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

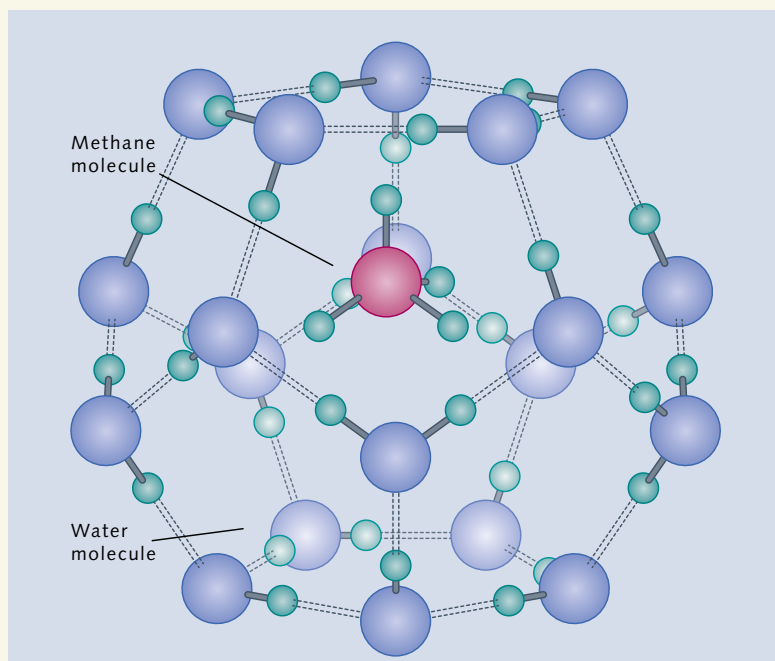
Methane hydrates develop naturally only in areas where sufficient methane is present. This gas can develop beneath the sea floor in two different ways:

- 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.

