AIMS^3

AIMS^3 – Alternate scenarios, Innovative technologies, and Monitoring approaches for Sub-Seabed Storage of carbon dioxide

CDRmare
INSIGHTS

New findings on sub-seabed storage of carbon dioxide: The six most important outcomes of AIMS^3 research

In the CDRmare research consortium AIMS^3, experts have spent the past three years investigating under which conditions carbon dioxide (CO_2) dissolved in seawater could be stored in the young basalt crust south of Iceland. In addition, they have developed new, deep-sea-capable sensors and monitoring systems for measuring the mineralisation of the stored CO_2 and assessing the environmental soundness of such a potential deep-sea storage project.

1 The deep-sea region surveyed, on the eastern flank of the Reykjanes Ridge and circa 800 kilometres south of Iceland, is a suitable candidate for the experimental storage of CO_2 in the oceanic crust. Monitoring devices installed in boreholes are now recording the most essential environmental parameters on the ocean floor.

2 In the boreholes, a new generation of fluid samplers and observatories are currently monitoring at what speeds and under which conditions (pressures and temperatures) fluids circulate in the basalt crust.

3 Carbonate system sensors developed as part of AIMS^3 facilitate the search for CO_2 leaks on the ocean floor. They are faster, smaller, more affordable and above all more energy-efficient than their predecessors.

4 Thanks to new and refined deep-sea robots and monitoring stations, the experts can now continually scan much larger areas of the seafloor for CO_2 leaks than in the past – and in the deep sea and German North Sea alike.

5 The observational data on the circulation, temperature and chemical composition of the pore water in the oceanic crust is now fed into new computer models, which the experts use to assess a given area of the seafloor's suitability for storing CO_2.

6 Initial estimates of the available storage volume in the young, warm basalt indicate that there is room for at least 24 billion metric tons of CO_2 along the ridge flanks to the north and south of Iceland. However, putting that potential to use would require substantial logistical and financial investments.

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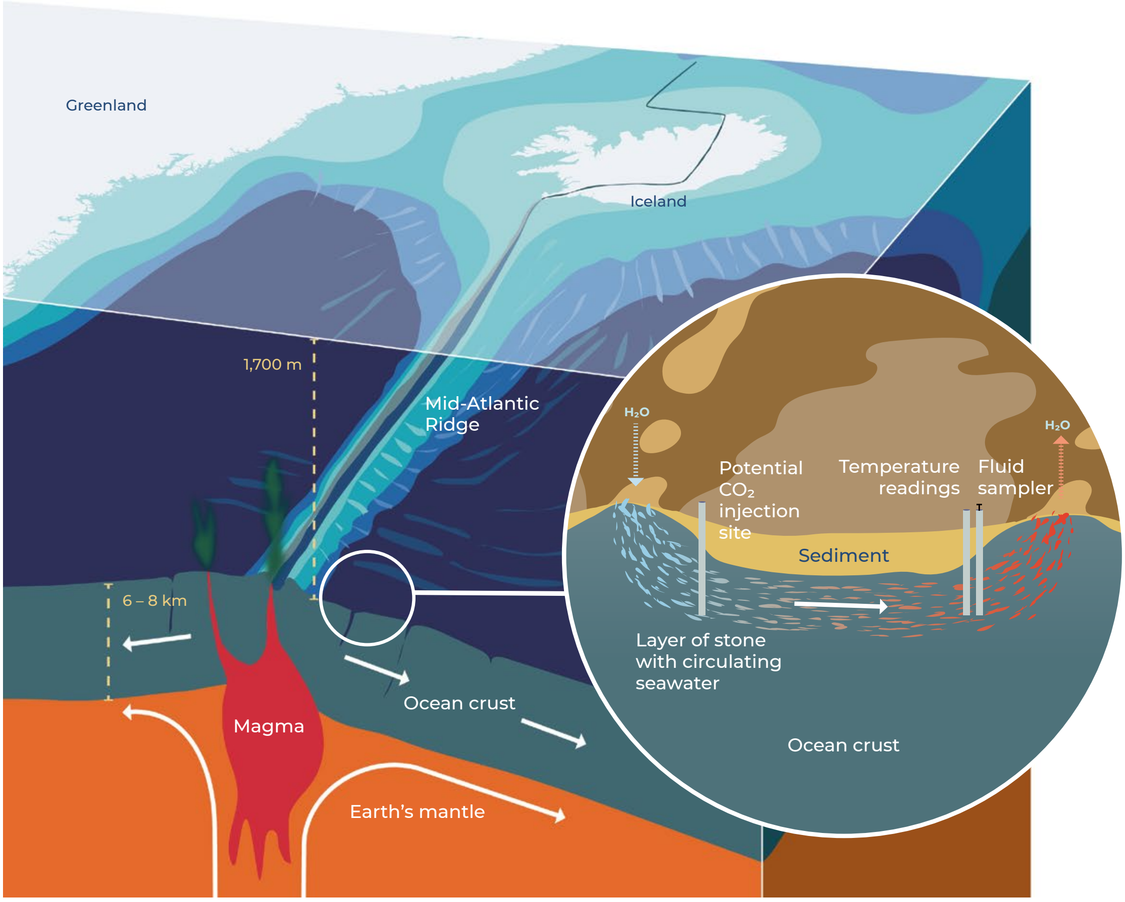
Key message 1

