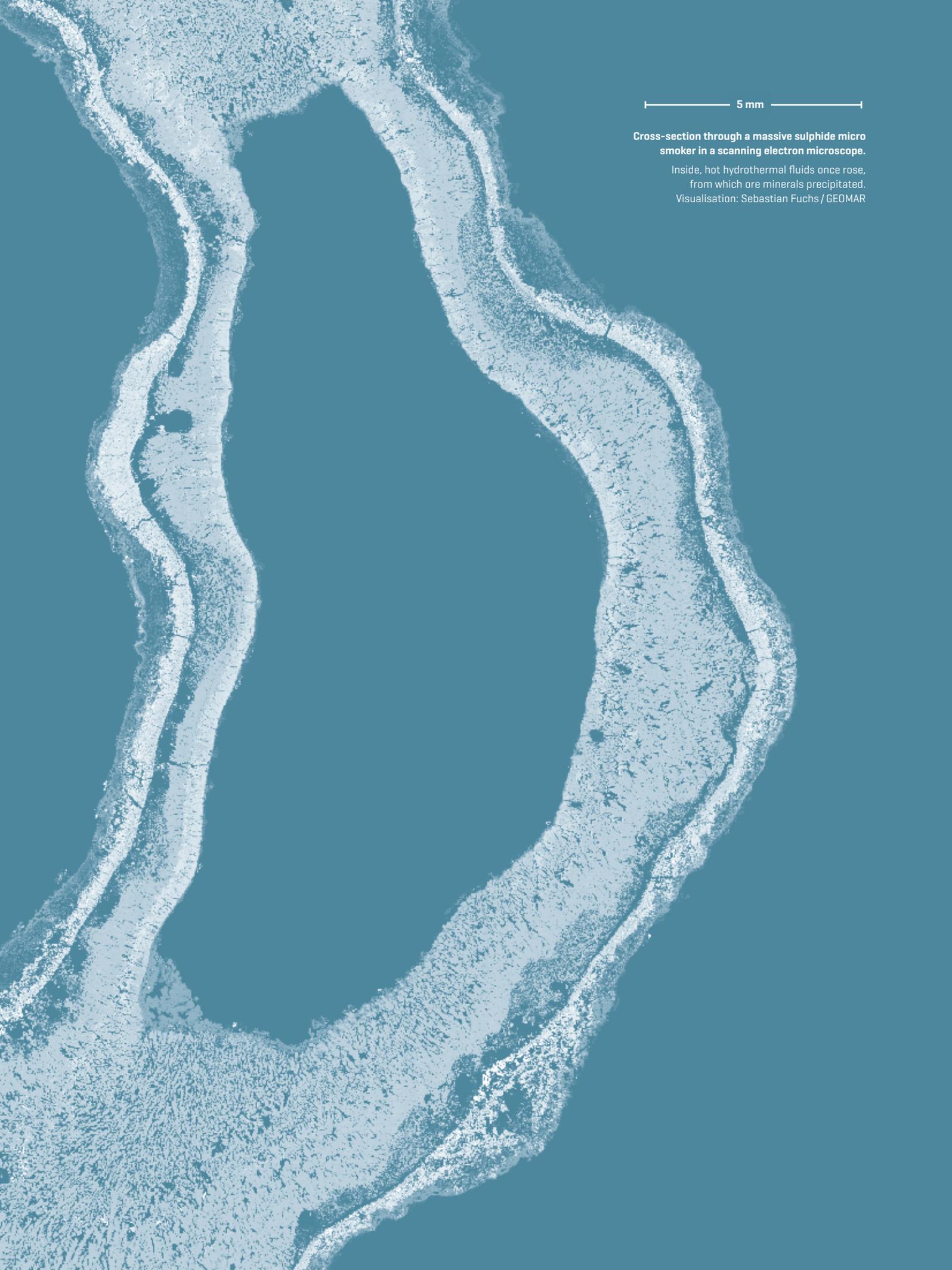# Mineral Resources of the Deep Sea

Formation, Potential and Risks

GEOMAR

5 mm

Cross-section through a massive sulphide micro smoker in a scanning electron microscope.

Inside, hot hydrothermal fluids once rose,
from which ore minerals precipitated.
Visualisation: Sebastian Fuchs / GEOMAR

The Seabed as Source of Raw Materials?

All the metallic raw materials currently in demand by mankind are extracted on land and are thus only found below a third of the earth's surface. The oceans, which at 71 percent make up the largest part of the earth's surface, have hardly been used so far. But the persistently high demand and the resulting sharp rise of raw material prices are now pushing deep-sea mining into the realm of profitability.

The seabed is already an important source of raw materials for mankind. Sand and gravel as well as oil and gas have been extracted from the sea for many years. In addition, diamonds have long been mined off the coasts of South Africa and Namibia as well as deposits of tin, titanium, and gold along the coasts of Africa, Asia and Australia. The extraction of raw materials from the sea is therefore not new. In the near future, however, a number of mineral resources that are to be extracted from the deep sea could gain economic importance. These include massive sulphides, which form in areas of volcanic activity at the plate boundaries in the oceans, manganese nodules on the sediment-covered deep-sea plains and cobalt-rich manganese crusts on the flanks of old submarine mountain ranges. In addition to economic aspects, the protection of the marine environment also plays an important role.

Marine science is research for the future: For many years, GEOMAR has been investigating marine raw material deposits. With an interdisciplinary research approach and in close cooperation with scientists worldwide, the various aspects relevant to the use of marine mineral resources are comprehensively examined. With this brochure, we intend to give you a closer look at the origin, economic potential and ecological risks of a possible exploitation of these deep-sea resources.

MASSIVE SULPHIDES

MANGANESE NODULES

COBALT-RICH CRUSTS

Contents

Recovery of a chimney fragment of a former black smoker in the Southern Central Indian Ridge from a depth of 3,320 metres. Photo: ROV-Team / GEOMAR

Future Demand for Metallic Raw Materials

The global supply of raw materials is becoming increasingly complex. On one hand it is driven by global economic growth and on the other by the development of new technologies. In addition to the mining of raw materials on land and an increasing proportion of recycled raw materials, mineral resources from the deep sea may also be able to make a contribution to meeting the future demand for metals.

Earth provides us with a multitude of natural mineral resources that we need for our high-tech society. At present, almost all of these raw materials are mined on land, in an area that accounts for less than a third of our planet's surface. However, it is becoming increasingly difficult to find rich deposits on land. This forces the mining industry to mine deposits with lower tonnages and to search for deposits in remote regions of Earth or at greater depths. This is associated with an increase in land use and negative consequences for the environment. At the same time, the demand for metals is increasing due to population growth, conversion to green technologies and general economic growth. The demand for raw materials such as copper, nickel and cobalt, which can also be found in the deep sea, will be strongly stimulated by the worldwide expansion of E-mobility. For example, cobalt and nickel are important components of lithium-ion batteries, whose market will continue to grow strongly in the future due to the increasing electrification of mobility and the expanding digitalization. In the case of copper, it is expected that, in addition to E-mobility, the worldwide increase in electrification and the associated expansion of the power grid will also trigger an impetus in demand.

In addition to rising demand, geopolitical interests may further restrict the availability of some metals. This became obvious a few years ago when China suspended exports of so-called rare earth elements and prices on the raw material markets exploded for a brief period of time. China currently produces 81 percent of the rare earth elements and thus effectively controls the market. As with other metals, there are therefore foreseeable risks for a secure supply of raw materials to the processing industry in Germany, Europe and worldwide. For this reason, a number of countries are interested in alternative raw material supply. Together with new mining methods on land and significantly higher recycling rates, deep-sea mining is also regarded as a possible alternative to secure supply of raw materials in the future.

Increase in demand for mineral resources. Illustration: CC-BY 4.0 petraboeckmann.de/Meeresatlas 2017, Source: Achzet

Pre-industrial era	Industrial revolution	Petroleum age	High-tech age
1700	1800	1900	2000
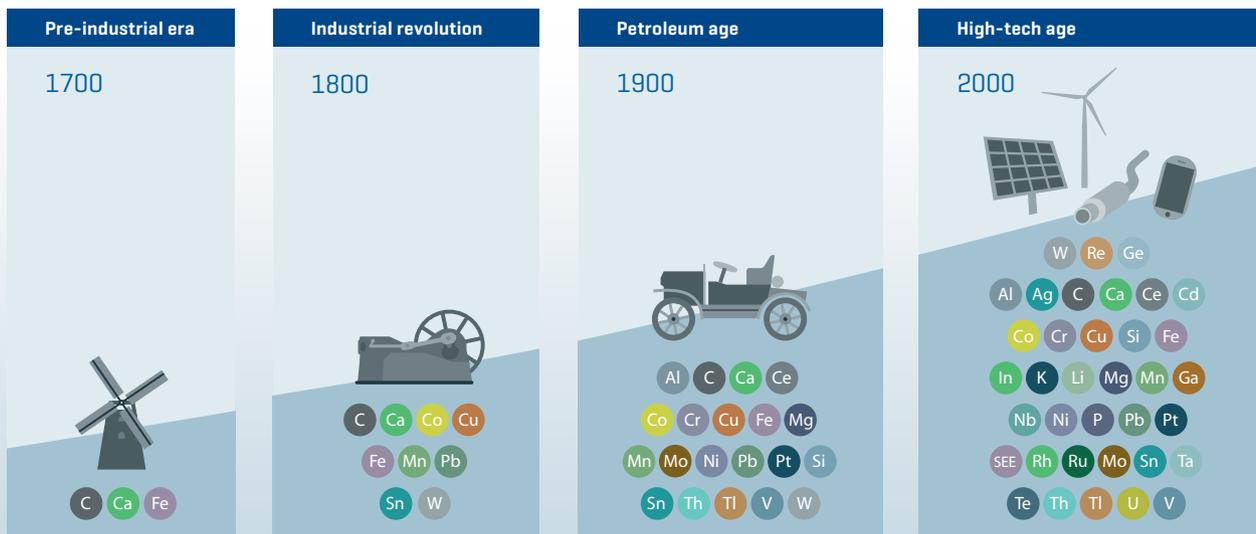
Machines and equipment were built from wood and iron and were powered by wind, water, or muscle power, while coal and wood served as energy sources.

The invention of the steam engine made it possible for the first time to produce and sell large quantities of goods, and the demand for mineral raw materials increased accordingly.

The invention of the combustion engine increased people's mobility. At the same time, electricity became more and more popular as a source of energy.

The digital revolution is increasing the global demand for copper and other specific metals as well as rare earth elements for modern communication and environmental technologies.

The research vessel SONNE.
SONNE is the youngest member of the German research fleet and is considered one of the world's most modern research vessels. A specially developed hull shape prevents bubbles from forming under the hull, which could interfere with the measurement of the seabed topography. Photo: Christian Berndt/GEOMAR

**Deploying AUV ABYSS from board of SONNE.**
This autonomous underwater vehicle is equipped with various echo sounders for bathymetric mapping in highest resolution. In addition, the AUV is equipped with a series of chemical and physical sensors as well as a video camera system. Photo: Emanuel Wenzlaff/GEOMAR
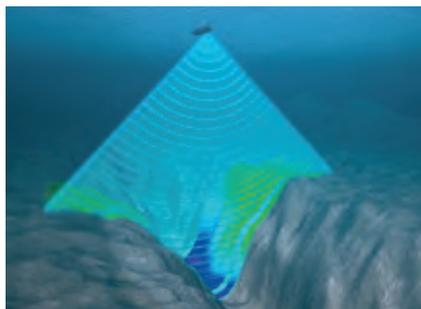
Ship-based echo sounders can generate several hundred individual fan segments that scan the seabed perpendicular to the ship's direction of travel in high resolution. Illustration: Wärtsilä ELAC Nautik

Techniques for the Investigation of Deep-Sea Resources at GEOMAR

One aim of the research group „Marine Mineral Resources" is to understand the formation of marine ore deposits and to advance the exploration of the seabed in order to estimate the potential of these deposits and predict their occurrence. A possible exploitation of raw materials in the deep sea, however, is associated with large-scale environmental impacts. The „Marine Geosystems" research unit at GEOMAR is investigating the processes and material turnover in and on the seabed in order to assess the expected damage to ecosystems in the deep sea and is developing new methods and concepts for environmental monitoring.
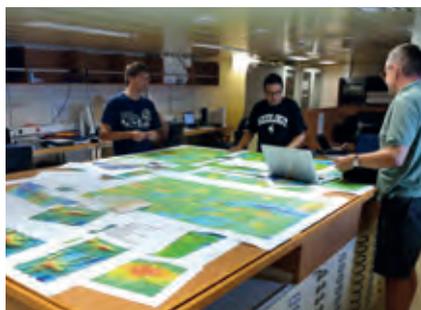

Analysis of bathymetric data: Based on high-resolution maps of the seabed topography obtained with AUV ABYSS, the scientists discuss how to proceed. Photo: John Jamieson, GEOMAR

Exploration of the seabed

Due to the location of the working areas in the Earth›s large oceans, scientists mainly rely on medium-sized and large German research vessels. In addition to ALKOR, which is based at GEOMAR, these include the research vessels METEOR in the Atlantic, MARIA S. MERIAN in the North Atlantic and SONNE for the Pacific and the Indian Ocean.