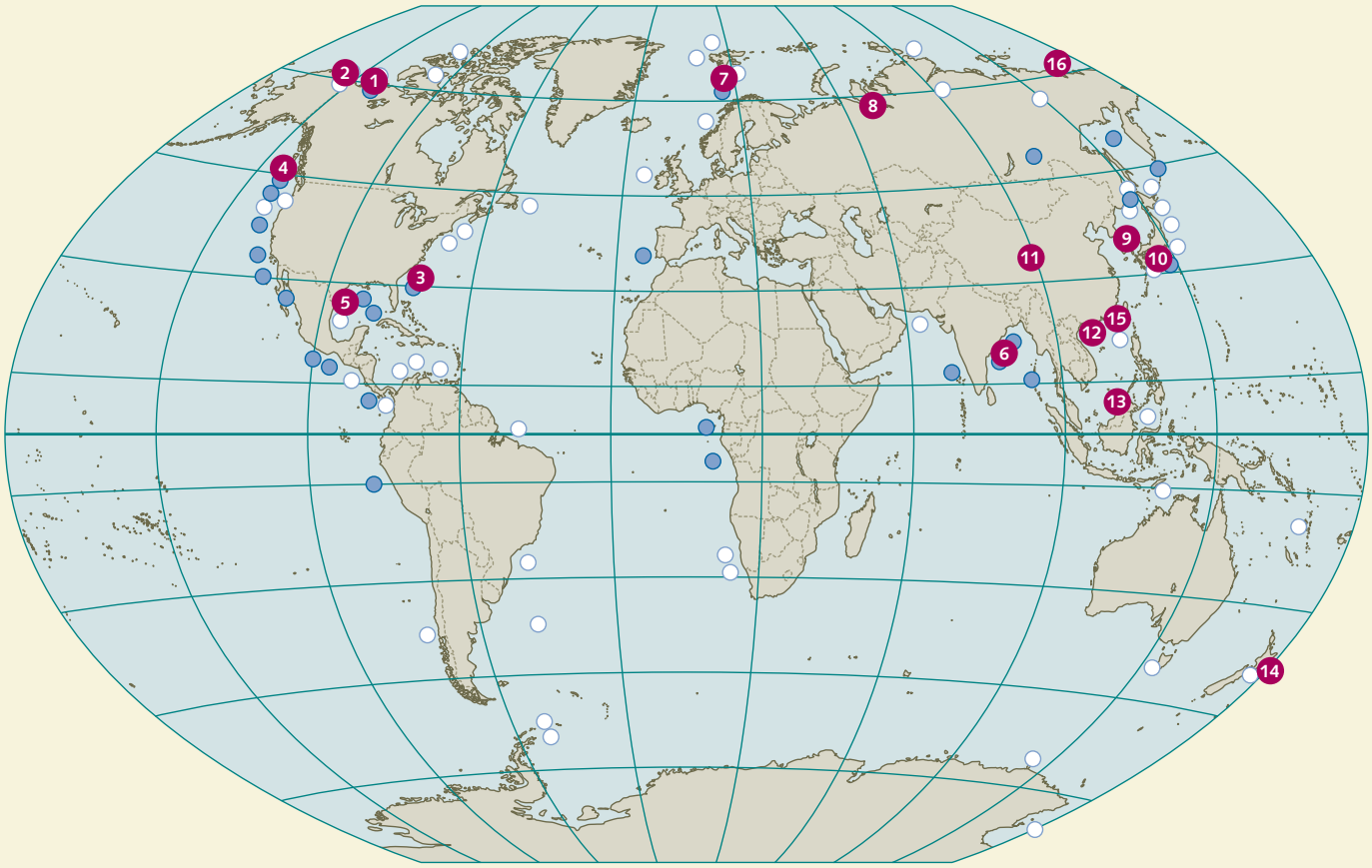
Flammable ice made of methane and water

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

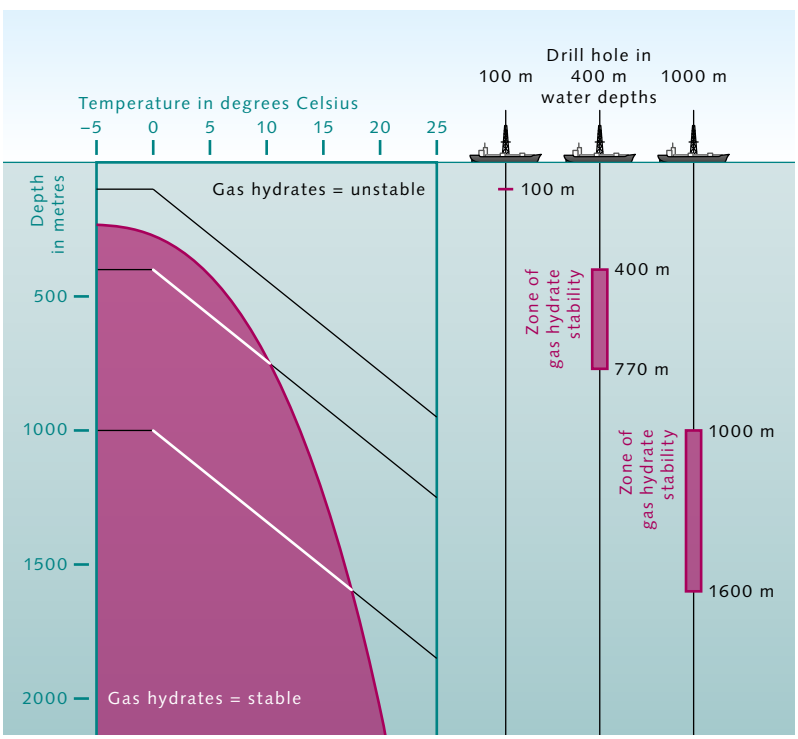
TAIWAN: Taiwan lies in a region where continental plates converge. In this area methane-bearing water is pressed out of the sediments so that methane is available for the formation of hydrates. The tectonic collision zone has been intensively studied by drilling since 2004. The drilling programme has 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.

