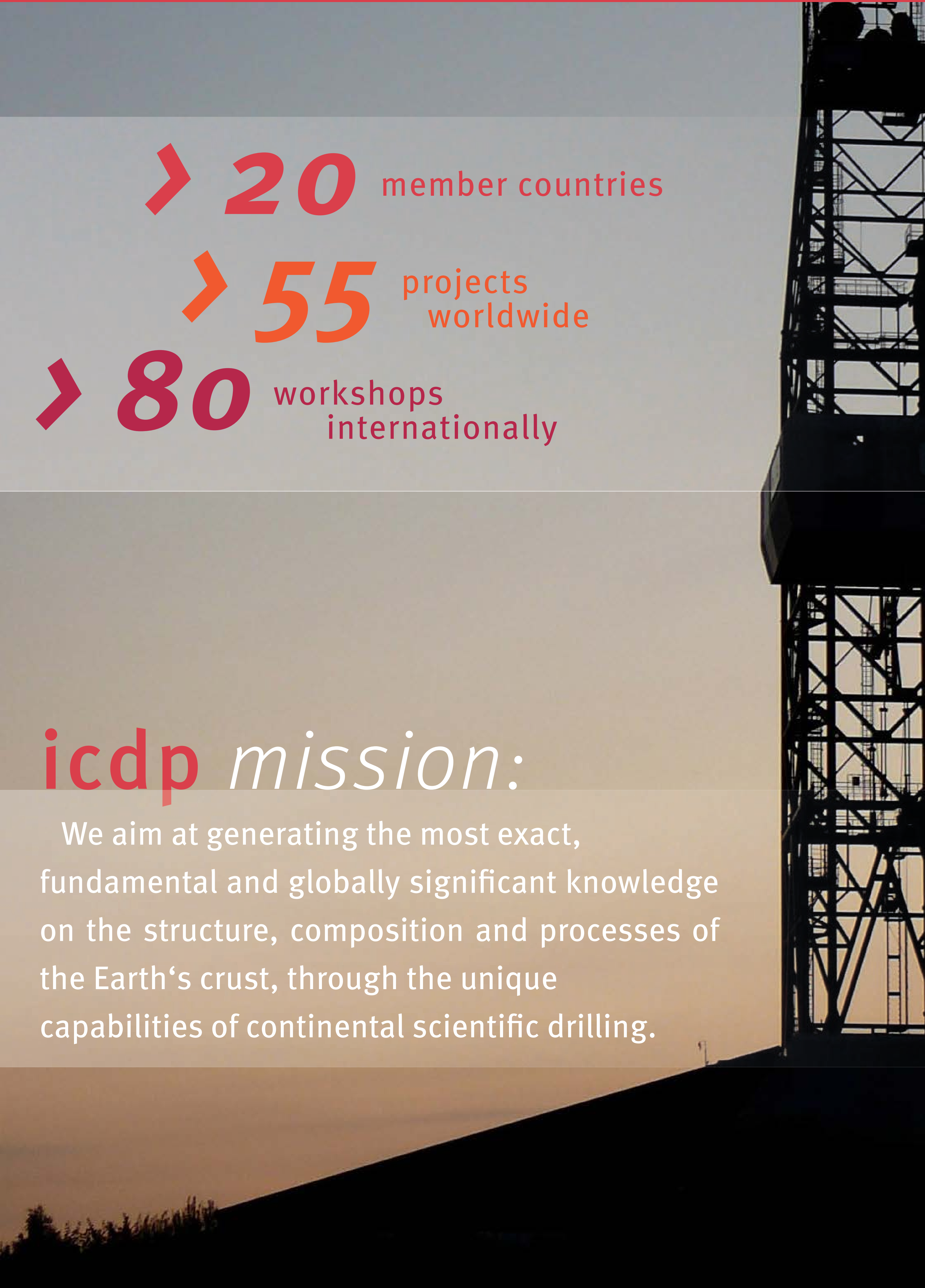
# icdp science plan
## 2020-2030

INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM



› 20 member countries

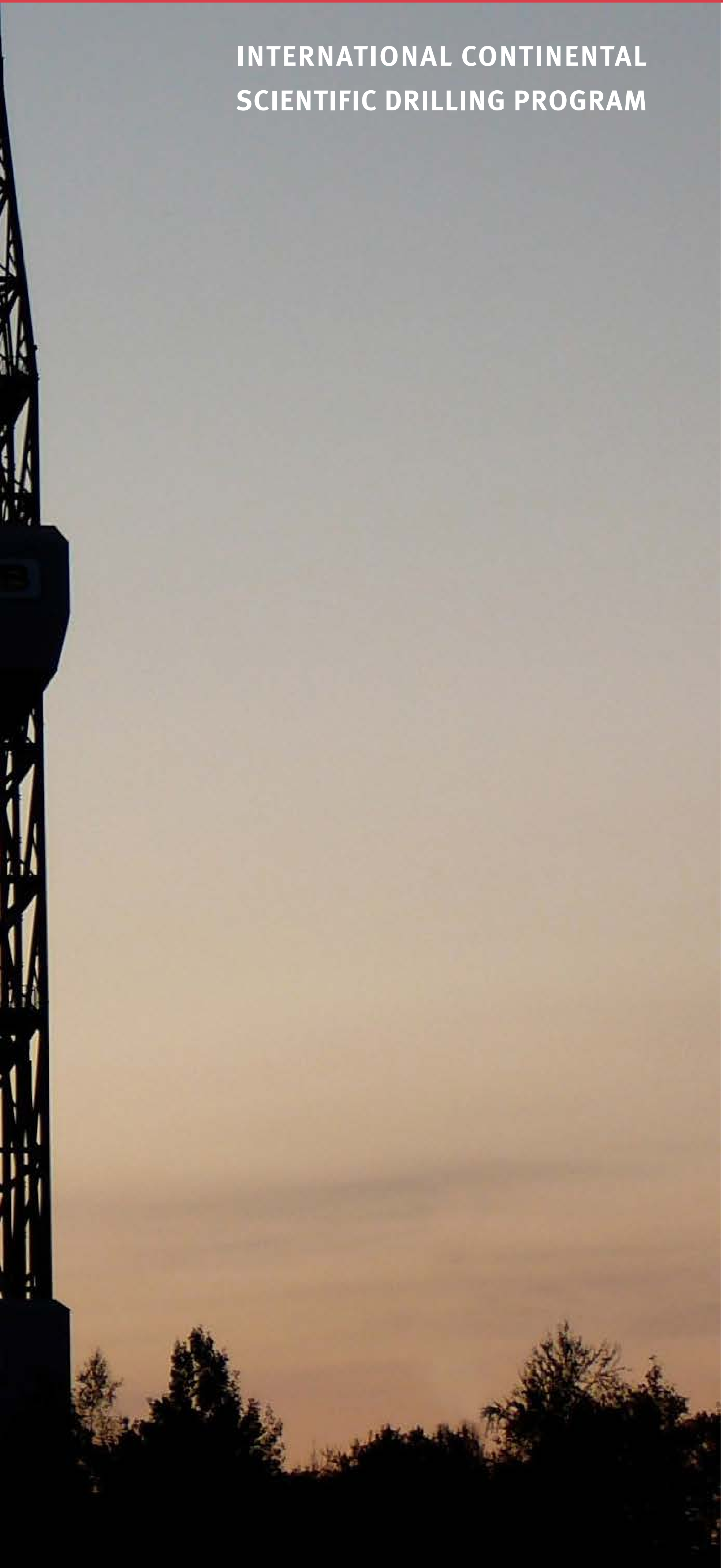
› 55 projects worldwide

› 80 workshops internationally

# icdp *mission:*

We aim at generating the most exact, fundamental and globally significant knowledge on the structure, composition and processes of the Earth's crust, through the unique capabilities of continental scientific drilling.

# INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM



*KTB scientific drilling project near Windischeschenbach, Germany*

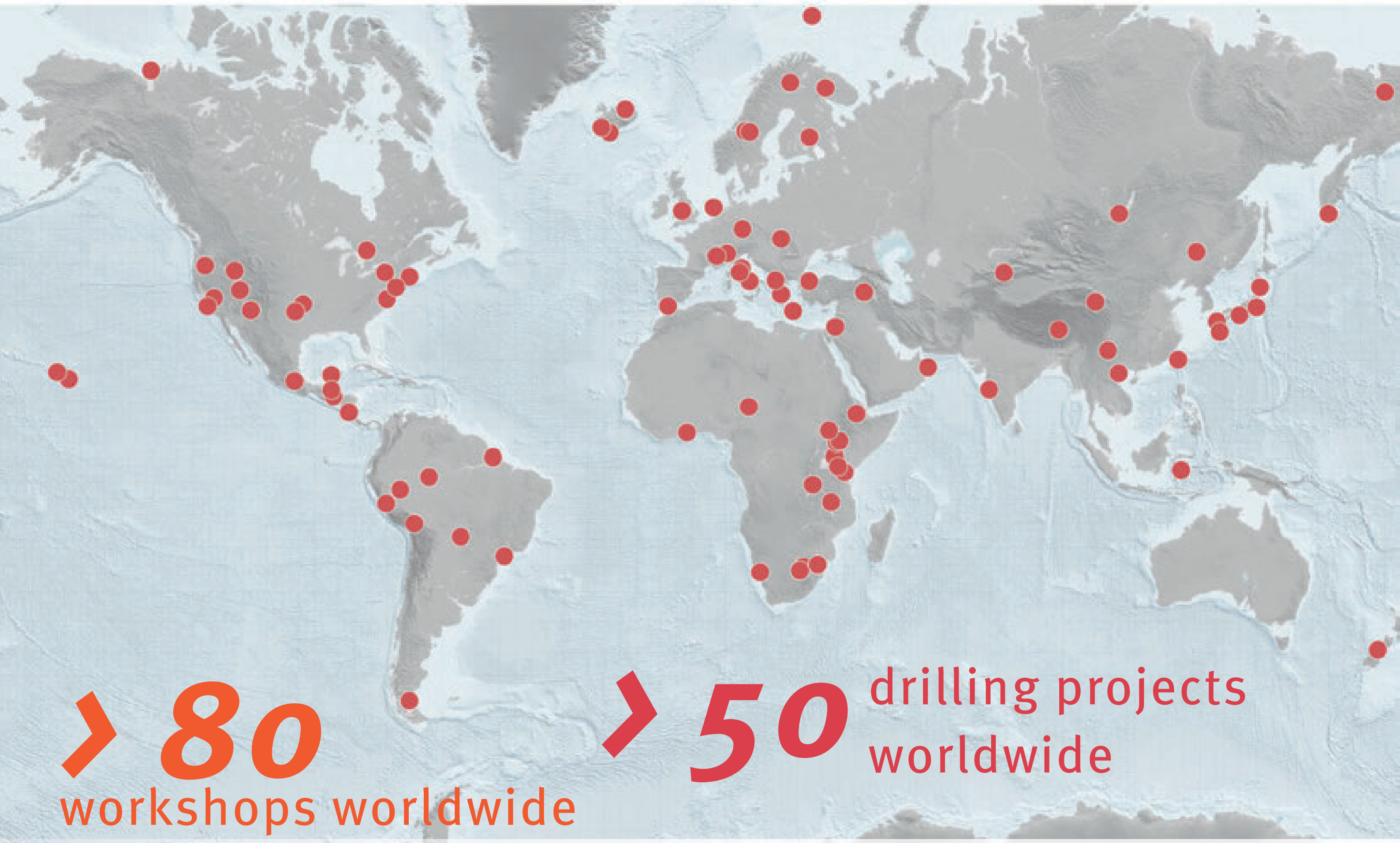
icdp

# icdp: international *continental scientific* drilling program

By whichever means we explore Earth from its surface, the information gained about our planet's interior is always indirect, a model put together using multiple types of evidence. Drilling is the only way to verify such models against reality. However, drilling and retrieving samples and data is costly, complex, and sometimes dangerous - this is exactly where the International Continental Scientific Drilling Program (ICDP) comes in.

The goal of the ICDP is to encourage Earth scientists to use the investigative tool of scientific drilling to test models from information gathered at the Earth's surface. Given the typically high cost of drilling and of research in boreholes, it is clear that any proposals for drilling with ICDP's help must address substantial scientific questions with a strong focus on societal needs.

This Science Plan lays out some of the most important issues that ICDP aims to investigate over the next decade. The key questions address fundamental science, but many also link to wider societal challenges encompassed in the United Nations Sustainable Development Goals (SDGs). In particular, ICDP projects can provide important information to underpin the SDGs related to clean water and sanitation, affordable and clean energy, sustainable cities and communities, and climate action.




*Worldmap of ICDP drilled and planned drillsites 2020*

# membership *benefits*

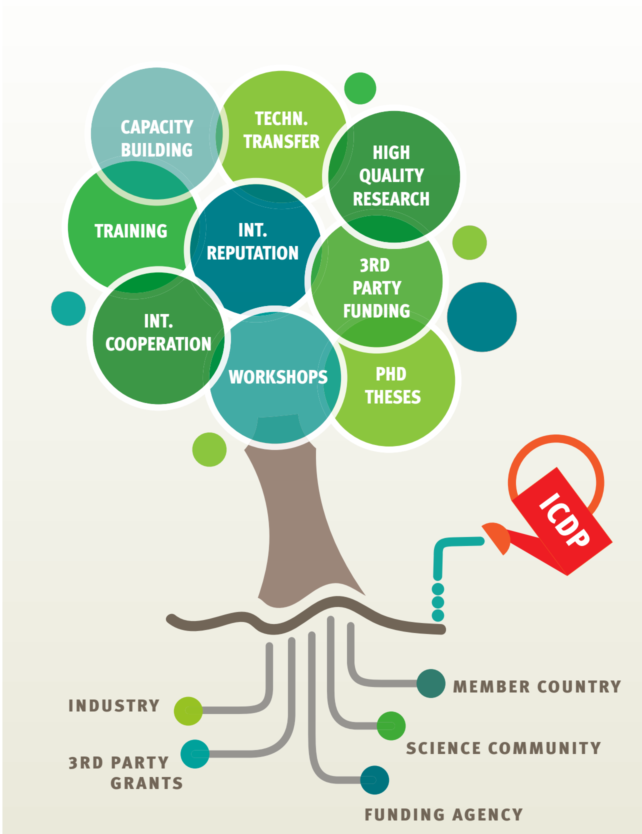
## Enabling high-quality scientific research

Geoscientists today, with their ability to decipher and understand the Earth system, play a key role in mitigating environmental damage, helping to reduce society's ever-increasing vulnerability to natural hazards, and satisfying society's soaring dependence on natural resources in sustainable ways. Scientific drilling, because of its unique ability to study directly the fundamental workings of the Earth, is an integral component of these efforts. However, research using drilling as a tool is costly and most achievable through large-scale projects. ICDP therefore aims to draw together co-funding to foster leading edge science at world class sites, and to tackle fundamental Earth Science challenges of high societal relevance.

The ICDP was formed in 1996 and has grown to include more than 20 participating countries across the world plus UNESCO. ICDP organizes peer evaluation of project proposals and combines the annual financial contributions of its members to part-fund research projects. The benefits of being a member are numerous. Scientists and engineers can apply for funding through proposals, they can lead projects seed-funded by ICDP, and they have priority access to data and sample repositories during the moratorium phase. Workshops, training, and education are offered to member countries and the services of the ICDP Operational Support Group and the ICDP Equipment Pool can be utilized. Furthermore, and most important for national funding agencies who usually lead the membership and raise the annual fee, the members possess a seat and a vote in the decision-making ICDP panels and can determine the policy, the funding strategy and individual grant choices. ICDP funding typically covers 10-50% of the full cost of a drilling project, but more importantly provides leverage for project teams to generate other funding.

ICDP proposals undergo a strong and independent evaluation by globally selected expert scientists, the Science Advisory Group (SAG), and experienced drilling project managers from member countries, the Executive Committee (EC), based on clearly stated criteria of scientific merit and societal relevance.

Thus ICDP-approved projects provide a basis for additional high-quality scientific research. For example, continued work on samples and data collected during ICDP projects typically leads to a large number of scientific publications and promotion of early-career scientists. The economic factor of ICDP investments is also noteworthy, as local drilling and service companies may be contracted for ICDP projects, allowing some investment to flow back into the country.




*ICDP's seed funding unites stakeholders to further key outcomes in Scientific Drilling*

# icdp co-funding

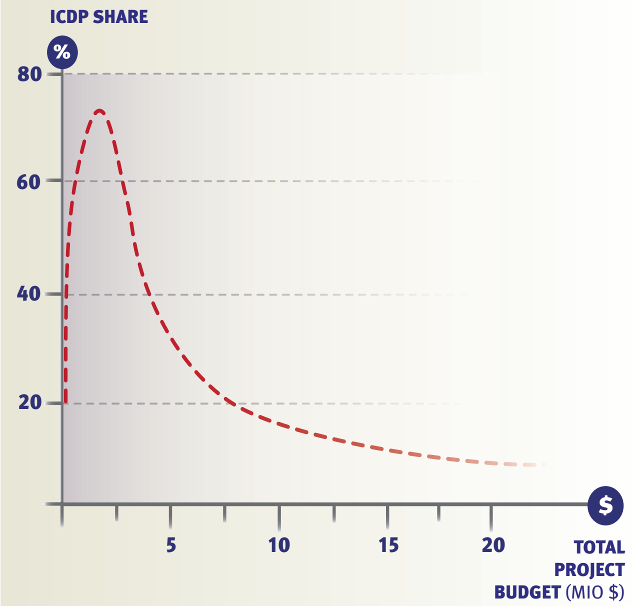
## One of ICDP´s greatest success stories

Once a drilling project has been approved within the program and the amount of ICDP co-funding has been allocated, the proponents work to secure additional funding, usually from their national funding agencies. Thus, the program's policy of supporting international teams is vital, in that it ensures there are a range of funding opportunities for each project.

**>54 Mio$ icdp funds**
**>220 Mio$ 3rd party funds**
**>274 Mio$ total invested**

icdp *co-funding*:

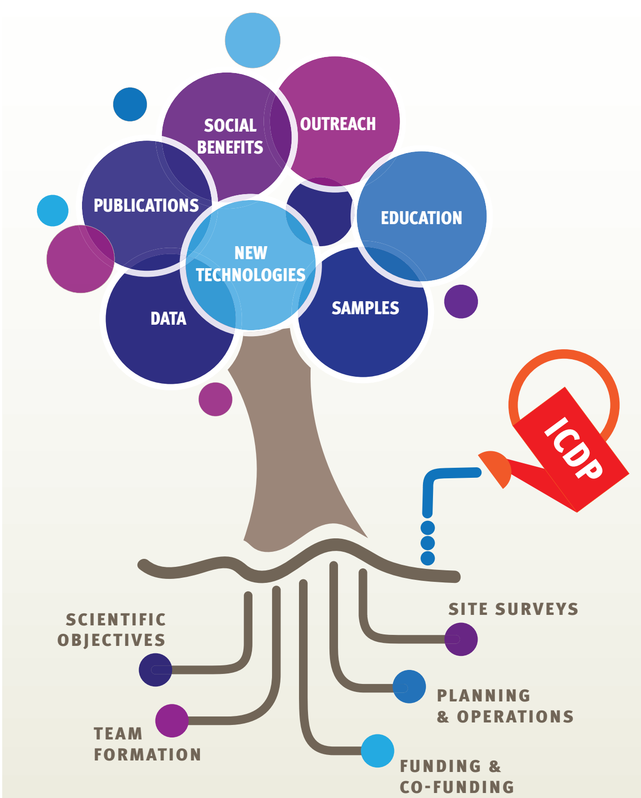
**5-70%**
(*average* **20%**)




*ICDP funding share versus total project budget over 57 past ICDP projects*

This 'seed money' philosophy, in combination with the excellent in depth-reviews by the ICDP Science Advisory Group, helps to 'open doors' and provides proponents with the opportunity to seek the necessary co-funding from additional sources. Designated ICDP funds are held at the host agency, the German Research Centre for Geosciences (GFZ), until enough money is accumulated to run the project.

The co-mingling of funds is one of the greatest success stories of the ICDP. A look back at the total funding obtained over the past more than two decades illustrates that ICDP's share per project, despite substantial variation, averages about 20% of the total operational costs. So far, ICDP has invested about US$ 54 million in more than 57 projects, whilst an additional US$ 220 million has been raised from various third-party sources.