One of the most important tools for exploring the seabed at depths of hundreds to thousands of metres is ship-based acoustic depth measurement (bathymetry). Modern multibeam echosounders can be used to map the seabed at high resolution. Additionally, GEOMAR is equipped with the ABYSS autonomous underwater vehicle (AUV) for more detailed investigation. Its name refers to the so-called abyss, a term that covers the seabed between 2,000 and 6,000 metres deep. At these depths, the streamlined AUV glides close to the seabed with up to four knots, independently avoiding obstacles.
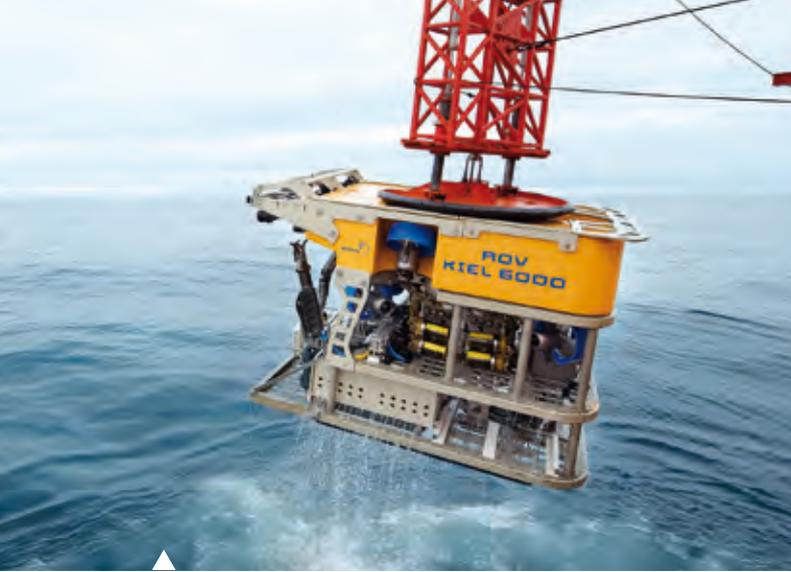
Eyes and arms in the deep sea.
ROV KIEL 6000 is one of the most versatile diving robots for scientific investigations worldwide. With a diving depth of down to 6,000 metres, the remotely-controlled vehicle is able to reach 95 percent of the world's seabed and carry out accurate sampling. Photo: Bernd Grundmann

The drilling ship JOIDES RESOLUTION.
With a length of 140 metres and a height of 60 metres, the drilling vessel is one of the largest research vessels in the world. JOIDES Resolution is used for the international Integrated Ocean Drilling Program (IODP) in all oceans of the world to learn more about the outer crust of Earth and the processes taking place in its interior. Photo: Arito Sakaguchi, IODP/TAMU

Sampling techniques

Numerous sampling methods are available to researchers. A simple chain bag dredge has been used for decades, but has the disadvantage that no targeted sampling is possible. Targeted samples are obtained with, for example, video-guided multicorer and grabs. Sampling with a submersible or with so-called Remotely Operated Vehicles (ROVs) is even more precise, but also more complex. GEOMAR uses JAGO, Germany's only manned research submersible, and two diving robots: ROV PHOCA for operations down to 3,000 metres and ROV KIEL 6000 for operations down to 6,000 metres of water depth. Drilling and coring is carried out to penetrate further into the seabed. For soft ground, so-called gravity corer are used. Mobile drilling platforms or drilling ships are used to determine the depth to which ore-bearing hard rocks occur. The collected samples are then described and prepared for analyses either on board of the research vessel or, latest, back on land, before being analysed using a variety of methods. Numerous laboratories are available at GEOMAR for this purpose, such as the Geochronology Laboratory, the Electron-Microprobe Laboratory, the Laser Ablation ICPMS Laboratory, and the Laboratory for Radiogenic Isotopes.

https://www.geomar.de/en/mmr

Video-guided grabs are equipped with a camera inside that sends real-time videos to the ship via a deep-sea cable. This allows the shovels to be closed in a controlled manner and rock samples to be taken. Photo: Sven Petersen/GEOMAR

Gravity corers are long steel tubes that are lowered vertically into the water. Equipped with weights of several tons, they penetrate up to 20 metres into the seabed and are retrieved to the ship together with the enclosed sediment. Photo: Elger Esser

Rockdrill 2, a drilling rig of the British Geological Survey, is capable of drilling through hard rock down to 15 metres and is deployed directly at the seabed. Here, the core is drilled in 10 1.5-meter long sections. Source: GEOMAR

Investigation on board: In the wet laboratory of the research vessel POSEIDON, the rock samples of an active underwater volcano that were collected with the submersible JAGO are inspected. Photo: Maike Nicolai/GEOMAR

Black Smoker in the crater of the Niua underwater volcano in the Lau basin between Fiji and Samoa.
In April 2016, an international research team led by GEOMAR mapped, for the first time, a complete hydrothermal field with centimetre precision in the Niua South Crater. The research vessel FALKOR of the Schmidt Ocean Institute served as the working platform, while the team used the Canadian ROV ROPOS for surveying. Photo: GEOMAR / Schmidt Ocean Institute / CSSF

Massive Sulphides

Black Smokers – Ore factories of the Deep Sea

Black Smokers are hydrothermal vents in volcanically active zones of the deep ocean. The black "smoke", which exits from the up to 30 meter high chimneys, consists of finely distributed sulphide particles. The chimneys themselves and the mounds they are commonly located on also consist of metal-sulphur compounds, the so-called massive sulphides.

SHORT PROFILE OF MASSIVE SULPHIDES	
Main occurrences	volcanically active zones at submarine plate boundaries
Water depth	1,000 to 4,000 metres
Main components	iron-rich sulphides
Economically interesting metals	copper and zinc (in traces also gold, silver, germanium, indium, tellurium and bismuth)
Application	Components for communication technology

In 1979, the American research submarine Alvin dived into the Pacific Ocean. Through the small portholes of the pressurized hull, the crew saw meter-high chimneys on the seabed at a depth of around 2,600 meters, from which apparently black clouds of smoke were expelled. The scientists had discovered the first hydrothermal vents, so-called "Black Smokers". Investigations showed that minerals were deposited around the springs, forming deposits of so-called massive sulphides. In the meantime, more than 410 occurrences are known in all oceans, although there are enormous differences in the size of these features. Hydrothermal vents are not only a source of raw materials, but also an extraordinary habitat.

In recent years the economic interest in massive sulphides has increased. The first mining licence for massive sulphides around a weakly active hydrothermal system was granted in 2011 for a deposit off the coast of Papua New Guinea. However, mining has not yet begun (as of 2020).


Black Smoker vent fragment.
The sample was taken in 2016 during a cruise with the research vessel Falkor at Niua Volcano in a water depth of 1,146 meters.
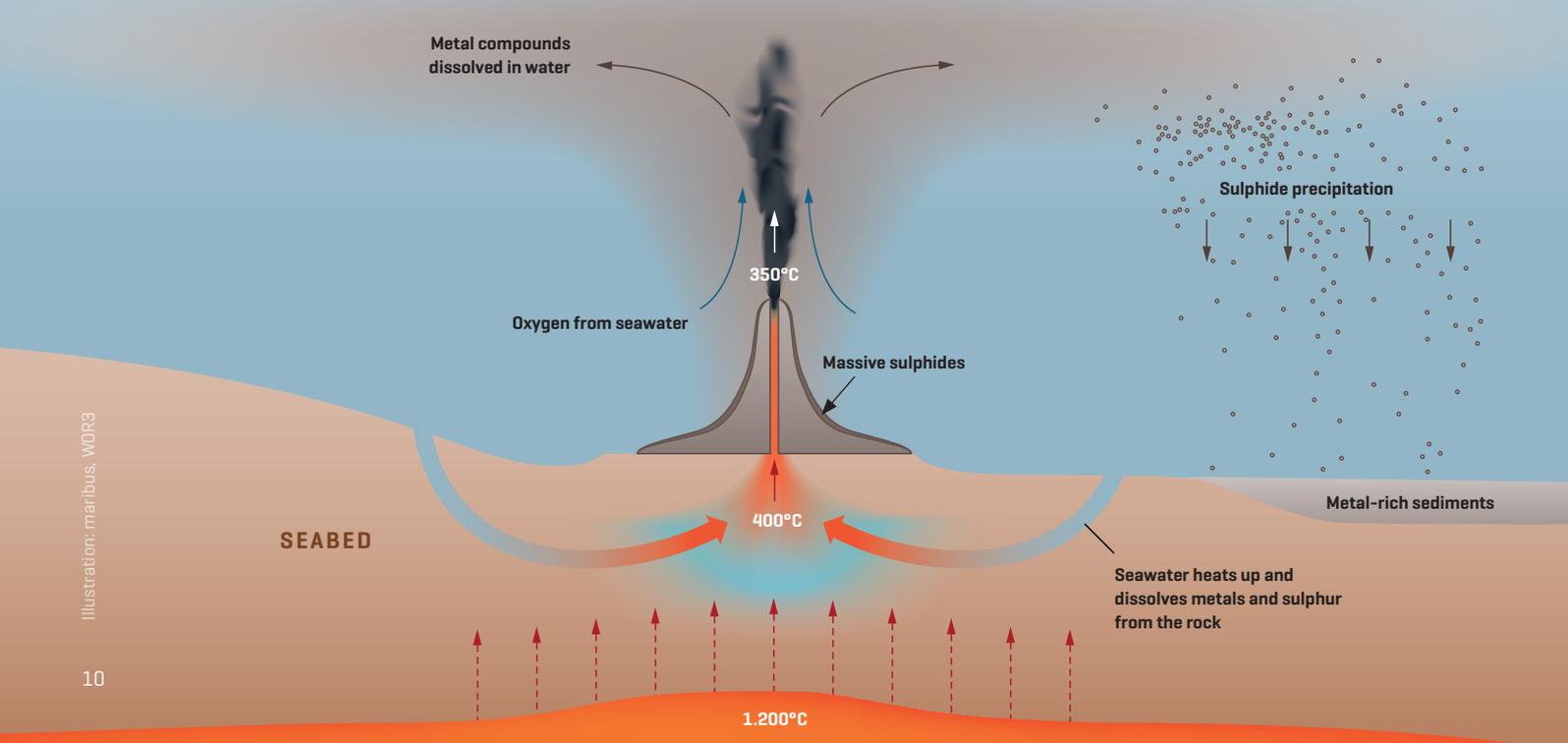Photo: Jan Steffen/GEOMAR

Formation of Massive Sulphides

The fascinating formations of black smokers in the deep sea are created by the interaction of volcanic activity and seawater at active plate boundaries.

At hydrothermal vents, seawater slowly seeps through cracks and crevices deep into the seabed where it interacts with magma chambers at a depth of two to three kilometres. There it is heated and rises again due to its lower density. Chemical processes turn the water into a weak acid. On its way back to the seabed, it leaches elements such as copper, zinc, iron, gold, silver and sulphur from the surrounding rock. Enriched with these substances, the solution, some of which is over 400 degrees Celsius hot, meets the deep ocean water, which is about two to four degrees cold. The metal-sulphur compounds precipitate and are deposited on the seabed as sulphide mounds, chimneys or metal-rich sediments.
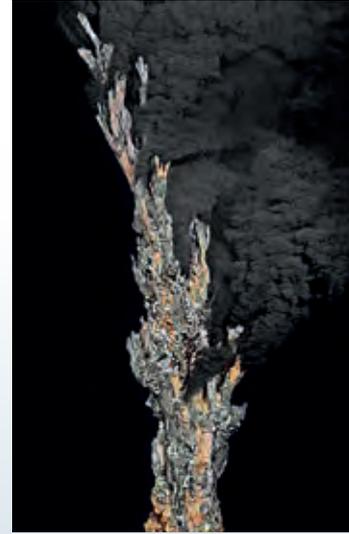
Five-metre-high vent of a black smoker in the central Atlantic.
The largest black smoker discovered to date was discovered at the Juan de Fuca Ridge. Its chimney was 45 metres high.
Photo: Nico Augustin/GEOMAR

Illustration: maribus, WDR3

Metal compounds dissolved in water

Sulphide precipitation

350°C

Oxygen from seawater

Massive sulphides

400°C

Metal-rich sediments

SEABED

Seawater heats up and dissolves metals and sulphur from the rock

1.200°C

1

2

3

4

Biodiversity

The first life on Earth could have originated at black smokers in the deep sea. In the course of millions of years, an ecosystem has developed here that is perfectly adapted to conditions that are commonly hostile to life.

In an environment of absolute darkness, extreme water pressure, toxic metal compounds and water heated to more than 350 degrees Celsius, a unique community of species can be found: dense populations of snails [1], mussels [2], crabs [3], shrimps [4] and tube worms [5] populate the hydrothermal vents. This ecosystem is based on mats of primeval microorganisms [6], which draw their energy from the conversion of sulphur and methane independently of light.

