Research Mission of the German Marine Research Alliance (DAM)
»Marine carbon sinks in decarboniation pathways«

FACT SHEET

Geological methods

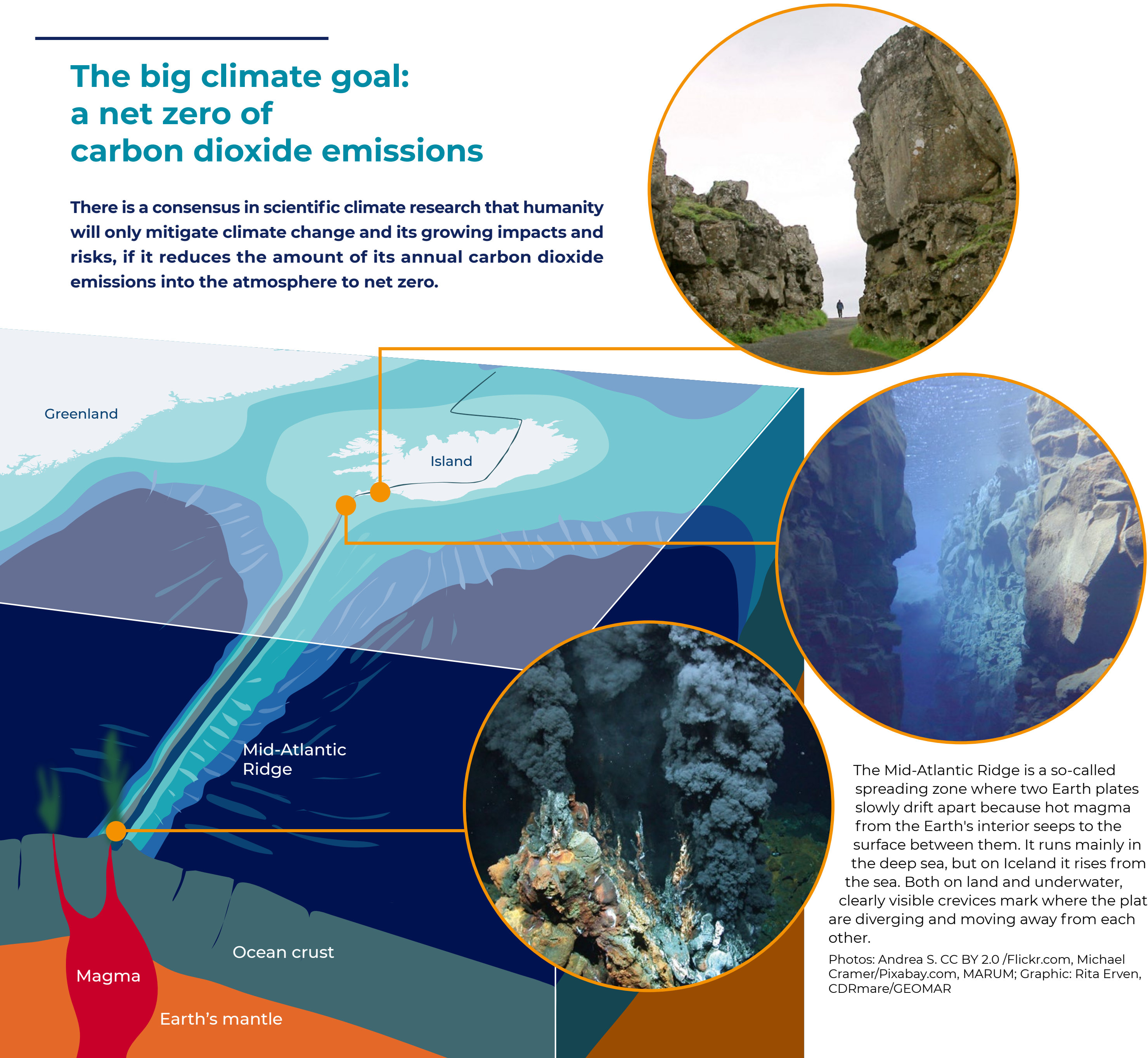
A deep-sea experiment on carbon dioxide storage in oceanic crust

On Iceland, water enriched with carbon dioxide has been injected into the upper ocean crust since 2014 – and successfully. The carbon dioxide mineralises within a short time and is firmly bound for millions of years. However, since ocean crust only rises above sea level in a few places on Earth, researchers currently investigate the option of injecting carbon dioxide into ocean regions where huge areas of suitable basalt crust lie at medium to great water depths. One possible advantage: In the deep sea subsurface, the carbon dioxide would either be stable as a liquid or dissolve in the seawater circulating in the rock.