*Project implementation with ICDP funding & operational support*

# technology *developments*

## Funding for key technology developments in Earth Sciences

Scientific drilling is always a major challenge as researchers investigate the Earth's interior in search of answers hidden at depth. Although ICDP works to minimize the risk of failure, drilling is not risk-free and research wells are necessarily testbeds for new technology in assessing Earth's interior. ICDP projects often push the scientific boundaries of drilling research, requiring novel methods and instruments for monitoring processes downhole or in the lab. Designing and testing these new technologies leads directly to applications in scientific drilling, whilst close cooperation with drilling industry service companies creates opportunities for transfer of these developments into commercial applications.

Examples of technology innovation include ultrahigh-temperature drilling methods applied at temperatures above 500°C on Iceland in the Iceland Deep Drilling Project (IDDP); continuous coring of soft sediments performed in several large lakes around the world; installation of highly-sensitive ground-motion, deformation and strain borehole monitoring suites; development of geophysical memory logging tools such as downhole x-ray fluorescence sensors; and the platform independent 'mobile Drilling Information System, mDIS'.

Scientists in ICDP have the opportunity to utilize tools and methods developed by ICDP from the ICDP Instrument Pool with deployment assistance from the Operational Support Group. In this way, inventions in scientific drilling can be implemented for several projects, with associated knowledge transfer.

**DRILLING, CORING MONITORING**

- *high-temperature drilling*
- *continuous complete coring*
- *fibre-optic installations*
- *continuous data recording*

**DATA MANAGEMENT**

- *integrated field and repository software*
- *rig-, log- and lab-data integration*

**FIELD LAB INSTRUMENTS**

- *multi-sensor logging*
- *ct-core scanning*
- *drill fluid analyses*
- *standardized analytics*

**DOWNHOLE MEASUREMENTS**

- *high-temperature logging*
- *retrievable monitoring strings*
- *multi-sensor logging*
- *logging while drilling*

**KEY TECHNOLOGY CHALLENGES IN SCIENTIFIC DRILLING**

# education and outreach

**Education and outreach are very important to ensure public acceptance and are an integral part in the policy of ICDP**

Almost everywhere that ICDP drills, there are concerns among local people about the impact in their area. Any drilling is commonly assumed to be part of a larger project that may have an effect on nearby communities. Therefore, it is crucial that each scientific drilling endeavor begins to communicate with the public as early as possible, explaining in a transparent and convincing way the non-commercial research goals and the techniques to be used.

Potential risks such as induced seismicity, contamination, and other environmental impacts need to be dealt with in a transparent manner and all risks clearly assessed. ICDP provides 'best-practice' based examples of effective outreach, founded on long experience over dozens of projects, which can underpin acceptance by locals and stakeholders alike. The duty to inform those involved or affected goes beyond the operations, also including research and publication of results. Some drilling information has been introduced into museums and other educational institutions in areas studied by ICDP projects. In addition, ICDP science projects often provide an opportunity for many early-career researchers to learn new skills and build their networks, strengthening the scientific drilling community.


*Drilling engineering explained during an ICDP Training Course at the Alpine Fault in New Zealand*

# billions of years *of earth* evolution

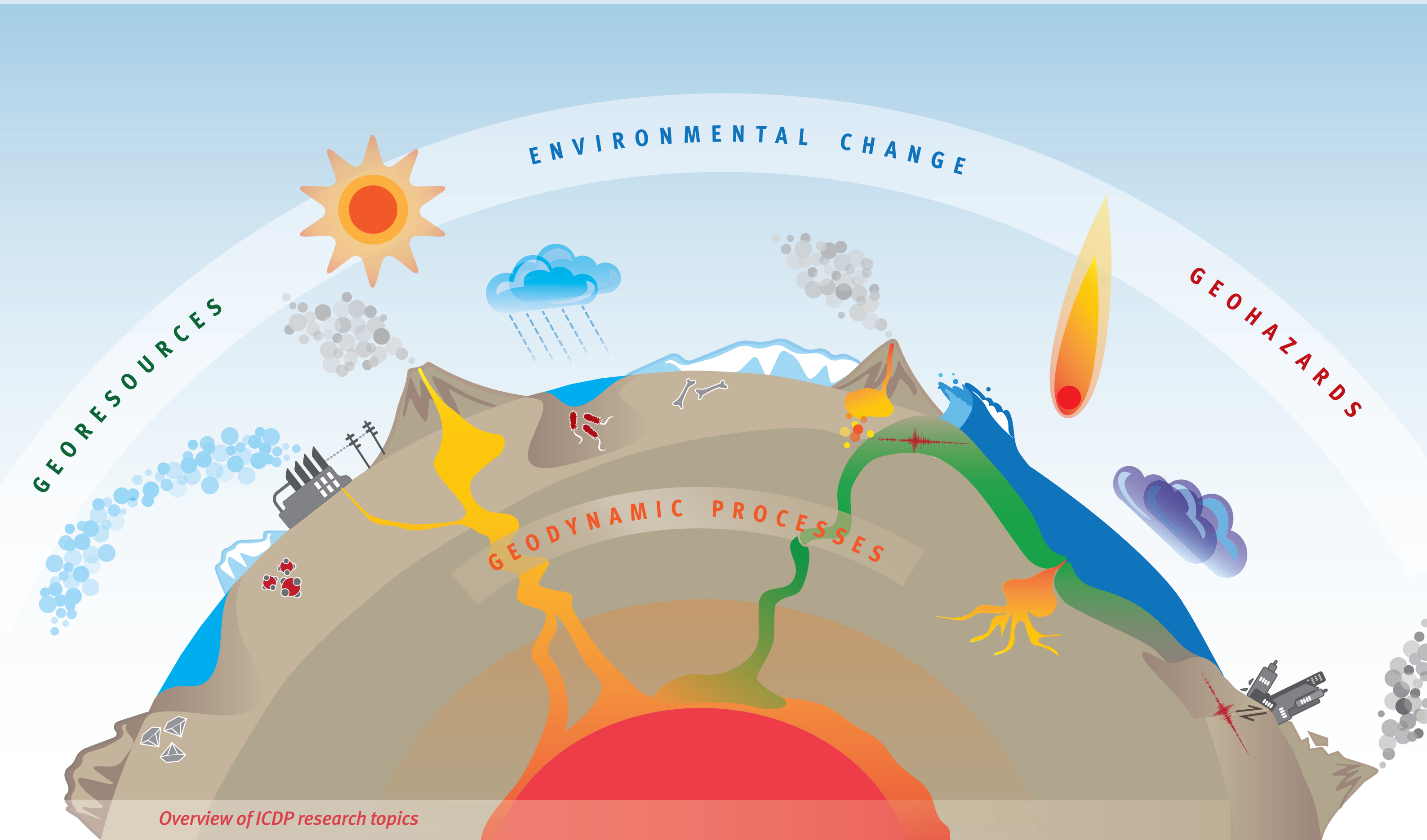
## ICDP's 4 prime science themes for the next decade

The most unique and important point of ICDP is that the continents provide access to a record of the Earth's history that stretches back about 4 billion years.

ICDP projects can investigate the thermal evolution of Earth, the onset of plate tectonics, the generation of the magnetic field, the origin and evolution of life, the effects of large impact events, the formation of the world's most significant ore deposits, the evolution and oxygenation of our atmosphere and oceans, past climates, global glaciations, mass extinctions that led to modern Earth, and perform in-situ monitoring and probing of volcanoes and fault zones. Such studies are crucial to answer fundamental questions related to the evolution of the Earth-Life system, the processes that generate geohazards, access to resources essential for modern society, and past and present climate change.

Only these kinds of projects truly have the potential to tell us about the billions of years of Earth evolution. In the following pages, ICDP's scientific challenges are presented in 4 themes: **Geodynamic Processes, Geohazards, Georesources and Environmental Change.**

## Billions of Years *of Earth Evolution*




*Overview of ICDP research topics*


# THEME 01: *geodynamic* processes

## Understanding the processes that shaped the planet's present conditions

Earth's evolution over 4.54 billion years has ultimately produced the habitat that we live in and resources that we depend on. Understanding the processes that shaped the planet's present conditions is essential to sustaining our environment and resources in the future. Key questions demanding our attention include:

*1) How and when did plate tectonics initiate and how has the Earth's crust and mantle evolved through time?*

*2) What controlled the development of Earth's hydrosphere-atmosphere-biosphere system, and how are the associated chemical elements recycled through time?*

*3) How did life on Earth originate and how did it influence the evolution of environmental conditions through time?*

### *Past accomplishments*

The continental crust is 20-80 km thick and comprises nearly 40% of the Earth's surface area. The physical and chemical evolution of our planet, driven by plate tectonics and plume activity over this time, is recorded within this crust. Crust older than four billion years is exceptionally rare, thus understanding the mechanisms of continental crustal growth and their relation to the evolution of the mantle over billions of years of Earth's history is a fundamental question. Several ICDP projects have made substantial contributions to our understanding of crust-forming processes and mantle evolution. For example, the Barberton Greenstone Belt Drilling Project in South Africa provided important insights into the composition of Archean mantle, while the Oman Ophiolite Drilling Project evaluated Cretaceous juvenile crust formation and chemical mass transfer in the mantle, as well as between the mantle, crust and ocean via hydrothermal alteration. The Collisional Orogeny in the Scandinavian Caledonides project (COSC) in Sweden has directly investigated tectonic processes operating in the depths of an ancient mountain chain.

*'Students on the rock' : Students standing on the Moho, the discontinuity marking the transition from the Earth's crust to the mantle.*

The evolution of life and its environments throughout Earth history has profoundly shaped our world. In the Precambrian, the biosphere experienced three fundamental evolutionary steps: the development of procaryotic life and oxygenic photosynthesis during the Archean, multicellular eucaryotic life during the mid-Proterozoic, and a major explosion at about 540 million years ago, which ultimately gave rise to our species. These ecological revolutions occurred in the aftermath of the stabilization of aqueous water at the Earth's surface about 4.2 billion years ago, and major pulses of atmospheric oxygenation at around 2.5-2.1 and 0.80 to 0.54 billion years. ICDP research has provided the foundation for our understanding of early ecosystems and environments, and the transition from an anoxic to partly oxygenated world, e.g. the Fennoscandia Arctic Russia – Drilling Early Earth Project (Far-Deep).