Photos: ROV-Team/GEOMAR

5

6
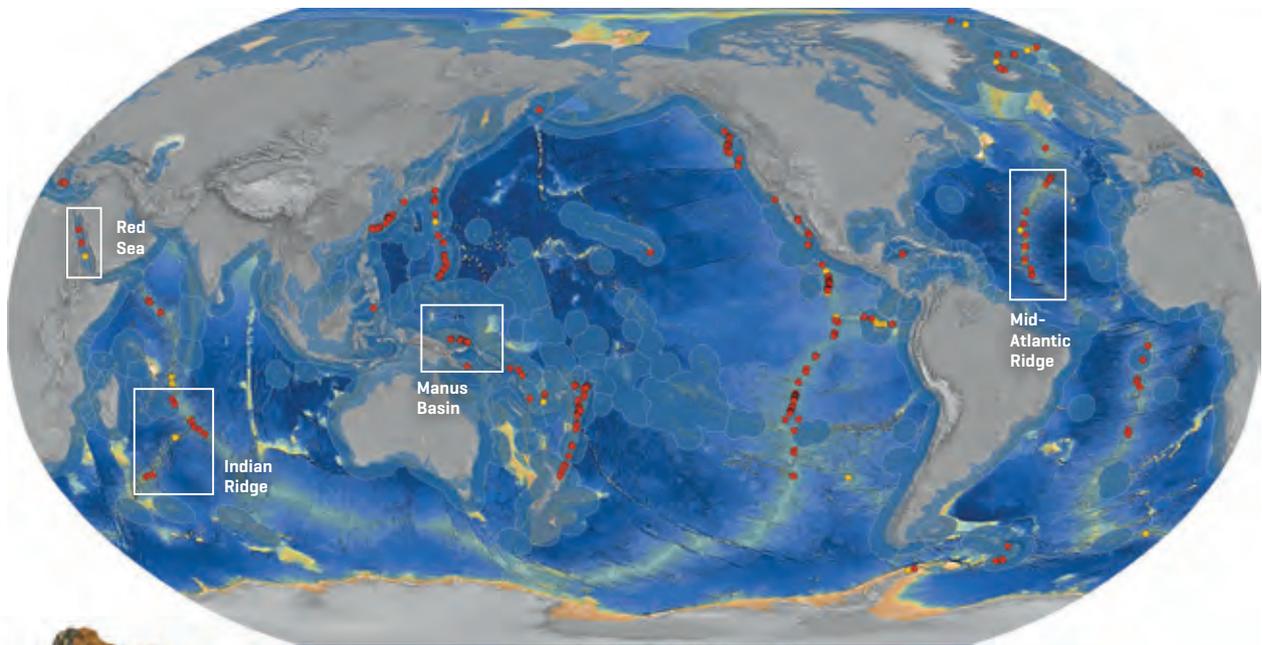
Distribution of known active (red) and inactive (yellow) black smokers in the ocean.
Areas of special economic interest and boundaries of exclusive economic zones (EEZ) are highlighted. Large areas, particularly in the southern oceans, have not yet been explored and occurrences in these regions can therefore not be shown on the map. (as of 2019). Map: Sven Petersen/GEOMAR

# Deposits and Resource Potential of Massive Sulphides

The ore metal contents and the economic potential of massive sulphides differ significantly from those of manganese nodules and cobalt-rich crusts. There are also enormous differences in the size of the individual deposits. In addition, the non-ferrous and precious metal contents of the deposits vary greatly depending on the region.

The black smokers along the mid-ocean ridges are predominantly built up from iron-rich sulphides which are of little economic interest. Copper and zinc together make up only about one eighth of the massive sulphides. The gold content is just over 1 gram per ton. A special class of deposits has formed on the ridges of the Atlantic and Indian Oceans at faults off the central volcanic ridge axis. Here, tectonic processes expose rocks of the upper mantle on the seabed. Massive

sulphides, which are bound to such rocks, show increased copper and gold contents. Other occurrences, commonly in the Southwest Pacific, such as in the Manus Basin, show the highest copper, zinc and gold contents and are therefore particularly interesting for possible future mining. In addition to the elements mentioned above, there are also a number of metals that can be found in traces of several grams per ton in such sulphides and could be included in an economic consideration. However, the contents of these rare and trace metals are subject to a very large heterogeneity and the results of the investigations on their distribution are still incomplete. The deposits of the Southwest Pacific are also found in comparatively shallow water depths of less than 2,000 metres and in the economic zones of neighbouring

Change in various metal prices from 2000 - 2019. Source: InfoMine.com
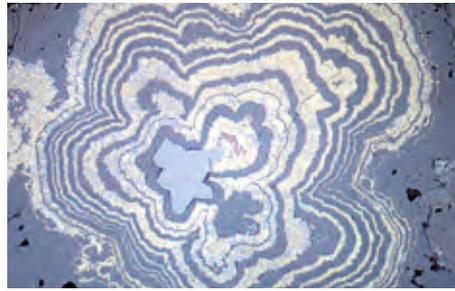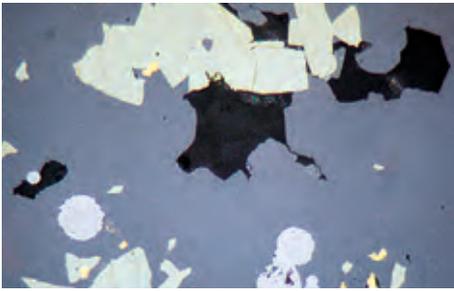
Microscopic images of massive sulphides.
Left: small, bright yellow gold grains as inclusions in various sulphides. The size of the gold grains lies between 2 - 10 micrometres. Right: The physicochemical properties of the hot solutions form alternating layers of zinc sulphides (medium grey) and copper sulphides (yellow, light grey, brown).

Black smoker from the Mid-Atlantic Ridge.
Many occurrences at mid-ocean ridges are predominantly built up from iron-sulphides.
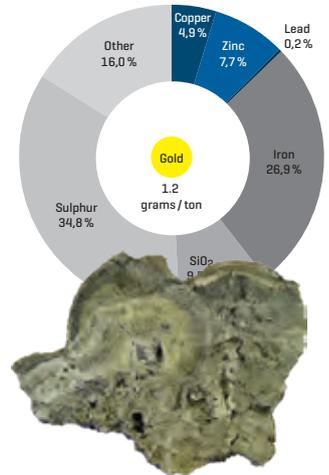
states, which makes them technologically and legally conducive to possible extraction. In January 2011, Nautilus Minerals received the first mining licence for a deposit of approximately two million tons of sulphides in the territorial waters of Papua New Guinea.

The largest known sulphide deposit is located in the Red Sea. Here the sulphides do not occur as black smoker, but in the form of iron-rich metalliferous muds with elevated contents of copper, zinc, silver and gold. This occurrence in water depths of around 2,000 metres has been known since the 1960s. Thanks to the muddy consistency of these deposits, mining appears technically unproblematic and was already successfully tested in the 1980s. A 30-year mining license for this deposit was granted in 2010, but it is not yet known if and when the mining will commence.

More than 90 percent of all known deposits are too small to be of economic interest. Up to now, exploration has always relied on anomalies in the water column. This means that an active black smoker can easily be found in the water column due to this "plume of smoke". These anoma-

lies can be detected over large distances and traced back to their source. However, such a search is only capable of finding active black smokers. In fact, most of these systems are geologically very young and therefore often also very small. There is a need for research into exploration methodology for finding larger, inactive ore deposits. This issue was addressed within the framework of the recent EU project "Blue Mining", where technologies for the search for these economically more interesting deposits were developed.

While the sampling of manganese nodules and cobalt-rich crusts at the seabed is sufficient for an estimation of their resource potential, for massive sulphides drilling is indispensable in order to obtain information from the interior of the deposits. Many investigations have shown that there are large differences in the metal contents between samples taken from the surface of sulphide mounds when compared to those from the interior. Since such drill holes only exist from a few deposits, it is hardly possible to estimate the global resource potential of massive sulphides.
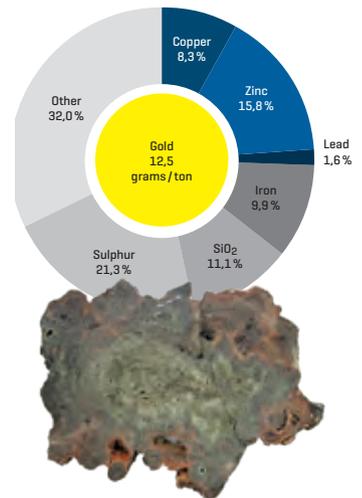
Black smoker from the eastern Manus Basin off Papua New Guinea.
The difference between the copper-rich core and a brownish zinc-rich exterior is clearly visible. The average gold content for this sample is 15 grams of gold per ton of ore.

+/-

At present, only a few of the known massive sulphide deposits appear to have sufficient size and metal content to be economically viable. To change this picture, it is necessary to develop new exploration technologies that go beyond the search for small, active deposits and are able to discover large, inactive deposits away from the volcanically active zones. Nevertheless, the resource potential of massive sulphides appears to be rather low when compared to that of manganese nodules or cobalt-rich crusts. However, due to the three-dimensional character of the sulphide deposits, the environmental impact of mining them is likely smaller compared to the large areas being disturbed by the mining of manganese nodules and cobalt-rich crusts.

Manganese nodules on the ocean floor in the Clarion-Clipperton Zone. The image was taken with ROV KIEL 6000 during the SO239 expedition with RV SONNE in April 2015.
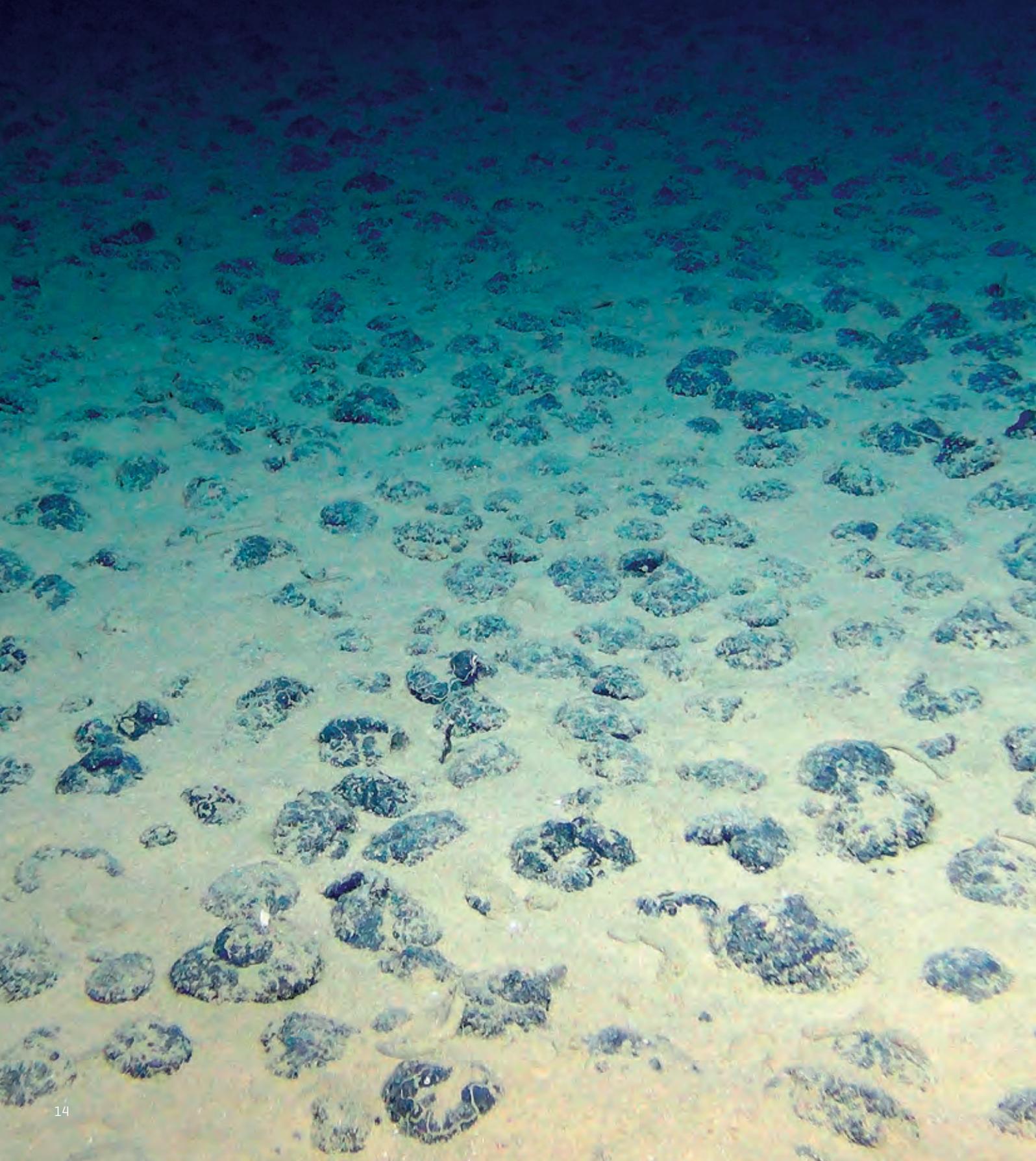
Manganese Nodules
Rich Mineral Fields on the Seabed

In the abyssal plains of the deep sea, metal-bearing lumps lie close together over thousands of square kilometres, like potatoes on a field: Manganese nodules are the most important potential source of raw materials in the marine realm, as they contain larger quantities of some metals than are currently known and mineable on land.

SHORT PROFILE MANGANESE NODULES	
Main occurrence	Sediment-covered deep-sea plains of all oceans
Water depth	3,000 to 6,000 metres
Main ingredients	silicates, manganese and iron oxides
Economically interesting metals	nickel, copper and cobalt (in trace amounts also rare earth elements, molybdenum, lithium and titanium)
Application	Batteries, environmental and energy technology

Manganese nodules in the deep sea have been known since the British Challenger expedition from 1872 to 1876. For a long time, however, they were only regarded as a curiosity. In the 1960s and 1970s, they were first targeted by the industrial nations, who recognised them as a possible source of raw materials. The manganese nodule enthusiasm in the 1970s went so far that alleged mining attempts even had to serve as camouflage for a cover-up operation of the United States Central Intelligence Agency (CIA) in the Central Pacific. Real mining tests quickly showed in fact, that the technology was not yet ready to function smoothly in several thousand metres of water.

In recent years, however, rising commodity prices and growing demand for metals have reactivated plans to mine these nodules from the deep sea floor. Still, mining licenses have not been granted and full-scale mining technology has not been successfully tested. Also, the questions about the large-scale and long-lasting harmful effects on the deep-sea environment cannot be conclusively answered at the moment.

Manganese nodule from the Northwest Pacific Ocean.
This sample was collected during expedition SO265 with the research vessel SONNE at Papanin Ridge from a water depth of 4,490 metres. Photo: Jan Steffen/GEOMAR

Formation of Manganese Nodules

Manganese nodules occur worldwide on the seabed mostly at depths of 3,000 to 6,000 metres. They consist of metals that are transported into the oceans by erosion or originate from hydrothermal vents in volcanically active areas of the oceans. Their growth rate is only a few millimetres in a million years, so larger nodules with a size of 15 centimetres can be up to 15 million years old.

