the thrill to drill

After a decade of
International Continental Scientific Drilling:
A prospect for the future
Lake Baikal Drilling Project  
Siberia, Russia; December 1997 until April 1998

Long Valley Exploration Well  
California, USA; July until September 1998

Hawaii Scientific Drilling Project  
Hawaii, USA; March to September 1999

Koolau Scientific Drilling Project  
Hawaii, USA; April to June 2000

Lake Titicaca Drilling Project  
Bolivia; April and May 2001

Chinese Continental Scientific Drilling Project  
Jiangsu, China; July 2001 until March 2005

Chicxulub Scientific Drilling Project  
Yucatan, Mexico; December 2001 to February 2002

Mallik Gas Hydrate Research Well  
NW Territories, Canada; December 2001 to February 2002

Gulf of Corinth Rift Laboratory  
Greece; June to September 2002

San Andreas Fault Zone Observatory at Depth  
California, USA; since June 2002

Unzen Scientific Drilling Project  
Kyushu, Japan; from 2002 to 2004

Taiwan Chelungpu Fault Drilling Project  
Taiwan; January to December 2004

Lake Bosumtwi Drilling Project  
Ashanti, Ghana; July to October 2004

Lake Malawi Drilling Project  
Malawi; February to March 2005

Drilling Active Faults in South African Mines  
Gauteng, South Africa; since April 2005

Iceland Deep Drilling Project  
Iceland; pilot coring in April 2005

Lake Qinghai Drilling Project  
Qinghai, China; August and September 2005

Chesapeake Bay Drilling Project  
Virginia, USA; September to December 2005

Lake Peten Itza Drilling Project  
Petén, Guatemala; February and March 2006

www.icdp-online.org
We think we know our planet, the Earth. We can visualize the roads, buildings, and natural features in our immediate neighborhood without much thought. We recognize mountains and coastlines in far away places where we may have once vacationed. Detailed maps, aerial pictures, satellite images, and the ubiquitous Google Earth give us the impression - albeit false - that no place on our planet remains unexplored. But who knows what it is like within the earth beneath our feet? A child playing in a sandbox feeling the urge to explore this underworld tries to dig a hole “to the center of the earth”. Geologists study every road cut, where machines and men with dynamite have exposed the layers of rock normally hidden beneath soil and thick vegetation. Geochemists analyze the lava that volcanoes have belched forth from the magma reservoirs deep within the earth. When rivers, with the raw power of moving water, carve their way through solid rock they reveal the earth of a bygone era. But even the 1.2 billion years of the earth’s history exposed by the powerful Colorado River in the Grand Canyon of Arizona is a mere scratch in the surface of our planet. No less is true of the deep pits miners have dug through layer upon layer of rock to reach the mineral riches of a coal seam or a mother lode. Even after more than 250 years of scientific geological investigation, it is still fair to say, that terra incognita begins indeed just a few dozens of meters beneath our feet.

The desire to explore this dark underworld goes beyond an academic interest in understanding the building blocks and structure of the planet whose surface we inhabit. The rocks beneath our feet are the source of the hidden dangers lurking in earthquakes and volcanic eruptions. Deep layers contain detailed information about the face of the earth millions of years ago, about the climates that once reigned and the geographical distribution of oceans and continents. Such information about the past is necessary so that humankind can prepare for the future. How can we mitigate the risks posed by earthquakes and volcanoes, and how can we deal with the inevitable climate change, without learning from the past? Deep layers of the earth also contain detailed information about how rocks form, how certain minerals become enriched and others depleted, knowledge which can help us to exploit the resources of our planet in a more sophisticated and at the same time more sustainable way.
Models and reality

But how can we get information about these deep layers? Geophysicists use seismic rays and electromagnetic waves to figuratively peel away the layers of the earth. These methods are similar to the various diagnostic techniques now used by physicians to peek into the human body without the need of a needle or scalpel. Geochemists, mineralogists and petrologists study the rocks which they believe were once part of the interior of the earth. And while comparing the earth with other bodies of the solar system, planetologists develop analogues for the structure of our planet. But the plethora of information gathered by all these means leads at best to models and hypotheses about the Earth’s interior. Until we can look more closely using robots which extend the reach of our senses, unless we can gather material from great depth under controlled circumstances, we will not be able to verify how reliable or misguided these ideas are which have been developed to explain the mysteries of the world beneath our feet.

By today’s standards the radius of the Earth, 6,374 kilometers, does not constitute an insurmountable distance. In fact, a jet plane flying between New York and Berlin covers almost the same span in less than eight hours. A traveler moving from one place to the other will notice definite changes in the language spoken, in the climate and certainly in the food served. But the overall conditions which make the planet habitable, like the chemical composition of the air, the barometric pressure and even the force of gravity, do not change enough to be noticeable. But, on a descent into the bowels of the earth, one enters a truly different world. However eloquently this story has been told by Jules Verne and other authors of science fiction, these writers were dead wrong. Even a few kilometers below the earth’s surface, the conditions are more than inhospitable. The temperature of the rock reaches 100 degrees Centigrade – the boiling point of water at the surface – at a depth of less than four kilometers. Less than one percent of the way to the Earth’s center, the lithostatic pressure - the weight of the rocks above you – has already become so large that it will crush the strongest steel. Gaining access even to moderate depths is therefore a unique and difficult technical challenge.

Deepest hole

One way to explore the dark underworld is by drilling. Since the invention of the rotary drill 100 years ago, men have pushed the limits of this technology deeper and deeper into the earth. The current record was captured by Russian technicians when their drilling equipment penetrated 12,262 meters deep into the earth beneath the Kola Peninsula in the Arctic. Their borehole “SG-3” beat the previous record holder, the gas well “Bertha Rogers 1-27” in Oklahoma (completed in 1974), by almost 2.7 kilometers. Until recently most boreholes on land, like the “Bertha Rogers” were drilled for the exploration and production of either hydrocarbons or water. Boreholes for purely scientific research were few and far between. In contrast, in the late sixties already, the community of marine geologists agreed that no single country could afford the enormous costs associated with the logistics of scientific drilling into the ocean floor. Building and operating a drill ship was just too expensive, even for economic powerhouses like the United States. The science funding organizations of more than a dozen countries have joined forces in the “Integrated Ocean Drilling Program” (IODP) to coordinate and implement the use of drill ships on the seven seas. For drilling on the continents, however, for a long time each country acted alone. Aside from issues of territory and sovereignty, one nation might not want others to know about the resources deep under its land or its technological capabilities for deep drilling. And when companies drilled, they definitely had no desire for their competitors to gain access to their findings.

This attitude changed in 1987, when Germany began a deep drilling project in the Oberpfälz, a remote region with old, crystalline rock in the southeast corner of the country. During the ten year duration of the “Continental Deep Drilling Program” - KTB for short after the German name - the scientific community drilled a pilot hole four kilometers deep and later the main hole to a depth of 9101 meters. In contrast to previous continental drilling projects, international cooperation in interpreting the findings was encouraged, access to the data was open, and measurements from many different fields of the Earth Sciences were integrated in order to make the most of the results.
ICDP’s founding
Building on KTB’s success and buoyed by the reunification of Germany in 1990, the GeoForschungsZentrum (GFZ) in Potsdam took the lead in establishing a coordinating committee for continental scientific drilling. In the late summer of 1993 more than 250 experts from 28 countries convened for the first “Potsdam Conference on Continental Scientific Drilling” and discussed the rationale for an international program. Less than three years later, on 26 February 1996, representatives of the US National Science Foundation, the Chinese Ministry for Land and Resources, and the German “Deutsche Forschungsgemeinschaft” signed a Memorandum of Understanding, in which they established the International Continental Drilling Program (ICDP). In the ten years since, its membership has grown to 13 countries and two organizations, while four more countries are currently negotiating joining.

