

1 Oil and gas from the sea



> Offshore gas and oil production began more than a century ago. With many shallow-water fields already exhausted, these natural resources are now being extracted at ever greater depths. Production rates are higher than ever, while oil pollution is decreasing. However, this is largely due to the stringent regulations applicable to shipping: the explosion at the *Deepwater Horizon* oil rig clearly demonstrated that safety is a long-neglected issue in the oil industry.



Sating our energy hunger

> Around a third of the oil and gas extracted worldwide comes from offshore sources. This figure is likely to continue to rise over the coming decades, for abundant oil and gas deposits still exist deep in the oceans. But with many oil and gas fields in shallow waters now more or less exhausted, companies have to penetrate greater depths to access these energy carriers.

Over 100 years of offshore resource extraction

There is a long tradition of offshore natural gas and oil production. The United States' first coastal oil rigs were constructed in the late 19th century. One of the pioneers of offshore oil production was industrialist Henry L. Williams, who began extracting oil from the Summerland field off the Californian coast near Santa Barbara in the 1890s. His first oil rigs were built on dry land, but in 1896, he finally ventured offshore, constructing a 100-metre pier from which he began drilling on the sea floor. Before long, others followed suit, and within five years, there were a further 14 piers and more than 400 wells in the area.

For these oil industry pioneers, building oil rigs far out at sea was simply inconceivable. Their rigs stood in a few metres of water, with piers connecting them to the mainland. It is a different story today. Offshore oil and gas production has become routine. There are currently around 900 large-scale oil and gas platforms around the world. Over time, engineers have penetrated ever greater depths, for with oil prices rising, deepwater

oil and gas production, although costly, is now a lucrative business.

With drilling and extraction technology also becoming increasingly sophisticated, it is now possible to extract oil and gas at ever greater depths. The water depth record for oil production is currently held by an international oil company which produces oil from a well, located in the Tobago field, 2934 metres below the surface of the Gulf of Mexico.

The water depth record for subsea gas production is currently around 2700 m and is held by a platform located in the Cheyenne gas field, also in the Gulf of Mexico.

Rising energy demand – for cars, heating and electricity

Humankind's energy hunger seems insatiable. In 2011, annual world primary energy consumption was estimated at 12,274 million tonnes of oil equivalent (MTOE) – 40 times Germany's annual energy consumption. "Tonne of oil equivalent" (TOE) is a metric used to measure and compare consumption of different energy resources. One tonne of oil equivalent (TOE) corresponds to the energy content of one tonne of crude oil.

Energy consumption in Europe has decreased in recent years due to the use of modern machinery and efficient electric engines, energy-saving measures and better insulation of buildings. Globally, however, energy consumption is increasing. Total consumption of energy has doubled since the early 1970s and, according to the International Energy Agency (IEA), is likely to grow by more than one-third to 2035.

The world's growing energy hunger is driven to a large extent by population growth in Asia and ongoing industrialisation in the emerging economies. China,

1.1 > By the late 19th century, oil industry pioneers were venturing offshore. At first, piers connected the oil rigs to the mainland.

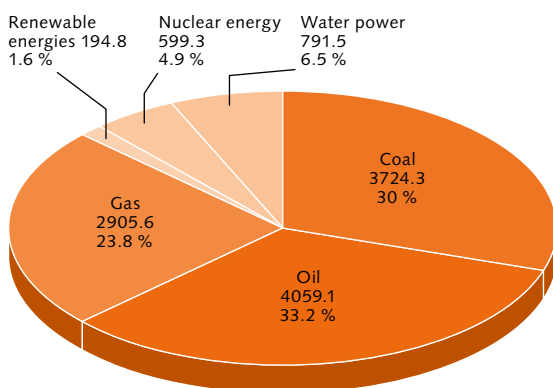


India and West Asian nations account for around 60 per cent of the world's growth in energy demand.

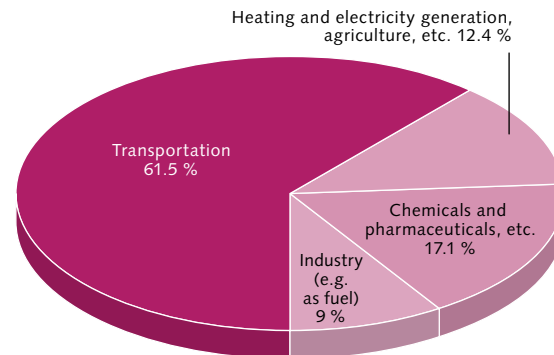
Today, energy production still largely relies on the burning of fossil fuels: natural gas, oil and coal. The early oil industry pioneers probably never imagined, even in their wildest dreams, just how much of their commodity humankind would ultimately burn or utilise for industrial purposes. Our modern world is almost entirely dependent on fossil inputs. We need them for heating and electricity generation, and of course to fuel our cars, railways, aircraft and shipping. Today, there are more than one billion vehicles – cars, buses and trucks – on the world's roads, burning vast quantities of petrol and diesel.

Oiling the wheels of the modern world

Oil is currently the most important fossil energy source, followed by coal and natural gas. Oil accounted for around 33 per cent of world primary energy consumption in 2011, followed by coal and natural gas with around 30 and 24 per cent respectively. The remainder comes from nuclear energy, hydropower and other renewables such as solar and wind energy. In 2011, global oil production reached around four billion tonnes, of which a full 61.5 per cent was consumed in the transportation sector. But oil is not only a fuel; it is also an



1.2 > Oil and coal are the world's most important fossil fuels. The figure shows global primary energy consumption in 2011, together with the percentage share for each energy source. For oil, primary energy consumption is shown in millions of tonnes. For the other energy sources, it is shown in MTOE.



1.3 > The transportation sector consumes more oil than any other sector. Oil is also an important industrial input, e.g. in the chemical sector.

important input in the pharmaceutical and chemical industries, e.g. in plastics production. Car paints and sprays, food storage containers and television sets are just a few examples of consumer items containing substances derived from oil.

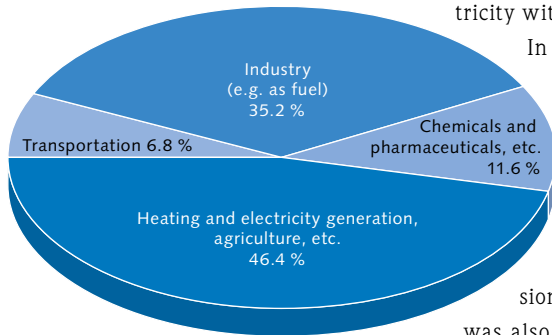
Currently, the United States of America (US) is the world's largest oil consumer, followed by China, whose economy has been growing strongly for many years. Highly industrialised Japan ranks third, with India, an emerging economy, in fourth place. Russia ranks fifth, but its oil consumption remains less than one-sixth the level of the US. In 2011, global oil consumption rose by 2.7 per cent compared with the previous year. The strongest rise in consumption – 6.1 per cent – was observed in the Australasia region. This contrasts with the trend observed in Europe, where consumption fell by 1.2 per cent.

Power and heat from gas

In 2011, global production of natural gas totalled 3337 billion cubic metres – 35 times higher than Germany's annual consumption of natural gas. Average annual gas consumption for a German household is around 3500 cubic metres. Natural gas is used primarily for heating and electricity production, but it is also a raw material in the chemical industry, e.g. in hydrogen production, ammonia synthesis and the manufacture of nitrogen-based fertilisers. In Germany, Denmark, other European countries and China, natural gas is increasingly replacing coal in power generation as it burns cleaner than coal. Here, gas is used in modern combined-cycle (gas and steam) power plants which not only generate elec-

Primary energy
The term "primary energy" refers to the energy forms required by a power station, boiler or engine to generate electricity or heat or to create motion. The term "final energy" is also used: this refers to the energy consumed by end users, such as households, for electricity and heating.

tricity but also recover waste heat, making them extremely energy-efficient. Many traditional coal-fired power plants, on the other hand, merely generate electricity with no waste heat recovery.



1.4 > Natural gas is mainly used for electricity generation and heating.

In Europe, demand for gas decreased by 8 per cent between 2010 and 2011, due to the weak economy, relatively high prices and warm weather.

The continuous expansion of renewable energies was also a factor. However, global

natural gas consumption increased by 2 per cent over the same period due to strong demand in Asia and the emerging economies. In China, for example, natural gas consumption increased by 20 per cent, while Japan's gas imports soared by 19 per cent after the 2011 Fuku-

shima Daiichi nuclear disaster. As an island nation, Japan relies heavily on liquefied natural gas (LNG) imports which are brought in by sea. As this is more expensive than transporting gas by pipeline, gas prices in Japan are relatively high.

The US was the world's largest consumer of natural gas in 2011, followed by the Russian Federation and Iran. Iran's high consumption is due firstly to the strong demand for gas to heat buildings during the country's cold winters and secondly to the use of gas injection to improve oil recovery in situations of declining pressure in oil wells. China is the world's fourth-largest consumer of natural gas, with Japan in fifth place.

How long will stocks last?

How long will stocks of fossil fuels last? There has been much debate about this question in recent decades.

1.5 > The world's 10 largest oil consumers: the United States is by far the largest user of oil.

Petroleum consumption, 2011		
Ranking – country/region	Billion tonnes	Percentage
1 United States	814.6	20.1
2 China	457.9	11.3
3 Japan	221.7	5.5
4 India	162.3	4.0
5 Russian Federation	136.0	3.4
6 Saudi Arabia	121.1	3.0
7 Brazil	120.7	3.0
8 Germany	111.9	2.8
9 Republic of Korea	110.8	2.7
10 Mexico	105.9	2.6
Rest of the world	1682	41.6
Total	4044.9	100

1.6 > The US is also the world's largest consumer of natural gas. As with oil, the 10 largest users account for a good 60 per cent of global consumption.

Gas consumption, 2011		
Ranking – country/region	Billion cubic metres	Percentage
1 United States	690.1	20.8
2 Russian Federation	474.3	14.3
3 Iran	153.3	4.6
4 China	130.7	3.9
5 Japan	112.5	3.4
6 Canada	104.8	3.2
7 Saudi Arabia	92.2	2.8
8 Germany	84.4	2.5
9 United Kingdom	80.2	2.4
10 Italy	77.9	2.3
Rest of the world	1316.9	39.7
Total	3317.3	100

Reserves or resources?

In the debate about finite fossil fuels, the terms “reserves” and “resources”, but also “range” and “static range” are often used interchangeably, although to some extent, they mean different things.

Reserves: To be classed as a reserve, an oil or gas deposit must fulfil three conditions: it must have been confirmed by drilling; it must have been accurately measured; and it must be recoverable economically at current prices using current technology.

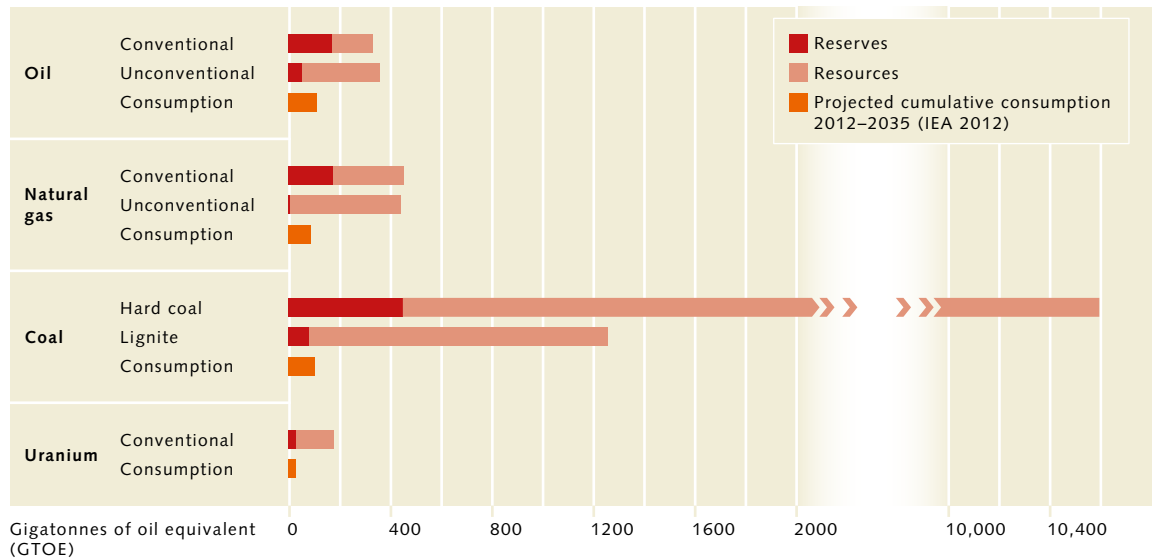
Resources: Resources are the geologically proven stocks of an energy carrier which are not yet regarded as recoverable economically because recovery requires new and expensive technology. The term “resources” also applies to stocks which are not yet proven but can be assumed to exist in a region based on its geological characteristics. The distinction between reserves and resources is sometimes fluid. The oil sand industry in Canada is the latest example of a transition from resources to reserves. Only a few years ago, these deposits were not recoverable economically. Today, thanks to its oil sands, Canada appears near the top of the list of countries with the largest oil reserves. These deposits can now be exploited, but as this requires new and complex technology, they are still classed as “unconventional”.

Range: The term “range” is often used to show how many more years a raw material will continue to be available. However, this statistic is extremely unreliable as no one can predict future demand with certainty. What’s more, in the debate about finite resources, the term “range” is rarely defined: does it mean the point in time when all deposits will be exhausted, or the point in time when demand can no longer be fully satisfied, such as when fuel shortages prevail? Experts therefore generally prefer to use the more precisely defined term “static range”.

Static range: “Static range” depicts the relationship between reserves/resources and present annual global production. The resulting figure shows how many more years the raw material will continue to be available, assuming that consumption remains constant and reserves/resources are fixed. In other words, this is a hypothetical/static scenario. In reality, however, production and especially consumption continually fluctuate. Future political and economic developments which may influence global oil consumption, production and markets cannot be predicted with certainty. What is more, as events in recent years have shown, major new deposits are constantly being discovered; this in turn affects the static range. The static range is therefore merely a snapshot of the extractive industry sector at a given point in time.



1.7 > With its oil sands, Canada has substantial oil reserves. However, extraction has destroyed large areas of forest.



1.8 > If reserves and resources are compared with the IAE's figures for projected cumulative consumption to 2035, it is clear that coal in particular will be available in sufficient quantities far into the future. Oil reserves, on the other hand, will be largely depleted by the mid 21st century. Although the demand for oil can still be met, this will require recourse to unconven-

tional sources in the foreseeable future, involving the use of new and sophisticated technology, which is likely to drive up the price of oil. With gas, the situation is rather more relaxed: consumption is lower and conventional resources are available in larger quantities. However, experts are predicting possible strong increases in natural gas consumption in future.

Conventional or unconventional?

Experts differentiate between conventional and unconventional reserves and resources. Conventional deposits can be developed and exploited using existing technology, whereas unconventional reserves and resources are recoverable only with new, sophisticated and therefore expensive technologies. The shale gas deposits in the US are an example of an unconventional resource.

Despite fears that oil in particular could become scarce, this situation has not yet arisen. At present, sufficient oil is still available worldwide to cover growing demand: thanks to more sophisticated technologies, many new on- and offshore oil fields are being discovered and offshore fields can be exploited at ever greater depth. New extraction techniques also allow more oil to be pumped out of the deposits than before. In some cases, disused wells are being reopened in order to extract the remaining oil which could not be recovered in the past.

In order to determine the future supply situation, scientists and the oil industry are attempting to predict energy demand trends over the coming decades with the aid of energy scenarios, such as those regularly published by the IEA. The findings are then compared with current estimates of reserves and resources.

Still enough oil

The remaining proven crude oil reserves and resources in 2011 totalled around 585 billion tonnes. Unconven-

tional oil accounted for 258 billion tonnes of this total. However, the global distribution of oil fields is extremely uneven. Almost 50 per cent of oil reserves and resources are accounted for by the OPEC states such as Iraq, Iran, Kuwait, Saudi Arabia and Venezuela, whereas only around 20 per cent are accounted for by the Australasia, Africa and Europe regions.

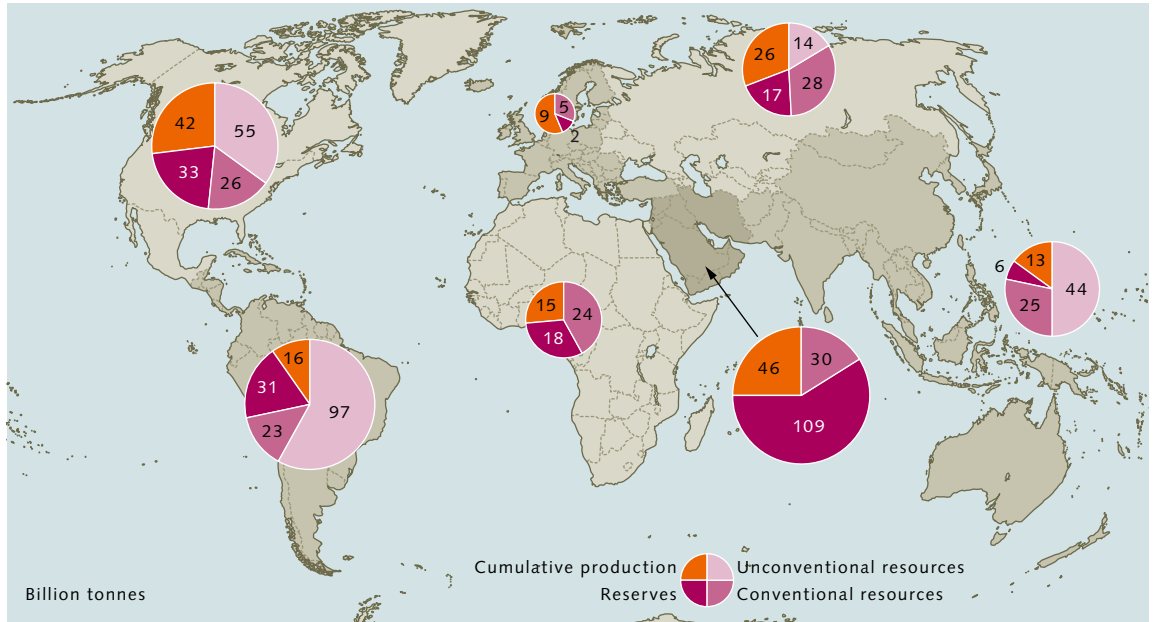
Given the scale of the current oil reserves and resources, it is clear that from a geological perspective, sufficient oil will be available worldwide over the coming years to accommodate a moderate rise in consumption. But will it always be possible to provide sufficient quantities of this energy carrier when it is needed in future? That cannot be predicted with certainty. To date, however, it has been possible to calibrate oil production so that there is always enough to meet demand.

Nonetheless, some critics have predicted a scenario known as “peak oil”. This refers to the point in time when the world’s annual oil production reaches an all-time high – a historic peak – and then starts to decline.

1.9 > LNG carriers are tanker ships specifically designed for transporting liquefied natural gas (LNG). Their characteristic spherical tanks make them instantly identifiable, even at a distance.



