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Why do scientists drill the ground beneath our feet?

Edited by
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icdp INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

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Why do scientists drill the ground beneath our feet?

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About this collection

Drilling a hole into the crust of our planet can help scientists unravel some of the many secrets that otherwise would remain hidden in its interior. Burning questions related to global climate change, evolution of ecosystems and species, including our own, the dangers posed by volcanoes and seismically active zones, and the sustainable extraction of heat and raw materials, demands answers that scientists can provide only using insights from scientific drilling.

For most people, drilling into the Earth means laying the foundation for extracting natural resources from under our feet. Recent discussions about new drilling-related technologies such as exploitation of unconventional gas resources, carbon capture and storage and geothermal energy brought deep drilling into the focus of public's attention. With this collection we want to point out that drilling also serves other scientific goals, of high social relevance to face global environmental, climate and economic crises.

With this volume we celebrate the 25+ anniversary of the community under the leadership of the International Continental Scientific Drilling Program ICDP.

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EARTH SCIENCES
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SECRETS BENEATH YOUR FEET—THE FASCINATING WORLD OF SCIENTIFIC DRILLING

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YOUNG REVIEWERS:

ANTONIO
AGE: 10

MOMO
AGE: 11

Why do scientists drill into the Earth? Drilling is a valuable tool to unravel secrets of the planet's history because lots of information is safely stored deep below our feet within the Earth. By taking samples from deep in the Earth and performing laboratory tests on them, scientists find rock materials, water, bacteria, and fossils that can help to unravel mysteries of life and the environment over millions of years. Drilling is also important for finding sustainable new resources, such as geothermal heat, which can be used to produce energy for our homes. Drilling can also help us understand and protect our planet. Another important reason for drilling is to install specific instruments deep in the Earth, to monitor Earth's movements. These instruments help us to better understand natural disasters like earthquakes or volcanic eruptions and can enhance the safety of billions of people worldwide.

DIGGING INTO THE PAST TO UNRAVEL OUR FUTURE

This article takes you on a journey deep below the Earth's surface, where hidden secrets from our past and valuable treasures for our future are awaiting to be discovered. Scientists use drilling to unlock Earth's treasures that contain important clues to unanswered questions. When we drill into the Earth's surface, we create holes called **boreholes**. A borehole is like a narrow shaft drilled several km deep into the Earth. The deepest borehole ever drilled is located on the Russian Kola Peninsula [1, 2]. The reason for drilling was the search for minerals and to collect information on the structure of the Earth's crust. The borehole reached more than 12 km in depth, approximately the length of 120 football fields. But did you know that the Earth has a radius of about 6,371 km? The Earth is separated into the crust, the mantle, the outer core and the inner core (Figure 1). The thin crust is just 30 km thick on the continents. Drilling into deeper parts of the Earth is not yet possible. Rising pressures and temperatures deep in the Earth make drilling challenging. The drilling machines and tools can break easily or melt like a snowman in the summer sun when the temperature get too high (>250°C).

BOREHOLE

A deep hole drilled into the ground to extract water, oil, gas, or minerals and to explore Earth's secrets and history.

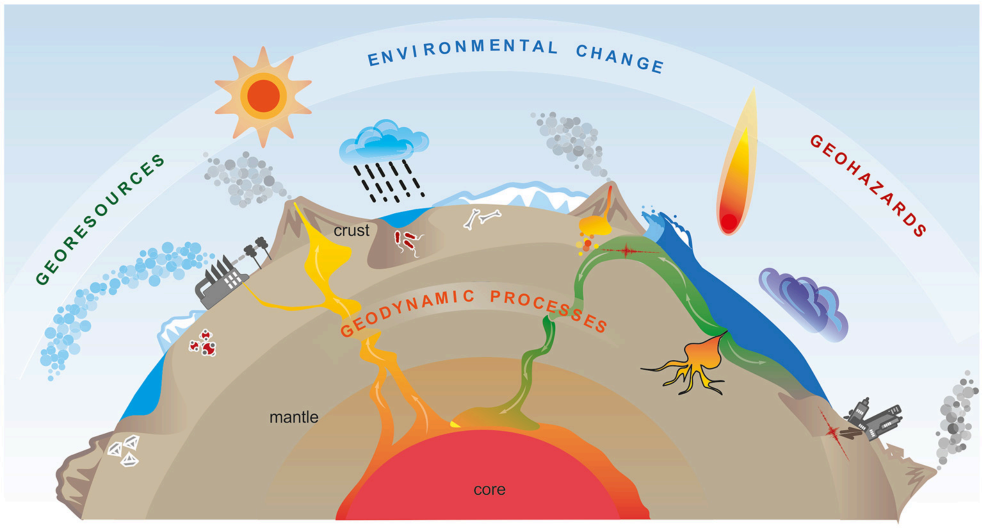

Figure 1

Figure 1

Topics that motivate scientists to drill into the Earth. The interior of the Earth is roughly divided into the extremely hot core, the semi-solid mantle, and the thin crust on which we live. Geodynamic processes transport heat from the core to the Earth's surface and are responsible for plate tectonics, earthquakes, and volcanic activities. We use georesources like heat, oil, gas, and coal to produce energy. Geohazards include earthquakes and volcanic activities but also events like meteorite impacts. Earth's environment includes everything around us, like the air, weather, water, ice, and living organisms (Figure modified from [3]).

Boreholes are drilled all over the world, on land and even into the seafloor. They are mostly used to find valuable goods like groundwater, oil, or metal resources. However, the goal of a few drillings is to explore our planet and help to unravel secrets of the Earth's history and the history of life [2]. Drilling helps scientists to get a better picture of the interior of the Earth. Lots of information can be obtained from rock material that is removed from the Earth by drilling (Figure 2A). The cylindrical shaped rock samples are called drill cores (Figures 2B, C). These can be analyzed, for instance, in the laboratory. It is also possible to take measurements inside the boreholes [1]. All information is important for our modern society.

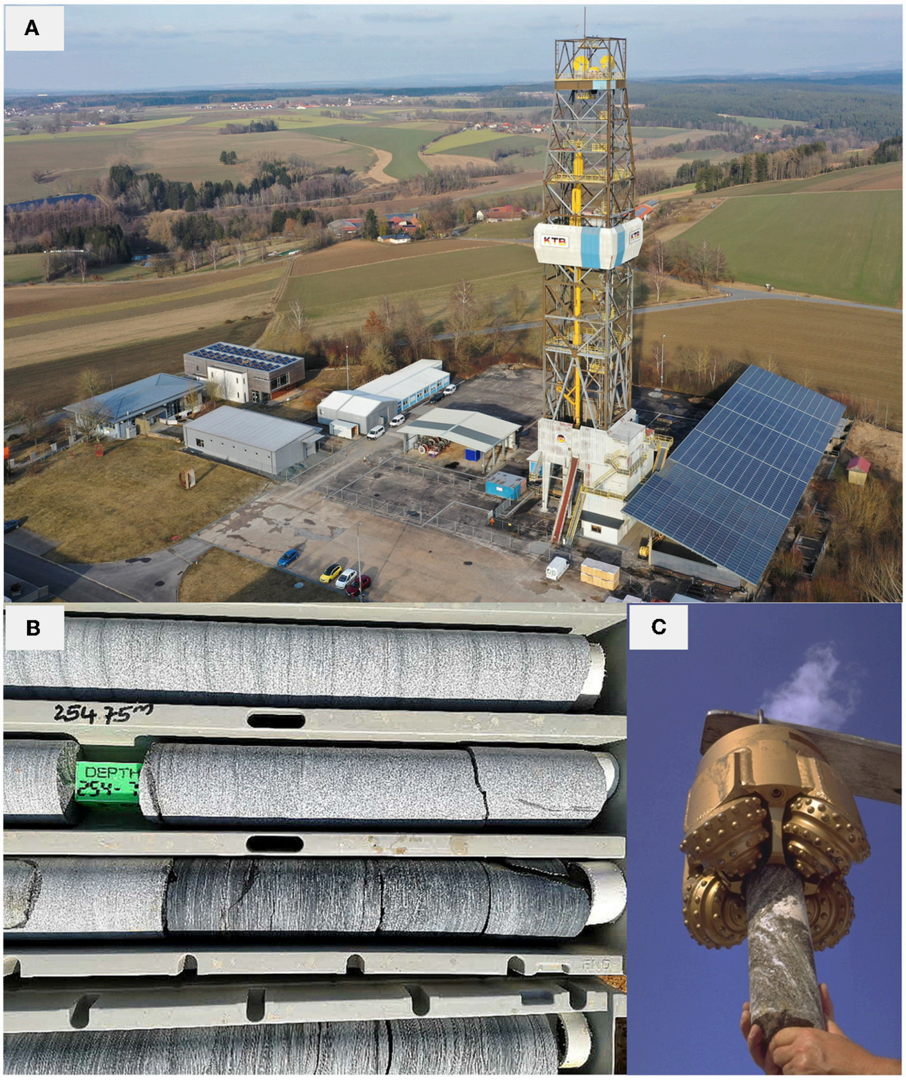

Figure 2

Figure 2

(A) The KTB-Borehole in southern Germany, drilled between 1987–1994, is one of the deepest scientifically used boreholes worldwide—at a depth of about 9,101 m [1, 4]. The drilling tower (officially called "derrick") marks the location of the borehole, which is directly below. **(B)** Samples from such boreholes provide key information about Earth. Such samples are called drill cores, and they can be taken from boreholes during the drilling process. **(C)** The core drilling bit cuts a cylindrical shaped column of rock with its rotating cones, which is then lifted to the surface with the drilling rig [5] (Figure credits: **(A)** Gunnar Pruß, GFZ Potsdam; **(B)** ICDP supported GRIND project).

CLIMATE AND ENVIRONMENT

The history of our environment, with its climate, plants, animals, and even tiny microbes, is recorded in sediment layers found in lakes and seas [2]. By drilling into these layers, the recovered drill cores can be read like a book. Each tiny layer of sand and clay contains traces of plants or fossils of tiny organisms of the past. From these, scientists can reconstruct what the temperatures and rainfalls were like hundreds to millions of years ago [2, 3]. The sediment layers add up to an animated picture of how landscapes, life, and climate changed over time. By gathering information from various places all over the world, scientists can understand what causes climate and environmental changes. They can distinguish which changes were caused by natural impacts and which changes are related to human activities.

Currently, researchers are very interested in understanding the reasons for rapid climate changes in the past. For example, 66 million years ago, a giant meteorite hit the Earth and caused the extinction of most animals, including the dinosaurs. This meteorite impact led to tsunamis, wildfires, dust in the atmosphere, and acid rainfalls that made our planet uninhabitable for most lifeforms. But how did the Earth recover and rebuild a stable, life-friendly climate? What can we learn from such past rapid climate changes and what do they tell us about our future? The answers are hidden below our feet, and scientists are working hard to uncover them.

GEORESOURCES

Earth's valuable materials, like minerals, oil, gas, coal, and heat, essential for the modern society.

GEOTHERMAL FIELD

An area where the Earth's heat comes to the surface, forming hot springs and geysers, with the potential to use this natural heat for clean energy production.

SUSTAINABLE ENERGY

Energy from sources that are naturally replenishing and do not harm the environment by releasing greenhouse gases, such as geothermal heat, solar, and wind power.

GEOTHERMAL ENERGY

The natural heat from the Earth's interior rising up to the surface that can be used for the production of clean energy.

GEORESOURCES

A healthy atmosphere is extremely important for life on Earth, next to food and drinkable water. But modern life requires further resources, such as energy sources for heating and power generation. **Georesources** are natural resources that come from the Earth. Drilling is a useful tool to search for these valuable resources. Unfortunately, conventional energy resources such as coal, oil, and gas contribute to air pollution and lead to climate change in the form of global warming. To preserve Earth's climate, we must discover more environmentally friendly ways to produce energy [3]. We can use renewable energy coming from the wind and the sun... but what can we rely on when it is dark and windless? The answer lies right below our feet.

The temperature within Earth's crust increases on average about 3°C every 100 m. In places where the crust is very thin, for example in volcanic areas, we can find **geothermal fields** where the heat from the Earth's mantle (typically more than 1,400°C) can rise to shallow depths in the crust. The heat stored in crustal rocks warms up deep groundwaters. By drilling into these rocks, we can access this heat reservoir and built power plants on top of the site, to use the heat as a source of clean, **sustainable energy** known as **geothermal energy** (Figure 3).

Shallow geothermal wells (Figure 3C) are becoming popular ways to heat people's houses. This system uses water that circulates through pipes underground and carries the heat to the surface, where it is used to warm up houses in winter. Deep geothermal wells (Figure 3B) can produce energy for nearby areas. Here, water is also used. It is pumped deep underground (a few kilometers) where it is even hotter. The water can get so hot that it turns into steam like it does when you boil it in a kettle at home. The high pressure underground pushes the steam back to the surface through a well, where it is used to run turbines that produce electricity pretty much like windmills do. However, to produce enough energy for big cities, we must drill even deeper and investigate ultra-high temperature systems (Figure 3A). These systems can be found in volcanic areas, for example, but are not well investigated yet—and investigating them is challenging.

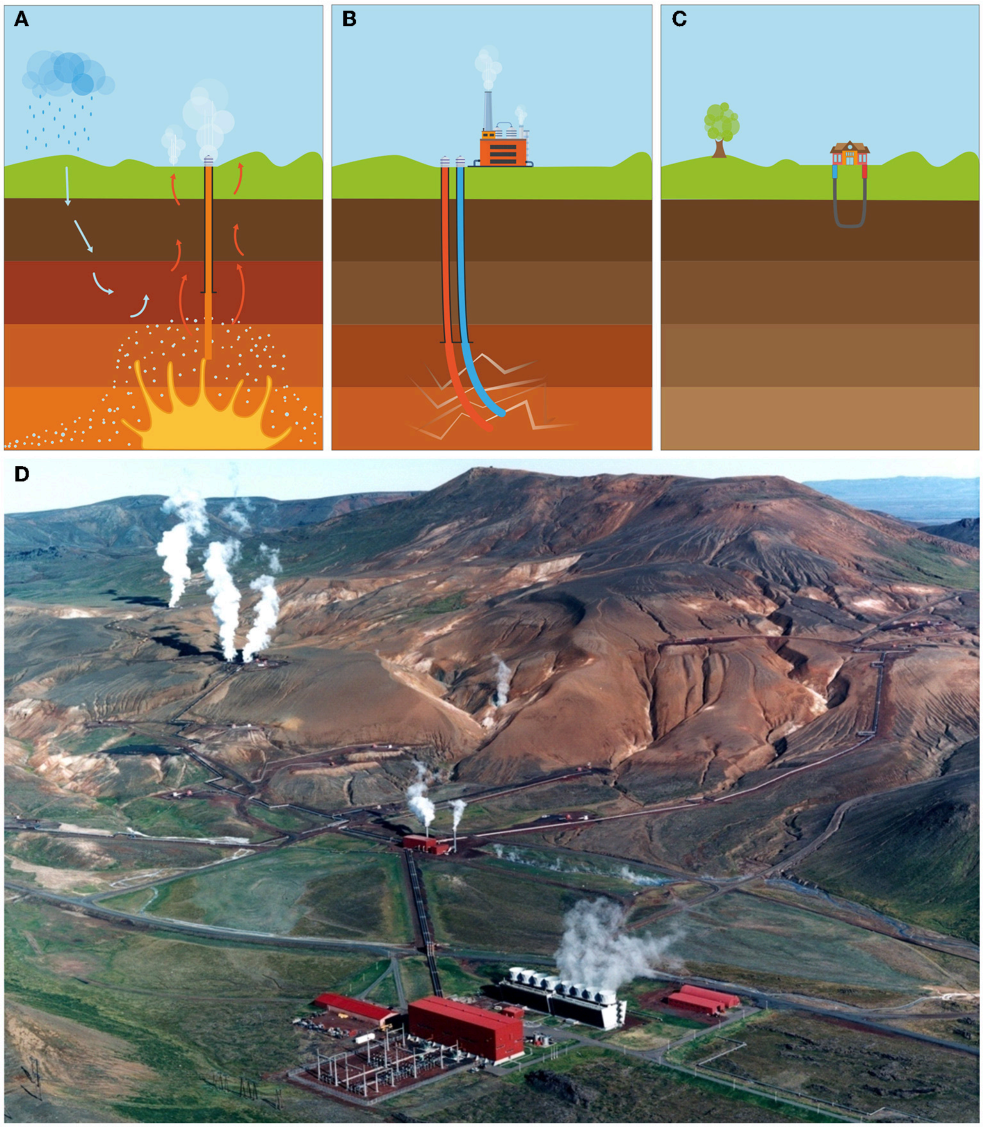

Figure 3

Figure 3

Currently, three categories of geothermal energy sources are investigated to help protect Earth's environment: **(A)** ultra-high temperature systems that exist in volcanic areas; **(B)** deep geothermal wells; and **(C)** shallow geothermal wells that are most often used to heat individual houses. The heat naturally stored underground is transported to the surface through drilled boreholes. **(D)** The geothermal power plant in Iceland, close to the Krafla volcano, generates electricity for local communities (Figure credit: **(A–C)**, [6]).