The deep-sea region surveyed, on the eastern flank of the Reykjanes Ridge and circa 800 kilometres south of Iceland, is a suitable candidate for the experimental storage of CO_2 in the oceanic crust. Monitoring devices installed in boreholes are now recording the most essential environmental parameters on the ocean floor.

In the course of two several-week-long ship-based expeditions to the Mid-Atlantic Ridge south of Iceland, researchers from the collaborative CDRmare project AIMS^3 surveyed the target area at depths from 1500 to 1700 metres. On the basis of heat-flow measurements in the seafloor and chemical analyses of water samples collected in the deep sea, they were able to determine e. g. that seawater circulates through the topmost basalt layer of Earth's crust on the eastern flank of the Reykjanes Ridge. Given this circulation, if carbon dioxide was injected, it would be naturally distributed throughout the basalt – and in the case of compressed CO_2, a significant amount of expensive drilling could be avoided.

In order to determine how porous the ocean crust is in the study area and at what speeds water circulates in the upper basalt crust, the researchers drilled a total of four boreholes, each circa 40 metres deep, in the crust and installed monitoring devices in them. The first two boreholes are located in the immediate vicinity of the plate boundary on the Mid-Atlantic Ridge. Here, Earth's crust is only 760,000 years old and covered by a thin layer of sediment. The second site is farther east, in a small deep-sea basin. Its basalt crust is 3.27 million years old and covered by a circa 30-metre-thick layer of sediment.

At both sites, the two boreholes are several tens of metres apart and placed so that the water in the basalt crust flows from borehole 1 to borehole 2. In the first borehole, sensors chiefly monitor the water and sediment temperature to determine the extent to which heat from Earth's core influences the fluid temperature and flow behaviour. In the second borehole, the researchers installed a new generation of deep-sea-capable fluid samplers



Based on temperature readings, the researchers have determined that seawater circulates in the uppermost basalt crust, warming in the process. Observatories and fluid samplers installed in the boreholes are now monitoring all environmental parameters needed in order to gain a better grasp of how water moves through the stone.

Graphic: Rita Erven, CDRmare

Key message 2

In the boreholes, a new generation of fluid samplers and observatories are currently monitoring at what speeds and under which conditions (pressures and temperatures) fluids circulate in the basalt crust.