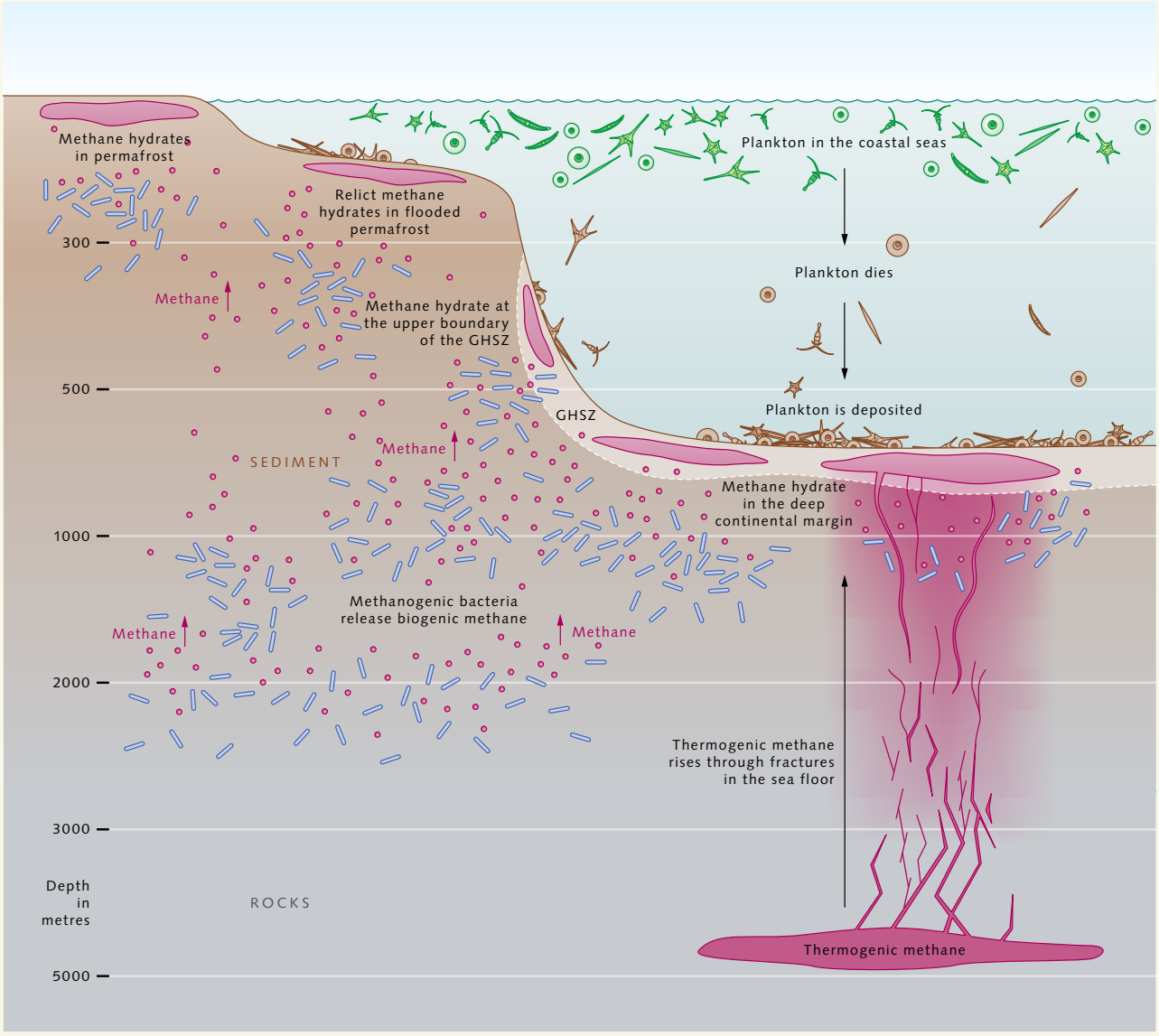
Marine regions farther from the coasts are, in contrast, relatively poor in nutrients. The production of biomass and amounts of plankton that sink to the bottom are thus low there. As a result, methane hydrates very rarely occur in the deep sea at large distances from the coasts.

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.

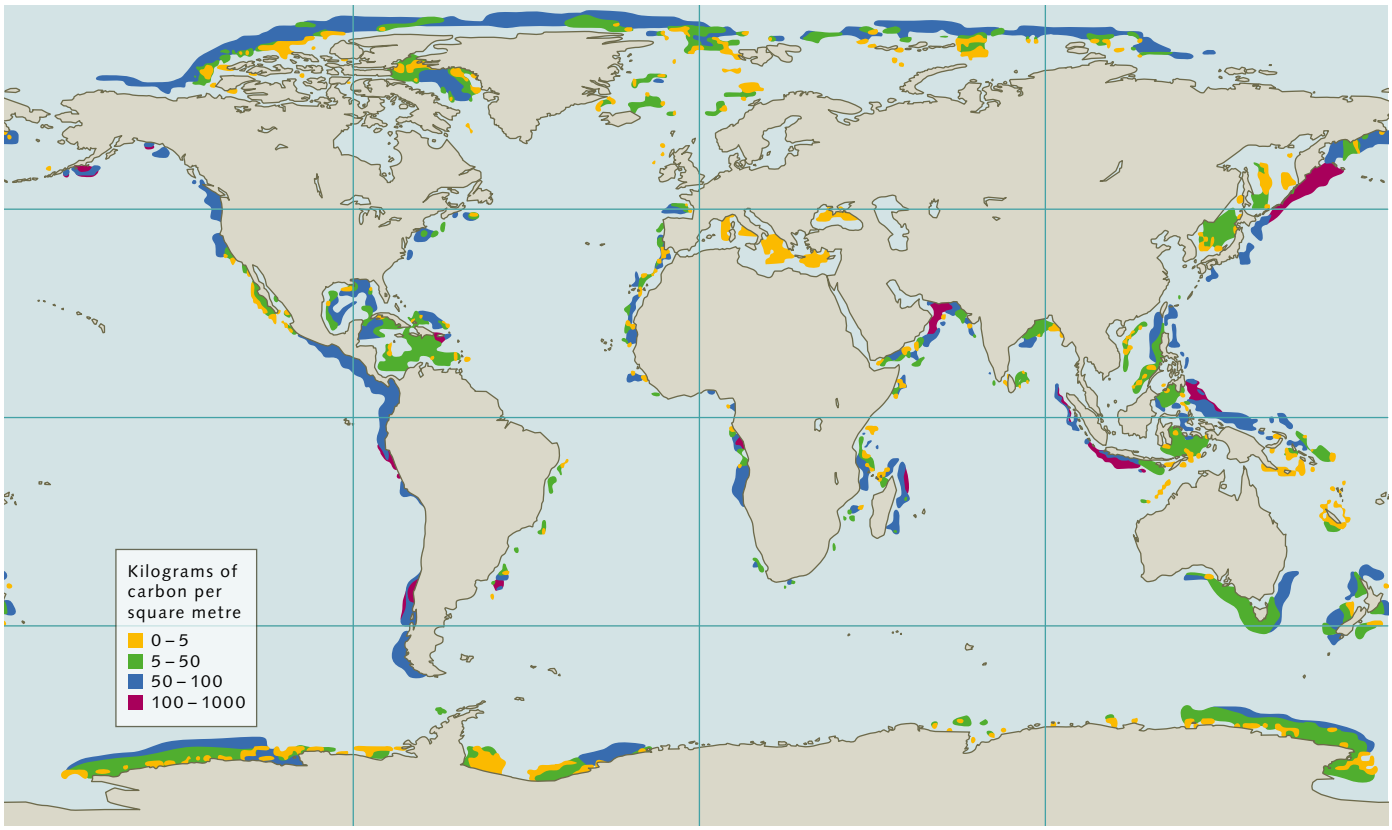
Carbon makes up 75 per cent of the mass of the methane molecule and can thus be used as a reference value. In this way the deposits can be compared with other fossil resource deposits.