Super deep wells (several kilometers) are needed, and they work similar to deep geothermal wells but at much higher pressures and temperatures. These super deep wells can create much more energy and are thus much more effective for producing electricity.

Currently, scientists are making exciting plans to take things to the next level, by drilling into the Krafla Volcano in Iceland (Figure 3B). The aim is to reach the 900°C hot magma, to make use of this giant energy resource [3]. Will such a borehole be stable and safe? Hopefully this drilling project will provide the answer.

GEODYNAMICS

Drilling is also a useful tool to better understand Earth's **geodynamics**. Geodynamics is all about understanding forces and processes that

GEODYNAMICS

A research field that explores dynamic processes that shaped the Earth over time, including tectonic plate movements that cause earthquakes and form mountains.

shape Earth. The crust, for instance, is a big puzzle of large and small plates, which can be separated into continental (land) and oceanic (underwater) plates. We know that the movements of these plates create mountains and valleys over time, at the same speed at which our fingernails grow. This process is called **plate tectonics**. But there are still mysteries to be solved [3]. Why and when did plate tectonics start? How do movements of plates influence Earth's atmosphere and climate? How did ice ages and warm periods affect the evolution of life on Earth? From drill cores, we already learned that life forms must have enriched the early atmosphere with oxygen. Marine shells stored many tons of carbon dioxide, a greenhouse gas. These processes likely made life on Earth possible. To better understand Earth's geodynamic cycles, scientists must drill deep into the crust to recover the rocky archives, which provide evidence and answers to these riddles.

PLATE TECTONICS

The Earth's crust is broken into large and small pieces forming a puzzle. These pieces move because of geodynamic forces and cause earthquakes, volcanoes, mountains, and valleys.

GEOHAZARDS AND RISKS

In addition to all that you have already learned, boreholes can literally help save lives! Scientists can place special instruments inside boreholes to measure, for instance, Earth's underground movements. The instruments record very small to really large vibrations and shape changes of rocks and faults (big cracks in the Earth, like the San Andreas Fault in California, USA). Such instruments can also be placed on the Earth's surface, but many human-made noises (such as vibrations caused by big trucks) or even strong winds distort surface measurements. By contrast, instruments placed in boreholes are far away from such disturbing signals and much closer to Earth's "heartbeat". This helps instruments to record only the really interesting signals, for instance those caused by earthquakes or magma movements beneath volcanos [3]. Such signals can be used as a warning system for people living nearby. If the signals change very drastically, for instance if there are an unusually large number of small earthquakes, scientists can send out an alert. This kind of system has already helped to protect people from **geohazards** and related risks caused by large earthquakes or volcanic activities. Furthermore, drilling into faults, for instance, can provide valuable information on how and why earthquakes occur [2, 3].

GEOHAZARDS

Dangerous natural events like earthquakes or volcanic eruptions, which can cause tsunamis, landslides, fires, and collapsed buildings.

THE IMPACTFUL ROLE OF SCIENTIFIC DRILLING

As you can see, the world of scientific drilling is fascinating because it opens up a whole new world beneath our feet. Drilling into the Earth is an important tool for scientists, as it helps to unravel mysteries of Earth's past and to find resources important for society—both today and in the future. Scientific drilling is a key to understand how our planet has changed over time and how it will continue to change. The newly gained information and access to more environmentally friendly resources can help us to better protect the environment. Furthermore, understanding geodynamic processes helps us to decrease the impact of natural disasters, including earthquakes and volcanic eruptions. Overall, research with boreholes is like using telescopes to look into the unknown under our feet! There is still so much more to explore, so let us continue to be curious about our planet and the environment around us.

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YOUNG REVIEWERS

ANTONIO, AGE: 10

Antonio really enjoys reading about interesting topics in science. He is an avid birder and enjoys the outdoors. In his spare time he likes to play soccer with friends.

MOMO, AGE 11

Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she is at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

AUTHORS

AGLAJA BLANKE

Aglaja studied geological science at the Free University of Berlin. During her studies, she was fascinated by earthquakes and volcanos and became a seismologist in 2017 when she received her master's degree. She continued her studies as a Ph.D. student at the German Research Centre for Geosciences (GFZ) in Potsdam, where she focused on the analysis of earthquake sources and damping of seismic waves in the Earth. Since 2021, Aglaja has been a postdoctoral researcher at GFZ, and she works on projects related to seismology and volcanology. She is also the panel coordinator of the International Continental Scientific Drilling Program. *a_blanke@gfz-potsdam.de

ULRICH HARMS

Uli studied mineralogy and geochemistry in Kiel and Berlin and, during his Ph.D., focused on the origin and age of Precambrian rocks in Africa. A leading question for him was how Earth's continental crust formed. After spending time as a postdoc at TU Berlin and the British NERC Isotope Geology Centre, he worked for the German Continental Deep Drilling Program in Hannover, where he got acquainted with scientific drilling. His career continued at the GFZ in Potsdam as a senior scientist and secretary of the International Continental Scientific Drilling Program (ICDP). He leads the ICDP Operational Support Group and organizes support for various ICDP projects around the world.

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DRILLING INTO ANCIENT ROCK TO LEARN ABOUT EARTH'S PAST

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YOUNG REVIEWERS:

JUDE
AGE: 15

NICO
AGE: 13

TOM
AGE: 10

Geologists are curious to learn what the Earth was like when the planet was young. We want to know about temperature, beaches, soils, climate, rivers, meteorite impacts, and volcanic activity because these factors determined how and where early life could exist. Only the oldest sedimentary rocks have this information, but these are usually covered by younger rocks. Old sedimentary rocks that still "tell a good story" about the history of the Earth are rare. We studied some of these. They are an unimaginable 3.2 billion years old and are found in the Makhonjwa Mountains near South Africa's border with Eswatini. We had to drill into the Earth to get to them because the surface is covered by forest and grassland. Sedimentary rock layers in these mountains do not lie flat anymore but are vertical, and sometimes even flipped over. To drill through as many layers as possible, we had to drill sideways!

ROCKS CAN HOLD SECRETS OF EARTH'S PAST

Earth is a very old planet. Life on Earth formed early, but we still do not know how. At first, the Earth and its climate were very hot, but the earliest bacteria soon managed to take carbon dioxide (CO_2) out of the atmosphere. This reduced the temperature and, from then on, CO_2-consuming life has kept Earth's surface temperature surprisingly constant for more than 4 billion years—even as the planet itself gradually cooled off. This gave life the long time it needed to slowly become more complex and larger: first fungi evolved, then amoebae, then plants and sponges, then larger animals all the way to giant dinosaurs, and now humans!

SEDIMENT

Natural material that is broken down by weathering and moved by wind, water, ice or gravity. Other sediment (like salt) crystallizes and settles from water; coal may form from plants. Sand and mud are common sediments.

SEDIMENTARY ROCK

A sediment in which the grains or minerals are compressed and connected by other minerals to each other, forming a solid rock. Common sedimentary rocks are sandstone or limestone.

We do not know any other planet where life exists. Therefore, we do not know whether it is difficult or easy for bacteria to evolve the surface of an "empty" planet and gradually spread, as they have done here on the Earth. Does this occur only rarely or is it common? How would we learn about this?

Much information lies in **sediments** that wash down from hills and mountains; are transported to the coast by water, winds, or glaciers; and are then deposited at the coast in flat layers. Other sediments may form when water evaporates, as they settle out in the form of tiny crystals. These sediments form what are called **sedimentary rocks**. But a lot happens at the surface of our planet: continents split and collide, and mountain ranges form. Most old sedimentary rocks are squished, have changed their composition, or have even melted to become granite! Other sedimentary rocks tilt, form big folds, or even end up in an upright position (Figure 1).

Very old sedimentary rocks only exist in a few locations, but they can teach us a lot. From sedimentary rocks, we can learn about ancient flowing rivers, tides, storms, temperatures, the composition of the atmosphere, and even the wind speed [1]. The oldest sedimentary rocks are 3.2 billion years old and lie in the Barberton Makhonjwa Mountains of South Africa and Eswatini (Barberton is a small town at the foot of the mountains). Because many of the rocks there are green, geologists call this region the Barberton Greenstone Belt [2].

LEARNING ABOUT "EMPTY" EARTH

We know that Earth was a very different planet back when ancient sedimentary rocks were forming. It would have been unrecognizable to us today: Earth rotated almost twice as fast, so days had only 13 h—lots of sunrises and sunsets! Also, the Moon was much closer, tides were probably higher and may have reached much farther inland, and Earth was covered with many active volcanoes. If animals had existed (which they did not), the sun would have burned their skin within a few minutes. There were no plants yet, and the air had no oxygen [1].

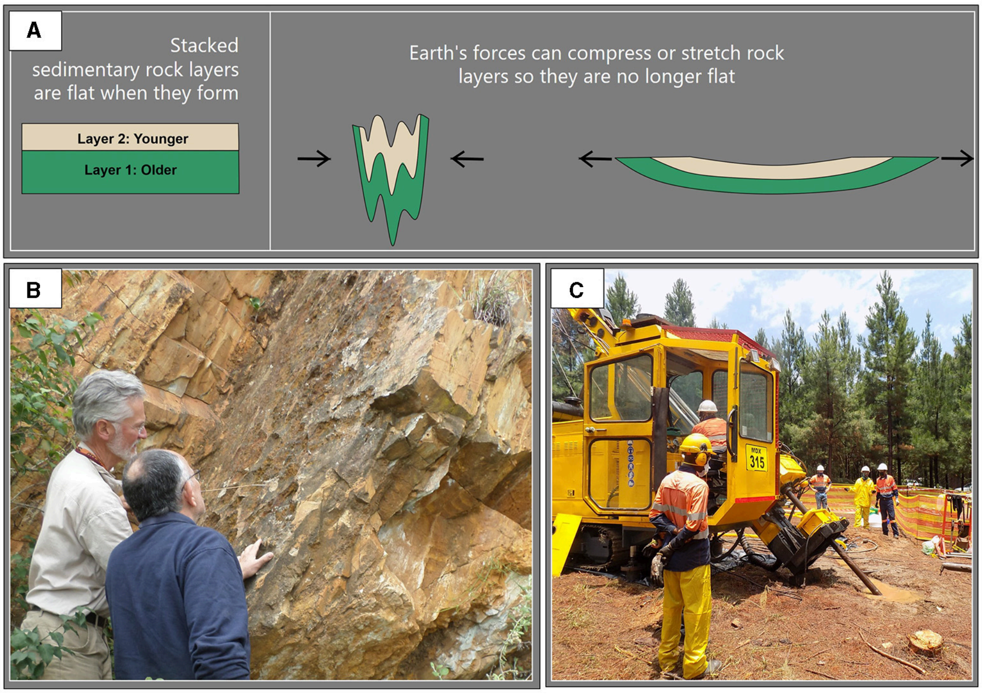

Figure 1

Figure 1

(A) Rock layers that were once flat can be affected by forces acting on the Earth's surface and become tilted or even upright over time. **(B)** An example of tilted but weathered rock layers. **(C)** The unweathered rock layers from the Barberton Greenstone Belt which we want to study are tilted but hidden beneath the soil.

We wanted to know more about the conditions on this "empty" planet that led to the appearance of life. Was Earth back then a deadly place? Or was it just gray and foggy? Answers to such questions come from carefully comparing the ancient rocks with what we see in the modern world. For example, a fossilized raindrop imprint on former mud would perhaps be a hint about ancient rainy weather. Fossilized rock with a rippled surface would hint at the presence of flowing water. Cracks in the rock would indicate that wet mud had dried out, and so on (Figure 2). The minerals in the rock also indicate what kinds of salts the early oceans had, whether there was oxygen in the air, and which type of soil formed.

But many of these comparisons can be done only on rocks that are still protected from rain, heat, and cold. They must be **unweathered** and as close to their original composition as possible.

UNWEATHERED

A rock not affected by rain, air, animals, plant roots, or bacteria at the surface. Most rocks near the surface are weathered. To get unweathered rock, one often has to drill a borehole.

WHERE TO DRILL?

We knew we needed to drill into the Earth to get to the rock layers we were interested in, because those rocks are now covered by forest and grassland. First, we had to figure out the best place to drill [3]. We met with other interested scientists to look at the rocks in the Barberton Greenstone Belt, discussed advantages and disadvantages of each site, and then voted where to drill. We decided to drill 8 **boreholes**, which would allow us to sample rock types that made up ancient rivers, sandy

BOREHOLE

A narrow round shaft bored in the ground, often vertically but sometimes inclined or even horizontally. This may be done for finding water, petroleum, or natural gas, or to investigate the rock.

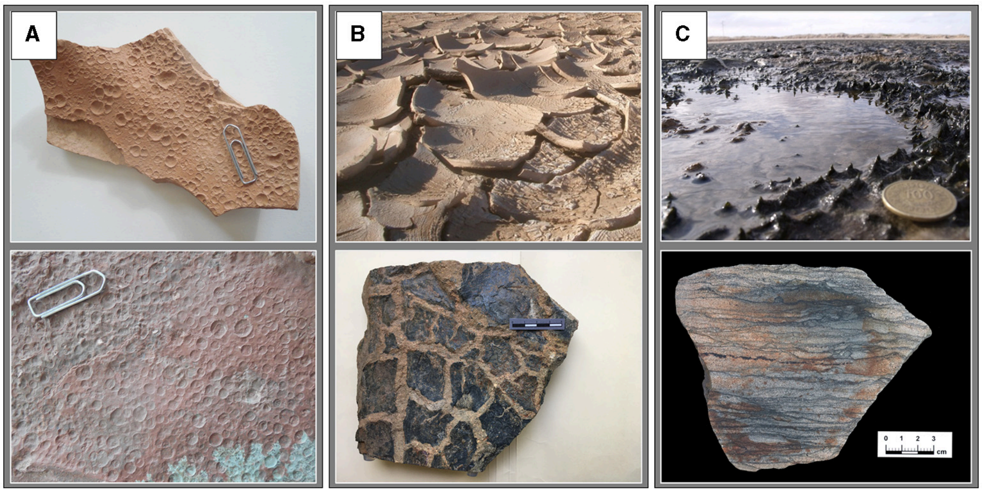

Figure 2

Figure 2

"Reading" history in sedimentary rocks. Images in the upper row are from today's sediments; images below are from very old rocks. **(A)** Raindrop imprints. Rock in the lower row is about 290 million years old. **(B)** Cracks which grew when mud dried out. Rock in the lower row is about 3,220 million years old. **(C)** Microbial mats made from dense growth of bacteria; coin for scale. Rock in the lower row is about 3,221 million years old.

coastlines, the shallow ocean, volcanic rocks, ancient soil, and a delta where the river met the sea.

We then had to ask for permission to drill on other people's land. Because our drill sites occur in a conservation area, and because past drilling near Barberton was often done to find gold, we had to convince the Barberton community that we were interested in understanding the rocks, not in finding gold [4]. After many presentations, people gradually realized that our results would not lead to the opening of new mines within their beautiful region.

At the same time that we were making these preparations, we were also getting the money together to drill and making sure that the places we had chosen were really the best ones.

