

2 Sea-floor mining



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



Resources for the world

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

Ore, mica, sand and gravel

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

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

Nearly all the mineral resources used today are derived from onshore deposits. Depending on the deposit concerned, these are extracted from underground mines or open-cast mines using enormous excavators

and wheel loaders. Sand and gravel are the exception, as these have for some time now been exploited not only onshore but also from shallow marine areas.

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

Fear of supply shortages

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

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

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

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

Rare earth metals

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



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

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

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

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

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

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

Measuring uncertainty

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

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

- Voice and accountability: measures perceptions of the extent to which a country’s citizens are able to participate in selecting their government, as well as freedom of expression, freedom of assembly and a free media;
- Political stability and absence of violence: measures perceptions of the likelihood of a government being destabilized by violence, political violence or terrorism;
- Government effectiveness: measures the quality of public services, the civil service and the degree of its independence from political pressures;
- Regulatory quality: measures perceptions of the ability of the government to formulate and imple-

How much metal does the ore contain?

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

ment sound policies and regulations that permit and promote private sector development;

- Rule of law: measures perceptions of confidence in and adherence to the rules of society, and in particular the quality of contract enforcement and property rights. It also measures the quality of the police and the courts, as well as the likelihood of crime and violence;
- Control of corruption: measures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the influence of elites and private interests.

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

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

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



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

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

If the resources are assessed according to both the weighted country risk and the HHI at the same time, they can be classified into 3 different risk groups: low risk, moderate risk and high risk resources. Copper is considered a low risk resource. It has a low country risk value and at the same time low corporate and country

concentration ratios. This is because copper is produced in politically stable countries, by a range of different companies.

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

How long will resources last?

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

Geoscientists are trying to answer this question by gauging the reserves and resources of the various sub-

stances. Essentially we know where certain ores can be anticipated, because resources usually occur in characteristic geological formations, the worldwide distribution of which is relatively well known.

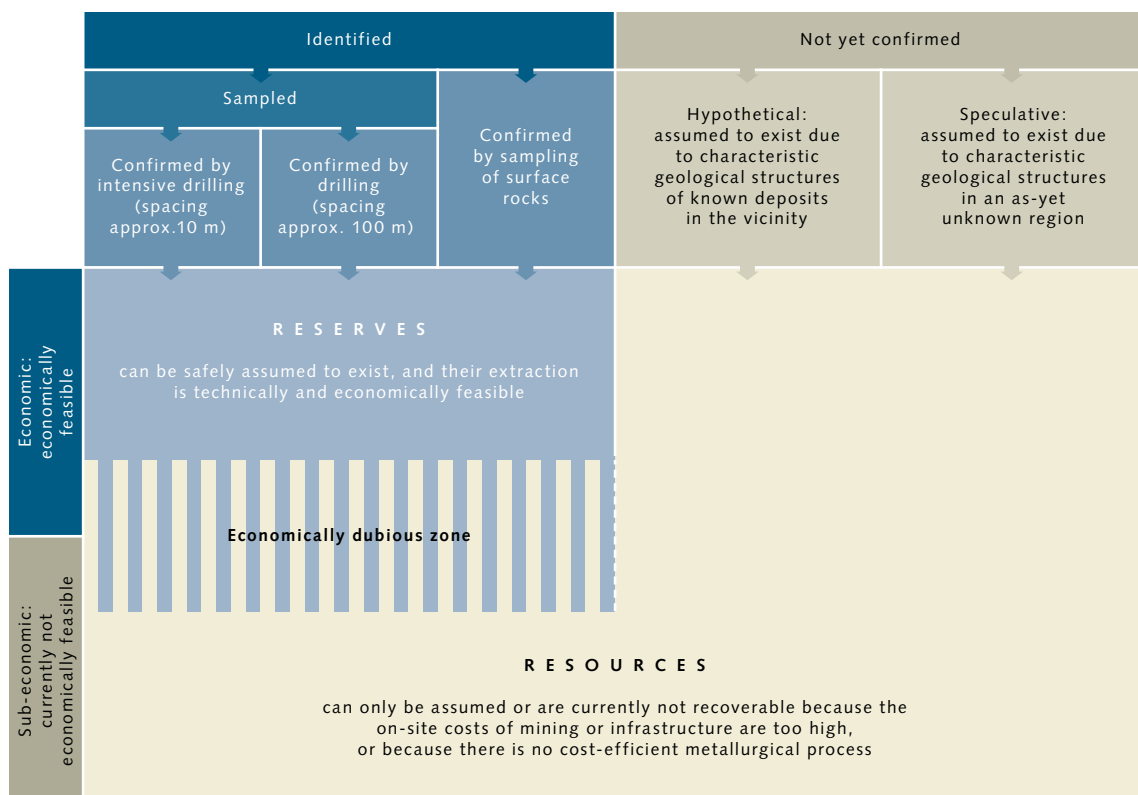
Platinum for example occurs mainly in the Bushveld Complex of South Africa in a layered igneous intrusion. This is a layer of rock caused by magmatic activity which has penetrated the adjacent rock strata. Platinum in such intrusions is also found in some other regions of the world. However, the platinum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

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

No such testing has as yet been carried out in many regions of the world because the exploration of new deposits in unknown terrains is extremely expensive

and complicated. For this reason interest has mainly been focused on areas in the vicinity of known occurrences. Major tracts of Australia, Canada, South America and West Africa remain largely unexplored. Assessing worldwide occurrences is therefore a very unreliable undertaking. Occurrences are classed into different categories, depending on the extent to which an area of land has been sampled or developed:

- **RESERVES:** Reserves are occurrences of resources which have already been proven and their extraction is economically feasible using current technology.
- **RESOURCES:** An occurrence is described as a resource when its metal content and volume have not yet been proven by sampling, or when its extraction and processing are economically unfeasible. One example is nickel laterite ore, a special type of nickel ore found in the residual soils of tropical and



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

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



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

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

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

cast mines will be developed onshore, because of their drastic intervention in landscapes.

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

Recycling rather than discarding?

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

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

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

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

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

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

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

- The development of new systems to recover industrial production waste;
- The introduction of recycling bins for private households;
- The priority development of recycling processes for metals at a high risk of shortages (country risk, country concentration);

- The creation of economic incentives to spur a functioning recycling market which specializes in resources from consumer goods, end-of-life vehicles and electronic scrap.

Could sea-floor mining be the answer?

