University of Bremen

MARUM —
Center for Marine
Environmental Sciences

The Ocean in the Earth System

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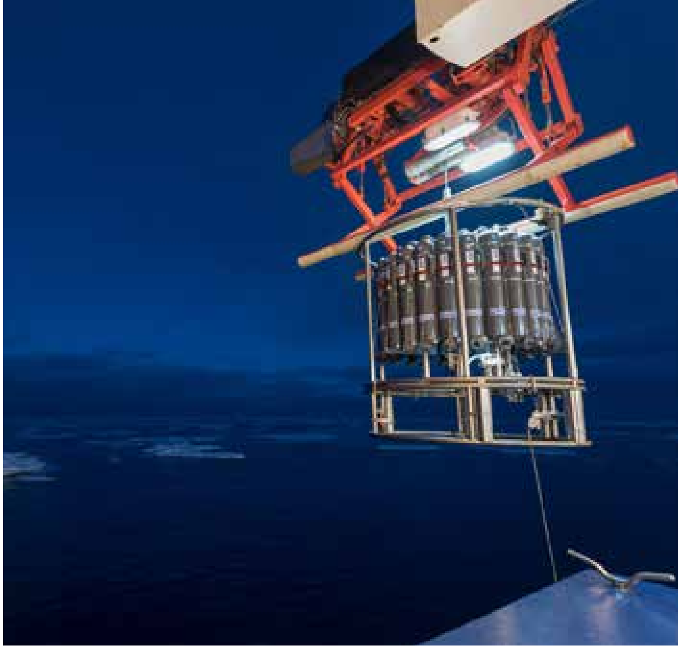


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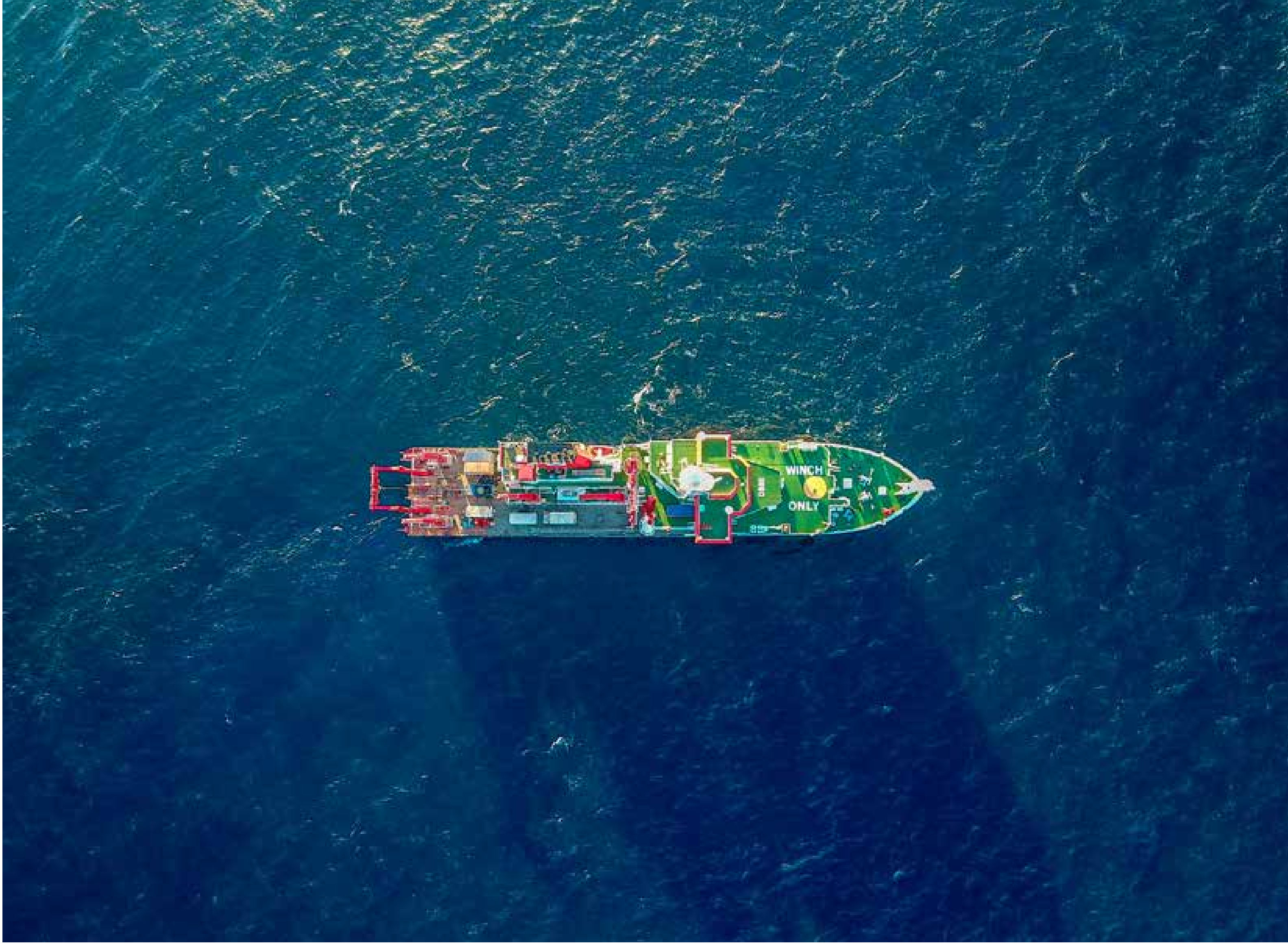

WINCH
ONLY

Exploration of the oceans requires the deployment of high-tech tools from research vessels.

The ocean in depth!

MARUM — Center for Marine Environmental Sciences at the University of Bremen

Our blue planet is fascinating. Its major components include the atmosphere, oceans and lithosphere, the biosphere — comprising large and small organisms, as well as the ice sheets and glaciers. These elements are all intricately connected through a myriad of complex interactions. Conditions are never static. The rapid progression of climate change, earthquakes and volcanic eruptions illustrates the dynamic nature of processes in the Earth's system. This is especially true for the seas and oceans, which cover about 71 percent of the Earth's surface.

Global ocean currents, hot and cold seeps on the sea floor, and many other phenomena are

“MARUM stands for research, education and the transfer of knowledge for a responsible approach to the ocean.”

Prof. Dr. Michael Schulz
Director of MARUM

among the factors that make the marine environment a central element in the Earth system. The oceans have an average depth of 3,700 meters and are distributed around the world. They also accommodate diverse ecosystems that are adapted to the prevailing environmental conditions. The deep ocean and the ocean floor are still widely unknown because direct measurements have only been sporadically carried out. But it is unquestionable that these regions fulfill important functions for the entire Earth system.

Due to global challenges such as climate change, sea-level rise, energy production from the seas, and the increasing interest in resources found in the oceans, marine research is being confronted with new tasks of great societal importance. This is reflected by the marine research program of the federal government, ‘MARE:N — Coastal, Marine and Polar Research for Sustainability’, as well as the sustainability goals of the United Nations. Goal 14 in particular, to ‘conserve and sustainably use the oceans, seas and marine resources for sustainable development’, explicitly addresses aspects directly related to the deep ocean. For example, the long-term capacity of the ocean to absorb carbon dioxide and the availability of raw materials in the sea both depend on processes in the deep ocean. However, we still know too little about the processes in the deep sea to provide all the answers necessary for appropriate action.

MARUM produces fundamental scientific knowledge about the role of the ocean and the sea floor in the total Earth system. The dynamics of the oceans and the seabed significantly impact the entire Earth system through the interaction of geological, physical, biological and chemical processes. These influence both the climate and the global carbon cycle, resulting in the creation of unique ecological systems. MARUM is committed to fundamental and unbiased research in the interests of society

The ROV MARUM-Squid being tested in the pool at MARUM prior to its next mission.

The laboratory infrastructure at MARUM provides ideal conditions for state-of-the art research.

Maintenance work on the MARUM-MeBo70

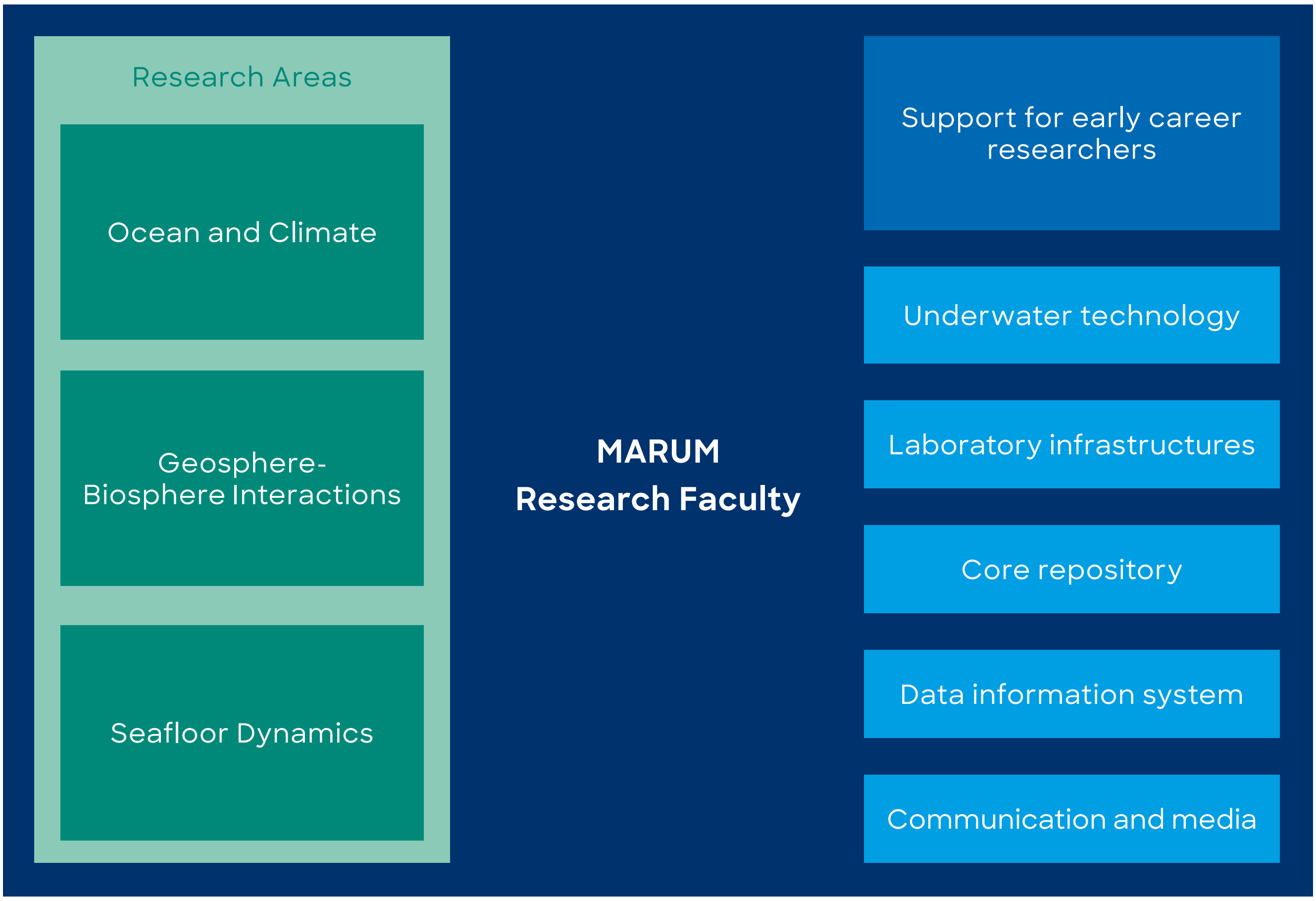
and the protection of the marine environment.

Since its foundation, the research center MARUM — Center for Marine Environmental Sciences, has developed into an internationally recognized facility for marine research that is firmly anchored at the University of Bremen. Since 2012, the Center has had the unique distinction of being the only Research Faculty of the University of Bremen. Through MARUM, the University of Bremen cooperates closely with the Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research in Bremerhaven (AWI), the Max Planck Institute for Marine Microbiology in Bremen (MPI), with Senckenberg by the sea in Wilhelmshaven (SGN), the Leibniz Centre for Tropical Marine Research in Bremen (ZMT), and with the University of Oldenburg and the private Jacobs University in Bremen.

