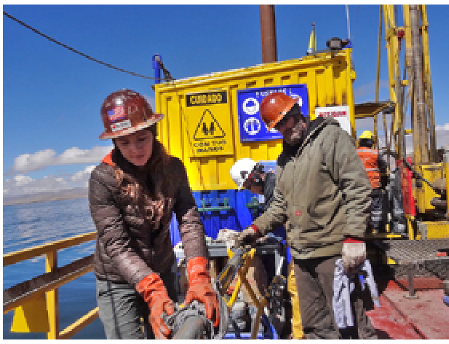
icdp | INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

The Thrill to Drill

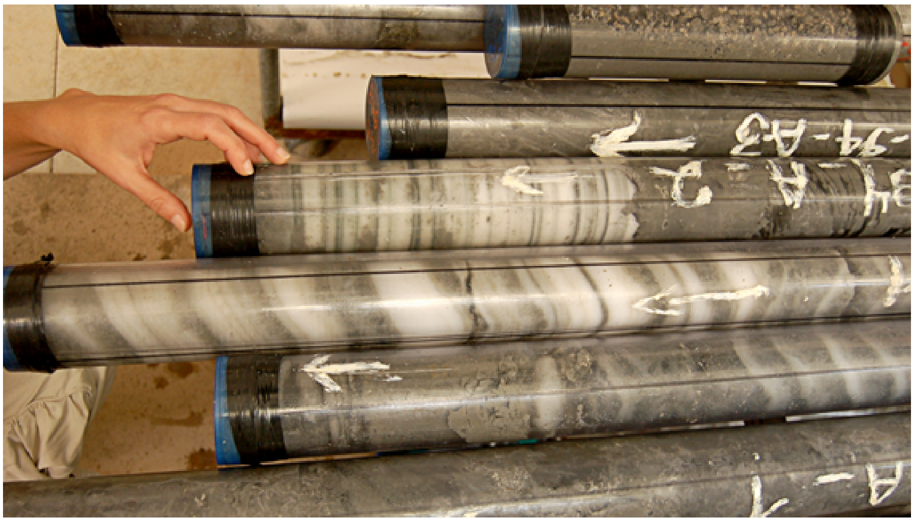


After more than two decades of
International Continental Scientific Drilling:
A prospect for the future

As most of the Earth under our feet is inaccessible, drilling is the only ground truth to correct our models and ideas about our planet's interior.

Drilling does not necessarily have to be done from the surface. Here, researchers follow the drilling progress while drilling boreholes in the Moab Khotsong gold mine (South Africa) in 3 kilometers depth. The project drilled several boreholes into and around seismogenic zones to study the rupture details and scaling of small and larger earthquakes.

For most people, drilling into the Earth means laying the foundation for extracting natural resources from under our feet. Indeed the vast majority of all drill rigs in the world are used either for establishing water wells or for the discovery and exploitation of mineral resources or hydrocarbons like oil and gas.



Thick sequences of salt have been discovered in drill cores from the Dead Sea. The salt precipitated during intervals of extreme aridity during the last three interglacial times.

There is, however, another aspect of drilling into the Earth's crust of which only very few people are aware. Poking a hole into the skin of our planet can help scientists solve some of the many mysteries which remain hidden in its vast interior.

During the past one and a half centuries geoscientists have made enormous strides in exploring the interior of the Earth indirectly by analyzing the chemical composition of lava from hundreds of volcanoes or by modeling the physical conditions at depth based on the interpretation of seismic waves. Although the insights gained by such endeavors can be very detailed and far reaching, they are strictly speaking only models. Like the X-ray of a human body, these models show a picture of what lies beneath the skin. But in contrast to the members of the medical profession, Earth scientists have no way of verifying if their interpretations of such images indeed reflect reality. The vast interior of the Earth – after all our globe has a diameter of more than 12,000 kilometers – is simply not accessible. The high temperature, the enormous pressure and the chemical composition down below prohibit any direct exploration, certainly not by any human researcher and not even by a remotely controlled robot.

At first glance, boreholes also do not seem to help us gain much insight. Even the deepest holes ever drilled merely scratched the thin veneer of the Earth's surface.

The drilling depth is limited mainly for technical reasons: The strongest drill rigs are not capable of lifting of the enormous weight of the long drill string necessary to penetrate dozens of kilometers deep into the Earth. Hence, the record holder, a borehole located in the Russian arctic, has a depth of just over 12 kilometers, roughly one thousandth of the diameter of the globe. All other holes ever drilled are considerably shallower than that. The typical boreholes from rotary drills are just centimeters, maybe a few decimeters across, which is extremely small when compared to the expansive surface of the Earth. Nevertheless, these boreholes penetrate the upper third of the Earth's crust, the very section of the planet on which mankind depends most. The crust is the space on which we live, it

Details about past and recent drilling projects, workshops and how to apply are under **www.icdp-online.org**

Did you know? *About 2000 years ago Chinese engineers developed a drilling system made from bamboo to drill for drinking water.*

The International Continental Scientific Drilling Program (ICDP) was founded more than two decades ago to contribute to solving some of the mysteries of this planet by drilling holes for scientific purposes.

Serpentine and foliated gouge in drill core from the San Andreas Fault in California. This core was the first ever retrieved from an active earthquake fault at depth.

contains the resources on which we depend, and it bears powerful natural hazards which pose a risk to human life and infrastructure. In short, however shallow and small a borehole may be and however arbitrary its location, it helps us gain understanding of the elusive world hidden beneath our feet.

The International Continental Scientific Drilling Program (ICDP) was founded more than two decades ago to contribute to solving some of the mysteries of this planet by drilling holes for scientific purposes. After years of preparatory work, representatives of the US National Science Foundation, the Chinese Ministry for Land and Resources, and the German Science Foundation signed a Memorandum of Understanding on 26 February 1996, in which they established the ICDP.