DRILLING

In Barberton, we organized places to live for a year, so that we could work every day (Figures 3A–C). As we mentioned, sedimentary rock layers in these mountains do not lie flat anymore but are vertical, and sometimes even flipped over. Luckily, the drillers knew how to drill sideways, which was good because some of the rock layers were standing on end and we wanted to access as many rock layers as possible. Our boreholes were each between 280–500 m long. Each borehole took about 6–10 weeks to drill.

Sometimes, the **cores** the drillers pulled out of the ground were cracked or weathered, making them impossible to study, but often they were just what we had hoped for (Figures 3D–F). Once we had the cores, we had to cut them in half neatly, right down the middle, so that we could see the layers more clearly. Then we had to label, photograph, describe, and store them. After 9 months, we

CORE

The long string of rock that has been drilled through. The core is then investigated.

Figure 3

Figure 3

The story of a drill core. **(A)** Drill site in the mountains. **(B)** Moving the core trays. **(C)** Phumi explaining the rock layers in the core to school children. **(D)** The black lines in the sandstones of this drill core were once microbial mats. **(E)** Thin layers of shale represent the tides near a former coastline. **(F)** "White gravel" consists of soft volcanic rock. **(G)** Loading more than 500 boxes with rock cores to be moved to the laboratories. **(H)** Rock cores in storage (a "core library"). **(I)** Our team, discussing who will do which analyses.

had filled more than 1,000 black plastic boxes with neatly described rock. The 500 boxes with the right halves of the cores stayed in South Africa, and the 500 boxes with the left halves were loaded in two shipping containers and shipped to Berlin, Germany, to be studied there (Figures 3G–I).

WHAT HAVE WE LEARNED SO FAR?

So far, we have learned that we indeed drilled through sediments that had been deposited in various ancient regions: at the foot of mountains, in rivers, in deltas, in tidal flats, along shorelines, even beneath deep ocean water. We can tell that there were tides from the sediment layering patterns [5] (Figure 3E). We may even be able to tell when the moon was full vs. when it was not! We can see that there were lots of volcanic eruptions, and much volcanic ash rained down and became mixed with the sand grains (Figure 3F); sometimes, the sediment had been outright soupy! Between the water-filled delta channels, there were regions that were only flooded once or twice a day but remained dry otherwise; bacteria grew especially well there and made thick layers that even contained air bubbles. Some bacteria may have grown near hot springs with boiling water.

WHAT IS NEXT?

As our research continues, there will be about 50 people from all over the world working with the cores, most of them young scientists (Figure 3I). They will try to find answers to a number of questions, such as: In what conditions did the earliest life forms grow on Earth's surface, 3.2 billion years ago? How did bacteria protect themselves from the sun's harsh rays? What did the bacteria "eat" and what kinds of waste products did they produce? Was the occurrence of bacteria exceptional and rare, or was it commonplace?

These questions will be answered by carefully analyzing the drilled cores in laboratories around the world. The information learned from these cores will be made available in presentations at universities and conferences. Importantly, the knowledge will also be shared with the people of South Africa and Barberton who live closest to this very special part of our planet.

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

JUDE, AGE: 15
I am a big fan of both dogs and cats, I have trained my cat to walk on a lead so we can go for walks together in my spare time. I also love music and spend a lot of time playing my guitar. I enjoy reading about biochemistry (especially plant related) and one day would like to study the subject at university.

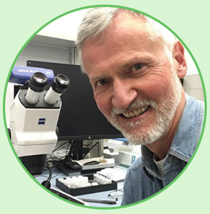
NICO, AGE: 13
Nico lives in Vienna but was born in London and likes playing chess. He loves reading fantasy books and can speak 3 languages (German, Spanish, and English) and can say a few words in Dutch, Italian, and Hungarian. Nico plays drums in his high school band.

TOM, AGE: 10
I was born in Madrid, and I came to Vienna 6 years ago because my mother got a job here. I like math and biology. I read a lot of novels, and sometimes non-fiction but not that often. I like to paint and go on my scooter.

AUTHORS

PHUMELELE MASHELE

Phumelele (Phumi) Mashele is a geology Ph.D. student at the School of Geosciences, Wits University in Johannesburg, where she studies properties of the last magma pulse of the Bushveld Complex, the world's largest deposit of chromium and platinum-group minerals. Phumi always admired old rocks as she grew up in several regions of northeastern South Africa, not yet knowing their global significance. She studied geology from 2012 at Wits University, where she earned a B.Sc. in geology, chemistry, and applied chemistry, and later obtained a B.Sc. Honours and M.Sc. in geology with geotourism elements. She enjoys sharing Earth history with members of her hometown communities, to inspire them for geoscience-based tourism businesses. Phumi has worked as a science outreach officer for several projects managed by the national government of South Africa and the International Continental Scientific Drilling Program.



CHRISTOPH HEUBECK

Christoph Heubeck is a geologist and professor at the Department of Geosciences, Friedrich-Schiller-University Jena. He was born and grew up in southern Germany, studied for his B.Sc. at Würzburg University but then left for the United States where he received a M.Sc. from the University of Texas at Austin (1988) and a Ph.D. from Stanford University, California (1994). He then worked in several locations in the US and Canada for a large petroleum company before becoming a professor, first at the Freie Universität Berlin (2000–2014), then at Jena (2014–present). Christoph is interested in sedimentary rocks and the evolution of sedimentary basins; his particular focus lies on the history of the early Earth, in particular the rocks of the Barberton Greenstone Belt in South Africa and Eswatini. He equally likes working in the mountains, in the laboratory, at the computer, and with people. *christoph.heubeck@uni-jena.de

EARTH SCIENCES
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A TIME MACHINE TO PANGEA'S CLIMATE PAST

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YOUNG REVIEWERS:

ABDUL HADI
AGE: 13

FATHIA
AGE: 9

HADIL
AGE: 13

LOUAY
AGE: 13

If you could time travel to the central U.S. 300 million years ago, you would find yourself at the equator of the supercontinent Pangea. At first you might enjoy a warm climate, surrounded by seas filled with life. But, after some millions of years, the seas would vanish as the climate turned increasingly hot, dry, and hostile. Billowing dust would engulf you, and nearly all life on Earth would vanish in an event called the Great Dying. How do we know? Geoscientists reconstruct past landscapes and climates by drilling into ancient sediments—tiny grains of sand and silt. These tiny particles tell us how fast the mountains rose and which way the wind blew. Microscopic fossils reveal water and air temperatures. And miniature bubbles trapped in salt preserve actual fossil water, from nearly 300 million years ago. Travel back in time with us to explore the Great Dying.

MOHAMMED
AGE: 15

NATHAN
AGE: 11

EARTH'S CLIMATE: PAST, PRESENT, AND FUTURE

Around 250 million years ago, during the Permian geologic time period, there was a mass extinction event called the Great Dying [1], during which life on our planet almost came to an end. Ninety percentage of life in the oceans and 70% of life on land vanished. Changes in Earth's climate system leading up to this event were very extreme. There was dramatic global warming and a huge change in Earth's atmosphere and the oceans. This time period is the only example we have of the complete melting of Earth's ice caps during a time when there was a diverse and healthy ecosystem on land. How do we know all of this?

Sedimentary rocks record the history of climate change, even climate change that happened hundreds of millions of years ago. Learning about the past helps us understand the processes that cause the climate to swing in different directions. This helps us prepare for the future and how our planet might respond to climate change. For example, Earth currently has ice caps at both the north and south poles, and researchers have been looking to the Permian to learn more about how our planet and the life it hosts might change in response to the melting of those ice caps. However, it is important to remember that the future is not a direct copy of the past.

SEDIMENTARY ROCKS

Form when small particles of minerals, ancient animals or plants, or other rocks are bonded together.

CLUES FROM CORES: THE ROCKS TELL THE STORY

The rocks tell the story. For example, if the climate was dry and dusty, the dust fell to the ground as a record of that dusty time. Or, if seawater covered the land, shells and bones of ocean animals settled down onto the seafloor and recorded hints of what the sea was like. These particles settled into layers, became buried by more layers, and, over millions of years, hardened into sedimentary rock. Today, **geoscientists** can drill into these rock layers and remove a **core** sample. A core sample is a long cylinder of rock only a few cm (or inches) wide that can be more than 1.5 km (a mile) long! Core samples are collected using a big, tower-like drill that is operated by a large crew of people (Figure 1). Geoscientists can read the story of how the climate and landscape changed over this very long time in the layers of rock in the core. The oldest material, and therefore the beginning of our story, is at the bottom of the core. The youngest, or most recent part of the story, is at the top, closest to the Earth's surface. Our story begins in ancient Oklahoma.

GEOSCIENTIST

A Geoscientist is a person who studies some part of the Earth and planetary systems—the air, water, rocks, soils, and ice—and how humans interact with these systems.

CORE

A core sample is a cylinder of rock or mud collected by inserting a long hollow tube or pipe into the Earth's surface and removing the materials inside.

PROJECT DEEP DUST: ROCK CORE FROM EQUATORIAL PANGEA

The shape of Earth's land has changed over time because continents are constantly moving. If you could time travel to the central U.S. 300

Figure 1

A drill rig at Earth's surface digs into the rock below. **(A)** Cut-away view of the rock core inside the drill pipe. This is the sample that will be pulled to the surface for geologists to study. **(B)** The drill bit at the end of the long pipe has tiny diamonds in it that are hard enough to cut through rock. The hole in the middle of the drill bit cuts a circle in the rock, leaving a long cylinder of rock inside the pipe—this is the core sample.

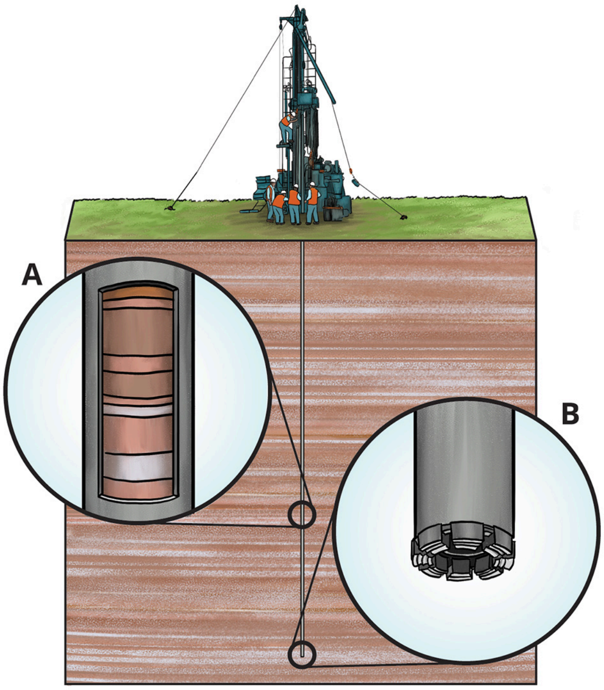

Figure 1

SUPERCONTINENT

A supercontinent is a giant landmass that includes many or all of the existing continents on Earth today.

GLACIAL PERIOD

A glacial period is a time in Earth's history when glaciers and ice sheets are common on Earth's surface.

INTERGLACIAL PERIOD

An interglacial period is a time in Earth's history when glaciers and ice sheets are rare on Earth's surface.

million years ago during the Early Permian, you would find yourself at the equator on the **supercontinent** named Pangea. This massive continent included what we now know as North and South America, Africa, Europe, Antarctica, Australia, India, and Siberia—combined (Figure 2). The enormous forces that pushed the continents together caused mountains to rise.

These mountains arose in the center of this supercontinent, along a line that stretched from Europe and northwest Africa, along eastern North America, and into central North America—what is today Oklahoma. Layers of sedimentary rock formed from tiny grains of sand and dust that washed down from these ancient mountains millions of years ago.

Our team is planning an expedition to collect new rock cores from Oklahoma, to learn about how and why the climate changed during the Permian. We are naming our project Deep Dust because we plan to drill deep—over 1,500 m—into rocks made of ancient dust [2], which provide a continuous record of how life and climate at the equator of Earth's largest continent evolved through a time of dramatic planetary change. What do we hope to find in these cores? Let us start with some history of the past.

EQUATORIAL PANGEA IN THE PAST

During the Early Permian period, the Earth cycled between cold **glacial periods** and warm **interglacial periods**. Ice caps grew during

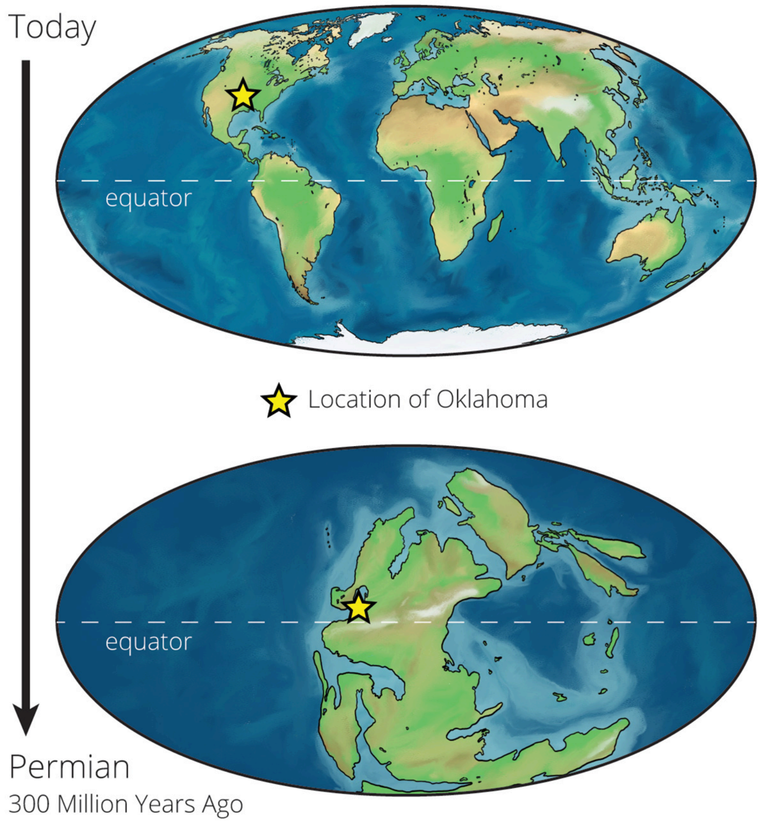

Figure 2

Figure 2

Continents are always moving. These maps show how the shape of the continents 300 million years ago, during the Permian period **(bottom)**, was very different from their shape today **(top)**.

glacial periods, which caused sea levels to drop, sometimes over 100 m (100's of feet), as Earth's water was locked away in ice. During this time, equatorial Pangea was home to a rich coastal ecosystem busy with insects, amphibians, and reptiles. As ice melted during warm interglacial phases, sea level rose, and the area transitioned to a shallow sea overflowing with life. Sea creatures covered the seafloor, and ancient animals swam through the warm waters. As the climate cycled through these warm interglacial and cold glacial periods, sea level rose and fell accordingly. The diverse ecosystems shifted back and forth as the animals and plants migrated along with the shoreline.

Over tens of millions of years, the heat of Earth's interior began to build up beneath the giant supercontinent. This heat caused the land to rise, and the shallow seas disappeared from equatorial Pangea's shores. Air temperatures began to rise, ice melted, and the supercontinent dried out, creating large deserts across the equator. Extreme winds ripped across the land as the climate turned increasingly hot, dry, and hostile. Salty, acidic lakes and cracked earth covered the landscape [3]. Billowing dust storms engulfed the region, and nearly all life on Earth vanished in the Great Dying. What does this look like in a core sample?

THE BOTTOM OF THE CORE: EARLY PERMIAN

Rocks at the bottom of the core from Oklahoma tell us about the beginning of the Permian period. We find layers of rock that formed in oceans, on land, and in lakes (Figure 3). These layers formed as the sea level rose and fell. We also find fossils. In rocks that formed in lakes, fossils of insects are found [4]. Although a core sample might not have the bones of an entire fish, there are many fossils of tiny sea creatures in the cores (Figure 3). These little creatures were the shape and size of a grain of rice and lived in shallow, clear water. Fossils of ancient marine animals found in the cores paint a picture of healthy and diverse ecosystems in equatorial Pangea 300 million years ago, when shallow seas were common.

