Getting to the Bottom **of the Deep Sea**

The ocean is her passion, the seabed her lab bench. **Antje Boetius** from the **Max Planck Institute for Marine Microbiology** in Bremen always has multiple objectives in her sights: from discovery and precautionary research to technological development and scientific communication. It's an act that involves a lot of juggling – sometimes in rubber boots, sometimes in high heels.

TEXT **TIM SCHRÖDER**

Lectures abroad, preparatory paperwork for expeditions, team meetings, committees: "If you want to meet up soon, it would be best if you come by immediately – otherwise, it won't be possible for another two weeks," says Antje Boetius on the phone. "How about five o'clock?" Friday, 5 p.m. – the weekend has already started for a lot of people, but she squeezes in the interview before calling it a day because she believes in the importance of scientific communication, and she has resolved to deal with inquiries about her work immediately.

"Yes, I work quite a lot," she says later, "around 14 hours a day. And on the weekend I like to work on my manuscripts – really." Boetius stresses the "really" as though she wants to leave no doubt about the fact that she enjoys her work. But that's obvious anyway. It's approaching evening and she comes across as energetic and fresh, as if the week had just begun. There's no doubt about it, Antje Boetius is passionate about her research.

The marine biologist's to-do list is endless. She is head of the Joint Research Group for Deep-Sea Ecology and Technology at the Max Planck Institute for Marine Microbiology in Bremen and the Alfred Wegener Institute (Helmholtz Centre for Polar and Marine Research) in Bremerhaven. She is also Professor of Geomicrobiology at the University of Bremen and Vice Director of The Oceans in the Earth System excellence cluster at the MARUM Center for Marine Environmental Sciences in Bremen. She has at least three balls in the air at all times – and juggles them all successfully.

SPECIES DIVERSITY ON THE SEABED

The main topic of her research is the role of the seabed and its inhabitants within the Earth system – a very broad topic, as the seabed accounts for two-thirds of the Earth's surface, and its biodiversity exceeds that of the terrestrial habitats. The issues Boetius tackles are equally diverse. "Around every five years, I change the focus of my work – sometimes I work on a particular biogeochemical process, such as the consumption of the climate gas methane; sometimes on the biodiversity on the seabed; and sometimes on the reaction of marine ecosystems to the melting of the sea ice and human interventions."

Irrespective of what she is working on, Boetius aims to spend as much time as possible at sea, observing nature directly. In total, she has spent several years of her life on research ships. When she talks about this, she sounds like an old sea dog who longs to be back on the high seas again. "I make sure that I go on an expedition at least once a year," she says.

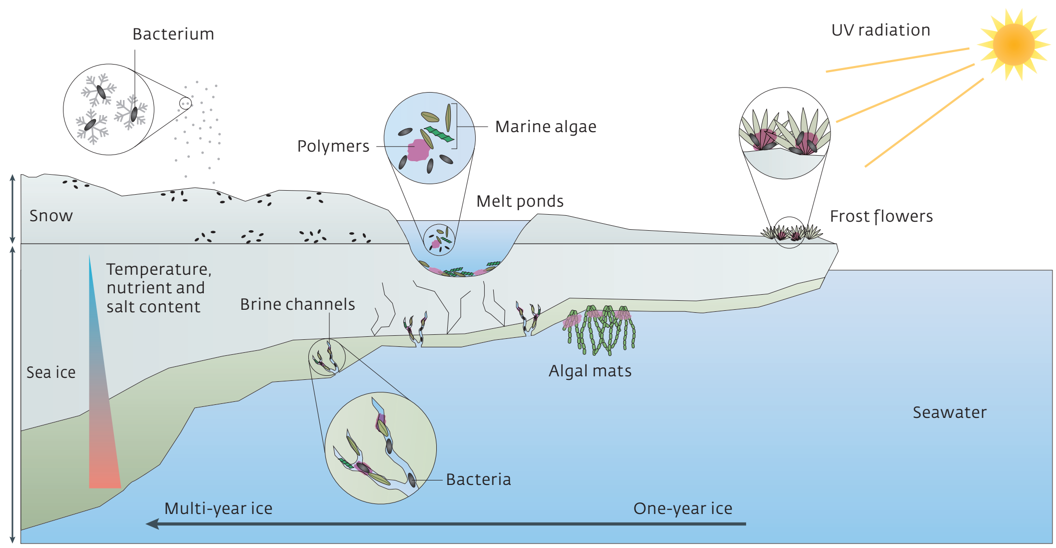
Boetius is a deep-sea researcher and has plunged to the remote ocean depths with diving boats many times – in the Atlantic, Indian and Pacific Oceans and in the Mediterranean and Polar Seas. Aided by spotlights, she has observed pale deep-sea fish, vividly colored sea cucumbers, bizarre giant worms and delicate brittle stars. What she is most interested in, however, are the smallest of life forms: bacteria. They may be microscopic, but they are extremely important, as they metabolize an enormous volume of substances and even influence the Earth's climate in the process.

