world ocean review

Living with the oceans. 2014

3

Marine Resources – Opportunities and Risks

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Preface

Following on from *World Ocean Review 2*, which explored the future of fish and fisheries, I am delighted to present the third volume in the series. In this *World Ocean Review* (WOR 3), we focus on marine resources and the opportunities and risks associated with their potential exploitation.

Two salient facts merit particular attention. Firstly, very little is known at present about the resources found in the world's oceans, and their exploration and especially their production pose immense technical challenges. And secondly, there is insufficient public awareness and debate about these resources and their utilization. Oil, gas, minerals and methane hydrates lie in the lightless depths of the oceans, and their extraction is hidden from sight. Even the products manufactured from them are not always obvious or tangible in our daily lives. This contrasts sharply with the large body of information available about the world's fish stocks and the fishing industry, and the public's justified interest in this topic. Obtaining food from the sea is fundamental to our lives and has formed part of our consciousness for thousands of years. In that sense, raising people's awareness of the problems associated with fishing is a relatively simple task. Indeed, politicians are now responding to growing public pressure – partly created by publications such as WOR 2 – and are turning their attention to more sustainable fishing in the hope that the extinction of numerous species of fish can still be averted.

But there is still a long way to go before we achieve a similar level of knowledge and public awareness of marine resources. In my view, it is crucial to launch a debate about the use of these non-living marine resources – for without our natural collective interest in these diverse problems, we cannot exert the pressure that is needed to ensure that marine resources are extracted and utilized in a sustainable manner.

In this volume, you will find information about the formation, exploration and production of marine resources: not only oil and gas but also ores, in the form of manganese nodules, cobalt crusts and massive sulphides. A separate chapter is devoted to methane hydrates. The extraction of all these resources poses major technical challenges and is a highly contentious issue due to the environmental risks involved. It could also become the basis for a powerful economic sector with the prospect of extremely high returns and significant political ramifications.

Yet if such large-scale business is hidden from view, this not only poses a threat to the environment: it also jeopardizes fundamental human rights and social justice. The multinationals in particular, such as Shell, ExxonMobil and Total, which have been producing oil in West Africa for years, saw no need to protect the natural environment or to ensure equitable sharing of benefits from oil revenue in the past.

There are very significant opportunities but also risks for the future in and on the seabed. I hope that WOR 3 will give you all the facts you need.

Nikolaus Gelpke
maribus gGmbH Managing Director, mareverlag publisher and IOI President

Humankind has lived with the sea and utilized its services since time immemorial. We are drawn to the sea, for the coasts offer many benefits to local communities. But with the world's population rapidly increasing, many of us are starting to worry about the future of the oceans and the coasts. How can a balance be achieved between conservation and use? Is development towards sustainable use of marine resources possible?

These questions are particularly relevant in the case of mineral and energy resources from the sea. Resources that regenerate quickly, such as fish, shellfish and algae, can in principle be exploited sustainably, provided that their habitats are secure and harvesting is regulated so that enough of the resource remains in the sea to allow reproduction. The challenges relating to fishing, for example, were discussed in *World Ocean Review 2*. Mineral and energy resources, however, form over many millions of years, and there is only a finite amount of these resources available for future generations. What's more, they often lie hundreds of metres under the seabed and can only be extracted with complex technology. How can these resources be exploited equitably and, as far as possible, sustainably? And can the environmental pollution associated with their extraction be minimized?

World Ocean Review 3 is dedicated to these marine resources. It focuses on their utilization as sources of energy and metals, and gives the facts about the known oil and gas deposits beneath the seabed and the fixed gas hydrate deposits on the continental shelves. It informs readers about the potential afforded by the three main types of mineral deposit: manganese nodules, cobalt crusts and massive sulphides.

Methane hydrates are the subject of much discussion at present. Very extensive deposits of what is effectively natural gas trapped in ice are believed to exist – perhaps larger than all the world's known oil and gas reserves combined. There are initial plans to extract gas hydrates on the continental shelves. This will create risks, but also opportunities. Methane hydrates are a cleaner fuel than coal. Could methane hydrate extraction be a bridging technology in the transition to a sustainable energy supply for our societies?

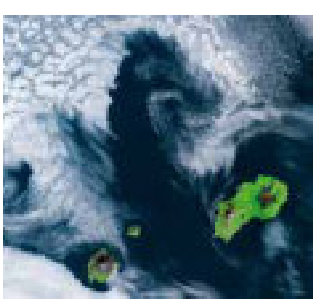
Marine resources have great potential, and it may be possible to start exploiting them profitably very soon. However, their extraction is fraught with risks and could potentially cause severe degradation of the marine environment. Is that what we want? If not, what mitigation options exist? What kind of framework must be negotiated at the national and global political level?

The future of the oceans is intimately linked with the future of marine and coastal resource extraction and therefore with most people's, if not everyone's, future. In that sense, I wish you an interesting and informative read.

Martin Visbeck

Prof. Dr. Martin Visbeck
Spokesperson of the Cluster of Excellence "The Future Ocean"




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

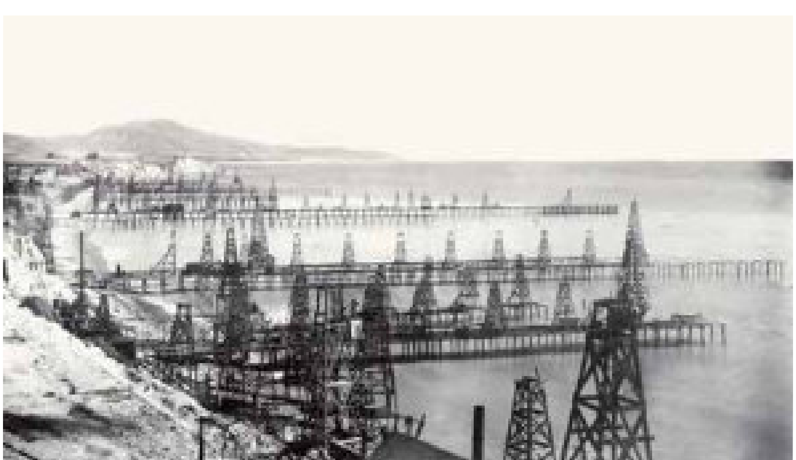
> Around a third of the oil and gas extracted worldwide comes from offshore sources. This figure is likely to continue to rise over the coming decades, for abundant oil and gas deposits still exist deep in the oceans. But with many oil and gas fields in shallow waters now more or less exhausted, companies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

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



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.

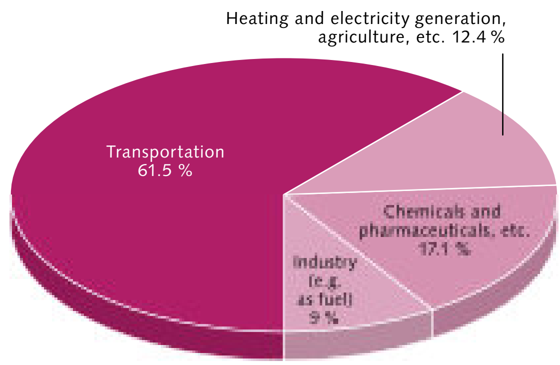
Energy consumption in Europe has decreased in recent years due to the use of modern machinery and efficient electric engines, energy-saving measures and better insulation of buildings. Globally, however, energy consumption is increasing. Total consumption of energy has doubled since the early 1970s and, 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, 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

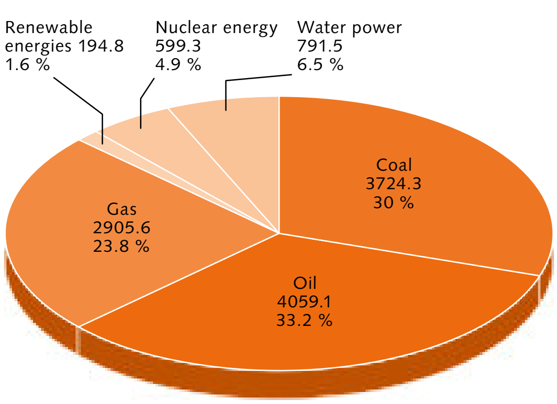
Oil is currently the most important fossil energy source, followed by coal and natural gas. Oil accounted for around 33 per cent of world primary energy consumption in 2011, followed by coal and natural gas with around 30 and 24 per cent respectively. The remainder comes from nuclear energy, hydropower 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 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.



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.

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.

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.



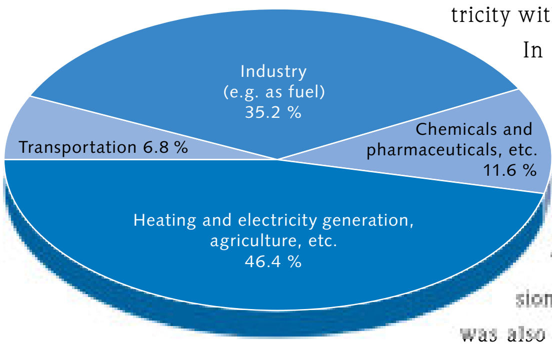
1.2 > Oil and coal are the world's most important fossil fuels. The figure shows global primary energy consumption in 2011, together with the percentage share for each energy source. For oil, primary energy consumption is shown in millions of tonnes. For the other energy sources, it is shown in MTOE.

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 electricity 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.

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 Fukushima 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.



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

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.

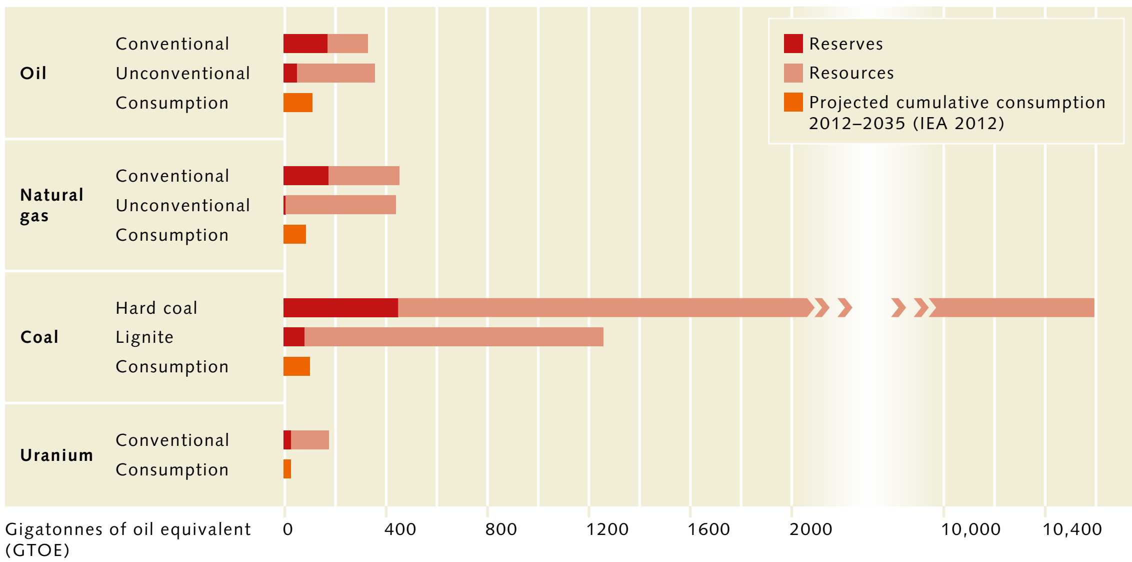
Reserves: To be classed as a reserve, an oil or gas deposit must fulfil three conditions: it must have been confirmed by drilling; it must have been accurately measured; and it must be recoverable economically at current prices using current technology.

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 unconventional 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.

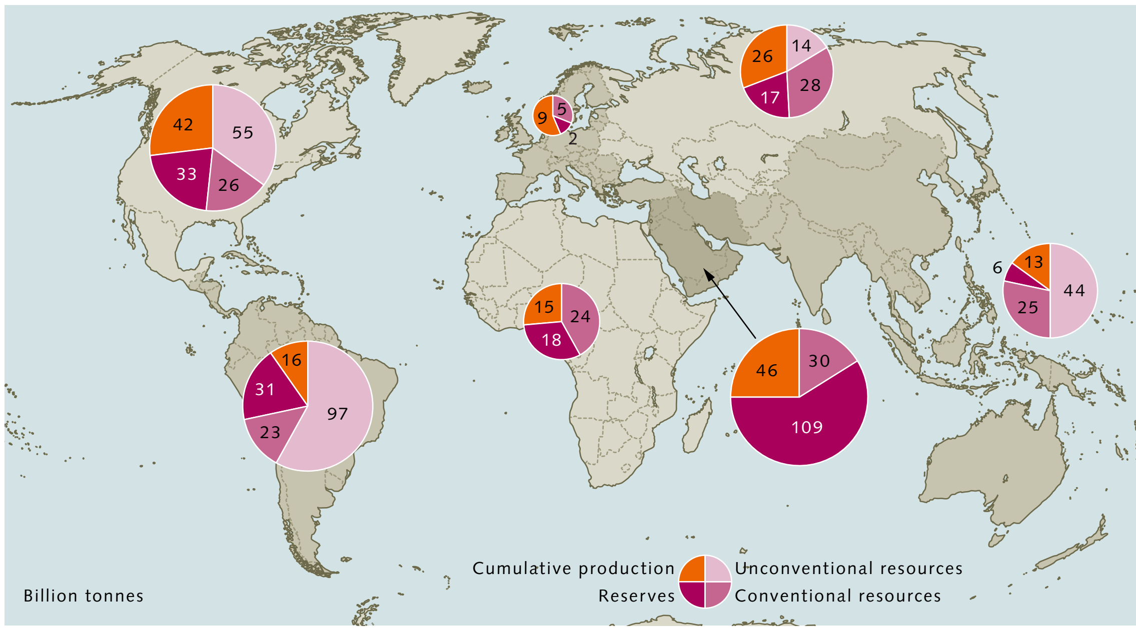
Still enough oil

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

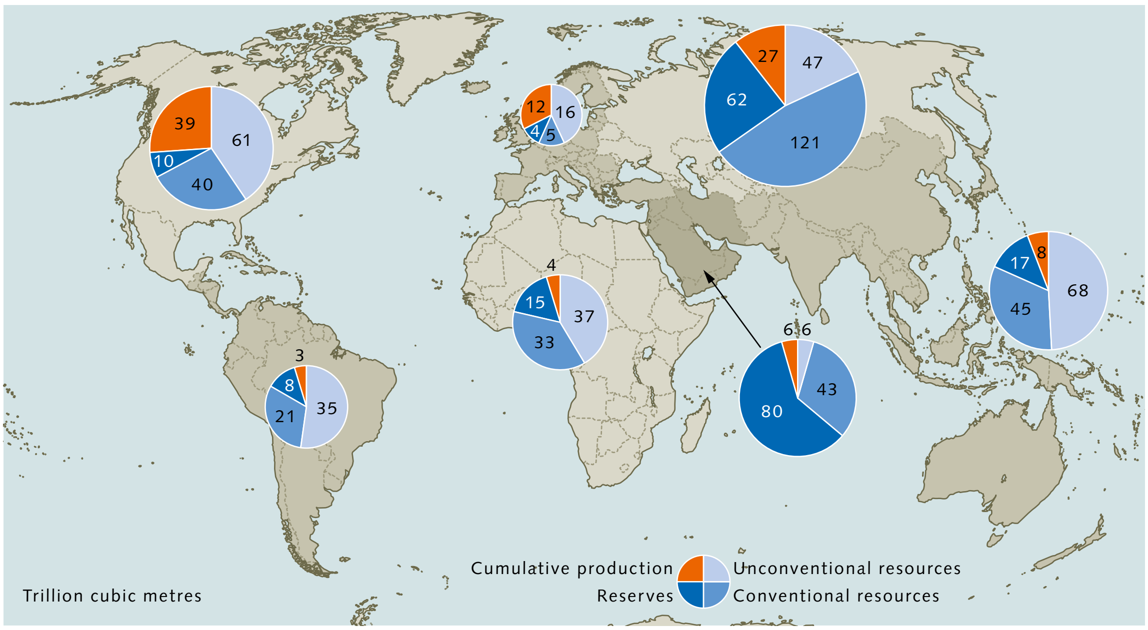
Some experts are now predicting a "peak plateau" over the coming years: this means that oil production will be sustained at a high level over a longer period of time. However, oil prices will continue to rise, as oil production will increasingly rely on unconventional deposits whose exploitation requires 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 deepwater 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.

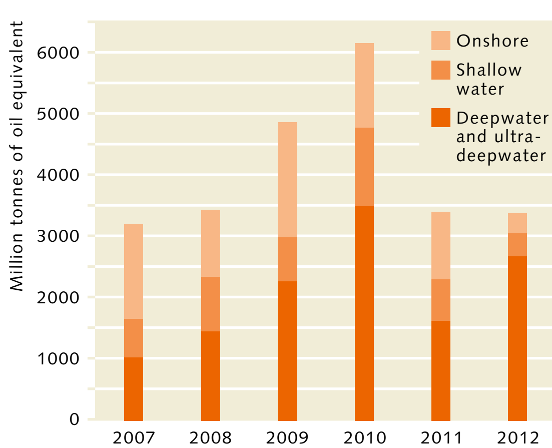
Many experts agree that deepwater and ultra-deepwater fields are the last bastion of oil production. Many of the once high-yielding fields onshore and in shallow waters are almost exhausted, so there is virtually no alternative to deepwater and ultra-deepwater production now and over the coming years.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

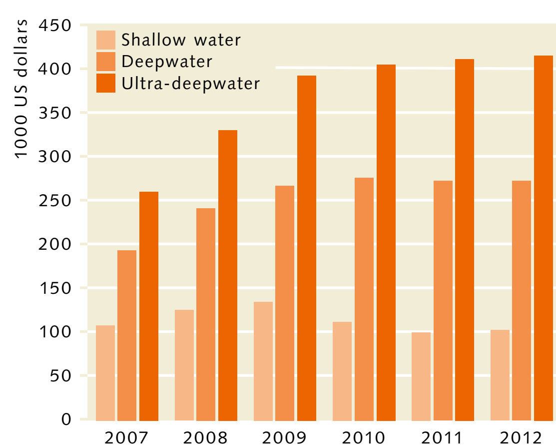
Promising maritime regions

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.

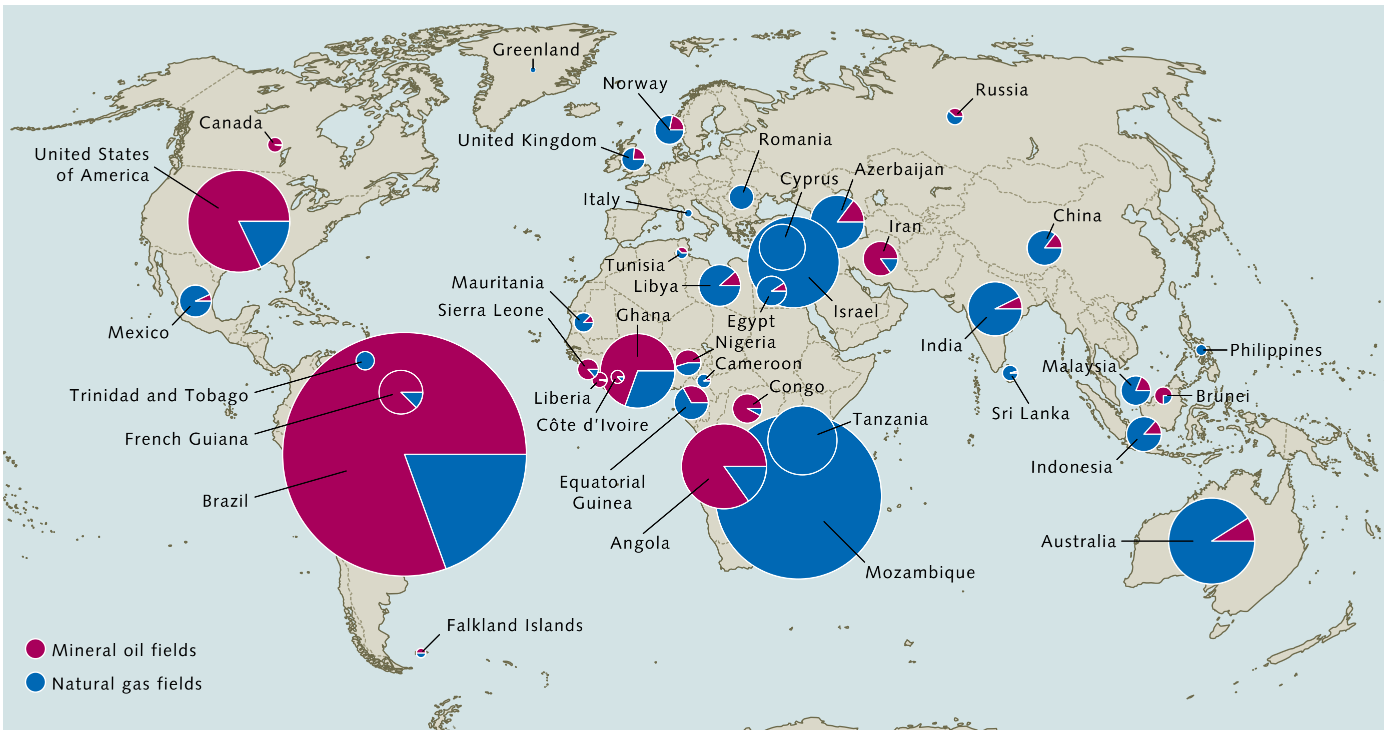
On the other side of the Atlantic, in the Kwanza Basin off the Angolan coast, oil fields have been discovered beneath a 2000-metre thick pre-salt layer. In the



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.

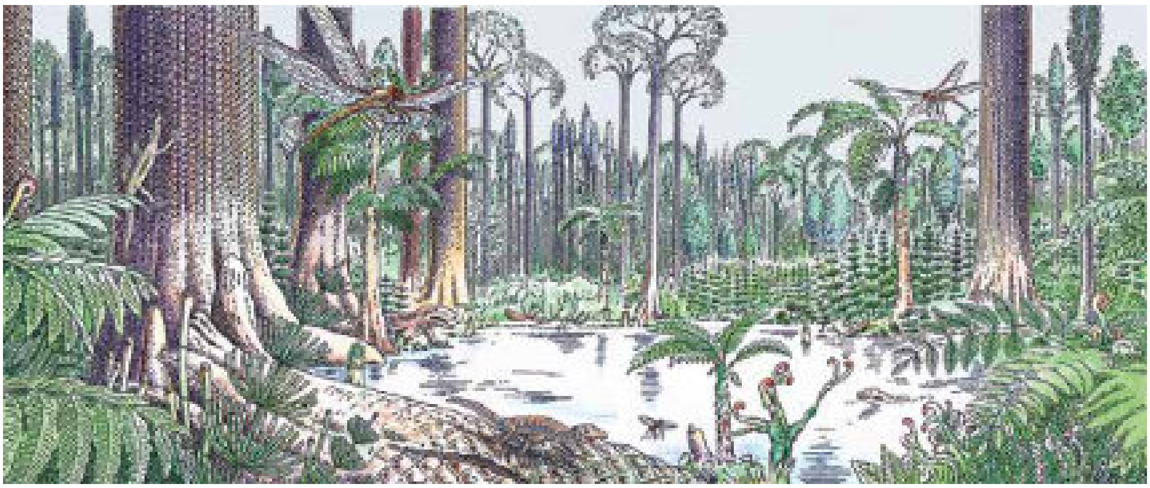
Over periods lasting many millions of years, so much of the organic sludge was deposited on the sea floor that, due to its enormous weight, it gradually changed to claystone and was finally compressed and hardened into a clay-rich shale. Even today it can be said that, to some extent, in these porous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

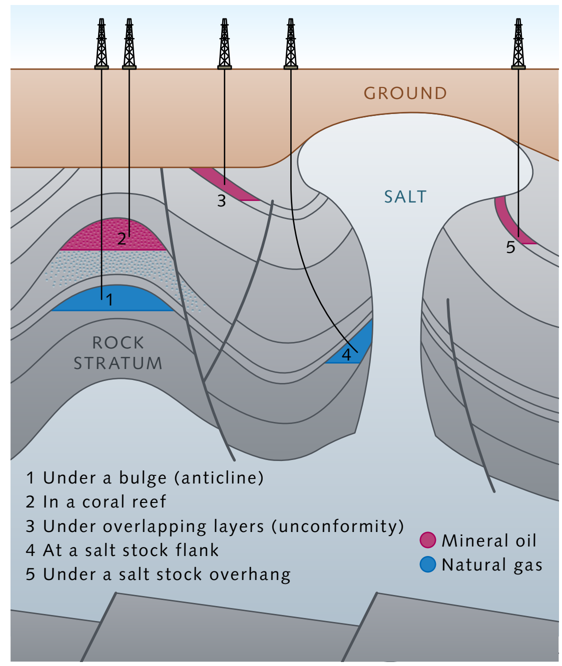
Gas or oil accumulations that are too small to be economically produced, however, occur much more frequently in nature.

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.

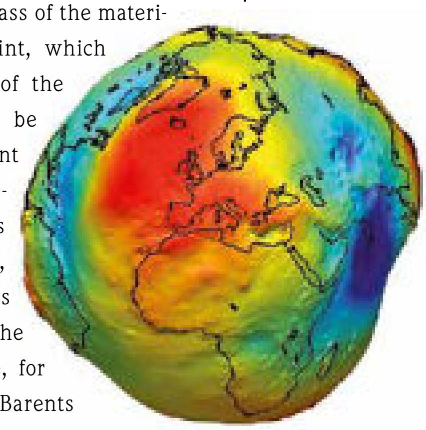
Prospecting begins with a determination of whether gas and oil can be expected to occur in a certain area. This includes an initial collection of data relating to the deep rock strata in order to determine the geological development of the area in question. Computer programs called basin analysis systems 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 measureable. 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.

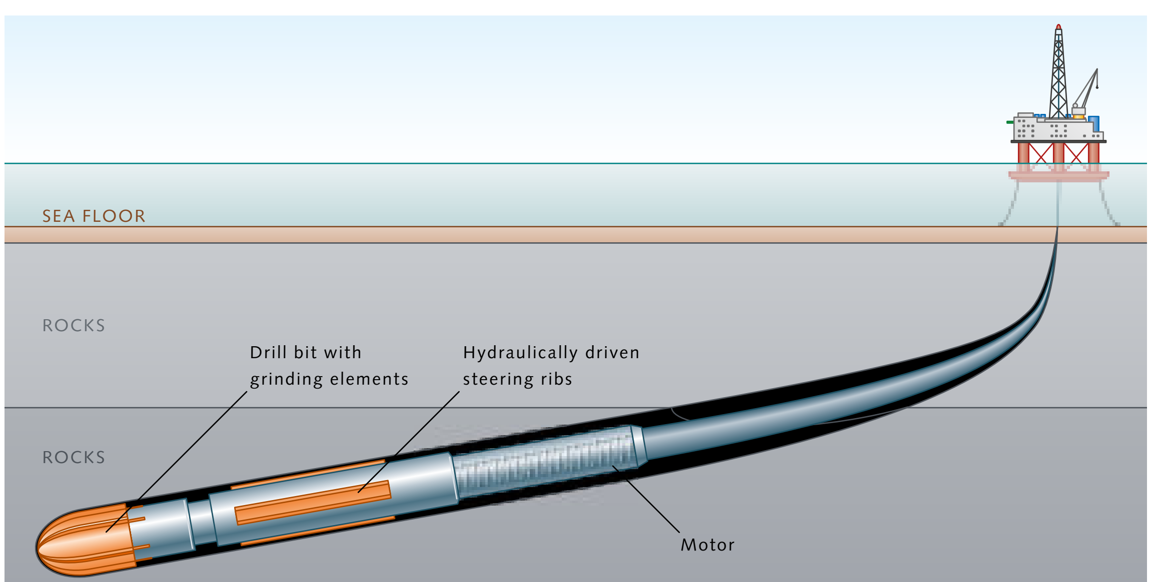
ELECTROMAGNETICS (georadar): In electromagnetic procedures, electromagnetic impulses are transmitted, like those of a radio antenna, but in this case radar waves are used. Similar to the sound waves of seismic methods, the electromagnetic signals are altered by the bottom structure.

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.

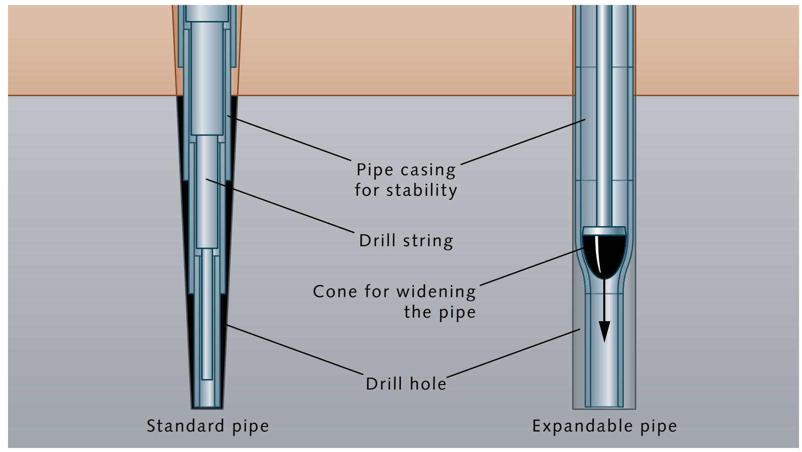
grinders made of hardened metal or ceramic. The drill bits grind the rocks. Today they are usually driven by a turbine located behind the bit. Rotation of this turbine is propelled by drilling fluid that is pumped into the hole under high pressure. This drilling fluid then transports the crushed rock 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 breaking, like a drinking straw that can bend a little without crimping.

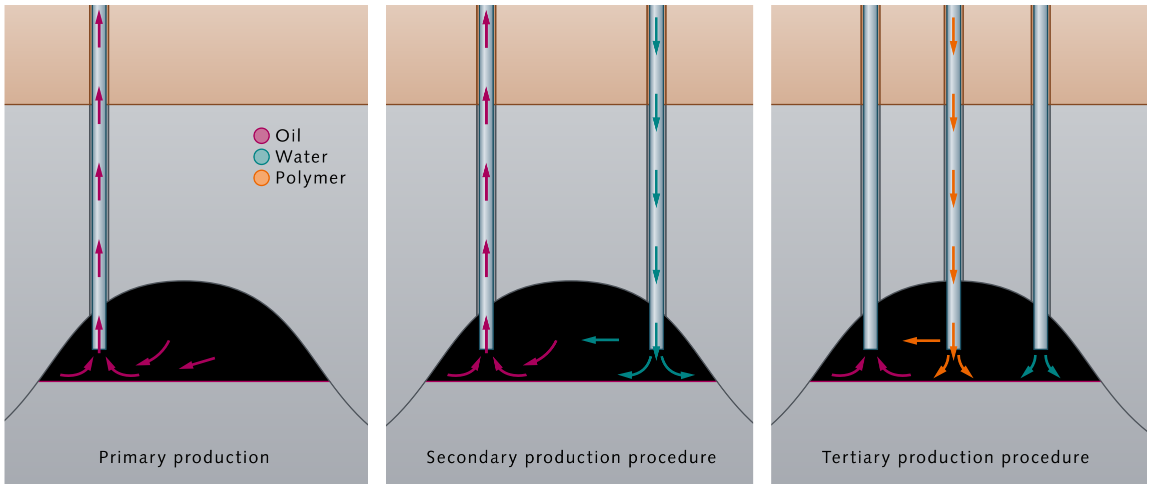


1.19 > To counteract the telescoping downhole reduction in well diameter, special new expandable pipes have recently begun to be employed. These are widened underground by pressing a hydraulically driven conical tool through the pipe. This technique is known as the solid expandable tubular method.

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.



1.20 > 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 reservoir 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.

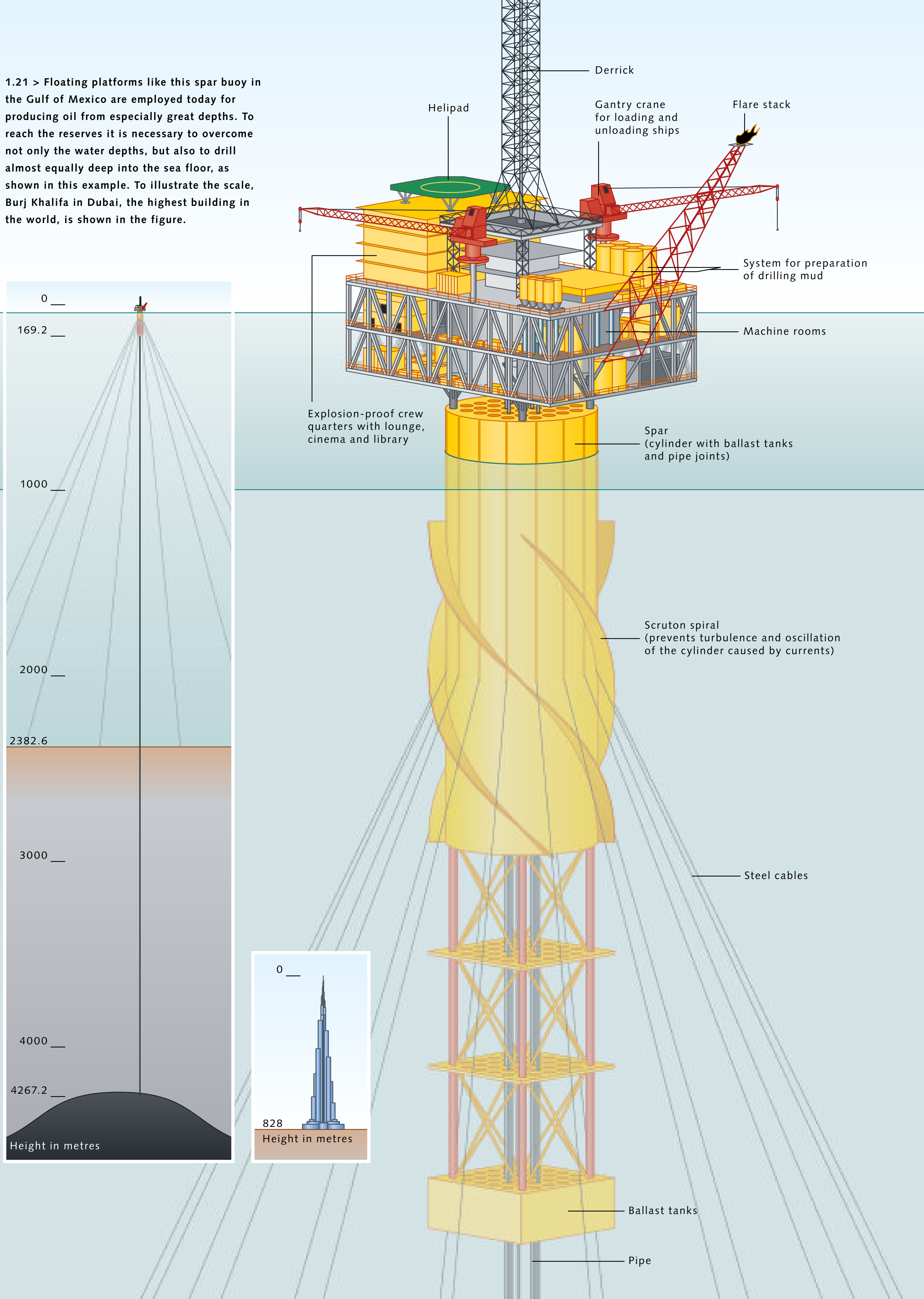
In the 1940s the first gas and oil rigs were built in less than 10 metres of water on piers or ramps connected to the land. Later, platforms were built standing fixed on the sea floor. Some of them are so tall they would tower over the Empire State Building in New York.

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.

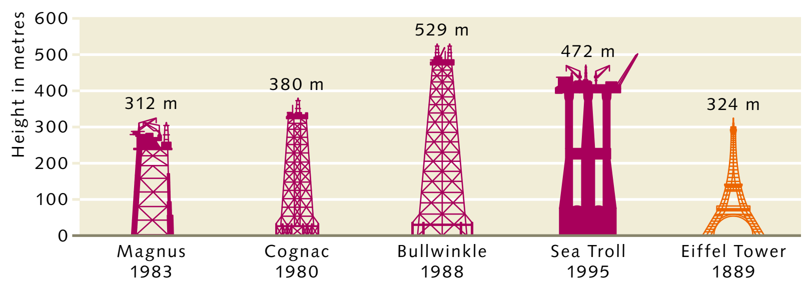
When the drilling of a well is finished, it is initially capped at the sea floor with a wellhead. This is a kind of sealing cap, approximately the size of an automobile, that prevents the gas or oil from escaping. Only then can the drill platform be moved away. Later a production platform will be installed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



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.

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

1.23

1.24

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.**

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 KizombaA **is part of a large oil production complex that consists of a production platform and several subsea units.**

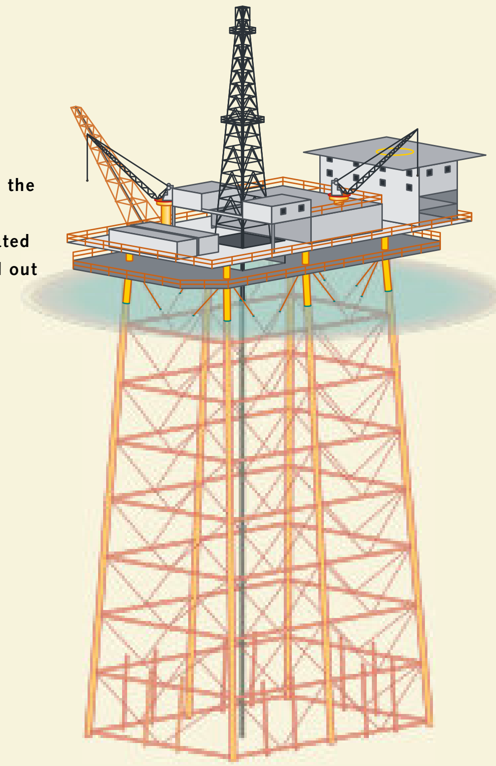
sea floor, but is permanently anchored to the bottom by thick steel cables. It is special in that the steel cables are kept tightened, so that the TLP remains stable in the water. The cables are tightened by partially flooding the buoyancy tank so that the structure sinks downward. Next the steel cables 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.

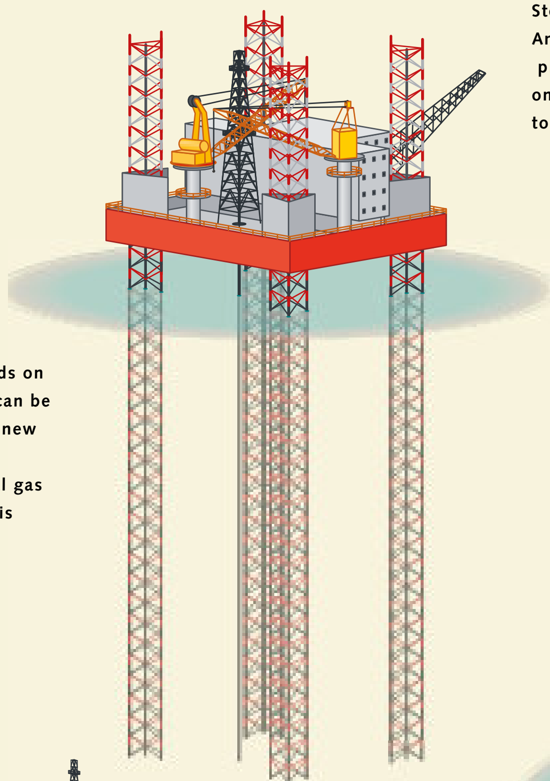
Types of platforms used in the gas and oil industry

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.



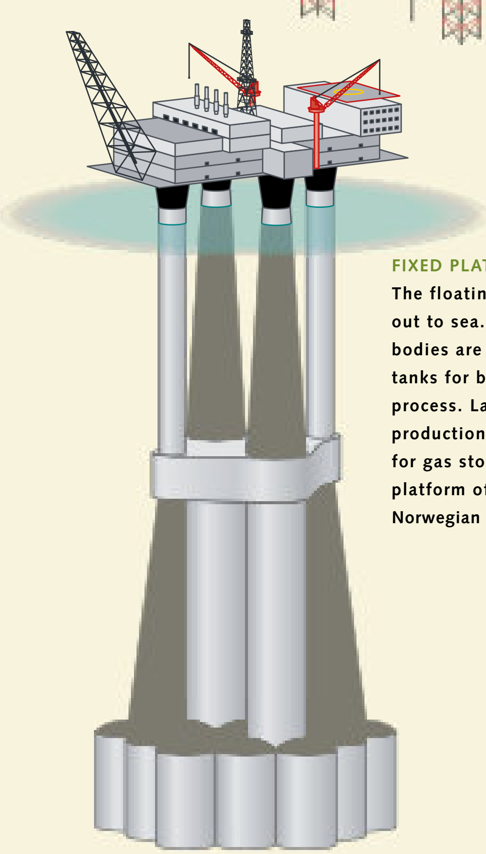
FIXED PLATFORM

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



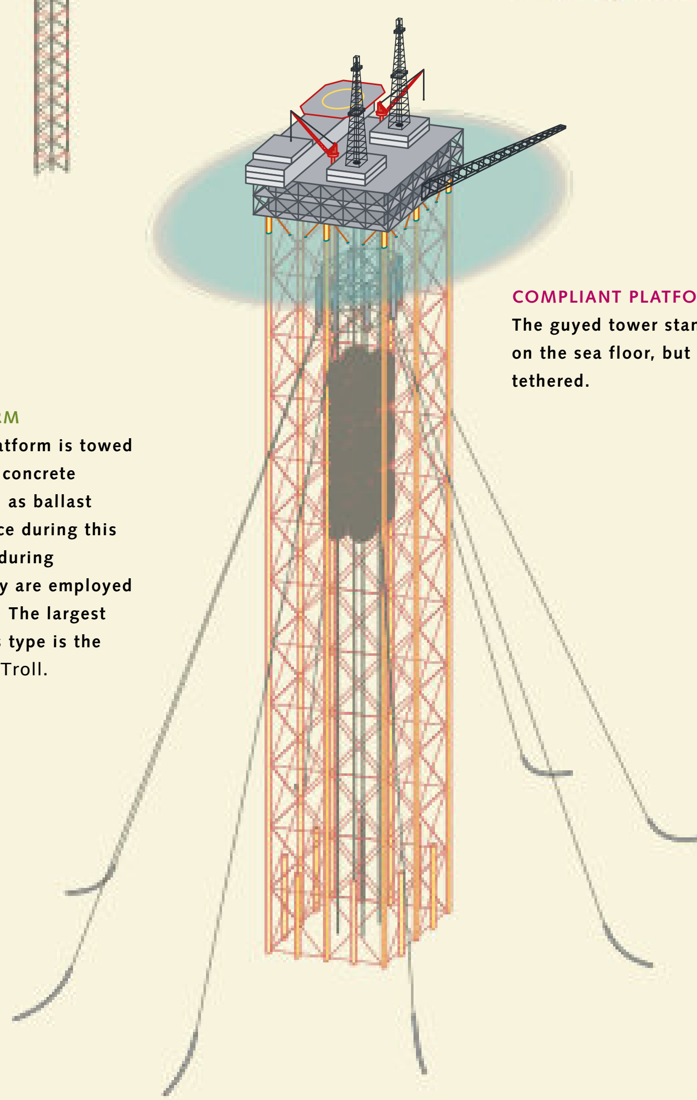
FIXED PLATFORM

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.



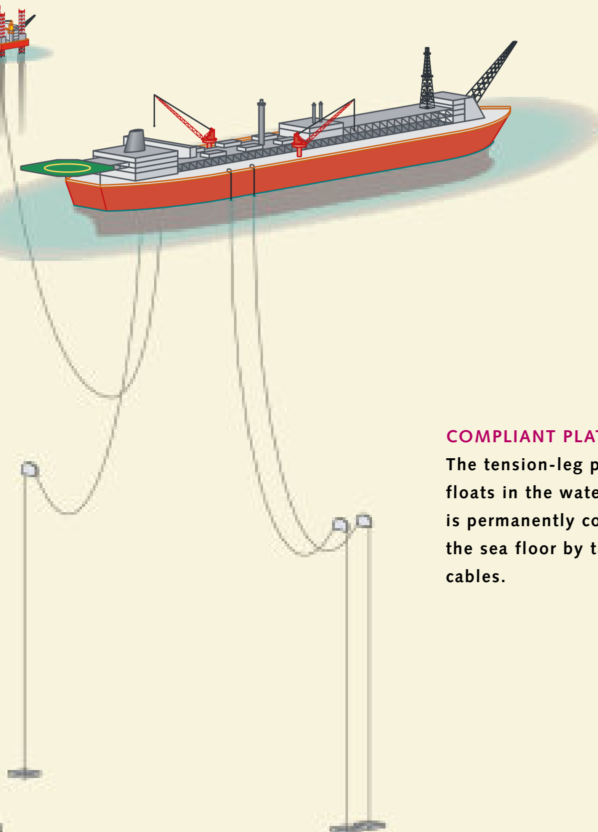
FIXED PLATFORM

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.

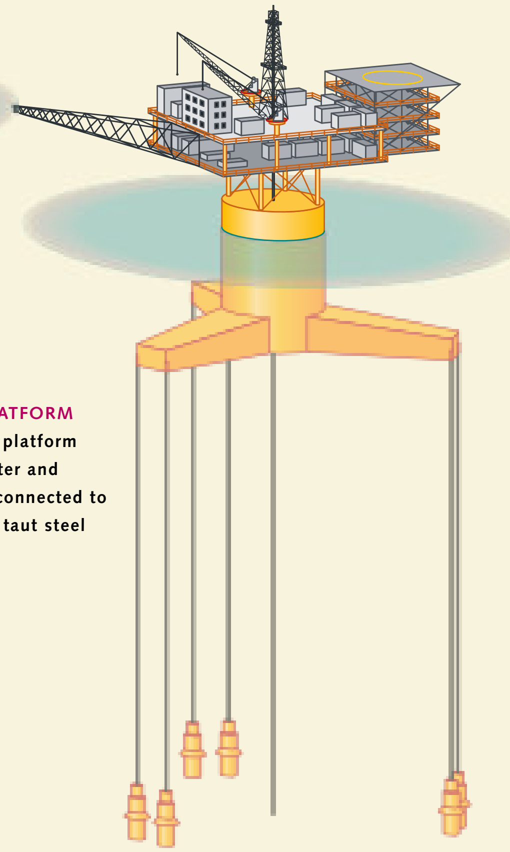


COMPLIANT PLATFORM

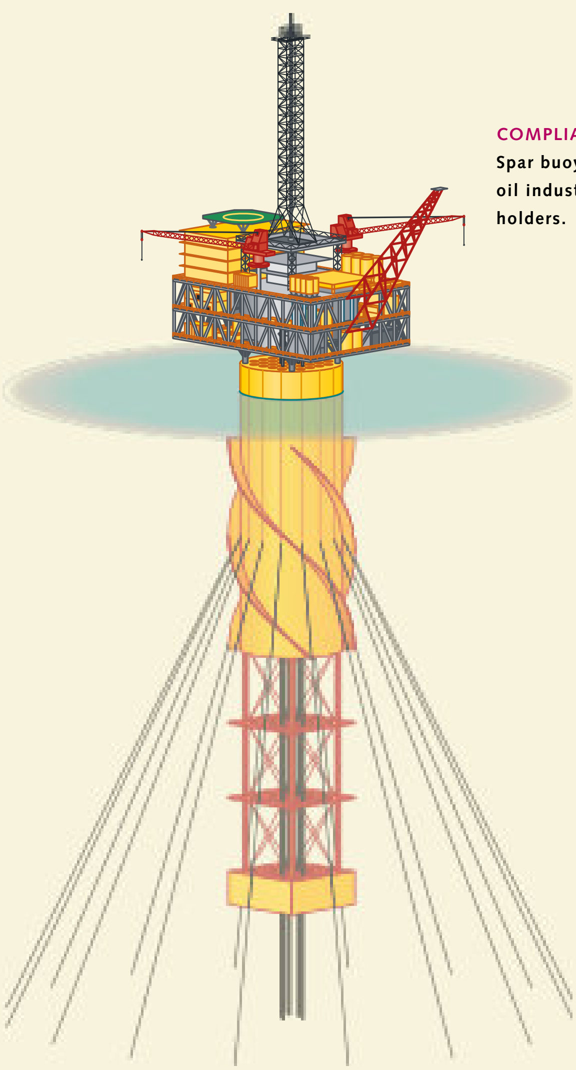
The guyed tower stands fixed on the sea floor, but is also tethered.



