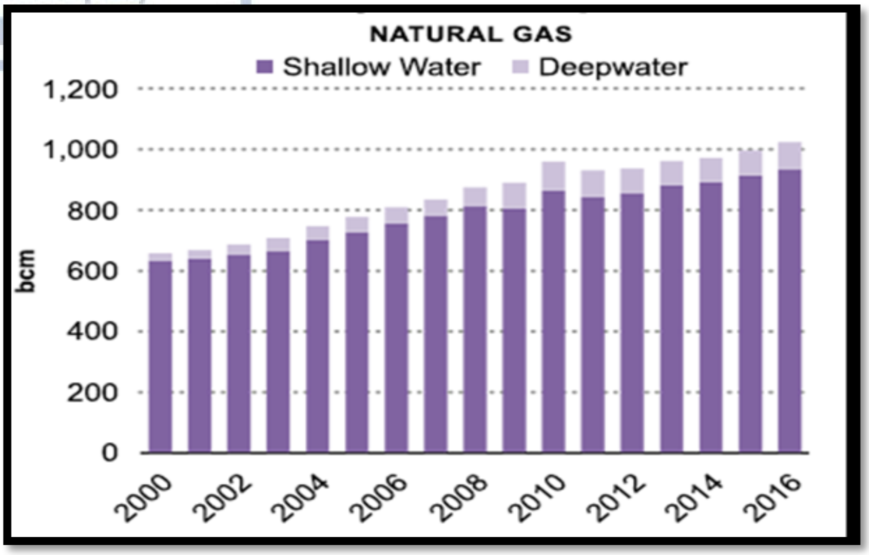

Figure 2-11. Global offshore gas production by water depth (Davis, 2018)

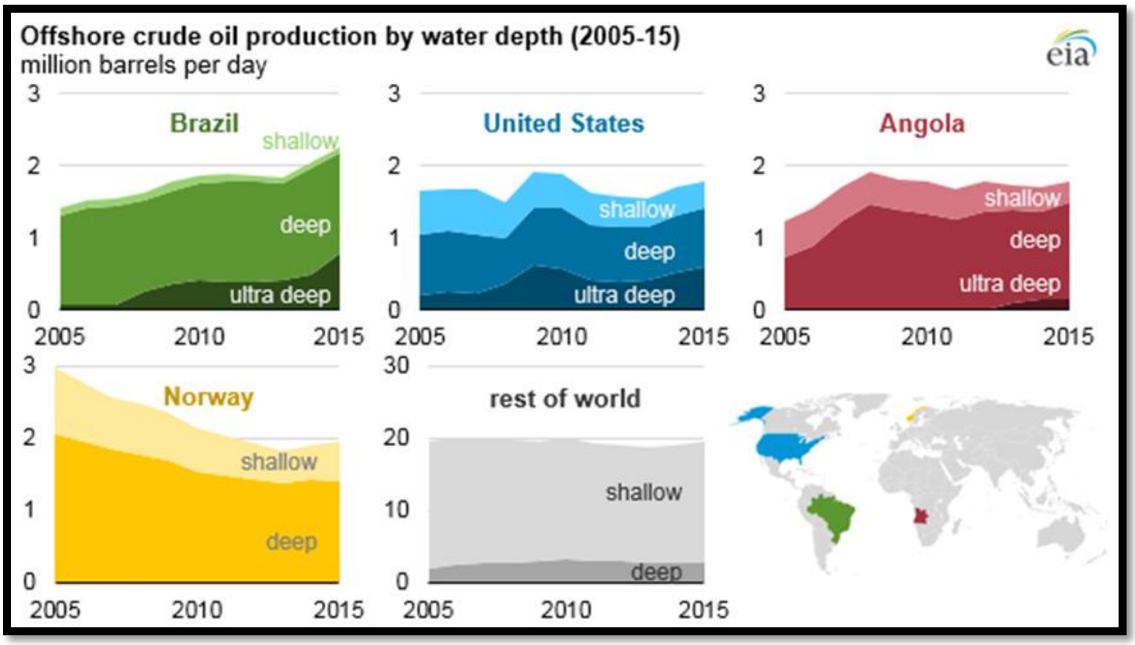

Figure 2-12. Offshore oil production by depth and region (US Energy Information Administration, 2016)

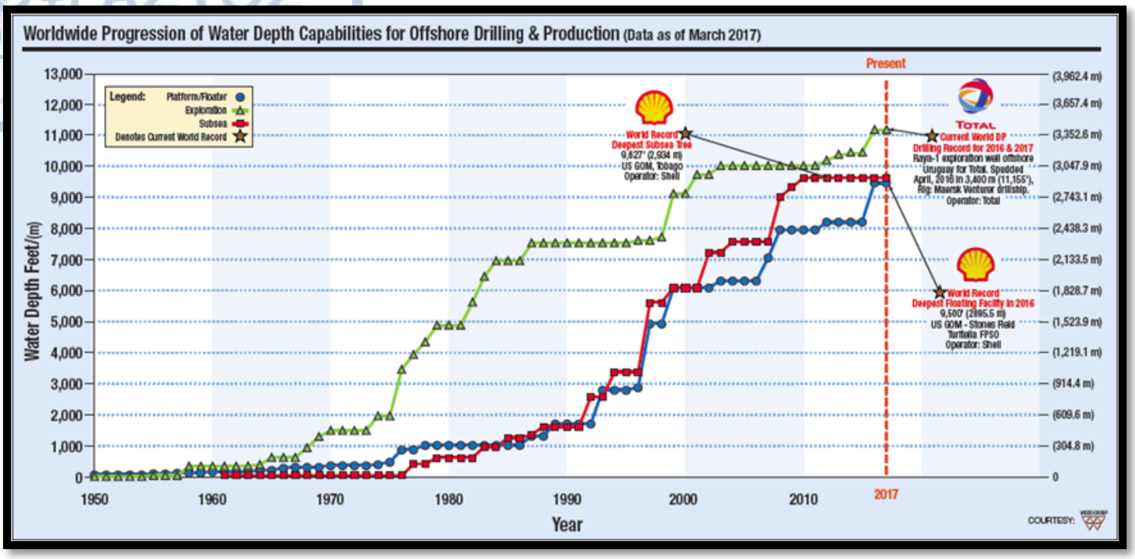

Figure 2-13. Progression of water depth capabilities for offshore drilling (Offshore Magazing - Wood Group, 2017)

From the previous graphs, we can see that there is an increasing trend in oil and gas production from deepwater wells around the world, except for Norway. The answer to the question, "Why to drill deeper" is obvious. According to the BP energy outlook 2019 edition, India and China mainly, but also other emerging third world countries, with their growing middle classes, will lead the way to energy production and consumption during the next decades.

Although there is much potential in environmentally friendly energy sources, such as solar and wind power, their energy potential and development rate are not able to fulfill the ever-growing global demand for energy, especially in these countries. Coal, oil and natural gas will be the main energy sources in the years coming.

2.3.3 Deepwater Oil &Gas Operations & Discoveries Worldwide

The map in Figure 2-14 below presents the distribution of all the conventional oil and gas field discoveries worldwide, in the first half of 2019.

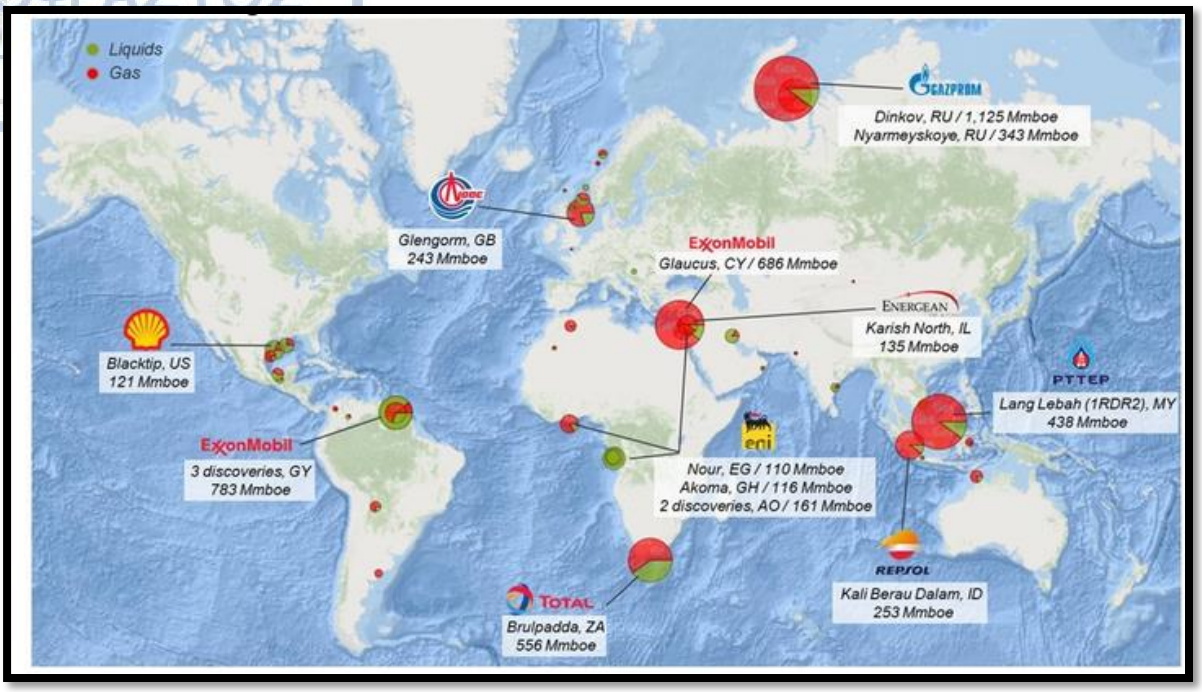

Figure 2-14. Map of global conventional discoveries in the first half of 2019 (Offshore Magazine, 2019)

Worldwide discoveries of conventional hydrocarbon reservoirs sum to 6.7 Bboe (billion barrels of oil equivalent) in the first half of 2019, with half of them to be located deepwater. Standard volumes of 1,123 MMboe (million barrels of oil equivalent) were discovered on a monthly basis, about 35% higher than the 827 MMboe discovered on the same basis in 2018. So far, natural gas maintains the main source in 2019 discoveries, comprising 63% of the total, a phenomenon that has not been seen since 2016 (Offshore Magazine, 2019).

Offshore deep-water oil and gas discoveries in Russia, Guyana, Cyprus, South Africa, and Malaysia are on the top. In 2019, 56 discoveries of conventional reserves were made, 30 of which are located offshore. So, it can be suggested that high-risk frontier plays in the deep-water are back on the battlefront for exploration companies.

Major international as well as national oil companies, with their high-risk desire and achievements in frontier areas, accounted for more than 80% of 2019 identified volumes.

In the first half of 2019, Russia led the way in terms of total discovered reserves, followed by Guyana, Cyprus, South Africa, and Malaysia.

Gazprom made two big natural gas discoveries in the Kara Sea (the northwestern part of West Siberia's Yamal Peninsula – Dinkov and Nyarmeyskoye. targets), with these discoveries to bear nearly 1.5 Bboe of recoverable resources. Dinkov, the larger of the two fields, holds 1.1 Bboe of resources, making it the largest discovery so far for the year 2019.

In the offshore area of Guyana, the ExxonMobil's series of oil discoveries go on in the Stabroek block, with three main discoveries reported in 2019 –Tilapia, Yellowtail (oil), and Haimara (gas-condensate). These three fields could jointly hold nearly 800 MMboe of recoverable reserves. ExxonMobil's success rate in the 15 wells drilled until now on the Stabroek block is 86%. First oil from the block (Liza Phase 1) is expected in mid of2020.

In the offshore area of Cyprus, ExxonMobil discovered the Glaucus gas field. The discovery is expected to hold 700 MMboe in recoverable resources and is the second major find in Cypriot waters after Eni's Calypso gas discovery, which has a comparable volume. ExxonMobil was lining up an appraisal campaign on this discovery in 2020. Eni and its partner Total were also preparing to start a five-well drilling program off Cyprus later in 2019. However, all these crucial drilling plans to confirm the large gas deposits have been put on hold, due to the coronavirus pandemic.

Total's Brulpadda exploration well finished in February 2019 in block 11B/12B made a large gas-condensate discovery in the Lower Cretaceous Post-rift Paddavissie Fairway in South African deep-water. Total and its partners in the block have stated that the discovery could hold 1 Bbbl oil or more.

In offshore Malaysia, the National Petroleum Exploration and Production Company (PTTEP), based in Thailand, made a major gas discovery with the Lang Lebah-1RDR2 exploration well in the SK410B license. It is estimated that the discovery could contain2 to 2.5 tcf of gas. This is believed to be the largest discovery ever made by PTTEP as an operator and is in association with Thailand's national energy company's strategy to expand its footprint in the area (Offshore Magazine, 2019).

For 2021-2025, Rystad Energy forecasts a record of 592 offshore project commitments: 356 shallow water, 181 deepwater, and 55 ultra-deepwater.

Deepwater commitments are expected to see the largest growth as their cost has now become much more competitive against continental shelf reserves. In terms of greenfield expenditure, it expects offshore project commitments in 2021-25 to be worth more than $480 billion, eclipsing the 2016-20 tally of around $320 billion by 50%. In the 2011-15 period, about $673 billion worth of commitments were made. Rystad expects ultra-deepwater activity to be primarily concentrated in South America, with more than 50% of the total committed value, while the Middle East is likely to lead shelf developments with 40% of the total value (Offshore Magazine, 2021).

2.4 The Greek Case

In this part of the work the current status on hydrocarbon exploration in Greece is examined. The following Figure 2-15 presents the exploration blocks in Greece, and the companies that have been granted rights on each block (according to the year 2019).

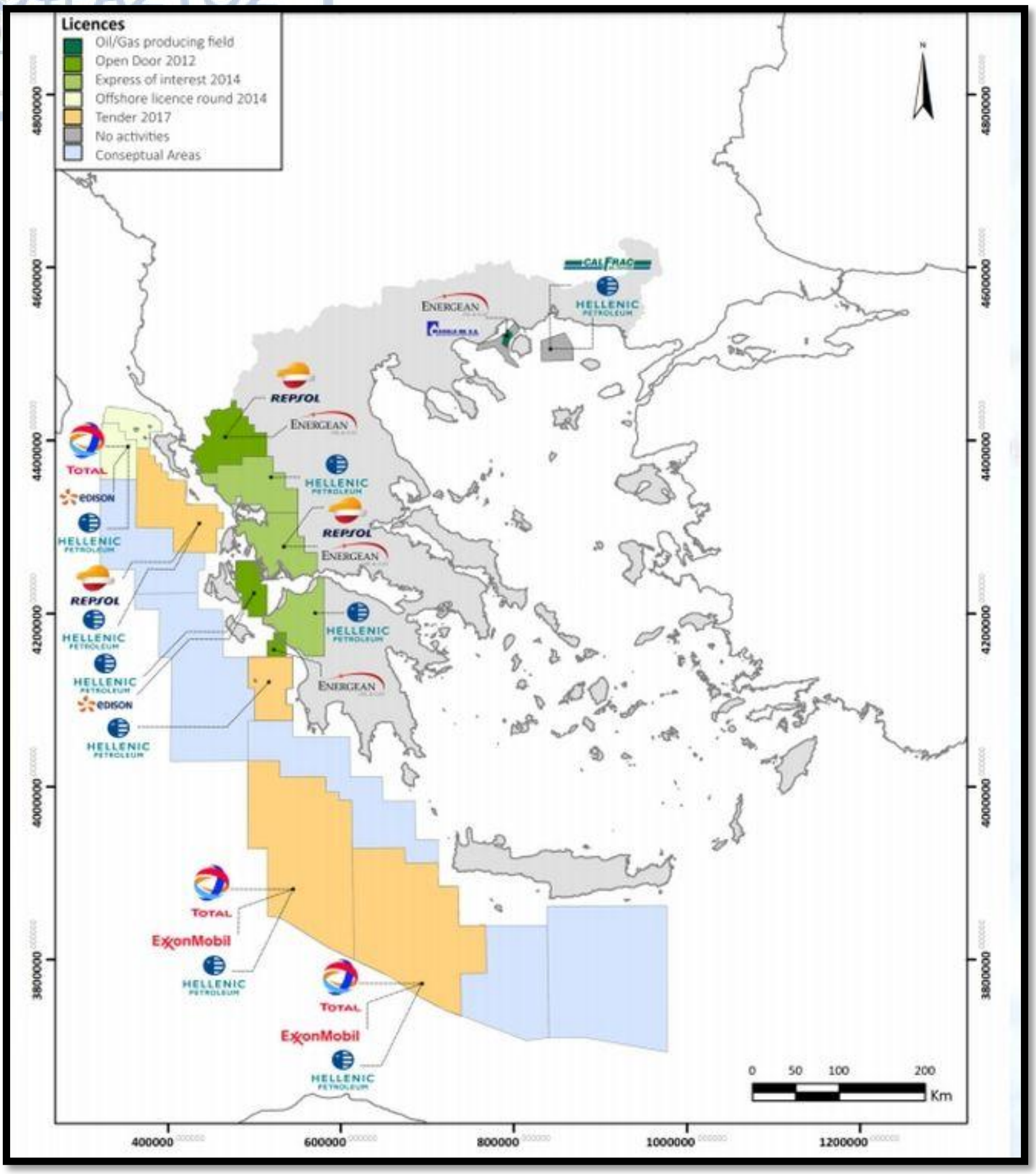

Figure 2-15: Greek exploration blocks (news247, 2019)

First attempts of hydrocarbon exploration in Greece took place at the beginning of the 20th century, but these activities were carried out in a rather irregular and random way until the 1960s and were mostly focused on onshore zones, as a result of surface oil shows, particularly in western Greece. It was not until the 1970s that the situation shifted with the discovery of the Prinos and the South Kavala fields, which remain the only producing fields in the country until today. Nevertheless, very little was done regarding exploration activities offshore, even after the discovery of the Katakolon field in the western Peloponnese in the early 1980s, until 2012 when an Open-Door offer was initiated.