Manganese nodules come in many shapes and sizes. They can be round, elongated or flat. Their appearance is determined by the shape of the core, the surrounding sediment and their type of growth. Manganese nodules grow when metal ions either dissolved in seawater (hydrogenetic growth) or from the sediment pore-water (diagenetic growth) are deposited onto a nucleus. This nucleus may consist of rock fragments, shell remains, or shark teeth. Over time, concentric layers form around the core.

Usually nodules grow both dia- and hydrogenetically, whereby the respective proportions differ in different regions. It is fascinating that manganese nodules grow extremely slowly. With every million years, their thickness increases only millimetre by millimetre. Hydrogenetic nodules grow up to 10 millimetres per million years, diagenetic nodules between 10 and 100 millimetres per million years. As a result, manganese nodules could only form where environmental conditions remained fairly constant over such long periods of time.

Section through a manganese nodule.
Inside, similar to the growth rings of a tree, they have a layered structure that can also be used as a geological archive. Photo: Linda Plagmann

Different growth processes.
Manganese nodules can grow hydrogenetically or diagenetically, or by a mixture of both. Heterogeneous growth rates can lead to asymmetric nodules. Photo: BGR

Illustration: maribus, WOR3, edited by C. Kersten/GEOMAR

Hydrogenetic nodules

Both diagenetic and hydrogenetic nodule growth

Metal ions in seawater are bound to nodules

SOLID BASALT

Diagenetic nodules

Dissolved metal ions from the pore water accumulate on the nodules

POROUS SEDIMENT
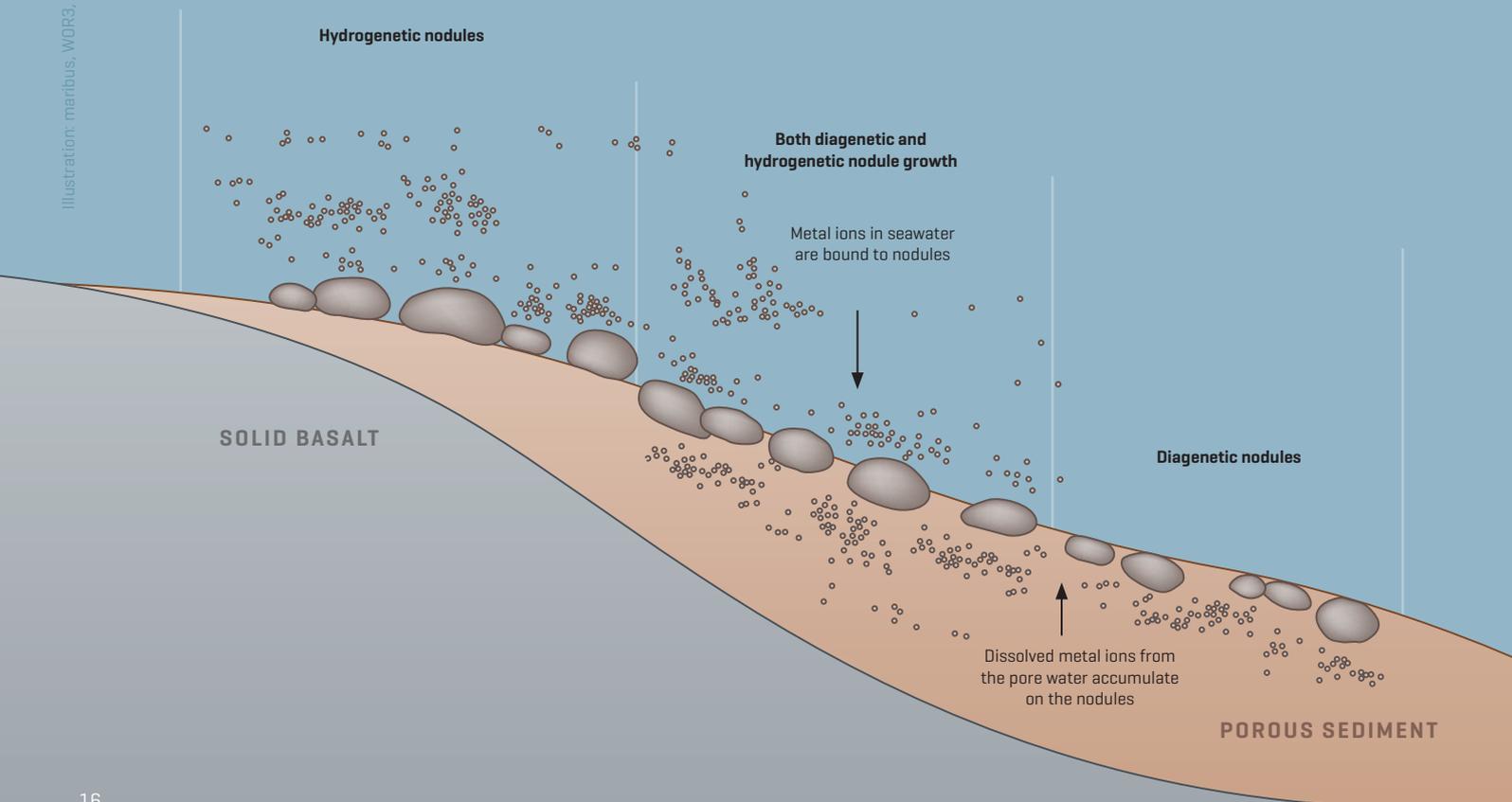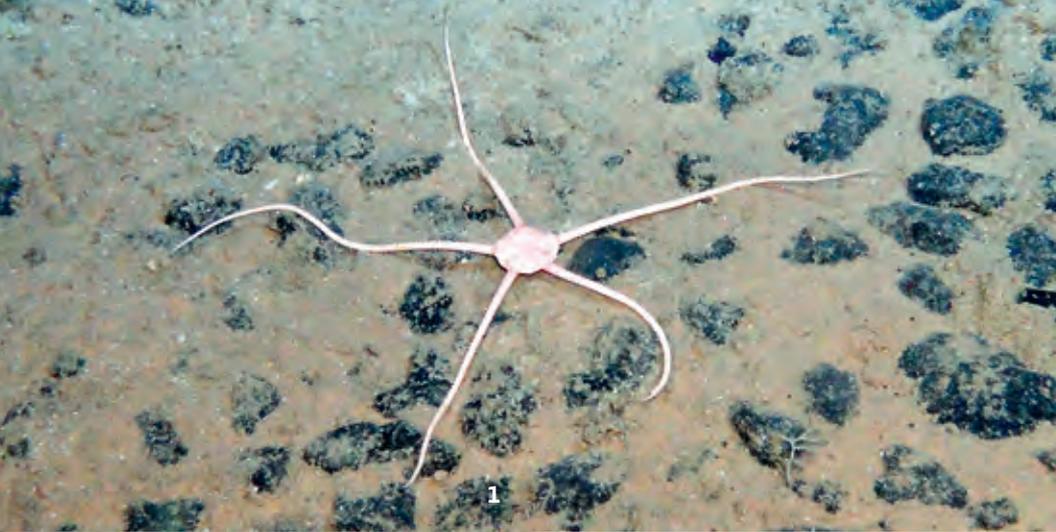
Biodiversity

In the 19th century it was still believed that life was impossible below a depth of a thousand metres. But even today, the deep sea surprises scientists. The perception that the large deep-sea plains in the central Pacific are uniformly flat and only sparsely populated has persisted until the present day. Another mistake, as researchers from the European MiningImpact project found out: The ecological diversity down there is enormous, especially where many manganese nodules cover the seabed: brittle star (1), sea anemone (2), starfish (3), sea urchin (4), soft coral (5), sponge (6) and sea cucumber (7).

Photos: ROV-Team/GEOMAR
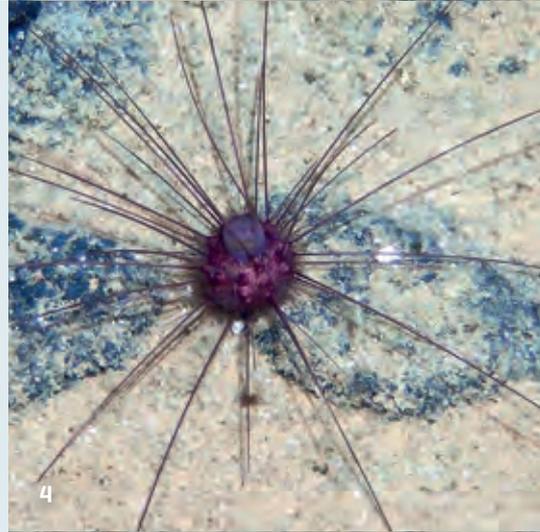
Distribution of Manganese Nodules in the ocean.
Areas with a significant number of nodules and boundaries of exclusive economic
zones (EEZ) are highlighted. Map: Sven Petersen/GEOMAR

Deposits and Resource Potential of Manganese Nodules
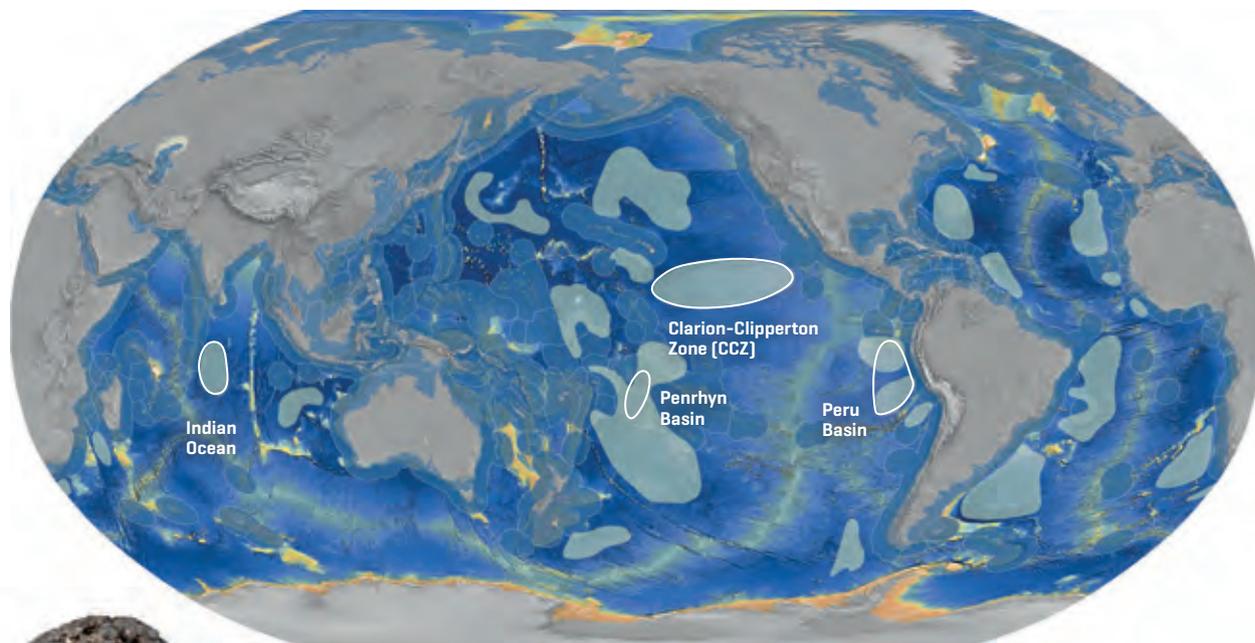
Although present in all oceans, only in a few areas the density of manganese nodules is sufficiently high for industrial mining. In these areas the deposits could be important for securing global future metal supply. However, there are currently no applications for mining licences, which is due to the fact that the regulations for exploitation are currently still being drafted by the International Seabed Authority.

Globally, approximately 38 million square kilometres are geologically suitable for the formation of manganese nodules. However, this is only a rough estimate, as large areas of the seabed have been insufficiently investigated. Economically interesting nodule abundances are currently known in four marine regions:

Clarion-Clipperton-Zone (CCZ): This zone is the largest manganese nodule area in the world with an area of around 9 million square kilometres, roughly the size of Europe. The CCZ is located in the Pacific Ocean and stretches from the west coast of Mexico to Hawaii. The manganese nodules are not evenly distributed here. In some places they lie close to each other, while in other areas there are no nodules at all. On average, the CCZ harbours about 15 kilograms of manganese nodules per square metre. Particularly productive areas may reach up to 75 kilograms per square metre. A total mass of manganese nodules of around 21 billion tons is estimated for the entire CCZ.

Peru Basin: About 1,000 kilometres off the Peruvian coast lies the Peru Basin. It is about half the size of the Clarion-Clipperton-Zone. Here, an average of ten kilograms of manganese nodules per square metre can be found. (See also DISCOL project on page 32).
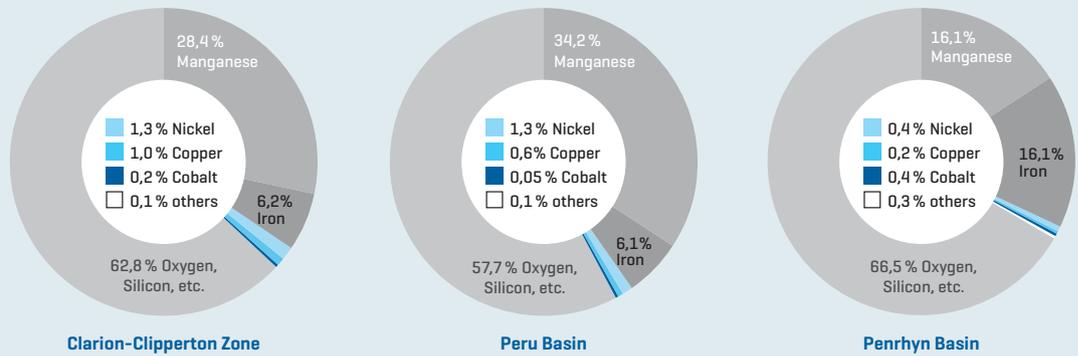
Penrhyn Basin: The third major manganese nodule area in the Pacific Ocean is located in the immediate vicinity of the Cook Islands, several thousand kilometres east of Australia. The area extends over approximately 750,000 square kilometres. Large areas in the coastal waters of the Cook Islands contain more than 25 kilograms of manganese nodules per square metre of seabed.