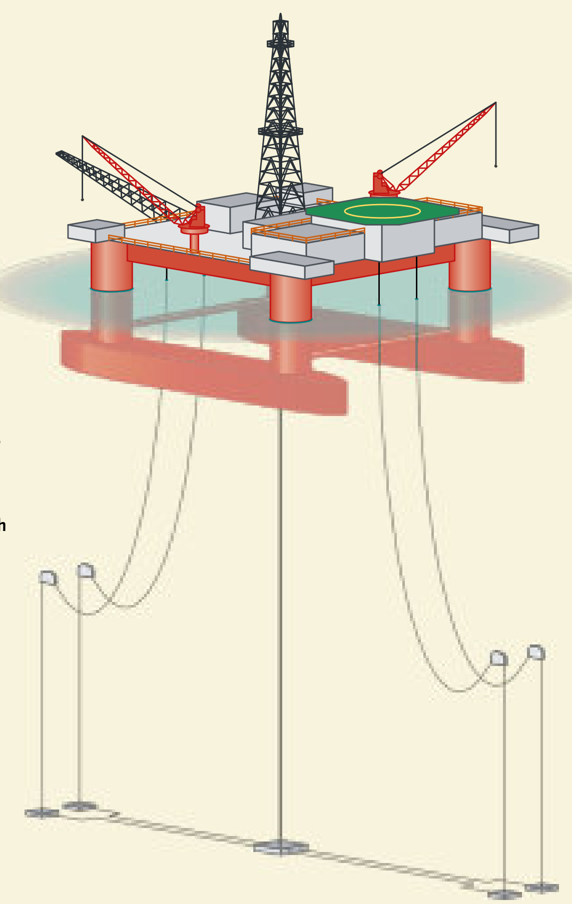
FLOATING PLATFORM
FPSOs such as the KizombaA float freely in the water. They are held in position with multiple engines or simple anchors. They can produce, store and process oil. Water is pumped into the sea floor through flowlines for secondary oil production.



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

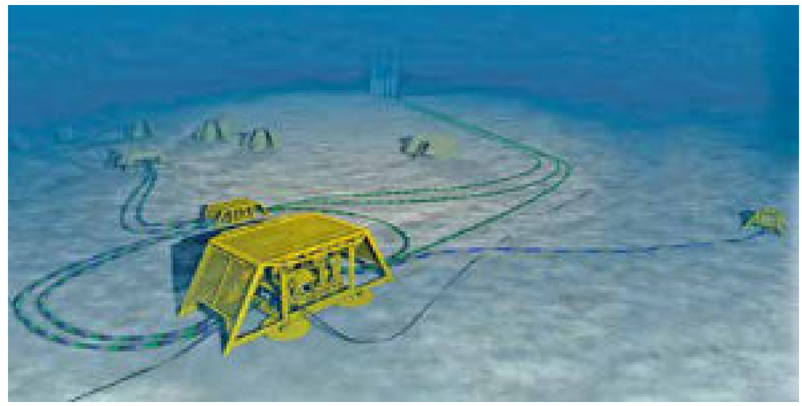
Today, gas and oil production operations are no longer limited to using large platforms on the sea surface. There is now an alternative, known as subsea completion systems. These comprise various water-tight components such as compressors, pumps and separators for gas and oil processing mounted on steel 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 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.



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.

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

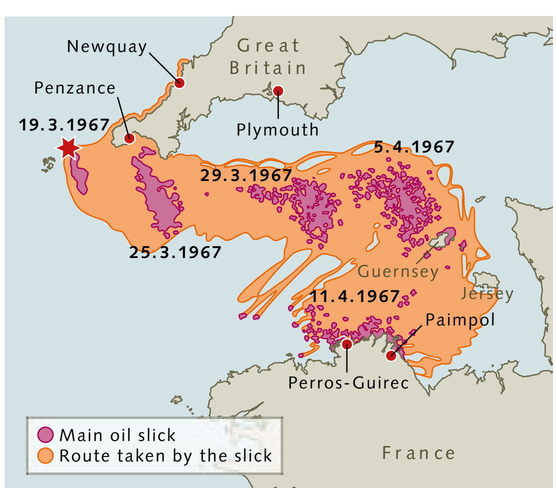
> Oil pollution continues to pose a threat to the marine environment – but very little of this pollution comes from major oil spills. The greatest problem is oil that enters the seas along less obvious pathways, such as inputs from effluents or shipping. Various conventions to protect the marine environment, 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

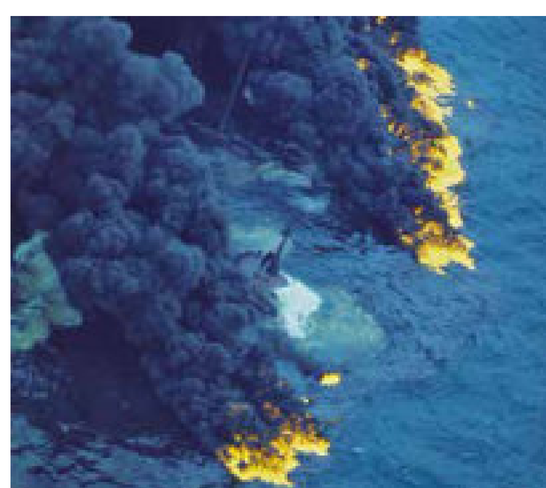
The global oil industry often exacts a heavy toll from the environment. Onshore, there is the problem of soil contamination by oil from leaking pipelines. Offshore, oil spilled from damaged tankers poisons marine life, coats and clings to the feathers of seabirds, and pollutes coastlines. The problems associated with the production and transportation of crude oil became all too apparent in the 1960s and 1970s, when the first supertankers 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

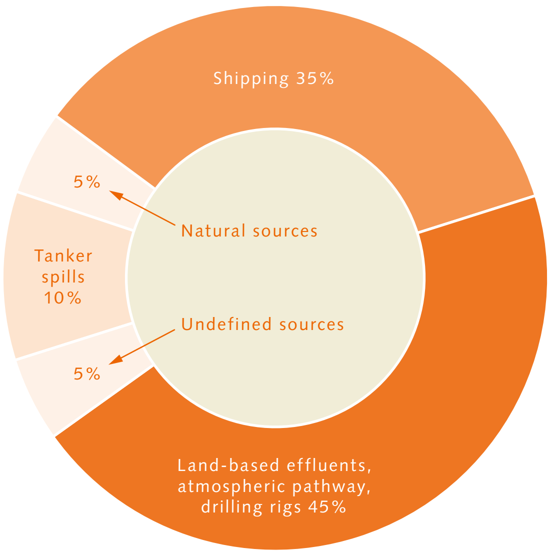
Tanker disasters and oil rig explosions still occur from time to time; one example was the *Deepwater Horizon* incident in spring 2010, in which a vast quantity of oil was released into the environment in a very short period of time. Yet in reality, this kind of spectacular disaster accounts for only 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

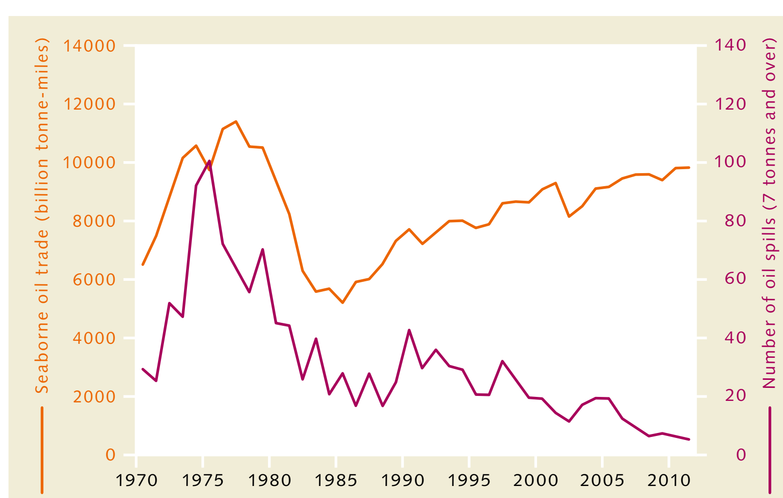
The good news is that the number of oil spills from tanker incidents or caused by technical failures or explosions on tankers has fallen dramatically in recent decades, despite steady growth in the seaborne oil trade. In the 1970s, there were between 50 and 100 large oil spills a year, compared with 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.



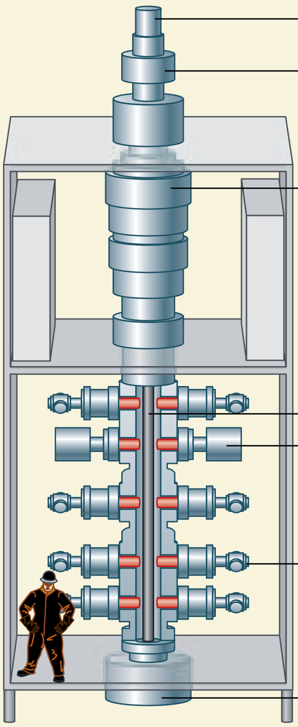
Deepwater Horizon – the offshore oil industry's worst-case scenario

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



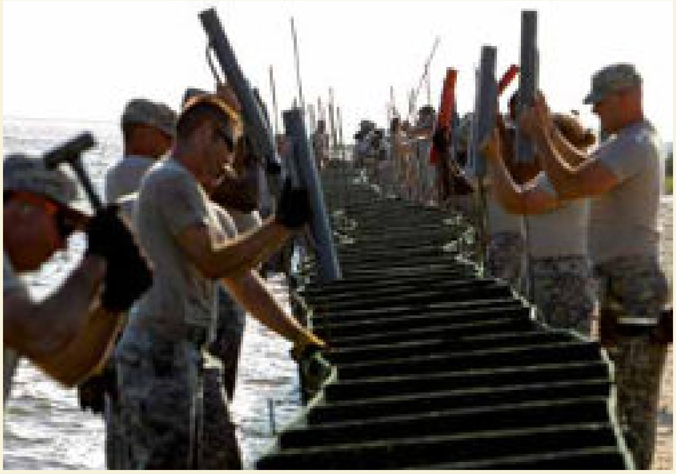
1.34 > A blowout preventer is a tower-like structure which acts as a large plug. Fitted with shut-off valves and shear rams, its purpose is to seal off wells on the sea floor. The Deepwater Horizon **disaster occurred partly because the BOP technology failed.**

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.



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

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.

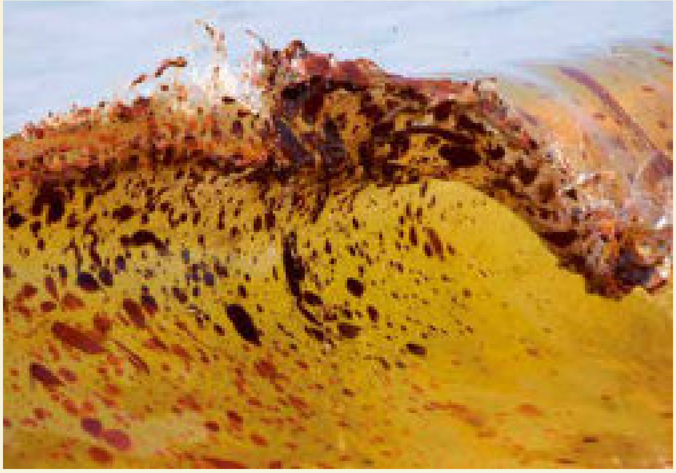
In its report, the committee describes in detail the technical failures and flawed decisions which, together, led to the disaster, and concludes that material improvements in the offshore oil development industry are required, not only in relation to technology, e.g. BOP construction, but also to management 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 compensation 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.



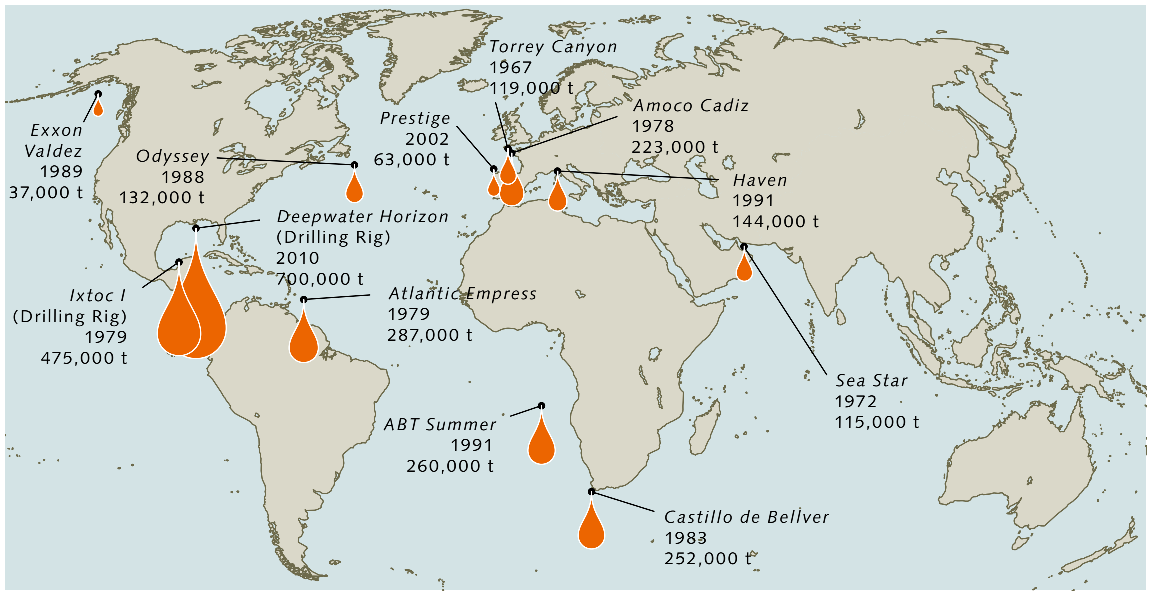
1.39 > Wind, wave action and currents caused the oil to spread.

of the companies involved were already well-established in the offshore 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.

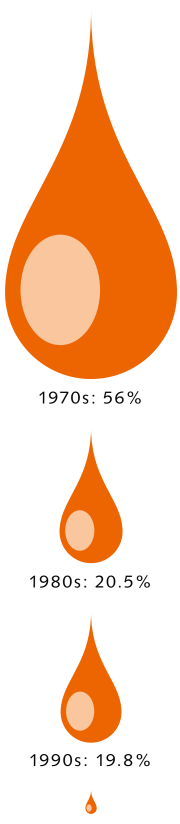
The extent to which biotic communities and habitats have been affected by the disaster is, to a large extent, still unclear, for it is difficult to determine whether certain types of damage to flora and fauna were indeed caused by contaminants in the oil or whether they perhaps predated the disaster.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

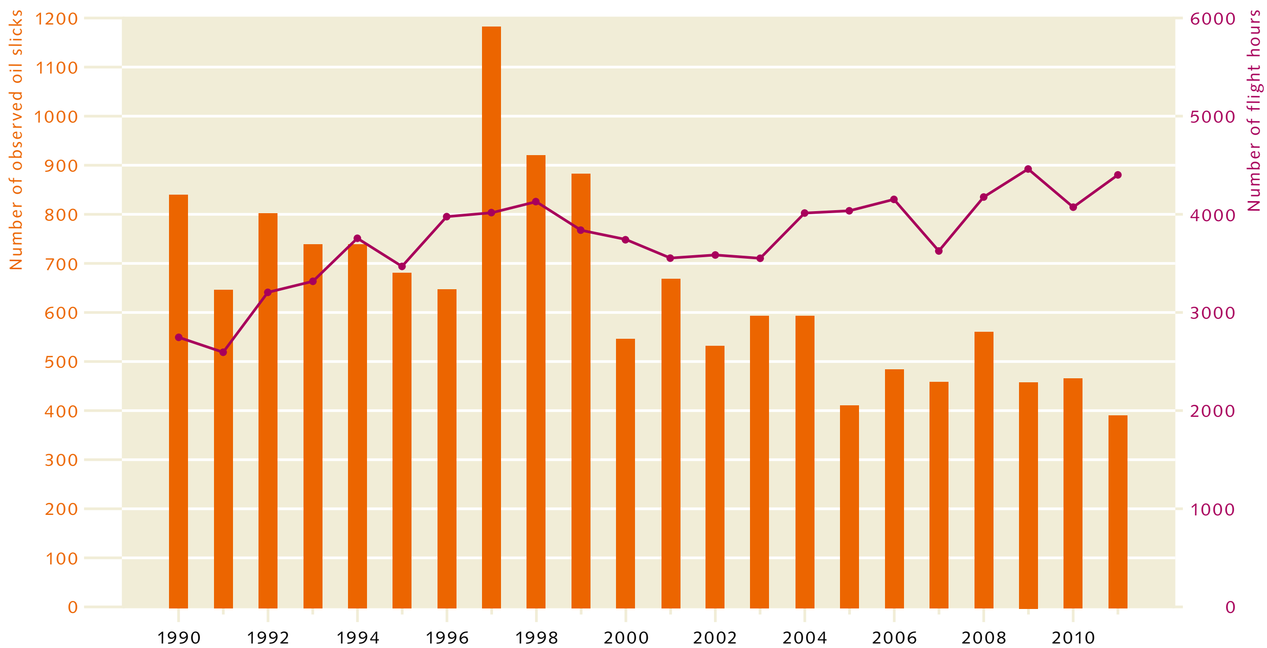
The Baltic Sea is protected under the Helsinki Convention, which entered into force in 2000. Under this Convention too, all the states bordering the Baltic Sea hold an oil spill response exercise, known as Balex (Baltic Exercise), which takes place in summer every year in a different area of the Baltic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

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.

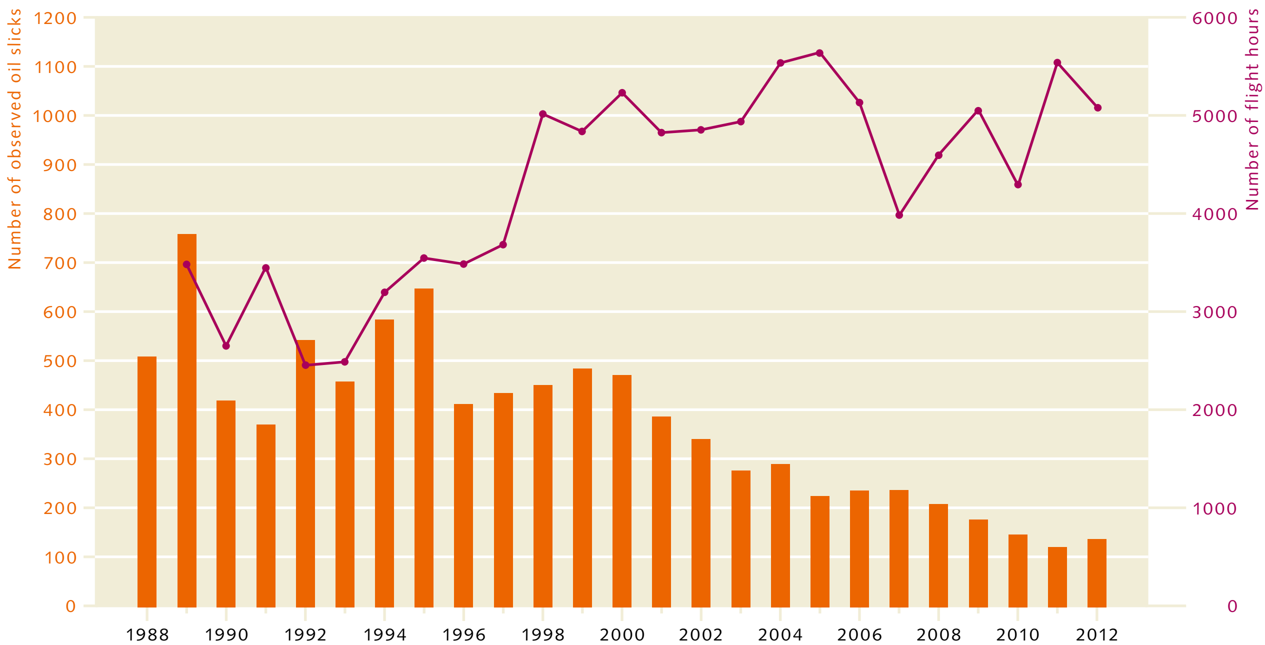


1.42 > The number of observed oil slicks in the North Sea area has halved since 1990.

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



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.

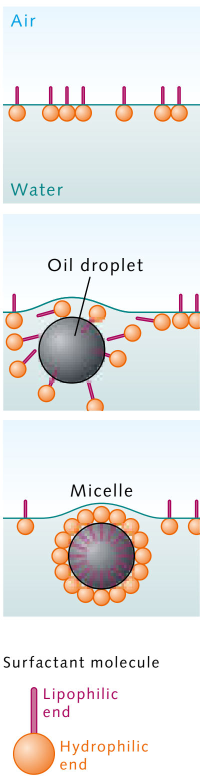
reporting and alerting. It is debatable, therefore, whether these nations would be able to mount an adequate response to a major oil spill unaided.

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-



1.44 > 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 temperatures. 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 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.

2 Sea-floor mining

> Diamonds, gravel and sand have been extracted from coastal waters for decades. To meet the growing demand for metals, there are plans to mine the ores found in the form of manganese nodules, cobalt crusts and massive sulphides at depths of up to 4000 metres. If and when such sea-floor mining is to start will depend on metal prices on global markets. Working in deep water is still uneconomic, and no appropriate mining equipment is available yet.

Resources for the world

> At present almost all the metals and industrial minerals utilized to manufacture consumer goods and machinery are extracted from onshore resources. In an effort to become independent of imports and safeguard themselves from future supply shortages, some countries are contemplating mining such resources from the ocean. But underwater mining is still too expensive and there is uncertainty about its environmental impact.

Ore, mica, sand and gravel

The manufacture of many high-tech applications and modern mass-produced electronic products such as photovoltaic installations, hybrid cars and smartphones requires abundant mineral resources. These resources include mineral ores from which metals such as copper, nickel, indium and gold are extracted, as well as non-metallic industrial minerals such as fluorite, graphite and mica.

Mica is utilized among other things as an insulator in tiny components for the microelectronics industry, and graphite is required for electrodes. Fluorite is used in the production of hydrofluoric acid to cauterize steel and photovoltaic components. Sand, gravel and stone for the building industry are also considered to be mineral resources.

Nearly all the mineral resources used today are derived from onshore deposits. Depending on the deposit concerned, these are extracted from underground mines or open-cast mines using enormous excavators and wheel loaders. Sand and gravel are the exception, as these have for some time now been exploited not only onshore but also from shallow marine areas.

For several decades we have also been aware of the presence of major occurrences on the sea floor which consist of many millions of tonnes of valuable metals. These have so far remained unutilized because onshore production has been capable of satisfying demand. In addition, deep ocean mining is still uneconomic because of the expense involved in harvesting the ores using ships and underwater robots. Unlike traditional onshore mining, the extraction technology has not yet been developed.

Rare earth metals

Rare earth metals are a set of 17 chemical elements which appear in the periodic table and which have similar properties. The unusual name stems from the fact that these metals used to be extracted from minerals ("earths") which were considered very rare. In reality, however, many of the rare earth metals occur frequently in the Earth's crust. On the other hand, there are few large deposits containing high concentrations of these elements. The largest occurrences are found in China, particularly in Inner Mongolia. Rare earth metals are used in many key technologies. They are needed for permanent magnets in magnetic resonance imaging (MRI), in the generators of wind turbines and for the production of accumulators, LEDs and plasma screens.

Fear of supply shortages

Experts assume that, despite steadily increasing demand, the onshore deposits will in most cases continue to satisfy our growing appetite for metals and minerals. They do predict future shortages of some resources, however.

For instance, those resources which are available or mined in only small amounts – such as antimony, germanium and rhenium – could become scarce, partially as a result of the growing needs of the BRIC countries (Brazil, Russia, India and China).

To compare, about 20 million tonnes of refined copper were produced worldwide in 2012, but only 128 tonnes of germanium.

Germanium is used for the radio technology in smartphones, in semi-conductor technology and in thin-film solar cells. There are concerns, particularly among the leading industrialized nations, that the supply of such significant industrial resources could become more precarious in coming decades. The following are some of the factors on which supply depends:

2.1 > Mineral ores for metal production are extracted from huge open-cast mines such as the Dexing copper mine near the eastern Chinese city of Shangrao. The excavators are working their way deep into the earth.

- Rising demand due to new developments: Some innovation researchers predict that the need for certain metals will increase significantly in the years to come as a result of new technological developments. Rare earth metals, for example, are elements which could be required in rapidly increasing quantities in future for the construction of engines for electric cars and generators in wind turbines.
- Rising demand and competition as a result of economic growth in the BRIC countries and emerging markets, as well as strong growth in the global population.
- Limited availability: Many resources are by-products of the extraction of other metals. For instance, both germanium and indium – which is vital for the manufacture of LCD displays – are by-products of lead and zinc mining. They occur in only small quantities in the lead and zinc deposits. In order to extract more germanium and indium, lead and zinc production would have to increase substantially. This would be uneconomic, however, because the demand for lead and zinc is not high.
- State monopolies: Many important industrial resources are found in only a few countries or are currently produced by only a few. These nations have an effective monopoly. For instance, China accounts for 97 per cent of the worldwide production of rare earth metals. Currently it is also the most important producer of other resources. Importing nations are concerned that China, or other nations, could restrict the availability of these resources by imposing high tariffs or other economic measures. The situation is aggravated by the fact that modern high-tech industries require resources of extra high quality or high purity. In many cases these, too, occur in only a few regions of the world.
- Oligopolies as a result of industry concentration: In some cases resources are mined by only a handful of companies. Competition for some resources has intensified even more in recent years due to major resource companies having bought out smaller ones.
- Political situation: Supplies from politically fragile states are also fraught with problems. One example is the Democratic Republic of the Congo which gen-

2.2 > Many metals today are mined in only a few countries, with China leading. The data originate from a comprehensive analysis of resources carried out in 2010, since when the situation has not changed significantly. No reliable figures are available for gallium or tellurium.

Leading metal producers and their percentage of world production

Elements	Largest producer	Second largest producer	Third largest producer	Application
Aluminium (Al)	Australia 31 %	China 18 %	Brazil 14 %	Vehicle bodies, consumer goods
Antimony (Sb)	China 84 %	South Africa 2.6 %	Bolivia 2.2 %	Flame retardants, electronic components, consumer goods
Arsenic (As)	China 47 %	Chile 21 %	Morocco 13 %	Semi-conductors, solar cells, optical components
Cadmium (Cd)	China 23 %	Korea 12 %	Kazakhstan 11 %	Accumulators, pigments, solar cells
Chromium (Cr)	South Africa 42 %	India 17 %	Kazakhstan 16 %	Stainless and heat-resisting steels
Cobalt (Co)	Democratic Republic of the Congo 40 %	Australia 10 %	China 10 %	Wear- and heat-resisting steels
Copper (Cu)	Chile 34 %	Peru 8 %	USA 8 %	Electric cable, electric motors, building industry
Gallium (Ga)	China	Germany	Kazakhstan	LEDs, solar cells
Germanium (Ge)	China 71 %	Russia 4 %	USA 3 %	Smartphones, solar cells
Gold (Au)	China 13 %	Australia 9 %	USA 9 %	Investment, jewellery, electrical industry
Indium (In)	China 50 %	Korea 14 %	Japan 10 %	Displays, alloys, photovoltaics
Iron (Fe)	China 39 %	Brazil 17 %	Australia 16 %	Steel, industrial magnets
Lead (Pb)	China 43 %	Australia 13 %	USA 10 %	Radiation shielding, batteries, metal working
Lithium (Li)	Chile 41 %	Australia 24 %	China 13 %	Accumulators, aviation- and space technology
Manganese (Mn)	China 25 %	Australia 17 %	South Africa 14 %	Stainless steel, LEDs
Molybdenum (Mo)	China 39 %	USA 25 %	Chile 16 %	Steel
Nickel (Ni)	Russia 19 %	Indonesia 13 %	Canada 13 %	Corrosion protection, corrosion-proof steels
Niobium (Nb)	Brazil 92 %	Canada 7 %	–	Stainless steels, jewellery
Palladium (Pd)	Russia 41 %	South Africa 41 %	USA 6 %	Catalysts (chemical industry), jewellery
Platinum (Pt)	South Africa 79 %	Russia 11 %	Zimbabwe 3 %	Catalytic converters, jewel-lery, metal coatings
Rare earth metals	China 97 %	India 2 %	Brazil 1 %	Permanent magnets, accumulators, LEDs
Selenium (Se)	Japan 50 %	Belgium 13 %	Canada 10 %	Semi-conductor and steel production, fertilizers
Silver (Ag)	Peru 18 %	China 14 %	Mexico 12 %	Investment, jewellery, chemical industry (catalysts)
Tellurium (Te)	Chile	USA	Peru	Stainless steels, semi-conductors, photo diodes
Tin (Sn)	China 37 %	Indonesia 33 %	Peru 12 %	Component of bronze, LEDs, displays
Vanadium (V)	China 37 %	South Africa 35 %	Russia 26 %	Steel alloys, cladding for nuclear fuel rods
Zinc (Zn)	China 25 %	Peru 13 %	Australia 12 %	Corrosion protection, batte-ries, construction industry

erates 40 per cent of worldwide cobalt production, but which has been destabilized by many years of civil war.

The availability of a resource to a country or company does not depend alone on the size of worldwide deposits, therefore, but on a combination of factors which determines the price. Of course, the price is also affected by the situation on the resource markets. For instance as demand for a resource grows, so does its price. In other cases resources may increase in price as a result of speculation alone, because markets overreact. One example here was the huge price hike of copper and other resources after 2006 when China snapped up major quantities of resources. At that time there could be no question of scarcity, however.

Measuring uncertainty

Experts are trying to assess the certainty of future resource supplies. They take state and corporate monopolies into account on the one hand, and the political situation in the prospective mining areas on the other, to produce a "weighted country risk".

This weighted country risk is ascertained on the basis of 6 criteria (indicators) against which the governance and prevailing political situation of individual states are measured. These indicators have been defined by the World Bank as follows:

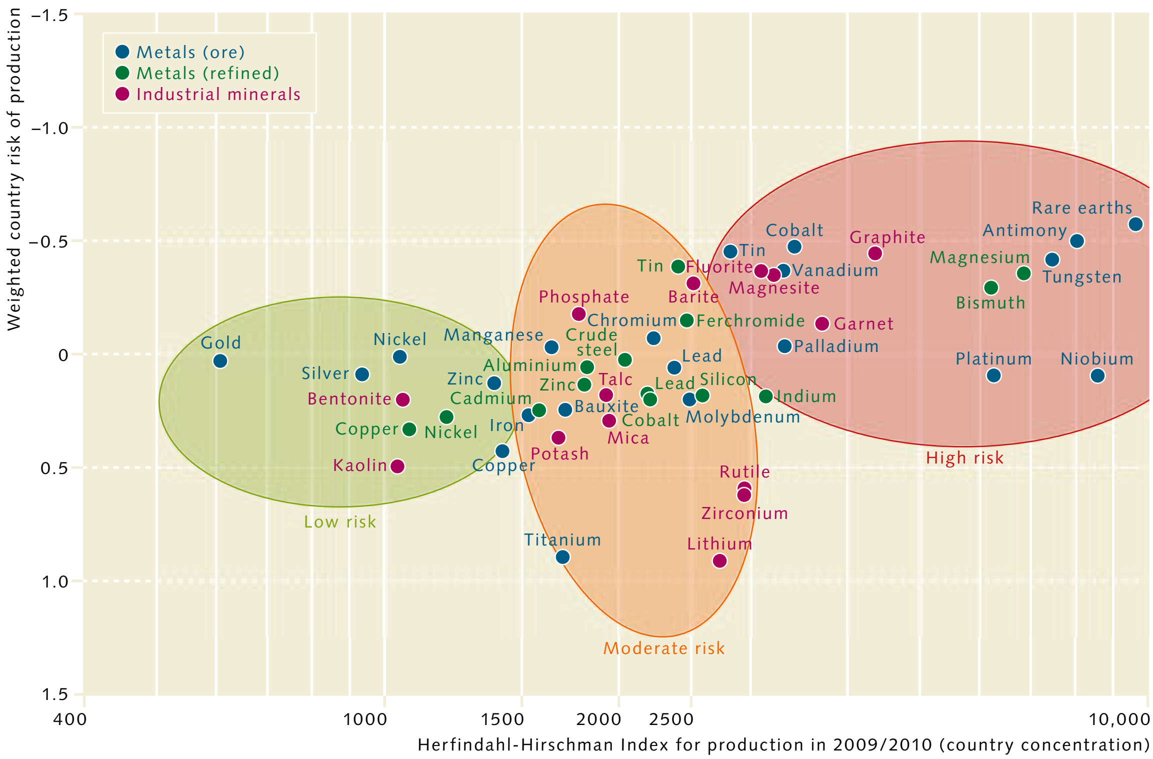
- Voice and accountability: measures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of assembly and a free media;
- Political stability and absence of violence: measures perceptions of the likelihood of a government being destabilized by violence, political violence or terrorism;
- Government effectiveness: measures the quality of public services, the civil service and the degree of its independence from political pressures;
- Regulatory quality: measures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development;
- Rule of law: measures perceptions of confidence in and adherence to the rules of society, and in particular the quality of contract enforcement and property rights. It also measures the quality of the police and the courts, as well as the likelihood of crime and violence;
- Control of corruption: measures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the influence of elites and private interests.

Numeric values are assigned to the 6 indicators, and these are totalled to reveal country risk values between +1.5 and −1.5. Values above 0.5 indicate a low risk, between −0.5 and +0.5 a moderate risk, and those below −0.5 are considered critical.

Economists are using the Herfindahl-Hirschman Index (HHI), a measure of market concentration, as they attempt to assess the extent to which resource supply is influenced by state or corporate monopolies. This mathematically determined index considers the number of

How much metal does the ore contain?

As a general rule metals are extracted from mineral ores. In many cases these are not present as pure metal, but in the form of compounds which contain both the metal sought and a range of other chemical elements. One example is copper. Copper ore does not contain pure copper, but either a copper-sulphur-iron compound (chalcopyrite) or a copper-sulphur compound (chalcocite). The metal must first be separated from such minerals by means of multi-step metallurgic processes. In many cases these processes are so complicated that they account for up to 30 per cent of the metal price. The metal recovered is described as "refined copper". Mineral ores, therefore, are made up of a combination of different substances and contain only a certain amount of metal. In most cases copper ores contain between 0.6 and 1 per cent of copper. Consequently one tonne of ore generates a maximum 6 to 10 kilograms of copper. In the case of platinum the yield is much lower: 1 tonne of ore usually contains between 3 and 6 grams of platinum. Nonetheless it is still worthwhile mining because the platinum price is high. In 2013 the price per gram was around 35 Euros.



2.3 > The security of individual resource supply is ascertained by looking at the reliability of exporting nations (weighted country risk) and the monopolization of individual resource markets. This diagram considers state monopolies in particular (country concentration). Resources which are considered safe (low risk) are highlighted in green, those at moderate risk in yellow, while those with an insecure supply situation (high risk) are highlighted in red.

companies competing in the market and their market shares, from which they can calculate the degree of concentration of that market. In terms of figures, the Herfindahl-Hirschman Index ranges between the highest value 1 where there is only one market participant (indicating a monopoly), and the lowest value 0, which is achieved when (theoretically) an infinite number of participants have the same market share. For practical reasons the values are multiplied by 10,000 to effectively remove the decimal point.

Accordingly, a resource market with an HHI below 1500 is considered “unconcentrated”. Above 2500 it is seen as “highly concentrated” or monopolized, and values in between indicate that a market is “moderately concentrated”.

If the resources are assessed according to both the weighted country risk and the HHI at the same time, they can be classified into 3 different risk groups: low risk, moderate risk and high risk resources. Copper is considered a low risk resource. It has a low country risk value and at the same time low corporate and country concentration ratios. This is because copper is produced in politically stable countries, by a range of different companies.

Rare earth elements and the metalloid antimony are considered extremely high risk resources. Deposits with a high content of antimony are found mainly in China, which supplies about 84 per cent of global production. The Herfindahl-Hirschman Index value is correspondingly high. Antimony is used for touchscreens and micro-electronic components; it is also very much in demand as a flame retardant for fire-resistant clothing and plastics.

How long will resources last?

Calculating the supply risk can naturally provide only a snapshot of the current situation. It does not tell us just how long we can expect the resources to be available in future.

Geoscientists are trying to answer this question by gauging the reserves and resources of the various substances. Essentially we know where certain ores can be anticipated, because resources usually occur in characteristic geological formations, the worldwide distribution of which is relatively well known.

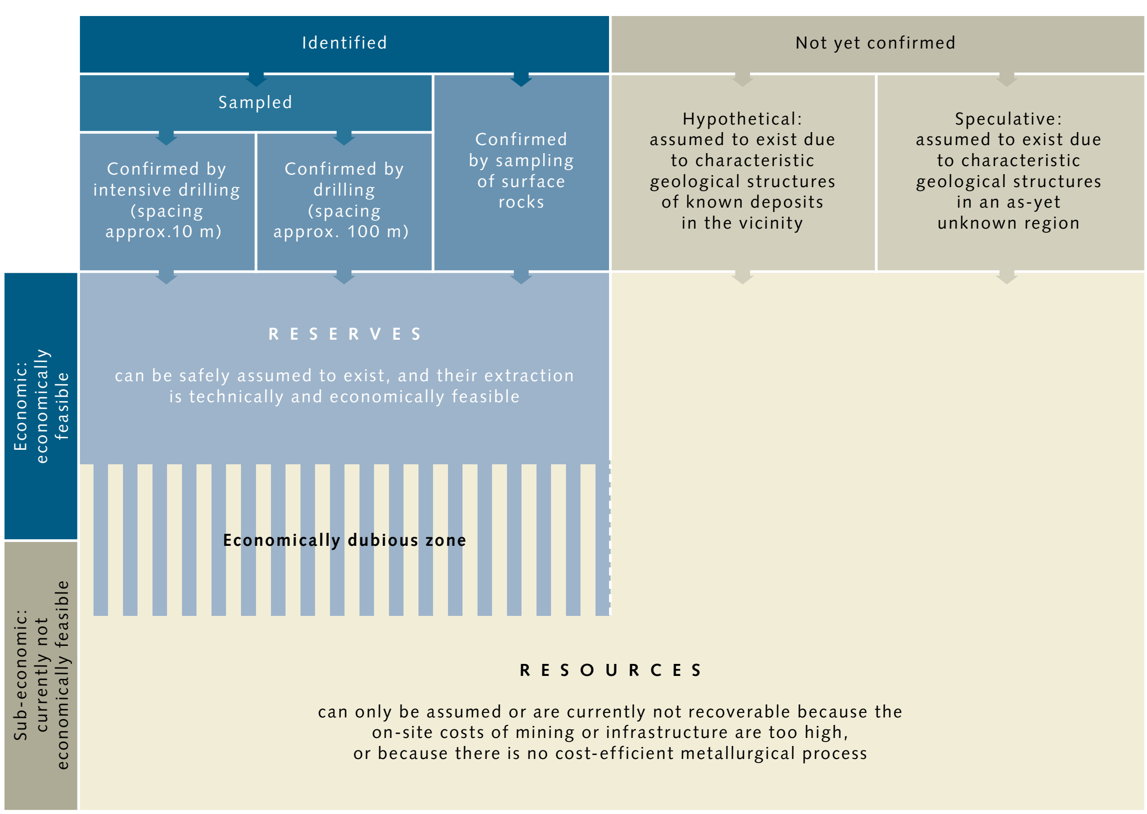
Platinum for example occurs mainly in the Bushveld Complex of South Africa in a layered igneous intrusion. This is a layer of rock caused by magmatic activity which has penetrated the adjacent rock strata. Platinum in such intrusions is also found in some other regions of the world. However, the platinum content of the ores is in many cases so minimal that extraction is not profitable.

Ground surveys, geological and geophysical analyses and test drilling must be undertaken before it is possible to ascertain whether metals occurring in a geological formation are concentrated enough to be considered a deposit.

No such testing has as yet been carried out in many regions of the world because the exploration of new deposits in unknown terrains is extremely expensive and complicated. For this reason interest has mainly been focused on areas in the vicinity of known occurrences. Major tracts of Australia, Canada, South America and West Africa remain largely unexplored. Assessing worldwide occurrences is therefore a very unreliable undertaking. Occurrences are classed into different categories, depending on the extent to which an area of land has been sampled or developed:

- RESERVES: Reserves are occurrences of resources which have already been proven and their extraction is economically feasible using current technology.

- RESOURCES: An occurrence is described as a resource when its metal content and volume have not yet been proven by sampling, or when its extraction and processing are economically unfeasible. One example is nickel laterite ore, a special type of nickel ore found in the residual soils of tropical and



2.4 > Mineral resource deposits are classified in different categories, depending on how well-known or sampled they are. Whether the resources can be extracted is another factor considered.

2.5 > Bauxite is extracted mainly in open-cast mines. A specialized machine like this one removes 800 tonnes per hour. Bauxite is primarily used to manufacture aluminium.

sub-tropical areas. Until the 1950s there was no economically-feasible industrial process to separate the nickel from the ore. The occurrences, although well-known, could not be utilized. The laterites were therefore ranked as resources. Once an appropriate metallurgical process was developed, they became an exploitable reserve. Today about 50 per cent of the nickel produced worldwide comes from such lateritic deposits.

Unlike natural gas and oil, metal reserves and resources are further sub-classified according to the extent to which they have been sampled. The economic feasibility of their extraction is also taken into account.

In view of the major areas of land worldwide which have not yet been properly sampled, geoscientists assume that many as-yet-undiscovered deposits exist and that these will theoretically be capable of meeting the growing need for mineral resources in the future. But it is debatable whether major underground or open-cast mines will be developed onshore, because of their drastic intervention in landscapes.

Many stretches of land have been completely transformed over past decades as a result of mining. People have lost their homes and important ecosystems have been destroyed. Copper mining was responsible for the enormous craters in the ground in South America. In Brazil large tracts of rainforest were destroyed by the open-cast mining of bauxite, another residual soil from which aluminium is extracted. Any expansion of onshore mining is therefore viewed with a great deal of scepticism.

Recycling rather than discarding?

An alternative to intensified ore mining could in future be the recycling of valuable resources. Just as aluminium and steel are already being melted down and reprocessed on a grand scale, other resources too could be recovered from waste and electronic scrap.

However, electronic waste is processed by only a few companies worldwide, which mainly recover copper, silver, gold and platinum.

From a process engineering point of view it would also be feasible, for instance, to recycle indium tin oxide film from smartphone screens. As yet, however, no industrial facility has yet been designed for routine processing.

Not only are discarded smartphones and computers of interest for recycling: waste also accumulates during production. Yet because processes for treating the waste and extracting the substances are lacking, the electronics industry can return only a portion of its waste into the production process. A process for gallium from LEDs would be highly desirable, for example.

Collection systems for end-of-life products and production waste are also lacking. Recycling is further complicated by the fact that a product may contain only tiny amounts of certain metals, making it scarcely worthwhile to reprocess. Experts are trying to create new methods to improve the identification and separation of the various processed substances.

Microchips and other microelectronic components in which a range of different substances are effectively fused together present a particular challenge. Because most electronic scrap cannot be recycled, many industrialized nations export it into developing and newly industrializing countries as waste. In some cases it is still being transported illegally overseas. Companies involved in such activity claim to recycle the scrap and are paid accordingly. But instead of recycling it in a technically complex manner, they save money by exporting it.

For this reason specialists are discussing the following measures and suggestions for the future recycling of metals:

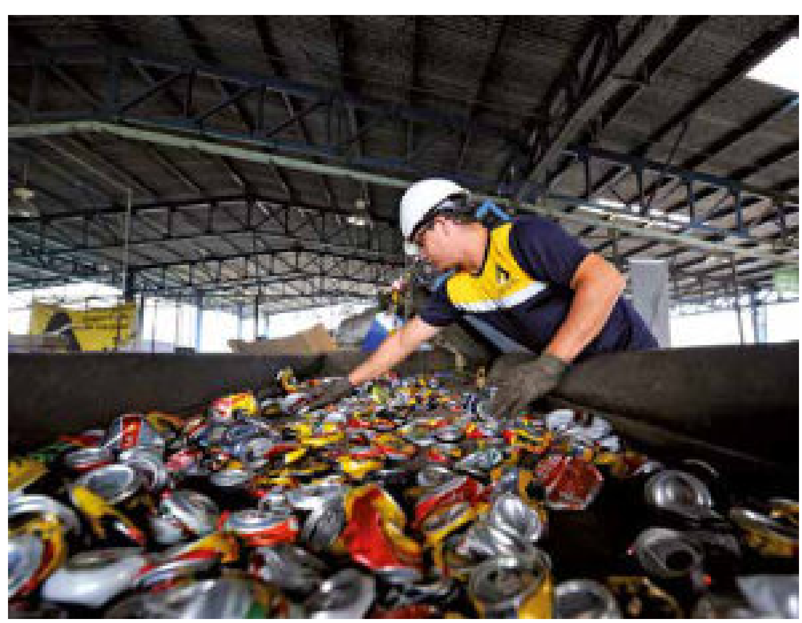
- The development of new systems to recover industrial production waste;
- The introduction of recycling bins for private households;
- The priority development of recycling processes for metals at a high risk of shortages (country risk, country concentration);
- The creation of economic incentives to spur a functioning recycling market which specializes in resources from consumer goods, end-of-life vehicles and electronic scrap.

Could sea-floor mining be the answer?

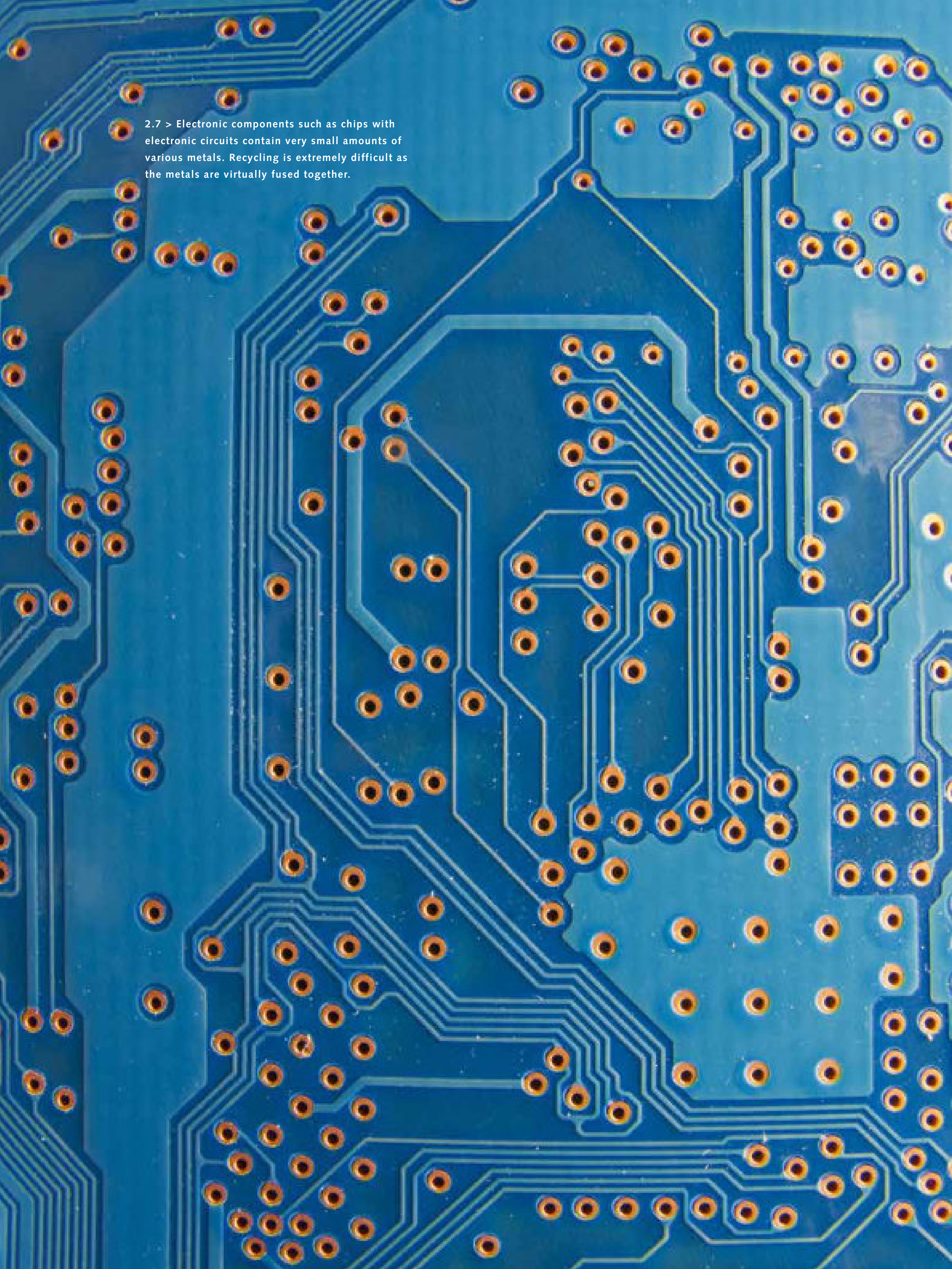
To make future resource supplies more secure, sea-floor mining could offer many states and companies a potential alternative, for both economic and geopolitical reasons. It would avoid the land-use conflicts which underground and surface mining bring in their wake, and could also help many nations without resource reserves to become a little less dependent on the exporting nations.