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.



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.

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.

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.

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.

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.

The first steps to methane hydrate production

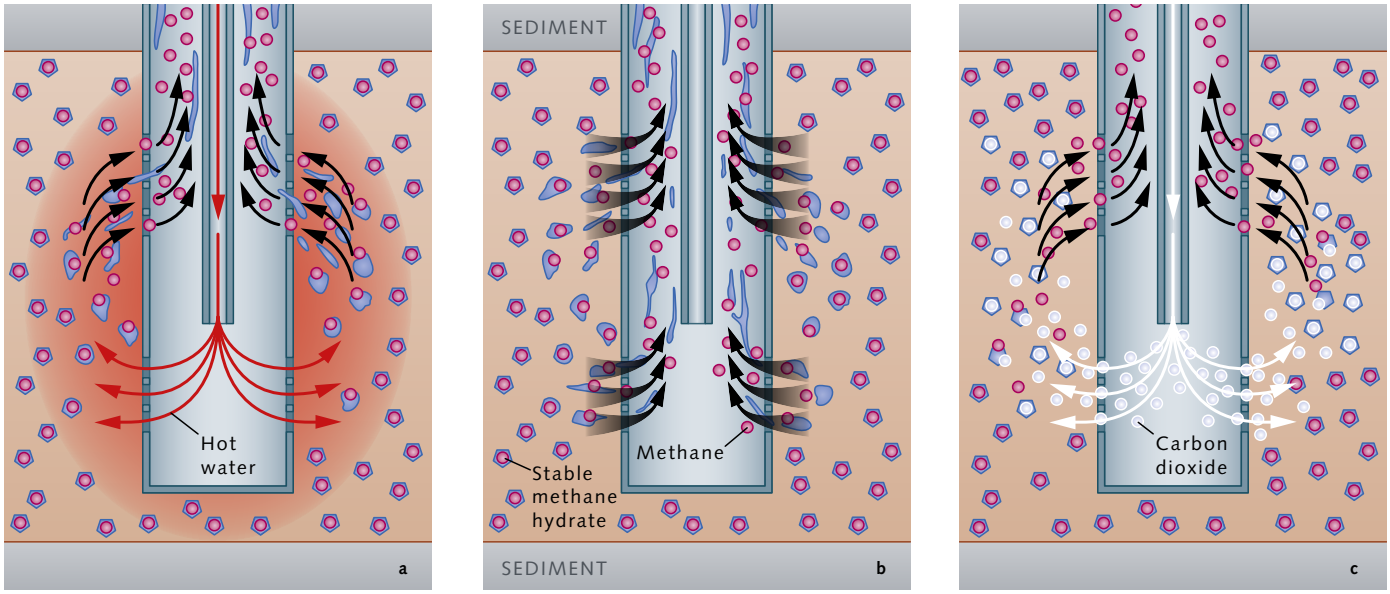
For more than 10 years international projects have been studying whether and how methane hydrate might be produced in the future. Scientists must first determine whether it is at all possible to release meth-ane from the hydrates in large amounts and, if so, which methods would be most practical. The 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.