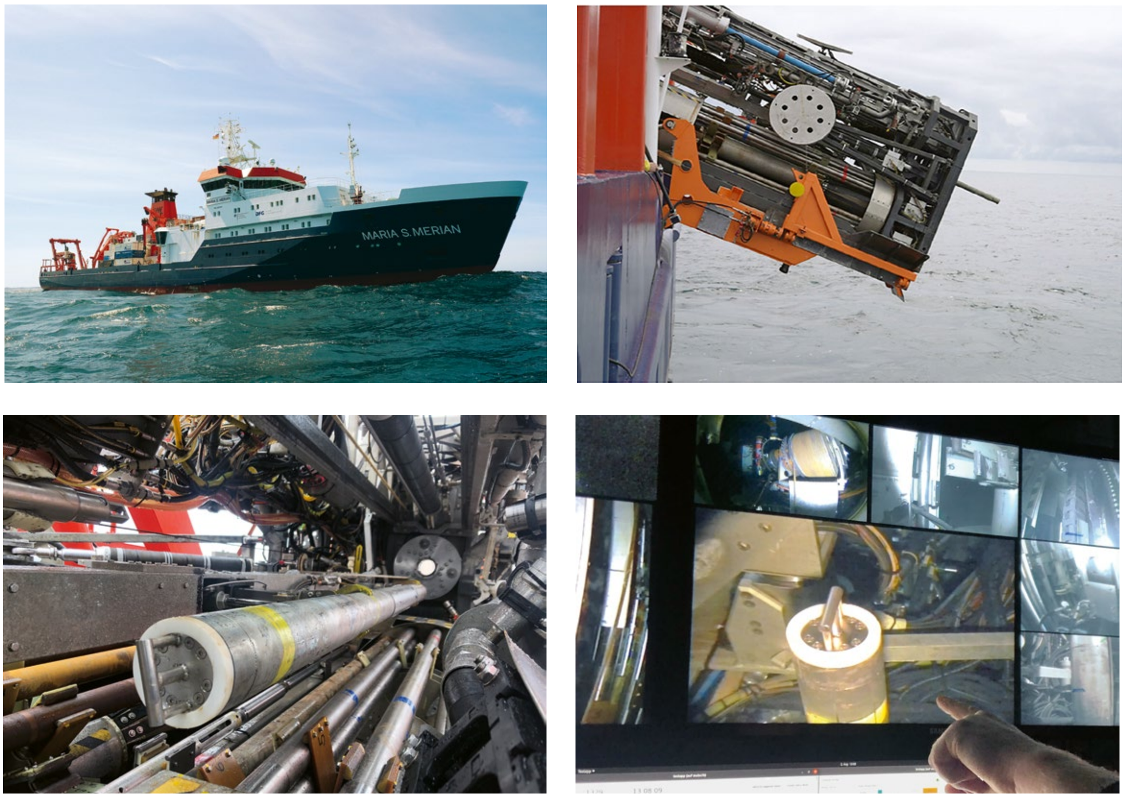
In order to determine how quickly water circulates in the porous upper basalt crust AIMS³ researchers have refined deep-sea-capable fluid samplers and deployed them in the boreholes. Each fluid sampler consists of a chamber filled with sodium chloride, a porous membrane, and a long hose extending down into the borehole.

The salt works like an osmotic pump: it produces suction, which draws liquids from the surrounding stone into the tubing – and can do so on demand, thanks to a new feature on the redesigned samplers. After a predetermined amount of time, a small motor moves a drop weight, which starts the sampling process.

The small diameter of the tubing (< 1 mm) prevents the recovered fluids from mixing. As such, the layering of fluids remains unaltered, which will allow the chemists in the team to determine how the fluids have changed in the course of the monitoring period two years from now.

This sampling method will deliver especially valuable information when, at some point in the future, the deep-sea researchers are allowed to release a »tracer« (isotopic signalling substance) in the first of the two boreholes. Then, using samples from the second borehole, they will be able to precisely determine how long the tracer needs to pass through the upper basalt crust from borehole 1 to borehole 2. This type of empirical data is necessary in order to predict how quickly compressed carbon dioxide would spread throughout the crust and whether its storage period would suffice for the formation of harmless carbonate minerals.

The first sampling phase will be completed in the late summer of 2025. Then deep-sea robots will dive down to the boreholes, retrieve the fluid samplers currently deployed there, and replace them with new ones for the second phase.



On the deck of the German research vessel Maria S. Merian (top left), the seafloor drilling device MARUM-MeBo70 is lowered into the water (top right). It has on board a specially prepared shaft that houses one of the new fluid samplers (bottom left). Once the deep-sea drilling is complete (bottom right), the shaft is installed in the borehole so that it can begin taking readings in the basalt crust.