MARUM is the home of the Cluster of Excellence 'The Ocean Floor — Earth's Uncharted Interface' and other national and international research projects.

The MARUM buildings with offices, laboratories and technology halls are located on the campus of the University of Bremen.

MARUM is divided into three interdisciplinary fields of research. The support of early career researchers is a cross-disciplinary task.



With the sea-floor drill rig MeBo200, developed at MARUM and shown here being deployed from the research vessel SONNE, cores up to 200 meters in length can be retrieved.

Research Area

Ocean and Climate

Sediments deposited on the sea floor can be used to quantify past changes in the marine environment. The sea floor thus represents a unique archive for environmental changes at time scales of decades to millions of years. This archive significantly advances our understanding of many natural processes that are relevant for humanity and that to a large extent determine the present state of the Earth system and its future development. In addition to the classical methods of marine geology, isotope geochemical analyses of organic and inorganic components, in particular, are used to reconstruct environmental changes and to analyze the underlying processes.

Additionally, materials carrying evidence of the terrestrial climate are transported by winds and rivers into the ocean and preserved there. Deep-sea sediments therefore comprise an integrated climate archive that makes it possible not only to identify variations in the marine environment, but

Climate and environmental signals are permanently stored in the shells of foraminifera, which are deposited in sediments on the seabed. They can be deciphered by applying various methods in the laboratory.

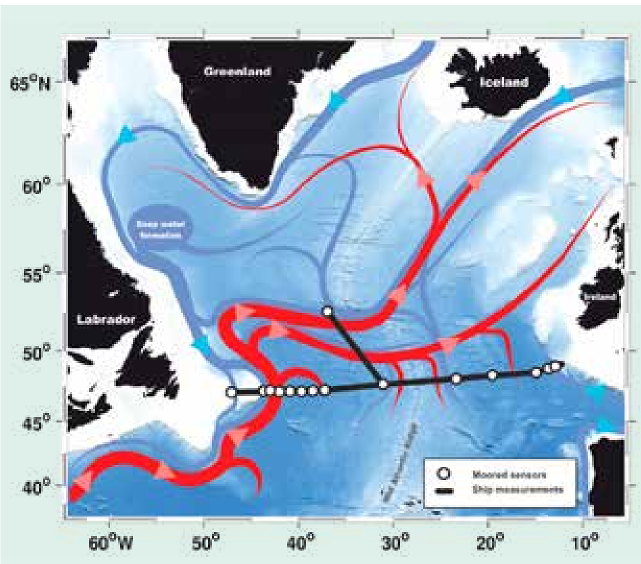
also to recognize contemporaneous changes on the continents as well as relationships between the two. These paleoceanographic and paleoclimatological studies make it possible, for example, to draw conclusions about changes in global ocean currents and biological productivity, which are of great importance for the functioning of the climate system. Particular examples include heat transport, carbon-dioxide storage, and shifts in the regions of precipitation.

Direct measurements of physical parameters and trace gases in the sea, combined with remote satellite measurements, are used to investigate variations in currents and fluctuations in the 'respiration' of the deep ocean on time scales of months to decades. Using sediments with high temporal resolution and coral skeletons, it is possible to study the ocean's role in climate processes at very detailed time scales covering periods of time for which direct measurements are not possible. Here, the role of amplification mechanisms, the interactions between climate subsystems, as well as the driving factors and the extent of possible local environmental changes, are of particular importance.

There are many climate indicators in paleoclimatology that allow direct comparisons with the results of climate models. Such comparisons make it possible to test the quality of the models for future climate conditions and further improve the models. Toward this end, even more comprehensive paleoclimatological data sets will be needed in the future, and these will allow even greater detail in describing the past climate conditions.

With a weight of several tons, a gravity corer can sample the seabed to a depth of about 20 meters.

Simplified circulation scheme of the North Atlantic. Red: warm surface water, blue: cold deep water.



Recovery of a current meter moored in the ocean and installed in a flotation sphere. The current meters are deployed at different water depths for a year or longer and measure the current speeds and directions. These data provide evidence about fluctuations in the strength of ocean currents that is important for climate research.

Sampling gas from a cold seep using the submersible robot MARUM-QUEST

Research Area

Geosphere-Biosphere Interactions

Geological processes occurring beneath the sea floor create extreme habitats that are characterized by unique ecosystems. At mid-ocean ridges, hot fluids with temperatures up to 400 degrees Celsius move upward through the ocean crust. These fluids are rich in reduced chemical compounds and when they contact oxygenated seawater, they produce a bountiful source of energy for microorganisms and thus create a basis for the prolific communities at 'hot vents'. Similarly, life also flourishes at 'cold seeps' on the continental margins and in marginal seas, where tectonic or geochemical processes release fluids enriched in methane and other gases along with organic compounds.

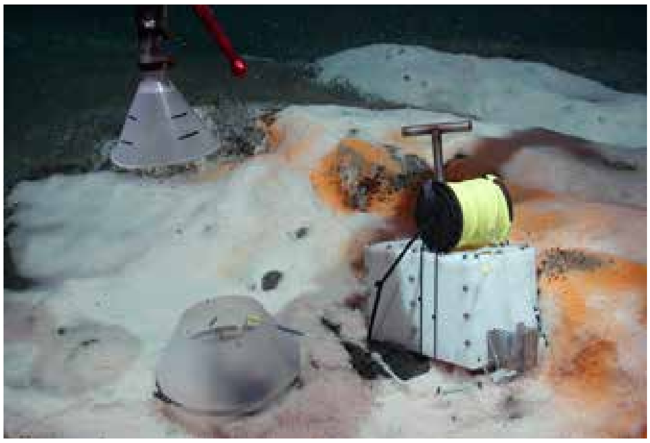
By contrast, the floor beneath the deep sea, where sediments are slowly deposited over long geological time periods, is generally characterized by extremely low levels of energy. Nevertheless, it offers the living conditions required by microbial communities (known as the deep biosphere) and is estimated to contain as much microbial biomass as all the waters of the oceans. Even after drilling to depths of thousands of meters into the sea floor, the lower boundary of the deep biosphere has not yet been discovered. Furthermore, we still have only a rudimentary understanding of the processes and adaptations that make life possible under high temperature and pressure conditions with unusual energy sources, or even where there is a definitive lack of energy.

Chemosynthetic biological communities in the Logatchev hydrothermal field on the Mid-Atlantic Ridge at a water depth of 3,000 meters

In the Gulf of Mexico, beard worms colonize asphalt layers that are formed at the sites of natural oil seeps at a water depth of 3,300 meters.

Many unique habitats on the sea floor and below have been extensively documented over the past 40 years. The systems already known, however, are only partially understood, and new ones are constantly being discovered. While there is no question that the processes taking place in global material cycles play a crucial role, concrete quantifications of material fluxes have so far been limited to rough estimates.

The existence of life under the extreme environmental conditions of the deep sea highlights the fact that we do not yet understand the limiting environmental factors that are ultimately in play for life on Earth — not to mention its possible presence on other planets. Our awareness that the extreme habitats of the deep sea exhibit great diversity does not obscure the fact that our knowledge regarding the stability or instability of these ecosystems is still very limited. The vulnerability of such systems to disturbances — especially the extraction of resources from the seabed, carbon dioxide sequestration, fishing, and the influx of microplastics — cannot yet be reliably assessed.



Measuring instruments deployed by a submersible robot autonomously record oxygen consumption on bacterial mats in the oxygen minimum zone; here at a water depth of 1,100 meters on the continental margin of Pakistan.

Hydrothermal seeps in 860 meters of water in the Menez Gwen hydrothermal field southwest of the Azores

Equipped with special echo-sounder systems, autonomous underwater vehicles like the AUV MARUM-SEAL can survey the seabed at great depths. Because these types of vehicles operate at distances of only 60 to 80 meters above the sea floor, it is possible to generate very high-resolution bathymetric maps from these data, such as this one of the Venere mud volcano in the eastern Mediterranean.

Research Area

Seafloor Dynamics

Sediments transported from the continents by winds, rivers and glaciers may be deposited on the sea floor with thicknesses of several kilometers. At the mid-ocean spreading centers in the deep sea, magma rises from the Earth's mantle and solidifies, forming new ocean crust and a worldwide underwater mountain chain with a total length of about 60,000 kilometers. Through the cycle of plate tectonics, this ocean crust is eventually subducted beneath the continents at the deep-sea trenches, where it submerges into the deep mantle and melts again.

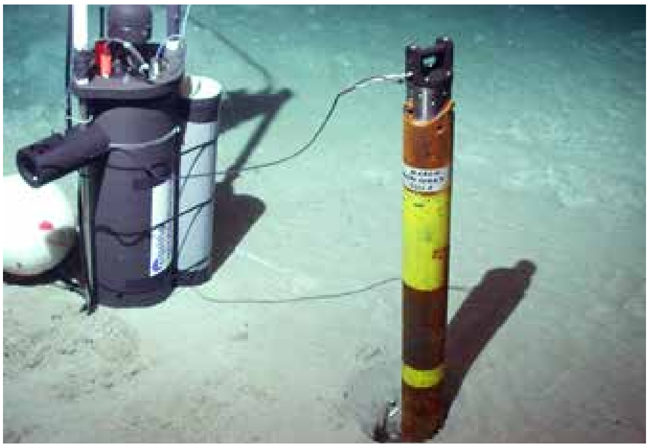
The newly formed, hot ocean crust interacts chemically and physically with seawater. Cooling and aging processes produce small fissures in the basaltic crust through which seawater circulates. At the same time, in the deep-sea trenches, water in the upper crust and in its overlying sediments lubricates the boundary layer between the continental crust and the subducting ocean crust. These fluids are forced out (as waters and gases) at greater depths, and emerge at the sea floor to form mud volcanoes or carbonate precipitates. Where the fluids escape upwards toward the ocean floor earthquakes may be produced due to the lubricating influence of the fluids on the movements between the crustal plates.

Earthquakes that originate below the sea floor, along with the accompanying slumps and tsunamis, are destructive for the infrastructures and ecosystems located in heavily populated coastal regions. Very strong, high-magnitude earthquakes, like those in Sumatra in 2004, Chile in 2010 and Japan in 2011, originate at great depths and thus cannot be directly studied. Recent investigations from physical borehole observatories show that quantitative assessment of the energy released at individual earthquake zones is possible and these can be useful in early-warning systems.

The processes involved in sediment mobilization, which are driven by numerous factors (precipitation, currents, seismicity, erosion / weathering), are highly variable. The distribution and movements of the sediments are largely controlled by the bathymetry of the sea floor (canyons, ridges, and flat areas). Sediments are constantly being deposited and reworked from the coastal areas to the deep sea. Submarine 'avalanches' (known as turbidity currents) and landslides can abruptly and profoundly modify the shape of the sea floor over distances of hundreds of kilometers.

In addition to these rapidly occurring processes, the sea floor is also subject to slow changes on geological time scales, at rates of millimeters to centimeters per year. These include tectonic processes and submarine volcanism in the oceanic crust. Because of the gradual nature of these dynamic changes in the sea floor over millions of years, colonization of such regions by a number of different organisms is possible, including cold-water corals. In this respect, the dynamics of the sea floor also significantly influence the development of the marine ecosystems there.

Near the Venere Mud Volcano in the eastern Mediterranean, this colony of beard worms is rooted in a calcareous crust at a water depth of 1,560 meters.



A borehole observatory for long-term monitoring is installed by the submersible vehicle MARUM-Quest on a mud volcano at a water depth of 1,950 meters in the Nankai Trough off Japan. This instrument measures pore pressure and temperature in the borehole and takes a time series of porewater samples using a capillary system.

Colonies of cold-water corals can extend for distances of several hundred kilometers and thus influence the circulation of seawater. These unique ecosystems are independent of sunlight. They obtain energy by filtering microplankton and suspended organic material out of the seawater.