Due to the high pressure, both the liquid carbon dioxide and the carbon dioxide-water mixture would be heavier than seawater, making leakage from the underground unlikely. But would carbon dioxide storage in the deep sea subsurface be technically feasible and ultimately also economically viable? The research mission CDRmare provides answers – with the help of the world's first deep-sea research experiment on carbon dioxide storage on cooled flanks of the Mid-Atlantic Ridge.

The big climate goal: a net zero of carbon dioxide emissions

There is a consensus in scientific climate research that humanity will only mitigate climate change and its growing impacts and risks, if it reduces the amount of its annual carbon dioxide emissions into the atmosphere to net zero.



The Mid-Atlantic Ridge is a so-called spreading zone where two Earth plates slowly drift apart because hot magma from the Earth's interior seeps to the surface between them. It runs mainly in the deep sea, but on Iceland it rises from the sea. Both on land and underwater, clearly visible crevices mark where the plates are diverging and moving away from each other.

Photos: Andrea S. CC BY 2.0 /Flickr.com, Michael Cramer/Pixabay.com, MARUM; Graphic: Rita Erven, CDRmare/GEOMAR

Human-made carbon dioxide emissions are caused by the burning of fossil fuels such as oil, natural gas and coal, as well as by changes in land use. So far, no one knows how humankind will be able to avoid 100 per cent of these emissions in the future in an ecologically and societally acceptable way. On the contrary, experts assume that Germany will still be emitting residual carbon dioxide and other greenhouse gases in the middle of the 21st century. In optimistic scenarios, their level is estimated at 10 to 20 per cent of current emissions. This corresponds to annual emissions of about 60 to 130 million tonnes of greenhouse gases, most of which are methane and nitrous oxide.

To compensate for these residual emissions, humankind will have to either capture carbon dioxide directly at the sources or remove it from the atmosphere to the same extent. The gas must then be further processed into long-life products or stored underground. This process is called carbon capture and storage (CCS). But one remaining key question is: Where on Earth can large quantities of carbon dioxide be safely and permanently stored underground?

Porous and reactive: The basaltic rocks of the upper ocean crust

The basalt rocks of the upper oceanic Earth's crust offer themselves as geological carbon dioxide reservoirs. If you think of cobblestones when you hear the word basalt, you actually have basaltic rock in mind. The rocks of the upper 100 to 400 metres of oceanic crust, however, have little to do with the dense, fine-grained rock we humans use to pave marketplaces or courtyard driveways. Instead, the upper ocean crust is highly porous and in some places criss-crossed by centimetre-sized vesicles.

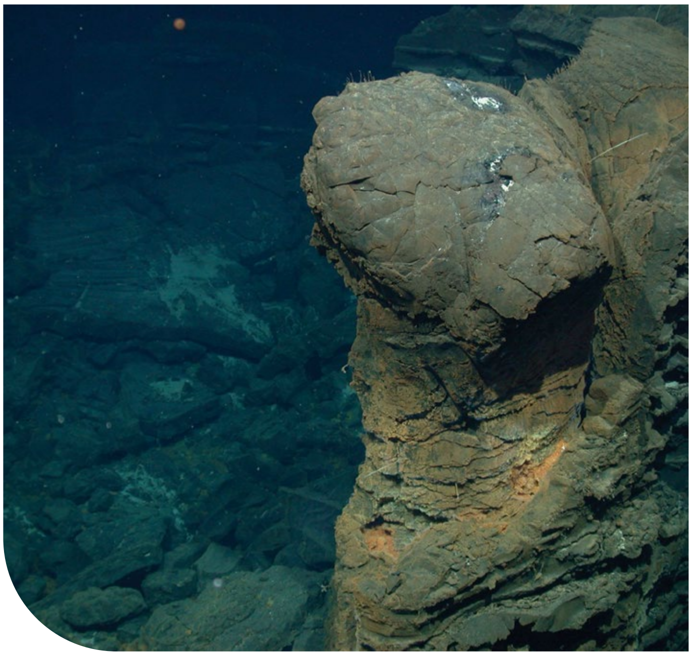
This characteristic vesicular, sometimes fractured structure evolves when the 6 to 8 kilometre-thick ocean crust forms. This happens along so-called spreading centres such as the Mid-Atlantic Ridge. In these zones of the Earth, two tectonic plates slowly diverge because hot magma from the Earth's interior ascends to the surface between them. Upon contact with the cold seawater, it is »quenched« at its surface. This fundamentally changes the structure of the rock near the surface. It blisters, fractures and cracks in many tiny places and finally forms a network of tiny cavities and veins, which from then on remain in the entire upper part of the basalt rock pervasively.