Member Countries
Germany  USA  Japan  China  Canada  Austria  Mexico  Norway  Poland  Czech Republic  Iceland  Finland  South Africa

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The mission of ICDP is summarized in the 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.”

Eight themes
From this rather abstract statement the members have developed eight important scientific themes for which continental drilling can provide insights. To become eligible for funding and support by ICDP, a drilling project must aspire to investigate one or more of these themes. They are:

1. Climate Change and Global Environment
2. Impact Structures
3. Geobiosphere and Early Life
4. Volcanic Systems and Geothermal Regimes
5. Mantle Plumes and Rifting
6. Active Faulting
7. Plate Collision Zones and Convergent Margins
8. Natural Resources

After a decade of the ICDP, 19 drilling projects on five continents have been completed, and several others are either in operation or have been approved by the program’s Science Advisory Group and its Executive Committee. The projects - several of which are highlighted in this brochure - range from drilling into what is probably most famous earthquake fault in the world, the San Andreas Fault in California; through peering into active volcanoes, like Mount Unzen in Japan or Krafla on Iceland; to coring the sediments in lakes on the Altiplano in the Andes or in the tundra of Siberia. Through these projects ICDP has truly become an international endeavor integrating not only nearly all aspects of the Earth Sciences, but also scientists from various countries with a variety of cultural, ethnical and academic backgrounds.
No topic in Earth science is currently as politically charged, and at the same time as important to society, as the issue of Climate Change. Not only pessimists are worried about the consequences of global warming. What will happen when - if the results of model calculations are correct - the average surface temperature of the planet rises by several degrees Centigrade within the next few centuries? Given the shrieking alarmism surrounding the issue, most people seem to forget or are perhaps not even aware, that the Earth is a planet of constant change. Since its formation 4.5 billion years ago, climate, ocean currents, the distribution of land and sea, the shape of the Earth’s surface, the rocks exposed - nothing ever stayed the same for a long time. Global change, even on a rapid scale is inevitable and has led to many catastrophic events during the Earth’s past.

The most recent of these dramatic changes happened 12,000 years ago - a mere blink of the eye on the scale of geologic time - at the end of the last northern Ice Age. Where cities like Stockholm, Moscow, Berlin, or Toronto exist today, ice sheets several kilometers thick covered the land. Globally, the sea level at the time was almost 100 meters below the current mean, exposing land bridges across the Bering Strait between Asia and North America, and across the North Sea between the Netherlands and Great Britain. Many large embayments in today’s oceans, such as the Gulf of Mexico or the Bay of Bengal, were considerably smaller and the adjoining land was correspondingly larger. Even on a small scale, geography in many places was completely different from today. For example two of today’s most spectacular anchorages in the world, the San Francisco Bay and Sydney Harbor, were dry land. The Golden Gate, spanned by undoubtedly the most famous bridge in the world, was a waterfall. There, California’s Sacramento River cascaded in to a flat marshland, before flowing into the Pacific Ocean 30 kilometers further to the west.

Rising seas
In an extremely short span of time, perhaps fewer than a thousand years, the Pleistocene landscape changed and became the surface of the Earth we know today. Islands and low lying coastal regions were flooded by the relentlessly rising sea. On the continents, land which had been covered by ice for thousands of years emerged from beneath the vanishing glaciers. This land, however, was not a pretty sight. Regions just liberated from the ice emerged as thousands of square kilometers of barren surface covered by sand, silt and gravel. In other parts of the world, weather and climate patterns changed profoundly, arid areas became wet and the climate in places where it had rained most of the time became moderate or even dry.

Humans, of course, witnessed these rapid and in many cases brutal changes in the environment - but our nomadic ancestors must have adapted to them with relative ease. They moved to better hunting grounds, and found areas were there was still enough food to gather. The few million people, who may have lived scattered across the globe at the end of the Pleistocene, will certainly have suffered some. The global change, however, ushered in the relatively stable climate period of the Holocene - allowing the human race new opportunities for rapid development.

Obviously, the 6.5 billion people of today, most of them living in megacities and densely populated coastal regions, cannot adapt as easily to climate change as our nomadic forebears. It is therefore very important to be able to predict the consequences of climate change. That, however, can only be achieved by understanding the many different permutations of global change during the Earth’s history. Although most episodes of change and stability are long past, many have left unmistakable traces deep in the ground. Some of the best archives 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.

Pristine sediments
One prime example of such a water body is Lake Bosumtwi in Ghana. This almost perfectly circular lake has a diameter of 8 kilometers. Its maximum depth is about 80 meters, although lake sediments extend more than 300 meters below the current lake bottom. Lake Bosumtwi was formed just over one million years ago immediately after its recovery scientists inspect a core of lake sediments on board the floating drill platform GLAD800.
by the impact of a large meteorite. Two factors have preserved the lake’s sediments in an undisturbed condition, its relatively high crater rim and the fact that no river flows either into or out of it. This makes it unique and ideal for climate studies. Because the lake is located in the monsoon zone of Western Africa, its sediments should hold the key to understanding the development of the climate in this part of the world - the yang and yin of monsoon and Sahel drought - during the last million years.

Between July and October 2004 the floating drill platform GLAD800 was brought to Ghana and more than two dozen holes were drilled into the lake bed. More than 1800 meters of sediment core were recovered for climate studies. The longest single core consisted of 294 meters of laminated mud. The pollen, detritus and minerals in each layer - a varve - gives information about the weather and environmental conditions of one year. To scientists, such varved layers are like a book, with each page holding the secret of the former climate. Because Lake Bosumtwi is actually a lake filling an impact crater, several holes were drilled through the sediment into the underlying, 2.2 billion year old rocks of the West African craton. As in the case of Chicxulub (see chapter “Impacts” pg. 8), the layers between the sediment and the basement rock have revealed details about the impact itself.

Almost 10,000 kilometers west of Lake Bosumtwi, on the other side of the Atlantic Ocean, lies another small body of water. It holds the key to the history of climate in the tropics of Central America. Hidden in the jungle of the lowlands of northern Guatemala, Lake Peten Itza is something of a complement to Lake Bosumtwi, half a world away. Both lakes are located in the Intertropical Convergence Zone, the region of moist tropical climate, whose position shifts during the year. This leads to a highly seasonable rainfall pattern in both locations. Researchers hope by comparing the varves of Lake Peten Itza with those of Lake Bosumtwi, they can find similarities and differences in the climate patterns of tropical Africa and its Central American counterpart. Again using GLAD800, nine holes were drilled into the sediments of Lake Peten Itza in early 2006. They revealed that during the last twenty or thirty thousand years, the climate in the lowlands of Guatemala rapidly changed several times, from dry to very moist and back. The most drastic such change occurred at the end of the last ice age, when the glaciers thousands of kilometers to the north melted. And even the onset of human agriculture as well as the decline of Mayan cultures due to droughts is archived in the sediment layers of the lake.

Sediments from Lake Qinghai on the northeastern margin of the Tibetan Plateau (satellite image, top right) were recovered during the drilling campaign in 2005.

A view below the bottom of Lake Peten Itza in Guatemala: this seismic profile shows the regular, undisturbed pattern of sedimentary layers. The black vertical lines represent actual holes drilled in early 2006 (middle).