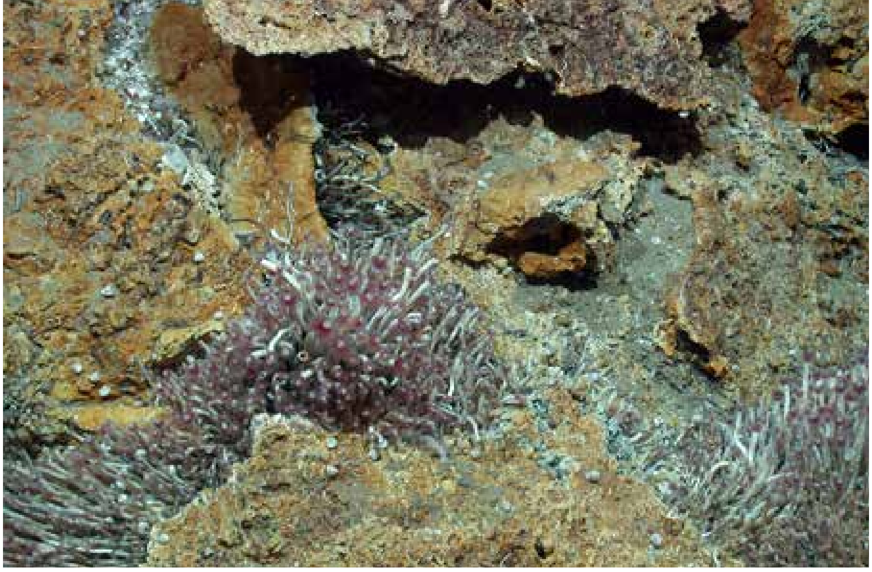
Bacterial mats in the Arabian Sea at a water depth of 730 meters

Cluster of Excellence at MARUM

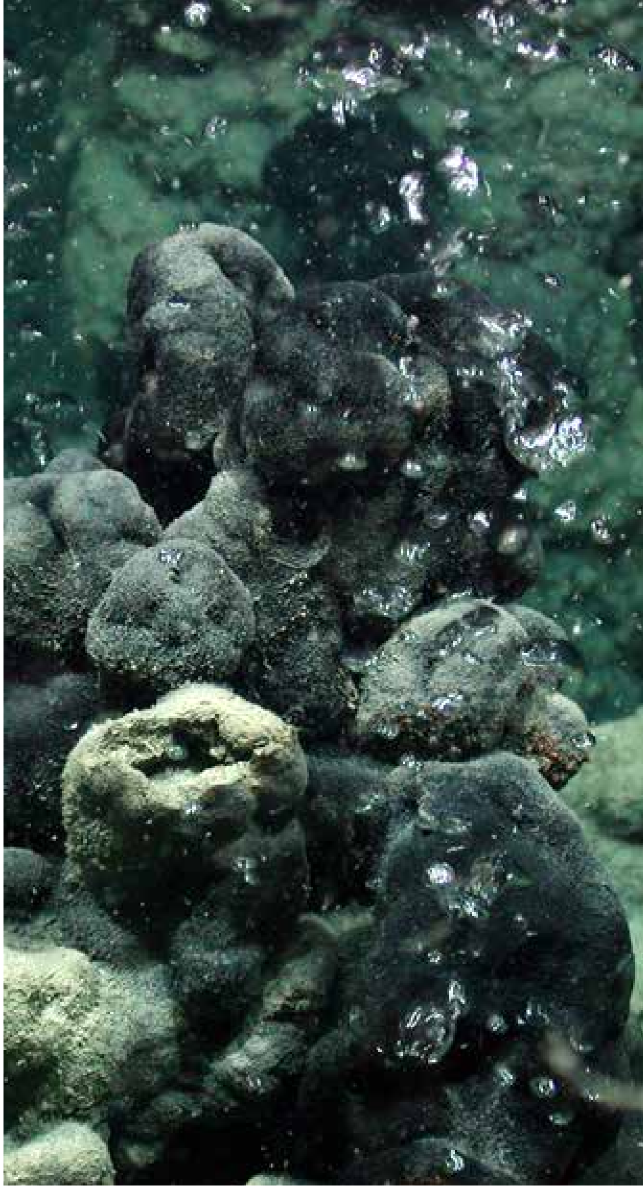
The Ocean Floor — Earth's Uncharted Interface

The ocean floor refers to the area of the seabed where the water depth is greater than 200 meters. This makes up the greater portion of the Earth's solid surface, and it is also the interface at which geological, physical, chemical, biological and hydrological processes interact with one another.

Because of its immense total area, our knowledge about the factors that control the transport of organic materials to the ocean floor and thus influence the global carbon cycle and the climate system is gravely lacking. What happens when carbon and other elements produced by the



top: Beard worms at a mud volcano
bottom: Basaltic ocean crust



Escaping methane bubbles at a carbonate chimney in the Black Sea, at a water depth of 260 meters

decomposition of organic material find their way into sea water or are released from the ocean floor into the water column? What is the fate of the countless types of plankton in the water column when they contact the ocean floor, and later at depth? The new Cluster of Excellence 'Ocean Floor' takes the initiative in this area, and researchers will concentrate exclusively on this still largely unexplored interface until 2025.

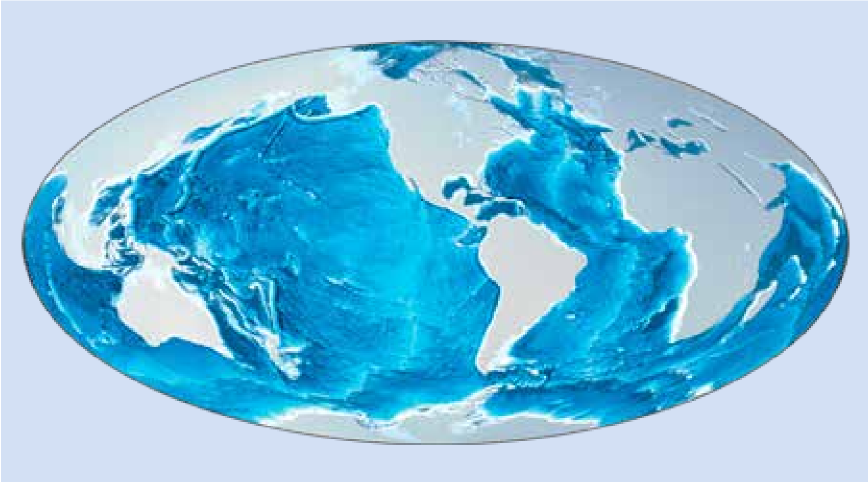
For about the past forty years it has been known that the deep sea is not a desert but rather an oasis of life, albeit a very delicate one. If the ecosystem is altered, it presumably would take decades to recover. Therefore, investigations in the Cluster also focus on how the sensitive ecosystems in the deep sea react to a changing environment and increasing water temperatures. Furthermore, the ocean floor is a unique archive that records the environmental conditions of past times in its sediments.

The cluster aims to open a new chapter in ocean-floor research by quantitatively studying the exchange processes at this important interface as well as its role within the Earth system. To these ends the researchers in the Cluster are involved in close interdisciplinary cooperation with other institutions in the region, including the Alfred Wegener

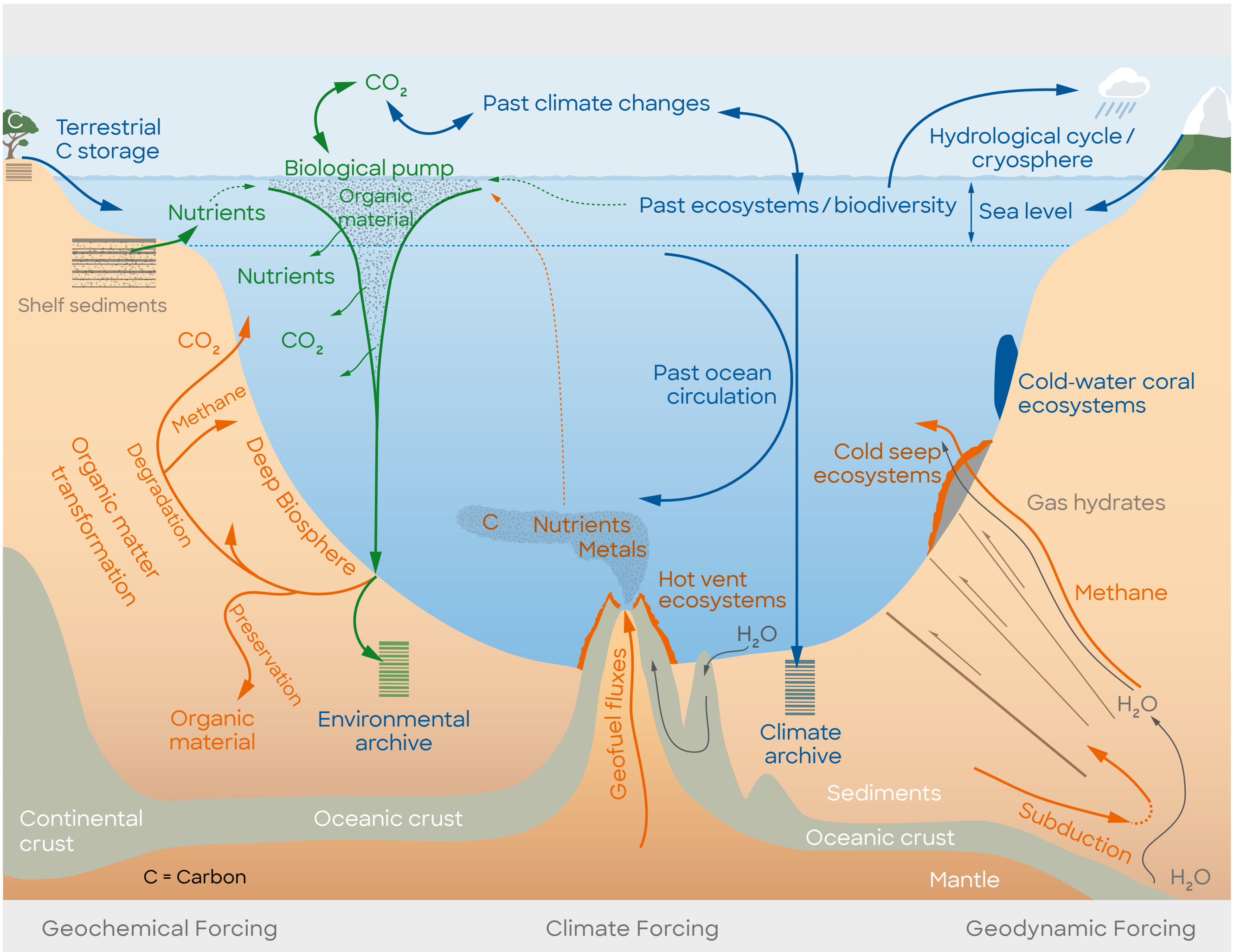
Institute, Helmholtz Centre for Polar and Marine Research in Bremerhaven, the Max Planck Institute for Marine Microbiology in Bremen, Senckenberg by the sea in Wilhelmshaven, the Leibniz Centre for Tropical Marine Research in Bremen, as well as with the University of Oldenburg and Jacobs University in Bremen. The Cluster of Excellence is based at the MARUM Research Center at the University of Bremen.

The unique fleet of technological equipment operated by MARUM is employed for this research: submersible vehicles, drill rigs and autonomous underwater vehicles. These are used to implement observation and sampling of the ocean. To tackle the new scientific challenges, not only new technology but also new analytical methods and models are being developed.

The ocean floor makes up 71 per cent of the solid surface of the Earth and has an average depth of 3,700 meters below the sea surface. It is not easily accessible. Studying it requires ship expeditions and the deployment of highly specialized underwater equipment.



Key processes that affect the ocean floor and are being studied within the framework of the Cluster



top left: Gas emission at a cold seep; top right: Sand ripples in the deep sea
bottom: Chemosynthetic symbiosis

Strong perspectives

Promoting young talent

The training of early-career researchers has a long and valued tradition at MARUM. Doctoral students and postdocs here, presently from more than 30 countries, are motivated by a stimulating work environment that is designed to support them in all areas of their academic endeavors and through all stages of their careers.