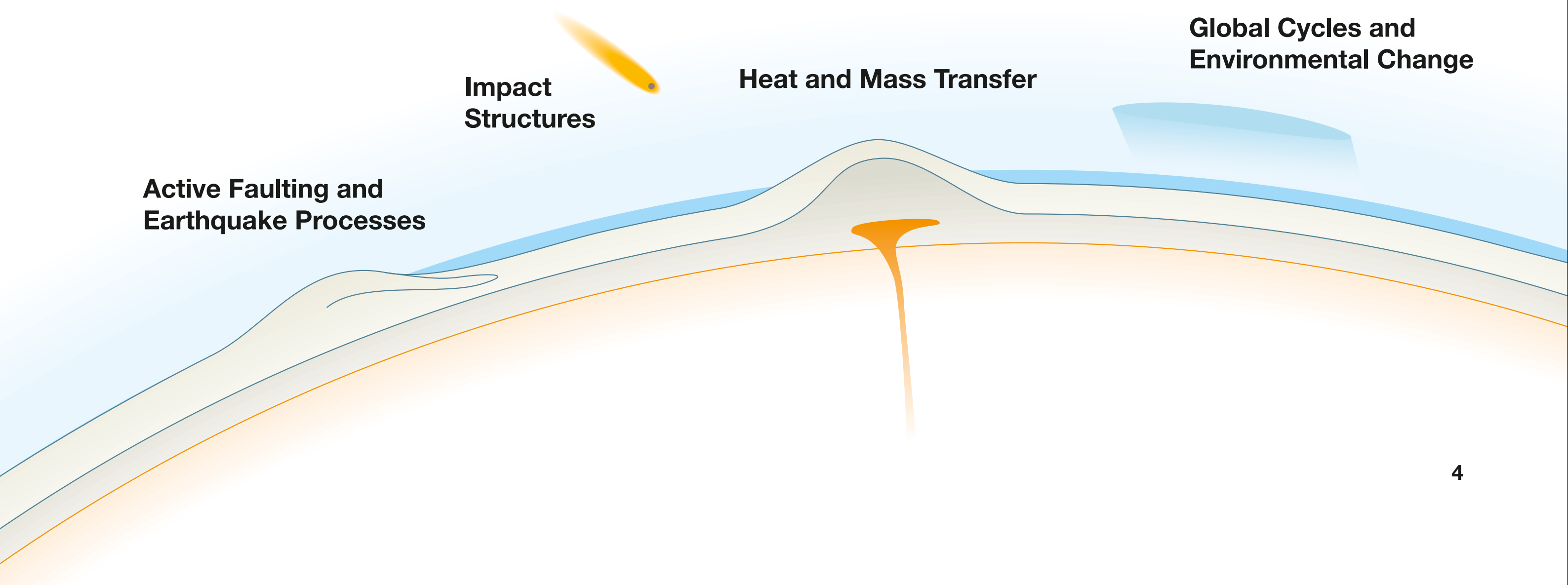
From its initial three founding members, the organization has grown to include 21 countries as members. Each nation is represented either by a premier Earth Science research institution or by a national funding agency for science. In addition, the United Nations Educational, Scientific and Cultural Organization (UNESCO) is a Corporate Affiliate.

The mission of ICDP is summarized in its charter by just one sentence: "Through the unique capacities of scientific drilling to provide exact, fundamental and globally significant knowledge of the composition, structure and processes of the Earth's crust".

In order to gain support by ICDP, each proposed drilling project undergoes a strict vetting process, in which a panel of international experts weighs its scientific merits. Their guiding principle is to ask if a drilling project addresses exciting research questions which Earth science has not yet been able to answer. However, neither the panelists nor the ICDP members live in an ivory tower. In addition to an outstanding research theme, the proposers of a drilling project must show that their plan is relevant to some of the most challenging questions facing humankind. A drilling project should address one of three societal challenges.

- **Will it help improve our understanding of climate and ecosystems?**
- **Will it show ways and means to extract natural resources in a sustainable, ecologically sensitive way?**
- **And thirdly: Can it help scientists in understanding the underlying processes which pose natural hazards like earthquakes and volcanoes?**

In the past twenty years ICDP has supported more than 45 drilling projects which fit one or more of these three categories. Boreholes were drilled on six continents. They range in depth from a few hundred meters to more than seven kilometers. In these projects drill bits have



Drill bits from the Deep Fault Drilling Project in New Zealand. The Alpine Fault, the target of this project, is probably at a late stage shortly before a major earthquake.

hit magma in active volcanoes and have penetrated earthquake fault zones. Rough necks and drilling engineers braved frigid arctic temperatures and humid tropical heat to extract sediment cores from lakes. Some projects drilled into billion year old rocks, while others probed zones where asteroids once violently impacted the Earth. Some drilling took place in the confined space of the deepest mines in the world, other boreholes were located in the vast open tundra of Siberia. All of these holes were drilled in the true spirit of international cooperation and open data exchange. For a complete list of finished projects see page 18.

Drilling on land can also provide insights into oceanic processes. ICDP drilling of the Samail ophiolite in Oman yielded valuable information on formation and emplacement of oceanic crust.

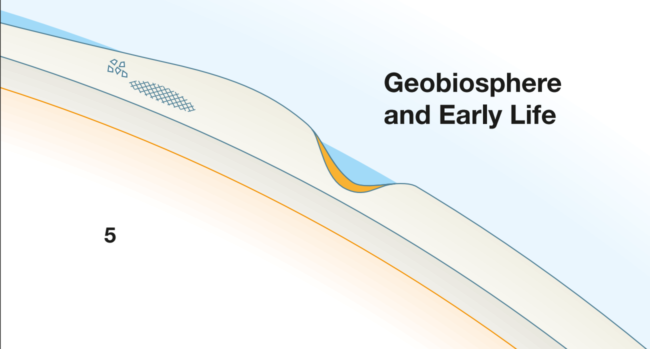
From the rather abstract mission statement of ICDP the members have developed five important scientific themes of Earth science for which drilling on continents can provide major insights. Besides satisfying the question of societal relevance, each project coordinated by ICDP over the last two decades, has addressed at least one of these major research themes defined as the core of any scientific drilling.

These are: Active Faults and Earthquakes, Global Cycles and Environmental Change, Heat and Mass Transfer, the Ubiquitous Hidden Biosphere, as well a Cataclysmic Events – Impact Craters and Processes.

The Koyna region in the Western Ghats of India is unique because of its seismicity triggered by regular loading/unloading of a reservoir. The pilot borehole provides critical parameters for understanding such reservoir-triggered seismicity.