1.10 > The global distribution of oil reserves and resources is uneven. The most important region is the Middle East with the Arabian Peninsula. In 2011, global oil consumption reached around four billion tonnes, compared with around 585 billion tonnes of oil reserves and resources. Cumulative production is the sum of all oil that has already been produced by a specific date in a given region.



But with new oil fields constantly being discovered and extraction technologies becoming ever more sophisticated, output has in fact steadily increased worldwide.

Some experts are now predicting a “peak plateau” over the coming years: this means that oil production will be sustained at a high level over a longer period of time. However, oil prices will continue to rise, as oil production will increasingly rely on unconventional deposits whose exploitation requires significant technical effort. They include oil sands, which are being exploited on a large scale in Canada, and shale oil, which is trapped in almost impermeable layers of rock and whose extraction therefore also requires major technical effort.

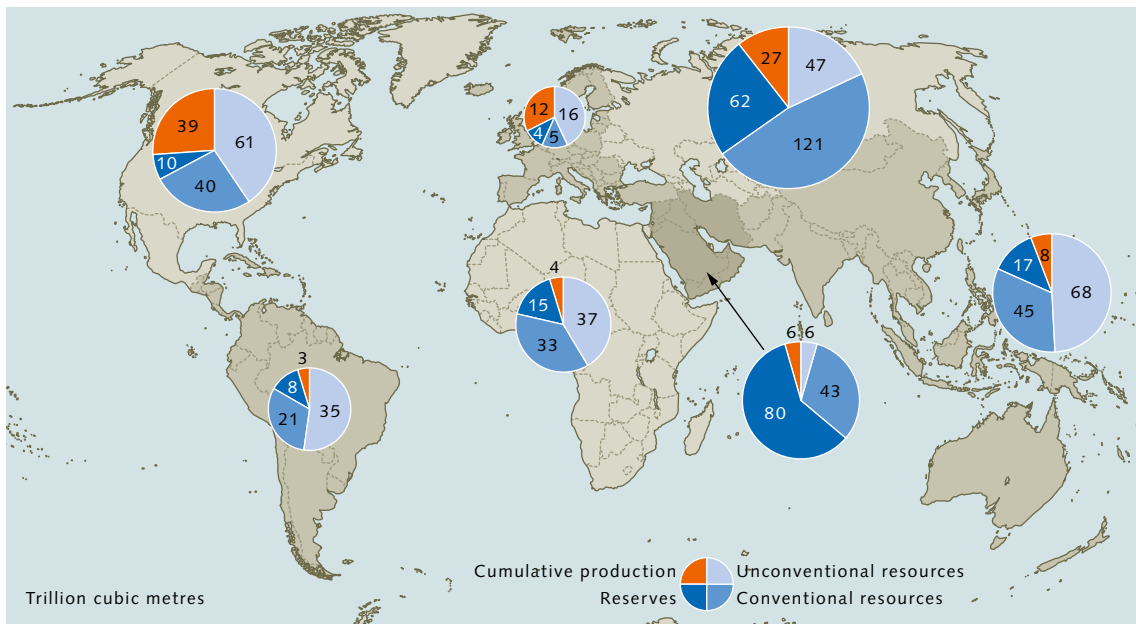
Offshore oil production at ever greater depths will also drive up oil prices. Experts predict that by 2015, as much as 12 per cent of oil will be extracted in deep-water projects at a depth greater than 200 metres, compared with only 2 per cent in 2001.

So it is hard to predict, at this stage, exactly when global oil production will start to decline or when oil will indeed become a scarce resource. If all the various oil resources are consistently exploited, this point is unlikely to be reached before 2035. Nonetheless, some countries have already experienced peak oil in their

own industries. One example is the United Kingdom: oil production in the UK peaked in 1999.

Fracking – opportunities and risks

In 2011, the world’s natural gas reserves and resources totalled around 772 trillion cubic metres. This figure is around 230 times higher than the amount of gas consumed globally in 2011. Resources account for the major share, amounting to 577 trillion cubic metres, with unconventional natural gas resources comprising around 60 per cent of the total natural gas resource base. One example is coalbed methane, also known as coal seam gas (CSG), a form of natural gas extracted from coal beds. CSG extraction using unconventional technologies is already under way in a number of countries, notably Australia. The US’s extensive shale gas deposits – another major unconventional resource – are attracting particular interest at present. Shale gas is a form of natural gas that is trapped in layers of almost impermeable rock. Although the rock is porous, enabling it to store natural gas, the pores are isolated from each other and, unlike conventional deposits, are not connected to each other by “necks”, or connecting channels. The extraction of shale gas began in the US



1.11 > Natural gas is also found in varying quantities in different regions of the world. As estimates of the gas hydrate deposits located on or near the sea floor are unreliable, these deposits are not considered here.

some years ago, using a technique which relies on the creation of artificial fissures in rock formations containing gas. A mixture of water and chemical agents is pumped into the target formation at high pressure. This comparatively new method of extracting natural gas from shale is known as hydraulic fracturing, or “fracking”.

Fracking has unleashed something of a shale gas revolution in the USA – such that the US is likely to become completely independent of natural gas imports over the next few years. According to current estimates, the US has almost 14 trillion cubic metres of shale gas resources. Globally, the recoverable shale gas potential amounts to around 157 trillion cubic metres. However, our knowledge of the extent to which shale gas deposits exist worldwide is still patchy, putting a question mark over these estimated figures. What’s more, fracking is a highly controversial technology, with critics fearing that the chemical agents used in fracking could leach out and contaminate groundwater.

The future of offshore oil and gas production

Today, most oil and gas extraction still takes place onshore. Nonetheless, a considerable amount of gas and oil

is already produced offshore. Offshore oil extraction currently accounts for 37 per cent of global production. At present, 28 per cent of global gas production takes place offshore – and this is increasing. Coal mining does not currently take place offshore.

For many years, offshore natural gas and oil production was restricted to shallow waters such as the North Sea or coastal areas around the US. However, as many older deposits have become exhausted, companies have increasingly moved into deeper waters. Three separate depth categories are defined:

- shallow water production at water depths of less than 400 metres;
- deepwater production at depths up to around 1500 metres, and
- ultra-deepwater production at depths greater than 1500 metres.

With the latest high-resolution geophysical exploration technology, scientists are now able to detect oil and gas deposits in the seabed and other geological strata to a depth of 12 kilometres. As a consequence, many major new deposits have been discovered or newly surveyed in recent years.

According to recent studies, 481 larger fields were found in deep and ultra-deep waters between 2007 and 2012. They account for more than 50 per cent of the newly discovered larger offshore fields, i.e. fields with an estimated minimum 170 billion barrels of recoverable reserves, corresponding to around 23,800 million tonnes of oil equivalent (MTOE). The deepwater and ultra-deepwater sectors are thus becoming ever more important. It is also interesting that the newly discovered offshore fields are generally around 10 times larger than newly discovered onshore fields, which makes deepwater and ultra-deepwater production an attractive prospect despite the higher costs. Globally, oil and gas extraction at water depths greater than 400 metres is currently limited in scale, amounting to just 7 per cent of production. This is partly because only 38 per cent of the proven deepwater and ultra-deepwater fields are currently in production. Most of these fields are still undergoing detailed surveying, while initial test drilling has already taken place in some cases.

Many experts agree that deepwater and ultra-deepwater fields are the last bastion of oil production. Many of the once high-yielding fields onshore and in shallow waters are almost exhausted, so there is virtually no alternative to deepwater and ultra-deepwater production now and over the coming years. But is oil production in these water depths viable? That ultimately

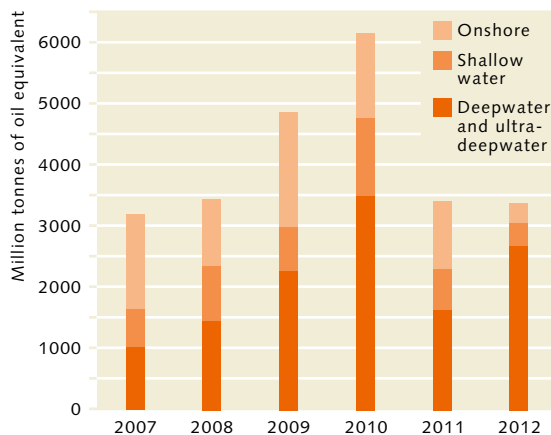
depends on oil prices. Generally speaking, the deeper the water, the higher the extraction costs.

The offshore oil industry extracts oil mainly from conventional sources. If oil prices continue to rise significantly over the coming decades, however, exploiting unconventional deposits, such as shale oil, offshore may well become an increasingly attractive proposition. But this is still a long way off.

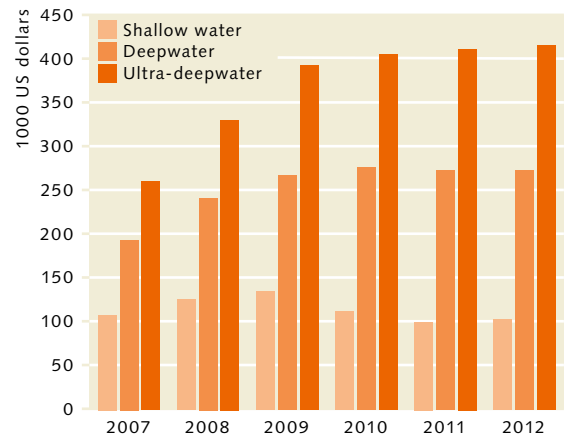
Promising maritime regions

A number of significant deposits have been discovered offshore since 2007. The Santos Basin off the coast of Brazil, for example, holds several major oil and gas fields with as much as one billion tonnes of oil and a billion cubic metres of natural gas, located under a massive pre-salt layer several thousands of metres under the sea floor. Deposits on this scale could potentially cover total world demand for gas and oil for many months. Despite geophysical surveys of the sea floor, these deposits remained undetected for a very long time because the salt layers caused perturbation in the signals from the measuring devices. Using more advanced technology, the deposits were finally detected a few years ago.

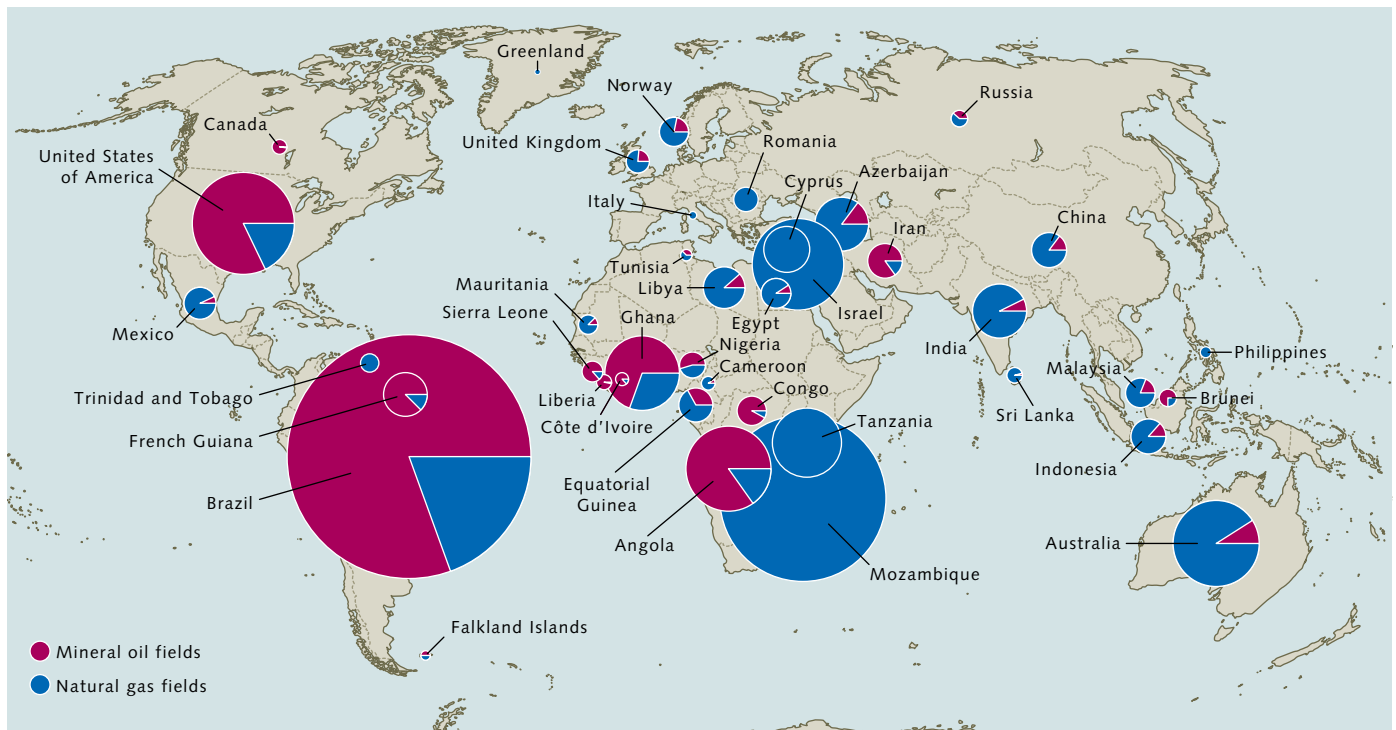
On the other side of the Atlantic, in the Kwanza Basin off the Angolan coast, oil fields have been discovered beneath a 2000-metre thick pre-salt layer. In the



1.12 > A glance at the volumes of offshore oil and gas fields newly discovered between 2007 and 2012 clearly shows that the bulk of the resource is located at depths of more than 400 metres.



1.13 > The deeper the water, the higher the costs: in 2012, one day of drilling in ultra-deep water, i.e. at depths greater than 1500 metres, cost around four times more than drilling in shallow water.



Black Sea and the Caspian Sea, new oil and gas fields at depths greater than 400 metres have also been discovered in recent years. Extraction has already begun in some cases, with countries such as Iran, Romania and Russia now engaged in deepwater production.

Important new oil fields were also discovered in the Gulf of Mexico and off the coast of Ghana and French Guiana. Spurred on by these findings, there are now plans to search for further deposits in similar geological formations off the coast of two neighbouring countries, Suriname and Brazil. Today, the deep and ultra-deep waters in the Gulf of Mexico and in the Atlantic off South America and West Africa are regarded as the most promising regions for oil exploration.

Between 2007 and 2012, major gas fields were discovered off the coast of Mozambique and Tanzania and in the Mediterranean close to Israel and Cyprus. Both fields are so abundant that they will revolutionise the supply of gas in these regions: Israel, for example, has the potential to become completely independent of gas imports from its Arab neighbours for the foreseeable future.

The Arctic region – a special case

As the Arctic sea ice melts as a result of climate change, hopes are growing among Arctic nations of tapping the oil and natural gas deposits in the northern polar regions. Current scientific studies suggest that there are indeed substantial deposits in this region. It is estimated that about 30 per cent of undiscovered gas and 13 per cent of undiscovered oil can be found in the marine areas north of the Arctic Circle. The substantial gas deposits are thought to be located mainly in Russian waters.

As yet, no one can say whether or when extraction will begin in the Arctic, especially as various legal questions have still to be clarified. Over recent years, a conflict has erupted among Arctic nations over territorial claims to the Arctic seabed. The Arctic nations expect to derive substantial revenues from these natural resources, but will have to be patient. Complicating matters, extraction in these regions is not economically viable at present: exploration alone will require expensive and complex ice-breaking operations.

1.14 > In recent years, the most significant discoveries of gas and oil fields in water depths greater than 400 metres were made in the South Atlantic and off the coast of West Africa.

Producing natural gas and mineral oil

> Throughout the Earth's history, natural gas and mineral oil have formed from the remains of marine algae and land plants, with large deposits accumulating in certain rock strata. Today, using modern drilling techniques and giant platforms, these resources are being extracted from ever greater depths. Production systems are even being installed on the sea floor.

Biomass – millions of years old

Natural gas and oil form over hundreds of millions of years from dead organic material that has accumulated on the bottoms of seas, lakes and swamps. Oil is formed primarily from dead microalgae, or **phytoplankton**, while coal and natural gas derive mainly from land plants. Especially large amounts of biomass accumulate in warm regions with lush vegetation or prolific algal growth.

Dead biomass normally decomposes in water where it is broken down by bacteria into carbon dioxide and water. This process consumes oxygen. With the input of large amounts of biomass, oxygen can be completely depleted by the bacteria. This creates oxygen-free zones where decay no longer occurs.

Thus, over time, packages of biomass several hundred or thousand metres thick can accumulate on the sea floor. Whether natural gas or mineral oil is formed from the biomass depends primarily on the temperatures at these depths.

Plankton cooked down to oil

Oil deposits formed through a series of consecutive processes. First, the phytoplankton accumulated on the sea floor. Together with fine rock and clay particles washed into the sea from the mountains and flatlands, the algal biomass was transformed into an organic-rich sludge.

Over periods lasting many millions of years, so much of the organic sludge was deposited on the sea floor that, due to its enormous weight, it gradually changed to claystone and was finally compressed and hardened into a clay-rich shale. Even today it can be said that, to some extent, in these porous shale layers at depths of 2000 to 4000 metres and at temperatures

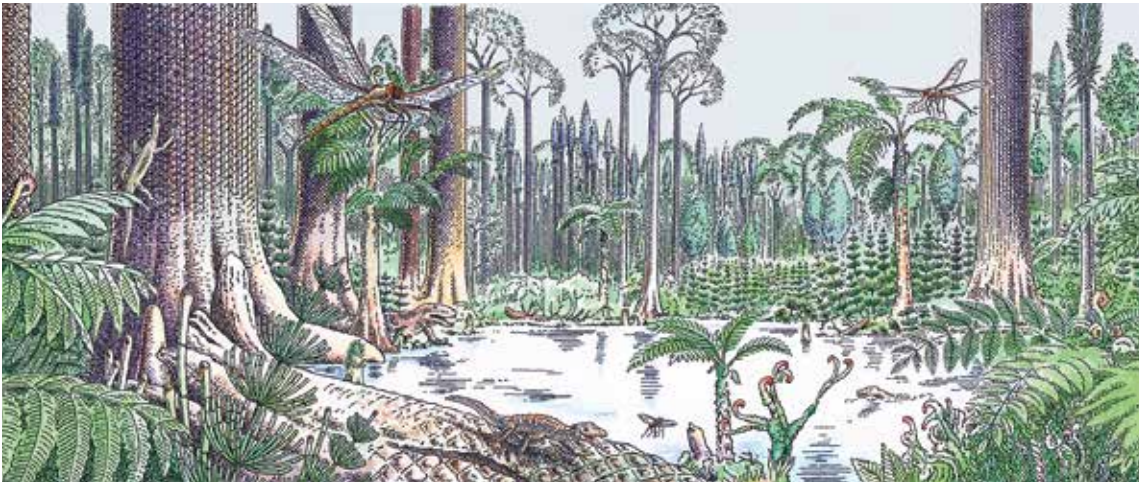
between 65 and 120 degrees Celsius the transformation of biomass into oil is taking place. This temperature range is called the “oil window”. Just like in a chemistry laboratory, the biomass here cooks down into a broad range of chemical compounds that are composed exclusively of carbon and hydrogen, and are thus referred to as hydrocarbons.