It is possible for PhD students to become members of the Bremen International Graduate School for Marine Scientists (GLOMAR), which is hosted by MARUM. With the support of a team of experienced scientific advisors, GLOMAR offers the doctoral students ideal training conditions as well as the important international and interdisciplinary networks that are crucial for advancing their careers.

MARUM offers its early-career researchers a variety of introductory and specialty courses that are tailored to their particular scientific disciplines, focus on interdisciplinary aspects, or contribute to the further development of personal skills. To this end, we work very closely with the relevant programs of our university and non-university partner institutes. This results in a regionally tailored and thematically very diversified continuing education program for early-career researchers.

With programs for individual mentoring, mutual support, sharing of best practice approaches in the supervision of students and doctoral candidates, and with career advice, postdocs are greatly supported on their paths to academic independence.

The GLOMAR PhD student community since 2006

Success rate: > 81 %

Duration of PhD phase: 3.7 yrs

Gender balance: 63 % : 37 %

Internationals: 48 %

> 60 % of Alumni stay in academia

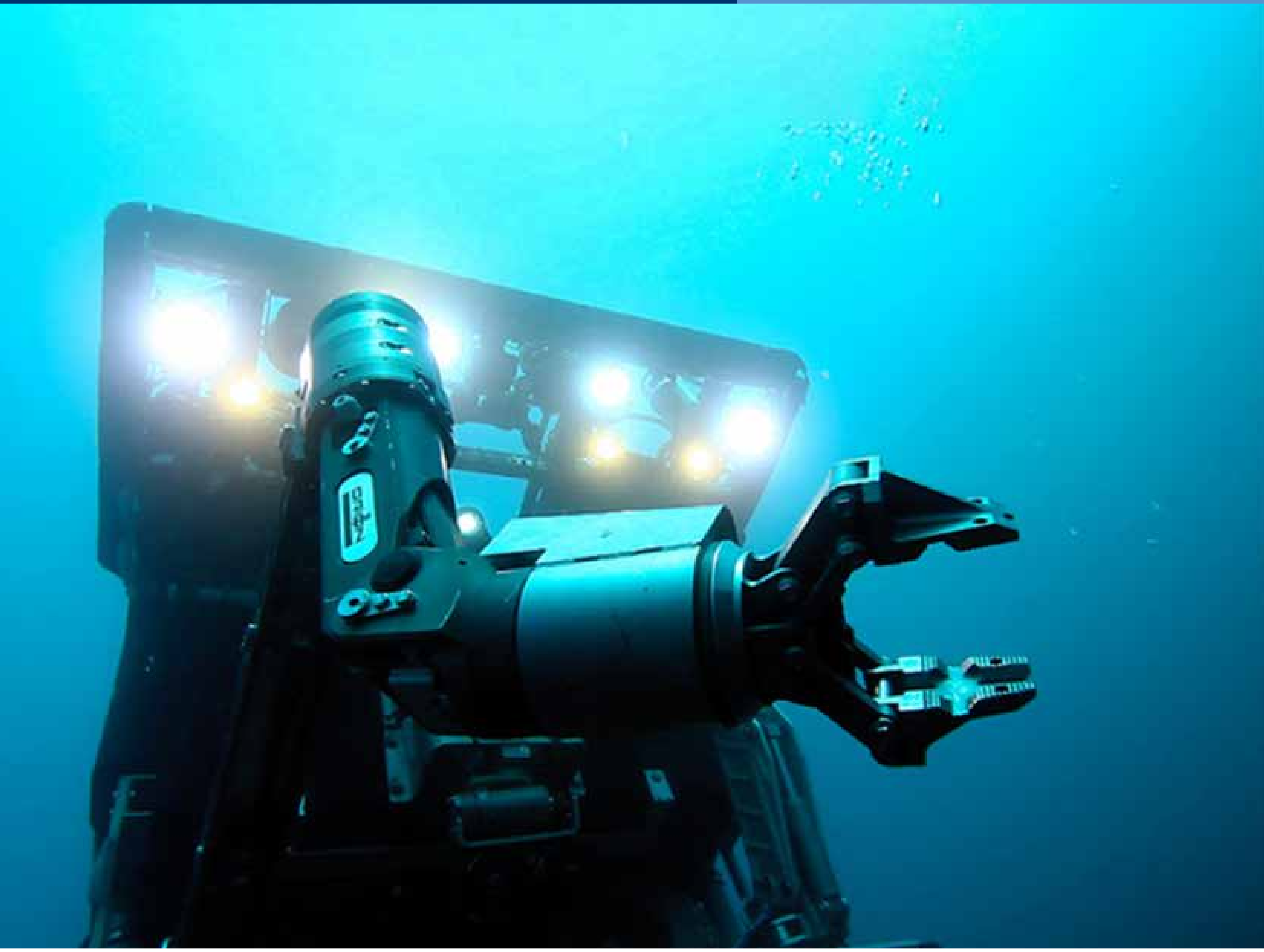
Because early- career researchers often decide to pursue non-academic careers, many of the offered programs focus on this aspect of professional possibilities. This effort also counts on the involvement of our constantly growing group of MARUM alumni.

Although the numbers of male and female doctoral students in the graduate programs are roughly equal, the proportion of women declines at more advanced career stages. In order to sustainably reduce this imbalance and to support women scientists in successfully continuing their academic careers, MARUM, in cooperation with the university program 'navigare', has been offering a successful mentoring program for young female scientists for many years.

Through their participation in all the decision-making bodies of MARUM, the early-career researchers not only gain insights into academic autonomy, they also actively participate in MARUM's research planning and in the continuing development of training concepts for young scientists.

With its unique infrastructure, MARUM is also a much sought-after partner for international cooperation in the development of promising young researchers. This is exemplified by the International Research Training Group ArcTrain, in which 12 German and 21 Canadian PhD students are studying climate-related environmental changes in the Arctic.

MARUM offers PhD students and postdocs ideal conditions and an inspiring environment.




QUEST


marum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Everything under control

Marine technology at MARUM

For more than 25 years MARUM has been deploying high-technology tools that are crucially important for scientific investigations of the ocean floor. Observations and measurements of the ocean floor are carried out directly in situ with remote-controlled and autonomous underwater vehicles, drill rigs and other instruments that can be deployed from research vessels. Worldwide, only a few institutions have fleets of modern underwater tools for ocean-floor research comparable to those at MARUM. Some of the equipment used is available on the open market, but MARUM also develops its own novel technology. In 2003, MARUM was the first facility in Germany to deploy a cable-attached and therefore remotely operated vehicle (ROV) for deep-sea research. Attached high-resolution cameras document their surroundings in very high quality. Guided by video cameras, the manipulator arms of the submersible vehicle obtain samples or install measuring devices at optimal locations for experiments on the ocean floor. The underwater systems presently include two ROVs with diving capabilities of 4,000 and 2,000 meters and an autonomous underwater vehicle (AUV) that can be deployed down to 5,000 meters. In addition, MARUM has broken new ground in seabed exploration with the development of two remote-controlled sea-floor drill rigs (MeBo70 and MeBo200). The MeBo200 system can be deployed at water depths to 2,700 meters and can drill as deep as 200 meters into the sea floor. MARUM's heavy maritime equipment is operated and continuously refined by highly specialized technicians and engineers, and is also made available to other working groups in Germany and internationally.

left page from top to bottom and f.l.t.r.:
A dive by the ROV (Remotely Operated Vehicle) MARUM-Quest, which is stationed at MARUM.

The ten-ton sea-floor drill rig MARUM-MeBo70 being deployed over the stern of the research vessel METEOR with the help of a specially designed launching frame.

Two pilots operate the submersible vehicle from a control container on board the research vessel.

MARUM-Quest is brought on board after a dive.

A wave glider in operation

The submersible vehicle MARUM-Squid on the working deck of the RV Meteor

The upper 50 centimeters of the sea floor is electromagnetically mapped using the multi-sensor benthic sled Neridis, developed at MARUM.

Underwater systems with deployment depths to

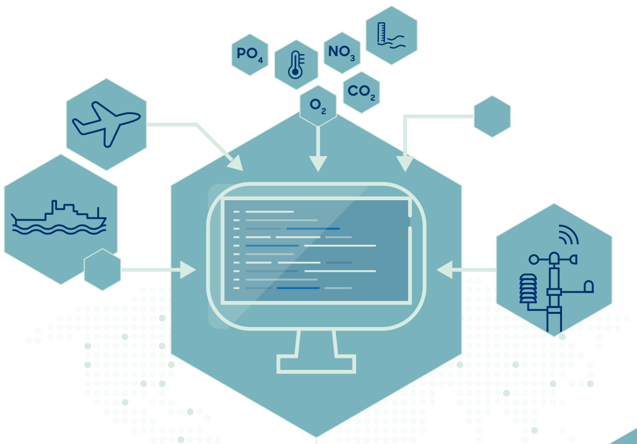
5,000 m

Orientation in a sea of data

The Data Information System PANGAEA

The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), and MARUM together operate an information system in which research data from the Earth system and the environment are archived and published. Because the system strives to embody a holistic view of the Earth, it is named after the supercontinent PANGAEA, in which all of the Earth's continents were united 200 million years ago. For more than 25 years, PANGAEA has assured the scientific community of long-term and reliable access to all data obtained through the exploration of our planet. This certified electronic library adapts and develops international standards for data publication, and blends seamlessly into the world's evolving data infrastructures. It integrates data into the established processes of scientific publication and supports the users of data archives. The data is subject to an internal review process similar to that required for scientific articles in professional journals, and can be cited by other scientists in their own work. PANGAEA can store any conceivable measured values from all disciplines of earth and environmental sciences — from the upper atmosphere to the deepest layers of the sea floor.

400,000
data sets



1. Collection of data and descriptive data (metadata)

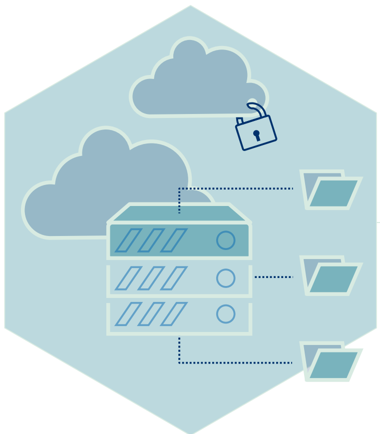
from the scientific community

- Measurement data
- Measurement series
- Long-term series
- Observations
- Experiments

- From ships, buoys, measurement instruments, planes, stations and laboratory instruments

2. Making the data useful

- Evaluate quality of the metadata for completeness and reproducibility
- Conform formats and descriptions
- Fill gaps (in cooperation with producer of data) for the purpose of reuse or further use



3. Archiving the data

- Structured data storage
- Assure permanent access to data and metadata
- Prevent loss of, or changes to data

4. Making the data accessible

- Tag data with an international, permanent and unique identifier (DOI)
- Ensure reusability and facilitate citation
- Make data searchable by sharing the metadata with other portals and systems such as Google

The graphic illustrates the workflow in PANGAEA from the collection of data to making it available on the network.

