Solutions for urgent social problems

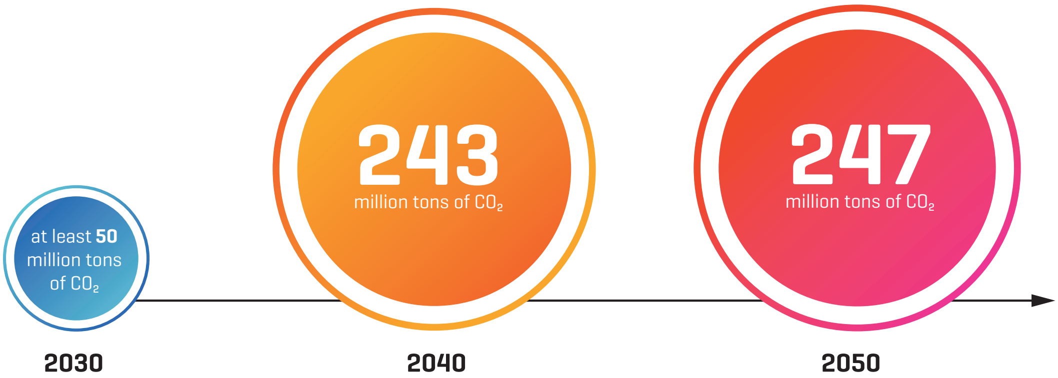
Storing CO_2 in flood basalts under the sea: options on a billion-ton scale

In the near future, mankind will have to remove many millions of tons of carbon dioxide (CO_2) per year from the atmosphere and store it safely underground. Extensive lava rock formations in the seabed, so-called flood basalts, offer themselves as large storage sites. Researchers at GEOMAR and their international partners are using new measurement and modeling methods to investigate how much CO_2 could be stored in these rock layers and how quickly the greenhouse gas would be converted into solid carbonate rock there. It would then be stored in a climate-safe way for thousands of years.

The challenge: offsetting residual emissions by extracting and storing many millions of tons of CO_2

Our society is facing an enormous challenge: in order to mitigate the drastic consequences of climate change and limit global warming to below 2 degrees Celsius, we will have to reduce our carbon dioxide emissions to an arithmetical zero in less than 30 years. To do this, we must firstly seize every conceivable opportunity to avoid CO_2 emissions as quickly and comprehensively as possible. In addition, we will soon be forced to remove many millions of tons of CO_2 from the atmosphere every year. This CO_2 removal will be needed to offset those residual emissions that cannot be avoided, for example in agriculture. There are various approaches to removing CO_2 from the atmosphere. These methods are known as carbon dioxide removal (CDR). At the same time, so-called carbon capture technologies are also used. They prevent the release of CO_2 by capturing it directly from the exhaust gas stream in cement works and waste incineration plants, for example. Both targeted CO_2 extraction and CO_2 capture generate large quantities of CO2. These must be stored in a climate-safe manner. In other words, they must not be allowed to escape back into the atmosphere. The preferred form of CO_2 storage is to inject the gas deep underground (geological storage). In this way, much larger quantities of CO_2 can be permanently stored than with any other known CO_2 storage method.

The demand for geological storage of captured CO_2 will rise sharply in the coming years. This is supported by calculations by the World Energy Agency (IEA), among others: if around 50 million tons of CO_2 are injected underground worldwide in 2024, one billion tons of CO_2 will have to be injected in 2030 in order to achieve the Paris climate target - in other words, 20 times as much! The EU Commission is pursuing expansion plans on a similar scale.



EU figures
The EU Commission is relying heavily on the capture and geological storage of CO_2 to decarbonize European industry. By 2030, at least 50 million tons of CO_2 per year are to be stored underground across the EU. Ten years later, it should be almost five times as much.