The Solar System is a violent environment and cratering occurs at the surface of all rocky bodies large and small. Today, more than 190 impact craters have been confirmed on Earth. In contrast to other planets and moons in our solar system, the recognition of impact craters on Earth is difficult because tectonic processes obscure or erase them, while sedimentation buries them. Consequently, drilling is required to obtain rocks for precise dates, to confirm the origin of such structures, and to understand their formation process. Over the past 25 years, ICDP has successfully contributed to the drilling of four impact structures ranging in size from the famous Cretaceous-Palaeogene (K-Pg) Boundary ~ 200 km wide Chicxulub crater in Mexico that led to the extinction of the dinosaurs, to the ~ 10 km Lake Bosumtwi in Ghana. These drilling projects led to new knowledge on the excavation process, the behavior of the target lithologies and of the projectile, the emplacement of impactites within and outside the crater, and the production of ejecta, as well as the complex sequence of physical, chemical and biological processes that followed the collisions. In combination with geophysical data, mainly seismic, the study of the core shed light on the internal 3D morphology of these structures.

*The COSC scientific drilling project (Sweden) providing unique insight into the roots of a Himalayan-type orogeny*

Crater drilling was often combined with other ICDP goals: The post-impact sediments recovered from the in-fill of the Lake Bosumtwi in Ghana and Lake El'gygytgyn in Russia also produced unique high-resolution paleoclimate records, respectively, a detailed 1 million year record of the West African Monsoon and a record of the transition from Arctic forest to a permafrost ecosystem between 3 and 2 million years ago in Northern Siberia. The 2016 Chicxulub offshore drilling in Mexico was a joint operation with our partner, the International Ocean Discovery Program (IODP). Of particular interest are the effects and dangers of impacts for the geological and biological evolution of our planet. For example, the huge Chicxulub impact event at 65 million years had a catastrophic influence on the biosphere. ICDP projects investigating impacts on Earth have provided important constraints related to impact processes and biological effects, e.g. the Chesapeake Bay Impact Structure Deep Drilling Project (CBAY) in the USA.

### *Fundamental questions*

Debate continues around significant questions such as when plate tectonics began, and how the Earth's crust has grown and evolved. Current models for crust and mantle evolution through time involve the creation and subsequent recycling of continental crust versus continuous or episodic crustal growth over the past 4 billion years. This debate is entwined with discussions on the geodynamic-magmatic environment associated with crustal growth and the role that arcs and/or mantle plumes play in the genesis of juvenile crust. Arcs represent accretion of juvenile crust, whereas mantle plumes supply juvenile melt to the crust via large igneous provinces and oceanic plateaus.

Understanding the various feed-back mechanisms controlling the relationships between plate tectonic processes, formation and emergence of large continental masses, and paleoclimate and environmental changes throughout critical periods of Earth history is also a major question for ICDP. These topics are critical to understanding the initial conditions that led to microbial evolution and the subsequent radiation of complex organisms and thus life.

Little is known about Earth's impact record during the first 2.5 billion years of its history. The oldest known impact structures on Earth are about 2 billion years old. However, evidence for earlier impact events between about 3.4 and 2.5 billion years exists in the form of spherule layers, likely representing distal impact ejecta. These layers occur in South Africa and Australia, and provide the only traces of Earth's early (Archean) impact record. In some of these spherule beds, siderophile element concentrations are anomalously high and correspond to impactor sizes of up to ~60 km in diameter – much larger than recent impacts. Such impacts potentially release huge amounts of energy, capable of causing major changes to the Earth's atmosphere, hydrosphere, and biosphere. The importance of these events makes their investigation vital.

*The Ediacaran-Cambrian transition in Namibia, one of the main targets of GRIND*

### *Future scientific targets*

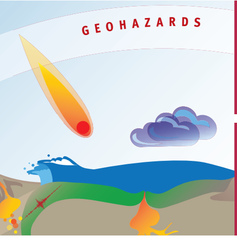
Over the next decade, ICDP's drilling targets will address some of these challenges:
Examples include the Bushveld Complex Drilling Project (BCDP), which plans to drill into the world's largest mafic-ultramafic intrusion in South Africa. On Iceland, the Krafla Magma Drilling Project (KMDP) proposes to drill into a rhyolitic magma body to investigate the physical/chemical/mechanical conditions of rhyolitic magmatism beneath the caldera. Both projects provide important opportunities to evaluate in-situ crust-forming processes in relation to juvenile mantle melts.

ICDP projects provide an opportunity to target the best-preserved stratigraphic sections worldwide to elucidate the development and evolution of life during the Precambrian. Already-approved projects will target the evolutionary development of oxygenic photosynthesis, e.g. the Barberton Archean Surface Environments project (BASE) in South Africa; and the interactions between atmospheric oxygen increase, global climate change, and the evolution of animals, e.g. the Geological Research Through Integrated Neoproterozoic Drilling: The Ediacaran-Cambrian Transition (GRIND) with drill sites in Namibia, Brazil, and China. Drilling the best preserved stratigraphic sections through critical intervals of environmental and biotic change located on different continents will provide a unique sample library from which multiple proxies can be developed and used for these key periods of global environmental and biological evolution. The BASE project in South Africa may also sample the early spherule layers, remnants of an ancient impact, which would provide unique insights into this critical time in Earth history.

Despite progress, it remains clear that a single drill-hole within a large impact structure only provides a limited view, even combined with larger-scale geophysical data. The Chicxulub case illustrates how two deep drilling projects 15 years apart multiply the acquired knowledge. In the future, selected impact structure drilling projects could improve our understanding of cratering process

*Posing with a 3 m core at 185 m at the GRIND drillsite in Namibia*

and their potential effects on the bio-geosphere. To do so, it is important to select structures that combine several of the following characteristics: excavated within different types of target lithologies; a large impact-melt pool that produced long-term hydrothermal activities or large mineral deposits; possibility to document the formation of the cavity, central-peak and margin collapse and compare the behavior of the target lithology with the results from numerical modelling; a link to ejecta recovered from the sedimentary record and/or potential effects on the Earth biosphere or climate. There are numerous advantages to combined impact structure drilling with other ICDP goals, such as paleoclimate or mineral exploration and these shall be further explored in the coming decade.




# THEME 02: geo*hazards*

## Understanding the full chain from hazard to risk

Geohazards pose an ever-increasing threat to humankind. This is driven in large part by dramatic global population growth in hazardous areas around the world, exposing communities to risks from both natural exposure and vulnerable infrastructure. The principal solid earth geohazards are earthquakes, volcanoes, and mass movements. Additional hazards come from space in the form of meteorite impacts. These hazards occur on very different time and space scales that strongly depend on local geological conditions, making each one of them challenging to assess and forecast. It is of utmost relevance to decipher their underlying causes and the physical processes that drive them, to understand the full chain from hazard to risk. Continental scientific drilling is a key means to investigate these outstanding science questions, which is why hazards are high on ICDP's agenda.

Key questions and challenges demanding our immediate attention include:

*1) What are the drivers initiating and controlling earthquakes, volcanic eruptions and mass movements such as landslides?*

*2) How do we distinguish faults, volcanoes and potential landslides that present an immediate threat from those with low hazard?*

*3) How do we build a better quantitative understanding of physical processes, allowing us to provide advanced warning time to mitigate the risks associated with geohazards?*

The scientific study of earthquakes, volcanoes and landslides began in the 19th century, with progress greatly accelerating at the close of the 20th century thanks to development of new technologies for studying the interior of the earth from the surface and space. However, there are major gaps in our understanding needed to tackle the key challenges that require study of faults, volcanoes and mass movement where the action occurs – at depth in the earth. Scientific drilling can make the difference by providing access to measure, observe and monitor key phenomena that drive these hazards at the source.

### *Past accomplishments*

Fault-zone drilling provides the only means to access the depths where the energy of earthquakes is stored and released, and has been a centerpiece of ICDP since its foundation in 1996. The San Andreas Fault Zone Observatory at Depth project (SAFOD) in California is a prime example for fault drilling. SAFOD followed the successful German super-deep continental drilling project (KTB) multi-step

**Geohazards:** *volcanic eruptions, mass movements, such as landslides, earthquakes and impact craters*

*The SUSTAIN drilling project, based on two cored holes at Surtsey volcano, an isolated oceanic island off Iceland*

approach of ‘pre-site surveying – pilot hole – main hole - monitoring’. It succeeded in drilling into a major transform fault at a key location at ~3 km depth, providing novel and unprecedented insight in the processes governing earthquakes. Now, SAFOD’s successor project on Reservoir Triggered Earthquakes at Koyna in India, is pushing the envelope by aiming to drill into the source zone of a reservoir-triggered magnitude M6.2 earthquake > 6 km depth. Important progress is also being made at shallow depth through the Deep Fault Drilling Project (DFDP) on the Alpine Fault in New Zealand and drilling into the top of the fault responsible for the great Tohoku earthquake in Japan (IODP JFAST project). ICDP has taken important steps forward by supporting other fault-zone drilling and monitoring projects such as the Taiwan Chelungpu-Fault Drilling Project (CFDP) and the permanent downhole Geophysical Observatory at the North Anatolian Fault (GONAF) in Turkey.

Important volcanoes where eruptions threaten the population and infrastructure, are sites of previous ICDP projects. These include the Naples-Campi Flegrei region in Italy that sits on a supervolcano and where the Vesuvius eruption destroyed the city of Pompeii in 79 AD; the Iceland hot spot with numerous active volcanoes; the Unzen volcano in Japan where the magma conduit was drilled by ICDP; Big Island of Hawaii, the most active of the Hawaii-Emperor volcanic chain; and the supervolcano at Yellowstone in the USA. A major eruption at any of these locations would have drastic consequences for humankind and thus they need to be investigated in detail.

### *Fundamental questions*

Our understanding of geohazards is constantly evolving through field observations, laboratory and theoretical studies. Recent progress is beginning to unravel how earthquakes, landslides and volcanic eruptions initiate through multidisciplinary research. Nonetheless, fundamental questions remain open in each of the principal geohazard themes: earthquakes, volcanoes, and mass movements.

How do earthquakes nucleate, propagate and stop? What are the width and structure of the principal slip zone at depth? What are the mineralogies, deformation mechanisms and frictional properties of fault rock? How is energy partitioned between seismic waves, aseismic deformation, frictional heating, rock comminution and other processes when the fault moves? What are the values of stress and pore pressure and how do they evolve during the seismic cycle? How does fault zone permeability and fluid pressure vary during and after earthquakes? Under what conditions are earthquakes likely to be induced by underground injection or construction of high dams, and how large can these earthquakes become? These examples of pressing open questions illustrate the need to develop a comprehensive understanding of the composition and properties of faults at the depths where earthquakes occur. The science community is asked to actively develop further concepts and project ideas. This may also include actively controlled earthquake experiments such as the current ICDP-SEISM initiative (Scientific exploration of Induced SEISMicity and Stress) and collaborations with the geothermal and petroleum industries.