In principle there are two scenarios where sea-floor mining is concerned: mining within the territorial waters of a nation, and mining in the deep sea which is considered a common heritage of mankind and a resource to be shared among all nations.

Nation states are responsible for regulating the mining activity in their own sovereign territory. In the case of the deep sea, however, the central authority is the International Seabed Authority (ISA), which grants licences for specific areas. The ISA is based in Kingston, Jamaica.



2.6 > A worker in a recycling factory in San José, Costa Rica, sorts tin cans from which aluminium is recovered.



2.7 > Electronic components such as chips with electronic circuits contain very small amounts of various metals. Recycling is extremely difficult as the metals are virtually fused together.

In particular the ISA ensures that the future profits gained from deep-sea mining activities are shared equitably. The objective is to prevent a situation occurring whereby only rich nations have access to promising resources.

The International Seabed Authority has already assigned numerous licensed areas to several states for exploration purposes; as yet they may only explore – not exploit. To date no actual mining has been carried out anywhere because the final set of rules governing the activity is still being debated. The ISA plans to establish the legal conditions for such seabed mining by 2016.

As far as sea-floor mining is concerned, interest is focused on 3 main types of resource deposit which contain different valuable metals:

- MANGANESE NODULES: Manganese nodules are lumps of minerals ranging in size between that of a potato and a head of lettuce. They cover enormous areas of the seabed of the Pacific and Indian Oceans. They are composed mainly of the chemical elements manganese, iron, copper, nickel and cobalt along with other substances such as molybdenum, zinc and lithium. Manganese nodules are mostly found at depths below 3500 metres.

- COBALT CRUSTS: Cobalt crusts are incrustations of minerals which form on the sides of submarine mountain ranges and seamounts. They develop as a result of the accumulation of minerals dissolved in the water and contain mainly manganese, iron, cobalt, nickel, platinum and rare earth elements. Cobalt crusts are found in the western Pacific at depths of 1000 to 3000 metres.

- MASSIVE SULPHIDES: Massive sulphides accumulate mainly at the openings of hot vents on the ocean floor. In these regions cold seawater penetrates through cracks in the sea floor at depths of up to several kilometres. The water near magma chambers then heats up to temperatures exceeding 400 degrees Celsius. As it does so, metalliferous minerals are released from the rock. Upon warming the solution rises rapidly and is extruded back into the sea. As soon as this solution mixes with the cold seawater, the minerals form a precipitate which accumulates around the hydrothermal vents in the form of massive ore deposits. Massive sulphides are found in many places on the sea floor which are or used to be volcanic. Depending on the region, they contain widely different amounts of copper, zinc, lead, gold and silver, as well as numerous important trace metals such as indium, germanium, tellurium or selenium.

If and when marine resources are mined depends mainly upon how resource prices actually develop worldwide. It is impossible to predict whether, as is the case with oil, world market prices will continue to rise. New onshore mining projects could lead to price reductions for certain resources, for example. In the past we have often seen that when mining of a major new onshore deposit begins, there is a surplus of the resource concerned. Cost savings also contribute to falling prices. There are many reasons behind such savings such as new mining technologies, automation or improved metallurgic processes.

On the other hand, prices rise as the demand for a resource increases. This could in future prove to be the case with resources which are highly sought after due to technological and social developments. One example here is the metal neodymium which is increasingly used in the construction of electric motors and wind turbine generators. Experts are in fact concerned that supplies of this metal could run short in the coming years. If the prices of metals that are also found offshore increase in the coming years as a result of such shortages, sea-floor mining could become economic. However, at this stage nobody can foresee whether such a situation will occur.

An exception could possibly be the massive sulphides found in the territorial waters of Papua New Guinea, which have been found to contain substantial amounts of gold and silver. Their retrieval has been planned for several years now, but for economic and contractual reasons production has been postponed repeatedly.

Sand, gravel and phosphate from the sea

The extraction of mineral resources from the sea is by no means a new activity. Many countries have in fact been extracting sand and gravel for decades. This loose rock is used to make concrete, as backfill on building sites and in harbours, and also as beach nourishment to protect coastlines.

How much marine sand and gravel is effectively taken worldwide is difficult to estimate because the data is not collected centrally. What the available statistics do show, however, is that Europe is the largest producer of marine-dredged sand and gravel, with sand being the most sought-after product.

According to estimates published by the International Council for the Exploration of the Sea (ICES), the organization responsible for the North Atlantic marine habitat, 93.5 million cubic metres of sand were removed from European waters in 2012. That figure equates to approximately the volume of 37 Great Pyramids of Cheops. The Netherlands accounted for the major share of about 63 million cubic metres. No less than 37 million cubic metres were needed by that country alone to replenish the North Sea coastline and offshore islands to balance out the sand masses washed away by the autumn and winter storms in the North Sea. Some of the sand is used each year to expand the port of Rotterdam.

The extent of sand and gravel consumption by the Netherlands is highlighted by the fact that the USA uses only about 57 million cubic metres of marine sand each year. In that country, the material is almost exclusively utilized for the purposes of coastal protection and beach replenishment.

Europe's second largest consumer of marine sand after the Netherlands is Great Britain. That nation used almost 12 million cubic metres in 2011, plus nearly 7 million cubic metres of gravel. Approximately 80 per cent of both products are used to manufacture concrete, particularly for construction work carried out in London and in southern parts of England.

No other nations regularly extract sand and gravel to such an extent. However, in individual cases, large amounts are indeed needed for building projects such as the expansion of Hong Kong airport and the port of Singapore.

What is more, despite the ready availability of desert sand, marine sand is also used to construct artificial islands such as the Palm Islands of Dubai. This is because the rounded grains of ocean sand are better for concrete production than the angular grains taken from the desert. Marine sand and gravel are used mainly where no suitable deposits can be found onshore. This is the case in both southern England and the Netherlands. However, because it is generally substantially more costly to remove them from the sea, onshore deposits tend to be preferred worldwide.

Sand and gravel are extracted by ships constructed specially for this purpose, which suck them from the ocean floor using a large pipe. This process is known as suction dredging. The pipes are up to 85 metres long and can have a diameter of up to 1 metre. As a rule, the dredging areas are around 3 kilometres long and several hundred metres wide. There are two different dredging processes. The first is static suction dredging during which the ship lies at anchor as it sucks up sand from a single spot. This produces pits of up to 10 metres in depth. The second process involves the ship pulling a suction pipe with a draghead behind it and slowly following a route through the dredging area. This method of material extraction removes a layer of sand 25 to 50 centimetres thick from the sea floor.

The extent of the damage and destruction that is inflicted upon marine habitats by the large-scale extraction of sand and gravel has long been a subject of heated discussion. The North Sea fishing industry, for instance, has voiced fears that fishing could be impacted negatively by suction dredging operations. Among other things, the critics of dredging have asserted that:

- Fish are driven away by the noise of the suction dredgers;
- The hunting and spawning grounds of the fish are destroyed by the dredging or the sediment that was stirred up;
- Fishing equipment such as lobster pots are ruined by the suction dredgers.

Since the start of the new millennium, therefore, a whole raft of biological studies has been carried out with the aim of assessing the impact of suction dredging on the marine environment. These investigations have shown that dredging does indeed have an impact, but have also revealed that such effects are limited to relatively small areas. An English study, for instance, proved that after 25 years of sand dredging, an area needs about 6 years to completely repopulate. In an area dredged for only a brief period or just once, the original conditions are already restored after 1 or 2 years.

A Dutch study even concluded that 2 years after dredging sand to expand the port of Rotterdam the fish biomass in the dredged area increased substantially. Why this is, is unclear.

What is certain, however, is that extraction does change the composition of the seabed sediments. When gravel or coarse-grained sand is removed, the sites afterwards often fill with finer sand which is washed in by the current. Fine-grained areas attract different sea dwellers than coarse-grained areas. These changes can persist over many years. However, as relatively small areas covering only a few square kilometres are dredged, the studies conclude that there can be no question of major habitat change.

2.8 > **A suction dredger extracts sand from the North Sea floor off the Dutch island of Ameland to widen the beach.**

2.9 > **The sand-water combination is pumped from the ship onto the beach using the "rainbow method".**

The conflict that erupted in Great Britain between the fisheries sector on the one side, and the sand and gravel industry on the other, was defused by awarding licences for marine areas in accordance with the Marine and Coastal Access Act 2010. Now, for the first time, the Act coordinates and regulates the maritime spatial planning of the waters off Great Britain and their use by fishing fleets, tourism operators, wind energy companies and the sand and gravel industry. By allocating specific areas for well-defined uses, it can be ensured that the associated activities remain far enough away from fish spawning grounds. This avoids a situation arising in which suspended sediments caused by dredging smother the eggs of herring and other species.

Some countries take a very critical view of the mining of sand and gravel. In South Africa for instance, dune sand is extracted for use in the construction industry. As dunes are a natural bulwark against the ocean surf critics are concerned that this activity could adversely affect the coastline.

Fishermen in India are protesting against the removal of sand from beaches. They are concerned that fish stocks are being compromised by the suspended sediment being stirred up and that catches will dwindle as a result.

For more than 10 years now sand has been illegally removed from Moroccan beaches and sold to other countries for concrete manufacture. This has transformed some beach areas into lunar landscapes. The tourism industry fears that damage to its reputation and financial losses may follow.

Apart from sand and gravel, phosphate is another mineral resource which has the potential to be exploited from the sea on a grand scale. Phosphate is mainly used as a feedstock for fertilizer production. Massive quantities are mined in West Africa and Tunisia, from where it is exported to many different countries. The importation and long-haul sea transportation are relatively expensive for distant nations, which would consequently prefer to make use of the marine resources off their own coasts. There are thus plans to mine phosphate at Chatham Rise, a submarine ridge off the east coast of New Zealand. These plans are meeting with a storm of protest from conservationists who fear that important habitats on the sea floor could be destroyed. Proponents argue that the proposed mining area is extremely small compared to the area affected by bottom trawling.

Debate has begun in Namibia and South Africa, too, about the harvesting of marine phosphate. Fishermen in Namibia are concerned that mining off the coast of Walvis Bay could destroy the hake fishing grounds. Environmentalists in South Africa, for their part, assert that the areas earmarked for sea-floor mining will be adjacent to species-rich Vulnerable Marine Ecosystems (VMEs) meriting particular protection. They are demanding that in-depth environmental impact assessments should be carried out before any mining begins.

Manganese nodule treasures

> Many thousands of square kilometres of the deep-sea floor are covered by metal-bearing nodules. They contain primarily manganese, but also nickel, cobalt and copper, which makes them economically promising. Although many countries and companies are already intensively investigating their distribution, it is not certain whether the manganese nodules will ever be mined. After all, at least for the intermediate future, there are enough metals available on land.

Metal-rich clumps

Together with cobalt crusts, manganese nodules are considered to be the most important deposits of metals and other mineral resources in the sea today. These nodules, with a size ranging from that of a potato to a head of lettuce, contain mainly manganese, as their name suggests, but also iron, nickel, copper, titanium and cobalt. In part, the manganese nodule deposits are of interest because they contain greater amounts of some metals than are found in today's known economically minable deposits. It is assumed that the worldwide manganese nodule occurrences contain significantly more manganese, for example, than in the reserves on land.

Occurrences of economic interest are concentrated particularly in the Pacific and Indian Oceans, in the wide deep-sea basins at depths of 3500 to 6500 metres. The individual nodules lie loosely on the sea floor, but can sometimes be covered by a thin sediment layer. Theoretically they can be harvested relatively easily from the sea floor. They can be collected from the bottom with underwater vehicles similar to a potato harvester. Prototypes in the late 1970s and early 1980s have shown that this will work.

2.10 > Slice through a manganese nodule: Over millions of years minerals are deposited around a core.

Four major occurrences

Manganese nodules occur in many marine regions. They are found in significant abundances in four regions of the ocean:

CLARION-CLIPPERTON ZONE (CCZ): With an area of around 9 million square kilometres, approximately the size of Europe, this is the world's largest manganese nodule region. The CCZ is located in the Pacific, extending from the west coast of Mexico to Hawaii. The nodules are not evenly distributed over this area. At some sites they are more densely grouped. No nodules at all are found in stony areas. On the average, one square metre in the Clarion-Clipperton Zone contains around 15 kilograms of manganese nodules. Especially rich areas can have up to 75 kilograms. The total mass of manganese nodules here is calculated to be around 21 billion tonnes.

PERU BASIN: The Peru Basin lies about 3000 kilometres off the Peruvian coast. It is about half as large as the Clarion-Clipperton Zone. The region contains an average of 10 kilograms of manganese nodules per square metre.

PENRHYN BASIN: The third important manganese nodule area in the Pacific is located in the Penrhyn Basin very near the Cook Islands, a few thousand kilometres east of Australia. It has an area of around 750,000 square kilometres. Large areas in the Cook Islands coastal waters have concentrations of over 25 kilograms of manganese nodules per square metre of sea floor.

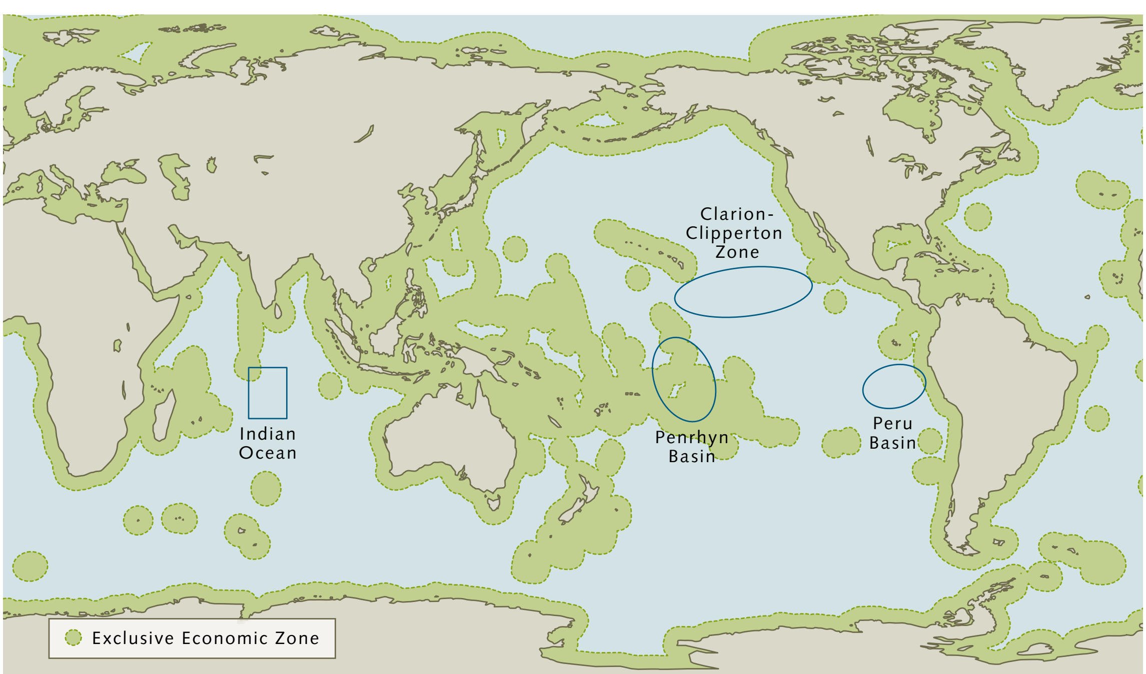
INDIAN OCEAN: So far only a single large area of manganese nodules has been discovered here, with an area comparable to that of the Penrhyn Basin. It is located in the central Indian Ocean. Each square metre of the sea floor here contains around 5 kilograms of manganese nodules.

How nodules grow

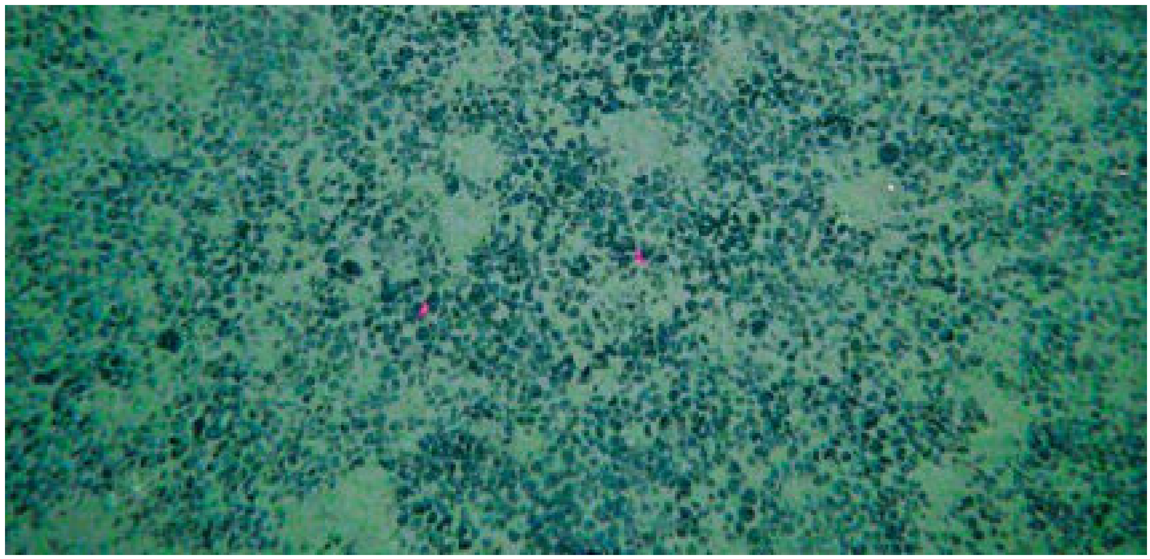
The formation of the manganese nodules is conceivably simple. Dissolved metal compounds in the sea water precipitate over time around a nucleus of some kind on

Metal content of manganese nodule occurrences in millions of tonnes			
Elements	**Clarion-Clipperton Zone (CCZ)**	**Global reserves and resources on land (both economically recoverable and sub-economic reserves)**	**Global reserves on land (economically recoverable reserves today)**
Manganese (Mn)	5992	5200	630
Copper (Cu)	226	1000+	690
Titanium (Ti)	67	899	414
Rare earth oxides	15	150	110
Nickel (Ni)	274	150	80
Vanadium (V)	9.4	38	14
Molybdenum (Mo)	12	19	10
Lithium (Li)	2.8	14	13
Cobalt (Co)	44	13	7.5
Tungsten (W)	1.3	6.3	3.1
Niobium (Nb)	0,46	3	3
Arsenic (As)	1.4	1.6	1
Thorium (Th)	0.32	1.2	1.2
Bismuth (Bi)	0.18	0.7	0.3
Yttrium (Y)	2	0.5	0.5
Platinum group metals	0.003	0.08	0.07
Tellurium (Te)	0.08	0.05	0.02
Thallium (Tl)	4.2	0.0007	0.0004

2.11 > Worldwide, manganese nodule occurrences contain large amounts of metals. The occurrences in the Clarion-Clipperton Zone (CCZ) alone hold around 10 times more manganese than the economically minable deposits on land today. The amount of thallium in the CCZ is even 6000 times more than in economically exploitable deposits. It must be kept in mind, however, that the possible marine deposits are compared to actual economically recoverable occurrences on land. Whether, and how much metal can be obtained from manganese nodules in the future is completely uncertain.



2.12 > Manganese nodules occur in all oceans. But only in 4 regions is the density of nodules great enough for industrial exploitation.



2.13 > Manganese nodules are present in various quantities in different areas of the deep sea. In this close-up view of the Pacific sea floor, the nodules are relatively close together.

the sea floor. The growth core can be, for example, a shark's tooth or a fragment of a clam shell, around which the nodule grows. This growth process can take place in two ways. In the hydrogenous process, metal compounds sinking through the water are precipitated. In large part this involves the manganese oxide mineral vernadite, which forms naturally in water. Compounds of other metals join in smaller amounts.

The second process is referred to as diagenetic growth. This process does not occur in the water column but within the sediments. Metal compounds that are present in the water between the sediment particles, the pore water, are deposited. This is sea water that penetrates into the sea floor and reacts with the sediments to become enriched with metal compounds. Where it rises up and out of the sediment, the metal compounds are likewise deposited around the nodule growth core. As a rule, this involves the manganese oxides todorokite and birnessite.

Most nodules grow both hydrogenously and diagenetically, whereby the relative influence of each process varies in different marine regions. It is fascinating how extremely slowly the manganese nodules grow. In a million years their size increases on the order of millimetres. Hydrogenous nodules grow up to 10 millimetres per million years, while diagenetic nodules grow between 10 and 100 millimetres. This means that manganese nodules can only grow in areas where the environmental conditions remain stable over this kind of time scale. The following factors are essential for the formation of manganese nodules:

- Low sedimentation rates of suspended material. Otherwise the nodules would be covered too rapidly;
- Constant flow of Antarctic bottom water. This water flushes fine sediment particles away that would otherwise bury the nodules over time. The coarser particles, such as the shells of small marine organisms and clam or nodule fragments, may be left behind to act as nuclei for new nodules;
- Good oxygen supply. The Antarctic bottom water, for example, transports oxygen-rich water from the sea surface to greater depths. Without this the manganese oxide compounds could not form;
- Aqueous sediment. The sediment has to be capable of holding large amounts of pore water. Diagenetic nodule growth can only take place in very aqueous sediments.

Furthermore, some researchers hold the opinion that bottom-dwelling organisms such as worms that burrow around in the sediment must be present in large numbers in order to constantly push the manganese nodules up to the sediment surface. This hypothesis, however, has not yet been proven.

Different regions, different compositions

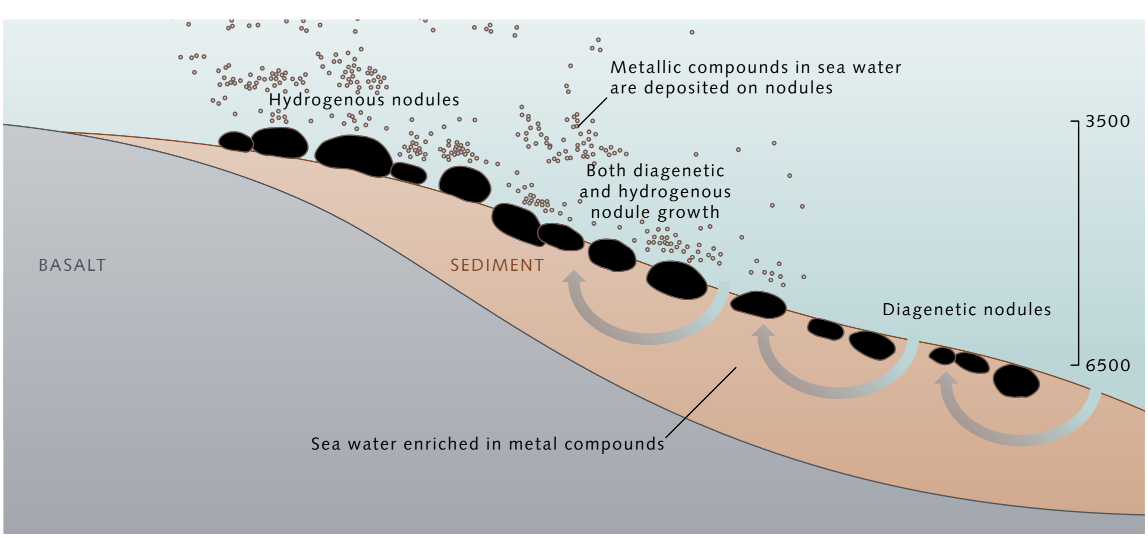
Although the conditions for the formation of manganese nodules are the same in all four of the major regions, their metal contents vary from place to place. The highest manganese content is 34 per cent in the Peru Basin nodules, while the highest iron content is in the Penrhyn Basin nodules with 16.1 per cent. The greatest content of cobalt, at a substantial 0.4 per cent, is also found here. In this area, therefore, the extraction of cobalt has the highest priority. According to expert estimations, 21 million tonnes of cobalt could be produced here, which is a great amount. The economically feasible reserves on land currently amount to around 7.5 million tonnes. Even adding the deposits on land that are not yet economically minable, only 13 million tonnes of cobalt could be retrieved – still significantly less than the nodules in the Penrhyn Basin could provide. After a record high before the economic crisis of 2008, however, the cobalt price has fallen steeply, so that mining of the deposits is not presently economical.

Nevertheless, given the large amounts of metals that are contained in the manganese nodules worldwide, it is certainly conceivable that the nodules may be mined in certain marine regions in the future. For many countries that do not have access to their own land reserves, manganese nodules offer a way to become independent from imports.

Who owns resources in the sea?

The international Law of the Sea precisely regulates who can mine manganese nodules or massive sulphide and cobalt crusts in the future. If the resources are located within the Exclusive Economic Zone (EEZ) of a country, the so-called 200 nautical mile zone, this country has the sole right to mine them or to award mining licences to foreign companies. This is the case, for example, in a part of the Penrhyn Basin near the Cook Islands.

The CCZ, the Peru Basin, and the Indian Ocean area, on the other hand, all lie far outside the Exclusive Economic Zones, in the realm of the high seas. Here, mining is centrally regulated by an agency of the United Nations, the International Seabed Authority (ISA), with headquarters in Kingston, Jamaica. In particular, the ISA ensures that the benefits from future activities related to marine mining are shared equitably. Its authority is based on various articles of the United Nations Convention on the Law of the Sea, which define the high seas as the common heritage of mankind. Activities on the high seas should thus serve the good of all people. Among other things, exclusive access to



2.14 > Manganese nodules grow when metal compounds dissolved in the water column (hydrogenous growth) or in water contained in the sediments (diagenetic growth) are deposited around a nucleus. Most nodules are a product of both diagenetic and hydrogenous growth.

2.15 > Chemical analyses reveal that manganese nodules from different marine regions vary significantly in their metal contents.

Chemical components of manganese nodules from different marine regions				
Elements	Manganese nodules of the CCZ	Manganese nodules of the Peru Basin	Manganese nodules of the Indian Ocean	Manganese nodules of the Cook Islands area
Manganese (Mn) **	28.4	34.2	24.4	16.1
Iron (Fe) **	6.16	6.12	7.14	16.1
Copper (Cu) *	10,714	5988	10,406	2268
Nickel (Ni) *	13,002	13,008	11,010	3827
Cobalt (Co) *	2098	475	1111	4124
Titanium (Ti) **	0,32	0.16	0.42	1.15
Tellurium (Te) *	3.6	1.7	40	23
Thallium (Tl) *	199	129	347	138
Rare earth elements and yttrium *	813	403	1039	1707
Zirconium (Zr) *	307	325	752	588

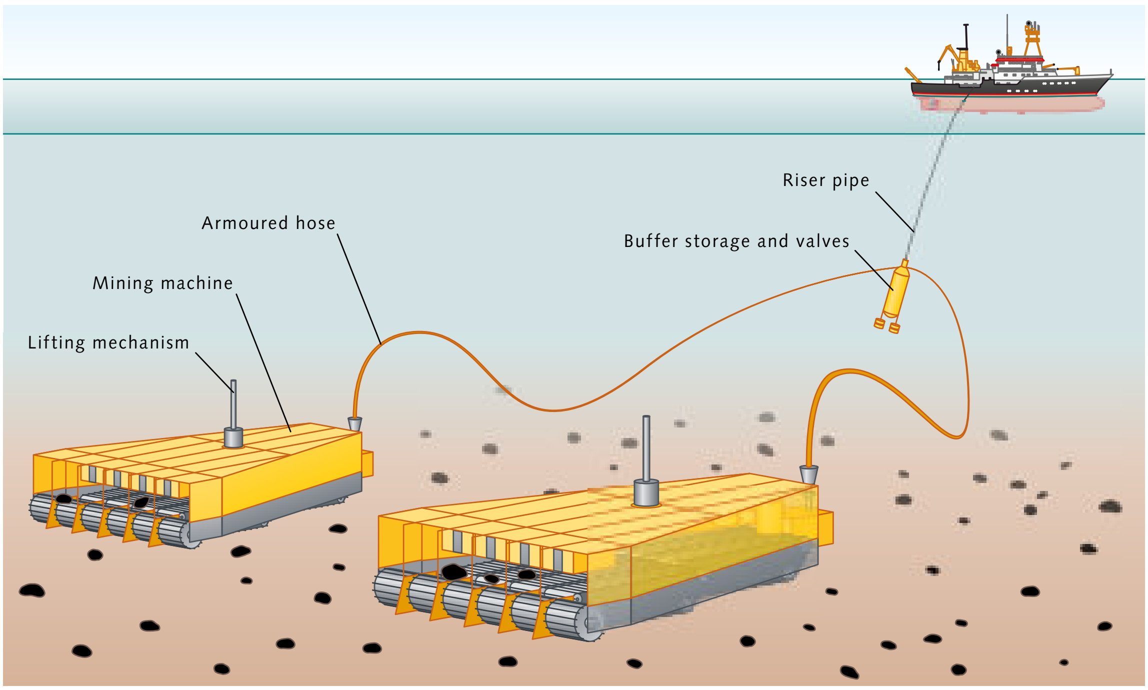
* Grams per tonne ** Percentage by weight

the promising resources in the deep sea by rich countries should be prevented.

For the manganese nodule areas this means that contractors apply to the ISA for an exploration area of up to 150,000 square kilometres. The individual contractor must pay a licence fee for these areas. The crucial condition is that the countries can only use half of their licence area, or a maximum of 75,000 square kilometres. After preliminary exploration, the other half is reserved for developing states. So far the ISA has awarded 12 licences for the Clarion-Clipperton Zone and one for the Indian Ocean, all to various states. The contractors are China, Germany, France, India, Japan, the Russian Federation, South Korea, and the Interoceanmetal Joint Organization, a consortium of Bulgaria, the Czech Republic, Slovakia, Poland, the Russian Federation and Cuba.

Two commercial companies have recently joined the applicants: the British company UK Seabed Resources Limited and the Belgian G-TEC Sea Mineral Resources NV. Since 2011 a number of developing countries (Nauru, Kiribati and Tonga) have submitted applications in cooperation with industrialized-country companies. These applications are related to areas explored by the original contractors and reserved for developing countries, which will now be consigned to Nauru, Kiribati and Tonga. The financial and technical means for further exploration and eventual development of these areas, however, will not be supplied by the 3 island nations but by the industry partners.

Up to now, the licences awarded by the ISA have all been exploration licences, which allow nations to investigate the potential mining areas more closely. This includes detailed studies to determine which parts of the region have the highest densities of nodules or nodules with especially high metal contents. The licences are awarded for a period of 15 years and can be extended one time for 5 more years. After that the mining must begin or the country will forfeit its mining rights. However, the ISA will not define the legal regulatory framework for future mining until 2016. There are still a number of unresolved questions. The mining techniques to be used in the future to harvest nodules have still not been determined, and there is no plan in place for effective protection of the marine environment from large-scale mining.



2.16 > In the future, manganese nodules will be picked up from the sea floor by harvesting machines and pumped to the ship through solid pipes. But as yet no such machines have been built. Conceptual studies envisage an apparatus furnished with a special body that prevents stirring up large amounts of sediment.

Mining machinery still not available

Manganese nodule mining at an industrial scale is presently not possible because there are no market-ready mining machines. Although Japan and South Korea have built prototypes in recent years and tested them in the sea, these still need improvement.

Three years ago the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe – BGR) invited tenders for a design study for suitable deep-sea machines that Germany wants to deploy in its own licence area in the CCZ. The participating companies included one that already makes machines for diamond mining in the Atlantic off Namibia. The equipment for diamond production, however, is deployed in only 150 metres of water near the coast. It still has to be adapted for water depths in the CCZ and working conditions on the high seas. After all, the machines for manganese nodule mining have to withstand the high pressures at water depths of 6000 metres. Furthermore, they must be able to work dependably over long time periods because repairs on deep-sea equipment are extremely costly, starting with the raising of up to 250-tonne machines to the surface.

It is presently estimated that in the German licence area of the Clarion-Clipperton Zone alone, around 2.2 million tonnes of manganese nodules would have to be extracted in order to make the mining economically feasible. This requires not only the mining machinery, but also the technology for subsequent working stages.

The extraction begins with the mining machines, which plough into the sea floor to a depth of 5 centimetres and cull the nodules out of the sediment. Most of the sediments should be separated out on site and left behind on the sea floor. The remaining nodule-sediment mixture is then pumped from the sea floor through rigid hoses to production ships at the water surface. On the ships the manganese nodules are separated from the sediment and cleaned. Finally they are loaded onto freighters that transport them to land, where they are processed and the metals separated out. This entire process chain still has to be developed. Furthermore, the metallurgical processes required to retrieve the various metals from the manganese nodules are not yet fully fledged.

Life in the manganese nodule fields

If manganese nodules were to be mined in the future it would be a severe intrusion into the deep-sea biological environment because the harvesting machines would plough up large areas of the sea floor. It is very difficult to assess precisely how and to what extent the deep-sea ecosystem would be impacted, because so far only small areas have been scientifically investigated. The few existing studies, however, clearly show that there is more life in the deep basins than was previously believed.

Many of the organisms live buried within the deep-sea sediments, especially in the upper 15 centimetres of the sea floor. The initial impression of a barren desert is deceptive. A large number of organisms also live in the open water. The deep-sea organisms are divided into different categories based on their size. For the differentiation of small species, the size of the sieve openings used to filter the animals out of the bottom or water samples is a useful criterion. The 4 following categories are generally used:

MICROFAUNA: This consists of organisms that are smaller than the openings of a very fine sieve of 0.03 millimetres. It comprises almost exclusively microorganisms.

MEIOFAUNA: This includes, for example, the copepods and nematodes (small worms), as well as foraminifera, a group of single-celled animals that live in calcareous shells. These organisms are retained on sieves with openings of 0.03 to 0.06 millimetres.

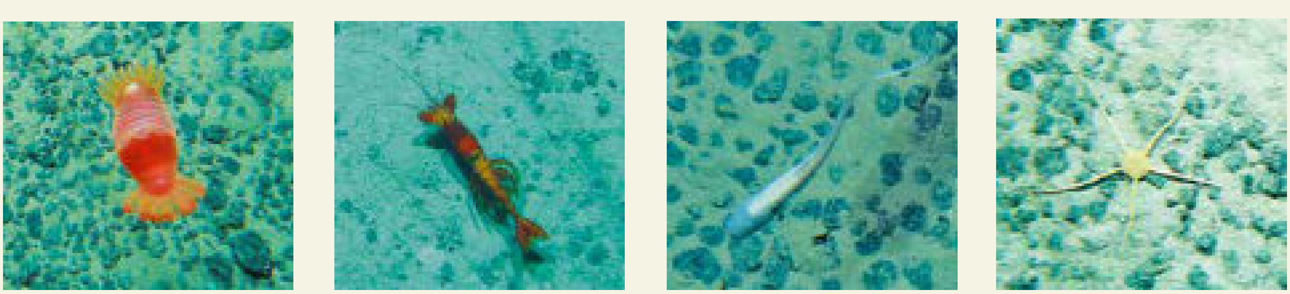
MACROFAUNA: This group includes animals that are caught on sieves with openings of 0.3 to 0.5 millimetres. Large numbers of macrofaunal organisms live in the sediments, especially bristle worms, but also crabs and mussels.

MEGAFAUNA: This includes animals that can be seen with the naked eye on underwater videos or photographs, for example, fish, sponges, sea cucumbers and starfish. These organisms are from 2 to over 100 centimetres in size.

A special feature of the Pacific manganese nodule areas is the presence of unusually large species of foraminifera. In contrast to their miniscule cousins, the *Xenophyophora* are up to 10 centimetres in size and are thus included in the megafauna. Xenophyophores live on top of the sediment and, like sea cucumbers, leave behind feeding tracks several metres long.

It is largely unknown how large the proportion of endemic species living in manganese nodule areas is. Marine biologists from various research institutes are presently evaluating bottom samples obtained on expeditions. Many endemic species have already been discovered.

Additionally, it is presumed that the species compositions in and on deep-sea sediments change every 1000 to 3000 kilometres, which means it would change within a manganese nodule area. The reason for this is that the nutrient conditions in different marine regions vary slightly, because nutrient levels are partially dependent on transport by near-surface water currents. When more nutrients are contained in the water, then algae can produce more biomass, which subsequently rains down to the bottom. Different organisms predominate depending on the supply of carbon. Compared to the nutrient-rich coastal areas, the differences in the amount of carbon between the various deep-sea regions are relatively small. Nevertheless, they apparently cause differences in species compositions. Marine biologists therefore insist that mining be regulated to the extent that the different species assemblages, and thus the character of the deep-sea areas in question, are at least in part preserved and that a successful recolonization is possible. These factors, as well as the protection of endemic species, should be considered in the mining regulations of the ISA.



2.17 > Various animal species, including sea cucumbers, deep-water prawns, fish and brittle stars, have been found in the CCZ.

Destruction of deep-sea habitats?

Scientists agree that mining manganese nodules would represent a dire encroachment on the marine habitat. The following detrimental impacts are assumed:

- While ploughing through the sea floor the harvesting machines stir up sediment. Ocean currents can move this sediment cloud through the area. When the sediments finally settle down to the sea floor again, sensitive organisms, particularly the sessile, immobile ones are covered and die.
- Directly in the ploughed area all organisms are killed that cannot escape the plough quickly enough, including snails, sea cucumbers and worms. And even if they are not hurt by the plough, they can be vacuumed up with the nodules and die during the cleaning process on the ship.
- The mining, pumping and cleaning of the manganese nodules creates noise and vibrations, which disturb marine mammals such as dolphins, and could force them to flee from their natural area.
- The sediment-laden water produced by the cleaning of manganese nodules is released into the sea from the ships. A sediment cloud is also created here. Present concepts envision a near-bottom discharge in order to minimize the spread of the cloud. Releasing it near the bottom also avoids clouding of the near-surface light-penetrating water layers. Biologists are concerned that clouding of the near-surface waters could disturb the growth of algae and other planktonic organisms.

It is certain that these problems cannot be completely eliminated. However, discussions are presently underway about how to reduce them as much as possible. In any case, the ISA requires environmentally sound manganese nodule production. And solutions actually appear to be possible. According to recent studies, the sediment cloud can be reduced by using a cowled rather than open harvesting machine. This would, in part, prevent stirring up of the sediment into the water column. Furthermore, the sediment cloud released by the ship could be reduced by pumping it through pipes back to the sea floor so that the particles settle relatively quickly. Engineers say, however, that this additional pipe system would make manganese production significantly more expensive. It is still not clear today how fast the habitats on the sea floor would rebound from this massive intervention. Several international projects have been carried out since the end of the 1980s to investigate the rate at which harvested areas of the sea floor would be recolonized. But these were quite small-scale interventions. For example, scientists in the German project Disturbance and Recolonization (DISCOL) ploughed up a sea-floor area of several square kilometres in the Pacific with experimental equipment and revisited the site over several years afterward. The results indicated that a period of 7 years were required before the ploughed area had adjusted back to the same density of bottom life as before. Yet some species had disappeared permanently, particularly those that were reliant on a hard substrate. This means that after 7 years the disturbed area was significantly species-depleted. In 2015, the German Federal Research Ministry will provide money for an expedition that will visit this area once again. Then, for the first time, the long-term effects will be observed after a period of 25 years. The DISCOL researchers stress that the damage caused by mining a large area of manganese nodules would be much greater. After all, in the experiment a comparatively small area was harvested. The disturbed area was resettled rather quickly from the undamaged surrounding areas. But if areas with many more square kilometres of sea floor are harvested, recolonization of the harvested areas would take many years longer.

The ISA therefore envisions that the licence areas would not be harvested all at once, but in smaller steps. Alongside harvested sites, untouched areas should be preserved. From these, the harvested areas can be recolonized. Marine biologists are trying to determine how the patterns of exploited and non-exploited areas should look in detail. It would thus be conceivable to limit the intensity of harvesting manganese nodule areas from the outset, proceeding in individual stages like the DISCOL project, alternating between harvested and unharvested strips. Such an approach would be completely possible today thanks to precise GPS navigation.

Metal-rich crusts

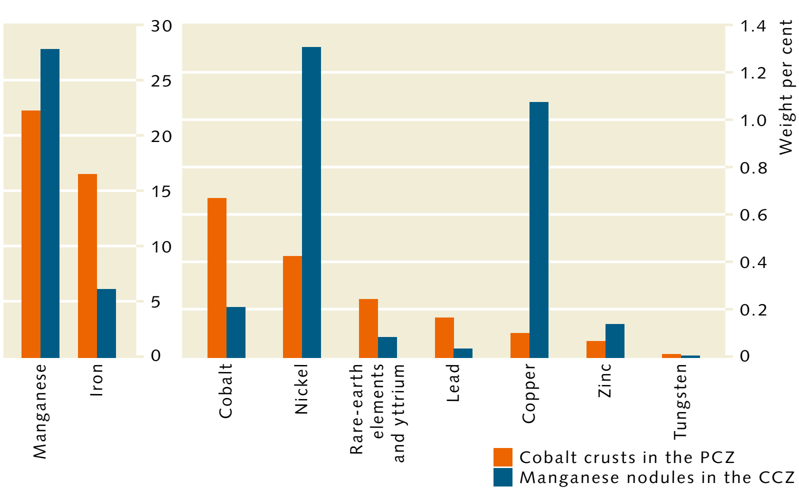
> Cobalt crusts are a promising resource on the sea floor because they contain large amounts of cobalt, nickel, manganese and other metals that could exceed the content in land deposits. They form on the rocky surfaces of undersea rises. For their extraction, machines are required that can separate the material from the substrate. To date, however, only conceptual studies exist.

A coating on the rocks

Seamounts
Seamounts grow through volcanic activity to great heights on the sea floor over millions of years. They are found in all of the oceans and reach heights of 1000 to 4000 metres. Smaller seamounts are also called knolls.

Cobalt crusts are rock-hard, metallic layers that form on the flanks of submarine volcanoes, called seamounts. Similar to manganese nodules, these crusts form over millions of years as metal compounds in the water are precipitated.

As with manganese nodules, deposition occurs very slowly. Crusts grow 1 to 5 millimetres per million years, which is even slower than nodules. Depending upon the concentration of metal compounds in the sea water, crusts with different thicknesses have formed in different ocean regions. On some seamounts they are only 2 centimetres thick, while in the richest areas thicknesses can be up to 26 centimetres. Because the cobalt crusts are firmly attached to the rocky substrate, they cannot simply be picked up from the bottom like manganese nodules. They will have to be laboriously separated and removed from the underlying rocks.



2.18 > Manganese nodules and cobalt crusts contain primarily manganese and iron. Because iron is plentiful in land deposits, it is not a key factor in marine mining. For the other elements making up lower weight per cents of the deposits, however, there are great differences to occurrences on land. In the manganese nodules nickel and copper predominate, while in cobalt crusts cobalt, nickel and rare earth elements are more significant.

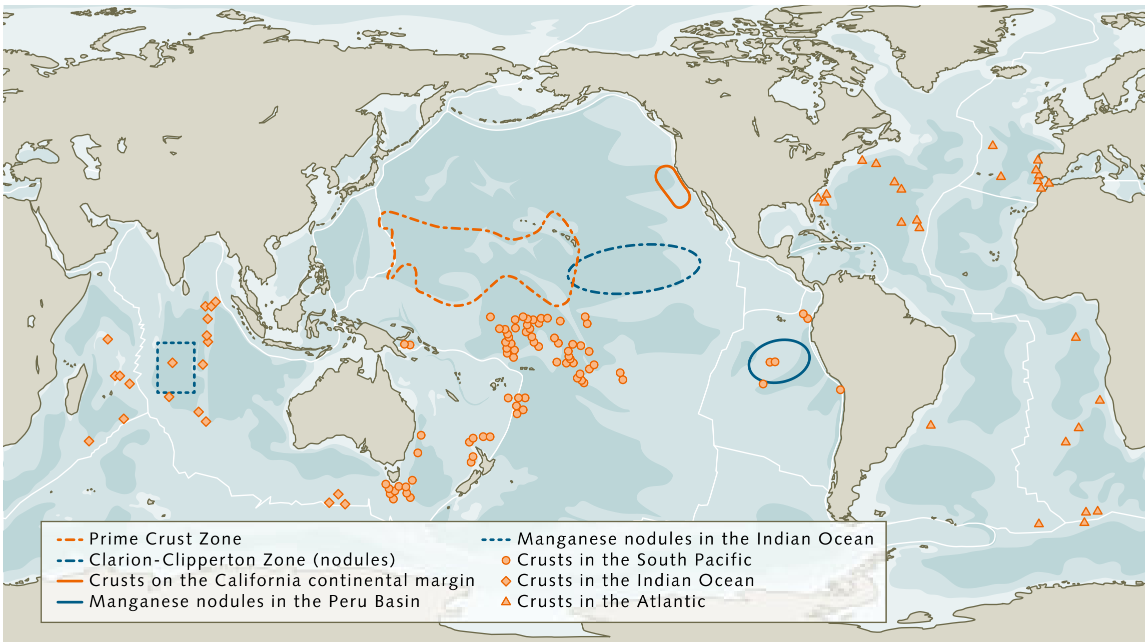
It has been estimated that there are over 33,000 seamounts worldwide. The exact number is not known. Around 57 per cent are located in the Pacific. The Pacific is thus the most important cobalt crust region in the world.

The western Pacific is of particular interest. The world's oldest seamounts were formed here during the Jurassic period around 150 million years ago. Accordingly, many metallic compounds were deposited here over a long period of time to form comparatively thick crusts. This area, around 3000 kilometres southwest of Japan, is called the Prime Crust Zone (PCZ). The amount of crust in the PCZ is estimated to total 7.5 billion tonnes.

A metal-rich crust

Like manganese nodules, cobalt crusts also represent a very large metal resource in the sea. As the name suggests, the crusts contain a relatively large amount of cobalt compared to deposits on land and to manganese nodules. The largest share of metals in the cobalt crusts, however, consists of manganese and iron. The crusts are often more precisely referred to as "cobalt-rich ferromanganese crusts". Tellurium is also comparatively abundant in cobalt crusts. Tellurium is necessary particularly for the production of highly efficient thin-film photovoltaic cells.

In absolute terms the crusts of the Prime Crust Zone do not contain as much manganese as the manganese nodules of the Clarion-Clipperton Zone. However, the quantities of manganese in the PCZ are still almost 3 times greater than the economically minable amounts on land today. Furthermore, in the southern area of the



2.19 > Cobalt crusts occur in different ocean regions than manganese nodules. Each of these resources has its own especially abundant regions. The most important cobalt crust area is the Prime Crust Zone (PCZ) in the western Pacific. The area of greatest manganese nodule concentration is the Clarion-Clipperton Zone (CCZ).

Metal contents in millions of tonnes

Elements	Cobalt crusts in the Prime Crust Zone (PCZ)	Global reserves on land (economically minable deposits today)	Global reserves and resources on land (economically minable as well as subeconomic deposits)	Manganese nodules in the Clarion-Clipperton Zone
Manganese (Mn)	1714	630	5200	5992
Copper (Cu)	7.4	690	1000+	226
Titanium (Ti)	88	414	899	67
Rare earth oxides	16	110	150	15
Nickel (Ni)	32	80	150	274
Vanadium (V)	4.8	14	38	9.4
Molybdenum (Mo)	3.5	10	19	12
Lithium (Li)	0.02	13	14	2.8
Cobalt (Co)	50	7.5	13	44
Tungsten (W)	0.67	3.1	6.3	1.3
Niobium (Nb)	0.4	3	3	0.46
Arsenic (As)	2.9	1	1.6	1.4
Thorium (Th)	0.09	1.2	1.2	0.32
Bismuth (Bi)	0.32	0.3	0.7	0.18
Yttrium (Y)	1.7	0.5	0.5	2
Platinum group	0.004	0.07	0.08	0.003
Tellurium (Te)	0.45	0.02	0.05	0.08
Thallium (Tl)	1.2	0.0004	0.0007	4.2

2.20 > Cobalt crusts are especially abundant in the western Pacific within a region the size of Europe, called the Prime Crust Zone (PCZ). When compared to deposits on land and to the manganese nodule area of the Clarion-Clipperton Zone (CCZ), it is notable that the occurrence of cobalt and tellurium in particular are comparatively large in the PCZ, with amounts exceeding both the land deposits and those in the CCZ.

PCZ, comparatively high contents of rare earth elements are found in the crusts.