Since then, Greek exploration and production prospective has attracted increasing interest, with several key companies being granted licenses in 2018, including Total, ExxonMobil, Repsol and Edison.

The majority of the granted exploration blocks are offshore, in the Ionian Sea, along the west coast of mainland Greece, and in the Mediterranean Sea, south of Crete. These marine areas are characterized by immense water depths (Figure 2-16). Even the deepest point of the Mediterranean Sea, the Calypso Deep (5,267 m), lies inside one of these blocks. The blocks offered for offshore exploration lie in areas with water depths ranging from a few hundred meters to 3,500m.

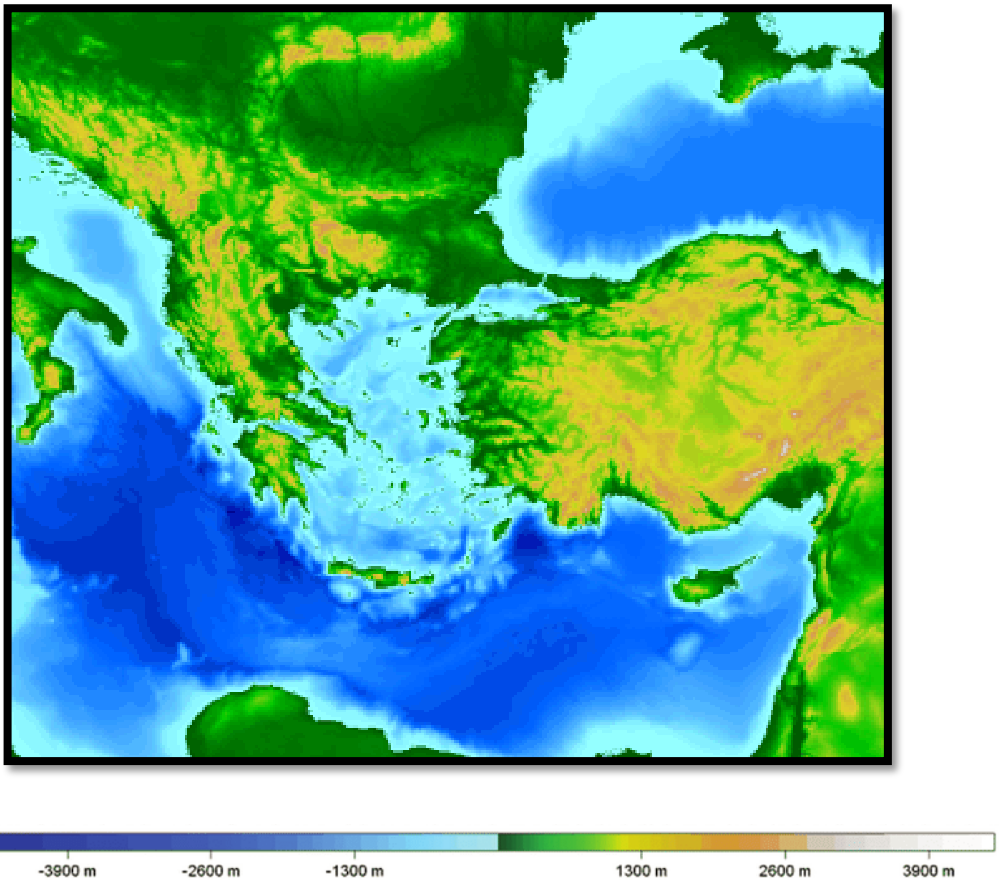

Figure 2-16. Map of eastern Mediterranean Sea with water depth (Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (CIBRA), 2005)

By comparing the above Figure 2-16 with the granted licenses for exploration (Figure 2-15), we can see that most of these granted blocks lie on deepwater bodies (deep blue).

Until recent years, technical restrictions placed limitations to the prospect of exploration in deep-water environments, particularly in the Mediterranean Sea. However, the petroleum industry has now begun to show significantly more interest in exploring these waters, especially after the recent discoveries in the Eastern Mediterranean, such as Zohr, Leviathan, Tamar, Aphrodite and Calypso. It seems that Greece will be in the foreground of oil and gas exploration and production in deep-sea environments during the next years.

CHAPTER 3

TYPES OF DEEPWATER DRILLING FACILITIES

The main aspect of an offshore drilling operation, whether in deepwater or not, is the platform or vessel which hosts the drilling equipment, the accommodation facilities for the personnel and other critical equipment for the smooth, safe and continuous functioning of the drilling operations. These platforms/vessels are used to drill wells for exploration, appraisal and development of an oilfield, produce the hydrocarbons from the reservoir, process the produced oil and gas, and in many cases even temporarily store them (FPSOs). Their complex and challenging nature lies in the fact that they not only have to drill rock formations, but they must also perform this task through a column of water, which in many cases is measured in kilometers.

There are many different types of offshore installations used by oil and gas companies. The type used on each occasion depends on the characteristics of the region (remotely or not) and the depth of the water column, as well as on the metocean conditions and the distance from the coast.

In general, drilling in deep waters can be performed by two main types of mobile deepwater drilling rigs: semi-submersible drilling rigs and drillships. Drilling can also be performed from a fixed-position installation such as a fixed platform, or a floating platform, such as a spar platform, a tension-leg platform, or a semi-submersible production platform (Figure 3-1). Most offshore exploration wells, many development wells-and most likely the majority of all deepwater well-are drilled using Mobile Offshore Drilling Units (MODUs). MODU is a term for floating drilling units such as semi-submersibles, jack-up rigs, etc. The first drillship went into service in California in 1956, and the first semisubmersible began working in the Gulf of Mexico five years later. These early units are now labeled as "the first-generation MODUs." The newest, high-capability MODUs are of fifth or sixth generation. Next, the main types of MODUs and other offshore deepwater facilities are briefly presented.

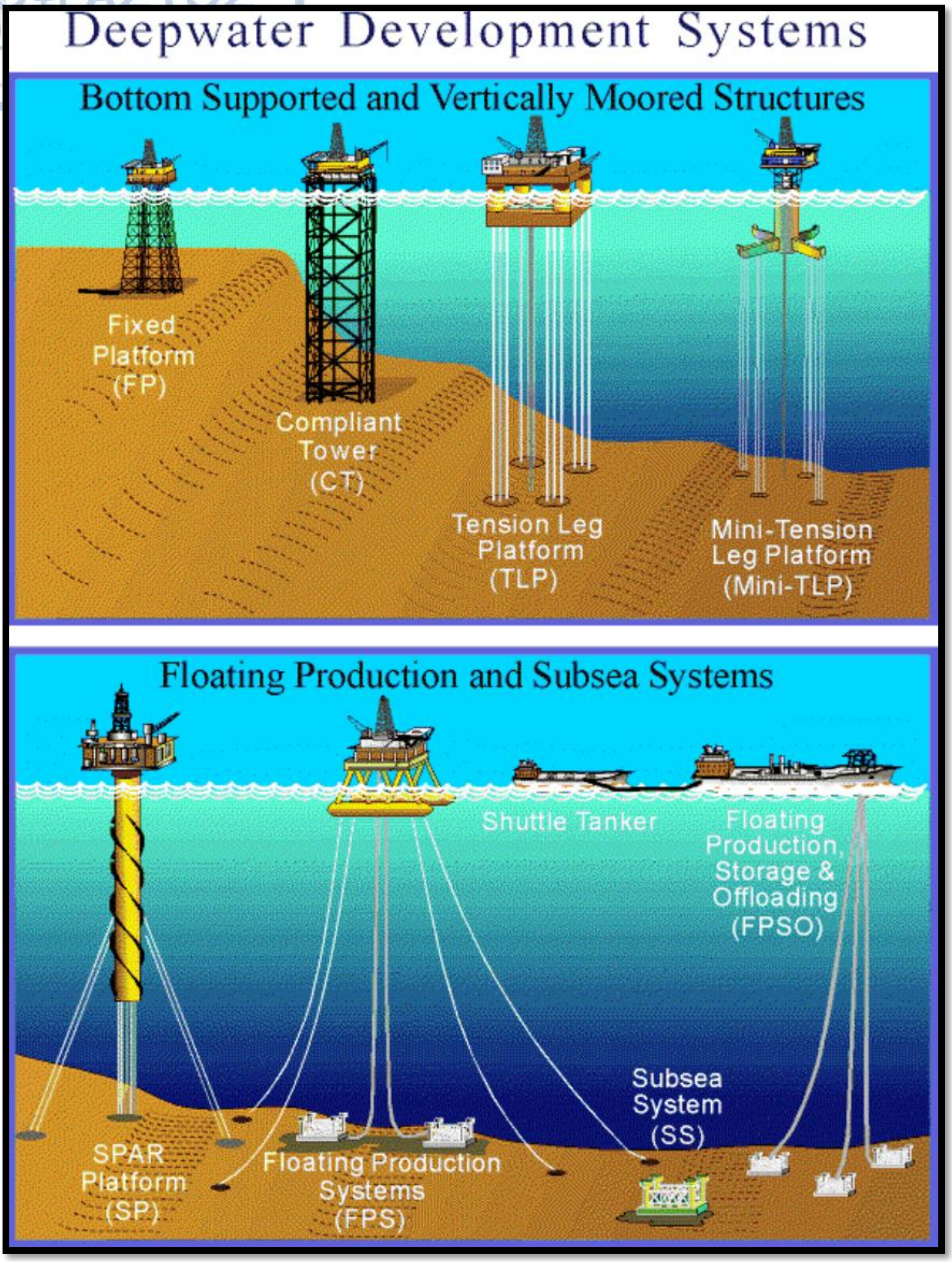

Figure 3-1. Types of offshore deep water drilling & production facilities (Regg, et al., 2000)

3.1 Fixed Platforms (FP)

This type of platform is built upon concrete or steel legs, and anchors directly on the bottom of the sea (Figure 3-2). Their construction cost is high. On the top of the structure, there is the deck that hosts the drilling rig and other facilities. Fixed platforms are huge constructions. Their volume but also their immobility makes them suitable for long-term use. There are many types of structures used as fixed platforms (steel jacket, concrete caisson, floating steel). Steel jackets are made of cylindrical steel parts and are attached to the seabed. Concrete caissons have oil storage tanks built inside the superstructure, which also allows them to float. Fixed platforms are used for water depths up to 500m.

Figure 3-2. Fixed platform (Oil States Industries, Inc., 2020)

3.2 Compliant Towers (CT)

This type of platform consists of a narrow flexible steel tower that is anchored on the seafloor and supports the deck on the top (Figure 3-3). This kind of structure is designed to withstand strong lateral forces. The water depth, in which they are used, varies from 400m to 1000m.

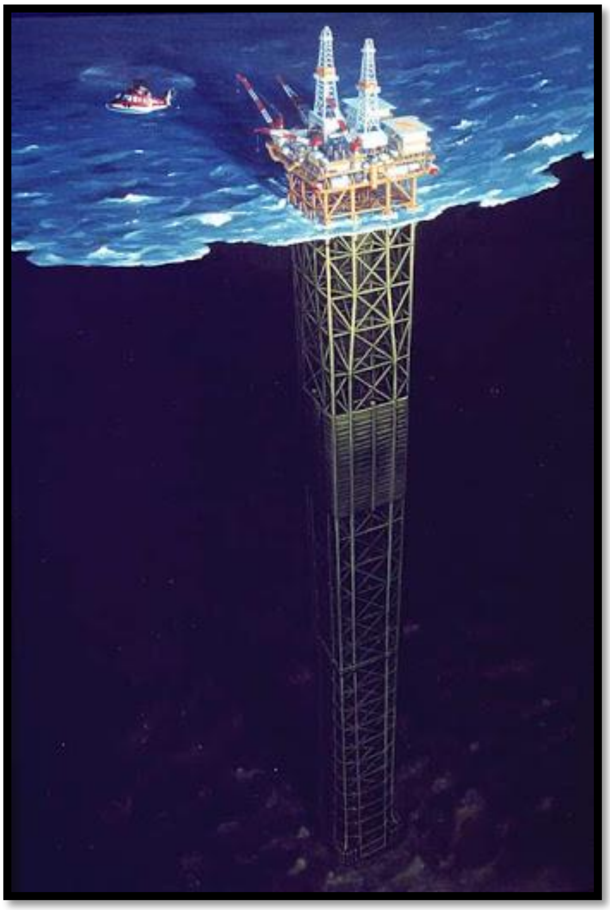

Figure 3-3. Compliant tower (Karamanos, 2020)

3.3 Tension-Leg Platforms (TLP) & Mini TLP

TLPs are floating structures, tied to the seabed and held in place by tendons that run down to the seafloor in such a way that diminishes every vertical movement. This kind of platform is used in water depths up to 2000m (Figure 3-4). Most TLPs are four-column structures and have many similarities with the semi-submersible platforms.

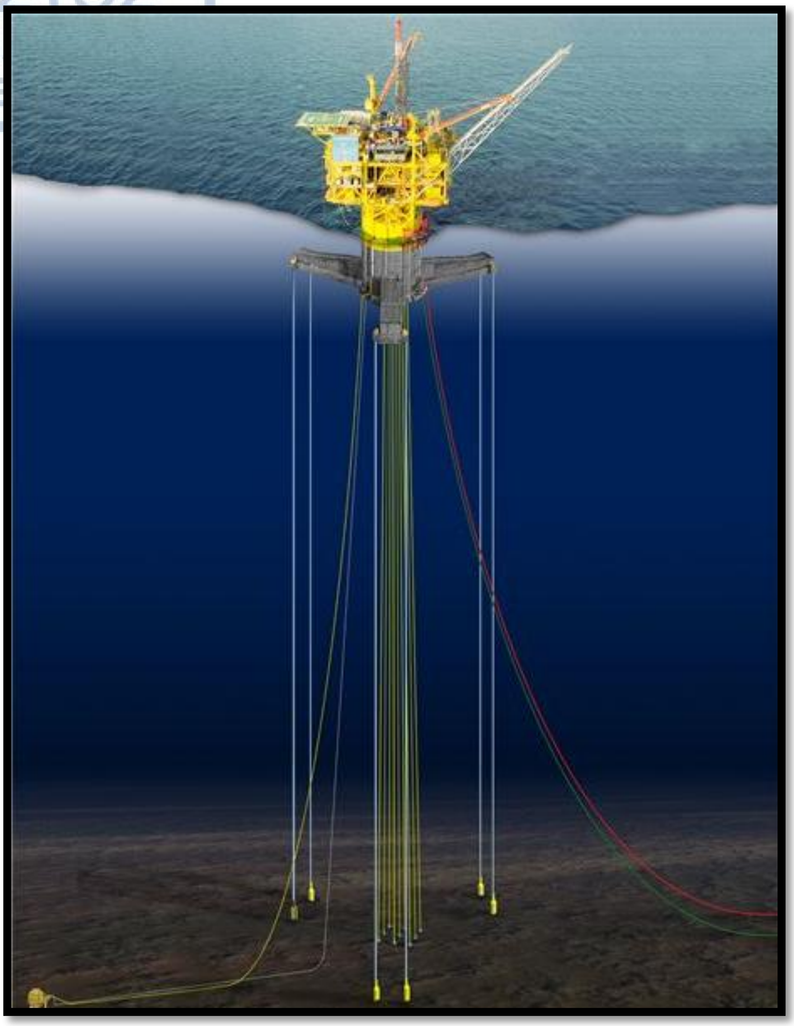

Figure 3-4. Tension-leg platform (Drilling Formulas and Drilling Calculations, 2017)

Mini TLPs and are relatively low cost, used in water depths between 600 and 3,500 ft (200 and 1,100 m). They can also be used as utility, satellite, or early production platforms for larger deepwater discoveries that would be uneconomic to produce using more conventional deep-water production systems.