Volcanic eruptions pose dramatic health and socioeconomic risks. In addition to the obvious risk to local populations, larger eruptions have global consequences for air traffic in the short term, and for weather and climate on longer time scales. Fundamental open questions related to volcanic hazards center on forecasting of the timing and magnitude of eruptions. How can known precursors of volcanic eruptions such as seismicity, tremor, gas flux and surface deformation be used to improve the timeliness and accuracy of eruption warning systems? Can we identify new observables that improve warning times to local population for mitigation of risks to people and infrastructure? Are there pre-eruptive signals that forecast the magnitude and thus threat level of future eruptions? While seismicity, tremor, gasses and surface deformation can be monitored above ground, scientific drilling is needed to sample the underlying conditions and processes within or around magma conduits and chambers. Experience gained from direct observation will also advance the knowledge needed to efficiently tap geothermal heat as a source of renewable energy.

Rapid, giant landslides are among the most powerful natural hazards on Earth. The largest ones can mobilize several million cubic meters of rocks or sediments. Their occurrence is controlled by multiple agents such as precipitation, tectonic uplift rates, or weak layers in the rocks (e.g. along clay mineral-rich sediment in the subsurface). Subaquatic mass movements and flash floods also occur, e.g. those affecting the vulnerable coast along the French and Italian Riviera. Moreover, landslides may impact water bodies and cause tsunami waves that multiply the hazard. Critical processes along potential slide planes, such as the effect of changing pore-water pressure, are not well understood. Drilling is able to recover cores from these key zones for laboratory studies and to monitor hole conditions using in-situ instruments.


*Stromboli volcanic eruption*

### *Future scientific targets*

Developing and testing theories of earthquake mechanics requires sampling and monitoring of the state of the fault in-situ. Deep drilling is essential for reaching the depths where earthquakes initiate and propagate. Shallower drilling can also achieve important science goals of studying fault structure and time-dependent post-earthquake effects, e.g. the IODP-JFAST project. To achieve these goals requires a global fault-zone drilling program, both on land and offshore in partnership with the International Ocean Discovery Program (IODP). Science evolves step by step by deriving new knowledge at key locations that can be used to build a comprehensive model of the earthquake machine, including a quantitative understanding of hazards. This knowledge will lead to new concepts for risk mitigation in order to protect people living in hazard-prone environments.

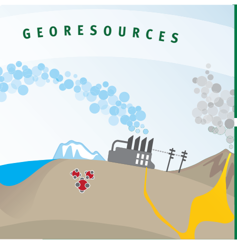
In-situ controlled earthquake experiments in underground laboratories, at dedicated sites or as part of enhanced geothermal or unconventional petroleum activities, are also an important component of the research program. Active experiments, while requiring extensive planning and discussions with civil authorities to gain acceptance, provide unique opportunities to answer questions of nucleation and initial rupture growth.

Volcanoes exhibit a wide spectrum of pre-eruptive behavior that challenge our ability to predict the timing and severity of eruptions. Some are restless for decades without building to an eruption (Yellowstone for one), while others can move from a dormant state to full eruption in a matter of days (Kasatochi Island, Alaska). Building a better understanding of the chemical and mechanical changes that lead to eruption is paramount, from non-explosive volcanoes that threaten local populations to large silicic calderas capable of disrupting climate, through large-scale catastrophic eruption. The high temperatures attainable at shallow levels at many active volcanic and near-surface magmatic systems also provide opportunities for clean energy resource development. Questions to be addressed in this area range from

*Landslide triggered from the Kumamoto earthquake in Japan*

a physical understanding of reservoir rocks to drilling technologies, logging tools for high temperature, and solutions to corrosion problems due to chemically aggressive formation fluids.

One of the most significant shortcomings in landslide understanding is the lack of direct observations to link long-term pre-conditioning factors, short-term triggers such as earthquakes or rainfall, and consequences such as mobilized volume or mode of emplacement and runout. Recent landslide events indicate the key role of complex and underexplored process-chains linking the proximal landslide with distal processes often affecting inhabited areas. The most dynamic settings with permanent reorganization of the morphology are deltas or steep, creeping slopes, both affecting regions with large lakes. At times of rapid warming due to human activities, thawing permafrost areas may affect the stability of entire mountain flanks and coastlines, because released fluid changes the stress field and stability in the underground. Drilling allows reliable assessments of cause-effect relationships, in particular when combined with new real-time sensing technologies (geotechnical drilling, borehole monitoring of e.g. pore-fluid pressure and flow, or local response to seismic shaking).




# THEME 03: georesources

## Improved understanding of the subsurface

We live in a rapidly changing environment, under pressure from population growth and climate change. As governments and industry commit to reducing greenhouse gas emissions, there will be a need to switch to low-carbon alternatives for energy and transport, which will require sustainable georesources. In addition, the Intergovernmental Panel on Climate Change, and United Nations projections indicate that $CO_2$ capture and storage will be essential to limit global warming to less than 2°C.

Key questions and challenges demanding our immediate attention include:

*1.) How can we improve our understanding of and gain access to low-carbon energy sources, particularly for geothermal energy?*

*2.) What is the most reliable way to remove $CO_2$ from smokestack emissions and – more challenging – from air, and store it permanently underground, either as supercritical fluid in pore space or as solid carbonate minerals?*

*3.) What is needed to understand the processes that concentrate raw materials that are essential for low-carbon technology, especially mineral and metal resources such as lithium and cobalt that are used to make batteries?*

*4.) How to identify future water resources?*

*Iceland's Hellisheiði Geothermal Power Station*

*The Campi Flegrei caldera cluster is the largest volcanic feature along the Bay of Naples, Italy*

Each of these topics require an improved understanding of the subsurface. Thus far, relatively few drilling projects have focused in this area, but in the future this will be a vital area of ICDP's research.

### *Past accomplishments*

Geothermal energy has been an area of interest to ICDP since its start, with projects such as the Iceland Deep Drilling Project (IDDP) addressing the feasibility and economic potential of supercritical geothermal systems.

Natural processes that convert $CO_2$ to solid carbonate minerals are a key focus of the Oman Ophiolite Drilling Project. There, one borehole sampled fully carbonated mantle peridotite that formed as a result of reaction of the mantle above a subduction zone with $CO_2$-rich aqueous fluids derived from devolatilization of subducting sediments at depth. Several other holes, comprising the 'Multi-Borehole Observatory', are used to sample core and water that record ongoing uptake of dissolved $CO_2$ to form carbonate minerals from groundwater during weathering of mantle peridotite. In addition, borehole hydrophones and surface seismometers are deployed to understand the distribution of fractures formed during peridotite weathering, perhaps due to volume changes associated with hydration and carbon mineralization. Understanding natural processes holds the key to designing engineered processes that emulate natural carbon mineralization processes but at accelerated rates.

ICDP involvement in understanding of critical raw material resources will grow significantly with the Bushveld Complex Drilling Project (BCDP) in South Africa. The Bushveld Complex, the largest layered intrusion known on Earth, contains a substantial proportion of global platinum group elements, chromium and vanadium resources. The BCDP will gather existing cores, and carry out new drilling where gaps in knowledge exist, to create a complete section through the Bushveld Complex that can be studied to develop a more complete understanding of ore-forming processes.

ICDP boreholes often pass through geological units that potentially host important aquifers, yet hydrogeological research has not been part of many ICDP projects. An exception is Lake Van in Turkey, a closed saline lake with a unique climate record of 600,000 years of varved sediments, where changes in the salinity of the pore water reflect lake level changes, allowing an understanding of the hydrogeological system.

### *Fundamental questions*

Geothermal energy is arguably the most attractive of low-$CO_2$ renewable resources, yet accounts for only a few tenths of a percent of global electric power production. It is broadly distributed, has the smallest footprint of any power source, and can provide baseload renewable energy. However, at present its use is impeded by high financial risk, long development times, the high cost of drilling, and the inefficiency of converting conventional geothermal energy to electricity. Exploitation of super-hot geothermal fluid, known to be associated with magma, could solve many of these problems and lift geothermal to the energy conversion efficiency of fossil fuel-fired sources (e.g. Krafla drilling initiative). Geothermal drilling has penetrated the geothermal/magma boundary multiple times but only by accident, so relatively little has been learned about this critical but unexplored crustal regime. These accidents have, however, demonstrated both drilling feasibility and an order-of-magnitude increase in thermal power output per well. Understanding such super-hot geothermal regimes is a major open question for ICDP.

There are several geologically significant, open questions regarding the potential use of engineered carbon mineralization for greenhouse gas mitigation. One choice lying ahead is whether to focus on (1) surficial weathering, of mine tailings and perhaps comminuted rock that is quarried and ground for the specific purpose of $CO_2$ removal from air, or (2) in-situ processes in which $CO_2$-bearing fluids are circulated through reactive rocks in the subsurface. Both have their merits and impacts. If in-situ processes are to succeed, a second open question is how to maintain open porosity and permeability during crystallization of carbonate minerals and other reaction products in pore space. One can pose this second question in terms of 'clogging' versus 'cracking', with the latter process – a positive feedback ensuring continued fluid flow and access to fresh mineral surfaces – arising from volume changes through fluid consumption, increasing solid mass, and decreasing solid density. What inputs or ambient conditions favor the positive feedback regime? Experimental and field studies should be designed to address this question.

The switch away from fossil fuels towards renewable and low-carbon energy sources brings with it a tremendous need for raw materials. Many of these are termed 'critical raw materials' because they are currently only produced in a small number of countries, and significant increases in demand are forecast. Whereas the mineral systems for major metals such as gold and copper are well understood, there is a pressing need for the scientific community to develop better geological models for deposits of critical raw materials such as lithium, cobalt and nickel (for batteries), the rare earth elements (for electric motors and wind turbines) and tellurium (for solar panels). Many deposits are under cover, and so drilling is essential to understand their genesis. Where exploration companies focus only on grade, scientific drilling can ad-

*Iceland's Myvatn geothermal area*

dress broader questions to develop comprehensive mineral deposit models and system understanding.