Strong currents around seamounts

Cobalt crusts form on all exposed rock surfaces on undersea rises, particularly on seamounts and knolls. Seamounts act somewhat like gigantic stirring rods in the sea to produce large eddies. Nutrients or other materials that rain down from the sea surface or that are transported by ocean currents are often trapped by these eddies at the seamounts. These can include metallic compounds that are deposited on the rocks. An important precondition for the formation of cobalt crusts is that the rock and the growing crusts remain free from sediments. This condition is met at the seamounts and other elevated areas. Currents carry the fine sediments away and keep the rocks and crusts exposed.

Deep oxygen enables crust growth

Cobalt crusts are created when metal ions in the water react with oxygen to form oxides, which are deposited on the rock surfaces at seamounts. Oxides, and thus cobalt crusts, can only form where sufficient oxygen is present in the sea water.

Paradoxically, however, the thickest cobalt crusts on seamounts are located near the ocean depth layer with the least oxygen. This oxygen minimum zone generally has a thickness of several hundred metres, and in most places it is located at a depth of around 1000 metres. It is produced by the bacterial breakdown of sinking dead biomass, a process that consumes oxygen in the water. Because the water here is not mixed by storms and waves, very little oxygen penetrates to this depth. So, theoretically, it would seem that neither oxides nor cobalt crusts should be formed.

This apparent contradiction, however, can be explained as follows: Because there is very little oxygen within the oxygen minimum zone, the metal ions can form few oxides, so the ions are enriched in the oxygen-poor water. At higher elevations of the sea floor such as seamounts, however, oxygen-rich deep water flows upward from the bottom. This can be sea water, for example, that cools intensely at the South Pole, sinks to the sea floor and spreads through the deep ocean. At the seamounts, this Antarctic deep water introduces oxygen to the oxygen-poor waters enriched in metal ions, and as a result metal-rich oxides are formed that subsequently precipitate onto the rock surfaces over time to produce crusts.

Cobalt crusts are found at water depths from 600 to 7000 metres. Studies at seamounts have shown that the thickest crusts and those richest in resources are located on the upper areas of the seamount slopes, where currents are most active. On the average these lie in water depths of 800 to 2500 metres, near the oxygen minimum zone. Analyses also show that the crusts between 800 and 2200 metres have the highest cobalt contents. Researchers do not know the reason for this.

Like a sponge, or the activated charcoal used as a filter in aquariums, cobalt crusts are very porous. Thanks to the many micrometre-sized pores, the crusts have a large internal surface area. In the same way that pollutants are trapped in the pores of an activated charcoal filter, metal compounds are deposited on the large surface areas of the crusts. Because the dissolved metals occur at very low concentrations in sea water, growth of the crusts requires very long periods of time. The crusts are mainly formed through the deposition of iron oxide-hydroxide [FeO(OH)] and manganese oxide (vernadite, MnO_2). The other metals are deposited with the iron oxide-hydroxide and vernadite on the crust surfaces rather like hitchhikers. The reason is that, in the ocean, various metal ions attach themselves to the iron oxide-hydroxide and vernadite molecules in the water. Iron oxide-hydroxide is slightly positively charged and thus attracts negatively charged ions such as molybdate (MoO_4^{2-}). Vernadite, on the other hand, is slightly negatively charged and attracts positively charged ions such as cobalt (Co^{2+}), copper (Cu^{2+}) or nickel (Ni^{2+}).

Incidentally, most of the metal ions contained in sea water originate from land. Over time they are washed out of the rocks and transported by rivers to the oceans. Iron and manganese, however, usually enter the ocean through volcanic sources on the sea floor called hydrothermal seeps.

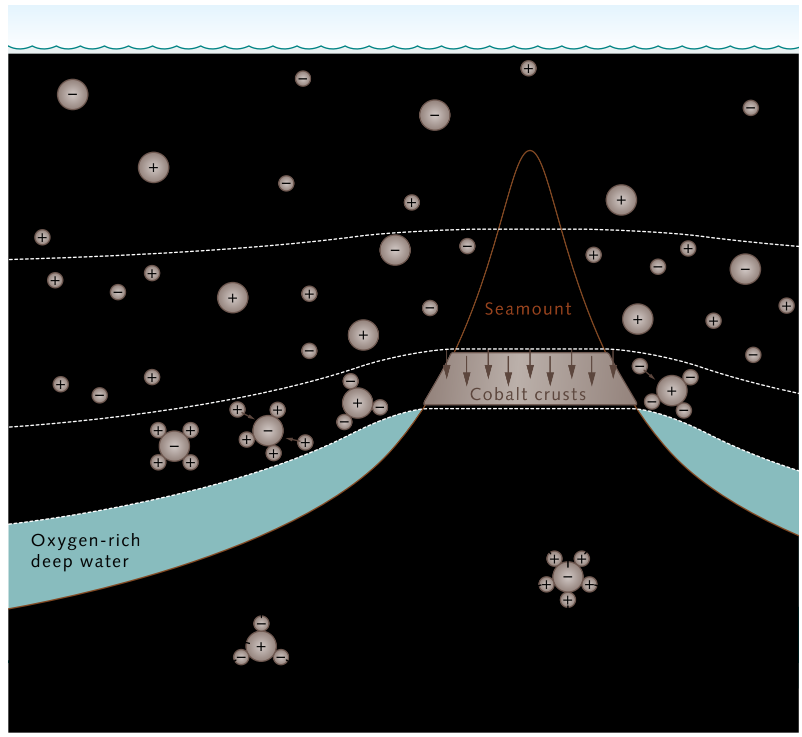
Crust mining in sovereign territory?

Manganese nodules and cobalt crusts are of equal interest for future marine mining because they contain traces of many industrially important metals that, because of the immense tonnage of the deposits, are of economic interest. But there are important differences with regard to the exploration and future mining of the crusts. One of these, for example, is the legal situation. In contrast to manganese nodules, most of the richest crust occurrences are not found in the international waters of the high seas but in the Exclusive Economic Zones (EEZs) of various island nations. Thus the International Seabed Authority (ISA) will not be responsible for determining the conditions for future mining there. Rather, the respective local governments will have jurisdiction. However, to date no country has presented concrete plans.

For those crust deposits in international waters, on the other hand, a binding system of regulations has recently been established. In July 2012 the ISA adopted internationally binding regulations for the exploration of such crust occurrences in regions of the high seas. It is true that China, Japan and the Russian Federation at that time had already submitted working plans to the ISA for future exploration in the international waters of the western Pacific, but the council and the assembly of the seabed authority first have to approve these. The working plans specify what basic information the countries want to collect in the upcoming years, including taking samples from the sea floor and analyses of the crusts, depth measurements or studies of faunal assemblages.

Problematic thickness measurements

The exploration of cobalt crusts is also fundamentally different from the manganese nodule situation in some technical aspects. Manganese nodules can be brought quickly and easily on board with a box corer, similar to a backhoe, and then sampled to measure the metal content, for example. Furthermore, the nodules are relatively evenly distributed over the sea floor. This allows relatively straightforward assessment of the deposits by photos and video recordings, particularly with respect to the size of the nodules. Sampling and measurements of the thickness of cobalt crusts, however, are much more difficult because rock boulders have to be torn or drilled out. Local thickness differences are poorly constrained and the spot sampling is extremely time-consuming and expensive.

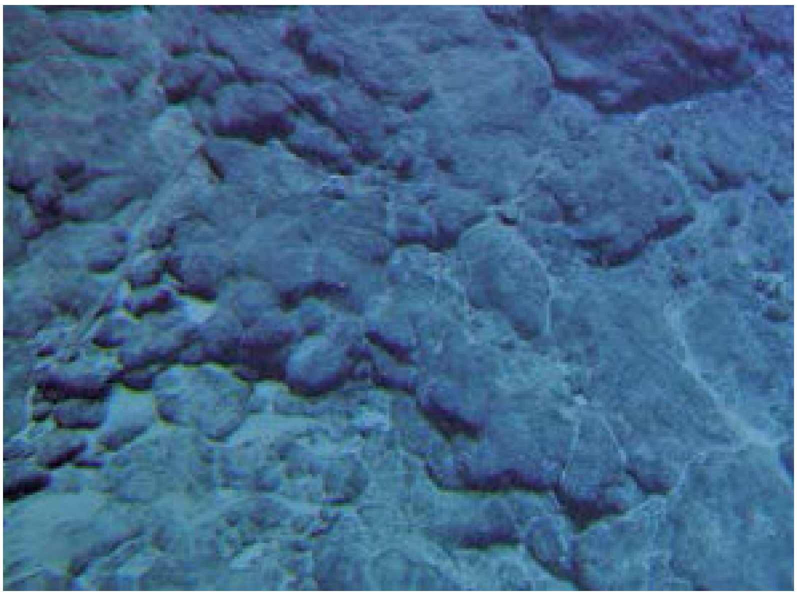


2.21 > Many metal ions end up in the cobalt crusts as "hitchhikers". In the water, the metal ions attach themselves to iron oxide-hydroxide and vernadite molecules, and are then deposited onto the porous surfaces with them.

Instruments that could be pulled through the water near the bottom to accurately measure the crust thickness while passing over would be much more efficient. This would allow large areas to be studied in a relatively short time. Scientists are therefore working to refine high-resolution acoustic instruments. These send sound waves into the sea floor and record the reflected signals, then calculate the layered structure of the sub-bottom. This kind of apparatus is standard technology in exploration for other resources on the sea floor. However, instruments precise enough to measure cobalt crust thicknesses to the nearest centimetre and to distinguish them from the underlying rocks are not yet available.

An alternative method of assessment might be gamma-ray detectors, which are already being used today for measuring rock layers on land.

Many rocks contain radionuclides, which are unstable atoms that can decay and emit radioactive waves, or



2.22 > Visually unimpressive, but extremely attractive for mining and metal companies: cobalt crusts on the sea floor.

gamma rays. The detectors can measure these rays. Because radionuclides are present in different combinations or numbers in every rock unit or stratum, different rocks can be distinguished from one another based on their gamma-ray patterns. The crusts and the underlying volcanic rocks of the seamounts are significantly different in their mixture of radionuclides. Because this method is very precise, the thickness of cobalt crusts can be quite accurately assessed. As yet, however, there are no appropriate detectors available for routine use in the deep sea.

Little more than conceptual studies

It is also still not clear how the crusts can be mined at all in large volumes in the future. So far only conceptual plans have been presented and laboratory experiments carried out. The concepts being worked on by engineers include caterpillar-like vehicles that peel the crusts away from the stone with a kind of chisel, and pump them to the ship at the surface through special hoses. Specialists estimate that more than 1 million tonnes of cobalt crust material will have to be extracted to make the mining economical. Presumably, this can only be achieved if the crusts have a thickness of at least 4 centimetres. The caterpillars need the capacity to handle this. Moreover, they will also have to be able to work on the rough terrain of the seamount flanks.

For mining the cobalt crusts – and likewise for the manganese nodules – the transport of minerals from the sea floor to the ship also remains a challenge. Pumps and valves must be extremely resistant to wear in order to withstand the high demands on equipment. Engineers are presently testing the durability of hoses and pump prototypes using glass marbles, gravel and rubble. But it will be at least 5 years before a prototype of a conveyer system with caterpillar vehicle, pump technology and riser string can be realized.

Species-rich seamounts

With regard to protecting the environment, it is actually fortunate that the technical solutions for economical mining are not yet available, because it is not yet known to what extent the mining of cobalt crusts will damage deep-sea habitats. So far only a few hundred seamounts around the world have been thoroughly investigated by marine biologists. Many marine regions along with their seamounts have not been investigated at all with respect to their biology. Biologists therefore deem it necessary to investigate additional areas and biological communities on seamounts before mining of the crusts begins. The later it begins the more time they will have for this.

It is known that the species assemblages of seamounts vary significantly from one marine region to another. Like mountains on land that, depending on their geographical position and height, provide different habitats for different species, the species composition and diversity on seamounts also varies. In the past it was assumed that many endemic species occurred here. More recent studies have not been able to verify this presumption.

Seamounts are also important for free-swimming organisms. This is probably related to the special current conditions here. The circling currents, for one, tend to keep nutrients near the seamounts. Secondly, nutrient-rich water is upwelled at seamounts from near-bottom currents, which leads to increased plankton growth. Because of this abundant supply of food at seamounts, both sharks and tuna are known to visit them frequently, for example in the southwest Pacific. These seamount areas are thus also very important for tuna fishing.

In light of the estimated total number of at least 33,000 seamounts around the world, the knowledge we have about them is still fairly limited because few have been thoroughly investigated. In order to at least roughly estimate the diversity of the deep sea and how strongly deep-sea habitats around the world differ from each other, the GOODS Report (Global Open Oceans and Deep Sea-habitats) on the worldwide marine and deep-sea habitats was commissioned by UNESCO and published in 2009.

This report divides the ocean into different bioregions. Depth was also especially considered. The report defined 14 bioregions within the depth range between 800 and 2500 metres, which is where the thickest and richest crusts also occur. The classification is based on biological information from deep-sea expeditions as well as oceanographic parameters, including carbon, salt and oxygen content, and the temperatures at certain depths. The structure of the sea floor, or topography, was also considered. This provided a distinction between flat deep-sea areas, hydrothermal seeps and seamounts. This classification system is still very rough, as the authors of the study admit, but the GOODS Report helps to predict which habitats can be expected in which marine regions.

Many animal species that live on or near seamounts are characterized by extremely slow growth rates and by producing relatively few offspring. The cold-water corals, for example, which live in the deep sea, can live for hundreds or even up to 1000 years. Some deep-sea fish also live to be more than 100 years old. They do not become sexually mature until around 25 years of age and only produce a few eggs at a time. Relatively large numbers of such species are often found at seamounts. Because they produce low numbers of offspring, they are particularly endangered by fishing or destruction of their habitats. If the adult animals die there may not be enough offspring to revive stocks.

Studies off Australia and New Zealand have shown that fauna at seamounts recover very slowly from intervention. For example, it has been shown that in areas where trawl nets have been used, even after an interlude of 10 to 30 years of inactivity, the fauna were significantly less species-rich than areas that had not been damaged by the trawl fisheries.

2.23 > At a depth of 2,669 m, black coral, primnoid coral, and feather stars cover a part of the Davidson Seamount off the coast of California.

Scarcely studied – life on the cobalt crusts

To date only a few expeditions have been carried out with the explicit goal of investigating the habitats of cobalt crusts. Studies carried out by Japan between 1987 and 1999 in cooperation with SOPAC member states (Secretariat of the Pacific Community Applied Geoscience and Technology Division) are one example. The aim of these expeditions was to study the habitats at locations of various mineral resources in the ocean – the cobalt crusts, manganese nodules and massive sulphides – in the Exclusive Economic Zones of the island nations Kiribati, the Marshall Islands, Micronesia, Samoa and Tuvalu.

Thousands of underwater photographs were taken in order to identify the presence of organisms. Although the areas photographed, at 0.35 to 2 hectares, were relatively small, the researchers discovered a great diversity of organisms. In the megafaunal size class (larger than 2 centimetres), many attached, or sessile, species

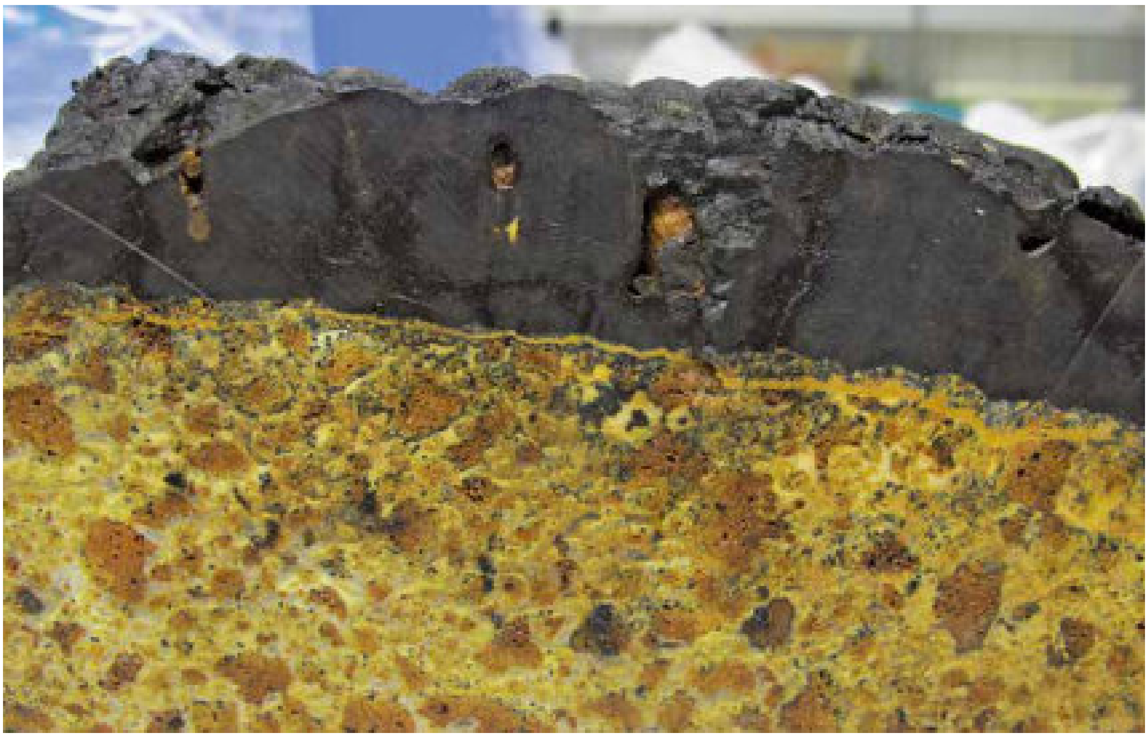
2.24 > Xenophyophores are poorly studied one-celled organisms that live in the deep sea, often on the slopes of seamounts. This specimen is 20 centimetres in size.

such as corals and sponges were identified. Sea pens and delicate colonies of small polyps were also described. The seamounts are characterized by a rocky substrate and strong currents, and these kinds of organisms are well adapted to these conditions. They are all filter feeders, and sieve food particles out of the water. Seamounts are an ideal habitat for them because the ocean currents provide them with abundant food. In addition, the photographs revealed crabs, starfish, sea cucumbers and squid, as well as xenophyophores, one-celled animals several centimetres in size belonging to a family that are usually less than one millimetre in diameter.

Assessing the impacts of mining

Scientists call for more detailed studies of the habitats on seamounts with abundant cobalt crust deposits before submarine mining can even begin. This applies particularly to the island nations in the southwest Pacific, whose territorial waters contain the richest crusts. After the joint studies with Japan, SOPAC members are now carrying out further research at seamounts that have been too poorly studied so far. Because cobalt crusts are limited to undersea rises, their extraction will be on a smaller scale compared to manganese nodules. The sediment cloud produced would also be significantly smaller than in the mining of manganese nodules, because no soft sediment would be stirred up. The details of cobalt crust mining impacts for the future are still unknown. According to experts, the following problems can be expected, which are very similar to those for manganese nodule mining:

- The machines used to strip the crusts would stir up rocks and particulates. Although these particle clouds would not be as large as in manganese nodule mining, there is still the fundamental hazard of a drifting cloud that would harm other habitats.
- In the harvested area all sessile organisms, the predominating groups of organisms on the cobalt crusts, would be destroyed.
- The use of harvesting machines and the pumping and cleaning of crust material would create noise



2.25 > In cross section the black cobalt crust, several centimetres thick, is easy to recognize against the light-coloured volcanic rock. This rock comes from the Louisville seamount chain in the southwest Pacific, which comprises over 70 seamounts.

and vibrations, which would disturb and drive away dolphins and whales.

- Waste water accumulated during harvesting of the crusts would be discharged back into the ocean. This would also produce a sediment cloud.
- The lights on the ships and harvesting machines could disturb marine birds and mammals as well as fish.
- The disposal of everyday ship refuse would pollute the ocean.

Proponents of mining stress that manganese nodules and cobalt crusts are present as thin layers lying directly on the sea floor or on the flanks of seamounts. In contrast to ore deposits on land, they are thus a two-dimensional resource that can theoretically be extracted with relatively little effort. On land, on the other hand, ores are extracted from mines or gigantic open pits, in which machines dig more than 100 metres deep into the earth. For production of these three-dimensional reserves, millions of tonnes of earth (overburden) have to be removed and transported before the actual ore can be extracted. This destroys entire regions and causes people to lose their homelands. Marine mining, however, would be a comparatively small intervention because only the surface of the sea floor or the seamount would be removed. There would be no need for infrastructures like streets or tunnels. There would also be no overburden piles.

Due to the paucity of marine biological studies, the advantages and disadvantages of marine mining can hardly be evaluated at present. It is still unknown to what extent the mining would change life in the sea and what the eventual consequences would be for people and fisheries. These open questions can only be answered through continued intensive research and the necessary financial support for appropriate expeditions.

Some researchers, sceptical biologists in particular, call for the harvesting of large experimental areas in pilot projects before industrial mining may commence, in order to be able to assess the impact of a large-scale mining operation. Ministries of research or the European Union, for example, could provide financial support for such a large-scale test mine.

Massive sulphides in smoky depths

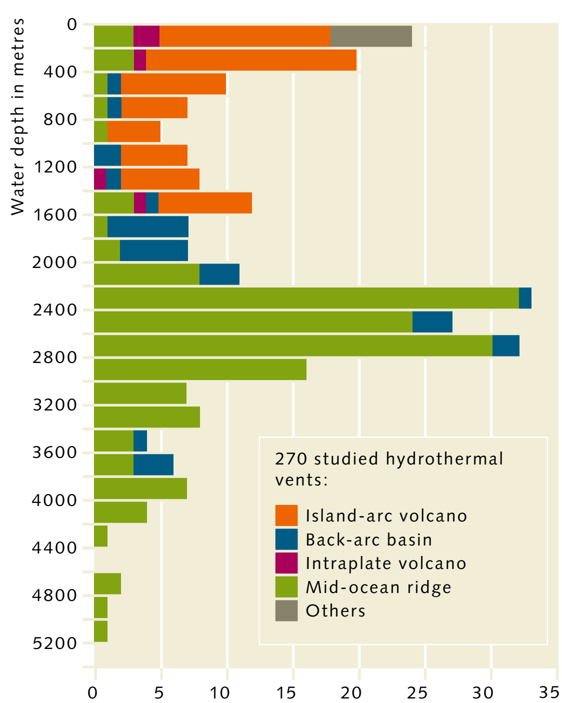
> Hydrothermal vents where metal-bearing sulphur compounds called massive sulphides are deposited were discovered in the Pacific in 1979. They are now known to occur worldwide. Although the total amounts found to date are by far not as great as the cobalt crusts and manganese nodules, some deposits contain significantly larger concentrations of copper, zinc, gold and silver. Off the coast of Papua New Guinea mining could begin as soon as 2016.

A very hot stream of water

Sulphides
Sulphides are chemical compounds of sulphur and metal. The components of massive sulphides include iron sulphide (pyrite), copper sulphide (chalcopyrite), and zinc sulphide (sphalerite), as well as sulphides of other metals such as gold and silver. The relatively high content of precious metals makes the massive sulphides promising for ocean mining.

Beside manganese nodules and cobalt crusts, a third type of metal-bearing mineral resource is found in the sea: massive sulphides. They consist of sulphur compounds, sulphides, which form massive deposits on the sea floor similar to cobalt crusts – thus the name. Massive sulphides originate at hot vents in the ocean where sulphide-enriched water flows out of the seabed.

These sites of escaping hot water are called hydrothermal vents. They are found along plate boundaries and at active undersea volcanoes, where the exchange of heat and elements between the crustal rocks and the ocean takes place due to interactions between the volcanic activity and seawater. Seawater penetrates several thousand metres into the bottom through fissures in the sea floor. At these depths the seawater is heated to temperatures of around 400 degrees Celsius by volcanic activity, whereupon it dissolves metals and sulphur from the ambient volcanic rocks. The heated water is less dense than the cooler water above, so it rises quickly and flows back into the sea. In the ocean, the plume of hot water cools again rapidly. This causes the dissolved metals to bind into minute sulphide particles and sink as fine precipitants to the bottom.



2.26 > Distribution of hydrothermal vents by depth and type of origin.

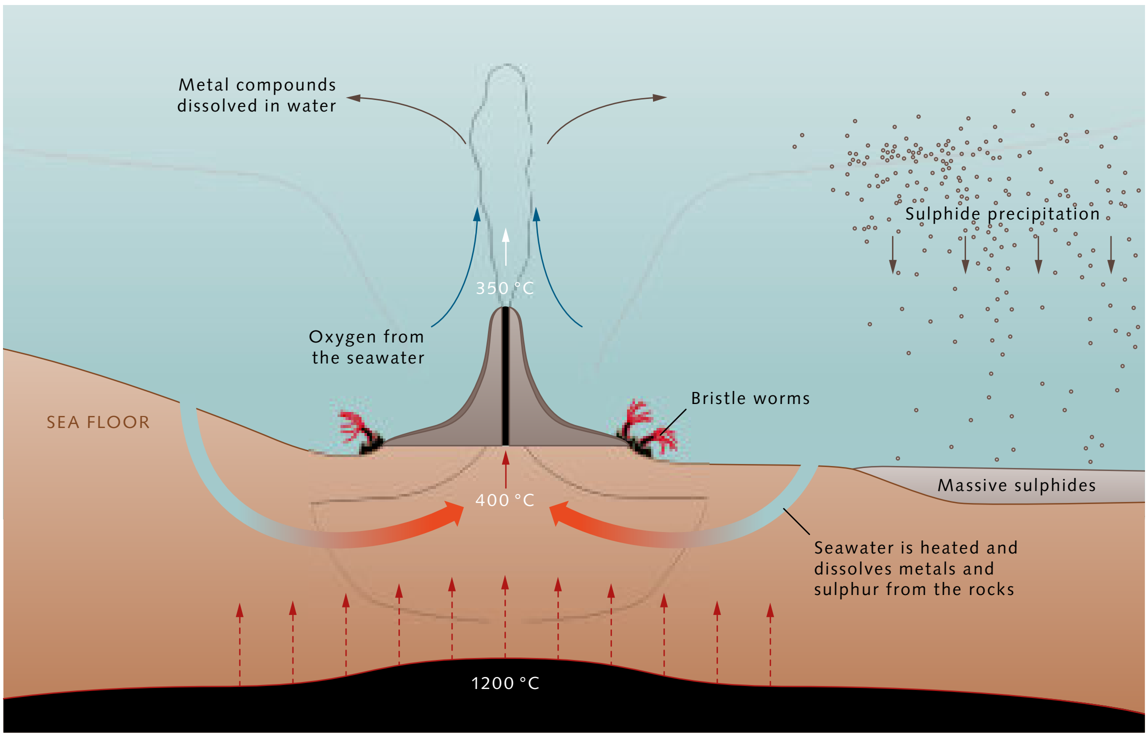
At many hydrothermal vents around the world the sulphides have accumulated to form tall chimney-like structures on the sea floor. Water shoots out of the fissures into the sea like a fountain. More and more material is gradually deposited on the sides of the openings and the tower continues to grow. Because of their appearance, these structures are also called smokers. As the escaping water is usually black-coloured by the minerals it contains, they are also called black smokers.

The first black smokers were discovered in 1979 during an expedition to the **East Pacific Rise**. They caused a sensation not only for geologists, but also for biologists because they were found to be populated by a diverse animal community. Scientists had not expected to find so much life in the deep sea. At that time it was considered to be a bleak and empty landscape.

Hydrothermal vents have now been found in all oceans. They usually form in water depths between 1000 and 4000 metres.

Massive sulphides occur around the world at plate boundaries. Geologists distinguish 4 different typical areas of origin for hydrothermal vents and the associated massive sulphides:

AT MID-OCEAN RIDGES: Mid-ocean ridges are mountain ranges in the ocean that circle the globe like the seam on a baseball. This is where the oceanic plates are



2.27 > Smokers form in magmatically active ocean regions. Water seeps through fractures in the sea bottom to depths of several thousand metres. Near magma chambers it is warmed to around 400 degrees Celsius and dissolves minerals from the rocks. Because of its low density it rises again and shoots out of the smoker back into the sea. Reaction with the cold seawater causes the formation of mineral particles that are then deposited onto the chimneys of the smoker or the nearby sea floor.

drifting apart. The separation produces fractures in the seabed through which water sinks to great depths to be heated at magma chambers.

AT ISLAND-ARC VOLCANOES: Island-arc volcanoes are formed when one oceanic plate is forced beneath another one under the sea. The subducted rocks melt at great depths and then rise as magma. Over time a large volcano grows. As long as the volcano does not reach the sea surface, it is called a seamount. Hydrothermal vents can form near the crowns of these underwater volcanoes. Many islands in the southwest Pacific have formed by this kind of subduction of oceanic plates and the rising of magma. There are usually a number of these volcanoes lined up in an arc along the subducting plate boundary because of the spherical form of the Earth. They are then called island arcs.

VOLCANOES BEHIND ISLAND ARCS (back-arc basins): When one plate submerges beneath another, tension is produced in the overlying plate. Subduction of the sinking plate causes the overlying plate to thin and pull apart, until it finally splits open. In many cases this kind of tension occurs several dozen kilometres behind the active island-arc volcanoes. This area is therefore referred to as the back-arc basin.

AT INTRAPLATE VOLCANOES: In addition to plate boundaries and subduction zones, volcanoes also form in the plate interiors. In these cases magma rises through fissures, burning its way through the Earth’s crust like a blowtorch. Because they form at individual sites or points, they are called hotspots. Single, isolated hydrothermal vents can also be found at these hotspots. The Hawaiian island group is an example of intraplate volcanoes. It was formed as the oceanic plate slowly moved across the hotspot. At various points magma has erupted to build up the islands.

Uncounted hydrothermal vents

To date, expeditions have discovered around 187 active hydrothermal vents with massive sulphides. An additional 80 known hydrothermal vents are no longer

Black, white, grey, and sometimes even yellow

Although they are generally referred to as massive sulphides, strictly speaking the deposits at hydrothermal vents are characterized by 3 different kinds of sulphur associations: sulphides, sulphates, and native sulphur. Which compounds predominate depends on the temperature of the hydrothermal vent as well as the chemical conditions in the hydrothermal fluid. The hottest known vent has a temperature of 407 degrees Celsius. At all others the temperature of the escaping liquid is significantly lower. Sulphides predominate at hydrothermal vents with temperatures between 330 and 380 degrees Celsius. Because these sulphur compounds are black, the vents are called black smokers. At white smokers, on the other hand, the prevailing temperatures are below 300 degrees Celsius. White sulphate compounds are more abundant here. There are also grey smokers that discharge both sulphides and sulphates. Yellow smokers occur in some regions. These are located at active volcanoes. The water temperatures here are below 150 degrees Celsius and primarily yellow native sulphur is extruded.

active, but massive sulphides are found here that were deposited in the past. Furthermore, 30 sites are known where high-temperature hydrothermal solutions flow out of the seabed but no massive sulphides have formed. There could, however, be sulphide deposits below the surface here. So there are a total of around 300 hydrothermal vents or massive sulphide deposits known today. 58 per cent of these are located at mid-ocean ridges, 26 per cent at the back-arc spreading zones, 16 per cent at island-arc volcanoes, and one per cent on intraplate volcanoes.

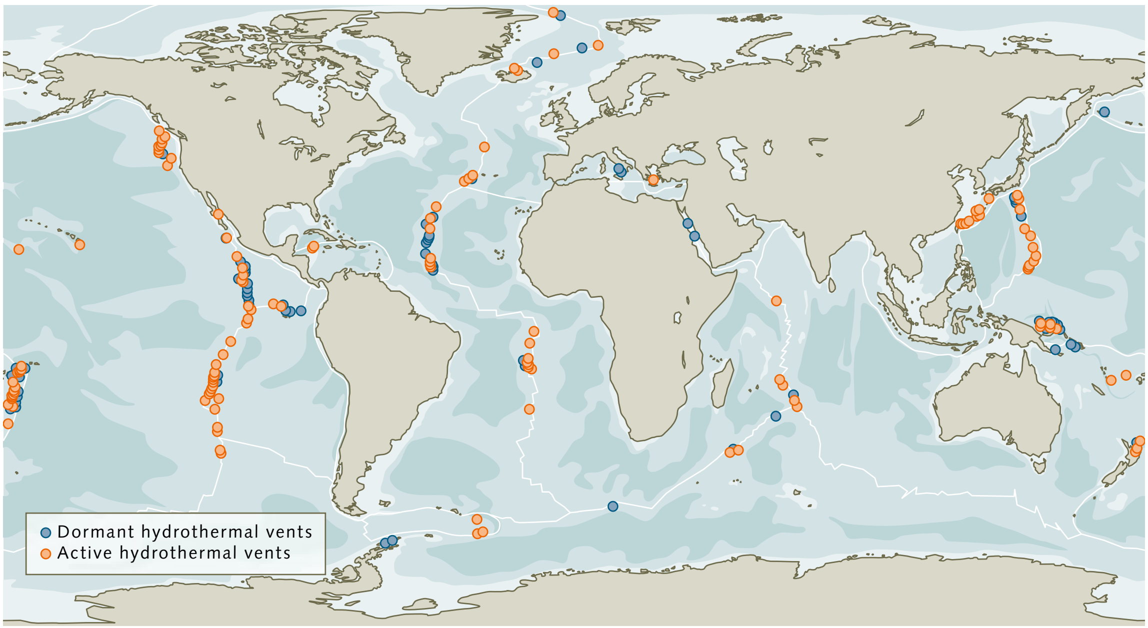
Researchers assume that the worldwide number of hydrothermal vents, and thus of massive sulphides, is much larger. This is based on estimates of the geothermal heat flux of the Earth. The amount of heat generated in the Earth's interior and that released by magmatism and volcanism is accurately known today. This heat amounts to 1.8 trillion watts, equivalent to the output of one million nuclear power plants. According to the estimates, a portion of the heat is released through hydrothermal vents. Based on the calculations, some researchers reckon that there is one hydrothermal vent for every kilometre of mid-ocean ridge or back-arc spreading zone. Considering that the mid-ocean ridges and back-arc spreading zones together have a total length of about 67,000 kilometres, and the island-arc volcanoes a length of around 22,000 kilometres, there could be around 90,000 hydrothermal vents worldwide. Researchers assume that large areas may be found every 50 to 100 kilometres that contain up to 100 black smokers. It is predicted that there are around 500 to 1000 sites around the world with large massive sulphide deposits.

The size and metal content of massive sulphides, however, are difficult to measure. This is because the hot-water plume escaping from active smokers disperses rapidly and the sulphides, in part, are carried away by the currents. Massive sulphide areas extending 10 to hundreds of metres can thus be formed that contain several million tonnes of massive sulphides. At a single glance, however, it is not possible to tell how large an occurrence is; this requires bottom samples or drill cores. This costly sampling process is also necessary to determine the metal content.

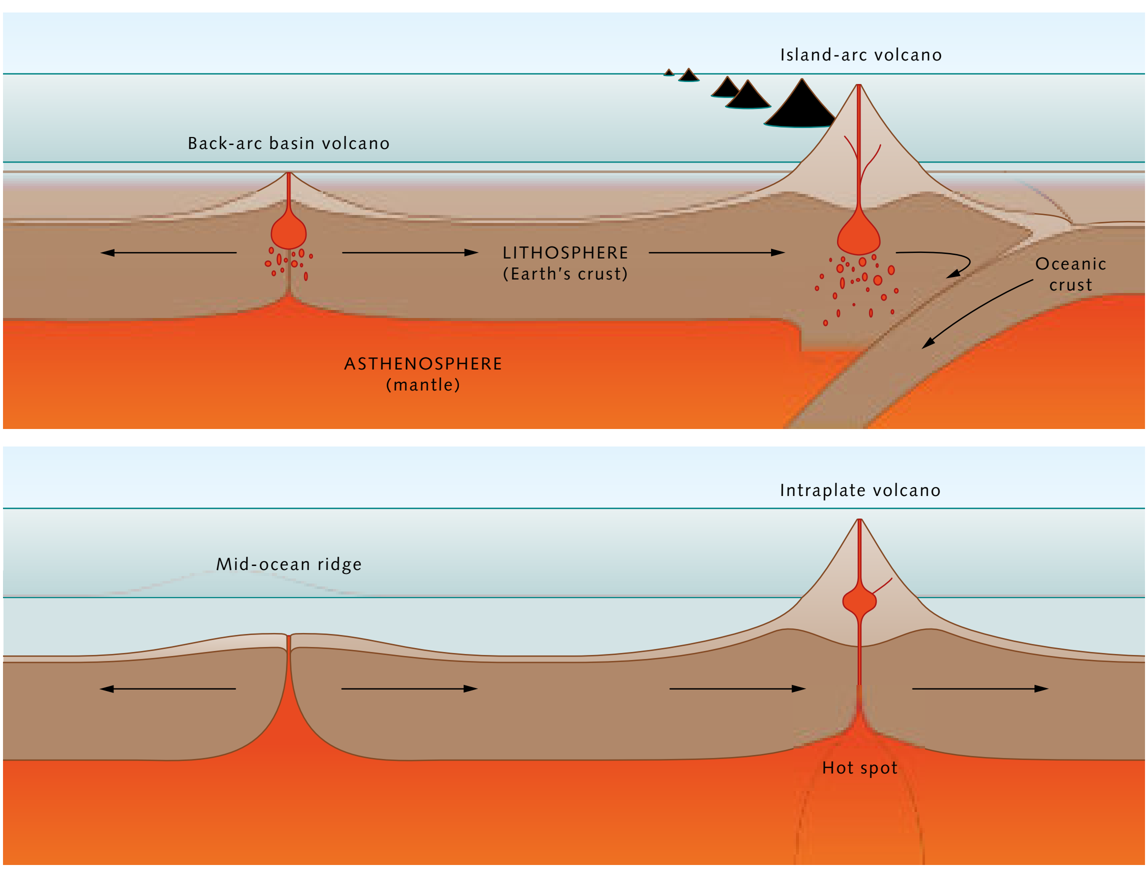
Based on the analyses of many bottom samples carried out in recent decades, researchers believe that massive sulphide deposits containing valuable metals such as copper and gold that are actually large enough for economic mining occur at relatively few hydrothermal vents. Moreover, many of the regions are in rough terrain that is unsuitable for the mining equipment.

Geological studies have shown that large deposits can only form when one or more of the following conditions are met:

- The hydrothermal vent was active for at least several tens of thousands of years, giving time for a sufficient amount of material to accumulate.
- The plates at the mid-ocean ridge or in the back-arc basin may only spread apart at very slow rates. Otherwise new fissures would constantly be forming with numerous small vents, and no single site with large amounts of sulphide enrichment could develop. Projections suggest that 86 per cent of all massive sulphide deposits occur at fractures where the plates are spreading apart at the low rate of no more than 4 centimetres per year. Only 12 per cent of the massive sulphide deposits are found at rifts where the spreading rate is 4 to 8 centimetres per year. In addition, these deposits are usually smaller in size.



2.28 > The number of hydrothermal vents is difficult to determine because they are dispersed around the world. 187 active and 80 inactive hydrothermal vents where massive sulphides have formed are known to exist.



2.29 > Hydrothermal vents develop in different kinds of magmatically active areas where water penetrates to great depths and is heated. These areas include island-arc volcanoes, for example, which are formed when rocks plunging far below the sea floor are melted. Behind the island arcs, the seabed ruptures due to the spreading motion of the Earth's crust, allowing magma to rise. Mid-ocean ridges form when oceanic plates drift apart. Intraplate volcanoes, on the other hand, originate at weak points in the crust.

The challenging search for hydrothermal vents and profitable massive sulphide deposits

Many hydrothermal vents have been found by coincidence during expeditions in magmatically active ocean regions. The search for new hydrothermal vents is difficult because areas just a few tens to a hundred metres in size must be found within the vast ocean. For this search, marine scientists usually employ sensors lowered from the ship on a steel cable. The sensors can recognize hot water plumes by measuring the turbidity of the water, the temperature, or chemical signals.

However, measurements can only be made at selected points at a particular site. In recent years, therefore, autonomous underwater vehicles (AUVs) have been increasingly used. The torpedo-shaped AUVs are also equipped with these sensors. They are capable of travelling freely through the water and diving down to the sea floor. After an excursion of around 20 hours they return to the ship.

With the help of autonomous underwater vehicles, as many as 10 new hot water plumes have been discovered on a single expedition. They cannot determine the precise position of the vent, however. Furthermore, it cannot be known whether there is actually a hydrothermal vent at the seabed with sulphide-rich black smokers. This can only be confirmed by the use of towed cameras, cameras on bathyscaphes or submersible robots, or with sonar instruments that can reproduce the image of individual chimneys using acoustic signals. It is therefore necessary to distinguish between proven and unconfirmed hydrothermal vents. Currently, in addition to the known occurrences, an additional 200 unconfirmed hydrothermal vents have been identified.

Old massive sulphide deposits at dormant hydrothermal vents are also best identified by camera observations near the bottom. A useful indicator for these is staining on the sea floor such as rust, which suggests the presence of iron. Initially, the size of such a deposit is roughly estimated. One technique researchers use to estimate thickness is to observe whether the deposit is higher than the surrounding sea floor. Using data from past experience the density of the sulphide is estimated. They then derive an approximate tonnage based on the area covered by the deposit and the estimated density.

It is now known that the estimates based on underwater pictures have frequently been too high, because subsequent analyses have often revealed that hardly any sulphides were in the seabed. As drilling is very expensive, however, efforts beyond the initial estimates are often not carried out.

Furthermore, still little is known about how the metals are distributed in the massive sulphide deposits. In some areas it has been confirmed that the metals are mainly concentrated on the surface of the deposit while in the interior the concentration drops sharply. A deposit is only profitable, however, when both the tonnage and the content of the desired metal are large enough. Many of the occurrences known today do not meet these conditions.

On the other hand, scientists assume that there are many old massive sulphide deposits hidden in the vastness of the deep sea that could be very interesting economically. It is true that the volcanically active zones in which active hydrothermal vents are found are usually only a few kilometres across. But since the entire ocean was formed, after all, through this kind of volcanic activity, it stands to reason that massive sulphide deposits must exist everywhere throughout the ocean. Over time, many of these occurrences have probably been covered by thick layers of younger sediments. It is thus very difficult or maybe even impossible to discover these. Even if the massive sulphide deposits could be found, mining them would only be economic if the sediment layers were thin and could be removed without much effort.

2.30 > A research ship crew member deploys an autonomous underwater vehicle (AUV) equipped with sensors into the sea.

Very few massive sulphide deposits occur at rifts with more rapidly spreading plates (greater than 8 centimetres per year).

- The hydrothermal vent is covered by sediments, which are enriched from below by sulphides rising from the subsurface. In this situation the fine sulphide particles form when the hot water reacts with the cooler water in the pores of the sediments. The metals can be highly enriched in such sediments because the sulphides are not dispersed by water currents, as they are at black smokers. There are, however, very few known deposits of this kind.

More precious than nodules and crusts

Compared to the billions of tonnes of manganese nodules and cobalt crusts, the estimated amounts of massive sulphides, at a total of a few hundred million tonnes, are much smaller. Estimates of the total amounts are extremely difficult, however, because to date only a fraction of the total occurrences have been discovered. Furthermore, presumably not all of the estimated 500 to 1000 large occurrences can yield valuable metals. The massive sulphide occurrences of the East Pacific Rise, and in part those of the Mid-Atlantic Ridge, contain mostly iron sulphide, which has no economic value.

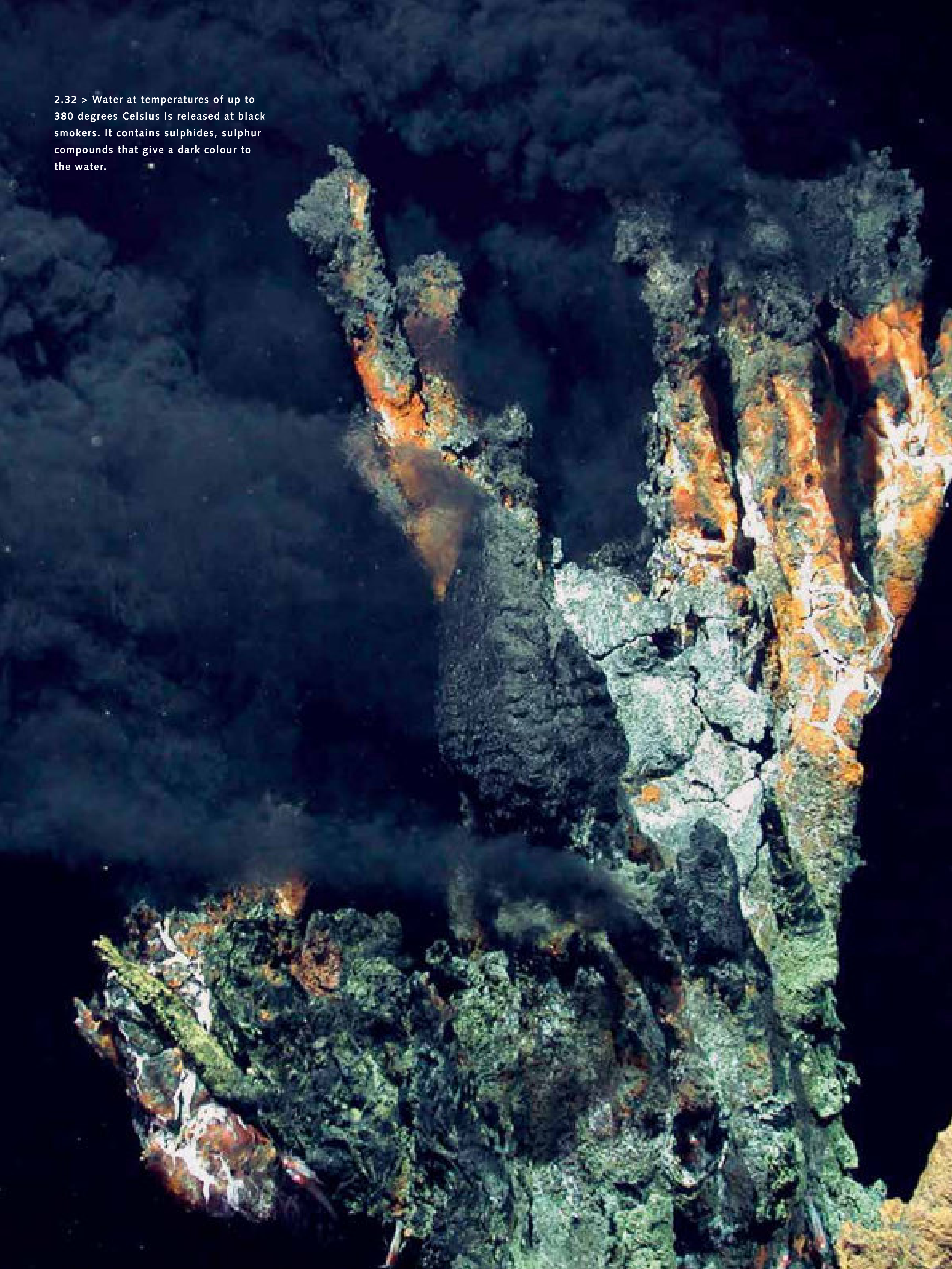
The deposits in the Bismarck Sea east of Papua New Guinea are one example of economically promising massive sulphides. They have high contents of copper and zinc. The contents of gold and silver are also considerable. The concentration of gold in some of the deposits here is around 15 grams per tonne. That is about 3 times as much as in typical deposits on land. The silver content here is commonly between 100 and 300 grams per tonne, with peak values of 642 grams per tonne in the Solwara Field in the western Bismarck Sea. This is significantly higher than the concentrations in manganese nodules and cobalt crusts, which only reach values of about one gram of silver per tonne. The highest proportions found on land are 100 to 160 grams of silver per tonne.

Many chemical elements are found in relatively small amounts in massive sulphides, including manganese, bismuth, cadmium, gallium, germanium, antimony, tellurium, thallium and indium. In some deposits, however, especially at island-arc volcanoes, these elements can be more highly concentrated.

Region	Gold (Au) in grams per tonne	Silver (Ag) in grams per tonne
Manganese nodules in the Clarion-Clipperton Zone (CCZ)	0.0045	0.17
Cobalt crusts in the Prime Crust Zone (PCZ)	0.013	4
Massive sulphides in Solwara 03 (central Manus Basin)	15.2	642
Massive sulphides in Solwara 09 (eastern Manus Basin)	19.9	296
Massive sulphides in Solwara 18 (western Manus Basin)	0.2	110

2.31 > Massive sulphides are notable for their high gold and silver content, which in part greatly exceeds that of manganese nodules and cobalt crusts. But by no means every massive sulphide occurrence is rich in precious metals. Even within a single region such as the Manus Basin of Papua New Guinea, occurrences are found with highly variable gold and silver contents.