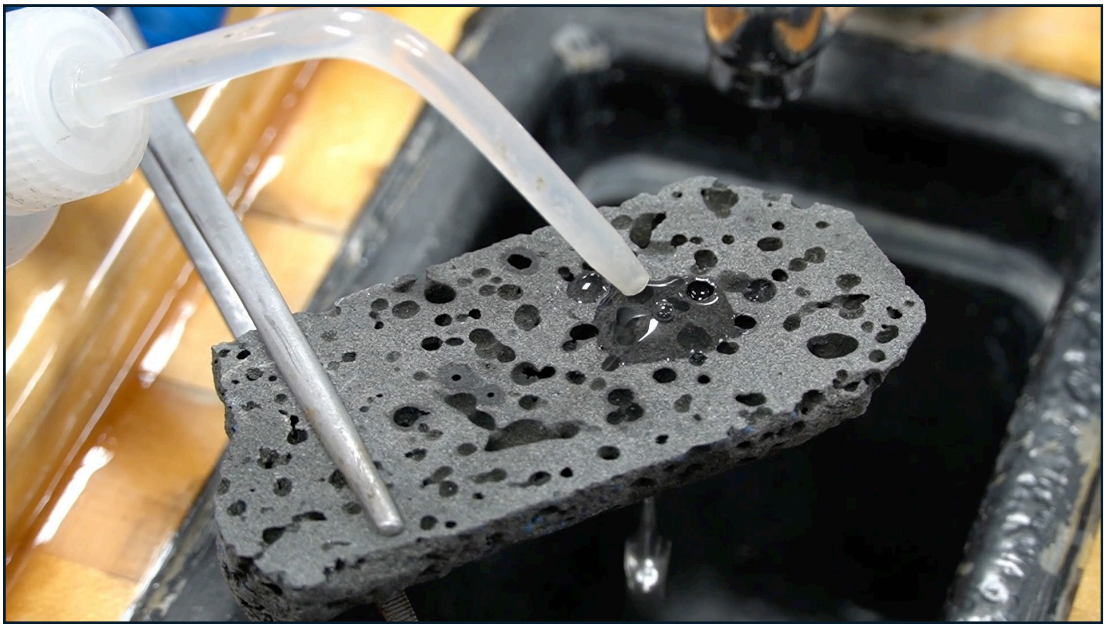
Graphic: M. Wolter/GEOMAR, Figures from the S3 scenario of the annex to the communication on the EU's climate target for 2040 (SWD(2024) 63)

The key question: Where can so much CO_2 be stored for a long time?

But where can so much carbon dioxide be stored underground? Countries bordering the North Sea such as Denmark, the UK, Norway, the Netherlands and Germany are exploring the possibility of injecting CO_2 into deep-lying sandstone formations under the sea. The storage capacity of the sandstone formations under the North Sea is enormous.
Up to 100 billion tons of CO_2 could be stored there. One disadvantage is that the injected CO_2 remains mobile in the sandstone for a long time and could rise to the seabed again through cracks or faults in the overlying rock. CO_2 deposits in sandstone must therefore be monitored for many decades.
In addition, the North Sea is an intensively used sea and CO_2 storage may rule out other uses (fishing, shipping, wind farms, etc.). Injecting CO_2 on land is unthinkable in many places. Because of the potential risks, the population often rejects such plans, especially in densely populated areas.

Marine flood basalts: Room for many billions of tons of CO_2?

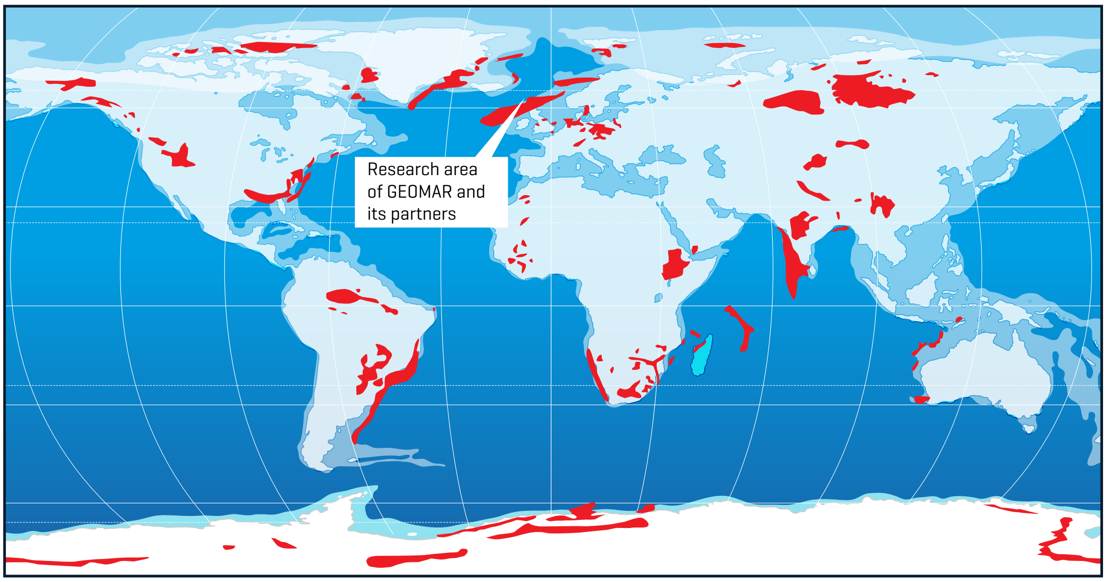
Researchers at the GEOMAR Helmholtz Centre for Ocean Research Kiel and their partners are therefore focusing on alternative deposits, so-called flood basalts. These are cooled lava flows that have primarily formed at the margins of the continental plates in the ocean floor, in Europe particularly off the west coast of Norway.
The lava had once risen from the earth's interior during the formation of the ocean basins and spilled over the earth's surface many times. As the lava flows were in direct contact with the atmosphere and were not covered by seawater, the red-hot rock was able to outgas as it cooled.



