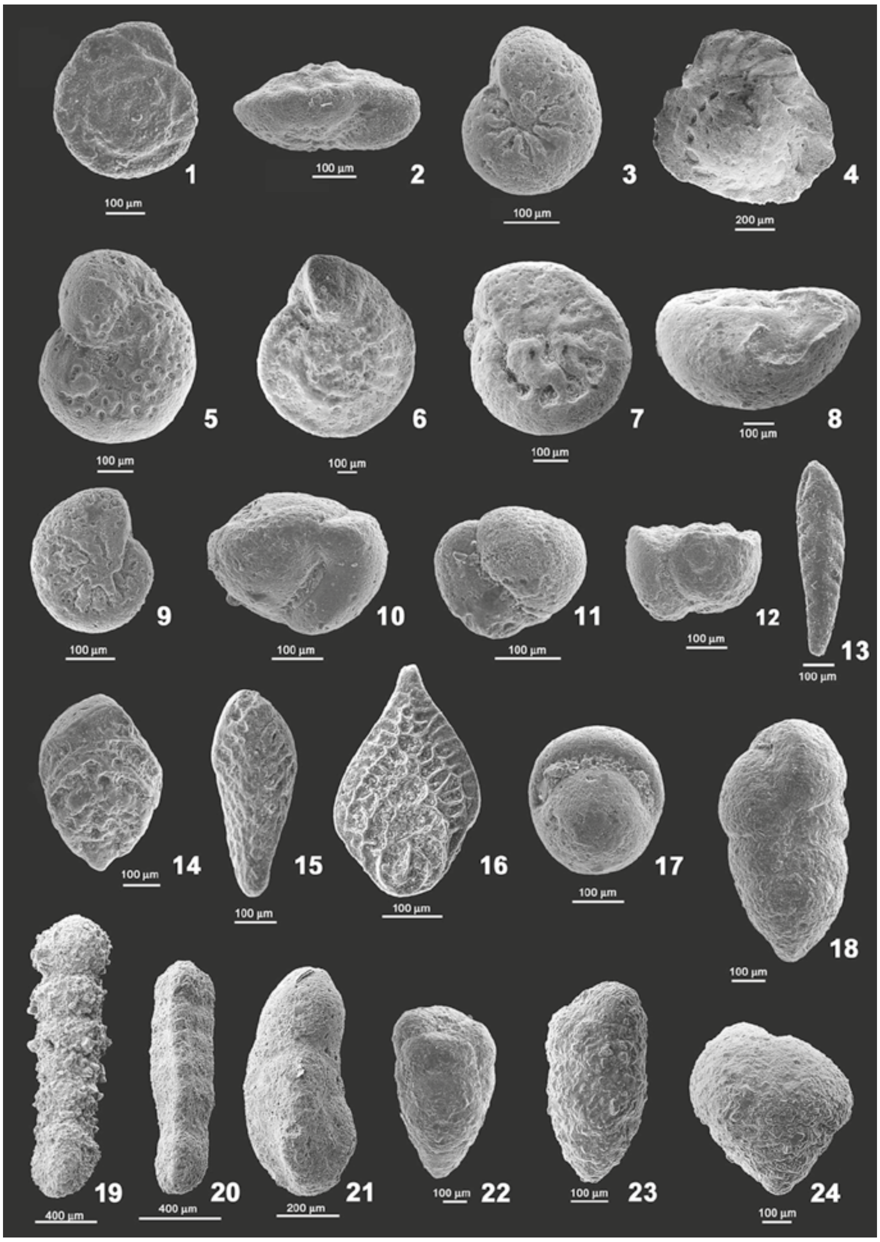
In Nunavut, an Inuit territory in Canada, Johnny Issaluk holds in his hands the photograph of a swamp in South Carolina. During the Palaeocene-Eocene Temperature Maximum (PETM) 56 million years ago, when the CO_2 concentration in the atmosphere was far higher than today, parts of the Arctic looked like this swamp.



These foraminifera fossils give an impression of the enormous biodiversity of the just pinhead-sized unicellular organisms. All the species shown here lived on the seafloor and died out during the PETM because the oceans were so acidic due to the high CO_2 concentration in the atmosphere that the calcareous shells of the unicellular organisms dissolved.

(from: Guisberti, Galazzo, Thomas, Clim. Past, 12, 213-240, 2016)

IN A NUTSHELL

- At the transition from the Palaeocene to the Eocene about 56 million years ago, the CO_2 concentration in the atmosphere was far higher than today.
- The temperature difference between the arid and desert zones along the Equator and the subtropical polar regions was smaller than it is today. Climate modelling is so far unable to reproduce these states adequately.
- The rate at which humans are currently releasing greenhouse gases into the atmosphere exceeds the natural rate in earlier »high CO_2« periods many times over.