Which metals are contained in the massive sulphides and at what concentrations depends principally on the composition of the rocks beneath the hydrothermal vents and on the temperature of the escaping water. The contents fluctuate, therefore, not only from region to region, but also within a single massive sulphide occurrence or at an individual black smoker. This is because the temperature drops with increasing distance from the hydrothermal vent. Minerals that are rich in copper often form in the core of the smoker. In the outer zone of the porous smokers the hot fluids are mixed with the cold seawater, and minerals with other metals are deposited, for example pyrite, sphalerite, or marcasite, which are rich in iron and zinc. This zonation is also observable at larger scales: at the margins of massive sulphide occurrences the smokers have lower outflow temperatures, so these precipitate different minerals. Because expeditions in the past have often only taken massive sulphide samples directly from the chimneys themselves, it is still not well known how the metals are distributed within an area. The composition of the massive sulphides varies not only with distance from the hot vent, however, but also with depth, and there is little data available regarding this. Only small numbers of expeditions or research ships have special drilling equipment available for taking samples. In order to assess how profitable a deposit is and how high the metal content is, much additional drilling will be necessary in the future.



2.32 > Water at temperatures of up to 380 degrees Celsius is released at black smokers. It contains sulphides, sulphur compounds that give a dark colour to the water.

First activity in the South Pacific

Like the cobalt crust occurrences, important massive sulphide deposits are found not only in international waters of the high seas, but also in the Exclusive Economic Zones (EEZ) of a number of island states. Here the appropriate local governments and not the International Seabed Authority will determine the conditions for future extraction activities.

Plans for mining in the Bismarck Sea off Papua New Guinea are already at an advanced stage. The government there is working with a Canadian company which, in turn, includes participation by large commodities companies from Canada, Russia and South Africa. The plans were temporarily on hold due to arbitration proceedings related to the payment of project costs. An arbitrator was finally able to bring the parties to an agreement in October 2013. It now appears that a contract will be awarded to a shipyard in the spring of 2014 for the construction of a special ship for massive sulphide mining. The seabed crawlers for working on the bottom have already been built. In the future, vehicles weighing from 3 to 300 tonnes will be used: one large and one small rock cutter plus a collecting machine to retrieve the pieces of massive sulphide. According to the manufacturer, the technical challenges can be easily overcome. The company has been producing heavy crawler vehicles called trenchers that are used to lay underwater cables. These have been operated in even deeper waters. The rock mixture will be pumped from the collecting machine into a large container that rises and sinks between the ship and sea floor. The container is filled with blocks of massive sulphides on the bottom and then raised to the ship, emptied, and lowered to the sea floor again. The partners expect mining operations to begin around 2016.

Limited exploration licences

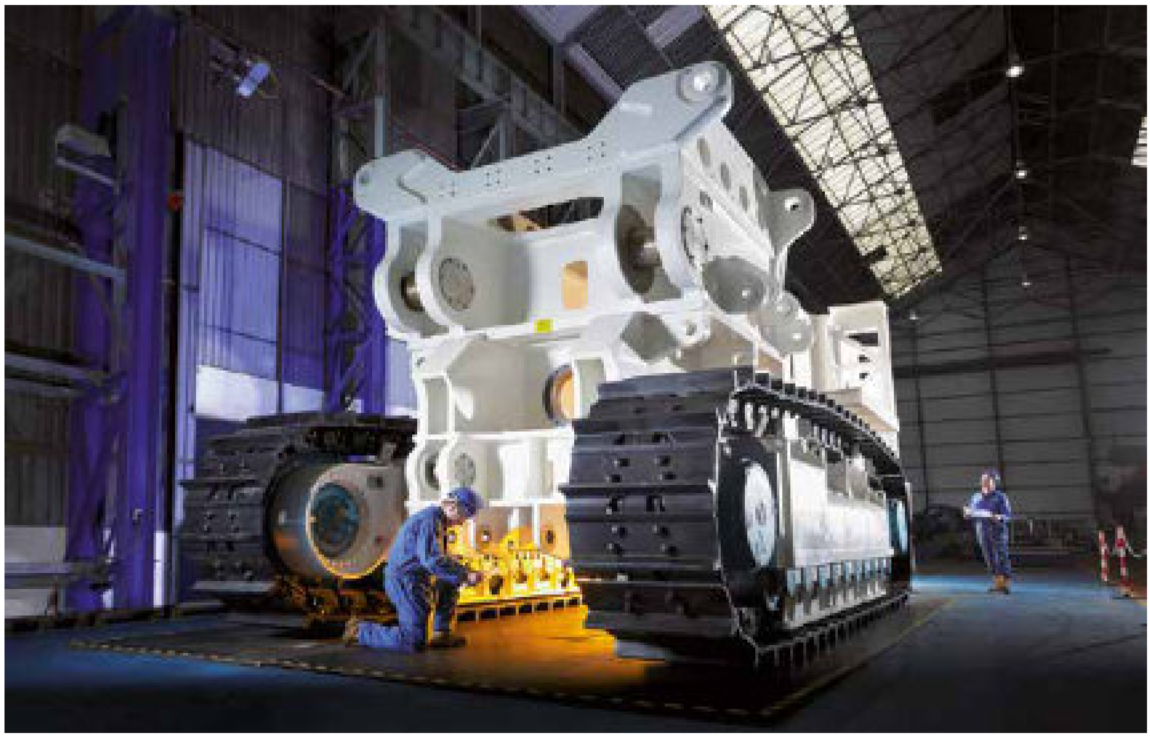
Comparable progress has not been achieved in international waters because exploration and mining there are centrally regulated and coordinated by the ISA. Licences have already been awarded to China and South Korea for areas in the Indian Ocean, and to France and Russia for areas on the Mid-Atlantic Ridge. Other states have just recently applied for, or will soon apply for exploration licences. Germany is planning for the Indian Ocean, for example. The ISA will first have to rule on these applications. Overall, however, the same scenario is expected for massive sulphide deposits as will likely occur for the mining of cobalt crusts and manganese nodules: while mining in international waters will not happen in the immediate future, individual states, in cooperation with mining or resource concerns, could get a head start by beginning to mine in their own EEZs. For Papua New Guinea, for example, mining is interesting because the massive sulphide deposits off their coast have high gold and silver contents.

Extreme habitat, many specialized species

Hydrothermal vents are not only providers of resources, but also extraordinary habitats. In spite of the hostile conditions, such as temperatures over 350 degrees Celsius and the slightly acidic hydrothermal fluids enriched in toxic metal compounds, a unique natural community has evolved here over millions of years, perfectly adapted to the inhospitable environment.

Normally the sun is the source of energy for life in the ocean. It causes algae to flourish, which use the sunlight and photosynthesis to construct high-energy molecules like sugar. This is called **primary production**, and is the base of the food web in the ocean.

But it is dark at the hydrothermal vents. Primary production here is performed by **chemoautotrophic** bacteria, which exploit the energy-rich chemical compounds found at the hydrothermal vents and alter them into molecules that can also be used by other organisms. The bacteria can endure water temperatures greater than 100 degrees Celsius and thus occur near the smokers. The bacteria or the products of their metabolism provide nourishment for higher organisms such as mussels, and these in turn for other organisms. Communities with up to 600 different species can thus be found at the vents, including, for example, snails of the genus *Alviniconcha*, which can tolerate temperatures up to 45 degrees Celsius. Many of these animal groups live exclusively at hydrothermal vents. Because of the con-



2.33 > Off Papua New Guinea, the mining of massive sulphides should begin by 2016. The heavy chassis of the rock cutter, which will work on the sea floor, is ready.

tinuous influx of nutrients, the organisms are present in great numbers. Expeditions have sometimes recorded hundreds to thousands of animals within one square metre of sea floor.

What is rare?

Whether there are endemic species living at the hydrothermal vents in the deep sea that only occur in a limited area, or in extreme cases only at a single massive sulphide deposit, is a vital question for mining, because it could bring about their extinction. Biologists are thus trying to determine the extent of distribution of certain species – whether they live in a larger oceanic region like the Indian Ocean at numerous hydrothermal vents or are limited to a smaller region such as the Bismarck Sea.

In fact, scientists have found differences between different ocean regions. Large tube worms predominate in areas of the eastern Pacific, but have never been found in the Atlantic or Indian Oceans, or in the southwest Pacific. At the Mid-Atlantic Ridge, on the other hand, large numbers of deep-sea shrimps are found living with **symbiontic** chemoautotrophic bacteria on their bodies, which provide them with nutrients. And finally, in the Indian Ocean, deep-sea shrimps as well as anemones and snails are found with symbiontic bacteria.

Because of the various discoveries, attempts have been made to categorize hydrothermal vents into biogeographic provinces based on similarities of the biological communities and the geological structures. To this end researchers have interpreted data from expeditions and used statistical methods to compare individual organism counts from 63 hydrothermal vents.

According to this analysis there are 6 different provinces in which, to a large extent, different species occur. The provinces are the Northwest Pacific, the Southwest Pacific, Northeast Pacific, Northern East Pacific Rise, Southern East Pacific Rise, and the Northern Mid-Atlantic Ridge.

Of course, to some degree, related or even the same species occur in different provinces. The researchers have thus tried to discover whether and how species

Metal-rich brines in the Red Sea

The sulphide-rich sediments at the bottom of the Red Sea are a special kind of sulphide deposit. The sulphides do not occur in solid form here, but as a viscous metalliferous sludge. The cause of sulphide formation in the Red Sea is also subsurface magmatic activity.

The Red Sea formed where the African and Arabian plates are moving apart. Each year the plates drift about 1 centimetre farther apart, so that the Red Sea is slowly but steadily growing. The fracture line between the plates runs almost exactly along the middle of the Red Sea from northwest to southeast. At some places in the rift zone there are deep basins where brines form on the bottom.

A 200-metre-thick layer of extremely salty, heavy water collects in these basins in the way that a haze of fog lies in a valley. With a temperature of over 60 degrees Celsius, this water comes from salt-rich rock layers on the flanks of the Red Sea and is concentrated here. Its salinity of around 26 per cent is 7 times as salty as normal seawater. It is therefore very dense and flows into the deep basins. Hydrothermal solutions enriched with sulphides rising up from the depths mix with the warm saline water, and the metals dissolved in the water combine chemically with sulphide particles. The particles sink to the bottom and form the metal-rich muds.

2.34 > The Atlantis II Deep lies in the middle of the Red Sea. Metal-rich sulphide brines rest at its bottom.

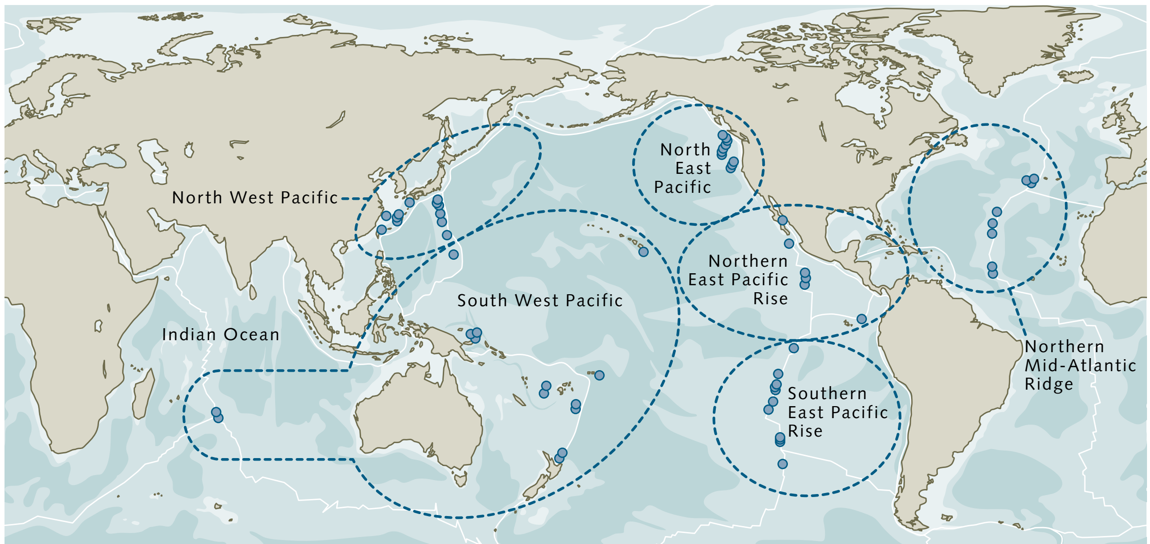
The largest deposit of sulphide sediments in the Red Sea is located in the Atlantis II Deep, a 2000-metre-deep basin the size of Manhattan that lies between Saudi Arabia and the Sudan. This is considered to be the largest sulphide deposit in the world, the massive sulphide deposits included.

This area was intensively explored as early as the 1970s, and valuable metals such as zinc, copper, silver and gold were found. At that time, working together with the Red Sea Commission – a cooperative between Saudi Arabia and the Sudan – a German industrial consortium drilled over 490 exploratory wells in the muddy bottom. This makes the area one of the most thoroughly studied sulphide occurrences in the world. Furthermore, in 1979, around 15,000 cubic metres of mud were brought to the surface using a prototype vacuuming system.

Like other marine mining plans, however, this cooperative was abandoned in the early 1980s because there were enough resources on the world market from land deposits. Later, due to higher metal prices on the world market, interest in the muds was renewed. In 2010 a Saudi Arabian-Canadian consortium received a production licence for 30 years. Again, the area was explored in cooperation with German researchers. But to date no concrete plans have been made because metal prices have recently fallen again.

In all, it is estimated that the Atlantis II Basin contains muds with a dry weight of around 89.5 million tonnes, which is a very large amount compared to the other massive sulphide occurrences on the sea floor. The metal contents in the sediments are lower, however, than in the massive sulphides of the Bismarck Sea, for example. According to current estimates, the muds of the Atlantis II Basin contain 3 million tonnes of zinc, 740,000 tonnes of copper, 6500 tonnes of silver and 46 tonnes of gold. Compared to the global reserves of these metals, these values lie in the single-digit per cent, or even the per mill range.

For the Sudan or Saudi Arabia, however, which have no metal reserves of their own to speak of, mining could become interesting in the future if metal prices rise again. However, standard mining equipment will first have to be developed. One problem is that the warm salty water is very corrosive to any kind of mining equipment.



2.35 > Different animal species predominate in the hydrothermal vent habitats of the various worldwide marine regions. Through statistical analyses of the fauna at 63 hydrothermal vents, researchers were able to identify 6 biogeographic provinces with clearly different species assemblages.

have been able to disperse over thousands of years from one province to another. The East Pacific Ridge appears to play a central role as a kind of hub of species dispersal. It must be kept in mind here, however, that more and more differences are being identified between similar species through modern genetic studies, and at many sites such genetic investigations have not yet been carried out. It is still uncertain whether some apparently indistinguishable species are truly identical.

Besides the species that are adapted in special ways to the hydrothermal fluids, there are also serious threats to those that are found on the massive sulphides of dormant hydrothermal vents. This habitat is colonized, for example, by deep-sea corals, sponges and barnacles. Similar to other deep-sea organisms, these are rare, grow very slowly, and produce few offspring. For these reasons they are especially endangered. If the parent animals die, then there are sparse young remaining to rebuild the stocks.

Generally speaking, there is still very little known today about the biology of deep-sea animals. There are still questions that must be answered before we can understand how and whether animal communities can recover after a disturbance on the scale of massive-sulphide mining. It is, for example, still unknown how abundant or rare the species are, in which habitats they live, how far apart these habitats are, and how or whether the animals can spread from one habitat to another. Only then would a recolonization of harvested areas be possible at all.

Before the mining begins ...

To minimize as far as possible the damage that could result from the mining of massive sulphides, experts suggest carrying out additional studies to determine the extent to which endemic species could be affected. This would necessitate distinguishing between massive sulphides at active hydrothermal vents and old massive sulphides at dormant vents. Because of the extreme level of specialization by denizens of the hydrothermal vents, they are assumed to be more likely to live in narrowly limited ocean regions and be endemic. The normal, common deep-sea species are more widely distributed. Because of their slow growth and low number of offspring, however, special care must be taken to prevent eradication of entire local stocks. Both of these kinds of species would presumably have a greater chance if the deposits were only partly harvested, preserving areas from which the harvested areas could be recolonized. Alternatively, massive sulphides could be exclusively produced in areas where it is known that other hydrothermal fields exist nearby that host the same species assemblages.

Conclusion

Ocean mining – not a gold rush but an option

For decades people have been extracting mineral resources from the sea, including diamonds off Namibia or sand from the coastal areas of Europe for filling depleted beaches. In Europe alone around 93 million tonnes of sand are extracted from the sea each year – a quantity which equals the volume of 37 Cheops Pyramids.

Governments and industrial corporations plan to produce even more from the sea in the coming decades. Specifically, they aim to extract hundreds of millions of tonnes of metal-bearing minerals that are found on the sea floor in 3 forms: firstly, as potato-sized manganese nodules; secondly, as hard coatings on the flanks of undersea volcanoes called cobalt crusts; and thirdly, as massive deposits that have formed at hot, mineral-rich deep-sea vents known as massive sulphides.

These resources are of interest because they contain large amounts of economically interesting metals, some of which greatly exceed the known amounts in deposits on land. The manganese nodules in the Pacific manganese nodule area of the Clarion-Clipperton Zone alone contain around 5 billion tonnes of manganese, which is some 10 times as much as the economically minable deposits on land today. Many of the marine metal occurrences have been known since the 1970s. Even then manganese nodules were excavated from the Pacific in pilot projects. For a long time mining of the sea floor remained unattractive because there were enough resources on land and metal prices were relatively low. But in the past decade, mainly due to growing demand in the newly industrializing countries, especially in China, prices have risen strongly.

Marine mining is interesting for various reasons. For one, demand for chemical elements contained in the marine deposits is rising because of new high-tech applications such as smartphones. For another, many of these elements are only mined in a few countries. China, in particular, has a dominant market position. Many states would therefore like to secure their own claims on the sea floor. It is problematic that many hundreds of square kilometres of seabed will be negatively impacted by ocean mining. Marine biologists are concerned that mining will destroy deep-sea habitats. To prevent a gold rush in the ocean, the International Seabed Authority (ISA) was established in Jamaica in 1994. It awards licence areas in international waters to interested states and ensures that developing countries will also be able to share in the benefits. In addition, the Authority has negotiated regulations for the protection of deep-sea environments. Licence areas cannot be completely mined out. Some areas have to remain untouched so that they can contribute to the recolonization of the mined areas.

To what extent, or whether at all the mining of the sea will develop is still uncertain. No mining equipment suited to the task is available yet, and some metal prices, after an interlude of extreme increases, have dropped again, so that deep-sea mining now appears less economical. However, some 200-nautical-mile zones, where the ISA is not responsible, are still thought to be promising. Within these zones the coastal states decide for themselves when and under what environmental and safety standards metals are extracted. Of particular interest are the 200-nautical-mile zone of Papua New Guinea, where massive sulphides with high gold and silver contents are found, and the Cook Islands, where cobalt-rich manganese nodules are located. Mining of the precious-metal-bearing deposits in Papua New Guinea appears to be economical today. An industrial consortium wants to begin mining there by the end of 2016.

3 Energy from burning ice

> In addition to abundant minerals, there are large amounts of methane hydrate beneath the sea floor. Some countries hope to become independent of energy imports by exploiting marine gas hydrate deposits near their own coasts. The technology for production, however, is not yet available. Furthermore, the risks to climate stability and hazards to marine habitats associated with extraction of the methane hydrates must first be clarified.

From plankton to hydrate

> The existence of methane hydrate has been known of since the 1930s. But only in the past 10 years has it become an object of serious consideration as a potential fossil energy source for the future. It is now possible to project the available global amounts with some confidence. Researchers are trying to identify the highest-yielding deposits.

The discovery of a new resource

Methane is a commonly occurring molecule in widespread use: it is the principal combustible component of natural gas. Depending on its quality, natural gas contains 75 to 99 per cent methane. Additional components may include the gases ethane, propane or hydrogen sulphide. At room temperature and normal atmospheric pressure at the Earth's surface, methane exists as a gas. At lower temperatures and higher pressures, however, it can, in the presence of water, form an ice-like solid called methane hydrate. In the hydrate, methane is compressed to a density of about 160 times that of natural gas. This means that one cubic metre of hydrate contains about 160 cubic metres of gas. So with breakdown of the hydrate a huge amount of methane gas is released.

We have known about methane hydrate since the 1930s. At that time natural gas providers complained that their gas lines and valves would freeze up in cold weather. What was disconcerting was that sometimes they froze at temperatures above the freezing point of water. Clearly the blockage could not have been caused by normal water ice. Researchers discovered that the ice-like deposits were a substance composed of methane and water. Additives were subsequently added to the gas to prevent the undesirable formation of methane hydrates.

Initially methane hydrate was believed to be a phenomenon limited to industrial plants. But in the 1960s Russian scientists created a minor sensation when they unintentionally retrieved chunks of methane hydrate while drilling into the Earth's surface.

They thus provided solid evidence that methane hydrate could occur naturally. Soon thereafter U.S. researchers verified the presence of methane hydrate in the permafrost of Alaska. This led them to the assumption that methane hydrates could occur commonly in nature, so they began to search for it globally, including beneath the oceans. The first large occurrences were discovered in 1971 on the floor of the Black Sea, and in the early 1980s off the coast of Alaska. Today it is known that methane hydrate occurs in all oceans, primarily on the continental margins.

It is estimated that around ten times more methane is stored in hydrates below the sea floor than is present in all other conventional natural gas deposits. Methane hydrate is thus seen as a very promising fossil energy source for the future. Exploration for methane hydrate deposits in the seas has consequently intensified over the past 10 years. Particular interest has been shown by countries like Japan, South Korea and Taiwan. They have almost no fossil energy reserves of their own and therefore depend on the import of large quantities of gas, coal and oil. With methane hydrates from their own territorial waters they could significantly decrease their dependence on imports and their exposure to energy prices, which have recently risen steeply.

First methane, then hydrate

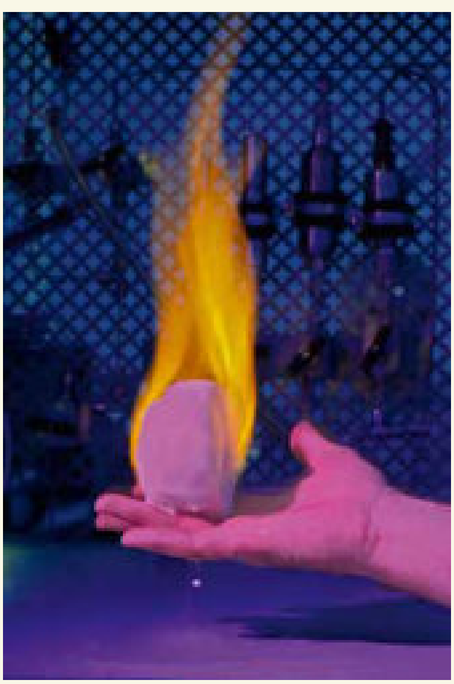
Methane hydrates develop naturally only in areas where sufficient methane is present. This gas can develop beneath the sea floor in two different ways:

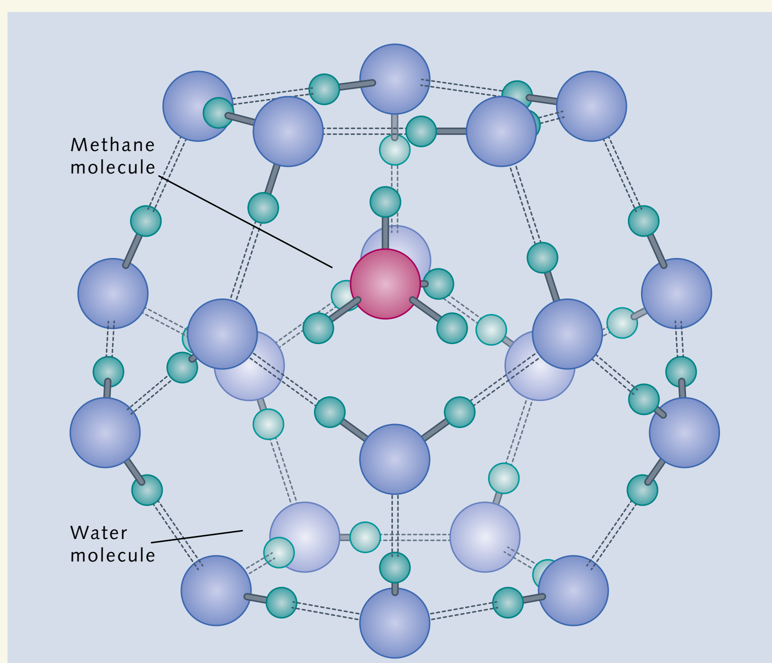
- Biogenic methane is formed in the sea floor by the microbial breakdown of biomass. The biomass consists of dead planktonic organisms such as microalgae or krill that sink through the water column to the sea floor and build thick sediment packages over time. Methane-producing microorganisms break down the biomass into methane and carbon dioxide.

Flammable ice made of methane and water

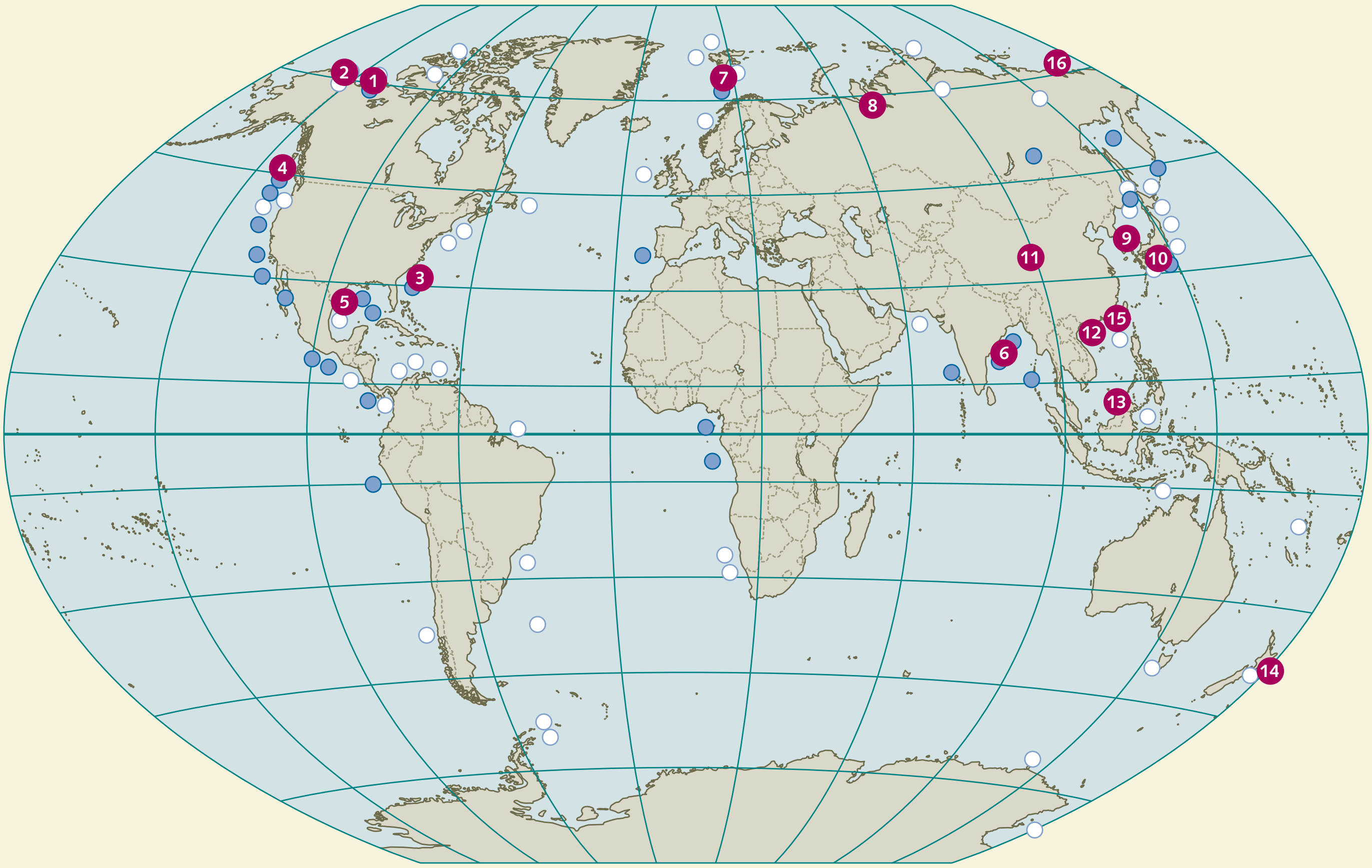
Methane hydrate is formed when water and methane gas combine at temperatures below 10 degrees Celsius and pressures greater than 30 bar, or 30 times normal atmospheric pressure. The methane is surrounded by water molecules and trapped in a molecular cage. Chemists therefore call this kind of molecular structure a clathrate (lat. *clatratus* = with bars, caged). Methane hydrates develop in permafrost regions on land or beneath the sea floor. They are usually covered by a layer of sediments. Their formation under the sea floor requires an environment of sufficiently high pressure and low temperature. The warmer the water is, the higher the water pressure needs to be. Thus, in the Arctic, methane hydrates can be found below water depths of around 300 metres, while in the tropics they can only occur below 600 metres. Most methane hydrate occurrences worldwide lie at water depths between 500 and 3000 metres. The hydrates are solid and white, similar in appearance to normal water ice. When they are brought up from the sea floor they begin to slowly break down. This releases the methane gas that can then be ignited.

Under normal conditions methane and water molecules do not react with one another. At room temperature they are moving too quickly to form chemical bonds. At lower temperatures, however, the molecular motion is retarded. Under higher pressures, the methane and water molecules approach each other so closely that the clathrate structure develops. If the temperature rises or the pressure decreases the weak bonds collapse. The clathrate then breaks down and methane is released.





3.1 > In methane hydrate the methane molecule is surrounded by many water molecules (H_2O). The water's oxygen atoms are shown in blue and the hydrogen atoms are green. Weak electrostatic forces between the atoms, called hydrogen bonds, hold the methane hydrate together. The methane molecule in the centre of the clathrate consists of 1 carbon (C) atom (red) and 4 hydrogen (H) atoms (green), which are arranged like the corners of a pyramid. Thus, the chemical formula for methane is CH_4. Under atmospheric pressure the methane hydrate slowly breaks down and releases the methane, which is flammable.



Major gas hydrate occurrences

3.2 > Methane hydrate occurs in all the oceans as well as some locations on land. White dots indicate occurrences identified by geophysical methods. The blue dots show occurrences proven by direct sampling. The most important research sites and areas worldwide are also highlighted with numbers.

1

MALLIK: High concentrations of gas hydrates were documented in sands of the Mallik site on Richards Island in Canada's Northwest Territories in 1972. This resulted in three landmark gas hydrate evaluation programmes with corresponding test wells being carried out here in 1998, 2002 and 2007/2008. These programmes confirmed that gas hydrates could be produced by drilling wells and that depressurization appeared to be the most favourable method.

2

NORTH SLOPE: Gas hydrates were discovered and tested in the North Slope region of Alaska in 1972 at the Northwest Eileen State #2 well. The objective of the test wells was to evaluate the oil reserves, but the drilling also enabled initial estimates of the reserves of gas hydrate. The magnitude of the hydrate deposits was estimated at around 16 trillion cubic metres. Little further attention was paid to the hydrate deposits until the Mount Elbert test well was drilled nearby in 2007. In 2008 the United States Geological Survey (USGS), the most important organization for official mapping in the USA, assessed a volume of 2.4 trillion cubic metres of recoverable gas in the region with the technology existing at that time. A well was drilled in Prudhoe Bay in 2011 to test for the production of gas hydrates.

3

BLAKE RIDGE: This area of the continental slope off the coast of North Carolina was one of the initial sites for gas hydrate research in the marine realm. Hydrate deposits were discovered during a seismic geophysical survey of the sea floor. The methane hydrate layers below the sea floor were revealed by conspicuous reflection patterns in the bottom seismic profiles, referred to as bottom-simulating reflectors (BSR). Scientific drilling in 1995 confirmed the existence of an extensive deposit. The gas volumes were assessed at around 28.3 trillion cubic metres. Concentrations of the gas here, however, are relatively low.

4

CASCADIA CONTINENTAL MARGIN: This area off the Pacific coast of the United States was drilled by the Ocean Drilling Program (ODP). The objective of this international programme is to acquire new knowledge about the structure of the Earth and its history through scientific drilling of a large number of holes in the sea floor. On two cruises in this region, in 2002 and 2005, the "hydrate ridge" off Oregon was drilled.

5

GULF OF MEXICO: Massive gas hydrate mounds were discovered on the sea floor here in 1995. These structures are particularly interesting because of the special biological communities that have developed here. Later, gas hydrates were found in marine sands in a well in Alaminos Canyon Block 818. These kinds of deposits are significant because it is relatively easy to recover hydrates from sands. In 2005, a joint project involving researchers and industry partners addressed the safety aspects of deepwater drilling. A second drilling expedition in 2009 revealed high concentrations of gas hydrates in sand reservoirs.

6

INDIAN OCEAN: Gas hydrates were investigated during a 113-day expedition at one site in the Arabian Sea, two sites in the Gulf of Bengal, and one site in the Andaman Islands. Off the southeast coast of India, at "site 10" in the Krishna-Godovari Basin, the researchers discovered a 130 metre-thick layer containing gas hydrate. This exhibited high hydrate concentrations.

7

SVALBARD: A number of studies have been carried out on the shelf off the western coast of Svalbard Island. Early in this century several active methane gas seeps were found. These presumably originate at the edge of the gas hydrate stability zone (GHSZ). Scientists believe that the hydrates are dissociating here due to climatic changes.

8

MESSOYAKHA: This oil and gas field in western Siberia provided the first solid evidence for the existence of gas hydrates in nature. Drilling and various measurements suggest that the gas hydrate contributes a share to the production of natural gas in this area.

9

ULLEUNG-BASIN: Deep-sea drilling was carried out in the Ulleung Basin off the coast of South Korea in 2007 and 2010. The expedition also retrieved cores. Numerous vertical "chimney" structures were discovered with high concentrations of gas hydrates. The hydrates apparently occur here in the pore spaces of sands and in deformed muds.

10

NANKAI TROUGH: The first resource-grade gas hydrates in marine sands were discovered in this area off Japan in 1999. Further geophysical studies and a second drilling programme in 2004 revealed the presence of gas volumes in the Nankai Trough of 1.1 trillion cubic metres. Around 566 billion cubic metres of this occur in high concentrations in sands. Methane was produced for the first time from a test well in the sea here in 2013. After the well in the Nankai Trough in 1999, the industry well in Alaminos Canyon Block 818 in the Gulf of Mexico in 2003 was the second discovery of gas hydrate in marine sands.

11

QILIAN MOUNTAINS: This mountain range on the Tibetan Plateau in western China has permafrost extending to depths of up to 100 metres. Drilling projects here in 2008 and 2009 confirmed the presence of gas hydrate occurrences in fractured sandstones and mudstones. These rocks were formed during the Jurassic geological period around 200 million years ago.

12

SHENHU BASIN: This area of the South China Sea was explored in early 2007 during marine geological mapping by the Guangzhou Marine Geological Survey (GMGS), a Chinese state institute for marine geology. Gas hydrate concentrations discovered in the fine-grained sediment layers were higher than expected, probably as a result of relatively high silt content and deposits of planktonic foraminifera, microscopic organisms with carbonate shells.

13

GUMUSUT-KAKAP: In this oil field off the shore of eastern Malaysia potential geohazards with respect to industrial production of deeper oil and gas deposits were studied for the first time in 2005. These include possible slumps or tsunamis. The project concentrated mainly on oil and gas deposits underlying gas-hydrate bearing layers.

14

NEW ZEALAND: Strong BSR seismic signals were recorded in the early 1980s during sea-floor investigations of this area on the margin of the Hikurangi Trough off the East Coast of New Zealand. Since then the region has been studied more intensively using a variety of other kinds of measurements. Further expeditions to various sites within the Exclusive Economic Zone of New Zealand suggest that gas hydrate deposits could be present in many other areas there.

15

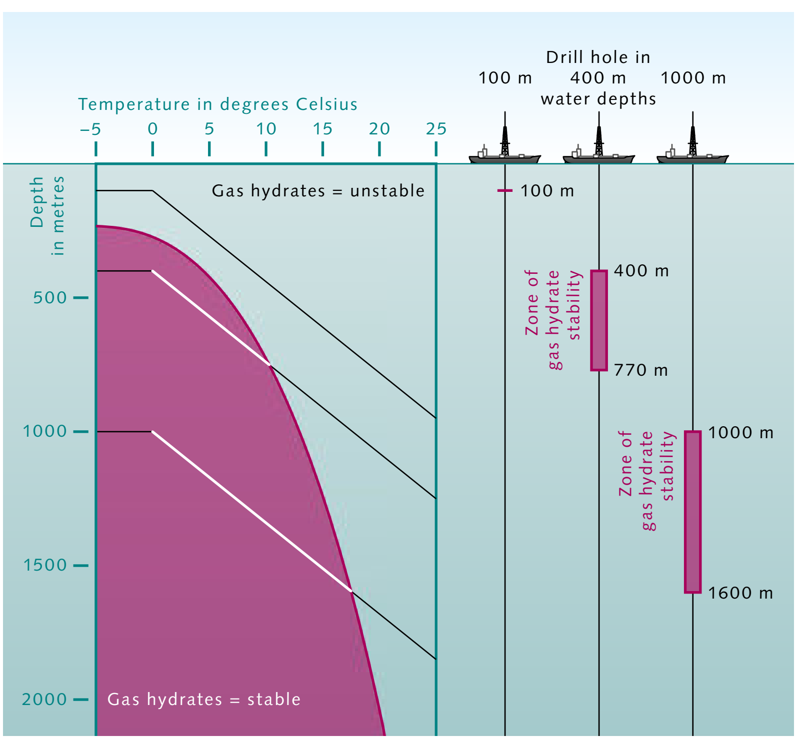
TAIWAN: Taiwan lies in a region where continental plates converge. In this area methane-bearing water is pressed out of the sediments so that methane is available for the formation of hydrates. The tectonic collision zone has been intensively studied by drilling since 2004. The drilling programme has produced clear evidence of the presence of gas hydrates. The hydrates presumably encompass around 11,000 square kilometres of sea-floor area, which is equal to the size of the West African country of Gambia.

16

EAST SIBERIAN SHELF: The East Siberian shelf is a former coastal area with permafrost that was flooded by sea-level rise after the last Ice Age. Scientific studies discovered high concentrations of methane in the sea water and upper layers of the sea floor. The origin of the methane is uncertain. It may possibly come from methane hydrates stored in the relict permafrost of the submerged coastal area.

This process is known as methanogenesis. Scientists estimate that 80 to 90 per cent of the methane stored in hydrates worldwide was produced biogenically by methanogenesis. The methanogenic bacteria are found at depths of around 10 metres to 3 kilometres in the sediment. Above this depth of 10 metres other microorganisms are active that do not produce methane. Microorganisms that require oxygen live directly on the sea floor and within the upper centimetres of sediment. These “aerobic”, or oxygen-feeding microorganisms, break down a large proportion of the sinking biomass. In the nearly oxygen-free sediments immediately below, on the other hand, microorganisms are active that require the sulphate radical for their metabolism, which is present in large amounts in these sediment layers. These organisms, called sulphate reducers, also consume biomass without producing methane. Only in the environment below 10 metres, lacking in both oxygen and sulphate, can the methanogenic microorganisms flourish.

- Thermogenic methane is generated chemically in the much deeper layers of the Earth’s crust without the activity of microorganisms. It is formed in a similar way as oil and natural gas. At depths of several kilometres, under high pressures and temperatures above 100 degrees Celsius, the remains of biomass millions of years old in hard sedimentary rocks are transformed into methane. This is achieved by purely chemical processes driven by heat. The thermogenic methane can then rise through fissures in the rocks up to the layers where pressure and temperature conditions allow the formation of hydrates.



3.3 > Gas hydrates occur where abundant biomass sinks to the bottom in areas of low temperature and high pressure – particularly on continental slopes. The higher the water temperature is, the greater the depths and pressures necessary for the formation of hydrates. At very great depths, due to the Earth’s geothermal energy, the temperature within the sea floor is too high for the formation of methane hydrate.

Thus the requirements for the formation of methane hydrates are the right temperature, the right pressure, and a sufficiently high methane concentration. These conditions are commonly found in areas near the coasts, particularly on the continental slopes at water depths below 500 metres. Most coastal areas are rich in nutrients, which are transported by rivers to the sea. Vast numbers of planktonic organisms thrive here, in turn providing food for higher animals. Coastal areas are therefore immensely productive and the amount of dead biomass that settles to the sea floor and is deposited as sediments is large.

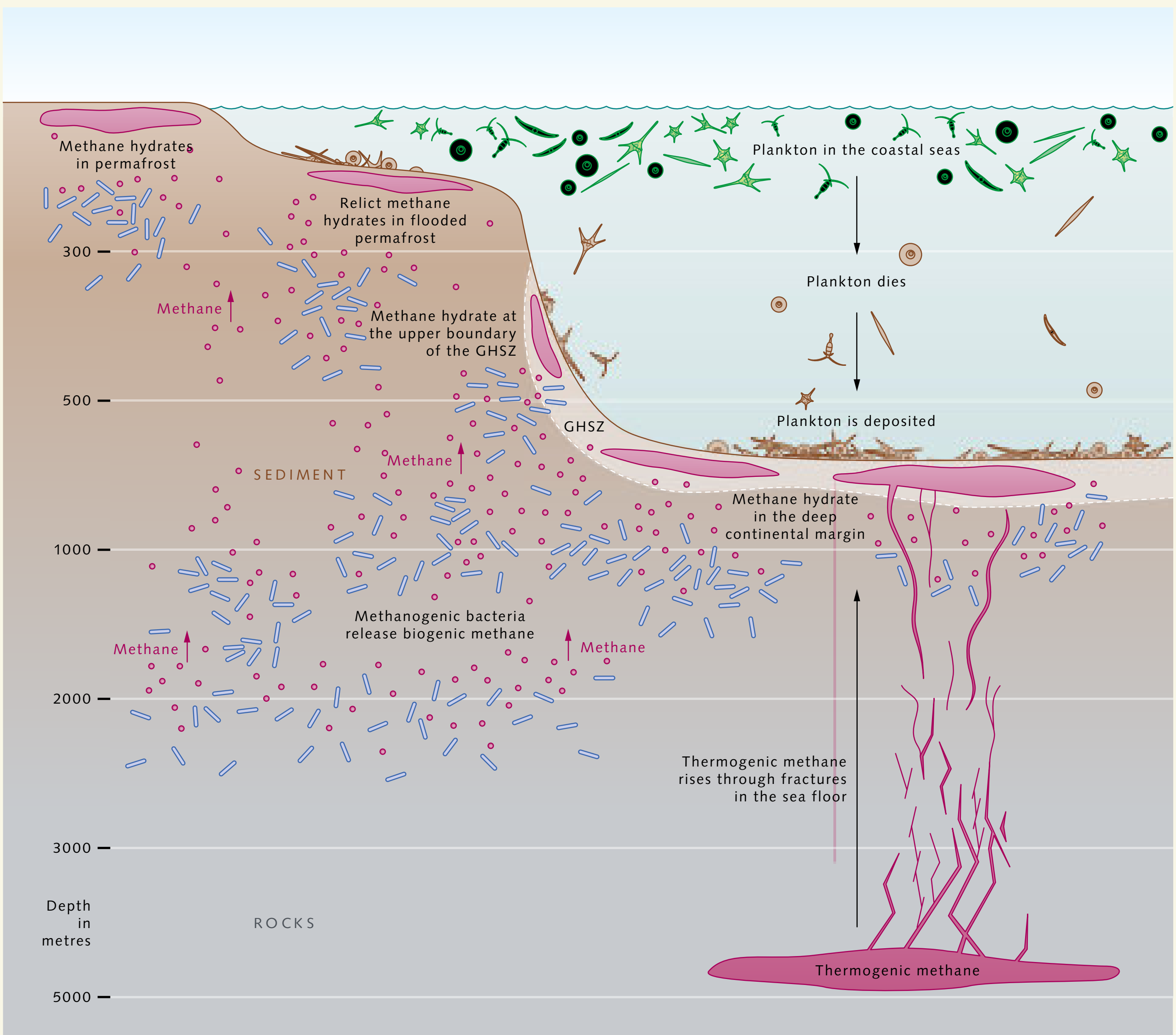
Marine regions farther from the coasts are, in contrast, relatively poor in nutrients. The production of biomass and amounts of plankton that sink to the bottom are thus low there. As a result, methane hydrates very rarely occur in the deep sea at large distances from the coasts.

The zone in which gas hydrates are stable in the sea floor is called the gas hydrate stability zone (GHSZ). This is the area in which temperatures and pressures necessary for the formation of methane hydrates prevail. Above the GHSZ the ambient pressures are too low for the methane and water to react with one another. Below the GHSZ it is too warm due to proximity to the Earth’s hot interior. With every kilometre closer to the

Formation of methane hydrate

Methane hydrate forms in the gas hydrate stability zone (GHSZ). This is where the required pressures and temperatures are present for methane and water molecules to combine and form a clathrate. Methane rises from the depths up to the GHSZ: in the deep upper sediment layers biogenic methane, produced by microorganisms, is released. In still deeper sediment layers, methane is created through the chemical transformation of biomass at very high pressures and temperatures (thermogenic methane). It can rise through fractures up to the gas hydrate stability zone. Methane hydrates are found in various regions: in Arctic permafrost, in relict permafrost that was flooded after the Ice Age, and on the upper and lower continental margins.

3.4



Earth's core the temperature in the crust increases by 30 to 40 degrees Celsius. The thickness and position of the GHSZ vary from one marine region to another. In some cases the GHSZ is only a few metres thick and lies directly below the sea floor. In others it can be up to 800 metres thick and comprise massive sediment deposits.

Estimating amounts of methane hydrate

Until now only a few methane hydrate deposits in the ocean have been thoroughly studied. Nevertheless, attempts have been made to calculate the globally available amounts of methane hydrates. These resulted in estimates of 500 to 55,000 gigatonnes of carbon.

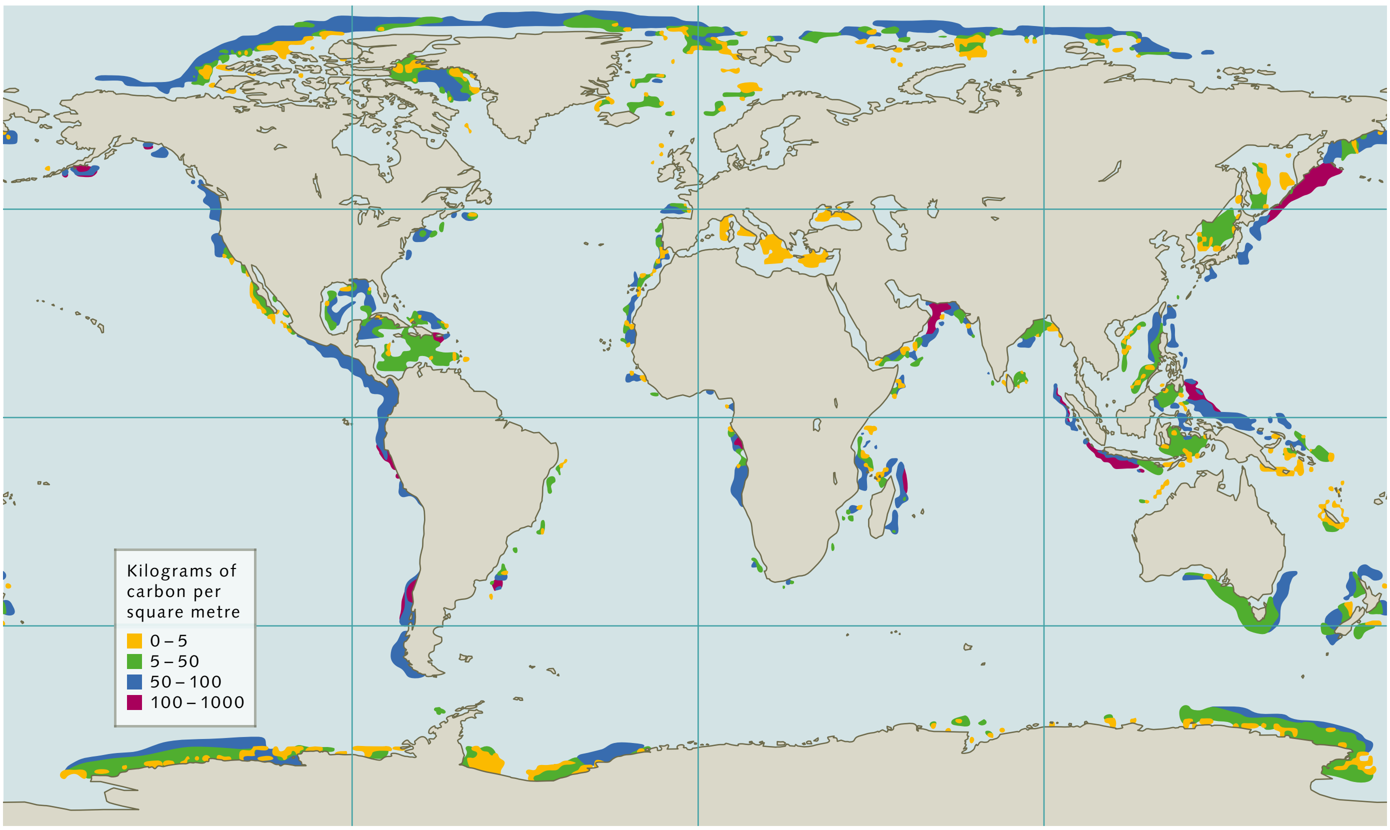
Carbon makes up 75 per cent of the mass of the methane molecule and can thus be used as a reference value. In this way the deposits can be compared with other fossil resource deposits.