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A digital elevation model showing Lake Bosumtwi in Ghana without sediment and water infill (right). The sediments of this closed basin contain a very sensitive climate signal of the tropics. Cores were drilled in 2004.
Impacts

Impact Structures

They are a staple in many science fiction novels. Sometimes even serious emergency planners wonder whether a well-placed thermonuclear weapon could be used to knock out these vagabonds of the Solar System in order to save mankind. We are talking about wayward asteroids, traveling through space at a velocity of thousands of kilometers per hour on a collision course with Planet Earth. Although the likelihood of such an impact happening in anyone’s lifetime is extremely rare, it is by no means zero. During the 4.5 billion year history of the Earth, many such celestial collisions have indeed taken place. For instance, the fact that the rotational axis of the Earth is tilted with respect to the plane of the ecliptic is most elegantly explained by an impact during our planet’s earliest existence. The moon, it is hypothesized, was knocked out of the baby Earth by another such collision. Asteroids and meteorites have hit the Earth’s surface even in recent times and left behind unmistakable traces. 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. Currently a total of 174 of such impact structures have been discovered by scientists, not only on the continents but also at the bottom of the sea.

Depending on the size of the celestial body, the effects of a collision with the Earth can be truly devastating. Upon impact, the kinetic energy of the asteroid converts almost entirely into a shock wave and an enormous amount of heat. The inferno can be strong enough to vaporize layer upon layer of the Earth’s crust within minutes. The consequences are dire indeed. Not only does the melting leave a deep scar in our planet’s surface. Billions of tons of dust and ash are ejected into the highest layers of atmosphere, dimming or completely blocking out the sunlight for decades. The scenario of a “nuclear winter”, which was played out during the Cold War, is - one almost dare not say - peanuts compared to the effects of meteorite impact.

The end of the dinosaurs

Geologists believe that at least twice during recent geologic times, such impacts have wiped out major portions of the fauna and flora on the Earth. These events were strong enough to define the transitions from one era of the Earth’s history to another. About 250 million years ago, one collision probably wiped out about 90 percent of the species living in the ocean and nearly three quarters of all land animals, among them 70 percent of all families of amphibians and half of the insect species - and thereby bringing us from the Paleozoic to the Mesozoic era. 185 million years later, at the boundary between the Cretaceous and the Tertiary, another hit by a meteor ended the era of the dinosaurs and gave rise to the dominance of the mammals.

Not all the geomorphological remnants of impacts can be recognized as easily as the craters in southern Germany or Arizona. Particularly in wet climates, erosion takes its toll very quickly. The craters left behind by an impact are filled by rocks of the surrounding hills. Even more importantly, the debris generated by the enormous heat and pressure during impact is buried under otherwise common soil and thereby escapes the sharp eye of the field geologist. This debris 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.

Hidden craters

Although the effects of erosion may bury a crater, the impacts have usually been strong enough to leave behind traces which can be picked up by other means. Under the right lighting conditions, an impact crater may show up as a circular structure on satellite images. Buried craters can also be detected during geophysical surveys, when they expose themselves through gravitational or magnetic anomalies. Such circular anomalies under the tip of the Mexican Yucatan Peninsula raised the interest...
of petroleum geologist Antonio Camargo more than 25 years ago. In the search for oil, he collected geophysical data in the sea off the northeastern Yucatan coast. He found anomalies with a radius of almost 100 kilometers that were centered on the coastal village of Chicxulub. For many weeks Camargo wondered what might have caused these giant circles. The rock formations were not right for them to be of volcanic origin, so another explanation was needed. Could they be the remnants of an impact crater? Since Camargo’s discovery, it has become clear that the circular structure is indeed an impact crater, buried beneath an almost one kilometer thick layer of limestone. Its age, roughly 65 million years, puts it at the Cretaceous-Tertiary boundary. Many other facets of scientific evidence suggest that it is very likely to be the crater left behind by the killer asteroid which is associated with the demise of the dinosaurs.

Because of the importance of this impact structure, ICDP’s Executive Committee decided to authorize a drilling proposal into the crater’s rim, approximately 62 kilometer off its center. During the winter of 2001/2002 the well “Yaxcopoil-1” was drilled about 40 km southwest of Mérida, Yucatan’s capital. It reached a depth of 1,510 meters. The top 795 meters consisted of post-impact Tertiary carbonate rocks, and in the bottom 615 meters, the drill went through pre-impact Cretaceous rocks. Sandwiched between them was a one hundred meter thick layer of impactites, composed of suevitic and impact melt breccias. They were no longer fresh by any means, as they have gone through significant chemical alteration during the last 65 million years.

Treasure trove
More than 900 meters of the well were cored and the whole well was logged by means of wireline geophysics to obtain a continuous set of in-situ petrophysical data of the borehole wall. The recovered rocks and the logging data have become a treasure trove for geologists, not only those who study impact structures but also those interested in the transition from one era of Earth’s history to the next.

Since the successful completion of the Chicxulub well, two more impact structures have been penetrated under the guidance of ICDP:

In 2004 scientists drilled into the sediments and rocks under Lake Bosumtwi in Ghana (see chapter “Climate”, pg. 6). One year later a 2,200 meter deep well was drilled into the seventh largest impact crater, and one of the best preserved on Earth: that under Chesapeake Bay at the east coast of the United States. Among the impact targets for future drilling are Lake El’gygytgyn on the Chukotka peninsula in the extreme northeastern tip of Siberia, the Sudbury crater in Canada’s Ontario province, the Mjølnir Crater in the Central Barents Sea off Norway.
Life is abundant on Earth. Myriads of creatures live in the tropical rainforests, from top-of-the-food-chain predators to birds and insects, from microscopic fungi to majestic hardwood trees. A coral reef is an example of an environment similarly rich in living organisms in the coastal regions of the oceans. Microorganisms and bacteria with a surprising spectrum of variability dominate the world of even a small compost heap. The zone on Earth in which living organisms can exist is called the biosphere. It is commonly defined as a very thin boundary layer encompassing the immediate surface of the Earth. The record altitude set by birds of prey while soaring effortlessly in thermal updrafts is typically considered to be the biosphere's upper limit. Where humus-rich soil hits bedrock, mostly just a few meters below the surface, may be viewed as its lower boundary. But are these definitions correct? There are many indications, that the biosphere reaches much deeper into the interior of the Earth than is commonly thought. Some scientists even speculate that this so-called deep biosphere harbors a greater biomass than the mass of all the living cells, prokaryotic and eukaryotic, in the “classically” defined biosphere along the surface of the Earth, taken together.

Deep in the Earth’s crust one cannot, of course, expect to find giant flesh-eating reptiles, like those Jules Verne’s character Professor Von Hardwigg encountered in his “Journey to the Center of the Earth”. But there are several scientific findings which suggest that life deep beneath our feet is indeed unexpectedly abundant. One previously unknown type of life was discovered in the 1970’s. Then, extremophiles were found, microorganisms which live under conditions commonly thought to be sterile or at least very hostile to life. Among the first recognized were thermophiles in the hot springs of Yellowstone National Park. These bacteria and archaea can survive temperatures of 50 degrees Centigrade or more. Another kind of thermophiles, some chemosynthetic archaea, was later discovered around the submarine hydrothermal vents along the Galapagos Rift, a spur of the East Pacific Rise. These microbes gain their metabolic energy not from photosynthesis, but by oxidizing methane or inorganic molecules, like hydrogen sulfide. By now at least a dozen different classes of extremophiles have been studied, ranging from acidophiles to xerophiles. Acidophiles are organisms which thrive in extremely acidic liquids with pH levels at or below 3, while xerophiles can grow in utterly dry, desiccating conditions, for example in the soils of the Atacama Desert.