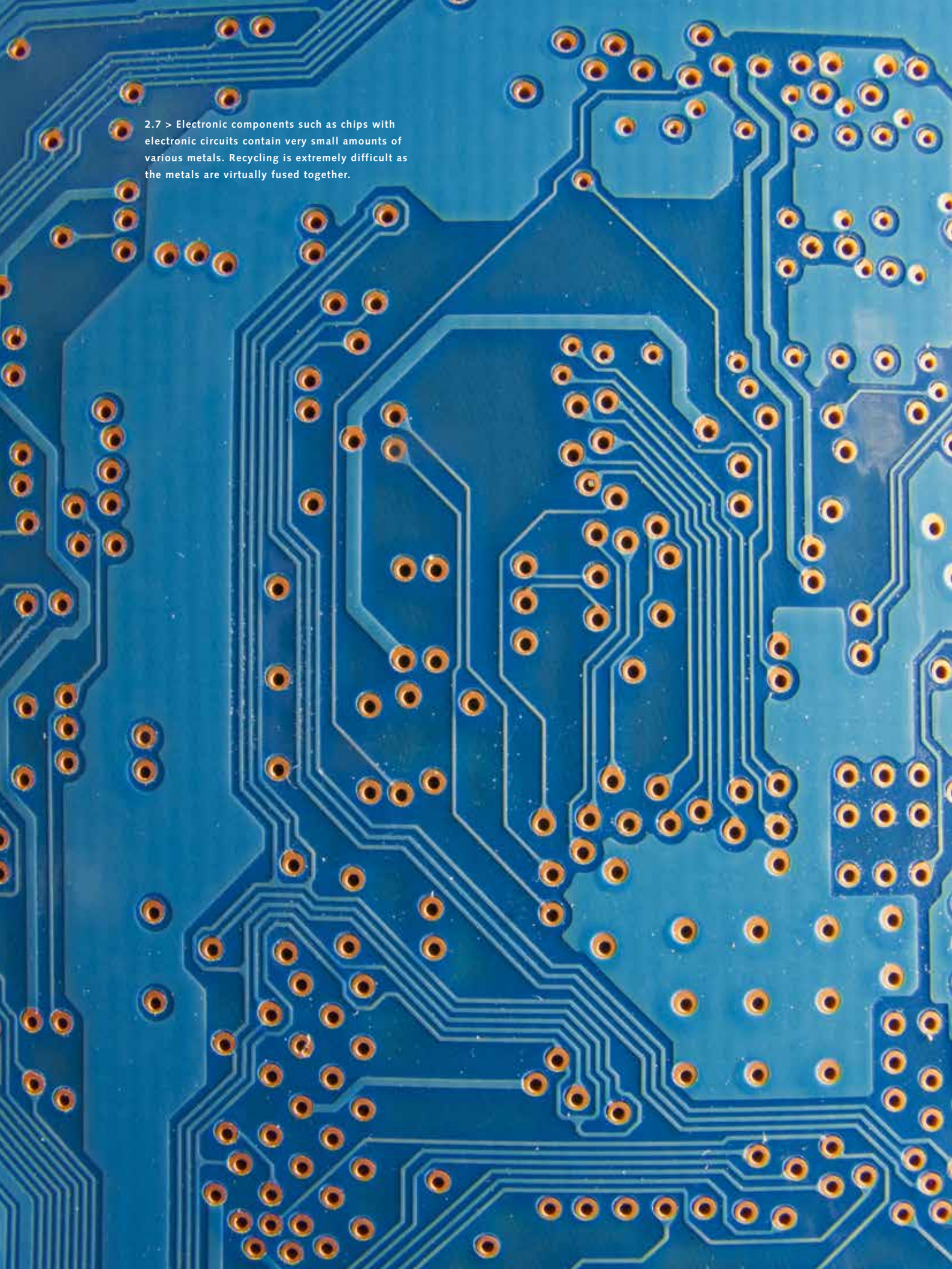
To make future resource supplies more secure, sea-floor mining could offer many states and companies a potential alternative, for both economic and geopolitical reasons. It would avoid the land-use conflicts which underground and surface mining bring in their wake, and could also help many nations without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

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

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

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





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

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

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

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

- **MANGANESE NODULES:** Manganese nodules are lumps of minerals ranging in size between that of a potato and a head of lettuce. They cover enormous areas of the seabed of the Pacific and Indian Oceans. They are composed mainly of the chemical elements manganese, iron, copper, nickel and cobalt along with other substances such as molybdenum, zinc and lithium. Manganese nodules are mostly found at depths below 3500 metres.
- **COBALT CRUSTS:** Cobalt crusts are incrustations of minerals which form on the sides of submarine mountain ranges and seamounts. They develop as a result of the accumulation of minerals dissolved in the water and contain mainly manganese, iron, cobalt, nickel, platinum and rare earth elements. Cobalt crusts are found in the western Pacific at depths of 1000 to 3000 metres.
- **MASSIVE SULPHIDES:** Massive sulphides accumulate mainly at the openings of hot vents on the ocean floor. In these regions cold seawater penetrates through cracks in the sea floor at depths of up to several kilometres. The water near magma chambers then heats up to temperatures exceeding 400 degrees Celsius. As it does so, metalliferous minerals are released from the rock. Upon warming the

solution rises rapidly and is extruded back into the sea. As soon as this solution mixes with the cold seawater, the minerals form a precipitate which accumulates around the hydrothermal vents in the form of massive ore deposits. Massive sulphides are found in many places on the sea floor which are or used to be volcanic. Depending on the region, they contain widely different amounts of copper, zinc, lead, gold and silver, as well as numerous important trace metals such as indium, germanium, tellurium or selenium.

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

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

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

Sand, gravel and phosphate from the sea

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

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

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

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

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

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

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

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

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

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

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

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

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



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



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

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

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

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

For more than 10 years now sand has been illegally removed from Moroccan beaches and sold to other countries for concrete manufacture. This has transformed some beach areas into lunar landscapes.

The tourism industry fears that damage to its reputation and financial losses may follow.

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

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

Manganese nodule treasures

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

Metal-rich clumps

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

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

Four major occurrences

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

CLARION-CLIPPERTON ZONE (CCZ): With an area of around 9 million square kilometres, approximately the size of Europe, this is the world's largest manganese nodule region. The CCZ is located in the Pacific, extend-

ing from the west coast of Mexico to Hawaii. The nodules are not evenly distributed over this area. At some sites they are more densely grouped. No nodules at all are found in stony areas. On the average, one square metre in the Clarion-Clipperton Zone contains around 15 kilograms of manganese nodules. Especially rich areas can have up to 75 kilograms. The total mass of manganese nodules here is calculated to be around 21 billion tonnes.

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

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

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

How nodules grow

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

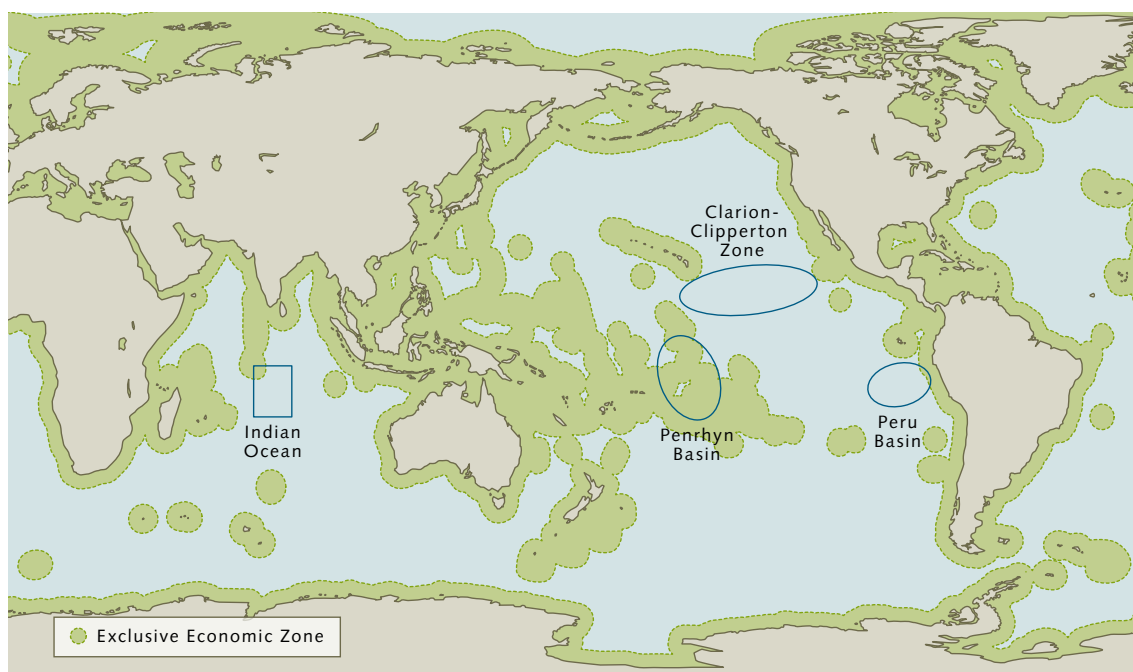


2.10 > Slice through a manganese nodule: Over millions of years minerals are deposited around a core.