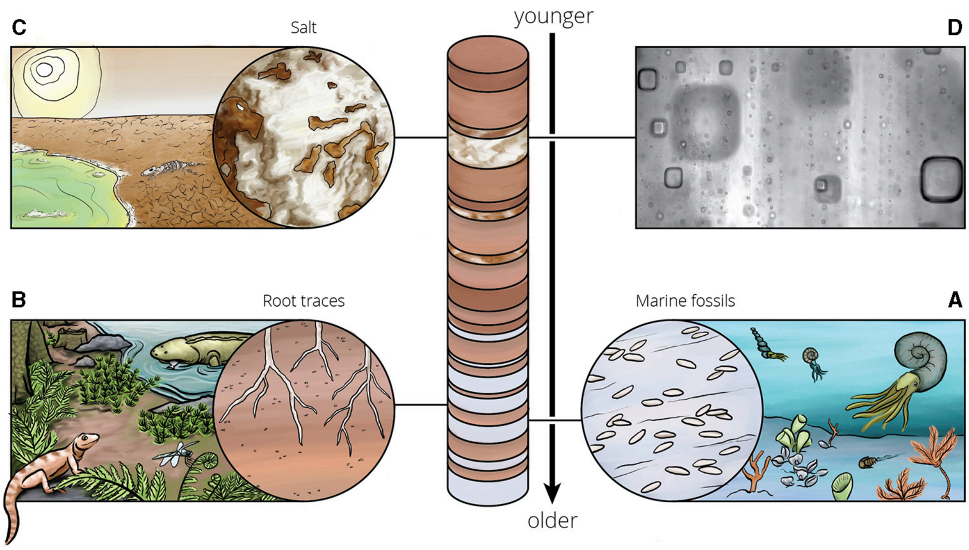

Figure 3

In a core, the oldest rock is at the bottom and the youngest is at the top. **(A)** Marine fossils from the early Permian are evidence of a healthy ocean ecosystem. **(B)** Ancient soils from the early Permian supported a diversity of insect, reptile, and amphibian life. **(C)** Salt found in later Permian rocks indicates a dry, hostile environment. **(D)** This microscope image shows the square pockets of fossil water trapped in salt that record temperatures of over 150°F!

Not all fossils are the remains of ancient animals. During the cooler glacial periods, the seas disappeared, and a different kind of fossil formed—ancient soil. **Soil** is material at Earth's surface that supports plants and other life. Traces of roots from Permian plants can be seen in ancient soils. These soils can also be identified by the **minerals** they contain. For example, ancient soils with a lot of clay suggest the area was warm and wet and could support healthy plant life (Figure 3).

SOIL

Is the uppermost layer of the Earth's surface that supports plant life.

MINERALS

Are non-living solids that have unique organized internal structures and occur naturally on Earth.

THE MIDDLE AND TOP OF THE CORE: A GRADUAL CHANGE

Higher in the cores, we see different kinds of rock. This represents a time closer to today, during the middle Permian. The marine fossils and deep soils are gone. Instead, we see minerals that form when water dries up, like salt (Figure 3). If you leave a glass of salt water out in your kitchen and wait for the water to dry out, you find crystals of salt left behind. And if you look closely enough, you might notice the salt crystals form perfect cubes.

The salt in the cores of the middle Permian formed as the region dried to become a desert, and salty lakes formed. As the salt crystals grew, they trapped tiny pockets of lake water. Because the salt grows as a cube, the pockets of water in the crystals also form cubes, which look like squares under the microscope (Figure 2). The tiny square bubbles preserve ancient water that dates from nearly 300 million years ago! Today, we can study this ancient water and learn about air temperatures when the crystals formed. From this, we know that the surface temperature reached over 73°C (163°F) during the day at the equator in this interior region of Pangea [5]!

Eventually the climate became too hot and dry for even salt to form. By the end of the Permian, only wind-blown dust is present in the cores [6]. The rocks provide a glimpse of this dusty and dangerously hot landscape in the center of Pangea.

BECOMING A GEOSCIENTIST

Project Deep Dust will collect new core samples from Oklahoma to help us learn details about how and why the climate changed during the Permian—but you do not need a giant drill to learn about Earth's past. All the rocks around you can tell stories if you learn how to read them. Learning about rocks is more than just identifying and sorting them into groups. If you become a geoscientist, you can use rocks to read the story of Earth's past—from thousands to hundreds of millions or even billions of years ago—including fossils that show how life on Earth has changed through its history. Study of the "deep" past gives us a look at the alien landscapes of ancient Earth.

ORIGINAL SOURCE ARTICLE

Soreghan, G. S., Beccaletto, L., Benison, K. C., Bourquin, S., Feulner, G., Hamamura, N., et al. 2020. Report on ICDP Deep Dust workshops: probing continental climate of the late Paleozoic icehouse–greenhouse transition and beyond. *Sci. Dril*. 28:93–112. doi: 10.5194/sd-28-93-2020

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CONFLICT OF INTEREST: AM is employed by Amiable Consulting.
The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

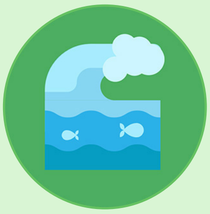
YOUNG REVIEWERS

ABDUL HADI, AGE: 13
My name is Abdul Hadi and I am originally from Syria. I love to play soccer and have been at YSA for 1 year. My favorite thing to do is to be with my friends. I also like to ride my bike and farming. In the future, I would like to become a doctor.

FATHIA, AGE: 9
I am Fathia from Syria. I love swimming and going to the gym. My favorite thing is studying and learning the English language. I also love running. I want to become a pediatrician in the future.

HADIL, AGE: 13
Hello everyone I am hadil, a young reviewer I am very interested in natural and geological phenomena that happen and I am curious to know more while remaining with positive energy.

LOUAY, AGE: 13
Hi dear, my name is Louay. I am 13 years old. I am a student in a school called "Le Giratoire". My favorite subjects are physics and chemistry. So, because I like physics and chemistry and I can speak English. Thank you for reading my biography.



MOHAMMED, AGE: 15
My name is Mohammed. I am from Syria. I love reading and practicing sports, especially soccer. Life has taught me to be active, loving, friendly, cooperative, respectful, and to avoid selfishness and lying. My goal in the future is to have higher degrees in computer science and learn all about it, and I will achieve that.

NATHAN, AGE: 11
My name is Nathan, I am in 4th grade and I like to play videogames and watch anime. When I grow up I want to be a soccer player. My favorite subject at school is math. I cannot wait to be in 5th Grade and have Science classes. My favorite color is purple, my favorite food is guacamole and my favorite animal is the white tiger.

AUTHORS

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Kat is a science and outreach coordinator who supports researchers who study the Earth by analyzing cores. She works to build community and increase access in education and the geosciences. Kat is also an artist who works with her hands, creating art using paint, wood, metal, fabric, yarn, or any other material she can get ahold of. She has degrees in science illustration, oceanography, geology, and archaeology—all of which help her support a diverse group of scientists interested in exploring the world around them. *cantn001@umn.edu

GERILYN SOREGHAN
Lynn Soreghan obtained her B.S. in geology (University of California Los Angeles), and Ph.D. in geosciences (University of Arizona) and has served on the faculty in geosciences at the University of Oklahoma since 1996. She studies sediments and sedimentary rocks as a means to shed light on Earth's climate, especially in deep time. She focuses on topics related to atmospheric dust and loess, rock weathering,

and glaciation, and is principal investigator of the ICDP-funded Deep Dust project, which aims to recover a complete record of continental paleoenvironments and paleoclimates from the equatorial Permian record of the Pangean supercontinent. *lsoreg@ou.edu

LILY S. PFEIFER

Lily Pfeifer is a professor of geology at Rowan University. Her research expertise is in sedimentology and paleoclimate. She studies ancient sedimentary basins, applying both traditional field methods and laboratory techniques to understand the climatic and tectonic processes that prevailed hundreds of millions of years ago. Broadly, her research—from Western Europe to the midcontinent U.S.—illuminates aspects of Earth's climate system that have implications for understanding present and future climate solutions.

KATHLEEN COUNTER BENISON

Kathy Benison grew up near the beach in Massachusetts, where she was interested in science and nature as a kid. She earned a B. S. in geology and chemistry from Bridgewater State College in Massachusetts, a M. A. in geology from Binghamton University in New York, and a Ph. D. in geology from the University of Kansas. Kathy is currently a professor of geology at West Virginia University, as well as a return sample selection-participating scientist for the Mars 2020 mission, and science editor for the journal Geology. She is mom to three adult children.

AMY MYRBO

Amy Myrbo loved ancient extinct mammals as a kid, and rediscovered geology while she was an English literature major in college (after being kicked out of high school). She received her Ph. D. studying lakes and lake core samples, and then helped run a coring facility at the University of Minnesota before becoming an independent consultant, helping Earth scientists get more grants with less stress (and using those English major skills)! She is dedicated to improving diversity and equity in the geosciences. She volunteers weekly at a horse rescue, wrestling hay bales and picking up poop.

BIODIVERSITY
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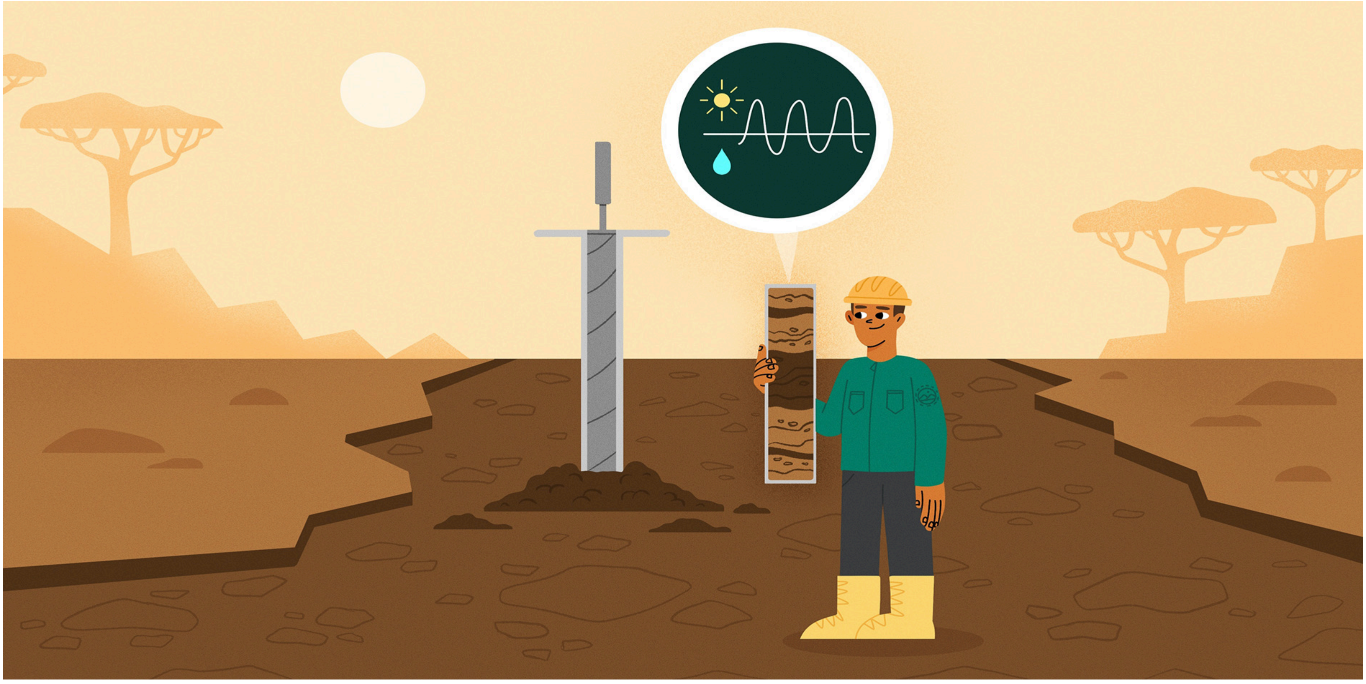

DRILLING IN AN AFRICAN LAKE TO FIND OUT WHETHER CLIMATE CHANGE DROVE HUMAN EVOLUTION

Verena Foerster**, Marine Simon and Frank Schaebitz

Institute of Geography Education, University of Cologne, Cologne, Germany

YOUNG REVIEWERS:


KARUBAKEE
AGE: 12


SEBASTIAN
AGE: 14


SHARVANI
AGE: 15

Why does drilling into a dried-out lake in eastern Africa get scientists excited? Simple answer: the lake's sediments store valuable information about how past climate change shaped the environment where our earliest ancestors lived. Those sediments serve as a natural record of Earth's ancient climate. While much is known about human evolution from fossil discoveries in eastern Africa, the role that climate change might have played for human biological and cultural evolution remained unclear for a long time. But now we have drilled 278 m into the ground at the bottom of the old Chew Bahir Lake in southern Ethiopia, which has given us some detailed answers. This natural record covers the last 620,000 years of climate history from one of the proven habitats of ancient *Homo sapiens*, and it can help us to unravel connections between climate and human evolution.

DID CLIMATE CHANGE INFLUENCE HUMAN EVOLUTION?

Did climate change in the past play a role in human evolution? To survive, our species developed incredible skills and abilities. But could the climate have had something to do with those crucial developments? To solve that riddle, we needed two components. First, we needed fossil discoveries that show what our ancestors looked like, where they hunted, and the areas they lived in. Second, we needed detailed climate information from the area where our ancestors lived [1]. But how and where could we get those two ingredients side by side?

Finding the first ingredient is easy: the Eastern African Rift is the perfect place! Archaeologists have found thousands of **hominin** fossils there. Some of them even date back before *Homo sapiens* (our species) appeared in this area [1, 2]. Scientists agree that the Eastern African Rift is an important hotspot in human evolution.

But what about the second ingredient—climate information? To get this, our team of scientists traveled to the heart of the Eastern African Rift (Figure 1), specifically to a dry lake named Chew Bahir in southern Ethiopia. We knew that Chew Bahir sediments could provide the second ingredient to solve our riddle. We could drill deep into the dried lake to get a 620,000-year record from the **sediment cores** from two deep **boreholes** (Figure 1)! Now we can decipher what the environment of our ancestors looked like and, most importantly, how it changed.

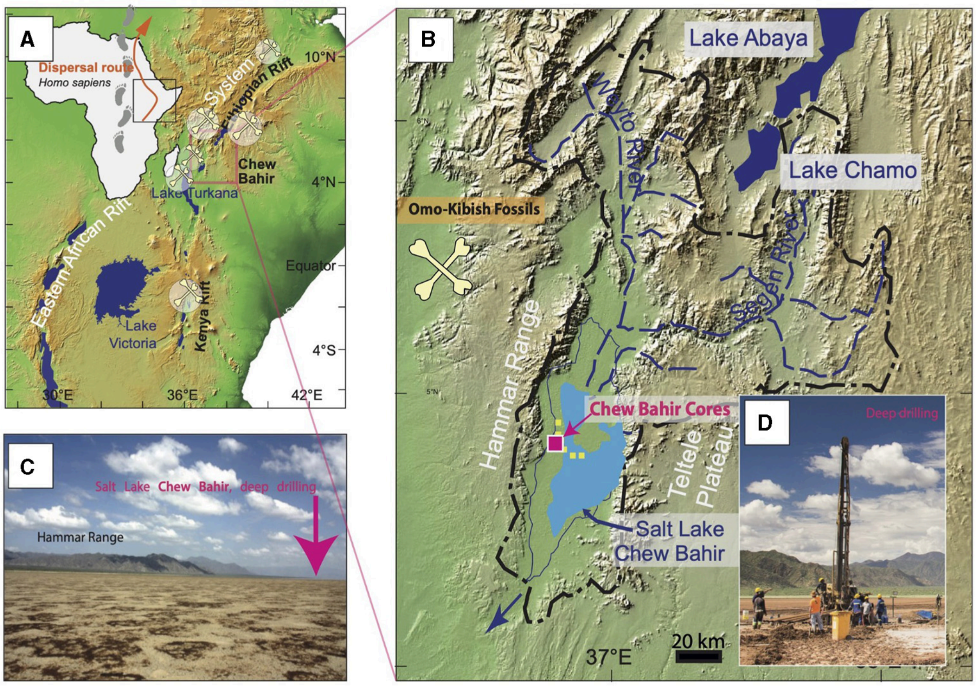

Figure 1

Figure 1

(A) Location of the drilling site amidst the Eastern African Rift System (EARS), which is home to many important fossil sites (bone symbols). The orange arrow shows the main northern route our ancestors took to populate the world. **(B)** The Chew Bahir Basin in the EARS, with the drill sites marked, where the scientists drilled 278 and 266 m into the ground of the former lake. **(C)** Today, the Chew Bahir Basin is only seasonally covered by a shallow salt lake. We cored during the dry season. **(D)** The drill rig used to obtain the long sediment cores that contain the valuable layers of sediment.