On land, areas in the equatorial region previously wooded turned into arid zones and deserts with local temperature peaks of well over 40 degrees, as plant fossils found in Wyoming or Tanzania indicate. The animals there adapted to the scarcity of plant nutrition by becoming smaller. This resulted in the onset of »dwarfism«, also among predators.

At the same time, the habitat of reptiles expanded close to the poles. Parts of the Arctic were a subtropical swamp and home – like the Everglades in present-day Florida – to ancestors of alligators, crocodiles and snakes. The warm climate and the previous disappearance of the dinosaurs rang in the era of mammals, whose habitat and diversity widened enormously. New species of animals emerged, among them whales and dolphins, camels, sheep, cows, and ultimately primates.

Volcanoes and methane hydrate

Up until today, what caused the Earth to heat up during the PETM is still a matter of debate. There were presumably several factors. First of all, there was the increased activity of volcanoes in the Mid-Atlantic Ridge, which not only released large quantities of CO_2 into the atmosphere but also covered Greenland, Iceland, Norway, Ireland and Scotland with lava.

In addition, large amounts of methane gas (CH_4) could have been released. This gas has a greenhouse effect 30-times greater than that of carbon dioxide. Methane forms during organic decomposition processes both on land and in ocean sediments, where dying organisms sink to the bottom and accumulate, layer upon layer, over millions of years. Under certain conditions, the gas is trapped within frozen water. During the PETM, the seawater warmed up even down to deeper levels, and as a result parts of the methane ice may have melted and released the potent greenhouse gas.

A combination of these processes triggered the gigantic increase of CO_2 and other greenhouse gases in the atmosphere. Between 2,400 and 4,500 gigatons of CO_2 probably accumulated within just 4,000 years. However, at a rate of about one gigaton per year, this natural release of CO_2 56 million years ago was considerably slower than today's emissions: Humans produce ten gigatons per year. Although the PETM event shows how our current climate could evolve in a »high-CO_2« world, scientists are, however, reaching their limits as far as the search for comparable natural geological situations is concerned.

Deep-sea drillings as climate archive

It is thanks to isotope geochemistry experts such as Professor Wolfgang Müller that we have an impression of the gigantic natural fluctuations that characterize Earth's climate in past geological eras. »Oceanic sediments are the best long-term climate archive we have on Earth because the stratigraphic sequence of dead organisms we find there is undisturbed,« explains Müller. He and his team have studied the shells of foraminifera extracted from such sediments. In this way, the scientists can reconstruct the temperature and CO_2 content of the ocean in different periods.

Many of the unicellular foraminifera, of which there are many species in the sea, build their shells from calcite, in chemical terms, calcium carbonate. To do so, they use dissolved carbonate extracted from the seawater. However, the more acidic the oceans become, the less carbonate is present, so that foraminifera find it more difficult to form their shell and thus may change size. In this way, samples from deep-sea drillings are still a source of information about CO_2 content in the oceans millions of years later.

In addition, geologists can reconstruct the temperatures which prevailed at that time by examining the magnesium content, which occurs as an impurity in the shell of the foraminifera. The unicellular organisms incorporate it into their calcium carbonate shells in place of calcium. And the warmer the ocean becomes, the more they do it. Dr David Evans, Müller's colleague, has further developed this »magnesium thermometer« and most notably applied it successfully to the Eocene environment.

Foraminifera also incorporate trace quantities of borate (BO_4) into their skeletons besides calcium carbonate. Boron has various isotopes. This means that the element's mass varies depending on the number of neutrons in the atomic nucleus. The most common is the isotope with six neutrons, but there are also stable isotopes with just five neutrons. Palaeoclimatology makes use of the fact that the frequency distribution of boron isotopes in seawater depends on the pH value. This makes it possible to draw conclusions about the CO_2 concentration in the water and, indirectly, also in the atmosphere. Müller and his team are also conducting similar studies on other marine organisms such as corals, molluscs and snails.

Improved climate models

Müller initiated and now coordinates the LOEWE consortium project VeWA, »Past Warm Periods as a Natural Analogue for our ›High-CO_2‹ Climate Future«, a collaborative project, funded by the LOEWE programme of the state Hessen government, between Goethe University Frankfurt and the Senckenberg – Leibniz Institution for Biodiversity and Earth System Research (SGN). Within this consortium, which started work in the summer of 2020, researchers in eleven subprojects are studying different climate parameters, starting from the late Cretaceous period – the era of the dinosaurs – up until the end of the Eocene, when Antarctica froze over again.

»If we have data about past warm periods and their ›high-CO_2‹ world that are as precise and reliable as possible, this is also a good test for present-day climate models,« explains Wolfgang Müller. »Because if, in retrospect, these models reproduce palaeoclimatic data (i.e. climate hindcasting), they can also be trusted to produce reliable predictions.