Metal content of manganese nodule occurrences in millions of tonnes

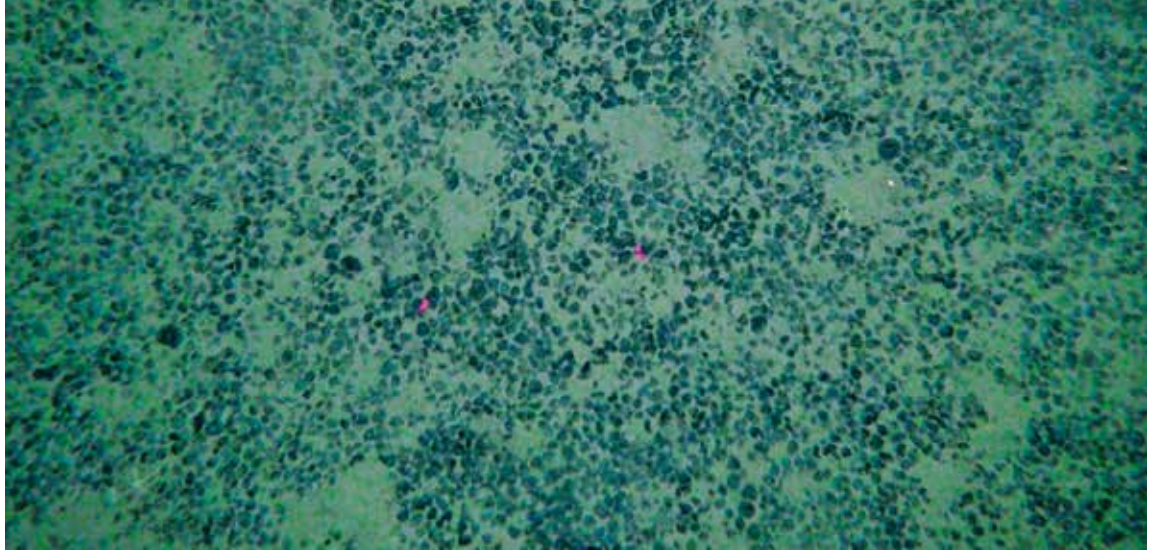
Elements	Clarion-Clipperton Zone (CCZ)	Global reserves and resources on land (both economically recoverable and sub-economic reserves)	Global reserves on land (economically recoverable reserves today)
Manganese (Mn)	5992	5200	630
Copper (Cu)	226	1000+	690
Titanium (Ti)	67	899	414
Rare earth oxides	15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

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



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

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



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

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

Most nodules grow both hydrogenously and diagenetically, whereby the relative influence of each process varies in different marine regions. It is fascinating how extremely slowly the manganese nodules grow. In a million years their size increases on the order of millimetres. Hydrogenous nodules grow up to 10 millimetres per million years, while diagenetic nodules grow between 10 and 100 millimetres. This means that man-

ganese nodules can only grow in areas where the environmental conditions remain stable over this kind of time scale. The following factors are essential for the formation of manganese nodules:

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

Furthermore, some researchers hold the opinion that bottom-dwelling organisms such as worms that burrow around in the sediment must be present in large numbers in order to constantly push the manganese nodules

up to the sediment surface. This hypothesis, however, has not yet been proven.

Different regions, different compositions

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

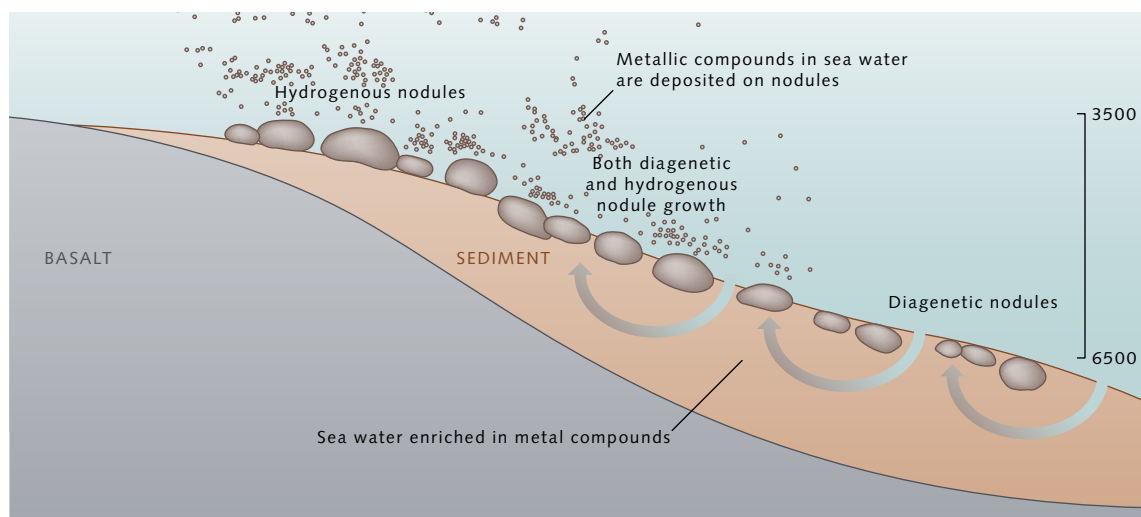
Nevertheless, given the large amounts of metals that are contained in the manganese nodules worldwide, it is certainly conceivable that the nodules may be mined in certain marine regions in the future. For many

countries that do not have access to their own land reserves, manganese nodules offer a way to become independent from imports.

Who owns resources in the sea?

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

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



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

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

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

* Grams per tonne ** Percentage by weight

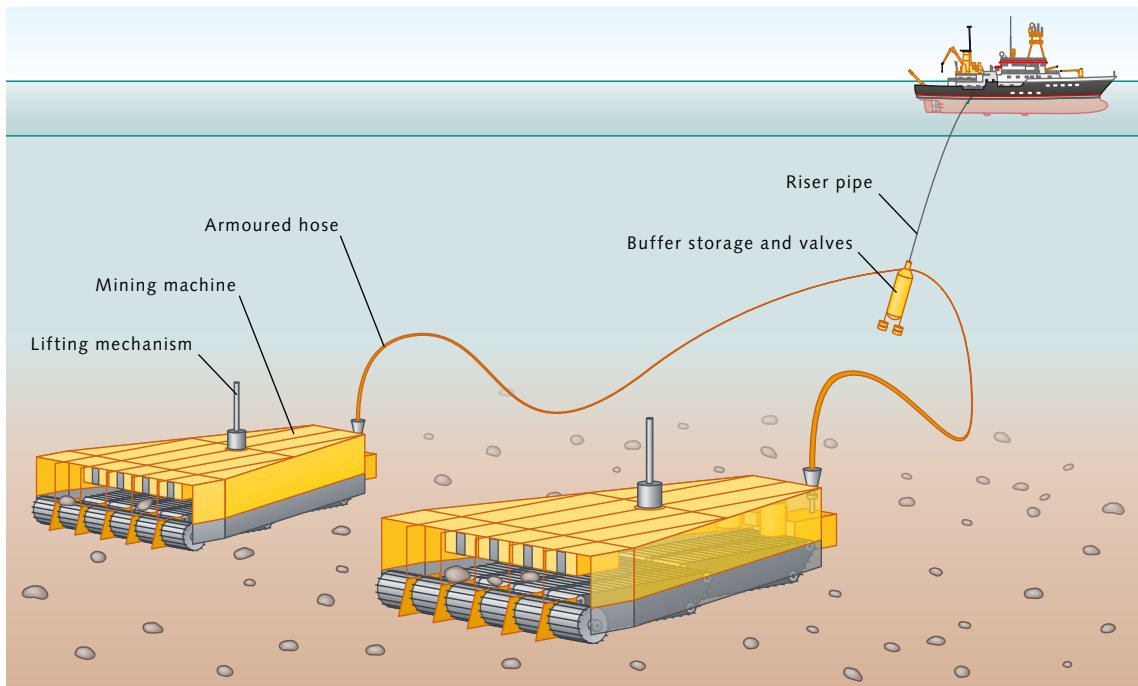
the promising resources in the deep sea by rich countries should be prevented.