Indian Ocean: So far, only one large area of manganese nodules has been discovered here, having a similar size than the Penrhyn Basin. It is located in the central Indian Ocean. On each square metre of seabed, about five kilograms of manganese nodules are present.

Manganese and iron are the dominant metals in manganese nodules. However, the most economically interesting metals are nickel, copper and cobalt, which together may reach contents of about two to three percent by weight. In addition, there are traces of a whole range of metals in the nodules that are important for the economy in high technology as well as in green technologies. These include molybdenum, rare earth elements, lithium and titanium.

Chemical analyses of manganese nodules have shown that the metal contents of manganese nodules in different marine regions differ significantly.
Source: Hein & Petersen, World Ocean Review 3

28,4 % Manganese

1,3 % Nickel
1,0 % Copper
0,2 % Cobalt
0,1 % others

6,2% Iron

62,8 % Oxygen, Silicon, etc.

Clarion-Clipperton Zone

34,2 % Manganese

1,3 % Nickel
0,6 % Copper
0,05 % Cobalt
0,1 % others

6,1% Iron

57,7 % Oxygen, Silicon, etc.

Peru Basin

16,1% Manganese

0,4 % Nickel
0,2 % Copper
0,4 % Cobalt
0,3 % others

16,1% Iron

66,5 % Oxygen, Silicon, etc.

Penrhyn Basin

A conservative calculation of the metals contained in manganese nodules of the CCZ estimates the presence of more than 6 billion tons of manganese, which exceeds the global economically mineable quantity on land. The situation is similar for nickel (270 million tons), copper (230 million tonnes) and cobalt (44 million tons). The manganese nodules of the CCZ alone thus contain three to five times more nickel and cobalt than all known economically exploitable land deposits combined. The amount of copper in the CCZ corresponds to about one third of the global land reserves. With these figures it becomes clear that manganese nodules have a huge resource potential and could be of importance for securing future global raw material supply. However, for economic production, around 2 to 3 million tons of manganese nodules have to be harvested each year. To achieve this, a deep-sea mining contractor would have to exploit an area of 200 to 300 square kilometres per year, roughly equivalent to the size of the city of Munich. Based on global production figures in recent years, the mining of manganese nodules from only five deep sea mining sites would contribute 10 percent to global nickel production, 25 percent for cobalt and less than 1 percent for copper. Under today's economic conditions, however, these production volumes would saturate the world market with manganese to such an extent that the price of manganese nodules could collapse.

When looking at the CCZ it must be considered that large areas of the CCZ are not suitable for commercial extraction because they contain manganese nodules that are too small for mining or that these areas are unsuitable due to their strong relief. The growing interest in manganese nodules is reflected by the increase in applications for deep-sea exploration licences. In 2001, the first licenses of the International Seabed Authority were awarded to six contract partners. India joined in 2002, followed by Germany, which holds a CCZ licence since 2006. After a period of calm, interest has increased significantly since 2012. Currently, 17 exploration licenses with a total area of 1.2 million square kilometres have been granted (see also pages 28-29).
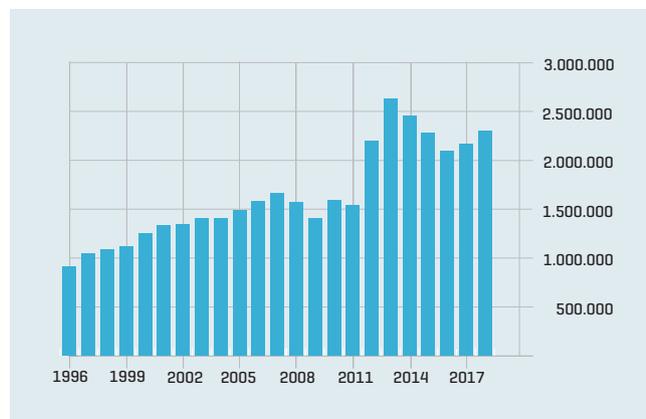

Global production of nickel in the years 1996 to 2018 in tons.
Source: USGS Mineral Commodity Summaries for Nickel (1997-2019)

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First experiments in the 1970s have shown that, in principle, it is possible to extract manganese nodules from great depths. However, it requires a step further from such tests lasting only several hours or days to industrial production over many months of the year. The adverse effects of large-scale mining on the environment have not yet been sufficiently investigated, even though major scientific projects have been dealing with them more intensively in recent years. Given the current market situation, manganese nodule mining would only be worthwhile for a few contractors, as otherwise the world market price for manganese, which is currently relevant for profitability, would plummet.

The Grimaldi Seamounts in the tropical Atlantic Ocean.
About 800 kilometres west of the West African state of
Guinea, these seamounts rise over 3,000 metres from the
approximately 4,000 metre deep ocean floor. They are
part of the Bathymetrist Seamounts, a chain of under-
water volcanoes formed less than 60 million years ago.
Visualisation: Nico Augustin/GEOMAR
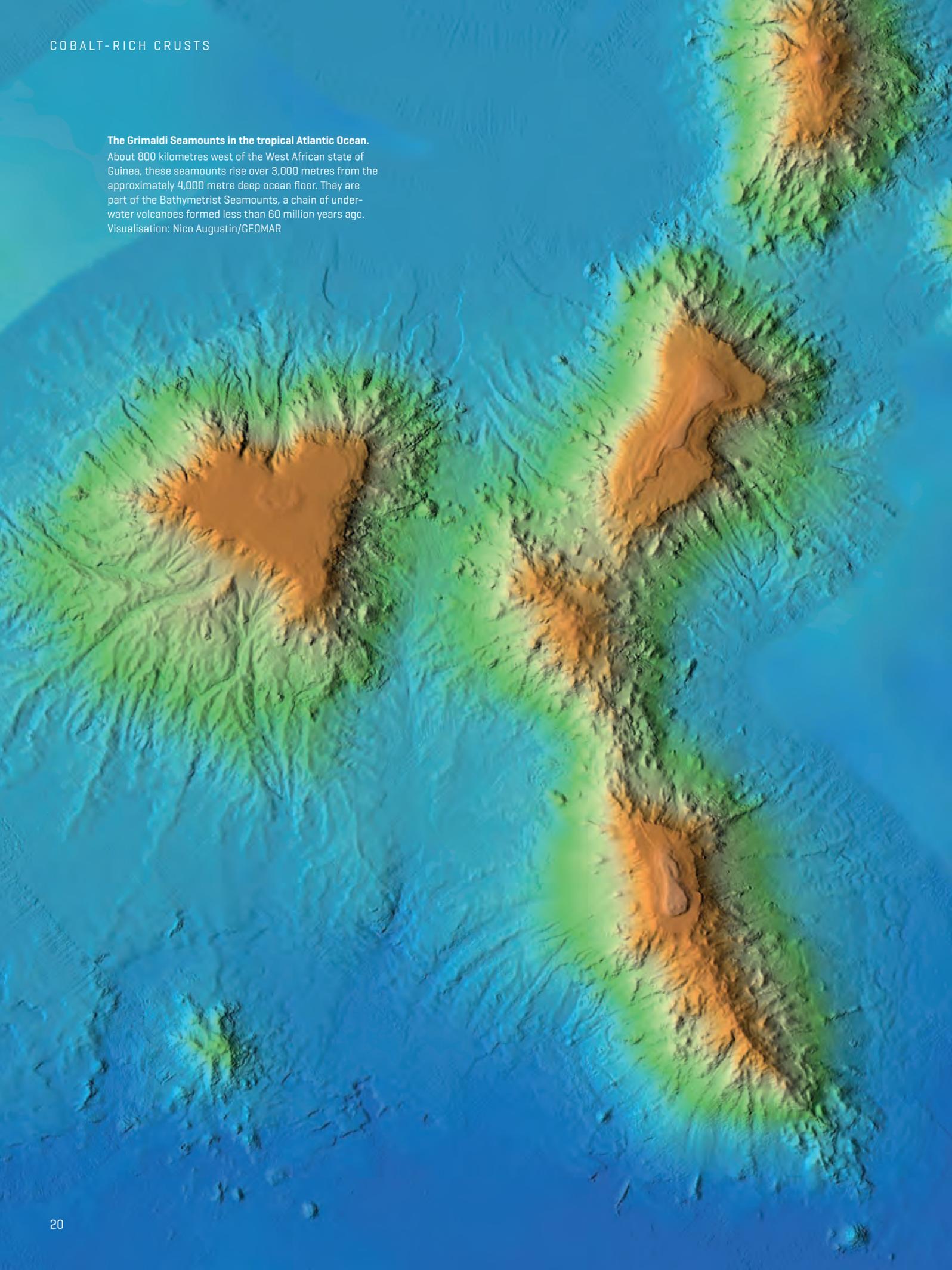
Cobalt-rich Crusts
Ore Treasure on the Slope of Seamounts

Due to volcanic activity on the seabed, seamounts have grown in height over millions of years. Seamounts occur in all oceans and commonly reach heights of 1,000 to 4,000 metres. They often form solid, metalliferous layers, which are known to experts as cobalt-rich iron-manganese crusts or cobalt-rich crusts for short.

SHORT PROFILE COBALT-RICH CRUSTS	
Main occurrence	Sediment-free slopes of old submarine volcanoes
Water depth	800 to 2,500 metres
Main ingredients	silicates, manganese and iron oxides
Economically interesting metals	cobalt, nickel, and rare earth elements (in traces also molybdenum, tellurium, zircon and platinum)
Application	High-tech metals, environmental and energy technology

There are around 33,000 seamounts in all oceans - probably. Because the ocean floors are by far not as precisely mapped as the continents. The figure is based on projections of previously known structures. So there are still many opportunities for new discoveries.

The cobalt-rich crusts on the sediment-free flanks of seamounts form in a similar way than manganese nodules, that is by deposition of metal compounds on the rock surfaces over millions of years. As with manganese nodules, this deposition takes place very slowly: per one million years, the crusts commonly grow 1 to 5 millimetres and thus even slower than the manganese nodules. Cobalt-rich crusts are also considered possible submarine ore deposits. However, since they are firmly connected to the rocky substrate, they cannot simply be picked up from the seabed like manganese nodules.

Fragment of a cobalt crust.
The sample was taken at the beginning of 2018 during the MSM70 expedition with the research vessel MARIA S. MERIAN at the Carter Seamount (part of the Bathymetrist Seamount Chain) from a depth of 2,750 to 2,450 metres. Photo: Jan Steffen/GEOMAR

Formation of Cobalt-rich Crusts

Cobalt-rich crusts occur on all exposed rock surfaces at submarine elevations, especially on seamounts. The rock surfaces absorb metals from the surrounding seawater and, over a long period of millions of years, form coatings of iron and manganese oxides, the thickness of which ranges from a few millimeters to a few decimeters, depending on the age of the seamounts.

Some seamounts behave like gigantic stirring rods in the sea, which create big vortices. These vortices also contain metal compounds, which are deposited on the rock surfaces. Another important requirement for the formation of cobalt-rich crusts is that the rock or the growing crusts are free of sediments. The conditions at seamounts are ideal for this: the currents carry away the fine sediments and keep the rock and the crusts clean. Cobalt-rich crusts can be found at water depths of 600 to 7,000 metres. However, the thickest and most valuable crusts are found in the upper part of the seamount slopes, where strong currents prevail. On average economically valuable crusts lie in water depths of 800 to 2,500 metres near the oxygen minimum zone.

The cobalt-rich crusts form when metal ions in the water react with oxygen to form oxides, which are deposited on the rock surfaces of the seamounts. However, oxides can only form where the seawater contains sufficient levels of oxygen. Paradoxically, in fact the thickest cobalt-rich crusts can be found on seamounts where the top is close to the oxygen minimum zone, an area where seawater contains the least oxygen. This contradiction can be resolved: Since very little oxygen is present in the oxygen minimum zone, the free metal ions accumulate in the oxygen-poor water. At seamounts, however, oxygen-rich deep water flows up from the seabed. This creates a mixing zone in which metal-oxides can form, which then precipitate on the rock surfaces and form crusts over time.