Crude oil is therefore a mixture of hundreds of different compounds that are initially separated in refineries or split into smaller molecular chains. The splitting process is referred to as “cracking”.

Not only are fuels such as petrol and diesel produced from the crude oil. Other products of the refineries include ethylene gas and propylene gas. The tiny hydrocarbon molecules of ethylene and propylene, which contain only a few atoms, are used in plastics production and many other applications.

The shale and other rocks in which oil forms are called oil source rocks. They contain up to 20 per cent organic material. Over millions of years the source rocks have gradually been compressed by the sediment and rock layers being deposited on top of them, resulting in the formation of oil. As increasing amounts of oil formed, more of it escaped from the source rock and rose slowly through the overlying rock and sediments. In some areas it even reached the surface. Near the northern German city of Celle, for example, tar pits formed naturally, containing a black liquid which, historically, has been used as lamp oil, a lubricant, and even as a natural remedy.

Oil reservoirs were formed whenever the upward travel of the oil was blocked by impermeable materials such as salt or clay layers. If these impermeable layers were underlain by a porous reservoir rock such as sand or limestone, it acted as a sponge, causing the oil to accumulate. Specialists call these formations under-



1.15 > 300 million years ago extensive clubmoss and horsetail forests were common. The plants were several metres high, much taller than today. Coal and natural gas were formed from them.

ground trap structures. In addition to oil and other hydrocarbons, the porous rocks also contain large amounts of water, which has to be separated out during production of the oil.

Because the continents, as a result of continental drift, have been moving for millions of years or more, the ancient seas in which the shales were formed no longer exist today. At a time around 120 million years ago, South America and Africa began to break apart. Initially a small tropical sea surrounded by land was formed in this process, in which a large volume of biomass was deposited. This sea then expanded to become the South Atlantic Ocean. Today the ancient sediments of the former tropical sea lie off the coasts of South America and West Africa.

Layer upon layer of peat

As a rule, natural gas is formed from terrestrial vegetation that once grew in flat coastal areas or in near-coastal swamps in subtropical and tropical climates. In swampy areas, peat usually formed first. Due to numerous cycles of sea-level rise and fall over the millennia, these wetland areas were repeatedly flooded. Fine sand and clay particles that were transported from the land to the sea were then deposited upon the submerged peat layers. When the water retreated with falling sea level, land plants colonized the areas again, allowing a new peat layer to form.

Over millions of years, the rising and falling of sea level created a layer-cake sediment pattern in which sandy and clayey layers alternated with thick peat layers. Ideal conditions for the formation of peat were present in large regions of central and northern Europe and in North America during a period from 290 to 315 million years ago. At that time these regions lay close to the equator. They were located in a warm, tropical zone, and were rich in vegetation. Not until later did these land masses drift several thousand kilometres northward to their present position.

With time, the layer-cake structure of alternating peat and clay layers was also covered by new sediments and compacted by their enormous weight. However, no oil was formed from the old peat layers, but first lignite and later hard coal. At a depth of 4000 to 6000 metres and temperatures between 120 and 180 degrees Celsius, natural gas formed in the coal over many millions of years. For the formation of natural gas, higher temperatures are required than for oil.

As a rule, natural gas contains around 90 per cent methane. This is accompanied by other gas-phase hydrocarbons such as ethane, propane and butane, as well as non-flammable gases such as carbon dioxide and nitrogen. An additional component is hydrogen sulphide, which has to be removed from the natural gas before it can be used. Hydrogen sulphide can convert to acid when the gas is burnt, which can lead to corrosion in power plants and heating systems.

Peat

Peat is defined as soil that contains more than 30 per cent organic material. This consists of partially decayed plant remains that could not be completely broken down in oxygen-free, standing swamp water.

Natural gas with an especially high content of hydrogen sulphide or carbon dioxide is called acid gas. If this is to be used it must undergo extensive cleaning. Natural gas also migrates gradually out of the source rock. If it is not trapped by dense rock layers then, like oil, it can rise all the way to the Earth's surface. The "eternal fires" in Iran are fed by rising gas and **condensate**, and were presumably lit initially by a lightning strike. There are many places around the world where fires fed by underground gas are still burning. Many of these were venerated by ancient cultures and have become sacred sites.

Wherever underground trap structures were present, the natural gas, just like oil, could accumulate in reservoirs. Generally, the accumulations are only considered to be reservoirs when they are large enough and the rocks permeable enough to make production of the hydrocarbons economically feasible. This is equally true for both gas and oil.

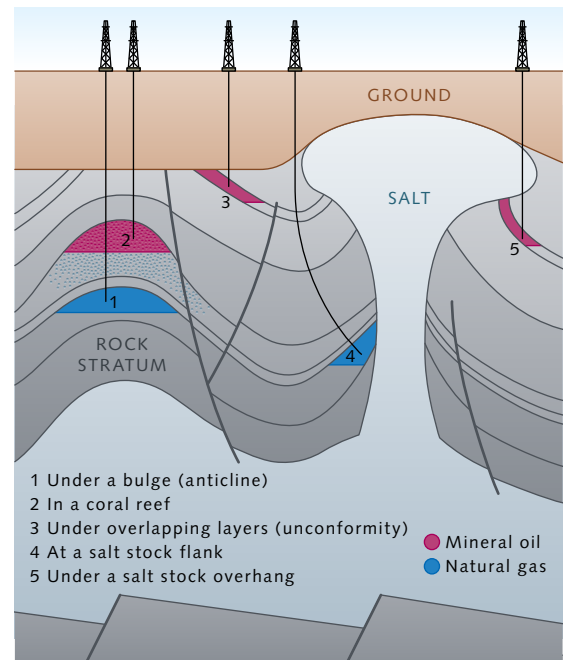
Gas or oil accumulations that are too small to be economically produced, however, occur much more frequently in nature.

Natural gas and oil trapped

Specialists distinguish different kinds of reservoirs in which large amounts of natural gas or oil have accumulated. Typical reservoir types include:

ANTICLINE: An anticline is an arching structure of rock layers, a kind of underground hill. It is formed when dense rock layers undergo pressure from the sides caused by movement of the Earth's crust. When the anticline is composed of impermeable rocks, the rising gas and oil can accumulate there, as in an inverted bowl.

FLANK OF A SALT STOCK: Salt stocks are large underground accumulations of solid rock salt that can be as much as thousands of metres thick. If an impermeable rock layer (a trap structure) abuts on the flank of a salt stock, then ascending oil and gas will be trapped between the rock layer and the flank, because the salt is also impermeable.



1.16 > Gas and oil accumulate in various kinds of underground reservoirs.

UNCONFORMITY: An unconformity arises at locations where rock layers abut obliquely, or at an angle to one another. Unconformities are formed by lifting, subsidence, or squeezing of rock packages that are subsequently overlain by younger sediments. If these overlying sediment layers are impermeable, ascending gas and oil can accumulate and concentrate in the underlying rock packages.

CORAL REEFS: In many instances, natural gas and oil collect in very porous limestone that has formed from ancient coral reefs.

SALT STOCK OVERHANG: Some salt stocks are mushroom-shaped with a wide dome at the top, which forms a kind of umbrella, known as the overhang. Gas and oil can accumulate beneath this. Salt stock overhangs are mainly the result of immense underground pressure. Salt rises because it is less dense than the overlying strata. It bulges upward into domes or the mushroom-shaped overhangs. These movements are referred to as salt tectonics.

Seeking natural gas and oil

The fact that there is still enough natural gas and oil in spite of globally rising energy demand is in part due to the discovery in recent decades of new reservoirs on land and in the sea, largely as a result of the development of new methods to detect the reservoirs. The search for resources involves both prospecting and exploration.

Prospecting is the search for unknown reservoirs. The stage of prospecting is followed by exploration, which involves the precise appraisal and development of the reservoirs and resources that have been found. If deposits are discovered during exploration, then additional wells are drilled to estimate the size and dimensions of the reservoir. This is the assessment phase. If the found reservoir is large enough then production can begin.

Prospecting begins with a determination of whether gas and oil can be expected to occur in a certain area. This includes an initial collection of data relating to the deep rock strata in order to determine the geological development of the area in question. Computer programs called basin analysis systems are employed to play back the geological history of the region. These programs simulate the millennia of sedimentation in the prehistoric marine basin and the transformation at great depths from sediments to rocks. The formation of fractures, trap structures and salt stocks, and the effects of movements of the Earth's crust due to continental drift are also simulated by such programs.

This is followed by extensive geophysical studies, in which the subsurface is examined similar to the way a patient is x-rayed during a medical examination. In principle, the same methods are used on land and in the sea. For investigations at sea, however, aircraft, ships, and special additional equipment are necessary. Important geophysical methods include:

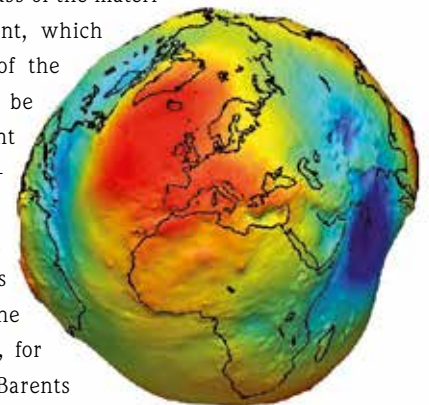
SEISMICS: Seismics are the most important prospecting tool deployed all over the world. The methods work in a manner that may be compared to ultrasound examinations by a doctor, in the sense that ultrasound waves are sent into the body from a transducer probe and are

reflected at different intensities by various organs or bones. The ultrasound machine creates an image of the inside of the body from the pattern of reflections detected. With seismic methods, acoustic waves that penetrate into the sea floor are transmitted by airguns on a research ship. The waves travel at different velocities depending on the type of rock they encounter. In the subsurface they are reflected at the boundaries between different rock types. From the specific differences in the sound waves' travel times, a computer can draw conclusions about the nature of the rock forming the seabed. Just a few decades ago seismic methods could only provide simple cross sections of the sub-bottom. Today modern 3-D seismic methods are employed. These are largely made possible by increasingly powerful computers that are capable of spatially representing bottom structures and reservoirs (Chapter 3).

GRAVIMETRY: Gravimetry was one of the first geophysical techniques to be used in the search for oil and natural gas. This method utilizes the Earth's gravitational force, which is not equally strong everywhere. That force rather varies with the mass of the materials in the ground at a given point, which depends in turn on the density of the rocks. Gravity measurements can be used to distinguish between different rock types or underground structures and thus draw inferences about possible reservoirs. However, the differences between the rocks must be sufficiently large for the method to work. This is the case, for example, in the strata beneath the Barents Sea in the North Atlantic. There are large salt stocks here, which have a significantly lower density than the surrounding rocks. Among other things, this allows the determination of salt stock flanks and overhangs. The tools that measure gravity are called gravimeters, and these are deployed on ships, aircraft and, for about the past ten years, on satellites.

MAGNETICS: The Earth possesses a magnetic field that extends between the North and South Poles. This mag-

1.17 > The strength of the Earth's gravitational field varies at different locations. It depends primarily on the density of the rocks. Very accurate gravity maps have been created in recent years with the help of satellites. In this figure, areas with strong gravity values are shown in red and are slightly raised. Regions with weaker gravity are blue and are shown as depressions. Scientists call this image the "gravity potato".



netic field is very constant. Certain bottom structures, however, can produce differences in this magnetic field, known as magnetic anomalies, which are measurable. The magnitude of the anomalies depends in part on how strongly the sub-bottom is magnetized. This magnetization, in turn, depends on the iron compounds – magnetite, maghemite and hematite – present in the sub-bottom. Hematite is less magnetic than the other two compounds. The magnetic field of a reservoir is generally found to be weaker. This is because the sedimentary rocks in which oil and gas are trapped are less magnetic than the surrounding rocks, for example volcanic rocks. Magnetic field measurements are usually made from aircraft carrying highly sensitive instruments. In this way, large areas can now be investigated within a relatively short time.

ELECTROMAGNETICS (georadar): In electromagnetic procedures, electromagnetic impulses are transmitted, like those of a radio antenna, but in this case radar waves are used. Similar to the sound waves of seismic methods, the electromagnetic signals are altered by the bottom structure.

When geophysical investigations in a marine region are completed, the next step is to drill exploration wells.

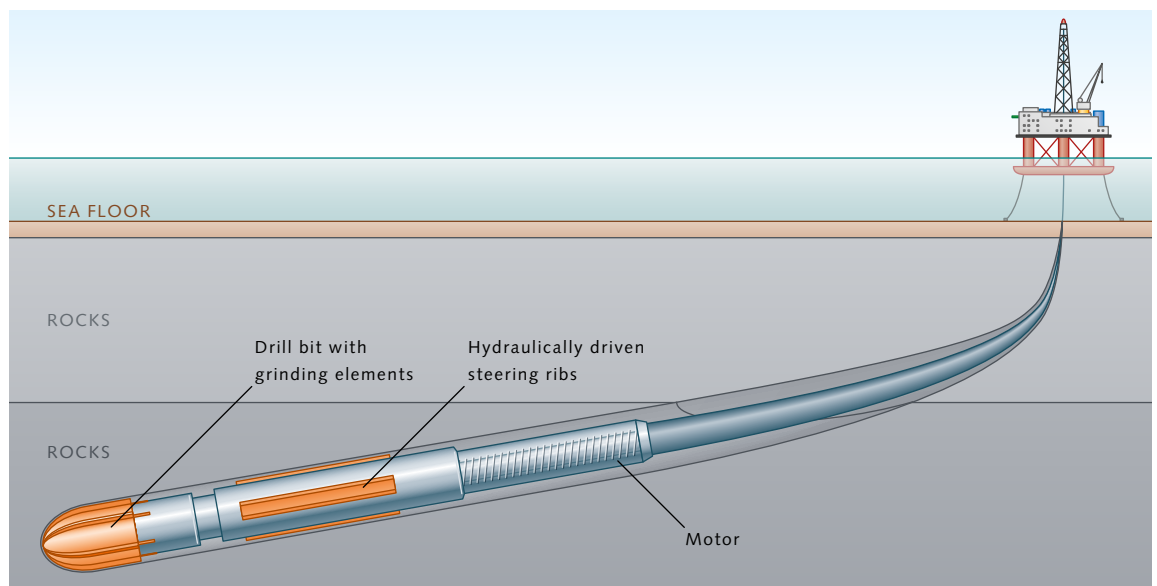
This is usually carried out by floating drill rigs, which are known in the industry as semi-submersibles. During drilling, the retrieved cuttings are continuously examined by specialists on board. They are interested in the kinds of rocks and their age as well as the composition of the drilled strata. Shale can be indicative of source rock, while sandstones suggest the presence of a reservoir. The remains of marine organisms such as the calcareous shells of marine algae, which lived at certain times and under certain climatic conditions, provide robust evidence for the age of the rock layers encountered.

Furthermore, during drilling the natural gas and hydrocarbon content of the cuttings are constantly measured. If the exploration activities reveal tangible evidence of a reservoir, additional wells are drilled to assess the size of the reservoir, how easily the resource can be produced, and the quality of the gas or oil. Only after all of this information is available can production begin.

Horizontal is better than vertical

To develop gas and oil reserves, it is necessary to drill through thousands of metres of thick rock layers. This requires drill bits as thick as tree trunks and with large

1.18 > With directional drilling technology, reservoirs within a wide radius can be developed from a single platform.



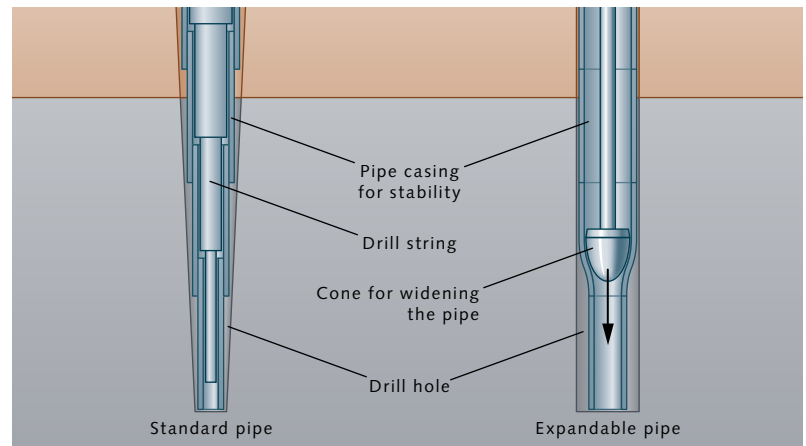
grinders made of hardened metal or ceramic. The drill bits grind the rocks. Today they are usually driven by a turbine located behind the bit. Rotation of this turbine is propelled by drilling fluid that is pumped into the hole under high pressure. This drilling fluid then transports the crushed rock out of the hole. The fluid rises with the cuttings, which are removed by sieving on the drill floor, and is then pumped back into the well. In order to drive the drill head into the subsurface, the drill string is lengthened piece by piece with ten-metre-long pipe joints that are screwed together. This rotary drilling technique has been in use for around 100 years.

Depending on the hardness of the layer being drilled, the bit becomes blunt after a time and has to be changed. Around 30 bits are needed for a 5000-metre well. To change the bit, the entire drill string has to be pulled out of the well and unscrewed piece by piece, then with the new bit the string is reassembled and lowered back into the hole. The time required to change the bit varies with the depth of the well.

In the early days of the industry it was only possible to drill vertically. To develop a large gas or oil field it was practically always necessary to erect multiple drill rigs, one beside another, because one well was not capable of extracting the oil from distant areas of the reservoir. In the meantime, directional drilling techniques have become available, making it possible to curve the line of drilling. This enables many wells to be operated from a single platform; it also allows the development of gas and oil fields over a distance of several kilometres.

With the first directional drilling methods it was initially only possible to drill at a predetermined specific angle. This involved incorporating a hydraulic motor into the front part of the drill string at the drill bit, whose axis was tilted a few degrees from that of the drill string. With this technique, as before, the drill string was driven from the drill rig. When the hydraulic motor was switched on, the drilling direction was diverted according to the pre-set angle. Because the angle only constituted a few degrees, the well was diverted in a broad arc. The curvature was so slight that the drill string was only minimally bent.

Furthermore, a special kind of steel was employed in the pipe so that it could bend slightly without break-



ing, like a drinking straw that can bend a little without crimping.