Additional tasks
- Training scientists in the area of research-data management
- Active support and guidance of scientists in research-data management in institutions and in projects
- Continuing development of standards for the exchange (interoperability) and integration of data in cooperation with national and international initiatives

Project development and management
- National research-data infrastructure (NFDI)
- German Federation for Biological Data (GFBio e.V.)
- German Network for Bioinformatics Infrastructure (de.NBI)

Exposing the invisible

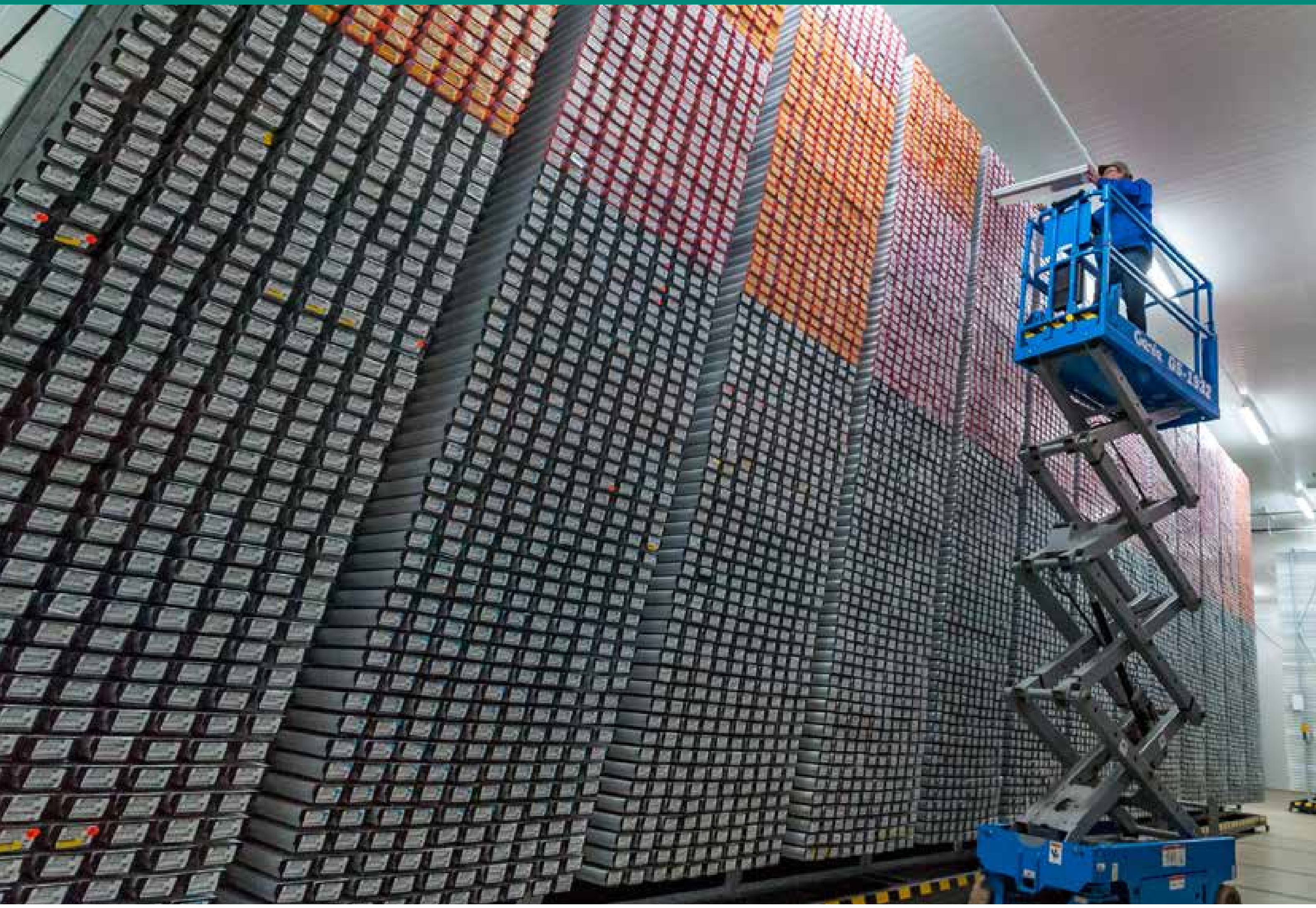
The Laboratory Infrastructure at MARUM

MARUM is equipped with a wide range of state-of-the-art analytical instruments. These tools have the ability to reveal important environmental information preserved in minerals and organic molecules, and in the isotopic compositions of organic and inorganic substances. The materials analyzed include calcareous fossils as well as other rocks and sediments. Additionally, water samples from the ocean and in the pore spaces of sediments are investigated. These analyses provide insights into the sources and histories of the rocks, the transformation processes operating on the organic materials and the microbial communities involved, as well as the changes in environmental conditions and ecosystems throughout Earth's history. The infrastructure for chemical analyses includes a number of key high-performance instruments and specialized laboratories:

- ultra-high-resolution mass spectrometry for the analysis of complex molecular compositions in marine environmental samples, such as the dissolved organic components in the sea
- comprehensive analysis of complex microbial lipids in marine and sediment samples
- several specialized laboratories for highly precise isotope analyses of light to heavy elements
- ultra-high-resolution temporal records of biomarkers in marine sediments for climate reconstruction
- geochemical mapping of element distributions in the micrometer range in rocks and sediments

In order to understand how environmental conditions influence isotope ratios and material cycles, MARUM also operates gene and culture laboratories for marine algae. These are essential for studying the diversity of these organisms and their growth with respect to climate changes under controlled conditions.

With its infrastructure, combined with the regional and international networking, the MARUM Research Faculty offers PhD students and postdocs the ideal conditions for their research.



Over 158 kilometers of sea floor

The Bremen IODP Core Repository

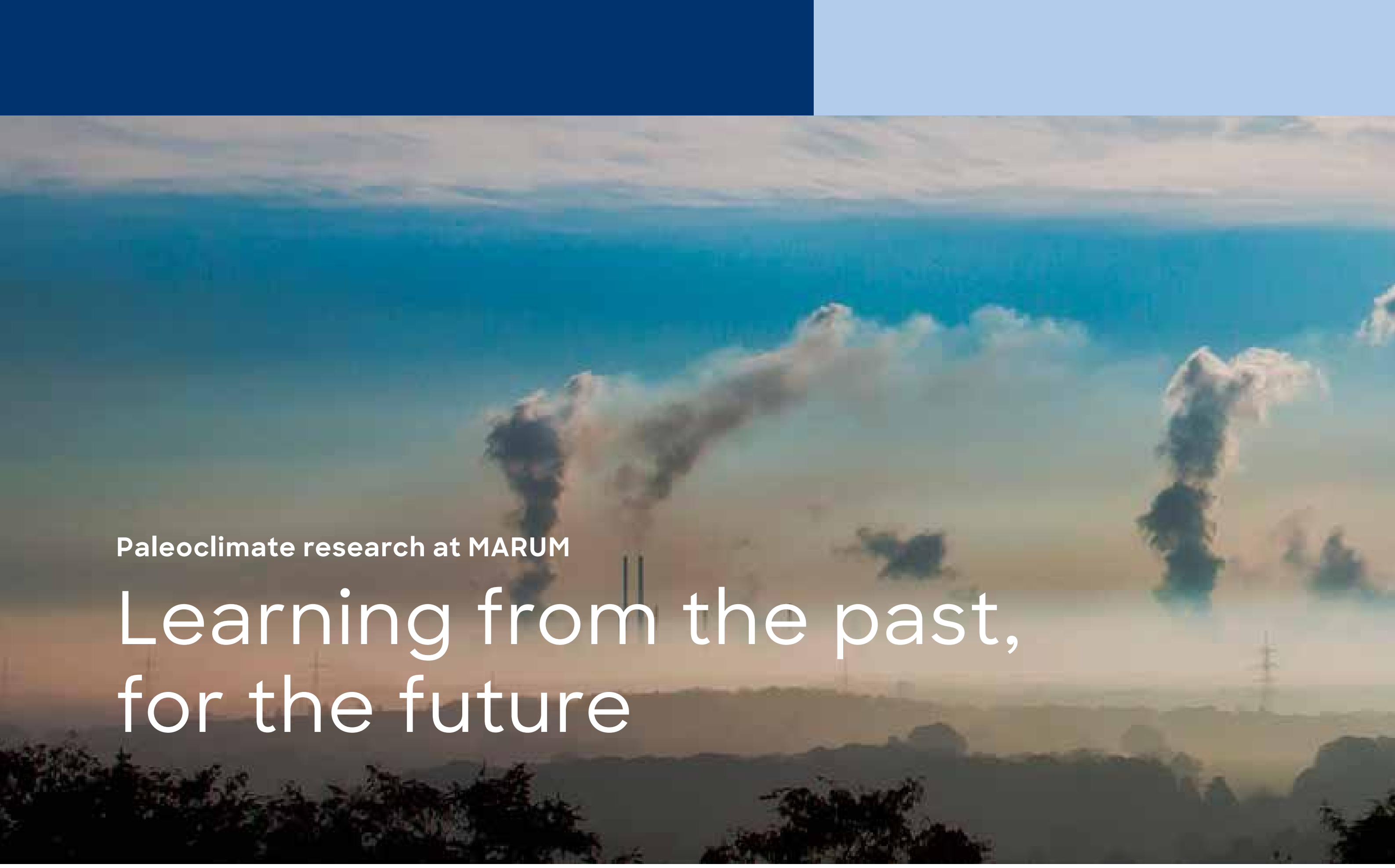
Of the three International Ocean Discovery Program (IODP) core repositories worldwide, the largest is housed at MARUM. This important research program brings together scientific institutions from 23 countries, including the United States, Japan and a consortium of European countries, to carry out expeditions that drill into the sea floors around the world using drilling ships and platforms. More than 250,000 core sections, the first of which were retrieved in 1968, are stored in the Bremen IODP facility. They come from the Atlantic and Arctic Oceans and the Mediterranean, Black and Baltic Seas. Each year, around 200 scientists visit the Bremen IODP Core Repository to study this unique sample material,

250,000 plastic liners stored in the five-and-a-half meter high shelves of the Bremen Core Repository contain ocean-floor cores of inestimable value for science, the fruits of more than 50 years of international drilling expeditions. Each of the core segments is one-and-a-half meters long and has a diameter of about seven centimeters.

while others request specific sets of samples to be sent to them. A total of around 50,000 samples are sent out annually. Germany and 14 other member countries comprise the European drilling consortium ECORD. It carries out IODP expeditions in marine regions that the larger IODP drilling ships are not able to access. These include the ice-covered waters of the Arctic Ocean and shallow coastal or inland seas. For these expeditions using specialized ships or drilling platforms, MARUM provides the mobile laboratory containers for microscopic analyses, geochemical measurements, and microbiological sampling. The samples from these expeditions are stored in Bremen.

200

scientists visit the Bremen Core Repository each year



Paleoclimate research at MARUM

Learning from the past, for the future

Climate change is posing increasingly great challenges for humanity. To assess its future development, a thorough understanding of the Earth's complex climate system is essential. A glimpse into the past helps researchers in this respect. Reconstructions of paleoclimate help us to understand how the system reacts to changes. This knowledge is then also used in calculations for modeling various future scenarios. At MARUM, scientists from multiple disciplines are researching this field. One of these is Heiko Pälike, head of the paleoceanography working group.

How can a view into the past lead to a better understanding of Earth's climate system?

Throughout the course of Earth's history climate has been constantly changing, but the changes caused by human influences are proceeding much more rapidly than ever before in the past. An important part of our research is to assess how the climate system has responded to these kinds of changes, for example, to different levels of greenhouse-gas concentrations. Climate archives from the geological past help us to investigate how climate conditions could change in the future. The climate system of the Earth is presently in a very delicate state of balance, but we are now in the process of hurriedly tweaking some of the adjustment screws, and the changes being observed cannot be explained without invoking human influence. For example, the extremely rapid input of carbon dioxide into the atmosphere not only leads to warming, it also increases the solubility of carbonates in the ocean. In the past, this has caused difficulties in the adaptive capability of some marine organisms. It is not clear to what extent and how quickly animal and plant habitats, the foundations of our environment, can adapt to such a rapidly changing climate system in the future. Many of the parameters applied in climate models still need to be calibrated on the basis of observations and measurements. This is only possible through the climate archives of the geologic past.

How do researchers study climate conditions that existed millions of years ago?

Sediment deposits contain microfossils and other measurable features that, under ideal conditions, provide an archival record of climate history. One aspect of our research involves deciphering of this climate archive. Sediment thicknesses of one or two centimeters in the deep ocean floor represent a time period of about 1,000 years. In practical terms, we work with the fossil shells

of organisms whose properties were influenced in some way by various environmental factors at the time of their formation. One example is the temperature at different water depths, which can be reconstructed for the past by examining the shells of marine organisms known to have lived within particular depth intervals. The Earth System reacts sensitively to changes in the greenhouse-gas budget, which determines the intensity of Earth's warming.