Seawater circulates steadily through this underground network of pores, with the consequence that the upper 400 metres of basalt rock functions as a huge conduit system for fluids (liquids and gases). It forms the largest water-bearing rock formation (aquifer) on Earth, directly beneath the ocean.

At the same time, the quenched and slowly cooling basalt rock fulfils many prerequisites for acting as a carbon dioxide reservoir. Its large pore volume, for example, offers sufficient space to introduce large quantities of liquefied carbon dioxide or carbon dioxide-enriched waters. In addition, the pore space offers a lot of rock surface on which the carbon dioxide dissolved in the seawater may mineralise. This means that it is bound by the formation as new minerals.

The chemical prerequisites for such mineralisation reactions are also given. The basalts of the upper ocean crust contain numerous elements such as iron and magnesium, which react with the CO_2 dissolved in the water. In the course of this reaction, carbonate minerals are formed – or, to put it simply, rocks in which the former carbon dioxide is then firmly bound for millions of years. This natural process takes place anyway in the upper basalt crust through which seawater flows. It could be accelerated by the targeted addition of carbon dioxide.

How much carbon dioxide theoretically could be stored in the upper ocean crust has not yet been thoroughly investigated. However, experts currently assume that the theoretical mineral carbon dioxide storage capacity of the mid-ocean ridges of our planet is many times greater than the amount of carbon dioxide that would be released if all fossil fuel deposits on Earth were burned. This is because potentially suitable rock formations are not only found along mid-ocean ridges, but also in so-called flood basalt provinces, which often form plateaus of vesicular basalts in submarine or terrestrial settings.



This underwater rock was formed during a submarine lava eruption on the Mid-Atlantic Ridge at a water depth of 2950 metres. It has the typical surface structure of cooled basaltic rock. The photo was taken by the diving robot MARUM-QUEST in the southern Atlantic Ocean.
Photo: MARUM, University of Bremen

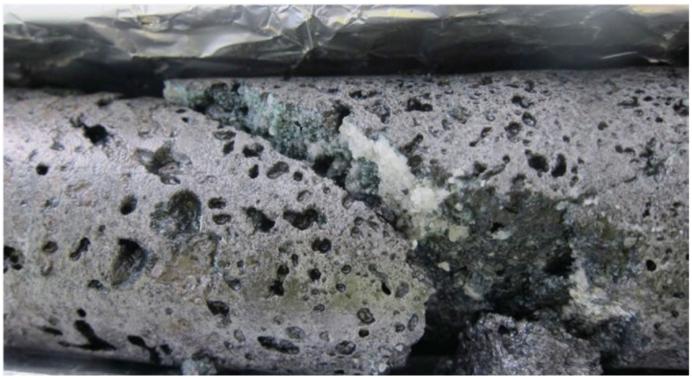
Lighthouse project on Iceland: Carbon dioxide mineralised in the reactive basalt rock

In the Carbfix project on Iceland, carbon dioxide that has been captured and dissolved in water has been injected into the upper ocean crust since 2014. The volcanic island is located exactly on the Mid-Atlantic Ridge, so that young, still hot and therefore very reactive basalt rock can be reached even with comparatively short drill holes. The mineralisation rates are correspondingly high: due to the high reactivity of Iceland's hot crust, about 98 percent of the injected carbon dioxide mineralises within two years and is thus firmly bound in the subsurface. By June 2022, Carbfix says it had injected more than 80,000 tonnes of carbon dioxide into the Earth's crust, but this consumed a lot of geothermal energy and large quantities of fresh water.

However, since there is a limited number of places on Earth where oceanic crust rises above the sea surface (for example, on Iceland and the Azores), scientists are turning their attention to greater water depths, where globally there are tens of thousands of kilometres of mid-ocean ridges in whose basaltic crust carbon dioxide could be stored.

This idea is supported by the fact that high pressures act at greater depths. Elevated pressure either helps to dissolve the injected carbon dioxide in the seawater circulating in the basalt crust – which would then become denser and heavier – or will enhance carbon dioxide dissolution in the injected seawater. This would compress it to such an extent that from a pressure of 280 bar on (from a water depth of about 2800 metres) it would be heavier than the seawater at a comparable depth and would no longer be able to ascend from the underground. Carbon dioxide leaks would thus be unlikely, with a possible residual risk depending on local temperature and pressure changes in the future.

However, CO_2 storage in the deep-sea subsurface would also bring disadvantages: Injected carbon dioxide would mineralise to a much lesser extent in cooled basalt crust than in warm rock. In addition, the work in the deep sea would incur high costs and the experts would run the risk of reaching the limits of technical feasibility.