Boetius was born in Frankfurt am Main and grew up in Darmstadt, far from the sea, but she made up for this distance from the water with her imagination. She is the first-born child in her family. Her mother is a teacher who taught her to read at an early age – she started reading when she was three and her favorite activity as a child was to bury herself in a book. Pirate novels, Treasure Island, Moby Dick and everything by Jules Verne. She loved them all.

She watched little or no television, and when she did, it was the diving

Photo: Achim Multhaupt/laif

Antje Boetius in her expedition gear: The equipment for the next trip is being packed in crates in the expedition hall of the Max Planck Institute in Bremen. On the left, a “deep sea lander,” a freefall device that measures the respiration of bacteria in the deep sea and can also take samples. The researchers first used it under closed ice cover near the North Pole.



Microorganisms in the atmosphere form condensation nuclei for snow crystals, which is how they end up in the Arctic ice (top left). Bacteria and single-celled algae populate snow, ice, melt ponds and frost flowers despite being exposed to stronger UV radiation from the sun there. The microorganisms in the ice secrete complex molecules (polymers) with which they can also influence the ice formation. When sea ice freezes, the salt and other dissolved substances are captured in tiny channels within the ice as highly concentrated brine. The brine channels, melt ponds, and especially also the underside of the sea ice, are special habitats for microorganisms. The *Melosira arctica* diatom can form thick biofilms under the ice.

Graphic: Nature Reviews Microbiology

films of Hans Hass and his wife Lotte and the adventures of Jacques-Yves Cousteau that attracted her attention. “It was amazing. To go on expeditions as a career, live on yachts, do research in a bikini, have all kinds of underwater adventures – all of that inspired me.” During this period of her life, her parents separated, but the family reunited for holidays. Antje, her siblings, her mother, her father and his new partner travelled to the sea together, usually to the Atlantic coast in Ireland, France or Norway. They camped in the open country, paddled along the shore in rubber dinghies and trawled the crystal-clear water for animals.

When she was 12, her father gave her a small set of equipment for nature exploration: a weather station, binoculars, stereo magnifying glasses and a small centrifuge. She knew what she wanted to do from an early age: to study in Hamburg, where there are a lot of ships and the sea on the doorstep. She wanted to experience the sea as a researcher.

Boetius has certainly fulfilled that early career wish. Today, she is often out and about on the high seas, particularly in the Arctic, with the German research icebreaker *Polarstern*, which enables her to explore the ice-covered waters of the North Atlantic. She wants to understand how climate change is altering life: the composition of the microorganisms in the ice, the production of algae in the water and thus also the food for deep-sea communities, and the deposits in the seafloor sediments.

ICE MELT IN THE ARCTIC

During the time she was travelling in the Arctic in 2012, the sea ice was melting at a faster rate than ever before. It was thin and littered with melt ponds, making it particularly bright below the ice. The marine alga *Melosira arctica* was able to grow particularly well under these conditions and form dense, seaweed-like forests under the ice. Due to the intense warming, however, the ice melted and the algae sank into the depths of the ocean in fist-sized clumps.