The large differences in these estimates are primarily due to the fact that researchers had to consider various influencing variables in their calculations and weighted these differently. For an accurate estimate of the worldwide methane hydrate reserves the scientists will have to, firstly, calculate as accurately as possible how much biomass was deposited in the sediments over millions of years that then became available for methanogenesis. Secondly, they have to assess how much methane has been able to eventually penetrate into the GHSZ. The following are among the aspects that need to be considered:

- climatic changes that have influenced the production of plankton and biomass through various epochs in the geological past;
- the activity of aerobic microorganisms and sulphate reducers that consume large amounts of the biomass in the upper layers of sediment;
- changes in the coastlines due to rising and falling sea levels during the glacial and interglacial periods. At certain times when marine regions were exposed there was no sedimentation at all. During other periods the sedimentation rates increased or decreased;
- the methane concentration in pore waters. Methane gas migrates upward through the pores, the water-filled spaces between sediment grains. The methane concentration in the pore waters is greater or less depending on how much methane rises from deeper layers. Regardless of the prevailing pressures or temperatures, methane hydrate can only form when there is a sufficiently high concentration of methane in the pore water;
- plate tectonics: regions where one continental plate sinks beneath another, called subduction zones, are of particular interest. As the plate descends, the pore water is squeezed out of the sediments like a sponge. It rises, carrying its methane component with it. These processes continue today. When the methane reaches the GHSZ it can substantially contribute to the formation of methane hydrate. The challenge, then, is to accurately calculate the amounts of ascending water and methane in the subduction zones.

More recent estimates of the worldwide amounts of gas hydrate, which attempt to consider all of these aspects, are on the order of 500 to 1500 gigatonnes of carbon. This is significantly less than the 55,000 gigatonnes that were postulated just a few years ago, but still decidedly more than all of the conventional reserves of

3.5 > Majestic stones: currents and waves have exposed ancient turbidites on the Point Loma Peninsula in California.



3.6 > Worldwide, methane hydrates occur primarily on the continental slopes. According to current estimates the largest deposits are located off Peru and the Arabian Peninsula. The figure only shows the biogenic gas hydrates. The amounts of thermogenic methane are not taken into account.

natural gas, which today are projected at around 100 gigatonnes of carbon. In addition to the total estimates, detailed calculations of methane hydrate reserves in specific ocean regions are of interest to researchers. These would give clues as to where it is most worthwhile to employ research ships for more targeted investigations. Ship expeditions are extremely expensive. Energy companies and scientists thus have a primary interest in focusing on large deposits that could produce great amounts of methane in the future.

Promising layer-cake sediments

The amounts of methane, if any, that can be produced from the GHSZ primarily depend on the sediments in which the methane is located. There are various types of hydrate-bearing sediments that are distinguished by the proportions of smaller or larger particles: sands and sandstones, clays, and mixtures of these.

Sands and sandstones have relatively large pore spaces, from which the methane can easily be retrieved. But there are only a few such sand bodies in the world that contain any methane hydrates at all. From compacted clay sediments, on the other hand, in which the particles are very dense, the methane hydrate cannot be recovered at all. Turbidites are widespread throughout the world. These are a combination of sand and clay sediments. In the layer-cake-like turbidite sediments, the sand and clay layers alternate. Over time, turbidites have formed primarily by mass slumps on the continental slopes. When too much sediment has been deposited a landslide begins on the slope. At the foot of the slope the sediments slide over one another in layers. Some of the turbidite layers are only a few centimetres thick. Occasionally, however, the individual layers can have thicknesses up to 10 metres. The feasibility of producing methane from hydrates in turbidites has been studied in recent months in test wells off Japan.

Methane hydrate – a new energy source?

> Methane hydrate deposits within national territorial waters represent a promising source of energy for the future, especially for countries that depend on imports of gas, coal and oil for a large share of their energy needs. But the necessary technology for industrial production of the hydrates is not yet available. Following successful test wells on land, initial research projects are now being carried out in the ocean, particularly in South-East Asia.

Importing countries	bcm
Japan	116
Italy	70
Germany	68
USA	55
Korea	47
Ukraine	44
Turkey	43
France	41
Great Britain	37
Spain	34
Others	279
Total	834

3.7 > In 2011, Japan and South Korea were among the 10 largest net importers of gas in the world, i.e. those countries that must import significantly more natural gas than they can produce or export themselves. Both countries bring the resources in by ship. Gas hydrates in their own territorial waters could offer an alternative. The abbreviation bcm stands for billion cubic metres.

Escape from dependence?

The huge size of worldwide methane hydrate deposits is reason enough to make them economically interesting. Methane hydrates are especially attractive for countries with very limited fossil energy resources that must import them at great cost. Japan, for example, meets its energy needs for the most part with oil, coal and gas imports. Japan was a large importer of energy even before the accident at the Fukushima nuclear power plant. Its dependence on imports has become even greater with the shutdown of Japanese nuclear plants after the accident. Energy resources are all transported to Japan by ship, with natural gas taking the form of Liquefied Natural Gas (LNG). Because of the high costs of liquefaction and transport, gas is very expensive in Japan. The natural gas price there is around four times the price in the USA.

The situation is similar in South Korea, where over 90 per cent of fossil fuels are imported, including natural gas and particularly coal for the production of electricity. Large consumers of electricity there include for example steel producers as well as the chip and electronics industries. Methane hydrates might also provide a way for other South-East Asian countries such as Taiwan or Vietnam to reduce their dependence on energy imports.

The first steps to methane hydrate production

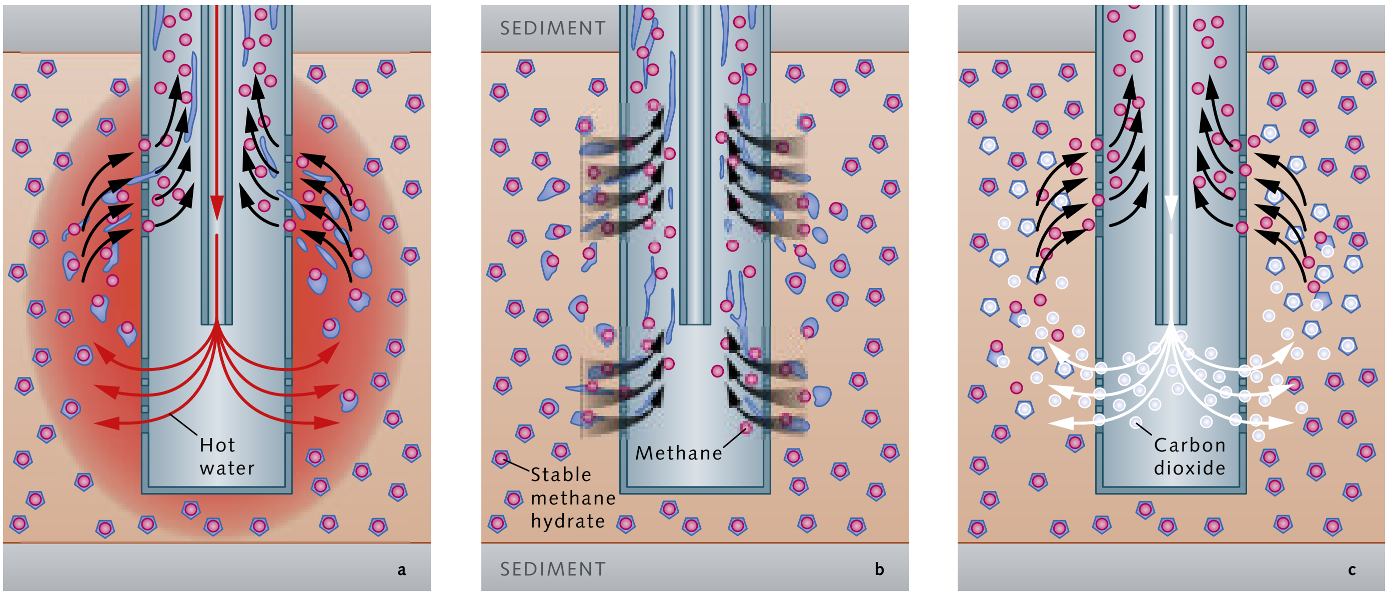
For more than 10 years international projects have been studying whether and how methane hydrate might be produced in the future. Scientists must first determine whether it is at all possible to release meth-ane from the hydrates in large amounts and, if so, which methods would be most practical. The production of methane hydrate is fundamentally different from the extraction of oil and natural gas. These conventional fuels flow naturally through the pores of the reservoirs to the well. Hydrates, on the other hand, are solid, and must first be dissociated before the methane gas can be extracted. Three different procedures are being considered for the recovery of methane:

WATER CIRCULATION: Hot water is pumped into the methane hydrate deposits through a well, raising the temperature to the point that the hydrate breaks down and methane is released.

DEPRESSURIZATION: High pressures prevail in the methane hydrate layers because of overlying water and sediment loads. Drilling into the deposits from above releases pressure like puncturing the inner tube of a bicycle tyre. With the drop in pressure the hydrate slowly dissociates and the methane is released.

CARBON DIOXIDE INJECTION: Methane is released from hydrates when they are infused with a gas. Carbon dioxide displaces the methane in the clathrate, replacing it in the molecular cage. One result of this is a stronger bond of the water molecule with carbon dioxide than it had with the methane. The carbon dioxide hydrate is thus significantly more stable than the methane hydrate. Researchers suggest that the carbon dioxide needed for injection could be obtained from the exhausts emitted by gas and coal power plants. Thus the carbon dioxide would not be released into the atmosphere, but transported in liquid form by ship or pipeline to the deposit and sequestered in the hydrates.

Various projects have been carried out by researchers and commercial companies in the past to investigate



3.8 > Methane hydrate can be dissociated by pumping in hot water (a) or by reducing the pressure in the well using pumps (b). If carbon dioxide is injected into the hydrate (c), the carbon dioxide molecule replaces the methane. In this case the hydrate does not dissociate.

whether methane can actually be produced on an industrial scale using these methods. Initial production tests were carried out around 10 years ago in the permafrost of the Mackenzie River Delta in northwest Canada by partners from Japan, Canada and Germany. These are considered to be a milestone because important knowledge for the future exploitation of methane hydrate was obtained. It was learned, for example, that the depressurization method is much simpler and more inexpensive than flushing with hot water. Additionally, filters were developed and tested to prevent sediments from flowing into the drill hole due to the high pressures. Though sand filters have long been available for use in the gas and oil industry, there has so far been no patent solution for the production of methane hydrates.

In 2011 and 2012 a Japanese-American industrial consortium carried out the Ignik Sikumi Project in the permafrost of northern Alaska with support from the United States Department of Energy (DOE). Here, for the first time outside the laboratory under natural conditions, the exchange of carbon dioxide and methane was tested. After only a few days, injected carbon dioxide was already fixed in the hydrate. It was then possible to produce almost pure methane gas for several weeks, and the gas yield was greater than mathematical models had predicted.

The first field test in the ocean was finally carried out in early 2013. Through a well in the Nankai Trough, an ocean basin 80 kilometres off the coast of Japan, Japanese researchers retrieved methane up to the surface over a period of one week from a water depth of 1000 metres. The gas hydrate was dissociated through depressurization. Japan has now set a goal to start the operation of a first large pilot production installation in 2018. The necessary technology for long-term operations, however, still has to be developed.

Getting started is the hardest part

Regardless of the method selected for methane extraction in the future, the production rates for all of them depend heavily upon how rapidly the hydrate dissociates under the sea floor. Laboratory experiments and test wells in the field have shown that presently all of the methods quickly reach their practical limits or have serious disadvantages:

- Flooding with water requires immense amounts of energy, which makes it uneconomical.
- With depressurization, dissociation of the hydrate decreases over time. This is due to a number of fac-

3.9 > In February 2012, using the research vessel *Chikyu*, a Japanese scientific team drilled for methane hydrates south of the Atsumi Peninsula. The following year, for the first time, the ship brought methane up to the ocean surface through a test well nearby.

tors. Firstly, the methane gas that forms with the breakdown of the hydrate increases pressure in the deposit, which impedes continued breakdown of the hydrate. Secondly, with the dissociation of the hydrate, water molecules are also released. The deposit thus becomes less saline, which chemically hampers hydrate decomposition. Thirdly, energy is required to break down the clathrate and to destroy the hydrogen bonds between the molecules. Chemically this is known as an endothermic reaction – one that consumes energy. Because this energy is removed from the surroundings in the form of heat, the ambient environment cools down. This cooling down also has a negative effect on the hydrate breakdown process.

- The injection method, on the other hand, proceeds too slowly. Various research groups, therefore, are searching for ways to accelerate the exchange of carbon dioxide and methane. These attempts have led to some initial successes: The exchange of carbon dioxide and methane proceeds more rapidly when the CO_2 is introduced into the reservoir as a warm supercritical fluid. In contrast to depressurization, the injection method has the advantage that some heat is released with the exchange of carbon dioxide and methane, which tends to sustain the dissociation process. This method is presently being advanced by German researchers.

Asia is heavily involved

Which of these methods will be best suited for production at industrial scales in the future is still uncertain. For this reason large amounts of money continue to be spent on research.

To date, close to 1 billion US dollars have been invested in gas hydrate research worldwide. Japan and South Korea are at the cutting edge. In the coming years these two countries will carry out additional production tests on the sea floor.

Significant efforts are also being undertaken in Taiwan, China, India, Vietnam and New Zealand to develop domestic gas hydrate reserves in the sea floor.

The search continues

The present task for the energy industry and research scientists is to thoroughly investigate promising areas of the sea floor for methane hydrate deposits. Regions with favourable pressure and temperature conditions that also exhibit thick sediment packages are of particular interest. Specialists searching for natural resources generally distinguish two distinct phases, prospecting and exploration.

Prospecting is the search for unknown deposits. Exploration follows this up with precise investigations and development of the reserves and deposits found. Development can only begin after exploration has demonstrated that sufficient amounts of resources can be extracted. Sites such as the Ulleung Basin off South Korea and the Nankai Trough off Japan have already been extensively explored. Many other areas in the world, such as the Exclusive Economic Zones (EEZ) of China, India, New Zealand or Taiwan are still in the prospecting phase.

Prospecting and exploration methods being applied today to investigate methane hydrate deposits include a number of techniques already used in the gas and oil industry, as well as new technology developed over the past 5 years, in part by a German joint project involv-ing around 20 university and industry partners.

First prospecting ...

The following techniques and measurement tools, both proven and novel, are now being employed to prospect for methane hydrates:

COMPUTER SIMULATION: For years now, computer simulation programs have been in use for the production of gas and oil which indicate the marine areas with potential reserves of oil and gas. Calculations by these programs take into account many variables, including the magnitude of plankton sedimentation in various ocean regions over millions of years, the thickness of sediment layers, and the prevailing pressures and temperatures at different depths. The simulations provide initial indications of where further prospecting with

Critical point
When a gas is subjected to high pressure it normally liquefies. If both temperature and pressure are increased at the same time, however, the gas attains a kind of hybrid state between gas and liquid. Scientists refer to this as the critical point of a gas. At this point the substance is referred to as a fluid. If the temperature or pressure is further increased it reaches the supercritical state, and becomes a supercritical fluid. The supercritical fluid is especially reactive. Supercritical CO_2, for example, reacts intensively with the methane hydrates so that greater amounts of methane are released rapidly.

The art of drilling in soft sediments

Methane hydrate reservoirs are different from conventional gas and oil reservoirs. The latter are usually located several kilometres deep in sediments that are millions of years old, and which have been compressed into solid rocks. These deposits are also usually overlain by solid impermeable rock layers. Methane hydrates, on the other hand, are located in much younger and softer sediments. Conventional drilling technology is, for one thing, very expensive, and furthermore, not adapted for the exploitation of gas hydrate deposits in soft sediments. German researchers and industries therefore want to develop a small drilling platform that can be placed on the sea floor, to which the drill, pumps and electrical supply can be attached. Such a system could work independently to a large extent to extract methane from the hydrate deposits. A forerunner of this mobile drilling rig (MARUM-MeBo) already exists. It has been deployed on research ships in recent years for exploratory drilling in water depths down to 2000 metres, and can drill to around 100 metres into the sea floor. The second generation MeBo is now being built to drill up to 200 metres into the sediments. This rig will continue to be developed and tested in the ocean in the coming years. In the future methane hydrate reservoirs may be exploited using an ensemble of these small and, compared to large drilling platforms, relatively inexpensive bottom-deployed rigs. These devices have the advantage that they can be deployed to the ocean floor with any multi-purpose vessel or research ship. Expensive operations by drilling or special-purpose vessels would not be necessary.

Today, before a company begins to exploit a gas or oil reservoir, the extraction is generally simulated by computer. Sophisticated simulation programs are already available for gas and oil, calculating how pressure in a reservoir changes over periods of five to ten years and how this can reduce the production rate through time. These well-established simulation programs, among other parameters, take into account the geometry and temperatures of the reservoirs. A research institute is presently working on a software version that will also be able to simulate methane hydrate production. The software has yet to be fed with real measurement data from the ocean and laboratory. These would include information about the formation and dissociation rates of hydrates. In about two years the software should be ready to be put into use. One of the program's strengths is that it can also simulate small reservoirs of around one square kilometre in detail, so it is capable of high spatial resolution.

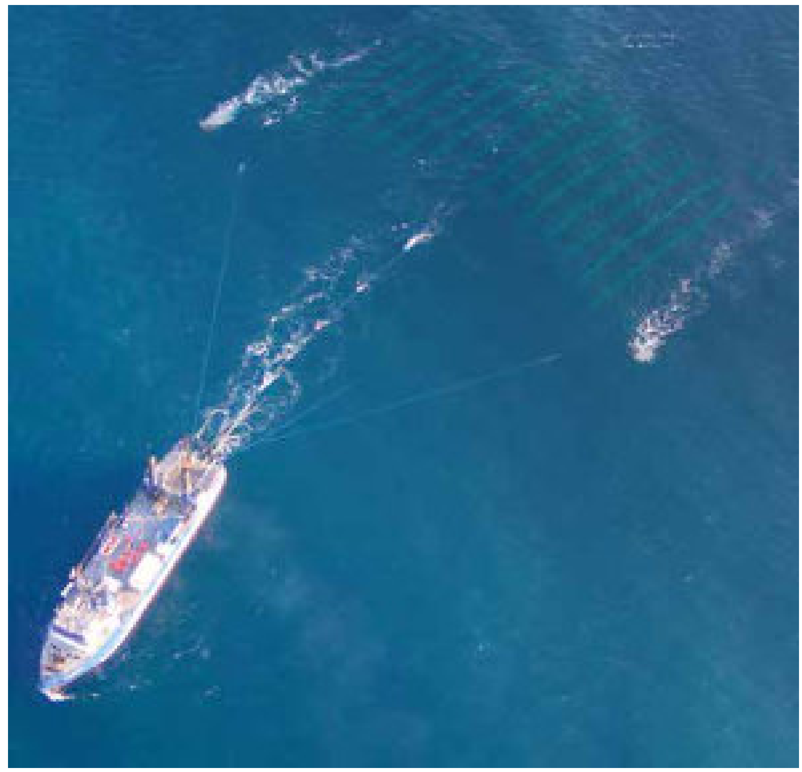
3.10 > The underwater rig MARUM-MeBo has been used for several years for drilling on the sea floor. It is flexible in that it can be deployed from different research vessels. Methane hydrate could be mined in the future using similar equipment.

research vessels could be worthwhile. Over the past 5 years German scientists, together with a software producer, have expanded a proven and tested computer program used by the gas and oil industry to create a simulation module for methane hydrate. This newly developed module takes into account the special environmental conditions required for the formation of methane hydrate, and provides important clues to undiscovered hydrate occurrences.

MULTIBEAM SWATH SOUNDER: This relatively new acoustic instrument can detect methane gas bubbles escaping from methane deposits through natural leaks. It is attached to the bottom of a ship and sends out fan-shaped ultrasound waves. It is thus able to scan a strip hundreds of metres wide on the sea floor. One of the challenges in using this instrument is to separate the reflection signal of the bubbles from numerous interference signals in the depth sounder. Special software has been developed for this purpose by scientists using the system. The swath sounder can be deployed early in the prospecting phase. Methane gas bubbles detected in the water can provide the first indication that methane hydrate is located in the sediments.

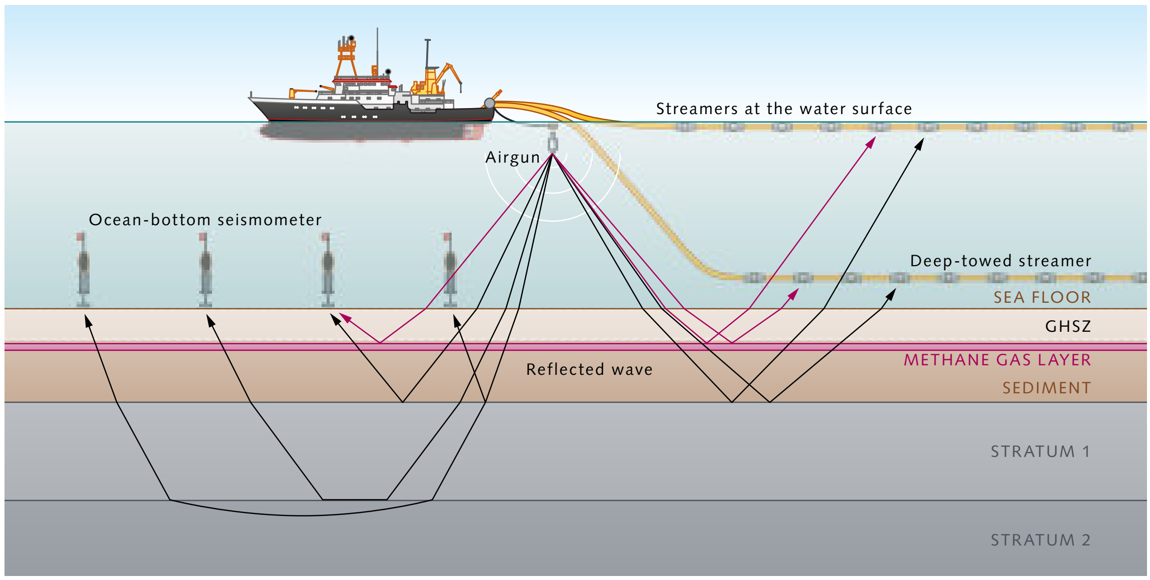
METHANE SENSOR: Until recently no measurement technique was available for directly determining the concentrations of methane in sea water. Water samples from various depths had to be retrieved by researchers and examined in the laboratory on board. But now there is a submersible mini-laboratory on the market about the size of a roll of wallpaper. It sucks the seawater in and ascertains the methane concentration directly in the ocean. The measurement data are transferred to the ship via a cable. The sensor complements the multibeam swath sounder because it can determine the deep methane concentrations with much greater accuracy.

MULTICHANNEL SEISMICS: Seismic methods use airguns to produce acoustic waves that penetrate into the seabed, where they are reflected by the different layers at different strengths or refracted. Receivers mounted on a cable several kilometres long called a streamer are towed behind the ship and record the reflected waves.



3.11 > For 3-D seismics, multiple parallel streamers are towed behind the ship. Because the receivers pick up slightly offset signals from different angles, an overall 3-D image of the bottom is produced.

The data from all of the receivers (channels) are then processed to create an image of the sea floor. While a spacing of 12 metres between the receivers is sufficient when prospecting for oil and gas, streamers to search for methane hydrate deposits have been developed with receiver spacings of only 1.5 metres. This provides a higher resolution and makes it possible to obtain an image of the sea floor on a finer grid. Multichannel seismics are also employed in the early stages of prospecting. They can reveal the presence of the bottom-simulating reflector (BSR). This is a strong reflection of the acoustic waves that is recognized as a conspicuous lighter layer in the seismic image. This effect is seen in different types of sediments. In the case of methane hydrate the strong reflector is produced by free methane gas below the gas hydrate stability zone. Below the GHSZ the temperature is too high for the formation of methane hydrate. Methane gas rising from greater depths in the sediments therefore collects here. Because it has a much lower density than the methane hydrate or the surrounding sediments, it is clearly



3.12 > For multichannel seismics, airguns generate acoustic waves that are reflected differently by different layers in the sea floor. The reflections are picked up by receivers that are anchored on the sea floor (ocean-bottom seismometers) or towed on a streamer behind a ship. Higher-resolution seismic images can be obtained using deep-towed streamers.

distinguishable from other layers in the seismic image data as the bottom-simulating reflector.

DEEP-TOWED STREAMER: To achieve a higher resolution of the seismic image, streamers can be towed through the water closer to the seabed, for example 100 metres above the sea floor. The advantage of this is that proximity to the bottom gives the streamers a wider-angle image of the sea bed. This allows them to get a low angle view beneath hard bacterial crusts that form naturally in some marine regions. These bacterial crusts are normally impenetrable for seismic waves.

3-D SEISMICS: At the first indication of possible methane hydrate presence, systems are employed to illustrate the depth and lateral extent of the deposits in the sea floor in three dimensions. For these 3-D systems, a parallel arrangement of several streamers is towed behind the ship. Because the individual streamers peer into the sea floor at slightly different angles, they provide a combined stereoscopic impression. The resolution of systems that have been developed over the past five years is remarkable. They create an image of the sea floor down to a depth of 500 metres in a 3 by 3 metre grid. A reservoir can thus be displayed as a large void. These 3-D methods can furthermore recognize fissures in the reservoir through which methane can escape, and detect large methane gas bubbles in the vicinity of the fissures. In addition, 3-D seismics can provide important information regarding favourable sites to take bottom samples during the subsequent exploration phase.

... then exploration

Whether methane hydrate deposits exist at all in an area is first determined during the prospecting phase. When their presence is confirmed then exploration, the detailed study of the marine area, can begin. With exploration methods it is possible to assess fairly accurately how much methane or methane hydrate is present in a deposit. The following techniques and devices are presently being used:

CORING: A classic method in the exploration of mineral resources is the drilling of cores. With a drill string lowered from a research ship, sediment cores are retrieved from hundreds of metres below the sea floor. These long cores, with the approximate diameter of a rain gutter, are cut into a number of metre-long sections on board the research vessel and studied later in a laboratory on land for the presence of methane hydrates. Special drilling tools that can maintain the high pressure as the methane hydrate sample is brought to the surface prevent dissociation of the methane hydrate until it is possible to analyse the core.

OCEAN-BOTTOM SEISMOMETER: Ocean-bottom seismometers (OBS) function like conventional seismometers. The receivers, however, are not attached to a streamer but are stationed on the sea floor. This allows greater observational depth coverage. Acoustic waves travel through strata at different speeds depending on their densities. The waves accelerate in dense structures such as methane hydrates, but propagate more slowly through less dense structures such as muddy sediments or gas voids. The ocean-bottom seismometer system calculates an image of the sea floor from the lag of reflected waves. Because the instruments can detect at greater distances than a streamer, they can record signals from greater depths. The present record is 12 kilometres. Ocean-bottom seismometers will be deployed off Korea in 2014.

ELECTROMAGNETICS: For the past ten years electromagnetic systems have also been employed by the gas and oil industries. These transmit electromagnetic impulses similar to those of a radio station antenna. Like acoustic waves for an ocean-bottom seismometer, different bottom structures change the electromagnetic signals to a greater or lesser extent. The physical principles of the two are not the same, however. This system takes advantage of the fact that different substances conduct electromagnetic impulses with varying levels of efficiency. Poorly conducting substances produce a resistance. Liquids, on the other hand, such as water, are very good conductors. The system very accurately senses these differences in conductivity or resistivity in the seabed. It is therefore possible to determine, using electromagnetic techniques, how much free methane gas is located below the GHSZ or how much is contained in the hydrates. The method, however, has disadvantages. For one, electromagnetic waves propagate in a circular pattern, in contrast to the directional explosion of the airgun. The conductivity values, and thus the methane deposits, are therefore difficult to pinpoint. Furthermore, the electromagnetic impulses weaken rapidly, so they cannot penetrate as deeply into the seabed as sound waves. In the past five years a mathematical technique has therefore been developed to combine the electromagnetic and seismic techniques. This method, called joint inversion, takes advantage of the strengths of both methods: the very high spatial resolution of the ocean-bottom seismometers and the precise conductivity values of the electromagnetic system, which provides information about the methane content. Much better characterizations of methane hydrate deposits can now be made than in the past, thanks to joint inversion methods.

The joint inversion method will be used off Taiwan starting in 2014 to investigate the formation of gas hydrates there. Taiwan is especially interesting because it is located at a subduction zone where methane-rich water is squeezed out of the sediment. Even today it is still not known how much methane is released at subduction zones. This inhibits assessments of the total amounts of hydrates existing worldwide. A detailed analysis of the subduction zone off Taiwan and the amounts of methane released there could thus help to make more accurate estimates of occurrences in the future.

3.13 > Clump of methane hydrate in a drill core.

The impacts of hydrate mining

> For a long time the risks associated with methane hydrate mining were uncertain. Today there is widespread consensus that drilling is responsible for neither tsunamis nor leaks in sea floor sediments through which large amounts of climate-damaging methane could escape into the ocean and the atmosphere.

Fear of disasters

In recent years the potentially negative impact of methane hydrate mining on the marine environment and climate has been a source of heated debate in professional circles. Concerns have been voiced that extracting the hydrates could release vast quantities of methane into the atmosphere. In this event the consequences would be disastrous, as methane is a greenhouse gas about 20 times more potent than carbon dioxide. Some scientists have claimed that such an increased release of methane from the oceans could accelerate climate change.

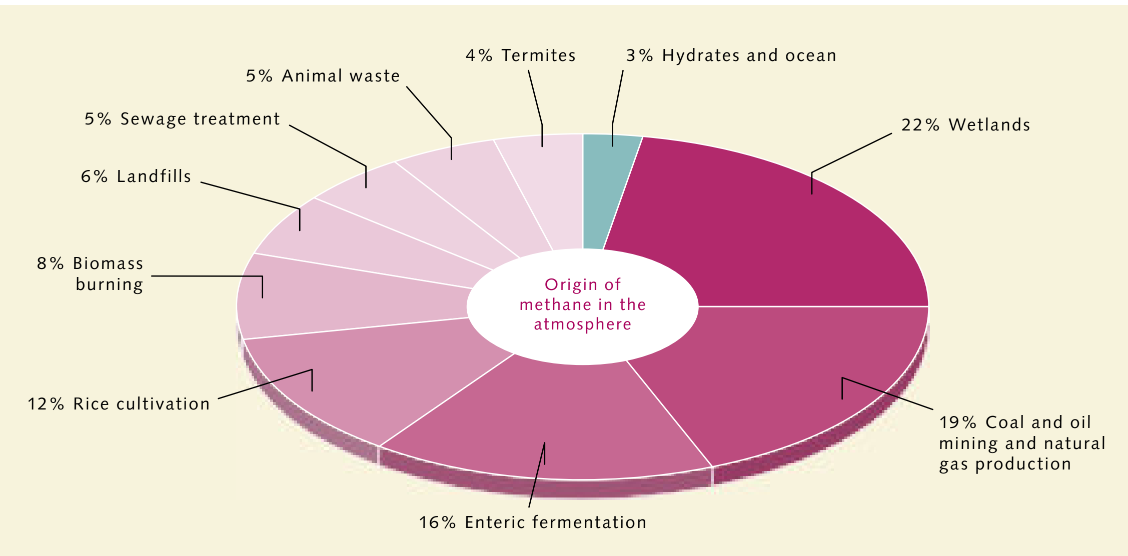
The possibility that hydrate mining could generate submarine landslides on steep continental slopes has also been discussed. Like avalanches in mountainous regions, submarine landslides are natural events. They occur on continental margins where thick layers of soft sediment have accumulated, such as near river mouths. Similar to the alpine snow, the sediment at some stage becomes so heavy that it begins to slide downhill. Gas hydrates cement the pores between the fine particles of sediment and thus stabilize the seabed. Some scientists have claimed that dissociating the methane hydrates would destabilize the sea floor, and in the worst case scenario huge packages of sediments could slide downhill, triggering powerful tsunamis along coastal areas.

3.14 > In freshwater lakes, such as this one near Fairbanks in Alaska, methane bubbles can freeze in ice.

Environmental damage from hydrate mining?

It is not uncommon for slopes to slide. There is even scientific evidence that landslides have been responsible for severe tsunamis. One such example is the Storegga Slide which occurred off the coast of Norway 7000 years ago, when a large section of the Norwegian continental slope collapsed and sank. The motion was so great that 20-metre waves struck the shores of Scotland. This incident had nothing to do with methane hydrates, however. The Storegga slope began to move because, after the Ice Age, the Scandinavian continental plate began to slowly rise, causing a portion of the slope to break off. Such major slides are very rare, only striking every few thousand years.

Smaller landslides, on the other hand, are very common. A certain number of slopes around the world have sufficient accumulation of sediment for even a small disruption to generate a slump. For this reason it is vital that any potential drilling site be closely evaluated in advance. Scientists assert that environmental impact assessments in future will evaluate the risk of landslides before methane hydrate mining can begin. However, uniform standards governing the survey of methane hydrate areas have yet to be developed. Japan and Korea, who are leading the way in this field, will for the time being choose shallow marine areas such as ocean basins for their activities, in order to largely preclude the risk of landslides.



3.15 > Atmospheric methane comes mainly from land-based sources – particularly wetland areas. Only a small proportion is contributed by marine methane hydrates. Even global warming will not substantially increase this amount.

Relatively small-scale methane hydrate mining does not cause landslides or trigger tsunamis. Moreover, the investment costs are so exorbitant that participating companies are unwilling to take the risk of their drilling equipment being destroyed on the seabed.

The introduction of carbon dioxide reduces the risk of landslides from hydrate mining. Carbon dioxide is injected into the hydrate to replace the methane being released. The CO_2 itself reacts with the water to form a solid hydrate, which re-stabilizes the sediments.

Point source disruption

In one other respect, too, experts now tend to consider methane hydrate mining as relatively benign. Unlike the mining of massive sulphides and manganese nodules, the disruption of fragile seabed habitats is isolated, because no major mass movement is involved. The sediment is churned up only in the immediate vicinity of the drilling site.

Even where several boreholes are drilled during the development stage of a reservoir, any disruption is relatively minor. Oil and gas industry experience shows that drilling does not affect the marine environment to any measurable extent – apart from disasters of the magnitude of the *Deepwater Horizon* oil platform in the Gulf of Mexico.

Could methane reach the atmosphere?

The notion that large quantities of methane can flow up out of the oceans is not new. Some people even believed that this was the reason behind the mysterious disappearance of ships in the Bermuda Triangle. According to this theory, enormous bubbles of methane rose from the depths and swamped the ships. We now know that such large bubbles cannot break loose from hydrates. Nor will hydrate mining cause significant amounts of methane gas to rise freely into the atmosphere. There are several reasons for this:

- Scientists recommend the mining of only methane hydrate deposits which are covered by a layer of sediment at least 100 metres thick. This amount of sediment prevents any methane bubbles which may form in the vicinity of the borehole from being released into the water.

- Unlike natural gas and oil, methane does not shoot up out of the borehole on its own. The hydrate must gradually break down (dissociate), resulting in the slow release of the methane. There is therefore no danger of a blow-out similar to the *Deepwater Horizon* oil platform in 2010. No large volumes of methane gas will be released to flow to the surface.

Greenhouse effect
Water vapour, carbon dioxide (CO_2), methane and other trace gases in the atmosphere at first allow the sun's energy (short-wave radiation) to pass through to the Earth. This energy is converted to heat on the Earth's surface and a large proportion is emitted back into the atmosphere in the form of long-wave radiation. Like the glass windows of a greenhouse, however, the gases prevent the long-wave thermal radiation from escaping into space. The Earth heats up.

If methane should nonetheless escape from the sediment through a poorly-sealed borehole, then only very little, if any, methane will be capable of entering the atmosphere. We know that most of the hydrate deposits lie at water depths of 500 to 3000 metres. Methane rising from these depths is broken down before reaching the surface. This is also true if drilling occurs in natural fractures and fissures in the sea floor. If methane hydrate were unintentionally extracted in such regions, methane could leak into the water through these fault areas. Modern exploration procedures, however, can reliably detect such fault areas in advance so that drilling here can be avoided.

Does global warming accelerate the breakdown of methane hydrates?

Methane is a powerful greenhouse gas, and we understand that it is responsible for 15 per cent of the greenhouse effect. For this reason scientists have in recent years tried to estimate how much methane is released into the atmosphere annually. Wetlands, where large volumes of dead plant material are broken down by methane-producing bacteria, are considered to be the main source. Other sources include the stomachs of cows and other ruminants, rice cultivation, and oil and gas production. How much methane, if any, will in future be released into the atmosphere as a result of global warming has long been the subject of controversial debate. Scientists base their calculations on 4 different types of methane hydrate reservoir types:

IN ONSHORE PERMAFROST REGIONS: Such methane hydrate reservoirs are found in regions such as Alaska, Canada and Siberia. They contain only approximately 1 per cent of the global volume. Their impact on the climate would be equally insignificant. In most of these regions the deposits are situated at depths of more than 300 metres. Scientists believe that global warming would, at most, cause the upper layers of methane hydrate to thaw. This process is likely to take several thousand years. Deposits at depths of about 20 metres would be much more sensitive to warming, but these are rarer and the total volume of methane is minimal.

IN FLOODED PERMAFROST REGIONS ON THE ARCTIC SHELF: Rising sea levels after the last Ice Age were responsible for the flooding of permafrost regions in the Arctic. Because the temperature of the water, being slightly above 0 degrees Celsius, is considerably warmer than that of the Arctic air, the flooded permafrost began to thaw. Now, several thousand years later, the thaw has reached the depth of the gas hydrate stability zone (GHSZ). The hydrates are slowly dissociating and releasing methane. This is occurring in many parts of the seabed, including the Siberian shelf. The impact of human-induced climate warming on this process will continue to be minimal. Computer models show that if any methane hydrates do in fact thaw, this process will be limited to those buried in sediments at depths of only 10 to 20 metres. Such deposits are, however, rare. As the water in the shelf regions is relatively shallow, this methane would indeed be released into the atmosphere. It is estimated that the flooded permafrost regions of the Arctic shelf contain less than 1 per cent of the global volume of methane hydrates.

ON CONTINENTAL MARGINS (UPPER BOUNDARIES OF THE GHSZ): These methane hydrate deposits are situated exactly where the GHSZ begins – mostly at depths of 300 to 500 metres. Because of their location at the upper boundary of the GHSZ they are particularly vulnerable to ocean warming. Even minimal warming would cause them to start to dissociate. In other regions gas hydrates act as a type of plug and obstruct deeper-lying methane gas bubbles. These plugs could also break loose to release additional methane gas. It is estimated that deposits along the continental margins and the upper margins of the GHSZ contain about 3 per cent of the global volume of methane hydrates.

ON DEEP-SEA CONTINENTAL MARGINS: The largest proportion, about 95 per cent, of methane hydrate deposits is found in the sediments of deep-sea continental margins at depths of 500 to 3000 metres, where water pressures are high. Rising seawater temperatures as a result of climate change have little effect on the stability of these hydrates. Firstly, the pressures are so high that a minimal temperature increase is not enough for

Bacteria consume methane

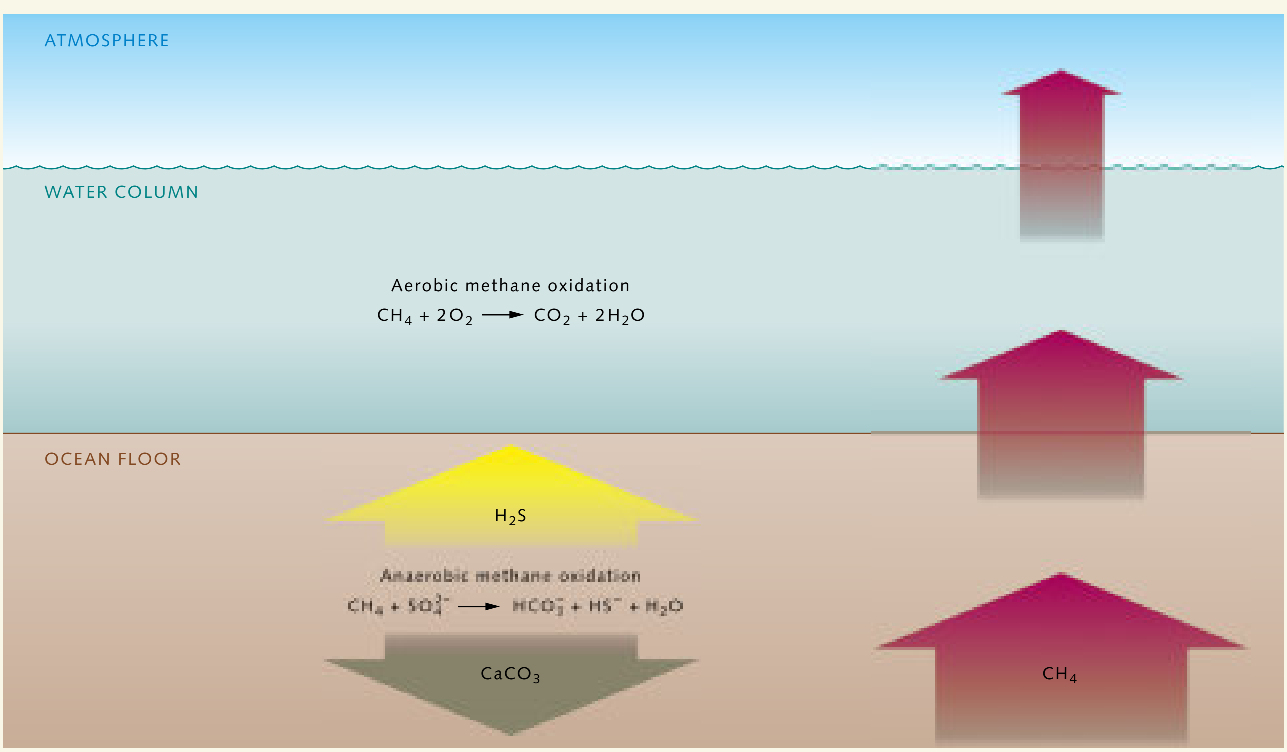
Methane rising up from the sediments is, to a large extent, consumed by microorganisms that live in the upper layers of the sea floor and in the water.

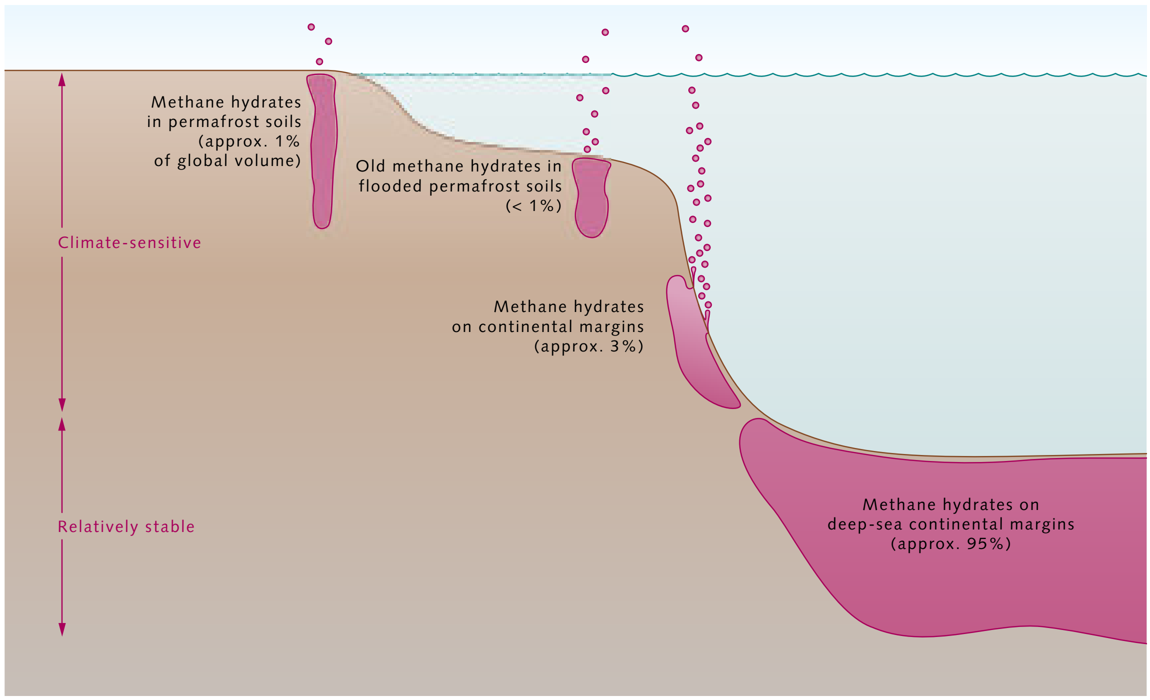
Anaerobic bacteria – bacteria that can survive without oxygen – are active in the ocean floor. They process the methane with the help of sulphate (SO_4^{-}), thus producing hydrogen sulphide anions (HS^-), hydrogen sulphide (H_2S) and bicarbonate (HCO_3^-). The bicarbonate can react with calcium ions (Ca^{+}) to form lime, or calcium carbonate ($CaCO_3$), which precipitates in the ocean floor.

Aerobic bacteria – which need oxygen – are active in seawater. Together with oxygen (O_2) they convert methane (CH_4) into carbon dioxide and water (H_2O). The methane therefore slowly breaks down during its journey from the seabed up through the seawater. The greater the depth from which the methane rises, the farther it has to travel and the less methane reaches the upper water layers and the atmosphere. However, we should not forget that aerobic methane oxidation in particular can change the chemical composition of the seawater. Firstly, the reaction of the oxygen with methane reduces the oxygen concentration in the water. This can give rise to problems because many marine organisms cannot survive in oxygen-deficient areas. Secondly, the carbon dioxide reacts with seawater to form carbonic acid which causes acidification of the seawater.

The explosion at the *Deepwater Horizon* oil rig in the Gulf of Mexico in April 2010, however, showed that the impact of the altered marine chemistry is small-scale and tends to be minor. Apart from the oil, large volumes of methane were also released into the water surrounding the accident site. After the calamity scientists measured a reduction in the oxygen content in the vicinity of the platform. The changes were minimal, and no negative impact on marine life could be verified. Having said this, we cannot be certain that lower oxygen levels and acidification around methane sources would not stress marine animals, resulting in poor growth and reproduction rates. For example, seawater acidification around volcanic springs near the Mediterranean island of Ischia has impaired the ability of many marine organisms to form their shells.

3.16





3.17 > Deposits of methane hydrates are found in different settings around the world. The effects of climate change and global warming are not the same for each setting. Most methane hydrates are buried beneath the deep ocean, where they are largely protected from dissociation.

the hydrates to break down. Secondly, it will take many thousands of years for the warming to spread from the surface to the deep water or the sediment.

Because many marine areas have not yet been adequately explored, it is impossible to say with any certainty what the exact proportional distribution is. Most scientists, however, agree that climate change will not trigger any catastrophic mass meltdown of methane hydrates, because by far the greatest hydrate volumes are stored in the sediments of deep-sea continental margins. One topic of discussion, however, is whether methane has ever before been released en masse from hydrates.

Apparently climate warming was responsible for periodic mass meltdowns millions of years ago. These then started a chain reaction and the methane gas is said to have heated the Earth even more. Some researchers believe that this could have been the case with the Paleocene-Eocene Thermal Maximum (PETM) roughly 55 million years ago. Within a period of 20,000 years during the PETM, worldwide temperatures rose by an average of 6 degrees Celsius. This is a great deal when we consider that climate researchers today anticipate significant changes to the climate from a global temperature rise of little more than 2 degrees Celsius. The causes of the Paleocene-Eocene Thermal Maximum remain a source of controversial debate among scientists, and some suspect that it could have been triggered or at least intensified by the release of methane gas.