This photo shows calcite formed in the basalt by the interaction between carbon dioxide-containing water and the rock at the CarbFix site on Iceland.
Photo: Sandra Ósk Snæbjörnsdóttir, Wiki Commons

A wide range of possibilities

Given the above complexity, the goals of a possible storage of carbon dioxide in the upper part of the ocean crust must be carefully weighed. The most cost-effective method would certainly be to dissolve carbon dioxide in seawater and inject it into the ocean crust at shallow water depths in low concentrations with high mineralisation rates – just as is already being done on Iceland in the Carbfix project. However, the few areas where the mid-ocean ridge protrudes above sea level are mostly far from industrial centres where most carbon dioxide is produced. Consequently, the greenhouse gas would first have to be transported in liquefied form over long distances before it could be injected into the basalt rock.

If, on the other hand, the liquefied carbon dioxide was injected directly into the pore vollume of the basalts at greater water depths, there would not only be more potential storage sites to choose from. Very large quantities of carbon dioxide could also be stored within a short time, which would automatically remain in the reservoir rock due to pressure and temperature, but would only mineralise there very slowly. The rate of mineralisation could be increased by adding seawater to the carbon dioxide and thus diluting it. However, this approach would require significantly more time to inject the same amount of CO_2, as the ocean crust on the ridge flank is colder than at Carbfix on Iceland, for example.

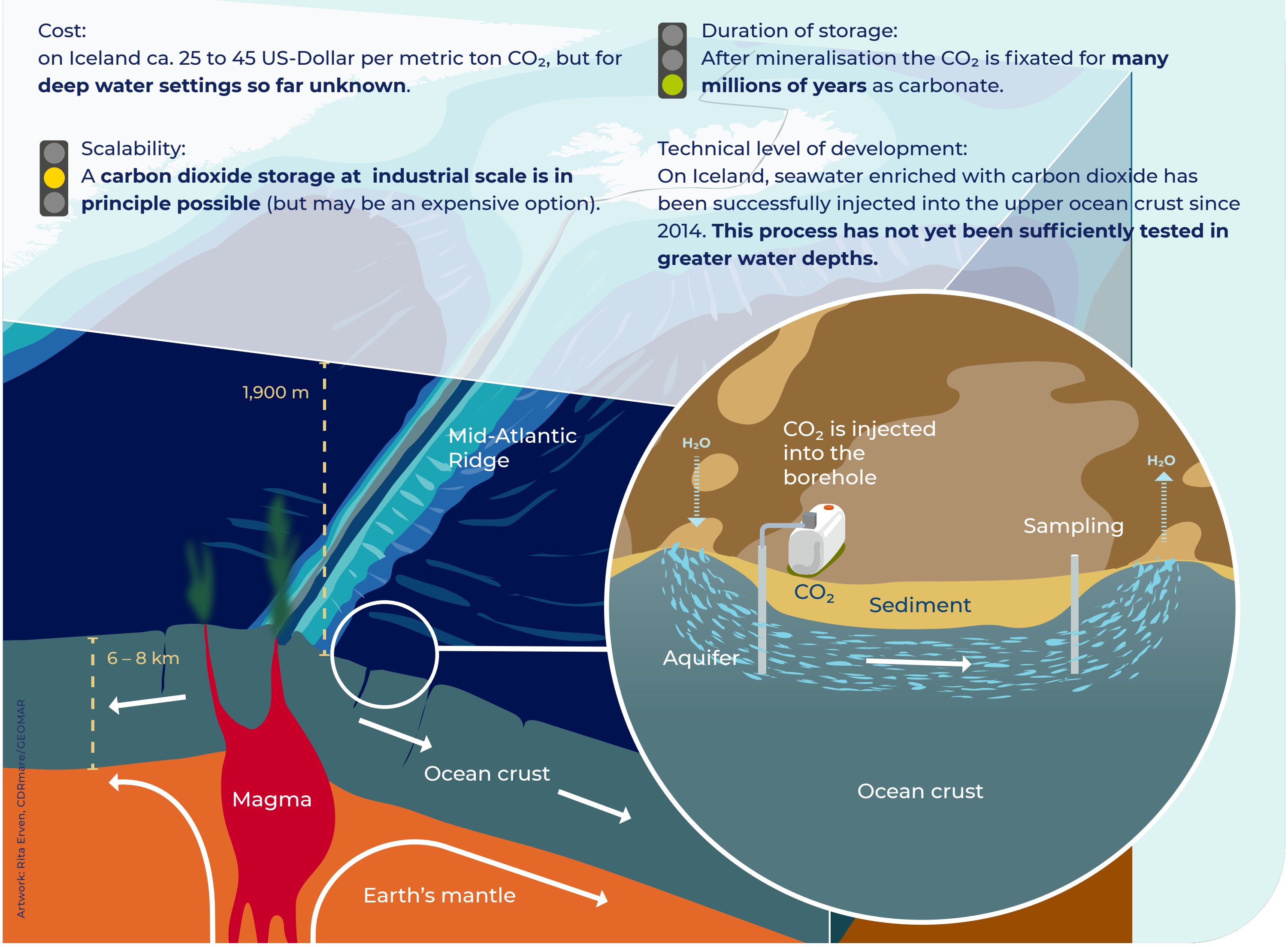
In search of the optimal solution: A carbon dioxide experiment in the deep sea