The rock from the upper layer of the flood basalts is so strongly permeated by vesicles that water quickly finds a way through.

Photo: S. Planke, VBER

This resulted in countless bubbles with a diameter of up to 2 centimetres in the upper part of the lava layers, which are a few meters to tens of meters thick. These vesicles (pore space) give the basalts enormous porosity and permeability – a material property that makes the lava rock an ideal storage rock. If all known flood basalts were suitable for CO_2 storage, hundreds of billions of tons of CO_2 could be stored in lava rocks worldwide. However, marine flood basalts have not yet been sufficiently investigated for their suitability as CO_2 reservoirs. Experts only know the vesicle structure from a few drillings and rock samples.



Flood basalts, marked in red here, occur both on land and in the ocean's subsurface – especially at continental slopes. GEOMAR researchers and their international partners are investigating flood basalts off the coast of Norway for their suitability as CO_2 reservoirs.

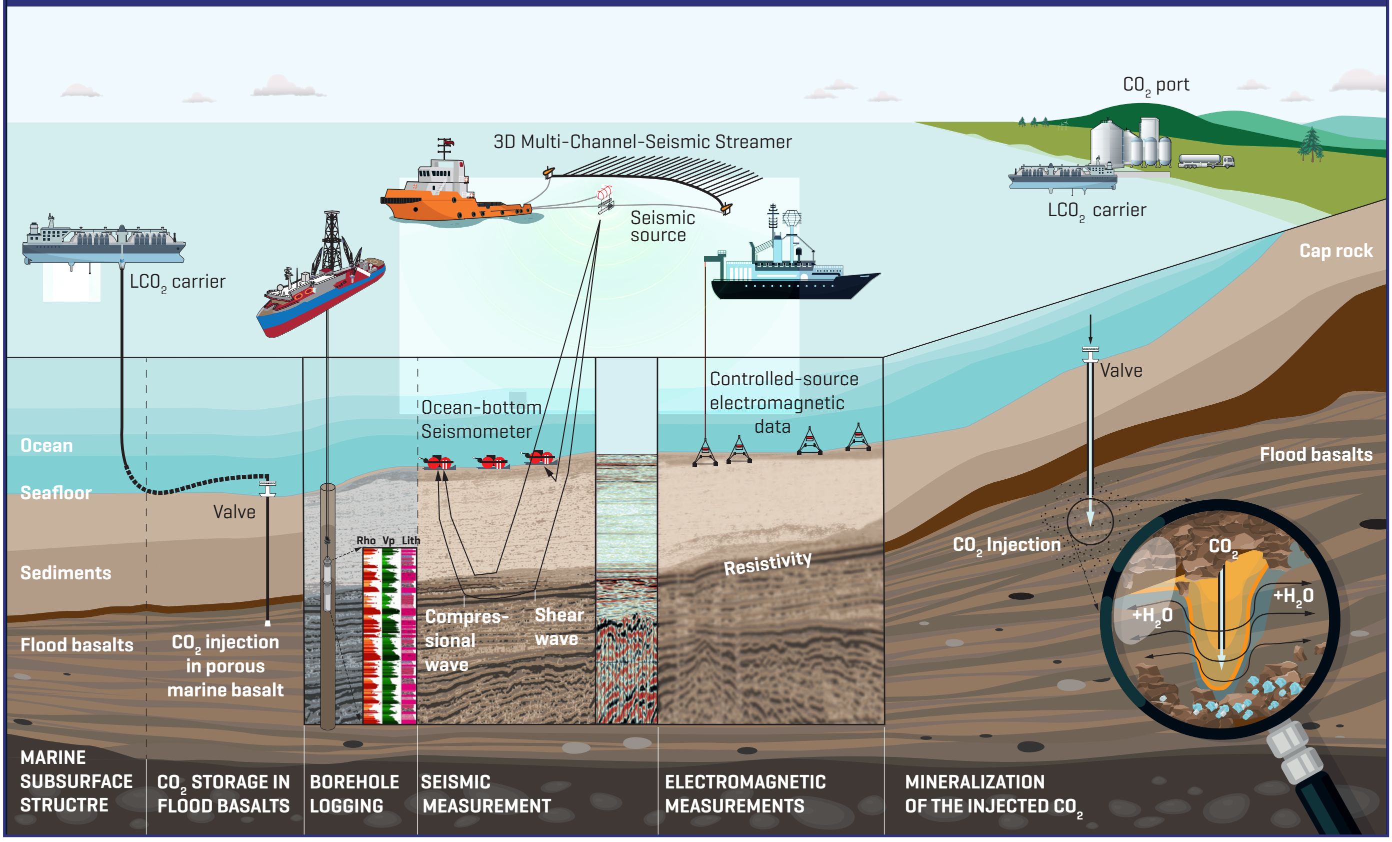
Map: M. Wolter/GEOMAR after a submission by John M. Millet et al. (2024), DOI: 10.1144/SP547-2023-102