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

Two commercial companies have recently joined the applicants: the British company UK Seabed Resources Limited and the Belgian G-TEC Sea Mineral Resources NV. Since 2011 a number of developing countries (Nauru, Kiribati and Tonga) have submitted applications in cooperation with industrialized-country companies.

These applications are related to areas explored by the original contractors and reserved for developing countries, which will now be consigned to Nauru, Kiribati and Tonga. The financial and technical means for further exploration and eventual development of these areas, however, will not be supplied by the 3 island nations but by the industry partners.

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



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

Mining machinery still not available

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

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

starting with the raising of up to 250-tonne machines to the surface.

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

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

Life in the manganese nodule fields

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

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

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

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

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

MEGAFUNA: This includes animals that can be seen with the naked eye on underwater videos or photographs, for example,

fish, sponges, sea cucumbers and starfish. These organisms are from 2 to over 100 centimetres in size.

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

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

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



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

Destruction of deep-sea habitats?

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

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

It is certain that these problems cannot be completely eliminated. However, discussions are presently underway about how to reduce them as much as possible. In any case, the ISA requires environmentally sound manganese nodule production. And solutions actually appear to be possible. According to recent studies, the sediment cloud can be reduced by using a cowed rather than open harvesting machine. This would, in part, prevent stirring up of the sediment into the water column. Furthermore, the sediment cloud released by the ship could be reduced by pumping it through pipes back to

the sea floor so that the particles settle relatively quickly. Engineers say, however, that this additional pipe system would make manganese production significantly more expensive. It is still not clear today how fast the habitats on the sea floor would rebound from this massive intervention. Several international projects have been carried out since the end of the 1980s to investigate the rate at which harvested areas of the sea floor would be recolonized. But these were quite small-scale interventions. For example, scientists in the German project Disturbance and Recolonization (DISCOL) ploughed up a sea-floor area of several square kilometres in the Pacific with experimental equipment and revisited the site over several years afterward. The results indicated that a period of 7 years were required before the ploughed area had adjusted back to the same density of bottom life as before. Yet some species had disappeared permanently, particularly those that were reliant on a hard substrate. This means that after 7 years the disturbed area was significantly species-depleted. In 2015, the German Federal Research Ministry will provide money for an expedition that will visit this area once again. Then, for the first time, the long-term effects will be observed after a period of 25 years. The DISCOL researchers stress that the damage caused by mining a large area of manganese nodules would be much greater. After all, in the experiment a comparatively small area was harvested. The disturbed area was resettled rather quickly from the undamaged surrounding areas. But if areas with many more square kilometres of sea floor are harvested, recolonization of the harvested areas would take many years longer.

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

Metal-rich crusts

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

Seamounts

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

A coating on the rocks

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

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

nese nodules. They will have to be laboriously separated and removed from the underlying rocks.

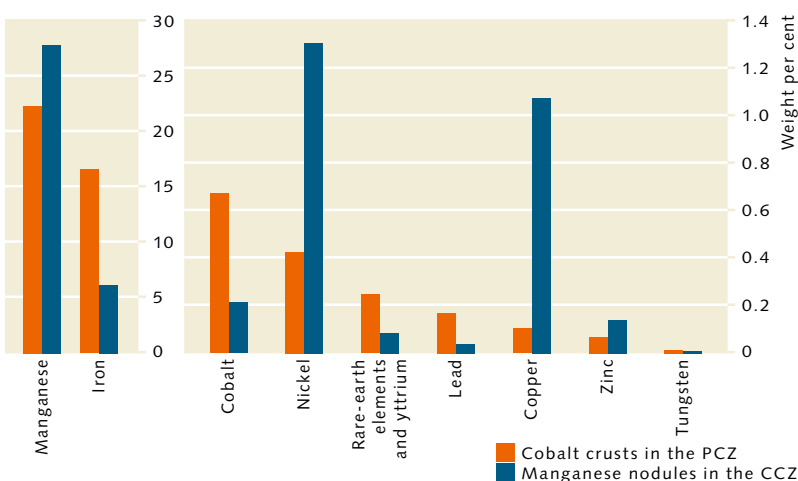
It has been estimated that there are over 33,000 seamounts worldwide. The exact number is not known. Around 57 per cent are located in the Pacific. The Pacific is thus the most important cobalt crust region in the world.