3.4 Semi-submersible platforms

Semi-submersible platforms have tanks (pontoons) that give them enough buoyancy to make the whole structure able to float. This kind of structure can move like a normal ship with the help of tugboats or specialized transportation ships. They can be submerged or move higher by changing the mass of water inside their tanks. They are stabilized with the anchor lines, attached to the seabed, or by using dynamically positioning, a system used in combination with rotating propellers (Figure 3-5). However, the wellhead is typically located on the seafloor, so extra precautions must be taken to prevent a leak. Semi-submersibles can be used in almost all depths, from 200m to 2000m.

Figure 3-5. Semi-submersible platform (The Editorial Team, 2017)

3.5 Spar Platform (SP)

A spar platform is a type of oil platform with a floating ability. Spar platforms are typically used in deep waters. This kind of platform consists of a large, single, vertical cylindrical construction, upon which the deck is placed. This cylinder also has helical strakes (Figure 3-6). On average, about 90% of the Spar Platform's structure is underwater. This design makes SPs less affected by harsh conditions (waves, wind, etc.). Spar platforms are tied to the seabed with an array of chains and steel wire ropes. Most SPs are used up to depths of 1 kilometer (3,000 feet), but new technology can extend them to functioning up to 3,500 meters (11,500 feet) below the sea level. That makes it one of the deepest drilling platforms in use today.

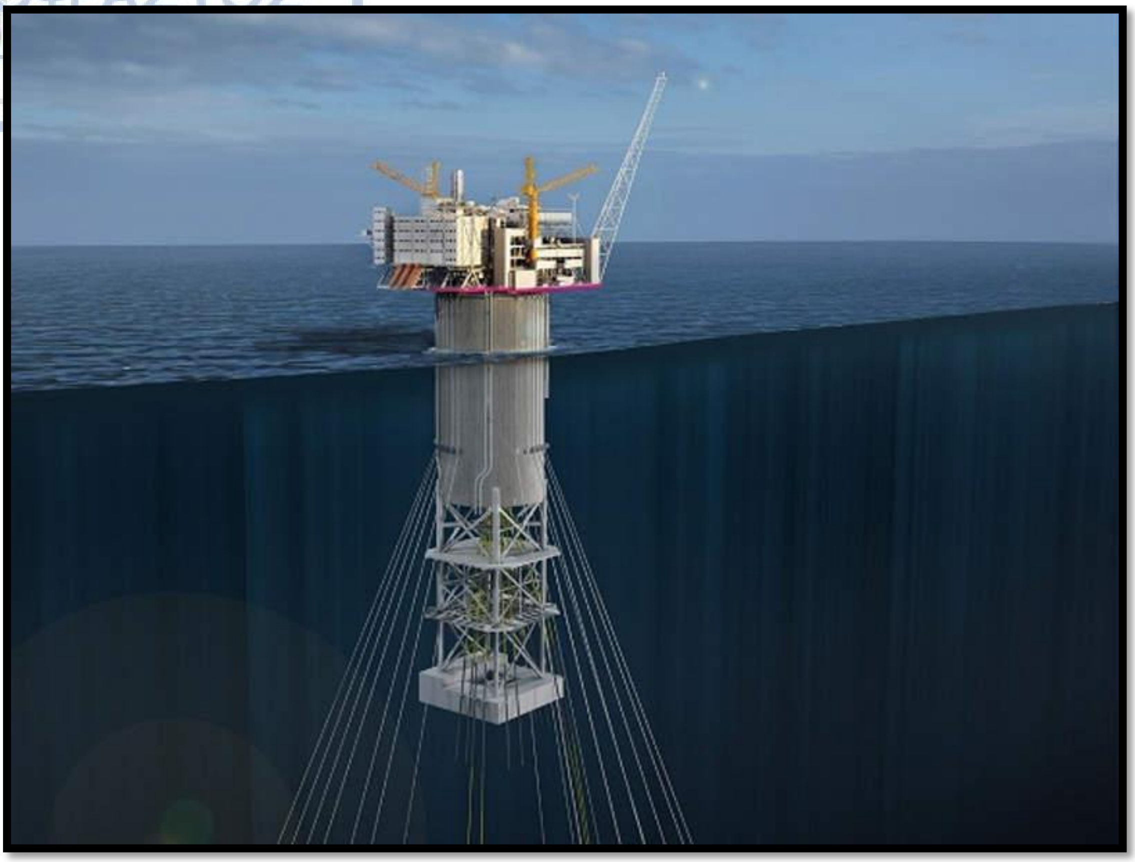

Figure 3-6. Spar platform (NS ENERGY, 2021)

3.6 Drill ships

Drill ships are a type of merchant vessel designed and optimized mainly for exploratory wells or scientific purposes in deep waters (Figure 3-7). They manage to maintain their stability with dynamic positioning systems. Drill ships can operate in water depths up to 4000m.

Figure 3-7. Drill ship (Offshore Magazine, 2019)

3.7 Floating Production, Storage and Offloading (FPSO) & Floating, Drilling, Production, Storage and Offloading (FDPSO)

FPSOs are vessels that can produce, process and store hydrocarbons from nearby wells. They are quite effective and preferable in remote and deep-water regions. FPSOs are economically preferable because they eliminate the need for expensive subsea pipes and onshore facilities and terminals. Oil and gas can be directly loaded on a tanker and transported to their destination. The use of FPSOs is also more attractive in small fields with a small-time horizon for exploitation.

FDPSOs is a relatively new variant of classic FPSOs, with the first of its kind setting sail in 2009. The key difference with this vessel is the modular drill that is attached to the hull of the ship, giving it more utility than a standard FPSO. With the addition of a drill, an FDPSO can perform nearly all major functions associated with offshore oil and gas production.

Figure 3-8. A FPSO unit (The Editorial Team, 2020)

Figure 3-9. FDPSO (Auke Visser´s International Super Tankers , 2022)

3.8 Subsea Systems

Subsea systems are generally multicomponent seafloor systems that allow for the production of hydrocarbons in water depths that would normally rule out installing conventional fixed or bottom-founded platforms. Through an array of subsea wells, manifolds, central umbilicals, and flowline, a subsea system can be located many miles away in deeper water and tied back to existing host facilities in shallow water. Host facilities in deeper water would likely be one of several types of floating production systems.

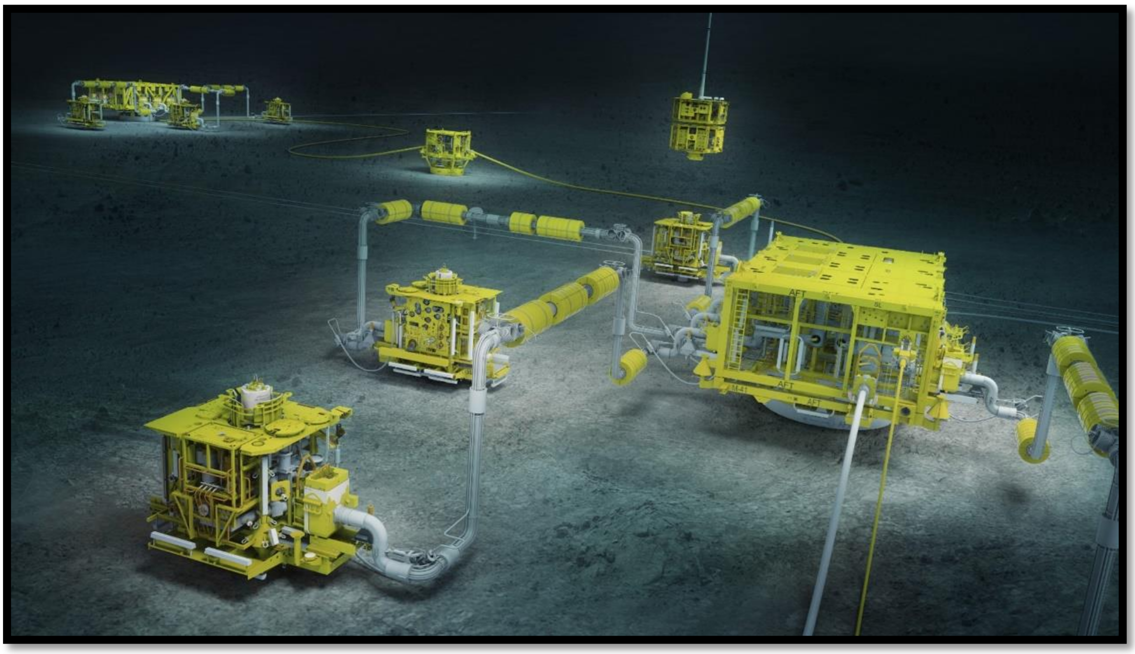

Figure 3-10. A subsea production system (AkerSolutions, 2021)

Figure 3-11 shows different arrangements of the subsea system components, which can be described as (Regg, et al., 2000):

- Single-well satellite
- Multiwell satellite
- Cluster-well system
- Template
- Combination of the above

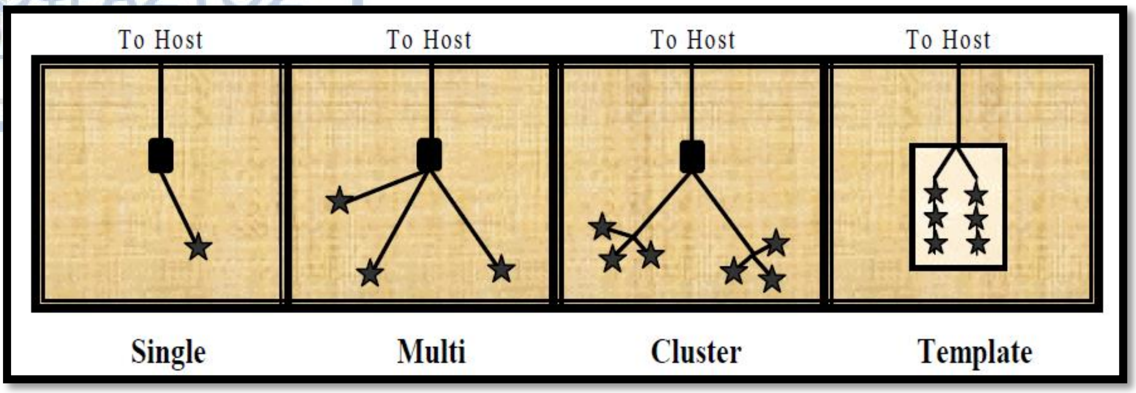

Figure 3-11. Various layouts of the subsea components (Regg, et al., 2000)

CHAPTER 4

CHALLENGES IN DEEPWATER AND ULTRA DEEPWATER DRILLING

4.1 Physical challenges in deepwater and open sea environments and hazards

Onshore drilling operations usually take place on a well-studied and well-established site with a very small number of environmental hazards and uncertainties, compared to offshore operations, and especially those which take place in deepwater environments, usually many kilometers away from the closest piece of land. The main physical challenges in deepwater and open sea environments are:

1) The remoteness of the facilities from shore or existing infrastructure. In many cases, there is a lack of infrastructure in the fields or in the region.
2) Water depth, potentially beyond 3,000 meters, is related to higher hydrostatic pressures at the seafloor, as well as with extremely low seawater temperatures.
3) Metocean conditions are related to severe surface conditions (winds, storms, waves, currents, heavy rain, snow, ice), as well as with deep ocean currents, often poorly understood, and/or with sparse data available.

Deepwater drilling operations may also be subjected to other open-sea hazards, such as:

- Poor visibility due to fog
- Tides and solitons (**soliton** or **solitary wave** is a self-reinforcing wave packet that maintains its shape while it propagates at a constant velocity)
- Combination of all the above

During offshore/deepwater drilling operations, the main situational demand is to prevent the vessel or platform and all connected equipment necessary to drill the well, from moving too much around the vertical line (from wellhead to ship or platform), against all environmental conditions. Excess on that movement could lead to loss of equipment, environmental pollution and, of course, and most important of all, injuries and even loss of human life.

4.1.1 Remote operating conditions

The remoteness and nature of offshore drilling operations is the key factor that prevents the personnel from physically interfering and changing the course, the time or the velocity and the duration of a physical phenomenon, like a storm. That is the reason why prediction and forecasting, as well as monitoring, are so fundamental for offshore operations. A correct and accurate prediction can ensure the health and safety of the personnel and equipment, and the viability of the offshore operations.

Deepwater drilling facilities in remote locations must be largely self-sufficient. When contracted, they come with a full crew and the equipment and supplies needed to carry out the assigned task, whether it is just a well or multiple wells. In the Gulf of Mexico, crews typically work a rotational schedule consisting of 21 consecutive days aboard the rig followed by 21 days off. In international locations, crews typically work a rotational schedule of 28 days on and 28 days off.

4.1.2 Water depth

Water depth itself imposes one of the most difficult to deal with factors in deepwater drilling. As water depth increases above 1000m, planning should take into consideration these conditions:

- Lower temperatures close to the seafloor
- Higher hydrostatic pressure on the seafloor
- The window between pore and fracture pressures narrows as seawater depth increases
- The above narrow drilling window imposes more casing strings to be installed

- Extended operating time and consequently more risks and costs
- Greater potential for shallow geological hazards and resulted risks
- Drilling tools, equipment, systems, and technologies may not be suited for deepwater. Need for new drilling tools, equipment, systems, and technologies (e.g. mooring, dynamic positioning.

4.1.3 Metocean conditions

4.1.3.1 Wind

The wind is a force of nature that has a direct impact on the sea state but also on the current movement. Wind conditions play a key role when making operational planning for any offshore drilling activity. Regional and seasonal wind variations should also be taken into consideration where operations are taking place.

4.1.3.2 Storms

Severe storms are a major open-sea concern, especially in operations where dynamically positioned or moored vessels are used. In time forecasting can alert the personnel to move vessels and equipment off place and out of the storm's trajectory. The time to secure well(s) and recover the subsea BOP and marine riser may also be required along with the evacuation procedure before a storm's extreme path impacts the operating installation, well infrastructure, or location.

The severity and characteristics depend on the regional geography and regional climate, where the operation is taking place. Tropical cyclones are a type of storm in warm tropical climates around and close to the equator (Figure 4-1). Cyclones are often a problem for operations and therefore they must be better studied and taken into consideration during operational planning. Hurricanes are more likely to be formed in the Atlantic or Northern Pacific and typhoons in Northwest Pacific.

Comparing the regional distribution of tropical storms shown in Figure 4-1, above with the geographical distribution of offshore activities, in Figure 4-2, below, one can observe that a large percentage of offshore operations takes place in areas where a tropical storm may form or pass. That means that tropical storms pose one of the most dangerous hazards for offshore operations because they can directly affect personnel safety and equipment integrity.

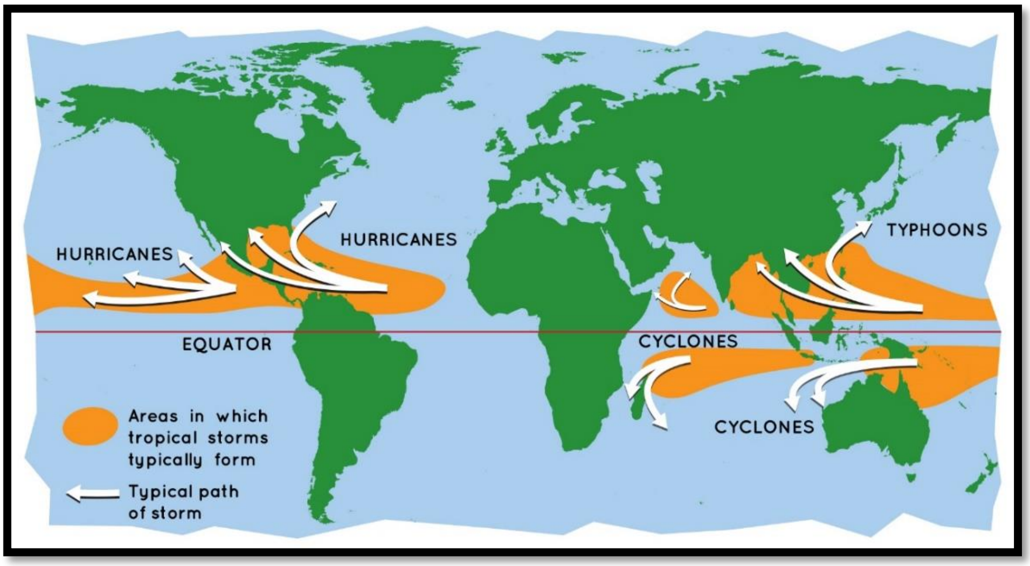

Figure 4-1. Regional distribution and paths of tropical storms (NASA Space Place, 2019)

Figure 4-2. Global locations of offshore oil and gas platforms (Vanegas Cantarero, et al., 2020)

4.1.3.3 Currents

An ocean current is a continuous flow of seawater caused by several forces which act on the water (wind, Coriolis effect, etc.). They flow for great distances. During operational design and planning, a sufficient description of regional current conditions and movement is required. This can be done by local measurements, model simulations, or empirical procedures. Where possible, a complete and precise current description needs to be known, so that all operational problems can be tracked and taken into consideration during planning.