CO_2 is firmly bound in the basalt

However, it is known that the basalt rock contains many iron, calcium and magnesium ions. If the injected CO_2 dissolves in the pore water of the rock and comes into contact with these mineral components, the substances react with each other (mineralization). This creates carbonate rock, in which the carbon is firmly bound for thousands of years.

A CO_2 storage project in Iceland (Carbfix) shows how quickly this process can take place in basalts: Because the storage rock there is young, warm and particularly reactive and the CO_2 was injected as an aqueous solution, 98 percent of the injected CO_2 was mineralized within two years. If similar rates are also possible in flood basalts, the monitoring of future CO_2 reservoirs could end much earlier than with CO_2 reservoirs in sandstone. In addition, the firmly consolidated pore structure of the basalts minimizes the risk of earthquakes when the gas is injected underground.

CO_2 storage in marine flood basalts: The methods at a glance

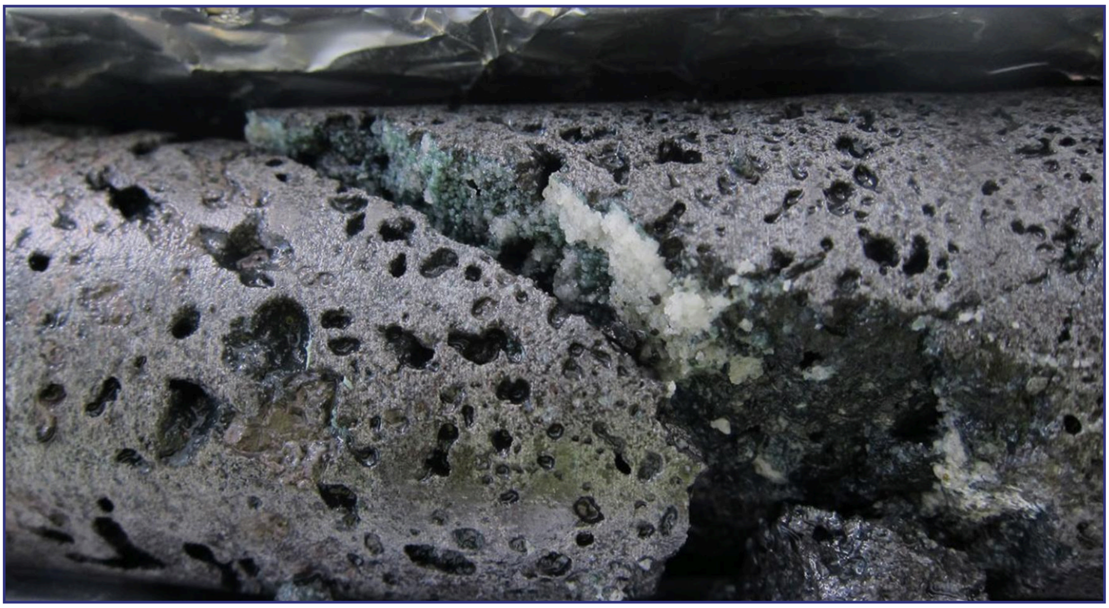


Marine flood basalts lie deep in the sea floor, buried under a mostly thick layer of sediments and sedimentary rock. However, to find out whether the basalt layers are suitable as CO_2 reservoirs, the GEOMAR researchers and their international partners are combining three **modern geoscientific methods.** Firstly, they are **drilling deep into the rock,** taking rock samples and measuring important parameters such as temperature and fluid composition in the boreholes. Secondly, they use **seismic measurements** to decipher how the basalt layers are stratified and test methods for monitoring a possible CO_2 reservoir. In the third step, the electrical resistance of the flood basalts is measured using **electromagnetic methods.** This allows conclusions to be drawn about the porosity and therefore the potential CO_2 storage volume of the rock. All this individual information is needed to assess the **technical feasibility** of CO_2 storage in the basalt layers and to estimate the rate at which injected CO_2 would mineralize in the rock.

Graphic: M. Wolter/GEOMAR

Layering of the flood basalts increases the safety of the storage facility

As the lava masses poured over the earth's surface many times during the formation of the flood basalts, today's reservoir rock consists of up to 100 superimposed basalt layers. Almost every one of these forms a possible storage layer, which increases the safety of possible CO_2 storage projects. If the CO_2 is injected into a deep layer and unexpectedly encounters a crack or fissure in the rock during the limited period between injection and mineralization, it would rise into the layer above, where it would be converted and firmly stored using the same mineralization process. A return to the surface is thus prevented as far as possible.



Diese Gesteinsprobe enthält weißes Karbonatgestein, welches sich am Carbfix•-Standort auf Island durch die Wechselwirkung zwischen CO_2-haltigem Wasser und mineralischen Bestandteilen im Basalt gebildet hat.

Foto: Sandra Ósk Snæbjörnsdóttir, Wiki Commons

Fewer conflicts with fishing, shipping and the operation of wind turbines