HOMININ

Our ancestors including modern and extinct humans; *Hominin* comprises the genus *Homo* that includes *Homo sapiens*, but also extinct ancestors in the evolutionary tree like *Homo erectus*.

SEDIMENT CORES

Sample of drilled up sediment layers from beneath the earth' surface, like lake floor, that captured the deposited material from the surrounding environment.

BOREHOLES

Holes in the ground that are caused by drilling and retrieving the drilled material, such as sediment cores.

HOW DO ANCIENT LAKE SEDIMENTS STORE CLIMATE INFORMATION?

Lakes like Chew Bahir are natural archives. From the moment they are formed, sediments build up at the bottom, layer by layer (Figure 2) due to erosional processes in the surrounding landscape. These erosional processes are mainly controlled by climate (precipitation, temperature, wind) and tectonics (uplift and/or sinking of the earth surface due to the earth internal power) [1]. Moreover, the vegetation growing in the vicinity of the lake produces pollen that sunk down to the lake floor and got stored there. Sediments therefore contain all kind of "proxy" information (biological, physical and chemical) about the environment and climate conditions of the past. This unique climate archive can be retrieved and interpreted through scientific drilling.

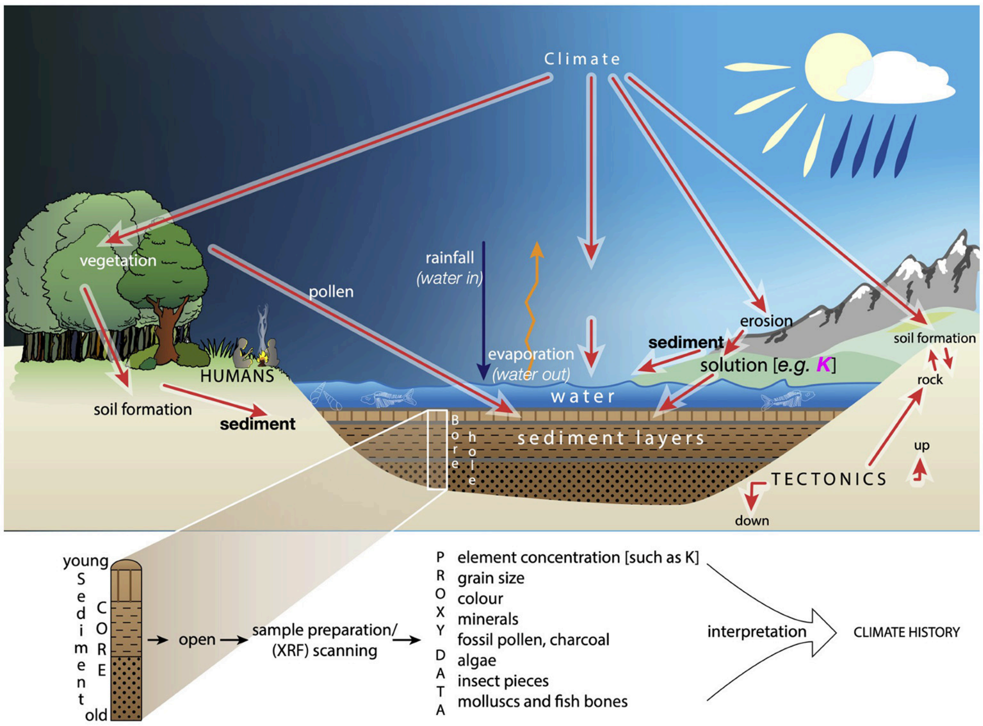

Figure 2

Figure 2

In a lake like Chew Bahir in southern Ethiopia, climate information is contained in the accumulated sediment. By scientific drilling, the sediment layers can be pulled up in sediment cores. Each section of the sediment can be cut open lengthwise and analyzed in the laboratory. Scientists can read the proxy data from the cores and use it to interpret patterns of climate change from the past (Figure idea by F. von Reumont).

Scientific drilling can be extremely challenging. To get sediment cores for our study, we first had to find a suitable lake and a good spot to drill deeply. Second, Chew Bahir is far away from cities, streets, running water, and electricity. We had limited time, and the entire team had to camp in the dried-out basin. So, it was quite an adventure! But our team managed to drill to depths of 278 m and 266 m by drilling day and night for 6 weeks [1]. We pulled up the sediment cores in sections that were each about 3 m long. The sections added up to about 500 m of core, weighing 3 tons! After transport to the lab, the sections were split open lengthwise for study.

"READING" MINERALS OR FOSSILS TO UNDERSTAND PAST CLIMATE

PROXIES

Indirect evidence, in this case in the biological, physical, and chemical indicators found in sediment cores, that can help scientists reconstruct past climate conditions and changes over time.

DROUGHT

A phase when climate conditions are very dry for many months or years.

X-RAY FLUORESCENCE

A geochemical measuring technique that uses X-rays to determine the contents of chemical elements in a sample.

Lake sediments contain numerous climate **proxies**. Proxies are materials in the sediment that can be analyzed to get information about the environmental conditions at the time that they were deposited into the sediment (Figure 2). These proxies are, for example, the colors and composition of minerals, or microfossils like small crabs, algae, or pollen. Such proxies are extremely useful for reconstructing environmental history.

Potassium is the climate proxy superstar of Chew Bahir [3]. Potassium is one of 80 elements that naturally exist on Earth, and is represented by a K in the periodic table of elements. It is an important nutrient for plants. Potassium can also be used to trace past climate changes in salt lakes like Chew Bahir. When water evaporates from the lake, the lake level drops and the remaining water gets saltier. The chemical reaction that traps potassium in the sediment goes faster in saltier water. This results in higher amounts of potassium in the sediment minerals. So, high potassium values in Chew Bahir indicate intense **droughts**. During those dry phases, Chew Bahir shrank to small, salty puddles. Sometimes it vanished completely. Thorny shrubs and grasses replaced most plants. In contrast, low amounts of potassium in the sediment cores point to phases with lots of rainfall, which resulted in deep lakes with lush vegetation.

So, if we know the amount of potassium, we can decipher climate history! To measure potassium in our sediment cores, we used a technique called **X-ray fluorescence** (XRF). X-rays scanned each sediment core section, similar to looking for a broken arm in the hospital. We measured every 0.5 cm of the cores with a special XRF scanner, which gave us more than 50,000 data points! Each point told us how much potassium was in each of the measured 0.5 cm. From those potassium values, we could infer the related climate conditions at that time.

TRACKING DOWN PAST CLIMATE CHANGES IN COMBINATION WITH HUMAN EVOLUTION

We could then combine the two ingredients we mentioned earlier—information about human evolution and what we knew about the region's climate thanks to our drilling. Two things really matter when interpreting all this information. First, the intensity of the climate change is important. How wet or how dry did it get? Such conditions would mean the presence or absence of vital resources for humans, such as food and water [2]. Second, the timescale of climate change is crucial. It makes a huge difference if the environment changes a bit every year or drastically all at once [2].

Looking at the 620,000 years of eastern African climate, we can see that climate changes did not always follow the same patterns. We identified three patterns of **climate variability**. In Figure 3, you can see phases with sharp shifts (Phase I), soft swings (Phase II), and frequent flickers (Phase III). To figure out when the pattern of change kicked into a different phase, we used mathematical analyses. Remarkably, each phase almost coincided with key developments in human evolution (Figure 3) [4]! Starting with the oldest part of the Chew Bahir climate record (Phase I), we saw wet and rather stable climate conditions. However, this stability was interrupted by dramatic, extreme dry periods. What did this mean for our ancestors? They were probably isolated into small groups of tough survivors. Fossils found in the area reveal a remarkable diversity in hominin groups during those times. Archaic tools mostly used by our earlier ancestors also started to disappear during Phase II, and tools common to the Middle Stone Age started to appear. We know that these tools were typically used by our species, *Homo sapiens*, so this was a clear hint that *Homo sapiens* emerged on the scene during this phase.

CLIMATE VARIABILITY

Changes in atmospheric conditions, including temperature, precipitation, and wind patterns, over time periods ranging from several months to millions of years.

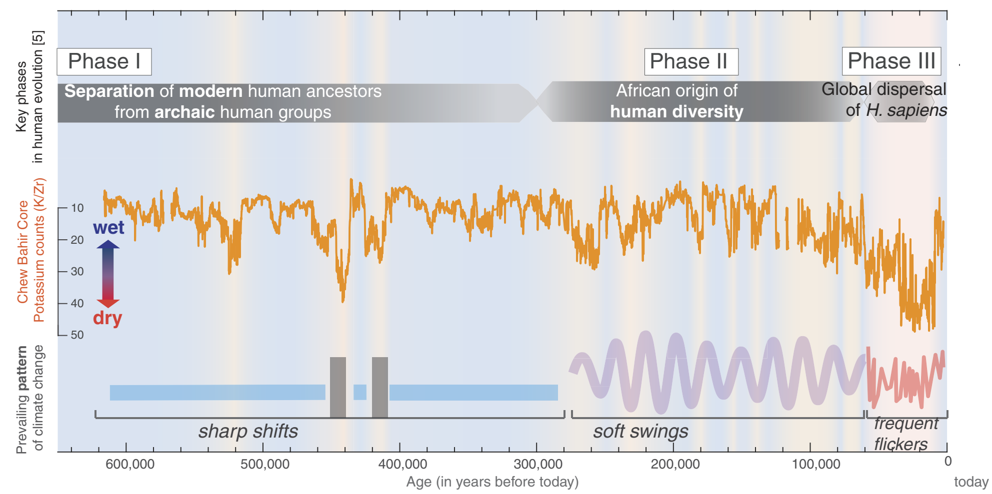

Figure 3

Figure 3

We combined what is known about human evolution from key fossil and archaeological findings with our climate record from Chew Bahir, based on potassium amounts in the sediment cores, which tell us whether the climate was wet (low quantity of potassium in the sediment) or dry (high quantity of potassium in the sediment). Importantly, we identified changes in the pattern of climate change and what these changes could have meant for our ancestors' living environments. The key phases of human evolution [4] roughly fit the identified changes in climate patterns.

Around 275,000 years ago, the soft swings between wet and dry climate started to intensify. This meant that living conditions in Phase II were changing more quickly—too fast for biological evolution to keep pace! New survival strategies were needed instead. To adapt, our ancestors had new ideas for tools and they organized into groups. This was the time of cooperation, cultural advances, and long-distance material transport.

Phase III, frequent climate flickering, started to kick in about 60,000 years ago. In this phase, there were super dry extremes interspersed with a long-term drying trend. How did our ancestors manage to survive those extremely difficult conditions? Getting more and more smarter and social since the previous phase may have saved them. Phase III is also the time when our ancestors dispersed into the rest of the world, and climate flickers might have been responsible. During short, wet phases, green corridors opened up across the deserts, into Arabia [4]. Those green pathways were like the gate beyond the African continent. During short, dry flickers, our ancestors moved to higher and greener mountain areas. Archeological findings there confirm that this was a successful strategy.

SO, DID CLIMATE CHANGE DRIVE HUMAN EVOLUTION?

We must remember, however, that human reactions are not entirely controlled by climate change. Many other factors influence our decisions, including our free will! So, there is not always a direct relationship between climate change and human evolution [5]. Our Ethiopian sediment cores show, however, that there are several patterns and levels of climate change. These important patterns range from climate chaos, with extreme flickers between desert and wetlands, to transitions that took thousands of years. The changing patterns gave our ancestors various options for dealing with their environment.

The response of our ancestors to climate changes depended on how much time they had to adapt. Long-term climate transitions occurred over several thousands of years, representing many human generations. Biological evolution also takes many thousands of years. Short-term flickers might have occurred even within a single human lifetime, causing people to respond within shorter time scales, for example by moving around and adapting their cultures. Overall, we can state, that climate changes in the past had an influence on human evolution and dispersal by setting the environmental frame and therefore creating new challenges in which human cultures could develop.

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ORIGINAL SOURCE ARTICLE

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KARUBAKEE, AGE: 12

I like to read about space related facts and am highly interested in knowing about the world history. I also like to read fantasy books and listen to music.

SEBASTIAN, AGE: 14

I like sports, reading, math, physics, and all things space!

SHARVANI, AGE: 15

The intricacies of the human body have always fascinated me, sparking my interest in pursuing a career in medical research. I take pleasure in delving into research articles spanning from environmental studies to human anatomy. I am convinced that there are countless unexplored phenomena waiting to be uncovered in our surroundings.

AUTHORS

VERENA FOERSTER

I am a geographer and enthusiastic mud-lover at the Institute of Geography Education at the University of Cologne, where we also train future geography teachers. I am fascinated by ancient mud as, in addition the excitement of deep drilling campaigns, the old lake sediments give us the unique opportunity to reconstruct the climate of the past. I completed my Ph.D. in physical geography, exploring how climate change and human evolution have been connected. My research concentrates on the development of climate proxy tools and discovering ways to wrap new research insights into learning material. *V.Foerster@uni-koeln.de

MARINE SIMON

I am a geographer, researcher, and teacher at the Institute of Geography Education at the University of Cologne. After being a geography and history teacher for young students in France, I moved to Germany. I started to work on how children learn geography and how we can help them learn new things better, such as climate change or migration. I am also passionate about how to make science and scientific methods understandable for children and for future scientists! In my free time, I like hiking, traveling, and playing music.

FRANK SCHAEBITZ

I am a former geography professor at the Institute of Geography Education at the University of Cologne. My specific scientific interest is to reconstruct past environments to understand recent and possible future developments. Due to my study of biology and geography, I always tried to bring both sciences together. Since my time as a student I have been fascinated by the evolution of our own species. This interest grew even more when, as a researcher, I could participate in scientific projects investigating human development and spread from Africa to Europe. This was only possible through great cooperation with an international team of specialists.

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UNRAVELING THE SECRETS OF LAKE OHRID, EUROPE'S OLDEST LAKE

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Lake Ohrid is located on the border of Albania and North Macedonia. It is believed to be the oldest and most biodiverse lake in Europe. Several hundred meters of sediments have built-up on the lake bottom since its formation. These sediments are a record of what happened both within the lake and in its environment in the past. Therefore, Lake Ohrid is a unique place to learn more about Earth's history. Drilling down into the lake bottom to get samples of sediment layers allowed us to unravel the secrets of the lake's history. The sediments revealed that the lake formed between 1.9 and 1.4 million years ago. They showed past environmental and climate changes in the Mediterranean region. Tiny fossils showed the evolution of the lake's biodiversity in the past, which benefitted from the lake's long and stable existence. The stability of Lake Ohrid's ecosystem is now threatened by increasing human impacts. Protecting this unique place is needed.

WHAT CAN LAKES TEACH US ABOUT THE PAST?

Lakes are found all over the world in many landscapes and climates. The environment of a region has a strong influence on the processes that occur in its lakes. One process is the build-up of particles, called **sediment**, on the lake bottom. Sediment can consist of mineral particles that enter or form in the lake, as well as the remains of plants and animals. The layers of sediments that form over time, from bottom to top, are like a history of past lake processes—lake sediments are a natural archive describing past environmental conditions in a region. Scientists study sediment layers to understand what processes happened in the lake since its formation.

SEDIMENT

Particles of rocks, soil, or other material like plants that are transported by water or wind and accumulate, for example, at the bottom of a lake or the ocean.