Boetius and her colleagues sent cameras down to the seabed, which provided them with astonishing images: the otherwise desert-like floor of the central Arctic was covered with a green algal carpet. Only a few sea cucumbers and brittle stars could make anything of the *Melosira* clumps. The deep-sea measurements carried out by the Max Planck researchers showed that the new food supply is being exploited mainly by bacteria that consume the oxygen in the seafloor on site. The researchers were able to report and describe this unexpected reaction of the Arctic ecosystem to the ice melt in a report they produced on board the research vessel.

The next Arctic expedition took place in 2014 and tackled a completely different topic. This time, Boetius and her team were at sea to explore the Gakkel Ridge north of Greenland. It was suspected that there were hot springs and special biocoenoses at a sea mount on the seafloor here, four kilometers below the ice. Such springs are known to exist at mid-ocean ridges, where new Earth crust is formed and the ocean plates drift apart. The seawater penetrates deep into the mantle there, is heated by magma chambers, reacts with the rock and spews back up into the ocean full of energy and minerals. This is how hot springs provide a nutritional basis for bacteria, which, in turn, provide sustenance for higher life forms. Life flourishes there in a way that is found almost nowhere else in the deep sea.

No one had previously observed life at the hot springs in the Arctic, though, because the sea ice was blocking the way. Since 2001, there had been indications of surprisingly strong heat emissions and smoke plumes in the sea, but no images had yet been obtained of these extreme habitats in the ice-cold

Polar Sea. Boetius and her team had a plan – and a great deal of luck: even with full ice cover, they were able to deploy underwater vehicles from the *Polarstern* and search the sea floor. On the last day of the expedition, they struck gold: small vents, known as black smokers, surrounded by unfamiliar gardens of white glass sponges appeared on the images they recorded. The international team is currently working through these findings. They want to prove that the spreading of the Arctic Ocean functions differently than predicted. This is the kind of discovery that fills Antje Boetius with enthusiasm.

Antje Boetius took her first steps into the world of science at an early age. Despite being bored by biology lessons at school, with their focus on the description of plants and animals, upon completing her German school-leaving examination in 1986, she moved to Hamburg to study marine biology. A relative suggested that she enroll to study with deep-sea researcher Hjalmar Thiel at the Institute for Hydrobiology and Fisheries Science there.

At that time, Thiel was among the scientists who were studying life on the manganese nodule fields at the bottom of the Pacific Ocean. Back then, the large-scale mining of the nodules was being considered for the first time. As part of the international DISCOL project, the team of scientists headed by Hjalmar Thiel and Gerd Schriever plowed a few square kilometers of the seabed in order to investigate how life in the deep sea would react to such an intervention. It appeared that the mining of the manganese nodules was about to become a reality, but no ecological studies had been carried out on the consequences.

Thiel invited the young student to meet with him. He began by advising her to study all aspects of biology and not to specialize too early. But Antje Boetius already knew that she only wanted to focus on the sea. “He told me to get back to him when I had completed my intermediate undergraduate diploma.” Antje Boetius was born in 1967, so she’s a baby boomer. The university lecture halls and labs were overflowing with students, and the waiting lists for the most interesting courses were long. She had to earn money to finance her studies, so she worked part-time as a waitress in a pizzeria and as a secretary in an insurance company – “a very strange world,” she says, “where everything is about money.” The highlight of her undergraduate studies was her first short ship expedition, which finally convinced her that she belonged on a research vessel. >

Boetius studied deep-sea mud volcanoes on an expedition to the Mediterranean with the *L’Atalante* research vessel in 2003.

Photo: IFREMER

When she started her main undergraduate studies in 1989, she was finally able to concentrate on marine research. She attended every lecture that had anything to do with water, including Thiel's deep-sea lectures. At one point, he was looking for assistants for a large-scale expedition on the *Meteor* research vessel in the northeast Atlantic, and to her delight, she was selected to participate. Before the trip started, however, Thiel put forward a surprise offer. He asked whether she would like to participate in an exchange program – there was a spot available at the Scripps Institution of Oceanography in the US. Scripps in La Jolla, one of the best-known marine research institutes in the world, directly on the surf beach! Give up her part-time jobs and interrupt her studies immediately after her first big expedition with the *Meteor*? What to do. But she didn't spend a lot of time deliberating, and started packing her bags for the trip to the US.