In addition, marine regions in which flood basalts occur are usually located far off the coast and are not used in as many ways as the North Sea or other shallow marginal seas. Conflicts with other forms of use are therefore less likely to occur. And should microearthquakes occur underground as a result of CO_2 injection, the risk to buildings and people would be low. However, the large distance from the coast would be a major cost driver in the event of implementation. Tankers would have to transport the CO_2 far out to sea.

Flood basalts in focus: exploring the storage potential with new methods

But how much CO_2 could actually be stored in flood basalts? And does each of the basalt layers really have the chemical properties needed to convert CO_2 into rock within a short period of time?
To answer these questions, researchers at the GEOMAR Helmholtz Centre for Ocean Research Kiel and their partners have developed a new method. They are combining three modern geoscientific investigation methods in order to collect high-resolution information about the stratification and composition of the flood basalts. Based on these data sets, they can then draw conclusions about the suitability of the individual basalt layers as CO_2 reservoirs and calculate how much CO_2 could be stored in the lava flows, which cover several hundred square kilometers.

The methods used include

Active and passive seismic surveys of the ocean subsurface

The sound velocity of the seismic signal and the density of the subsurface are recorded. Both parameters allow researchers to gain detailed insights into the layering of the lava flows. This knowledge can be used to determine the depth to which a borehole would have to reach to store CO_2. The scientists can also assess how much CO_2 would have to be injected into the basalt rock in order to be able to track it from the sea surface using seismic measurements - an important aspect for monitoring potential CO_2 storage projects in flood basalts. Initial research results indicate that it may be possible to track the gas in the basalt rock with much smaller amounts of CO_2 than the researchers had expected.

Measurements of the electrical resistance of flood basalts

The electrical resistivity of flood basalts depends on both the porosity of the rock and whether water or gas is circulating through the cavities. Seawater conducts electromagnetic waves very well, whereas CO_2 would slow them down. The measurement results therefore allow conclusions to be drawn about the porosity and therefore the potential storage volume of the rock.

Drilling for rock samples and on-site measurements

In the research area around 370 kilometers off the west coast of Norway, partners of the GEOMAR experts have already carried out a series of deepsea drillings. They were able to take rock samples from the various basalt layers and install various measuring instruments in the boreholes. The borehole measurements complete the ship-based investigations. The rock samples serve as the starting material for chemical analyses. The results of these analyses are in turn incorporated into the computer simulations of the storage potential of the flood basalts.

Laying the foundations for a CO_2 storage

The current research work will be completed in summer 2026. The goal of the GEOMAR experts is to create the scientific basis for a CO_2 storage experiment in the flood basalts off the coast of Norway in close cooperation with their international partners. However, in order to actually carry out such an experiment, the help and financial support of industry is needed.

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