A helicopter was needed to ferry supplies to the Mallik drill site in the Mackenzie River Delta in northern Canada. Three wells were drilled during the winter months 2001/2002.

Geothermal yardstick
Currently the known upper temperature limit for life anywhere in the Earth’s biosphere is 121 degrees Centigrade. The upper limit has climbed to higher and higher temperatures over the years, as new extremophiles are cultivated from increasingly hot environments. On the basis of this temperature, one can estimate the limits within the Earth of thermophilic living conditions. As anyone who has ever visited a deep mine knows, it gets hotter the deeper you go. Geothermal gradients, the yardstick for this increase in temperature, fall in the range from 10 to 60 degrees Centigrade per kilometer. Combining the upper temperature limit for life and geothermal gradients with mean surface temperatures lying between 0 and 25 degrees Centigrade, we find thermophiles could exist all the way down to 12 kilometers below the surface. Methane is most likely to be the “food” for these bacteria.

This simple hydrocarbon is also abundant in the permafrost regions of the Arctic, not as a gas but - together with water - as a solid. Some consider these gas hydrates an important energy source for the future. Others see in them a threat to our current climate, because if the hydrates melt, large amounts of the greenhouse gas methane will enter the atmosphere. It has also been speculated 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 in the Mackenzie Delta of the northwestern Canadian Arctic with ICDP’s support. There a gas hydrate rich layer more than 200 meters thick is buried in 900 meters depth under the permafrost. Methane loving microbes were found in several cores gathered during the drilling campaign in 2002. Because their concentration was considerably lower than expected, the results added to the mystery of extremophiles in the deep biosphere.
Earthquakes and bacteria

Even more exotic than microbes living in gas hydrates is a hypothesis suggested for the Eger Graben, a rift structure in the region where Germany and the Czech Republic border each other. There researchers found a strong correlation between the intensity of an earthquake swarm and the content of methane in spring water: The more small earthquakes happened, the higher the methane concentration. The link between the two seemingly unrelated occurrences is probably bacteria which live deep underground. With each new earthquake, small cracks form in the granite basement of the Eger region. The hydrogen, which forms when natural radioactivity in the rock dissociates water into its two components, can then escape. It in turn is gobbled up by bacteria at depth, which produce methane as a byproduct of their metabolism. The more earthquakes, so the logic goes, the more hydrogen is released, the more the bacteria have to “eat” and the more methane they produce. Finding these bacteria and studying their metabolism is one of the goal of a drill project suggested for the Eger Graben.

Although the current thermal threshold for extremophile life at 121 degrees Centigrade has been penetrated by many drill holes, so far nobody has investigated where the lower limit of the biosphere really lies. That will certainly change in the future because microbial investigations can augment practically every drilling project. However, for such projects some precautions are necessary in order to prevent contamination of a drill hole with microbes from the surface. With such measures, the drilling operations can yield important results, which will add to our understanding of the mysteries of the deep biosphere.

Bacteria are probably the cause for the higher methane content of mineral springs in the Eger Rift, a graben structure in the German-Czech Border region. Hydrogen released by earthquake swarms (shown in a three-dimensional graph, top) provides the energy for the microbial metabolism.

Sterile handling and fluid extraction are necessary to recover microbiological life from drill cores (middle).

Frozen methane, also known as gas hydrates, clearly shows as red layers in this seismic section (right). The microbes growing in these hydrate layers are part of the deep biosphere.

the thrill to drill
Aside from earthquakes, the Earth shows the destructive forces originating within itself nowhere more spectacularly than in erupting volcanoes. Cubic kilometers of solid and liquid rock may be pulverized into gigantic plumes of ash and fine particles within just a few hours. With a deafening roar, these particles are ejected from a volcano’s throat with the speed of a racing car, generating ash clouds which rise all the way into the stratosphere. During the eruption of Mount Vesuvius in southern Italy in 79 A.D., a dozen cubic kilometers of rock were pulverized. More than twice that amount was ejected almost a hundred years ago, when Novarupta in a remote region of Alaska blew. In the most powerful eruption recently witnessed by man, Tambora on the Indonesian island of Sumbawa exploded mightily in 1815. Within a few days, a 3,000 meter high mountain became a one kilometer wide, gaping hole in the ground, a caldera which is now partially filled by an ocean bay. The 50 cubic kilometers of ash which Tambora spewed into the atmosphere dimmed the sunlight for years to come, causing famine all over the world.

The enormous power of a volcano is not an abstract force affecting only remote or sparsely populated regions of the world. In the past 500 years, more than 200,000 people have lost their lives due to volcanic eruptions. During the last century alone, an average of 845 people died each year from volcanic hazards. And the total value of property destroyed by volcanoes cannot be tallied in monetary units. Even small eruptions, like that at Mount St. Helens in the American state of Washington in May 1980, may leave behind a zone of complete devastation, covering dozens to hundreds of square kilometers.

Prediction
To reduce the hazard posed by the approximately 600 active fire mountains in the world is one of the goals of volcanology, a multifaceted, interdisciplinary branch of the Earth sciences. Researchers working in the field have found ways to monitor volcanoes closely enough to detect signs of imminent eruptions. During the last decade or so, many lives have been spared, because scientists were able to predict the activity of dangerous volcanoes. Nonetheless, sometimes even the most experienced scientists are still caught in the violence of an eruption.

Only a small fraction of the volcanologists need to do their work in the immediate proximity of an erupting fire mountain. Much of what we know today about the inner workings of volcanoes is inferred from the study of rocks and deposits, laid down in eruptions long ago. Through mineralogical and petrological investigations of volcanic and igneous rocks researchers can extract information about the temperature and the chemical composition of the melt in a former magma chamber. Geologic surveys of the immediate neighborhood of a volcano can determine its reach. Knowing how far lava streams and pyroclastic flows have worked their way down the flank of a volcano in the past, can help to determine the extent of possible danger zones in future eruptions.

Ground truth
However scientists look at it, either from within a volcano’s danger zone or from afar at a dormant fire mountain: Volcanic regions are peep holes into the hellfire burning within the bowels of the Earth, looking glasses which may 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 volcanology: 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 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?

Scientists and drill operators were literally playing with fire, when they sank several drill holes into Kilauea Volcano in Hawaii. It had erupted in 1959 with spectacular lava fountains and left behind a lake of molten lava. Within a few weeks, the lake had a thin crust of solidified rock. Only one year after the eruption had subsided, a drill rig was mounted on this precariously thin layer of rock. Researchers wanted to find out if the lava underneath was still liquid. Barely 7 meters below the surface, the drill bit encountered molten lava at almost 1100
degrees Centigrade - a unique drilling record, which still stands more than 40 years later.

Pyroclastic flows

Attempting to break that record never entered into the minds of an international team of scientists, who in April 1999 decided to drill - with ICDP’s help - into Mount Unzen in Nagasaki province on the Japanese island of Kyushu. This mountain had erupted many times between 1990 and 1995. The devastating pyroclastic flows rushing down its flanks in these eruptions took a heavy toll on life and property. The project consisted of two phases. First, two holes were drilled into the side of the volcano in order to determine its stratigraphy, the order in which the layers of volcanic material were deposited. The information collected helped to understand the history of Unzen’s growth and its structure.