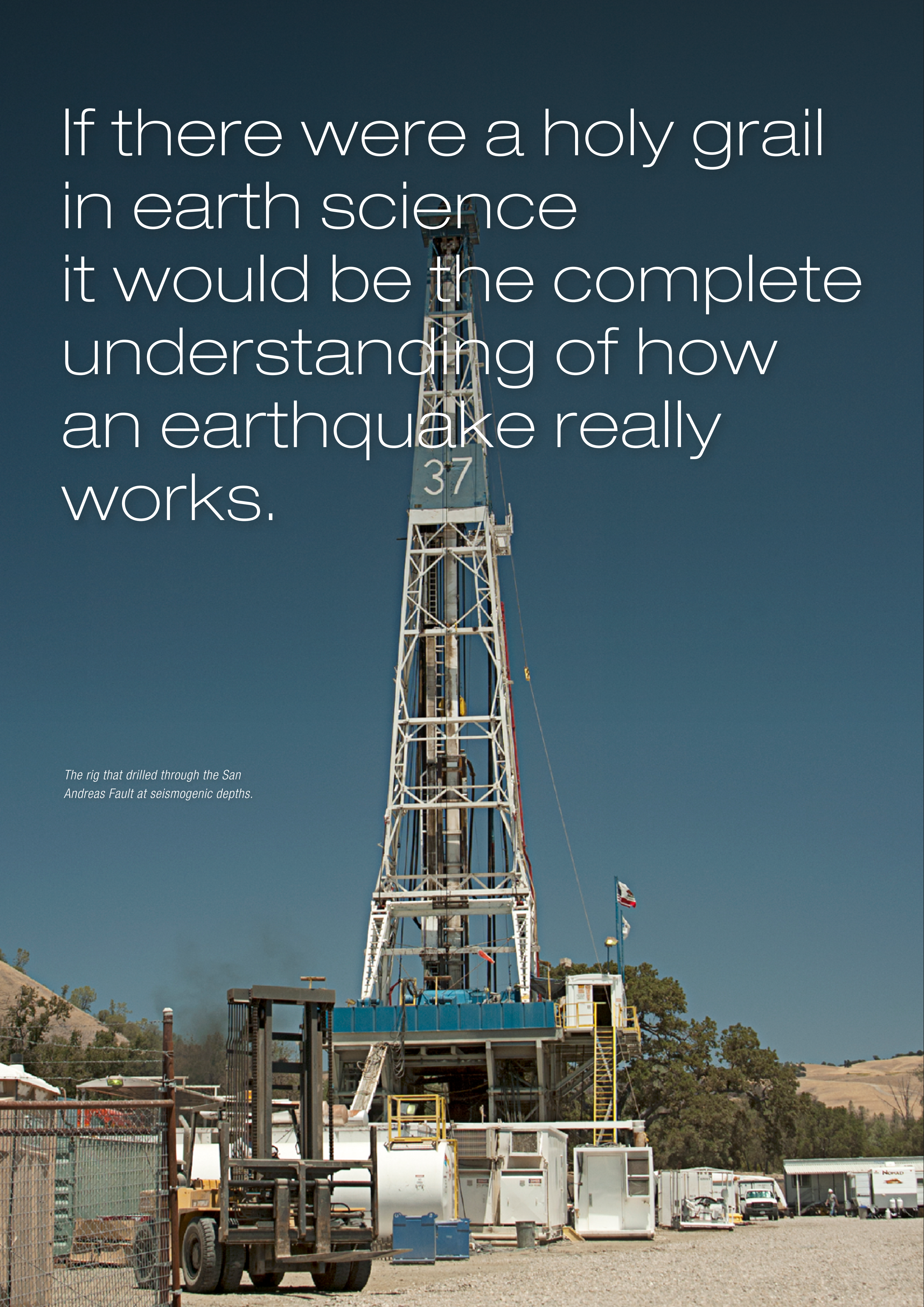
In the following pages, we will look in detail at examples of each of these research themes. We will explain underlying research questions, describe the technical and logistical challenges, which can sometimes be hair raising, and will analyze the results. ■

The current member countries of the ICDP-program are: Austria, Belgium, Czech Republic, Finland, France, Germany, Iceland, India, Israel, Italy, Japan, Netherlands, New Zealand, Norway, P.R. China, South Korea, Spain, Sweden, Switzerland, U.S.A. and the United Kingdom. The UNESCO is a Corporate Affiliate.



Did you know? *The first modern oil well was drilled in 1848 near the Azerbaijani capital Baku.*

If there were a holy grail in earth science it would be the complete understanding of how an earthquake really works.



The rig that drilled through the San Andreas Fault at seismogenic depths.

A better characterisation of fault behaviour is the first step towards an improved understanding of hazardous zones. During the last two decades, ICDP fault zone drilling obtained valuable samples and measurements from active fault zones from depths reaching several kilometres.

Earthquakes set free some of the most destructive natural forces on our planet. Even the accumulated energy of a major hurricane churning for days pales in comparison to the seismic energy released by a strong quake. But despite more than a century of research, scientists still lack a detailed understanding of the processes which take place in the Earth's crust before and during an earthquake. In some cases, a fault breaks from depth all the way through to the Earth's surface, where it can be studied. But the main action during an earthquake rupture happens hidden away several kilometers below ground, where the two flanks of a fault slip past each other at lightning speed. Researchers have created numerical models and impressive computer simulations to show how an earthquake might work, but many basic questions about fault behavior remain unanswered.

To shed light on the mysteries of earthquake faults and the temblors they produce, ICDP has supported several projects to drill into areas where quakes are actively generated. In one of these projects a drill penetrated what is undoubtedly the most famous earthquake fault of all, the San Andreas Fault in California. Near the hamlet of Parkfield, halfway between San Francisco and Los Angeles, drill cores from within the fault zone were brought to the surface from a depth of almost 3 kilometers. And what a surprise they contained! That the rocks in the actual fault zone were sheared and fractured by the constant churning of the fault was expected by the experts. They also predicted that some of the rock would be physically and chemically altered by the heat and pressure and water inside the fault to become serpentinite. But what the researchers did not expect were white veins in the serpentine rock. They consisted of talc, one of the slipperiest, weakest minerals on Earth. This find showed that the fault had produced its own lubricating material, which like the talcum powder used in baby care, reduces friction and makes things glide past each other almost effortlessly.

The San Andreas Fault is one of thousands of earthquake-generating interfaces in the Earth's crust. In California, two lithospheric plates, the Pacific and the North American Plate slide past each other horizontally, causing strike-slip earthquakes. There are other faults in which the two flanks move in a different fashion. In rift zones or areas of active crustal spreading, earthquakes occur on normal faults. In contrast, thrust faults

Scientists follow the explanation of the drilling engineer while drilling the Alpine Fault in New Zealand.

View from the rig floor during scientific drilling in Koyna, India, where a new drill pipe is lifted to the drill rig.

Did you know? *The first geophysical borehole measurements were performed in 1927 in a well in Pechelbronn, France.*

Quaternary displacement of the San Andreas Fault at Elkhorn Scarp, California.

dominate in active orogenic belts and subduction zones, where one plate dives beneath another.

One classic example of a thrust fault exists on the western slope of the central mountain range in Taiwan. In 1999 a devastating quake with a magnitude of 7.7 occurred along this Chelungpu Fault, causing vertical displacements on the surface of up to 8 meters. Because this fault dips under the shallow angle of only 30 degrees, it could be penetrated by a relatively shallow borehole with a depth of less than 2000 meters. The drill cores brought to the surface from this project confirmed that fluids play an important role in lubricating faults during an earthquake.

The Alpine Fault, New Zealand, is thought to fail in large earthquakes every 200-400 years and last ruptured in 1717 AD. Drilling the Alpine Fault provided an opportunity to study a major fault late in the cycle of stress accumulation ahead of a future earthquake.