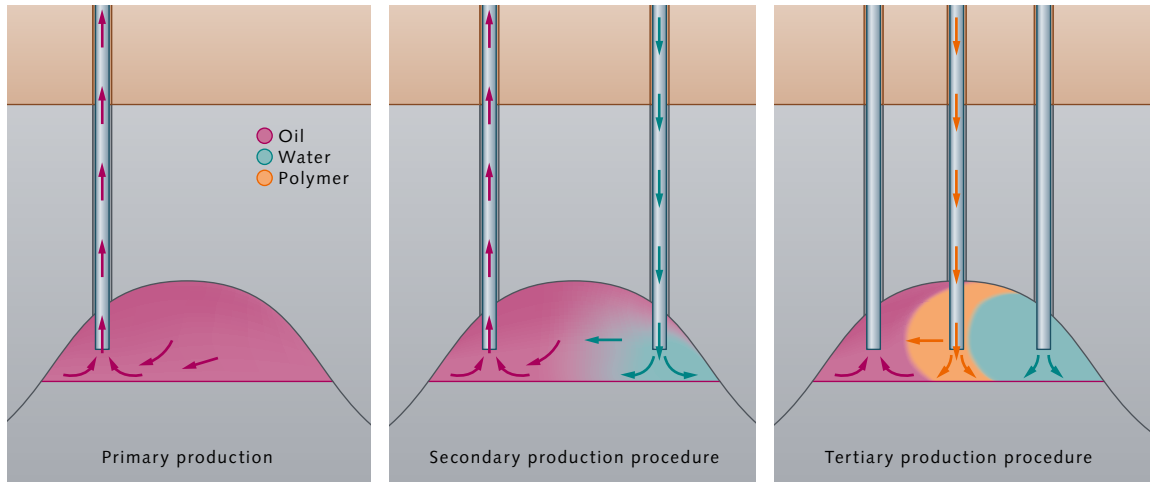
With modern directional drilling techniques, however, it is possible to adjust the direction while drilling. For this method, a steering unit with steering ribs, the steering sub, is mounted behind the drill bit. It is fitted like a ring around the drill pipe, which is driven from the drill rig. The steering ribs are hydraulically activated to press against the wall of the hole and wedge the steering sub. This produces a force that diverts the drill bit from its path. By activating the appropriate steering ribs it is possible to direct the drill bit in any desired direction. Sensors monitor the spatial position of the drill bit as it advances. A computer program corrects the course automatically as necessary. The motors and generators for the hydraulic system are located directly behind the steering sub.

Today, with extended reach wells, drilling firms are able to drill horizontally to distances greater than 12 kilometres. Furthermore, from a horizontal well it is possible to branch off to other wells. This is called multilateral drilling. These horizontal wells diverge and bifurcate like the root system of a tree, ensuring maximum extraction from the reservoir.

Extended reach drilling can also be used from a land base to extract resources from offshore reservoirs. These methods have been used already for many years for oil production on the German North Sea coast, for example, as well as in current projects in the Caspian Sea.

1.19 > To counteract the telescoping downhole reduction in well diameter, special new expandable pipes have recently begun to be employed. These are widened underground by pressing a hydraulically driven conical tool through the pipe. This technique is known as the solid expandable tubular method.

1.20 > Oil production can be broken down into three phases: During primary production, oil flows into the well under its own natural pressure. Later, pumps maintain the flow of oil. In the secondary phase, water is pumped into the reservoir to artificially increase formation pressure. To prevent the water from flowing past the oil into the well, the tertiary production phase involves injection of a polymer between the water and oil. Alternatively, the viscosity of the oil can be reduced by pumping in hot water or solvents.



For successful drilling it is important to flush the drill hole with an aqueous solution. Not only does the solution transport the drill cuttings away from the bit, it also cools the bit. Furthermore, due to its own weight, the solution produces a counter pressure that supports the drill hole to prevent caving. The aqueous solution is pumped through the drill string down to the drill bit, where it then enters the space between the drill pipe and the surrounding rock. It rises to the surface again inside this space.

But the fluid is not able to protect the hole indefinitely against caving. For this reason steel pipes are intermittently cemented in the drill hole to support the walls. The problem with this is that the drill bit has to continue to advance deeper, and new pipe joints have to be pushed through the part that is already cemented. The subsequent pipe joints, then, have to have a smaller diameter than the cemented pipe. The hole is thus reduced in size downhole like a telescope. A well may have a diameter of up to 70 centimetres at the surface and, at a depth of several kilometres, have a diameter of only a little more than 10 centimetres. For future extraction at high rates, however, a large diameter is more effective.

New pilot projects are therefore employing flexible steel pipes. When they are in place, a hydraulic piston, called a conical expansion tool, is pushed through the pipe to widen it, creating a pipe with a uniform diameter.

When oil dries up

In essence, the same techniques are employed when drilling for gas or for oil. The extraction process, however, is different for the two resources because oil is viscous and only flows to the well naturally for a limited time as long as the reservoir pressure is high enough. The flow dries up as the reservoir empties and pressure drops. The reservoir pressure must then be artificially increased by technological methods. Thus, three clearly distinct phases of oil production can be characterized:

1. PRIMARY PRODUCTION

During primary production the oil initially flows to the well under its own natural pressure. When the reservoir pressure decreases and the oil flows more slowly, pumpjacks are deployed to pull the oil up to the surface. With primary production, only around 5 to 30 per cent of the original oil present in the reservoir, on average, can be extracted.

2. SECONDARY PRODUCTION

To better exploit the reservoir, secondary production methods are employed following the primary production phase. The most common method is flooding with water. In this approach, water is injected under pressure into the side of the reservoir to force the oil toward the well. The reservoir pressure is artificially increased by pumping in the water. In rare cases, natural gas is

pumped into the reservoir. This is generally only done in regions where natural gas is available in abundance. The valuable natural gas is later recovered. Secondary production increases the proportion of extractable oil to as much as 45 per cent of the reservoir.

3. TERTIARY PRODUCTION

At some point, the secondary production methods reach their limit. Because water and oil have similar densities, it can happen during secondary production that the injected water flows past the oil and into the well, with the result that very little oil is produced. For this reason, tertiary methods are used to decrease the viscosity of the oil. Hot water or solvents are pumped into the reservoir for this purpose. Alternatively, it is possible to stop water flowing around the oil by introducing a synthetic liquid, a polymer, into the area between the oil and water. This polymer is so viscous that the water cannot flow through it. The pressure of the injected water is thus transferred through the polymer to the oil, forcing the oil out of the reservoir. Furthermore, additives are now being developed that will increase the viscosity of the water. This could also prevent the water from flowing past the oil.

Tertiary methods are also referred to as enhanced oil recovery (EOR) techniques. They are applied today to open up oil fields again that had previously been shut down because production had become uneconomic. Although they are more expensive than primary production, the EOR techniques have become economically viable due to rising oil prices. With tertiary methods, up to 60 per cent of the original oil in a reservoir can be extracted. This means that the pore spaces in a reservoir can never be completely emptied of oil, in part because of physical forces that hold the oil in the pores. Around 40 per cent of the oil remains underground whichever method is used.

According to oil industry estimates, enhanced oil recovery techniques accounts for about 4 per cent of worldwide oil production today. It is believed that this could rise to 20 per cent by the year 2030. This is because many oil fields around the world will be so extensively exploited that it will be necessary to switch to tertiary methods. In natural gas deposits, the reser-

voir pressure similarly decreases when the gas is extracted. To retrieve the remaining gas, however, it is in most cases sufficient to employ pumps to suck the gas out and thus achieve the maximum yield.

Powerful technology for great depths

In their search for new gas and oil reserves in the sea, energy companies have penetrated to ever greater water depths. This was partly in response to the oil crises of the 1970s, which prompted the development of new deposits, for example in the North Sea. Many reservoirs on land and in shallow shelf areas near the coasts have been depleted or are already in the enhanced oil recovery phase. Interest in new reservoirs in the deep sea is thus increasing.

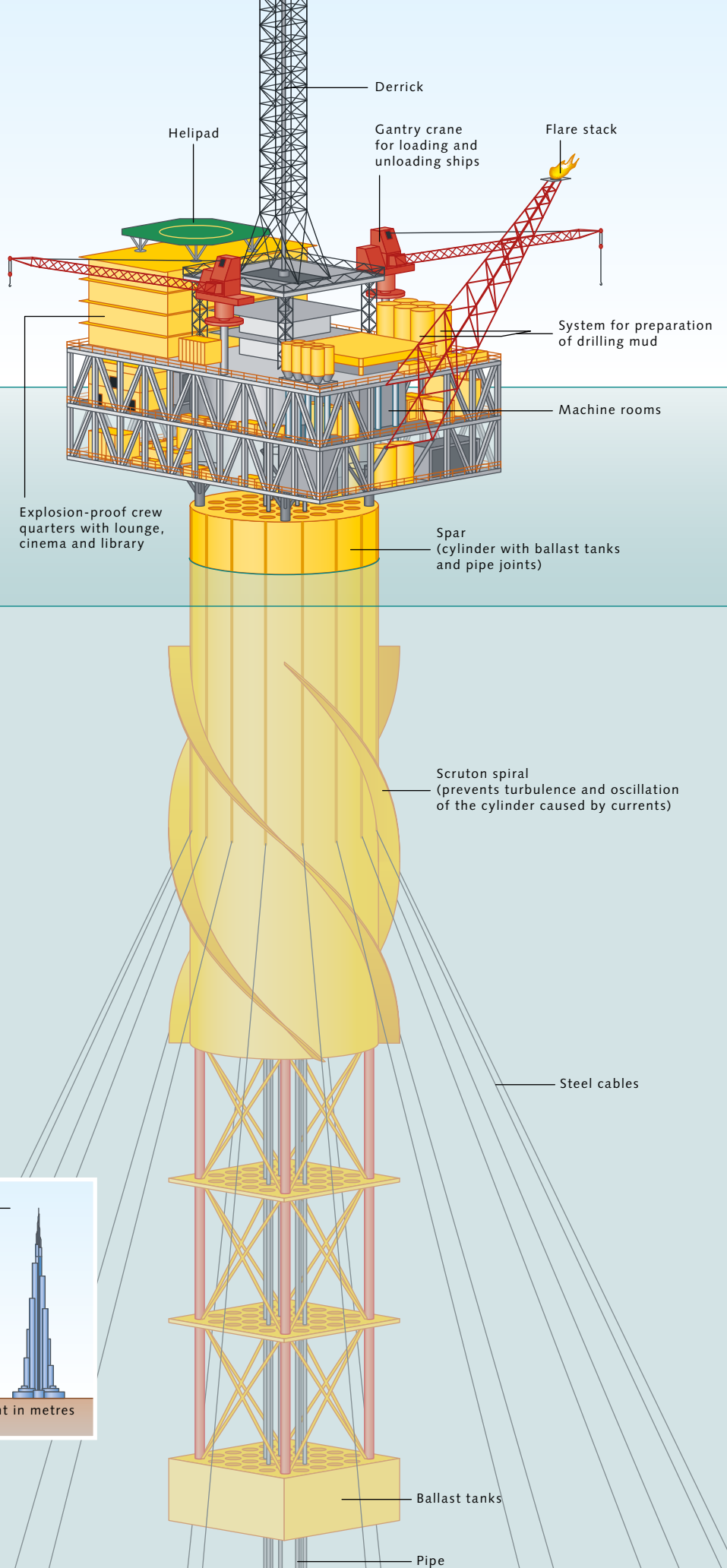
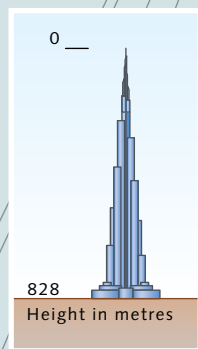
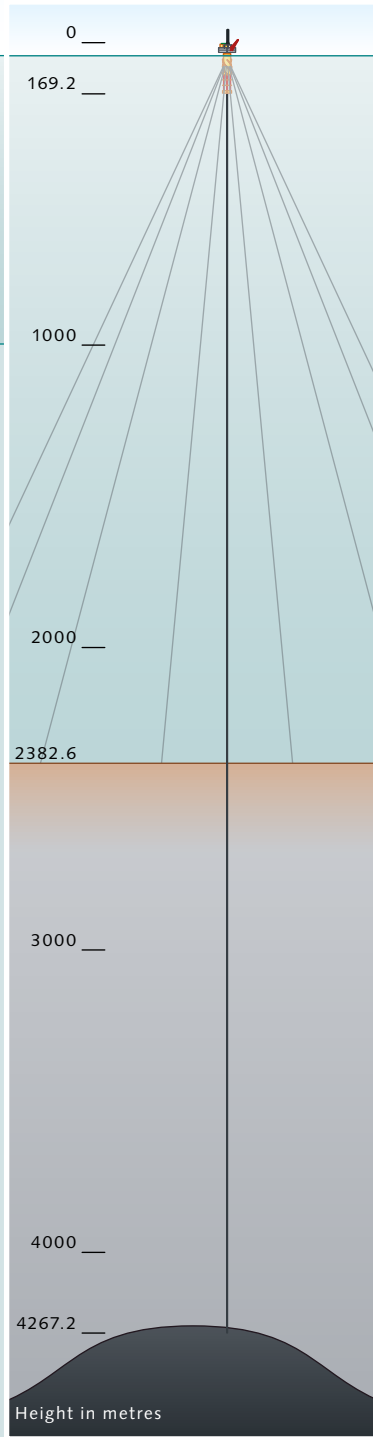
In the 1940s the first gas and oil rigs were built in less than 10 metres of water on piers or ramps connected to the land. Later, platforms were built standing fixed on the sea floor. Some of them are so tall they would tower over the Empire State Building in New York.

Today's rigs extract gas and oil from water depths of almost 3000 metres. Because the construction of fixed rigs in water deeper than 400 metres is laborious and expensive, floating rigs are commonly used today for wells in great depths.

When scarcity struck – the oil crises

The term "oil crisis" is used to describe two periods during the 1970s when the oil supply on the world market decreased as a result of political crises, leading not only to higher oil prices but also to an economic crash. The first oil crisis was triggered by the 20-day Yom Kippur War between Israel on one side and Egypt and Syria on the other. The Organization of the Petroleum Exporting Countries (OPEC), dominated by Arab countries, cut back on production in order to pressurize western countries into withdrawing support for Israel. The second oil crisis followed in 1979–1980, after the monarchy in Iran under Shah Mohammad Reza Pahlavi ended with the Islamic Revolution. Soon afterwards, Iraq declared war on Iran. The political instability caused another shortage of oil on the world market. The oil crises ultimately led many countries to tap their own new reserves in order to become more independent; one example is oil production in the North Sea.

1.21 > Floating platforms like this spar buoy in the Gulf of Mexico are employed today for producing oil from especially great depths. To reach the reserves it is necessary to overcome not only the water depths, but also to drill almost equally deep into the sea floor, as shown in this example. To illustrate the scale, Burj Khalifa in Dubai, the highest building in the world, is shown in the figure.



Specialists differentiate here between drilling and production rigs. Drilling rigs are used to open up a gas or oil field. Floating drill platforms are often used to drill down to the reservoir. They are then towed to their next deployment area. Alternatively, there are also large drilling ships which, in contrast to platforms, do not have to be towed but can travel from one reservoir to another under their own power.

When the drilling of a well is finished, it is initially capped at the sea floor with a wellhead. This is a kind of sealing cap, approximately the size of an automobile, that prevents the gas or oil from escaping. Only then can the drill platform be moved away. Later a production platform will be installed in its place. Then the wellhead is opened again and the natural gas or oil is extracted from the reservoir.

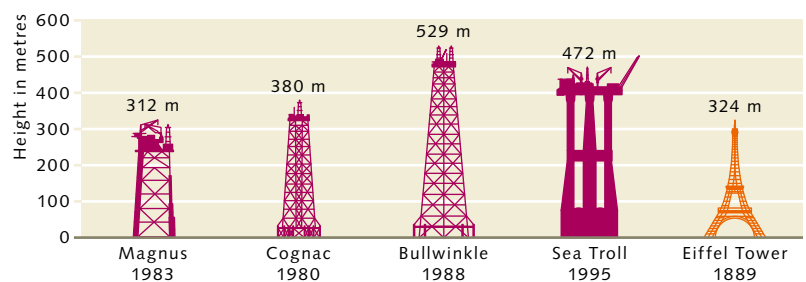
In moderate water depths, production rigs today are still erected with legs planted on the sea floor. At greater depths, however, floating platforms are employed. In addition, there are production ships, known as Floating Production Storage and Offloading Units (FPSOs). These are especially flexible and are often deployed for smaller gas and oil deposits. When one reservoir is exhausted they travel on to the next one. Rigs are also in use that can be employed for both drilling and production.

Small industrial cities at sea

Whether it's a drilling or production rig, a platform standing on the sea floor or a floating platform, each of these rigs is like a small industrial city. There can be fitness and conference rooms on board, bedrooms and lounges for up to 200 workers, and of course the equipment for drilling or production. On drilling platforms, this includes, first of all, the drill rig with the derrick, through which the drill string is lowered into the rock formations. The drill string is rotated either by a power unit in the derrick or by a rotary table directly on the platform, a kind of rotating disc with the drill string secured in the centre. There are also pumps that force the drilling fluid into the well.

For production, on the other hand, pumps are needed to draw the gas and oil to the surface when the reservoir pressure starts to drop. Because the resource is

always mixed with sand and water, there are facilities on deck that separate and process the conglomeration. In addition, there are tanks for gas and oil as well as pumps to transport the resource to land by pipelines or to fill tanker ships. The power supply for the many items of equipment and for the living quarters is produced by generators.



Because oil usually contains a small amount of natural gas, processing systems are also required on oil production platforms to separate the gas from the oil. In the past, gas was usually flared off and wasted. Unfortunately, that is sometimes still the case today. But now it is being put to use more often, in many cases for generating electricity on drilling and production platforms. If it accumulates in large amounts it is pumped to land via pipeline.

Today there is a large variety of standing or floating drilling and production rigs that have been developed for particular applications. They fall into three categories, as follows:

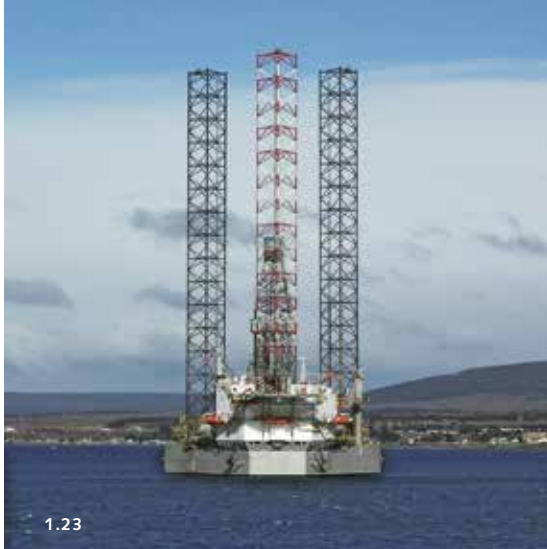
FIXED PLATFORM: This type stands on legs on the sea bottom. Fixed platforms include:

- **Jackup rigs:** Jackup rigs are large floating platforms with extendible legs. Cranes, living quarters and drilling or production systems are installed on board. They are brought to their destination by towboats or under their own power. Once a jackup rig has arrived at its site of deployment, the legs are lowered to the sea floor so that the platform stands on the bottom. The advantage is that when a job is finished the platform can be towed to a new location. The drilling platform *Constellation II* shown in

1.22 > Over time, oil production continued to shift further out to sea. Because the drill platforms still stood on the bottom, they had to be ever bigger and taller. Today, at greater depths floating platforms are mainly used.