By unraveling how the lake's environment has changed, scientists can also learn how the climate has varied in the past. For example, the types and amounts of minerals in the sediments can tell a story about the erosion around the lake. Changes in erosion can be related to climate conditions, such as the frequency and amount of rainfall. Specific minerals can also reveal changes in the source and amount of lake water. Scientists investigating minerals in the sediments can, for example, reconstruct if the water level dropped in the lake when rainfall was scarce. Fossils of plants, tiny shells, and skeletons of animals found in the sediment can tell us about the species that lived in the lake. As species adapted through time to various environmental conditions in the past, their fossils now tell us about changes in the climate.

THE SCOPSCO PROJECT—STUDYING LAKE OHRID'S SEDIMENTS

Lake Ohrid is located in the central Mediterranean region, on the border of Albania and North Macedonia. The lake is about 30 km long, 15 km wide, and up to about 290 m deep (Figure 1). Lake Ohrid has many **endemic species** which live only in this lake. Their high number indicates the long existence of the lake. Lake Ohrid is thus one of the few lakes worldwide that allow us to study how the environment and the life in the lake developed. Scientists from several countries started a joint project to investigate the lake and its sediments. The project is called Scientific Collaboration on Past Speciation Conditions in Lake Ohrid (SCOPSCO), and it focuses on many questions, such as: *How and when did the lake form?*; *What can we learn from the sediments about the past climate?*; *How did species develop within the lake?*; *What can we learn about the future from our observations of the lake's past?*

ENDEMIC SPECIES

Species found only in a single defined place and nowhere else on the planet.

A **hydro-acoustic survey** was performed to find the best spot to drill down into the sediments. This survey showed a view of the underground sediment structures for the first time [3]. In places where the sediment structures are undisturbed, scientists can obtain

HYDRO-ACOUSTIC SURVEY

A technique that uses sound waves to create a picture of underground structures.

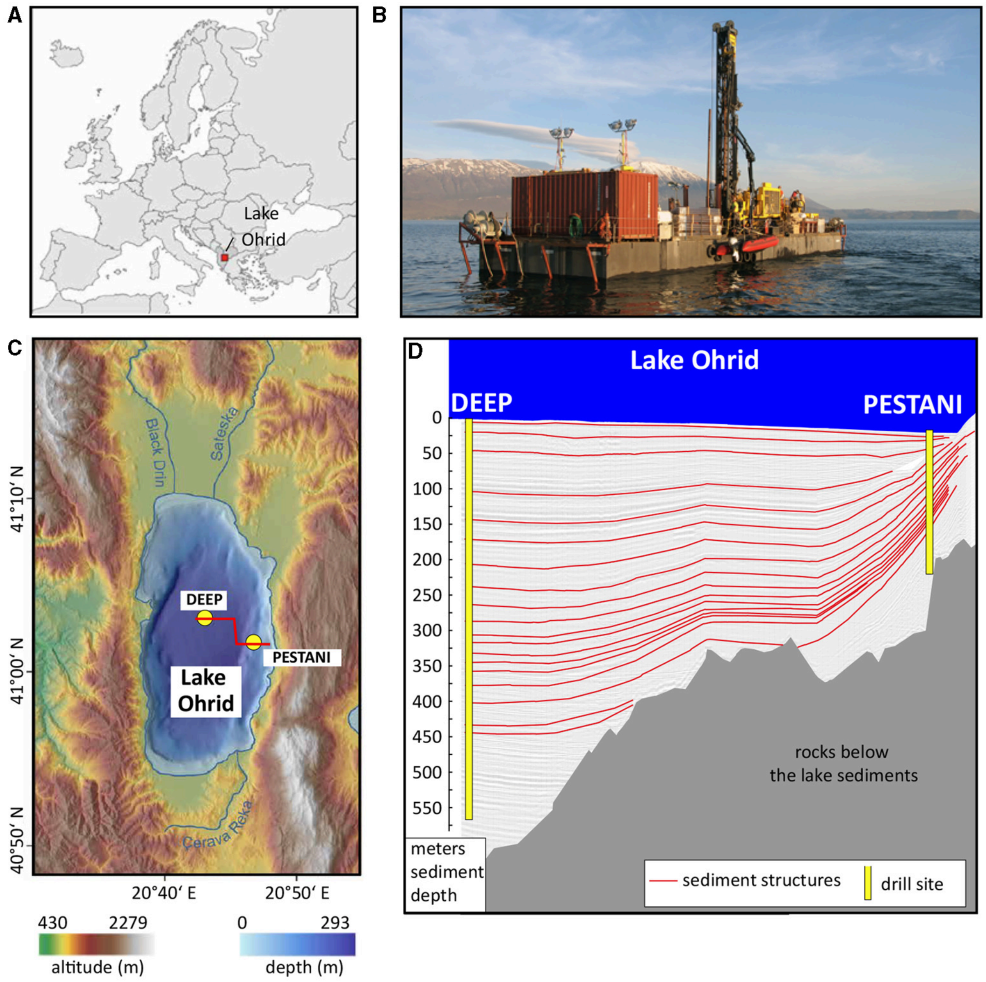

Figure 1

Figure 1

(A) Location of Lake Ohrid within Europe and **(B)** drilling platform used for recovering the lake sediments. **(C)** Map of the lake showing the location of the hydro-acoustic profile (red lines) and the drilling sites (yellow spots). **(D)** The results of the hydro-acoustic profile show undisturbed sediment structures (red parallel lines) at the drill sites DEEP and Pestani. **(A, C)** were modified from [1] and **(D)** was modified from [2].

a complete record of the lake's history (Figure 1D). A team of about 30 scientists from several countries, along with professional drillers, drilled the lake's sediments in 2013. The deepest drill hole (DEEP site) reached 569 m below the lake floor, in the center of the lake [2, 4]. All sediments deposited since the lake's formation were recovered there. Drilling produces long cylinders of sediment called **cores**. Sediment cores were opened lengthwise and analyzed to study sediment layers (Figure 2A). Sediment samples were sent to researchers around the world for detailed analysis. They analyzed the size of sediment grains as well as the elements, minerals, and evidence of living things to understand sediment formation and past environmental conditions.

CORES

Cylindric-shaped pieces of rocks or soil which can be retrieved by drilling into the Earth's underground.

HOW AND WHEN DID LAKE OHRID FORM?

Dating of old sediments in lakes is challenging. One way to do so is to use known past environmental events, like volcanic eruptions. Eruptions can leave ash deposits that make their way to the sediment.

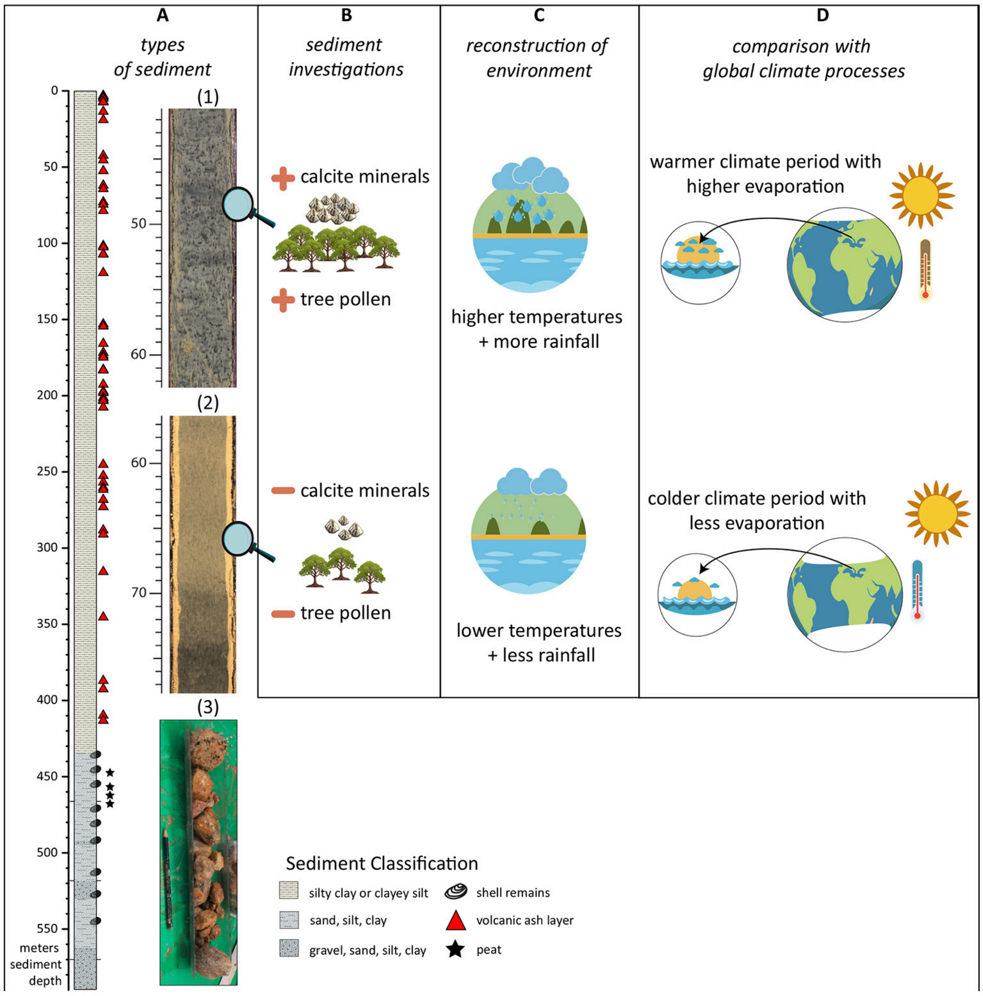

Figure 2

Figure 2

(A) The sediments drilled in Lake Ohrid have different grain sizes, volcanic ash, shells and peat layers. Pictures (1–3) show different types of sediments. Before the lake formed, coarse grained sediments from ancient rivers were deposited (picture 3). When a bigger lake formed, the sediments became more fine-grained (pictures 1–2). The sediments revealed information about the past environmental and climatic conditions. If sediment investigations showed higher (lower) amounts of calcite minerals and tree pollen **(B)**, the local environment experienced more (less) rainfall and higher (lower) temperatures when the sediments were deposited in the lake **(C)**. **(D)** Shows the global climate during these times.

The exact composition of an ash layer in the sediment can reveal which volcanic eruption it came from. If scientists know the date of that eruption, they can use that info to date the sediment layers. The sediment record from Lake Ohrid contained 16 layers of ash from known, dated volcanic eruptions [5]. Another event that can be used for dating is a change in Earth's magnetic field. Such events were identified in the Lake Ohrid sediments, which provided additional information on the age the sediment. More age information came from variations in sediment composition. All age information was combined to calculate a specific age for each sediment depth [4].

Sediment data provided unique information on the age and origin of Lake Ohrid [2, 4]. Hydro-acoustic data suggest that the formation of Lake Ohrid started with a narrow valley. The lowermost sediments obtained by drilling documented the earliest phase of the lake, which began around 1.9 million years ago (Figure 2). The sediments consisted of small, rounded rocks and smaller gravel, which indicated that a river drained the valley. Toward the top, finer-grained sediments and occasional layers of plant material called peat were found, along with shell remains. This tells us that the narrow valley eventually widened, and a series of small ponds formed in the valley. Fossil algae and specific compositions of minerals suggested that these ponds were partially connected, but they existed for only a short time. The valley continued to widen, and at 1.36 million years ago, a permanent, larger lake developed and has existed since then [2, 4]. Now we know that Lake Ohrid is 1.36 million years old!

PAST CHANGES IN MEDITERRANEAN RAINFALL PATTERNS

The sediments of Lake Ohrid are a natural record of 1.36 million years of environmental change. Natural records of similar age are extremely rare. The sediment compositions tell us that the climate varied over time [4]. Changes in amounts of some minerals, such as calcite, as well as variations in the amount of tree pollen, are related to the amount of rainfall. Looking for these changes in the sediments can help us determine past rainfall patterns. The data suggest that rainfall increased during specific warm periods (Figure 2). During these periods, the position of the Earth relative to the Sun caused the planet to receive more solar energy during summer. This warming period increased the temperature of the Mediterranean Sea, leading to increased evaporation and moisture in the atmosphere. Thus, more clouds formed and increased the rainfall over Lake Ohrid.

HOW HAS BIODIVERSITY EVOLVED IN LAKE OHRID?

One of the most exciting questions in biology is what drives the evolution of new species and the disappearance (extinction) of existing species. Fossils of tiny algae from the sediments of Lake Ohrid can help scientists answer these questions [1]. Formation and extinction of species can be directly compared with the rate of environmental changes recorded in the sediments. This made it possible to determine the effects of these environmental events on the evolution of the lake's species. The fossil record shows that new species evolved within a few thousand years after the lake's formation, indicating a very rapid **adaptation** of these new species to the Lake Ohrid ecosystem (Figure 3). However, during the early, shallow phase of the lake, environmental conditions like temperature, water level, and nutrients changed very rapidly. As a result, many new species died out as quickly as they emerged. Once the lake reached stable, deep water conditions, **species richness** stabilized (Figure 3C). This stability was achieved by two processes. First, fewer new habitats were created as the lake stabilized, so the evolution of new species also decreased (Figure 3D). Second, the extinction rate decreased as the size and depth of the lake increased, protecting organisms from environmental changes (Figure 3E). These new findings could explain the extremely high species richness in Lake Ohrid.

ADAPTION

Ability of an organism to change to new conditions.

SPECIES RICHNESS

Number of species present in a specific area or ecosystem.

Figure 3

(A) Shows three intervals (gray shapes) of the evolution of Lake Ohrid during the past 1.7 million years (Ma). The basin was first characterized by rivers and small ponds (A1). Starting about 1.4 Ma ago, a larger lake developed (A2, A3). **(B–E)** Show how species developed after a permanent lake had formed and slowly got deeper. Microfossils found in the sediments show that new species evolved and died out rapidly in the shallow lake (A2). As the lake deepened, speciation and extinction rates became very similar and remained similar over a long period of time (A3). Figure based on [1–3].

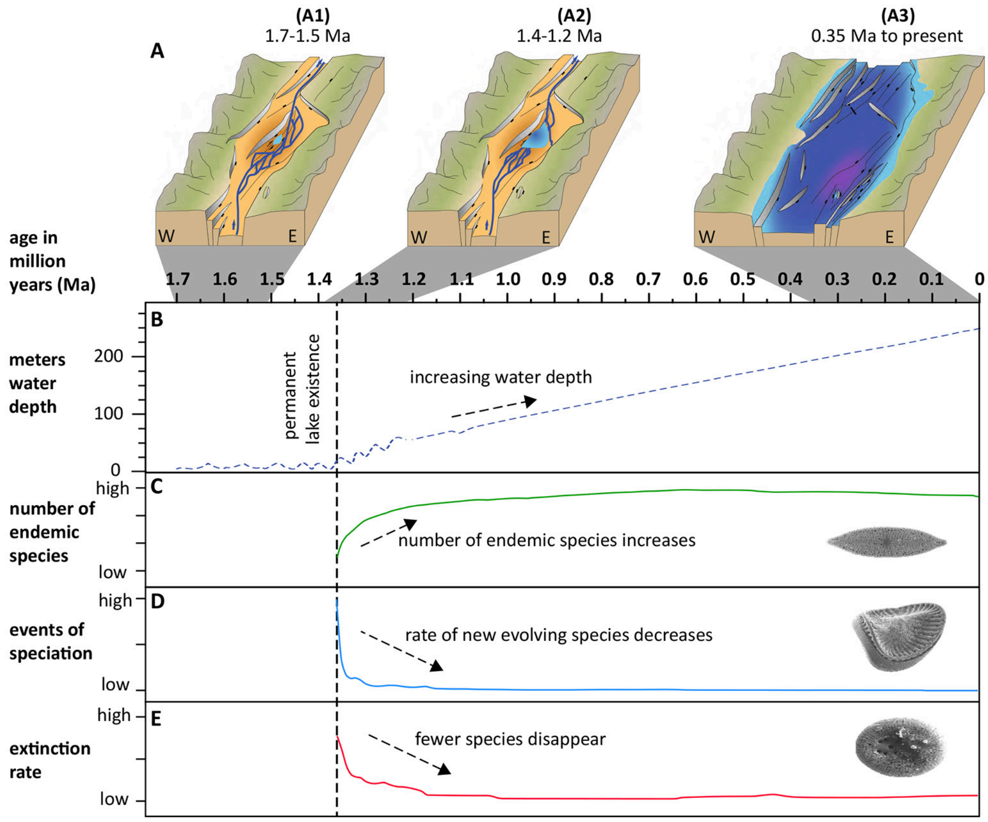

Figure 3

WHAT HAVE SEDIMENTS TAUGHT US ABOUT THE FUTURE?