Loop currents occur in deepwater-specific areas, such as the Gulf of Mexico (Aird, 2019). Their flow is restrained on the upper 1000m of the water column.

High currents can occur in specific offshore deep-sea environments because of tides, rivers, and stream flows into the sea. They pose a challenge for the management of the stability of the drilling vessel.

Figure 4-3 shows the distribution and flow of sea currents on global scale.

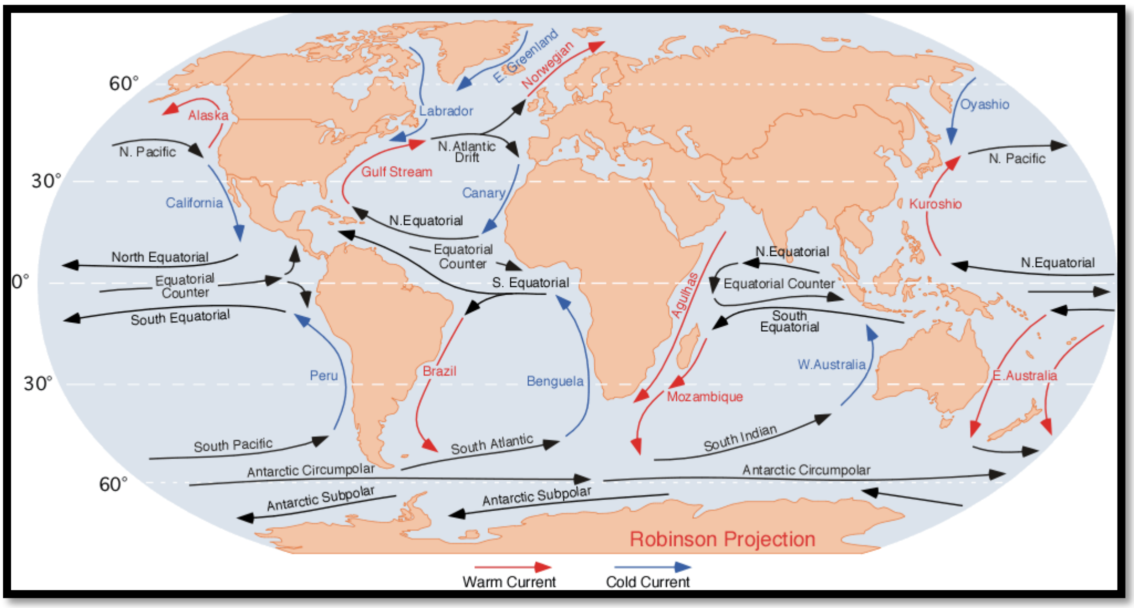

Figure 4-3: Ocean current flows around the globe (Wikipedia, 2022)

4.1.3.4 Ice

On far northern or southern seas, close to the poles, the existence of ice is an aspect that needs to be carefully examined. Ice or icebergs result from the flow of glaciers into the sea, but also from the effect of global warming. Operational planning in such ice-infested areas must have ice management policies and procedures to sustain the integrity of the installation when ice threats are present.

4.1.4 Other hazards

4.1.4.1 Visibility

Reduced visibility due to fog, but also poor visibility below sea surface has an impact on offshore operations. Regions with excess presence of fog lead to summer operating periods. Subsurface reduced visibility also causes problems and drawbacks. A reason for the reduction in subsurface visibility is the plankton blooming season (Aird, 2019).

4.1.4.2 Deepwater sand waves

Asymmetric sand waves were observed on a recent project in the western part of the Barents Sea. These patterns were up to 6m tall, at a depth of 500-700m. The sand waves are created and maintained by ocean currents. They pose a threat to the integrity and stability of the seabed installations and equipment.

4.1.4.3 Solitons

Solitons are gravity waves with high frequencies and large amplitudes. They are closely associated with sea currents too. Solitons can cause costly disruptions to offshore drilling operations. Their wavelength varies from dozens to hundreds of kilometers, their period from just a few minutes to many hours, and their amplitude, from just a few to hundreds of meters. Solitons are created because of water movement over the seabed with uneven topography and strong currents. They are closely related to tidal waves. They can result in equipment failure, due to the extreme shear forces and lateral deviation the cause.

4.1.4.4 Tides

Tides are a consequence of the relative movement of the Earth-moon system. They are very well studied and predicted, and operating companies have access to that data through third-party contractors. The further we move into the open sea, the lesser the tidal range is (tidal range varies from 1 up to several meters). Tides should always be considered by the operation personnel when measuring wellhead or downhole depth, where accuracy and precision are required.

In Figure 4-4 the regional distribution of tidal ranges around the globe is presented, measured in meters.

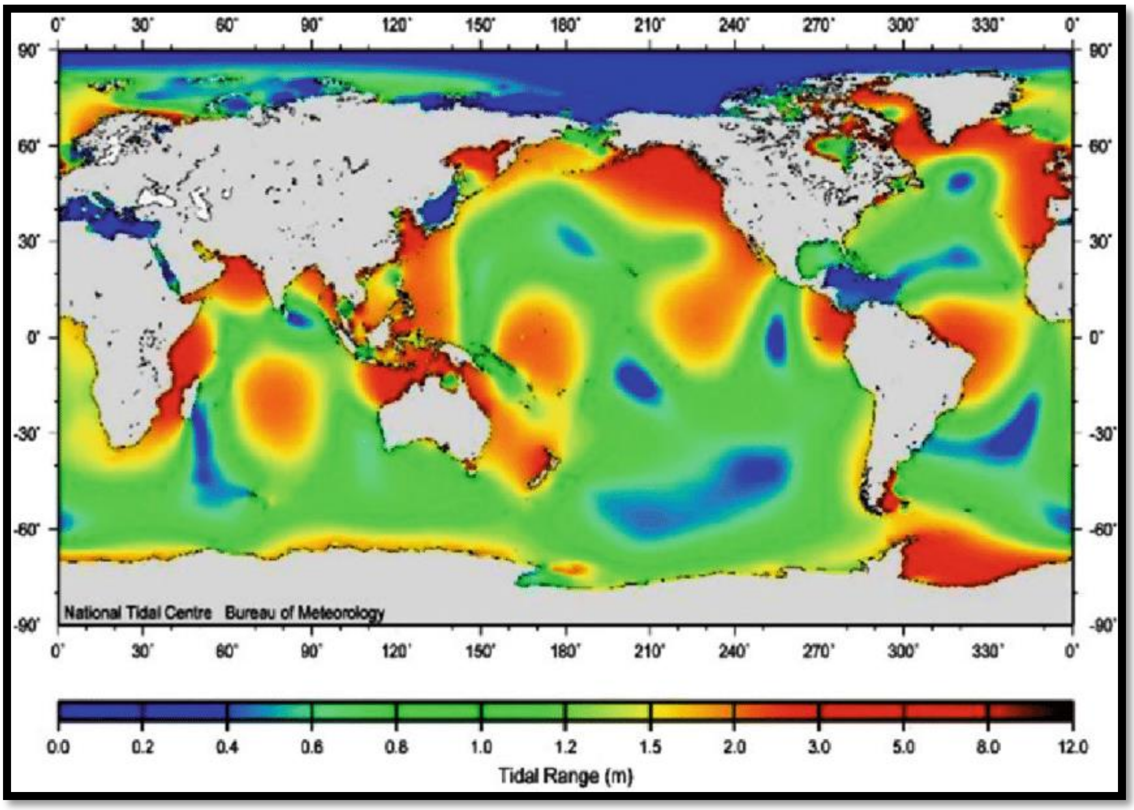

Figure 4-4. Tidal range around the globe (Williams, et al., 2019)

4.2 Technical challenges and solutions

Deepwater and ultra-deepwater drilling operation is a very complex and demanding technical and scientific activity. The demands on human, scientific, technical, and equipment resources are quite high. Only in recent years, the technological and scientific progress has allowed oil companies to perform deep-water drilling operations in an economically feasible way.

Deepwater drilling is much more complex than shallow-water drilling. The remoteness of the location, the environmental hazards, and the water depth itself are the main factors that make deepwater drilling a very challenging but marvelous technical achievement.

The technical and scientific complexity of this kind of operation makes them quite expensive too. The deepwater program (drilling, completion, etc.) is estimated to amount up to 50—60% of the total program cost, which can account for from 1-2 billion dollars, up to tens of billions. The design and the preparation of the operation by the company is also a very challenging activity. Every aspect of the operation (from vessel selection up to casing design and drill bit selection) must be thoroughly examined (Cummings, et al., 2015).

In this section, the progress made in deepwater drilling will be examined from its technical perspective. The challenges are very high, but also the technology advancements have helped drive down the costs and shorten lengthy drilling times.

It is obvious that in deep water and ultra-deepwater drilling activities, the most suitable platform to be used is the drillship or the semi-submersible platform. In most cases, the water depth is measured in kilometers. This means that the vessel or platform floats some kilometers above the wellhead which lies on the seabed. The first technical challenge that must be dealt with is the horizontal and vertical stability of the vessel/platform.

Next, it will be examined how the vessel/platform connects to the wellhead. The connection string (risers)[1] is very important because it guarantees environmental safety by separating and isolating the drilling activity, with all its products from the sea environment. On the other hand, the capability of marine risers, deepwater riser damage through fatigue and hydrostatic pressure and/or hydrodynamic phenomena, as well riser handling are some of the aspects that need to be thoroughly examined when designing a deepwater well.

Every well, onshore or offshore, has a blowout preventer (BOP)[2] during the drilling operation. In the case of deepwater wells, a subsea BOP is used. Its general purpose and function are the same as of the onshore BOP, but there are some differences since it lies some kilometers below the surface of the sea.

A subsea wellhead[3] system is a means that provides hanging off and sealing off the casing used in the well. It is located on the seafloor below the subsea BOP. In deepwater wells, the wellhead lies on the seabed with some kilometers of water above it. Many operations have to take place down there. These operations obviously cannot be performed by humans. The industry has given a solution to this issue by using ROVs (Remotely Operated Vehicles).

The main goals when drilling a deepwater well are to achieve optimal well control, to maintain a stable and safe well, improve wellbore integrity, reduce drilling costs and protect the environment. The narrow operating window between pore pressure and fracture pressure in deepwater fields is a major challenge. With managed-drilling

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[1] A drilling riser is a conduit that provides a temporary extension of a subsea oil well to a surface drilling facility. Drilling risers are categorized into two types: marine drilling risers used with subsea blowout preventer (BOP) and generally used by floating drilling vessels; and tie-back drilling risers used with a surface BOP and generally deployed from fixed platforms or very stable floating platforms like a spar or tension leg platform (TLP) (Wikipedia, 2018).

[2]A blowout preventer (BOP) (pronounced B-O-P, not "bop" is a specialized valve or similar mechanical device, used to seal, control, and monitor oil and gas wells to prevent blowouts, the uncontrolled release of crude oil or natural gas from a well. They are usually installed in stacks of other valves (Wikipedia, 2021).

[3]A wellhead is the component at the surface of an oil or gas well that provides the structural and pressure-containing interface for the drilling and production equipment. The primary purpose of a wellhead is to provide the suspension point and pressure seals for the casing strings that run from the bottom of the hole sections to the surface pressure control equipment. While drilling the oil well, surface pressure control is provided by a blowout preventer (BOP). If the pressure is not contained during drilling operations by the column of drilling fluid, casings, wellhead, and BOP, a well blowout could occur (Wikipedia, 2021).

concepts, drillers can safely drill through narrow margins and reach target depths with fewer casing strings. Well control aspects include kick causes, kick detection, kick tolerance, stuck pipe, surge and swab effects and the well kill procedures.

High pressure-high temperature (HPHT) wells also present considerable challenges, like hydrate formation, resulting in plugging of pipelines and well control equipment.

Except for environmental hazards, the complexity of the reservoirs that lie far below the seabed attracts certain geological hazards too for deepwater drilling. These hazards can be divided into two main categories: shallow geological hazards, and deep geological hazards. These hazards are also discussed in this work since they present even more challenges on pressure management (drilling fluids[4]), casing[5] design, and cementing of the well.

Based on the above, deepwater well design challenges and construction drivers are summarized in Figure 4-5.

[4] In drilling engineering, drilling fluid, also called drilling mud, is used to aid the drilling of boreholes into the earth. Often used while drilling oil and natural gas wells and on exploration drilling rigs, drilling fluids are also used for much simpler boreholes, such as water wells. One of the functions of a drilling mud is to carry cuttings out of the hole (Wikipedia, 2021).

[5] Casing is a large diameter pipe that is assembled and inserted into a recently drilled section of a borehole. Similar to the bones of a spine protecting the spinal cord, casing is set inside the drilled borehole to protect and support the well (Wikipedia, 2022).

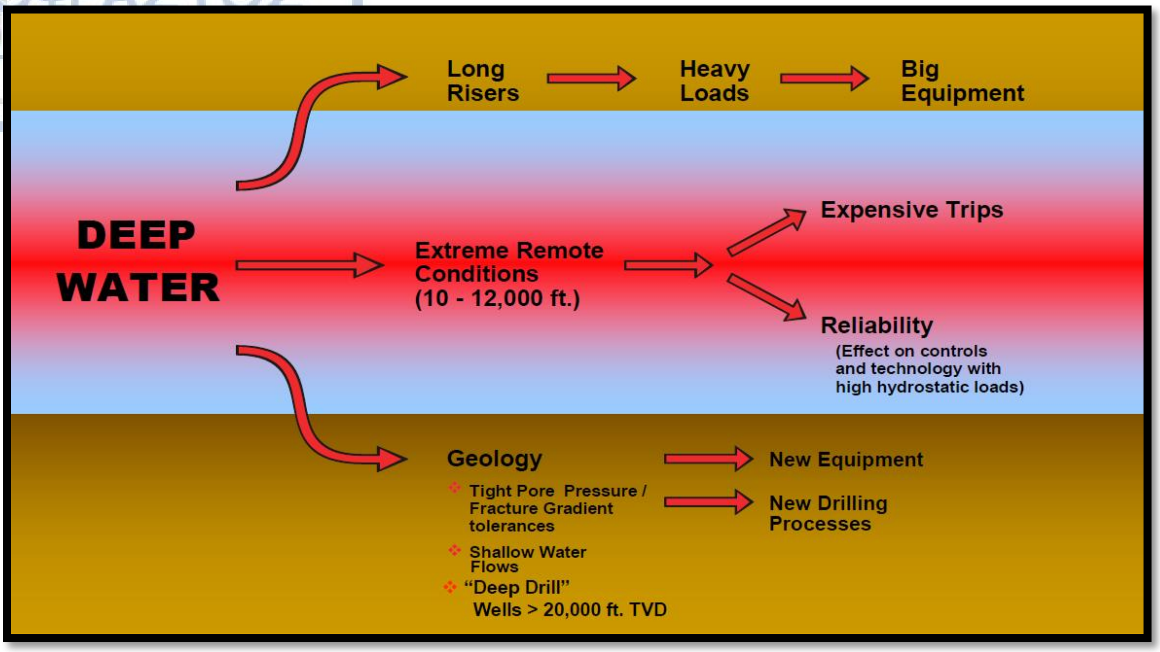

Figure 4-5. Deepwater well design challenges and construction drivers (Aird, 2016)

4.2.1 Station keeping

Maintaining a vessel's or platform's fixed position over wells that lie many kilometers below on the seabed is a unique feature of deepwater drilling. There are two main systems for station keeping:

- Spread mooring
- Dynamic positioning

Each system has advantages and disadvantages. Even in ultra-deepwater drilling, in which we might think that DP is more suitable, a mooring system could also be an option. The decision on which system is more appropriate to be used in each case depends not only on economic and technical factors but also on regional and environmental considerations.

4.2.1.1 Mooring systems

A mooring system consists of mooring lines, an anchor, and connectors. A mooring line connects the platform/vessel with the anchor on the seabed.

There are three main types of mooring lines:

- Synthetic fiber rope
- Wire rope
- Chain
- Combination of all three

The choice regarding which one must be used depends mainly on environmental factors (wind, waves, currents). Chain mooring lines are the most widely used, mainly in shallow water. Steel wire ropes are lighter than chain lines and present better physical properties, so they are more suitable for deep water. However, synthetic fiber lines are the lighter of all, being yet the most expensive.