The second phase was more ambitious: The researchers wanted to penetrate the conduit through which the gas-loaded magma had roared, and from which the material had spewed which became the deadly pyroclastic flows cascading down its sides. Drilling vertically downward directly from Unzen’s central crater was not an option. Thus, the hole (USDP-4) was sunk into the volcano’s flank. Initially, the drill ground its way about 500 meters vertically into the edifice. At that point, the operators deviated the bit by an angle of 75 degrees – directing it almost horizontally. After another 1500 meters they reached the conduit and drilled right through.

Volcanic dikes

Although the magma feeders of a volcano are often called its “plumbing”, Unzen’s conduit is by no means a simple pipe. Instead, it is a 500 meter wide zone, consisting of many fingers. The degassing melt flowed through one or another of these conduits at different stages of the eruption. To everybody’s surprise, this zone was comparatively cool. The remnant temperature of the hottest finger was only 180 degrees Centigrade, less than a quarter of the searing heat of the material which had erupted until five years before. The only explanation for this dramatic decrease is that since the eruption, millions of liters of groundwater fed by the large precipita-

Drilling into an active volcanic zone helps not only to understand the fundamental workings of those fire mountains and to mitigate the volcanic hazards. Volcanic drilling can also tap the vast reservoirs of geothermal riches and help to understand the formation of mineral resources, which are a direct consequence of the fire within the Earth (see chapter “Resources”, pg. 20).

Mount Unzen (large photo below and aerial view bottom left) is one of the most dangerous volcanoes in Japan. A deviated hole was drilled into the conduit in 2003/2004 (blue line large photo).

The cores from Mount Unzen contained dacitic lava (shown in a thin section, middle right) and intruded dykes (bottom right).
The song writer of a top-ten-hit from the 1950’s wanted to make us believe that Hawaii was an “island made from dreams”. But those who have driven through the vast lava fields near the resort town of Kona on the Big Island, or who have witnessed the “waterfall” of fresh lava from Kilauea volcano into the Pacific Ocean will have realized that this Polynesian island chain has other origins. The Hawaiian Islands are born from deep within the Earth, from a melt of rocks which rises directly out of the Earth’s mantle, dozens of kilometers beneath the volcanic summits on the islands.

While tourists watch in awe as glowing lava oozes down Kilauea’s slopes, scientists are puzzling over these fire mountains in the Central Pacific. Most of the 600 or so active volcanoes of the world are located at the margins of the big lithospheric plates which make up the Earth's crust. Take the volcanoes of Italy for example, like enormous Mount Etna in Sicily, restless Stromboli in the Tyrrhenian Sea or dangerous Vesuvius, which threatens Naples and its neighbors. They are located along the boundary between the African and the European Plates. Mount Unzen in Japan, whose conduit was penetrated by an ICDP drilling project (see chapter “Volcanoes” pg. 12), lies at the edge where the Pacific meets the Eurasian Plate. The volcanoes of the Andes, like giant Cotopaxi in Ecuador and Villarica in Southern Chile, dot the demarcation line between the Pacific and the South American Plates. Volcanism at these convergent margins occurs, according to the theory of plate tectonics, because in these areas crust is subducted into the mantle. As a consequence the crust melts and - simply put – the hot, molten rocks become buoyant and make their way back to the surface, where their eruptions build volcanoes.

Perforated seams
Even Iceland, like Hawaii an island in the middle of an ocean, is located on a plate boundary straddling the margin between Europe and North America. This is a divergent margin, however, where the two plates move away from each other. They leave behind a region of very thin crust. Molten mantle rocks can easily push through this zone of weakness and give birth to islands like Iceland or the Azores. In general, the edges of the plates, whether convergent or divergent, can be considered to be the perforated seams in the Earth's crust through which magma can ascend all the way to the surface.

In contrast, Hawaii is far away from any of these seams. Between the island chain and the closest plate boundary in California lie approximately 3,000 kilometers of nothing other than solid Pacific Plate. How in the world, ask many scientists, can volcanism occur so far away from all known volcanic zones? One of the keys to answering this question can be found to the west and north of the Big Island of Hawaii. Looking at the ages of its sisters to the northwest, researchers recognized that the islands become older, the further they are from the currently active volcanoes. The rocks on Maui, the Big Island’s immediate neighbor, are about 1, those under Honolulu on Oahu about 3.5 millions years old. This relationship between age and distance continues all along the chain of shoals, reefs and seamounts to the northwest of Hawaii until it reaches 81 million years at the end of the Emperor Seamounts close to the Aleutian Trench.

Magmatic blow torch
About 35 years ago a hypothesis was proposed to explain this relationship. A narrow plume of very hot, molten magma is supposed to rise from deep within the mantle. Like a blow torch, its melt burns through the oceanic crust above. Although the plate above this “Hot Spot” moves, the plume itself is extremely steady and very stable. The result is a line of torch holes, an island chain, with volcanoes lined up like a string of pearls.

While the hypothesis about Hot Spots sounds logical and seems to make sense, it is just that, a hypothesis which has not yet been proven. Several other mechanisms for explaining the origins of the Hawaiian and other island and seamount chains in the Pacific have been proposed and experts are still discussing the issue, sometimes rather heatedly.

Longest core
Drilling is one of the means scientists are using to try to solve the mystery of Hawaii’s origin. In 1999 a drill rig was set up on the Big Island, near the airport in Hilo, to begin the Hawaii
Scientific Drilling Project. The long-cooled lavae from Mauna Kea were penetrated in stages and the hole has reached a depth of 3,340 meters in the year 2004. As the drillers have brought up an almost complete core, the recovered rock samples provide the longest continuous stratigraphic record from any ocean island volcano, dating back at least 600,000 years. This core not only reflects the structure of the volcano itself, it is also a detailed sample 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, which taken together give a detailed picture of the development of the Hot Spot.

Hot spots are considered to be responsible not only for island and seamount chains, but also for the massive episodes of volcanism which flooded several large areas on the continents. The Deccan Traps, for example, cover a large region in central India, while flood basalts are the "base rocks" of a major portion of Siberia north of 60 degrees latitude. It is deemed possible that mantle plumes were able to burn holes through the thick continental crust and then flood the surface with mafic lavae, generating what are now called "Large Igneous Provinces". Another such area covers parts of Idaho, Washington and Oregon in the northwestern United States. There, according to the Plume-Hypothesis, the Columbia and Snake River basalts are associated with the hot spot which currently feeds the volcanoes and geysers of Yellowstone National Park. By drilling into these massive basalts, researchers hope to solve some of the mysteries which still surround Hot Spots.

Volcanic glass and alteration minerals in a core recovered from drilling though Mauna Kea's lava under the microscope. The mineralogical features are shown in detail (large picture above).

The Hawaiian Islands (map above) drifted over a plume of molten magma reaching all the way to the boundary between the Earth's mantle and its outer core.

A geologic sketch of Mauna Kea (left). Counting from the bottom of the Pacific Ocean, this Hawaiian volcano is the most massive mountain in the world.

the thrill to drill
Predictions, the Danish atomic physicist Niels Bohr once said, are very difficult, especially those about the future. While Bohr’s skepticism applies to all fields, most scientists keep trying to look into the future anyway. More than 20 years ago earthquake researchers Bill Bakun and Allan Lindh from the United States Geological Survey (USGS) dared fate. In 1985 they forecast that within the following eight years an earthquake of magnitude 6 would strike along the San Andreas Fault under the small California town of Parkfield, halfway between San Francisco and Los Angeles. More than eleven years after the prediction had expired, the town was finally shaken by just such an event. On a Tuesday morning near the end of September 2004, an earthquake with the predicted magnitude of 6 struck - and luckily did not cause any harm.