Experts believe that the dissociation of gas hydrates will contribute little to global warming during the next few centuries. But if we look at longer periods of time, through several millennia, it is certainly possible for increased quantities of methane to be emitted. Initially the human-induced, anthropogenic carbon dioxide emissions would lead to an extended period of warming, as most of the carbon dioxide released would still be present in the atmosphere in more than a thousand years – long after we are supplying our energy needs from renewable sources. Such long-term warming would cause the hydrates to slowly break down. It is therefore not inconceivable that the long-term effect of today's carbon dioxide emissions could intensify the dissociation of gas hydrates, adding further momentum to the greenhouse effect.

Conclusion

Valuable resource or greenhouse gas?

Methane hydrates are found in the soft seabed of continental margins all around the world, at water depths of 300 to 3000 metres. The largest deposits are encountered below 500 metres. Methane hydrates are formed from water and methane gas at certain temperatures and high pressures. The warmer the water, the higher the water pressure needs to be, and the deeper the deposits are then buried.

According to current estimates, global hydrate deposits contain about 10 times more methane gas than conventional natural gas deposits. Therefore they should be taken very seriously as a potential energy resource. Test drilling has shown that it is certainly possible to harvest methane hydrates in the ocean floor. Nations such as Japan and Korea in particular, which at present are forced to import most of their energy resources, hope that methane hydrates will help them reduce their dependence on expensive foreign fuel supplies. However, methane hydrate mining in the soft sediments calls for different procedures from those used to exploit marine oil and gas, and the drilling and production technology needed is not yet available. It is expected that the appropriate equipment will be developed within the next few years; initial prototypes are already in hand. Feasibility studies are also currently being carried out. Compact production equipment for placement on the sea floor is envisaged.

One major obstacle is that, unlike conventional natural gas, the methane is firmly entrapped in the hydrates and does not flow freely into the borehole. The methane hydrates must first be dissociated in situ, which makes the flow rate of such deposits slower than conventional gas production. It remains to be seen whether hydrate extraction at great depths is economically viable at all.

As most methane hydrates form on the continental slopes, critics were at first worried that drilling into the soft sediments could possibly trigger landslides, and in turn tsunamis. In the meantime, geoscientists have conducted further research and have ruled out such concerns. Avalanche-like landslides are a natural phenomenon, they say, and quite regular occurrences. The drilling could in principle generate such slumps, but these would be too minor and their energy levels too low to cause tsunamis.

There were also fears that drilling on the ocean floor could cause large amounts of methane to erupt from the seabed, rise through the water and ultimately into the atmosphere. As methane is a powerful greenhouse gas, this would exacerbate global warming. Scientists now know that this will not happen because, unlike gas and oil, the methane is bound up in hydrates and cannot flow out of the borehole on its own. It is gradually released as the hydrate slowly breaks down in the soil during mining. The type of blowout that can occur in an oil borehole is therefore inherently impossible. Even if methane is released from the seabed into the water, it will be broken down by bacteria as it migrates through the water column to the surface.

Today there is a broad consensus in the scientific community that global warming will not generate an intense release of methane during this century – or even during the next several centuries. However, if we consider longer geological periods of time the situation looks quite different. Climate change could warm up the oceans so much in the next few millennia that substantial volumes of hydrate – particularly in shallow marine areas – could dissociate. The released methane that is not completely broken down during its short path to the surface could end up in the atmosphere after all.

4 Clean production and equitable distribution

> To ensure that ocean mining does not escalate into a competition for the most promising claims, a UN agency administers the marine minerals in the international seabed area, ensuring that the environment is protected and that developing countries can share in the benefits. Commercial activities in coastal states' waters, however, are regulated by national law. As the offshore oil industry shows, this does not always afford adequate protection for the environment.

The international community's responsibility

> The future exploitation of marine minerals in international waters is regulated by the International Seabed Authority (ISA). It ensures that marine minerals are equitably distributed among the world's countries and that damage to seabed habitats is minimized. Clear regulations and environmental standards are thus in place before exploitation begins. For environmentalists, however, the nature conservation provisions governing marine mining do not go far enough.

Doing things better

With many onshore oil, gas and ore deposits now more or less exhausted, the pressure on offshore resources is increasing. Oil and gas have been produced offshore for decades, and companies began extracting these fossil resources in deep water some time ago. By contrast, ore extraction from the seabed has not yet begun.

Disasters such as the *Deepwater Horizon* oil rig explosion and numerous tanker incidents have highlighted the dangers of offshore oil production and transportation.

But onshore too, mining, quarrying and oil production are destroying rainforests and human settlements and polluting soils and rivers. The challenge now is to prevent degradation on this scale from occurring in the marine environment in future by ensuring that marine resource extraction is safe and clean.

Humankind's most comprehensive treaty

The primary instrument governing the protection of seas is the United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS was adopted at the 1982 UN Conference on the Law of the Sea and came into force, after protracted negotiations, in 1994. It is the "constitution for the seas". The most comprehensive international treaty ever concluded, it establishes rules for all types of use: navigation, fishing, oil and gas extraction, seabed mining, marine conservation and marine scientific research.

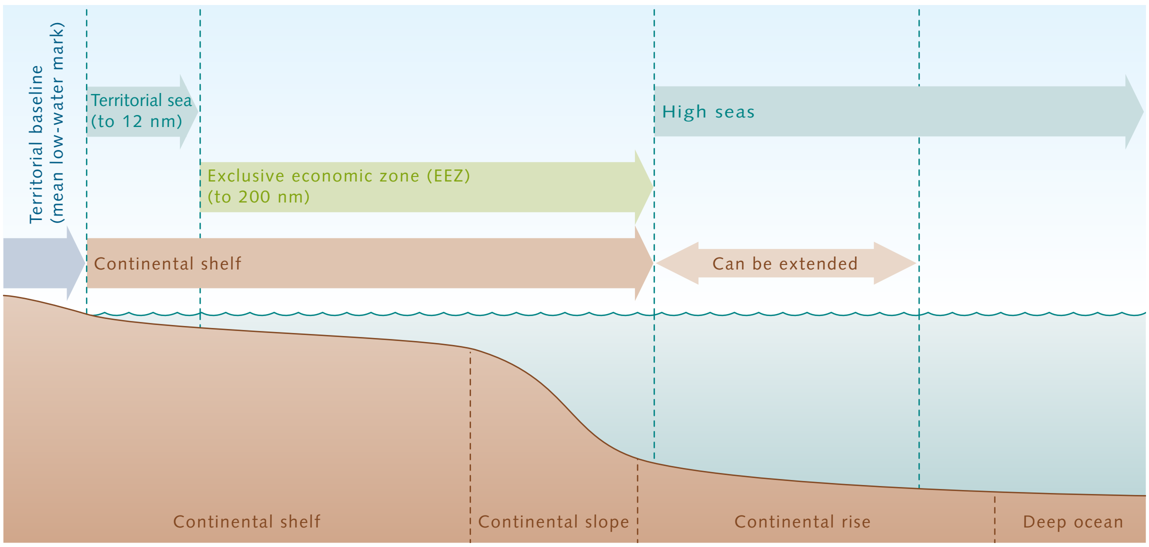
To date, 165 states and the EU have signed and ratified the Convention. UNCLOS establishes the general obligation for states parties to protect the marine environment, which is then elaborated in more detail in specific regulations for the various types of use.

UNCLOS applies in principle to all maritime zones and to all states which, by ratifying the Convention, agree to be bound by this legal regime. However, states' jurisdiction and powers to implement legislation vary in each of the maritime zones. The following legal zones are distinguished:

TERRITORIAL SEA: The territorial sea – the 12-mile zone – is the sovereign territory of the coastal state. Activities in this maritime zone are governed by the laws and regulations adopted by the coastal state. Coastal states that have ratified UNCLOS must ensure that their legislation is in line with its provisions.

EXCLUSIVE ECONOMIC ZONE (EEZ): The exclusive economic zone starts at the seaward edge of the territorial sea and extends to a distance of 200 nautical miles (approximately 370 km) from the coastal baseline. The EEZ is therefore sometimes known as the 200 nautical mile zone. The seabed and the water column form part of the EEZ. Unlike the territorial sea, this zone does not form part of the coastal state's sovereign territory. However, each coastal state has exclusive rights to exploit the natural resources there, such as oil and gas, minerals and fish stocks. Other nations may only exploit these resources with the coastal state's consent. Resource extraction in the EEZ is governed by the legislation adopted by the coastal state, which must be in line with UNCLOS provisions. For other types of use, particularly shipping, the principle of freedom of the high seas applies in the EEZ as well.

CONTINENTAL SHELF: The continental shelf comprises the seabed that extends, with a steep or gentle gradient, outward from the coastal baseline and constitutes the natural geological prolongation of the coastal



4.1 > The United Nations Convention on the Law of the Sea divides the sea into various legal zones, with the state's sovereignty decreasing with increasing distance from the coast. Every state has a territorial sea, not exceeding 12 nautical miles, which extends from the baseline. In the territorial sea, the sovereignty of the coastal state is already restricted, as ships of all states enjoy the right of innocent passage through it. In the exclusive economic zone (EEZ), which extends for up to 200 nautical miles from the coastal baseline, the coastal state has exclusive rights for the purpose of exploring and exploiting the natural resources, whether living or non-living, of the waters. This means that it is entitled to exploit any oil and gas fields, mineral resources and fish stocks found here. On the continental shelf, which is defined as the natural prolongation of a country's land territory and may extend beyond the EEZ, the coastal state has sovereign rights for the purpose of exploring and exploiting the natural resources, whether living or non-living, on or under the seabed.

state's land territory. The continental shelf is of particular economic relevance as it is here that large oil and gas fields, gas hydrates and massive sulphides are found. The "inner continental shelf" has the same spatial scope as the EEZ (200 nautical miles). In some cases, the continental shelf drops to such a depth that it forms part of the deep ocean floor. However, in many parts of the world, there are regions in which an outer continental shelf is geologically identifiable which starts within the EEZ and stretches beyond the 200 nautical mile limit, thereby extending the coastal state's sphere of influence. The state may apply to establish these extended outer limits of its continental shelf by submitting scientific evidence to the Commission on the Limits of the Continental Shelf (CLCS) in New York. The Commission then makes a binding recommendation on recognition of this outer limit, which may not exceed 350 nautical miles from the baseline. Alternatively, a coastal state may request recognition of an outer limit up to 100 nautical miles seawards – and in some cases even more – from the 2500 metre isobath as the extension of its continental shelf beyond the limits of the EEZ.

HIGH SEAS: After the 200 nautical mile limit is the maritime zone known as the high seas. No state may subject any part of the high seas to its sovereignty. The high seas are open to all states. Nonetheless, regulations apply to the exploitation of the resources of the high seas. Fishing, for example, is regulated by Regional Fisheries Management Organizations (RFMOs), which set a Total Allowable Catch for individual species. By contrast, just one organization – the International Seabed Authority (ISA) established by the United Nations – is responsible for controlling the allocation and exploitation of resources in and on the seabed. The Authority's jurisdiction extends to all mineral resources of the seabed beyond national jurisdiction, which UNCLOS defines as the common heritage of mankind.

Deep sea
The deep sea refers to the totally dark layers of the ocean below around 800 metres. On some coasts and continent shelves, the transition from the land to deep sea is so abrupt that a depth of 800 metres or more is reached within the EEZ. The coast of Japan is just one example.

In simple terms, then, a distinction can be made between national and international maritime zones. The ISA has jurisdiction over marine mining in international waters, including – at least in theory – oil and gas production. However, oil and gas fields are mainly found in the EEZs, so the extraction of these resources in international waters is not an issue at present.

UNCLOS – a long time in the making

Whereas gas and oil fields are mainly located in the EEZs, high-yield manganese nodules and, to some extent, cobalt-rich crusts and massive sulphide deposits are found in the high seas. Experts often use the term "the Area" to denote the seabed, ocean floor and subsoil in international waters beyond the limits of national jurisdiction.

For many years, the allocation of the Area's seabed resources was a contentious issue for the international community, and this was one of the main reasons why UNCLOS did not enter into force until 1994, 12 years after its adoption by the UN Conference on the Law of the Sea. UNCLOS was conceived in the 1970s, which was a time of great change in two respects. Firstly, with the discovery of extensive manganese nodule deposits in the Pacific, the sea seemed to be a vast repository of natural resources which were there for the taking. Secondly, many former French, British and Portuguese colonies had become sovereign states and were now seeking to cement their political and economic independence, inter alia by asserting their claims to marine resources. Accordingly, in 1982, UNCLOS initially provided for the establishment of an International Seabed Authority (ISA), which in turn was to set up a body, known as the "Enterprise", to serve as the ISA's own mining operator. The idea was that benefits would be shared equitably among the various states. Under the Convention, the industrialized countries would share their scientific knowledge and mining technology free of charge for the benefit of all. The former colonies and developing countries ratified UNCLOS immediately, but there were protests from the industrial nations.

In subsequent years, the modalities for a future marine mining regime were renegotiated in order to achieve a consensus on UNCLOS. Among other things, the requirement for no-cost technology transfer was dropped, and the establishment of an "Enterprise" was postponed indefinitely. These new rules and amendments were finally incorporated into the 1994 Agreement on Implementation, which supplements the Convention. Today, the rules and regulations contained in the Convention and the Agreement are implemented by three international bodies:

- the International Tribunal for the Law of the Sea (ITLOS) in Hamburg;
- the Commission on the Limits of the Continental Shelf (CLCS), which decides on the extension of individual states' exclusive economic zones;
- the International Seabed Authority (ISA), which controls seabed mining in the Area.

Both the Convention and the Agreement establish the rules applicable in "the Area", the 12-mile zones and the EEZs. For example, states parties are required to adopt legislation to limit and control mining activities and must protect and preserve rare or fragile ecosy-

4.2 > The island state of Nauru is the world's smallest republic. With an area of around 20 square kilometres, it is roughly twice the size of Capri.

stems and the habitats of endangered species. Cross-border pollution must be avoided. Companies and states may be held liable for any damage caused.

Clear rules for marine mining

The Convention and the Agreement establish a legal framework formulated in general terms. They do not provide any detailed instructions for practical action. The ISA has thus adopted regulations for each of the three types of mineral resources found in "the Area" – manganese nodules, cobalt-rich crusts and massive sulphides – with detailed provisions on the mining of these resources. At present, these regulations only cover the first two phases of marine mining, i.e. prospecting and exploration. As prospecting merely involves general seismic surveying of the seabed by ship, with minimal ground sampling, prospecting activities simply have to be disclosed to the ISA. Exploration, on the other hand, involves intensive seabed sampling and therefore requires a licence from the ISA. Regulations for commercial exploitation do not exist as yet; a draft regulatory framework for exploitation of manganese nodules is expected in 2016 at the earliest.

The absence of a regulatory regime for exploitation is due in part to a number of unresolved environmental issues. Intensive exploration is under way in various areas, and scientists on research vessels are constantly collecting new information about seabed habitats. The findings will feed into the future exploitation regime, which should be in place long before mining of manganese nodules starts. No country currently has any specific plans to begin nodule exploitation.

4.3 > The International Seabed Authority (ISA), based in Kingston, Jamaica, is responsible for ensuring the equitable sharing of benefits derived from seabed minerals.

One authority for all states

The ISA is a small authority with just 40 permanent members of staff, who come from a variety of countries. It owes its existence to the fact that the international community was able to agree that the use of seabed resources should benefit all states. The ISA is developing clear rules before the exploitation of marine minerals begins. It is the first time in history that such an approach has been taken, and contrasts starkly with the situation onshore where, regardless of the type of resource – coal, oil or gas – exploitation has invariably taken precedence, resulting in environmental degradation, until it was recognised that mistakes had been made and remedial action should be taken.

The ISA is also responsible for deciding whether a state or company should receive a licence. To date, the ISA has granted around 25 exploration licences. No exploitation licences have been issued as yet. States wishing to explore an area of the sea must apply to the ISA for an exploration licence, for which a fee of 500,000 US dollars is payable. Private companies can also apply for a licence, subject to their application being sponsored by their home state. The sponsoring state provides guarantees that the company has sufficient financial and technical capability, and accepts liability for the company's activities. An exploration licence is valid for 15 years and may be renewed once for a further five years. It is noteworthy that all the regulations can be expanded and updated on an ongoing basis so that the ISA can bring them into line with new scien-tific findings or extraction technologies.

Under ISA rules, developing countries which lack relevant expertise of their own can participate in deep-sea mining in "the Area" by entering into cooperation with a mining company, provided that the company establishes a subsidiary in the developing country. This is now possible following a decision by the International Tribunal for the Law of the Sea, whereby the developing country must accept liability for the company concerned. One of the first countries to take this path is the island state of Nauru, which is cooperating with a mining company via a subsidiary incorporated in Nauru.

Already regulated: manganese nodule exploration

So far, the regulatory regime for manganese nodules, known as the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, RPEN, is the most advanced one. This mineral is easier to extract than cobalt-rich crusts and massive sulphides and is likely to be the first to be exploited in "the Area".

The first exploration licences were issued as early as 2001 to six applicants, or "pioneers": China, Japan, France, Russia, South Korea and the Interoceanmetal Joint Organization (a consortium involving Bulgaria, Cuba, the Czech Republic, Poland, Russia and the Slovak Republic).

The framework for manganese nodules contains 40 Regulations. Among other things, these Regulations state that the applicant must divide the area for exploration into two parts of equal estimated commercial value, each covering no more than 150,000 square kilometres – making two areas, each equivalent to the combined area of England and Wales. The ISA selects one of the two areas for itself – this is then a "reserved area" – and issues an exploration licence to the applicant for the other area.

The "reserved area" can continue to be reserved for the "Enterprise", to be established at a later date, or may be made available to developing countries wishing to engage in marine mining operations in future. The identity of these countries is still unclear, however. As the "reserved area" has already undergone prospecting, the developing country can dispense with this costly procedure and start exploration directly.

Under ISA rules, the maximum area of 150,000 square kilometres allocated to a state under the licence is subsequently reduced over time. Portions of the area explored – amounting to 75,000 square kilometres after eight years from the date of the contract – progressively revert to the ISA. This procedure is known as "relinquishment". This means that the contractor cannot place any areas in reserve but must decide early on which area of seabed he wishes to continue to explore with a view to mining there in future. This ensures that a nation does not seize all the most attractive sites for itself. The relinquishment clause does not apply if the total area allocated to a state for exploration is smaller than 75,000 square kilometres.

The regulations governing manganese nodules also contain provisions on the conduct of exploration activities and establish a requirement for environmental impact assessments. Such an assessment must be carried out, for example, during exploration phases with intensive sampling, and must include testing of the equipment and methods to be used. In addition, if trial sediment plume generation is carried out during exploration, this requires an environmental impact assessment. The aim is to determine the impact of large-scale operation of mining vehicles on the seabed. The contractor must report regularly to the ISA on the progress of exploration activities. The ISA may also deploy independent observers on the contractor's research vessels. There are plans to soon make the rules on exploration even more stringent and detailed. To date, the ISA has approved 13 applications for licences for manganese nodule exploration.

Exploring massive sulphides in blocks

The rules applicable to prospecting and exploration for massive sulphides and cobalt-rich crusts are similar to those which apply to manganese nodules, but there are some variations on points of detail.

The Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area, adopted in 2010, apply to the known hydrothermally formed deposits of sulphides, including some 165 deposits whose exploitation appears to be viable. Under the Regulations, the area covered by each application may not exceed 300,000 square kilometres in size. The subsequent exploration must then be confined to a small part of this area, comprising not more than 100 blocks of at most 10 by 10 kilometres. The blocks must be arranged by the applicant in at least five clusters. The ISA's purpose, in adopting these provisions, is to ensure that companies or states do not secure high-yielding sites for themselves across a wide area but confine their activities to small areas. As a result, the actual exploration area ultimately amounts to no more than 10,000 square kilometres (100 blocks of 100 square kilometres). These Regulations also contain a relinquishment clause. Within specified time periods, the contractor must relinquish the major part of the area allocated for exploration, with the remaining area allocated after relinquishment not exceeding 2,500 square kilometres. This remaining area would presumably offer the applicant the best prospects for exploitation of the resource, with the rest being relinquished to the International Seabed Authority. So here too, the area ultimately remaining for commercial exploitation is significantly reduced. Applications for prospecting and exploration of massive sulphides have been submitted by China, France, India, Russia and South Korea. Germany is currently preparing an application.

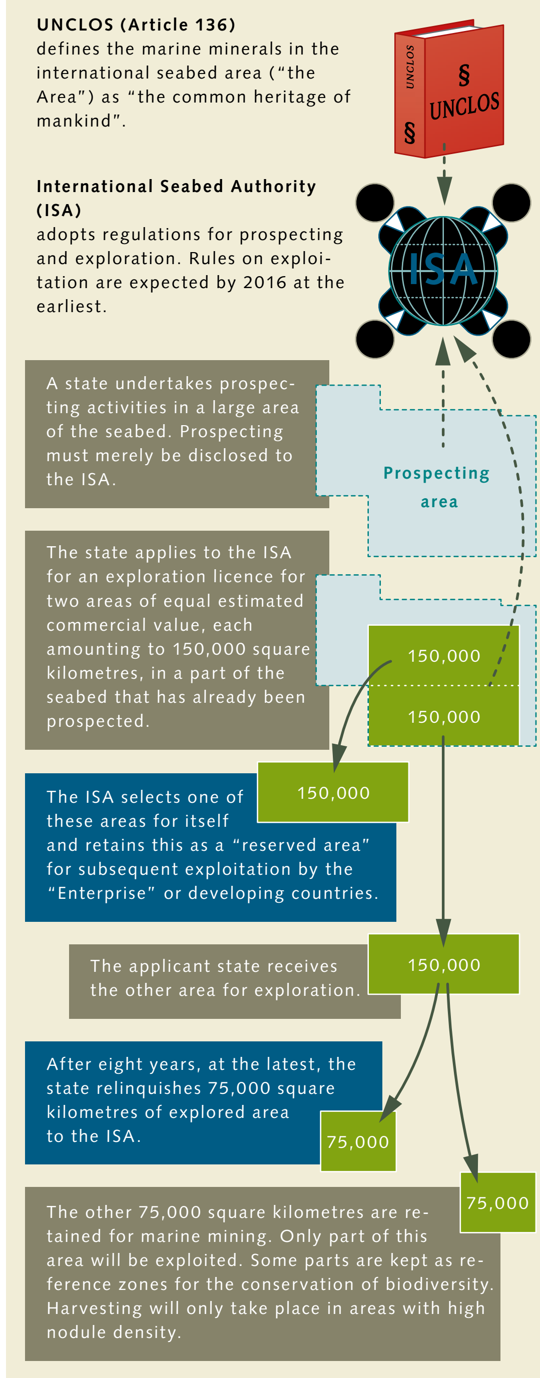
Rules on the exploration of cobalt-rich crusts

The latest Regulations on Prospecting and Exploration for Cobalt-rich Ferromanganese Crusts in the Area were adopted at the 18th session of the ISA in 2012. Here, the challenge was to develop rules for a resource for which no feasible mining technology currently exists. Furthermore, the crusts are found on seamounts, which are known to be particularly species-rich habitats, and many of which are already at risk from fishing and bottom trawling. Mining would intensify the pressure on these habitats.

Under the Regulations, the area covered by each application for prospecting must be located entirely within a geographical area measuring not more than 550 by 550 kilometres. The area covered by subsequent exploration must comprise not more than 150 cobalt crust blocks no greater than 20 square kilometres in size, which must be arranged by the applicant in clusters consisting of no more than five blocks. By the end of the tenth year from the date of the contract, the contractor must have relinquished to the ISA at least two thirds of the original area allocated to it.

The ISA is currently considering a Russian application. China and Japan have already been issued with exploration licences, making China the first country in the world to hold exploration licences for all three types of marine mineral resources.

Exploration and future exploitation of manganese nodules



4.4 > Under the ISA Regulations, a country is initially allocated a large exploration area, half of which must later be relinquished to the ISA. This half is then reserved for developing countries. However, the state may not exploit the remaining half in its entirety. Some parts of the area must be excluded in the interests of deep-sea fauna conservation.

Clearing the way for exploitation

Under all three sets of Regulations, the ISA, by granting a licence, expects the states engaged in exploration to maintain standards of good conduct. Should it transpire, during exploration, that the applicant is causing excessive damage to the natural environment or is failing to comply with the rules, an application to extend the exploration period or to exploit the marine mineral in future may be denied. Indeed, the ISA has the power to withdraw the licences for all three marine minerals. Regulations on the exploitation of marine minerals have not yet been finalized. However, in 2012, the Secretary-General of the ISA presented a workplan and timetable for the formulation of regulations on manganese nodule exploitation, to be established prior to 2016. The regulations are to include the following provisions:

- Exploitation should start with a mining test on a 20 to 50 per cent commercial scale. It is anticipated that the data and information obtained from this mining test will feed into the regulations, particularly as regards safety and the protection of the marine environment.

- Comprehensive environmental monitoring must be established and other environmental impact assessments performed throughout the exploitation phase. Monitoring means continuous long-term scientific observation and documentation of all operations, whereas environmental impact assessments are additionally carried out for individual activities. Monitoring and assessments should be updated regularly to take account of the latest scientific knowledge and mining technology.

- Contractors must provide detailed information about the entire production process, including information on collection techniques; depth of penetration into the seabed; methods for nodule separation and washing on the seafloor; methods for transporting the nodules to the surface; methods for discharging production residues (tailings); location and duration of the mining test; and environmental impacts.

Precautionary approach
The precautionary approach is applied in risk management and was among the principles adopted at the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro. According to the precautionary approach, where there are threats of serious or irreversible damage to the environment, lack of full scientific certainty shall not be used by states as a reason for postponing measures to prevent environmental degradation. The precautionary approach was incorporated into the Rio Declaration as Principle 15.

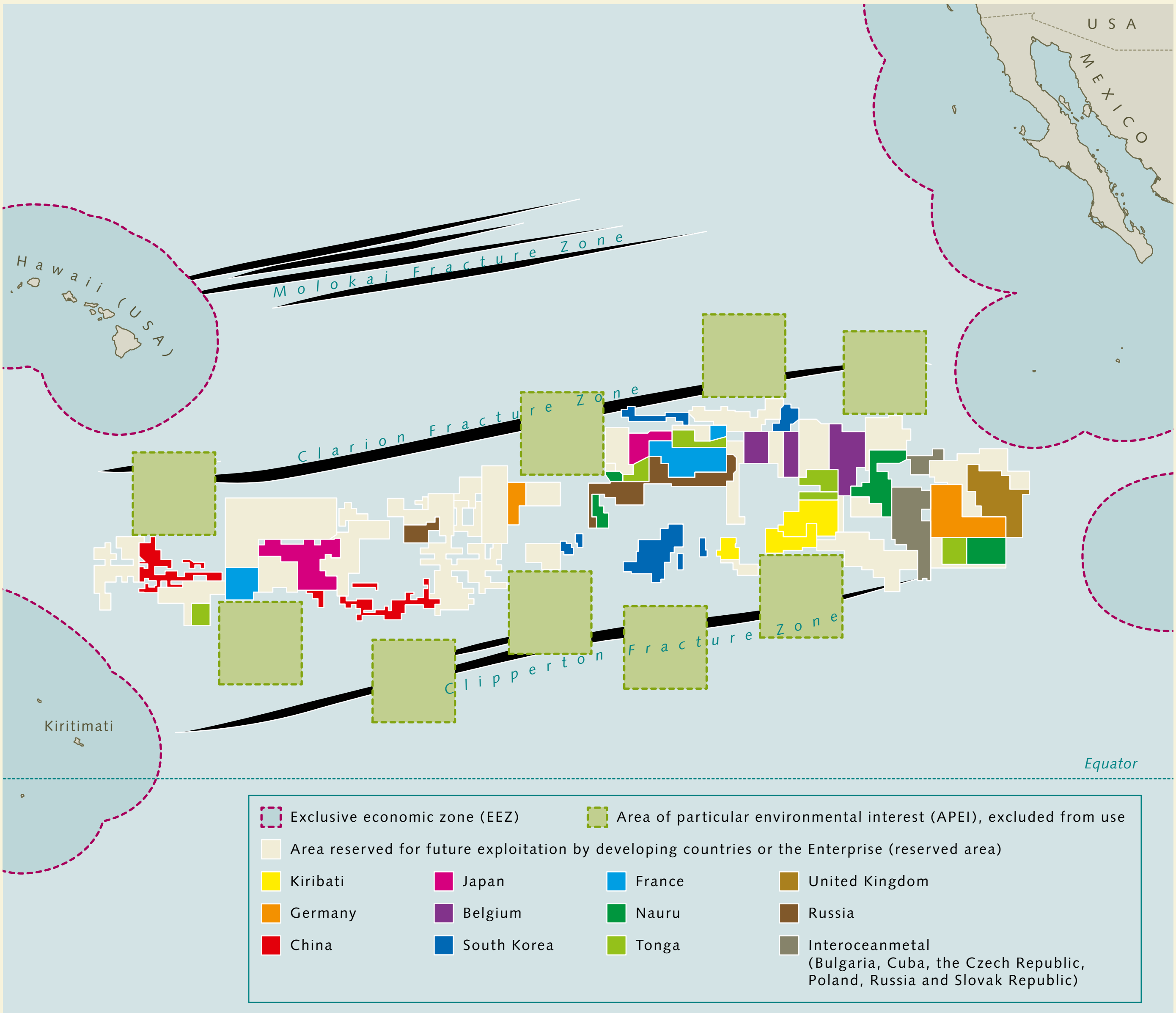
One option currently under discussion is to issue provisional mining licences for approximately three years, in line with the precautionary approach, with a view to gathering experience. Regular licences would then be issued to applicants after three years if no concerns arise.

It is unclear, at present, how high the mining royalties should be in future. It is essential to determine whether the best system would be based solely on mining royalties or involve a combination of royalties and profit-sharing for the ISA. In addition, a fixed annual fee – in an amount that has still to be determined – could become due at the start of production. For the mining companies, these financial arrangements – alongside environmental protection obligations – will be a crucial factor in their decision on whether or not to begin marine mineral exploitation in "the Area".

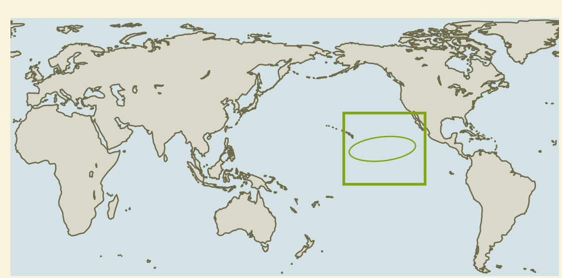
For the future, the ISA is planning to incorporate the comprehensive set of rules, regulations and procedures for prospecting, exploration and exploitation of marine minerals in the international seabed area into a single item of legislation known as the Mining Code.

The "Enterprise" – the ISA's commercial arm

Interestingly, the debate about the establishment of an "Enterprise", as the commercial arm of the ISA, has recently resumed. This was prompted by a proposal received by the ISA from an Australian/Canadian mining company to develop a joint venture with the "Enterprise" and to contribute the requisite mining technology. The establishment of such an undertaking is entirely possible, in principle, within the framework of the UNCLOS Agreement on Implementation and would in no way conflict with the concept of equitable benefit sharing. The "Enterprise" would not compete with indi-vidual states for areas of the seabed but would undertake mining operations in unallocated areas. The benefits would then be shared equitably. This would mean that there would be two strands to the ISA's work in future: it would continue to act as the authority responsible for issuing licences, and would also operate as the "Enterprise". At present, however, there are no clear rules for the establishment of the "Enterprise", and



4.5 > The Clarion-Clipperton Zone (CCZ) in the Pacific has the world's largest known deposits of deep-seabed polymetallic nodules, covering an area approximately the size of Europe. To date, the International Seabed Authority (ISA) has issued 12 exploration licences for the CCZ. Designation of the reserved areas and areas of particular environmental interest (APEIs) has already taken place.



the ISA therefore regards the founding or planning of a joint venture as premature. It is likely to be some years before relevant rules are in place.

Mining and nature conservation – squaring the circle?

By far the largest known deposits of marine mineral resources in the world are in the Clarion-Clipperton Zone (CCZ) in the Pacific, where many billions of tonnes of manganese nodules extend across an area the size of Europe. In order to protect and preserve habitats of a significant size in this vast area, the ISA adopted an environmental management plan for the CCZ at its 18th session in 2012. The plan identifies nine Areas of Particular Environmental Interest (APEIs) in the CCZ, where extraction of marine minerals is prohibited. Each APEI consists of a quadrilateral core area of at least 200 km in length and width, surrounded by a buffer zone, 100 km wide, in order to ensure that benthic communities in the APEIs are not buried or adversely affected by mining plumes drifting in from areas where extraction is under way. This means that there are, in total, nine 400 by 400 km protected areas in the CCZ, each with a total area of 160,000 square kilometres. Together, the nine APEIs thus cover almost 1.5 million square kilometres – around one-sixth of the CCZ and equivalent to an area twice the size of Turkey. At present, an environmental management plan and APEIs only exist for the CCZ; there are none for other licence areas, such as those in the Indian Ocean, although according to experts similar arrangements are needed elsewhere as well.

The environmental management plan goes even further. Not only does it designate 9 APEIs; it also obliges contractors to designate areas that are representative of the full range of habitats and species assemblages before exploitation begins. These reference zones should be of sufficient size, have similar topography and biodiversity to the impact zone, and must not be mined. In practice, this means that the licence areas will not be worked in their entirety, but only in specific sections. The aim is to preserve natural habitats as a basis for the subsequent recolonization of the mined area. The ISA is currently developing guidelines for such reference areas. However, critics point out that there is currently a lack of information and data relating to habitats in the CCZ and a lack of standards for the surveying and assessment of habitats as a viable basis for the selection of reference zones. This would be vital in view of the overall purpose of the zones, namely to preserve representative habitats. They also stress that special protection is needed for habitats with endemic biotic communities.

The demise of the commons

Despite criticism that the ISA lacks the capacities needed to implement comprehensive protection regimes in all the international waters, the ISA's work is regarded as well-nigh exemplary, for it operates in accordance with the precautionary approach, one of the guiding principles established, inter alia, in the Convention on Biological Diversity. Moreover, the ISA ensures the equitable distribution of resources defined as the common heritage of mankind. Scientists thus view with concern the efforts being made by some states to extend their jurisdiction beyond the limits of their EEZs into the outer continental shelf. The exemptions in the UNCLOS provisions on the continental shelf, which are invoked by these countries, mean that they would then be able to claim exclusive rights to the marine mineral deposits located in these outer areas.

According to experts, these exemptions – which were originally to be invoked in exceptional circumstances – are creating some bizarre scenarios. Russia, for example, is currently claiming around 40 per cent of the international Arctic seabed as its continental shelf, arguing that the undersea mountains in the central Arctic, such as the Gakkel Ridge, are a geological formation originating in the Russian EEZ, and that in accordance with this definition, Russia should be able to extend its area of jurisdiction to 350 nautical miles. UNCLOS also provides for the extension of the continental shelf to 100 nautical miles (nm) seawards from the 2500 metre isobath. This would enable Russia to extend its jurisdiction even further, beyond the 350 nautical mile limit. As the Russian authorities see it, the permissible combination of these two methods should allow Russia to claim 40 per cent of the Arctic seabed

More protection regimes for the international seabed area?

A further point of criticism is that so far, the ISA has not extended protected status to any valuable seabed habitats outside the licence areas, despite the fact that as the Authority established and legitimized by UNCLOS, it is ideally placed to do so. At present, designating marine protected areas in the high seas is extremely complicated due to the plethora of organizations involved. What's more, some protection regimes relate solely to specific marine fauna, particularly fish, in the water column, while others focus exclusively on the conservation of biotic communities on the seabed.

The International Maritime Organization (IMO), for example, can designate Particularly Sensitive Sea Areas (PSSAs) in which shipping is restricted or prohibited, e.g. to protect important fishing grounds, whale breeding areas, or areas of archaeological significance. One example is the Great Barrier Reef along the coast of northeast Australia. The possibility of extending PSSA status to the Sargasso Sea in the western Atlantic is also under discussion in IMO circles at present. The Sargasso Sea hosts vast amounts of the macroalgae Sargassum, masses of which float on the surface of the water and provide an important habitat for many marine fauna. However, Particularly Sensitive Sea Area status merely restricts commercial shipping by regulating transit through the area.

In other regions, fishing may be restricted in marine protected areas (MPAs). Such areas have been proposed under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), a regional marine protection agreement which has been signed and ratified by a number of Western and Northern European countries. The fisheries management organization responsible for the Northeast Atlantic has taken account of the OSPAR Convention and has closed most areas of the Northeast Atlantic to bottom trawling.

These examples show just how complex a task it is to designate protected areas, which, in any case, only protect individual areas of the sea. Making matters worse, the regulations pertaining to protected areas are only binding on the few states which have signed up to the relevant agreement. Other states can simply ignore the regulations. What is needed, therefore, is a general obligation to protect habitats in their entirety from seabed to surface. In practice, however, no such arrangements exist.

In the areas covered by the OSPAR Convention in the Mid-Atlantic Ridge, only bottom trawling is currently prohibited. To establish a comprehensive protection regime, it would be helpful if the ISA were to recognise these MPAs and extend protected area status to the seabed in these regions. This would protect seamounts and banks not only from bottom trawling but also from mining interests in future. At present, however, the ISA cannot recognise these areas because its jurisdiction extends solely to seabed mining. In order to protect valuable marine areas in international waters, an implementing agreement to UNCLOS for the conservation of marine biodiversity would have to be adopted first of all. A United Nations working group has been preparing such an agreement for some years, but it is proving to be a slow process.

This is almost inexcusable, for a comprehensive protection regime for valuable marine areas has been demanded at the highest level for many years. Back in 1992, for example, the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro adopted the Convention on Biological Diversity (CBD), whose objective is the conservation of biological diversity in both terrestrial and marine ecosystems throughout the world. Recent decisions adopted by the Conference of the Parties to the Convention on Biological Diversity (CBD) call for the establishment of marine protected areas in marine areas beyond the limits of national jurisdiction, and for ecologically or biologically significant marine areas (EBSAs) in need of protection to be identified.

The **United Nations Conference on Sustainable Development (Rio+20)** in 2012 therefore urged the international community to bring the ongoing process to develop an implementing agreement to UNCLOS on the conservation of marine biodiversity to a swift conclusion. At present, however, the instruments available under UNCLOS and, indeed, to the ISA for the designation of marine protected areas are very limited. The ISA cannot designate any marine protected areas outside marine mining areas, nor can it recognize such areas. In view of the great pressure on seabed habitats, it is unacceptable that the preparation of the implementing agreement is taking so long.

The OSPAR Commission has observer status in the Assembly of the International Seabed Authority and is negotiating with this and other maritime organizations, such as the International Maritime Organization (IMO) and the International Commission for the Conservation of Atlantic Tunas (ICCAT), on the establishment of comprehensive marine protection regimes in the near future. A key prerequisite, however, is the adoption of an implementing agreement to UNCLOS on the conservation of marine biodiversity, in order to provide general protection for biological diversity in fragile habitats.

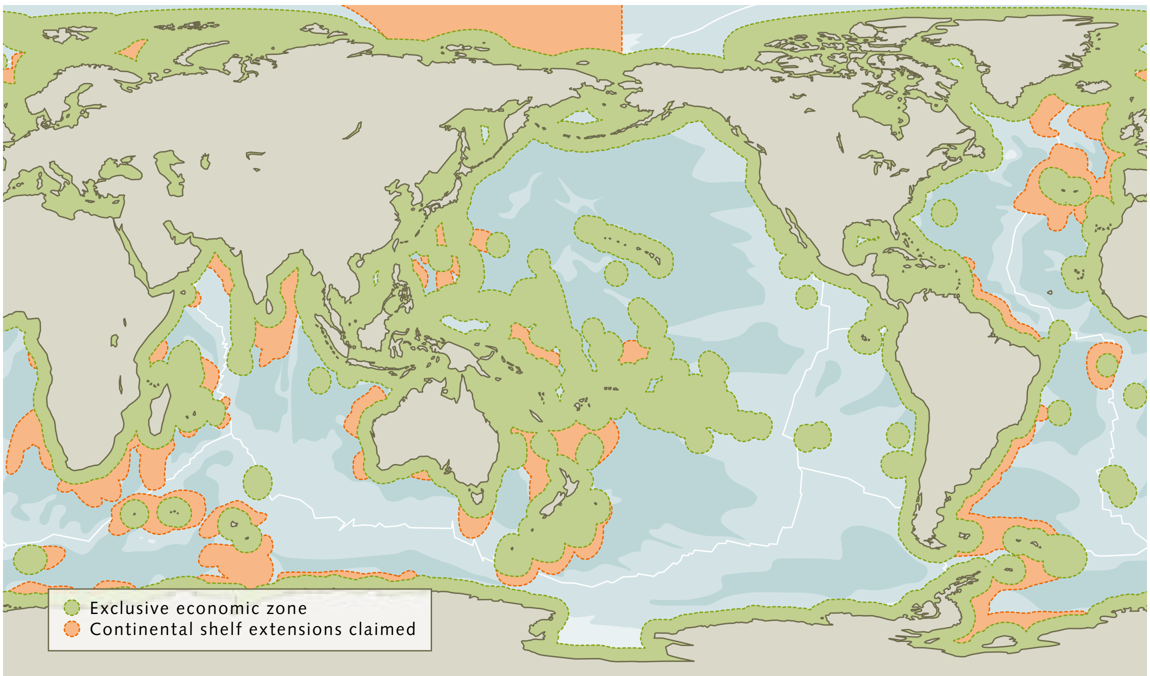
Go-it-alone approaches instead of concerted international action

The United Nations Convention on the Law of the Sea (UNCLOS) regulates the use of the seas, which cover 71 per cent of the Earth's surface. UNCLOS has been signed and **ratified** by 165 states and the European Union, making it a powerful instrument of international law. However, around 40 countries – for many different reasons – have not acceded to the Convention. Nonetheless, these states are bound by many of its provisions which – as the codification of **customary international law** – are universally applicable, such as those pertaining to the protection of the marine environment. In addition, a further norm applicable under customary international law entitles states to claim an EEZ even if they have not ratified UNCLOS. The most notable example of a state that has signed but not ratified the Convention is the United States. Although the US President and Administration have long supported ratification, the US Senate has yet to give its consent. As matters stand, however, the Senate is finding it impossible to achieve a majority position in favour of ratification.

In the US, UNCLOS has long been the subject of public debate. Recently, a number of senior officials in the US Navy and Coast Guard called publicly for the US to accede to the Convention. They point out that without accession to the Convention, the US's only option, in order to assert its rights, is to maintain a military presence on the high seas, but in view of the increasing claims from many other nations to the outer continental shelf, this is certainly not enough. There is a fear that key marine areas with large resource deposits, especially in the Pacific region, will be claimed by other countries and lost to the US. Furthermore, the officials and, indeed, numerous politicians regard ratification as essential in order to maintain the US's credibility in other maritime disputes and to ensure that the US can negotiate on equal terms. As the US can only enforce claims to continental shelf expansion via UNCLOS and the Commission on the Limits of the Continental Shelf (CLCS), the US has no prospect of long-term legal certainty in maritime matters unless it ratifies the Convention. Above all, if other countries submit overambitious claims to extend their jurisdiction beyond the EEZs – for example, in the Arctic – the US lacks the legal instruments that it needs to take effective counteraction.

The reaction from opponents of accession to UNCLOS came swiftly and was predictably fierce. Numerous Republican politicians, for example, argued that a situation in which licence fees have to be paid to developing countries would be unacceptable. In their view, this newfangled principle of benefit sharing is a bottomless pit that poses a major threat to US companies. So when will the US ratify the Convention? Only time will tell. Other countries have not acceded to the Convention because they are involved in disputes over their maritime boundaries. Iran, for example, is withholding ratification because of disputes over the delimitation of the EEZs in the Caspian Sea, where major oil fields are located. Peru, too, is unwilling to accede to the Convention due to simmering conflicts with neighbouring Chile over the delimitation of the EEZs. What's more, around 50 years ago – long before the creation of EEZs – Peru laid claim to a maritime domain, extending for 200 nautical miles, as its territorial sea and sovereign territory, and enshrined this in its constitution. If Peru were to accede to the Convention, it would be forced to downgrade this maritime area to the status of an EEZ and would merely enjoy usage rights there in future. This would also require a constitutional amendment, which is politically unattainable in Peru at present.

For many countries, national interests far outweigh common interests. That also explains why the Arctic littoral states frequently resort to symbolic gestures to defend their claims to the resources that lie beneath the ice. Russia courted media attention very effectively when on 1 August 2007, Russian researchers planted the national flag on the Arctic seabed at a depth of more than 4000 metres, underlining Russia's claim to the territory beyond its EEZ. Shortly before Christmas in 2010, Canadian Immigration Minister Jason Kenney symbolically issued Santa Claus with a Canadian passport, on the grounds that the North Pole is part of Canadian territory, and reaffirmed that "Mr Claus" was now entitled to enter and exit Canada at will. This gesture, although tongue-in-cheek, was intended to underline Canada's claims to the Arctic and was reported by the media all over the world. Although the competing claims to the Arctic seabed can hardly be described as a bitter dispute, some countries are flexing their muscles, for there is much at stake: new seaways, as well as access to oil and gas fields. Researchers have also found small deposits of manganese nodules in the Arctic, although these are not thought to be economically significant. Ultimately, it is the Commission on the Limits of the Continental Shelf (CLCS) which must decide, based on geological data, whether the national territorial claims are justified or not. It is uncertain, at present, which nations will be permitted to extend their jurisdiction. However, both Canada and Russia recently commissioned new ice-capable naval vessels and awarded contracts for the construction of new Arctic naval bases, not only as a means of safeguarding their coastal security but also as a demonstration of power.



4.6 > With the expansion of the coastal states' exclusive economic zones (green) into the outer continental shelf (orange), the international waters and seabed area are reduced, representing a loss to the international community. Antarctica, however, has special status. Some states are claiming an EEZ here, as shown on the diagram, but these territorial claims are not recognised under international law.

and the marine mineral deposits located there. However, the Commission on the Limits of the Continental Shelf dismissed Russia's application in 2009 and called for more detailed geological surveys. Since then, Russia has launched several expeditions to collect geological data as evidence that the undersea ridges in international Arctic waters are submerged extensions of the geological formations found in its EEZ. In late 2013, Canada also announced that it was claiming an extension of its Arctic continental shelf as far as the North Pole. In 2014, Russia plans to resubmit its application with new data – coinciding, incidentally, with Denmark's expected application to extend its continental shelf north of Greenland. Denmark, Canada and Russia are not isolated cases. Currently, 78 countries are claiming a continental shelf expansion beyond their existing EEZs. The ISA has received seven applications backed up by information to justify expansion, and a further 46 provisional submissions for which scientific information may be submitted at a later date. The Commission has not yet dealt with these latter submissions because – as in the case of Russia – there is still a lack of detailed scientific data proving that the geological formations in and outside the EEZ are connected. According to experts in the Law of the Sea, this trend towards continental shelf expansion profoundly undermines the original concept of "the Area" as a form of commons, based on the principle that the seabed and its resources should be used for the benefit of all nations equally. What's more, in some regions, the 200 nm EEZs already occupy most of the sea area. In the Pacific, for example, the individual island states lie so far apart in some cases that despite their small land area, they can claim vast areas of the sea as their exclusive economic zones, which means that the international community has no claim to many of the resources found there. The EEZs already occupy around one third of the total area of the sea, and the claims for continental shelf expansion submitted to the Commission would increase this by a further 8 per cent.

An end to this trend is not yet in sight. Some submissions have already been approved by the Commission, such as those lodged by the United Kingdom and Ireland to extend their continental shelves farther out into the Atlantic. The United Kingdom has a particular interest in producing oil here and is seeking partners to engage in oil production in this new territory.

Commons

The term „commons" is used to denote land that is used collectively by members of a community; examples are fields, grazing areas and woodland pastures. Economists and social scientists also use the term in non-agricultural contexts, applying it, for example, to fisheries in international waters. The "tragedy of the commons" is a phrase that is frequently heard, the tragedy being that these shared resources, being available to everyone, are quickly depleted and destroyed by individuals acting according to their self-interest.

The coastal states' responsibility

> Large oil and gas fields and extensive deposits of massive sulphides are found in various countries' coastal waters. If a state wishes to extract the marine resources located in the area under its jurisdiction, it must do so within the legal limits established by the United Nations Convention on the Law of the Sea (UNCLOS), but its own mining and environmental legislation also have a crucial role to play. However, these laws do not always provide an adequate level of protection, as the impacts of the DeepwaterHorizon**oil rig explosion have shown.**

Each country must play its part

The exploration and exploitation of certain marine minerals on the deep ocean floor are governed by detailed regulations adopted by the International Seabed Authority (ISA). They also cover aspects of environmental protection. The exploitation of marine minerals in the international seabed area in future will thus be regulated by a uniform set of rules that are applicable worldwide. However, no such regime exists for the coastal states' exclusive economic zones (EEZs) and continental shelves. Although the United Nations Convention on the Law of the Sea (UNCLOS) obliges every state party to protect and preserve the marine environment, it is a matter for each individual state to adopt its own detailed legislation on the use of its exclusive economic zone (EEZ), on marine mining on the continental shelf, and on the protection of the marine environment. However, as the ongoing pollution of coastal waters and disasters such as the *Deepwater Horizon* oil rig explosion show, this does not guarantee that the marine environment will indeed be protected. And yet states have a particular responsibility, because the coastal waters within the EEZs are the world's most intensively utilized marine areas, providing food and income for very large numbers of people. Over time, the pressure on the EEZs has increased. At one time, the coastal waters mainly supplied fish. During the last century, the tourism industry expanded and later, industrial sites were established along the coasts and oil and gas drilling rigs were installed on the continental shelf. Effluents from factories and intensive farming are still polluting coastal areas, and over the next five years, marine mining is likely to have a considerable impact as well, particularly the extraction of massive sulphides, which are mainly found on the continental shelf.