Is there a convincing example of a sudden release of greenhouse gases in Earth's history, and what does science know about it?

As a result of a sudden (by geological standards) warming about 56 million years ago, the flora and fauna were drastically altered, especially in the ocean. During the Eocene, from 56 to 35 million years ago, the temperature of deep-ocean water was around ten degrees Celsius warmer than it is today. Researchers are in agreement that the temperature increase at the beginning of the Eocene was caused by the release of large quantities of carbon from the ocean floor. Because of the analogy with the present-day temperature increase related to the greenhouse effect, many scientific studies are looking at this event in the past in order to better understand the situation and the impact on the environment today. The total amount of carbon released 56 million years ago, as estimated by various methods, corresponds roughly to the amount that has been released as carbon dioxide since the beginning of the industrial era. We have thus achieved these comparable amounts in a much shorter time period, at rates between ten and 100 times as fast. Furthermore, the warming was associated with far-reaching effects on physical, geochemical and biological processes. This resulted in reduced temperature gradients between the equator and the poles, a weakening of the wind system, changes in ocean circulation, reduced oxygenation, enhanced ocean acidification, and a decrease in nutrients in the ocean.

"We are working to improve climate models even more"

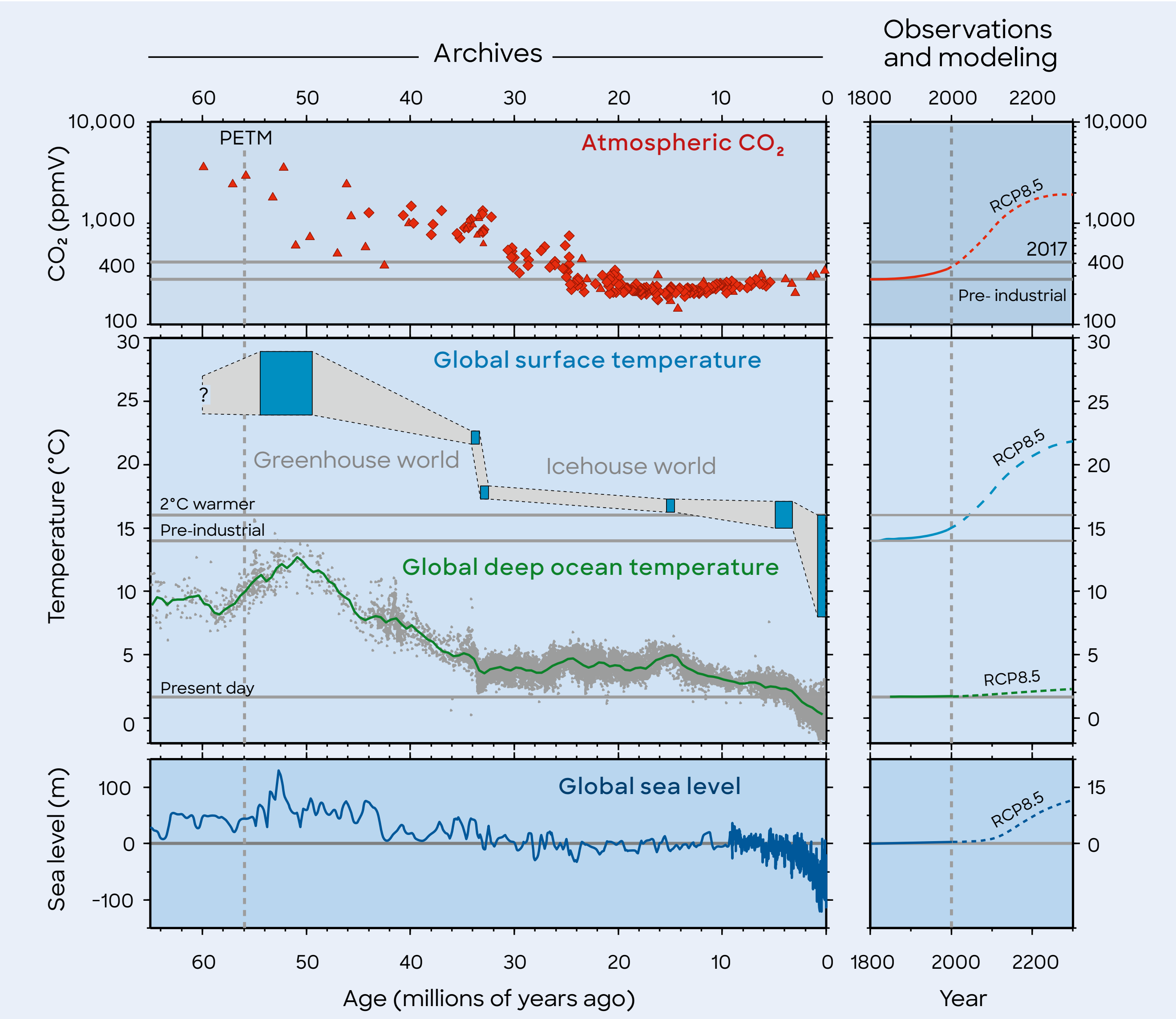
Prof. Dr. Heiko Pälike
Head of work group
Paleoceanography

Considering the difference in boundary conditions, can the situation in the past be compared with the present?

In the past, of course, the distribution of continents and the ocean circulation were different from today. However, many of the relevant processes were based on physical and chemical principles that are as true now as they were then. The distribution and size of ice sheets in the Arctic and Antarctic, for example, were different, so it is not possible to make completely accurate predictions based on geological observations alone. But, in principle, we understand very well how to use the events from that time to improve our understanding of future climate. The research results of the geologic past are simulated using climate models in order to understand important processes in our climate system, and to calculate possible future climate scenarios. One aspect that has not yet been sufficiently studied is the extent to which organisms react to climate changes. We have quite a good overview of which organisms lived in the sea at that time. But one of our research goals is to understand their functions within the ecosystem, and how quickly living organisms are able to adapt to changing environmental conditions.

Moreover, situations can arise in the climate system where irreversible changes suddenly occur that are further amplified by feedback mechanisms. For example, warming leads to the melting of ice and the melting to a reduced albedo, which causes an increase in warming. This, in turn, facilitates the release of the greenhouse gas methane, which further amplifies the initial warming. These effects are known as positive feedback. There are, however, also some negative feedbacks in the Earth system. For example, during periods of elevated temperatures and carbon-dioxide values, the natural weathering of rocks is intensified, which ultimately leads to the removal of carbon dioxide from the atmosphere and ocean, and its deposition as carbonate in the deep sea. This process, however, requires time frames of over a million years.

Simplified representation of the reconstruction of various climate indicators covering the past 66 million years, and comparison with a future scenario



What are your research priorities for the next two years?

One very concrete goal of research is to greatly improve our understanding of the sensitivity of the Earth system. With respect to geographic distribution, how much warming can we expect to see per quantity of carbon dioxide released? This parameter has been considered as a constant in the existing models, but it is actually dependent on the prevailing environmental conditions. To assess these influences, geological observations and the use of improved measurement methods for studying sediment cores is imperative. Only in this way will we be able to improve the models of future climate development.

Right image: This 1.5-meter-long core section documents the beginning of abrupt warming at the boundary from the Paleocene to the Eocene about 56 million years ago. For climate researchers, the Paleocene-Eocene Thermal Maximum (PETM) is of particular importance because of its analogy to the present-day increase in the greenhouse effect. A sudden release of large quantities of carbon at that time led to a rapid rise in temperatures as well as increased ocean acidity. The extreme dissolution of carbonate, whose presence is reflected in the light areas of the core section, caused an abrupt change in color initially to an almost pure brown clay. This core was retrieved during IODP Expedition 208 by the drilling vessel JOIDES Resolution on the Walvis Ridge off Namibia. The water depth at the drilling site was 4,760 meters, and the core section comes from a depth of around 140 meters below the sea floor.

Removing a sediment core liner on board the RV JOIDES Resolution during Expedition 320 of the Integrated Ocean Drilling Program (IODP).

Annual thematic workshops are an important element of the training program. As part of the second meeting geophysical and geotechnical methods were used to measure various landslides, and sediment cores were taken.

European funding for research on submarine landslides

Interdisciplinary training in the european network SLATE

Landslides occur not only on land, but also in marine regions comprising soft sediments. These are common on the continental margins and slopes, but also include fjords, river deltas, volcanic islands and marine ridges. The underwater landslides, however, can be many times as large as those on land. When the ground beneath the surface of the sea starts to move it can involve thousands of square kilometers of ocean floor. The international training network SLATE, funded by the European Commission and coordinated by MARUM, is examining the causes and effects of these kinds of events.

SLATE stands for Submarine LAndslides and Their impact on European continental margins. The network was established in 2017 and it is funded through the Marie Skłodowska-Curie (MSC) program. The shifting masses of material and the energy released by landslides can trigger tsunamis, which are a threat not only to the coastal regions of Europe, but also to infrastructures near, on and under the water. These can include, for example, production pipelines and communication cables.

Although submarine landslides have been intensively researched for decades, their causes, mechanisms and consequences are still not thoroughly understood. What are the key factors that facilitate submarine landslides? How does the material continue to move after it has slumped? And how can the resulting geohazards, such as tsunamis, be reliably predicted? Researchers in the European training network are addressing these questions. Working with multiple disciplines and diverse partners, their goal is to gain a better understanding of the processes preceding, during and after landslides. This includes examining the parameters that can drive and facilitate submarine landslides.

A team of leading researchers and specialists from prominent academic and non-academic institutes contribute comprehensive and interdisciplinary expertise. This pool of expertise encompasses the fields of marine geophysics, sedimentology, civil engineering, geotechnical engineering, offshore technology, tsunami research and hazard assessment. A cohort of 15 early career researchers is trained and mentored across multiple disciplines.

“Combining complementary courses, field trips and joint annual workshops, this integrative approach is fostering a new generation of highly motivated and exceptionally qualified young scientists to address the challenges associated with landslide-related hazards,” explains the coordinator of the network, Prof. Katrin Huhn, in her assessment of the training.

Their research projects are based on modern methods and data sets. The data are derived from comprehensive, high-resolution and replicated ocean-bottom investigations, direct monitoring, state-of-the-art laboratory and in-situ measurements, and the latest modeling and process simulation approaches. The early career researchers examine case and general studies and develop new models. “SLATE thus provides process-oriented knowledge and new expertise for assessing hazards — especially with regard to the controlling factors and dynamics of underwater landslides,” continues Katrin Huhn. It also considers how landslides can impact society and the economy.

“Our goal is to better understand submarine landslides in order to minimize the geo-risks associated with them.”

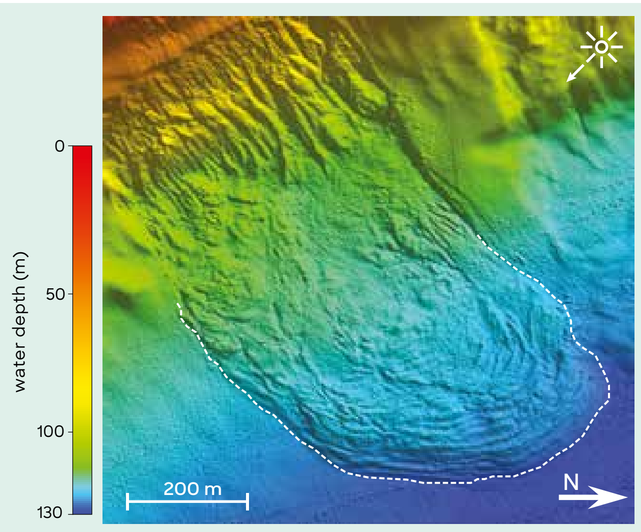
Prof. Dr. Katrin Huhn-Frehers
Head of work group
Modelling of Sedimentation Processes

Three of the 15 total SLATE projects are currently being carried out at MARUM. In a laboratory-based generic study, Ting-Wei Wu is striving to quantify how earthquakes affect the stability of ocean-slope sediment deposits. For this purpose, she simulates seismic shaking, or earthquakes, on sediment samples of different types and mineralogical compositions.