Given the fact that the quake happened so much later than forecast, one could call the prediction an utter failure. But in hindsight, it may have been the beginning of one of the most interesting endeavors in modern Earth science. The announcement in 1985 created quite a bit of excitement, especially because at the time the seismological research community was experiencing a bout of prediction euphoria. Again and again, earthquake researchers found signals or other parameters which might be interpreted as clues to approaching earthquakes. They ranged from strange behavior of livestock and pets before a quake, to shifts in the concentrations of gases dissolved in the groundwater. Parkfield looked like a perfect place to investigate all these hypotheses scientifically. Within a few years after the prediction, the region was riddled with hundreds of instruments set up by scientists from universities, research institutions and government agencies. From water levels in wells to the stresses in the crust, the instruments measured almost every conceivable geophysical parameter, even some that did not appear to have much to do with earthquakes. Parkfield’s inhabitants declared their town “the earthquake capital of the world”.

Inside a rupture zone
The San Andreas Fault is considered to be one of the most dangerous earthquake zones in the world. From the Gulf of California in the south to Cape Mendocino in the north it runs through the most populous state in the U.S. It has repeatedly produced large, damaging quakes in San Francisco and in the Greater Los Angeles area. And along most of the 1,200 kilometer-long fault, no particular pattern has been observed in the timing of events. Parkfield is the exception, with its apparently regular pattern of quakes. Although the San Andreas and many other earthquake faults have been studied for more than one hundred years, researchers still do not have a good understanding of the physical processes which take place directly in the rupture zone of an earthquake. Although modern measurement and modeling techniques allow seismologists to recreate the intricacies of an earthquake rupture after it has occurred, they have no tools to determine, when, where and how the next temblor will strike. Too few of the physical and chemical conditions within the seismogenic zone of a fault are known to be able to predict what will happen next.

During the years which passed while the Earth’s crust under Parkfield sat with hardly a jiggle, a small but determined band of scientists from Stanford University and the USGS drew up more big plans. Inspired by the KTB deep drilling project, they unveiled their new scheme: to drill deep into the most famous fault in the world. And because no other segment of the San Andreas Fault had been studied as well as the area around Parkfield, the group proposed it as the perfect spot. Drilling into an active fault is more than just a thrill for Earth scientists. They want to answer fundamental questions about the physical and chemical processes controlling faulting and earthquake generation within a major plate-boundary fault. This, on top of the basic information to be gathered about the fault’s structure, would open new doors to seismological research.

Directed drilling
Actual drilling began with a pilot hole in 2002. It was located 2 kilometers from the fault and reached a depth of about 2,200 meters. In June 2004, drilling on the main hole began just a few meters away from the pilot hole. When the drill bit reached a depth of almost 2 kilometers, project managers diverted it from its vertical path and angled it toward the fault. In August 2005, at a depth of more than 3 kilometers,
the drill bit penetrated the fault. Surprisingly, it is not a simple, relatively narrow interface where the neighboring blocks - in fact the North American and the Pacific plates - slide past each other. Millions of years of movement have generated a thick zone of fractured rock and weak crust.

In the near future the project will be extended, and several holes are planned that will penetrate the earthquake fault zone at various depths. Some of them will reach all the way into a volume, where small earthquakes occur at regular intervals. Each of these holes will be filled with instruments so that the generation of earthquakes can be recorded right at their origin. This observatory-at-depth within a seismogenic zone will be a first for geoscience.

Fault in a rift zone
The San Andreas Fault is only one of the dozen or so types of earthquake-generating boundaries in the Earth’s crust. In California, the plates slide along each other horizontally, causing strike-slip earthquakes. Other types of fault, like major thrust zones in active orogenic belts or normal faults in active rift zones, have either been drilled or are candidates for such projects. A fault in a rift zone was penetrated at the Gulf of Corinth, Greece, and in Taiwan a major fault in a collision zone was probed by drilling. Faults are even an arena for intensive collaboration between ICDP and its marine counterpart IODP, because more than 90 percent of the global seismic energy is released in subduction zones, which start at submarine trenches. The Nankai Trough off the coast of Japan is a promising site for both on-shore and off-shore fault-zone drilling. There researchers will be able to monitor fault conditions in the long term, investigate the transition from the shallow aseismic zone to deeper seismogenic regions, and study the mechanisms which generate earthquakes and tsunamis.

Earthquakes along plate boundaries can cause catastrophic damage, like this dam in Taiwan (top) after the Chi-Chi-Earthquake in 1999.

A view from underneath: This computer generated image (right) shows the hypocenters of the earthquakes along the San Andreas Fault (dots) under Parkfield and the location of the pilot hole (yellow line) drilled in 2002.
Collisions

At first glance stone and mountains are forever. Nothing seems more solid and durable than a piece of rock. Measured over timescales of years or decades, a landscape of rocky hills and fertile lowlands seems hardly to change at all. Given this perception, steep, impressive mountain ranges are time and again equated with eternity in poem and prose. But the form and composition of the surface of the Earth are far from constant. Mountains are worn down by wind- and rain-driven erosion. The forces of the weather are, however, by no means the only powers changing the surface of our planet. From deep within, the Earth itself acts much more powerfully, with forces that are far more destructive than erosion, but at the same time strong enough to create new rocks and to build new mountains. For erosion to work, the puzzle pieces which make up the Earth’s surface must first be disintegrated into small grains. Only then can these be carried away to their burial ground in valleys and sooner or later into the deep sea. The force from the Earth’s interior, on the other hand, can literally move mountains. It can push them vertically, so they grow to new heights, it can move them for hundreds of kilometers horizontally, or - in its destructive form – it can plow them deep into the Earth’s mantle, the gigantic layer between the Earth’s crust and its core.

Hot currents

It has been less than half a century since the development of plate tectonics. The powerful internal forces which can build and destroy mountains were an important element in the framework of this theory. The engine driving these forces is a set of huge convection currents which - like boiling water in a pot - circulate throughout the Earth’s mantle. The crust - actually an ultrathin veneer on the outer surface of this high temperature and high pressure maelstrom - is torn by these moving currents, split into a dozen or so continent-sized plates.

Because of the enormous heat stored within the Earth, the mantle is often described as a “deep magma ocean of molten rock”. However, while some clear evidence for localized melting has been found, the mantle as a whole is mostly not molten at all. Its rocks, in fact, have the viscosity of glass, a substance commonly thought of as rigid and brittle. But glass does flow - if one has the time to wait long enough: After a hundred years or more, a window pane will be measurably, if not visibly, thinner at the top and thicker at its bottom. On a geologic scale, in which time is measured in millions of years, such extremely slow flow rates add up to form the convection currents in the mantle. The much cooler and less dense plates of the Earth’s surface float on these currents of hot viscous rock.

Plates are squeezed

Earth scientists still do not completely understand the actual forces which drive the plate movement. Whatever the driving force, the plates ram into each other or push each other out of the way in collision zones, or convergent margins, as they are called in technical terms. In some of these zones, one plate is squeezed beneath the other in a subduction process. The descending plate can be followed down to 700 kilometers beneath the surface by observing the occurrence of earthquakes.