In order to underpin future political and social discussions on carbon dioxide storage in the upper ocean crust with comprehensive knowledge for action, geologists are conducting the first scientific CO_2 injection experiment in the North Atlantic deep sea as part of the research mission CDRmare. With it, they want to define the spectrum of conceivable carbon dioxide storage options in the oceanic crust – with Iceland as the land-based starting point on the one hand, and the findings from the deep-sea experiment as the deep-water counterpart on the other.

The aim is to explore whether all the theoretical preliminary considerations on carbon dioxide storage in the upper oceanic crust are correct and purposeful, and whether CO_2 injection into the deep-sea sub-surface is feasible. For example, the question arises as to which methods could be used to reliably monitor the storage site in the deep sea over long periods of time, or what the cost would be for implementation and continued storage, and whether there are possible pitfalls that have not been taken into account so far. The researchers also want to assess which methods will achieve the best cost-benefit ratio. This also includes an answer to the question in which concentration and in which quantities carbon dioxide should be injected into the basalt rock to enable optimal reaction processes.

It is important to note that scientific drilling is planned as part of the mission and that the associated small-scale injection experiment serves solely research purposes. Even if all the scientific work is successfully completed and the upper ocean crust proves to be very suitable, this does not mean that large-scale carbon dioxide storage would begin at this very location, or elsewhere. The main objective within the research mission CDRmare is to close existing knowledge gaps on carbon dioxide storage in oceanic crust and to find out whether carbon dioxide storage in the deep sea would be the more sustainable, effective and, in the long term, more affordable option compared to storage on land or in the deep sandstones under the North Sea.

Carbon dioxide storage in oceanic crust



Cost:
on Iceland ca. 25 to 45 US-Dollar per metric ton CO_2, but for **deep water settings so far unknown.**

Duration of storage:
After mineralisation the CO_2 is fixated for **many millions of years** as carbonate.

Scalability:
A **carbon dioxide storage at industrial scale is in principle possible** (but may be an expensive option).

Technical level of development:
On Iceland, seawater enriched with carbon dioxide has been successfully injected into the upper ocean crust since 2014. **This process has not yet been sufficiently tested in greater water depths.**

Artwork: Rita Erven, CDRmare/GEOMAR

Where and when is the carbon dioxide injection experiment to take place in the deep sea and what is known about the nature of the upper ocean crust site?

The experiment is scheduled to start in summer 2025 in large water depths of the North Atlantic, probably in the area of the eastern flank of the southernmost tip of the Reykjanes Ridge. This lies in the region around 58° north and 32° west and thus about 800 kilometres south of Iceland. However, an alternative drilling site is also being investigated. This is located further north on the Reykjanes Ridge, about 300 kilometres south of Iceland (62° north / 26° west), and lies in much shallower water.

At a water depth of about 1900 metres, there are a number of small sedimentary ponds on the ridge flank that offer themselves as study sites for the researchers. One of these basins has already been drilled in the past as part of an international geological research project. For this reason, it is already known that the upper basalt crust in this marine region is about 1 to 2 million years old and has a sufficiently high porosity. Its rock temperature is well below the critical limit of 31 degrees Celsius, above which liquid carbon dioxide becomes supercritical. This means that the density of the carbon dioxide would change in such a way that it may no longer be possible to distinguish between the liquid phase and the gas phase. In addition, the pressure at depth is high enough to keep liquid CO_2 stable.

Moreover, it is known that in sediment ponds such as the one chosen, seawater circulates through the upper basalt crust at a steady pace and over distances of 20 to 50 kilometres. As long as the carbon dioxide (liquefied or enriched in seawater) is sufficiently dense, such subsurface circulation would actually facilitate the storage or mineralisation of carbon dioxide, because it would help to distribute the injected carbon dioxide over a wide area in the basaltic rock.