Not all earthquakes are of natural tectonic origin. Sometimes human activity plays a role in triggering a temblor, which in extreme circumstances can be deadly. That was the case in 1967 in the region around the Koyna Dam in western India, when more than 170 people were killed in a magnitude 6.6 earthquake. This quake was the result of induced seismicity caused by the increasing water pressure when the large reservoir behind Koyna Dam was filled. During a recently completed drilling project, the basaltic and granitic rocks in the vicinity of the dam were sampled. For the first time their permeability could be measured directly, and its relationship to triggered seismic events be investigated.

In a very unusual project to drill into an active fault, ICDP sponsored scientists recently set up a drill rig inside a gold mine in South Africa at a depth of more than 3 kilometers. The mining activity there regularly sets off small quakes with magnitudes of 2 or less. The foci of these quakes are often only a few tens of meters away from the drifts and adits of the mine. Hence the fault areas of the microquakes can be reached without too many technical difficulties by underground drilling equipment. The cores from these drill holes into zones of active microseismicity are currently being studied. ■

Did you know? *The Kola Superdeep Borehole (Russia), drilled between 1970 and 1989, reached the deepest artificial point on Earth at more than 12 kilometers depth.*

Earth's rapidly changing climate requires adaptation strategies. Drill cores from lakes and other sediments help in understanding the climate system and putting regional precepitation patterns associated with monsoons and El Niño in a global context.

It has often been said, but it remains true nonetheless: In order to forecast the future of our climate, we must understand its past. The core problem is that reasonable estimates of human influence on the climate are only possible if we know about the natural variability in the long term behavior of the Earth's atmosphere. During the past decades scientists have made great strides in reconstructing the climate of the last few hundred thousand years. While these global estimates give some guidance for forecasting the future, they often lack regional details which can be very important. Did the climate in the tropics change in sync with variations in higher latitudes? What about cycles in arid zones versus those in regions affected by monsoons?

To broaden the database about climate change on regional levels, researchers have to unlock the mysteries of the past at many different locations on Earth. But how does one go about collecting information about long gone climates, when there are no direct records of parameters like temperature or rainfall? After all the oldest reliable meteorological observations are at best 250 years old – a mere blink of eye when compared to the thousands or millions of years of Earth's recent geologic history. Hence researchers rely on indirect information – so called proxies - to unravel long term variations in the climate.

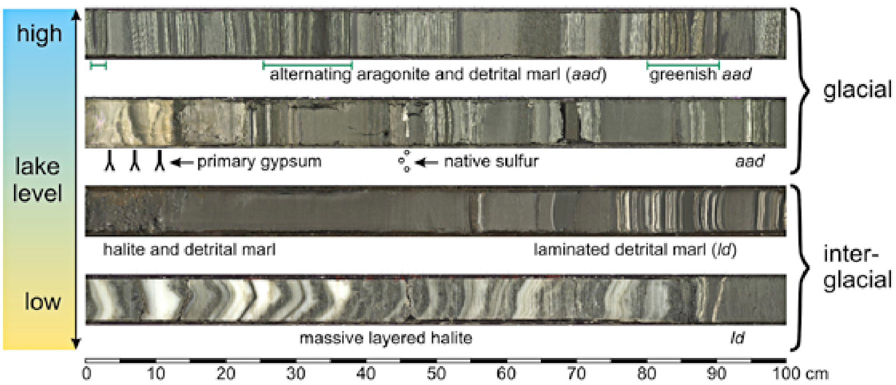
In most cases, this information is hidden in the sediment layers of the uppermost parts of the Earth's crust - which of course can be accessed by drilling. Because of the enormous societal relevance of this topic, almost half of all drilling projects supported by ICDP have included at least one aspect directed at unraveling local climate histories.

Some of the best archives of the recent climate are found in the sediments of freshwater lakes. They contain a combination of pollen, plant detritus and minerals from which paleoclimatologists can reconstruct the climatic conditions of long ago. In fact, most undisturbed lake sediments exhibit clear layering. Like tree rings, each of these sediment layers – they are called varves - contains information about the weather and environmental conditions of one year. To scientists, the changes in the varve layers over the decades and centuries are like a book, with each page holding the secret of the former climate.

A prime example of such a fresh water lake is Lake Ohrid on the border between Macedonia and Albania in the Balkans. This 30 kilometer long and 15 kilometer wide lake has a depth of almost 300 meters and is considered one of Europe's deepest lake. The lake has been in continuous existence for over a million years, which led to an outstanding biodiversity with more than 200 endemic species. The

Immediately after its recovery, scientists inspect a core of lake sediments on board the drill platform.

Exemplary identification of sedimentary facies on drill core from the ICDP Dead Sea drilling project and paleoclimatic interpretation: glacial times are characterized by higher lake levels, while interglacials by lower ones.



Did you know? *Even the deepest boreholes penetrate only approximate 1/1000 of the Earth's diameter.*

ICDP's Deep Lake Drilling System in operation on the Dead Sea.

Drilling in the Songliao Basin in China reached a final depth of more than 7000 meter and sets several new records in ICDP drilling.

sediment cover at the lake bottom is almost 700 meters thick. During an ICDP sponsored drilling project, more than 2100 meters of sediment core were recovered from four drill sites in the lake. They are a unique object to study both the development of the lake's biodiversity as well as the climate history of the northeastern Mediterranean. Other regional climate histories have been recovered from lakes in different climate zones, like in the low lands of Guatemala, in Ghana, in eastern Turkey, on the Tibetan Plateau, on the Indonesian island of Sulawesi and from Lake Titicaca high in the South American Andes.

Recovering drill cores from deep under the bottom of lakes requires a technique different from those used in drilling projects on land. The drill rig and all its peripheral equipment is mounted on a floating platform. The platform, in turn, has to be positioned very stably over the prospective drill site in the lake bottom. The drill bit and all necessary rods first have to dive through what may sometimes be several hundred meters of water, before they can penetrate the lake bed. Several different floating drill platforms have been used during the various ICDP lake drilling projects.

However, not all ICDP sponsored climate related drilling projects deal with the more recent, or quarternary, history of climate change. During a project in the Songliao Basin in the Heilongjiang Province in northeastern China, researchers unraveled almost the entire climate history of the Cretaceous age, which ended about 65 million years ago. A conventional, land based rig drilled more than 6.5 kilometers deep into the sediments of this basin. Almost 4 kilometers of drill core were recovered, containing climate and other geologic information about the period, which lasted more than 70 million years, in which dinosaurs and other reptiles dominated the Earth. A drilling project in the Petrified Forest National Park in the American state of Arizona went even further back in time. Its cores have revealed information about the climate of the Triassic period more than 200 million years ago. ■

Core on deck! After core arrival, the core barrel is cleaned and the core recovery is determined.