Combinations include chain and wire mooring lines for water depth up to 2000m, chain and fiber lines, and chain, wire, and fiber lines in ultra-deepwater operations.

The mooring system depends on the strength and holding capacity of the anchor. The anchor holding capacity depends on the digging depth and the seabed soil.

There are three main types of seabed anchoring:

- Drag embedment anchor (DEA)
- Suction piles
- Vertical load anchors

In DEA anchoring, an anchor is dragged along the seabed until it reaches the required depth. It uses soil resistance to keep itself in place. This type of anchoring does not perform well under vertical forces.

Suction piles are tubular piles installed in the seabed. A pump sucks out the water from the top of the tube. This makes the pile move deeper into the seabed. They are suitable for unstable sea beds. Vertical load anchors are similar to DEA. However, they can withstand both vertical and horizontal forces.

There are five types of mooring systems:

- Catenary (up to 1500m)
- Taut leg (up to 2500m)

- Semi-taut (up to 2500m)
- Spread
- Single point

The catenary mooring system (Figure 4-6) is the most widely used. It bears its name from the shape of the hanging line. On the seabed, the lines lie horizontally. This type is more suitable for shallow waters because as depth increases (the line has to be longer than the water depth) the overall weight of the lines increases too.

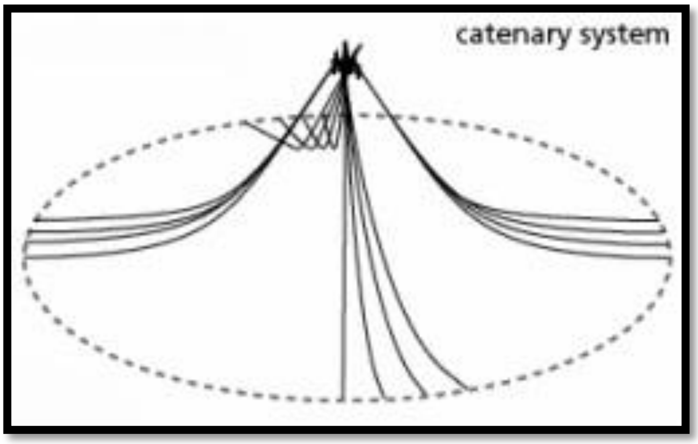

Figure 4-6. Catenary mooring (ABC Moorings, 2021)

The taut leg system (Figure 4-7) comprises polyester ropes. The lines go down to a 30-40^{o} angle until they meet the anchor which is loaded vertically. The semi taut combines taut lines and catenary lines. It is ideal for deepwater operations.

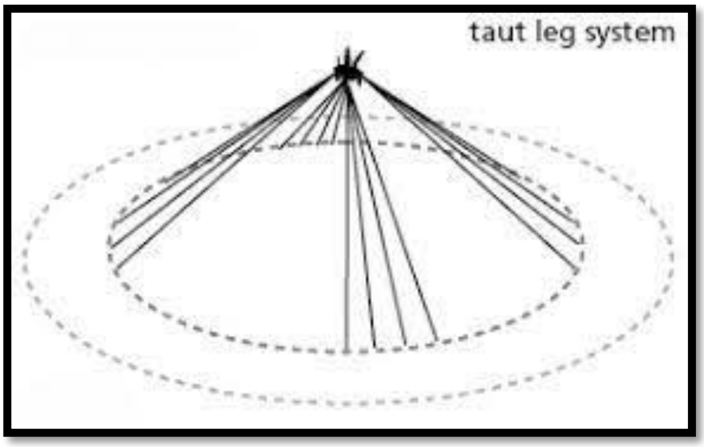

Figure 4-7. Taut leg mooring (Offshore Moorings, 2021)

A spread mooring system (Figure 4-8) consists of two groups of lines (bow and stern) that connect the vessel to the anchors on the seabed. The symmetrical distribution of the lines keeps the vessel in its fixed position. This type of system does not allow the vessel to rotate.

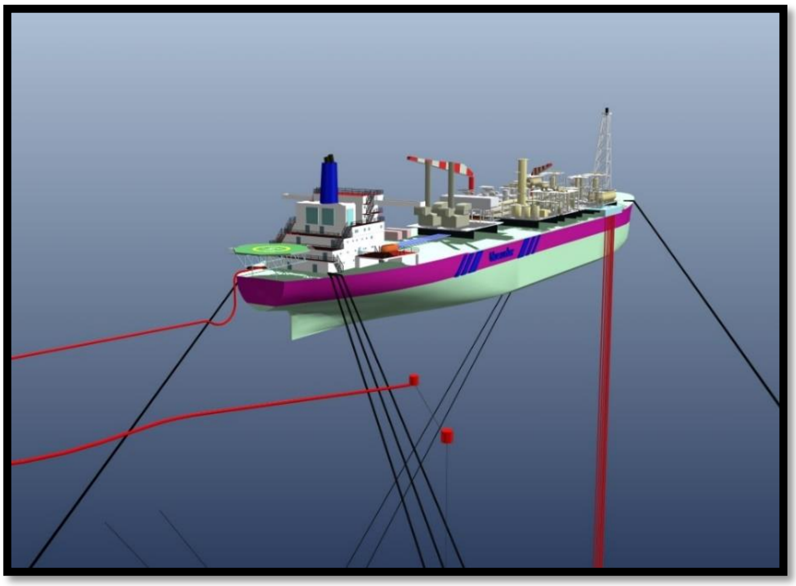

Figure 4-8. Spread mooring (Bluewater, 2021)

A single point mooring system (Figure 4-9) holds all the lines on a single point below the vessel. It has the ability for 360° rotation.

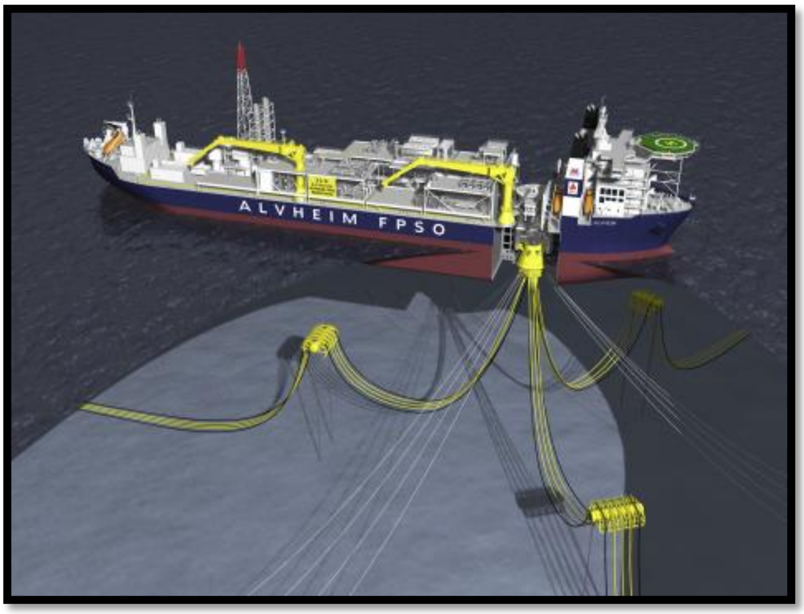

Figure 4-9. Single point mooring system (Ma, Luo, Kwan, & Wu, 2019)

4.2.1.2 Dynamic positioning systems

Dynamic positioning is a computer-controlled station-keeping method. It does not use lines or anchors. It maintains the vessel's or platform's position with an arrangement of propellers and thrusters. It uses many types of sensors (position reference sensor, wind sensor, motion sensor) and gyrocompasses[6] that feed the main computer with information about the vessel's position and the magnitude and direction of natural forces (wind, waves, currents) that affect the vessel's stability. This system is used mainly in drill ships, but also in many cases in semi-submersible platforms.

The computer uses a mathematical model that receives the information feed from the sensors. This information combined with the location of the propellers or thrusters helps the computer calculate the steering angle and output of each thruster, to correct and maintain the vessel's fixed position. This allows drilling operations to take place in locations where mooring is not feasible (due to deep water, unstable seafloor, etc.). Table 1 summarizes the pros and cons of each station-keeping method.

Table 4-1: Station-keeping method comparison (Wikipedia, 2022)

Station keeping method comparison	
Anchoring	**DP**
Advantages: • No complex systems with thrusters, extra generators, and controllers. • No chance of running off position by system failures or blackouts. • No underwater hazards from thrusters.	**Advantages:** • Maneuverability is excellent; it is easy to change position. • No anchor handling tugs are required. • Not dependent on water depth. • Quick set-up. • Not limited by obstructed seabed.

[6]A gyrocompass is a type of non-magnetic compass which is based on a fast-spinning disc and the rotation of the Earth (or another planetary body if used elsewhere in the universe) to find geographical direction automatically. The use of a gyrocompass is one of the seven fundamental ways to determine the heading of a vehicle. Although one important component of a gyrocompass is a gyroscope, these are not the same devices; a gyrocompass is built to use the effect of gyroscopic precession, which is a distinctive aspect of the general gyroscopic effect. Gyrocompasses are widely used for navigation on ships (Wikipedia, 2022).

Station keeping method comparison	
Anchoring	**DP**
Disadvantages: • Limited maneuverability once anchored. • Anchor handling tugs are required. • Less suitable in deep water. • Time to anchor out varies between several hours to several days. • Limited by obstructed seabed (pipelines, seabed).	**Disadvantages:** • Complex systems with thrusters, extra generators and controllers. • High initial costs of installation. • High fuel costs. • Chance of running off position in case of strong currents or winds, or due to system failures or blackouts. • Underwater hazards from thrusters for divers and ROVs. • Higher maintenance of the mechanical systems.

As shown in the above table, each system has its pros and cons. The decision on which is going to be used relies on water column depth, environmental conditions, seafloor state, costs, and of course, and most important of all, previous experience.

4.2.2 Drilling Risers

Drilling risers are large-diameter tubes that connect the subsea BOP which lies on the seabed with the drilling vessel/platform (Figure 4-10). Its importance is quite critical because risers participate in the circulation of the drilling mud, ensuring that the mud coming out of the well will reach the vessel, without spilling out on the seafloor, or elsewhere in the water column. The riser could also be considered as an extension of the wellbore[7] to the surface.

[7] The wellbore is the drilled hole or borehole, including the open hole or uncased portion of the well. Borehole may refer to the inside diameter of the wellbore wall, the rock face that bounds the drilled hole (Schlumberger Oilfield Glossary, 2022).

Figure 4-10. Drilling risers (Wikipedia, 2018)

The main functions of the drilling risers are:

- Participation in mud circulation
- Isolation of the drilling process from the surrounding environment
- Guidance for tools and equipment from the surface down to the wellbore
- Carrying out the subsea BOP
- Retrieving of the subsea BOP after completion of the drilling process

Besides drilling risers, there are six more types of marine risers, all used for production (production risers):

- Attached risers
- Pull tube risers
- Steel catenary risers
- Top tensioned risers
- Riser towers
- Flexible risers

Before any operation, a riser analysis must be carried out. This dynamic analysis covers the complete length of the riser system, from the conductor[8] up to the flex joint[9]. The main drilling riser concern occurs on the upper end of the system because of the vessel horizontal motion (surge, sway, roll, pitch). The vertical motion of the vessel barely affects the riser system because of the presence of the flex joint and the marine riser tensioner[10]. The main concern on the lower end is the angle, and the loads that the riser system applies on the subsea BOP and wellhead.

A typical drilling riser arrangement, comprising marine risers, subsea BOP, wellhead, and conductor pipe, is presented in Figure 4-11. The buoyancy joints reduce the overall load applied on the BOP.

In general terms, the drilling riser is a string under tension that obtains stability, lateral load resistance, and structural integrity (Aird, 2019). It should also be mentioned that a riser can resist lateral environmental loads (currents, wind, etc.), within its structural dimensions. Riser tension is the most basic element in the drilling riser system. Each time the mud weight changes, the riser tension must be changed too, by the use of the marine riser tensioner.

[8] The conductor is the casing string that is usually put into the well first, particularly on land wells, to prevent the sides of the hole from caving into the wellbore. This casing, sometimes called drive pipe, is generally a short length and is sometimes driven into the ground. Conductor pipe is run because the shallow section of most wells onshore is drilled in unconsolidated sediment or soil rather than consolidated strata typically encountered deeper. Offshore, the drive pipe or structural casing may be installed prior to the conductor for similar reasons (Schlumberger Oilfield Glossary, 2022).

[9] Flex joints at the top and bottom of the drilling riser reduce the angle of the riser at its top connection to the vessel and at its bottom connection to the BOP. This local angle reduction provides a moderate reduction in angle that extends the conditions in which drilling operations can be conducted. The flex joint is a passive, elastomeric component, which has become popular for deep water (Chakrabarti, 2005).

[10] A marine riser tensioner is a device used on an offshore drilling vessel which provides a near constant upward force on the drilling riser independent of the movement of the floating drill vessel. The marine riser is connected to the wellhead on the sea bed and therefore the tensioner must manage the differential movements between the riser and the rig. If there were no tensioner and the rig moves downward, the riser would buckle; if the rig rises then high forces would be transmitted to the riser and it would stretch and be damaged. Tensioners have historically been composed of hydraulic actuated cylinders with wire sheaves. More recently, active electrical motors have been used for compensation purposes (Wikipedia, 2018).

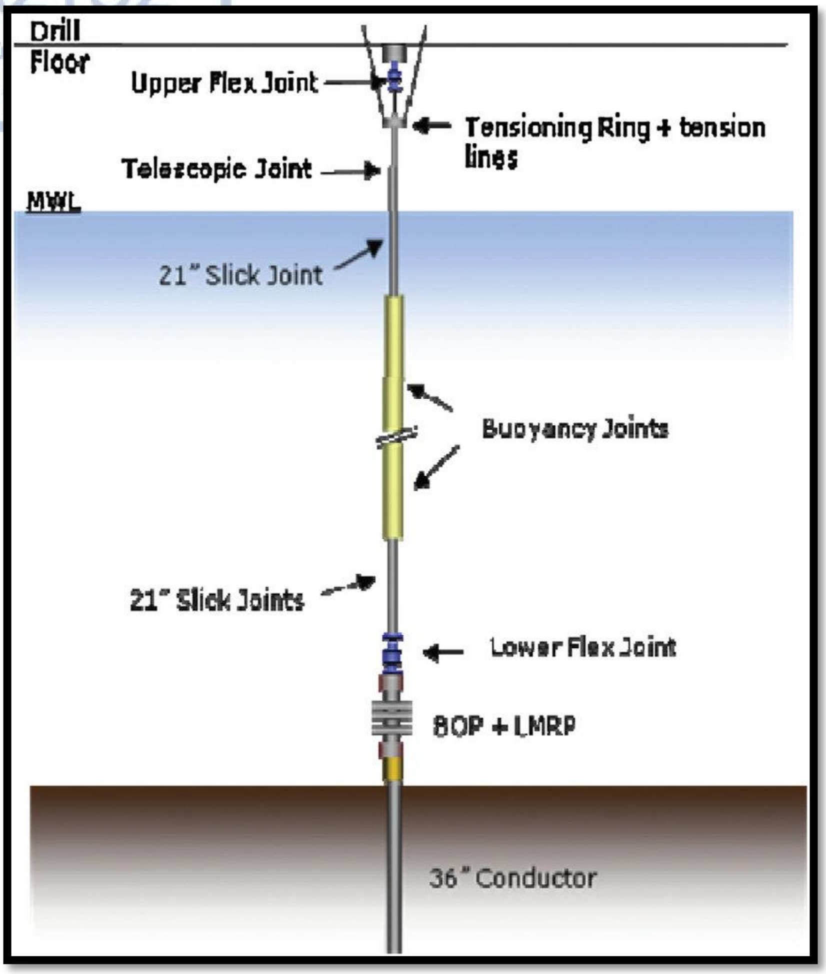

Figure 4-11. Typical drilling riser system arrangement (Chang, et al., 2018)

4.2.3 Subsea BOP (Blowout Preventer)

The BOP is a crucial component of every drilling operation (onshore or offshore - Figures 4-12 and 4-13, respectively). It is composed of an array of valves and mechanical parts, and its main function is to seal, control, and monitor oil well during drilling to prevent unwanted blowouts[11]. The BOP is the main drilling component that guarantees the safety of the personnel, the protection of the environment, and the integrity of the well.

[11]A blowout is an uncontrolled release of crude oil and/or natural gas from an oil well or gas well after pressure control systems have failed. Modern wells have blowout preventers intended to prevent such an occurrence. An accidental spark during a blowout can lead to a catastrophic oil or gas fire (Westergaard, 1987).