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

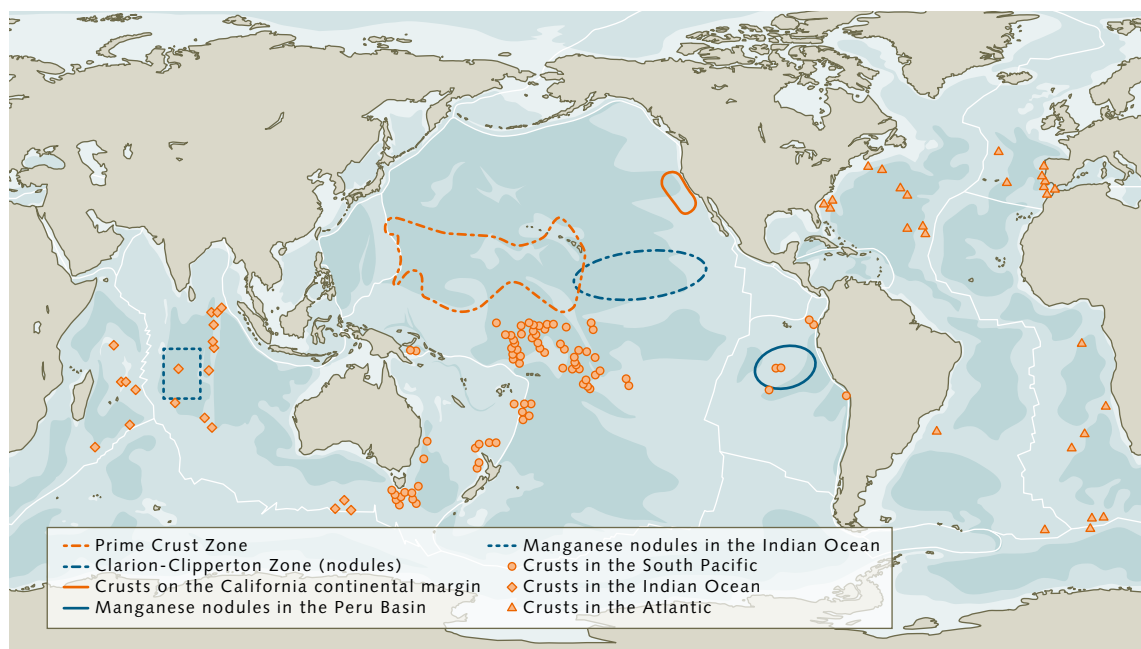
A metal-rich crust

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

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



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



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

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

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

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

Strong currents around seamounts

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

Deep oxygen enables crust growth

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

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

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

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

Like a sponge, or the activated charcoal used as a filter in aquariums, cobalt crusts are very porous. Thanks to the many micrometre-sized pores, the crusts have a large internal surface area. In the same way that pollutants are trapped in the pores of an activated charcoal filter, metal compounds are deposited on the large surface areas of the crusts. Because the dissolved metals occur at very low concentrations in sea water, growth of the crusts requires very long periods of time. The crusts are mainly formed through the deposition of iron oxide-hydroxide [FeO(OH)] and manganese oxide (vernadite, MnO₂). The other metals are deposited with the iron oxide-hydroxide and vernadite on the crust surfaces rather like hitchhikers. The reason is that, in the ocean, various metal ions attach themselves to the iron oxide-hydroxide and vernadite molecules in the water. Iron oxide-hydroxide is slightly positively charged and thus attracts negatively charged ions such as molybdate (MoO₄²⁻). Vernadite, on the other hand, is slightly negatively charged and attracts positively charged ions such as cobalt (Co²⁺), copper (Cu²⁺) or nickel (Ni²⁺).

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

Crust mining in sovereign territory?

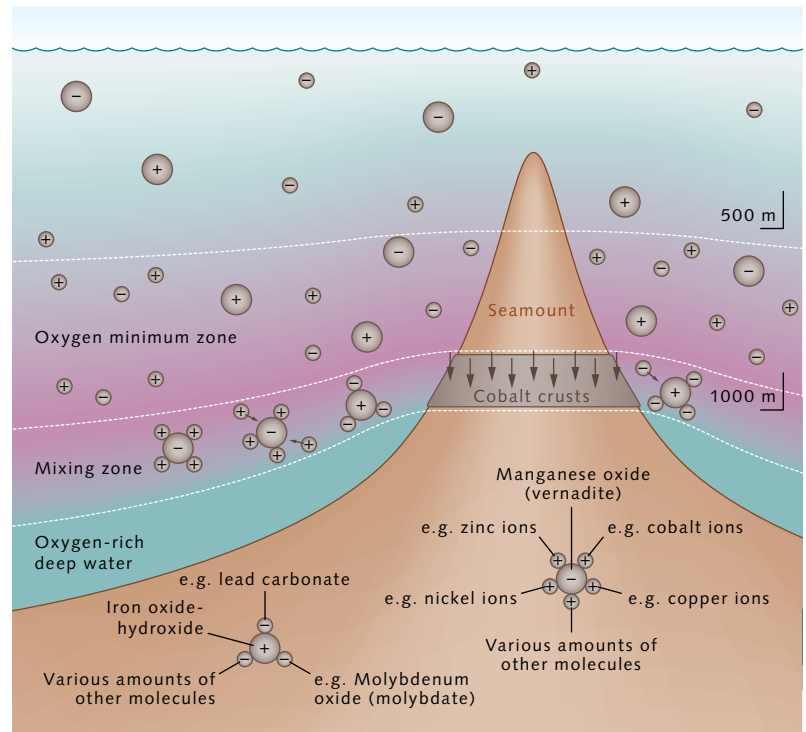
Manganese nodules and cobalt crusts are of equal interest for future marine mining because they contain traces of many industrially important metals that, because of the immense tonnage of the deposits, are of economic interest. But there are important differences with regard

to the exploration and future mining of the crusts. One of these, for example, is the legal situation. In contrast to manganese nodules, most of the richest crust occurrences are not found in the international waters of the high seas but in the Exclusive Economic Zones (EEZs) of various island nations. Thus the International Seabed Authority (ISA) will not be responsible for determining the conditions for future mining there. Rather, the respective local governments will have jurisdiction. However, to date no country has presented concrete plans.

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

Problematic thickness measurements

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

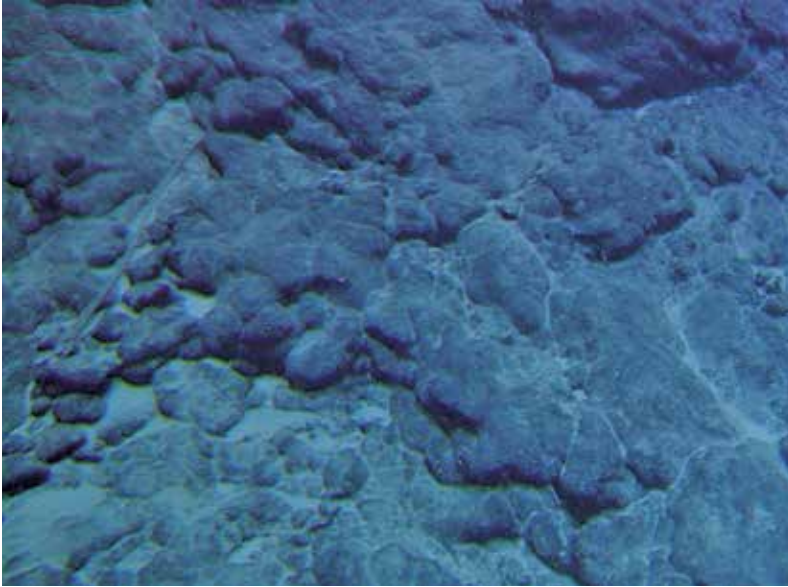


2.21 > Many metal ions end up in the cobalt crusts as “hitchhikers”. In the water, the metal ions attach themselves to iron oxide-hydroxide and vernadite molecules, and are then deposited onto the porous surfaces with them.

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

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

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



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

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

Little more than conceptual studies

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

this. Moreover, they will also have to be able to work on the rough terrain of the seamount flanks.

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

Species-rich seamounts

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

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

Seamounts are also important for free-swimming organisms. This is probably related to the special current conditions here. The circling currents, for one, tend to keep nutrients near the seamounts. Secondly, nutrient-rich water is upwelled at seamounts from near-bottom currents, which leads to increased plankton growth. Because of this abundant supply of food at sea-

mounts, both sharks and tuna are known to visit them frequently, for example in the southwest Pacific. These seamount areas are thus also very important for tuna fishing.

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

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

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

Studies off Australia and New Zealand have shown that fauna at seamounts recover very slowly from inter-



vention. For example, it has been shown that in areas where trawl nets have been used, even after an interlude of 10 to 30 years of inactivity, the fauna were significantly less species-rich than areas that had not been damaged by the trawl fisheries.