Water, arguably the most essential natural resource, is not the focus of most ICDP drilling projects, although pore water in the retrieved cores contains important information on geology, geomicrobiology, and the water cycle. Where relevant, hydrogeological investigations of aquifers and their water resources have the potential to be important secondary targets for ICDP projects, in many cases also of direct societal relevance.

### *Future scientific targets*

Understanding georesources for a low-carbon future will be a powerful driver for science over the coming years. Further development of ICDP links with the geothermal industry and joint project development could underpin scientific exploration of magma-geothermal coupling, combined with needed engineering and technological development. Such a project would equally benefit green energy, fundamental magma and crust-formation science, and reliable volcano monitoring.

*Alkaline spring in travertine of the Oman ophiolite*

With regard to carbon mineralization, and/or geological storage of $CO_2$, ICDP could develop pilot experiments at key localities, similar to the ongoing CarbFix Project in Iceland, and the past Wallula Project in Washington State, USA. Also, related use of injected $CO_2$ for enhanced oil recovery is an economically viable, expanding technology with significant industry resources. In contrast, past studies of engineered, subsurface carbon mineralization are rare. ICDP could make a significant contribution with future emphasis on carbon mineralization in mantle peridotite and basaltic lavas, particularly at and near the coastline where water is readily available as a $CO_2$-transport fluid. There is considerable room for synergy between this kind of study and investigations of enhanced geothermal systems, both of which involve circulation of water and/or supercritical $CO_2$ through high temperature, subsurface porosity.

In the area of critical raw materials, there are fundamental scientific questions that can be addressed by ICDP. Many of these elements are only mined in the top few hundred meters of the crust, but ICDP can drill deeper to investigate the processes at depth that are vital for formation of ore deposits. Elements such as lithium, cobalt, nickel and the rare earth elements are typically concentrated by magmatic-hydrothermal processes such as partial melting, fractional crystallization, liquid immiscibility and hydrothermal alteration/deposition. Drilling offers an opportunity to target these processes directly by investigating deeper parts of such systems, in order to build up models for the wider mineral system.

Overall, it is evident that ICDP can contribute significantly to understanding modern and fossil magmatic-hydrothermal systems, studying the role of fluid-rock interaction in creating geothermal circulation, and in generating mineralization that both locks up $CO_2$ and concentrates metals. A particularly exciting opportunity for ICDP would involve bringing all these scientific communities together to investigate all the interactions within such systems.


# THEME 04: *environmental* change

## Continental drilling: sedimentary archives telling us how Earth evolved

During the past 4.5 billion years, Earth has undergone tremendous changes in internal composition, degree of differentiation, and surface processes. Life took hold early, quickly caused significant effects on Earth's surface parameters, and continues to control many physical and chemical aspects of the planet. The Earth's climate evolved through various stages with changes that sometimes occurred gradually and at other times abruptly, caused by natural variations in $CO_2$ levels associated with biogeochemical cycles and incoming solar radiation modulated by orbital variations. Human civilization thrived in the most recent warm period, but as we enter the Anthropocene, a single species began to alter the global climate significantly for the first time in Earth's history, thus causing numerous challenges for future generations.

Records of the interactions between Earth's internal processes with the biosphere and with physico-chemical earth-surface processes throughout the entire earth history are stored in sediments - they hold the key to understanding how past and future environmental change did and will continue to alter the Earth's surface.

Key questions and challenges demanding our immediate attention include:

*1.) What can we learn from past 'greenhouse' conditions in Earth's climate to better anticipate future changes in the hydrological cycle?*

*2.) What is the role of the subsurface biosphere in controlling biochemical fluxes and carbon cycling?*

*3.) How was hominid dispersal pushed or pulled by environmental change along the migration paths from origin to destinations?*

*4.) How do Archean rocks archive deep-time earth-surface processes and their interactions with an early atmosphere?*

*Dead Sea Deep Drilling Project in Israel (DSDDP)*

Answering questions about the environments in which the earliest life forms on Earth lived and spread is relevant, both because Archean strata provide a blueprint for our exploration strategies on Mars and other planets and because Archean strata demonstrate the obstacles and hindrances which early life faced on a hot, tectonically dynamic Earth. They also indicate bio-signatures that may be promising when analyzing the spectra of exoplanets for life.

Today's continents preserve invaluable strata that recorded critical processes relevant in the various states of Earth's past environment. To unravel the last ca. 200 million years of Earth history, ocean-drilling targets complement continental archives in exploiting environmental change; a land-to-sea combination provides seamless knowledge of environmental processes across the critical continent-ocean transition. For time windows exceeding the age of in-situ oceanic crust, only continental drilling can recover the sedimentary archives that tell us how Earth evolved.

### *Past accomplishments*

Many ICDP projects have addressed a multitude of scientific objectives that rely on analysis of sedimentary drill cores. The strata addressed in these drilling projects range from sediments deposited deep in time all the way to modern lacustrine basins providing new insights into Plio-Quaternary environmental changes. To unravel more recent Earth history from lake basins, in 1998 ICDP developed the GLAD lake drilling system, which was later followed by the Deep Lake Drilling System (DLDS). Their utilization has been enormously successful, as the community has been able to drill ~20 lakes and paleolakes on 5 different continents.

These projects focused on paleoclimate records of the mid- to late Pleistocene and have provided some of the first records of rainfall, temperature, and terrestrial ecosystems extending beyond the last ice age. These records have opened new windows on late Quaternary orbital-scale climate variations, such as the relationships

*Fish fossil found in lake sediments from drill core within the Bosumtwi impact structure in Ghana*

between changes in the Earth's orbit and low-latitude tropical 'megadroughts' and Arctic 'superinterglacials' extending our understanding of the response and sensitivity of Earth's climate to global forcing.

As an example of such a lake-drilling project, the Dead Sea Deep Drilling Project (DSDDP) in Israel successfully advanced knowledge in paleoclimate, tectonics and subsurface biosphere and combined these aspects in an interdisciplinary approach. After years of exploration of the exposed lacustrine strata at the marginal terraces of the lake, an international deep drilling project was performed by ICDP in 2010/2011 with the aim to recover a continuous core from the deepest zone in the Dead Sea to fill the gaps in the marginal exposures. The longest individual core sequence recovered, reaching 455 m sediment depth (750 m below present-day Dead Sea lake level; 1,177 m below sea level) covers the past 220,000 years.

### *Fundamental questions*

In the coming decades, climate change will severely stress humans and their infrastructure through profound changes in the temperature and the water cycle. Nearly two-thirds of the world's population already has to cope with water scarcity for all or part of the year. Understanding past climate regimes is an essential task in understanding these upcoming climate changes.

As our climate warms in the future, both theory and models predict that, at the global scale, high-precipitation regions should receive more rainfall, and dry regions less. However, it is not clear that this 'wet-get-wetter' prediction will hold over land. Moreover, the scant paleoclimate records that do exist for 'hothouse' high-$CO_2$ Earth conditions suggest that precipitation changes during warm intervals. Although recent advances in climate modeling have begun to heal this mismatch, we do not yet fully understand the rates or governing mechanisms of these changes.

Given the importance of water to human well-being, a critical task for the ICDP community will be to provide reliable and societally-relevant information about past changes in hydrology via a strategically distributed network of high-resolution reconstructions, with a particular emphasis on past warm periods. On a longer time scale, Earth's climate has varied from intervals of warm, ice-free 'greenhouse' conditions associated with high atmospheric $CO_2$ (>3 times preanthropogenic levels) to icehouse intervals with low $CO_2$ and continental-scale ice sheets at one or both poles. The human trajectory of atmospheric $CO_2$ release is projected to soon reach levels that Earth has not experienced at any point in the last 3 million years. Earth's climate operated in a different mode during these green-house worlds, with conversion of the Earth's deserts to savannahs, with widespread intervals of ocean anoxia documented by Ocean Anoxic Events, ocean acidification, and algal blooms. These warmer time intervals provide a means to evaluate the operation of Earth's coupled ocean-atmosphere-biosphere system under atmospheric $CO_2$ concentrations that may be reached in this century under 'business as usual' scenarios, and the response of ecosystems to intervals of climate much warmer than experienced during the rise of human civilization.

Ocean drilling has provided regionally distributed records of the ocean during some of the more recent intervals of warm climate (Pliocene to Late Cretaceous), but concerted sampling targets on the continents are required to sample not only the continental record of climate change but also the record of ancient oceans missing or poorly represented in the seafloor sediment record but available on land.

Scientific investigations of high-resolution sediment records from lakes and continental basin systems are among the best approaches to determine the history of continental climate change at adequate spatial and temporal scales to be relevant to current and future societies. Continents are

*The Towuti Drilling Project (TDP) recovering long sediment cores from Lake Towuti, on the island of Sulawesi, Indonesia*

*Lake Van in Turkey, a closed saline lake with freshwater potential provides insight into precipitation history and the hydrogeological system*

expected to warm more dramatically than the oceans in response to greenhouse-gas forcing; our inability to test this prediction is largely due to a lack of high-quality continental records during hothouse intervals.

Humans are unquestionably playing a major role in shaping modern ecosystems and environments, but deeper time records are essential to understand the extent of human impacts and the role that environmental change has played in shaping human history. In particular, the scientific community still lacks long, continuous continental records of African paleoenvironmental evolution spanning the full history of hominid evolution from late Miocene to present. Such records are essential to understand the relationship between environmental change and human evolution as they will allow tests of the linkages between climate trends and variability, terrestrial habitat expansion, contraction, fragmentation, and rift tectonic events against the numerous evolutionary transitions in the hominin fossil record.

A network of shorter, Pleistocene records could also unravel the influence of climate change on human dispersals, and in particular whether humans were 'pushed' from tropical Africa by arid conditions or drawn out of Africa by more favorable conditions in the near East. Understanding the role of environmental change in these migrations could provide insight into human dispersals in the archaeological record more broadly.

Future environmental change will strongly alter the 'critical zone', the permeable near-surface layer from the tops of the trees to the bottom of the groundwater. Scientific drilling can help to understand the past and current dynamics of this zone: it is to date unclear how changes in this zone affect surface processes, landscape evolution, chemical and physical weathering processes and the related biogeochemical cycles. Drilling can even go beyond this zone to investigate the entire deep continental biosphere, which contains an estimated 2–20% of the biomass on Earth, mostly in the form of microorganisms.