Antje Boetius has never regretted the decision. She is very enthusiastic about the direct contact between the researchers and students there, and the considerable attention paid to the students. She completed so many internships and courses at Scripps that the time she spent there was fully counted toward her degree coursework; all that remained for her to do on her return was to write her degree thesis. To that end, she immediately participated in several research expeditions. And it was on one of these that she met her future partner, a crew member from Bremerhaven. Boetius packed the insights she gained from over four months of expedition into her thesis. "It was all very tightly calculated, but I learned so much in the process."

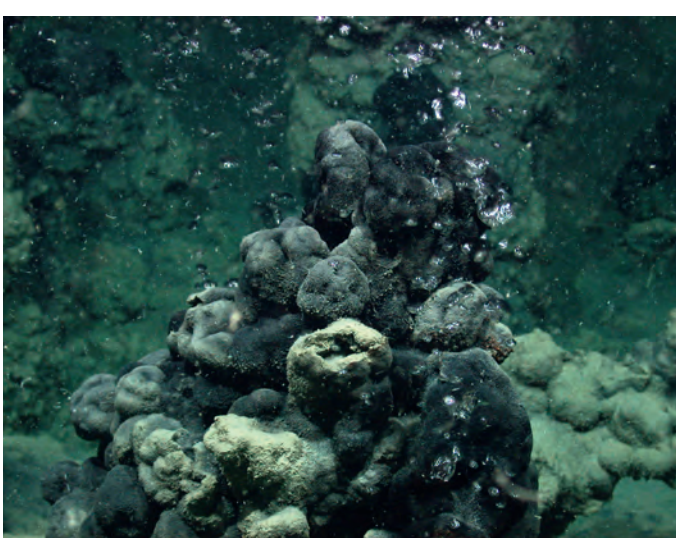
BREMERHAVEN – NOT USA

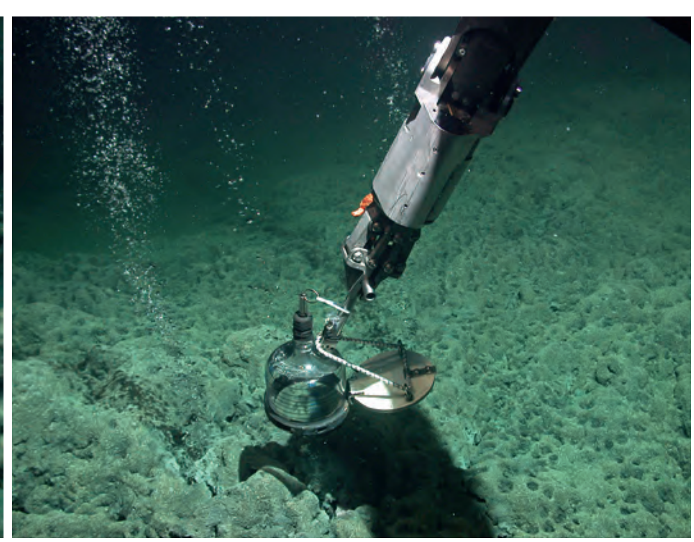
It had long been clear to Boetius that she wanted to continue in research and that the next step would involve doing a PhD. She had already familiarized herself with the microbiology of the sea floor on the research expeditions, but she didn't yet know where she should do her dissertation. She was longing to return to the US and the atmosphere at the institutes in California. On the other hand, her boyfriend was in Bremerhaven. The decision was made when her mentor from Scripps gave her a crucial piece of advice: if she wanted to make progress in the area of deep-sea microbiology, there was no better place to study than at the Alfred Wegener Institute with Karin Lochte, who is now Director of the Helmholtz Centre. So Boetius remained in Bremerhaven.