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

Scarcely studied – life on the cobalt crusts

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

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

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



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

Assessing the impacts of mining

Scientists call for more detailed studies of the habitats on seamounts with abundant cobalt crust deposits before submarine mining can even begin. This applies particularly to the island nations in the southwest Pacific, whose territorial waters contain the richest crusts. After the joint studies with Japan, SOPAC members are

now carrying out further research at seamounts that have been too poorly studied so far. Because cobalt crusts are limited to undersea rises, their extraction will be on a smaller scale compared to manganese nodules. The sediment cloud produced would also be significantly smaller than in the mining of manganese nodules, because no soft sediment would be stirred up. The details of cobalt crust mining impacts for the future are still unknown. According to experts, the following problems can be expected, which are very similar to those for manganese nodule mining:

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



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

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

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

Proponents of mining stress that manganese nodules and cobalt crusts are present as thin layers lying directly on the sea floor or on the flanks of seamounts. In contrast to ore deposits on land, they are thus a two-dimensional resource that can theoretically be extracted with relatively little effort. On land, on the other hand, ores are extracted from mines or gigantic open pits, in which machines dig more than 100 metres deep into the earth. For production of these three-dimensional reserves, millions of tonnes of earth (overburden) have to be removed and transported before the actual ore can be

extracted. This destroys entire regions and causes people to lose their homelands. Marine mining, however, would be a comparatively small intervention because only the surface of the sea floor or the seamount would be removed. There would be no need for infrastructures like streets or tunnels. There would also be no overburden piles.

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

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

Massive sulphides in smoky depths

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

A very hot stream of water

Sulphides

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

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

These sites of escaping hot water are called hydrothermal vents. They are found along plate boundaries and at active undersea volcanoes, where the exchange of heat and elements between the crustal rocks and the ocean takes place due to interactions between the volcanic activity and seawater. Seawater penetrates several thousand metres into the bottom through fissures in

the sea floor. At these depths the seawater is heated to temperatures of around 400 degrees Celsius by volcanic activity, whereupon it dissolves metals and sulphur from the ambient volcanic rocks. The heated water is less dense than the cooler water above, so it rises quickly and flows back into the sea. In the ocean, the plume of hot water cools again rapidly. This causes the dissolved metals to bind into minute sulphide particles and sink as fine precipitants to the bottom.

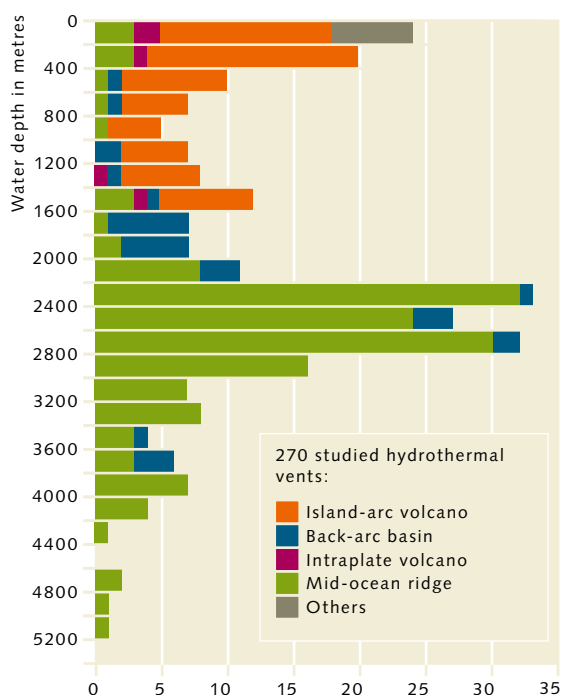
At many hydrothermal vents around the world the sulphides have accumulated to form tall chimney-like structures on the sea floor. Water shoots out of the fissures into the sea like a fountain. More and more material is gradually deposited on the sides of the openings and the tower continues to grow.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

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

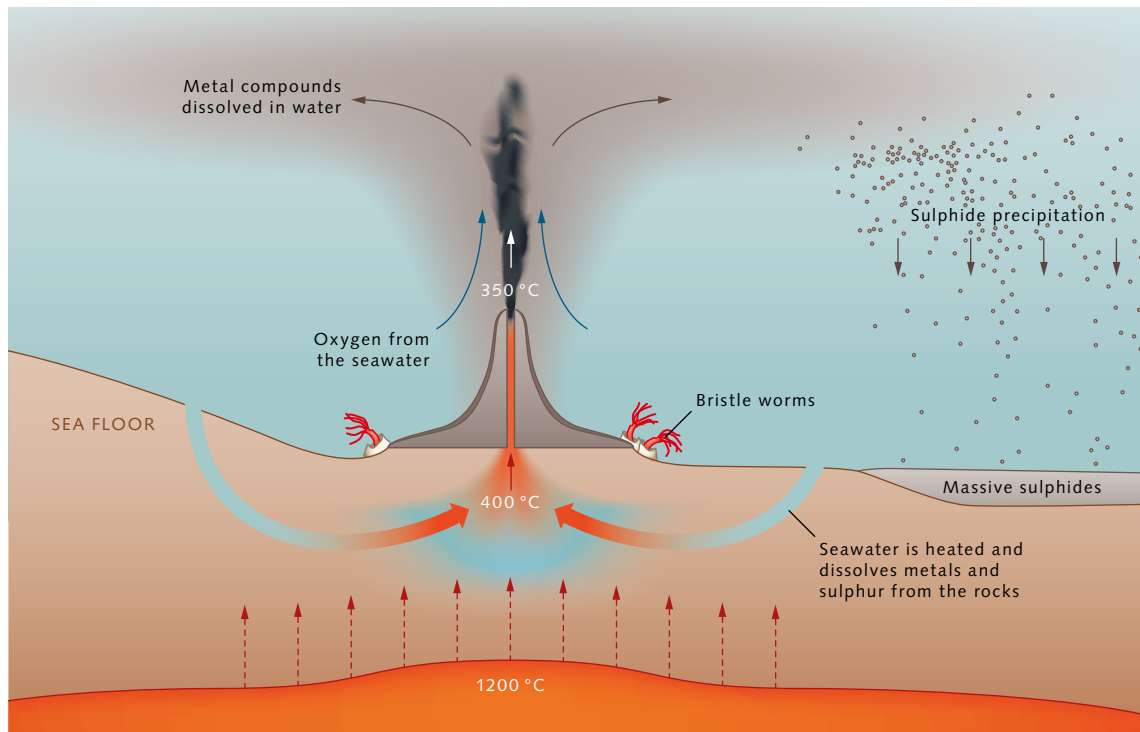
Hydrothermal vents have now been found in all oceans. They usually form in water depths between 1000 and 4000 metres.

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

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



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



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

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

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

VOLCANOES BEHIND ISLAND ARCS (back-arc basins): When one plate submerges beneath another, tension is produced in the overlying plate. Subduction of the sinking plate causes the overlying plate to thin and pull

apart, until it finally splits open. In many cases this kind of tension occurs several dozen kilometres behind the active island-arc volcanoes. This area is therefore referred to as the back-arc basin.