Photos: MARUM

Key message 3

Carbonate system sensors developed as part of AIMS³ facilitate the search for CO_2 leaks on the ocean floor. They are faster, smaller, more affordable and above all more energy-efficient than their predecessors.

Prototypes of the new sensors have already been successfully deployed on test cruises. In the project's second phase, the goal is to make them ready for serial production and especially for use on autonomous research platforms and devices.

Three new deep-sea-capable sensors were developed: an optical sensor that measures the concentration of dissolved CO_2 in the seawater, a second that measures its acidity (pH value), and a third that analyses the amount of inorganic carbon dissolved in seawater. In this regard, the researchers attempted for the first time to condense complex lab-based measuring processes to the point where each would fit on a single sensor.

All measurements are taken in a matter of seconds; after all, the sensors will be used on mobile underwater probes and vehicles, not on stationary monitoring platforms. Rapid and precise analyses are essential; because otherwise, it won't be possible to determine where questionably high CO_2 values were detected.

The basic technical requirements also include extremely low energy consumption. When used to monitor CO_2 depots under the sea, the systems will not be supplied with power by a research vessel. They will operate autonomously on the seafloor for months at a time and will only have the energy in their batteries at their disposal.

Given these qualities, the new sensors are not only suitable for deep-sea use; they can also be used in shallower waters – e. g. to monitor future CO_2 depots under the German North Sea or, more generally, ocean acidification.

These images show the new optical CO_2 sensor developed at the Fraunhofer Institute for Physical Measurement Techniques in Freiburg. It can be used in seafloor stations and in the advanced underwater vehicle IMGAM alike.

Photos: Fraunhofer Institute for Physical Measurement Techniques (IPM)

Key message 4

Thanks to new and refined deep-sea robots and monitoring stations, the experts can now continually scan much larger areas of the seafloor for CO_2 leaks than in the past – and in the deep sea and German North Sea alike.

In the first phase of the collaborative CDRmare project AIMS^3, two modular monitoring systems, designed to scan the seafloor and near-floor deep water for carbon dioxide leaks, were refitted or made from scratch. One of the prototypes belongs to the category »deep-sea-capable lander systems« and consists of a basic frame equipped with batteries, mission-specific monitoring devices, and flotation devices. After being weighed down with a metal plate, it is lowered into the deep sea. Once its mission is complete, an acoustic signal is transmitted, releasing the metal plate and allowing the lander and its data to slowly ascend back to the surface.

One unique feature of the new AIMS^3 lander: its internal parking bay for a small, cigar-shaped underwater robot. This self-piloting robot, just as the lander itself, can be fitted with the new carbonate sensors and, in future, will circle around the lander on a cable tether. Because the cable is gradually but steadily extended and retracted, at regular intervals the robot can fly orbits around the lander, using its own sensors to cover a radius of up to several tens of metres. Accordingly, its total monitoring area is more than 1,000 square metres, substantially larger than what a lander system can cover on its own. As such, this new duo are the ideal candidates for monitoring the seafloor in the immediate vicinity of boreholes, where CO_2 is injected into the upper oceanic crust. The first joint test runs featuring the lander and its orbiting robot are scheduled for the project's second phase, after which tests will gradually be conducted at greater and greater depths.

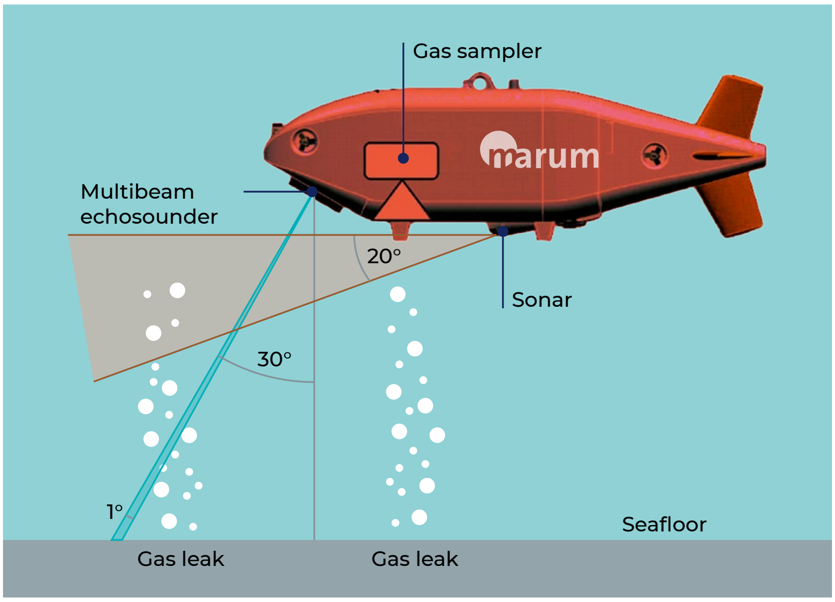
The new deep-sea-capable AIMS^3 lander features a parking bay from which a small robot will, at regular intervals, launch and scan the surrounding area for CO_2 leaks. Currently, both devices are prototypes. Their first joint test runs are scheduled for the project's second phase.