Complex inner structure.
Similar to a sponge or activated carbon, which is often used as a filter substance in aquariums, cobalt-rich crusts are very porous. Thanks to these pores, which are only a few micrometres in size, the crusts have a large inner surface. Just as pollutants remain suspended in the pores of an activated carbon filter, metal compounds are deposited on the large surface of the crusts. Photo: James Hein / USGS
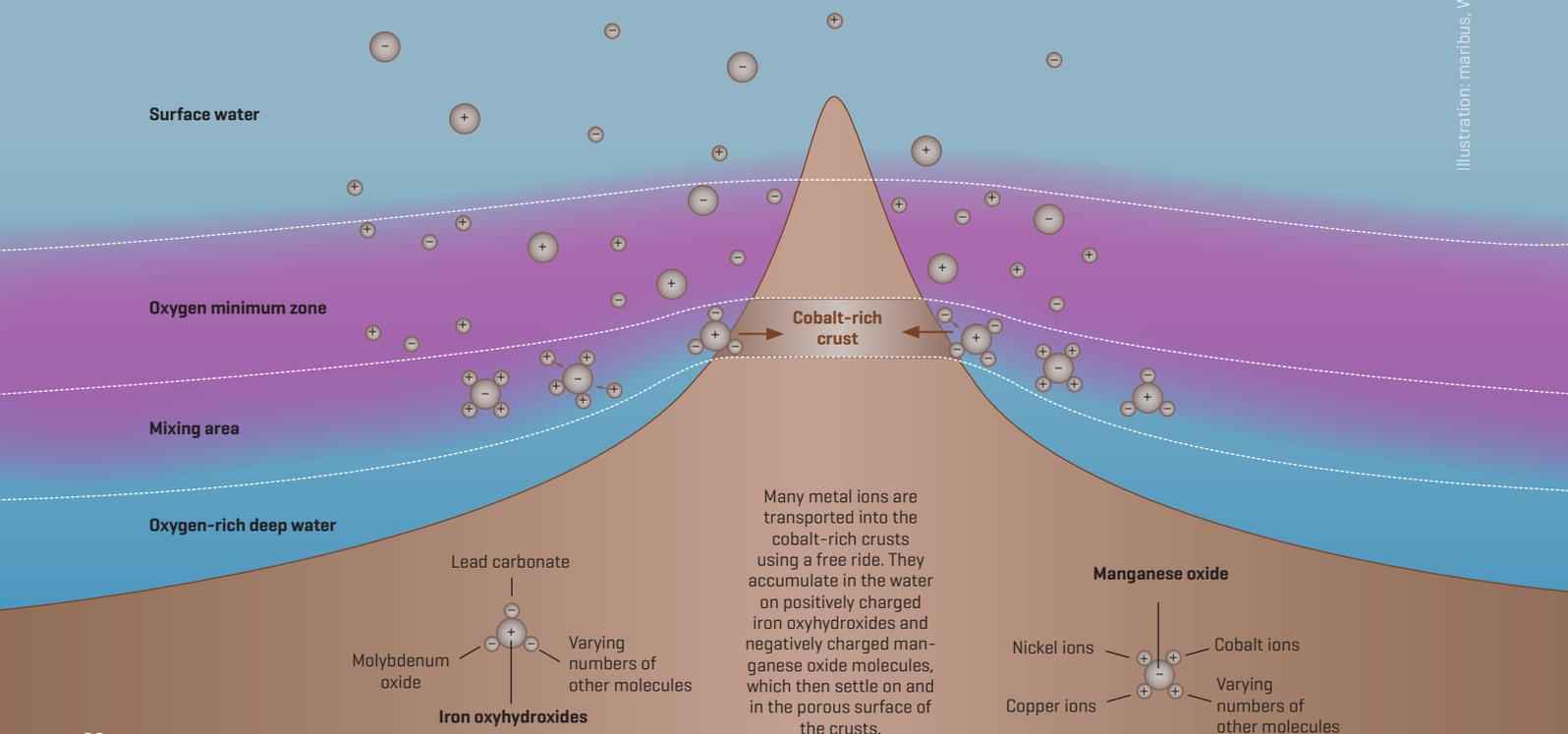
Illustration: maribus, WOR3

Surface water

Oxygen minimum zone

Mixing area

Oxygen-rich deep water

Cobalt-rich crust

Lead carbonate

Molybdenum oxide

Varying numbers of other molecules

Iron oxyhydroxides

Many metal ions are transported into the cobalt-rich crusts using a free ride. They accumulate in the water on positively charged iron oxyhydroxides and negatively charged manganese oxide molecules, which then settle on and in the porous surface of the crusts.

Manganese oxide

Nickel ions

Copper ions

Cobalt ions

Varying numbers of other molecules

1

2

3

Biodiversity

The species composition at seamounts differs considerably from ocean to ocean. The images shown here show organisms at seamounts in the Clarion-Clipperton-Zone in the Central Pacific: deep-sea crab (1), soft coral (2), anemones and goose barnacles (3), antipatharia coral (4), shrimp (5) stalked sponge (6) and sea cucumber (7).

The large biodiversity at seamounts is due to the special current situation: On the one hand, nutrients are retained by circulating currents near the top of the seamounts, on the other hand, nutrient-rich water is additionally carried up from greater depths by the currents surrounding the seamounts, which leads to increased plankton growth.

Photos: ROV-Team/GEOMAR

4

5

6

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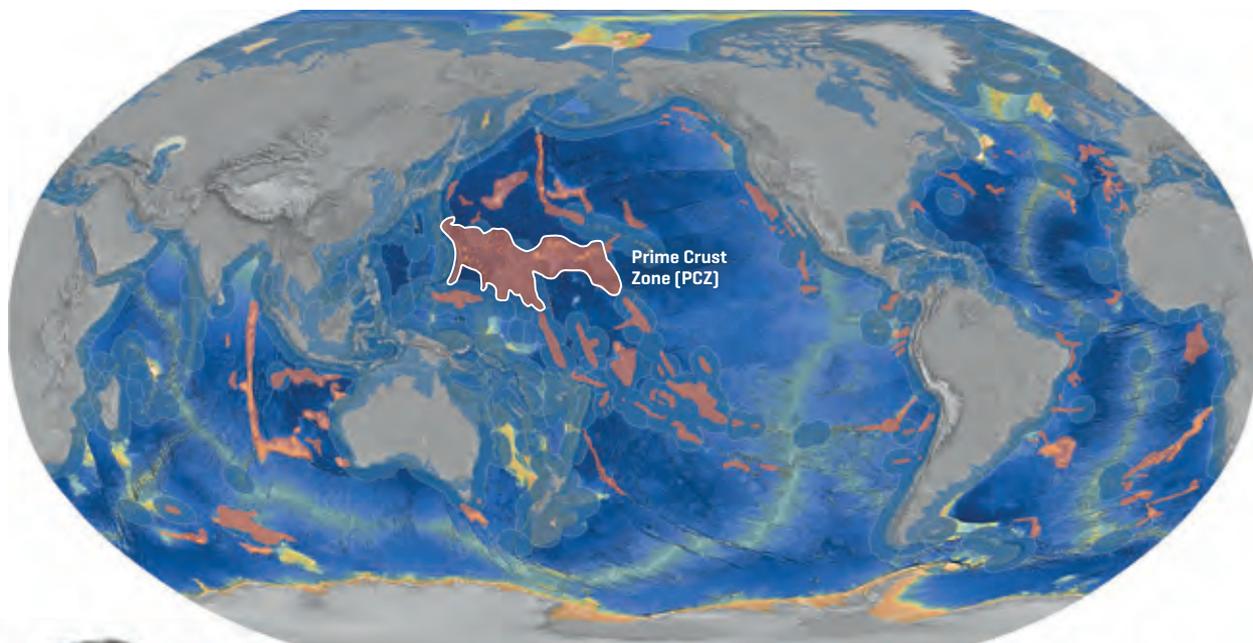
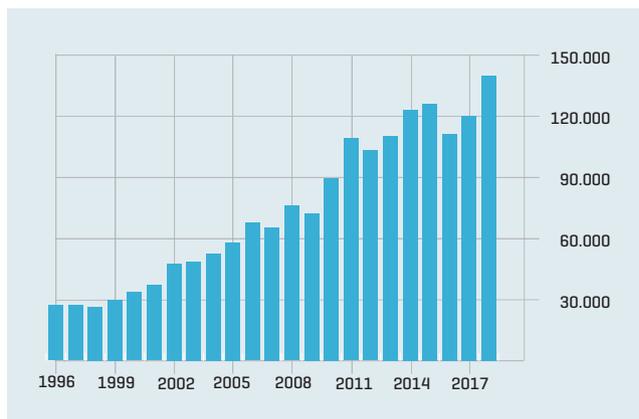**Distribution of cobalt-rich crusts in the ocean.**
Areas of special economic interest and boundaries of EEZ are highlighted. In contrast to manganese nodules, the cobalt-rich crusts mainly occur within the 200 nautical mile zones of the respective coastal states. Map: Sven Petersen/GEOMAR

Deposits and Resource Potential of Cobalt-rich Crusts

Globally, about 23 million square kilometres are geologically suitable for the formation of economically interesting cobalt-rich crusts. This area can be further limited by a combination of factors such as topography and morphology of the seabed, age of the ocean crust and global sedimentation rates, resulting in an area of about 3 million square kilometres, which could be of economic interest for the exploration of cobalt-rich crusts.

As in the case of manganese nodules, manganese and iron are the dominant metals enriched in the crusts. The main economically interesting metals are cobalt, nickel and the rare earth elements. Cobalt is currently the most important trace metal and often reaches concentrations above 0.5 percent.
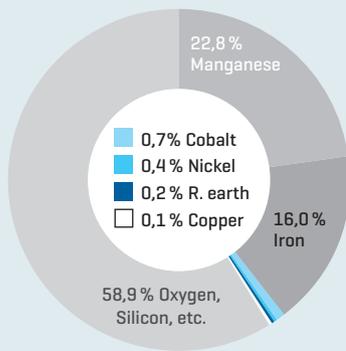
Economically interesting crusts with a thickness of more than four centimetres and elevated metal contents are predominantly formed on sediment-free slopes of old seamounts in water depths between 800 and 2,500 metres. Experts estimate that there are at least 33,000 seamounts worldwide. Of these, about 57 percent occur in the Pacific Ocean. The Pacific Ocean is thus the most important cobalt-rich crust region in the world, with the Western Pacific being of particular interest. Here you can find the oldest seamounts, which formed about 150 million years ago. Correspondingly, many metal compounds were deposited here, and over time formed comparatively thick crusts. This area, located about 3,000 kilometres southeast of Japan, is called the Prime Crust Zone (PCZ).

Global production of cobalt from 1996 to 2018 in tons.

The increase in demand reflects the increased use of cobalt in lithium-ion batteries (e.g. for electric vehicles). Source: USGS Mineral Commodity Summaries for Cobalt (1997-2019)

22,8 % Manganese

0,7 % Cobalt
0,4 % Nickel
0,2 % R. earth
0,1 % Copper

16,0 % Iron

58,9 % Oxygen, Silicon, etc.

Average metal content of cobalt-rich crusts in the Prime Crust Zone. Source: Hein and Koschinsky, 2014

Sample from approxiamtely 1,700 metres water depth from a seamount of the Louisville chain in the southwest Pacific. The crusts from this region contain up to 1.6 percent cobalt and are significantly enriched in rare earth elements, molybdenum and titanium. Photo: BGR

The rare earth elements are enriched in cobalt-rich crusts, and their concentration of, on average, 0.16 to 0.25 percent is even higher than that in manganese nodules. This makes cobalt-rich crusts an interesting source of raw materials for high-tech metals and applications in environmental and energy technology. Other metals, such as molybdenum and tellurium, occur predominantly in trace concentrations of a few grams per ton. Whether such concentrations are economically recoverable is still being investigated.

Estimates of the tonnage of the crusts in the Prime Crust Zone alone reach over 7.5 billion tons, which contain about four times more cobalt and nine times more tellurium than the known reserves of these metals on land. Similar to the manganese nodules, the cobalt-rich crusts are a raw material whose marine extraction could provide a secure supply for the industry for many years. However, direct sampling and measurement of the thickness of cobalt-rich crusts is difficult, as rocks have to be torn off or drilled out. The local variability in grade and tonnage is hardly known, and the punctual examination is extremely complex and expensive. Precise instruments, which could measure the thickness of the crusts to the centimetre and distinguish them from the underlying substrate rock, do not yet exist.

Unlike manganese nodules, most of the economically interesting crust deposits are not found in international waters of the high seas, but in the EEZ of various island states. Only the respective governments can decide on future mining. However, there are currently no concrete plans in any of these countries. Since 2012, the International Seabed Authority has had a binding set of rules on exploration for crust deposits in international waters. Since then, China, Japan, Brazil, Russia and, since 2018, Korea have acquired exploration licenses for cobalt-rich manganese crusts. However, only concepts for possible mining equipment are available, and industrial-scale tests have not yet taken place.

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Cobalt-rich crusts are a promising seabed resource as they contain large amounts of cobalt, nickel, manganese and other metals, some of which could exceed the contents of land deposits. However, there are only a few occurrences in international waters for which exploration licenses have been applied for. Since cobalt-rich crusts are firmly attached to the rocky substrate, they cannot simply be picked up from the seabed like manganese nodules, but would have to be separated from it at great expense. The direct environmental impact of mining is assumed to be similarly serious to that of massive sulphides and manganese nodules, although, compared to manganese nodules, only smaller mining areas would be affected.

During a MiningImpact expedition, the manipulator arm of the deep-sea robot ROV KIEL 6000 collects a manganese nodule with a sponge attached to it for later analysis in the laboratory. Photo: ROV-Team, GEOMAR

Environmental Impacts of Deep-Sea Mining

The ore deposits of the deep sea differ in many respects, such as their area, chemical composition and biological habitat. Nevertheless, fundamental environmental impacts from future deep-sea mining operations can be defined.

With the mining methods currently under discussion (see also pages 30-31), the extraction of metal ores removes the seabed surface together with the fauna living on and within it. In addition, the mining equipment suspends the sediments of the seabed as well as small particles of ore material. This creates plumes of smallest particles, only a few hundredths of a millimetre in size, which are drifting with the bottom currents even to areas outside the mined area, where they are deposited on the seabed blanketing its fauna. This means that the impacted area of the seabed is expected to be many times larger than the actual mining area.

The environmental impact caused by deep-sea mining is present for many decades to even centuries. The impacts consist mainly in the loss of habitat on the seabed, in greatly reduced population densities of all faunal classes from microorganisms to megafauna, in a changed composition of faunal communities and in reduced ecosystem functions such as productivity and nutrient fluxes.

Scientific investigations in recent years have also shown that manganese nodule fields represent a very special deep-sea ecosystem. Both, the biodiversity and the abundance of organisms are much higher in the manganese nodule habitat than in the soft abyssal seabed without manganese nodules.