For her doctoral studies, Boetius travelled to the Siberian continental shelf with the *Polarstern* for the first time in 1993. She took samples from the ice-covered deep sea and analyzed how the lack of nutrients influences the activity of the bacteria on the seafloor. "My dissertation was no sensation at the time," she says. "But the samples I took are a valuable source of information for new studies today. Nobody would have imagined back then that just 20 years later we would be working in completely ice-free areas." Thus, her data provides an important reference point when it comes to establishing how the Arctic bacterial communities are adapting to climate change.

"During this period, I was at sea for almost half the year and completely engrossed in expeditions. I simply wanted to be outside and gave little or no thought to my career," she says self-critically. It is important for researchers to stay informed about the general situation in science, to get to know new methods and carve out a research field for themselves. "I tell that to my doctoral students today, as it has become even more difficult to become independent at an early stage in your career."

In the Black Sea, bacteria populate gas sources at a depth of 260 meters and form towers standing several meters tall. These are supported internally by lime (left). The researchers use a glass bell jar to measure the gas emissions at a cold spring 850 meters below sea level in the Black Sea (right).





Photos: MARUM – Center for Marine Environmental Sciences, University of Bremen

Boetius and her colleague Torben Klagge before a dive: The researchers studied the oxygen-free zones in the Black Sea in 2010 from the research submarine *Jago*. The German *Maria S. Merian* research vessel is in the background.

Photo: Karen Hissmann GEOMAR

On completing her doctorate, she went to the Leibniz Institute for Baltic Sea Research in Warnemünde as a postdoc with Karin Lochte and worked for a time in the Indian Ocean. At the time, in the mid-1990s, new molecular biology techniques were emerging with which researchers could identify genetic relationships from the genomes of bacteria, particularly by comparing the ribosomal nucleic acids (16S rRNA sequencing). Marine microbiologists were using these methods to determine the diversity of unknown microorganisms and their distribution and activity.

For that reason, in 1999, Boetius moved to the Max Planck Institute for Marine Microbiology in Bremen, where she familiarized herself with the new methods in marine microbiology. Back then, methane deposits in the sea were becoming a major focus of scientific interest. Methane hydrate – also known as gas hydrate – is a solid, ice-like compound between seawater and methane that forms in the depths of the ocean at low temperatures. Such hydrates are found in different locations in the oceans. Scientists all over the world are fascinated by them, as they could offer an interesting source of energy – but they could also cause landslides and tsunamis. Moreover, they are teeming with life: bizarre worms, mussels and unfamiliar microorganisms.

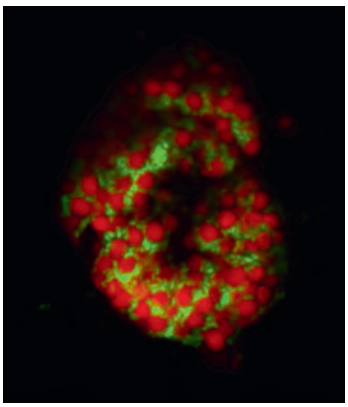
METHANE AS A FOOD SOURCE

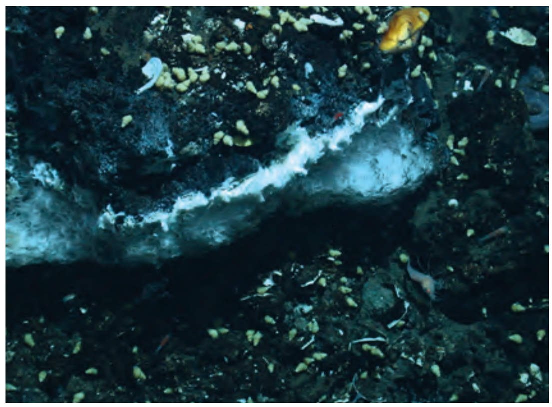
But no one knew what the communities of animals in gas hydrates live on, as there was no known organism that could make direct use of methane. It was suspected that organisms from the Archaea kingdom decompose the methane and possibly obtain energy in this way. Boetius was able to participate in a GEOMAR expedition to Hydrate Ridge, in the Pacific, and studied the sediment samples taken there. She combined the 16S rRNA sequencing with another detection method known as fluorescent in situ hybridization (FISH). The FISH technique enables the microscopic differentiation of the bacterial species in a sample based on their genetic fingerprints. Specific nucleic acid molecules marked with fluorescent dyes attach to the ribosomes of certain bacteria and cause them to light up.