What geologists have lacked so far is comprehensive knowledge of the chemical conditions in the basaltic crust. How many reactive minerals does the rock contain? How warm and carbon-rich is the pore water circulating in the rock? And how quickly would injected CO_2 be distributed in the rock and subsequently mineralise?

In the research mission CDRmare, geoscientists will drill about 40 metres deep into the basalt rock on the eastern flank of the Reykjanes Ridge in summer 2023 and install temperature, pressure and chemical sensors in the boreholes. These will subsequently record all the important physical and chemical parameters of the upper ocean crust. Two years later, in the summer of 2025, the research team will inject CO_2 through one of the boreholes into the basalt and monitor its distribution and chemical reactions with the pore water and the surrounding rock over the long term in a number of surrounding boreholes. The scientists will inject the carbon dioxide both in pure, liquefied form and mixed with seawater in various concentrations up to »sparkling water« (about 2 percent carbon dioxide). In this way, they want to find out which method allows the largest amount of carbon dioxide to be permanently stored and how quickly the injected carbon dioxide mineralises in each case.

The drilling and experiment were preceded by extensive preliminary explorations in the summer of 2022. During this first research cruise, the area was geophysically surveyed, the sediment layer in the targeted basin was comprehensively investigated, and a research device known as a lander was placed on the seabed to record the biogeochemical material flows. Based on the various results, the optimal drilling sites for the injection experiment were then determined.

For drilling in sediment and crustal rocks in the deep sea, geoscientists use a so-called robotic seafloor drill rig, which is being lowered into the water in this picture. Its two rosettes carry enough drill pipe to penetrate up to 200 metres deep into the seabed to take samples or set up observatories.

Photo: MARUM, University of Bremen

How is the CO_2 injection in the upper oceanic crust planned?

In former or ongoing large-scale projects for carbon dioxide storage in the geological subsurface of the ocean, two methods have so far been used to carry the captured carbon dioxide to the injection site. Either a pipeline transports the gas to the drilling site on the seabed, or ships moor at a specially constructed platform on the sea surface, from which the carbon dioxide is then pumped to depths. The latter is necessarily limited to shallow to moderate water depths.

For the deep-sea research experiment as part of the research mission CDRmare, neither of these two methods is an option. Instead, the liquid carbon dioxide will be placed on the seafloor in tanks, which are part of a seabed station. Once at depth, a remotely operated vehicle (ROV) will carry out the rest of the work. It will connect the seabed station with the upper end of a cased borehole using gas-tight lines. Liquefied carbon dioxide or carbon dioxide mixed with seawater is then pumped into the borehole at pre-programmed intervals. From there, the carbon dioxide is released into the fractured upper oceanic crust and is distributed in the rock by the circulating pore water.

The researchers will drill additional boreholes in the immediate vicinity of the injection well in downstream direction of the subseafloor flow. These will also be cased and equipped with custom-built deep-sea measurement technology. With the help of these borehole observatories, the scientists will be able to record all the physical and geochemical parameters needed to follow the distribution and mineralisation of the carbon dioxide injected in the neighbouring borehole over the entire length of the borehole. Based on the observation data and samples taken, fundamental circulation processes in the subsurface will be deciphered.

How do the researchers monitor the fate of the injected carbon dioxide?

After the sedimentary rocks, the ocean is the largest carbon reservoir on our planet. Its water masses therefore already contain a lot of carbon naturally – especially in the form of dissolved carbon dioxide, dissolved hydrogen carbonate and dissolved carbonate. It is hence the scientists' task to unambiguously distinguish in field experiments on carbon dioxide storage which portion of the carbon contained in the deep and pore water is of natural origin and which portion was injected during the experiment.

In addition, there is the challenge of finding methods with which the distribution of the injected carbon dioxide in the basaltic crust and possible chemical reactions can be monitored in both space and time. Both can be done either by geochemical measurements directly in the rock or by taking samples of pore water, which are then analysed. So far, however, there are only a few solutions suitable for deep-sea research, and above all hardly any sensors suitable for deep-sea use – the basis for fast, comparatively inexpensive measurements.

In the research mission CDRmare, scientists and engineers jointly develop new deep-sea sensors for the rapid (quasi real-time) determination of temperature, pH, pCO_2 and dissolved inorganic carbon content (DIC) in the pore water of the upper crust, in the overlying sediment layers and in the near-bottom deep water. These sensors will be used to equip control wells in the immediate vicinity of the injection well as well as all measurement systems that monitor the seabed and the lower water column around the injection sites for possible carbon dioxide leaks.