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

Uncounted hydrothermal vents

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

Black, white, grey, and sometimes even yellow

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

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

Researchers assume that the worldwide number of hydrothermal vents, and thus of massive sulphides, is much larger. This is based on estimates of the geothermal heat flux of the Earth. The amount of heat generated in the Earth's interior and that released by magmatism and volcanism is accurately known today. This heat amounts to 1.8 trillion watts, equivalent to the output of one million nuclear power plants. According to the estimates, a portion of the heat is released through hydrothermal vents. Based on the calculations, some researchers reckon that there is one hydrothermal vent for every kilometre of mid-ocean ridge or back-arc spreading zone. Considering that the mid-ocean ridges and back-arc spreading zones together have a total length of about

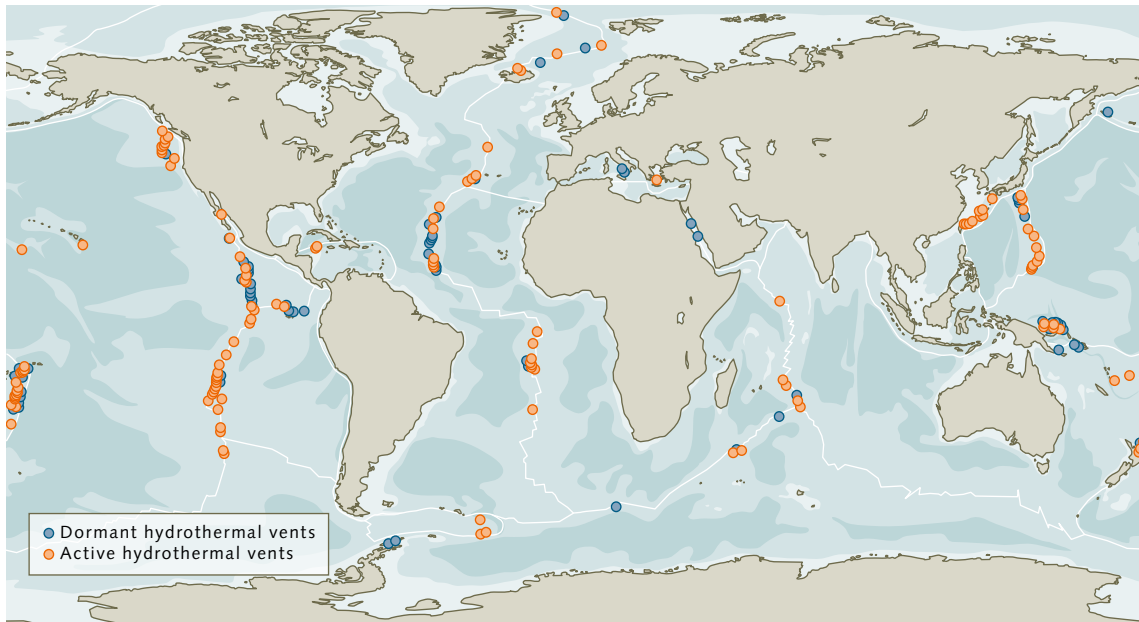
67,000 kilometres, and the island-arc volcanoes a length of around 22,000 kilometres, there could be around 90,000 hydrothermal vents worldwide. Researchers assume that large areas may be found every 50 to 100 kilometres that contain up to 100 black smokers. It is predicted that there are around 500 to 1000 sites around the world with large massive sulphide deposits.

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

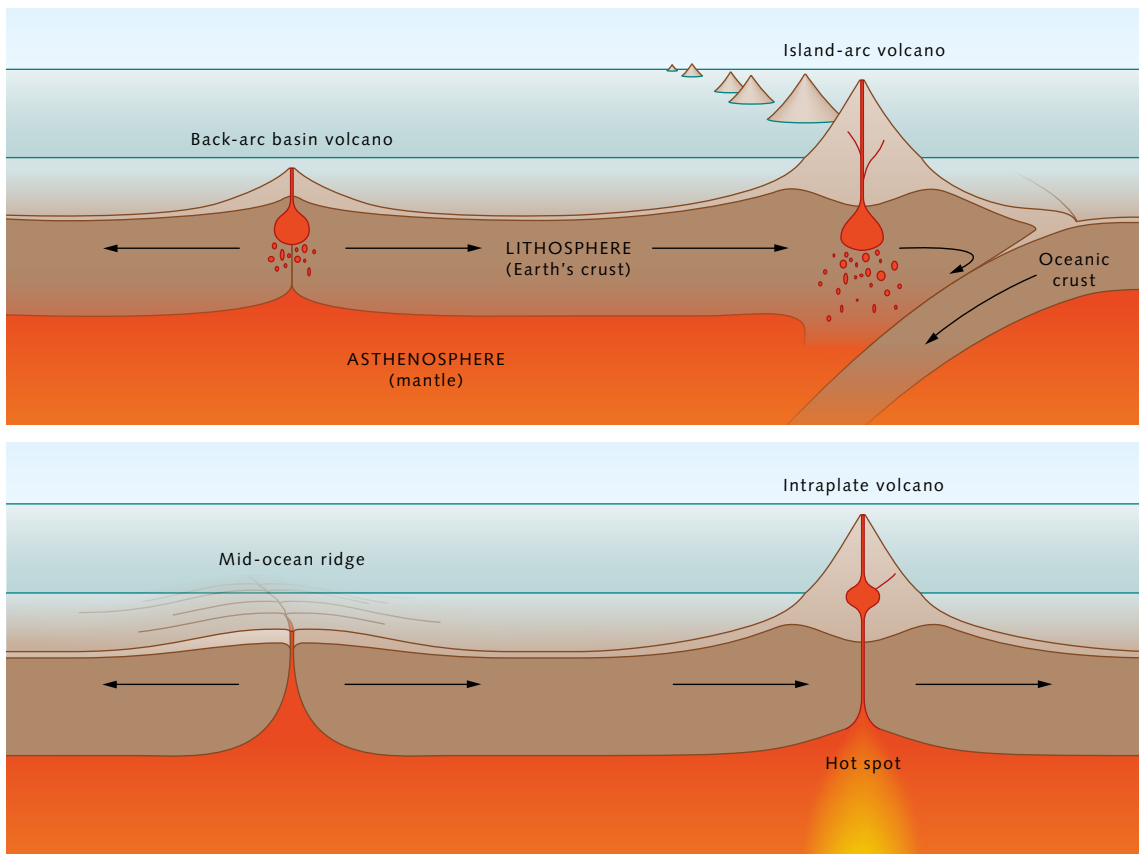
Based on the analyses of many bottom samples carried out in recent decades, researchers believe that massive sulphide deposits containing valuable metals such as copper and gold that are actually large enough for economic mining occur at relatively few hydrothermal vents. Moreover, many of the regions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

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

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



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



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

The challenging search for hydrothermal vents and profitable massive sulphide deposits

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

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

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

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

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

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

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



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

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

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

More precious than nodules and crusts

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

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

Many chemical elements are found in relatively small amounts in massive sulphides, including manganese, bismuth, cadmium, gallium, germanium, antimo-