4.7 > A boy plays in a carpet of algae at the seaside in Qingdao in China. Excessive use of fertilizers is one of the causes of algal blooms. Coastal waters are being polluted elsewhere as well, despite international marine protection agreements.

Marine mining – controlled by governments

Given the very important role played by the marine environment and the range of pollutants to which it is exposed, states should be treating the marine areas under their jurisdiction with particular care. Indeed, UNCLOS contains comprehensive provisions to that effect. However, they are framed in very general terms, and countries have considerable leeway to decide how to transpose these provisions into national law. In some cases, national legislation does not adequately protect the sea from overexploitation and pollution. What's more, not every country safeguards compliance with environmental legislation or regularly monitors its industrial enterprises. Although relevant legislation is in place, environmental pollution and degradation still routinely occur in many countries. For experts, therefore, the worry is that some countries could well adopt a similarly lax approach to marine mining on their continental shelves. They could even attract potential

4.8 > In July 2010, a waste tank at a copper mine in the coastal province of Fujian in China burst open, spilling toxic slurry into a river and killing 1900 tonnes of fish.

investors by offering them the chance to carry out mining operations with no obligation to achieve stringent and costly compliance with environmental regulations, and without having to worry about checks or inspections.

Toothless legislation

A recent comparative analysis of the mining industry in the G20 states reveals the difficulties arising in the implementation of existing environmental legislation in some countries. The findings for the Latin American G20 countries Argentina, Brazil and Mexico are particularly interesting. Although the study relates to onshore mining, it identifies specific problems which are likely to affect marine mining in future as well. In all 3 countries, detailed regulations and standards for environmental protection are in place, but a number of central challenges stand in the way of robust compliance:

- Government agencies tasked with overseeing the mining industry are poorly equipped with personnel, and there is also a shortage of skilled labour in some cases, as well as problems accessing funding. As a result, very few site visits or inspections of mines take place. Instead, assessments are generally confined to desk reviews of applications and documentation.
- Government agencies tasked with overseeing the mining industry are too close, either spatially or administratively, to political decision-makers. In some cases, assessors' offices are located in regional government buildings, enabling politicians to exert influence over their activities.
- Even if the regulatory agencies are able to work independently, concerns are often ignored. Critical findings are not taken seriously or are disregarded by decision-making bodies, such as mining authorities.
- There are very few quality standards or certification schemes for consultancies that prepare environmental impact assessments, making it very easy for industrial enterprises to commission biased reports that gloss over the negative impacts of mining.

Critics point out that the environmental degradation that could potentially occur in marine mining could well go undetected or be covered up. In onshore mining, open conflicts have often occurred in the past between local communities and industrial enterprises or government agencies, turning the spotlight on environmental degradation. Marine mining, on the other hand, takes place at great depth and is hidden from sight.

Following a good example?

Not everyone shares these concerns. In the view of some experts who specialize in the Law of the Sea, the ISA Regulations have established universally applicable standards of best practice for marine mining. Although these do not constitute binding regulations that must be incorporated into national legislation on deep-sea mining on the continental shelf, the ISA instruments serve, nonetheless, as a model to which coastal states must, at the very least, aspire. What's more, if it transpires that a state is causing massive environmental damage on its continental shelf, it may face prosecution in an international court such as the International Tribunal for the Law of the Sea (ITLOS); for example, legal proceedings may be initiated by neighbouring countries whose waters have been polluted.

Both cobalt-rich crusts and massive sulphides are mainly found on the continental shelves of island states that have no mining industry of their own. It is very likely that future mining operations here will be undertaken by international extraction industry companies on a contractual basis. It is not in these companies' interests to destroy the marine environment on the state's continental shelf, for if a company that causes such degradation were to apply for a licence to extract resources in the international seabed area in future, the ISA would be justified in refusing the application due to a lack of confidence in the company concerned – resulting in its loss of access to profitable seabed areas.

A further relevant factor, in the view of some experts in the Law of the Sea, is that when selecting mining areas, mining multinationals will not necessarily give preference to unreliable states with lax legislation, for experience has shown that cooperation with these countries can be extremely problematical for the companies concerned. Negotiated contracts are not always complied with, and in politically unstable regions, there is also a risk of political upheavals, possibly resulting in the cancellation of the contracts by the new governments and leaders and hence the loss of

4.9 > A tanker's useful life ends – and an oil disaster begins. In November 2002, the *Prestige* **sank off the northwest coast of Spain, spilling around 60,000 tonnes of oil into the sea and polluting almost 3000 kilometres of French and Spanish coastline.**

the company's investment. A very much higher level of legal stability is afforded by marine mining in international waters ("the Area"), which is properly regulated under ISA licences, with reliable contract periods and firm agreements.

Can oil disasters be prevented in future?

Marine mining is still a vision for the future. Offshore oil production, on the other hand, is a long-established industry which generates billions in profits every year. Unlike marine mining, however, the oil industry's environmental and safety standards were not established before extraction commenced, but have been developed over time – generally in response to accidents or larger oil pollution incidents. In compliance with UNCLOS, most countries now have environmental legislation and regulations for offshore oil production, but accidents and spills still occur. There is a concern that the number of major oil spills will increase in future as a result of the trend towards drilling at ever greater depths, and that these incidents will be almost impossible to control, as was the case with *Deepwater Horizon,* for example.

Much thought has therefore been given to ways of improving the situation. Two key issues arise here: firstly, how incidents can be avoided and the environment can be protected, and secondly, who is liable in the event of a disaster. Experts propose the following solutions:

- better safety standards and more stringent controls for the operation of drilling and production rigs;
- clearly defined liability in the event of an incident occurring;
- creation of funds to pay for clean-up operations after major spills and to provide compensation swiftly and with minimal red tape to injured parties.

The issue of liability, in particular, is currently the subject of intense debate. When an incident occurs, public attention generally focuses on the facility operators, on the grounds that they have failed to comply with national safety and environmental standards. The ensuing legal disputes often drag on for years, greatly delaying the payment of compensation to injured parties. However, the states with jurisdiction over the area in which the installations are located also bear responsibility.

The situation becomes more complicated if neighbouring countries' waters are polluted as well. One example is the fire at the *Montara* wellhead platform in the Timor Sea, off the northern coast of Western Australia, in 2009. This incident was very similar to the *Deepwater Horizon* disaster. The blowout released between 5000 and 10,000 tonnes of oil, contaminating Indonesian fishing grounds. The *Montara* platform was located in the Australian EEZ, but Australia refused to pay compensation. The question, then, is how state liability and payment of compensation can be regulated more effectively in future.

4.10 > The operation of nuclear power plants, such as the one seen here at Onagawa, 80 kilometres north of Fukushima on the east coast of Japan, is classed by jurists as an "ultrahazardous activity" because accidents at industrial plants of this type can have extremely serious and far-reaching consequences.

Guaranteed compensation after tanker incidents

The situation would be much simpler if a uniform set of rules on liability were adopted and recognised at international level, also governing the payment of compensation to injured parties. This type of international liability regime, which would be binding on all states, makes sense not only for the oil industry but for all other ultrahazardous activities in the EEZs or on the continental

Oil – a dirty business in West Africa

The very poor regulation and control of the oil industry in some countries nowadays are exemplified by the situation on the Atlantic coast between Angola and Côte d'Ivoire in Africa. There are major oil fields here, mainly in Angola and Nigeria. However, both these countries have failed to utilize the oil revenue in a manner which creates prosperity for all.

The situation in Nigeria is catastrophic: here, oil production in the Niger Delta has fuelled ongoing armed conflicts and has polluted wetlands, mangrove forests and the habitats on which thousands of people depend. One reason for this disastrous situation is that the Nigerian government does not share the benefits accruing from the oil industry equitably. It negotiates cooperation agreements with oil multinationals and issues production licences, receiving many billions of dollars in revenue from these arrangements every year. But although a formula for the distribution of revenues between the federal budget, the governments of the individual states and the local authorities exists, very little money flows back to the oil-producing regions. According to experts, this is due to a high level of corruption in the upper echelons of government. What's more, under the 1978 Land Use Act, land where oil is found falls under the direct control of the state, and in most cases, no compensation is paid to communities or private owners. Among other things, this injustice results in pipelines being illegally tapped and large quantities of oil being bunkered and sold abroad, especially in neighbouring Benin, Côte d'Ivoire and Senegal. The tapping of pipelines is also polluting large areas of the Niger Delta. According to experts, the annual revenue from this illegal oil industry is an estimated one billion US dollars a year.

At present, various rebel groups are fighting for control of the illegal oil industry. The situation is also difficult because even before the oil boom began in Nigeria in the 1970s, conflicts had erupted between various ethnic groups, even escalating into civil war. These conflicts were fuelled by politicians who channelled the profits from oil to those groups which served their particular political interests. In some cases, politicians supplied the rebel groups with arms, worsening the conflicts.

Nigeria's oil wealth has led to an oil war. Although the multinationals are not directly involved in the hostilities, oil production in such politically unstable regions raises all manner of questions. Even the multinationals' social engagement has often led to new conflicts in Nigeria. To the multinationals' credit, they have attempted, of their own volition, to improve living conditions for local communities in the oil-producing regions through financial support and social engagement. But even here, conflicts have frequently arisen between communities receiving support and their neighbours who went away empty-handed. The oil companies bear a share of the responsibility for what is happening in the oil-producing countries, as became apparent in 2013, when the Anglo-Dutch company Shell faced legal action in a court in The Hague for the environmental damage caused in the Niger Delta. Between 2004 and 2007, there had been several attacks on pipelines in the Niger Delta, spilling large quantities of oil and polluting villages, farmland and fish ponds. Farmers, fisherfolk and a Dutch environmental organization therefore took Shell to court. The court dealt with a total of five charges, with Shell being accused of having failed to provide adequate security for its pipelines. The court found Shell's Nigerian subsidiary to be liable on one count: Shell had neglected its duty of care and had shown particular negligence. In 2006 and 2007, this has enabled sabotage to be committed in a very simple way by opening the valves on an oil well with an adjustable spanner. On the four other counts, however, the court ruled that because the pipelines were laid underground and were adequately secured, Shell was not liable.

There have been many other incidents similar to those dealt with in these legal proceedings. According to an independent assessment of the environmental impacts of oil contamination in the Niger Delta, commissioned by the United Nations Environment Programme (UNEP), there is massive environmental damage in the Niger Delta. The project team surveyed pipelines, oil wells and oil spill sites, and their report concludes that pollution is extensive. There is a particularly serious problem with toxic hydrocarbon pollution of soil and water. In 49 cases, hydrocarbons were found in soil down to depths of 5 metres, and in 41 cases, the hydrocarbon pollution had reached the groundwater. Furthermore, fishing has declined sharply in the region as fish stocks have decreased, presumably because of the pollution.

In Nigeria, around 15 per cent of oil is produced offshore in coastal waters, rather than onshore, and this is increasing. Although offshore oil production is more expensive, it is considered to be more secure, as the drilling rigs are less accessible to rebels and are therefore relatively well protected against attack. But even here, attacks have occurred. In 2008, rebels from one of Nigeria's largest militant groups, the Movement for the Emancipation of the Niger Delta (MEND), attacked an offshore oil rig 120 km off the coast in a demonstration of seaborne power. Nonetheless, the expansion of the offshore oil industry, according to social scientists in Nigeria, could help to mitigate the problems facing the region and reduce the potential for conflict, for unlike onshore oil production, communities are not directly impacted by the offshore industry, and pollution of soils and drinking water is avoided.

Unlike the situation in Nigeria, all Angola's oil production takes place offshore, and the set of problems affecting the sector is different. But in Angola too, very few people share in the benefits of the country's oil wealth, and the gap between rich and poor is very wide.

4.11 > In the Niger Delta, oil stolen from pipelines is processed in illegal refineries such as this one by the Imo River, causing additional water pollution.

The main oil-producing region is found in the coastal waters off the Angolan province of Cabinda, an exclave of Angola located in neighbouring Congo. And yet Cabinda is one of the country's poorest regions, and apart from a few coastal roads, it has very little infrastructure. The Angolan capital Luanda, on the other hand, is the most expensive city in the world. In no other city are rents and living costs as high as they are here. Angola is now the largest oil-producing country in sub-Saharan Africa. Contracts are negotiated between the state-owned oil company Sonangol and multinationals. These production agreements contain formulae for the sharing of profits from oil production between the host country and the multinationals. However, the actual amount of profits is generally unclear, as the data published are invariably incomplete, incomprehensible or inconsistent. As is evident from the extreme contrast between rich and poor, the profits from Angola's oil industry benefit only the elite.

Although experts applaud Angola for introducing stringent anti-corruption legislation and for taking action publicly to combat corruption, it is safe to assume that some of the oil revenue is being misappropriated at the top echelons of government. This is partly because Sonangol is not controlled or regulated by independent authorities. Angolan and international non-governmental organizations are therefore calling for more transparency and public debate in order to achieve more equitable distribution of profits and sharing of benefits.

Environmental pollution on a scale comparable with Nigeria has not occurred in Angola. However, in 1991, an explosion occurred on board the oil tanker *ABT Summer* off the Angolan coast, spilling its cargo of around 250,000 tonnes of oil and polluting the coastline. Fortunately, no major oil spills have occurred since then. Nonetheless, Angolan non-governmental organizations are critical of the ongoing pollution of coastal waters by oil discharged in effluent from the rigs, and estimate that more than 10 smaller oil spills occur every year.

A contentious issue is whether the decline of fish stocks off the coast is due to these oil spills, or whether overfishing has played a greater role.

shelves as well. The term “ultrahazardous activity” is used by jurists to denote activities which, although not prohibited, can cause accidents that involve a substantial risk of harm, particularly transboundary pollution. Examples are the operation of nuclear power plants, chemical works and, in this case, oil drilling rigs. It is uncertain whether states will agree to adopt common rules.

Such an approach is entirely feasible, however. The International Convention on Civil Liability for Oil Pollution Damage was adopted for tanker operations back in 1969 and was updated in 1992. With this Convention, there is now a binding legal regime at international level for dealing with civil claims for compensation for oil pollution damage involving oil-carrying ships. Its main purpose is to ensure that compensation is paid swiftly and without excessive red tape to injured parties following tanker incidents. Legal proceedings are instituted before the courts of the state where the incident took place. The Convention, which has been ratified by 109 countries, establishes a robust international liability regime based on the application of uniform rules. Often, international civil law proceedings become very protracted because there are major differences between countries’ legal systems. For example, there may be different legal language, procedures and time limits, such as periods of limitation. What’s more, a legal dispute may drag on because conflicting evidence is submitted in expert opinions and second opinions, with the result that injured parties receive no compensation at all.

Often, legal disputes centre on the question of fault: in other words, who is responsible for the damage. Another contentious issue, very often, is whether an incident could have been averted had parties acted differently. Thanks to the Convention, this is no longer relevant in relation to tanker incidents, for the Convention places liability for such damage on the owner of the ship from which the polluting oil escaped or was discharged. This liability, in general, is strict: in other words, it applies whether or not the owner is at fault or could have averted the damage. There are only a few specific exceptions, such as civil war or a natural disaster of an exceptional character, in which no liability for pollution damage attaches to the owner.

Compensation payments from one large fund

Because the owner of the ship from which polluting oil escaped or was discharged bears strict liability, the Convention establishes a system of compulsory liability insurance for owners. Under the Convention, the costs of damage are initially met by the shipowner’s insurer. If the costs of damage exceed the amount provided under this insurance, a compensation fund comes into operation and, in a multi-stage process, meets further costs up to an amount of approximately 1 billion US dollars. This International Oil Pollution Compensation Fund (IOPC) was established under the International Convention on Civil Liability for Oil Pollution Damage. The Fund guarantees that injured parties actually receive compensation. It covers the costs of clean-up operations after tanker incidents and makes compensation payments to injured parties such as fishermen and the tourism industry. The oil-importing nations pay contributions into the Fund, which they then claim back from their national oil-processing industry. The rate of the contributions to be paid is based on the volume of oil imported.

The appealing aspect of the Fund is that payments are made immediately after an incident, irrespective of the question of fault – in other words, regardless of whether the incident was caused by human error on the part of the tanker captain or by the shipowner’s failure to properly maintain the vessel. This is critical, especially in situations when insurance payments are delayed as a result of legal disputes. The injured parties receive compensation from the Fund swiftly and without excessive red tape.

In some cases in the past, the Fund has negotiated directly with injured parties, thus avoiding lengthy delays in payment of compensation and removing the need for the parties concerned to pursue the matter through the courts. Once the Fund has compensated the victims, it can reclaim the money from the shipowner or his insurer. The Convention and the Fund form a two-pronged instrument that is both unique and unbeatable: the Convention creates legal certainty, and the Fund ensures that compensation is disbursed after every single incident in which damage occurs.

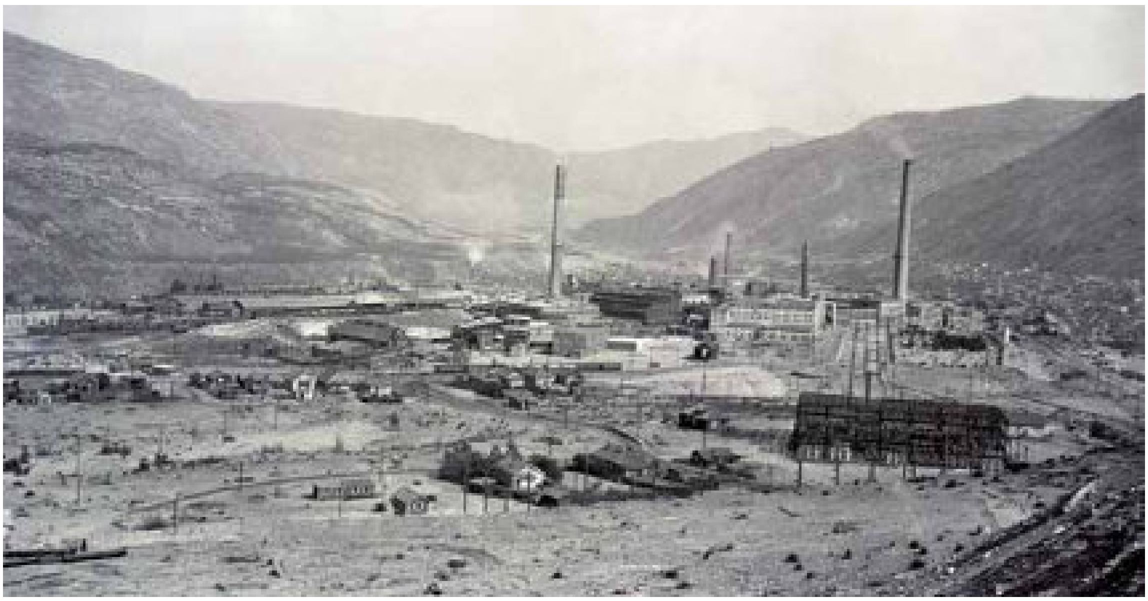
4.12 > The oil slick from the *Hebei Spirit* tanker, which was holed off South Korea in December 2007, polluted many kilometres of coastline. The authorities mobilized 12,000 clean-up workers, who attempted to remove the oil, sometimes using very basic equipment such as buckets and shovels. The costs of this type of clean-up operation are immense.

No fund for drilling rigs

The Convention and the IOPC Fund were developed in conjunction with the International Maritime Organization (IMO) and apply solely to vessels, not to fixed installations such as drilling rigs or anchored semi-submersible platforms. Although a similar model is conceivable in principle for these installations as well, there appears to be little interest on the part of the oil industry. At present, oil companies are covered by insurance, but this is merely general liability insurance up to an amount of 1.5 billion US dollars. Some drilling projects are uninsurable. But as the explosion at the *Deepwater Horizon* rig showed, this kind of general liability insurance does not come close to covering the costs of damage caused by a major oil spill. Nonetheless, the oil companies rejected an insurance scheme developed by reinsurers over a period of several years, which would have covered individual drilling projects and provided a 10 to 20 billion US dollar payout for environmental damage and follow-up costs. Experts believe that there is a very simple reason why the oil companies rejected the scheme: the oil companies are so wealthy that they regard this level of insurance cover as irrelevant. The interest in a liability convention and fund modelled on those in place for tanker incidents is correspondingly low. This is regrettable, for such a scheme would make legal disputes or proceedings after oil rig disasters a much less common occurrence in future.

Strict liability

Experts in the Law of the Sea regard a strict form of civil liability, such as that which now applies to tanker operations, as ideal. However, the adoption of conventions governing liability for other types of ultrahazardous activity, thereby establishing a uniform civil liability regime at the international level, is likely to be some years away. A transitional solution could be to introduce new regulations on state liability, meaning that it is the state, in every case, which covers damage caused by ultrahazardous activities, rather than a private company. At present, a state is only liable if it breaks the rules – for example, because its legislation or regulations are inadequate or because it has failed to fulfil its supervisory obligations in respect of chemical plants or drilling rigs. In order to avoid protracted legal disputes over issues of liability, a system that jurists term “strict state liability regardless of fault” may be a viable solution for ultrahazardous activities. This means that the state is always liable, regardless of whether or not the operator of the installation is at fault. Similar situations are familiar in every-day life. If a dog bites a child, the dog owner is liable in every case, whether or not he has trained his dog properly and sent it to dog training classes – in other words, whether or not he is at fault. He is “liable regardless of fault”. There are good arguments for introducing this form of liability for the operation of drilling rigs as well, for it is, after all, the state which authorizes the performance of this “ultrahazardous activity”. Furthermore, in many cases, states issue licences to companies, often charging very substantial licence fees, and thus have a stake in the company’s profits. If this form of state liability were introduced, protracted lawsuits and disputes, such as those which arose between Australia and Indonesia in the case of the *Montara* platform, could be avoided. At present, the concept of state liability is *only* enshrined in international law for large-scale transboundary pollution: here, international law establishes liability for *culpable* behaviour that violates the rules. The principle is enshrined at the highest level of international law and **customary international law**. It was first recognised in international jurisprudence more than 70 years ago as a result of the Trail Smelter case – the first major transboundary pollution incident – in the 1920s. Smoke from the Trail Smelter in Canada, which processed lead and zinc, had contaminated Canadian farmers’ fields in the surrounding area and caused damage to crops. The Canadian operator responded by building tall chimneys, so that the toxic smoke would be transported away from the fields. As a consequence, the pollution reached Canada’s neighbour, the USA, and destroyed US farmers’ crops. Compensation was paid out to the Canadian farmers very quickly, but lawyers acting for the US farmers and the Canadian company failed to reach an agreement on compensation. The case was therefore referred to the International Joint Commission (IJC), an independent



4.13 > The Trail Smelter in the Canadian province of British Columbia became famous for a legal dispute between Canada and the USA. It took years for US farmers to receive compensation for damage to crops and soil contamination.

binational organization established in 1909 to negotiate agreements on boundary waters between the USA and Canada. The arbitration process became extremely protracted because the parties disputed to what extent the damage to crops was in fact caused by smoke. A final decision was not reached until 1941. The company made a relatively small payout to the US farmers.

Space law for earthly problems?

"Strict state liability regardless of fault" is not yet a reality. What's more, because states enjoy immunity, a citizen or affected country cannot pursue, let alone enforce, legitimate claims through courts. In fact, international law and international customary law leave unanswered the question of how justice is to be done when damage occurs, and it is unclear which institution should dispense justice or fix penalties in such cases. The question, then, is whether, and how, a state can bring legal action against another state or force it to pay compensation. Due to the lack of clear rules, states generally reach agreement via diplomatic channels, often behind closed doors, which means that the injured parties cannot influence the process. After the *Deepwater Horizon* disaster, Mexico received compensation for the financial losses caused by the oil pollution, but this was achieved as a result of diplomatic negotiations with US authorities. There is still only one instance of "strict state liability regardless of fault" being enforceable at the international level, namely in space law. Under the Convention on International Liability for Damage Caused by Space Objects, adopted in 1972, another state may, in respect of damage sustained in its territory due to the crashdown of a space object, present a claim to the launching state. As a general principle, the state from whose territory a space object is launched is liable.

For all other cases of transboundary pollution or damage, the situation continues to be problematical. Without a uniform international regime on civil liability for particularly high-risk activities in deep-sea mining or offshore oil production, there are currently only two options for obtaining justice or compensation: either to bring an action before the courts of a foreign state, or to reach an amicable agreement on compensation between the home state and the polluting state. In the majority of cases, however, both options are likely to involve a tough battle for justice.

Prevention – the best strategy

A clear liability regime and rules on compensation are important in order to make good any damage that occurs. Far more important, however, is to prevent environmental pollution in the first place. To that end, stringent technical safety standards occurs. Far more important, however, is to prevent environmental pollution in the first place. To that end, stringent technical safety standards are required. Here, the regulations applicable to oil-carrying ships serve as a good example. The requirement for tankers to be fitted with a double hull ensures that unlike the situation in the 1960s and 1970s, damaged tankers do not immediately start to spill oil. This has done much to avoid major incidents and pollution. Political benchmarks have also been set, with the adoption of agreements that declare certain areas of the sea completely off-limits to tanker traffic. There are several reasons why such high standards have been set in this particular industry. Firstly, tanker incidents have a significant media impact. The public pressure on policy-makers increased considerably from one oil disaster to the next. Furthermore, the principle of cause and effect is very straightforward in the case of an oil spill. If a captain runs his vessel aground, the circumstances which led to the grounding can generally be determined very quickly. On an oil rig, on the other hand, there are many people working simultaneously all over the installation, which means that clarifying the causes of an explosion is more difficult. There are many activities that are critical to security in the operation of a rig, and these can be analysed and improved.

This in turn is an argument in favour of a liability regime similar to that which exists for tanker incidents. A liability convention would create an obligation for rig operators and oil producers to contribute to a fund. As with the IOPC Fund, injured parties would then receive compensation swiftly, before the complex question of fault and the cause of the incident have been clarified. The adoption of a relevant convention and creation of a fund would also be a major step towards a new culture of safety in offshore operations, which is now well-established in the tanker industry.

Reducing consumption

Unfortunately, some environmental damage from industrial operations will always occur. The key task, therefore, is to reduce this damage to an absolute minimum. As long as people need resources, the extractive industries will have an adverse effect on habitats. The most important question, then, is how consumption of these resources can be reduced. One way forward is to develop recycling technologies and set up supply chains for reusable materials. Even in the established recycling industries, there is still room for improvement: one example is aluminium, with only around one third currently being recovered. All over the world, companies are working intensively to develop new processes for the recovery of special metals, such as rare earth elements, from computers and smartphones. These devices offer great potential for recycling as they are available in very large quantities, contain large amounts of special metals, and have short lifecycles. This means that the metals can be recovered and made available to the primary industry very quickly.

Furthermore, many environmentally sound and energy-efficient technologies now exist. Solar and wind energy plants and energy-efficient vehicle drive systems have reached a sophisticated stage of development. Dispensing with consumption is also helpful, for resources that are not consumed do not need to be extracted in the first place. The Western industrial nations in particular have maintained a very high level of consumption for some time. The transformation of the industrial nations into consumer societies began after the Second World War. Philosophers and social scientists refer to "1950s syndrome" – the period of rapidly rising living standards from 1949 to 1966, when energy consumption increased dramatically. At that time, supplies of energy and raw materials appeared to be inexhaustible and were correspondingly cheap.

This was reinforced by the discovery of major oil fields in the Middle East and the development of nuclear energy. There was enough oil, it seemed, to last for centuries. Food also became more affordable as a result of intensive farming and animal husbandry, which in turn were made possible by intensive use of machinery and energy. This era, researchers claim, was a historical anomaly and far from being the norm. We recognise this today, for we are now faced with increasing resource scarcity and a rapidly growing world population.

Conclusion

Can commercial exploitation of marine minerals be safe and equitable?

There are many signs that 2016 will mark the start of marine mining in the international seabed area, with the commencement of manganese nodule harvesting. This will open a new chapter in the commercial exploitation of marine resources, for the minerals in the international seabed area do not belong to individual states but are defined as the common heritage of mankind, and, according to the United Nations Convention on the Law of the Sea (UNCLOS), their benefits are to be shared equitably. UNCLOS is the most comprehensive international treaty ever concluded. It has been ratified by 165 states and the European Union and came into force in 1994. The International Seabed Authority (ISA) was established in Jamaica at the same time. This UN organization ensures that the marine minerals found in the international seabed area are equitably distributed and that developing countries can also share in the benefits. States wishing to extract marine minerals from the international seabed area must apply to the ISA for an exploration licence. To date, the ISA has issued 25 countries with exploration licences, which contain clear rules and environmental standards. Once exploration has finished, parts of the explored area must be relinquished to the ISA and are reserved for developing countries. ISA regulations governing the commercial exploitation of marine minerals are expected by 2016, initially for manganese nodules, and then for massive sulphides and cobalt-rich crusts. Only then can exploitation begin. The ISA's work is regarded as exemplary, for it is the first time in history that rules, regulations and procedures have been adopted before exploitation begins. It is also notable that within the future mining areas, the ISA has defined zones for the protection of deep-sea fauna, where extraction of marine minerals is prohibited. Environmentalists criticize the fact that at present, pursuant to UNCLOS, the ISA cannot extend protected status to any zones outside the mining areas; they argue that the ISA is ideally placed to do so. The critics are therefore calling for UNCLOS to be amended.

In the waters under the jurisdiction of coastal states, there are no uniform rules applicable to marine mining. Under UNCLOS, every state is obliged to protect and preserve the marine environment, but in many places, the oil industry or effluent from land installations is causing severe pollution of the marine environment, partly because the authorities are too lax in their controls. Environmentalists view marine mining as a further source of disruption. A lack of controls is particularly worrying if a state allows "ultrahazardous activities", such as the operation of nuclear power plants or offshore drilling rigs, to take place in the area under its jurisdiction. Often, incidents at installations of this kind affect neighbouring countries as well, resulting in legal disputes between countries over compensation claims. Jurists are calling for "strict state liability regardless of fault" for states engaged in any kind of ultrahazardous activity, in order to facilitate international justice. At present, injured parties often obtain little or no compensation. Currently, an effective liability regime exists only for tanker incidents; this was established many years ago under the International Convention on Civil Liability for Oil Pollution Damage. The Convention also introduced a liability fund to which oil-importing countries contribute. Under the Convention, the shipowner is liable if an incident occurs, whether or not he is at fault. If the claims exceed the sum insured, the fund comes into operation and provides compensation. This liability regime could serve as a model for other industries, such as offshore oil production.

Overall conclusion

3

Humankind's hunger for resources is insatiable. We need oil to power the world's one billion motor vehicles. We use around 20 million tonnes of refined copper annually to produce items such as electric cables and electric drives, and we utilize exotic metals such as neodymium in a wide range of industrial applications. Global consumption of energy has doubled since the early 1970s and, according to the International Energy Agency (IEA) in Paris, is likely to increase by more than one-third by 2035 due to world population growth and development in the major emerging economies of China and India. In consequence, the seas are attracting growing interest as a resource reservoir. The deep oceans host large oil and gas fields and ore deposits. Extracting this mineral wealth is a very appealing prospect.

Although gas and coal will be available in sufficient quantities well beyond the end of this century, oil is likely to be the first fossil resource to become scarce. Oil is currently the world's most important fossil fuel, with a good one-third of production now taking place offshore. The offshore oil industry is well-established.

In the early days, drilling took place solely in shallow coastal waters, but today, the oil industry has conquered the deep. With new geophysical methods of exploration, scientists can now search for oil and gas fields in the seabed and underlying geological strata up to a depth of 12 kilometres below the ocean floor. With these sophisticated methods, many large new deposits have been discovered in recent years, and known deposits have been resurveyed. During the period from 2007 to 2012, 481 major discoveries were made at water depths greater than 1500 metres, accounting for more than 50 per cent of all major offshore oil discoveries. Deepwater production is therefore likely to become increasingly significant. It is interesting that the offshore discoveries are, as a rule, 10 times larger than those discovered onshore.

As the explosion at the *Deepwater Horizon* oil rig shows, ultra-deepwater oil production is an ultrahazardous activity. Wells can only be accessed using special submersible vehicles, so incidents are almost impossible to control. Many causal factors led to the disaster: engineers on board misinterpreted readings from the well, and safety valves which should have closed off the well failed to activate. On the rig itself, the division of responsibilities was unclear. This was doubly problematical because operatives from several different subcontractors were working on board at the same time. Human errors thus went undetected.

In response to the disaster in the Gulf of Mexico, the offshore oil industry has developed special technology, known as capping stacks, for subsea incident response. Capping stacks can be deployed to stop the flow of oil from a gushing deep-water well. They are now on emergency standby at bases in the major oil-producing regions, including the Gulf of Mexico and the coast of Brazil. New regulations have also been introduced for onboard management of oil rigs in the Gulf of Mexico. One person with ultimate work authority on a rig must now be informed about every single step taken by subcontractors.

But these measures are unlikely to go far enough to avoid incidents and damage running into many billions of Euros in future. The tragedy is that the injured parties – such as fishermen and tourism businesses – often face lengthy delays in obtaining compensation because the oil companies and government become locked in legal disputes over the issue of liability. If an oil spill affects neighbouring countries as well, the lawsuits become even more complicated. This situation could be avoided if a straightforward liability regime were established, similar to that which exists for tanker operations. Here, an international convention has been adopted, which places strict liability for damage on the owner of a ship. The owner must therefore cover the costs of the damage. If these costs exceed the amount provided under the owner's insurance, an international fund comes into operation and disburses compensation swiftly without excessive red tape. A similar scheme would make sense for the offshore oil industry as well, but has been rejected by the oil multinationals. In the case of tanker operations, the oil-importing nations pay into the fund and then claim their contributions back from their national oil-processing industry.

Oil production in politically unstable regions, such as some West African countries, raises all manner of questions. Problems arise because profits from the oil industry are distributed inequitably, and due to corrup-

Overall conclusion

tion, there is little sharing of benefits. Very often, it is the local communities in the oil-producing regions that go away empty-handed. In Nigeria, for example, conflicts frequently occur, with various rebel groups fighting for control of the oil industry. Oil spilled from sabotaged pipelines and illegal micro-refineries has polluted large areas of the Niger Delta. In Angola – now the largest oil-producing country in sub-Saharan Africa – there is, fortunately, no open conflict, but here too, the sharing of benefits from oil production is extremely inequitable. There is a very high level of poverty throughout the country, and yet the capital Luanda is one of the most expensive cities in the world.

Methane hydrates – an alternative fossil energy source – are the subject of much discussion at present. Methane hydrates are solid ice-like compounds made up of methane, a component of natural gas, and water. The methane gas that forms hydrates rises from depth to the ocean floor. Most of the methane is produced biogenically by bacterial decomposition in deep layers of sediment, but a smaller proportion originates at even greater depth and is produced thermogenically deep underground by chemical conversion of biomass at high pressure and high temperatures. Methane hydrates form at water depths of around 500 to 3000 metres. Here, the water pressure is high enough, and the seawater temperature cold enough, for methane and the water in the sediment to solidify to form hydrates. The methane becomes so densely compacted that one cubic metre of solid methane hydrate can contain around 160 cubic metres of methane gas. Experts believe that the world's methane hydrates contain 10 times more gas than is available in all the conventional deposits. Methane hydrates are mainly of interest to countries which currently import most of their energy resources. Fossil fuels are particularly expensive in South Korea and Japan, as they have to be brought in by ship. Both these countries have extensive methane hydrate deposits in their coastal waters and are keen to make greater use of them in future. As yet, however, they lack the technology required for large-scale production of methane gas from hydrates.

As methane hydrates act as a kind of cement that binds soft sediment, critics fear that the extraction of methane hydrates will destabilize the continental shelf, potentially triggering tsunamis. According to scientists, however, extraction will be confined to small-scale drilling in shallow areas, thus avoiding major slumps. There is also a fear that ocean warming will release large quantities of methane, a potent greenhouse gas, from the deep seas into the atmosphere. Here too, researchers voice reassurance: according to their data, 95 per cent of all global deposits are found at depths greater than 500 metres and are therefore likely to remain protected against warming for a very long time.

For high-tech applications and modern mass-produced electronic devices such as photovoltaic systems, engines for hybrid cars and smartphones, many different resources are now required, such as metals extracted from ore. These too are present in large quantities in and on the seabed. Metals are found mainly in three types of mineral deposits: manganese nodules, cobalt crusts, and massive sulphides. Large numbers of manganese nodules, about the size of a potato or a head of lettuce, are found on the sediments in some areas of the seabed. They form extremely slowly, over the course of millions of years, around tiny cores – such as fragments of shell – on the seabed. Various processes are involved in their formation, including the precipitation of metals from seawater. There are four major areas of manganese nodules worldwide, the largest being the Clarion-Clipperton Zone (CCZ) in the Pacific, which extends across an area the size of Europe. The nodules contain manganese, iron, and many other metals that are important for industry. Cobalt crusts, on the other hand, are rock-hard deposits that have formed on seamounts. Seamounts are found in marine areas all over the world. Particularly crust-rich seamounts have been discovered in the Prime Crust Zone (PCZ) 3000 kilometres southwest of Japan, with an estimated 7.5 billion tonnes of crusts.

Like manganese nodules, cobalt crusts are formed by the precipitation of chemical compounds containing metals from seawater. Cobalt crusts, which form on the flanks of seamounts, also contain manganese and iron beside cobalt and other metals. Massive sulphides, on the other hand, form around undersea hot springs through the precipitation of sulphide minerals from fluids below the sea floor. Massive sulphides are of interest because they contain high levels of gold and silver. The deposits in the Bismarck Sea near Papua New Guinea appear to offer great potential.

Manganese nodules, cobalt crusts and massive sulphides are important for industry, for various reasons. Many metals are now extracted by what are, in effect, monopolies in a small number of countries, especially China, so resource-poor industrial countries such as Germany and France are keen to become more independent by staking claims to areas of the seabed.

To ensure that marine mining in the international seabed area does not result in countries squabbling over the best claims, it is regulated by the International Seabed Authority (ISA). This UN organization issues exploration licences and also ensures that valuable mineral deposits are reserved for developing countries. ISA regulations governing the future exploitation of marine minerals are currently being developed and are expected by 2016, initially for manganese nodules. Only then can exploitation in the international seabed area begin. It is notable that the protection of the marine environment features prominently in the ISA regulations. Within the future mining areas, the ISA requires zones to be designated for the protection of the seabed environment, with extraction of marine minerals prohibited here. It is the first time in history that rules for the allocation of a resource and for environmental protection have been adopted before exploitation begins. To date, the ISA has issued 12 licences for manganese nodule exploration in the Clarion-Clipperton Zone and one licence for the Indian Ocean.

Whereas the future exploitation of marine minerals in the international seabed area will thus be regulated by a uniform set of stringent rules, no such regime exists for the marine areas under the coastal states' jurisdiction. Although the United Nations Convention on the Law of the Sea (UNCLOS) obliges every state party to protect and preserve the marine environment, pollution is still a routine occurrence in many coastal waters. There is a fear that marine mining will create a new set of environmental problems here. Environmentalists are concerned that large-scale extraction will pose a particular threat to endemic seabed species. Marine biologists are therefore calling for further detailed environmental studies, before exploitation commences, to better assess the risks posed. However, there is a real fear that in some areas, mining operations will commence before these assessments have been completed.

Although chemical analyses show that very few cobalt crusts and massive sulphide deposits are sufficiently rich in metals to make exploitation worthwhile at present, many critics oppose the mining of these resources on principle. Both types of deposit form permanent structures on the seabed, and over time, these have developed into habitats for species-rich biotic communities based on sessile organisms such as sponges and corals. Large-scale extraction, in the biologists' view, can only be justified if mining companies leave some zones untouched as a starting point for the recolonization of harvested areas.

Will large-scale marine mining ever become reality? That remains to be seen. It is likely to be more expensive than onshore mining, but has the potential to avoid land-use conflicts. Over the next two years, the island state of Papua New Guinea plans to work with a mining multinational to extract massive sulphides containing gold and silver in its 200-mile zone, and it is likely that after 2016, manganese nodule extraction will begin in the Clarion-Clipperton Zone. But according to geoscientists, there are still many undiscovered deposits onshore, and theoretically, these could well be sufficient to meet the growing future demand for mineral resources. The most likely scenario, then, seems to be moderate exploitation of offshore marine minerals as a supplement to onshore extraction as required.

Global demand for fossil energy carriers and mineral resources will not decrease in future unless humankind takes action. This not only means developing new sources of supply; it also means devising new technological processes for resource recycling, including the establishment of collection systems and international transport chains. What is needed is a long-term strategy for clean energy and resource extraction for the benefit of future generations. We hope that the *World Ocean Review 3* can make a small contribution to the formulation of such a strategy.

Glossary

Acidification (ocean acidification): a large proportion of the carbon dioxide that enters the atmosphere through combustion processes is taken up by the ocean, causing the seawater to acidify. Strictly speaking the seawater remains basic. But when the acidity, or pH value, of the water decreases in the direction of less basic, it is referred to as acidification of the water.

Antarctic Bottom Water: oxygen-rich, highly saline ocean water that sinks to the bottom in the Antarctic and flows northward along the bottom around the globe, all the way to the North Atlantic.

Chemoautotrophic: microorganisms that produce energy for their metabolism from chemical compounds are called chemoautotrophic. Chemoautotrophic organisms are distinguished from photoautotrophic organisms such as plants, which produce their energy from sunlight.

Condensate (gas condensate): a mixture of relatively heavy hydrocarbons that can accumulate during natural gas production. The components of this natural-gas by-product include pentane as well as larger molecules, sometimes ring-shaped (aromatics and cycloalkanes). As a rule, because of its composition, gas condensate is a liquid at room temperature and mean sea level pressure. Because its makeup is similar to that of the light constituents of oil, it can be separated from the natural gas and processed in refineries to petrol, among other products.

Continental slope: the area of the sea floor where the flat, near-coastal continental shelf falls more steeply into the deep sea.

Customary international law: a form of unwritten international law, which consists of rules that come from general practice accepted as international law. A further element of customary international law is opinio juris – a belief on behalf of a state that it is bound by the law in question. Examples are the prohibition of torture, recognition of air space, and recognition of the 12-mile zone as the sovereign territory of the coastal state. These rules are binding on all states under international law, whether or not they are the subject of a treaty. A key prerequisite is that the relevant opinio juris is accepted as law by the overwhelming majority of countries. Customary international law applies even if it is only relevant to certain countries. For example, customary international law holds that the 12-mile zone is sovereign territory, although some countries do not have a coastline.

East Pacific Rise: a mid-ocean ridge located in the southeast Pacific.

Endemic: Plant and animal species that only occur in a particular and limited area of the world are called endemic. Endemic species are very susceptible to extinction due to degradation of their habitat.

G20: group of 20 major economies, comprising 19 industrial and emerging countries plus the European Union. Germany, France, the United Kingdom and Italy are members in their own right. Countries are ranked in descending order by gross domestic product.

Mid-ocean ridge: ridges or mountain ranges on the sea floor similar to the seams of a baseball, extending around the entire globe. They originate in areas where continental plates drift apart beneath the ocean. Hot magma rises at these fracture zones in the central ocean regions, is cooled in the water, and piles up through time to form enormous mountains.

Phytoplankton: planktonic plants that are mostly microscopic in size. They include microalgae. Planktonic organisms typically have little or no power of self-locomotion, and thus drift with the water currents.

Primary production: the production of biomass by plants or bacteria. The primary producers obtain their energy from sunlight or from certain chemical compounds, and through their metabolism synthesize energy-rich substances such as carbohydrates. These substances, in turn, represent a subsistence basis for animals and humans.

Ratified, ratification: formal and binding validation of an international convention or treaty. Various countries may conclude a treaty but this does not automatically make it valid or legally operative under international law. Nor is it enough simply to sign the treaty document. Each state must, in addition, make a formal declaration expressing its intent to be bound by the relevant treaty. This is known as ratification. As a rule, the head of state or a high-ranking politician signs an instrument of ratification. The prerequisite for ratification is generally a legal act adopted under national law, such as an act of Parliament, in which Parliament assents to the provisions of the treaty. In Germany, for example, treaties concluded by the Federal Republic must be approved by the Bundestag. Only then can the instrument of ratification be deposited.

Residual soil: degradation of rock resulting in accumulation of low-solubility material, in part due to biological processes.

Rio+20: United Nations Conference on Sustainable Development, which took place in 2012, exactly 20 years after the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro.

Symbiotic: individuals of different animal species that coexist in such a way that one organism profits from the other are called symbiotic.

The Glossary explains the meaning of specialist terms which are particularly important for an understanding of the text but which cannot be defined in the individual chapters due to space constraints. Glossary terms are printed in bold in the body of the review, making them easy to identify.

Abbreviations

APEI Area of particular environmental interest

AUV Autonomous underwater vehicle

BALEX Baltic Exercise (international oil-spill response exercise in the Baltic Sea)

BGR Bundesanstalt für Geowissenschaften und Rohstoffe; German Federal Institute for Geosciences and Natural Resources

BONNEX Bonn Convention Exercise (international oil-spill response exercise in the North Sea)

BOP Blowout preventer (for gas and oil from a well)

BRIC Brazil, Russia, India and China (BRIC States)

BSEE US Bureau of Safety and Environmental Enforcement

BSR Bottom simulating reflector

CBD Convention on Biological Diversity

CCZ Clarion-Clipperton Zone

DISCOL Disturbance and Recolonization (research project)

DOE US Department of Energy

EBSA Ecologically or biologically significant marine area

EEZ Exclusive economic zone

EOR Enhanced oil recovery

FPSO Floating production storage and offloading units

GHSZ Gas hydrate stability zone

GOODS Global Open Oceans and Deep-Sea habitats (research report)

GPS Global positioning system

HHI Herfindahl-Hirschman Index

ICCAT International Commission for the Conservation of Atlantic Tunas

ICES International Council for the Exploration of the Sea

IEA International Energy Agency

IJC International Joint Commission

IMO International Maritime Organization

IOPC International Oil Pollution Compensation Funds

ISA International Seabed Authority

ISM Code International Management Code for the Safe Operation of Ships and for Pollution Prevention

LCD Liquid crystal display

LED Light emitting diode

LNG Liquefied natural gas

MARPOL International Convention for the Prevention of Pollution from Ships

MPA Marine protected area

NOAA US National Oceanic and Atmospheric Administration

NOWPAP Northwest Pacific Action Plan

OBS Ocean-bottom seismometer

OPA US Oil Pollution Act

OPEC Organization of the Petroleum Exporting Countries

OSPAR Oslo-Paris Convention, Convention for the Protection of the Marine Environment of the North-East Atlantic

PCZ Prime crust zone

PETM Paleocene-Eocene thermal maximum

PSSA Particularly sensitive sea area

REMPEC Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea

RFMO Regional fisheries management organization

RPEN Regulations on Prospecting and Exploration of Polymetallic Nodules

SOPAC Secretariat of the Pacific Community Applied Geoscience and Technology Division

SOS Sea swell-independent oil skimmer

TLP Tension leg platform

UNCLOS United Nations Convention on the Law of the Sea

UNEP United Nations Environment Programme

VME Vulnerable marine ecosystem

Contributors

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Page numbers printed in **bold** draw attention to passages within the text which are especially important for an understanding of the concept in question.

Partners

The›Future›Ocean: The Kiel-based Cluster of Excellence brings together marine scientists, earth scientists, economists, medical scientists, mathematicians, lawyers and social scientists to share their knowledge and engage in joint interdisciplinary research on climate and ocean change. The research group comprises more than 200 scientists from 7 faculties of the Christian-Albrechts-University of Kiel (CAU), the GEOMAR Helmholtz Centre for Ocean Research in Kiel, the Institute for World Economy (IfW) and the Muthesius University of Fine Arts.

IOI: The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

mare: The bimonthly German-language magazine mare, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. mare's mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine, which has received numerous awards for its high-quality reporting and photographs, its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

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Nikolaus Gelpke
Managing Director of *maribus gGmbH*

World Ocean Review is a unique publication about the state of the world's oceans, drawing together various strands of current scientific knowledge. The following report, the third in the series, focuses on marine resources and the opportunities and risks associated with their potential exploitation. It is the result of collaboration between the following partners:

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