Did you know? *A bore hole is not an empty hole, filled with air. Indeed, drill mud is circulating in the borehole to cool the drilling tools, for dragging out the drilled rock chips and and to prevent the hole from collapsing.*

Transfer of heat and mass, like magma, hot fluids or groundwater, are the basic processes responsible for the physical and geological world we live in. Heat and mass transfer has been studied in numerous ICDP projects conducted at plate boundaries, hot spot volcanoes, and permafrost areas.

Scientists from the Oman Scientific Drilling Project are investigating rock chips (cuttings). When no drill cores are available, cuttings are the means of choice.

Viewed purely from a perspective of a physicist, the Earth resembles a giant pressure cooker. It contains an enormous amount of heat, some of it is left over from the time of the Earth's formation 4.5 billion years ago, some is generated by the decay of radioactive elements inside. And the pressure in the Earth's interior, caused by the weight of the overlying rock and the expansive forces of the heat, is immense. Overall, like a good pressure cooker, our planet contains its heat and pressure very well, but unlike the cooking pot, it has a substantial number of vents or leaks. More than 600 active volcanoes and countless geothermal fields dot the landscape on the continents. And at the bottom of the seas the extended mid-ocean ridges are the centers for the break-up of the Earth's crust and hence the source of almost 80 percent of the volcanism on the globe. Together these leaks are the locations where mass and heat from within the Earth escape to the surface.

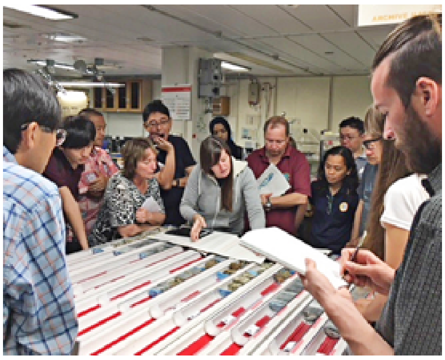
Although they are fed from the same internal source and are often immediate neighbors, volcanoes and geothermal fields are fundamentally different. When fire mountains erupt, cubic kilometers of solid and liquid rock are pulverized and often over just a few hours spew into the atmosphere in gigantic plumes of ash and fine particles. These volcanoes can be very destructive. In the past 500 years, more than 200,000 people have lost their lives in eruptions. During the past century alone, an average of 845 people died each year from volcanic hazards. In contrast, in geothermal areas only heat escapes. Because the heat mostly takes the form of hot water and steam, it is used in many parts of the world to partially satisfy regional energy needs.

Three boreholes were drilled in the Snake River Plain (Idaho, USA) for tracking the Yellowstone Plume in time and space.

Both regions have in common that they are peep holes into the hellfires burning within the bowels of the Earth, looking glasses which help us to understand the dynamics of the interior of our planet. What is valid for many other fields of Earth science also holds true for studying these hot zones: The information gained through observations from the Earth's surface leads to models and hypotheses of how its interior works. Only drilling can provide the ground truth for such models. Drilling is never easy, but to make volcanoes divulge their secrets by penetrating them requires special efforts with their own technical challenges. How

Did you know? *The longest borehole is the currently over 13 kilometres long borehole in the Tschaino oil field offshore Sakhalin Island, Russia.*

ICDP Scientists preparing a probe for measurements in the Kimberly borehole in the Snake River Plain of Idaho (USA).



A so-called sampling party: scientists studying and sampling drill core from the Oman ophiolite drilling project.

do you drill into a rock that was molten only weeks or months ago? How do you keep the restless magma within the Earth from finding your borehole and using it as a conduit for a new eruption?

One of the most themally active areas on the globe is Iceland, the island in the North Atlantic dominated by volcanoes, where the use of geothermal energy is also commonplace. During an ICDP sponsored drilling project in search of very hot, supercritical water near Krafla volcano in the northeast of the country the drill bit got stuck at a depth of about 2000 meters. When it was finally pulled up to the wellhead under great difficulty, the drillers understood why it would not go any deeper. It was covered with remnants of fresh magma, chilled to rigid glass. This accidental penetration of magma was controlled by the cool drilling mud pumped through the drill string.

Recently a second borehole was drilled within the framework of the “Iceland Deep Drilling Project”. This well on the Reykjanes Peninsula was successful, as it reached supercritical water at a depth of almost 4700 meters. At a temperature of 426 degrees Celsius and a pressure of 34 Megapascal, this deep water had transformed into a completely new phase, where the distinction between liquid and vapor had vanished. Theoretically, a well sunk into such a reservoir is able produce up to ten times more electricity at the same flow rate as a conventional well. The next step is that Icelandic engineers will test the technical feasibility of this process.

To investigate a volcano’s plumbing, Japanese researchers drilled into Mount Unzen, one of the most active volcanoes in the country. Their goal was to understand how magma is transported from depth to the crater. To find this out, they penetrated Unzen’s conduit. Unlike the pictures scientists draw, they found that Unzen’s conduit is by no means a simple cylindrical hole resembling a pipe. Rather, it is a 500 meter wide zone, consisting of many fingers. The degassing melt flows through one or another of these conduits during the various stages of an eruption.

A completely different kind of volcanism was investigated through a drilling project in the northwestern United States. There the Snake River Plain of Idaho contains massive flood basalts and rhyolites which were erupted over the last 15 million years, as the North American Plate moved over the Yellowstone Hot Spot. This is thought to be a narrow plume of very hot, molten magma rising from deep within the mantle. Like a blow torch, it burns through the crust above it. Although the plate above this Hot Spot is moving, the plume itself is extremely steady and very stable. Currently this hot spots feeds the volcanoes and geysers of Yellowstone National Park.

The Hawaiian Islands are also the result of a hot spot. A drilling project near the town of Hilo on Hawaii’s Big Island reached a depth of more than 3300 meters. The well was almost completely cored, with the recovered rock samples provide the longest continuous stratigraphic record from any ocean island volcano. The oldest rocks recovered date back at least 600,000 years. This core not only reflects the structure of the volcano itself, also provides a detailed history of the plume. As Mauna Kea slowly moved over the plume, magma of different ages and from various depths reached the edifice and piled on top of each other like pancakes on a plate. Each layer has its own characteristics. Taken together they give a detailed picture of the development of the Hawaiian Hot Spot. ■

Did you know? *The German KTB superdeep borehole was the initial spark for ICDP. The main hole with its depth of 9101 meters is still used as an observatory.*

The deep subsurface biosphere forms the largest ecosystem on Earth and harbours a significant part of all life on Earth. ICDP projects investigate the limiting factors of life in depth which helps to answer questions about the origin and development of life on our planet and about possible extra-terrestrial life.