CLIMATE MODELS

Computer calculation of how the climate and its parameters behave according to several factors, such as temperature, rainfall, or wind.

BUFFER CAPACITY

The ability to maintain stable conditions, even under changing external conditions, which is helpful to protect living things.

Scientists use **climate models** to make predictions about future climate change. These climate models need a good understanding of the ocean and atmosphere processes involved. We can learn about these processes by studying sediments which tell us about how these processes influenced the climate of the past. Information from Lake Ohrid sediments showed that the environmental causes of extreme precipitation in the past were similar to modern processes. This is important to know because it is difficult to understand how future precipitation will change based on the current climate models. Information about the change in precipitation is of great interest to the people living around the Mediterranean Sea because the winter rainfall of this region affects the types of plants that can grow there. The Lake Ohrid's sediments also allowed us to study how life developed after its formation. Once Lake Ohrid was established as a permeant lake, its high **buffer capacity** protected species from many natural environmental changes, such as climate change. However, the increasing human activities in and around Lake Ohrid threaten this balance. An imbalance could cause many of the lake's endemic species to go extinct.

In summary, studying the sediments of Lake Ohrid uncovered past environmental processes from which we can learn how the climate system changed and how the environment has responded to these changes. This helps us to prepare for future changes and to develop plans to protect the environment.

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Julia is a 12 year old student at Fairfield Wood Middle school. She enjoys learning about the world. Her passion is music and she plays several instruments, writes songs, and jams with her friends. She loves her dog Joy that never refuses a hug.

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Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she's at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

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Sebastian is a marine geophysicist at Kiel University. He mainly studies underground structures of sediments in the oceans to analyse geohazards and sediment transport processes that shape the structure of the seafloor. To do this, he uses various acoustic systems such as a variety of echo sounders. The same systems can also be used in lakes, and so lakes became another area of interest for Sebastian. When he is not at sea or on a lake, Sebastian enjoys playing team handball, cycling, and hiking. He is also a youth team handball coach.

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HOW DO ORE DEPOSITS FORM?

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YOUNG REVIEWERS:

AVA
AGE: 14

ISA
AGE: 15

MOMO
AGE: 11

SEAN
AGE: 15

Ore deposits are masses of ore (rocks rich in metal) that are mined to obtain the metals needed for the machines and devices we use in everyday life, but how do ore deposits form, and where do we find them? Nowadays, recycling supplies some metals but by no means all of them, and not in sufficient amounts. So, for many years to come, we will continue to depend on ore deposits. To improve the chances of finding new deposits, geologists need to understand what processes concentrate metals into ores. This is the goal of scientific research on ore formation, and the best method is to drill boreholes through a deposit to obtain a continuous series of rock samples—drill cores—from top to bottom. The Bushveld drilling project in South Africa is described here as an example. This project targets the world's largest ore deposit of platinum, a key metal for green energy technologies.

INTRODUCTION

This article describes what ore deposits are and how they form. There are still many open questions, and this is a hot research topic because all the metals we depend on for everyday life come from ore deposits. The demand for metals keeps increasing as the world's population grows and we shift from fossil fuels to environmentally friendly **green energy**. Recycling helps supply some metals but not enough to satisfy the demand [1]. Figure 1 shows supply and demand curves for platinum, a high-value metal in great demand for green energy technologies. These are just predictions but according to the plot, the supply of platinum from mining and recycling will not meet the rising demand. This means we must either increase the supply—by finding new deposits or through better recycling—or reduce the demand.

GREEN ENERGY

Green energy describes energy that comes from renewable sources like wind or solar power.

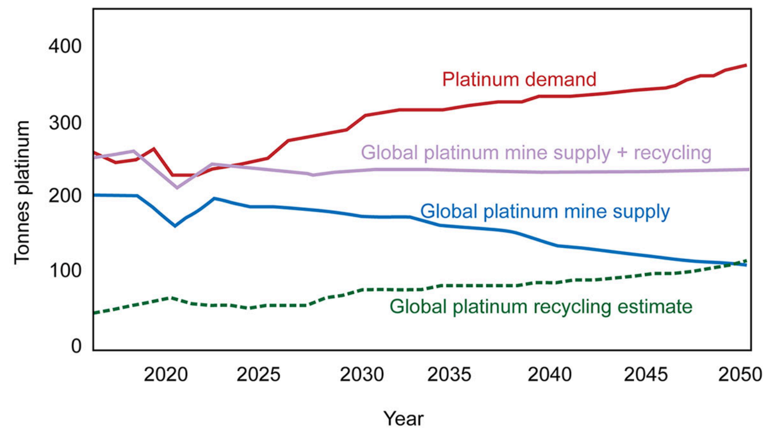

Figure 1

Figure 1

Estimated supply and demand curves for platinum. Platinum supplies from mining (blue) and recycling (green) are combined to create the violet curve. According to these curves, platinum demand (red) will exceed supply soon, unless mining or recycling are increased or the demand for platinum is reduced [Figure adapted from this website and used with permission; platinum demand data from [3]].

WHAT ARE ORE DEPOSITS?

Ore deposits are places on the Earth where geologic processes have concentrated metals enough that we can mine them efficiently. The metals in most ore deposits were originally dissolved and transported in fluid deep in the earth, often over long distances, before crystallizing in the form of solid ore. Also, very few metals exist in their pure form in nature. Gold is an exception, but almost all others combine with elements like oxygen, carbon, or sulfur to form what we call ore minerals. After mining, ore minerals must be processed to obtain the pure metal. Processing uses lots of energy and water, and the leftover materials must be recycled or stored in waste dumps. These are negative aspects of mining.

There many kinds of ore deposits [1], so this article describes just the two that are the most important source of metals for green energy technologies. They are called hydrothermal and **magmatic deposits**, and the difference between them is the way metals are dissolved and transported. In **hydrothermal deposits**, metals are dissolved in hot water (think of hot springs), but in magmatic deposits, metals are carried in liquid molten rock called magma (think of lava).

MAGMATIC DEPOSIT

An ore deposit formed by crystallization from a magma.

HYDROTHERMAL DEPOSIT

An ore deposit formed by crystallization from a hydrothermal fluid.

POROUS

A material is said to be porous when it contains open spaces or pores, like a sponge.

Hydrothermal deposits are often found in quartz veins that fill open cracks in rocks (Figure 2). Hydrothermal ores were transported by hot fluids circulating in the Earth, so it is easy to see why they are found in cracks and fissures like this vein. But hot fluids can also permeate (soak through) **porous** rocks like sandstone or limestone. This process forms hydrothermal ores that are spread out through the porous rocks.

Figure 2

Figure 2

Co-author Marta Codeço in front of a hydrothermal quartz vein (wide white stripe through the rock) in the Panasqueira mine, Portugal. This mine is the second-largest source of tungsten in Europe (Photo credit: Robert Trumbull).

Magmatic deposits contain metals that were transported by molten rock called magma. Most people know magma as lava flowing from a volcano, but it forms deep in the Earth. The melting temperature of rocks is around 1,000°C, but the exact temperature depends on the minerals that the rock contains. If melting minerals contain metals, they are released into the magma. Since magma is liquid and usually less dense than solid rock, it flows upwards through the crust. Sometimes magma erupts at the surface as lava or volcanic ash. But deep beneath every volcano, there is a reservoir of magma called a magma chamber. Ore deposits can form in both the surface environment and in magma chambers, as explained below.

HYDROTHERMAL FLUID

The term literally means hot aqueous fluid, generally water rich in dissolved salt and minerals at temperatures from 200 to 500°C.

SOLUBILITY

This term describes how much of a substance can be dissolved in another.

HOW DO HYDROTHERMAL ORE DEPOSITS FORM?

Hydrothermal deposits form by the interaction of hot water, called **hydrothermal fluid**, with rocks. Hydrothermal fluids are between about 200 and 500°C, and they react chemically with the rocks they pass through, causing minerals in the rocks to dissolve and releasing metals into the fluid. Exactly which metals and how much of them dissolve depends on the **solubility** of the minerals that contain them.

For example, rock salt is a mineral that is very soluble in water, even at room temperature. Other minerals like feldspars and micas are much less soluble than salt, but they can dissolve at high temperatures, releasing metals like lead, iron, titanium, tin, and lithium into the hydrothermal fluid.

Once they are dissolved, metals can move for long distances through cracks and pores. Ore deposits form when the metals come out of the solution again and crystallize as ore minerals. **Crystallization** often happens when the hydrothermal fluid flows into colder rocks and cools—think of rock candy growing from a sugar solution. Other processes like boiling, reaction with oxygen, or changes in pH can also cause crystallization. Geologists study ore deposits in detail to find out what caused the ore minerals to crystallize where they did. This knowledge helps them decide where to look for more.

CRYSTALLIZATION

The process of forming crystals by transformation from liquid to solid or by exceeding the limit of solubility.

HOW DO MAGMATIC ORE DEPOSITS FORM?

Magmatic ore deposits form by melting minerals in deep rocks, transporting the metals upwards in the liquid magma, and crystallizing the ore minerals to form a deposit. There are two places where this crystallization happens. One is near or at the surface of volcanoes. Because the pressure is very low, bubbles form in the magma—think of opening a bottle of a fizzy drink. This process is called **degassing** (loss of gas), and it releases water vapor, carbon dioxide, and sulfur into the air. Degassing is why some volcanoes have a plume of "smoke" (really steam) above them, and why they stink of sulfur. Degassing can form ore deposits because the hot fluids released contain metals. Technically, these are hydrothermal deposits because they form from hot fluids. However, because the fluids come from magma, we use a special term: magmatic-hydrothermal. Much of the world's copper comes from magmatic-hydrothermal deposits. The crystallization of ore minerals from magmatic-hydrothermal fluids follows the same processes just described for hydrothermal deposits.

DEGASSING

The process of losing gas from a solution by exceeding the limit of solubility, like CO_2 released from carbonated water.

The second place where magmatic ores form is in magma chambers. These are located deep enough (several km down) that magma cools slowly—over hundreds or thousands of years. This gives time for ore minerals to crystallize and separate from the liquid magma by floating or sinking within the chamber. If the crystals form layers, the metal content in the layers can be high enough for mining (Figure 3). Thus, ore formation in magma chambers is all about crystallizing ore minerals and concentrating them into mineable deposits. Many factors play a role here. The temperature and composition of magma determine which minerals crystallize and when. The density determines if crystals sink or float. The magma fluidity affects how fast the crystals separate. And the cooling rate determines if there is enough time for crystals to settle into layers before the magma solidifies. Geologists must understand these factors to find new deposits.

Figure 3

Figure 3

Rock outcrops containing magmatic chromium ore (black layers) in the Bushveld Complex, South Africa. The ore layers contain about 50% by weight of chromium metal. They formed by crystal accumulation in a magma chamber (Photo credit: Wikimedia Commons, CC-BY-2.0).

WHY IS SCIENTIFIC DRILLING IMPORTANT?

It is uncommon to find ore deposits exposed on Earth's surface. Usually, they are at least partly covered by grass, trees, snow, or desert sand, or they may be deeply eroded. So, to study ore deposits in detail, there is nothing better than drilling into the Earth and pulling up a cylinder of rock called a **drill core**. Drill cores are thin (typically 5–10 cm in diameter), but they can be hundreds or even a few thousand meters long. Furthermore, many drilling projects make more than one hole, so they can get a 3D record of the rocks beneath our feet.

DRILL CORE

A cylinder of rock extracted from the ground by drilling. Drill cores are usually 5–10 cm thick and from several hundred meters to over 3,000 m long.

A detailed 3D record of ore deposits lets geologists search for features in the ores and the surrounding rocks that give clues to the ore-forming process. Examples are cracks and porous zones in the rock, changes in color or texture, and changes in the type and abundance of minerals. The next step is to take samples to the laboratory and determine the metal content and the kinds of ore minerals present. Drill cores are ideal for chemical and mineral analyses because they are "fresh from the ground," unaffected by years of weathering and erosion at Earth's surface.

The International Continental Scientific Drilling Program (ICDP) is a multi-national organization that provides money and technical advice to research projects that use drilling for scientific research. The largest ICDP project to study ore deposits is the Bushveld Drilling Project (BVDP) in South Africa. The target of the BVDP is the world's largest magmatic ore deposit of platinum and related metals [2]. These metals have many applications, and a surge in demand is expected for green-energy technologies [3]. The Bushveld platinum ores are found as layers in an ancient, now rock-solid magma chamber (Figure 3). No one knows exactly how these layers formed, and the only way to find out is to study them in detail, together with the rocks above and below. When completed in 2024, the BVDP project will have collected more than 10 kilometers of drill cores through the magma chamber and its ore layers. This collection of drill cores will be studied by international teams of geologists to work out how the ore layers formed. If we can answer that, it will be easier to find other platinum deposits in the future.

LOOKING AHEAD

Platinum is one of several metals that are essential ingredients for environmentally-safe sources of energy, so our future depends on an adequate supply. More and better recycling is going to be part of the solution, but ore deposits will be the main source of metals for many years to come. As today's deposits are depleted by mining, new ones must be found. Scientific research plays a key role here, because the Earth is a big place and knowing where to find new ore deposits requires understanding how they form.

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YOUNG REVIEWERS

AVA, AGE: 14

Hi I am Ava, I am 14 years old and I live in Australia. I am interested in languages, medicine and music. My favorite subjects at school are Italian and Biology. I would like to pursue a career as a surgeon some day. My hobbies are reading, playing piano, traveling and listening to music.

ISA, AGE: 15

Hi I am Isa, 15 years old and I like reading books and math. I also enjoy computer science and little bit of geology. I live in Florida (North America). My hobbies are cooking (rice, arepas, and pasta), baking (cakes and cookies) and writing (fantasy and plays). My favorite animal are koalas because they are cute and they have nice ears.

MOMO, AGE: 11

Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she is at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

SEAN, AGE: 15

Hi I am Sean, I am 15 years old and I live in Australia. I enjoy school and love to play sport, especially soccer. My favorite teams are Liverpool, North Melbourne and Manly, and my favorite subjects at school are maths, psychology and P.E.

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EARTH SCIENCES
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DRILLING INTO THE EARTH: HOW DEEP CAN WE GO?

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YOUNG REVIEWERS:

LEAF
AGE: 9

MOMO
AGE: 12

Drilling into the Earth is important for collecting resources like water and raw materials, and it is also done for scientific reasons, to learn about the planet. A method called rotary drilling is often used to drill holes deep into the Earth. To understand how deep we can drill, you need to understand how rotary drilling is performed and what the challenges are. This article explains how we drill deep holes and introduces the equipment needed for rotary drilling. The deeper we drill into the Earth, the higher the temperature and pressure. As temperature and pressure increase, drilling equipment will eventually fail. Another challenge is preventing the hole from collapsing. We will explain how these challenges can be tackled and how deep we can drill with current drilling techniques.

WHY DRILL INTO THE EARTH?

Journey to the Center of the Earth is a classic science fiction novel published by Jules Verne in 1864, expressing human curiosity about Earth's interior. We know little about the inside of our planet, and the only way to prove our theories is to drill. A common reason

BOREHOLE

A deep, cylindrical hole made in the ground.

to drill deep **boreholes** into the ground is to access underground materials that we need, such drinking water, which is often near the surface, as well as oil, gas, and other raw materials found in deeper ground. Another reason for drilling is geothermal energy, which is an environmentally friendly type of energy that uses the natural heat of the Earth to produce electricity or to heat buildings. Scientists also drill into the Earth to learn more about the planet. See this article for more information on scientific drilling.

DEEPEST HOLES IN THE WORLD

So, how deep can we drill? In 1989, the Kola Superdeep Borehole in Russia reached a depth of 12,262 m, which remains the deepest we have ever reached into the Earth [1]. The German Continental Deep Drilling Program (KTB) was another scientific drilling project, carried out from 1987 to 1995, that reached 9,101 m [2]. Both projects tried to drill very deep for scientific reasons, but they stopped because of money and equipment issues.