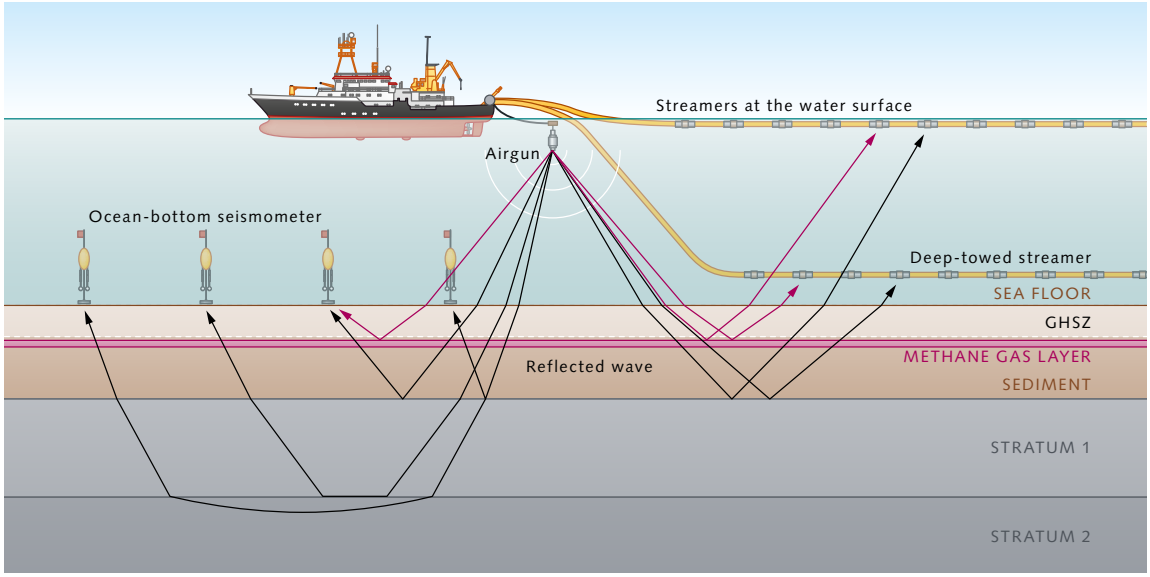
MULTIBEAM SWATH SOUNDER: This relatively new acoustic instrument can detect methane gas bubbles escaping from methane deposits through natural leaks. It is attached to the bottom of a ship and sends out fan-shaped ultrasound waves. It is thus able to scan a strip hundreds of metres wide on the sea floor. 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 pres-

sure 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.

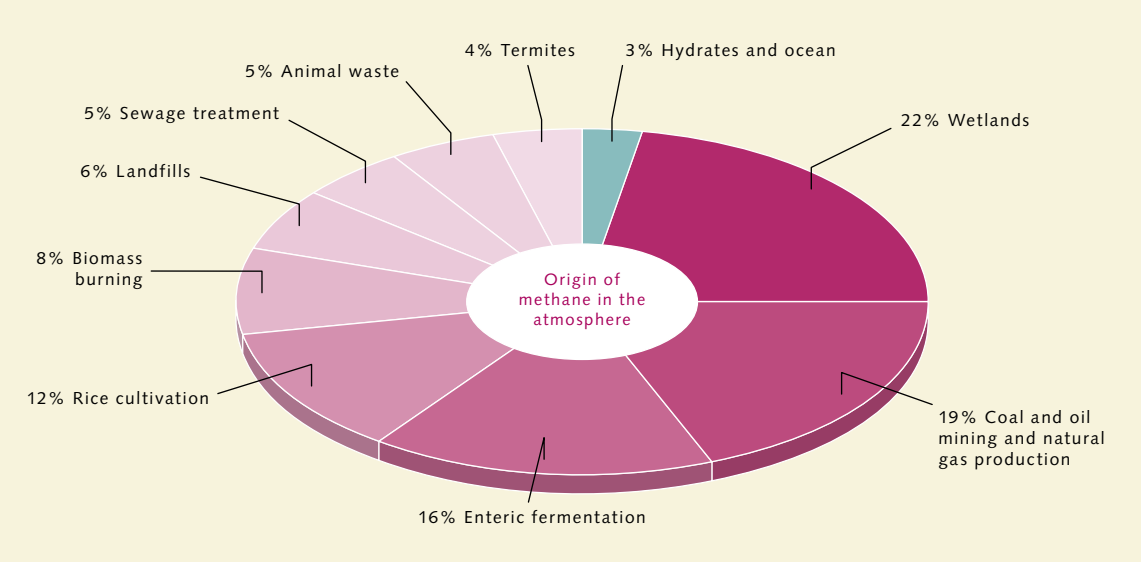
The possibility that hydrate mining could generate submarine landslides on steep continental slopes has also been discussed. Like avalanches in mountainous regions, submarine landslides are natural events. They occur on continental margins where thick layers of soft sediment have accumulated, such as 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 1per 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