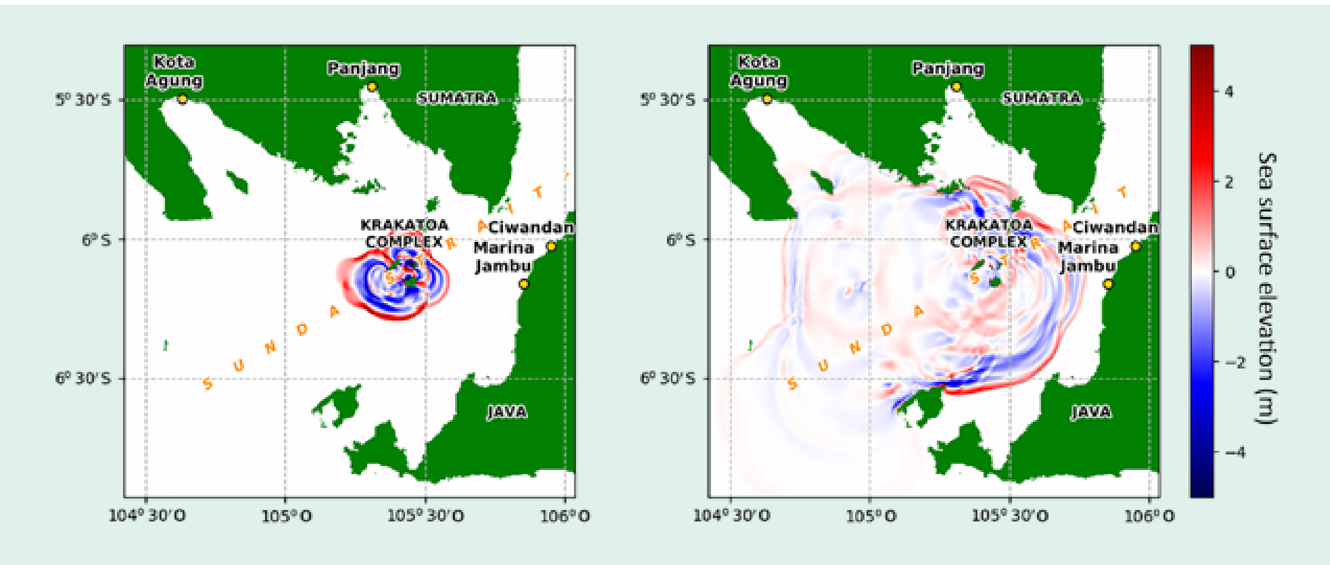
Ricarda Gatter, as an aspect of her PhD research, studies the importance of the layers that induce submarine landslides. For this, she uses macro- and microanalyses of sediment-core material from regions where landslides have occurred throughout the past millennia. Her goal is to create a new understanding of the relationship between sediment structure and the physical properties of sea floor areas that slump, and thus determine what happens immediately prior to a landslide.

Emiel Hassefras uses modern modelling techniques based on 3D geophysical data to obtain a better understanding of the role of ascending gases, their decomposition, and the resulting migration of free gases as a potential trigger for submarine landslides.

In addition to MARUM, the partner institutes of SLATE include NGI Oslo (Norway), NOC Southampton (Great Britain), Ifremer Brest (France), Igeotest Figueres (Spain), CISC Barcelona (Spain), CNR Ismar Bologna (Italy), OGS Trieste (Italy), and the Universities of Durham (Great Britain), Innsbruck (Austria) and Kiel.



In addition to investigating large landslide bodies in the ocean, the SLATE scientists also study smaller slump masses in Alpine lakes. The slump shown in the bathymetric map occurred in 1918 in Lake Zürich near the town of Oberrieden. Because of the many analogies, especially in the triggering processes, lakes can be viewed as relatively easily accessible "ocean laboratories".

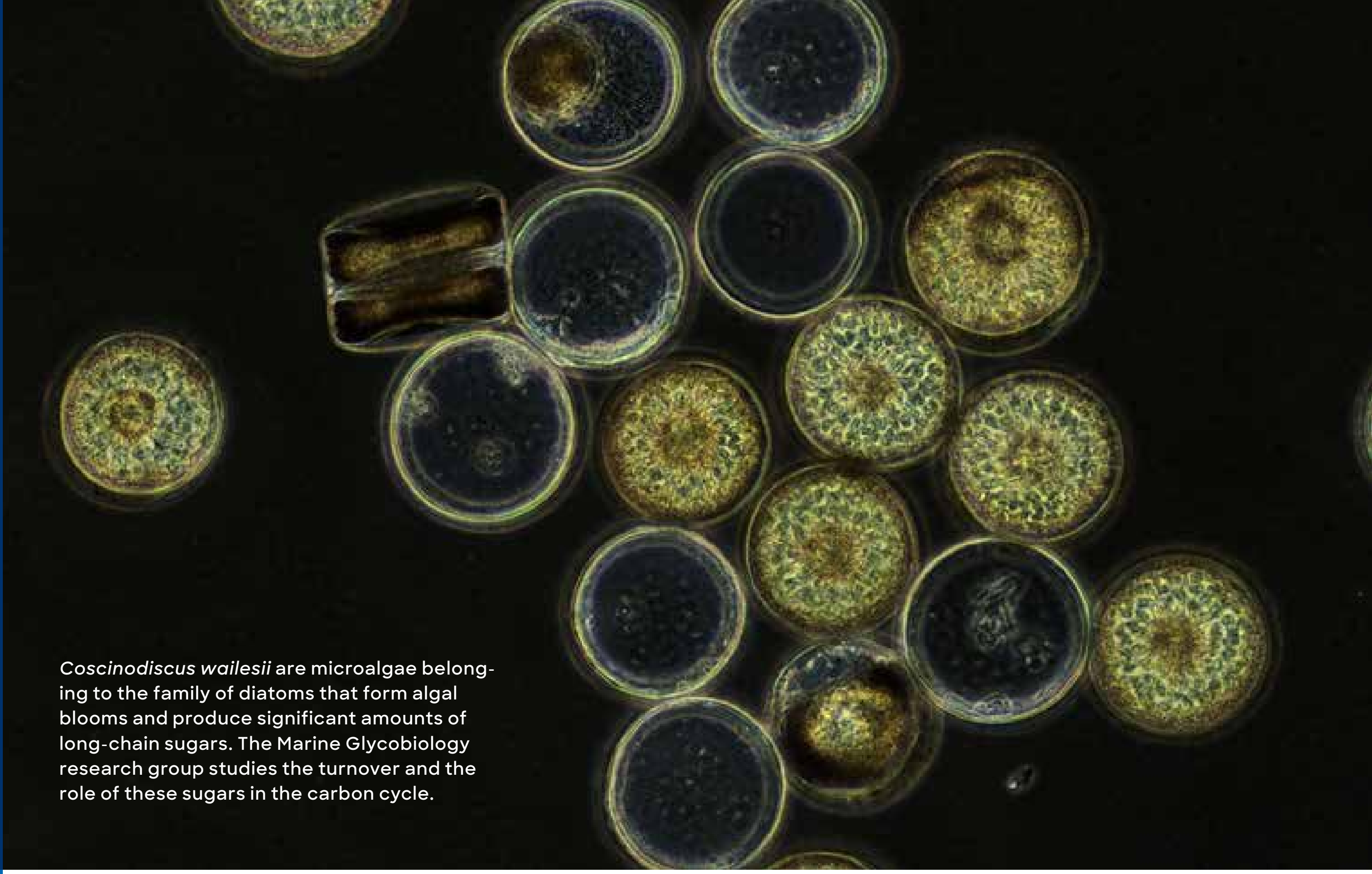


Like the landslide events themselves, the tsunamis they produce also represent a large natural threat. With the new, high-resolution and multidisciplinary data sets obtained through SLATE, models can be better parameterized for more accurate simulations of wave heights, and can thus improve assessments of the danger of tsunamis. This example shows the wave propagation at 600 (left) and 1,500 seconds (right) after the slumping at Krakatoa in 2018.

At biannual meetings, SLATE PhD students present and discuss their results with international scientists, but also with partners from industry and the non-academic sector.

The diverse training program presented by a team of international experts includes field work as well as laboratory studies on sediment cores.

A look back into Earth's history can help to understand the processes that lead to landslide events in the ocean. Large sediment packages that slumped in a past ocean can be seen exposed today on land. PhD students in SLATE participate in field excursions to take a closer look at these landslides — this one in the Emilia-Romagna region (Italy).



Coscinodiscus wailesii are microalgae belonging to the family of diatoms that form algal blooms and produce significant amounts of long-chain sugars. The Marine Glycobiology research group studies the turnover and the role of these sugars in the carbon cycle.

Black box of the marine carbon cycle

The role of microalgae in the ocean ecosystem

There are many processes in the ocean that have not yet been scientifically explained. One of these, in particular, is the highly complex carbon cycle. The Marine Glycobiology research group, led by Prof. Dr. Jan-Hendrik Hehemann, which is housed both at MARUM and the Max Planck Institute for Marine Microbiology, investigates microalgae and their function within the carbon cycle. One important focus of the team is polysaccharide compounds and their role in the ocean ecosystem.

Like plants on land, algae carry out photosynthesis in the sunlit upper water layers of the ocean, using carbon dioxide from the atmosphere as a building material for their growth. Microalgae in the surface waters produce a total amount of biomass similar to that of all the terrestrial plants, in spite of the fact that they make up only a small proportion of the organisms living in this environment. This is because of their comparatively short life spans. “Microalgae live fast and die young,” says Jan-Hendrik Hehemann. Algae bloom within a period of days and then disappear soon thereafter. Microscopically small planktonic algae are the foundation of the marine food chain, upon which bacteria as well as larger animals feed.

When microalgae are active, they secrete polysaccharides, which sink through the water column to the ocean floor and transport carbon to the deep sea. The polysaccharides are thus a significant component of the “biological pump”, which is responsible for the transport of

Jan-Hendrik Hehemann studies the importance of algal polysaccharides in marine material cycles.

The bladder wrack algae *Fucus vesiculosus* grows on rocky coasts like this one on Helgoland. The cell-wall sugar fucoidan is especially important in helping it to withstand the tides and waves.

carbon and carbon dioxide from the surface waters into the deep sea. The role of microalgae in this process is not yet understood in great detail. To address this question, Jan-Hendrik Hehemann's research group studies the interactions between enzymes and sugar molecules. In their investigations of microalgae that live in the upper-ocean layer penetrated by sunlight, Hehemann and his colleagues have employed a newly discovered enzyme. Their findings indicate that a large proportion of the algal biomass, an average of about one-fourth, is composed of the long-chain sugar molecule laminarin. The concentration of this molecule in the algal cells increases significantly over the course of the day, whereby the activity levels of algae vary at different times of the day. Quantitatively, around twelve gigatons of carbon are synthesized annually in the form of laminarin by algal photosynthesis. However, only a small portion of that is permanently removed from the atmosphere.