1.23 > The jackup drilling rig *Constellation II* is commonly used in the development of natural gas fields off South America. While under way, its legs are raised and loom above the platform like towers.

1.24 > The lattice framework construction of the *Bullwinkle* platform was prefabricated on land and towed into the Gulf of Mexico in 1988.



1.23



1.24

Figure 1.23 is an example of a jackup rig. Among other tasks, it is used to drill test wells for natural gas.

- **Steel platforms:** Steel platforms are built on lattice framework towers. The steel frame possesses the special advantage of having low resistance to wind and waves. Steel construction is often seen in the Gulf of Mexico and in the North Sea. The pipes used to anchor the tower on the sea floor are several metres thick because they have to support a weight of tens of thousands of tonnes. The largest platform of this type is the *Bullwinkle* oil platform, which was erected in 1988 in the Gulf of Mexico as a production platform. It is a full 529 metres tall. The water depth at its deployment location is 412 metres. The steel construction was fabricated on land and then towed out to sea. Steel structures the size of *Bullwinkle* shown in Figure 1.24 are only used as production platforms in large and high-yield gas or oil fields.
- **Concrete platforms:** Concrete platforms rest on top of giant hollow bodies made of reinforced concrete. Because of their size and costly construction, they too are mainly used as production platforms in large gas or oil fields. Because of the very high water

pressure at great depth, the hollow bodies are spherical or cylindrical in form. They are fabricated on land and then towed to the deployment location. They are partially flooded to prevent the structure from tilting. Enough air remains within the hollow space, however, for the structure to remain stable in the water like an enormous ship. At its site of deployment, the entire structure is then lowered to the sea floor. Later, during production, the hollow bodies can be used as tanks to store extracted gas and oil. A good example of this type of platform is the *Sea Troll* natural gas production platform, which began operations in the Norwegian Troll gas field in 1996. The 472 metre structure was fabricated on land and then towed out to sea. The water depth at the site is 303 metres.

COMPLIANT PLATFORM: There are also variants of this platform type, such as steel towers that are supplemented with steel cables to anchor them to the sea floor. The following are especially common:

- **Tension-leg platforms:** The tension-leg platform (TLP) is one of the most common types of compliant platform. As a rule, it consists of a platform resting on a large buoyancy tank with multiple supports. Thus the TLP is not in fact a tower standing on the



1.25



1.26

1.25 > The Norwegian *Sea Troll* is the largest natural gas platform in the world. It was moved to its deployment area by several towboats.

1.26 > The FPSO *Kizomba A* is part of a large oil production complex that consists of a production platform and several subsea units.

sea floor, but is permanently anchored to the bottom by thick steel cables. It is special in that the steel cables are kept tightened, so that the TLP remains stable in the water. The cables are tightened by partially flooding the buoyancy tank so that the structure sinks downward. Next the steel cables are installed. Finally, the ballast is pumped out again and the TLP floats upward. As a result, the tension in the steel cables between the sea floor and the buoyancy tank is increased. Because the buoyancy tank lies deep in the water, even in storm conditions the TLP does not move like a ship, which rides with the waves. The waves simply roll past under the platform and around the cables. Because a tower fixed on the sea floor is not necessary, this type of structure also offers the particular advantage that it can be employed for natural gas and oil fields located in greater water depths.

- **Spar buoys:** Closely related to the tension-leg platform is the spar buoy construction type. These are not tethered by multiple cables, but are supported by a long cylindrical hull that stands vertically like a giant pipe in the water. This hull provides lift like a buoy. This type has only been used in oil production for the past 20 years or so. An advantage of this configuration is that its thin cylindrical shape offers

little resistance to currents in the sea and so it is not severely stressed by them. The cylindrical hull contains tanks for gas and oil as well as ballast tanks that can be used to raise and sink the spar buoy structure in a manner similar to a TLP. Like the tension-leg platform, the spar platform is anchored to the sea floor with permanently embedded tethers. The term “spar” is not an abbreviation, but simply refers to its being based on the cylindrical structure, in analogy to the round wooden or metal spars on a sailboat.

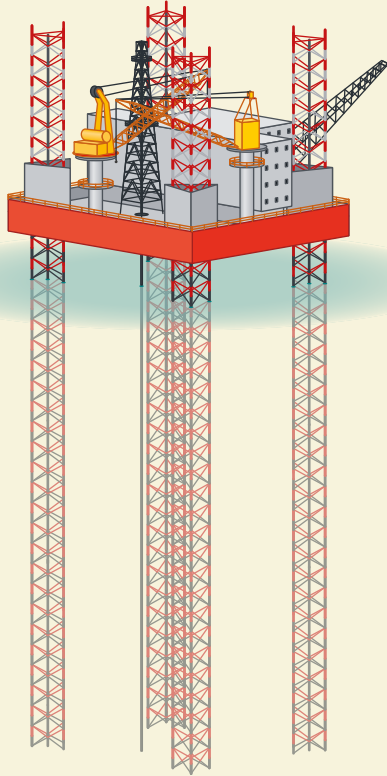
FLOATING PLATFORMS: The floating platforms include small semi-submersibles that are held in position through their own power or by simple anchors. These platforms usually do not have a permanent anchoring system in the sea floor like the TLPs. They are frequently moved to new reservoirs for drilling operations. The floating platforms include drill ships as well as the FPSOs. These are usually deployed near production platforms or subsea facilities with which they are connected by flowlines or cables. Processing facilities for gas and oil are often present on the FPSOs, as well as large tanks from which tanker ships are usually filled. One example is the 285-metre long FPSO *Kizomba A* shown in Figure 1.26, which is deployed off Angola for oil production.

Types of platforms used in the gas and oil industry

1.27 > A wide variety of drilling and production platforms have been developed in recent decades for the extraction of natural gas and oil from the sea. These can be classified into different categories.

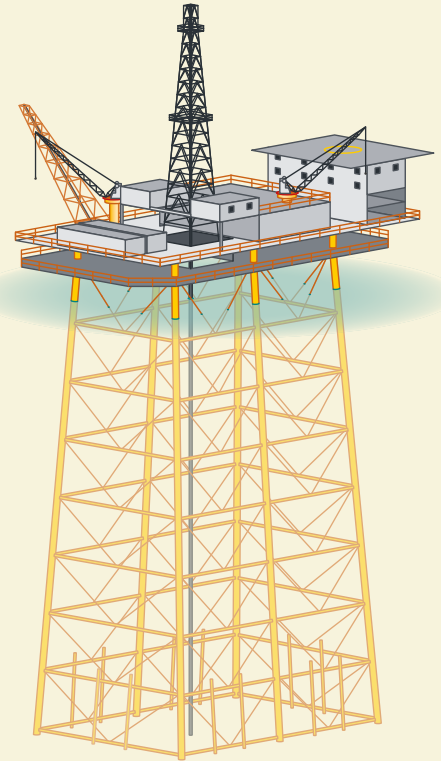
FIXED PLATFORM

The jackup rig stands on extendible legs. It can be quickly moved to a new site, for instance to develop new natural gas fields. An example is *Constellation II*.



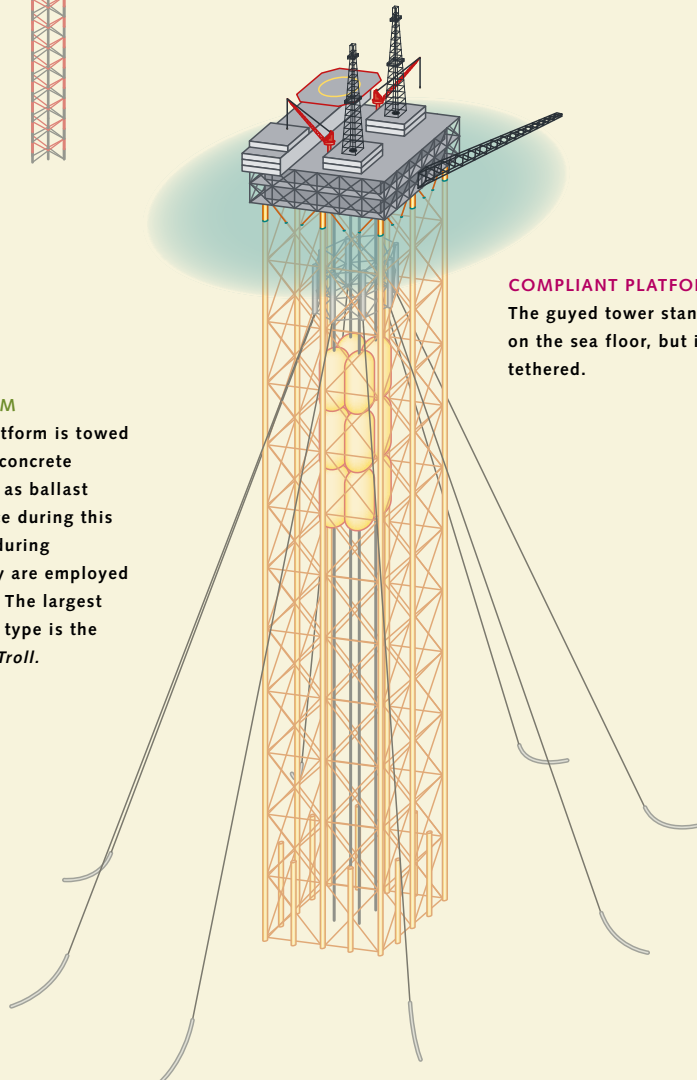
FIXED PLATFORM

Steel structures such as the American *Bullwinkle* platform are prefabricated on land and then towed out to sea.



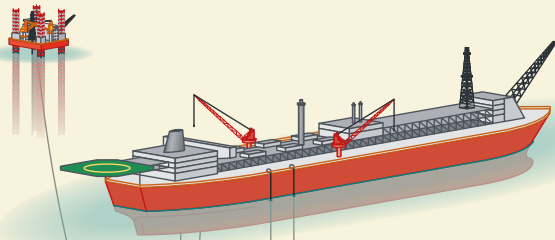
FIXED PLATFORM

The floating platform is towed out to sea. The concrete bodies are used as ballast tanks for balance during this process. Later, during production, they are employed for gas storage. The largest platform of this type is the Norwegian *Sea Troll*.



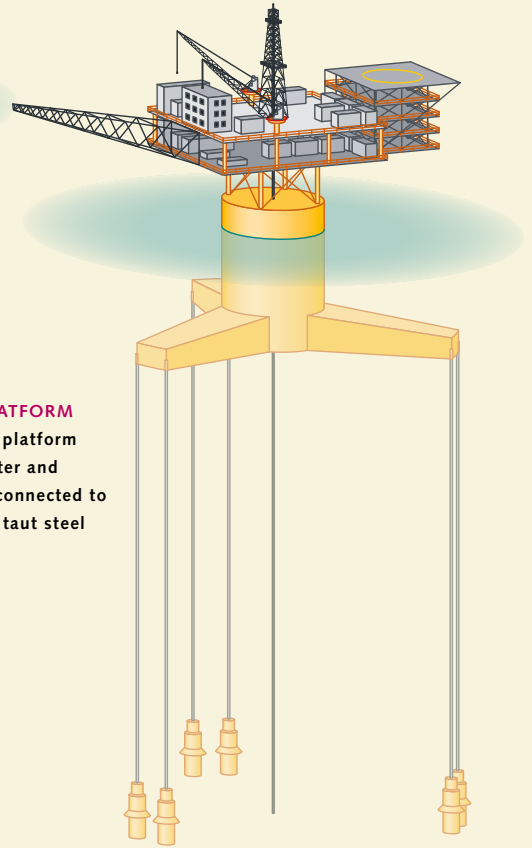
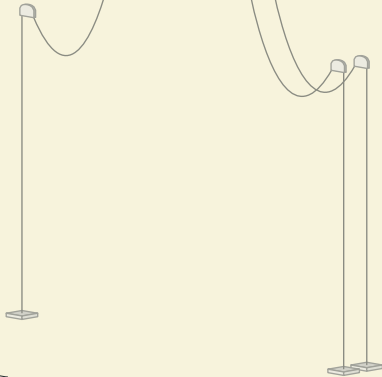
COMPLIANT PLATFORM

The guyed tower stands fixed on the sea floor, but is also tethered.



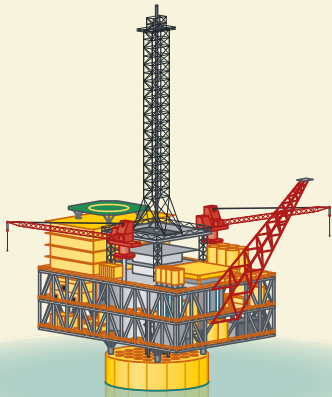
FLOATING PLATFORM

FPSOs such as the *Kizomba A* float freely in the water. They are held in position with multiple engines or simple anchors. They can produce, store and process oil. Water is pumped into the sea floor through flowlines for secondary oil production.



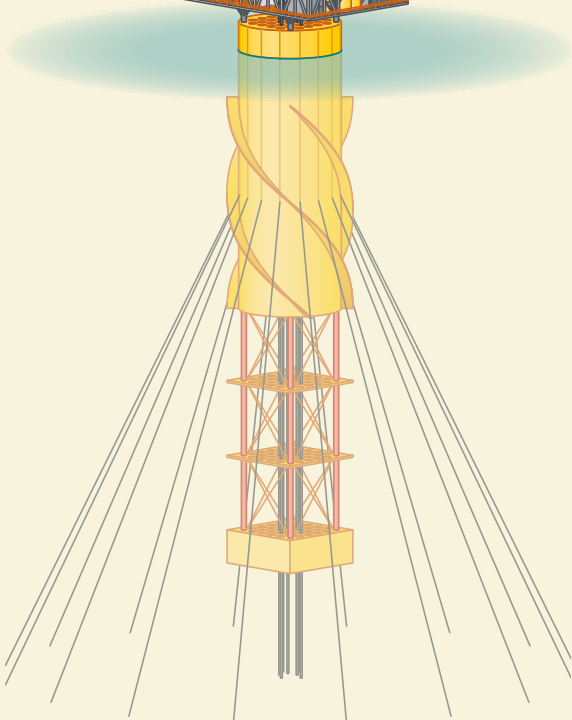
COMPLIANT PLATFORM

The tension-leg platform floats in the water and is permanently connected to the sea floor by taut steel cables.



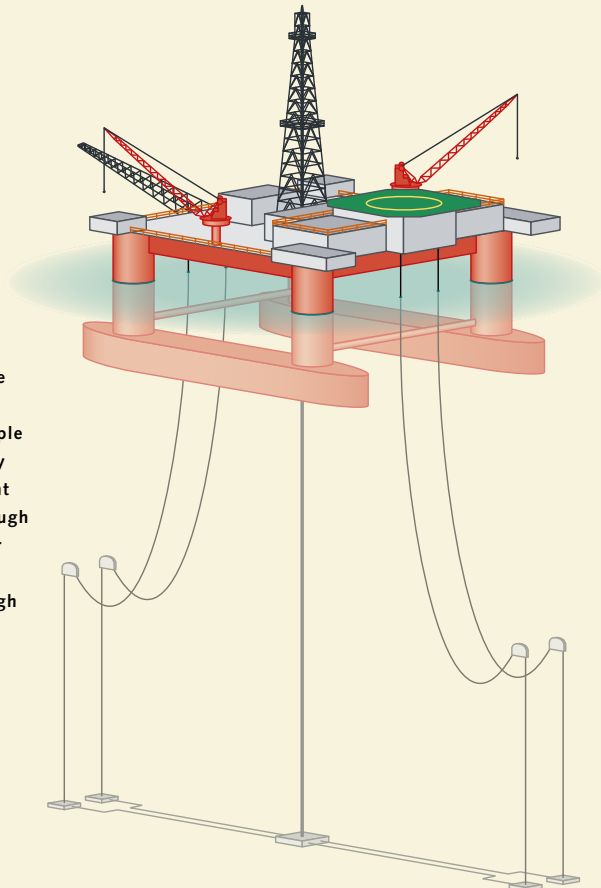
COMPLIANT PLATFORM

Spar buoys are among the oil industry's depth-record holders.



FLOATING PLATFORM

The semi-submersible platform floats freely in the water. It is held in position with motors or several simple anchors, and can be quickly moved to a new deployment site. Water is pumped through lines into the formation for secondary oil production. Oil is then extracted through the pipe string under the platform.



1.28 > Production platforms have been a part of the offshore oil and gas industry for decades. Important production regions include the coastal waters off South America and West Africa and, as seen in this photo, the Gulf of Thailand.



Production technology on the sea floor

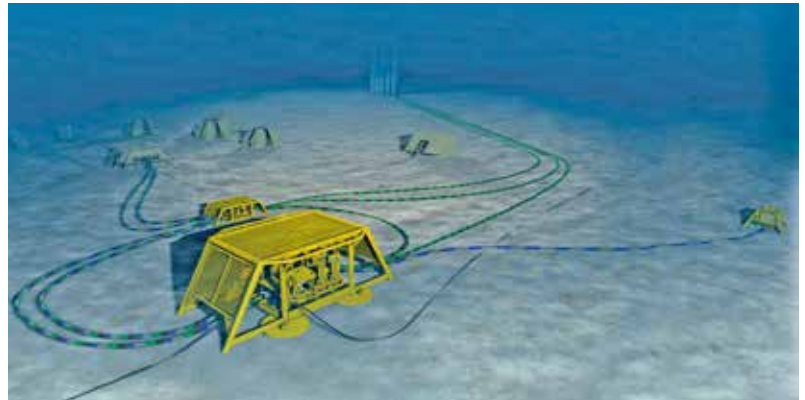
Today, gas and oil production operations are no longer limited to using large platforms on the sea surface. There is now an alternative, known as subsea completion systems. These comprise various water-tight components such as compressors, pumps and separators for gas and oil processing mounted on steel frames. The components are placed directly on the sea floor. With the help of underwater robots, they are then connected together to form large production ensembles. Such subsea completion systems are not considered to be platforms, and thus effectively form their own class of offshore facility. They will generally be deployed in deep and ultradeep areas.

Subsea equipment has a number of advantages. For one, the systems work more efficiently when the pumps and compressors are closer to the source, which is on the sea floor, and for another, it is possible to clean and process the gas- or oil-water-sand mixture locally without having to pump it to the drill platform. This means that the production technology is much simpler and saves significant costs.

In addition, thanks to underwater technology, less production equipment is needed in large gas and oil fields. Even using directional drilling methods from a drill platform, the radius in which extraction can take place remains limited. However, if the pumps and compressors are emplaced directly on the sea floor, it becomes possible for gas and oil from numerous wells in a wide radius to be pumped to a common production station. From that station, the product can be sent onshore or to an FPSO, for example.

These kinds of subsea installations are now in operation in the Gulf of Mexico, off South America, West Africa and Norway. In the Perdido oil field in the Gulf of Mexico, for example, individual oil platforms at the water surface are connected to as many as 30 wellheads on the bottom. A single platform can thus produce oil from a number of wells.