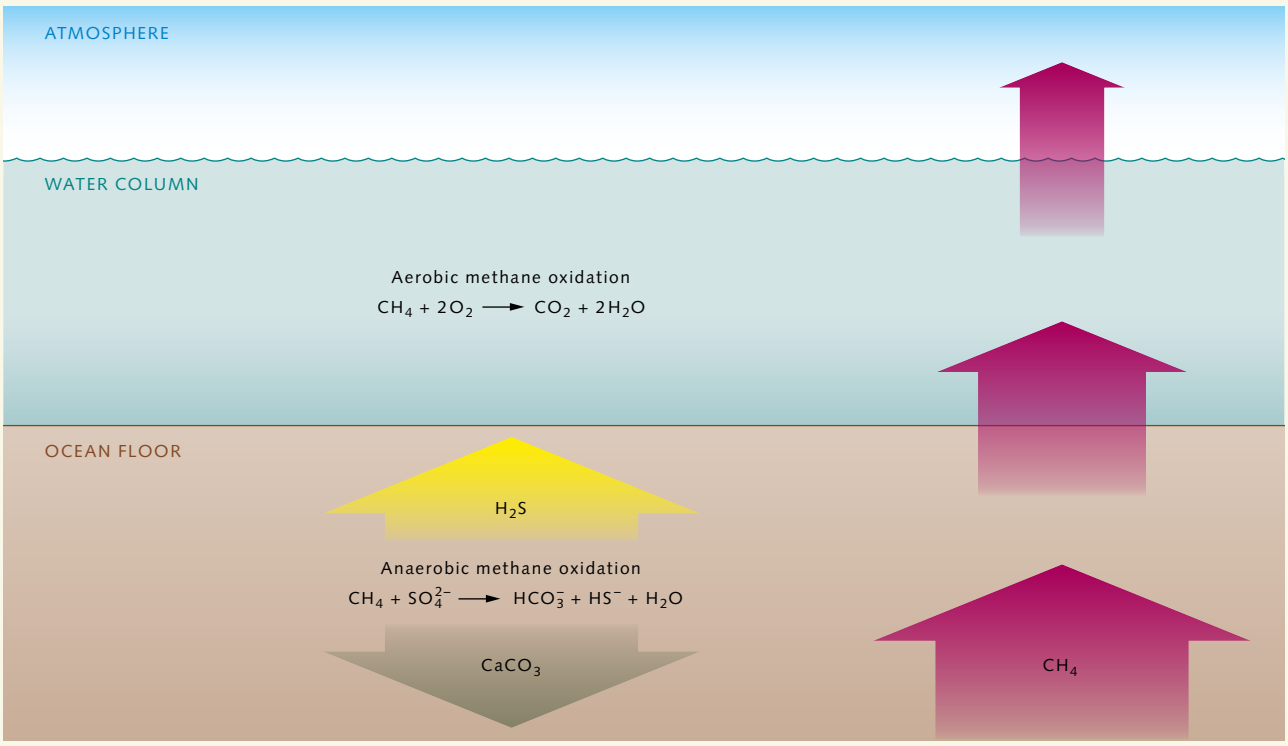
Methane rising up from the sediments is, to a large extent, consumed by microorganisms that live in the upper layers of the sea floor and in the water.