Figure 4-12. Onshore BOP (Drilling Knowledge, 2017)

Figure 4-13. Subsea BOP (Dockstr, 2021)

Whether referring to an onshore BOP or a subsea one, their function and the way they carry it out are the same. The difference between them is the environment in which they operate. There are two main types of BOPs: Ram and annular. In most cases, both are used together on a single system, as shown in Figures 4-12 and 4-13.

Ram BOPs use a pair of steel shears, called rams. Between the rams, there is free space, through which the whole drilling process takes place. The rams are connected to high-pressure hydraulic valves, and, if needed, e.g. in case of a kick[12], the rams close and cut the drilling string[13], killing the well, thus containing the kick. Annular BOPs close only the annular[14] space between the inner BOP surface and the drilling string, thus containing the kick in there, without killing the well.

BOPs are controlled by control stations mounted around the rig, or directly by manually closing the valves. In deepwater operations, this is not possible, due to the water depth. Subsea BOPs are controlled by:

- Hydraulic signal (via a hydraulic umbilical)
- Electric signal (via a control cable)
- ROV (direct intervention of an ROV with use of its robotic arms)
- Deadline switch (Auto shear)

In deep and ultra-deepwater drilling operations the subsea BOP (SSBOP) is connected to the vessel/platform via the riser. The SSBOP is placed above the subsea

[12] Well kicks are an early warning sign for problematic well control. Unpredictable and extreme pressures beneath the surface can lead to formation fluids to start to flow back up the wellbore. Well kicks can be diagnosed by a sudden change in drilling rate, pressure fluctuations, or gases trapped in the mudlogging unit. Usually behaving like a violent hiccup, well kicks are early warning signs to more serious and dangerous problems occurring during drilling. Industry safety procedures are constantly revised with the intent of eliminating the chance of well kicks and blowouts (Viewtech Borescopes, 2021).

[13]A drill string on a drilling rig is a column, or string, of drill pipes that transmit drilling fluid (via the mud pumps) and torque (via the kelly drive or top drive) to the drill bit. The term is loosely applied to the assembled collection of drill pipes, drill collars, tools and drill bit. The drill string is hollow so that drilling fluid can be pumped down through it and circulated back up the annulus (the void between the drill string and the cased/open hole) (Wikipedia, 2021).

[14]The annulus of an oil well or water well is any void between any piping, tubing or casing and the piping, tubing, or casing immediately surrounding it. It is named after the corresponding geometric concept. The presence of an annulus gives the ability to circulate fluid in the well, provided that excess drill cuttings have not accumulated in the annulus, preventing fluid movement and possibly sticking the pipe in the borehole. For a new well in the process of being drilled, this would be the void between the drill string and the formation being drilled (Wikipedia, 2022).

wellhead. It is lowered down with a riser and connects to the wellhead. The subsea BOP is much bigger and heavier than the onshore one, so it adds extra load to the riser system. Higher capacity riser tensions must be used, especially in deep water, where the overall load is even greater.

In some cases, a surface BOP is used, which is placed on the deck of the platform/vessel, to reduce the overall load by being installed on the top of the riser system.

In any case, the ability of the BOP to stop a flow in a well control incident and maintain high shut-in pressures are the major concerns for deepwater BOPs. Although nearly all deepwater BOPs in use today are rated to 15,000 psi, only one manufacturer currently produces 20,000 psi units. The industry has identified the need for BOPs rated to 25,000 psi to drill ultra-deepwater high-pressure / high-temperature wells in the future.

Another example of technology seeking to keep up with the industry demands is the questionable reliability of BOP shears, which successfully cut through high-grade steel drill pipe under peak operating conditions. As a result, requirements have recently been added to existing regulations, that specify the configuration of BOPs to ensure adequate capacity, redundancy, and shearing capacity to avoid loss of well control.

4.2.4 Subsea wellhead

The subsea wellhead system (Figure 4-14), like its onshore "cousin" (Figure 4-15), provides pressure and structural interface for the well. It is the main component that hangs off and seals off the casing strings used in the well. It is also the structural part of the well, which holds the subsea BOP on the upper end. The wellhead-BOP system creates a pressure-controlled environment that provides safe access to the well. The subsea wellhead is placed on the seabed and must be installed remotely.

Figure 4-14. Subsea wellhead (OneSubsea - A Schlumberger Company, 2022)

Figure 4-15. Typical onshore wellhead (OMS Oilfield Services Pte Ltd, 2022)

The main functions of the wellhead system are:

- Suspension of the casing strings and the tubing[15] (production/injection)
- Pressure sealing and isolation of the well
- Pressure monitoring and easy access to the annular space between the various casing strings
- Foundation for the BOP and the Christmas tree[16] (production)

Conventional subsea wellheads are used in many deepwater operations. As depth increases, the wellbore pressures need a more complex well design with more casing strings. These deepwater challenges require a new generation of larger wellhead systems.

The subsea wellhead inside diameter is designed with a landing shoulder located in the bottom section of the wellhead body (Petrowiki). The casing hangers[17] are placed on the previously installed hanger. The casing system is held in place by the previous casing hanger. This casing hanger system provides isolation for each casing string and works as a pressure barrier between the strings.

A subsea wellhead system consists of (Figure 4-16):

- Drilling guide bars
- Low-pressure housing
- High-pressure housing
- Casing hangers
- Metal to metal annulus sealing
- Bore protectors and wear bushings
- Running and test tools

[15] Tubing is the normal flow conduit used to transport produced fluids to the surface or fluids to the formation. Its use in wells is normally considered a good operating practice (Petrowiki, 2015).
[16] In petroleum and natural gas extraction, a Christmas tree, or "tree", is an assembly of valves, casing spools, and fittings used to regulate the flow of pipes in an oil well, gas well, water injection well, water disposal well, gas injection well, condensate well and other types of wells (Wikipedia, 2022).
[17] In petroleum production, the casing hanger is that portion of a wellhead assembly which provides support for the casing string when it is lowered into the wellbore. It serves to ensure that the casing is properly located. When the casing string has been run into the wellbore it is hung off, or suspended, by a casing hanger, which rests on a landing shoulder inside the casing spool. Casing hangers must be designed to take the full weight of the casing and provide a seal between the casing hanger and the spool (Wikipedia, 2021).

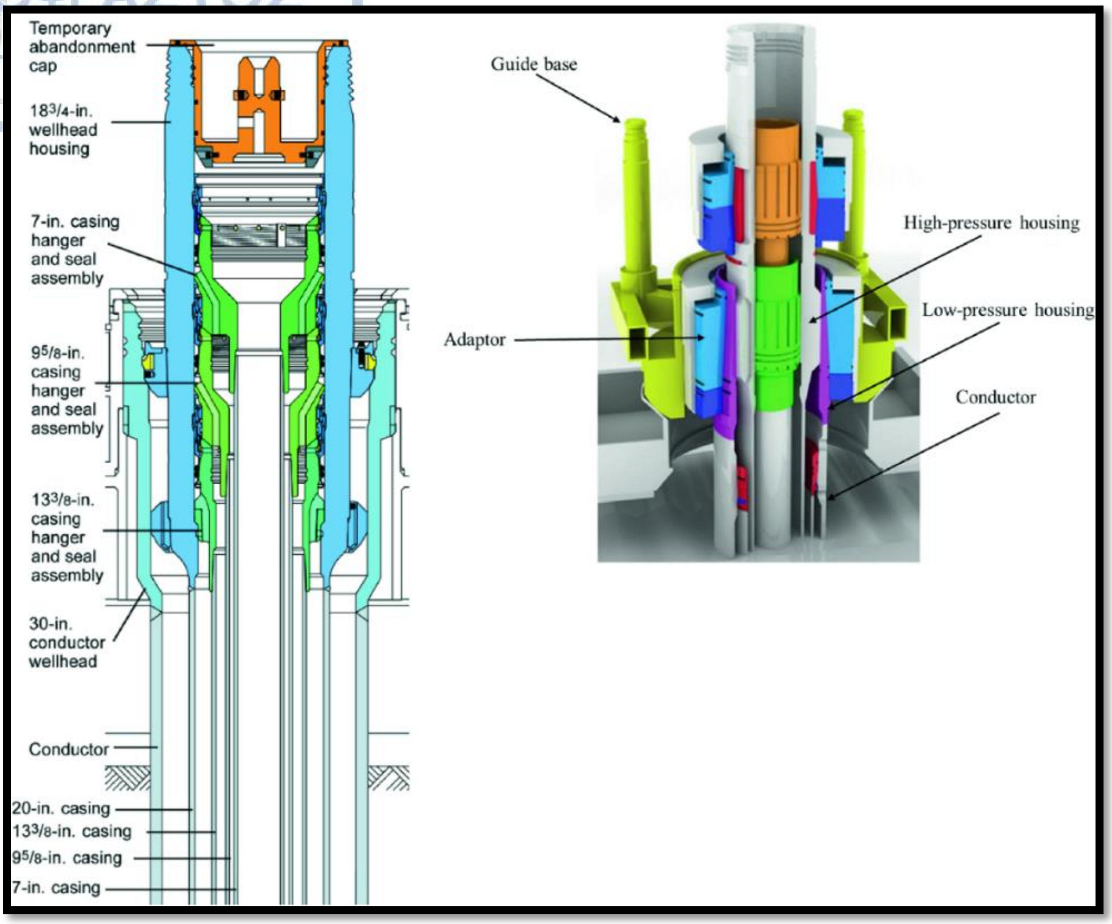

Figure 4-16. Subsea wellhead diagram (Khalifeh & Saasen, 2020)

As the oil and gas industry moves into even deeper waters, the technical requirements for the wellhead have evolved, according to the challenging nature of deepwater operations. Seabed soil in deep and ultra-deep waters is mushy and unconsolidated in most cases, which poses an important problem for the well foundation, and needs to be dealt with by new well designs. Subsea sedimentary basins also host aquifers[18] in a greater frequency than in shallow water and onshore basins. These zones must be sealed off with more casing strings, so a bigger wellhead is needed to host more casing strings. The unconsolidated and mushy seabed can be overcome with the reconfiguration of the conductor and the intermediate[19] casing.

[18]An aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) (Wikipedia, 2022).
[19] Intermediate casing is the casing which is generally set in place before production casing and after surface casing to provide protection against the abnormally pressured or weak formations. The casing enables the use of drilling fluids with different density, which is crucial for controlling the lower

This reconfiguration on the design needs a bigger wellhead. Such an example is the 18 ¾ Big Bore Subsea Wellhead System, shown in Figure 4-17.

Figure 4-17. 18 ¾ Big Bore Subsea Wellhead System (Petrowiki, 2015)

4.2.5 Drilling the well

Wells are drilled deepwater to obtain geological information (exploration wells) and/or developing a new field (development wells) and/or producing hydrocarbons (production wells) or aiding production in mature fields (infill wells). Regardless of the type of the well to be drilled deepwater, it will have a planned total depth and a planned minimum bottom hole diameter. These are the two features that mostly influence the well design, specifically in deepwater environments. There are several key factors to be taken into consideration when planning and drilling a well, especially

formations. It is generally set in the transition zone between the normal pressure zones and the abnormal pressure zones. It is often considered as the longest section of the casing present in a well. Most of the wells are drilled with running an intermediate casing (Petrowiki, 2021).

in deepwater. The interaction among them needs also to be considered since it is significant for the design, complexity, cost and risk of the well.

These key factors to be examined in this work are pore pressure/fracture gradient window, shallow and deep geological hazards, drilling through salt, HTHP conditions, the number of casing/liner strings, cementing problems, well control issues, rig and equipment issues, BOP issues and limitations, drilling fluid considerations. Finally, issues related to ROVs' use in deepwater environments are also examined (Kelessidis, 2009).

4.2.5.1 Pore pressure/Fracture gradient window

One of the most well-known deepwater challenges is the narrow 'window' between pore pressure and fracture gradient. This 'window,' through which a deepwater well can be safely drilled, is often smaller than in a well drilled onshore or in shallow water to the same depth. Difficulties increase when a deep well needs to be drilled deepwater.

Fracture gradient is determined mostly by the weight of the overburden, which influences the stress regime at any given depth. Since a saltwater column is lighter than a rock column of equivalent height, formations to be drilled deepwater present a lower cracking threshold. On the other side, pore pressure is determined by the height of the overburden (height of the column of fluid contained in the formation pores). That means that the deeper the seawater the 'window' between pore and fracture gradients becomes narrower (Figure 4-18).

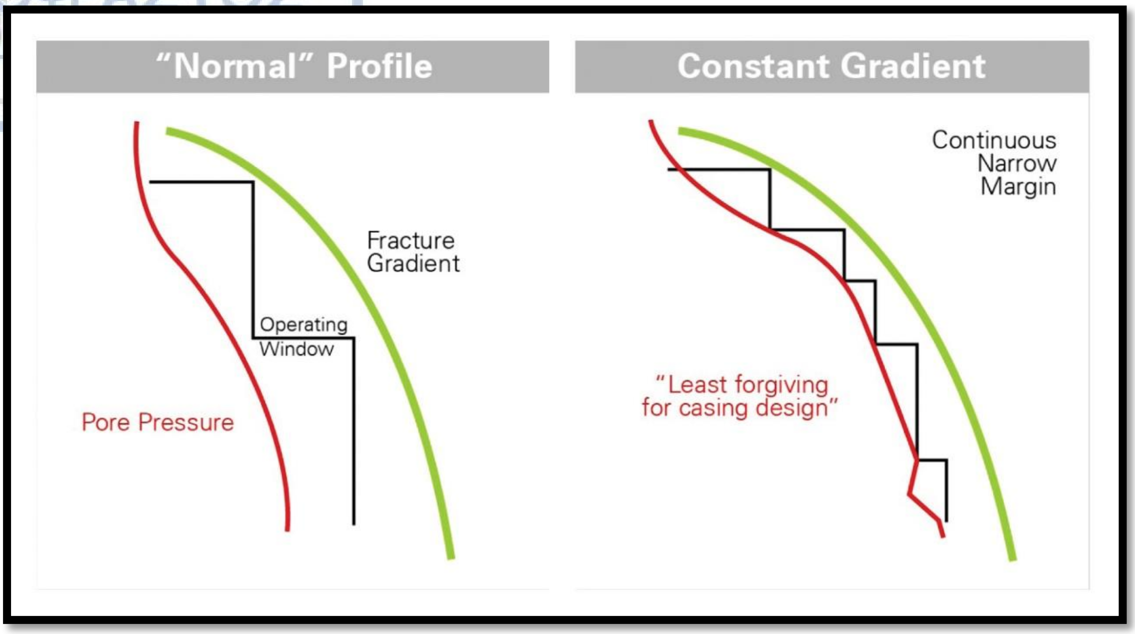

Figure 4-18. The narrow margin between the pore pressure and fracture gradient in deepwater wells requires multiple casing strings to be set (Shaughnessy, 2013)

The narrow drilling 'window' for deepwater wells affects drilling in two ways:

i. Control of mud weight and downhole pressure becomes intriguing (drilling fluids composition, well control issues).
ii. An increased number of casing and liner strings must be installed to maintain mud weight within the drilling window.

4.2.5.2 Shallow well sections

Right below the ocean floor, the rock is relatively young, unconsolidated, and may contain a lot of water due to its low compaction. Drilling through this shallow layer with drilling mud weight much higher than the normal seawater gradient may cause formation rupture and fluid leakage. For this reason, when drilling through the shallower well sections seawater is usually used as the drilling fluid. At this time subsea well control equipment is usually not yet installed, mainly due to the lack of foundation (surface casing hasn't been installed yet).

Therefore, if the well encounters a pressurized shallow formation containing water or gas, its pore pressure will exceed the hydrostatic pressure of the seawater drilling fluid, and shallow water or gas blowout may occur. To avoid this situation, the usual preventive measures include mapping of shallow hazards to identify risk areas, and emergency procedures for pumping mud from the drilling platform in the event of an accidental outflow of the wellbore. Shallow hazards may be slumps, faults extending up to seabed, manmade objects, soft clay, mudslides shallow gas, gas hydrates, mud volcanoes, shallow abnormal pressure zones.

4.2.5.3 Deep well sections

As drilling proceeds deeper, the window between pore pressure and fracture gradient becomes narrower. This problem worsens as the wellbore diameter gets smaller and smaller. The drilling mud, which must be circulated via the increasingly restrained annulus between the drill string and the wellbore, provides extra pumped pressures, over and above static hydrostatic pressures. To maintain well stability, under these conditions, surging and swabbing phenomena must be properly managed through careful wellbore design, mud synthesis and monitoring.

Sometimes situations imply that the well cannot be drilled safely to a programmed depth. It isn't generally known, for example, that the drilling of the Macondo well has was stopped early because of the very narrow window between pore pressure and fracture gradient which impeded drilling ahead. The blowout took place during the works carried out so that the well could be temporarily abandoned until future completion operations to be properly planned.