Finely laminated sedimentary sequences in lake cores provide a unique opportunity to investigate microbial abundances in microenvironments on the high-resolution scale.

Slumbering creatures living deep underground play an important role in Earth science – well at least in the lore of many indigenous peoples. They believe that earthquakes are caused when such animals suddenly move. In Japan it was a giant catfish, in China it was a frog and in the Philippines a snake. In Indian folklore it was even more complicated because in their view the Earth was held up by four elephants, which stood on the back of a turtle. Scientifically this is, of course, nonsense, but there is indeed life deep below our feet and it is surprisingly abundant. Some scientists even speculate that the biomass harbored in the so-called deep biosphere is greater than the mass of all the living cells taken together in the classically defined biosphere on the surface of the Earth and in its oceans and atmosphere.

The deep biosphere is not made up of regular plants or animals like those found on the continents or in the oceans. As sunlight does not reach into the depths and regular food chains do not exist there, photosynthesis and the kinds of metabolism known from the ecosystems around us cannot sustain a biosphere inside the Earth's crust. Instead the lifeforms deep within the Earth are dominated by extremophiles, microorganisms which live under conditions commonly thought to be sterile or at least very hostile to life. Among them are thermophiles, bacteria and archaea which can survive very hot temperatures. The record holder is called Strain 121, a single-celled microbe belonging to the archaean kingdom. It not only survives but even multiplies at temperatures of up to 121° Celsius – hence its name.

Rather than light and photosynthesis forming the base their metabolic energy systems, some of the microbes oxidize methane or inorganic molecules, like hydrogen sulfide. At least a dozen different classes of extremophiles have been studied, ranging from acidophiles to xerophiles. The first are organisms which thrive in extremely acidic liquids with pH levels at or below 2, while the latter can grow in utterly dry, desiccated conditions, like the soils of the Atacama Desert.

Another sort of microbes lives in the groundwater of kilometer deep gold mines in South Africa. Some of the water there has been trapped for tens of millions of years. During several ICDP sponsored drilling projcts inside the mines,

Sunrise at the Mallik site in the Northwest Territories of Canada. Scientific drilling at Mallik sampled gas hydrates trapped below the permafrost.

Did you know? *More than 20 years after ICDP's founding 40 drilling projects have been completed with more than 75 kilometers of drill core retrieved.*

CO_2 bubbles indicate the active mofette in direct vicinity of the drill site. Scientific Drilling was undertaken to determine to which extend the microbial communities are conditioned by CO_2 and how the microbial activity is potentially affected by seismic activity.

researchers collected organic matter dissolved in the water. They found clear indications of isolated microbial communities eking out a living using dissolved hydrogen gas and inorganic carbon released by the rocks, with little or no contributions of organic carbon from the surface.

During a drilling project near the equator in Indonesia, scientists collected enough material to understand some of the fundamentals of the metabolism of extremophiles. Lake Towuti, in the southern part of the island of Sulawesi, teems with an abundance of endemic fish, snails and freshwater shrimp. Because the lake is located within a basin surrounded by the ultramafic rocks of an ophiolite, the material leached from these rocks by weather and erosion provides an abundance of iron minerals. These minerals, in turn, are metabolized by a very rich microbial community at the bottom of the lake. As a consequence the lake sediments are rich in several metals, including iron, chromium and nickel, which the microbes precipitate during their metabolism. By analyzing several cores drilled from the lake sediments, researchers discovered how long term changes in climate influence the life of these microbial communities.

A completely different type of microbes was investigated in a drilling project north of the Arctic Circle in the Mackenzie Delta in northwestern Canada. The permafrost there contains large amounts of gas hydrates, a solid made up of the simple hydrocarbon methane and water. Some consider these hydrates an important energy source for the future, while others see them as a threat to our current climate, because if the hydrates melt, large amounts of the greenhouse gas methane will enter the atmosphere. Speculation has also arisen that extremophile microbes are living in these hydrates. To study these and other questions, Earth scientists drilled three parallel wells into the Mallik gas hydrate field with ICDP's support. There a layer rich in gas hydrates more than 200 meter thick is buried at a depth of 900 meters under the permafrost. Methane loving microbes were found in several cores gathered during the drilling campaign. Because their concentration was considerably lower than expected, the results added to the mystery of extremophiles in the deep biosphere.

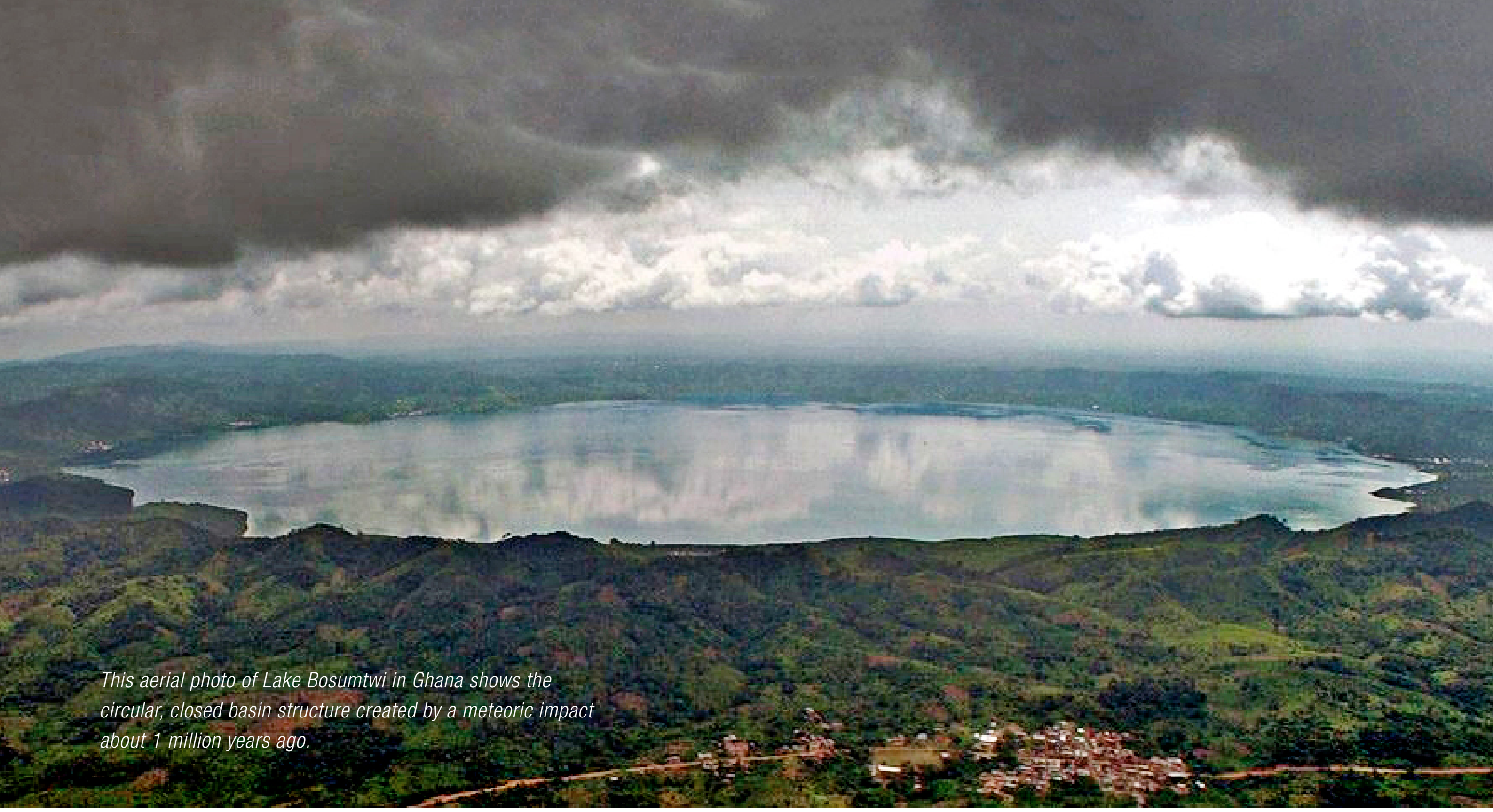
Drilling into the world of the ubiqitous, but hidden biosphere, however, has its special challenges. In principle, microbial investigations can augment practically any drilling project. But to be successful major precautions need to be taken. The reason: the drill bit and the string can easily be contaminated with the regular microbes found at the surface of the Earth. Conversely, a drill core being recovered from depth can contaminate the sides of the well or be contaminated as it is lifted through the well bore to the well head. To prevent such contamination the drill rig must be operated in quasi sterile conditions. ■