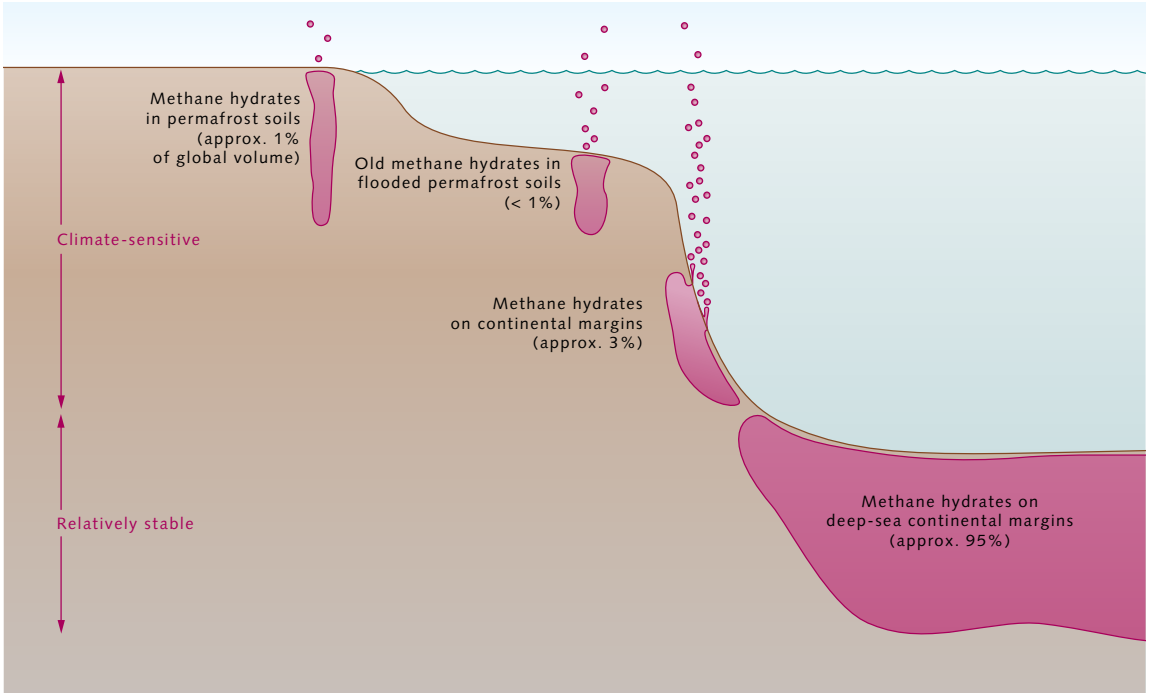
Anaerobic bacteria – bacteria that can survive without oxygen – are active in the ocean floor. They process the methane with the help of sulphate (SO_4^{2-}), thus producing hydrogen sulphide anions (HS^-), hydrogen sulphide (H_2S) and bicarbonate (HCO_3^-). The bicarbonate can react with calcium ions (Ca^{2+}) 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.