Besides that, other deep geological hazards that may be encountered are abnormal pressure zones, salt layers, and domes, high pressures-high temperatures, and faults. These hazards must be examined thoroughly during the geophysical study to be dealt with properly during drilling.

4.2.5.4 Well control

Well control is a critical issue in deepwater drilling and should be considered in well planning, design and construction. The main well control issue is kicks. In the worst case, an uncontrolled kick may develop into a blowout. A good example is the Macondo incident on April 20, 2010, at the Gulf of Mexico, in which there were explosions aboard the Deepwater Horizon (Figure 4-19).

Figure 4-19. Deepwater Horizon Fire - April 22, 2010. Photo courtesy of the US Coast Guard (Flickr, 2010)

The problems aroused when trying to restore control at Macondo well have highlighted the difficulties associated with stopping an uncontrolled discharge from a deepwater well. Access to the wellhead laid on the ocean floor at a depth 4,992 ft (well beyond whatever the depth allowable to divers, which is typically less than 1,500 ft), led the Incident Response Command to report that the corrective actions were "*... closer to Apollo 13 than Exxon Valdez*" (US Coast Guard - National Incident Commander, 2010). The problems encountered worsen when more difficulties immerse, such as the limited supply of specialized rigs and equipment suitable for great depths, and the formation of gas hydrates in the low temperature / high-pressure environment.

A kick is an unintended inflow of formation fluids (gas and oil) into a wellbore during the drilling operation. A kick occurs when well pressure due to hydrostatic mud column and associated friction pressure is lower than pore pressure. The higher formation pressure tends to force formation fluids into the wellbore. Regarding kick detection, the first sign of pore fluid entering the wellbore can be masked by the compressibility of the mud column (both by its own weight and by circulating pressure while the mud pumps are running). Turning off the pumps relieves some of the compression and causes the mud to flow back at the rig. The additional frictional force applied during pumping can also lead to a temporary overbalanced situation, in which the effective weight of the drilling mud exceeds the pore pressure so that mud is lost into the porous formations. When the pumps are turned off, the lost mud is returned to the wellbore and a phenomenon known as the "ballooning effect" appears. This can result in backflows of mud up to 50 barrels being recorded at the surface. If loss of compression or ballooning is misinterpreted as a kick, time can be wasted circulating out a non-existent kick. Once a kick has been successfully identified and the well control equipment closes to stop the surface flow, the additional pressure required to circulate out the influx may break down the formation. This will complicate the well control operation and great care must be taken in planning and conducting such an exercise.

4.2.5.5 Drilling Fluids

The main functions of the drilling fluids include (Σταματάκη, 2003):

- Removal of cuttings[20] from the well
- Suspension and release of the cuttings
- Control of the formation pressures
- Sealing of permeable formations

[20] Cuttings are small pieces of rock that break away due to the action of the bit teeth (Schlumberger Oilfield Glossary, 2021).

- Maintain wellbore stability
- Minimize formation damage
- Cool and lubricate the bit
- Transmission of hydraulic energy to the downhole tools and bit
- Formation evaluation through the examination of the cuttings
- Control corrosion
- Minimize impact on the environment

The drilling mud circulation starts on the surface, where the mud is pumped into the drill string and moves through it down to its bottom end, where it comes out through jet nozzles installed on the drill bit[21]. After cleaning the bottom hole from cuttings, drilling mud returns to the surface through the annulus (borehole-drill string, casing-drill string, riser-drill string), carrying away rock cuttings.

Drilling fluid or drilling mud is one of the most important elements in every drilling operation (onshore or offshore). There are four main types of drilling fluids:

- Water-based mud
- Oil-based mud
- Gaseous-based mud
- Polymer-based mud

The selection of the most appropriate type of drilling fluid for each well section is based on one or more of the following criteria:

- Cost
- Application and performance
- Production concerns
- Logistics
- Exploration concerns
- Environmental impacts and safety

[21]Drill bits are cutting tools used to remove the in-situ rock to deepen the borehole, that is almost always of circular cross-section. Drill bits come in many sizes and shapes and types, that make them suitable for many different types of formations. In order to create boreholes drill bits are usually attached to the bottom end of the drill string, which drives them to cut through the rock, typically by rotation (Wikipedia, 2022).

In deepwater drilling operations, the drilling fluids must travel, not only through the drilled formation but also through the water column (inside the riser system), which in many cases is hundreds of meters or some kilometers in length. This extra height enhances the gap between the condition extremes that the fluids will encounter, such as the hydrostatic pressure and temperature. For example, the fluids will encounter temperatures varying from 0°C to 150°C. These extreme variations affect the properties of the fluids (rheology, etc.) and their ability to perform their main functions.

To overcome this problem, a solution followed by the industry, when drilling deepwater wells is to drill the first meters of the well using seawater as the drilling fluid. As seawater is much lighter than a typical drilling mud, it is more appropriate to drill the weaker shallow formations. In deeper formations, mainly synthetic mud is used, because of its better and more suitable physical and chemical properties.

Another solution is provided by a new drilling technique that has been introduced by the industry, the Dual Gradient Drilling (DGD). In Dual Gradient Drilling, the riser system is filled with a drilling fluid with the same properties as normal seawater (specific weight). This way, the fluid inside the riser resembles the water column, and the whole drilling process looks like an onshore drilling operation since DGD practically diminishes to zero the water column. This method is presented in Figure 4-20.

The main advantages of this method are:

- Extension of casing depths (ability to operate in deeper waters)
- No need for extra casing strings and liners[22]
- Larger wellbore size

[22]A casing string that does not extend to the top of the wellbore, but instead is anchored or suspended from inside the bottom of the previous casing string (Schlumberger Oilfield Glossary, 2022)

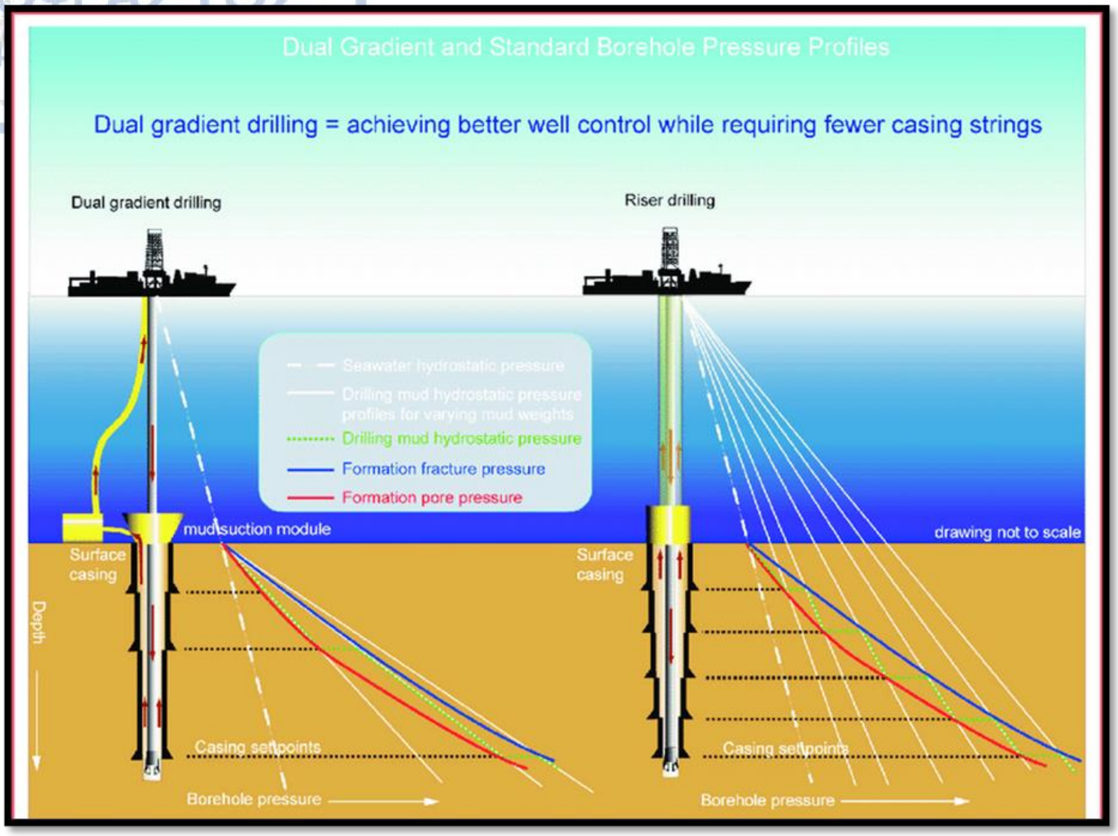

Figure 4-20. Dual Gradient Drilling (Myers, 2008)

4.2.5.6 Casing

Geological complexity increases in deep water wells. This, in combination with the narrow drilling window between pore pressure and fracture gradient, requires an increased number of casing or liner strings (“tubulars”) to allow for changes in mud weight. In deepwater wells, it is common to use up to ten tubular strings, including contingencies, compared to the five typically used in more conventional wells (Figure 4-21).

Due to technological advancements, an increased range of specialized casing and liner sizes was made available to meet the requirements of deepwater wells. Specialised strings can be run in the well and then expanded in-situ, to case the open hole sections of the well without reducing its diameter. As the number of strings increases, tolerances in the well become tighter and additional attention to quality assurance is required. To forestall wear and to assure a long service life, more than 20 years in many cases, high-quality tubulars are often used for critical sections of the well.

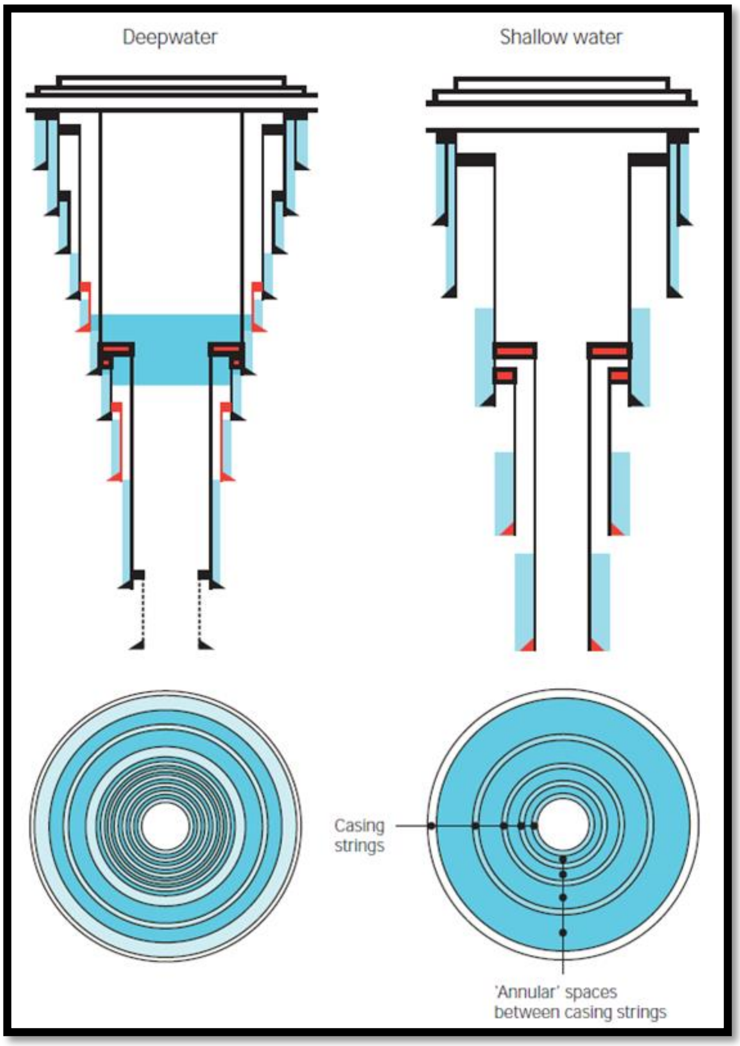

Figure 4-21. Comparison between wellbore designs in deepwater and shallow water (Lloyd's, 2011)

Nonetheless, even with the highest grade of tubulars pipe in the well, some of the standard well design criteria cannot be met. For example, a typical load case used for standard casing design is the ability to force an influx back into the formation by pumping water under pressure to the last installed casing depth, during a well control operation. A deepwater well design will generally fail this test, and the industry has made adjustments to deepwater load cases so that casing burst ratings are not exceeded.

4.2.5.7 Cementing

Most of the risks related to the cementing operations in a deepwater well are associated with the cementing of the conductor pipe and the surface casing. Understanding the relevant technical challenges is the key to design cement slurries that meet deepwater specifications and provide the required zonal isolation. These challenges are:

- Low temperatures: The depth of the seawater directly affects the temperature of the seabed (deeper water - lower temperature). In the low temperatures of the deepwater environment, more time is needed for the cement to set and achieve the required compressive strength. As a result, the WOC[23] time is longer.

- Low Fracture Gradient: In many deepwater areas, there are unconsolidated formations below the seafloor. To avoid the risk of causing losses due to the narrow space between the pore pressure and the fracture gradient, a low-density cement system is required to ensure cement coverage over the zones of interest.

- Shallow Flow Hazards: In deepwater areas, there is a high potential for shallow gas flows and gas hydrates. If the drilling operation fails to control these problems, they may instigate serious consequences, such as well control hazards, excessive wellbore washouts, and destabilization of formations near the wellbore.

New cementing slurries and cementing additives have been developed for deepwater operations worldwide, which provide rapid cement hardening, control of potential gas flows, and long-term zonal isolation. To overcome shallow gas migration problems, a cement system with a WOC time shorter than the one for the traditional Portland cement systems is needed. This kind of cement slurries exhibits specific

[23] WOC: Wait-On-Cement. To suspend drilling operations while allowing cement slurries to solidify, harden and develop compressive strength. The WOC time ranges from a few hours to several days, depending on the difficulty and criticality of the cement job in question. WOC time allows cement to develop strength, and avert development of small cracks and other fluid pathways in the cement that might impair zonal isolation (Schlumberger Oilfield Glossary, 2021).

particle size distribution to ensure, apart from shorter WOC time, low fluid loss and low permeability, as well.

Cementing additives manifest the necessary slurry and set cement properties for deepwater. They control the rheological properties of the cement slurry, providing low viscosities and rapid gel strength development to control shallow flow even at the low temperatures found in deepwater environments.

4.2.6 Other technical challenges

4.2.6.1 High Pressure/High Temperature (HPHT)

The well depths increase, downhole pressures and temperatures increase as well. Industry definitions of HPHT conditions vary, but wells with downhole temperatures greater than 350°C and pressures greater than 24,500 psi generally fall into this category. Until the mid-1990s, the tools used at the bottom of the drill string were generally considered as "dumb iron" - basic steel drilling tools not likely to be affected by high pressures and temperatures. Nowadays, many of the current measurements-while-drilling (MWD) tools or logging-while-drilling (LWD) tools are rated for a maximum downhole pressure of 25,000 psi and their reliability decreases as temperature rises above 300° C. With expected downhole pressures above 35,000 psi and temperatures over 450° C in deepwater wells planned in the future, this is another example of technology struggling to keep up with the demands of the industry.

4.2.6.2 Salt drilling

Many of the target formations in deepwater wells lie beneath massive, thick salt deposits. These salts have properties that distinguish them from other sedimentary rocks, so careful planning is required to avoid drilling problems. Salt formations are very difficult to predict because the physical structure of the salt prevents seismic resolution. The lack of available seismic data also complicates the mapping of the underlying, pre-salt geologic formations. Identifying the salt base and determining the underlying pore pressures are two of the biggest problems here.

Another important property of salt is its low density. Since it is lighter than the overlying formations, it can move within these formations. Salt domes form when massive salt lobes migrate to the surface due to gravitational forces and work their way through younger, denser formations. It is easy to understand why changes in the stress regime in the formations immediately above and below a salt dome can create uncertainty when drilling. Salt mobility can also cause creep, causing mobile salt to enter the drilled well. Creep can lead to short-term problems such as pipe sticking, which can usually be mitigated by increasing the weight of the mud. Longer-term problems may be casing failure, which can cause well control problems. This problem can be prevented by using thick-walled casing in well design.

4.2.6.3 ROVs (Remotely Operated Vehicles)

ROVs are underwater robotic vehicles, that allow underwater operations and tasks to be performed without the physical presence of a human. The controller is located on a vessel (Figure 4-22). The ROV connects to the vessel via an umbilical cable. That link houses the electric cable, that supplies the necessary power to the ROV to function, but also a data cable, that transmits information from the operator to the ROV and vice versa.