These measurements are complimented by deployment of specially developed deep-sea fluid samplers for the first time. The borehole fluid samplers collect samples of the fluids in the basaltic crust and store them in 100m-long tubes as a time series. Subsamples are later analysed in the laboratory for their chemical properties and compared with the deep-sea water. In this way, changes in the composition of the pore water and other fluids can be documented in high temporal resolution and linked to the CO_2 discharge from the seabed station.

The injected carbon dioxide is also tagged with an isotopic marker. This way it can be precisely identified at any time, so that the researchers can clearly determine how quickly the carbon dioxide has been distributed in the basalt, at what rate it has been firmly bound by mineralisation, and whether it has penetrated areas outside the basaltic crust.

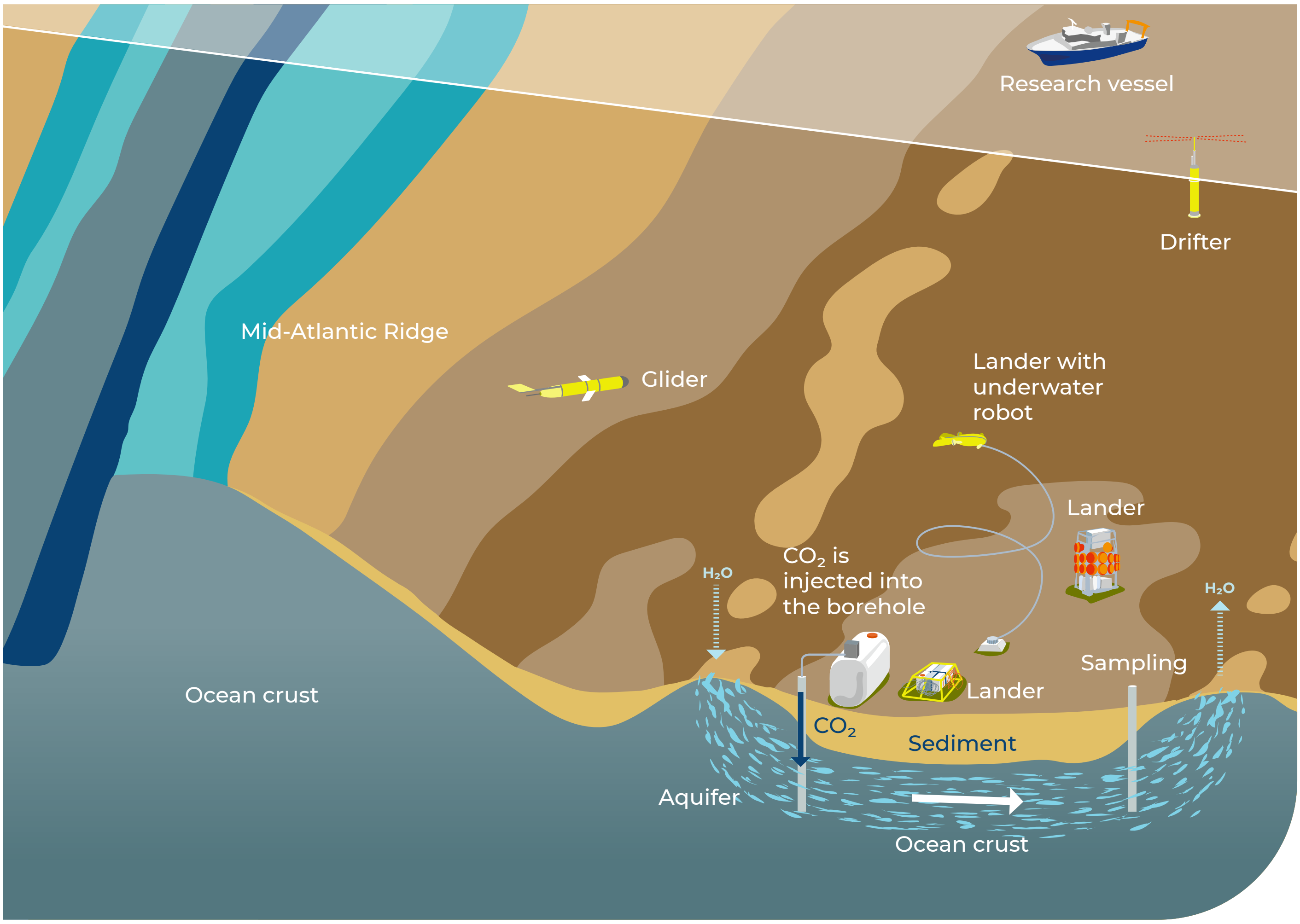
How is the injection experiment being monitored?