During the time of Earth's evolution, when a protective ozone layer was still missing, life could only survive and develop in places that were protected from the sun's deep-UV ionizing radiation, i.e. beneath the ocean surface or the shallow continental subsurface. It is possible that traces of these ancient life forms may still be seen as lineages branching early from the universal tree of life.

Microorganisms may also travel to the deep subsurface with slowly diffusing or percolating ground water, rapidly deposited sediments or advective transport of water due to seismic events or geothermal convection. With the emergence of oxygenic photosynthesis, surface life proliferated and provided a source of reduced carbon and nitrogen to the shallow subsurface. By comparison, the deep subsurface is generally lacking energy and nutrient sources, forcing the deep biosphere into a mode of slow-life. Thus, microorganisms originating from surface ecosystems adapt to the subsurface by metabolically slowing down, and the deep biosphere could represent a living record of earlier life on Earth. Up to now, ICDP drilling projects investigated the magnitude and impact of microorganisms during early diagenesis through analyzing both sediments and biological remains. Moreover, bio-signatures of former and current microbial activity recorded in the sediments as well as their impact on biogeochemical cycles were identified.

Many open questions can be resolved by ICDP drilling: How the diversity and activity of microbial life varies with depth, geochemistry, sediment composition and age and how the diversity of active and non-active microbes relate across the lacustrine basin at given time slices are important questions. Two other fundamental questions concern how microbes resolve the paucity of nutrients and energy, and what are the limits of subsurface life in lakes under contrasting physicochemical conditions. Once buried, microbes may first slow down their metabolism if the conditions are not favorable. In general, we do not yet know how the evolution of life works in the deep sub-surface and whether it is as stable as it has been assumed to be. Is the deep biosphere the next horn-of-plenty for novel biochemical solutions to global climate change, carbon cycling and capture, energy conversion, medicine? Can the deep biosphere give answers to astrobiological questions, such as 'Is there life on Mars?'

*Calcite crystals of microbial origin*

*The Continental Scientific Drilling Project of Cretaceous Songliao Basin (SBDP) reached 7018 m depth with a newly designed drill rig and recovered up to 40 m long cores of more than 20 cm diameter. The core samples allow the unravelling of the climate and environmental evolution of the entire Cretaceous period.*

### *Future scientific targets*

ICDP is well poised to implement multiple projects to address the stated paleoenvironmental critical issues, with at least ten projects in various stages of development to investigate critical time intervals such as Mio-Pliocene warming, the Paleocene-Eocene Thermal Maximum, and, more generally, the Cenozoic.

Deeper in time, the Barberton Archean Surface Environments project (BASE) will explore Archean sedimentary rocks of the 3.2 billion years old Moodies Group of the Barberton Greenstone Belt in South Africa. Drill cores will allow us to reconstruct past environmental parameters, ranging from the weathering regime to the tidal range and the meteorite impact flux rate. These data will shed new light on early Archean global surface conditions including redox state, temperature and composition of ocean water, early diagenetic fluids, and the atmosphere. Future drilling initiatives will emphasize the marine-terrestrial link by targeting the ocean-continent transitions in a series of amphibious drilling programs. They will recover records representing this critical zone characterized by high gradients in many paleoenvironmental variables.

# how to *realize an* icdp project

## Partnership & Cooperations

International groups of scientists with a project idea of far-reaching societal relevance that requires continental drilling can apply for funding through ICDP. In order to minimize the proposal writing workload ICDP offers to review the scientific relevance of initial ideas through a so-called pre-proposal. If positively assessed by ICDP’s scientific review panel, the Science Advisory Group (SAG), proponents are invited to submit a workshop proposal. This will entail a further detailed scientific justification, basic site survey, draft plans for drilling location and depth, as well as a kernel of an international scientific team. The ICDP-funded workshop then serves to broaden the thematic spectrum and participation, and form an international team of leading experts in the respective field that prepares a full proposal to ICDP. Full proposals include detailed plans for drilling, science, costs, budget and management. For these demanding tasks the projects can rely

**ASSEMBLY OF GOVERNORS (AOG)**

main oversight and governing body with delegates from funding agencies of ICDP member countries.

**EXECUTIVE COMMITTEE (EC)**

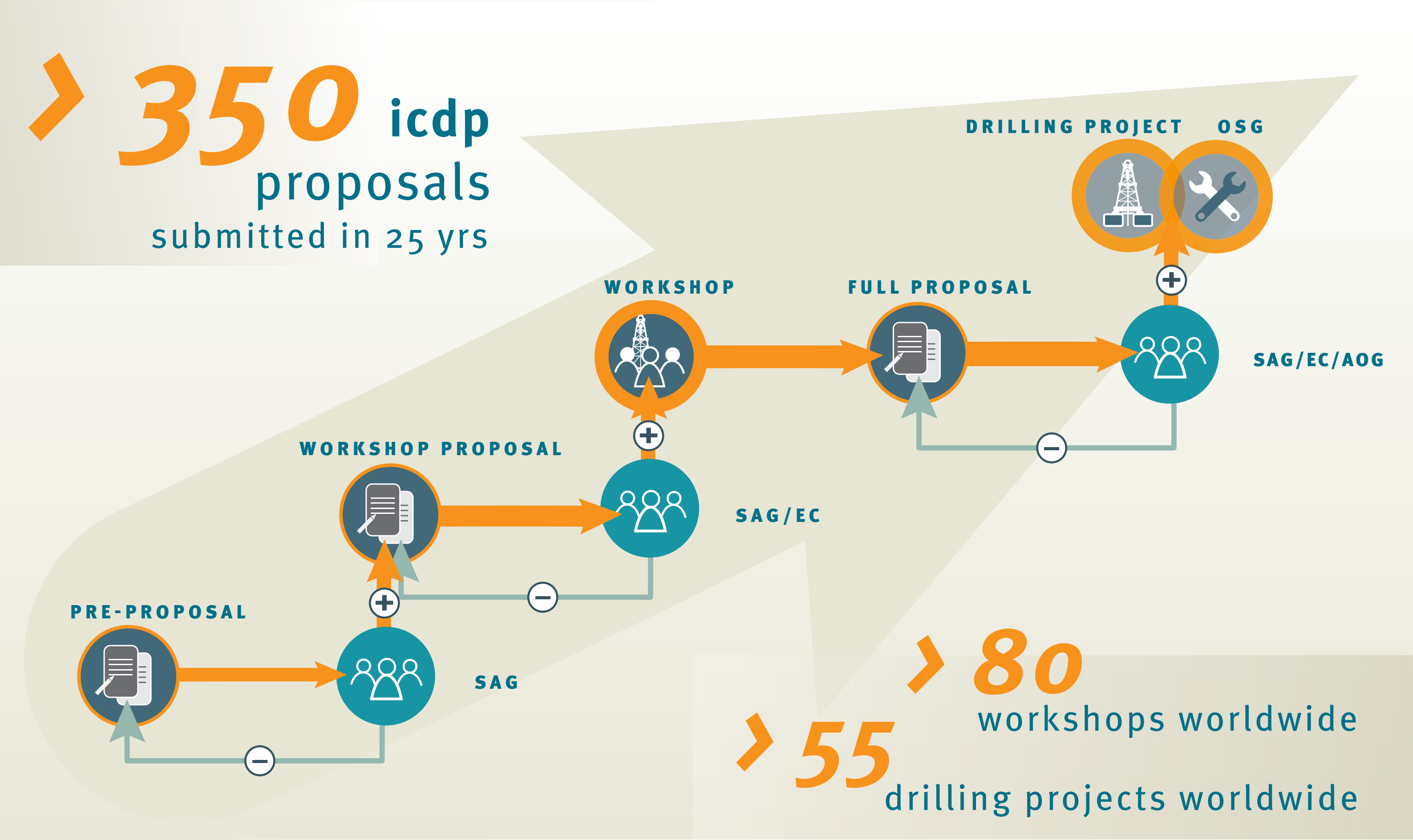
panel for the operational management with science managers from ICDP member countries.

**SCIENCE ADVISORY GROUP (SAG)**

ICDPs panel for in-depth scientific evaluation of proposals with experts nominated based on scientific qualification.

**OPERATIONAL SUPPORT GROUP (OSG)**

ICDP´s group of experts in all drilling-related disciplines that assist PIs to develop proposals, to plan and execute drilling projects.