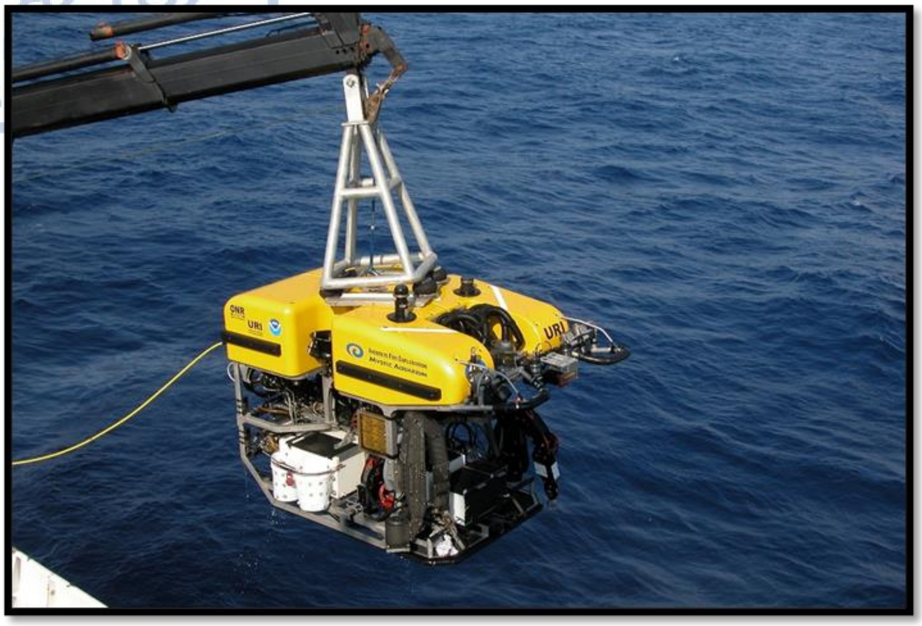

Figure 4-22. ROV for deepwater operations (Wikipedia, 2022)

All types of ROVs contain a camera (or cameras) that feed vital information to the controller for the navigation of the vehicle. This array of visual devices provides critical data and information to the rig personnel about the seabed, the well, the drilling equipment, and the tools that lie on the seafloor.

ROVs also contain many types of sensors, depth sensors, temperature sensors, current sensors, and orientation sensors. These sensors provide data about the position and surroundings of the vehicle. Acquisition of this information, along with the camera feed, enables the operator to safely navigate the vehicle on the sea bed. The motion and the navigation of the ROV are performed by an array of thrusters that enable movement in all directions.

The main functions of an ROV in a deepwater drilling operation include:

- Drilling observation support
- Seabed tools and equipment monitoring and inspection
- Shallow gas, water flow, hydrate[24] monitoring

[24] Gas hydrates may represent a significant natural hazard. Dissociation ("melting") of hydrate generates large volumes of gas that may weaken the seafloor, causing submarine landslides and tsunamis (GNS Science, 2021).

- Operating tasks (retrieving, cutting, cleaning, clearing, washing)

There are four main types of ROVs, according to their size and functional capabilities:

- Small electric vehicles
- High capability electric ROVs
- Work class vehicles
- Heavy work class vehicles

High capability electric ROVs are similar to small electric vehicles with the ability to dive even deeper (up to 6000m). They only bear cameras and lack the means to perform heavy tasks and duties, required in deepwater drilling operations.

Work class vehicles are able of serious underwater work (Figure 4-23). Although their lifting ability is limited, they have mechanical/robotic parts (arms, manipulators, grabbers) that allow them to perform various underwater works. They are extensively used in drilling operations either in construction support or for inspection purposes.

Figure 4-23. Work class vehicle with mechanical arms (gspoffshore.com, 2021)

Heavy work class vehicles are similar to working-class ROVs, but with a much larger lifting ability.

As the oil and gas industry moves even deeper, ROVs will be an even more important means in deepwater activities. Some ROVs are built specifically for oil and gas operations, equipped with tools designed only for manipulating and handling drilling equipment.

4.2.7 Major Challenges in Deepwater Drilling of Ultra-Deep Wells

Deepwater drilling has many challenges for engineers and technicians, with some of them listed in the schematic below (Figure 4-24). However, drilling below the seabed can be significantly slow down, because of the very hard rock formations encountered, as the wells go deeper into the Earth. There are reports on wells that reach depths greater than 15000 ft mentioning that 50% of all the operational cost (OPEX) is spent in the last 10% section of the well because of the very low rates of penetration achieved in such depths, of around 2-3 feet per hour.

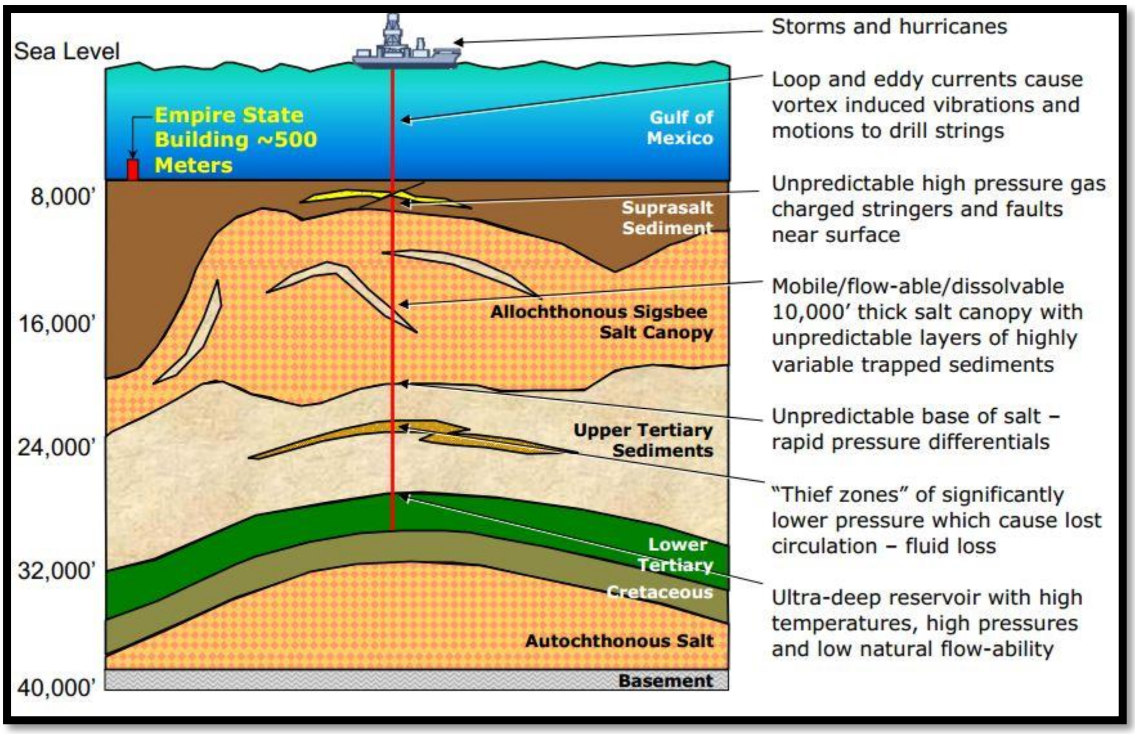

Figure 4-24. Challenges of Deepwater Drilling (Close, McCavitt, & Smith, 2008)

When drilling in mature deepwater fields, narrow pressure windows are increasingly common, posing a formidable challenge. This condition is characterized by a small difference between the pore pressure - the fluid pressure inside rock pores pushing out - and the fracture gradient - the fluid pressure needed outside the rock to fracture it. When using conventional drilling techniques, a small change in wellbore pressure can represent the difference between profitable success or costly failure. Common risks include borehole instability, pressure cycles that require breakouts, downhole mud losses, surge and swab effects, and even kicks. Fortunately, narrow pressure windows can be addressed using managed pressure drilling (MPD), a technique to precisely control the annular pressure throughout the wellbore. MPD is a tool to manage equivalent circulating density. It has revolutionized drilling in the major deepwater and ultra-deepwater areas, such as Brazil, West Africa, the North Sea, and the Gulf of Mexico, where it has been used for more than 10 years. Coupled with early kick detection, the technique helps operators avoid issues caused by narrow pressure windows (Offshore Magazing - Wood Group, 2017).

Ultra-deep drilling in the Gulf of Mexico confronts salt layers that usually extend beyond the lower tertiary sediments, which are 30 to 60 million years old. It is very difficult for seismic surveys to see through these salt layers and extremely difficult to drill through them. Because of the existence of salt, the bedrock underneath is not compressed, it is flimsy, making the drilling process extremely difficult and this is a reason why these wells are much more expensive. Huge volumes of oil and gas may lie below salt rock formations as they have been proved.

Ultra-deep wells also face High Pressures and High Temperatures (HPHT wells) which pose risks in terms of materials used in the well. New improved, denser and thicker materials are needed, leaving less space for electronics installed on Logging While Drilling tools. This results in the need for more sophisticated equipment to extend the current, already extreme capabilities and costs. The high pressure at the seabed in ultra-deep waters requires specifically made unmanned submarines for setting up the platform and/or subsea equipment, as the pressure at roughly 3000 m of water can be as high as 310 bar (~4500 psi). At these water depths, temperatures can be as low as 40 F (~4,4°C), which may provoke drilling fluids to gel, risking the formation of gas hydrates.

In most cases of deep waters, bedrocks and sedimentary formations are young and present significant differences from the shelf and onshore depositional formations. Adverse temperature gradients, negative from the surface to the seabed and positive from the seabed to the bottom hole, present unique challenges for drilling fluid properties and well hydraulics. Drilling operations in very deep water, where temperatures are extremely low, involve the use of synthetic-based drilling fluids because of their lower tendency for gelling at low temperatures. Nevertheless, due to low fracture gradients, serious fluid losses may occur thus significantly raising the costs. Low temperatures modify the properties of casing cement, demanding new composition of cement slurries. Furthermore, as more casing strings need to be installed in deepwater wells in comparison with conventional wells, further challenges are introduced, like, ultra-good hole cleanup for effective cementing of narrow annuli, and the use of optimal cementing techniques.

Field exploration in ultra-deep waters requires quite large constructions which are more vulnerable to catastrophes, by hurricanes or rough seas. Deep waters call for enormous structures to support drilling and production platforms. A new type of platform designed for deep waters is the spar model, a huge single cylinder extending 200 m under sea level, with a solid weight at its base to hold the structure from leaning. This type of floating platform holds into place by mooring lines. One example of the spar design is Perdido, which is the deepest drilling and production facility in the world, placed in 2382 m of water, operated by Shell in the Gulf of Mexico (Figure 4-25).

The deepest wells ever drilled had a scientific purpose aiming primarily in retrieving intact cores from the depths of the earth's crust and in measuring several rock properties. Of course, one can ask whether there was any oil or traces of oil found while drilling these wells. There have been publications about laboratory analysis of hydrocarbon gases measured while drilling at the ultra-deep scientific well, in the Kola Peninsula in the former Soviet Union which reached a depth of more than 12000 m.

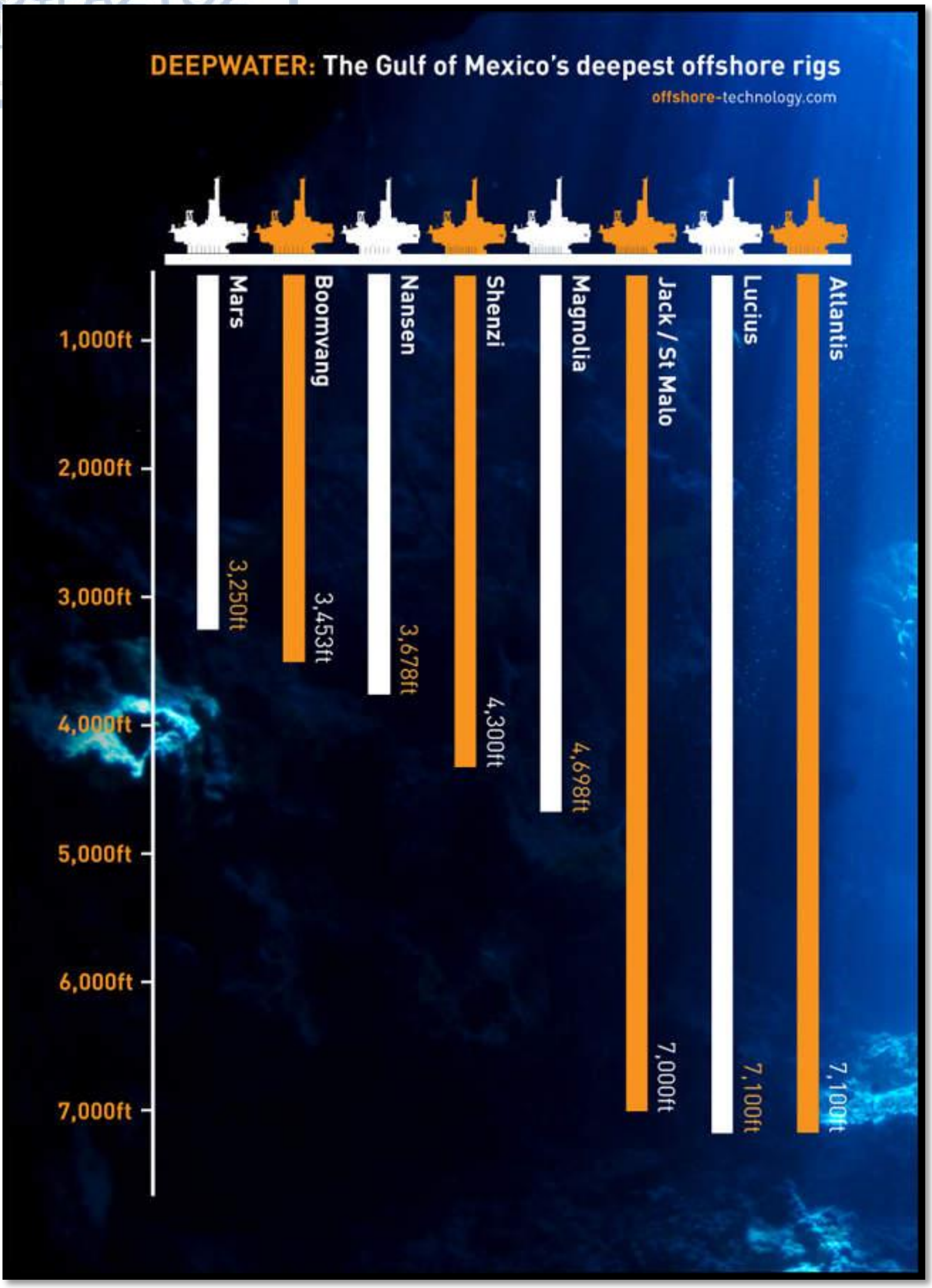

Figure 4-25. Deepest wells in the Gulf of Mexico (West, 2012)

CHAPTER 5

CONCLUSIONS

Having discussed most of the aspects regarding deep and ultra-deep-water drilling, the following conclusions can be drawn. These conclusions will focus on the limits of drilling technology, and if technical challenges in deep water drilling can be dealt with.

Human nature has taught us that there are no limits in human mind and creativity. As long as, there are creative and skilled minds, solutions will be given for any problem. But these solutions are quite expensive in most cases. That's why the cost poses the one and most difficult barrier in human creativity. Such an example is space exploration. During the 60's, U.S. governments had given NASA unlimited resources, both human and economic. The result was that in a period of less than 10 years, the first human stepped on the moon. In the early 70's, Nixon administration greatly reduced the budget for NASA. This decision was taken because of the great cost of the ongoing Vietnam war, but also because of internal problems. The outcome of this decision was that space exploration came to a halt, and NASA was forced to focus on more economically viable and cheaper missions. It is speculated by many, that if NASA had kept on its exponential technological progress, that was followed during the 60's, by the mid 80's the first human could have landed on Mars.

The same concept applies in drilling technology. As long as there is an ever-growing need for fossil fuels, there will be funding on deep sea projects. Companies will keep on investing on deep sea activities, and by investing in such projects, they also invest in research and development, regarding deep sea and ultra-deep sea drilling.

Considering the evolution in water depth capabilities from the 1950's until recently, it is easily speculated that if the same rate will continue to exist, in 10 years from now, we will be able to drill in much deeper seas, than we do now. This will depend on the funding of such projects.

Technology is the outcome of human creativity. In order for creativity to become existing technology, there is only one obstacle, funding. Especially in our case, the costs are quite high. If the oil companies decide to drill in deeper seas, they will do it.

Apart from costs, in modern societies, there is sensitivity, regarding environmental issues. So, environmental risks could also be another factor that places limits for deep sea projects. In order to drill in deeper seas, a balanced formula must be found, that takes into consideration both the costs, as well as the environmental issues. If this formula is found, then the barriers are taken down.

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