Regardless of the fact that the conditions in the deep sea probably preclude the escape of the injected carbon dioxide, the wells and their immediate surroundings are to be closely monitored. Developing the appropriate technology is a major challenge. The devices and their many sensors not only have to withstand the cold ambient temperature and the high confining pressure in the deep sea. Since ship deployments are expensive, they also have to operate independently and energy-efficiently so that they can remain deployed for long periods of time – completely without signals or maintenance from the ship.

In the research mission CDRmare, scientists develop new deep-sea lander systems that will scan the upper part of the seabed and the near-bottom water for carbon dioxide leaks and chemical anomalies. Such systems usually consist of a basic framework equipped with batteries, mission-specific measurement technology and buoyancy bodies, and are lowered into the deep sea weighted down with a metal base plate. Once the mission is completed, the metal plate is released via acoustic command and the lander rises back to the sea surface with its data.

For the CDRmare mission, the landers will be equipped with the new deep-sea sensors as well as a parking bay for small, autonomously operating tethered underwater robots. These vehicles also carry the specially developed deep-sea sensor technology and will circle around the landing station guided by cables. As the tether is unwound and rewound incrementally, the robots will spiral around the lander at regular intervals, covering radii of tens of metres with their measurements. This means that the seabed area monitored by such a robotic lander is several hundred square metres, and thus has a significantly larger footprint of monitored area compared to a standard lander system.

Should the new measuring systems successfully pass their endurance test in the deep sea, the costs of monitoring submarine CCS sites will be significantly reduced. In addition, the systems could then also be used at any time in shallower ocean regions – for example, in the North Sea, where captured carbon dioxide is to be stored on an industrial scale in sandstone formations in the future.



Schematic diagram of the planned experimental setup: measuring devices such as drifters, gliders and underwater robots with a landing station monitor the seabed and the water column for carbon dioxide leaks.

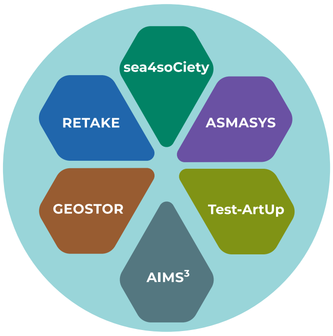
Graphic: Rita Erven, CDRmare/GEOMAR

Is a single deep-sea experiment sufficient to generate adequate action knowledge on the various options for carbon dioxide storage in the upper ocean crust?

Research in the deep sea is technically complex and very expensive. For this reason, geologists invest a lot of time and energy in the development of software and computer models that can be used to simulate the structure and composition of the Earth's crust as well as all material cycles between the ocean, the sediment layer and the Earth's crust. The computer models of mid-ocean ridges are now so good that the measurement data from a few projects or research experiments are sufficient to calculate scenarios for many comparable operations in other water depths. Based on these results, the scientists can then carry out cost-benefit analyses and derive appropriate options for action. Current projects include, for example, Carbfix on Iceland, the CO2Basalt research project on the Vöring Plateau off the coast of Norway and a scientific project called SolidCarbon in the Cascadia Basin off the coast of Canada.

In CDRmare scientists collaborate closely with the organisers of these international projects and share the scientific data. Their goal is to compile all available data sets on the structure, composition and geochemical processes in the upper ocean crust at the Mid-Atlantic Ridge. Then, with the help of computer models, they calculate for different locations how much carbon dioxide could be stored in the so-called ridge-flank aquifers, what the costs would be and what environmental problems, risks and potential damage would have to be expected. In the next step, they will discuss their findings and the options for action derived from them with various interest groups from politics, business and civil society in order to find out how people feel about carbon dioxide storage in the upper ocean. storage in the upper ocean crust and whether such an approach would be worthy of support and sustainable.

All natural and social science research results from CDRmare will be summarised at the end in a comprehensive report on carbon dioxide storage in the ocean subsurface.



All research activities described here are carried out within the CDRmare consortium »AIMS³ – Alternative Scenarios, Innovative Technologies and Monitoring Approaches for Carbon Dioxide Storage in Oceanic Crust«.

Within the research mission CDRmare of the German Marine Research Alliance (DAM), which involves about 200 researchers in 6 consortia, different methods of marine CO_2 removal and storage (alkalinisation, blue carbon, artificial upwelling, CCS) are investigated with respect to their potential, risks and trade-offs and brought together in a transdisciplinary assessment framework. CDRmare has been funded by the German Federal Ministry of Education and Research with 26 million euros since August 2021 and will run for three years.

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