The deeper the rocks of the Earth’s crust are buried in these subduction zones, the hotter they become, and the more they are compressed by the pressure of the rock above and by the momentum of the collision itself. In most cases, the pressure finally grows so high that the crustal rocks lose their original identity. As pressure and heat transform the minerals, they rearrange their crystal structure or alter part of their chemical composition. This process is called metamorphosis. Since there are metamorphosed rocks everywhere we know that it must have happened throughout the Earth’s history. Every piece of marble, each chunk of quartzite and all gneiss are the products of such changes.

With the help of plate tectonics, researchers can explain with relative ease, how pieces of the crust are buried to depths where pressure and temperature are so high that metamorphosis occurs. But one of the unresolved puzzles, one may even call it the Holy Grail of plate tectonics, is the question of how the products of such changes, the metamorphites make it back to the surface of the Earth. What force is able to raise them back up from depths of 50 kilometers or more?
Diamonds and eclogite
This question is particularly puzzling for rocks which have undergone metamorphosis at “ultra high pressures” (UHP). These conditions are so harsh - a pressure of more than 20 thousand times the normal air pressure at sea level and temperatures of more than 500 degrees Centigrade - that ordinary charcoal changes to diamond and regular quartz becomes coesite.

While standard, low pressure metamorphosis is ubiquitous, this UHP process seems to be relatively rare. To date only about 20 regions or terranes in the world are known to contain rocks, which at one time in their life cycle have undergone this kind of hyper-metamorphosis. Such UHP terranes are typically identified by the occurrence of eclogite, the result of high-pressure metamorphism of mafic igneous rock (usually basalt or gabbro) as it plunges into the mantle in a subduction zone. The eclogites typically contain crystals of dark-red garnet and the very strong mineral, zircon. Because these crystals in turn contain microdiamonds and coesite as impurities, scientists are sure that they have gone through UHP-transition.

Of the twenty regions which contain UHP eclogites, China has by far the largest. The Sulu-Dabie-Altun Mountain Belt starts north of Nanjing at the coast of the Yellow Sea. It trends first towards the South and then turns west running all the way to the Altun Mountains in Western China. In total, it is more than 4,000 kilometers long. At the end of the last century, Chinese scientists decided to drill into this belt to help understand the intricacies of the UHP metamorphosis and to help solve the question of how the metamorphosed rocks move down and up again through the crust.

Zircons and coesite
Within the framework of Chinese Continental Scientific Drilling Program a site was chosen in Donghai County in Jiangsu Province near the eastern end of the giant belt. Drilling began in 2001 and when the project ended almost four years later, a hole had been sunk 5.1 kilometers deep into the heart of the mountain belt. In many of the cores brought to the surface by the drill rig, researchers found the products of UHP, namely zircons and coesites. They were generated by hyper-metamorphosis about 230 million years ago. The process must have oc-
When most people think of drilling into the Earth, they think of wells for oil and natural gas. There is no doubt that since the first oil boom hit the world, in the American state of Pennsylvania in 1859, the vast majority of wells have indeed been sunk either in the search for hydrocarbons, or to get the crude oil out of the ground and to the refineries. Nobody has ever counted all wells drilled for such purposes, but they may very well number into the hundreds of thousands. The oil industry and many wildcatters have mastered the art of successful drilling, hoping that the great expense of sinking a well will at some time in the future be more than offset by the riches of the Earth which the borehole produces.

When one adds the many holes drilled for the exploration of minerals - like coal seams and ore bodies - it is very likely that 99 percent of all deep wells ever drilled have been sunk not for scientific study but for economic purposes. Taking this, and comparing the deep pockets of the oil and mineral industry to the funding for the Earth sciences, one may very well ask why an organization devoted to the advancement of science and the understanding of the Earth, like ICDP, becomes involved with drilling for “Natural Resources”.

“We are not about to compete with industry in drilling wells with a purely economic focus,” says Rolf Emmermann, the chairman of ICDP’s Executive Committee. But he points out the synergies which are inherent when science and industry collaborate. The companies and their field support services have unbeatable experience in drilling and logging wells, and interpreting the results. At the same time, Earth scientists have an almost insatiable appetite for probing the unknown. Particularly when drilling deep, or in very rough environments with high temperatures, abrasive rocks or corrosive fluids, both groups can undoubtedly learn from each other.

Geothermal energy

However there is more to ICDP’s involvement in drilling for natural resources than just finding technological synergies in cooperating with the business world. The world’s never-ending and ever-growing appetite for energy requires new solutions in dealing with the riches the Earth’s crust holds. We all know by now that endlessly pumping crude out of underground reservoirs is not the answer to the energy needs of the future. Renewable sources must replace fossil fuels wherever possible. As in the case of coal, oil and gas, by far the greatest reservoirs of renewables lie within the Earth itself. According to the World Energy Authority’s estimate of 2004, twice as much geothermal energy could be tapped using currently available technologies than from all other renewable energy resources - wind, solar, biomass and hydropower - combined. The scientists of this UN agency also computed the heat stored in the upper three kilometers of the continents. It is about \( 12 \times 10^{12} \) Gigawatt hours. If this “continental heat” could be harvested completely, it would supply the energy needs of mankind for the next 100,000 years at the present rate of consumption - and keep in mind, the continents cover only about a quarter of the Earth’s surface.

Of course, this heat cannot be extracted completely, but as every homeowner in Central Europe who runs a heat pump knows, at least some of the Earth’s heat beneath our feet can be used relatively easily. Currently geothermal energy is exploited in 24 countries. The world’s biggest energy user, the United States, leads the field, producing almost one third of the total.

Origins of heat

But what is the source of the enormous amount of heat inside the Earth? A major fraction has been stored within our planet since its birth about 4.5 billion years ago. When the Earth formed millions small chunks of primordial rocks clumped together in a gravitational free fall. As energy cannot be destroyed but only converted from one form into another, their potential energy turned into heat. Because rocks in general are very poor heat conductors, most of this heat is still stored within the Earth, where it is - among other things - the driver of plate tectonics, and of the convection currents in the Earth’s core which generate the magnetic field. The Earth’s second internal source of heat is the same as in a nuclear reactor: Radioactivity. It is the heat from the random radioactive decay of unstable isotopes, which - figuratively speaking - keeps the fire inside the bowels of our planet burning. Both heat sources together raise the temperature in the Earth’s inner core to about 6,000 degrees Centigrade.
As previously mentioned, rocks are very good insulators. There are places, however, where the heat of the Earth’s interior is released with great vigor, volcanoes, of course. At these hot spots red glowing fountains of lava are the undeniable proof, that there is a lot of heat beneath our feet. In general the heat flow is largest at the edges of the tectonic plates. That is particularly true at divergent plate margins, where plates move away from each other, and the hot Earth’s mantle is covered with only a very thin veneer of crust. One such divergent spreading center with unusually high heat flow is the Mid-Atlantic Ridge.

Steam for free
Iceland, the island where volcanoes and glaciers meet, straddles this ridge, which is also the tectonic boundary between North America and Europe. For centuries the Icelanders have made use of the Earth’s heat, which they get for free in many hot springs. But it is one thing to bathe in a hot mineral spring on a cold day just south of the Arctic Circle and another to make use of the geothermal energy industrially. In Iceland many boreholes have been drilled to harvest the heat of the Earth, which, on the island, comes in form of hot water or steam. More than 80 percent of single family homes, apartment buildings and offices in Iceland are heated geothermally. Almost 20 percent of the electricity generated in Iceland is geothermal. The rest is generated from hydropower and only 0.1 percent of Iceland’s electricity is produced by burning fossil fuels.