Illustrations: MARUM

Another independent monitoring approach the AIMS^3 researchers are refining is a torpedo-shaped autonomous underwater vehicle (AUV), which features a forward-looking sonar system. This system allows it to detect major density changes in the water column, e.g. rising gas bubbles. Once it detects a stream of bubbles, its onboard Artificial Intelligence (AI) system helps it to park over the leak site and capture part of the bubbles. To do so, it uses a funnel-shaped opening on its belly. At the end of the opening, there is either an autoclave sampler that preserves the gas for subsequent analysis back on board the research vessel, or the newly developed carbonate system sensors, which can analyse the rising gas on the spot.

Whereas the lander system was designed for several-months-long autonomous missions on the seafloor, the AUV can only be deployed when researchers on board the research vessel are nearby. Above all, it is to be used when e.g. large amounts of CO_2 are injected and additional monitoring methods covering a substantial area are called for. The AUV would then proceed to the area in question on a pre-set course and begin to systematically monitoring it.

Though both the new and refitted systems are designed for depths of up to 2,000 metres, they can also be used in shallower waters at any time – e. g. in the German North Sea, where in future, carbon dioxide is to be stored in sandstone formations on an industrial scale.



The autonomous underwater vehicle (AUV) IMGAM features a cutting-edge sonar system and Artificial Intelligence (AI). It can detect gas leaks on the seafloor, autonomously position itself over them, and collect samples of the rising gas for subsequent analysis – or use the new sensors to analyse them on the spot.

Graphic and photo: MARUM, graphic modification: Rita Erven, CDRmare

Key message 5

The observational data on the circulation, temperature and chemical composition of the pore water in the oceanic crust is now fed into new computer models, which the experts use to assess a given area of the seafloor's suitability for storing CO_2.

The physical and chemical data from the ocean floor and overlying bottom water is (also) used to validate numerical ridge flank models. Data from seafloor rock samples, collected by the researchers during the two ship-based expeditions, are also integrated. Laboratory tests of the porosity and permeability inform us about the upper basalt's properties at different crustal ages. A further source: geological data from past deep-sea drilling at the Reykjanes Ridge.

Once all these results have been supplied to the computer model, it can better reflect local differences in its calculations. This in turn allows the researchers to draw more accurate conclusions regarding how the CO_2 would spread throughout the oceanic crust of Reykjanes Ridge deep-sea region and whether it would be suitable as a CO_2 depot.