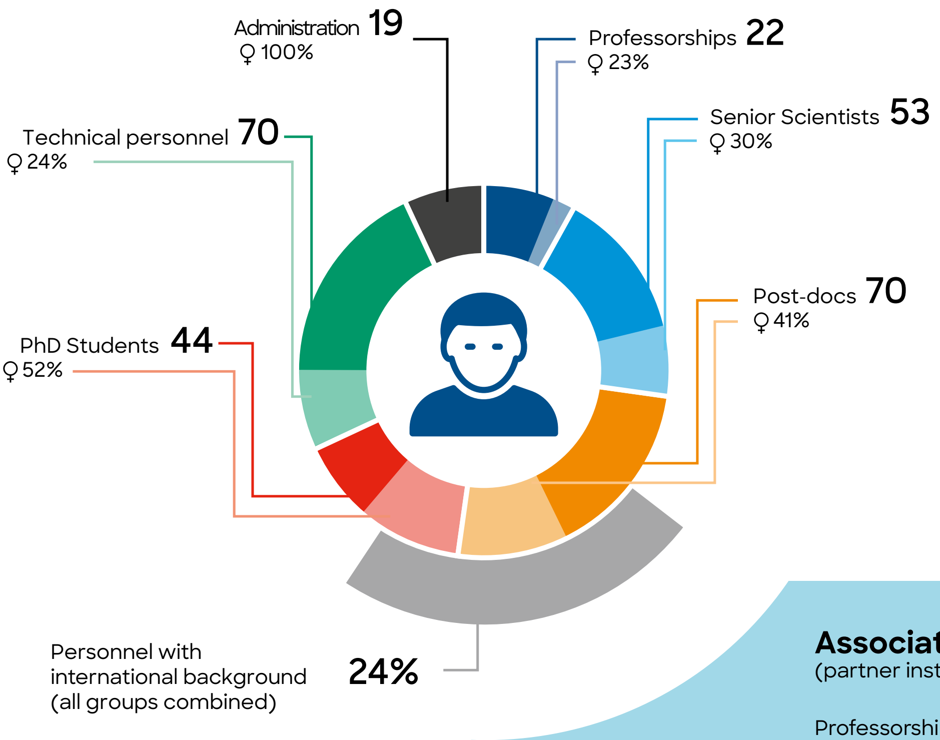
When diatoms die after the bloom, they sink toward the bottom. The researchers in the laminarin study discovered that this sugar molecule accounts for around half of the organic carbon in the sinking diatoms. "Laminarin thus plays an important role in the transport of carbon from the ocean surface to greater depths. Whether laminarin remains there over the long term is an important question that we now have to address," stresses Hehemann.

Most of the biomass that arrives from the surface into the deep ocean is recycled there. The remainder sequesters carbon in the marine sediments, thus regulating the concentration of oxygen and carbon dioxide in the atmosphere. As the particles sink downward, the long-chain sugar molecules act as a glue to hold the cells and mineral material together, causing the particles to become larger and denser, and thus to sink more rapidly. This adhesive apparently resists certain bacterial enzymes that would otherwise cause it to dissolve and the particles to break down into their component parts.

Exactly how the adhesive functions, however, is not known. To find this out Hehemann and his colleagues have investigated which sugar compounds occur abundantly during an algal bloom. In the process, they also discovered an abundance of enzymes that are known for the degradation of sugars like laminarin. By contrast, enzymes that break down long-chain, fucose-containing sugars were absent. The latter wrap themselves around the particles like an antifouling material, protecting them from being degraded by bacteria. "Furthermore, our results indicate that the algal sugar molecules that form the adhesive matrix of the cells and particles are stable, and could thus represent an as yet unexplored mechanism for carbon sequestration in the ocean."

MARUM in numbers

Personnel

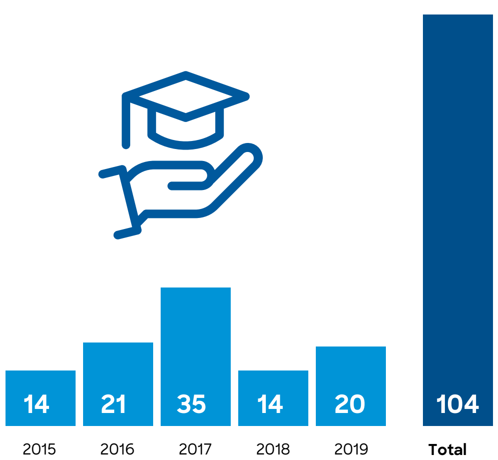


Associated personnel
(partner institutes)

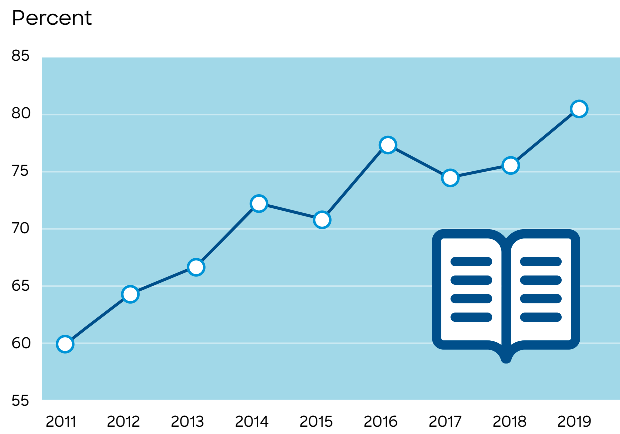
Professorships 18
♀ 33%

Senior Scientists 23
♀ 35%

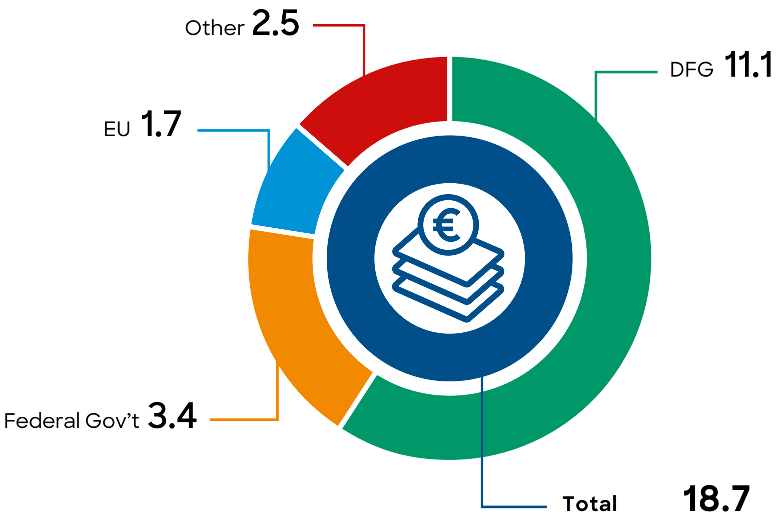
PhD graduates



Publications
with international participation



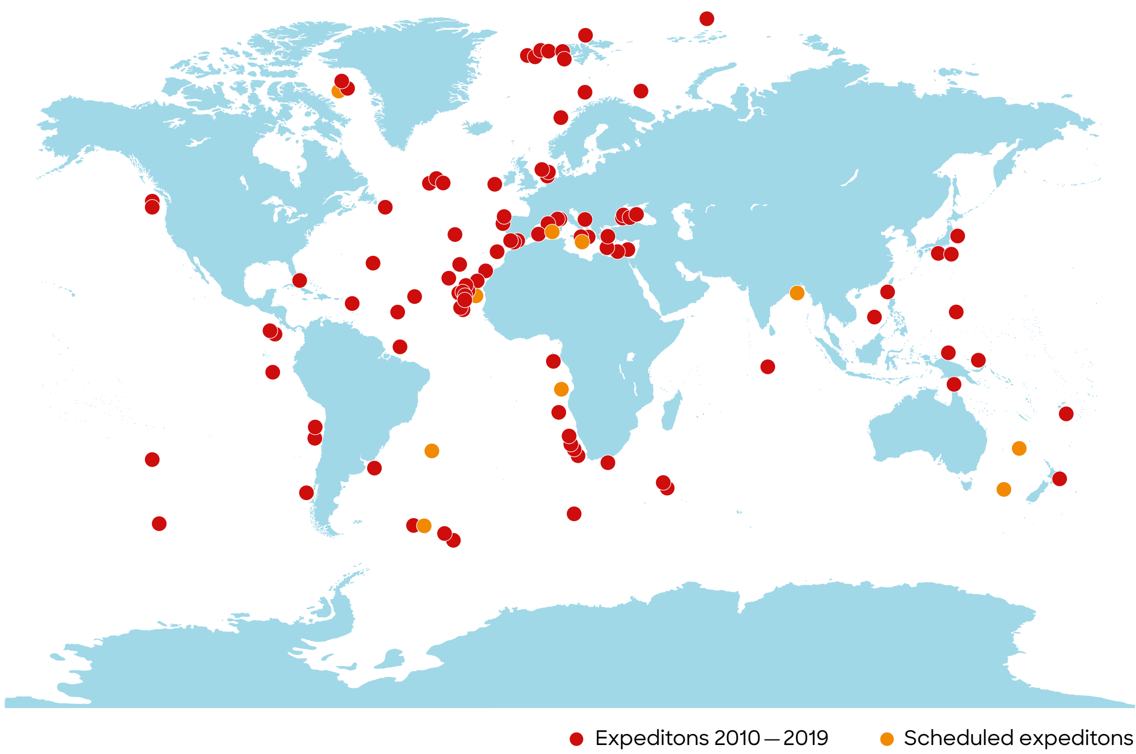
External funding



(2015 – 2019 average, million Euros/year)

Ship expeditions

17 / Jahr
2015 – 2019 average
(3 with IODP)



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Translation
Walter Hale, Bremen

Photos
Title page, p. 5 (No. 1), p. 10 top: MARUM, Thorsten Klein. p. 4 (No. 1 — 7), 5 (No. 3), 6, 8 (3), 10 bottom, 11 top, 14, 20, 21 (3), 22 (No. 2 / 6), 24, 26 (2), 27, 28, 29 (2), 31 (kl.), 42 (No. 1/2), back cover: MARUM, Volker Diekamp. p. 4 (No. 8), p. 22 (No. 3 / 4), 42 (No. 3) Sean Diaz. p. 5 (No. 2): MARUM, Marcel Schröder. p. 7: Margit Wild. p. 9: MARUM, Albert Gerdes. p. 11 bottom: MARUM, Dagmar Kieke. p. 12, 13 (4), 15 (3), 16, 17 (3), 19 (3), 42 (No. 4/5): MARUM, ROV-Teams. p. 22 (No. 1): HYDRA, Christian Lott. p. 22 (No. 5): MARUM, Sebastian Meckel. p. 22 (No. 7): MARUM, Tilo von Dobeneck. p. 30 / 31: pxhere. p. 33 bottom: MARUM, Heiko Pälike. p. 33 right: MARUM / IODP, Ursula Röhl. p. 34, 37 (3): SLATE; p. 35: private. p. 38: Max Planck Institute for Marine Microbiology (MPI MM), Craig S. Robb. p. 39 left: MPI MM. p. 39 right: MPI MM, Mikkel Schultz-Johansen.

Graphics
p. 9, 18, 21, 32, 40 / 41: MARUM / Büro 7. p. 11: MARUM, Dagmar Kieke / Linn Sanguineti. p. 14 Map: after M. Loher, p. Ceramicola, P. Wintersteller, G. Meinecke, H. Sahling and G. Bohrmann (2018): Mud volcanism in a canyon: morphodynamic evolution of the active Venere mud volcano and its interplay with Squillace Canyon, Central Mediterranean. Geochemistry, Geophysics, Geosystems. doi:10.1002/2017GC007166. p. 25: MARUM / PANGAEA / GfG — Gruppe für Gestaltung, Bremen. p. 30: MARUM / Büro 7. Data modified and extended according to IPCC und Hansen et al. 2013 (Phil Trans R Soc A, doi:10.1098/rsta.2012.0294). Modeling of the sea level according to DeConto and Pollard 2016 (Nature 531, doi:10.1038/nature17145). Modeling of global deep water temperature from CMIP5-derived model ensembles for water depths > 3 kilometers (Giorgetta et al., doi:10.1594/WDCC/CMIP5.MXELr8). p. 36 oben: nach M. Sammartini, J. Moernaut, F. p. Anselmetti, M. Hilbe, K. Lindhorst, N. Praet and M. Strasser (2019): An Atlas of Mass-Transport Deposits in Lakes. Submarine Landslides: Subaqueous Mass Transport Deposits from Outcrops to Seismic Profiles, 201 — 226. p. 36 bottom: nach T. Zengaffinen, F. Løvholt, G. Pedersen et al. (2020): Modelling 2018 Anak Krakatoa Flank Collapse and Tsunami: Effect of Landslide Failure Mechanism and Dynamics on Tsunami Generation. Pure Appl. Geophys. 177, 2493 — 2516. doi.org/10.1007/s00024-020-02489-x.

Design
Büro 7, Bremen

Print
Girzig+Gottschalk GmbH

Circulation
1st edition, 500 pieces

Bremen, 07-2021

MIX
Paper from responsible sources
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