A method developed in 2020 at the Department of Geosciences promises even more accurate temperature data from the geological past. This technique developed by the research group led by Professor Jens Fiebig, which is also participating in the VeWA consortium, is based on the fact that the isotopic composition of the carbonates, more precisely the degree of »clumping« of their heavy isotopes, in the skeletons of sea and land dwellers is temperature-dependent. In addition, however, the respective circumstances under which mineralisation takes place also play a role, that is, the mechanism and speed of carbonate formation. This influence can now be subtracted. In the framework of the VeWA project, this isotope-based method will be applied to different carbonate archives of the Cretaceous period and the Eocene.

This should also help to improve climate simulations, which are currently unable to adequately reproduce a key indicator of past warm periods, namely the temperature gradient between the Equator and the poles. The smaller »meridional temperature gradient,« as it is known in technical language, shows that the tropical

About Wolfgang Müller

Prof. Dr. Wolfgang Müller, born in 1967, has been professor for geology and palaeoenvironmental research, with a special focus on isotope geochemistry, at Goethe University Frankfurt since 2017. He studied geology at the University of Vienna (Austria). In 1998 he earned his doctoral degree at ETH Zurich. As a postdoctoral researcher, he spent his time in Switzerland and above all in Australia. From 2004 to 2017 he held a faculty position at Royal Holloway, University of London, where he was most recently professor for isotope geochemistry. He is initiator and spokesperson of the LOEWE project »VeWA« (Past Warm Periods), which began in the summer of 2020.

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oceans heat up comparatively less in warm periods, but instead a lot of heat is transported from the tropics to the poles. Researchers plan to investigate this process in the framework of several VeWA subprojects.

During the PETM, foraminifera quickly died out and could no longer form any sediments. In drill cores – here a photograph by palaeoclimatologist James Zachos – this is visible as an abrupt, dark-brown colouration of the otherwise chalky-white sediment layers.

A lesson for the future

»If we wait for greenhouse gases to return naturally to pre-industrial levels, it will take far too long on the human time scale,« says Müller. After the PETM event, for example, the cooling phase lasted over 100,000 years. Weathering of silicate rocks, such as basalt, granite or gneiss, plays an important role in this context. In this process, CO_2 is extracted from the air in the form of carbonic acid and many weathering products are transported via rivers into the ocean. There, marine organisms incorporate the carbonate into their shells, where it is stored as carbonate sediments for a long time, with the result that the CO_2 content in the atmosphere decreases. In one of the VeWA subprojects, researchers led by Professor Silke Voigt are especially studying the temperature-dependent weathering of silicates with the help of the isotopic composition of the element lithium, the lightest metal of all.

Can we tell from past warm periods what will happen if we fail to reduce CO_2 emissions? One of the research priorities in the VeWA project is the Eocene »hothouse«, when the CO_2 concentration in the atmosphere was, at times, greater than 1,000 parts per million (ppm). By comparison, today's figure is almost 415 ppm, which is already more than 130 ppm above pre-industrial levels, and CO_2 concentration is currently increasing by two to three ppm per year. Müller illustrates the substantial climate effects that can result from even relatively small fluctuations in CO_2 of »only« 100 ppm: »We know from Antarctic ice cores, which record the eight main cycles of warm and cold periods over the last 800,000 years: During the last cold phase 20,000 years ago, sea levels were 130 metres lower than today, and the atmospheric CO_2 concentration was 180 ppm. That's only 100 ppm below pre-industrial levels, but it was four degrees colder worldwide nonetheless.« At that time, the North Sea was dry, North America was connected with Russia, Australia with Papua New Guinea, and Indonesia with the Asian mainland.

For palaeoclimatologists like Müller it is high time to reverse the trend. »Without rapid countermeasures, we may well risk approaching a tipping point,« he says, »even if we don't exactly know where these are«. At such a point, even a small external influence is sufficient to trigger abrupt changes in the climate system with self-amplifying effects that would no longer be reversible. If, for example, the polar ice caps were to melt due to an even stronger greenhouse effect, less sunlight will be reflected, which will heat up the Earth further still. Additional greenhouse gases will be released out of the thawing permafrost, especially potent methane, which will further intensify the greenhouse effect. And sea levels will rise rapidly as a result of destabilised ice sheets, like those present on Greenland.

»Unfortunately, people are very slow to change their habits,« says Müller regretfully. He points out that the last three summers in Europe have already been warmer than average, and he would like to see rapid and greater political pressure through a price for CO_2. He is nonetheless optimistic that we can – through more moderate consumption of resources and especially the use of renewable energies – still avoid steering towards the extreme climate of the geological warm periods. That is why it is also important to him and his colleagues in the VeWA consortium »Past Warm Periods« that knowledge of climate change is more quickly disseminated more widely among the wider public. For this reason, the twelfth VeWA subproject is dedicated to science communication: the results and background of the VeWA consortium will be presented at the Senckenberg Museum and elsewhere around Frankfurt through a number of activities, including a travelling exhibition, funded by the LOEWE initiative. ●

The author

Dr. Anne Hardy, born in 1965, studied physics and holds a doctoral degree in history of science. As a freelance journalist, she specialises in natural science and medical topics.

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