But even in a country like Iceland, where renewable energy resources play a dominant role, there is room only for improving the utilization of geothermal energy. There are also fundamental scientific issues regarding the condition and movement of fluids within the Earth’s crust to be studied. This is why ICDP is involved in the “Iceland Deep Drilling Project” on the Reykjanes Peninsula in the southwest and in the Krafla volcanic field in the northeast of the country. This project was initiated jointly by the government and the power industry of Iceland. Their goal is to improve the economics of geothermal resources by improving the power output of geothermal wells with respect to their drilling cost. Currently, typical high-temperature geothermal wells produce a two-phase mixture of water and steam at temperatures in the range of 200–320 degrees Centigrade. Such a well in Iceland, 2.5 kilometer deep and producing - say - dry steam at about 235 degrees Centigrade, may yield approximately 5 Megawatts of electric power and costs about 4 million Dollars to drill. If one could tap a reservoir with much higher temperatures and pressures, one could drastically improve the electric power output.

Supercritical water
One such possible “unconventional” energy source is supercritical water. Such conditions are reached when water is heated to at least 375 degrees Centigrade and simultaneously pressurized to 22 Megapascal, about 220 times the normal air pressure on the Earth’s surface. Then the distinction between liquid and vapor vanishes, water transforms into a completely new phase, it becomes supercritical. A well sunk into such a reservoir could produce up to ten times more electricity than a conventional well at the same flow rate. This gain will very quickly offset the additional cost of drilling, which in Iceland is estimated to be 9 million Dollars.

Geologists believe that supercritical water plays a very important role, not only in the movement of minerals within the Earth’s crust. It may even be instrumental in the formation of ore deposits. Its physical and chemical properties are so different from regular hot water that it leaches out the mineral components in rock more quickly and in completely different ways. Only by drilling into reservoirs of supercritical water can these phenomena be studied. The drilling project in Iceland is a natural laboratory for studying these phenomena, because the goal over the next decade is to drill several 4 and 5 kilometer deep wells into the supercritical conditions. One test well with a depth of 3.1 kilometer was completed in 2005. In its bottom, the water had not quite reached supercritical conditions, but was at least 300 degrees Centigrade.

Iceland makes more use of geothermal energy than any other country in the world. Power plants operate on the Reykjanes peninsula (top) and near Krafla volcano (middle). Supercritical fluids are the target zone for the Iceland Deep Drilling Project (bottom).
"I wish I could go down there and check it out." There is probably no Earth scientist in the world who, at one point or another in his career, has not sighed this sentiment in frustration. Almost all of them wish they could dive into the Earth and see for themselves what rocks make up the deep layers, how hot and how dense they are and what their detailed mineralogical composition is. Other researchers wish, they had an observatory at depth, measuring tools with which they can register the physical and chemical processes, which happen inside our dynamic planet. The reason for this wish is obvious: By whichever means geoscientists explore the Earth from the surface, the information they gain about our planet’s interior is always indirect, a model put together using logic and supported by a multitude of circumstantial evidence. Drilling is the only way to compare these models with reality. But sinking a hole is often considered to be out of reach for researchers. 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, that they cannot successfully be dealt with by a scientist.

Drilling is indeed an expensive proposition. The oil and gas industries estimate that they have to spend about 5 million Dollars to drill a standard hole of 3 kilometers. Under especially challenging circumstances, that price can double, triple or simply go through the roof. How, ask many researchers, can one justify such costs to a funding agency, if the results of a purely scientific drill hole are far less certain even than those in the risky business of sinking oil wells. This is exactly where ICDP comes in. The goal of this program is to encourage Earth scientists to consider drilling as part of their own research program, to make drilling the reality check for the models and ideas they have developed. “We want to bring scientific drilling on the continents within the reach of every member of the Earth science community,” says Rolf Emmermann, the chairman ICDP’s Executive Committee.

Projects funded by ICDP should address questions of global importance to the Earth science community-at-large, along the lines of the eight major themes described in this booklet. Last but not least, the drilling should take place at a site which can be considered to be a “World Geological Site”, where one or more of the fundamental open questions of the Earth sciences can hopefully be answered. In short, the proposed location should be a prime example for other, similar structures on Earth which have not yet been adequately explored.

Securing funds
There is no rule of thumb, determining how much of a project ICDP will fund. It depends solely on the proposal itself and its evaluation by the Science Advisory Group. 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, to provide a whole suite of services. Expertise in the OSG ranges from workshop initiating, to project planning and managing through “Joint Research Ventures”, as well as to providing hands-on support for the logistics and the actual operations of drilling. Regular training courses on handling, studying and in-
terpreting drill cores and well logs are also part of their repertoire.

But however good the funding, however professional the support, drilling is not for the faint-hearted. Whether or not a hole can be called a success, will only be known after every meter has been drilled and logged and after every core carefully studied. Uncertainty and the unexpected must always be part of the equation for a successful hole. While these boundary conditions may appear to be limiting, drilling is still the only “real” window into the Earth’s interior. Only by bringing samples directly from the depths to the surface can scientists really understand what is happening underground.

**Type localities**

But even if hundreds of holes were to be drilled for scientific purposes, each of them would still only be a tiny pin prick in the Earth’s crust, if the drill sites would not be chosen carefully. Drilling projects funded by ICDP should be at a “type locality” for globally important questions in Earth sciences. And by no means need all scientific drilling projects reach the depths of the super deep holes like Kola in Russia or KTB in Germany. A whole suite of urgent and fundamental questions about the Earth’s past and the processes within our planet can be answered by shallower boreholes. So can sediments divulge their secrets, for example their climate archive, just a few hundred meters below the surface. In some cases zones where earthquakes originate can be reached in 3 or 4 kilometers below the surface and sometimes even the Earth itself moves - by a still poorly understood process - rocks from the deep lithosphere much closer to the surface.

But there is another, fundamental limitation to even the most extensive drilling: The Earth has a diameter of 12,748 kilometers, in contrast, the deepest existing drill hole reaches a depth of 12,262 meters - roughly one thousandth of the diameter. However dramatically drilling technology may evolve in the future, to reach a depth of 15 or 20 kilometer seems to be beyond the reach of very optimistic observers. As many projects have shown, drilling for scientific purposes is an enormous, time-consuming challenge. But despite all difficulties: Drilling into our planet’s crust is one of the most compelling frontiers in Earth science today. The adventure of drilling may allow us to solve a few of the many mysteries which have been hiding for millions of years in the dark terra incognita deep below our feet.

ICDP’s website provides a wealth of information about the drilling program as a whole and about individual projects, including data sets and sample photos.

http://www.icdp-online.org

Scientists interested in support for proposal development and funding for drilling projects should point their browsers to

http://www.icdp-online.org/proposals
The InnovaRig, built by Herrenknecht-Vertical GmbH, Schwanau, Germany, was developed specifically to satisfy the needs of scientific drilling. The rig is able to perform standard, directional or even air-lift-drilling down to a maximum depth of 5,000 meters. Hole diameters range from 59 to 711 millimeters and cores with diameters of up to 123 millimeters can be extracted. The rig is designed to be outfitted with special “scientific” add-ons such as continuous on-line gas analysis in the drilling mud, geophysical downhole logging and continuous data acquisition, storage and distribution. The rig can be used in densely populated places, because special care was taken to reduce noise emissions. InnovaRig is owned by the GeoForschungsZentrum Potsdam and operated by a drilling contractor. It is available for ICDP projects.