Strangely, two cell types that appeared to have grown onto each other always lit up under Boetius's microscope. They were bacteria that process sulfur compounds and microbes from the Archaea kingdom. She eventually realized what was going on here: the methane in the sea floor is processed jointly by the two. The solution to the mystery about life on the hydrates is cooperation! The bacteria create the right energy conditions for the archaea to be able to breathe the methane and, in return, benefit from the latter's decomposition products.

The renowned scientific journal NATURE published the story about the archaea-bacteria symbiosis, which provided the first indications of "anaerobic methane oxidation" on gas hydrates. The article met with great interest in the life and earth sciences, given that methane is a major greenhouse gas.

The scientific world had been asking itself for decades why the gas-rich





Left Shining duo: An accumulation of methane-oxidating archaea (red) and their symbiosis partners (green). The colors are generated by nucleic acids labeled with fluorescent dyes.

Right Methane hydrate in the Gulf of Mexico at a depth of almost 3,000 meters. Microorganisms feed on the methane it contains and, in turn, provide food for worms, snails and crabs.

ocean releases so little methane into the atmosphere, and how the climate would change if the methane hydrates dissolve due to the warming of the oceans.

MOVING UP THE CAREER LADDER

Boetius had achieved a major coup. While still a postdoc she was able to launch a major project at the Max Planck Institute to investigate the micro-world on the hydrates. The project was funded by the German Federal Ministry of Education and Research, and involved all of the departments at the Bremen-based Institute. Her career really took off then and a series of other projects followed. In 2003 she took over the leadership of the Microbial Habitats Research Group at the Max Planck Institute in Bremen. That same year, she was appointed to a professorship at the International University Bremen, the predecessor of Jacobs University.

She commenced numerous new projects on deep-sea research, many of them in cooperation with researchers from different countries. In 2008 she established the Joint Research Group between the Max Planck Institute and the Alfred Wegener Institute, and was appointed to a professorship for geomicrobiology at the University of Bremen. In addition to the projects on the discovery of extreme habitats and the function of methane decomposition, she added other important research questions in the area of precautionary research to her repertoire: What happens when the ocean acidifies? How do microbial communities react to a lack of oxygen and over-fertilization? When does the sea floor recover after the removal of manganese nodules?

"I'm always interested in new tasks and challenges," says Antje Boetius. "You just have to allow fate the chance to come up with one." Like when she approached Thiel as a young school-leaver, or during her undergraduate studies when she applied for a place on the research voyage despite having very little chance of being chosen.

She requires a certain amount of individual initiative from her 60-plus staff members. "We work on projects in alternating teams so that each doctoral student and technician has several contacts – and I can always be reached by e-mail." And something else is important to her: "When we go on an expedition together, we get to know each other in all kinds of situations. That creates trust."

Boetius has led regular expeditions since 2006. She organizes the scientific tasks on board and coordinates the research work with the captain and crew. On big research vessels, researchers from a large number of disciplines working on a diverse array of experiments and topics are usually tossed in together. As an expedition leader, she follows the example of her mentor Hjalmar Thiel and his colleagues. "I learned back then that, while you have to work hard on board to ensure that all of the tasks and sample collections are completed in a short time, it is also important to take breaks to celebrate and dance, because when the mood is good, everything works better." That's why she always has, not just rubber boots, but also her pumps on board with her.