Sponge covered with sediment documented in the DISCOL area. In 1989, seafloor disturbances simulating some effects of deep-sea mining were introduced there. Sponges are important host organisms for mobile fauna, such as brittle stars, isopods, or barnacles, and contribute significantly to nutrient cycles in benthic marine ecosystems. The photos were taken in 2015 by ROV KIEL 6000 during the SONNE expedition SO242.

Manganese nodules on the seafloor of the Pacific Ocean form a very special abyssal ecosystem with a very large biodiversity and abundance of fauna. Among other things, they provide an important breeding ground for deep-sea octopods. The octopods attach their eggs to stalked sponges, which only grow attached to the manganese nodules. They hatch their eggs hanging from the stalk probably for several years and die afterwards. Researchers observed this previously unknown octopod species in 2015 in the Peru basin in a water depth of more than 4,000 metres - a new depth record for this species. Their special dependence on manganese nodules as breeding grounds emphasizes that industrial mining of valuable metals in the deep sea must be preceded by thorough investigations of the ecological consequences.
Photo left: ROV-Team / GEOMAR, photo right: AWI-OFOS Launcher team

Regulations for Deep-Sea Mining

In the 1970s there was, for the first time, a great interest in the raw materials of the deep sea. This phase of euphoria and the fear of exploitation of the oceans by the industrialized countries at the expense of humanity finally led to the 1982 United Nations Convention on the Law of the Sea (UNCLOS), in which the resources of the deep sea were defined as the common heritage of mankind. In 1994, the United Nations established the International Seabed Authority (ISA) to administer and regulate marine mining.

Exclusive Economic Zones (EEZ) and "the Area"

According to UNCLOS, deep-sea mining in "the Area" may only take place if it benefits humankind as a whole. For this reason, the constitution for the seas has been adapted so that a coastal state has access not only to its territorial waters (12 nautical mile zone) but also to the EEZ. Within this extended zone of 200 nautical miles, a country has access to the water column and the seabed. All areas beyond national jurisdiction (ABNJ) are called "the Area". According to Article 136 of UNCLOS, this area is considered the common heritage of mankind. This is where the competence of the International Seabed Authority to issue exploration and, in the future, exploitation licences begins. Of the total area of the ocean, 50 percent are currently subject to international UN legislation, 41 percent belong to the EEZ of individual coastal states, and 9 percent are covered by the current applications for the extension of the continental shelf. As far as marine raw materials are concerned, one half of the ocean is still under international administration.

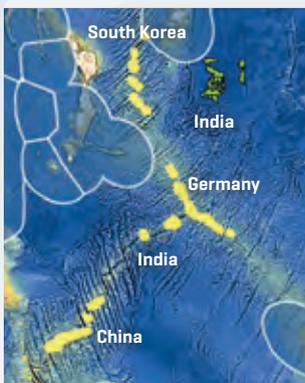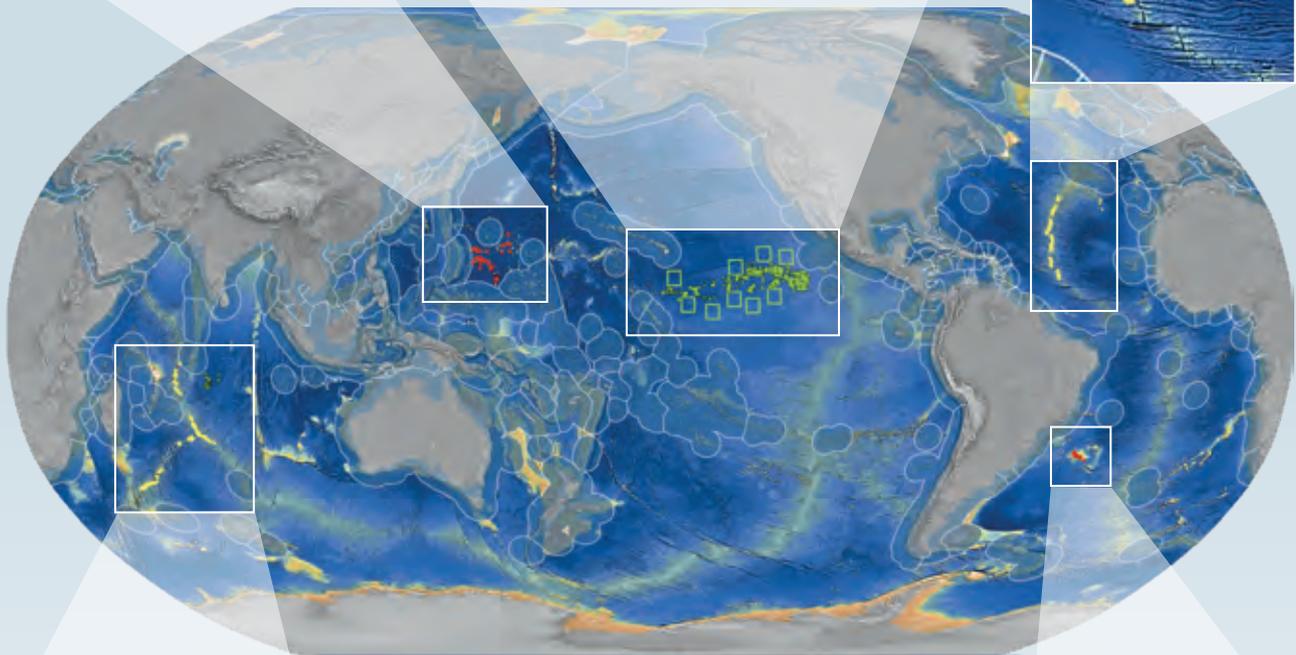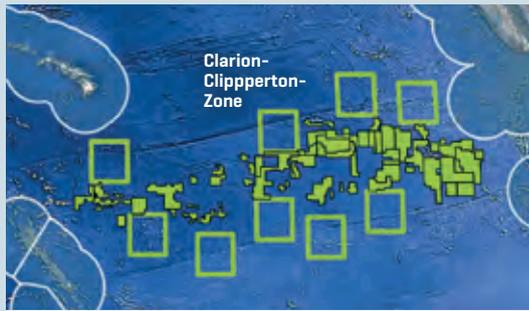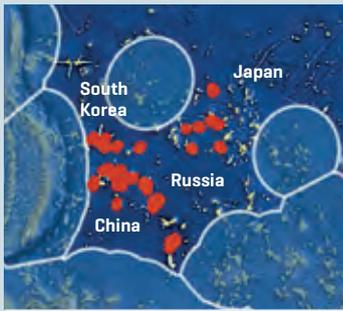### The International Seabed Authority (ISA)

The ISA, based in Jamaica, is an independent international organisation with168 member countries and the EU. It regulates and monitors all activities for the economic use of the seabed and its subsoil in "the Area". The ISA is currently developing the so-called "Mining Code". This will regulate the exploitation of mineral resources from the seabed in "The Area", i.e. beyond the areas of national jurisdiction. The current draft regulations from 2019 also contain environmental standards and threshold values to comply with as well as guidelines for environmental monitoring of mining operations.

Allocation of raw material licence areas

As deep-sea mining in "the Area" is not yet permitted, the central task of the ISA is to administer exploration licenses, update the rules for exploration and develop rules for exploitation. Both, public and private companies can apply for an exploration license. Licence applications must be endorsed by their home country. The approving state, which must have enacted a suitable marine mining law, checks compliance with the suitability requirements and the financial and technical performance of the company. It is obliged to actively monitor and is liable for this activity.

By mid-2019, 29 exploration licenses have been granted, 17 for manganese nodules, 7 for massive sulphides and 5 for cobalt-rich crusts. The contractors come from 20 different countries, 12 from Asia, 12 from Western and Eastern Europe, 4 from Pacific Island states and one from South America. Of the licence areas for manganese nodules, 16 are located in the Clarion-Clipperton-Zone in the eastern Pacific Ocean, which is considered the most economically interesting region for this raw material due to its rich manganese nodule deposits with high metal contents. India's license area is located in the central Indian Ocean. Three licence areas for massive sulphides are located on the Mid-Atlantic Ridge and four areas on the Southwest Indian and Central Indian ridges. Of the five license areas for cobalt-rich crusts, four are located in the Northwest Pacific and one in the South Atlantic off the coast of Brazil.

Each exploration license has a term of 15 years with the possibility to be extended several times for 5-year periods. Concurrently, a license grants priority to subsequent mining activities and also entitles the holder to test technology, e.g. for exploitation. The contracts contain work plans for the entire 15 years, which must be updated every 5 years and implemented by the contractors. Each contractor is obliged to submit an annual report on his exploration activities to the ISA. Furthermore, the contracts contain a programme for the training of trainees from developing countries by the contractors.

Current License Areas

Global map of the exploration areas for manganese nodules (green), cobalt-rich crusts (red) and massive sulfides (yellow) issued to date by the International Seabed Authority. The EEZ of the coastal states are bordered in white. The enlarged map sections show the five regions with the license areas, including the states in favour of mining of crusts and sulphides. The map of the Clarion-Clipperton-Zone shows the exploration areas for manganese nodules in green as well as the nine protected areas (squares bordered in green). The selection of the protected areas was determined within the framework of an ISA environmental management plan. Map: Sven Petersen/GEOMAR

A detailed overview of the current contractors in the individual areas by the International Seabed Authority can be found here: www.isa.org.jm/contractors/exploration-areas

Deep-Sea Mining Technologies

The extraction of raw materials from the deep sea represents a large technical and logistical challenge. So far, mainly concepts and small-scale studies exist, but only a few mature devices and systems. It is still a long way to go before industrial exploitation can begin.
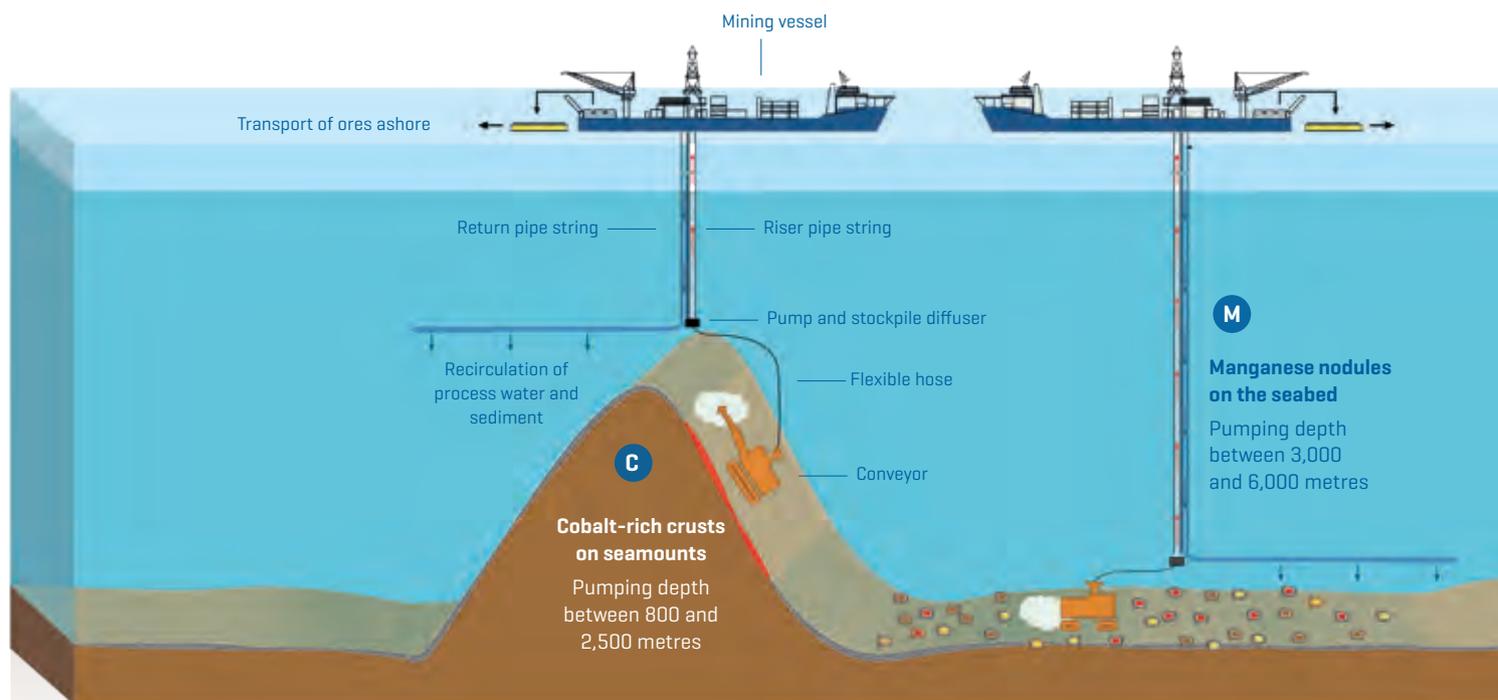
(C) Cobalt-rich Crusts

The challenges for the exploitation of cobalt-rich crusts are higher than for massive sulphides. The terrain is much more difficult, and the cobalt-rich crusts must be separated from the underlying substrate rock so that the ore is not diluted. So far only concepts for mining equipment seem to exist. Similar to the other two raw materials, the ore is to be conveyed to the ship via a pump-supported pipe string.

(M) Manganese Nodules

The first technologies for mining of manganese nodules were successfully tested in the 1970s. In modern concepts, manganese nodules are harvested by collector machines, i.e. crawlers that scrape the manganese nodules from the seabed. The nodules are then transported by pump systems through a pipe string, a so-called riser, to the mining vessel. On board the ship, the nodules are separated from the water and the sediments and then loaded onto transport ships bringing the ore ashore for processing. The wastewater and sediments are pumped back close to the seabed to minimize the spread of these sediment plume. In recent years, great efforts have been made to advance this technique and test prototypes. The existing mining equipment that is currently tested, although several metres wide and several metres long, is still considerably smaller than the industrial collectors that will ultimately be used.