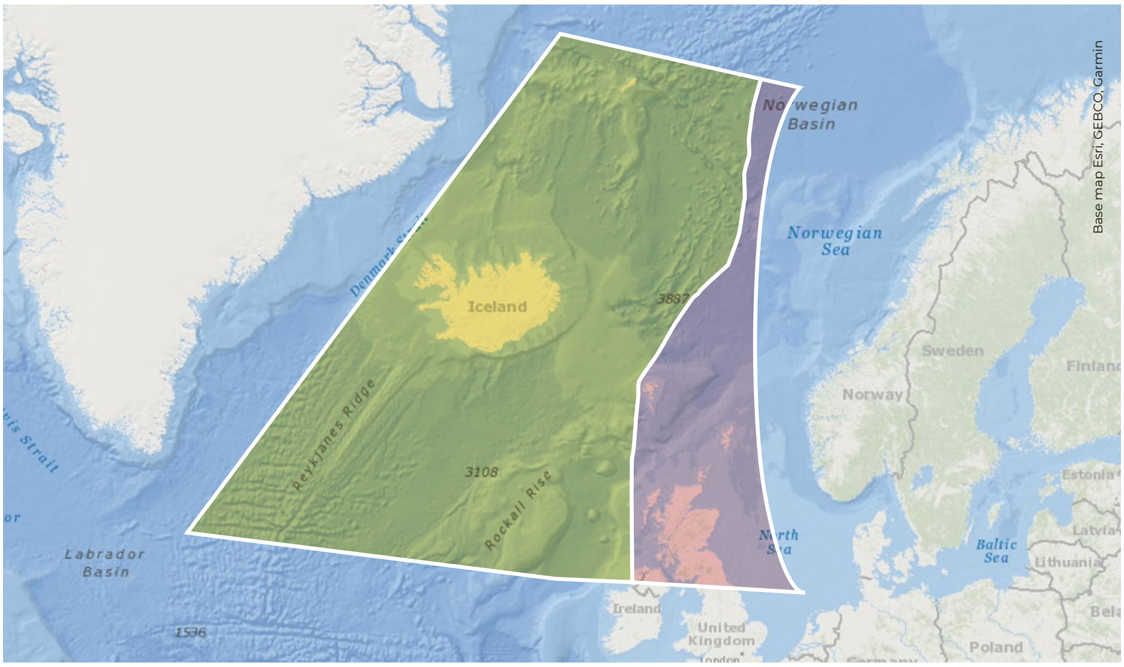
For example, the initial results of modelling in the collaborative CDRmare project AIMS³ show that, below a depth of 200 to 300 metres, the upper oceanic crust on the Reykjanes Ridge is so impermeable that CO_2 compression on a major scale would be extremely difficult at this depth. Consequently, storage projects would only be feasible in the layers higher up.

Key message 6

Initial estimates of the available storage volume in the young, warm basalt indicate that there is room for at least 24 billion metric tons of CO_2 along the ridge flanks to the north and south of Iceland. However, putting that potential to use would require substantial logistical and financial investments.

Researchers from the AIMS^3 consortium have for the first time calculated the CO_2 storage potential of the comparatively young and warm basalt deposits in the regions to the north and south of Iceland. To do so, they first analysed a map so as to estimate the basalt deposits' total area. They then used data from past deep boreholes and seismic reflection profiles to determine the thickness of the basalt layers and gain insights into their porosity. Based on this data, the experts subsequently calculated how large the actual storage volume would be if the goal was to sequester liquid CO_2.

What they concluded: between 34 and 168 billion metric tons of CO_2 could be stored in the 233,000-square-kilometre basalt zone surrounding Iceland. The Faroe-Shetland basalt, adjacent and lying to the east, has an area of 42,000 square kilometres and is dominated by porous basaltic rock. Between 16 and 81 billion metric tons of CO_2 could be stored there. However, given the fact that both regions are a considerable distance from sites where large amounts of hard-to-avoid CO_2 emissions from industrial processes are produced, the costs of the transport and subsea storage of the CO_2 would be extremely high.



Base map Esri, GEBCO, Garmin

This map shows the two basalt regions for which the CO_2 storage potential was calculated in the collaborative project AIMS^3. The young and warm basalt of the Reykjanes Ridge is marked in green. To the east lies the more porous Faroe-Shetland basalt, marked in violet.

Graphic: Rita Erven, CDRmare based on a map created by Mohamed Elfil, 2024, Master's thesis, University of Bremen

IMPRINT

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AIMS^3 – Alternate scenarios, Innovative technologies, and Monitoring approaches for Sub-Seabed Storage of carbon dioxide is a research consortium within the scope of the CDRmare research mission. In the German Alliance for Marine Research (DAM) research mission CDRmare, various marine CO_2 removal and storage methods (alkalinity enhancement, blue carbon, artificial buoyancy, CCS) are investigated with regard to their potential, risks and trade-offs, and consolidated using a transdisciplinary assessment framework.