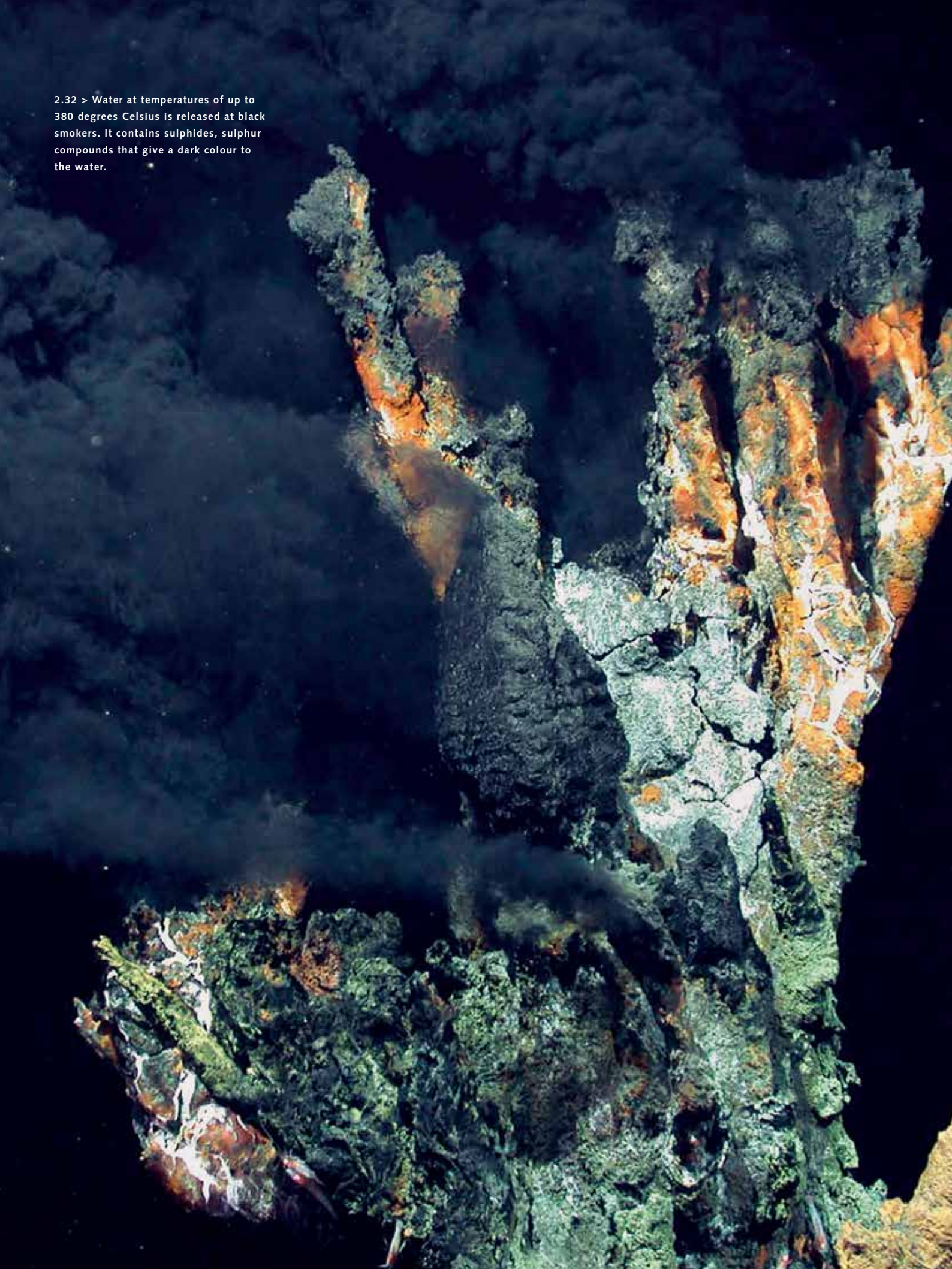
Region	Gold (Au) in grams per tonne	Silver (Ag) in grams per tonne
Manganese nodules in the Clarion-Clipperton Zone (CCZ)	0.0045	0.17
Cobalt crusts in the Prime Crust Zone (PCZ)	0.013	4
Massive sulphides in Solwara 03 (central Manus Basin)	15.2	642
Massive sulphides in Solwara 09 (eastern Manus Basin)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

ny, tellurium, thallium and indium. In some deposits, however, especially at island-arc volcanoes, these elements can be more highly concentrated.

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

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

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



First activity in the South Pacific

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

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

Limited exploration licences

Comparable progress has not been achieved in international waters because exploration and mining there are centrally regulated and coordinated by the ISA. Licences have already been awarded to China and South Korea for areas in the Indian Ocean, and to France and Russia

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

Extreme habitat, many specialized species

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

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

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

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



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

What is rare?

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

In fact, scientists have found differences between different ocean regions. Large tube worms predominate in areas of the eastern Pacific, but have never been found in the Atlantic or Indian Oceans, or in the southwest Pacific. At the Mid-Atlantic Ridge, on the other

hand, large numbers of deep-sea shrimps are found living with **symbiotic** chemoautotrophic bacteria on their bodies, which provide them with nutrients. And finally, in the Indian Ocean, deep-sea shrimps as well as anemones and snails are found with symbiotic bacteria.

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

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

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

Metal-rich brines in the Red Sea

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

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

A 200-metre-thick layer of extremely salty, heavy water collects in these basins in the way that a haze of fog lies in a valley. With a temperature of over 60 degrees Celsius, this water comes from salt-rich rock layers on the flanks of the Red Sea and is concentrated here. Its salinity of around 26 per cent is 7 times as salty as normal seawater. It is therefore very dense and flows into

the deep basins. Hydrothermal solutions enriched with sulphides rising up from the depths mix with the warm saline water, and the metals dissolved in the water combine chemically with sulphide particles. The particles sink to the bottom and form the metal-rich muds.

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

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

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

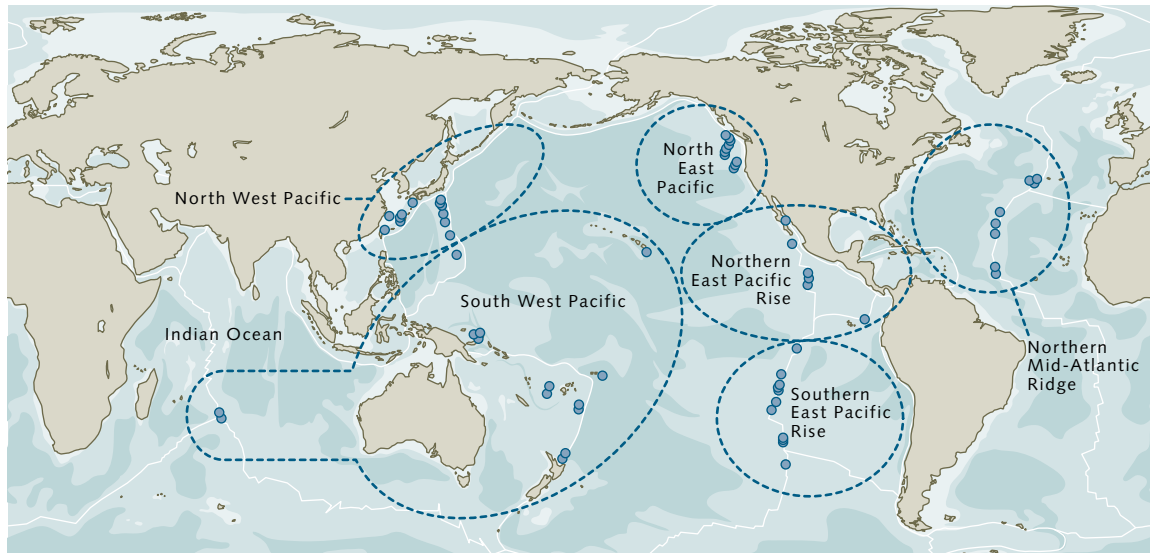
In all, it is estimated that the Atlantis II Basin contains muds with a dry weight of around 89.5 million tonnes, which is a very large amount compared to the other massive sulphide occurrences on the sea floor. The metal contents in the sediments are lower, however, than in the massive sulphides of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

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



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

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



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

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

Generally speaking, there is still very little known today about the biology of deep-sea animals. There are still questions that must be answered before we can understand how and whether animal communities can recover after a disturbance on the scale of massive-sulphide mining. It is, for example, still unknown how abundant or rare the species are, in which habitats they live, how far apart these habitats are, and how or wheth-

er the animals can spread from one habitat to another. Only then would a recolonization of harvested areas be possible at all.

Before the mining begins ...

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

CONCLUSION

**Ocean mining –
not a gold rush but an option**

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

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

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

Marine mining is interesting for various reasons. For one, demand for chemical elements con-

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

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

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