In the Ormen Lange gas field on the Norwegian continental shelf, on the other hand, around 50 wellheads have been installed in an area of almost 500 square kilometres on the sea floor. These are connected to a small



1.29 > Gas and oil in deep water are increasingly being extracted with subsea systems that are located on the sea floor. These are modular systems. The individual components such as wellheads or compressors are linked to ensembles by flowlines.

number of common subsea production stations under water that pump the gas onshore via pipeline. For these kinds of projects, new special equipment and machines are constantly being developed. Today, there are already underwater compressors on the market that are capable of increasing the pressure in natural gas reservoirs when they begin to empty and the formation pressure decreases, thus allowing continued production.

The development of subsea equipment remains a challenge because the various working parts and the electronic components not only need to be watertight and withstand high water pressures; they must also be highly reliable. On offshore platforms, compressors, pumps and compactors can easily be maintained, but with systems at great water depths, this is less straightforward. There, a defective machine would be a serious problem.

Work is therefore being carried out around the world to develop robust systems that will function around the clock for many years. The elements of such systems include compressors that pump natural gas into the pipelines. Compressor bearings are normally lubricated with oil. In subsea equipment, however, electronically controlled magnetic bearings, in which the axle floats, are now in use. The processing of oil and gas by means of subsea systems has reached a state of maturity at which it generates over 20 billion US dollars, and according to experts, this figure could double by the year 2020.

Oiling the oceans

> Oil pollution continues to pose a threat to the marine environment – but very little of this pollution comes from major oil spills. The greatest problem is oil that enters the seas along less obvious pathways, such as inputs from effluents or shipping. Various conventions to protect the marine environment, better surveillance of seaways, and contingency plans all play a part in reducing the volume of oil entering the sea. Lessons also seem to have been learned from the explosion at the *Deepwater Horizon* oil rig.

The *Torrey Canyon* disaster – a wake-up call

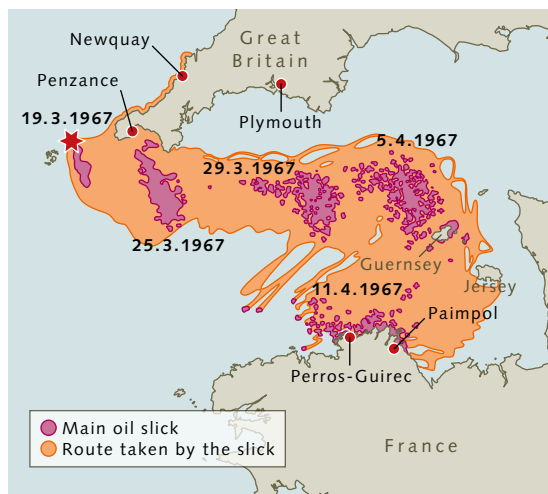
The global oil industry often exacts a heavy toll from the environment. Onshore, there is the problem of soil contamination by oil from leaking pipelines. Offshore, oil spilled from damaged tankers poisons marine life, coats and clings to the feathers of seabirds, and pollutes coastlines. The problems associated with the production and transportation of crude oil became all too apparent in the 1960s and 1970s, when the first super-tankers came into service, increasing the potential threat to the environment. It was then that the world witnessed its first major oil spills, often affecting many thousands of people. The first of these disasters occurred in 1967, when the tanker *Torrey Canyon*, which was carrying 119,000 tonnes of crude oil, hit rocks and was wrecked near the Isles of Scilly off southwest England. The oil formed a slick measuring some 1000 square kilometres and caused massive pollution of coastlines around Cornwall, Guernsey in the Channel Islands, and France.

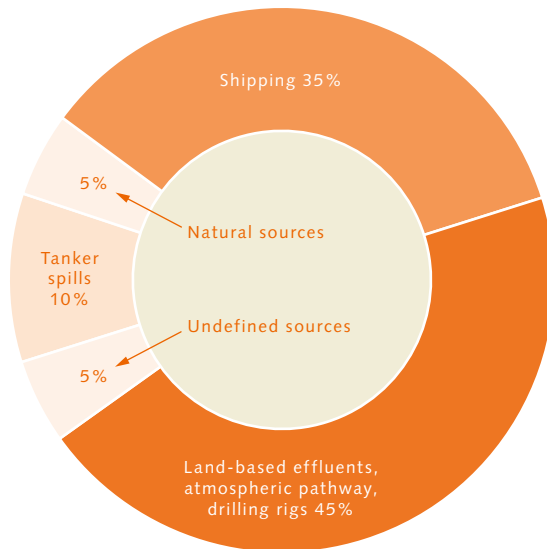
Oil pollution – an insidious threat

Tanker disasters and oil rig explosions still occur from time to time; one example was the *Deepwater Horizon* incident in spring 2010, in which a vast quantity of oil was released into the environment in a very short period of time. Yet in reality, this kind of spectacular disaster accounts for only a small percentage of global marine oil pollution. Most of the oil travels along less obvious pathways. Of the estimated one million tonnes of oil entering the marine environment annually, around 5 per cent comes from natural sources. In the Gulf of Mexico, for example, crude oil seeps naturally out of underground fissures and cracks and rises from the reservoirs to the ocean floor. Elsewhere, as in the Caspian region, large amounts of crude oil erupt from underground reservoirs into the water via mud volcanoes. These are not true volcanoes but mounds on the seabed. They contain watery sediment which heats up deep underground, causing it to rise. In some cases, it transports oil from nearby reservoirs upwards as well.

1.30 > In March 1967, the *Torrey Canyon* hit rocks off the south coast of England. The oil from the stricken tanker caused massive pollution along the coast of southern England, and within three weeks had drifted as far as Brittany and Normandy in France.

1.31 > The Royal Air Force dropped bombs in an attempt to sink the vessel and its remaining cargo, igniting the oil slick. The pall of smoke from the burning oil was visible more than 60 miles away.





1.32 > Oil enters the sea along various pathways. The largest share comes from inputs from effluents and from routine oil rig operations.

Oil tanker disasters account for around 10 per cent of global marine oil pollution. Around 35 per cent comes from regular shipping operations; this includes oil released during incidents involving all other types of vessel, as well as oil from illegal tank cleaning. The largest share, amounting to 45 per cent, comes from inputs from municipal and industrial effluents and from routine oil rig operations, together with a small amount from volatile oil constituents which are emitted into the atmosphere during various types of onshore burning processes and then enter the water. A further 5 per cent comes from undefined sources. This includes smaller inputs into the sea by polluters who go undetected. These percentages naturally do not apply to 2010 and other years in which major oil spills have occurred. The *Deepwater Horizon* disaster alone released around 700,000 tonnes of oil into the sea – more than two-thirds the amount that would normally enter the marine environment over the course of an entire year.

Progress on combating pollution

The good news is that the number of oil spills from tanker incidents or caused by technical failures or explosions on tankers has fallen dramatically in recent decades, despite steady growth in the seaborne oil

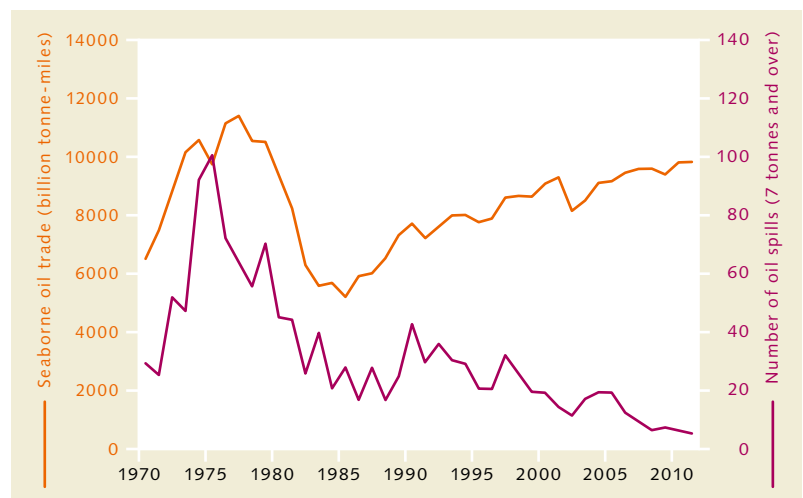
trade. In the 1970s, there were between 50 and 100 large oil spills a year, compared with fewer than 20 a year since the start of the millennium. The statistics cover oil spills above seven tonnes; there is no systematic collection of data on smaller incidents.

Consistent with the reduction in the number of oil spills from tankers, the volume of oil spilled has also gradually decreased. Of the total volume of oil spilled from tankers between 1970 and 2009, only around 3.7 per cent was spilled after 2000. The largest amount of oil entered the marine environment in the 1970s – around 15 times more than in 2000 to 2009.

According to experts, this decrease is primarily due to the international conventions and regulations to protect the marine environment, which were progressively introduced after the various oil disasters. One of the most important is the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which since 1983 has formed the basis for the designation of marine protected areas where tanker traffic is wholly or partly restricted. The Convention brought the number of oil tanker disasters down during the 1980s. MARPOL 73/78 also paved the way for the introduction of double hull tankers. It is now mandatory for all new tankers to be fitted with a double hull, so that if a vessel is involved in a collision which penetrates the outer hull, the tanks inside generally remain intact.

Another milestone was the adoption of the Oil Pollution Act (OPA) in the United States, which was signed

1.33 > Although seaborne oil trade has increased since the 1970s, the number of tanker spills has decreased. The statistics cover oil spills above seven tonnes.



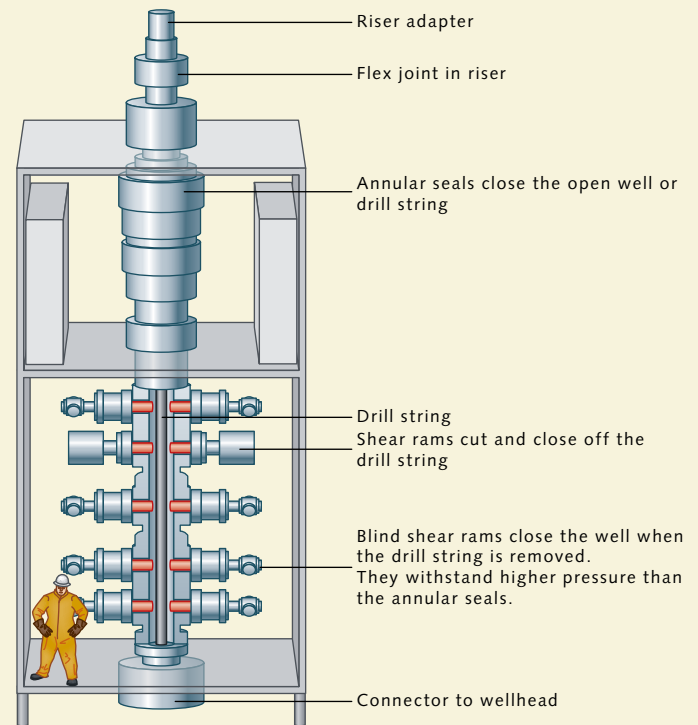
Deepwater Horizon – the offshore oil industry’s worst-case scenario

The explosion at the *Deepwater Horizon* mobile drilling rig on 20 April 2010 caused the largest accidental oil spill in the oil industry’s history, releasing around 700,000 tonnes of crude oil into the Gulf of Mexico. Only the Gulf War oil spill from Kuwait in 1990 released more oil into the marine environment. Eleven workers on *Deepwater Horizon* lost their lives and 16 others were seriously injured in the blowout. In its final report, published in December 2011, a US committee of experts concluded that a series of technical failures and flawed decisions led to the disaster. This precipitated a controversial debate about responsibility and ways of avoiding similar disasters in future.

Deepwater Horizon was a semi-submersible mobile offshore drilling unit, designed to drill wells in new oil fields in ultradeep water. Drilling rigs of this type are operated by service companies which are contracted by oil companies to carry out drilling operations. To start with, drilling only penetrates a few metres into the sea floor. Sections of pipe, known as casing, are then placed in the drill hole. The casing has two functions: firstly, it provides structural integrity for the drill hole and prevents it from caving in immediately. And secondly, the casing head supports the blowout preventer (BOP), which is installed on top of the casing on the sea floor. The BOP is a structure around 10 metres high, fitted with shut-off valves to prevent any uncontrolled surge of oil and gas from the drill hole during or after drilling. The BOP surrounds the drill string like an over-sized cuff. As a further safety measure, the BOP is also fitted with devices known as shear rams: in the event of the valves failing, these act as twin jaws, cutting off the drill string and stopping the flow of oil from the drill hole or the BOP.

Once the service company has opened the well, its work is done. The drill string is removed and the BOP valves are closed, securing the drill hole. The rig then travels under its own power, or is towed, to the next well. The BOP remains closed until a production rig is installed on top of it. The valves on the BOP are not opened until the BOP is connected to the production rig with a pipe or hose, and extraction of the oil can begin.

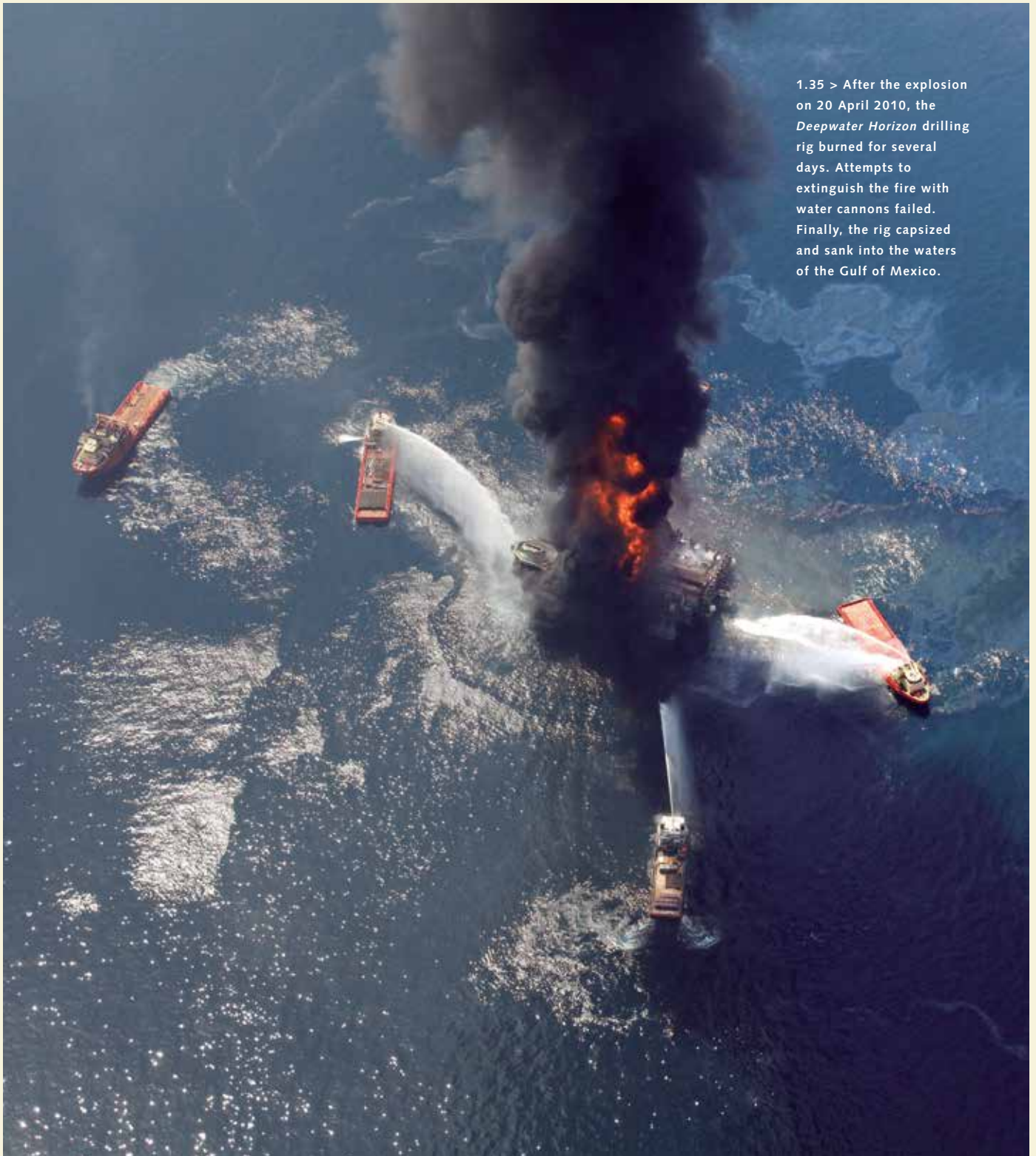
The *Deepwater Horizon* explosion occurred at the end of drilling operations during the process of sealing the well at a water depth of around 1500 metres, before oil production began. The critical moment came when the drilling fluid was being pumped out of the drill hole. This drilling fluid is pumped in during drilling in order to transport the crushed rock out of the hole. It also stabilizes the drill hole; otherwise, the high pressure in the reservoir would normally cause the oil – and the gas that it often contains – to burst through the walls of the drill hole and surge out of the hole. The drilling fluid produces the necessary counter pressure. Once the drilling has finished, the drill string and the drill bit are removed from the hole and the drilling fluid is displaced with sea water. However, water is much lighter than drilling fluid and therefore exerts less downward pressure in the well to balance the flow of gas and oil. The well is therefore additionally sealed



1.34 > A blowout preventer is a tower-like structure which acts as a large plug. Fitted with shut-off valves and shear rams, its purpose is to seal off wells on the sea floor. The *Deepwater Horizon* disaster occurred partly because the BOP technology failed.

with a cement plug far down in the rock. While this operation is being performed, the specialist drilling contractors on deck perform pressure tests to check whether the cement seal at depth is tight. These cementing operations are also carried out by specialist service providers. In other words, on an oil rig – as on any construction site – there are always operatives from several different companies, whose work must be precisely coordinated.

In the case of *Deepwater Horizon*, the tests indicated that there were pressure problems and that the cementing was inadequate. However, the engineers on board made a fatal error: they misinterpreted the pressure test results, assuming that there were distortions in the readings, and continued to displace the drilling fluid with sea water. Then the accident occurred: high pressure forced the gas out of the reservoir into the wellbore. The cementing failed, so the gas surged through the drill string to the rig, where it accumulated on deck and was ignited, probably by a spark from an engine room. Under normal circumstances, the blowout preventer, which had already been installed on the sea floor, would have prevented this gas surge. However, the shear rams failed as well. As a result of the explosion, the



1.35 > After the explosion on 20 April 2010, the *Deepwater Horizon* drilling rig burned for several days. Attempts to extinguish the fire with water cannons failed. Finally, the rig capsized and sank into the waters of the Gulf of Mexico.



1.36 > The oil slick reached the Louisiana shoreline.

well went completely out of control, causing vast amounts of oil to gush out into the sea for almost three months. Remote-controlled underwater robots were used in an attempt to trigger the shear rams on the BOP, but without success.

In its report, the committee describes in detail the technical failures and flawed decisions which, together, led to the disaster, and concludes that material improvements in the offshore oil development industry are required, not only in relation to technology, e.g. BOP construction, but also to management and safety systems and, above all, communication between the various service companies and the operator. The offshore drilling industry faces particular challenges and problems in deep waters, evident from the fact that it took the operator, BP, a considerable time to seal the gushing well on the sea floor. It was not until July 2010, three months after the blowout, that engineers managed to install a capping stack – a tall steel structure – on the BOP. The capping stack captured the oil flowing out of the BOP and funnelled it to a production rig.