Table of figures

Cover: curraheeshutter/istockphoto.com; p. 2: Brian J. Skerry/National Geographic Creative; p. 7 from top: Ralph Hinterkeuser; Maurice Tivey, Woods Hole Oceanographic Institution/NSF/ROV Jason; NOAA Okeanos Explorer Program/ Wikimedia Commons; Claudius Diemer, albedo39 Satellitenbildwerkstatt, www.albedo39.de; Brian J. Skerry/ National Geographic Creativ; p. 8/9: Ralph Hinterkeuser; fig. 1.1: G. H. Eldridge/U.S. Geological Survey; fig. 1.2: BP; fig. 1.3: IEA; fig. 1.4: IEA; fig. 1.5: BGR (Bundesanstalt für Geowissenschaften und Rohstoffe); fig. 1.6: BGR; fig. 1.7: Jiri Rezac/Greenpeace; fig. 1.8: BGR; fig. 1.9: Alessandro Viganò/iStockphoto; fig. 1.10: after BGR; fig. 1.11: after BGR; fig. 1.12: IHS; fig. 1.13: IHS; fig. 1.14: IHS; fig. 1.15: Jürgen Willbarth; fig. 1.16: after Wirtschaftsverband Erdöl- und Erdgasgewinnung; fig. 1.17: ESA; fig. 1.18: after RWE Dea; fig. 1.19: after RWE Dea; fig. 1.20: maribus; fig. 1.21: after Bryan Christie Design; fig. 1.22: after Clauss et al.; fig. 1.23: Rémi Jouan, CC-BY-SA, GNU Free Documentation License, Wikimedia Commons; fig. 1.24: Bettmann/CORBIS; fig. 1.25: STR New/Reuters; fig. 1.26: Victor M. Cadelina, Jr.; fig. 1.27: after Clauss et al.; fig. 1.28: think4photop/iStockphoto; fig. 1.29 FMC Technologies/statoil ASA; fig. 1.30: Meteo France Mothy; fig. 1.31: Time & Life Pictures/Getty Images; fig. 1.32: maribus; fig. 1.33: ITOPF, Fernresearch, Lloyds List Intelligence; fig. 1.34: after The Times Picayune; fig. 1.35 Gerald Herbert/picture alliance/AP Images; fig. 1.36: picture alliance/dpa/Erik S. Lesser; fig. 1.37: Brian Snyder/Reuters; fig. 1.38: Lee Celano/Reuters; fig. 1.39: Dave Martin/picture alliance/AP Photo; fig. 1.40: maribus; fig. 1.41: ITOPF; fig. 1.42: Bonn Agreement; fig. 1.43: Helcom; fig. 1.44: maribus; fig. 1.45: Rajavartiolaitos; fig. 1.46: DREW WHEELAN/picture alliance/landov; fig. 1.47: MATTHEW HINTON/picture alliance/landov; p. 52/53: Maurice Tivey, Woods Hole Oceanographic Institution/NSF/ROV Jason; fig. 2.1: picture alliance/CHINAFOTOPRESS/MAXPPP; fig. 2.2: Hein et al.; fig. 2.3: BGR; fig. 2.4: BGR; fig. 2.5: Wirtgen GmbH; fig. 2.6: Florian Kopp; fig. 2.7: Javier Marina/agefotostock/Avenue Images; fig. 2.8: Photo courtesy British Marine Aggregate Producers Association; fig. 2.9: Photo courtesy of the Eastern Solent Coastal Partnership, www.escp.org.uk; fig. 2.10: Charles D. Winters/NatureSource/Agentur Focus; fig. 2.11: Hein et al.; fig. 2.12: after Hein et al.; fig. 2.13: BGR; fig. 2.14: after Koschinsky, Jacobs University, Bremen; fig. 2.15: Hein & Petersen; fig. 2.16: after Aker Wirth; fig. 2.17: BGR; fig. 2.18: after Hein; fig. 2.19: after Hein et al.; fig. 2.20: Hein; fig. 2.21: maribus; fig. 2.22: JAMSTEC; fig. 2.23: NOAA/MBARI 2006; fig. 2.24: IFE, URI-IAO, UW, Lost City Science Party, NOAA/OAR/OER; fig. 2.25: BGR; fig. 2.26: Hannington; fig. 2.27: maribus/Sven Petersen; fig. 2.28: Geomar; fig. 2.29: maribus; fig. 2.30: Geomar/picture alliance/dpa; fig. 2.31: after Hein & Petersen; fig. 2.32: MARUM – Zentrum für Marine Umweltwissenschaften, Universität Bremen; fig. 2.33: Mike Smith Photography/Nautilus Minerals; p. 94/95: NOAA Okeanos Explorer Program/Wikimedia Commons; fig. 2.33: maribus; fig. 2.34: after Bachraty et al.; fig. 3.1: Dietmar Gust, Berlin; fig. 3.2: after U.S. Department of Energy; fig. 3.3: Geomar; fig. 3.4: maribus; fig. 3.5: Eurico Zimbres/Wikimedia commons; fig. 3.6: Geomar; fig. 3.7: IEA; fig. 3.8: maribus; fig. 3.9: Kyodo/Reuters; fig. 3.10: graphic design: A. Dibiasi für MARUM – Zentrum für Marine Umweltwissenschaften, Universität Bremen; photo: V. Diekamp, MARUM – Zentrum für Marine Umweltwissenschaften, Universität Bremen; fig. 3.11: Geometrics/Craig Lippus/VP Seismic Division; fig. 3.12: Geomar; fig. 3.13: Anonymous/picture alliance/ASSOCIATED PRESS; fig. 3.14: National Geographic Image Collection / Alamy; fig: 3.15 NASA Goddard Institute for Space Studies; fig. 3.16: Geomar; fig. 3.17: after Ruppel; p. 118/119: Claudius Diemer, albedo39 Satellitenbildwerkstatt, www.albedo39.de; fig. 4.1: after Proelß; fig. 4.2: ARM, Courtesy: U.S. Department of Energy's Atmospheric Radiation Measurement Program; fig. 4.3: ISA (International Seabed Authority); fig. 4.4: maribus; fig. 4.5: after ISA; fig. 4.6: after GRID-Arendal; fig. 4.7: China Daily Information Corp. – CDIC/Reuters; fig. 4.8: Stringer China/Reuters; fig. 4.9: STR New/Reuters; fig. 4.10: Issei Kato/Reuters; fig. 4.11: Akin-tunde Akinleye/Reuters; fig. 4.12: Kim Jae Hwan/AFP/Getty Images; fig. 4.13: Columbia Basin Institute of Regional History; p. 144: Brian J. Skerry/National Geographic Creativ

All the graphics in the World Ocean Review 3 were produced exclusively by Walther-Maria Scheid, Berlin. The figure and photo credits state the original sources which were used as a basis for the preparation of the illustrations in some cases.

Publication details

Project manager: Jan Lehmköster
Editing and text: Tim Schröder
Copy editing: Dimitri Ladischensky
Coordinator at the Cluster of Excellence: Erna Lange
Editorial team at the Cluster of Excellence: Erna Lange, Dr. Sven Petersen, Dr. Lars Rüpke, Dr. Emanuel Söding, Dr. Klaus Wallmann
Design and typesetting: Simone Hoschack
Photo-editing: Simone Hoschack, Jan Lehmköster
Graphics: Walther-Maria Scheid
Printing: Ruksaldruck GmbH & Co. KG
Paper: Balance Silk, FSC-certified

ISBN 978-3-86648-221-0
Published by: maribus gGmbH, Pickhuben 2, D-20457 Hamburg, Germany

www.maribus.com

MIX
Paper from responsible sources
FSC® C104247
FSC
www.fsc.org

Print CO_2 compensated
Id-No. 1434587
www.bvdm-online.de