ROTARY DRILLING

A drilling method to drill deep boreholes. A drill bit installed at the end of a drill string is rotated and penetrates into the ground.

DRILL BIT

A tool designed to make a cylindrical hole; in this case it is attached to the drill rig.

DRILL STRING

A column of hollow pipes that carries drill mud into the borehole and helps to turn the drill bit.

CASING

A pipe that is assembled in a drilled section of a borehole that helps to make the borehole stable, so that it does not collapse.

HOW IS DRILLING PERFORMED?

Rotary drilling is the most common method used to drill deep holes into the ground. The machine used to perform rotary drilling is called a drill rig (Figure 1), and it has many parts. On the drill rig, a tool called a **drill bit** is attached to the end of a hollow steel pipe called a **drill string**, which is rotated by a strong motor and pushed into the ground. As the drill bit turns, it makes a cylindrical borehole. To drill deeper, additional pipes are added to the drill string once the previous pipe is deep within the Earth.

While drilling, the drilled rock pieces, called cuttings, must be removed from the borehole. This is achieved by pumping fluids called drill mud through the hollow drill string and the drill bit. The drill mud carries the cuttings from the bottom of the hole to the surface. The hole must remain stable during drilling so that it does not collapse, which can be achieved by proper drill mud management and good **casing** design. The casing is a heavy steel pipe that holds up the fragile wall of the borehole. It is usually fixed with cement to the borehole wall [3].

With every kilometer we drill into Earth's crust, the pressure increases equal to the weight of a pony standing on an area of the size of a fingernail (an average of 280 kg/cm^2) and the temperature increases by roughly 30°C. These conditions require very strong tools and materials. The hardness of the rock is another challenge—the harder the rock, the slower the drilling progresses and the faster the drill bits wear out. When bits wear out, we replace them by pulling up the entire string.

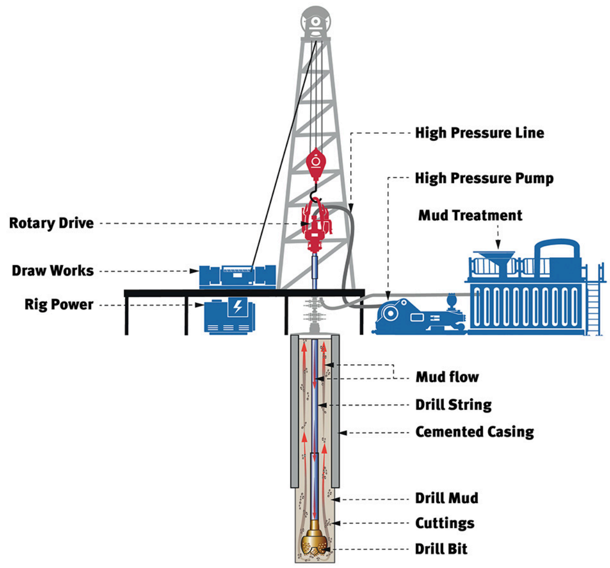

Figure 1

Figure 1

A drilling rig is a complex machine with many components. In general, for rotary drilling, a drill bit is attached to a drill string, which is rotated by a strong motor (rotary drive). Cuttings are removed from the borehole by pumping drill mud through the drill string. The casing helps to stabilize the borehole so that it does not collapse.

DRILLING RIG STRENGTH DETERMINES HOW DEEP WE CAN DIG

Several factors determine how deep we can drill. The first is the "strength" of the drilling rig, which depends on two main things: **hook load capacity** and **hydraulic pressure capacity**. Hook load capacity refers to how much weight the rig can handle. As we noted, the drill string is essential for drilling because it transmits energy from the rig to the bit and is the flowline for the circulating drill mud. The drill string rotates the bit, gives it weight, and guides it. The deeper the drilling goes, the longer and therefore heavier the drill string gets and the closer it gets to the rig's hook load capacity. The weight of the casing must also be taken into account. Casing is usually heavier than the drill string. For example, in the KTB project, the heaviest drill string weight reached 358 tons, while the biggest casing section weighed 690 tons—close to KTB rig's 800-ton hook load capacity (Figure 2). If the weight of the drill string or casing exceeds the drill rig's hook load capacity, then a part of the rig can break, which could hurt people working on the rig and damage the equipment. In such cases, drilling activity must pause temporarily or even stop for good.

HOOK LOAD CAPACITY

The maximum force of the drill string and/or casing that a drill rig can carry or pull safely.

HYDRAULIC PRESSURE CAPACITY

The maximum force per area exerted by a fluid in a fluid-containing system. Exceeding the hydraulic pressure capacity causes the system to fail.

The second aspect of drill rig strength is hydraulic pressure capacity. This refers to the system's ability to circulate drill mud. As we explained, drill mud removes the rock cuttings from the borehole by bringing them to the surface. Drill mud also rotates, cools, and lubricates the drill bit. High-pressure pumps push the drill mud from a tank system, through high-pressure lines, down the drill string to the bit. On the way from surface to the bottom, some of the pressure is naturally lost, but there must still be enough pressure left to bring the cuttings from the

Figure 2

The KTB drilling rig in Germany. It has a hook load capacity of 800 tons and, between 1987 and 1994, it drilled one of the deepest scientifically used boreholes worldwide—at a depth of about 9,101 m. The drilling tower, called a derrick, has a total height of 87 m and marks the location of the borehole, which is directly below.

Figure 2

bottom to the surface, like a strongly flowing creek where the water flow is fast and strong enough to carry away sand grains. The power of the pump and the amount of pressure the equipment can handle set the drilling depths limits.

OTHER LIMITS TO BOREHOLE DEPTH

In addition to drill rig strength, there are some other things that affect how deep the borehole can get. One of these is borehole stability, which we mentioned earlier. The borehole must remain stable during drilling and, the deeper we drill, the more stress the rocks around the borehole walls are under. Eventually the borehole can collapse. This can be prevented by adjusting the properties of the drill mud. For example, drill mud density can be changed to balance the pressures between the drill mud and the fluids in the surrounding rocks.

Casing is also used to strengthen unstable zones while drilling, but the deeper we go, the more hostile the conditions of high temperature and pressure become, and more casing sections are required. The condition of the casing and drill string is another crucial aspect for successful drilling. In general, the deeper we drill, the more strain the drilling equipment is under and the greater the risk of equipment failures. A casing or drill string can easily break under its own weight when it gets too heavy.

To drill as deep as possible, we can choose specialized drill bits that best fit the conditions. In general, there are two main types of drill bits. Figure 3A shows an example of a roller-cone bit and Figure 3B shows a fixed cutter bit with diamond cutting elements. Regardless of what kind of drill bit is used, the bit must be pressed into the ground hard enough to cut through rock but not so hard that we end up bending the drill string. This is achieved by using heavy, thick-walled, hollow pipes, called **drill collars**, between the drill pipes and the bit. The drill collars in the drill string provide a force on the bit that can be fine-tuned from surface. This force is called weight on bit.

DRILL COLLAR

A heavy thick-walled, hollow steel pipe that provides weight on bit for drilling.

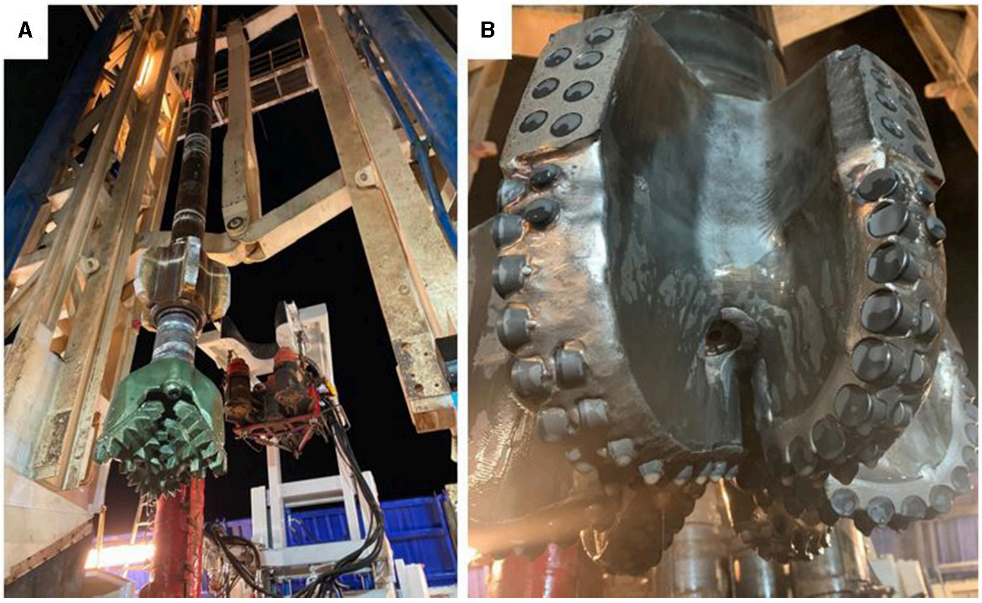

Figure 3

Figure 3

(A) A new milled tooth roller-cone bit installed on a drill string. This type (milled-tooth) is typically used for soft formations. Roller-cone bits are generally used to drill a wide variety of formations, from very soft to very hard. **(B)** A used fixed cutter bit with diamond cutting elements when pulled out of the borehole. This type of bits perform better in soft to medium-hard rocks, with low to moderate abrasiveness and hardness, and high homogeneity.

CAN WE MAKE RIGS TO DRILL DEEPER?

As you can see, there are many technical factors that limit the depth to which we can currently drill into the Earth using rotary drilling. At a certain level of temperature and pressure, *something* is bound to give out! Technical advances may be able to increase the hook load capacity and hydraulic pressure capacity of the high-pressure pumps, but there will be a limit. The most important limiting factor is probably the sheer weight of the casing and the drill string, which will cause the drill string to break under its own weight. In the Kola drilling, special light-weight aluminum drill pipes were used, which allowed drilling to more than 12 km depth. But the Kola site had an advantage. Located in Northwestern Russia where the land is very cool, the temperature was still below 200°C even at 12 km depth. Technically, it might be possible to go slightly deeper than the Kola borehole—but only by a couple of km.

DRILLING DEEP FOR SCIENCE

Most drilling projects have no need to dig super deep into the Earth. For example, the mining and energy industries do not need to do so—they can get the products they need at easier-to-reach depths. Drilling super deep into the Earth is only interesting for scientific reasons. For example, drilling into the Earth's mantle for the first time would be highly interesting for comparing the actual findings with scientists' predictions of what that depth will be like. We could consider drilling into the mantle offshore, in places where there is "only" 5 km of water depth plus 5 km of seafloor to drill through before reaching the mantle. Such a project is technically possible. China's newly built (2023) ocean drilling ship Mengxiang aims to be the first to reach Earth's mantle offshore.

So, now you know why it is important to drill into the Earth and you have learned about some of the challenges that are faced while drilling to great depths. Even though there are depth limits with current drilling technologies, drilling projects are still important for collecting materials and studying the Earth. Hopefully, in the future, we will find ways to drill even deeper and learn even more about the planet we call home!

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YOUNG REVIEWERS

LEAF, AGE: 9

I am in fourth grade, and my favorite subject is art and science. I love observing changes in the world. I like to work as a Young Reviewer as I can observe many more changes using scientist's equipment. In my spare time, I like hiking, swimming, and riding bikes with my friends.

MOMO, AGE: 12

Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she is at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

AUTHORS

SAID KAMRANI-MEHNI

Said studied industrial engineering and management at Clausthal University of Technology. During his studies, he was fascinated by drilling technologies and worked almost 14 years in the drilling industry as a rig manager, drilling superintendent, and project manager. In 2022, he decided to change from industrial drilling to scientific drilling, and he started to work as a drilling engineer at the German Research Center for Geosciences in Potsdam. The deepest borehole he managed reached a depth of 6,133 m. In his spare time, he loves to hang out with his family and friends or play chess. *said@gfz-potsdam.de

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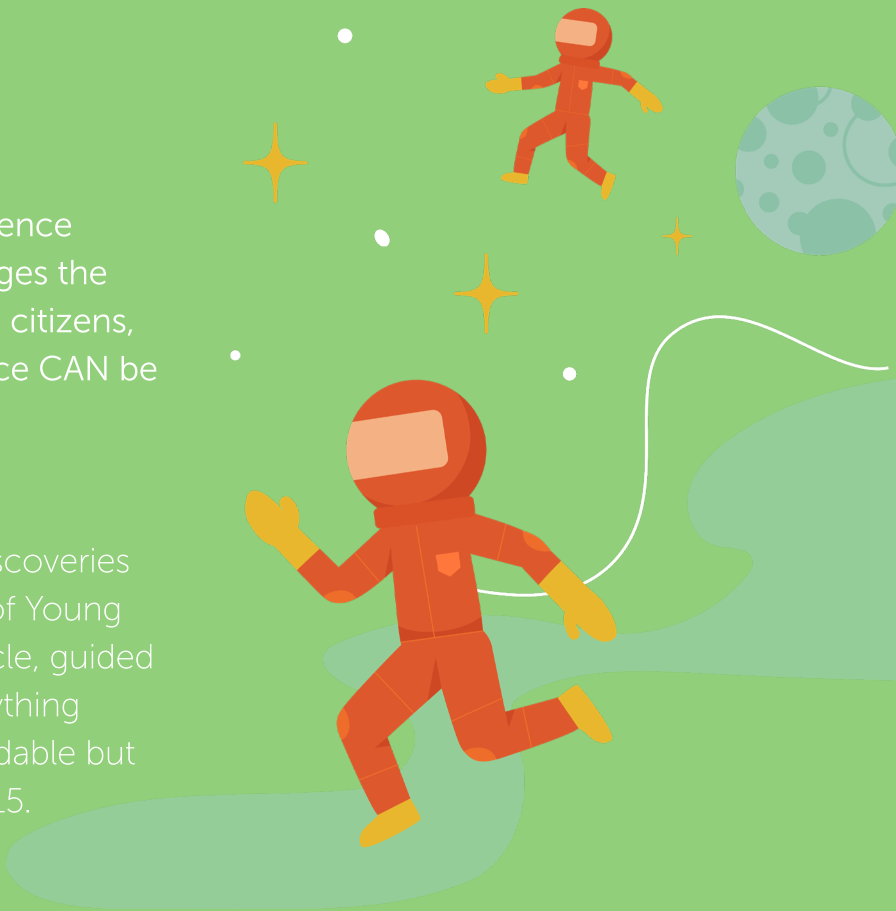

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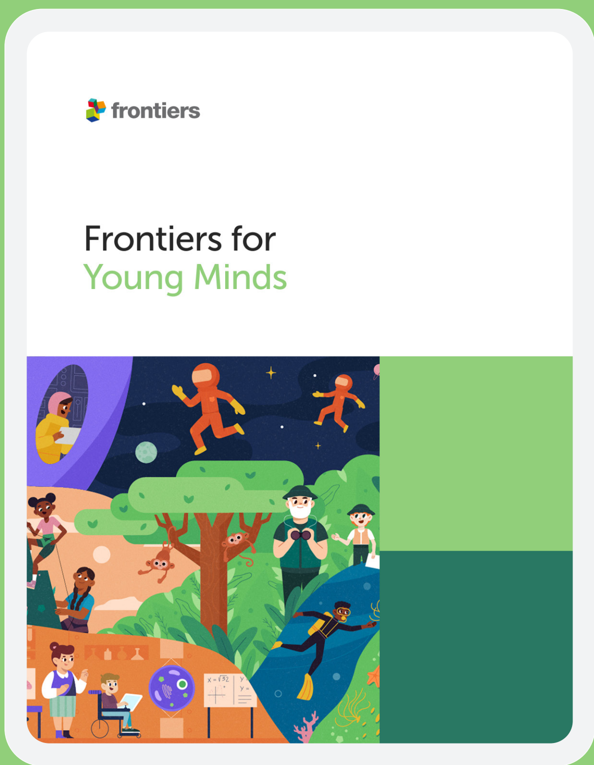

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