The committee estimates the total economic costs of the disaster to be in the tens of billions of dollars. For example, after the disaster, a ban on commercial fishing and aquaculture was imposed across 200,000 square kilometres of the Gulf of Mexico in order to prevent fish and seafood contaminated with toxic hydrocarbons from getting to market. Although the ban has now been lifted across much of the Gulf of Mexico, some restrictions remain in force in severely affected areas such as the Mississippi Delta, where oyster farming is still prohibited. The tourism industry in Louisiana, Mississippi, Alabama and northwest Florida was also hit hard. The U.S. Travel Association estimates that the economic impact of the oil spill on tourism across the Gulf Coast over a three-year period could be as high as 23 billion US dollars. Fines totalling around 4 billion US dollars have already been imposed on BP, with a further 8 billion US dollars paid in compen-



1.37 > Barriers were erected in a futile attempt to protect Dauphin Island.

sation to settle tens of thousands of civil claims out of court. According to economists, the blowout at *Deepwater Horizon* has cost the company around 42 billion US dollars.

So far, no comprehensive scientific study has been carried out to determine which specific measures, and how many of them, have been implemented to make offshore oil development safer. However, various aspects have improved: manufacturers are now equipping their BOP systems with more reliable valves and shear rams, for example. The relevant US authority – the Bureau of Safety and Environmental Enforcement (BSEE) – has also strengthened the provisions on safety in offshore drilling operations, for example by reinforcing stop-work authority (SWA) rules. This empowers and requires any rig worker, irrespective of their position, to stop work and report an activity that is creating imminent risk. If a worker reports a violation, a more senior engineer must respond and take corrective action. Stop-work authority rules were already in existence before the *Deepwater Horizon* incident, but “red flags” from field-level personnel were often ignored.

In addition, companies are now required to establish, in writing, who has ultimate work authority on a rig for decision-making at any given time. This person must now be informed about every step in the work process. This was often lacking in the cooperation between the various service providers in the past: decisions were not always properly coordinated, or were taken by different people. As a result, mistakes sometimes went unnoticed – as in the case of *Deepwater Horizon*. Independent auditors now carry out checks on the rigs to ensure that the decision-making authority is clearly established, that the stop-work authority rules are being enforced, and that communication has improved. Are all these measures sufficient to avoid accidents in future? Only time will tell. It is noteworthy that over the past three years, a new industry has developed, specializing in the production and deployment of capping stacks for the deepwater oil industry. Some



1.38 > Barges lined up to seal off Lake Pontchartrain near New Orleans.

of the companies involved were already well-established in the off-shore industry, but others are new businesses. Furthermore, various oil companies have joined forces and set up their own projects to develop or supply capping stack technology and personnel for subsea incident response, not only in the Gulf of Mexico but worldwide. The companies have set up bases around the world, for example in Stavanger in Norway, Cape Town in South Africa, Angra dos Reis near Rio de Janeiro, and Singapore, with between six and 10 capping stacks kept on standby at each location, ready for deployment in an emergency. The aim is to reach a faulty well within hours or days. Special vessels are used to install the capping stack on the defective BOP. The oil can then be piped from the capping stack to a production rig in a controlled manner. In addition, various contingency plans are now in place as the basis for a managed response to disasters on the scale of *Deepwater Horizon*. These were developed, in some instances by several oil companies on a collaborative basis, at the insistence of the US government and are extremely detailed. Among other things, they envisage the use of semi-submersible rigs, which can be towed to the site of the incident and used to pump oil out of the capping stacks into tankers.

Biologists are still engaged in field studies to obtain a detailed picture of how the oil pollution has affected the water and coastlines, focusing on the status of diverse fauna, flora and habitats. These field studies are broken down into nine work packages which deal with the following: the water column and sediments in the Gulf, the shoreline, fish, marine mammals and sea turtles, nearshore habitats and communities, corals, crabs, birds, and submerged aquatic vegetation.

The extent to which biotic communities and habitats have been affected by the disaster is, to a large extent, still unclear, for it is difficult to determine whether certain types of damage to flora and fauna were indeed caused by contaminants in the oil or whether they perhaps predated the disaster. The problem is that the affected region extends

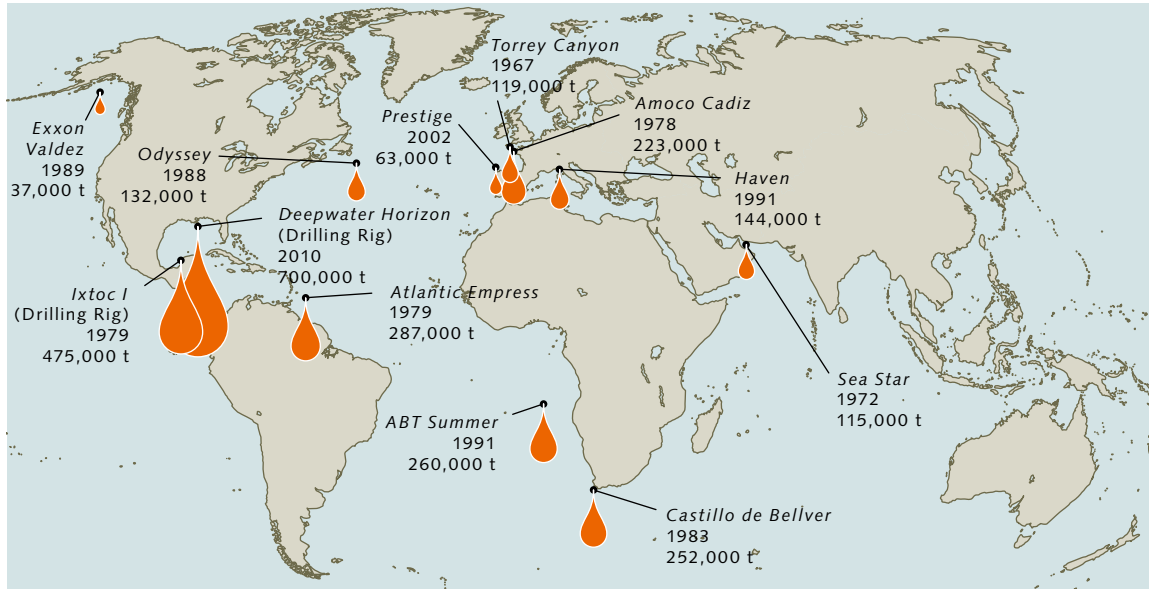


1.39 > Wind, wave action and currents caused the oil to spread.

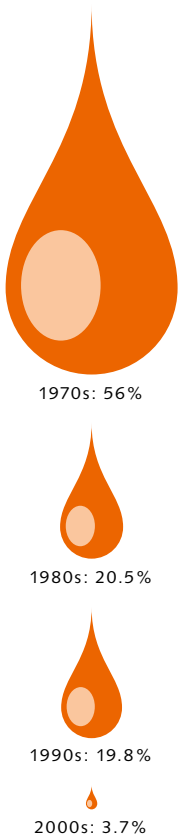
across five US states and their respective coastlines and waters, covering a vast area. What's more, the Gulf of Mexico has never previously been studied as intensively as it is today. For many geographical areas, or indeed for certain species of flora and fauna, no data predating the disaster are available. It is also unclear how many larger animals were killed by the disaster. According to surveys by the US authorities, up to November 2010, cleanup workers had collected around 6000 dead seabirds, 600 sea turtles and 100 marine mammals, such as seals and dolphins, which had washed up on the heavily impacted coasts of Louisiana and Alabama and had apparently been killed by the oil. However, according to some experts, the real death toll could be up to five times higher.

Furthermore, the number of dead animals washed up along the coasts has increased since the disaster. According to the National Wildlife Federation, there was an average of 24 dead sea turtle strandings annually from 2007 to 2009. This increased to 525 in 2011, 354 in 2012, and more than 400 in 2013. According to the National Oceanic and Atmospheric Administration (NOAA) in the US, the number of dead dolphins washing up on Gulf beaches has increased from an annual average of 63 between 2002 and 2009 to 229 in 2010, 335 in 2011, 158 in 2012, and more than 200 in 2013. It is too early to say for sure what has caused the higher death toll. Nor is it clear to what extent the oil that gushed from the deep well has damaged seabed habitats, but some researchers are convinced that the reproduction and growth of many benthic (bottom-dwelling) organisms will be disrupted for a long time to come. Other scientists take the view that the impacts are less severe than expected because large amounts of the oil were broken down by bacteria fairly quickly. Fears that the Gulf Stream might carry the oil from the Gulf of Mexico along the Florida coast into the Atlantic and perhaps even to Europe soon proved to be unfounded; the oil pollution remained confined to the Gulf of Mexico.

1.40 > The *Deepwater Horizon* explosion is the largest oil spill in the oil industry's history. The map shows the location of the world's 10 largest oil spills and other incidents.



1.41 > Of the total volume of oil lost as a result of tanker incidents around the world from 1970 to 2009, the largest amount was spilled in the 1970s and the smallest during the period 2000 to 2009.



into law in 1990 – one year after the *Exxon Valdez* ran aground in Prince William Sound in the Gulf of Alaska in March 1989, spilling crude oil along a 2000 kilometres stretch of coastline which included several bird sanctuaries and nature reserves. Even today, some areas are still contaminated with oil residues, which have biodegraded very slowly in Alaska's cold temperatures. As a result of this disaster, the US took the initiative on the protection of the marine environment and adopted legislation – the OPA – to protect its territorial waters, ahead of other countries. Under the legislation, ships entering US waters are regularly inspected, primarily to ensure that they comply with safety standards and regulations pertaining to the adequacy of qualifications and training of crew members. The OPA also established a double hull requirement for tanker vessels operating in US waters. Much of the OPA's content has been incorporated into international regulations as well, including provisions on reliable radio technology for onboard communication and a vessel identification system to enable shipping control authorities to check a ship's course and position at any time.

Following a comprehensive analysis of the tanker incidents that occurred in the 1980s, the International Maritime Organization (IMO) in London adopted the International Management Code for the Safe Operation

of Ships and for Pollution Prevention (International Safety Management Code, or ISM Code) in 1994. The development of the ISM Code was based on the recognition that a number of serious incidents had manifestly been caused by human errors by crew members. The primary objective of the ISM Code is therefore to ensure the safe operation of vessels and thus protect persons on board ships and avoid damage to the environment. According to the ISM Code, entities responsible for the operation of ships must ensure, among other things, that each ship is manned with qualified, certified and medically fit seafarers, who must undergo regular training to prepare them for emergencies, the aim being to prevent incidents in future.

Joint action – more effective than going it alone

Despite the existence of these agreements, an effective cross-border response to marine pollution incidents involving oil was lacking for some time. Granted, Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden and the United Kingdom signed the Agreement for cooperation in dealing with pollution of the North Sea by oil and other harmful substances (Bonn Agreement) in Bonn in 1969, just two years after the *Torrey Canyon* disaster, with the accession of the

European Union and other European countries following in 1983. However, there was an ongoing lack of well-coordinated contingency plans for a systematic response to major oil spills, and in many cases, the division of responsibilities remained unclear until only a few years ago.

The *Pallas* incident is a good example. The cargo vessel *Pallas* caught fire in the North Sea in 1998. Danish and German rescue teams evacuated the crew, but left the abandoned vessel with no one at the helm in rough weather. The ship drifted out of Danish into German territorial waters, but the German authorities were unable to agree which agency was responsible for the vessel. The *Pallas* finally beached on a sandbank in Germany's Wadden Sea. Fortunately, only around 90 tonnes of oil were lost, but countless seabirds were oiled and several square kilometres of the Wadden Sea – an ecosystem extremely sensitive to oil pollution – were contaminated. As a result of the incident, Germany set up the Central Command for Maritime Emergencies (CCME) (*Havariekommando*), which is responsible for mounting an oil spill and marine pollution response and for fire fighting at sea. The CCME also directs the deployment of large emergency towing vessels, which have been stationed along the North Sea and Baltic Sea coasts in recent years. These powerful vessels are used to tow disabled ships into deeper waters or to a safe haven, thus preventing them from running aground and leaking oil, as occurred with the *Pallas*.

International cooperation is more effective nowadays as well. Various contingency plans are now in place, backed up by international exercises to practise the oil spill response. These take place every year over several days and involve as many as 50 vessels from various countries. Under the Bonn Agreement, for example, ships from all the signatory countries come together for the joint Bonn exercise in the North Sea.

The Baltic Sea is protected under the Helsinki Convention, which entered into force in 2000. Under this Convention too, all the states bordering the Baltic Sea hold an oil spill response exercise, known as Balex (Baltic Exercise), which takes place in summer every year in a different area of the Baltic Sea. The contingency plans include provisions stating how information is to be

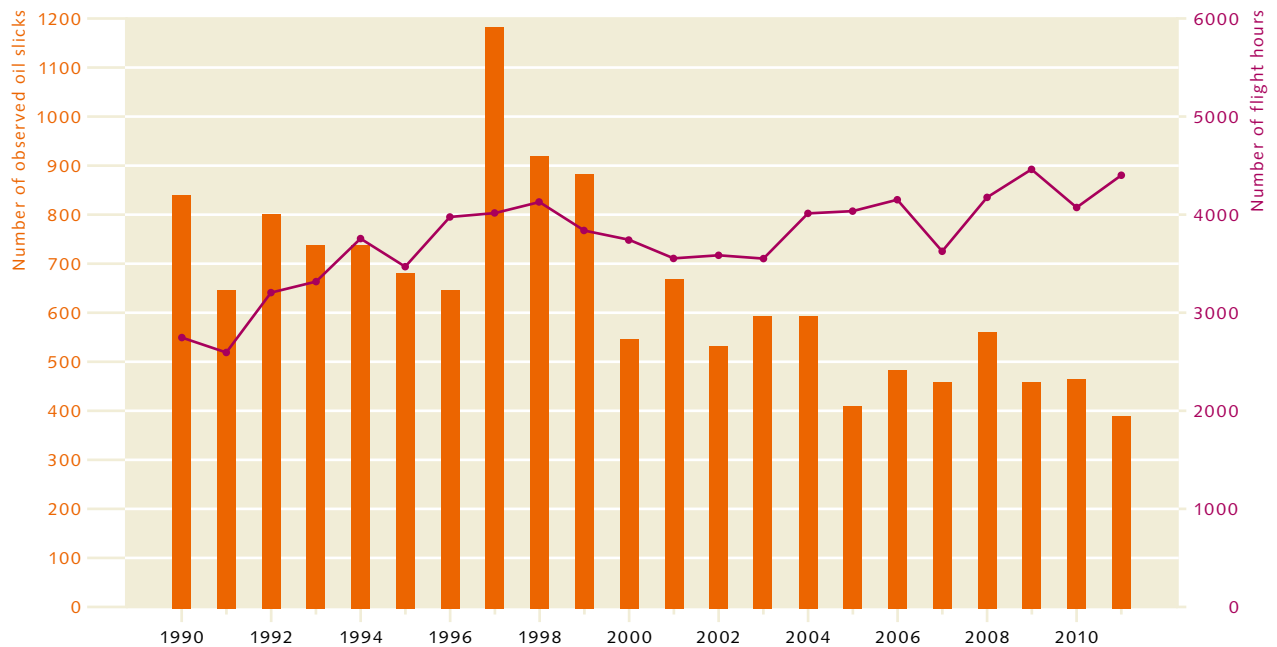
The MARPOL Convention

The MARPOL Convention is an international agreement which covers, and has done much to reduce, pollution of the marine environment by ships. It was adopted by the International Maritime Organization (IMO) in 1973, and was modified and expanded in 1978, resulting in the designation MARPOL 73/78. The Convention consists of a main agreement and several annexes. The main agreement sets forth the general obligations under the Convention and defines its scope of application, whereas the technical annexes contain clear and detailed provisions on dealing with sewage, garbage, oil and noxious/harmful substances on ships. Annex 1, which deals with oil, entered into force in October 1983. Among other things, it requires the disposal of waste oil in approved shore facilities and makes double hulls mandatory for tankers. In accordance with Annex 1, crews must also keep an oil record book, in which the total quantity of oil and oily water on board and the total content and identity of tanks must be recorded.

passed on, e.g. by email, radio or fax, and who is responsible for decision-making. They also specify which ships are to be deployed and when.

Analogous to the agreements on the North Sea and the Baltic Sea, the Barcelona Convention deals with the protection of the Mediterranean Sea. The Barcelona Convention was signed in 1976. The Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) was set up in Malta the same year and is responsible for dealing not only with oil-related incidents but also with other forms of pollution. One of its primary objectives was to develop and strengthen the technical capacities of coastal states in the Mediterranean region to combat oil pollution. REMPEC also organizes exercises, albeit less regularly than in northern Europe. In most cases, the exercises do not involve all the Mediterranean coastal states but only those from a specific area of the Mediterranean. Workshops are also organized, but again, these generally target coastal states from a specific Mediterranean region, usually the European or Arab countries.

As the history of oil spills shows, many of the measures described were adopted only after serious incidents had occurred. This applies to the oil spill response in South East Asia as well. On 7 December 2007, a drifting crane barge rammed the tanker *Hebei Spirit* close to



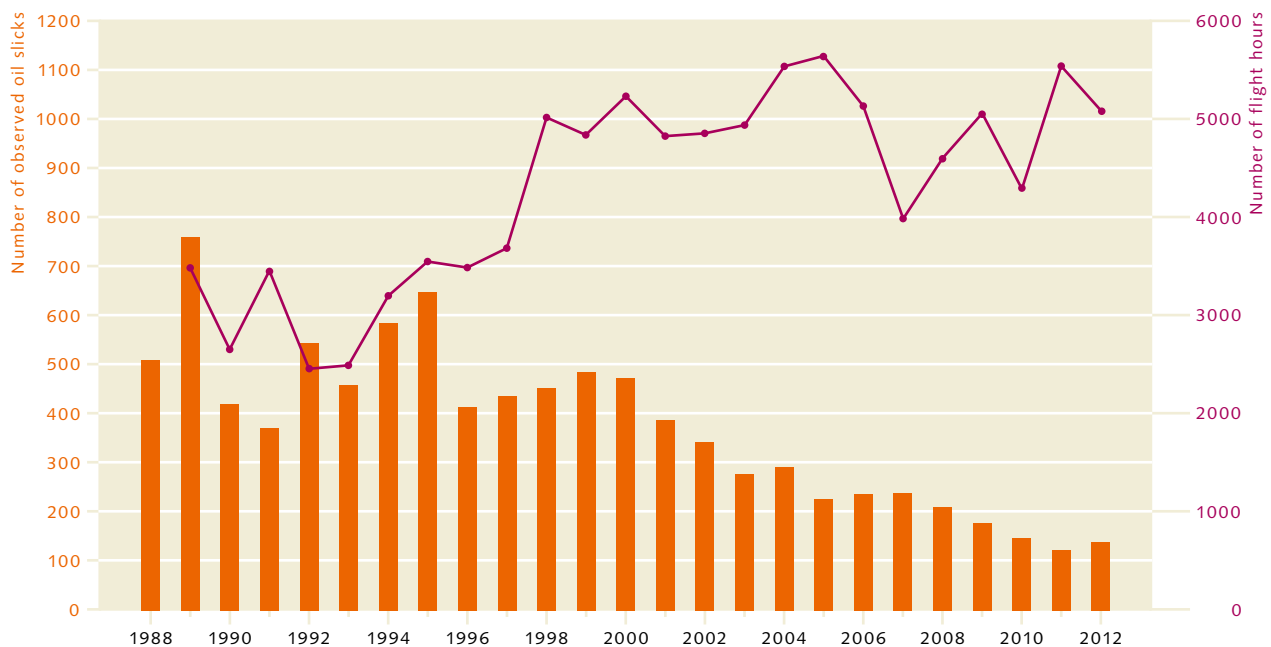
1.42 > The number of observed oil slicks in the North Sea area has halved since 1990.