Drilling into an active mofette to study the impact of CO_2 -rich mantle-derived fluids on the geo–bio interaction in the western Eger Rift (Czech Republic).

Did you know? *The hottest borehole drilled during the ICDP program was in Iceland, where a core was retrieved at a temperature of 426 degrees Celsius.*

Cataclysmic Events – Impact Craters and Processes

Drilling the Chicxulub Crater was a joint attempt by oceanic (IODP) and continental (ICDP) scientific drilling programs. The picture shows the drill rig installed on a liftboat at the drill site off the coast of Yucatan. The height of the drilling platform is adjusted according to the water depth along the three columns.



This aerial photo of Lake Bosumtwi in Ghana shows the circular, closed basin structure created by a meteoric impact about 1 million years ago.

Since the origin of the Earth, cratering constitutes a fundamental geological process shaping the Earth's surface. Impact events have driven the geological and biological evolution on Earth. The formation and understanding of impact structures are key for ICDP but also to society in general.

A core sample from the Chicxulub Crater is carried with great care from an on-board laboratory to a storage facility.

Looking at a map of the moon one quickly realizes that the surface of our immediate companion in space is covered with countless circular structures. They come in all sizes, from rings with radii of a few meters to craters which have diameters of hundreds of kilometers. These round structures are not caused by volcanic activity. Instead they are caused by impacts of smaller celestial bodies like asteroids and meteorites, which have bombarded the Moon throughout its long history. The Earth, of course, has experienced a similar fate to that of our neighbor. In contrast to the moon, however, most traces of the impacts on our planet have been wiped out. Weathering and erosion have gnawed at the craters. Their remnants are hidden beneath the cover of soil and plants. And as a water planet on which more than 70 percent of the surface are covered by oceans, many of the asteroids which hit the Earth did not generate a crater because they landed in water and not on land. Still, more than 170 impact structures have been recognized on the Earth's surface.

Now, only a few of the young impact craters are reasonably well preserved. The "Nördlinger Ries", an almost perfectly circular depression in the limestone plateau of southern Germany, was formed by an impact 15 million years ago. The arid climate of the American state of Arizona helped preserve the "Barringer Meteor Crater" in nearly pristine condition, since its formation 50,000 years ago. For most other impact structures, particularly

Did you know? *ICDP's Songliao Basin Drilling sets a new world record in core drilling, gaining up to more than 41 meter of core in one core run.*

those in wet climates, erosion takes its toll very quickly. The craters left behind by an impact are filled by rocks from the surrounding hills. Even more importantly, the debris generated by the enormous heat and pressure during the impact is buried under otherwise common soil and thus escapes the sharp eye of the field geologist. The debris, however, is of utmost interest to scientists who study the earliest phases of the Solar System. It consists not only of Earth rocks from before the impact, which have been reworked and melted together by the heat and the shock wave of the impact, like "suevite breccia". The debris also contains fragments of the impact body itself. Of particular interest are rare isotopes which were abundant during the formation of the solar system but have been depleted in the rocks of the Earth during geologic times.

Drilling into an impact crater is sometimes the only way to unravel the physical and chemical processes which occurred during and immediately after the impact. Over the past two decades, four impact structures were investigated under the auspices of the ICDP. Undoubtedly the logistically most challenging of these undertakings was the "Lake El'gygytgyn Drilling Project" just north of the polar circle in the far eastern reaches of Siberia. The lake fills an impact structure, which is up to 70 meter deep and has a diameter of about 18 kilometers. It was formed when a kilometer-sized asteroid hit the region about 3.5 million years ago. In order to access the very remote site, the 75 ton drilling platform had to be transported to the lake during the winter over a specially constructed 350 kilometer long snow road. Once it reached the frozen lake, it was erected on the ice surface. In order to support its weight, the natural ice sheet had to be strengthened by pumping more water to the surface. There it froze and increased the thickness of the ice over the lake. Once drilling started, the first impact deposits were reached at a depth of more than 300 meter below the lake bottom. They were then explored and cored for an additional 200 meters.

This extremely difficult and successful drilling project served two purposes. One goal was to gather rock samples from the actual asteroid impact. At the same time climate scientists were very interested in recovering lake sediments from above the impact zone, because they contain hitherto unknown information about of the history of the climate in this very remote region of the Arctic over the past million years. Two cores gathered during two other drilling projects into impact structures, one into Lake Botsumtwi in Ghana and the other into the Chesapeake Bay on the East Coast of the United States, also contributed to unravelling recent climate history. It is typical of many drilling projects supported by ICDP, that an individual borehole is not the focus of a single scientific question, but that each contributes information to multiple goals serving a variety scientific fields.