As the expedition leader, she's on her feet from early morning till late at night. The hours aren't regular as the ship works around the clock. Good contact with the crew is important. "As researchers, we are merely guests on board the ship. I rely on the crew, as these people have many years of experience with the ship, the weather and our research equipment." She ensures, for example, that the images that are transmitted from the depths of the ocean to the ship can be viewed on the bridge, and that the crew understands the research task. "So everyone can be part of what's going on."

Beyond the expeditions, however, Boetius has also taken on a range of management functions, for example as Chairperson of the Scientific Commission of the German Council of Science and Humanities, which is appointed by the German federal government, and Chairperson of the Research Buildings Committee. Every year, this committee evaluates applications involving total costs of 450 million euros for the construction of research buildings at universities. She is still delighted about the trust placed in her and the other members of the Council of Science and Humanities to develop the best possible strategies. "We get to decide on applications from a wide range of scientific dis-

Photos: Viola Krukenberg, MPI for Marine Microbiology (left), MARUM Center for Marine Environmental Sciences, University of Bremen (right)

In summer 2012, Boetius appeared on the German television program *Tietjen und Hirschhausen* with hosts Willi Weitzel (left) and Guido Cantz (second from the right). Through such media appearances, she hopes to inspire interest in science and the ocean.

ciplines." She is very pleased with the positive response she has received on all of the committees, and with the diversity of experiences and contacts they provide. "Sometimes I even amaze myself – one minute I'm in oilskins on board the ship and the next I'm in a cocktail dress at an event attended by the German President. But I'm certain about one thing: my experience with strong winds, heavy seas and never-ending horizons always stands me in good stead."

Scientific communication is also important to Boetius. She is currently the Chairperson of the "Science in Dialogue" steering committee, an initiative of the German research organizations. Whether for television, radio, podcasts or newspaper articles, she is happy to respond to all requests – especially from children who ask her how they can become marine researchers and how much money they could earn at the job. She collects the letters from children in a folder. She loves the conversation she has with young people, not only because they remind her of her own roots as a scientist, but "because this basic curiosity about everything in the world is so crucial and is still a driving force for me as a researcher."

"Discovery research" is how she describes what she does today. She wants to understand the variety of ecosystems and the spatial distribution of organisms in unknown regions in the deep sea, not least with a view to identifying effective protective strategies for the sea. Discovery research as carried out by Humboldt? She laughs: "No, more as carried out by Maria Sibylla Merian, the 17th-century nature researcher from Frankfurt. There have also been influential female discoverers." The spirit of Maria Merian probably isn't the only one that motivates her; the way she beams when she talks about her work suggests that she might just also have something of diver and filmmaker Lotte Hass about her. ◂

GLOSSARY

16S rRNA sequencing: The 16S ribosomal RNA is one of three RNA molecules that control the formation of proteins in bacterial ribosomes. The 16S rRNA gene changes very slowly through mutation, making it particularly well suited for identifying family relationships between bacteria. Based on the analysis of 16S rRNA genes, researchers can not only identify the species diversity in a sample, they can also determine how often the individual species arise.

Archaea: Single-celled organisms that have no cell nucleus. In the past they were referred to as archaebacteria. However, their cells are clearly different in structure from bacterial cells, which is why they are now classified as a third domain of life along with bacteria and eukarya – organisms that have a nucleus. Based on some of their characteristics, archaea are even closer to the eukarya than the bacteria. Many archaea species are adapted to extreme environmental conditions. They are found, for example, in deep-sea hot springs and in salt lakes.

Methane hydrate: Also known as gas hydrate, it consists of methane that is trapped in ice. In the sea, it forms in the methane-saturated pore water of the seabed where the pressure is high and the temperature low enough: at a depth of around 300 meters in the Arctic. The surroundings of methane hydrates are particularly species-rich, as some microorganisms can use the methane to generate energy. Their waste products, such as hydrogen sulfide, are used by other microbes, as well as mussels, worms and crabs, which live in symbiosis with bacteria. It appears that there is far more methane hydrate on Earth than oil and gas. However, its mining and exploitation for energy generation are technologically challenging and not economically viable.