Taeanhaean National Park in South Korea. The tanker was holed and lost 11,000 tonnes of crude oil. Within a matter of hours, the oil slick was many kilometres long. It polluted the tourist beaches and contaminated mussel farms. According to experts, the oil spill caused damage amounting to around 250 million Euros. Back in 1994, South Korea and its neighbours China, Japan and Russia had signed an agreement – the Northwest Pacific Action Plan (NOWPAP) – to protect this sea area, but a joint contingency plan was still lacking. Just 11 days after the *Hebei Spirit* incident, nations took action: at South Korea's behest, the countries concerned adopted the Regional Oil Spill Contingency Plan. Since then, the countries have held various joint oil spill exercises. The most recent, in May 2012, was organized jointly by China and South Korea and took place off the South Korean coast.

Some of the oil-exporting nations in the developing world have yet to achieve the same level of progress. This applies, for example, to the West and Central African countries. Although many of these countries have produced contingency plans in recent years, there is often a lack of proper coordination and technical equipment. According to an international study, even the major oil-exporting nations – Cameroon, Ghana, Nigeria

and Angola – lack specialized oil spill response vessels. Cameroon and Ghana only have small towing vessels and a number of booms available for use in emergencies, and Angola and Nigeria have no inventory of oil spill response equipment at all. According to the relevant contingency plans, this is to be supplied by the oil companies, if required. This includes coastal cleanup equipment, such as specialized tanker lorries with suction gear. In the event of an incident, dispersant spraying systems are to be deployed from chartered ships or helicopters.

The study identifies a further problem: although many of the West and Central African countries have set up emergency telephone numbers, they are often not functional. Document distribution and information exchange between the relevant authorities and institutions are clearly dysfunctional, too, and information is sometimes lacking in detail. This makes it more difficult to ensure good coordination between all the various agencies in the event of an incident. In other countries in West and Central Africa, the situation is even more sobering. Six countries have no contingency plans at all, while others lack the fundamental elements that should be a given in any oil spill response, such as a central emergency telephone number or radio frequency for



reporting and alerting. It is debatable, therefore, whether these nations would be able to mount an adequate response to a major oil spill unaided.

Aerial surveillance stops polluters

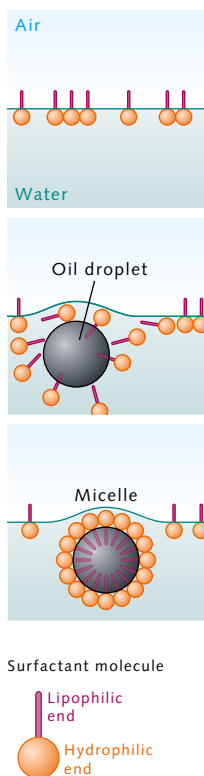
As regards the ongoing but less visible oil pollution of the marine environment by ships, the situation has improved in various regions of the world. Again, the MARPOL Convention has made a contribution here. MARPOL defines seven of the world's sea areas as "special areas" which are provided with a higher level of protection than other areas of the sea. Only tankers which comply with specific safety standards are permitted to transit these sea areas; these include limits on the size of tanks on oil tankers in order to minimize the amount of oil that could escape in the event of an incident causing damage to the hull. The special areas are:

- the Antarctic Area (since 1992);
- the "Gulfs" area (since 2008);
- the Mediterranean Sea (since 1983);
- the North West European Waters/North Sea (since 1999);
- the Baltic Sea (since 1983);

- the Black Sea (since 1983);
- the Southern South African Waters (since 2008).

In several of these special areas, such as the Mediterranean, the North Sea and the Baltic Sea, aerial surveillance has been in operation for many years. As oil spills can be easily detected by aircraft fitted with special camera systems, vessels whose crews have cleaned out the tanks at sea or discharged oil can be identified very quickly. As causing pollution in the special areas results in criminal prosecution, aerial surveillance has had a deterrent effect, resulting in a noticeable decrease in the number of illegal discharges. The black lumps of oil which often washed up on beaches in the 1980s are rarely seen in Western Europe nowadays. Furthermore, for some years now, efforts to detect oil pollution have been supported by satellite data. However, satellite images can sometimes be misleading: algal blooms are occasionally misinterpreted as oil slicks, for example. Many of the relevant authorities therefore generally deploy aircraft to check out pollution alerts. The benefit of satellite surveillance from space, however, is that it provides a broad overview of large areas of the sea. In China and some European countries, various research projects are currently under way to improve data evalu-

1.43 > In the Baltic Sea, the number of observed oil slicks has decreased by almost three quarters. Experts attribute the improvement in the situation in Northern European waters to the deterrent effect of aerial surveillance, among other things.



1.44 > Surfactants are deployed in the oil spill response. Their molecules have a hydrophilic end, which binds to water, and a lipophilic end, which binds to oil. They surround small oil droplets and break up larger quantities of oil.

ation. A joint programme has also been launched in Norway, involving the military, environmental agencies, meteorological institutions and universities, to investigate to what extent satellite data can be used in the surveillance of Norway's territorial waters in future.

Despite the clearly positive trend in Europe, the number of oil spills here is still relatively high compared with other regions of the world. This is due to the high volume of merchant shipping in this region, particularly in the English Channel, which frequently causes pollution incidents. Only Asia has more oil spills, mainly in the Strait of Malacca between Indonesia and Singapore. In Chinese waters, the number of oil pollution incidents has actually increased in recent years, due to the country's economic growth and burgeoning exports and imports, which have resulted in a substantial increase in shipping. In the US, on the other hand, the amount of oil entering the environment has decreased dramatically since 1990. US authorities attribute this reduction primarily to the stringent provisions of the Oil Pollution Act.

Constraints on the oil spill response

When crude oil spills into water, the oil spreads out and forms a thin film that floats on the surface of the water. Depending on the temperature, the volatile organic compounds (VOCs) in the oil, such as benzene, evaporate within a matter of hours. These can constitute as much as 30 to 50 per cent of the oil's original mass.

Oxygen and ultraviolet (UV) radiation from the sun also react with the oil, changing its chemical properties. Finally, within a few days, a dense and viscous oil slick forms, mainly consisting of large hydrocarbon molecules. During the first few hours or even during the first few weeks, the oil is modified by the following chemical and physical processes:

- evaporation of volatile organic compounds (VOCs);
- spreading of the spilled oil in large oil slicks drifting on the surface waters;
- formation of dispersions (small oil droplets in the water column) and emulsions (larger droplets of oil-in-water or water-in-oil);

- photooxidation (molecular changes to the oil constituents caused by natural sunlight) and solution.

Once the chemical and physical properties of the oil have been modified, it becomes almost impossible for oil spill control vessels to skim the oil off the surface of the water. Some of the oil sinks to the sea floor. For that reason, it is particularly important to mount a rapid response whenever oil pollution incidents occur.

In Western Europe, the oil spill response relies primarily on specialized vessels equipped with devices known as sweeping arms. These skim the oil/water mixture off the surface of the water and transfer it to storage tanks on board. Until the 1990s, these vessels had very limited capacity, so the tanks filled up very quickly. Over the past 15 years or so, however, many ships have been fitted with oil separators which remove the oil from the water. The clean water is then pumped overboard. This has increased the vessels' response capacities. However, there are constraints on the use of sweeping arms, as the slender devices cannot be deployed in high winds or heavy swell. German researchers have therefore been working on the development of a sea swell-independent oil skimmer (SOS) for some years. Suspended between the hulls of a catamaran, the SOS will have the ability to operate in storms and rough seas, moving into an oil slick and siphoning the oil film off the water.

Dispersants can also be used to prevent the formation of an oil slick. These substances break up oil slicks in accordance with the same principle by which washing-up liquid dissolves residual grease from food. Dispersants contain surfactants, whose molecules have a lipophilic and a hydrophilic end. They work by bonding to the oil molecules and separating them from water molecules – thus breaking up an oil slick into small droplets, which they then surround and isolate. Experts call these droplets "micelles". The advantage is that bacteria can break down the numerous small micelles much more easily than a large slick. Chemical dispersants were used in very large quantities after the *Deepwater Horizon* explosion. They were sprayed on the surface from aircraft but were also used deep underwater on the sea floor, where they were mixed with the oil



1.45 > During an oil spill exercise off Helsinki, the multipurpose vessel *Hylje* uses a sweeping arm to capture foam that is specially designed to simulate an oil slick.

emerging from the well. According to critics, the use of dispersants is problematical because some surfactants are toxic. Proponents of dispersant use, on the other hand, argue that surfactants are very heavily diluted in water and therefore pose no threat to marine life. For the advocates of dispersant use in oil-spill response, the benefits far outweigh the potential environmental risks.

There are limits, however, to dispersant use as well. It is almost impossible to spray them on target during storms, when aircraft are often grounded anyway.

Even today, the response to major oil spills can never be entirely satisfactory. In the view of oil spill response experts, prevention is therefore the best strategy. Seaways with modern traffic control systems and well-trained maritime pilots who can play a monitoring role are part of a preventive approach. Ship owners must also ensure that their vessels are seaworthy and equipped with appropriate technology and that crew members are properly qualified.

Coasts at risk

Oil is a naturally occurring mix of hydrocarbons which is broken down by bacteria in a biological process.

These bacteria are particularly active under the following conditions:

- high temperatures, promoting bacterial activity;
- a large surface area (if necessary, the surface area of the slick can be increased through the use of dispersants which promote the formation of dispersions);
- a good oxygen supply;
- a good supply of other key nutrients;
- a low number of predator organisms which would reduce the number of bacteria.

As the breakdown of oil by bacteria is much slower at lower water temperatures, oil disasters in cold-water areas are particularly devastating. For example, oil residues from the *Exxon Valdez* tanker disaster are still present in the shoreline strata of Prince William Sound, where they can be found at many different sites. In some cases, the oil has penetrated several centimetres below the surface.

How long does it take for an oiled coastline to recover? This depends on the type of shoreline. Exposed rocky and sandy shores with strong surf and wave action generally recover within a few months or, more



1.46 > For a month after the *Deepwater Horizon* disaster, droplets of oil accumulated along the beach at Grand Terre Island on the Louisiana coast.

rarely, within a few years. Sandy beaches are affected to varying degrees. Coarse-grained sand facilitates oil penetration, slowing the breakdown of the oil. Again, beaches with heavy surf generally recover more quickly than extensive beaches with little wave action.

Oil pollution is particularly problematical in mangrove forests, which are unique, species-rich habitats. Covered in oil, the vegetation dies, destroying the habitats of many other species of flora and fauna. What's more, oil penetrates to great depths in the soft sediments of mangrove forests and remains in the ground for long periods. Salt marshes are similarly affected: here too, the vegetation forms characteristic and rare habitats for very well-adapted flora and fauna. These ecosystems are lost when oil kills off the vegetation.

Oil pollution also poses a particular threat to soft substrates and sandbanks, such as those found in the Wadden Sea on the North Sea coast. Here, most organisms live in or on the sea floor and are therefore particularly at risk from oil slicks. Mangroves, salt marshes and soft substrates take at least two years, and sometimes more than 20 years, to recover from oil pollution. For such sensitive habitats, even smaller oil spills can become a very serious problem.

According to environmentalists, there is a special threat to the Arctic waters, due to the Arctic nations' plans to carry out oil drilling here in future. Russia and the US, in particular, have ambitions to develop the oil and gas reserves in their northern regions. But developing these reserves is likely to pose major challenges. Drift ice could destroy drilling and production rigs, and tankers could be wrecked in the ice.

When Shell Oil Company began test drilling in Alaska in 2012, for the first time in 20 years, it faced massive protests from environmental groups. They warned about the particular risks posed by drilling in sea ice, the possibility of tanker incidents, and the likely impacts of an oil disaster.

Much of the Arctic is still a natural habitat with unique and largely untouched ecosystems, which could be massively damaged by oil – not least because an effective oil spill response is almost impossible to mount in an icy environment, and because the oil would biodegrade very slowly in the region's very cold tempera-

tures. And indeed, the drilling programme was beset by problems. Equipment was damaged by the ice, and a drilling rig, *Kulluk*, ran aground. After the project came under severe criticism in an official report in the US, Shell cancelled its 2013 drilling programme. Among other things, the report drew attention to the inadequate safety standards for Arctic drilling.

In spring 2013, Shell signed a memorandum on cooperation with the Russian energy company Gazprom, focusing on hydrocarbon exploration and development on Russia's Arctic shelf. Critics fear that safety standards will be even lower here, and are warning about the risk of a major oil disaster. It is difficult to predict the future of oil exploration and development in the Arctic regions of the US, where industry and environmental organizations are currently at loggerheads over the level of protection that should be afforded to the Arctic. Industry associations warn that excessively stringent safety regulations will make the development of an oil industry economically non-viable, whereas environmental groups are calling for a total ban on oil production in the Arctic. Experts take the view that oil companies in the US will continue to have their sights firmly fixed on the Arctic's oil reserves, and that US companies will step up their efforts to exploit these resources as soon as other countries, but particularly Russia, discover major oil reserves in their exclusive economic zones.

Should coasts be protected or abandoned?

Major incidents often result in the formation of massive oil slicks, extending for hundreds of kilometres. In these situations, it is impossible to protect the entire coastline. The response must therefore focus on the most important and sensitive stretches of shoreline. Protecting nature reserves or habitats for rare fauna and flora is regarded as a priority, and economically important zones, such as aquaculture facilities, should also take precedence. Sensitivity maps now exist for many regions of the world. They provide detailed information about the oil pollution sensitivity of various stretches of coastline, and identify the species of flora and fauna occurring there. Key factors are species' rarity, the level

1.47 > Seabirds are among the most obvious victims of oil spills. This heron was completely coated in oil from *Deepwater Horizon*.



of risk posed to them by oil pollution, and how likely it is that species would die out locally in the event of an oil pollution incident. Often, it is not the seabirds or marine mammals which are most at risk, but rare species of plant or insect. All this information is also used to prepare contingency plans. Response teams are now supported by computer programs which provide access to databases containing sensitivity data. This information can be linked with up-to-date meteorological data to calculate the route of the oil slick and the extent to which important areas will be affected. In this way, response teams can direct oil spill response vessels to areas in particular need of protection or ensure that booms are set up to defend them.

The effects of oil on flora and fauna

After numerous oil pollution incidents, we now have very detailed information available about the effects of oil on flora and fauna. The most obvious effect is the damage caused to seabirds' plumage. As a result of oil contamination, the plumage can no longer perform its vital functions of repelling water and providing thermal insulation. As a result, the bird loses body heat and dies. A similar effect can be observed in marine mammals, such as otters, which can die of cold if their fur is coated

with oil. Furthermore, birds and mammals often ingest oil when they attempt to clean their oil-coated feathers or fur, and this can poison them. Fish absorb toxic hydrocarbons through their skin and gills. In plants, oil contamination interrupts gas exchange through the leaves and nutrient transfer by the roots, which causes the plant to die.

Filter feeders such as mussels and other organisms often ingest oil along with their food. The toxic hydrocarbons in the oil and the clogging up of their internal filtration systems generally kill them very quickly. If the mussels survive, the toxins can be passed along the food chain when the contaminated mussels are eaten. The effects of the toxic hydrocarbons vary from species to species. Experiments with crab or mussels show that it is mainly their metabolic processes and growth which are impaired. In other organisms, reproduction is adversely affected. Poisoning by oil can cause genetic damage: in herring, for example, numerous freshly hatched progeny were malformed. Furthermore, many marine fauna lose their sense of direction, as many of them use very fine concentrations of certain substances in the water as a means of finding their way around their environment. This is disrupted by certain hydrocarbons, making it more difficult for them to forage or identify partners for reproduction.

CONCLUSION

**Less marine oil pollution –
despite growing energy demand**

The international debate about climate change and carbon dioxide emissions notwithstanding, our energy consumption is increasing year by year. Global energy demand has doubled since the early 1970s and is likely to grow by a further one-third by 2035. The world's insatiable energy hunger is mainly caused by population growth in Asia and ongoing industrialization in the emerging economies.

Even with the expansion of renewables, experts predict that fossil fuels – coal, oil and gas – will continue to provide most of our energy. Whereas there is enough coal and gas to meet demand well beyond the end of this century, oil production is likely to decrease by 2050. Many coal and gas deposits onshore and in shallow marine waters are almost completely depleted. Tertiary recovery techniques, which involve pumping hot water or polymers into the reservoirs to extract the remaining oil, are now being employed in an attempt to increase yields.

The industry is also moving into ever deeper waters. Although deep-water gas and oil extraction is around four times more expensive than shallow-water production, rising oil prices are making it more economically viable. Oil is now being extracted at depths of more than 2900 metres below the surface of the sea, and the water depth record for subsea gas production is currently around 2700 metres.

Various types of platform are used by the oil and gas industry. Drilling operations generally involve the deployment of specialized drilling rigs, which are then replaced with production rigs once drilling is complete. In many regions today, production systems are also being installed directly on the sea floor. These subsea systems involve the

use of compressors, pumps and power supply modules in a single seabed facility.

As the blowout at the *Deepwater Horizon* drilling rig in the Gulf of Mexico in 2010 showed, oil production at great depths presents particular challenges. In the case of this particular blowout, it took a full three months to cap the flow of oil from the seabed. Oil disasters on this scale are a tragedy. Thankfully, however, such large-scale incidents, or indeed tanker disasters, now account for just 10 per cent of marine oil pollution in an average year.

A much greater problem is the ongoing marine pollution that travels along less obvious pathways – in other words, the chronic contamination of the marine environment from numerous smaller sources, such as oil discharges from shipping as a result of illegal tank cleaning or carelessness during loading. But as the European countries have demonstrated, pollution incidents of this kind can be reduced with intensive aerial surveillance of coastal waters.

The good news is that marine oil pollution has decreased worldwide in recent decades. International conventions and agreements on the protection of the marine environment have made a very significant contribution here, for example by introducing a mandatory requirement for double hull tankers.

Surveillance of seaways has also improved dramatically, thanks to better radar technology and vessel identification systems. And many countries have adopted detailed contingency plans for an organized and internationally coordinated oil spill response.

Despite this positive trend, the amount of oil entering the oceans every year – around one million tonnes at present – is still far too high, with oil continuing to contaminate countless marine habitats and organisms.

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