Mining technologies for marine mineral resources.
Source: GRID Arendal 2013 [www.grida.no/resources], edited by Christoph Kersten/GEOMAR

Mining vessel

Transport of ores ashore

Return pipe string — Riser pipe string

Pump and stockpile diffuser

(M) Manganese nodules on the seabed

Pumping depth between 3,000 and 6,000 metres

Recirculation of process water and sediment

Flexible hose

(C)

Conveyor

Cobalt-rich crusts on seamounts
Pumping depth between 800 and 2,500 metres

S Massive Sulphides

Collectors are also to be used for the mining of massive sulphides. However, these crawlers not only have to pick up the material but also to break up the rock on the seabed. For this purpose, grinding machines will be used, similar to those used in tunnel construction. In addition, the massive sulphides are often present as three-dimensional mounds. The excavation equipment must therefore work its way into the terrain. The first mining equipment has already been built on a 1:1 scale and was tested on the seabed in Japan's territorial waters. In addition, several excavation machines have been completed by a Canadian/Australian company that had planned to start excavating massive sulphides in the territorial waters of Papua New Guinea in 2020. However, the company has been liquidated in the course of financial insolvency. Similar to the other two raw materials, the ore is pumped to the ship via a pipe string.

Massive sulphides at plate boundaries or hotspots

Pumping depth between 1,000 and 3,500 metres
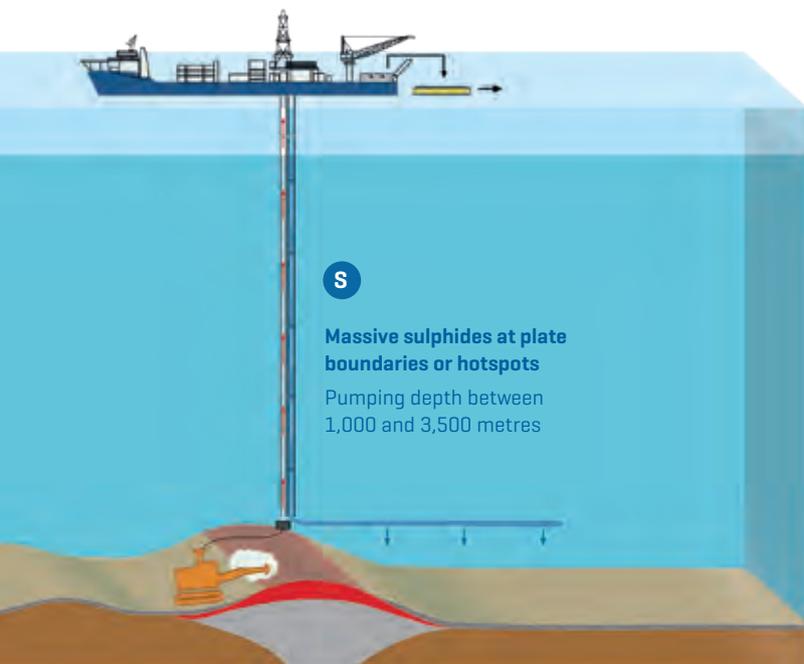
The deep-sea mining process using the planned exploitation of massive sulphides off Papua New Guinea as an example.

1: Crawlers are released from the mining vessel, which also contains the extraction system and ore storage tanks.

2: The rock cutter is used to break up the massive sulphides on the seabed.

3: The collector collects the broken ores and pumps them via the riser up to the mining vessel.

4: On the vessel, the ores are separated from seawater and sediment and transported to the storage tanks.

5: The massive sulphides are transferred to a transport vessel which brings the ores ashore for further processing. Picture series: © Nautilus Minerals

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An elevator lander on the seabed of the DISCOL area.
With this device, several experiments can be carried out simultaneously on the seabed. In the foreground: Manganese nodule held by the manipulator arm of ROV KIEL 6000. Photo: ROV-Team/GEOMAR

Sensor instruments deployed on a plough track.
Different biological, chemical and oceanographic data were collected inside and outside the plough tracks. The investigations showed that after 26 years even bacterial activities in the tracks are still reduced by about 30 percent compared the undisturbed seabed. Photo: ROV-Team/GEOMAR

In 1989, during the DISCOL project, researchers towed a plough-harrow 78 times across the abyssal seafloor. Using the ABYSS autonomous underwater vehicle, the researchers were able to produce high-resolution maps that show the precise location of the tracks after 26 years. Source: GEOMAR

Monitoring of the Environmental Impacts of Deep-Sea Mining

What consequences for the abyssal ecosystem result from mining of metal resources in the deep sea? How can the unavoidable environmental impacts be kept to a minimum? Which environmental standards and threshold values can be defined? And how can compliance with mining regulations be monitored? The international project MiningImpact, coordinated at GEOMAR with researchers from 11 European countries, aims to assess the long-term impacts and environmental risks of deep-sea mining of manganese nodules. In 2015, three expeditions were carried out in the Clarion-Clipperton-Zone (CCZ) and in the DISCOL area in the Peru Basin to investigate the ecosystem's response to seafloor disturbances after several decades. During another expedition in 2019 technology for the environmental monitoring of deep-sea mining activities developed at the institutes was tested.

ROV Kiel 6000 returns from a mission. During SO242 a total of 23 dives amounting to more than 250 hours were carried out with the diving robot. Photo: Peter Linke/GEOMAR

Flashback, 1989, DISCOL project (DISturbance and re-COLonisation): German marine scientists are conducting an unique experiment. They plough about eleven square kilometres of seabed in a deep-sea plain far offshore Peru. They remove manganese nodules from the surface, suspend the sediment, and destroy the fauna on a small scale. All of this serves a scientific purpose — the scientists want to find out what ecological consequences manganese nodule mining would have, how long it would take for the ecosystem to recover, and if it would be possible to manage deep-sea resource extraction in an environmentally friendly way.

First inspection of manganese nodules on board RV SONNE.
The manganese nodules are measured and weighed, and the fauna growing attached to them is determined and counted. Photo: Bastian Barenbrock

Prototype collector Patania II of the Belgian company DEME-GSR.
The function of this prototype of an industrial manganese nodule collector will soon be tested in the license areas of the CCZ. Photo: DEME-GSR

26 years later, in 2015, state-of-the-art technologies helped an international research team to assess the possible longer-term consequences of mining. During the SO242 expedition with the research vessel SONNE, precise maps of the plough tracks on the seabed were produced. Photos and videos gave the researchers a comprehensive and detailed impression of the environmental impact. The diving robot ROV Kiel 6000 was used to collect targeted samples from the disturbances, measure microbial activities and carry out toxicological experiments on the seabed at a depth of more than 4,000 metres.

The main results that were derived by the MiningImpact project from investigating these small seabed disturbances with respect to the anticipated much larger future industrial-scale deep-sea mining operations are that the environmental impacts will be long-term and will affect all ecosystem compartments. For many decades to centuries, the composition of faunal communities will be altered, and population densities and biodiversity of fauna as well as ecosystem functions such as productivity and microbial activity will be greatly reduced.

An environmental risk that has been difficult to assess so far is the spread of the suspended sediment plumes and the additional impact area at the seabed resulting from it. In spring 2019, MiningImpact therefore carried out extensive tests of sensors and methods for environmental monitoring in some licence areas of the CCZ.

Due to the sustained destruction of the deep-sea ecosystem in the mining areas and their vicinity, the international regulations of ISA must therefore include not only strategies for comprehensive environmental monitoring but also concepts for environmental management and adaptive spatial planning. This poses a major challenge because the deep-sea and in particular the manganese nodule habitats are highly diverse and variable and species connectivity over long distances is not understood at the moment. The MiningImpact project develops proposals for solutions.

Stalked sponges form an important structure in the manganese nodule areas. The sponge stalks are attached to the manganese nodules and serve as specific habitat for other deep-sea fauna. Among others, brittle stars, barnacles, and isopods live on these up to one metre long structures. Photo: ROV-Team/GEOMAR

Link Tips

Deep Sea Minerals: A physical, biological, environmental, and technical review

The English brochure series, in which a network of around 60 leading experts was involved, was compiled in 2013 as part of the European Union-funded project "Deep Sea Minerals in the Pacific Islands Region: a Legal and Fiscal Framework for Sustainable Resource Management Project". Volumes 1A, B and C examine the geology and related biology of the three major deep-sea mineral deposit types in the Pacific and the ecological and technical aspects of their production. Volume 2 deals with the socio-economic, legal and fiscal aspects of deep-sea mining.

Website, PDF-Download: www.grida.no/publications/184
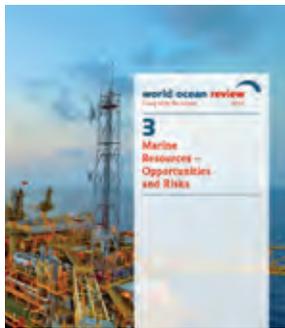
WOR3: Marine Resources – Opportunities and Risks

The "World Ocean Review" is a unique publication about the condition of our seas and reflects the current state of science. Published in 2014, the third edition is dedicated to the metallic and energetic resources of the ocean and their use. In addition to facts about the exploitation of known oil and gas deposits below the seabed and the formation and potential of gas hydrate deposits on the continental margins, WOR3 provides detailed information about the opportunities and risks of using mineral resources: manganese nodules, cobalt-rich crusts and massive sulphides.

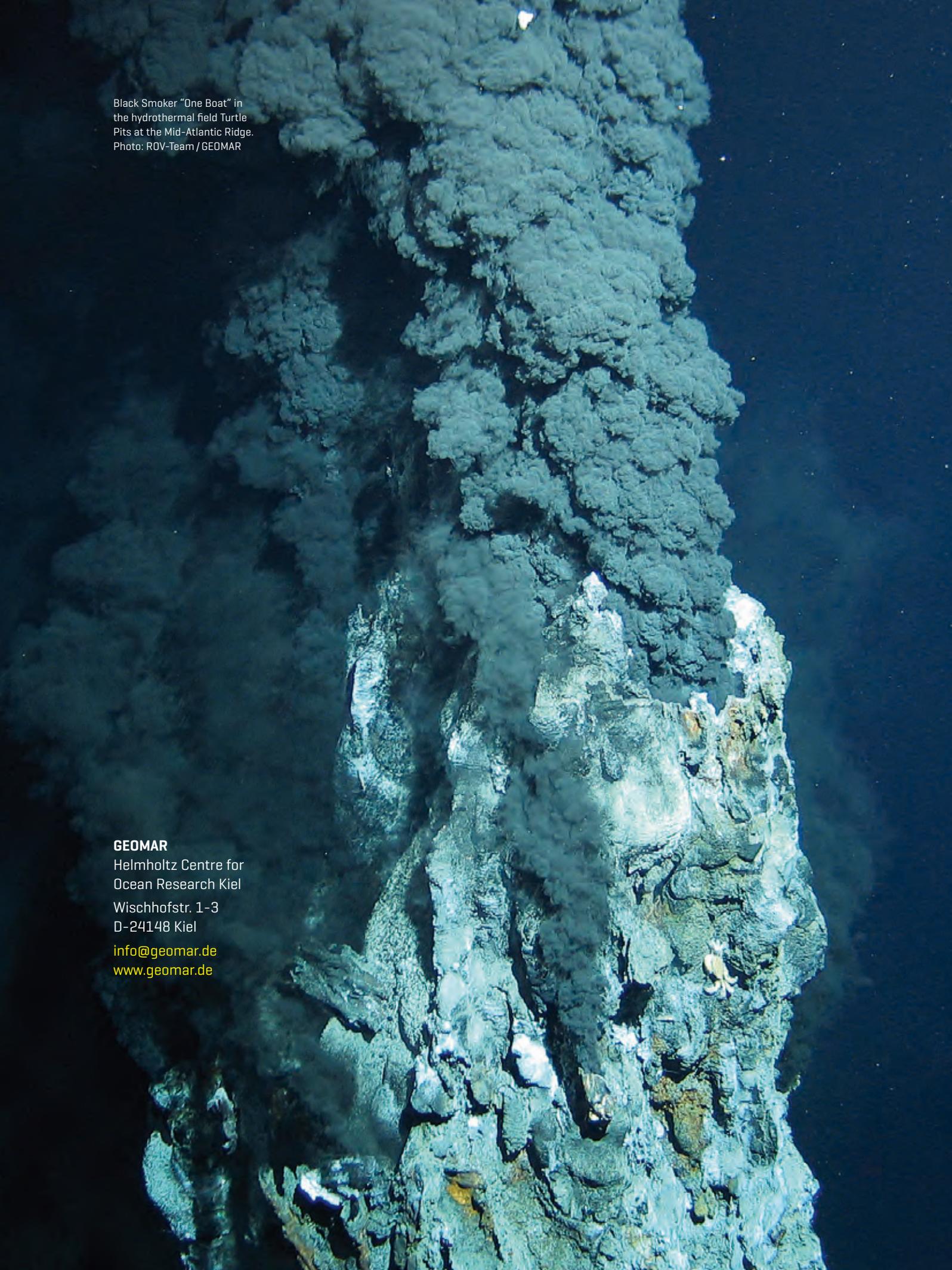Website, PDF-Download: https://worldoceanreview.com/en/wor-3

Cross-section through a manganese nodule in the scanning electron microscope.

A rock fragment serves here as the nucleus for the deposition of minerals. The fine layers show the different growth periods over time. Visualisation: Sebastian Fuchs/GEOMAR

Size (mm)	5	10	15	20
Age (Mio. Years)	1	2	3	4

Black Smoker "One Boat" in
the hydrothermal field Turtle
Pits at the Mid-Atlantic Ridge.
Photo: ROV-Team / GEOMAR

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