While the bolide which created the crater at the El'gygytgyn site in Siberia was relatively small, an asteroid which hit the Earth about 66 million years ago was a giant. With a diameter of about 15 kilometers, it created a crater about 150 kilometers wide and about 20 kilometers deep. Its impact on the Earth was so powerful, that about 75 percent of plant and animal species on Earth suddenly became extinct, including all species of land-based dinosaurs. The crater, named after the small town of Chicxulub on Mexico's Yucatan-Peninsula, was the target of ICDP sponsored drilling projects twice. One 1510 meter deep hole into the impact layers was drilled on land in 2001/2002. It found a one hundred meter thick layer of impactites, composed of suevitic and impact melt breccias, sandwiched between limestone sedimentary rocks above and thick pre-impact Cretaceous rocks below. Based on the results from this borehole, a second hole was drilled offshore in a joint project with ICDP's counterpart for drilling in the oceans, the International Ocean Discovery Program (IODP). It penetrated more than 1300 meters beneath the seafloor and revealed the structure of the peak ring, the crater rim, which formed within minutes after the asteroid hit. ■

Goodbye to the researchers and crew and keep up the good work.

Did you know? *During drilling, no pressure is applied on the drill string from the surface. In fact, the weight on the drill bit, needed for making depth progress, is provided by the string itself.*

Scientific drilling is the ultimate tool to retrieve subsurface samples and data for Earth science. ICDP encourages researchers to use it.

Inspite of all the strides geoscientists have made in understanding the structure of the Earth and the processes within it and on its surface, the information they gain about our planet's interior is always indirect. This leads to models based on logic and supported by a multitude of circumstantial evidence. Drilling is the only way to compare these models with reality. But researchers often consider sinking a hole to be financially out of reach. Their common perception is that the cost of drilling is far beyond the scant funding Earth scientists receive, and that the logistics associated with operating a rig are so complicated, they cannot successfully be dealt with by a scientist.

This is where ICDP plays a role. It is our goal to encourage Earth scientists to consider scientific drilling as one of their research tools, to make drilling the reality check for the models and ideas they have developed. We help fund such drilling projects and coordinate the on-site research. Funding agencies are invited to join the ICDP and pool financial and operational resources, so that drilling projects can be supported.

Given the costs of sinking, coring and logging a borehole, and the current levels of funding for Earth science, it is clear that the questions addressed by proposals for drilling with ICDP's help, must be substantial. Their relevance must go beyond answering a specific, local question or one small aspect of a research direction. Projects funded by ICDP address questions of global importance to the Earth science community, along the lines of the themes described in this booklet. The drilling should take place at a location which can be considered to be a "World Geological Site", where one or more of the still open fundamental questions of the Earth sciences has a chance of being answered. ICDP projects bring together researchers from different countries and different fields of Earth science to "make the most" of each borehole. Hence: Research teams with a critical need for scientific drilling on land are invited to submit project proposals to ICDP.

There is no rule of thumb for determining how much of a project ICDP will fund. That depends solely on the proposal itself, its evaluation by our independent review panel, the Science Advisory Group, and the ICDP Management. In any case, researchers submitting a proposal should be prepared to bring in a portion of the expected project costs from other sources. Usually a stamp of approval by ICDP helps in securing these third party funds.

The ICDP is served by the Operational Support Group (OSG) at its home in Potsdam, Germany, which provides a full suite of services for initiating and planning scientific drilling projects, as well as managing and executing them. Regular training courses on handling, studying and interpreting drill cores and well logs are also part of their repertoire.

As many projects have shown, drilling for scientific purposes is an enormous and time-consuming challenge. Despite all the difficulties: Drilling into our planet's crust is one of the most compelling frontiers in Earth science today. The adventure of drilling may help us to solve a few of the many mysteries which have been hiding for millions of years in the dark terra incognita deep beneath. ■

The projects of ICDP:

Lake Baikal Drilling Project · Long Valley Exploration Well · Hawaii Scientific Drilling Project · Koolau Scientific Drilling Project · Lake Titicaca Drilling Project · Chinese Continental Scientific Drilling Project · Chicxulub Scientific Drilling Project · Mallik Gas Hydrate Research Well · Gulf of Corinth Rift Laboratory · San Andreas Fault Observatory at Depth · Unzen Scientific Drilling Project · Taiwan Chelungpu Fault Drilling Project · Lake Botsumtwi Drilling Project · Outokumpu Deep Drilling Project · Lake Malawi Drilling Project · Drilling Active Faults in South Africa Mines · Iceland Deep Drilling Project (IDDP-1) · Lake Quinghai Drilling Project · Chesapeake Bay Drilling Project · Lake Peten Itza Drilling Project · Fennoscandia Arctic Russia Drilling Early Earth Project · Potrok Aike Maar Lake Sediment Archive Drilling Project · Lake El'gygytgyn Drilling Project · New Jersey Coastal Plain Drilling Project · Lake Van Drilling Project · Dead Sea Deep Drilling Project · Snake River Scientific Drilling Project · Barberton Drilling Project: Peering into the Cradle of Life · Lake Ohrid Drilling Project · Colorado Plateau Coring Project · Collisional Orogeny in the Scandinavian Caledonides · Hominin Sites and Paleolakes Drilling Project · Deep Fault Drilling Project · Lake Towuti Drilling Project · Geophysical Observatory at the North Anatolian Fault · Lake Junín Drilling Project · Deep drilling of the Chalco Basin, Valley of Mexico · Chicxulub Drilling the K-Pg Impact Crater (jointly with IODP) · Songliao Basin Drilling Project · Lake Challa Drilling Project · Iceland Deep Drilling Project (IDDP-2) · Koyna Drilling Project for reservoir triggered seismicity · Oman Ophiolite Drilling Project · Surtsey Volcano Drilling Project (SUSTAIN) · Drilling Into Seismogenic Zones In Deep South African Gold Mines (DSEIS)

Did you know? *Drilling is not confined to the Earth's continents and oceans. NASA's rover Curiosity has drilled a short hole into the Gale Crater on Mars. But what would we find if we could do more extraterrestrial scientific drilling? What lies under the polar ice caps of Mars or under the surfaces of the icy moons of Jupiter and Saturn?*

Published by:
International Continental
Scientific Drilling Program
GFZ German Research Centre
for Geosciences, Potsdam, Germany

Editors Ulrich Harms, Thomas Wiersberg
Text Horst Rademacher
Design and Layout Dirk Biermann, Potsdam
Printing GS Druck & Medien GmbH

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This driller is not leaning sleepyly against the drill string. Instead he is listening intently for signals from the deepest section of the borehole. When drilling a core, the rocks have to be captured in the core barrel at the end of the drill string. When the barrel latches close, it makes a characteristic click against the drill string. Using his wrench as a hearing aid, the driller waits until he hears this click, before he lifts the string out of the hole to safely retrieve the core. Such cores are at the heart of most ICDP drilling projects.

INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

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www.icdp-online.org