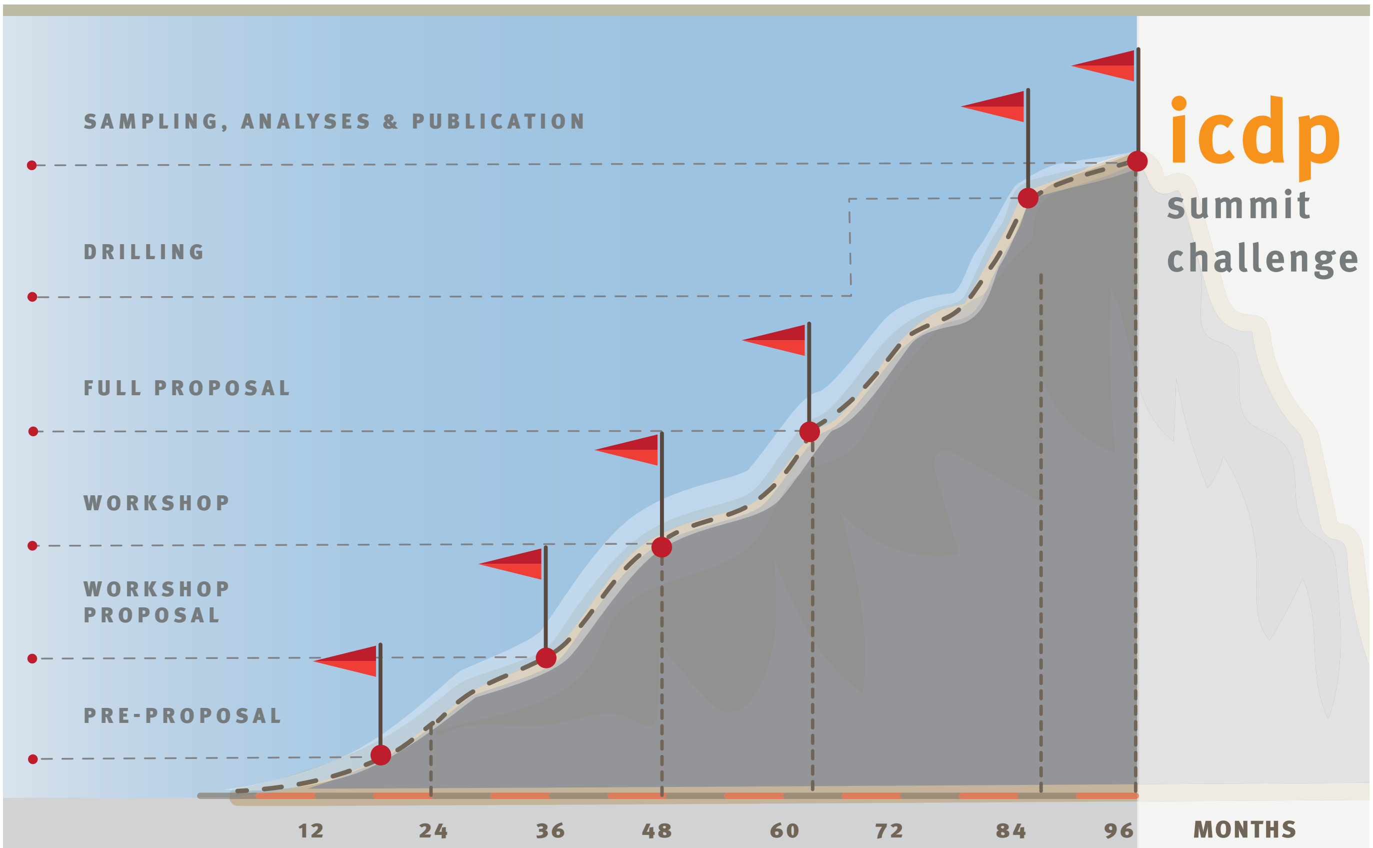

*Development of projects in the framework of ICDP* on support from the Operational Support Group (OSG) that is based at GFZ Potsdam, Germany.

Once a full proposal is approved by ICDP and the co-funding organizations, the Principal Investigators prepare the implementation of the project. Permitting at authorities and contracting all necessary services such as drilling, together with the detailed planning of on-site and laboratory science work, is supported by respective experts from OSG if needed. Experience gained in predecessor projects is made available to plan and conduct drilling, sampling, measuring and also to coordinate the publication of papers and data in scientific journals as well as the long-term curation of samples and scientific data.


*ICDP best practice brochure for scientific drilling*

## icdp *Primer*:

The Operational Support Group (OSG) provides a regularly updated primer on key topics in planning and conducting scientific drilling projects. It serves as a best practice reference for those who tackle a continental scientific drilling project for the first time.




*Lifetime of ICDP projects depicting mean duration of achieving milestones in project execution*

# land to sea *(L2S) drilling* transects

**A successful breakthrough**

ICDP and its offshore sibling, the International Ocean Discovery Program (IODP 2013-2023), bring together more than 25 countries. Despite targeting two distinct geographical domains on Earth, scientific continental and ocean drilling are strongly aligned in their scientific objectives by having access to critical geological records attainable only by sustained and innovative drilling strategies. Through concerted efforts in land-to-sea (L2S) drilling we can make major scientific breakthroughs in several challenges to humankind, most of which are documented in the science plans of both programs. Combined scientific land and ocean drilling will emphasize transects from the ocean basins onto the continents, in research areas near and along coastlines, enabling innovative collaborative drilling campaigns from land to sea.

Common science goals position us to assemble the most comprehensive and fully integrated knowledge base of Earth's paleoclimate with an eye on projected future climate and environmental changes from both the terrestrial and oceanic archives. Other scientific frontiers require a combined focus to improve our understanding of the interplay between fresh water and seawater along coastlines, the transition between continental and oceanic crust, and the formation of sustainable georesources from microbial life, volcanoes, and related element cycles. ICDP and IODP together can furnish a more holistic assessment of natural hazards from earthquakes to tsunamis to explosive volcanism, while deepening our fundamental knowledge of how the Earth system recovers following meteorite impacts or the emplacement of large-scale igneous provinces on land or in the oceans. To advance allied science objectives, both programs will strengthen the collaboration in L2S drilling campaigns to explore the interconnected Earth system along transects from active and passive continental margins onto land.

As an example, precise knowledge of active and passive plate margins, their structural transition from on-shore


*Core on deck on a purpose-designed geotechnical vessel equipped with a permanent drilling rig*


*Busy on the drilling rig platform during an offshore phase of an IODP Expedition*

to off-shore, and associated magmatic and sedimentary budget will illuminate formational processes and timescales of these important, often nutrient-rich, environments. In addition, the correlation of submarine and terrestrial stratigraphy is crucial for assessing global budgets, especially the ‘carbon cycle’, as these regions can host important carbon reservoirs and be suitable for the sequestration of $CO_2$. Also, global sea level changes not only directly impact coastal communities, they also affect the stability of methane hydrate reservoirs on continental shelves, with potentially devastating consequences for the ‘carbon cycle’ and Earth’s ‘climate factory’. These examples stress that L2S studies are crucial to tackle key challenges for humankind considering that about 40% of the world population lives less than 100 km from the coastlines.

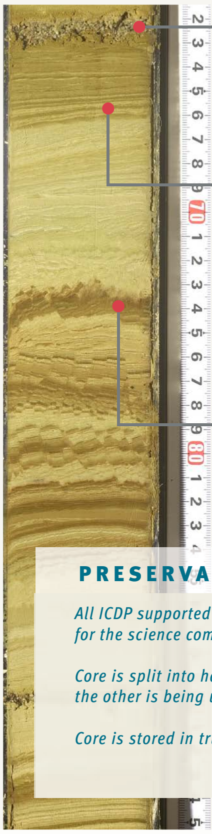
Future plans for both scientific ocean drilling and continental drilling emphasize the need to consider planet Earth as an interconnected and dynamic system, taking into account the coupling between deep Earth processes and their short timescale geological, environmental, economic, and societal effects. The new focus on interconnections requires reinforcing collaborations between ocean and continental drilling, and the development of integrated L2S campaigns when the science requires crossing these boundaries. Like the scientific problems that span from land to sea, our investigations must do the same.

# a look *ahead*

Continental scientific drilling has never been more important than today. Urgent societal challenges and questions, such as how to sustain human progress without causing further environmental degradation, how to reduce society's vulnerability to natural hazards, and how to satisfy its dependence on natural resources sustainably call for answers that valuable core material can deliver.

Strengthening international cooperation and coordination towards delivering world-leading science and to ensure broad acceptance and cost-efficient operation of the program and the funded projects – this is where the **International Continental Scientific Drilling Program, ICDP,** is aiming in the near future.

### VALUE OF CORE



**VOLCANIC ASHES**

*Volcanic ashes provide history of volcanism and age dating*

**SEDIMENTS**

*Annually laminated sediments show climate and environmental conditions over time; pollen show vegetation in the lake catchment, chemistry shows sediment and fluid flux, evaporation and productivity to reconstruct dry-wet or cold-warm periods*

**MICROFAULTS**

*Seismic-induced microfaults show earthquake events and frequency*

### PRESERVATION OF CORE

*All ICDP supported samples are preserved and long-term available for the science community*

*Core is split into halves, one remains intact as archive half while the other is being used for sampling for scientific investigation*

*Core is stored in trusted repositories and accessible for sampling*

*A split core of sediments, volcanic ashes and earthquake-induced faulting shows the value of core from Lake Van in Turkey*

# icdp cores: *4 billion years of Earth history*

*Core Samples from Outokumpu, Finland*

# icdp infos

# & references

*Find further information on ICDP at:*
**www.icdp-online.org**

*ICDP media for press, public and science:*
**www.icdp-online.org/media**

*For a digital version of the ICDP Science Plan:*
**https://www.icdp-online.org/media/icdp-science-plan/**

*ICDP on social media:*
**Twitter: icdpDrilling**
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*Links to ICDP members and funding agencies:*
**www.icdp-online.org/members**

The products of each of the ICDP funded projects comprise scientific samples, data and publications. ICDP is taking care to make this legacy available for future scientific investigations through partnerships with trusted core repositories. Data and publications for each individual project can be found on our website at:
**www.icdp-online.org/projects**

*Core and other sample materials of ICDP projects online:*
**www.icdp-online.org/facts/project-facts/by-tables/repositories/**

**All images by ICDP except:**

**p07 top:** Impact crater (Francesco Ungaro, Pexels)
**p08 below:** Students standing on the Moho, the discontinuity marking the transition from the Earth's crust to the mantle (© Geoverbund ABC/J)
**p09 top:** The scientific drilling project COSC provides unique insight into the roots of a Himalayan-type orogeny (COSC)
**p10 below:** The Ediacaran-Cambrian transition in Namibia, one of the main targets of GRIND (A. Prave)
**p11 top:** Posing with a 3 m core at 185 meters in Namibia (GRIND)
**p12 below:** Geohazards: volcanic eruptions, mass movements, such as land slides, earthquakes and impact craters ( J. Feignon, I Putu Krishna Wijaya, GFZ Potsdam, C. Koeberl)
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**p15 top:** Landslide triggered from the Kumamoto earthquake (picture alliance / AP Photo)
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**p19 top:** Alkaline spring in travertine of the Oman ophiolite (Oman Science Team)
**p21 top:** Fish fossil in drill core from lake sediments in Bosumtwi impact crater, Ghana, at section break of core 5B located at 240 m blf during an ICDP project in 2004 (C. Koeberl)
**p22 below:** The Towuti Drilling Project (TDP) recovering long sediment cores from Lake Towuti, on the island of Sulawesi, Indonesia (TDP)
**p23 top:** Lake Van (Turkey), a closed saline lake with freshwater potential provides insight into precipitation history and the hydrogeological system (NASA/USA)
**p24 below:** Calcite crystals of microbial origin (Henrik Drake_imaggeo.egu)
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**p29 top:** Busy on the drill rig platform during an offshore phase of an IODP Expedition (ECORD/IOPD)
**p31 below:** Drill bit seen from the end of the drill string (D. Smith, ECORD/IODP)

*Drill bit seen from the end of the drill string*

# icdp osg: *operational* *support group*

**Providing a working infrastructure**


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INTERNATIONAL CONTINENTAL
SCIENTIFIC DRILLING PROGRAM

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including contributions by the **icdp** OPERATIONAL SUPPORT GROUP

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